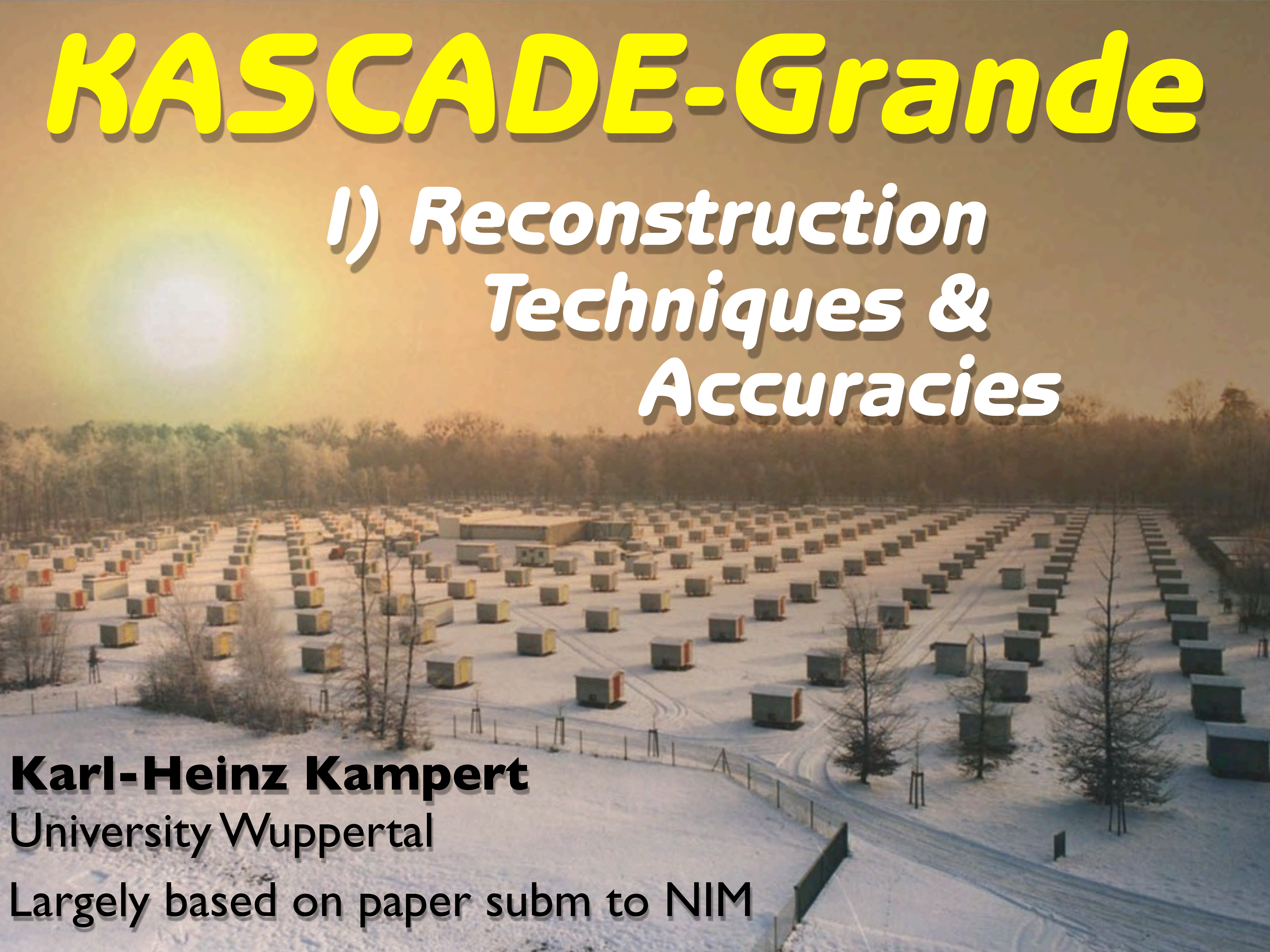
KASCADE-Grande

I) Reconstruction Techniques & Accuracies



Karl-Heinz Kampert
University Wuppertal

Largely based on paper subm to NIM

Outline

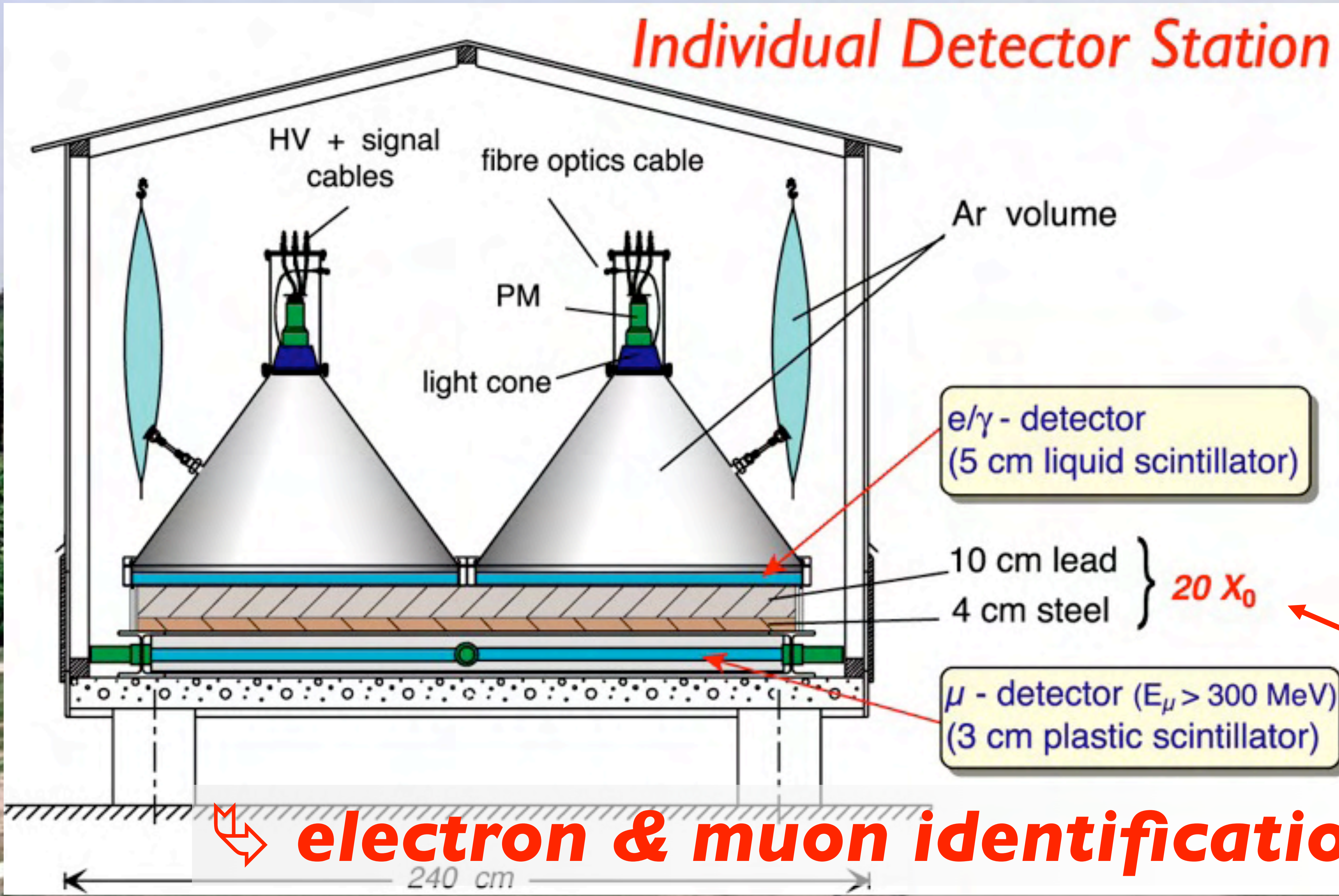
- brief reminder about basic properties of KASCADE and KASCADE-Grande
- triggers
- calibration
- from energy to particle numbers
- reconstruction method
- reconstruction efficiencies

(Karlsruhe Shower Core and Array Detector)

$\sim 5 \cdot 10^{14}$ - $\sim 5 \cdot 10^{16}$ eV

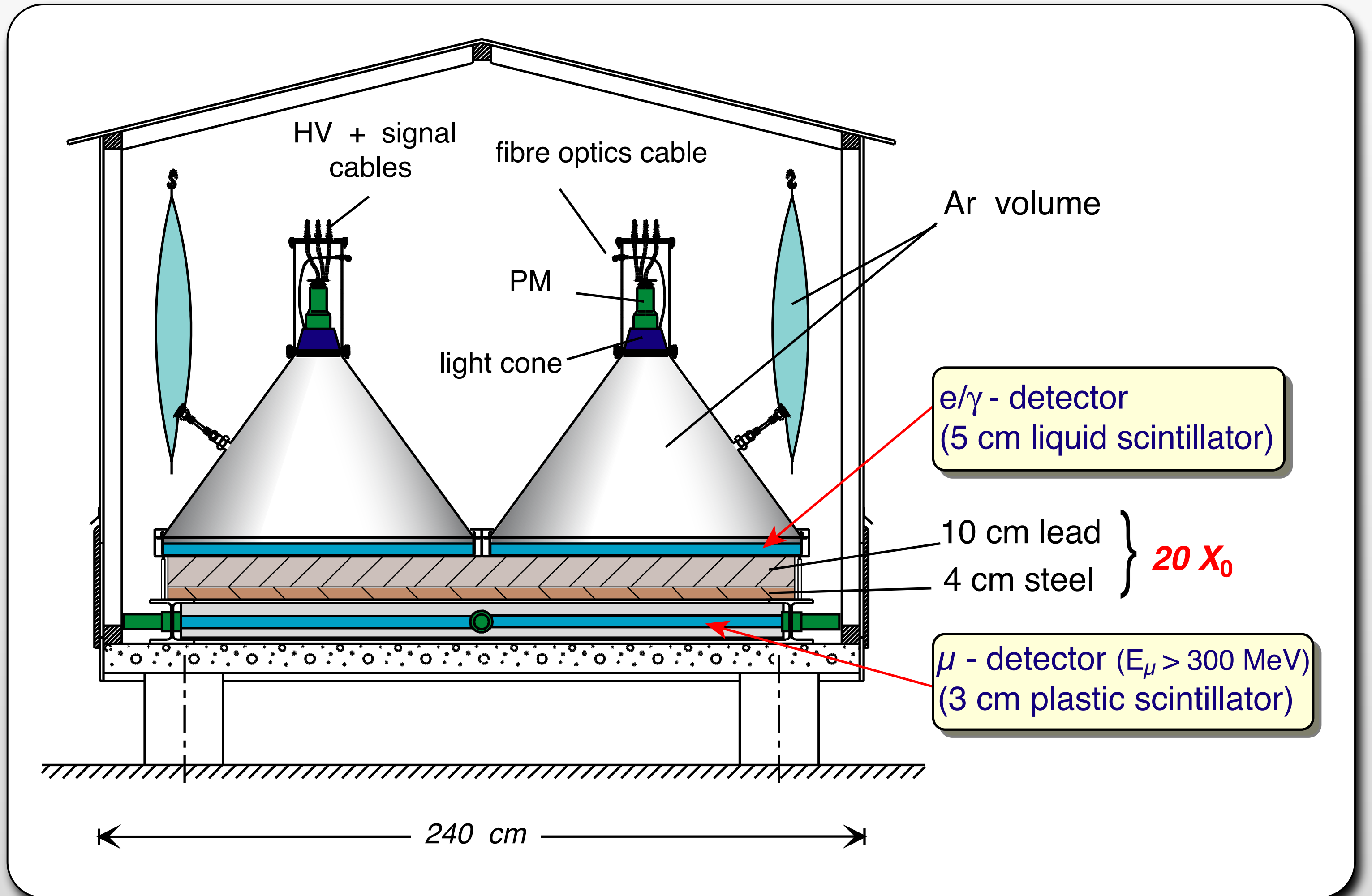
closed down 2009

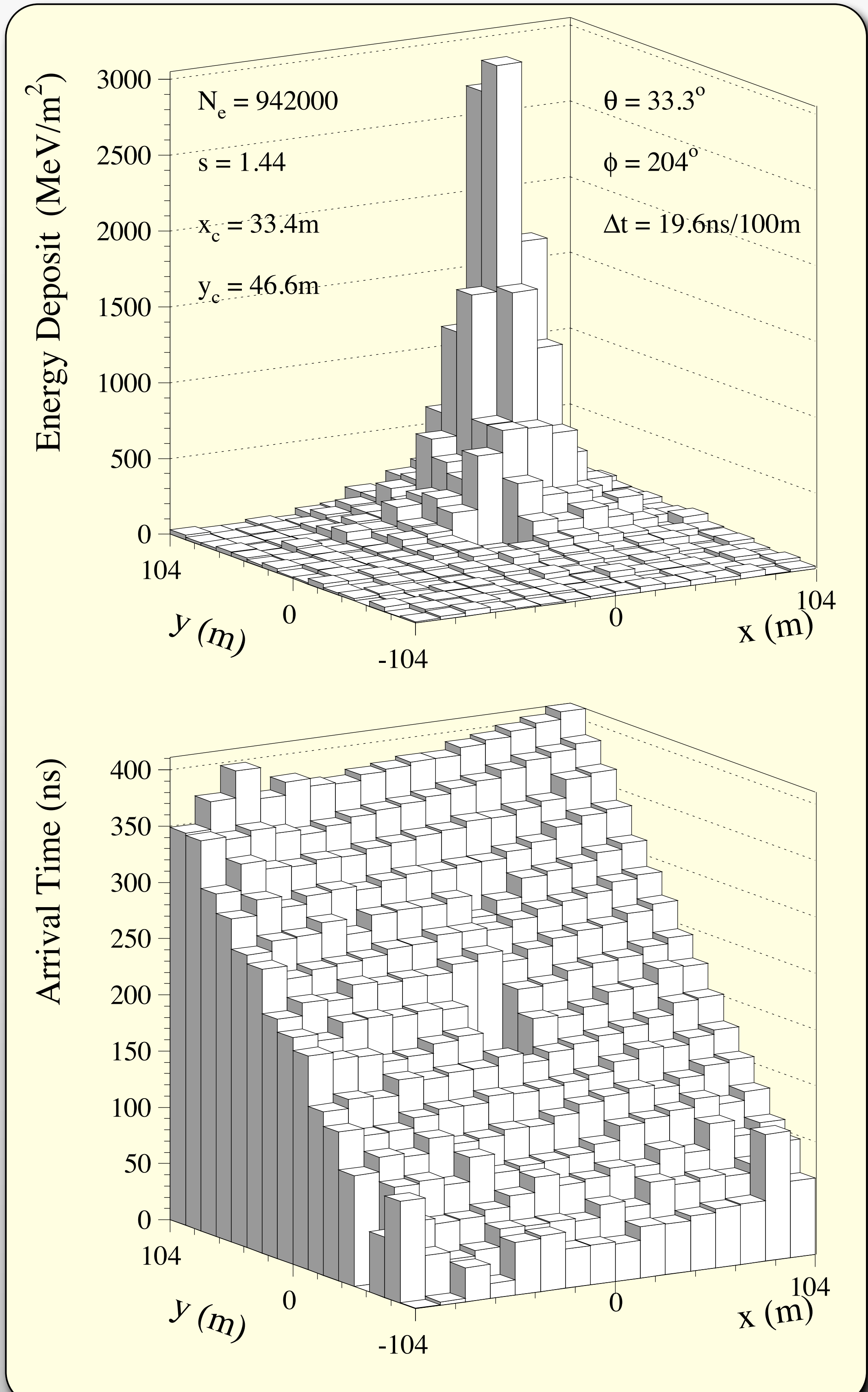
Nucl. Instr. Meth. A513 (2003) 490



⇒ electron & muon identification

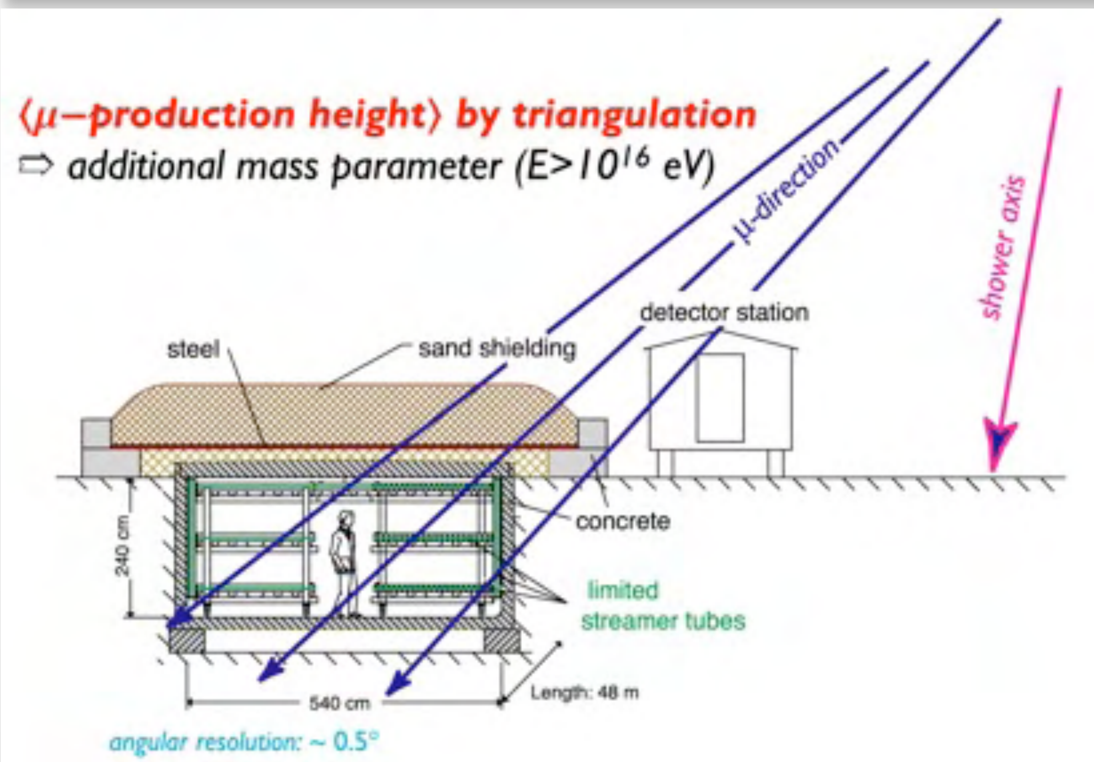
e & μ Measurements in KASCADE

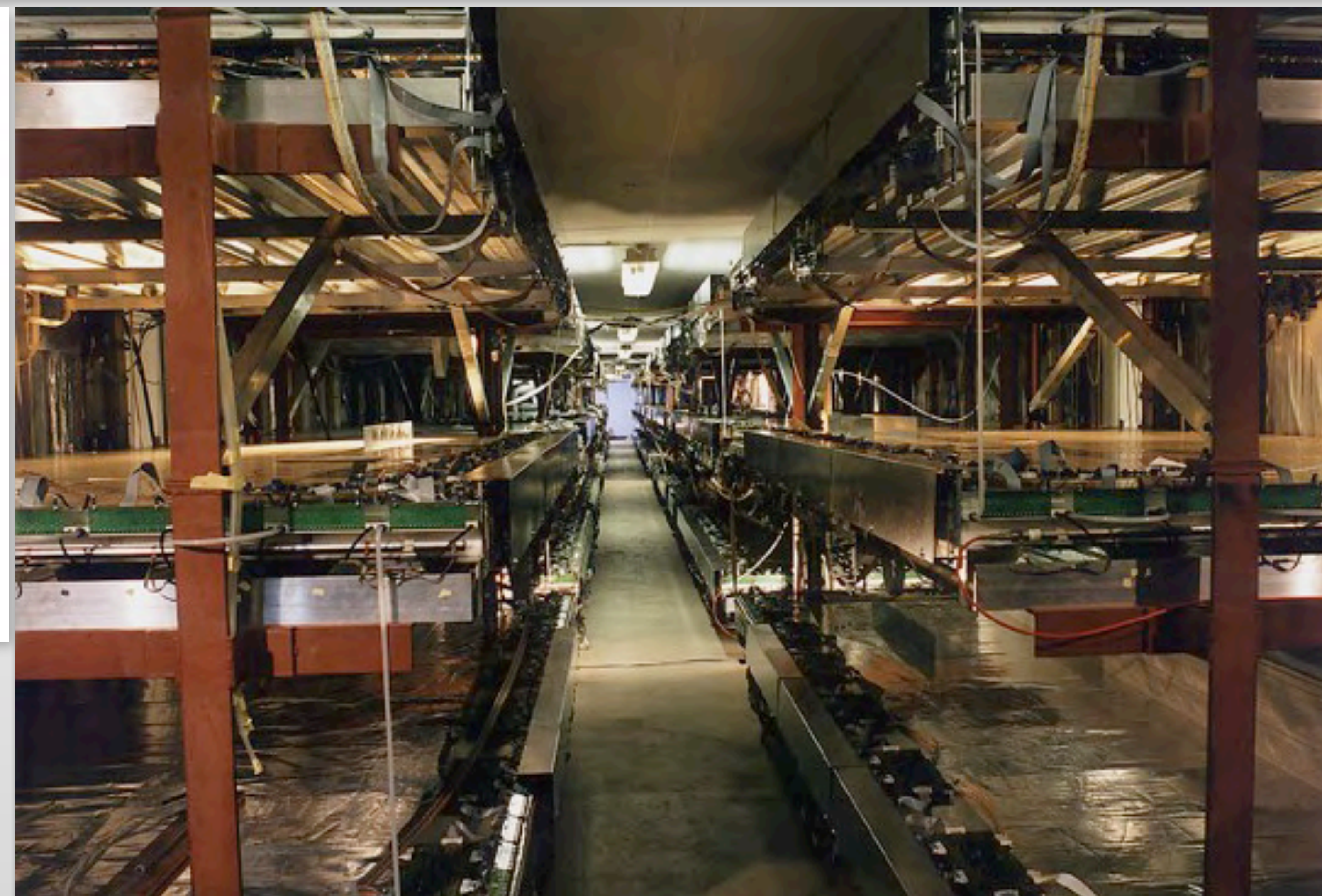




- *High quality electron and muon measurements*
- *Energy spectrum, composition, anisotropy studies*

