CRs in the 'Knee'-Region
– Some Results from KASCADE –

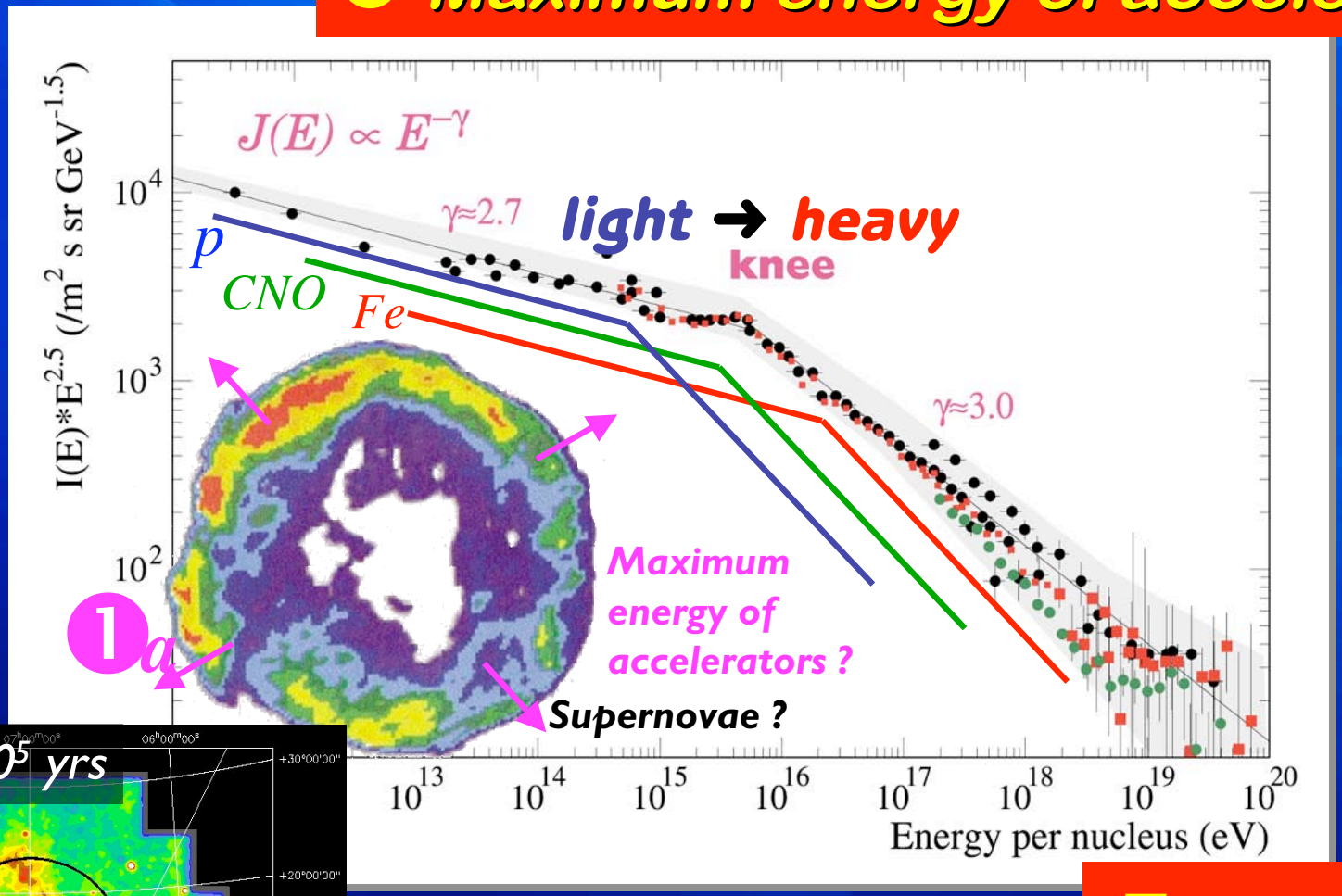
Karl-Heinz Kampert (University Wuppertal)
for the KASCADE-Collaboration

- *Astrophysics Motivation: Quest of the Knee*
- *Experimental*
- *Selected Results on:*
  - *Tests of high-energy interaction models*
  - *CR energy spectra & Composition*
  - *sources of systematic uncertainties*
- *Brief Status of KASCADE-Grande*
- *Perspectives*

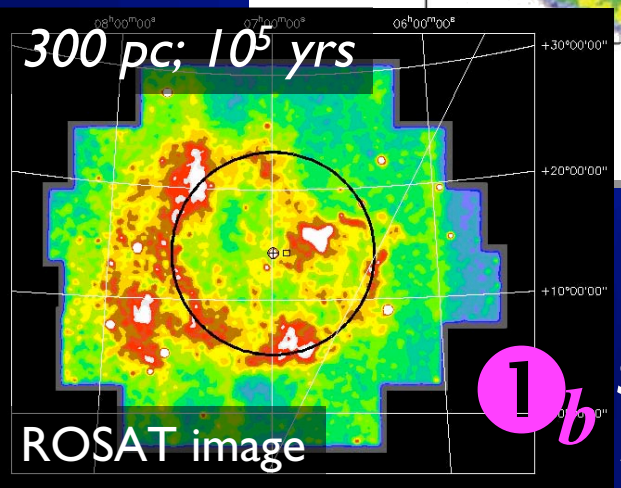
CRACOW EPIPHANY CONFERENCE ON ASTROPARTICLE PHYSICS
8 - 11 January 2004, Cracow, Poland

Origin of the "Knee" ??

❶ Maximum energy of accelerator ?



$$E_{max} \propto R \cdot B \cdot Z$$

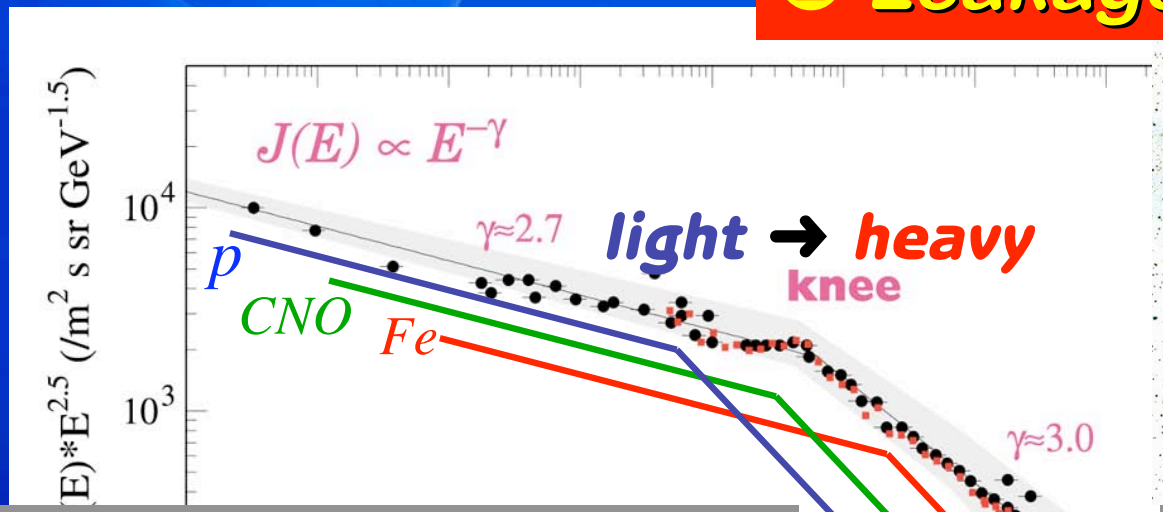


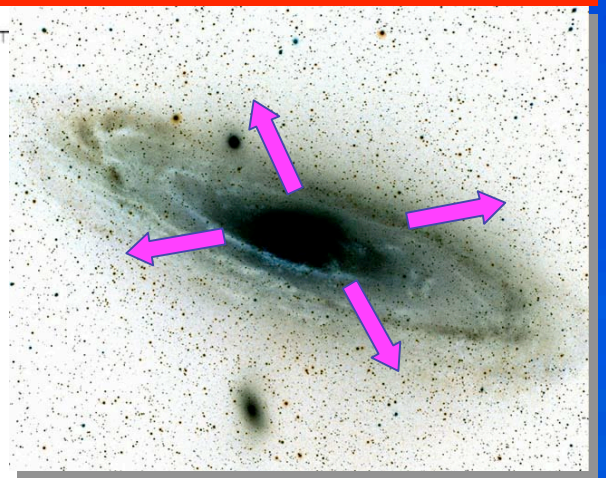
Single Source Model ? *(Erlykin & Wolfendale)*

Monogem Ring as prime candidate (Thorsett et al., ApJL 2003)

Origin of the "Knee" ??

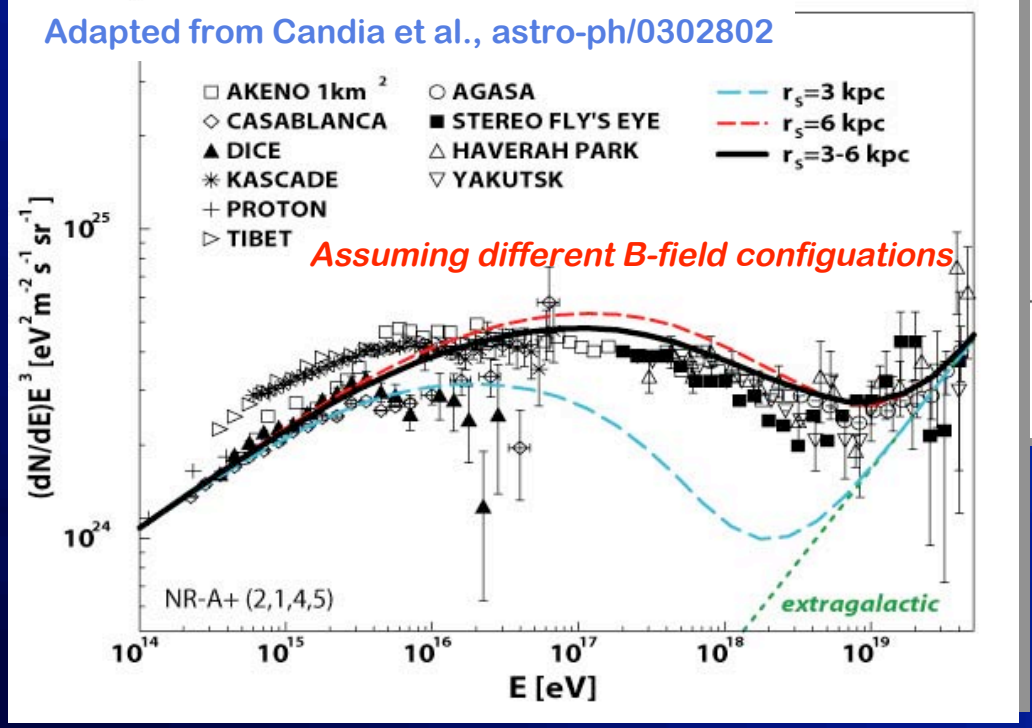
❷ Leakage from Galaxy ?





+ Anisotropies

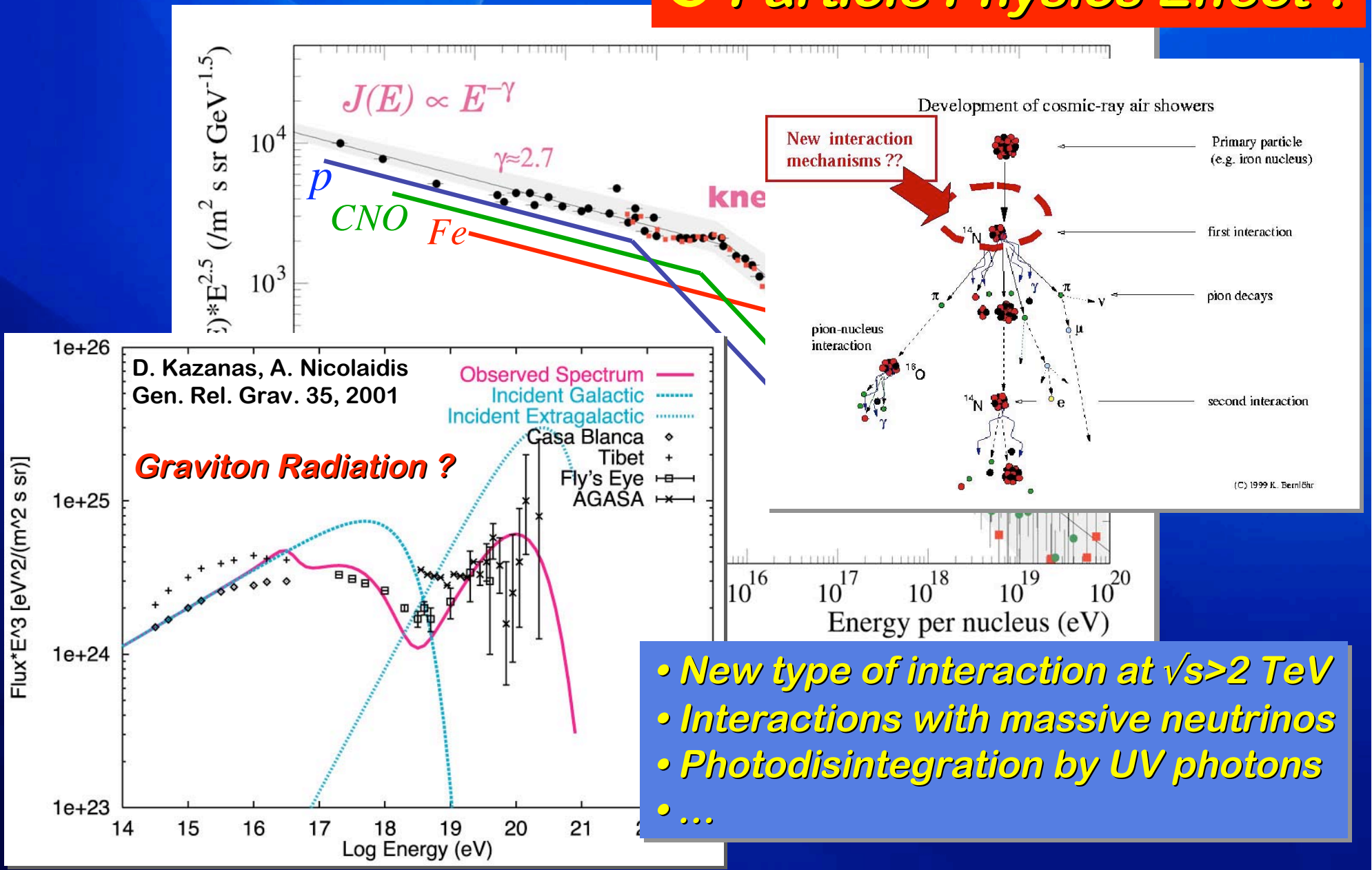
Adapted from Candia et al., astro-ph/0302802



$$E_{max} \propto R \cdot B \cdot Z$$

Origin of the "Knee" ??