Muon Tracking in KASCADE



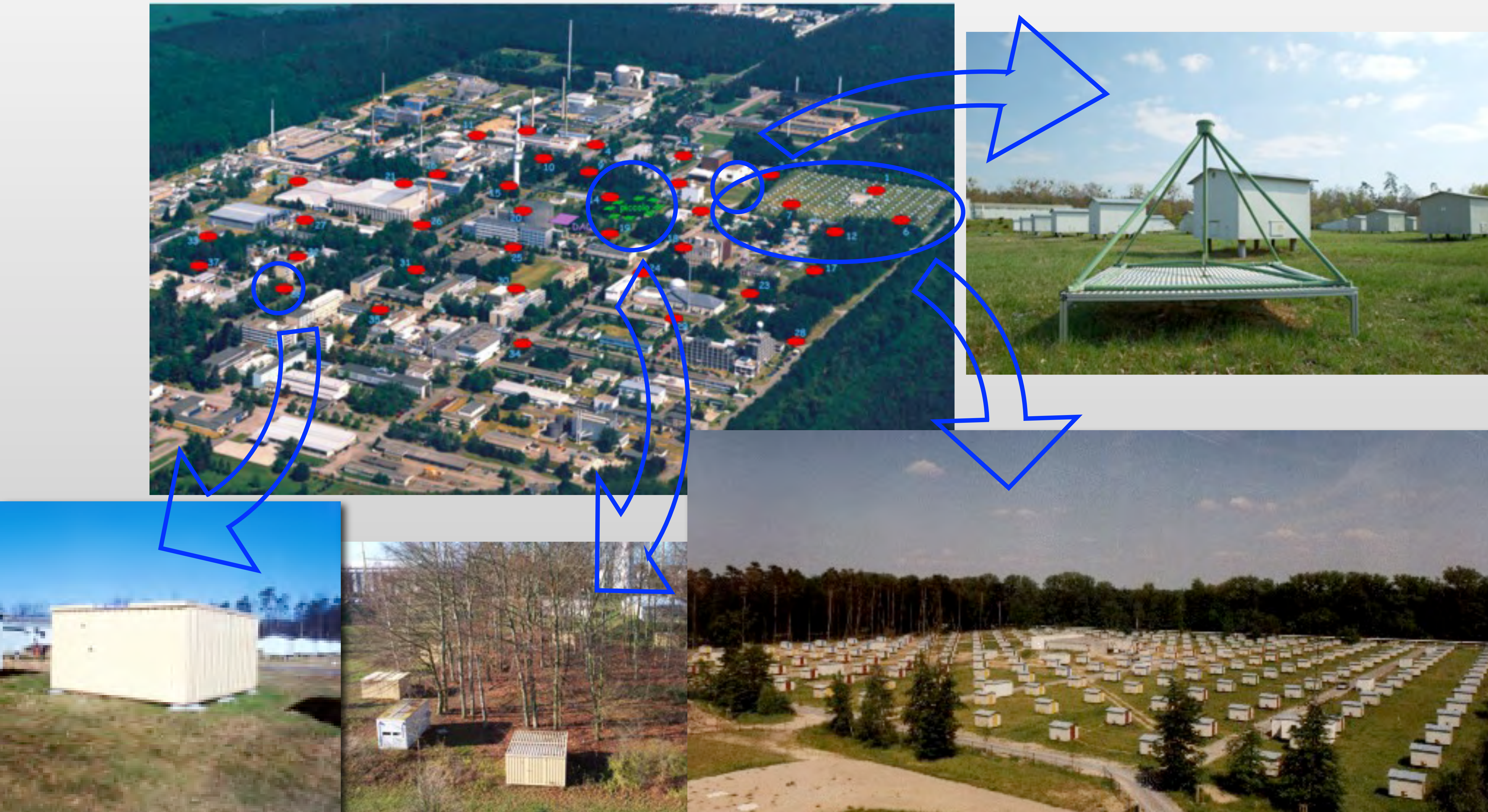


150 m^2 muon tracking
500 m^2 streamer tubes

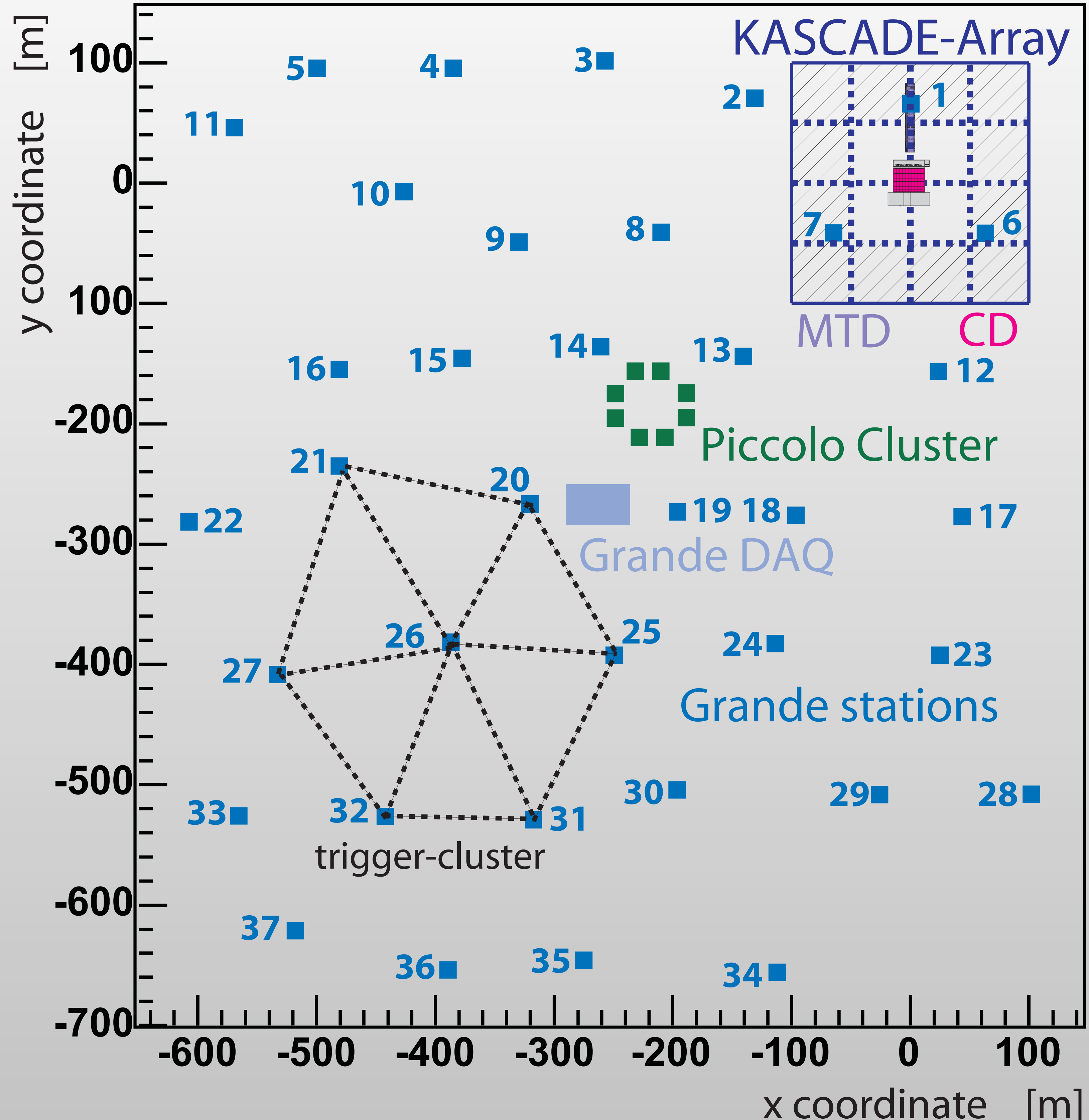
- ➥ *Measurements of muon production height,*
- ➥ *more info on composition and on hadronic interactions*

KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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



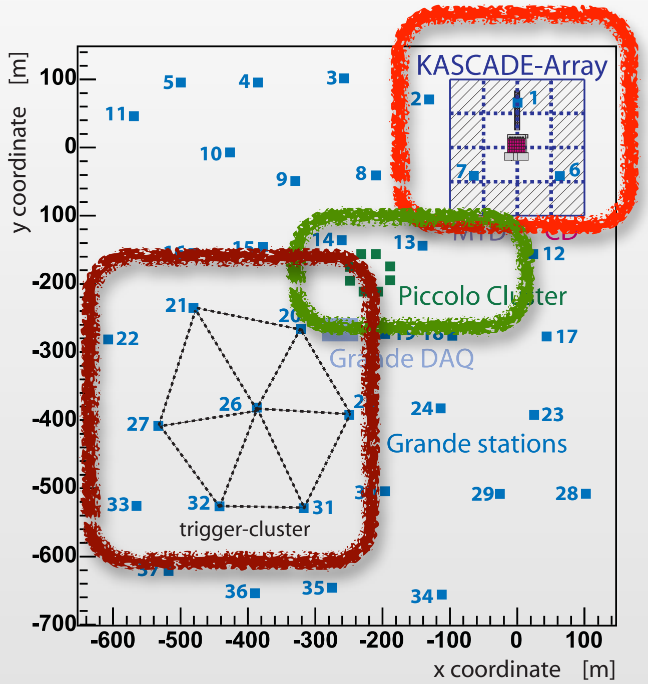
KA-Grande Layout



Some Numbers:

- ~ 0.5 km^2 area
- 252 stations of 3.2 m^2
  N_e & N_μ-counting
- 37 stations of 10 m^2
  N_{ch}-counting
- ~ 1000 m^2 μ-counting
  @ partial tracking
- hadron calorimetry

Triggers



KASCADE

- em-station multiplicity > 15/60 (inner stations)
  > 10/32 (outer stations)
- fully eff. @ $E > 8 \cdot 10^{14}$ eV
- external trg. from Piccolo and from Grande 7/7

Piccolo

- provide fast trigger to KASCADE for showers landing in Grande area
- multiplicity of ≥ 2/8 stations
- fully eff. @ $E > 10^{16}$ eV

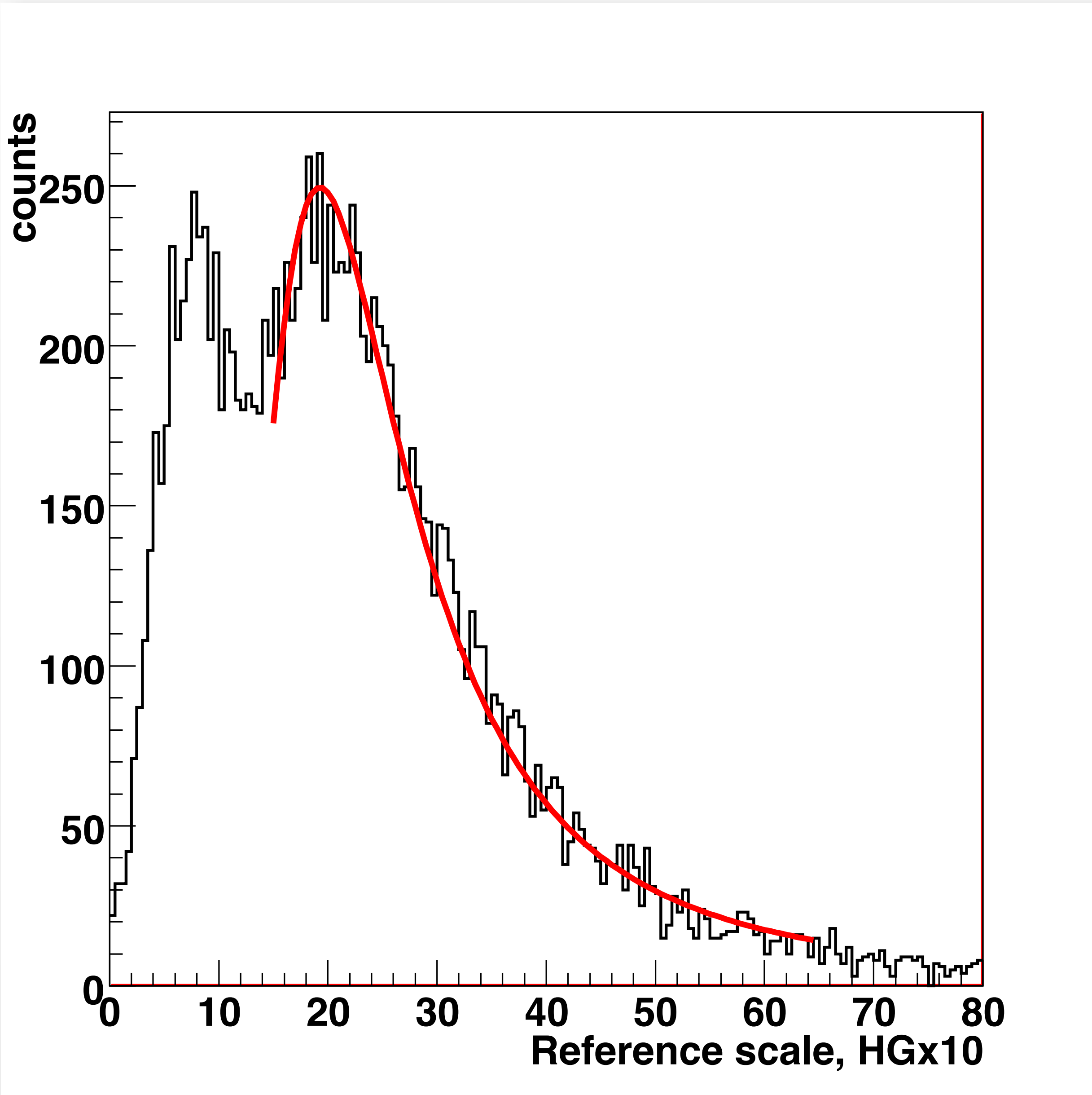
Grande

- arranged in 18 trigger clusters of 6+1 stations
- internal trigger by multiplicity within a trigger cluster > 4/7 (5 Hz)
- external trigger by KASCADE (see above, 3.5 Hz)

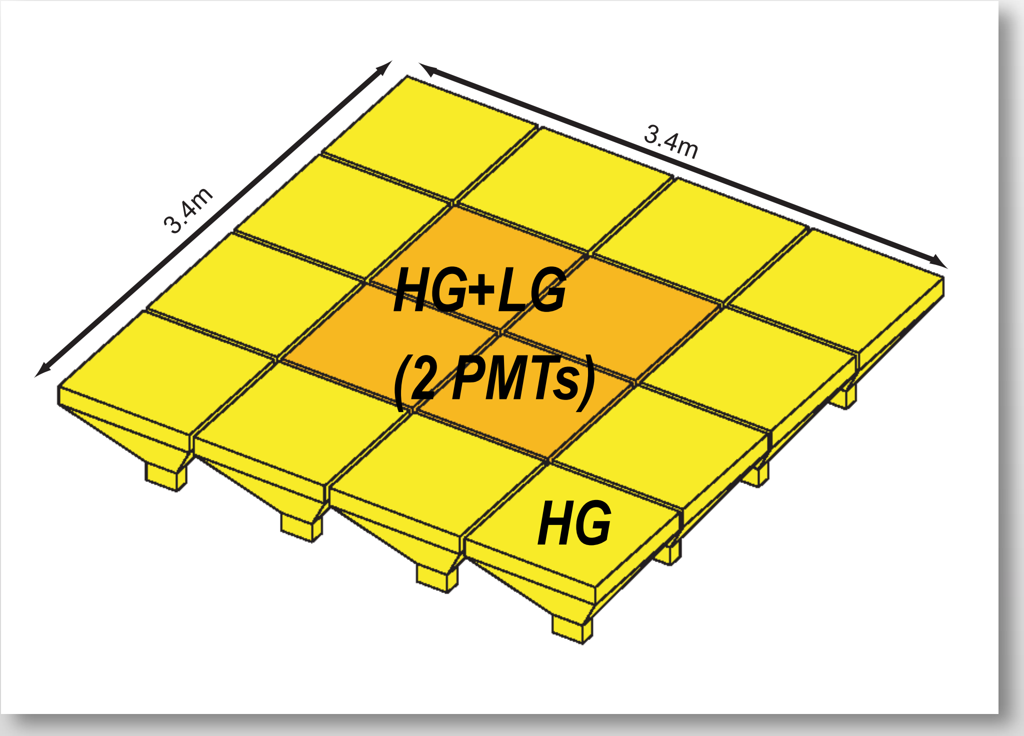
KA-Grande in Numbers

Detector	Particle	Area (m^2)	Threshold
Grande array (plastic scintillators)	charged	370	3 MeV
Piccolo array (plastic scintillators)	charged	80	3 MeV
KASCADE array (liquid scint.)	e/γ	490	5 MeV
KASCADE array (shielded pl. scint.)	μ	622	230 MeV
Muon tracking det. MTD (streamer tubes)	μ	3×128	800 MeV
Multi wire proportional chambers at CD	μ	2×129	2.4 GeV
Limited streamer tubes at CD	μ	250	2.4 GeV
Calorimeter at CD	h	9×304	10-50 GeV

Calibration

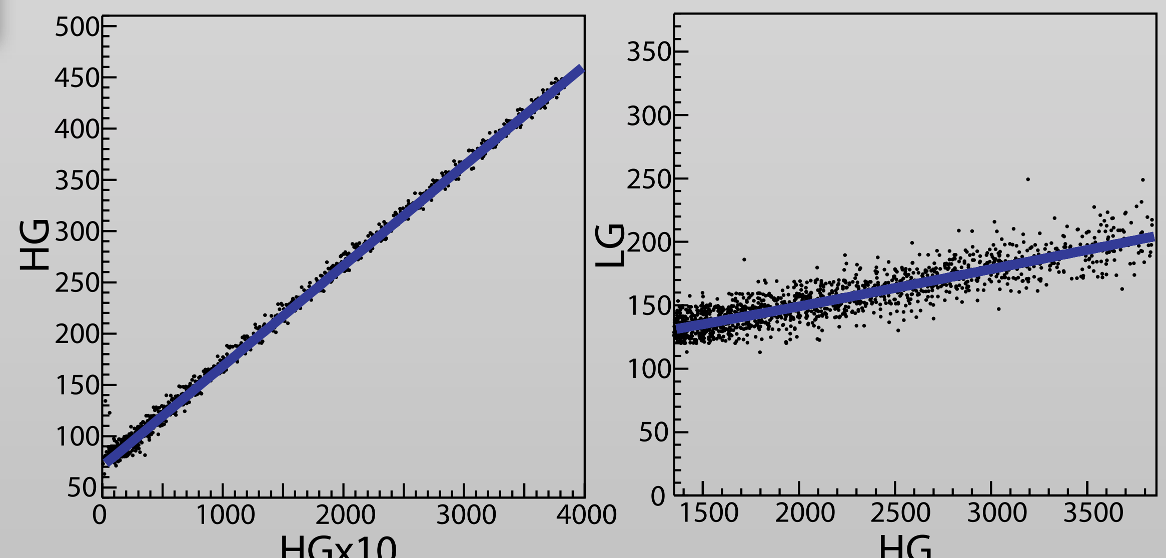


detect mip-peak during data taking in high-gain channel for each single PMT

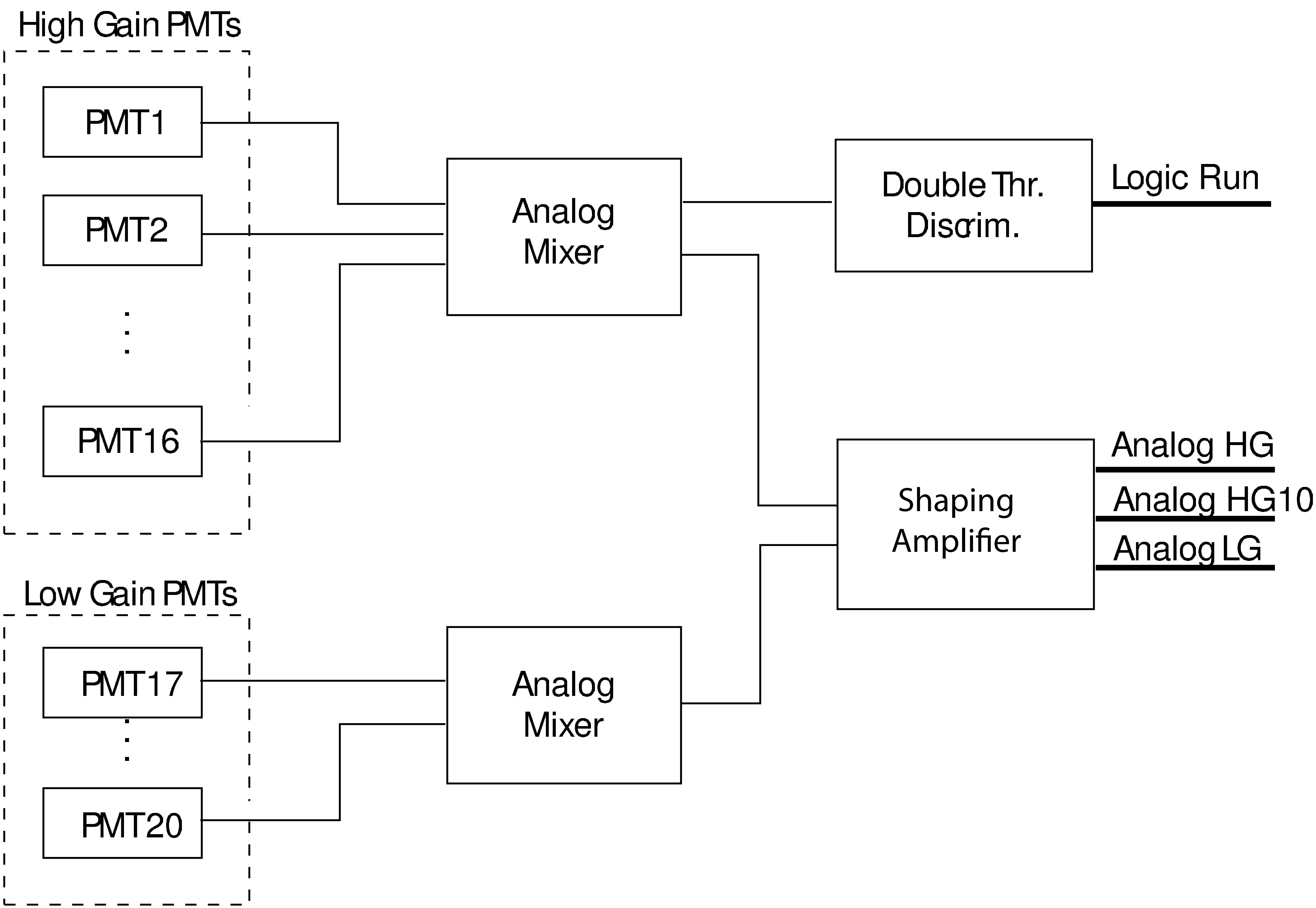


Grande station (16 scint. mod.)

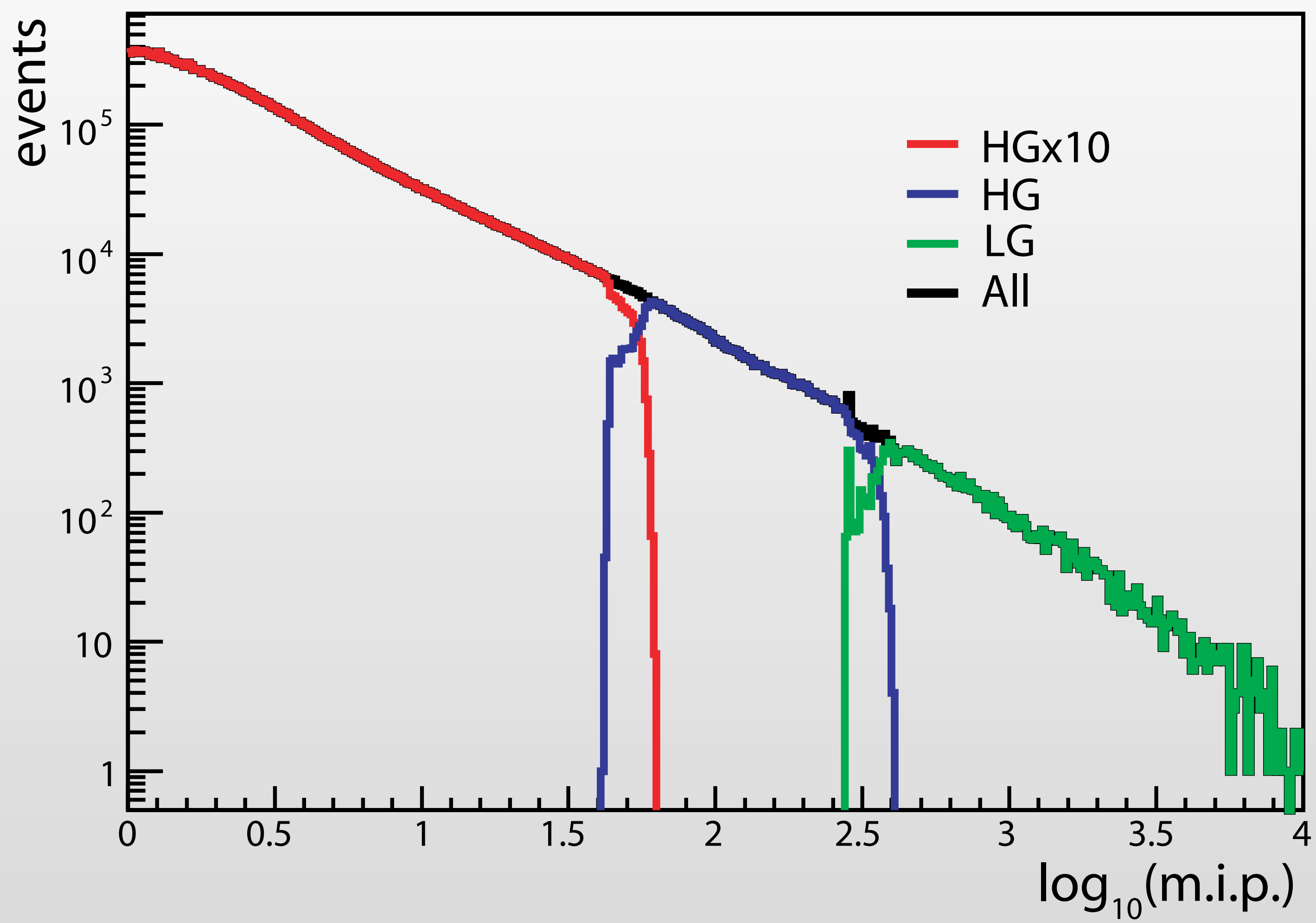
cross calibration of Low- and High-gain channels in pulser runs



Station Electronics

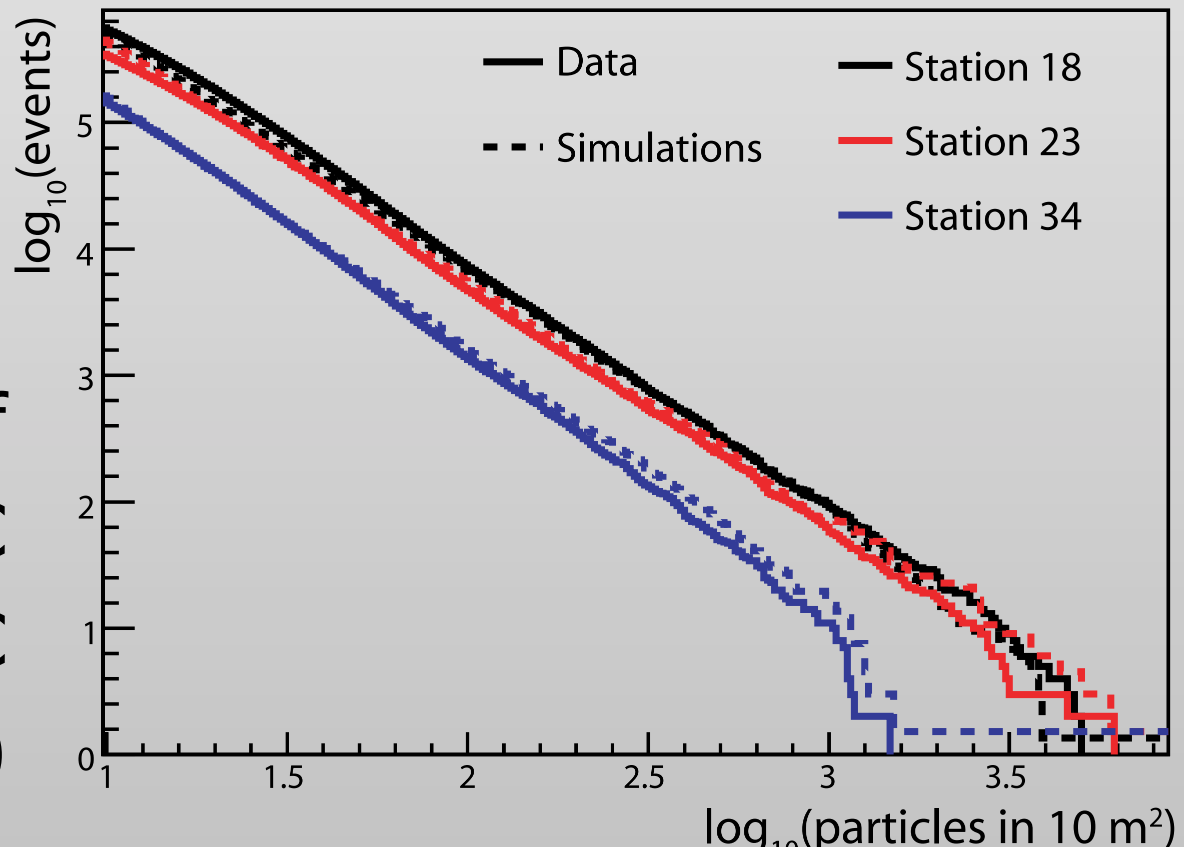


Verfication of Calibration



matching of mip-distributions of individual stations

~ 10% accuracy

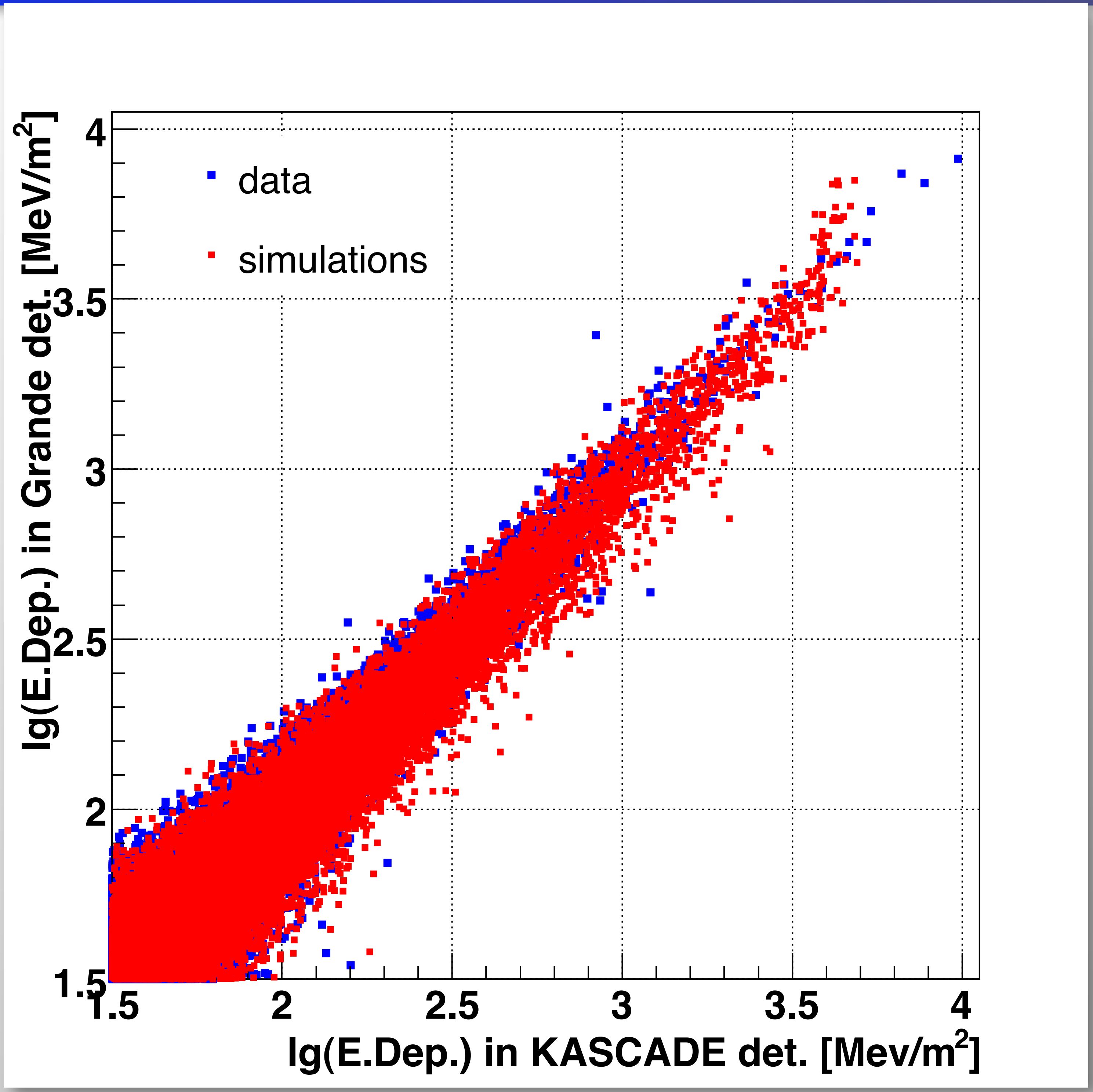


integral particle density spectra of single station: data vs MC

good agreement between data & MC

(differences originate from geometry)

Cross Check: KASCADE-vs-Grande



Good agreement between KASCADE and Grande stations

and with EAS simulations + det. MC

From E-deposit to Particle Numbers

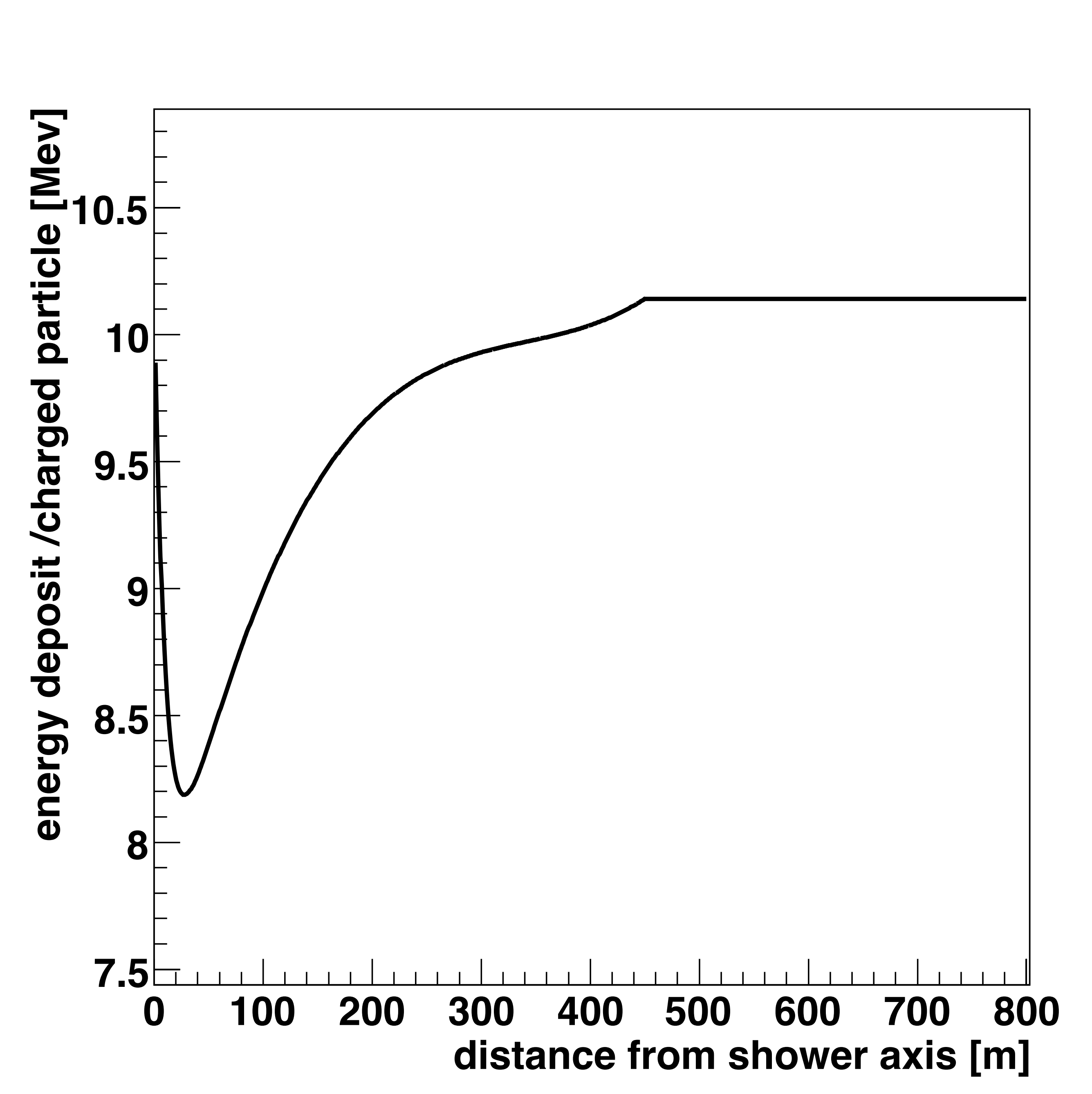
1st step: energy deposit → # of crossing EAS particles

conversion done by
Lateral Energy Correction Function (LECF)
determined from CORSIKA + Geant based Detect. MC

$$LECF(r) = \Delta E(r)/n_{ch}$$

accounts for energy dependence of stopping power and energy release from photons and from secondary particles in surroundings

LECF (Grande Stations)



$$LECF(r) = \begin{cases} e^{(1-0.1\cdot r)} + 7.51 + 0.02\cdot r + 5.5\cdot 10^{-5}\ r^2 + 5.4\cdot 10^{-8} r^3 & , r \leq 450 \\ LECF(450) & , r > 450 \end{cases}$$

Arrival Directions

χ^2 minimization of arrival times
between Grande stations and CORSIKA showers yields
shower front parameters

shower front:

$$\bar{t} = 2.43 \cdot (1 + \frac{r}{30\mathrm{m}})^{1.55} \ \mathrm{ns} \qquad \sigma_{\bar{t}} = 1.43 \cdot (1 + \frac{r}{30\ \mathrm{m}})^{1.39} \ \mathrm{ns}.$$

Uncertainty of timing measurement:

$$\sigma_t = \sqrt{\sigma^2_{\tau,instr} + \frac{\sigma^2_{\bar{t}}}{N}}$$

$$\chi^2_t = \sum_i \frac{(t_{meas,i} - t_0(\overline{r_{axis}}, \bar{\theta}) - (z_i - z_0(\overline{r_{axis}}, \bar{\theta}))/c - t_{1,i}(r))^2}{\sigma_t(r)^2}$$

Core Location, Age, Shower-Size

Maximum Likelihood: measured particle density compared to modified NKG function

$$\rho_{ch}(r) = N_{ch} \cdot f_{ch}(r) = N_{ch} \cdot C(s) \left(\frac{r}{r_0}\right)^{s-\alpha} \left(1 + \frac{r}{r_0}\right)^{s-\beta}$$

$$C(s) = \Gamma(\beta - s)/(2\pi r_0^2 \cdot \Gamma(s - \alpha + 2) \cdot \Gamma(\alpha + \beta - 2s - 2))$$

α=1.6, β=3.4, r_0=30 m

$$L = \prod_i \frac{n_i^{N_i} e^{-n_i}}{N_i!} \prod_i \frac{1}{\sqrt{2\pi}\sigma_i} e^{\frac{-(N_i - n_i)^2}{2\sigma_i^2}} \prod_i \int_{N_i}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_i} e^{\frac{-(N - n_i)^2}{2\sigma_i^2}} dN$$

$N_i < 10$ $\quad$ $N_i \geq 10$ $\quad$ used for saturated stations

N_i: measured no. of particles in station n_i: expected no. of particles in station i

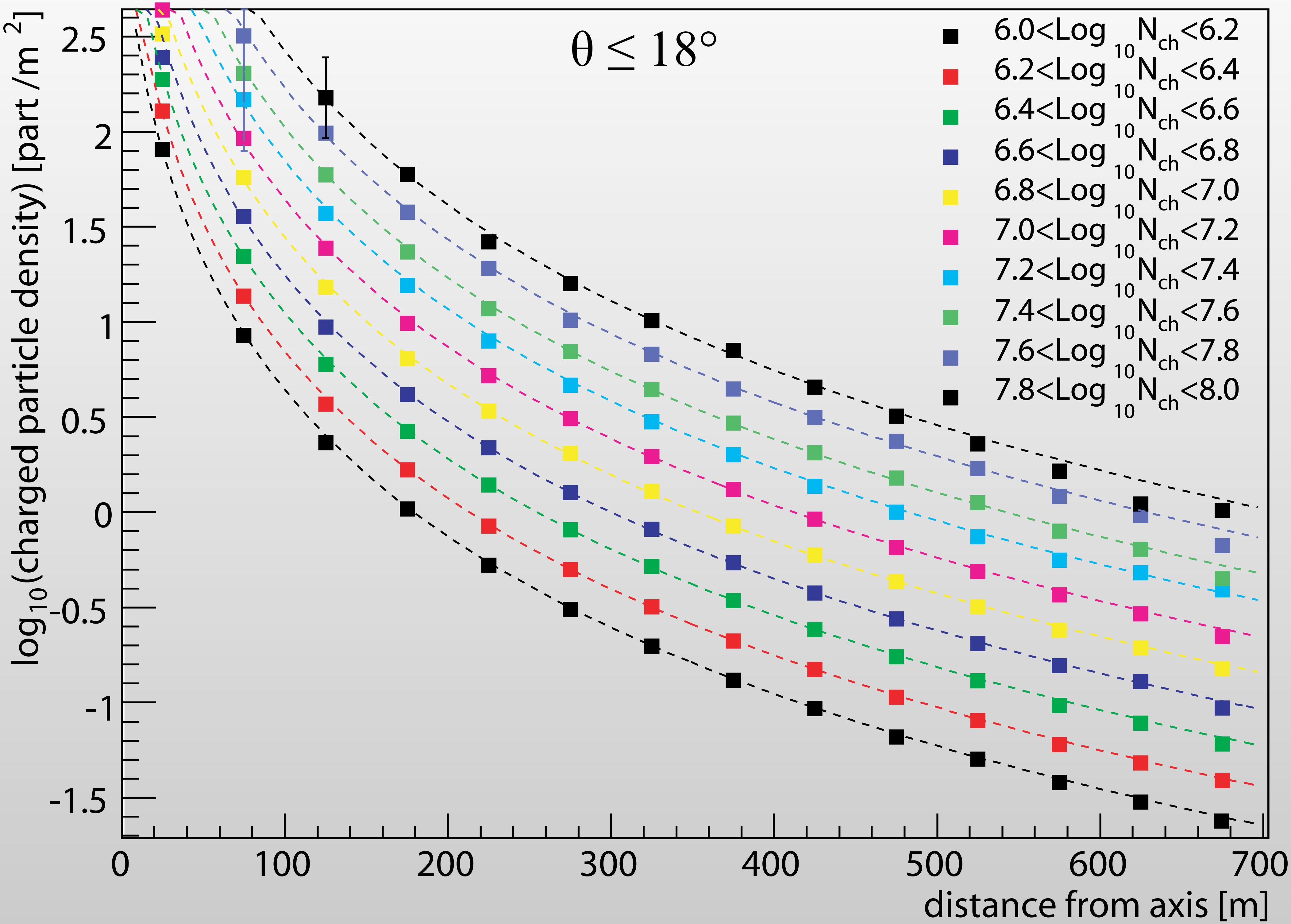
Iterative Procedure

(1) The shower parameters are estimated analytically.
(2) The core position is moved over a 7×7 grid with 8 m spacing. In each position s and N_{ch} are fitted and the position providing the minimum χ^2 is chosen as starting point.
(3) The arrival direction is reconstructed by the time fit.
(4) The lateral distribution of charged particles is fitted using $\rho_{ch}(r)$ with N_{ch} and s as free parameters.
(5) The lateral distribution fit is performed with free parameters x_c and y_c.
(6) Step 3 and 4 are repeated to obtain the final values for the arrival direction, N_{ch} and s.
(7) N_μ is obtained (see Daniel Fuhrmann‘s talk)

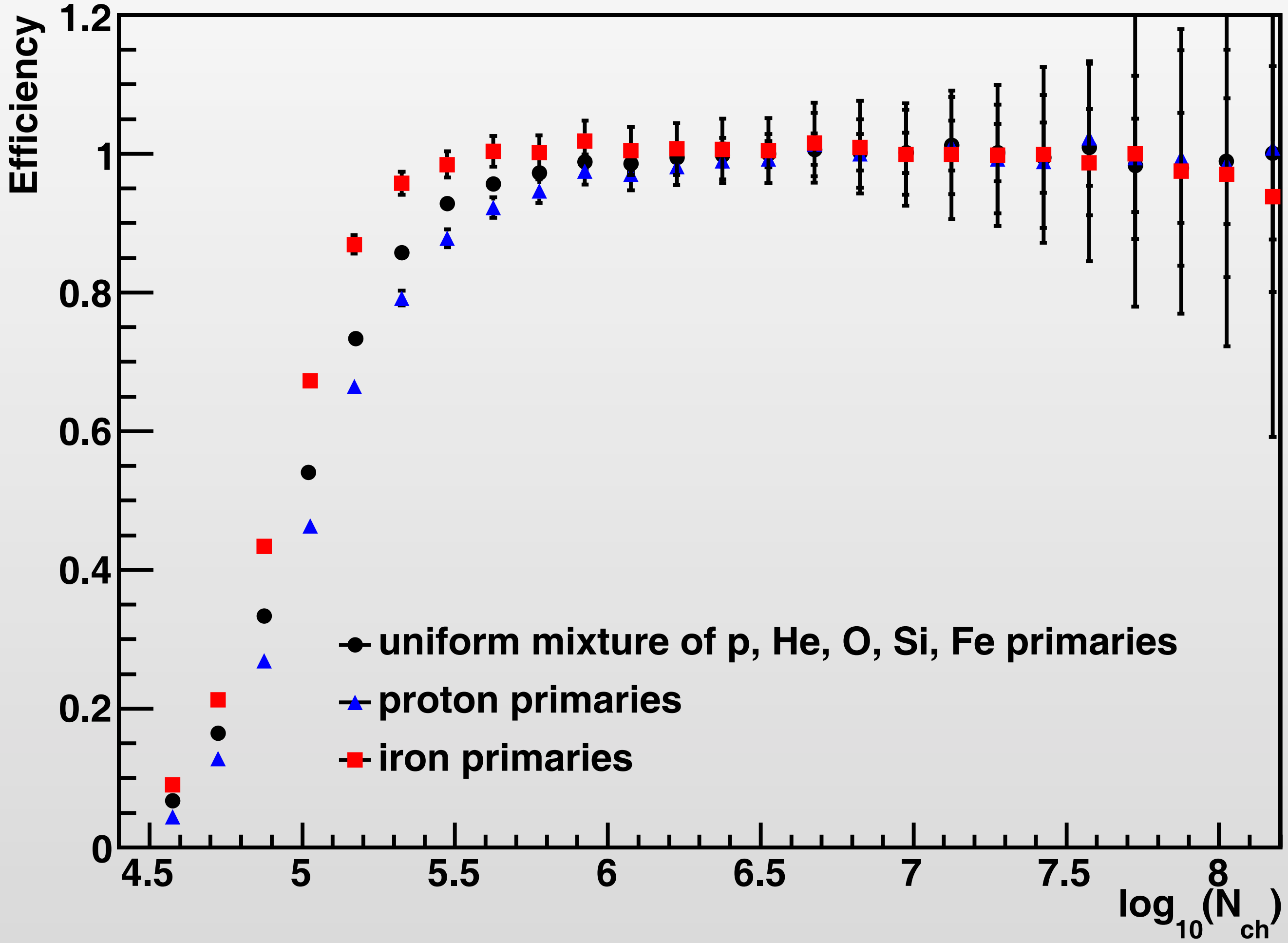
Event Selection Cuts

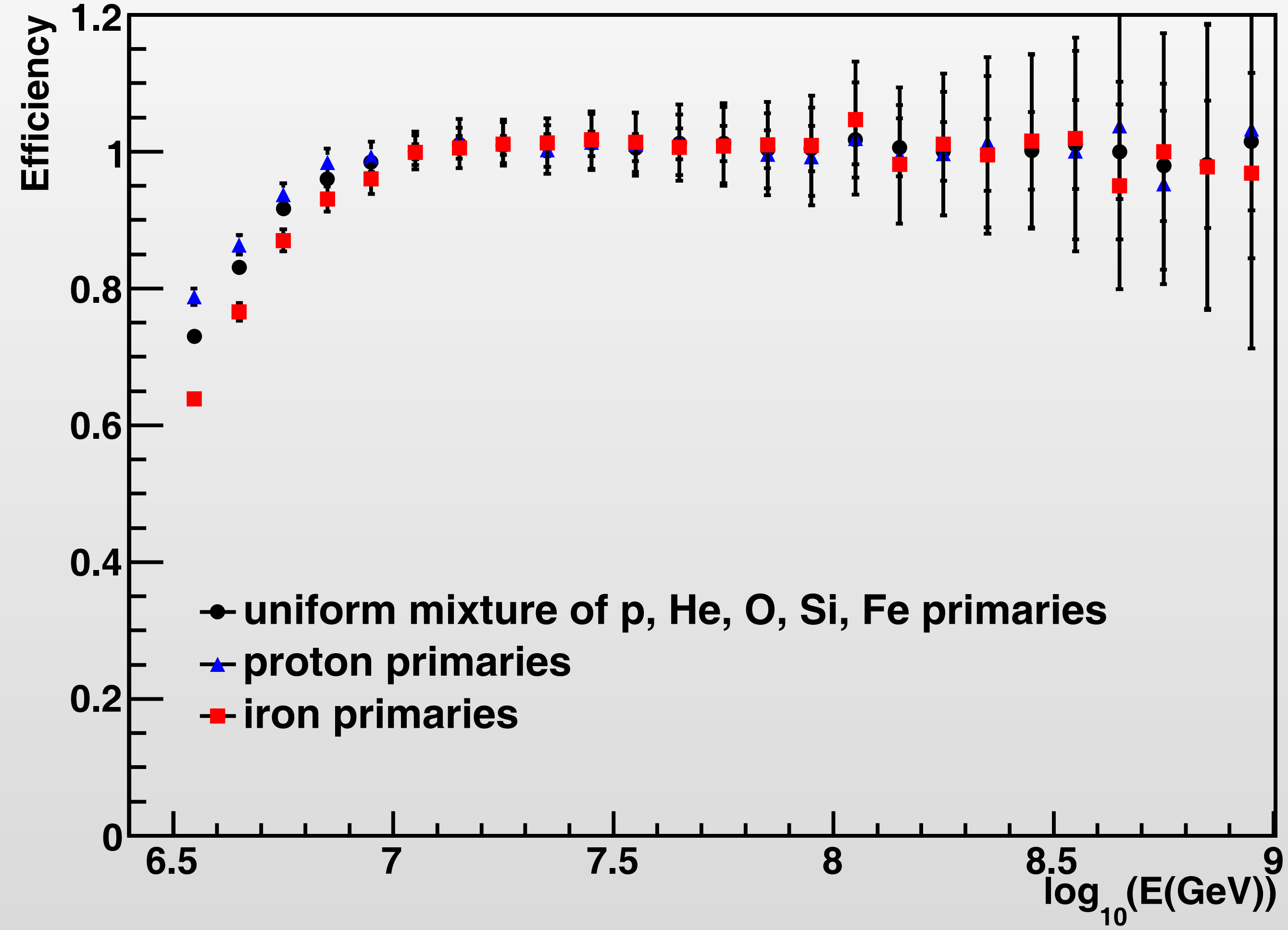
1) highest energy deposit in central station of hexagon
2) ≥ 12 stations with valid TDC signal
3) N_{ch}(detected) / N_{ch}(total) above a certain threshold
4) zenith angle ≤ 40°
5) core in central fiducial area of 470 x 380 m^2

LDF of charged particles



Trigger & Reconstr. Efficiency



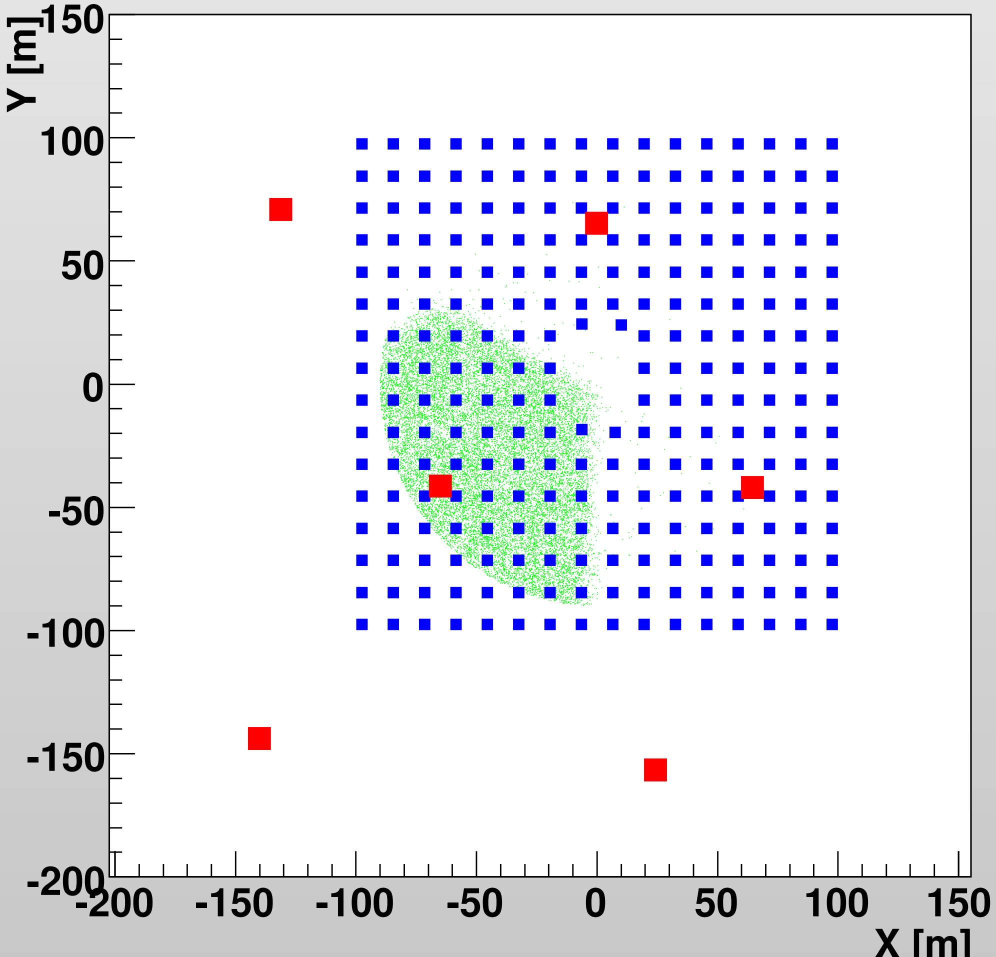


Fully efficient above $\log(N_{ch})=5.8$ and 10^{16} eV

Reconstruction Accuracies

- Analyze uncertainty of fit parameters
- Compare Data to MC
- Compare reconstructed parameters of KASCADE and KASCADE-Grande in region of overlap, i.e. $5.8 \leq N_{ch} \leq 7.2$ and core location in green area