❸ Particle Physics Effect ?



- New type of interaction at $\sqrt{s}$>2 TeV
- Interactions with massive neutrinos
- Photodisintegration by UV photons
- …

KASCADE

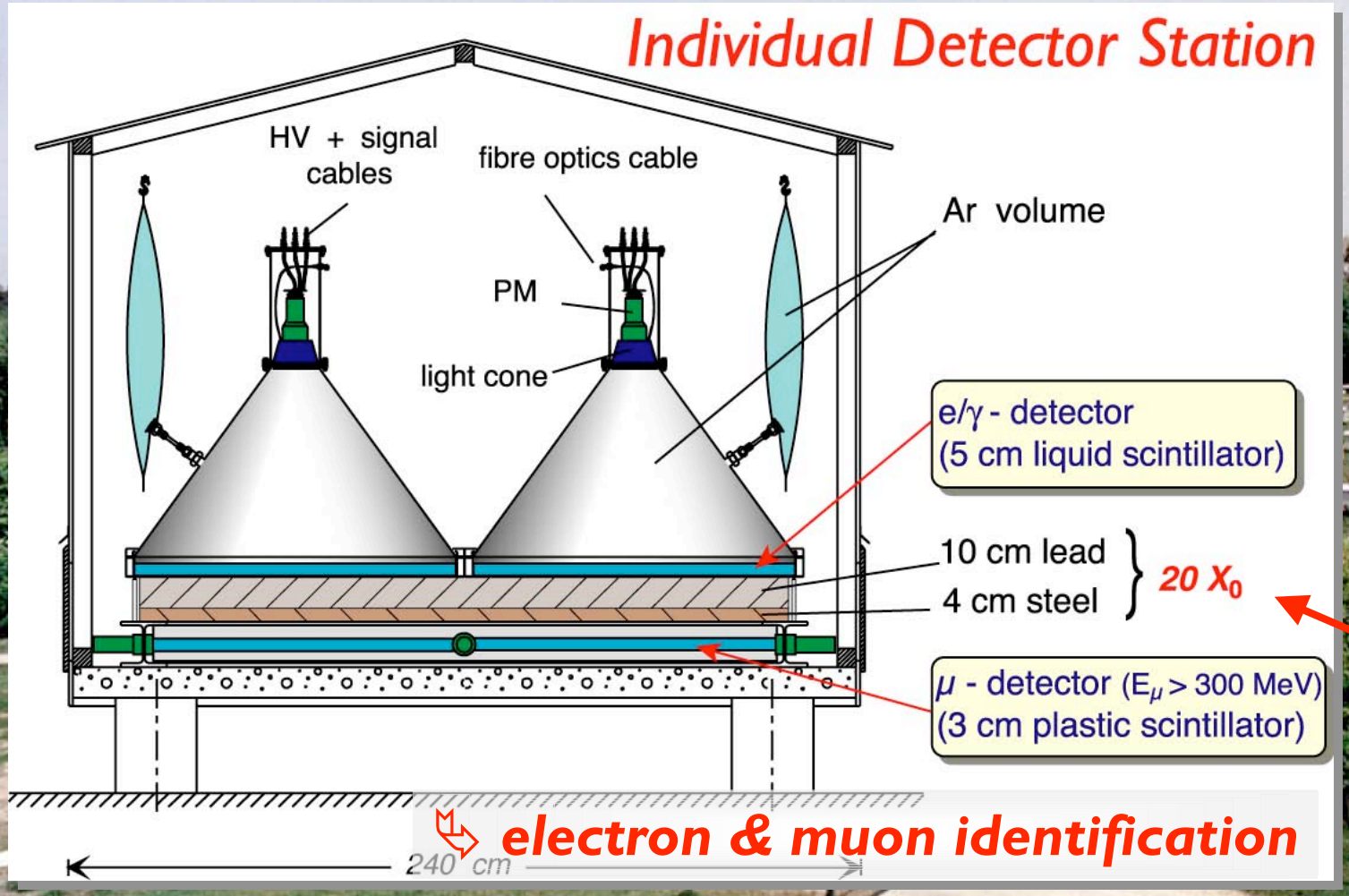
Nucl. Instr. Meth. A513 (2003) 490

(Karlsruhe Shower Core and Array Detector)

KASCADE

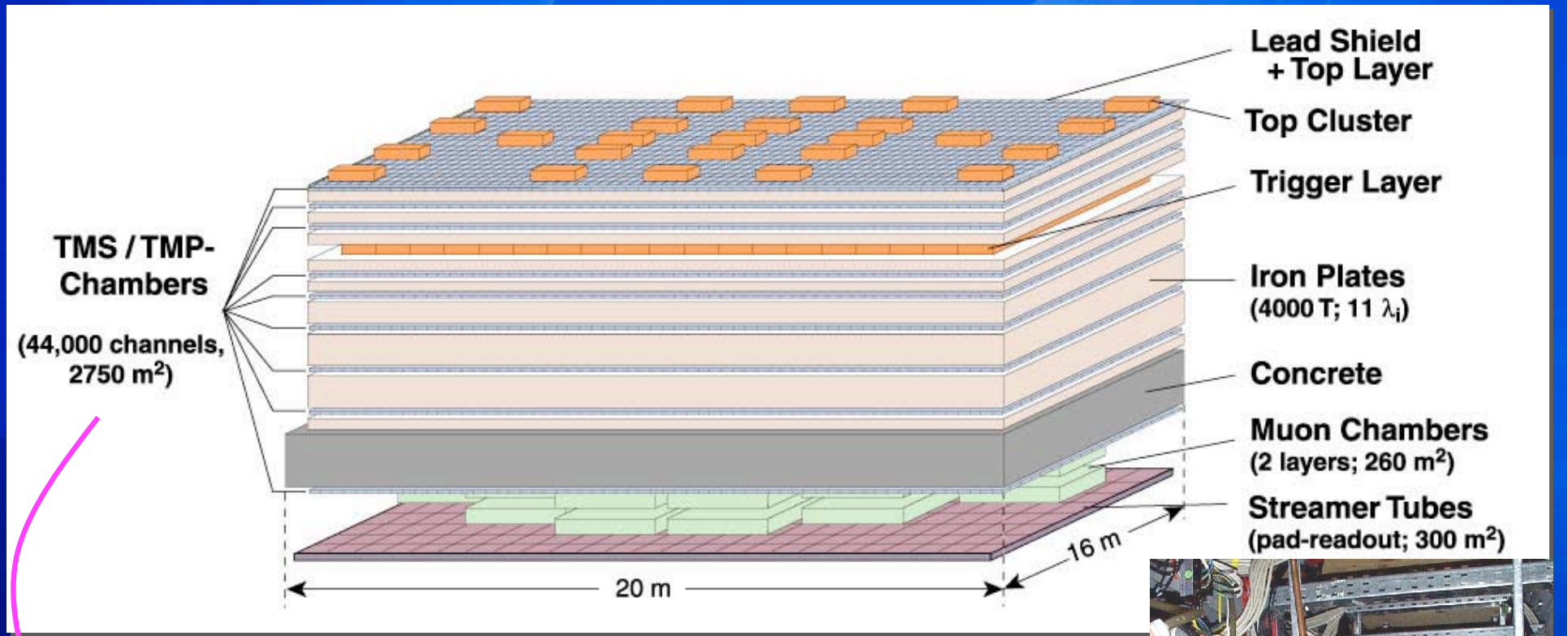
Nucl. Instr. Meth. A513 (2003) 490

(Karlsruhe Shower Core and Array Detector)

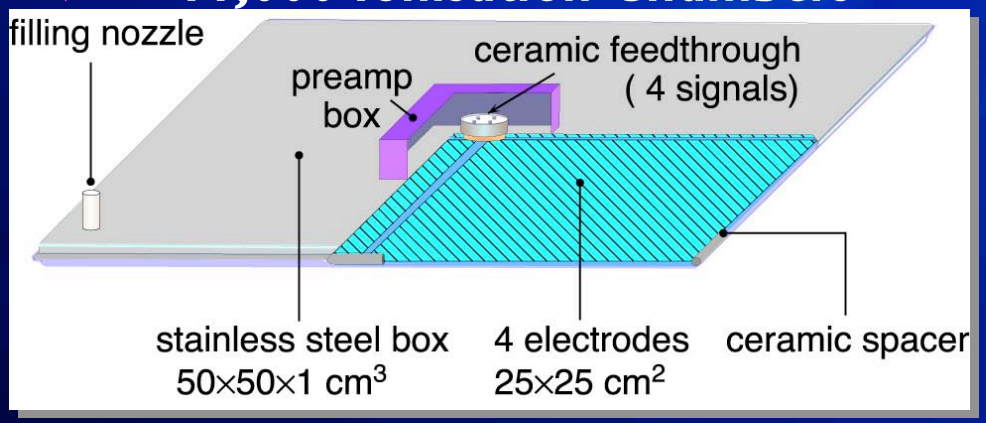


electron & muon identification

KASCADE Central Detector



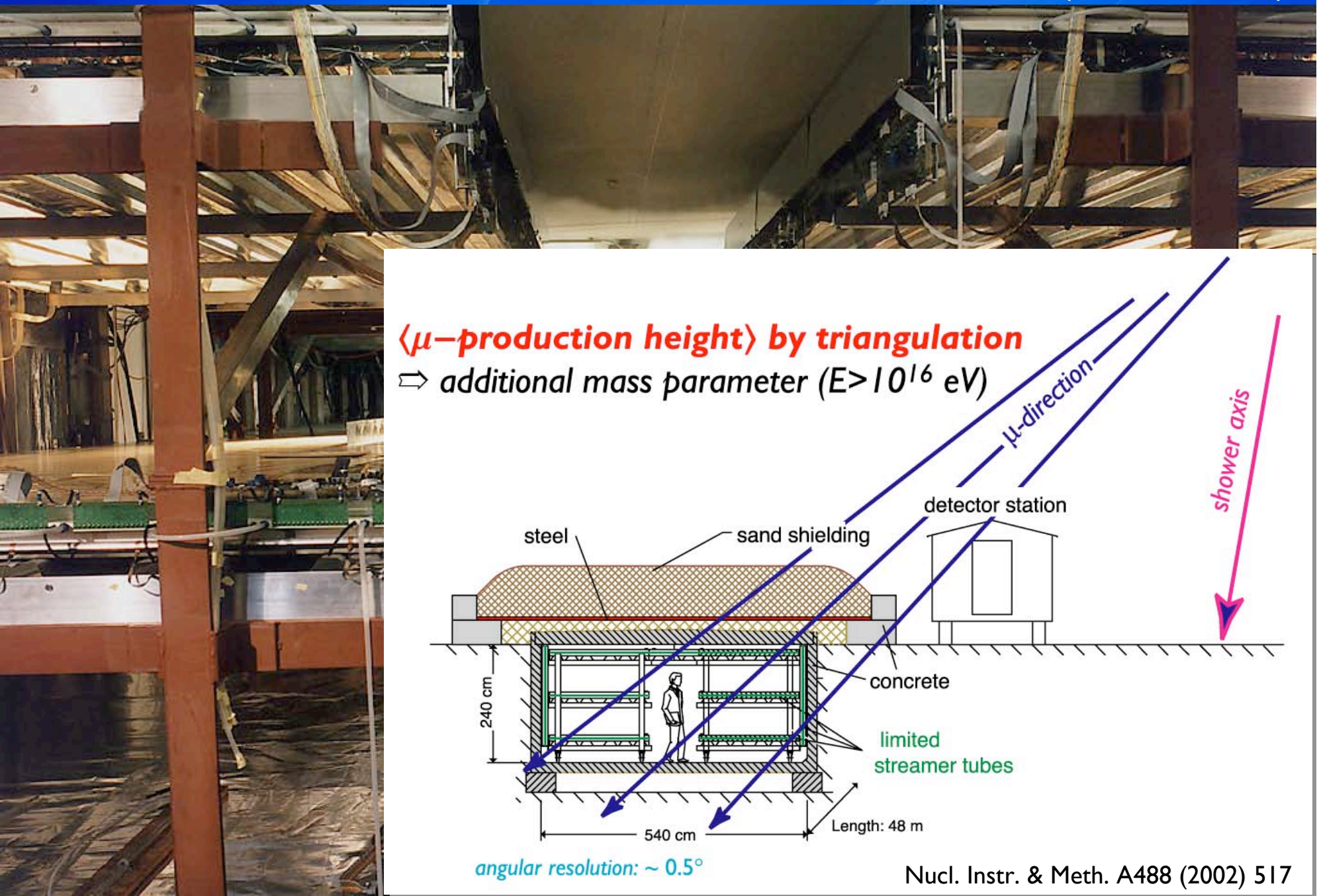
11,000 Ionisation Chambers



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

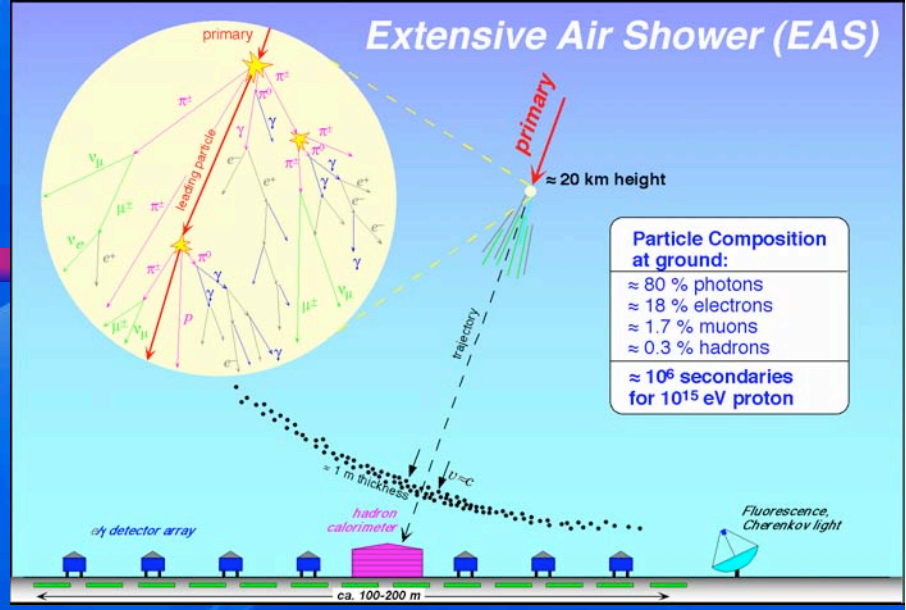
Myon-Tracking Detector

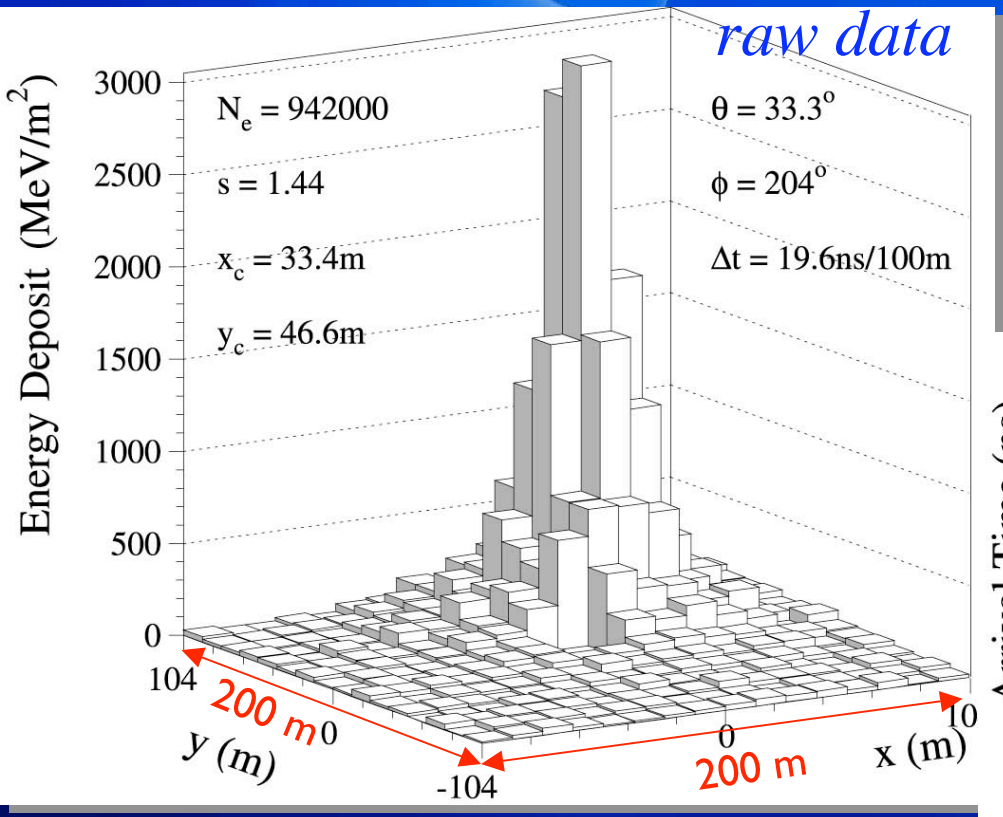
(50 × 5.5 m^2)

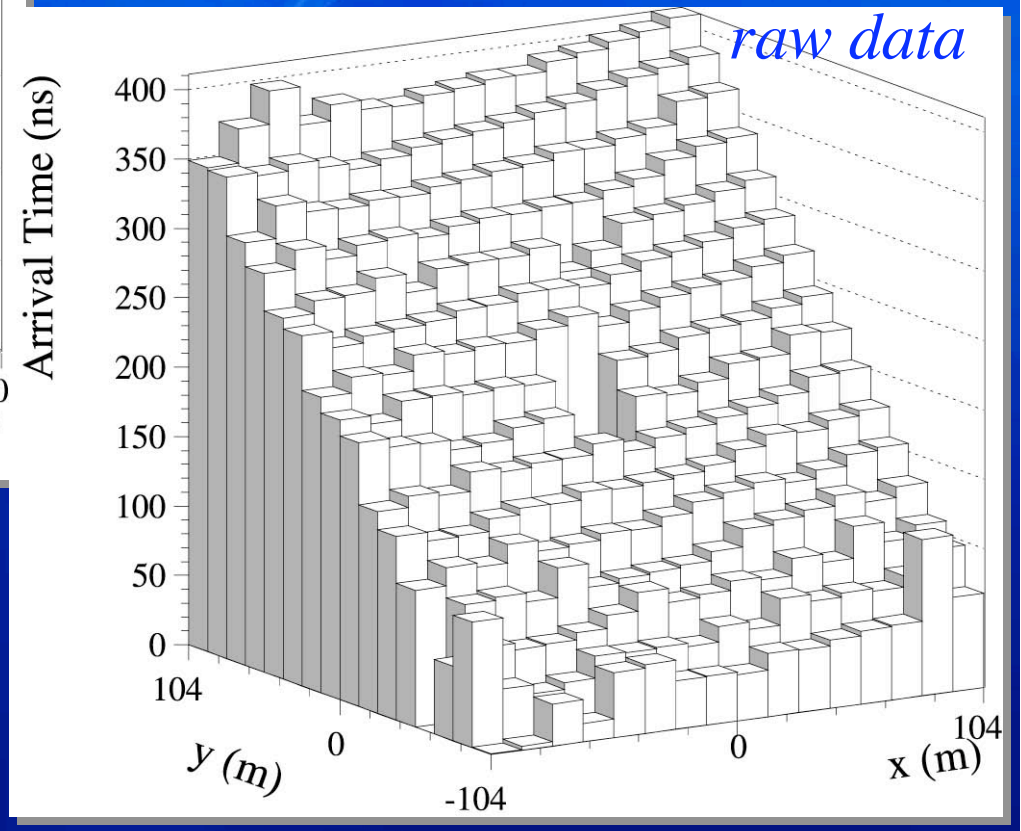


Nucl. Instr. & Meth. A488 (2002) 517

Single Airshower in e/γ-Detectors







particle density

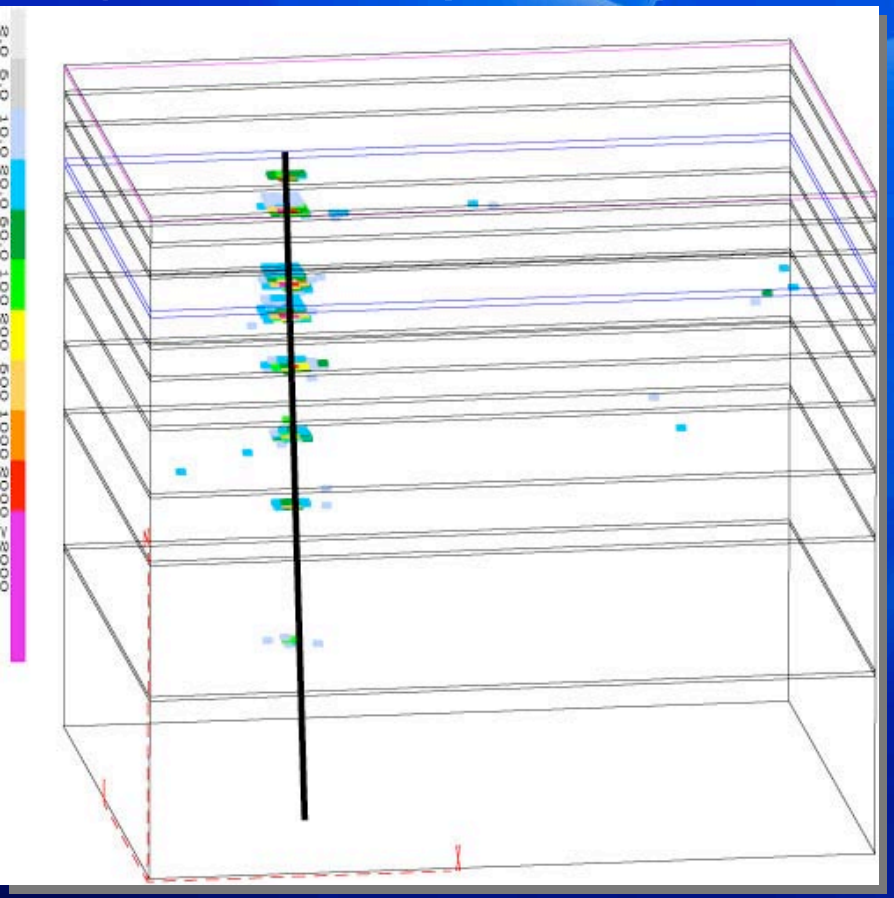
(200 x 200 m^2)

$E_0 \sim 10^{16}$ eV

arrival times

Single Events in Calorimeter...