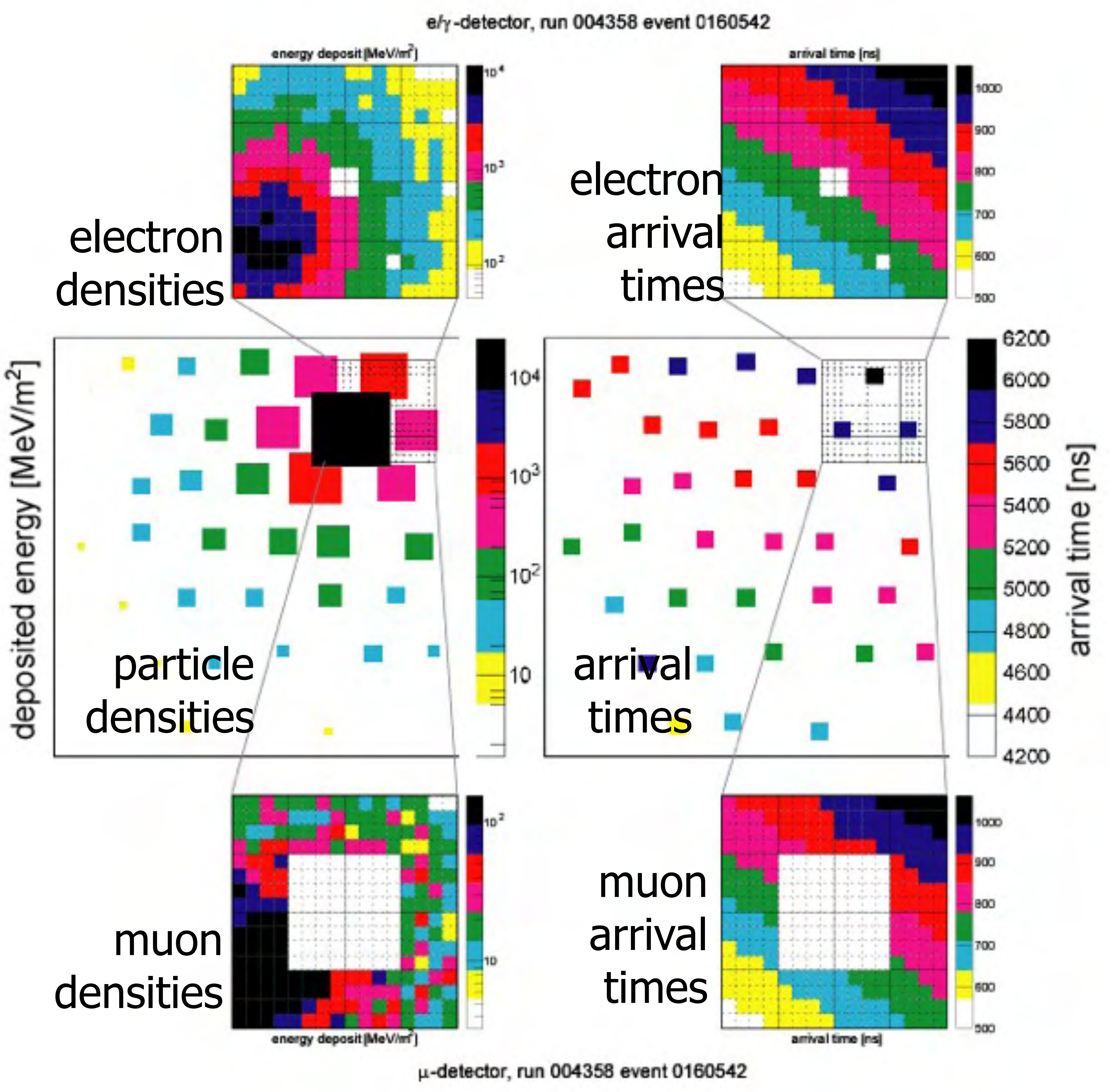
  (few % of events)



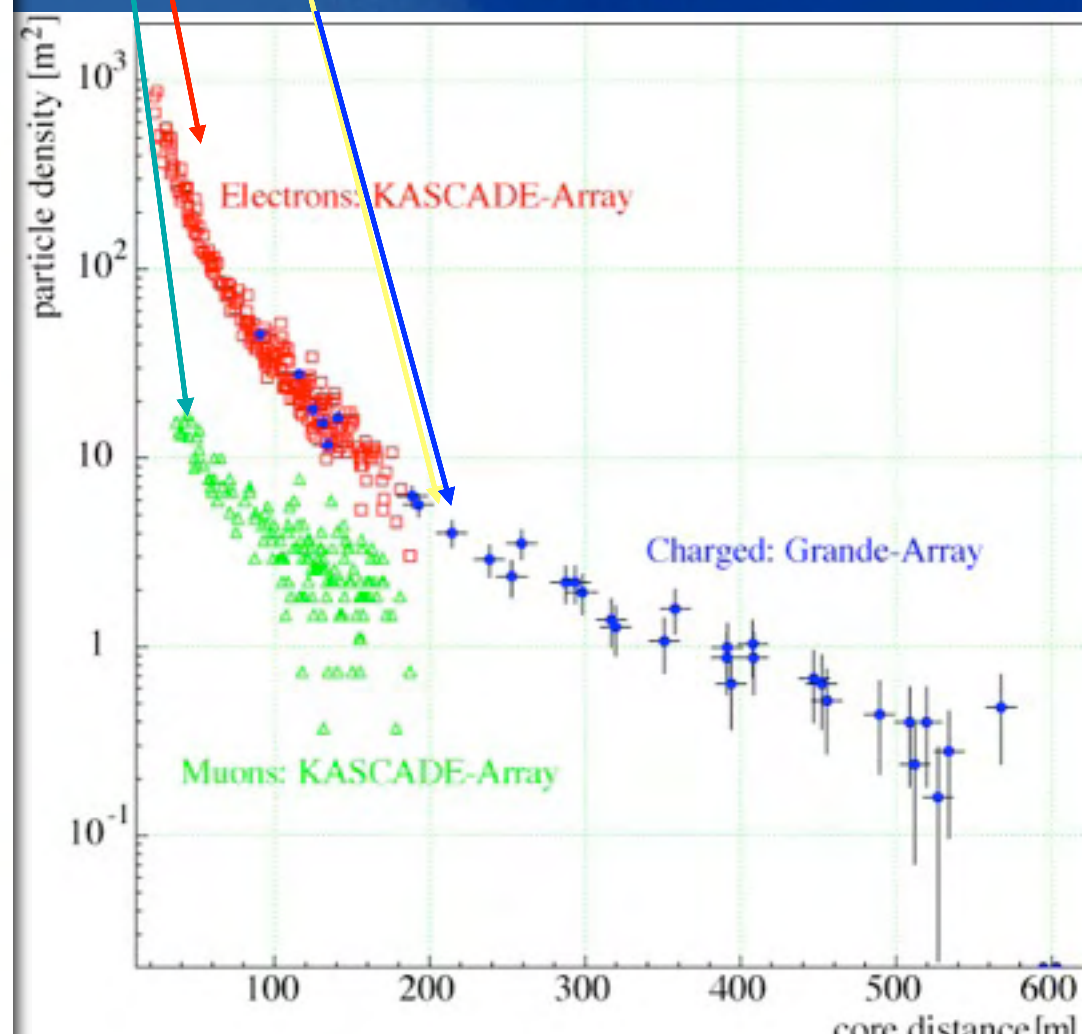
KASCADE sampling fraction ≈ 15 times higher than in Grande, i.e. KASCADE can serve as reference
(number are: 1.2·10-2 vs $7.5 \cdot 10^{-4}$)

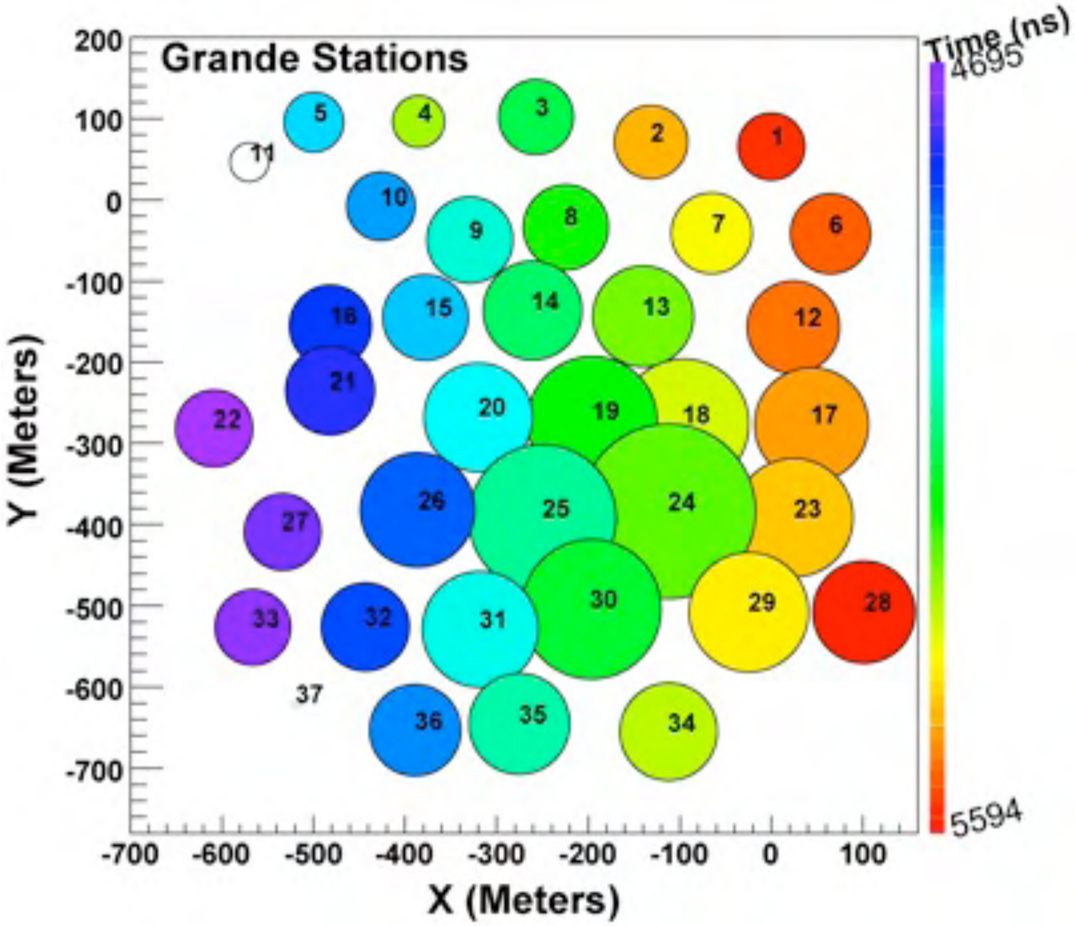
Example of Combined Event

KASCADE-Grande: Karlsruhe Shower Core and Array Detector - Grande



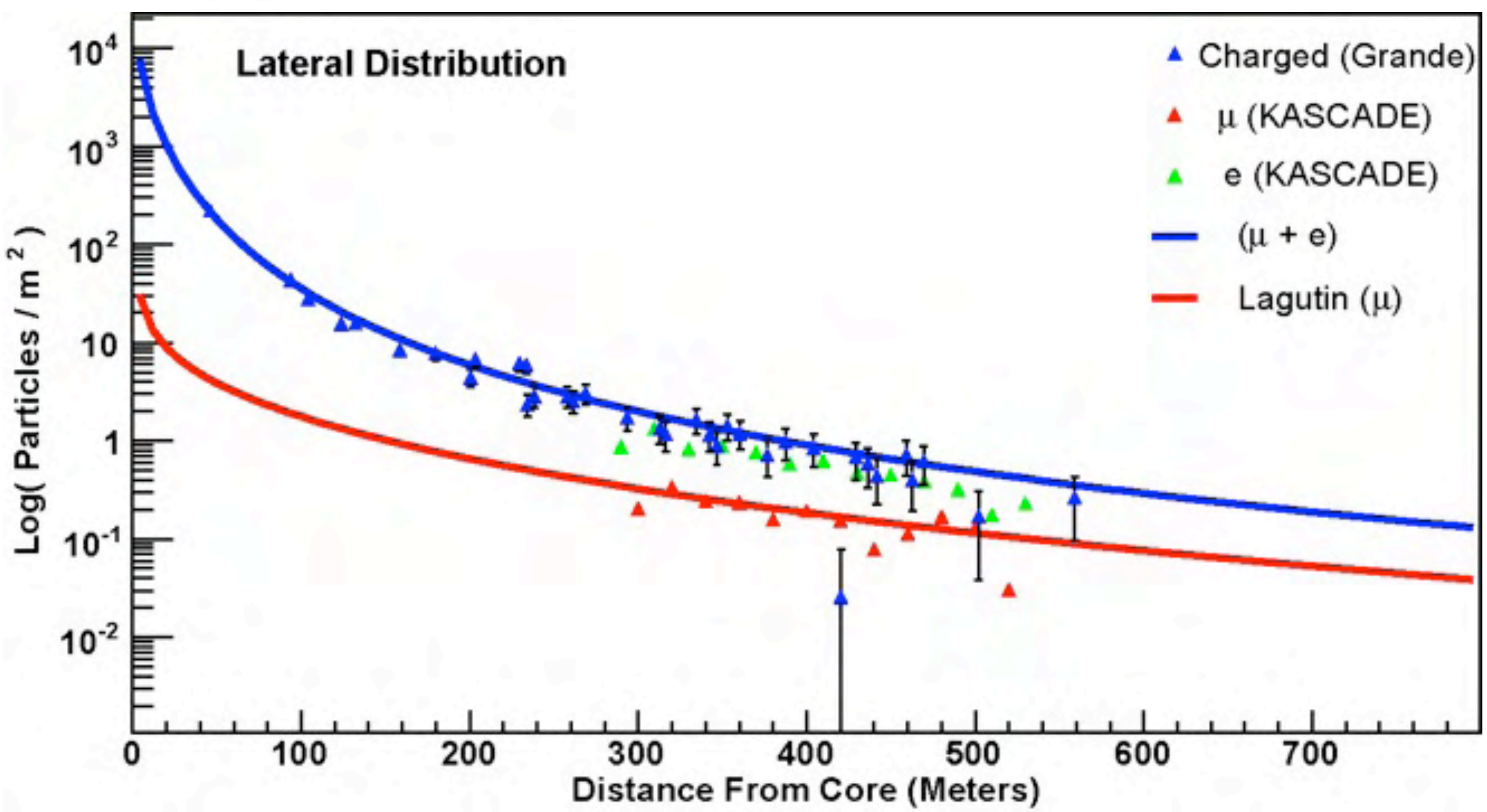
EAS as seen by KASCADE & KASCADE-Grande



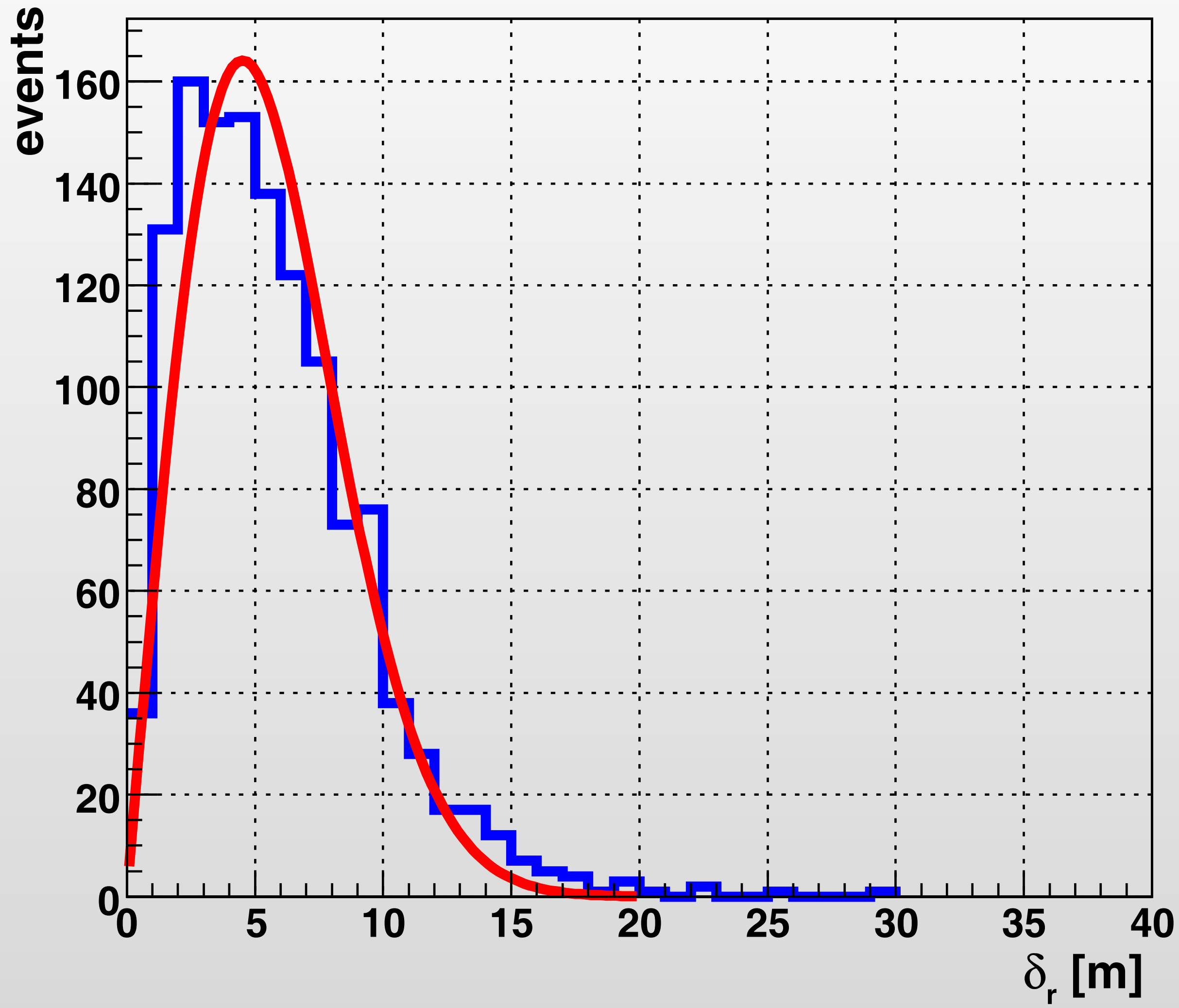


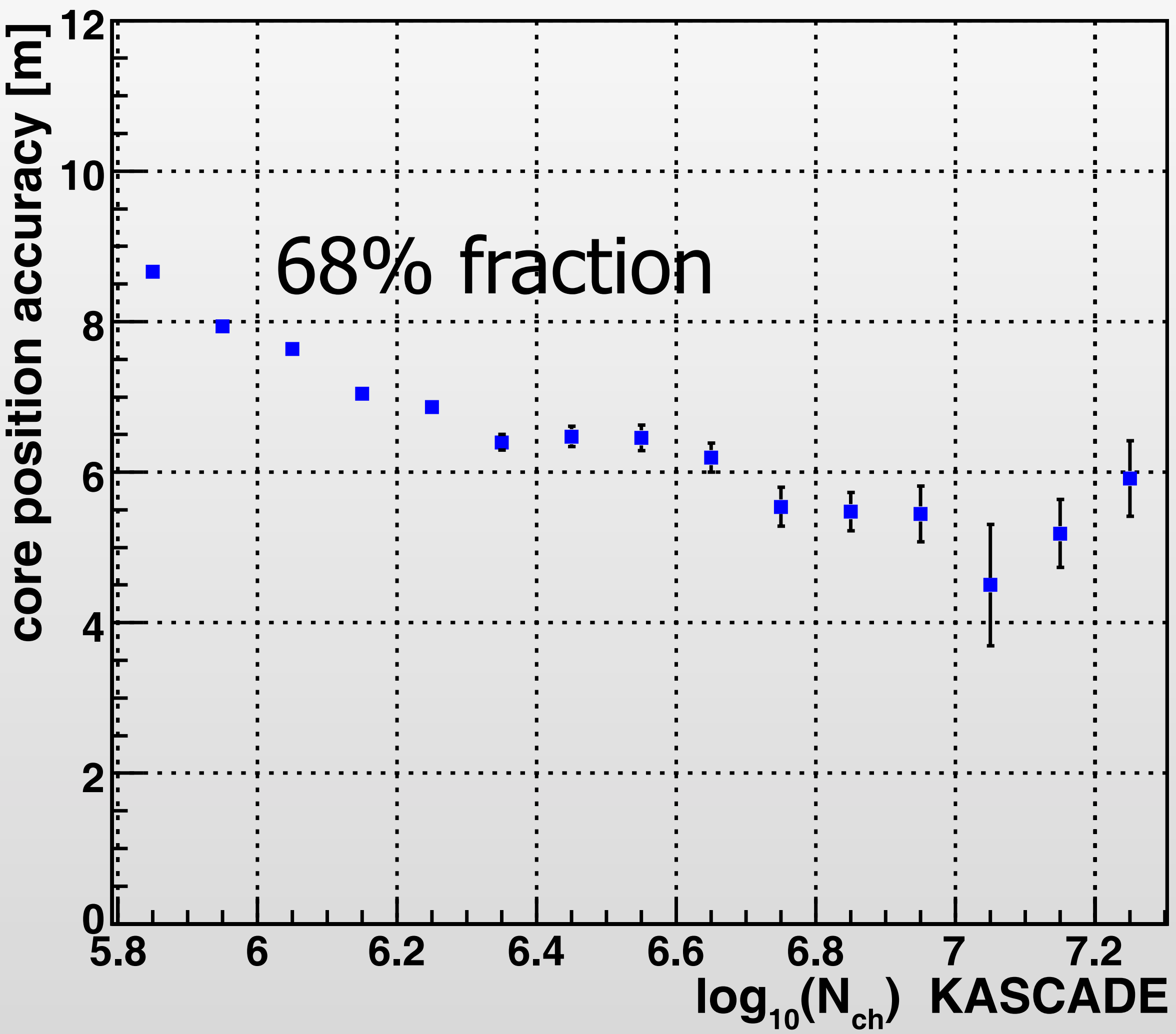
KASCADE-Grande : Single event reconstruction

a single event measured by KASCADE-Grande:
core (-155,- 401) m
log10(N_{ch}) = 7.0
log10(N_{μ}) = 5.7
No saturation
Zenith = 24.2°
Azimuth = 284°