Single Hadron (21 TeV)

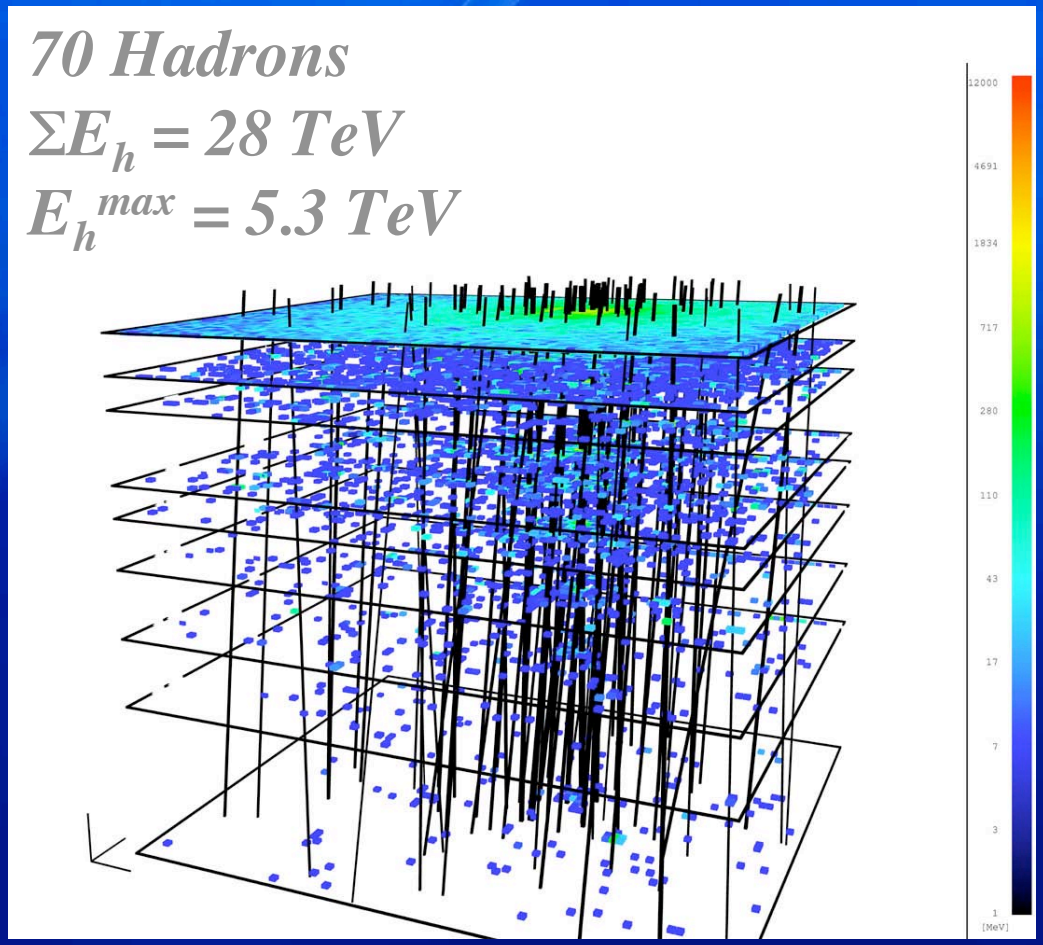


Hadrons (E>100 GeV) in Shower Core

70 Hadrons

$\Sigma E_h = 28\ TeV$

$E_h^{max} = 5.3\ TeV$



Observables of KASCADE per shower

- **from Detector Array**
  - *shower direction (θ,ϕ),*
  - *shower core (x,y)*
  - *electron size (N_e)*
  - *muon size (N_μ^{tr})*
  - *lateral particle distr. (s,R_m)*
- **from μ tracking Detector**
  - *μ size > 800 MeV (N_μ^{MTD})*
  - *local μ-density (ρ_μ)*
  - *lateral μ-distr. (s_μ,R_μ)*
  - *μ-production height (h_μ)*
- **from Calorimeter**
  - *number of hadrons with E > 100 GeV (N_h)*
  - *sum of hadronic energy (ΣE_h)*
  - *enerergy of leading hadron (E_h^{max})*
  - *parameters of spatial hadron distribution (R_h, λ, …)*
- **from MWPC system**
  - *# of μs > 2.2 GeV (N_μ^*)*
  - *local μ-density (ρ_μ)*
  - *hit pattern, 'spottiness'*
- **from trigger plane**
  - *# of μs > 490 MeV (N_μ^{tp})*
  - *local μ-density (ρ_μ)*
  - *particle arrival times (τ_μ)*

Observables of KASCADE per shower

- **from Detector Array**
  - shower direction (θ,ϕ),
  - shower core (x,y)
  - electron size (N_e)
  - muon size (N_μ)
  - lateral particle distr. (s, R_m)
- **from μ tracking Detector**
  - μ size > 800 MeV (N_μ^{MTD})
  - local μ-density (ρ_μ)
  - lateral distr. (R_μ)
  - μ-production height (h_μ)
- **from Calorimeter**
  - number of hadrons with $E > 100$ GeV (N_h)
  - sum of hadronic energy (ΣE_h)
  - energy of leading hadron (E_h^{max})
  - parameters of central hadron distribution (R_h, λ_2, …)
- **from MWPC system**
  - # of μs > 2.2 GeV (N_μ^*)
  - local μ-density (ρ_μ)
  - hit pattern, 'spottiness'
  - # of μs > 490 MeV (N_μ^{tP})
  - local μ-density (ρ_μ)
  - particle arrival times (τ_μ)

- **Complementary Information**

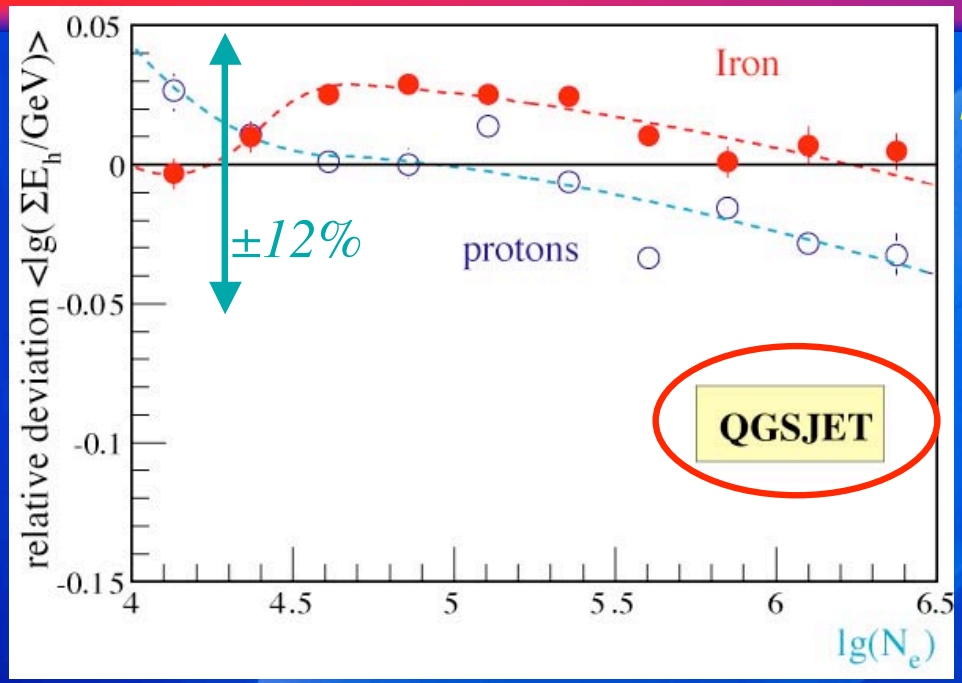
➔ **improved sensitivity**

- **Redundancy**

➔ **understand systematics**

Total Hadronic Energy in Shower Core

sim-data / data

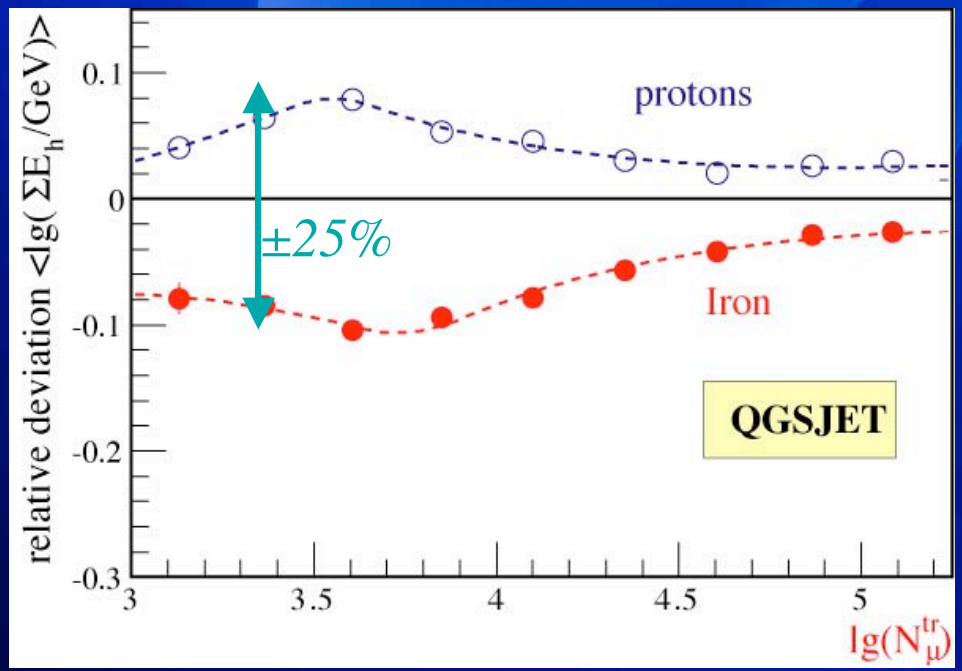


binning in N_e →

p-simulations should resemble data

✓

sim-data / data



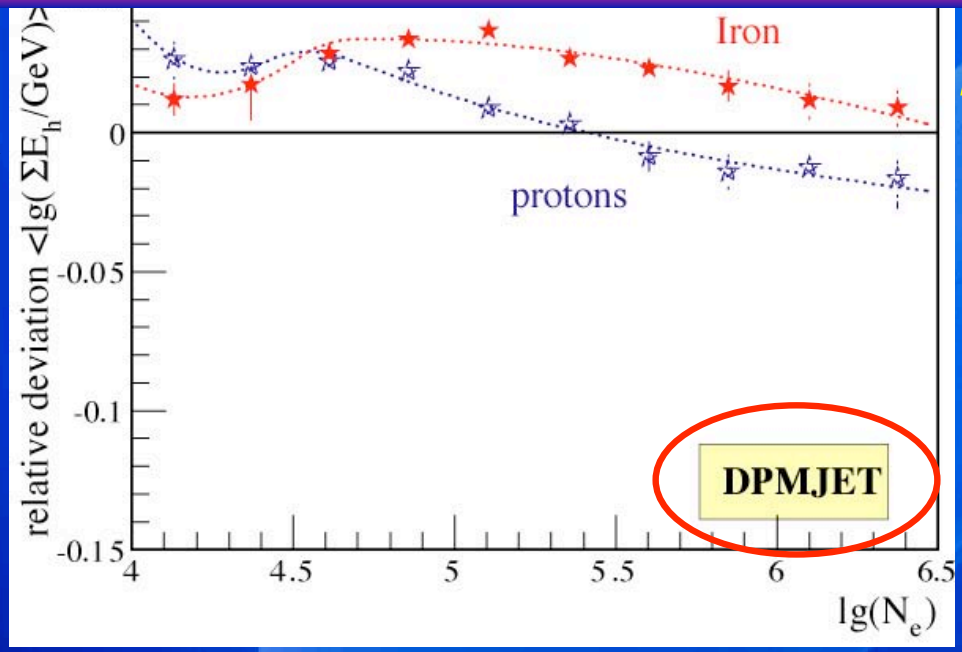
binning in N_μ →

p/Fe simul. should be above/below data

✓

Total Hadronic Energy in Shower Core

sim-data
data

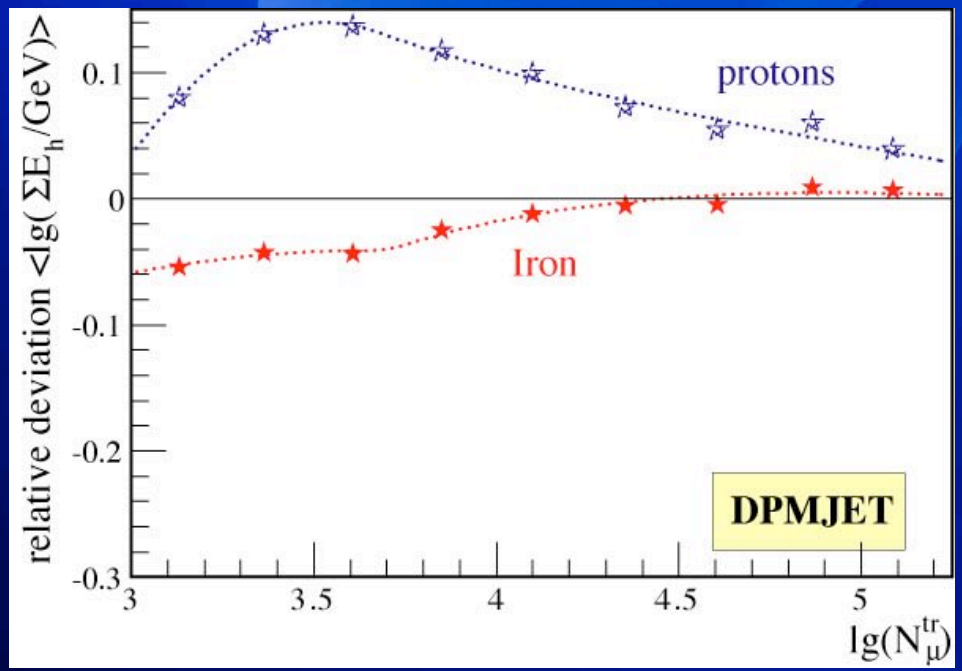


binning in N_e →

p-simulations should resemble data

(✓)

sim-data
data

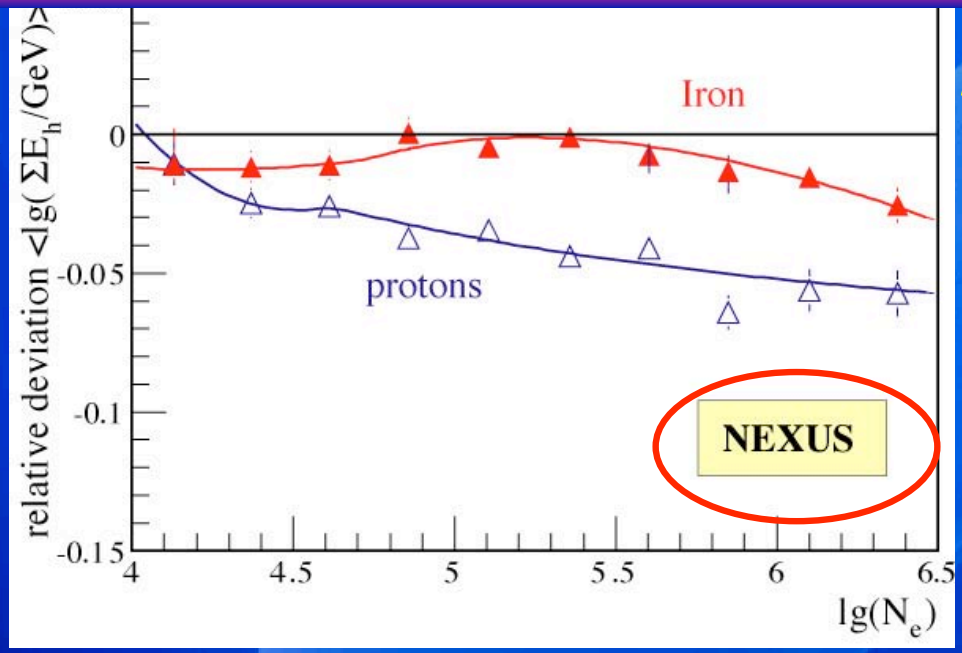


binning in N_μ →

p/Fe simul. should be above/below data

Total Hadronic Energy in Shower Core

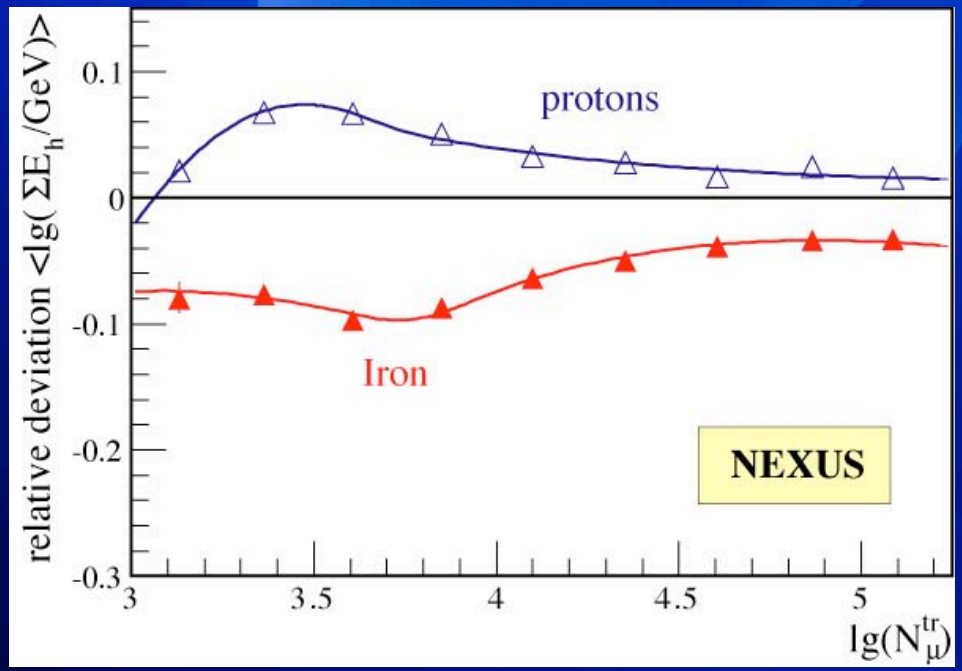
sim-data / data



binning in N_e →

p-simulations should resemble data

sim-data / data



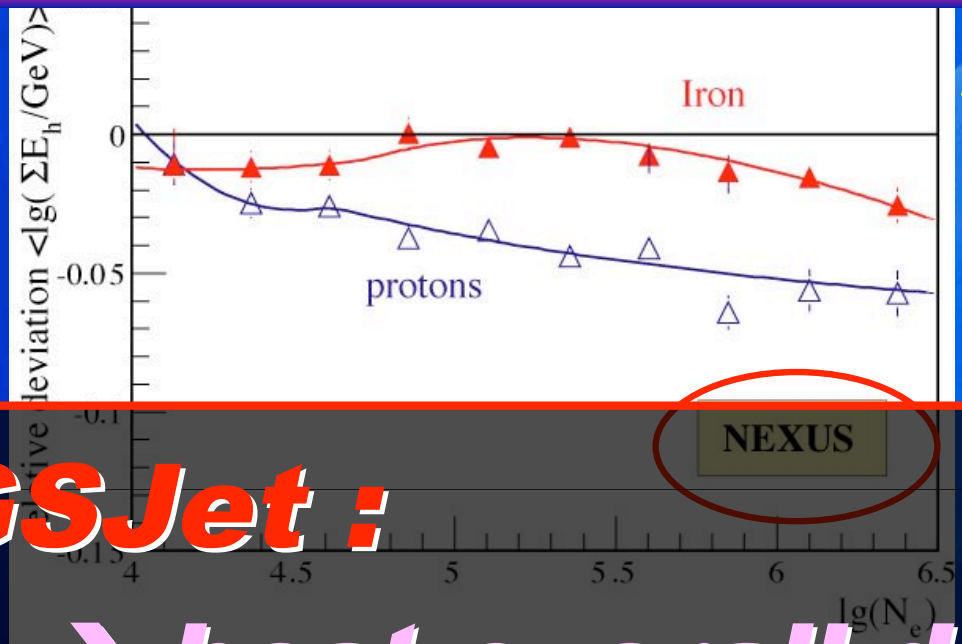
binning in N_μ →

p/Fe simul. should be above/below data

✓

Total Hadronic Energy in Shower Core

sim-data / data



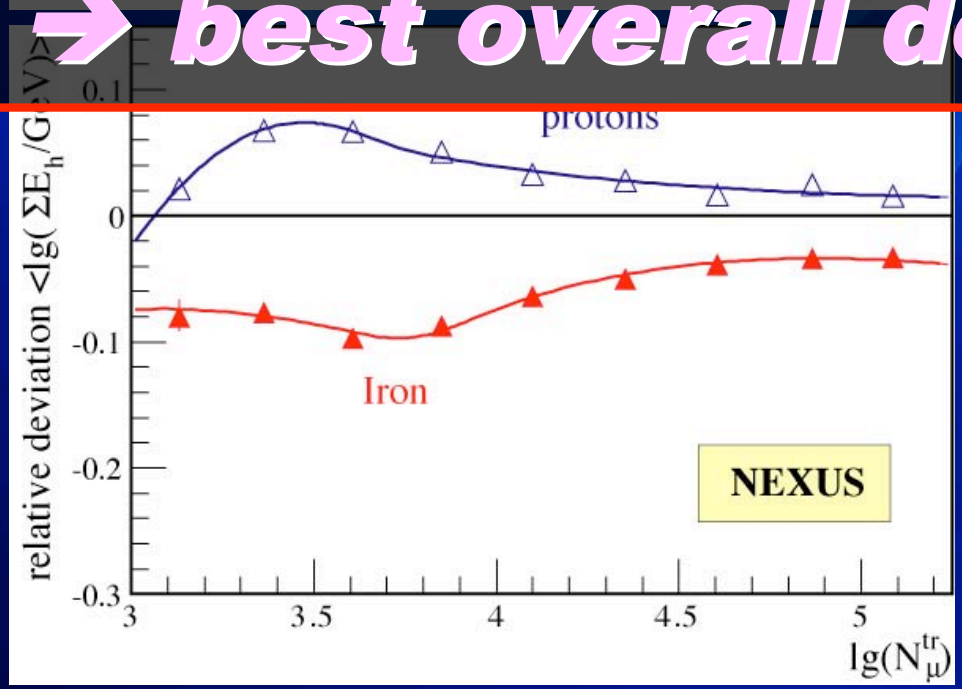
binning in N_e →

p-simulations should resemble data

QGSJet :

→ best overall description

sim-data / data

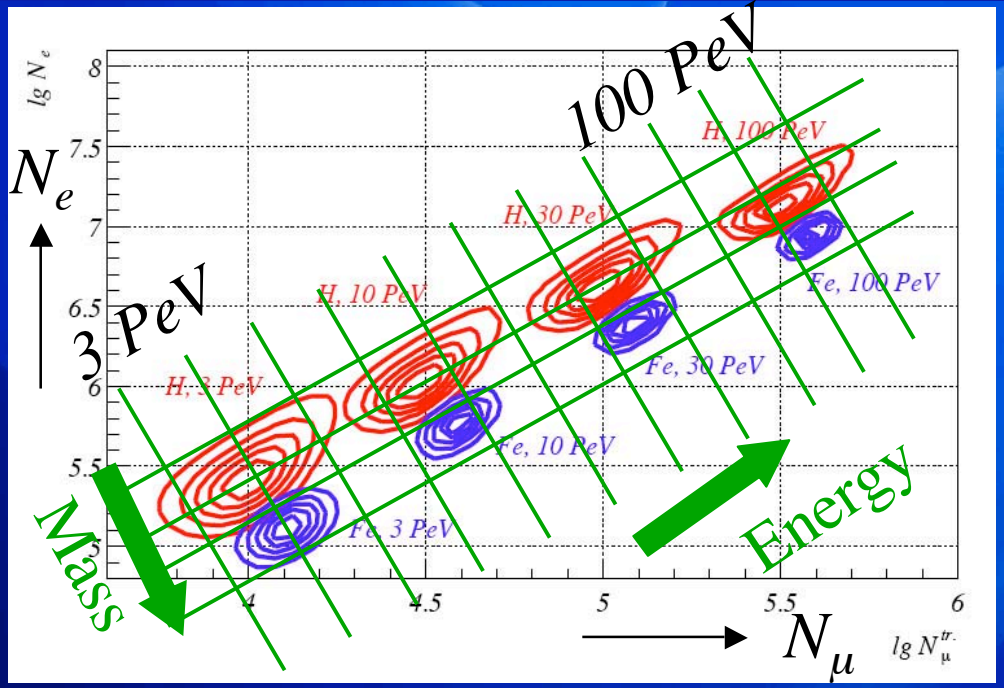


binning in N_μ →

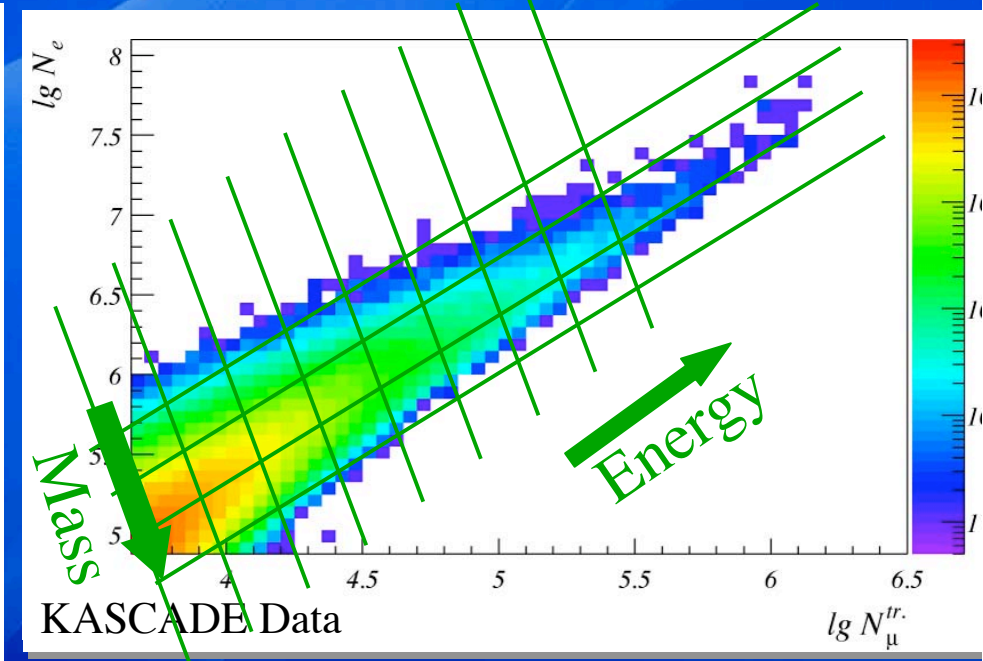
p/Fe simul. should be above/below data

✓

(N_e , N_μ) ⇔ (Energy , Mass)