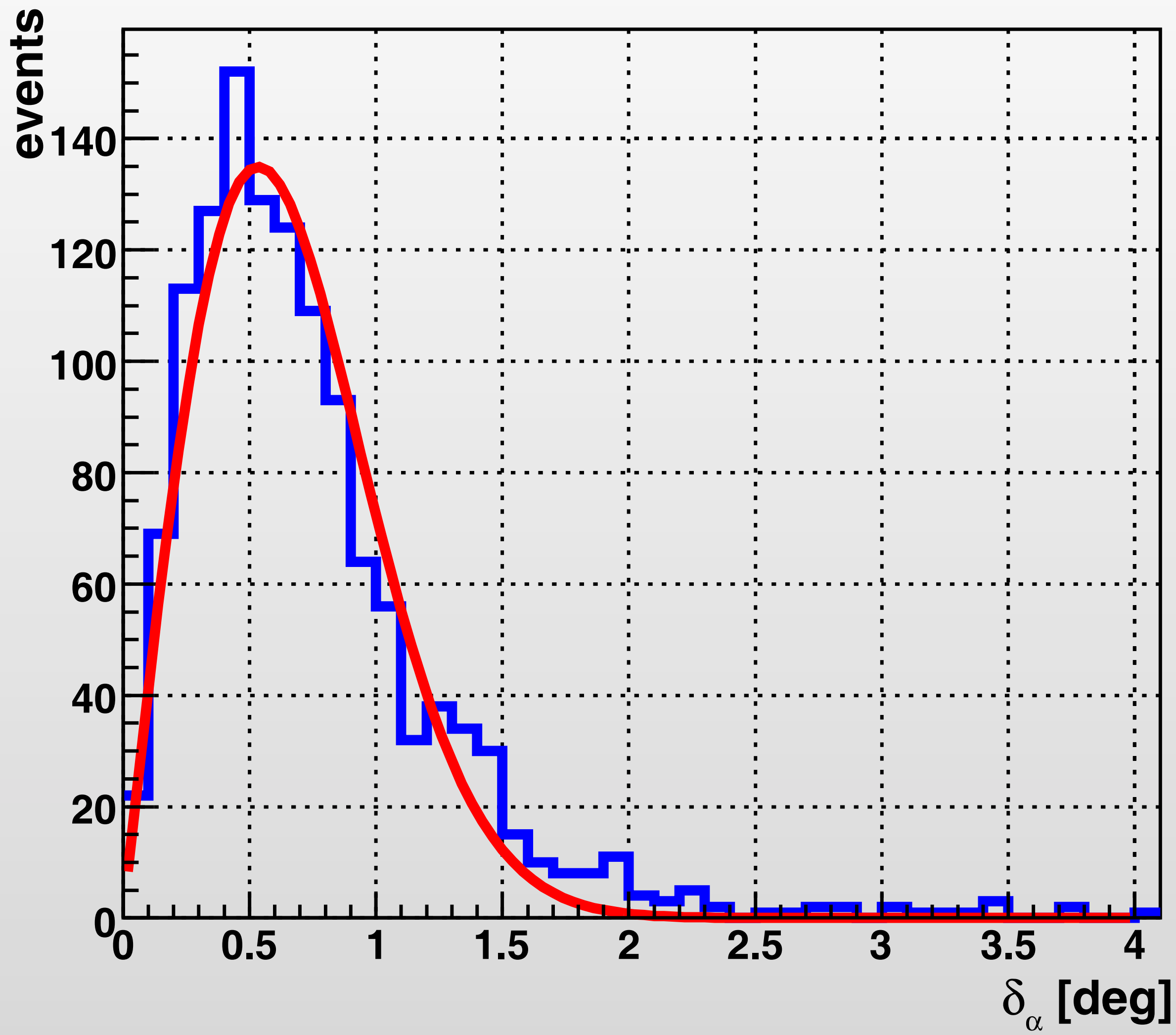
Core Location

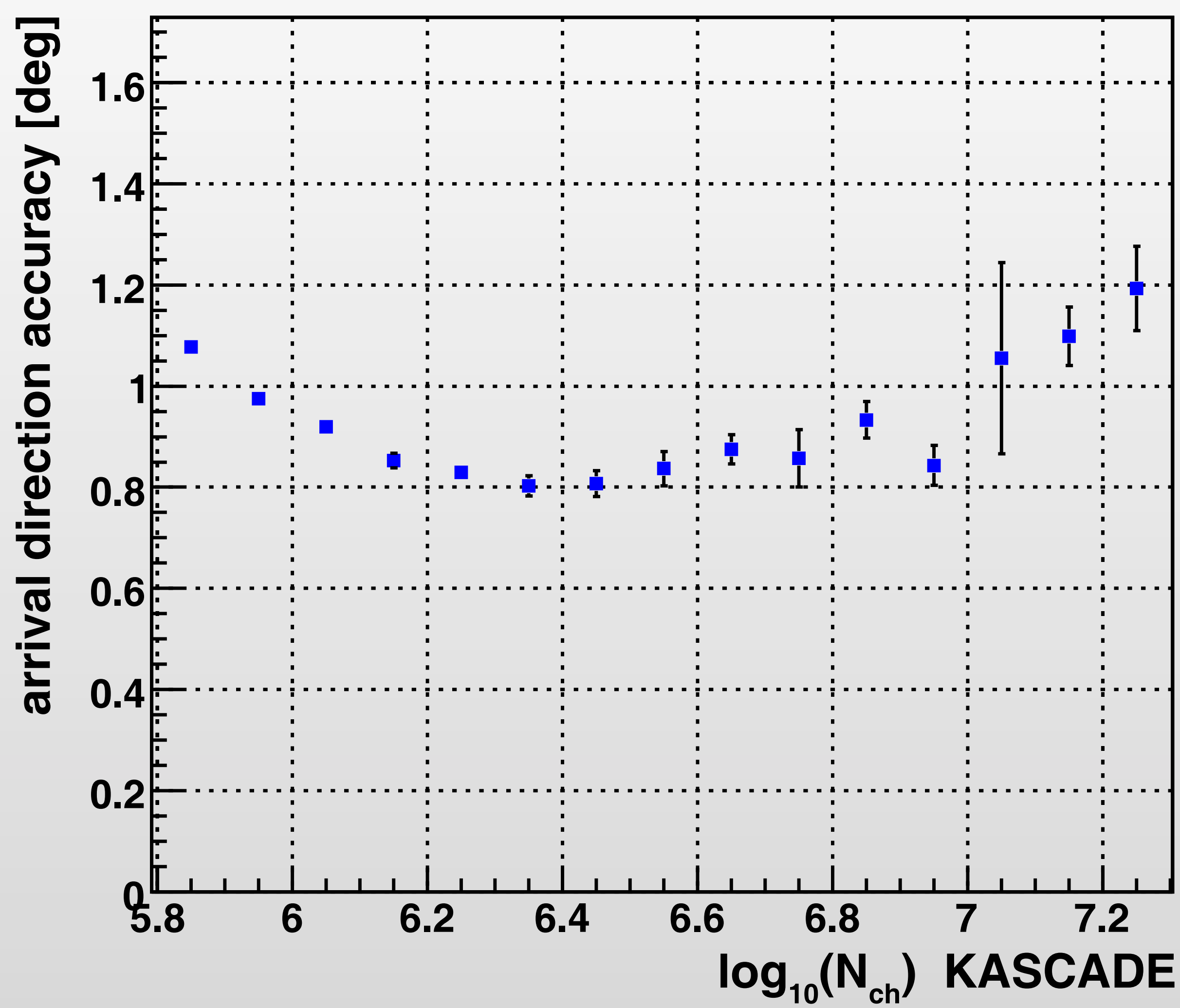




resolution ~ 5-8 m

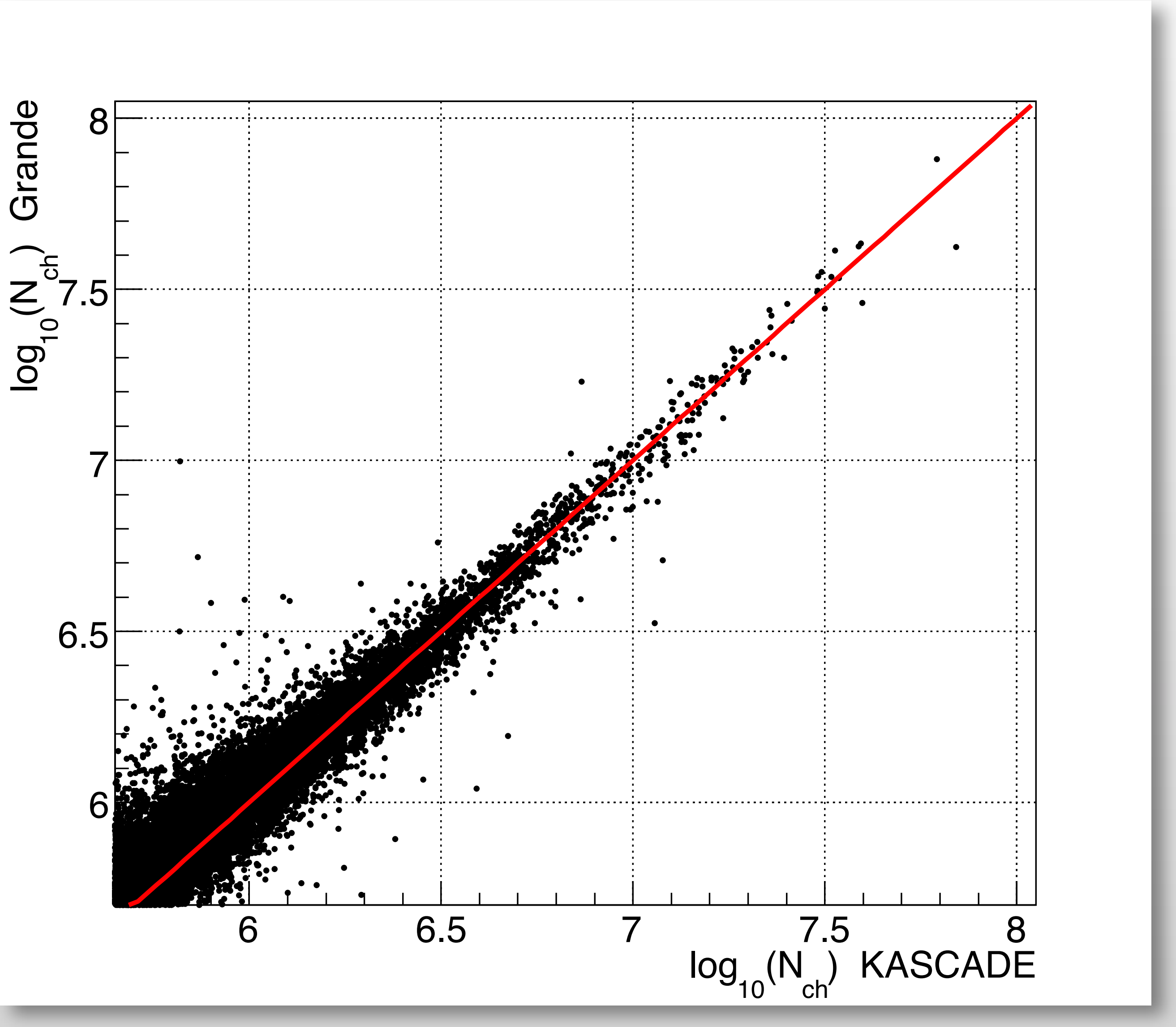
Arrival Direction

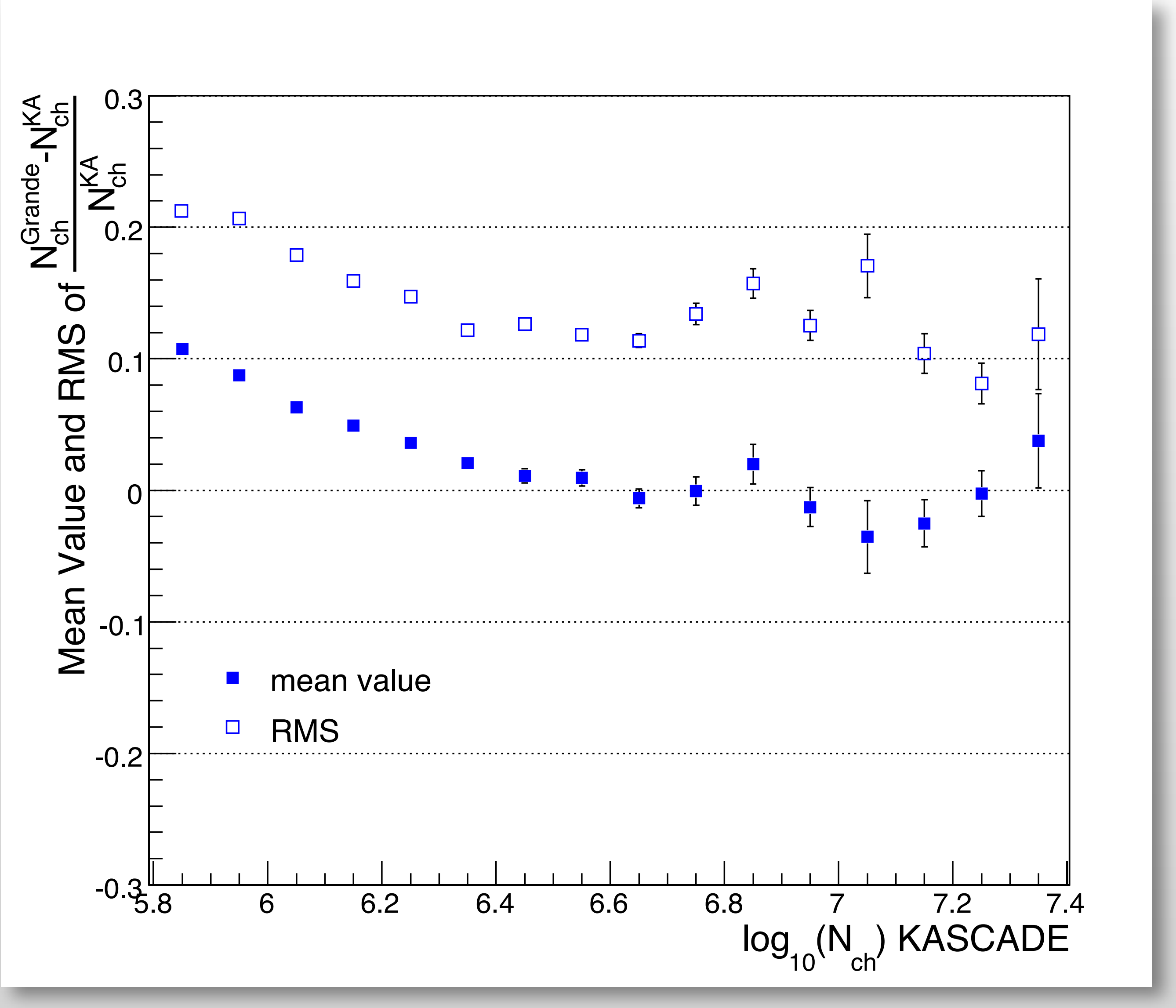




resolution ~ 0.8°

Comparison of Shower Size





systematic shift < 10%

statistical resolution ~ 10-15%

N_{ch}, N_{μ}, N_e...

Physics analysis of KASCADE-Grande uses (at present)

- **N_{ch}**
- core position, and
- direction from Grande (this talk)

- **N_{μ}** from KASCADE (see Daniel's talk)

- **N_e** (if needed) from $\rho_{ch}(r) - \rho_{\mu}(r)$

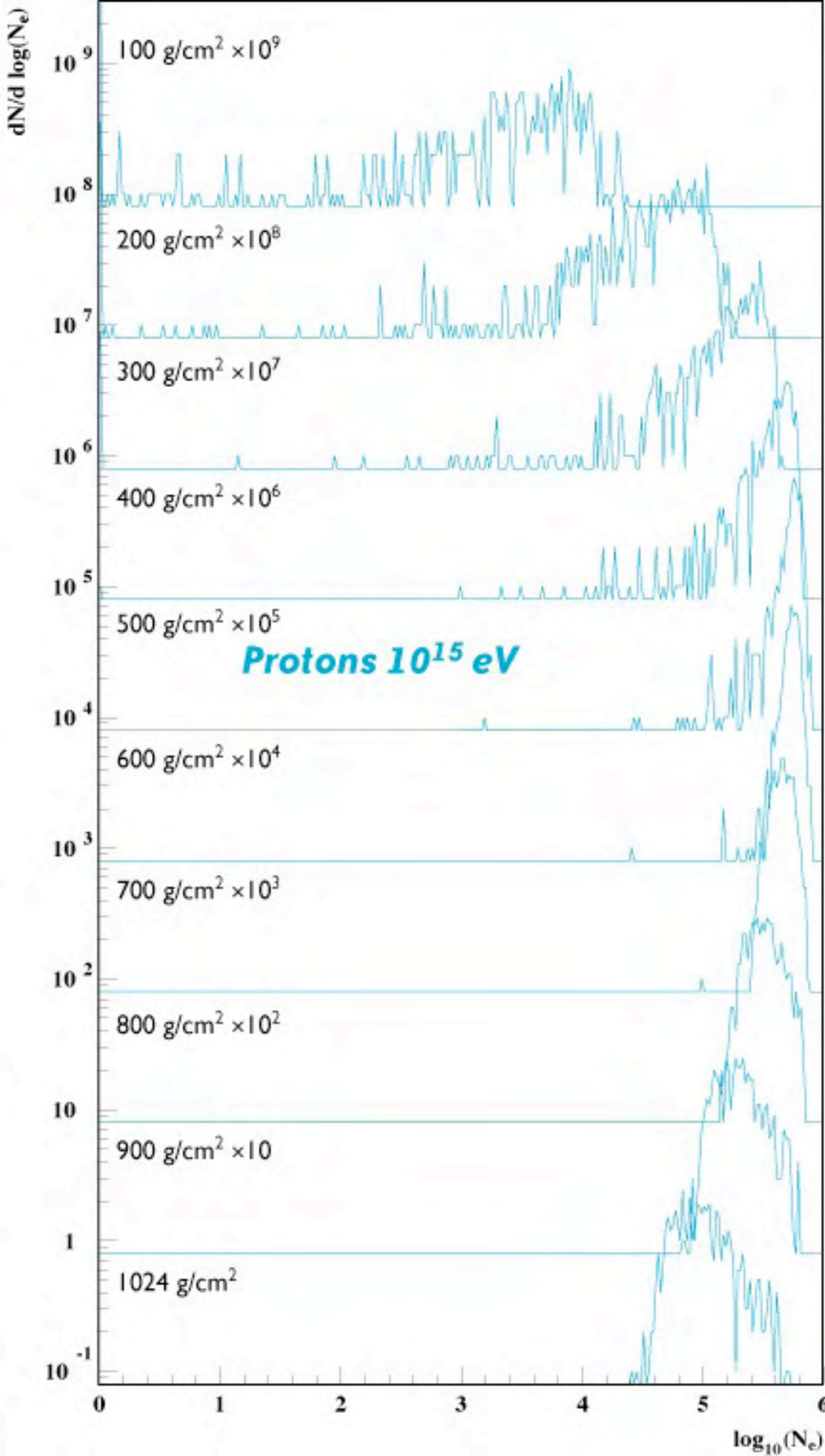
KASCADE-Grande

II) Energy spectra from Unfolding

Largely based on
PhD Thesis of Holger Ulrich

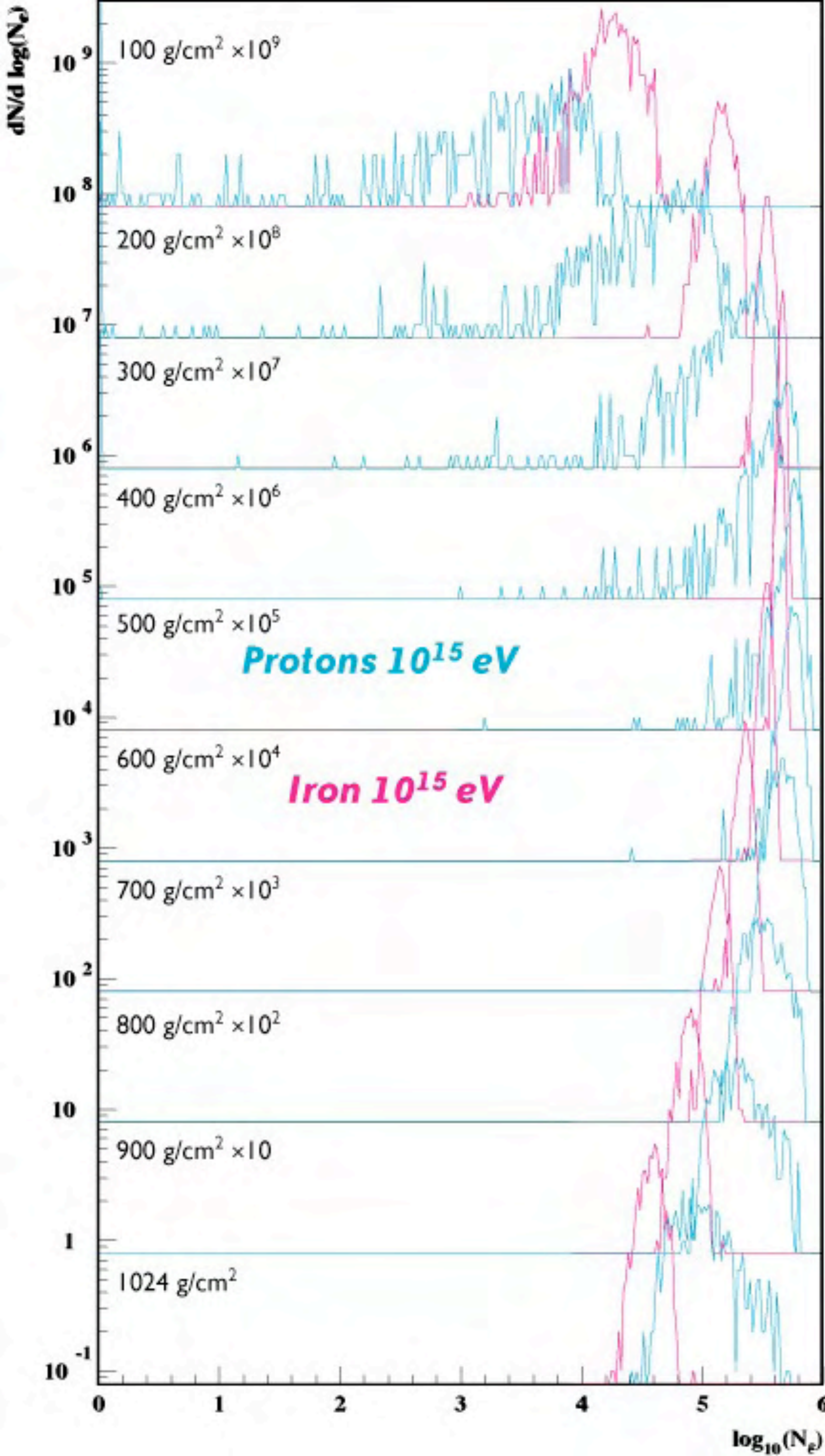
Electron-Shower Size at different altitudes…

$E=10^{15}$ eV



IceCube

KASCADE



Electron-Shower Size at different altitudes...

$E=10^{15}$ eV

Near the shower maximum p and Fe showers yield similar electron numbers
⇨ bad for composition !

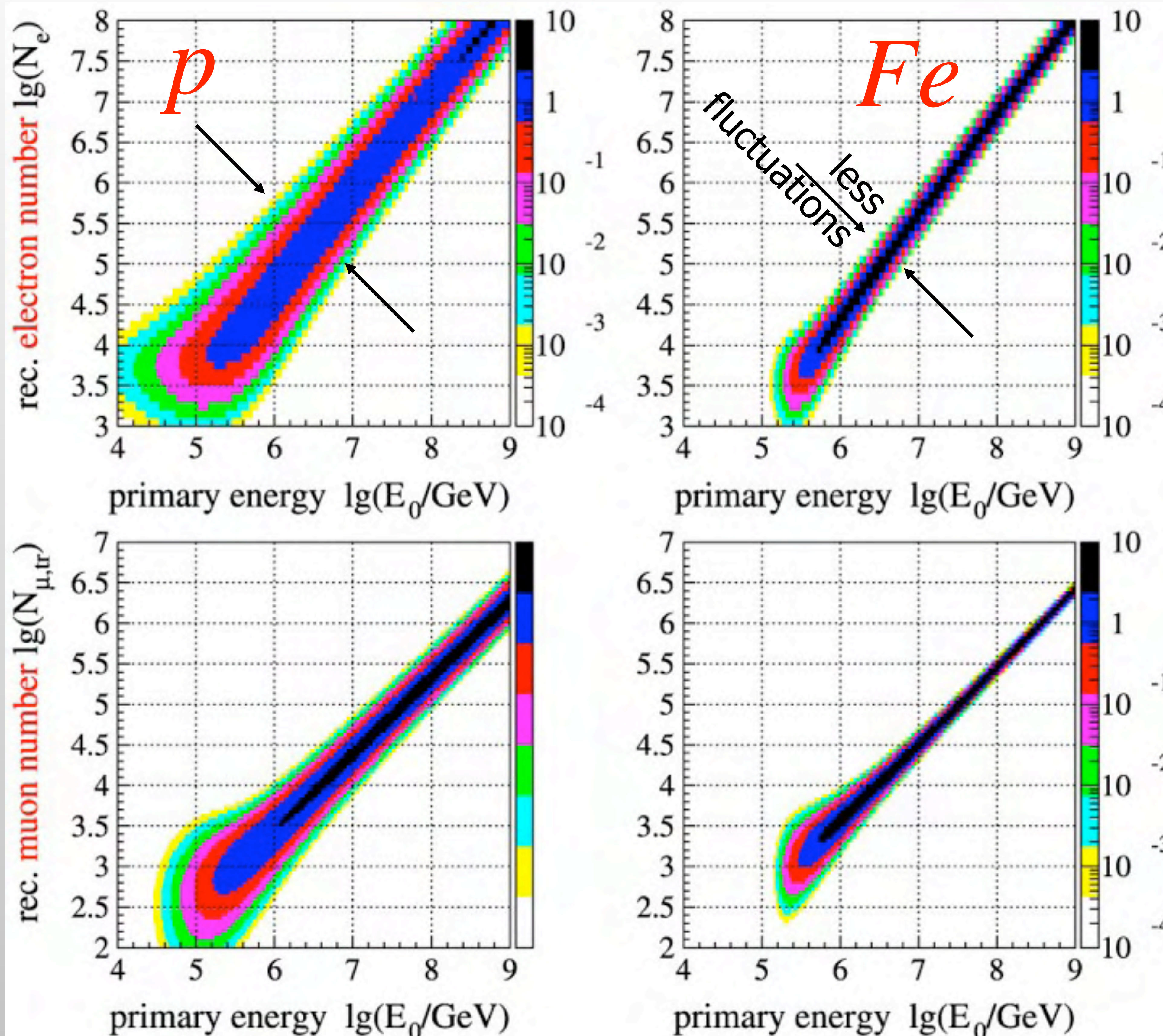
IceCube

excellent position (for GeV μ's)

KASCADE

some suffering from fluctuations

Electron & muon counting ⇨ E_{prim}

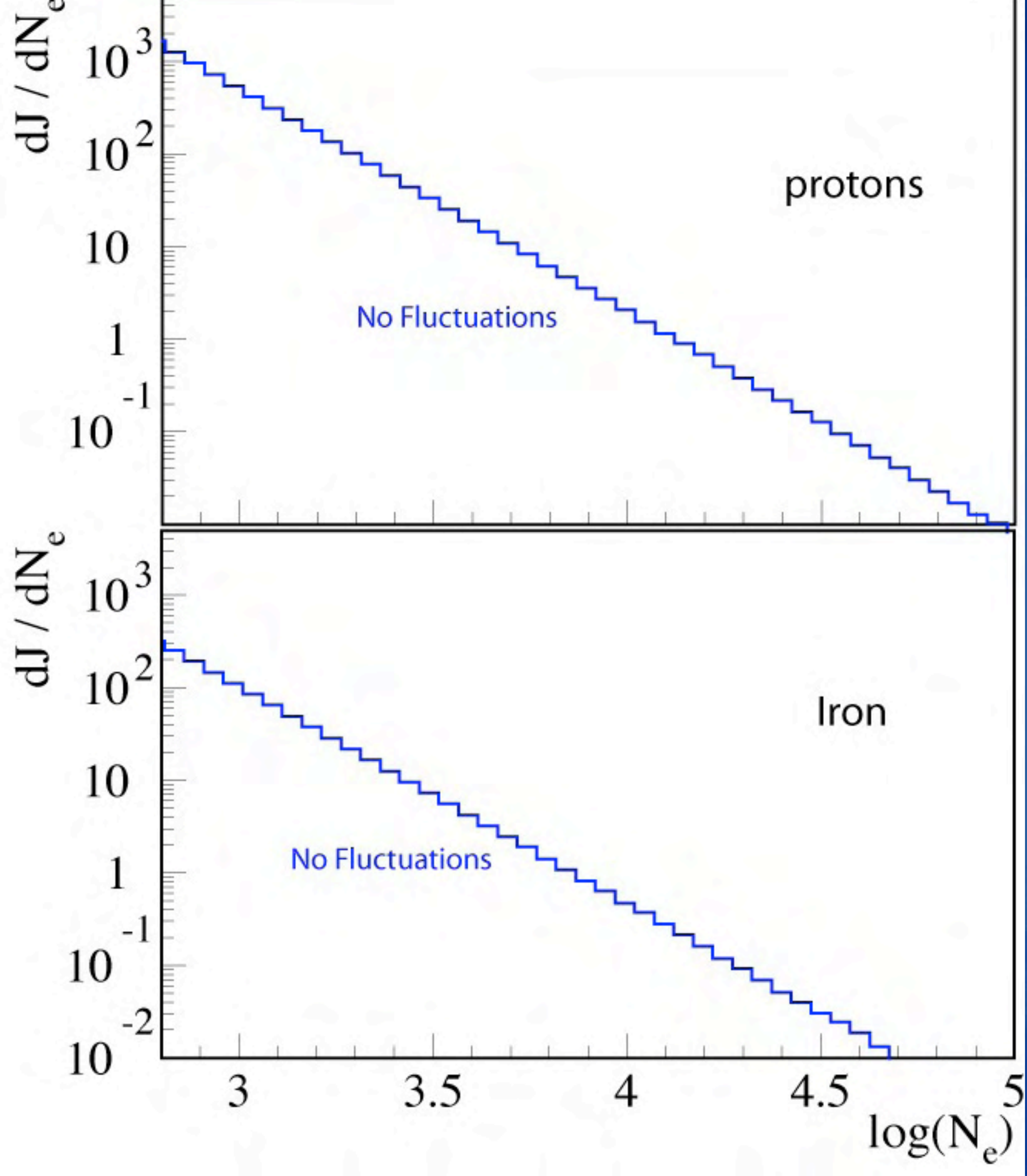


N_e

Relations depend on Energy & Mass !!