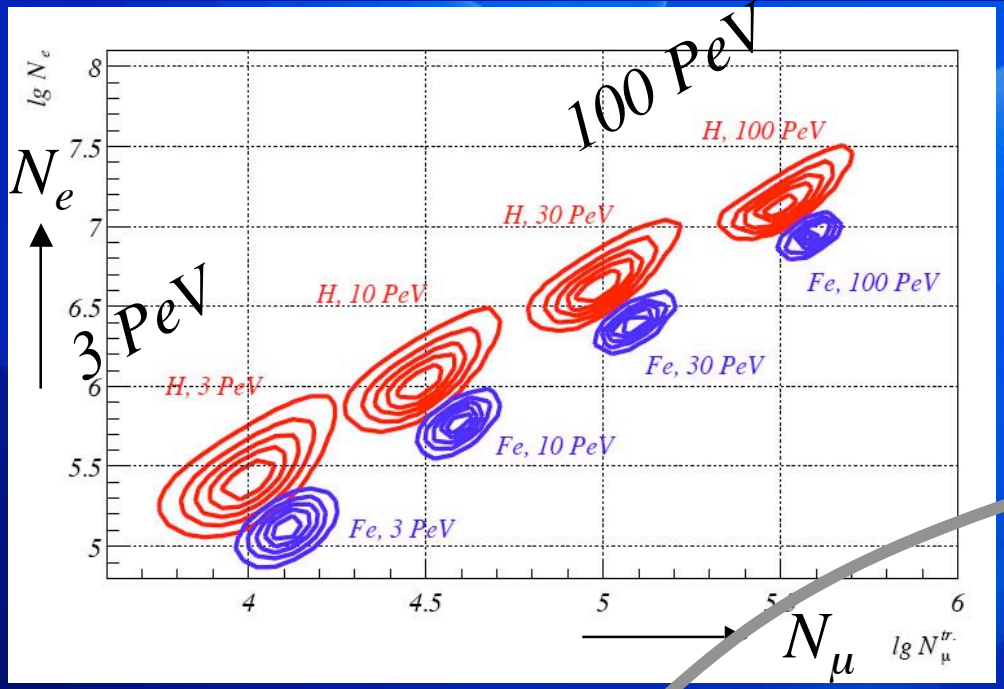


CORSIKA Simulations

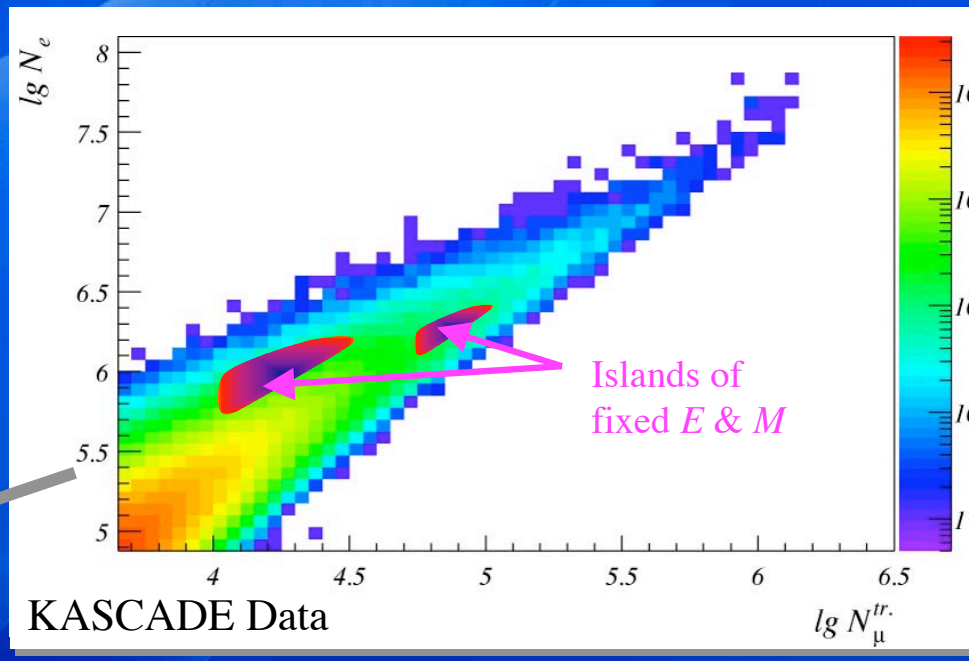


Data

(N_e , N_μ) ⇔ (Energy , Mass)



CORSIKA Simulations

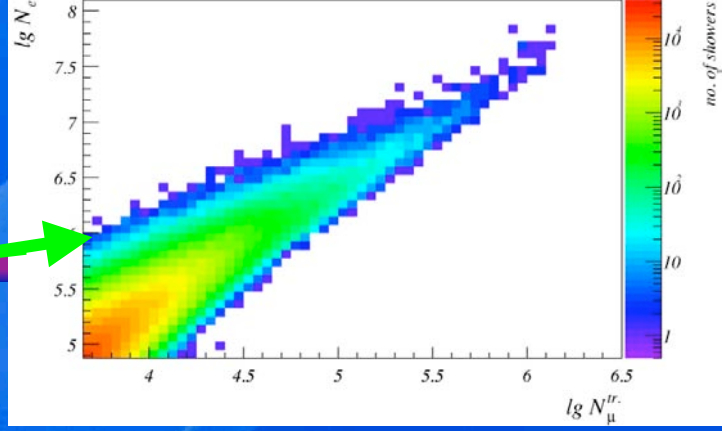


2-dim N_e-N_μ distribution ⇔ system of coupled Fredholm-Equations

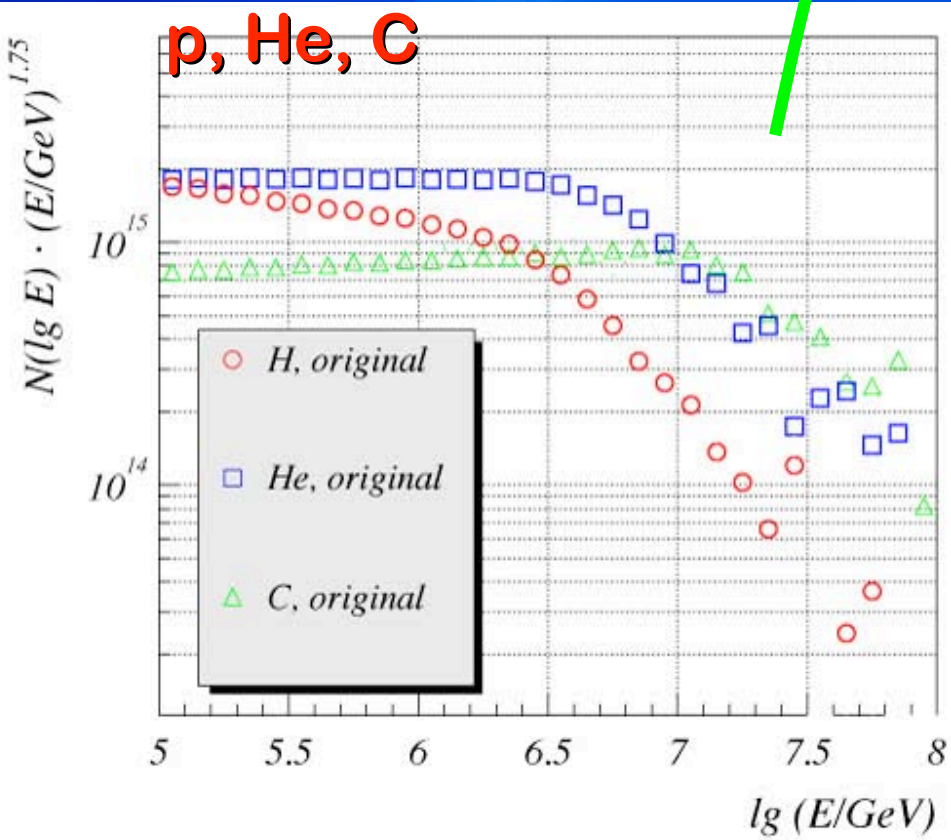
$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

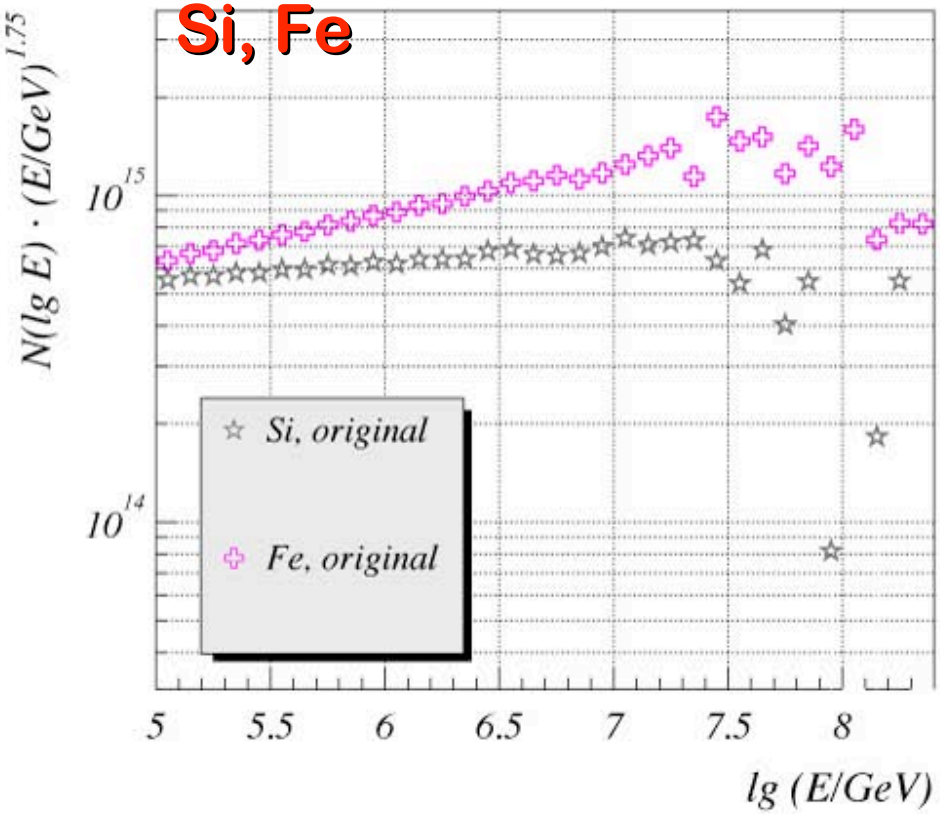
H. Ulrich, Doct. Thesis 2003

Test of Unfolding



Synthetic input spectra
generated by assuming 5 diff. primaries
(p, He, C, Si, Fe) and a rigidity dependent knee





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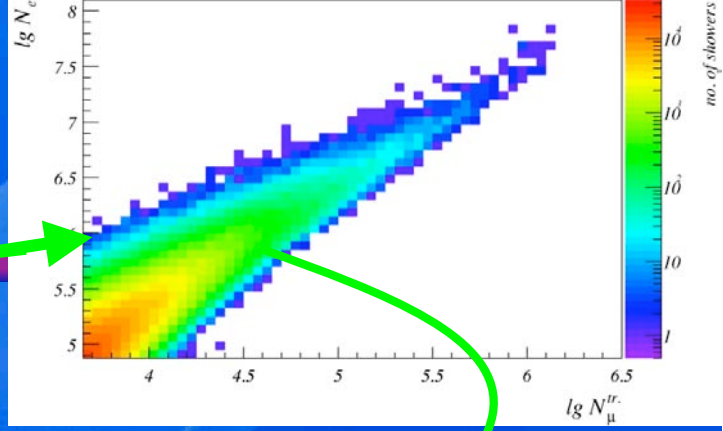

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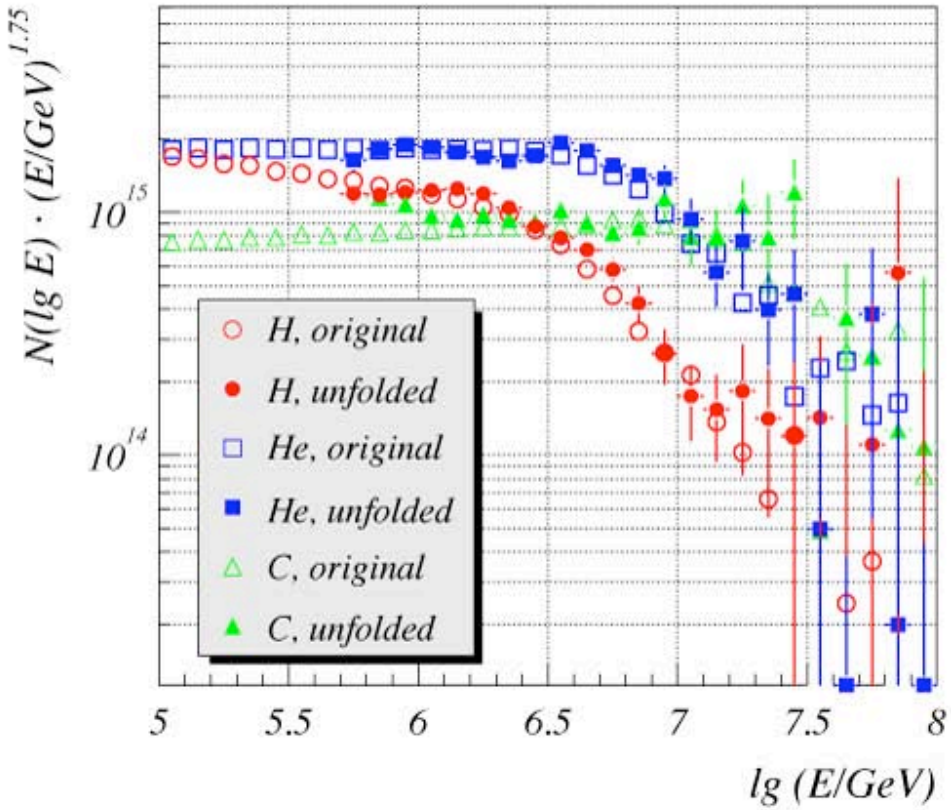
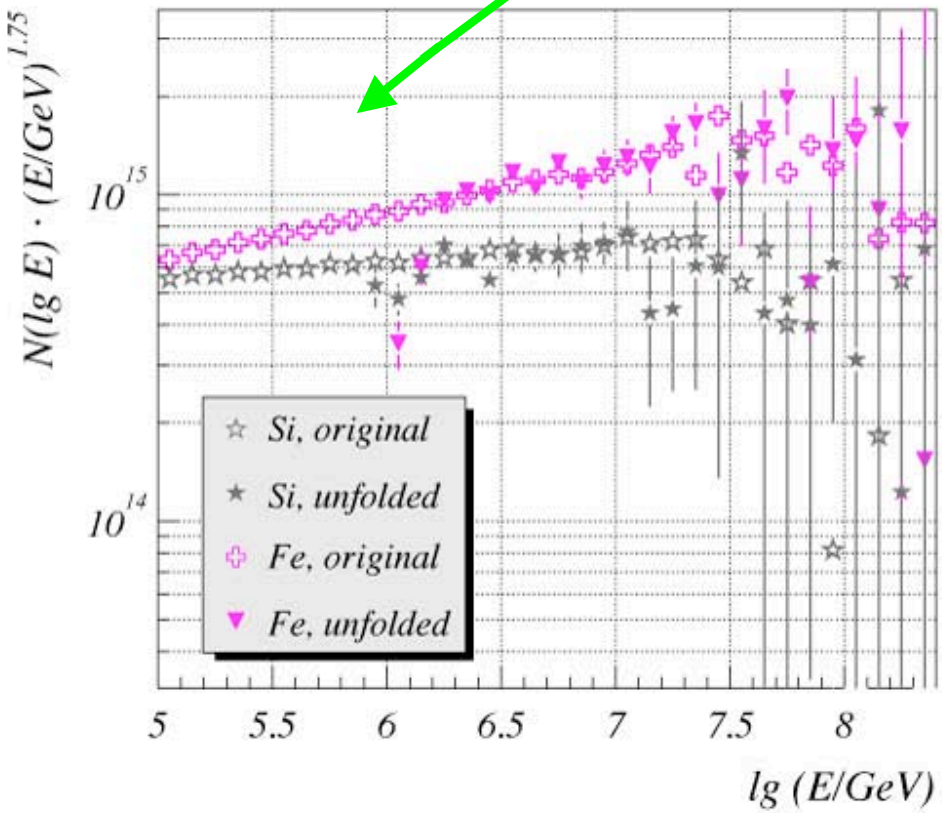
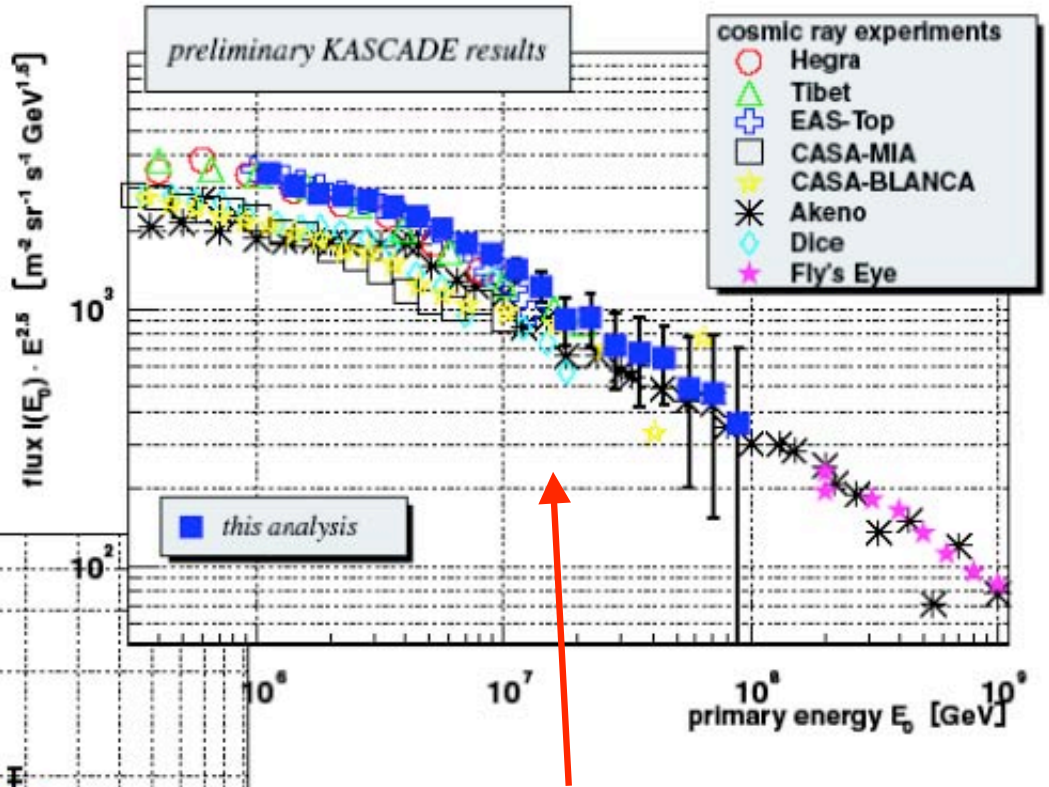
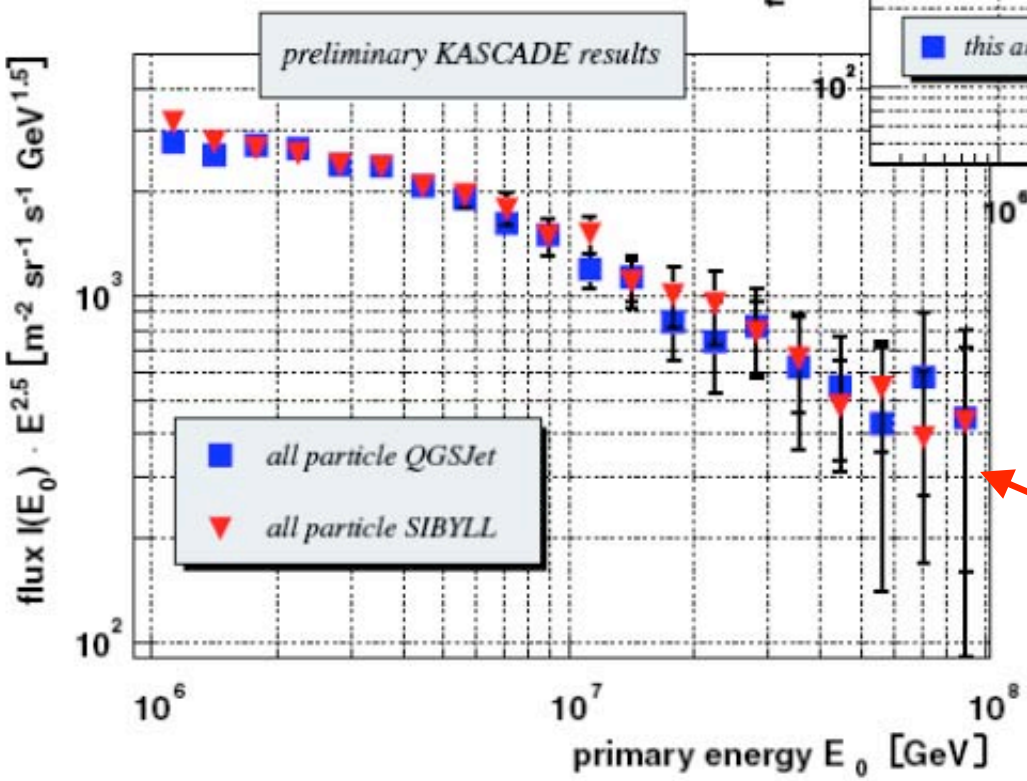




All-Particle Spectrum

- Knee at about 4×10^{15} eV
- Spectral indices:
  $\gamma_1 \sim 2.75$
  $\gamma_2 \sim 3.1$
- Only statistical errors are drawn