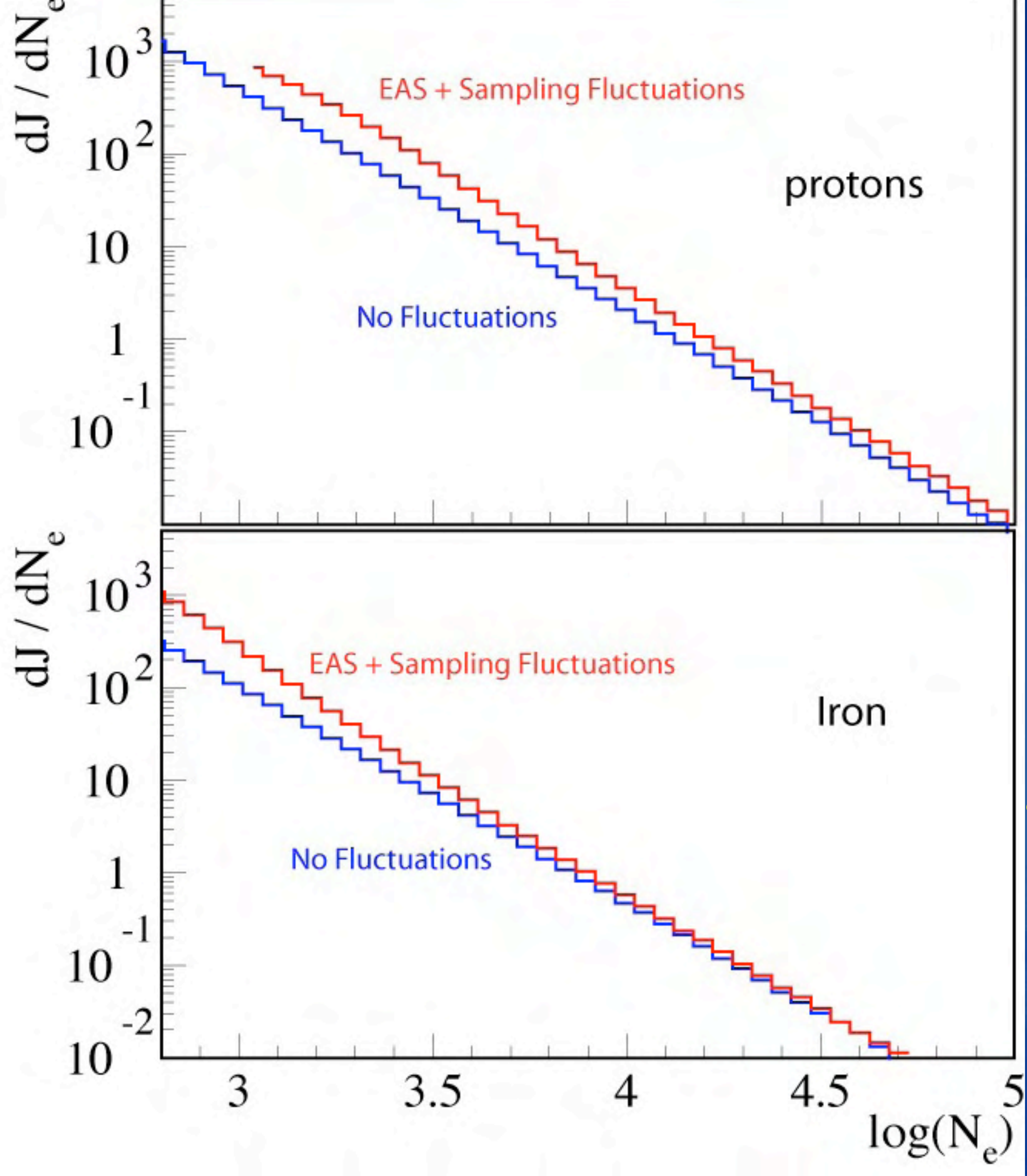
and atm. depth

N_μ



Consequence:
all experimental distributions are affected;

e.g.: N_e-distr. for $dJ/dE \sim E^{-2.78}$ at sea-level



Consequence:

all experimental distributions are affected;

e.g.: N_e-distr. for $dJ/dE \sim E^{-2.78}$ at sea-level

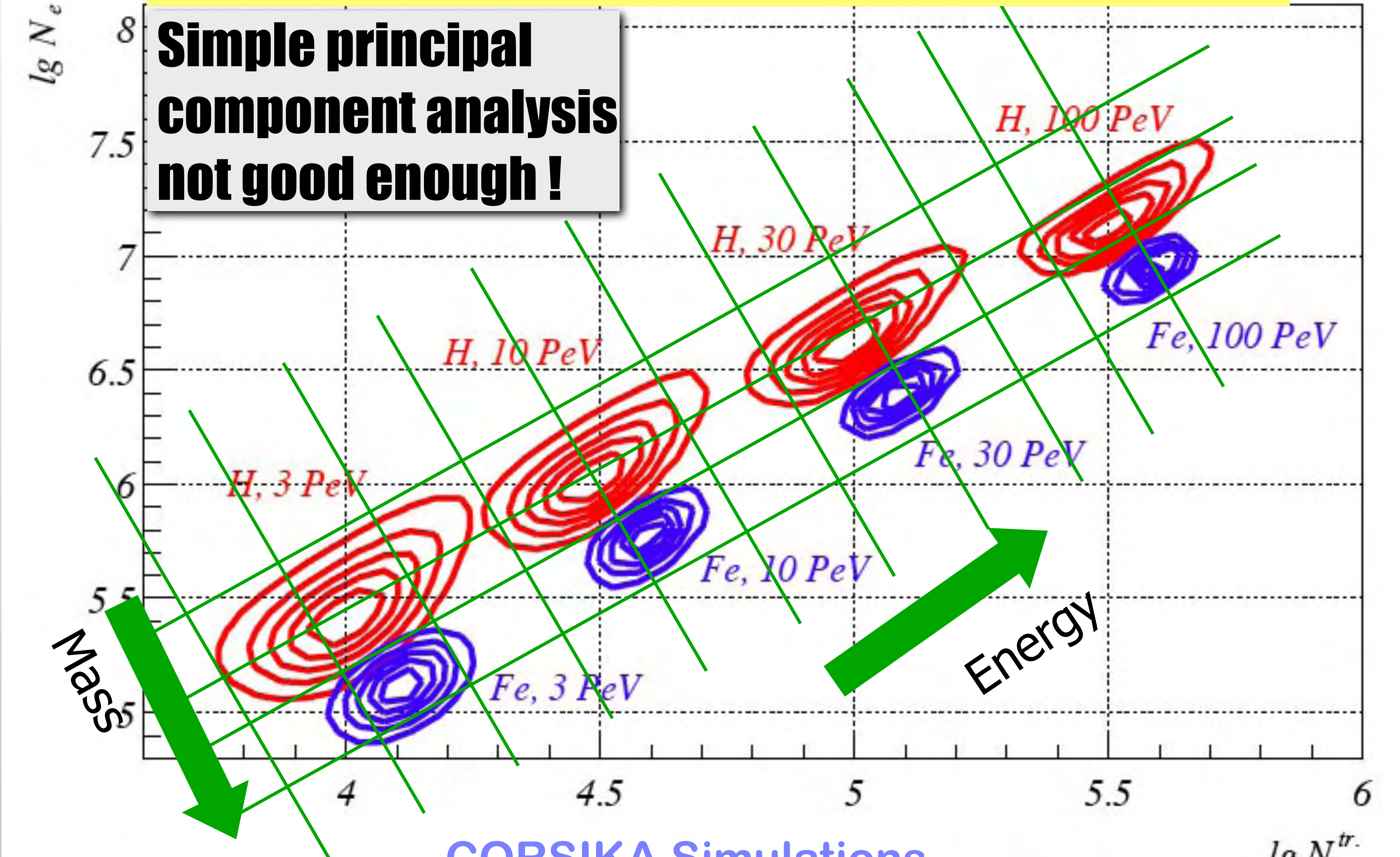
Note:

- Spectrum steepens because of smaller fluctuations at higher energies
- observed all-particle distr. biased towards protons, particularly at low energies

Electron & muon counting ⇨ E_{prim} ,A_{prim}

$$\log E\,(\mathrm{GeV}) = 1.98 + 1.08\cdot\log(N_{\mu}) + 0.037\cdot\log(N_e)$$

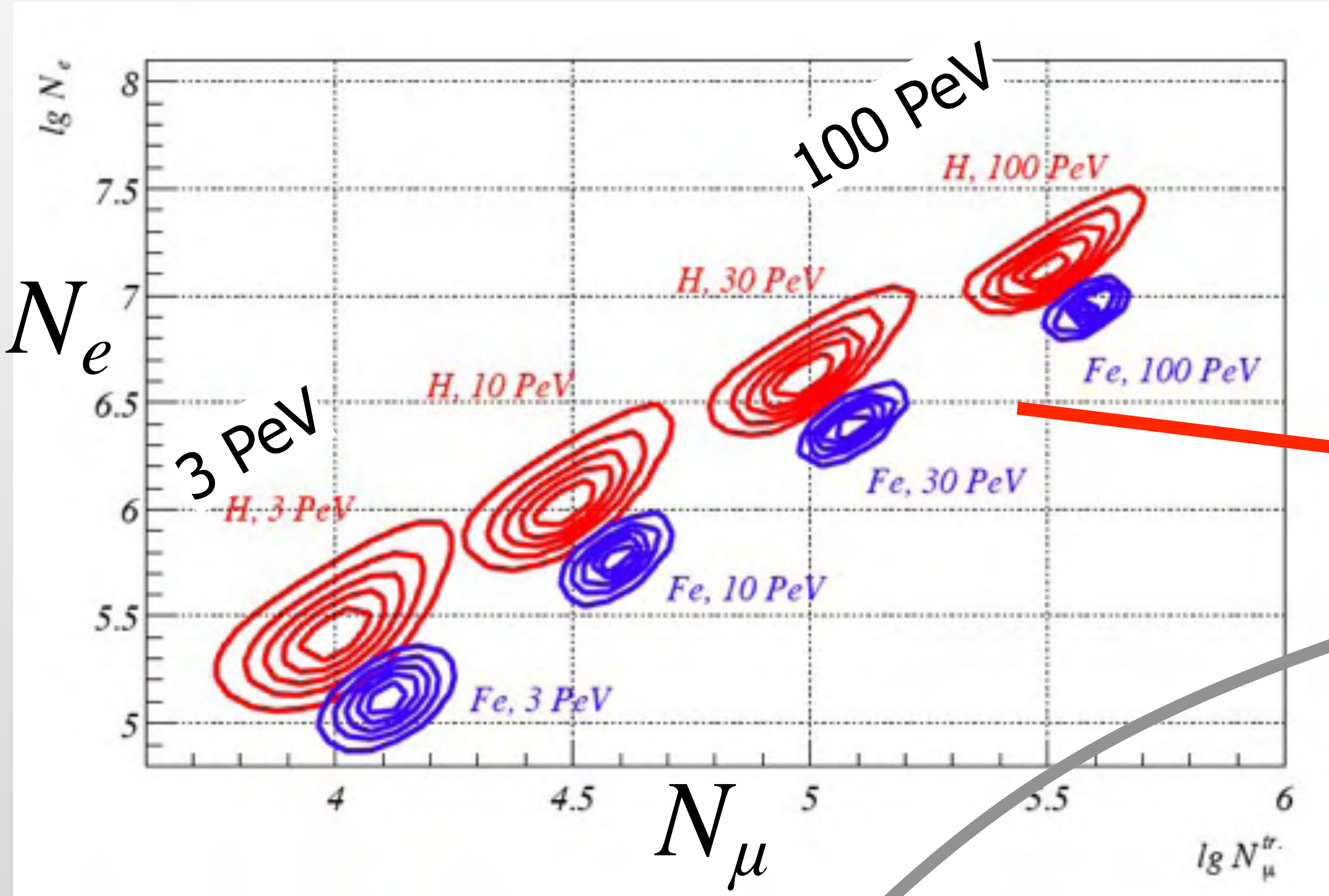
Simple principal component analysis not good enough !



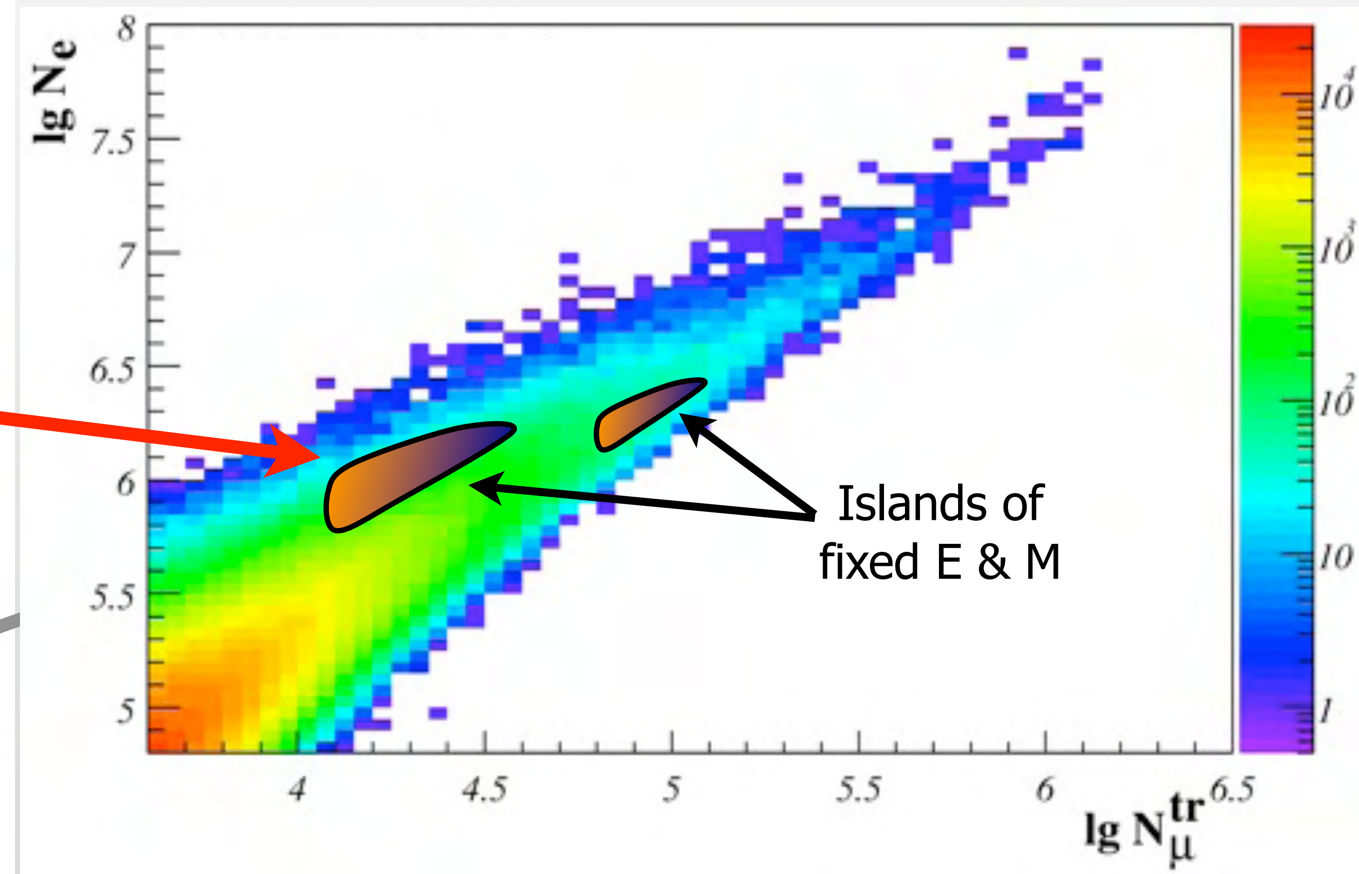
CORSIKA Simulations

(N_e , N_μ) ⇔ (Energy , Mass)

CORSIKA Simulations



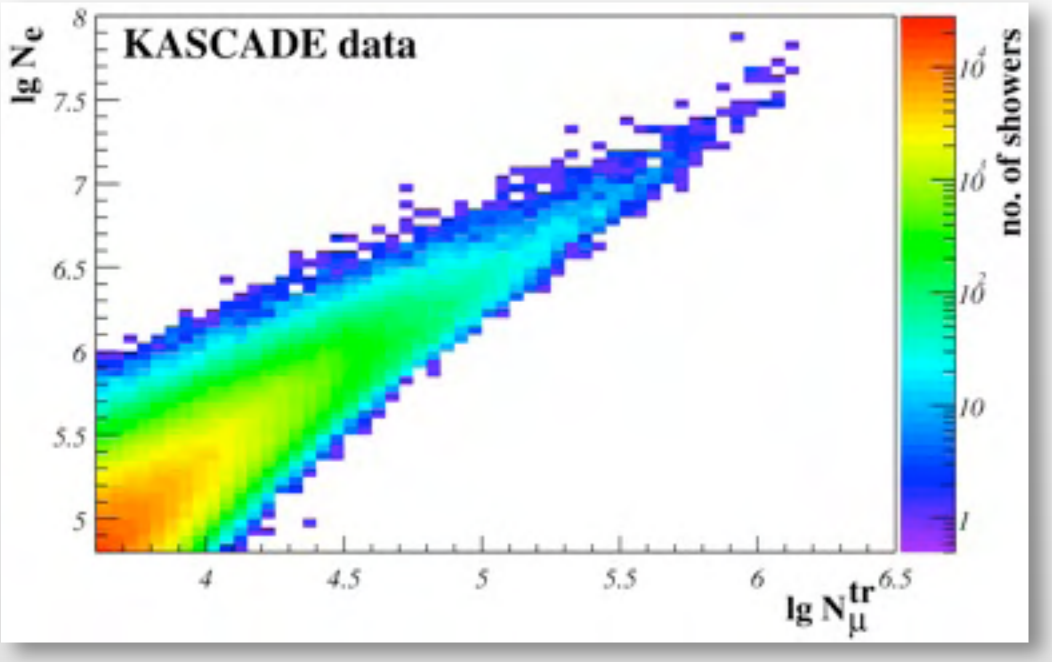
Data



2-dim N_e-N_μ distribution
⇔ system of
coupled Fredholm-Equations

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

2D-Histo as coupled Integral Eqns



No. of events N_i in each cell of 2D-Histo results from different primaries of various energies, i.e. each cell contains info about primary energy spectra:

$$N_i = 2\pi A_s T_m \sum_{A=1}^{N_A} \int_{0^\circ}^{18^\circ} \int_{-\infty}^{+\infty} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E}$$

$$\times\, p_A((\lg N_e, \lg N_\mu^{tr})_i \,|\, \lg E)$$

$$\times\, \sin\theta \cos\theta \,\mathrm{d}\lg E\, \mathrm{d}\theta$$

A_s: sampling area
T_m: measurement time
primary E-spectra

conditional probability to measure N_e and N_μ from primary of mass A & energy E

Note, p_A is an integral itself: $p_A = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} s_A \epsilon_A r_A \,\mathrm{d}\lg N_e^{true}\, \mathrm{d}\lg N_\mu^{tr,true}$

2D-Histo as coupled Integral Eqns

$$N_i = 2\pi A_\mathrm{s} T_\mathrm{m} \sum_{A=1}^{N_A} \int_{0^\circ}^{18^\circ} \int_{-\infty}^{+\infty} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E}$$

A_s: sampling area
T_m: measurement time
primary E-spectra

$$\times\, p_A((\lg N_\mathrm{e}, \lg N_\mu^\mathrm{tr})_i | \lg E)$$

conditional probability to measure N_e and N_μ from primary of mass A & energy E

$$\times\, \sin\theta \cos\theta \,\mathrm{d}\lg E \,\mathrm{d}\theta$$

Note, p_A is an integral itself: $p_A = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} s_A \epsilon_A r_A \,\mathrm{d}\lg N_\mathrm{e}^\mathrm{true} \,\mathrm{d}\lg N_\mu^\mathrm{tr,true}$

$s_A = s_A(\lg N_\mathrm{e}^\mathrm{true}, \lg N_\mu^\mathrm{tr,true} | \lg E)$ describes intrinsic shower fluctuations

integration over zenith angle can be incorporated in s_A

$\epsilon_A = \epsilon_A(\lg N_\mathrm{e}^\mathrm{true}, \lg N_\mu^\mathrm{tr,true})$ describes detection & reconstr. efficiency

$r_A = r_A((\lg N_\mathrm{e}, \lg N_\mu^\mathrm{tr})_i | \lg N_\mathrm{e}^\mathrm{true}, \lg N_\mu^\mathrm{tr,true})$

ε_A and r_A do not depend on zenith angle

describes properties of reconstr. procedure, i.e. systematics

I.e.: 2D-Histo can be understood as system of coupled integral eqns

2D-Histo as coupled Integral Eqns

$$N_i = 2\pi A_\mathrm{s} T_\mathrm{m} \sum_{A=1}^{N_A} \int_{0^\circ}^{18^\circ} \int_{-\infty}^{+\infty} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E}$$

$$\times\, p_A((\lg N_\mathrm{e}, \lg N_\mu^\mathrm{tr})_i | \lg E)$$

$$\times \sin\theta \cos\theta \,\mathrm{d}\lg E\, \mathrm{d}\theta$$

$$\Rightarrow \quad N_i = A_\mathrm{s} T_\mathrm{m} \Delta\Omega \sum_{A=1}^{N_A} \int_{-\infty}^{+\infty} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E}$$

$$\times\, p_A((\lg N_\mathrm{e}, \lg N_\mu^\mathrm{tr})_i | \lg E) \,\mathrm{d}\lg E$$

$$\Rightarrow \quad N_i = \sum_{A=1}^{N_A} \sum_{j=1}^{n} R_{ij}^A x_j^A$$

the integral written as sum over n energy intervals

2D-Histo as coupled Integral Eqns

$$\Rightarrow \quad N_i = \sum_{A=1}^{N_A} \sum_{j=1}^{n} R_{ij}^A x_j^A$$

the integral written as sum over n energy intervals

with $$x_j^A = A_\mathrm{s} T_\mathrm{m} \Delta\Omega \int_{\lg E_j}^{\lg E_j + \Delta \lg E} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E} \mathrm{d}\lg E$$

and $$R_{ij}^A = \frac{\int_{\lg E_j}^{\lg E_j + \Delta \lg E} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E} p_A((\lg N_\mathrm{e}, \lg N_\mu^\mathrm{tr})_i | \lg E) \mathrm{d}\lg E}{\int_{\lg E_j}^{\lg E_j + \Delta \lg E} \frac{\mathrm{d}J_A}{\mathrm{d}\lg E} \mathrm{d}\lg E}$$

as matrix eq.

$$\Rightarrow \quad \vec{Y} = \sum_{A=1}^{N_A} \mathbf{R^A} \vec{X}^A \quad \text{with } \vec{X}^A = \begin{pmatrix} x_1^A \\ x_2^A \\ \vdots \end{pmatrix} \quad \text{and} \quad \vec{Y} = \begin{pmatrix} N_1 \\ N_2 \\ \vdots \end{pmatrix}$$

2D-Histo as coupled Integral Eqns

as matrix eq.

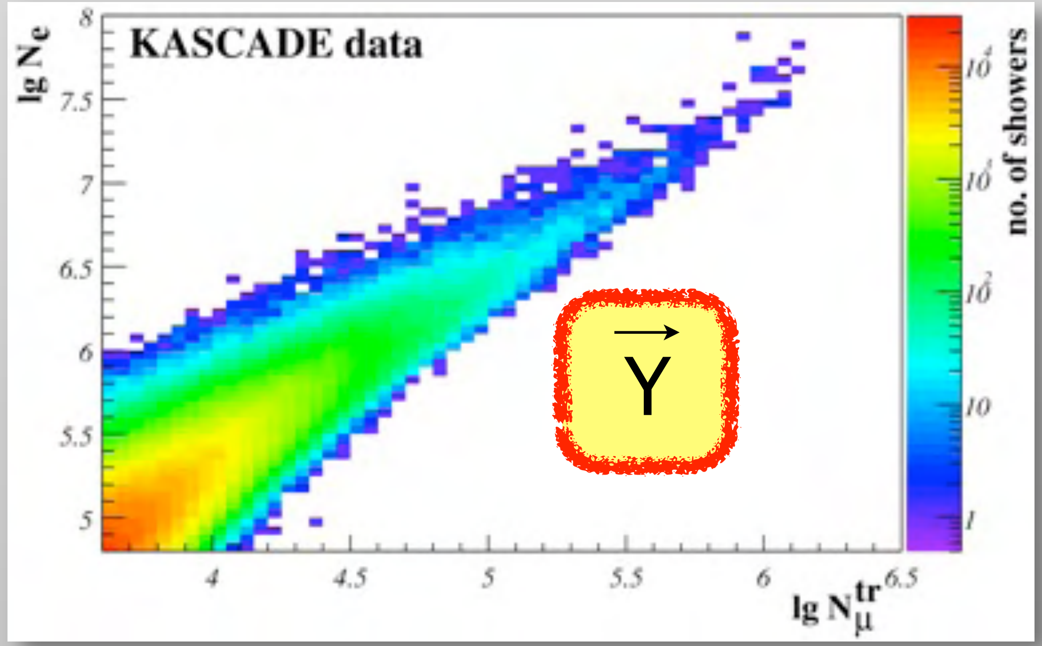
$$\Rightarrow \quad \vec{Y} = \sum_{A=1}^{N_A} \mathbf{R}^{\mathbf{A}} \vec{X}^A \quad \text{with } \vec{X}^A = \begin{pmatrix} x_1^A \\ x_2^A \\ \vdots \end{pmatrix} \quad \text{and} \quad \vec{Y} = \begin{pmatrix} N_1 \\ N_2 \\ \vdots \end{pmatrix}$$

even more compact writing:

$$\Rightarrow \quad \vec{Y} = \mathbf{R}\vec{X} \qquad \text{with} \quad \mathbf{R} = \begin{pmatrix} \mathbf{R}^1 & \mathbf{R}^2 & \cdots \end{pmatrix} \quad \text{and} \quad \vec{X} = \begin{pmatrix} \vec{X}^1 \\ \vec{X}^2 \\ \vdots \end{pmatrix}$$

R^1, **R**^{2}, .. : response matrices of different primary mass groups

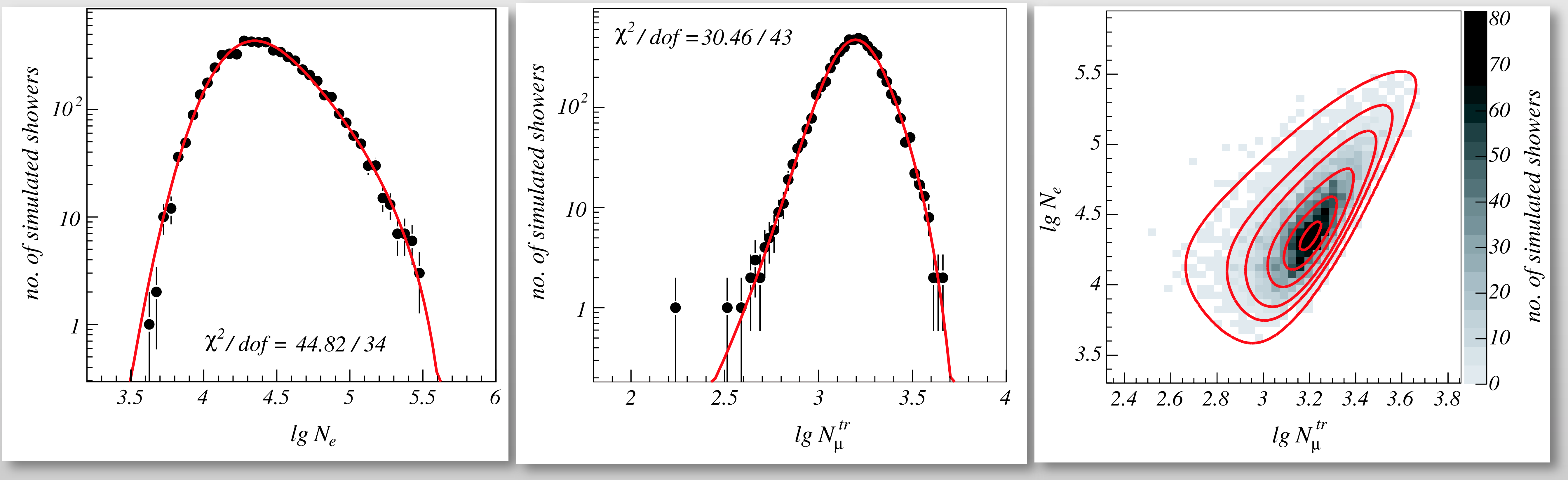
represents prim. energy spectra



Main Task: **Determination of transfer matrix R**

Determination of Transfer Matrix

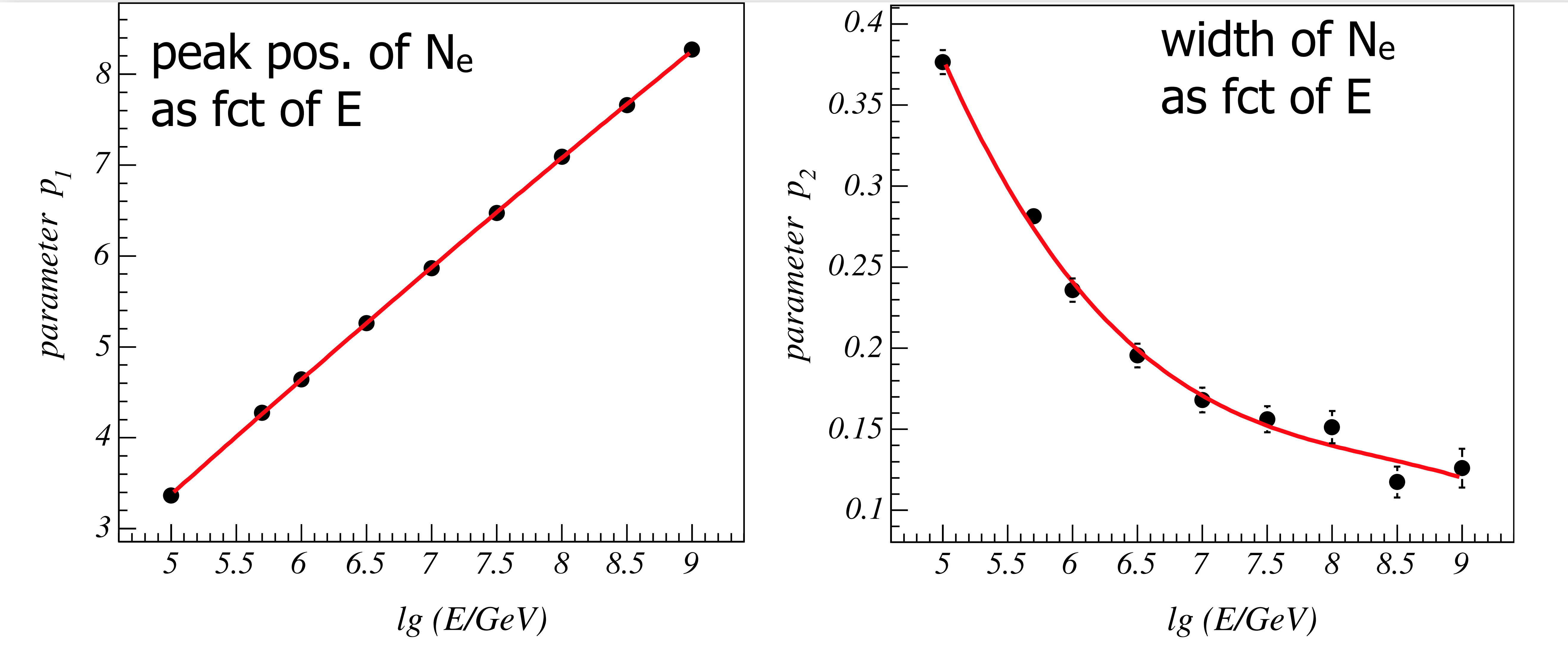
- We have chosen to simulated large no. of CORSIKA showers with fixed primary energies including full detector MC and event reconstruction algorithms.
- Obtained distributions have been parametrized with ‚appropriate' fit-functions



0.5 PeV protons (QGSJet)

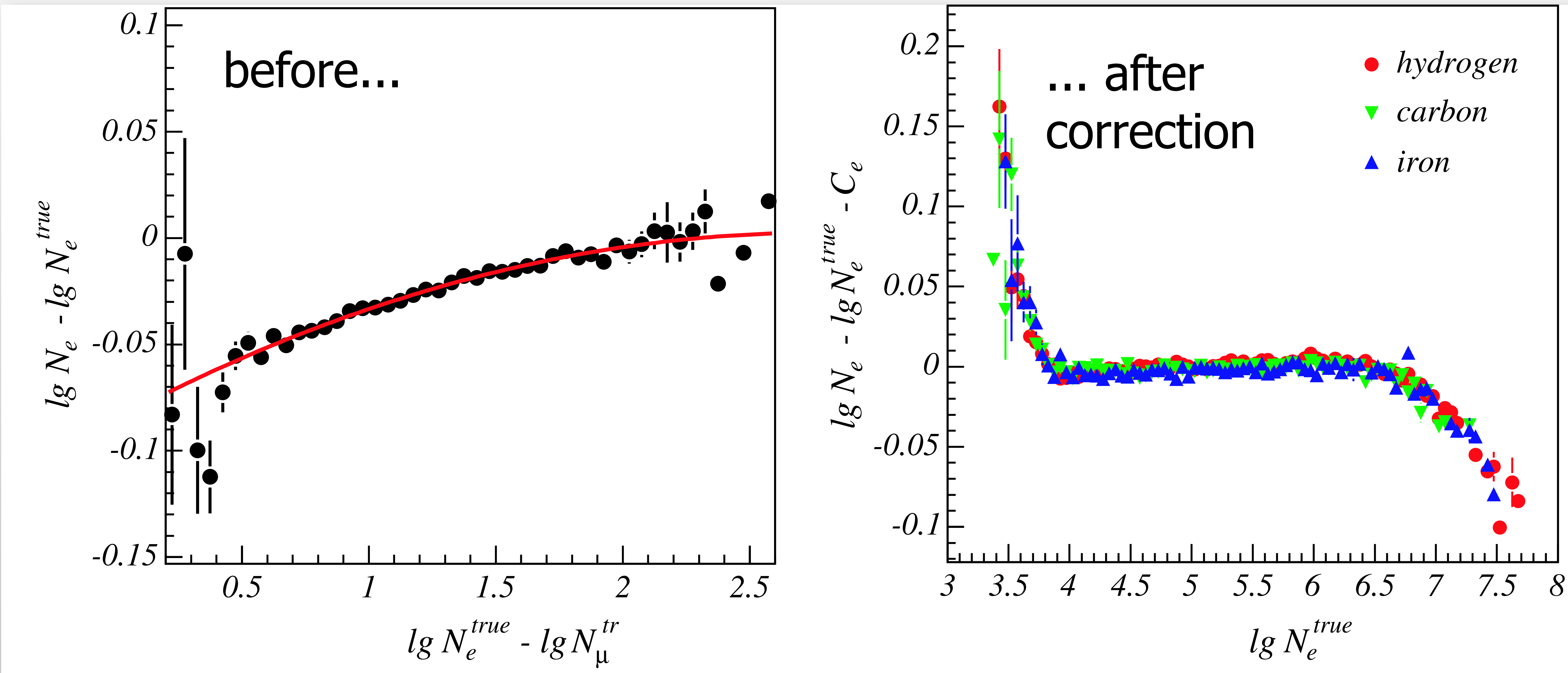
Determination of Transfer Matrix

- energy dependence of fit-parameters, e.g.:



Determination of Transfer Matrix

- correction of mass dependent systematic reconstruction offsets in N_e



Solving the Matrix Equation

Gold Algorithm to find $\vec{X}$ from $\vec{Y} = \mathbf{R}\vec{X}$

iterative procedure, requires modified $\vec{Y}_{mod}$ and Response Matrix $\tilde{\mathbf{R}}$, defined via diagonal matrix **C** containing statistical uncertainties of data

$$\tilde{\mathbf{R}} = \mathbf{R}^{\mathrm{T}}\mathbf{CCR} \quad \text{and} \quad \vec{Y}_{\mathrm{mod}} = \mathbf{R}^{\mathrm{T}}\mathbf{CC}\vec{Y}$$

$$\text{yielding} \quad \tilde{\mathbf{R}}\vec{X} = \vec{Y}_{\mathrm{mod}}$$

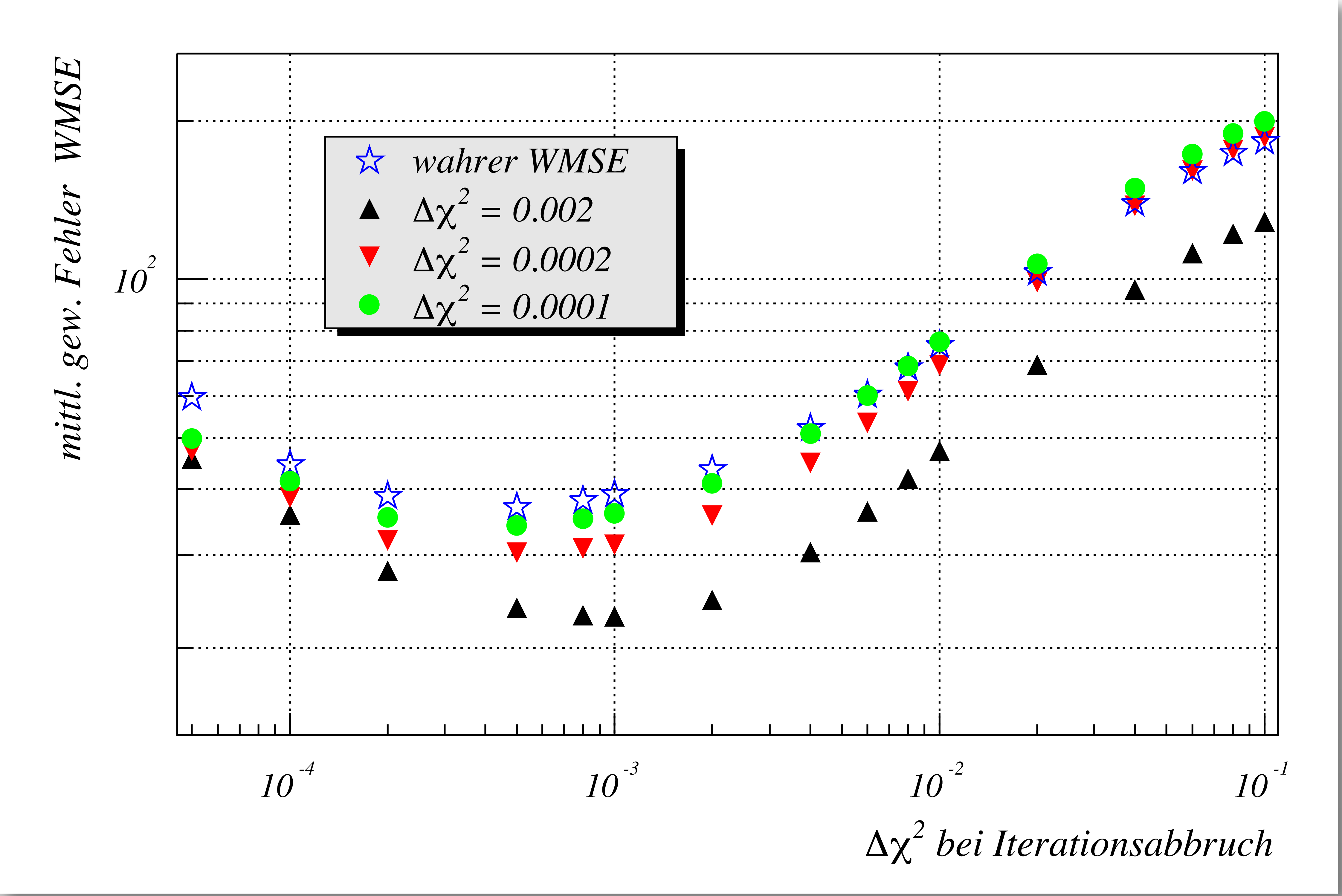
the estimated solution x_i in the k^{th} iteration reads:

$$x_i^{k+1} = \frac{x_i^k y_{\mathrm{mod},i}}{\sum_{j=1}^n \tilde{R}_{ij} x_j^k}$$

stopping criterion: minimize weighted mean square error (WMSE)

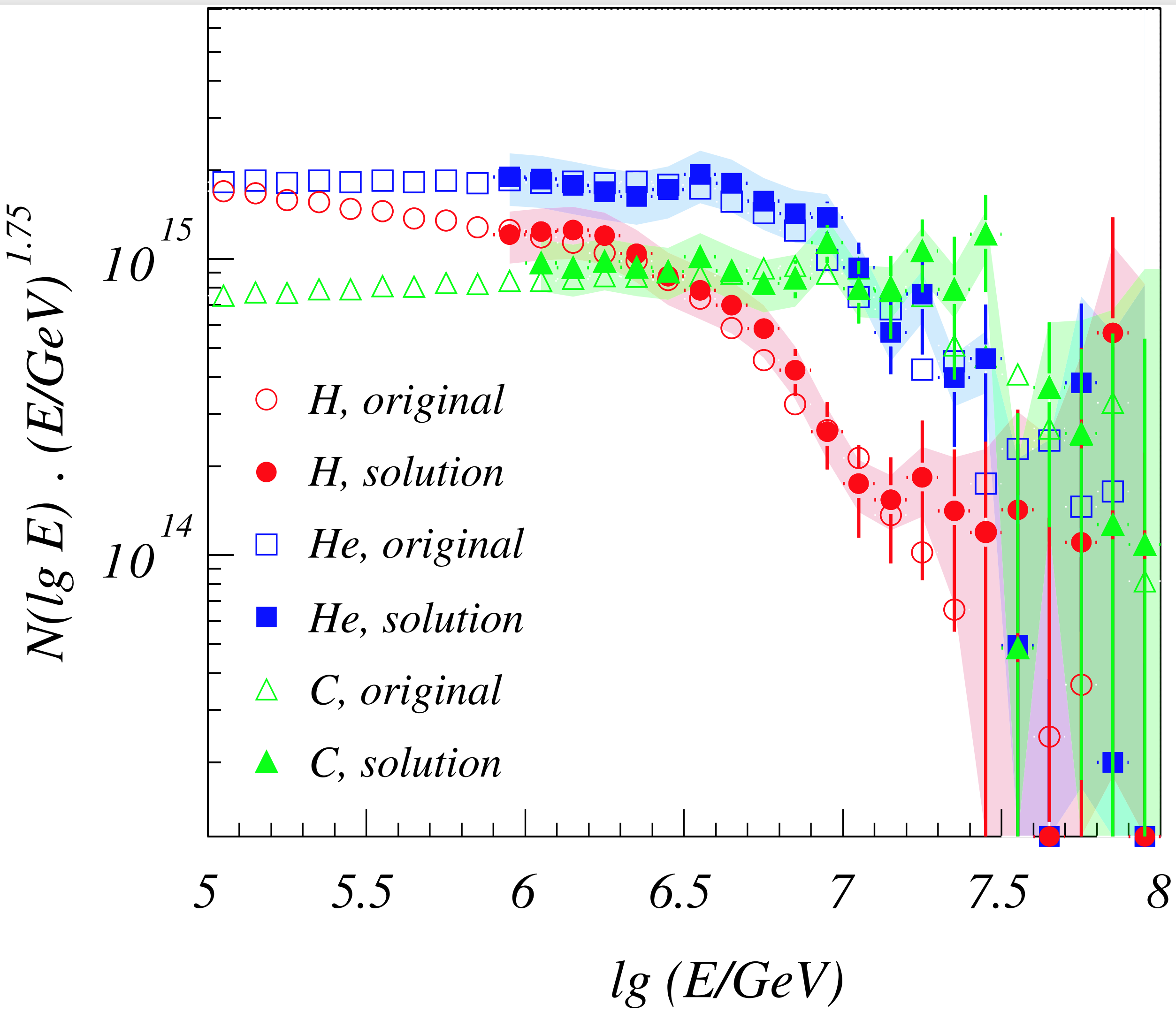
Bayesian based unfolding very similar

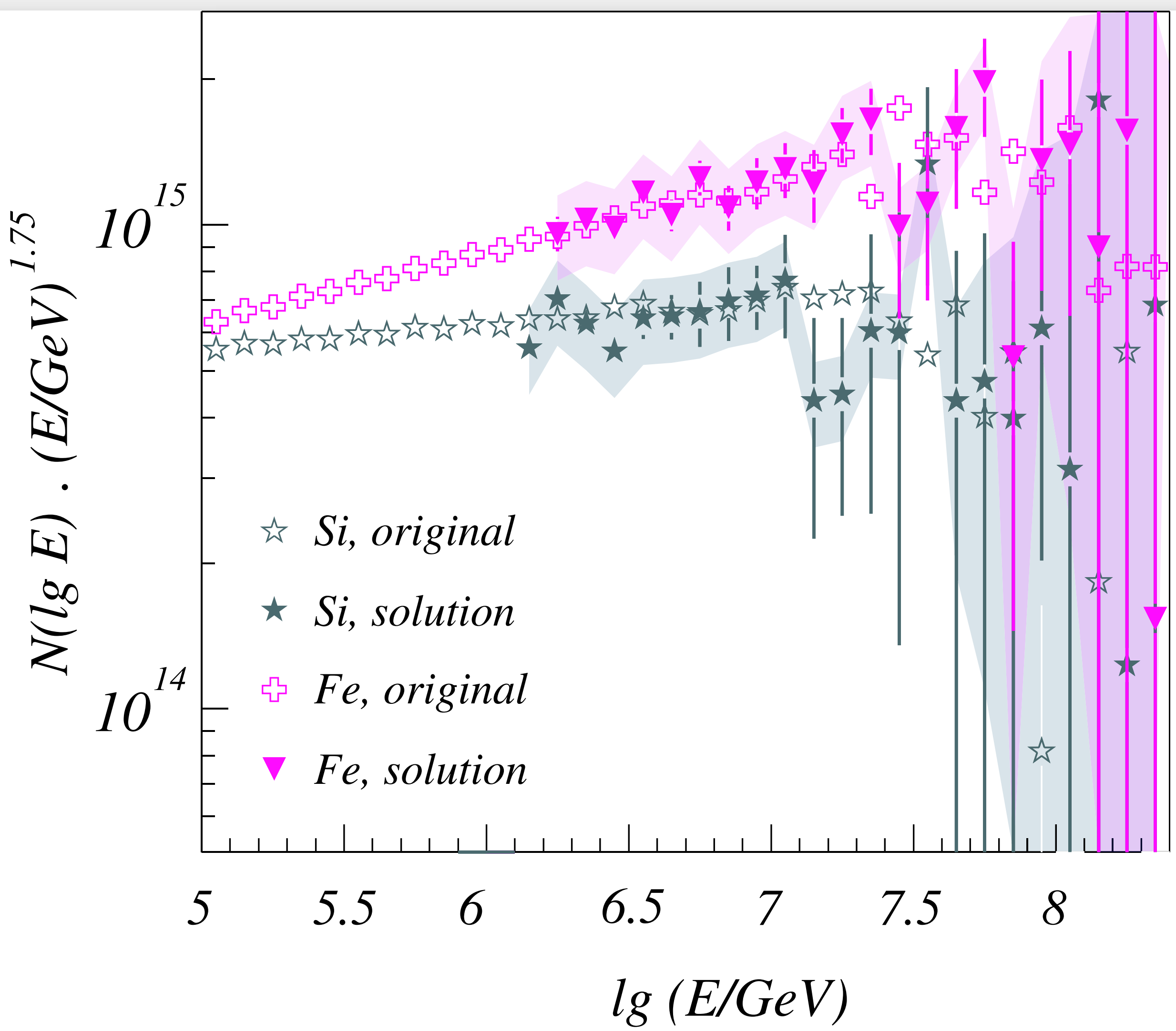
Stopping Criterion



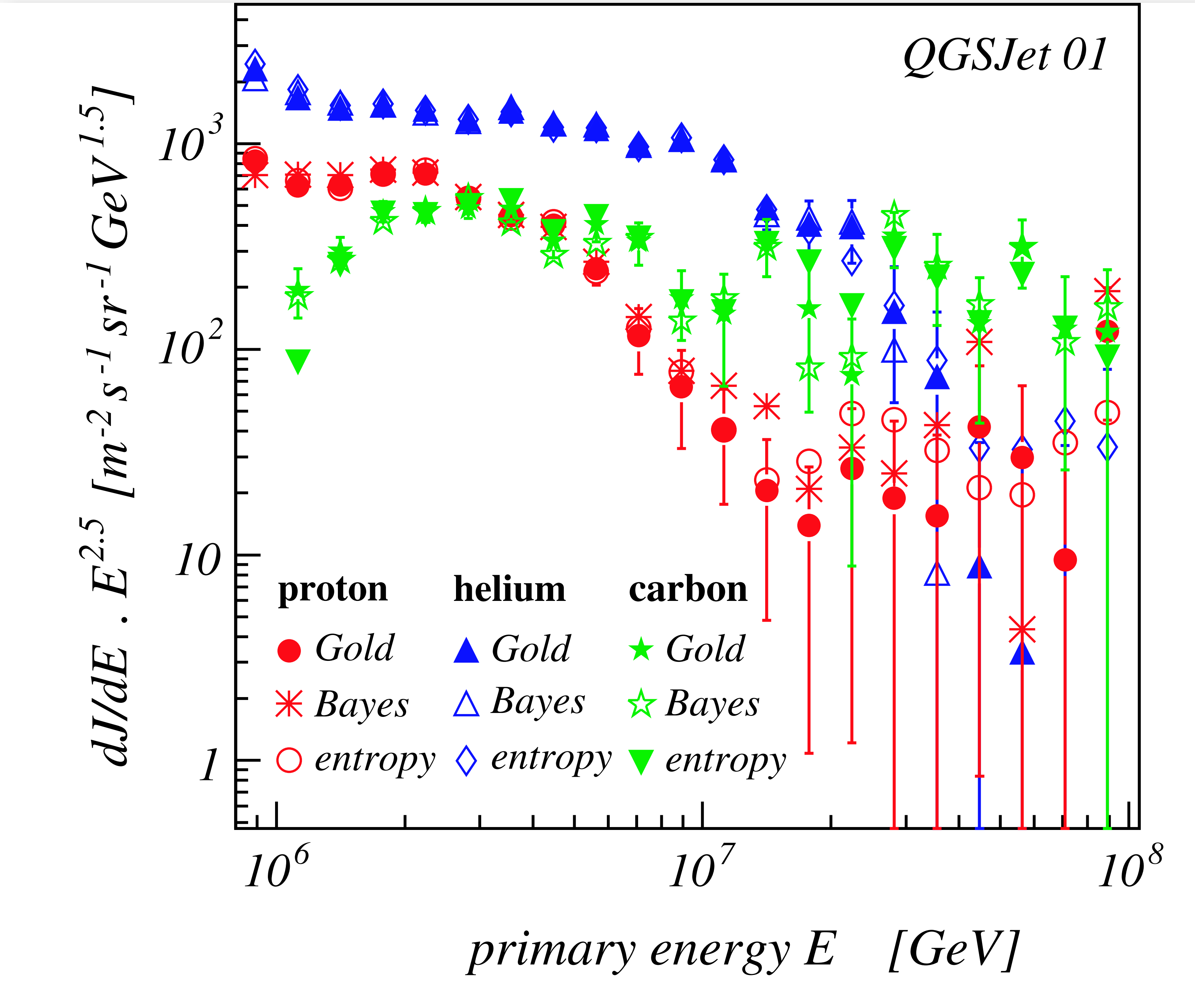
Test of Method

Use artificial input energy spectra
➛ generate N_μ-vs-N_e plot
➛ do unfolding to reproduce input spectra





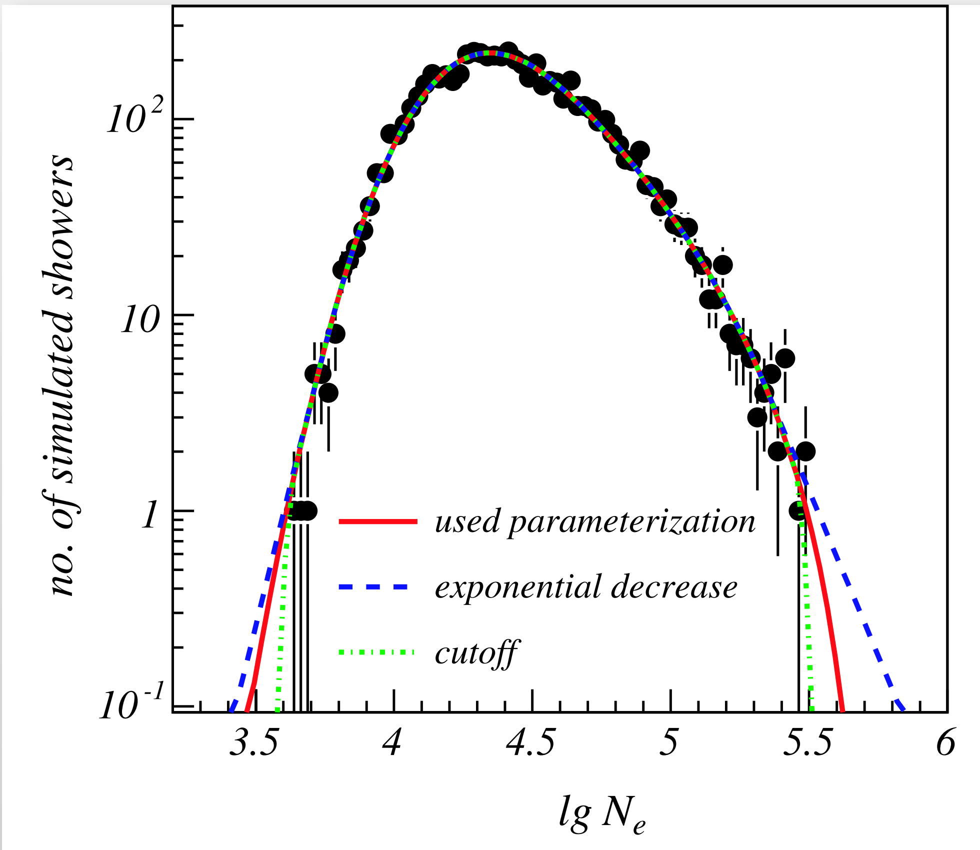
Comparing different Unfoldings

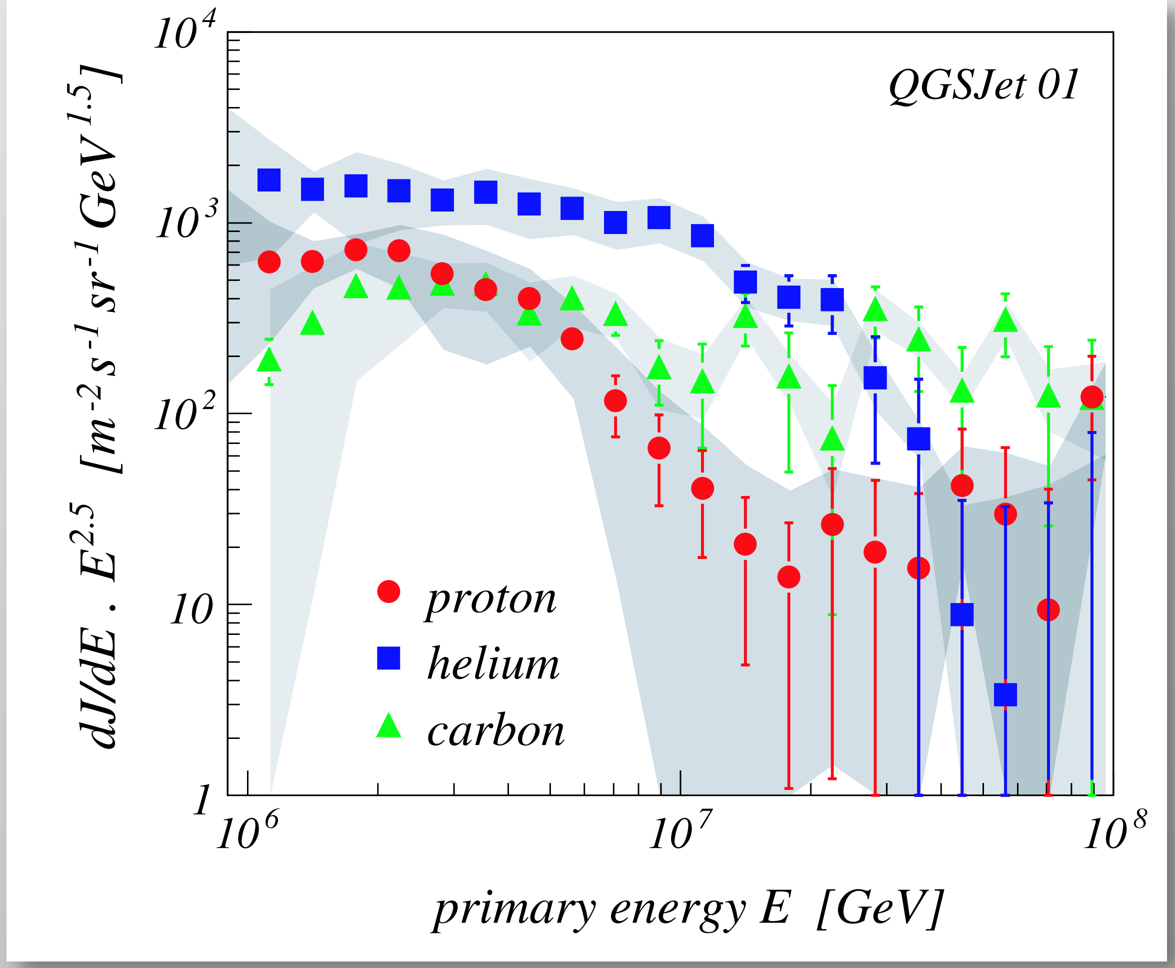


no significant differences between methods

Estimation of syst. Uncertainties

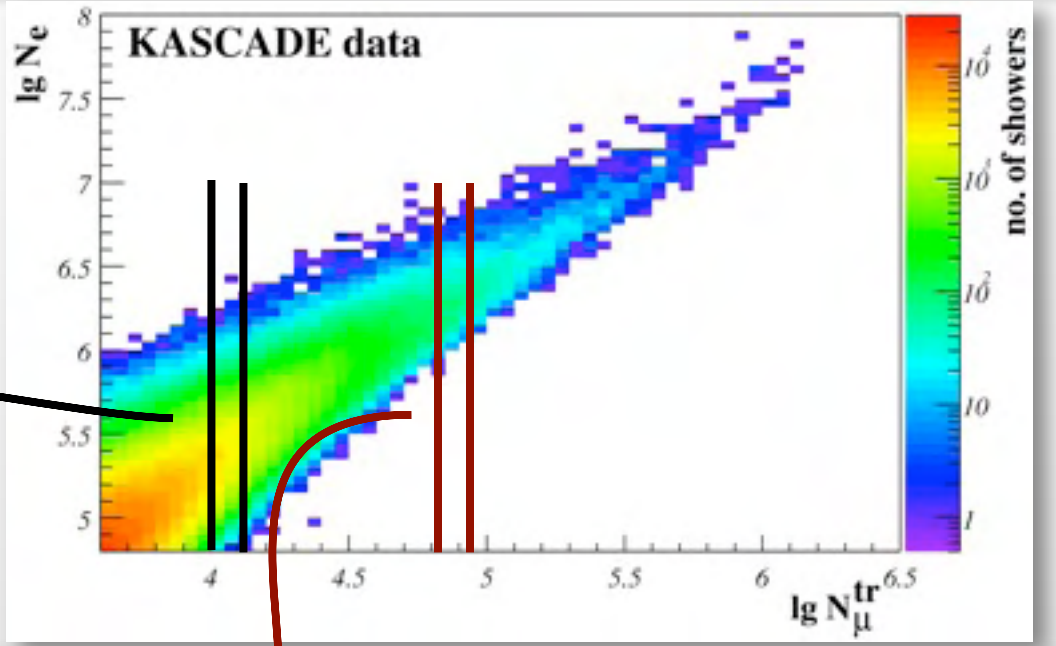
modify fit function or parameters of fit function to N_e and N_μ and redo unfolding:

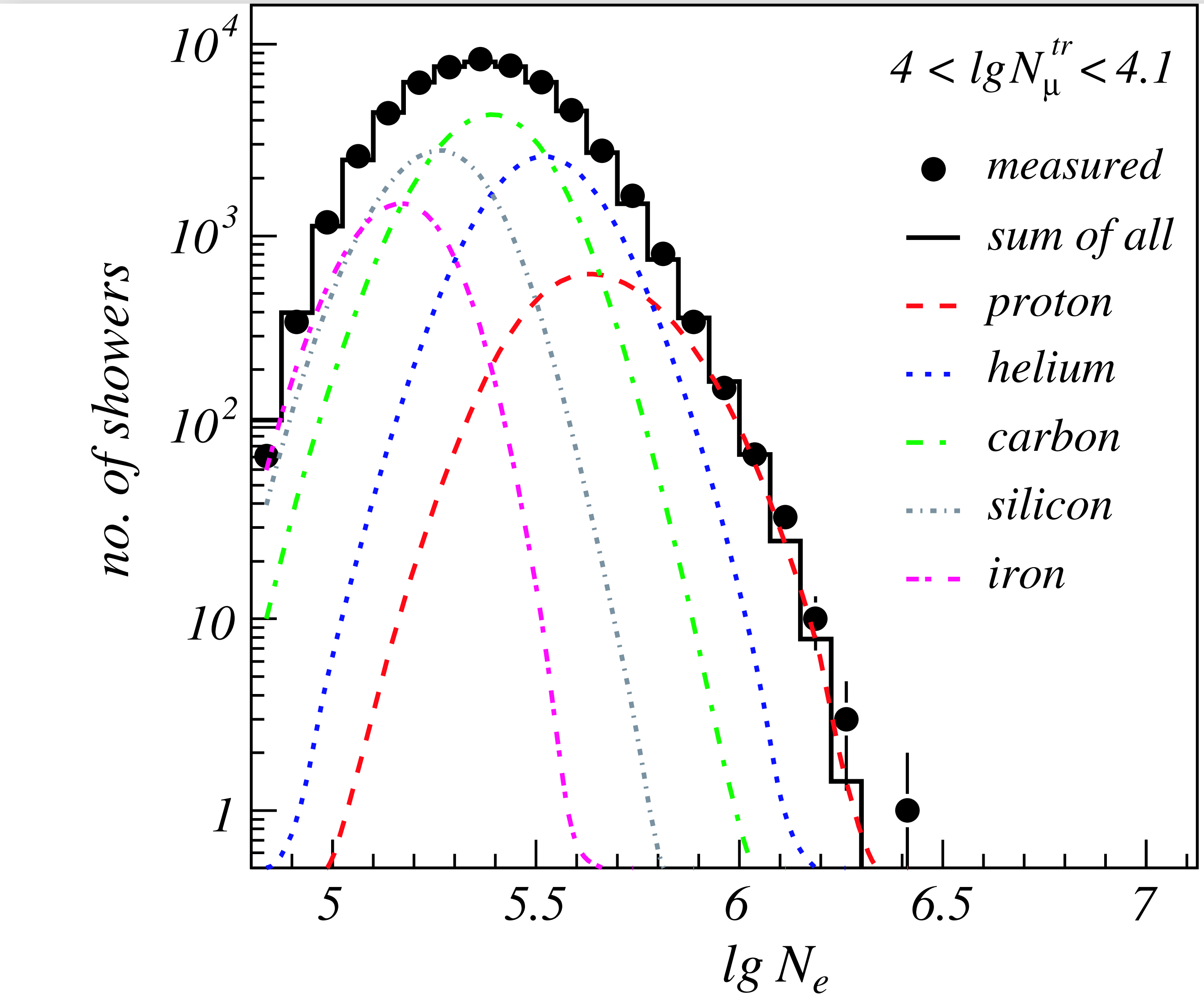


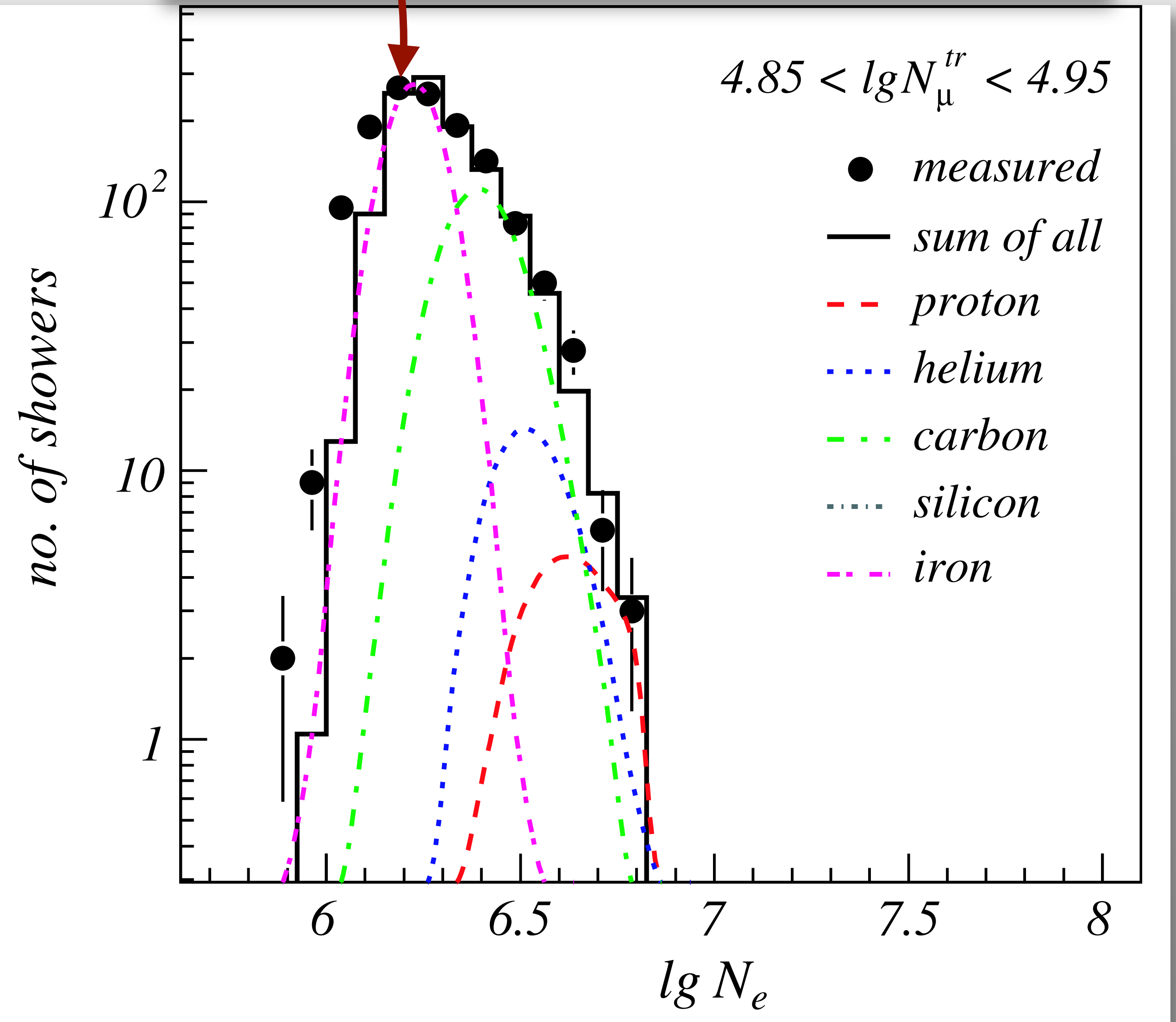


How Many Mass Groups to Reconstruct ?

if χ^2 doesn't improve when adding a new mass group, limit is reached
(more mass groups cause instabilities)







Comments/Summary

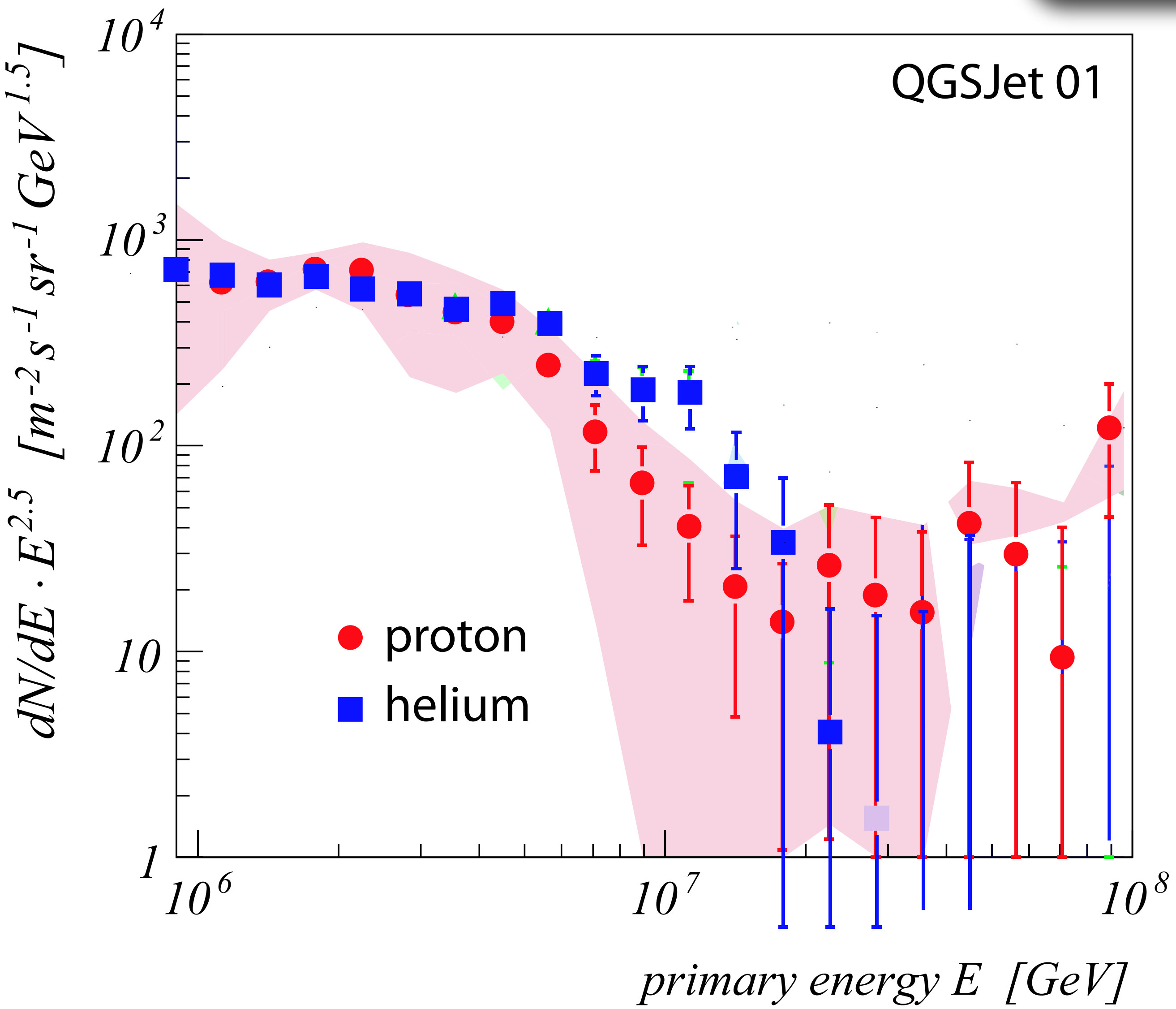
- two observables needed to reconstruct E & M by unfolding techniques
- good resolution & small fluctuations help a lot
- KASCADE: systematic uncertainties dominated by EAS simulations, not by data !
- 3 or more observables: unfolding technically possible, but highly complex
  - may be better to combine observables again and reduce to two
- event-by-event mass estimator only allows analysis of <A> as a fct of E, which is rather insensitive to tests of astrophysical models...
- ... but useful, e.g. for CR astronomy

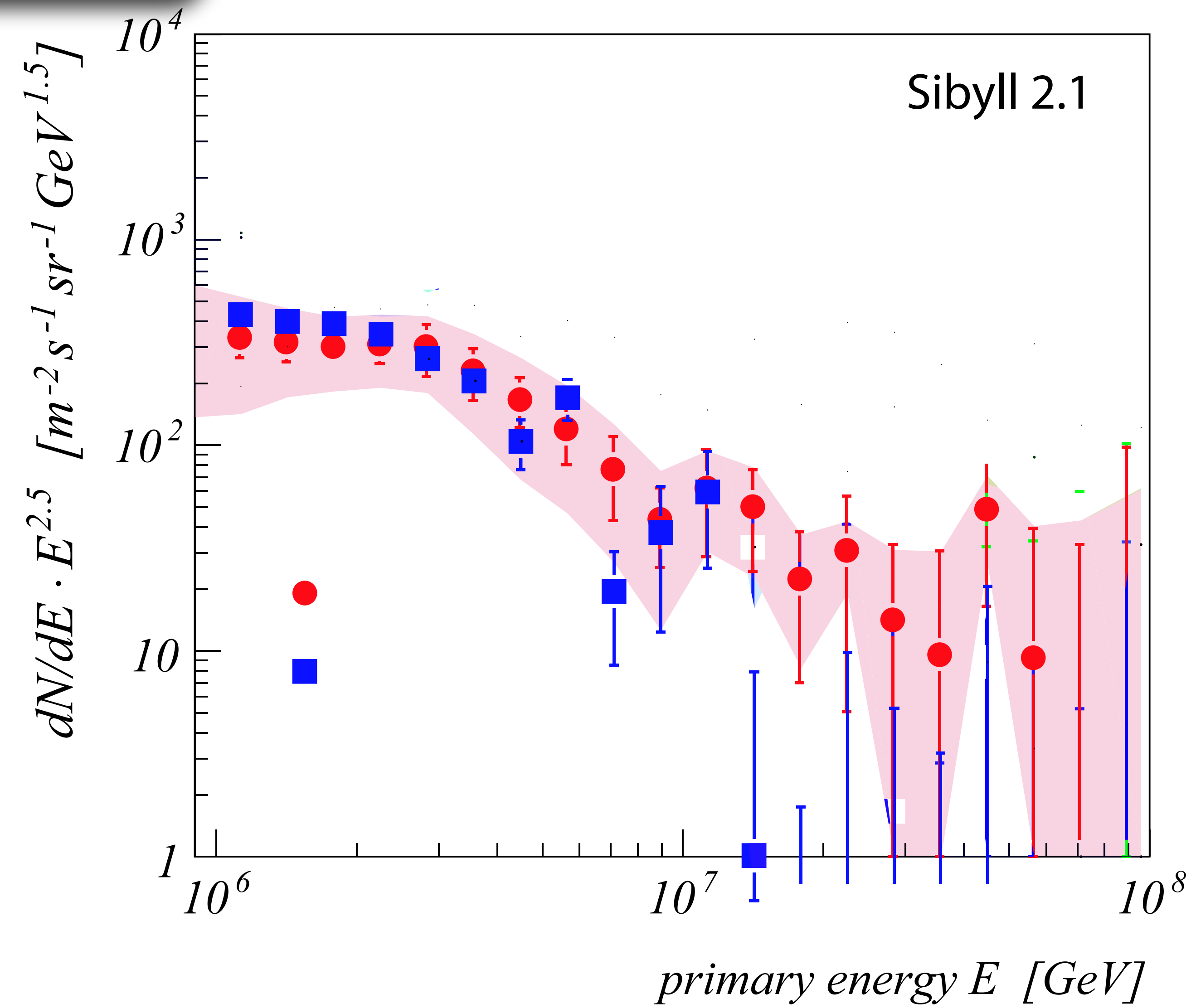
? E/Z or E/A ?

QGSJET

$E_{He}/2$

SYBILL





? E/Z or E/A ?

QGSJET

$E_{He}/4$

SYBILL