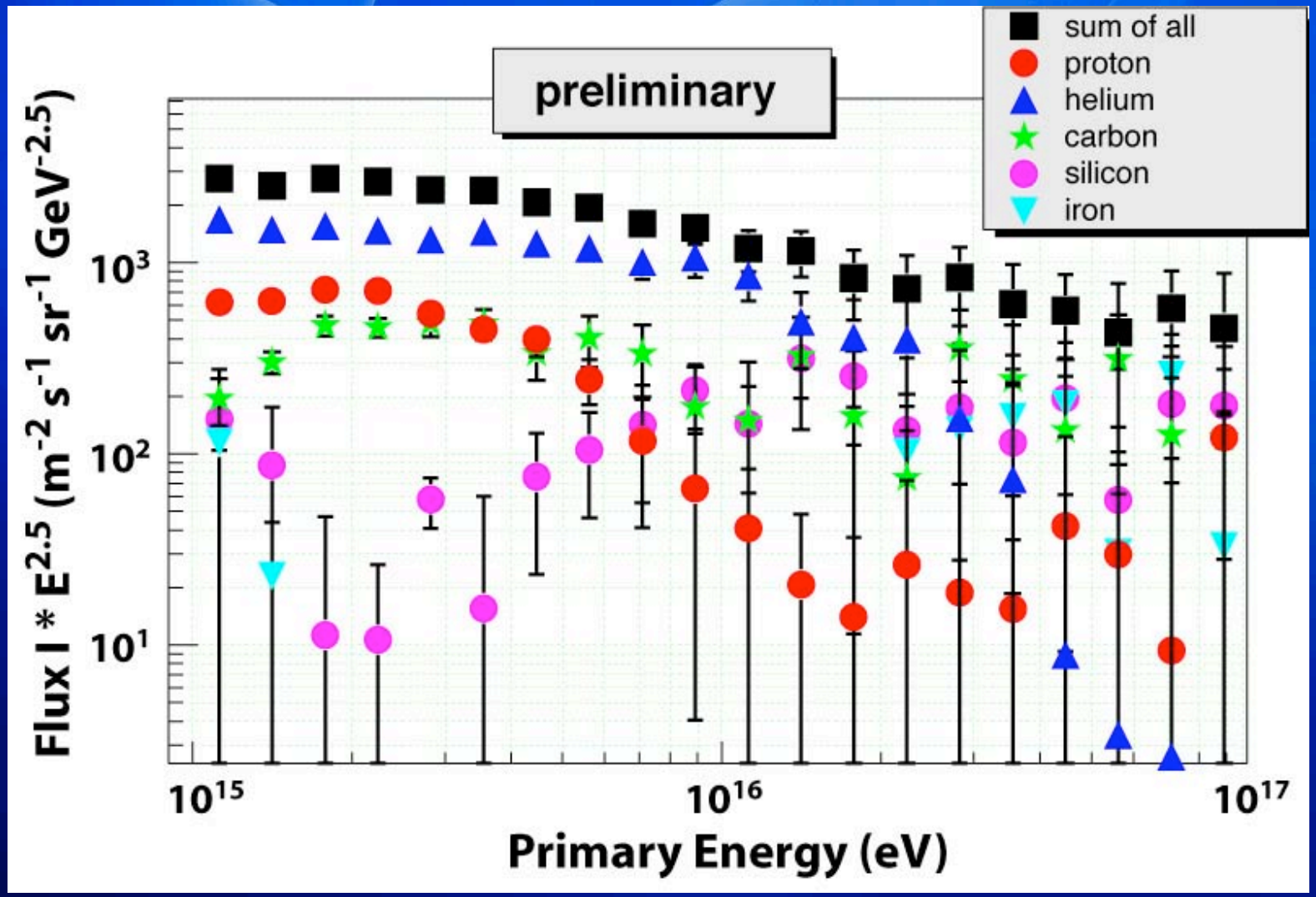




Comp. of Expts

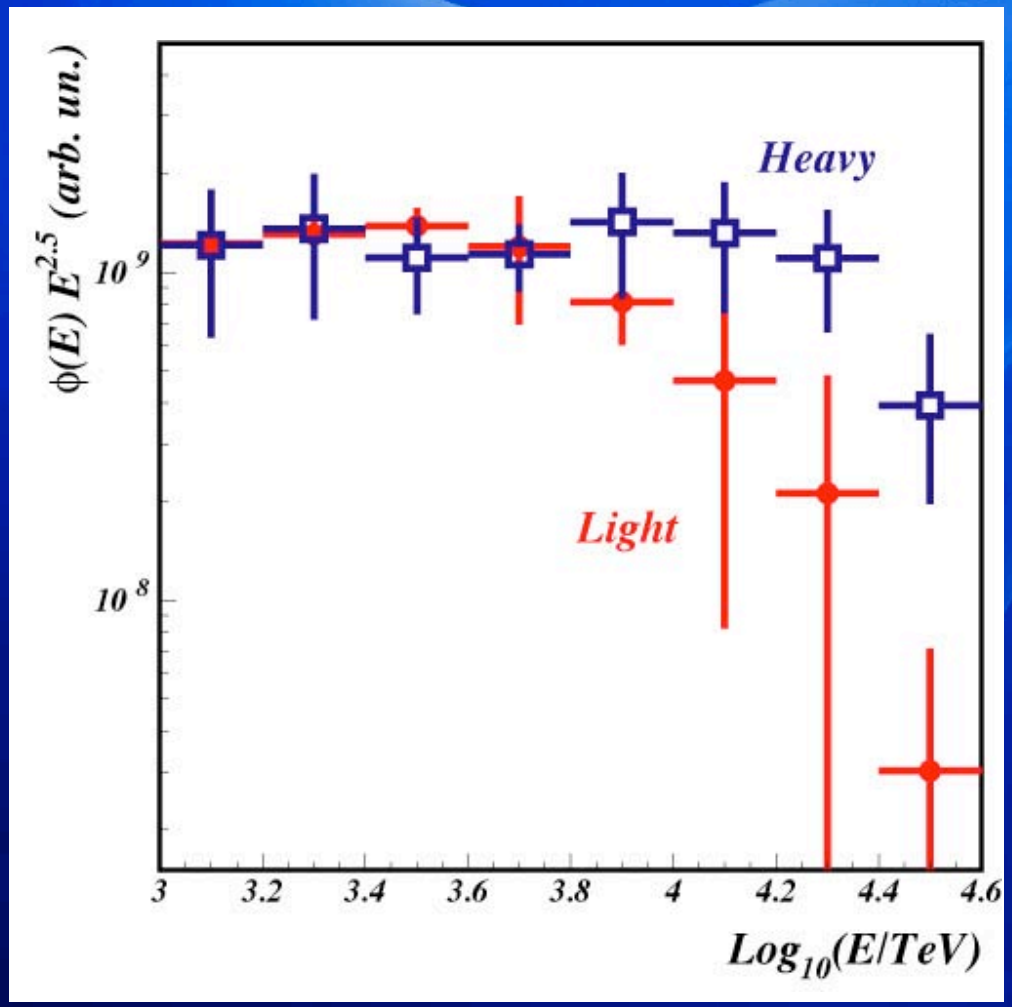
Comp. of int. Models

E-Spectra of Mass-Groups



H. Ulrich, Doct. Thesis 2003

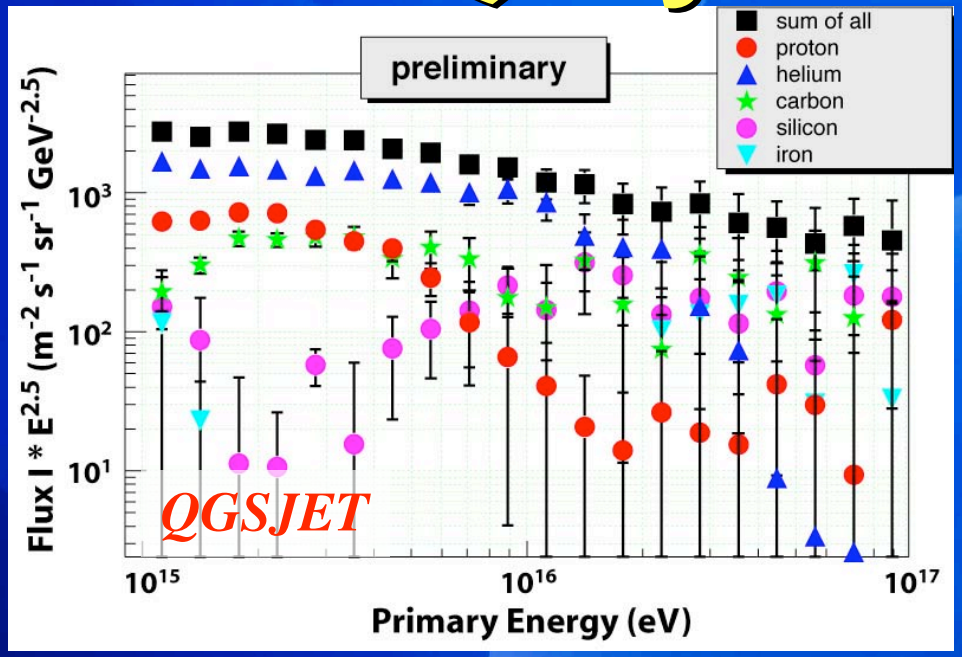
E-Spectra of Mass-Groups

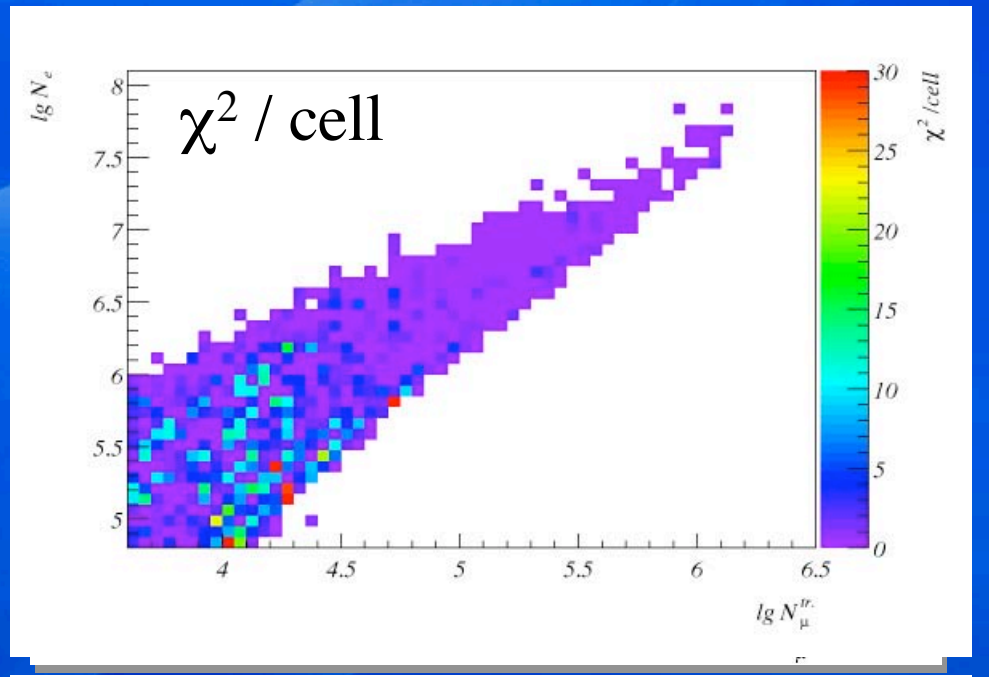


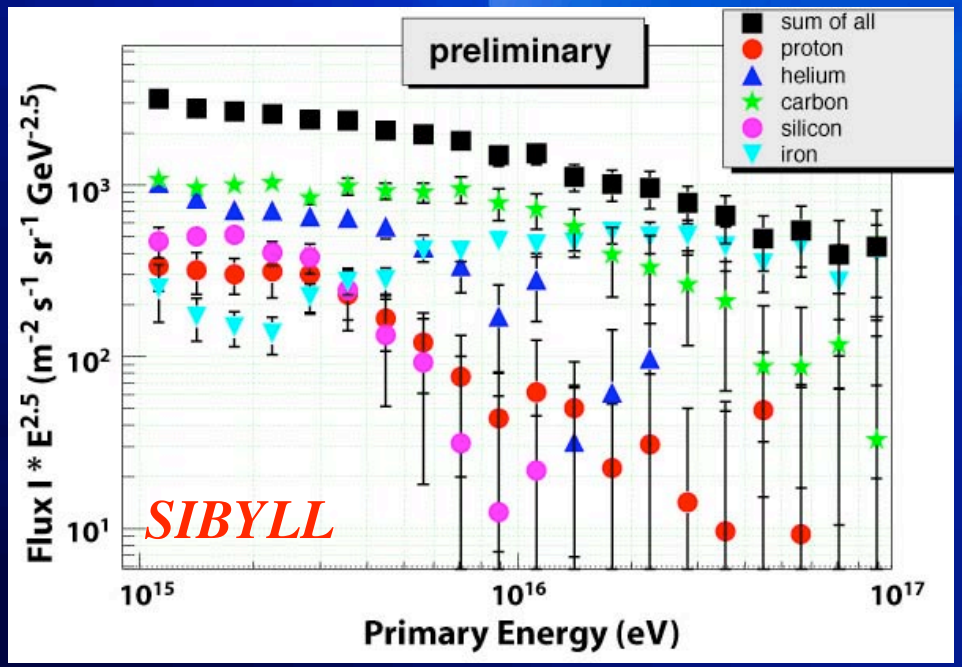
Good agreement e.g. to EAS-TOP & MACRO

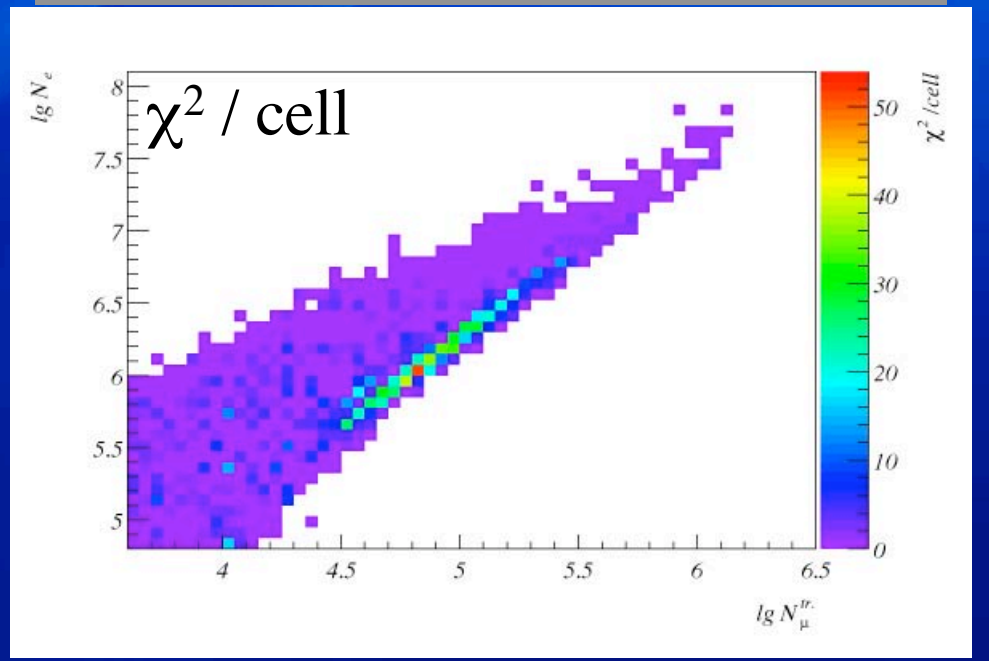
astro-ph/0305325

QGSJet vs SIBYLL

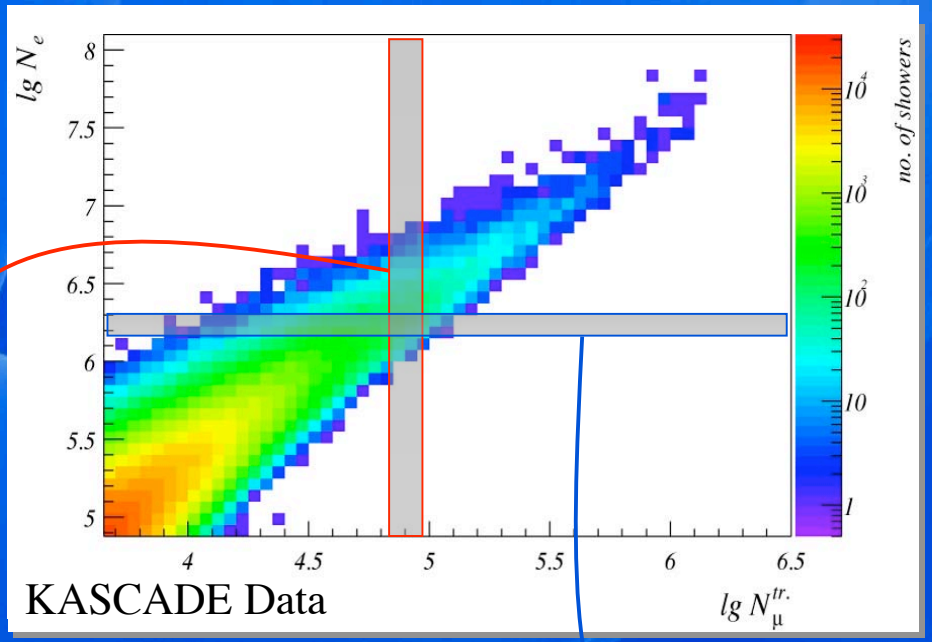


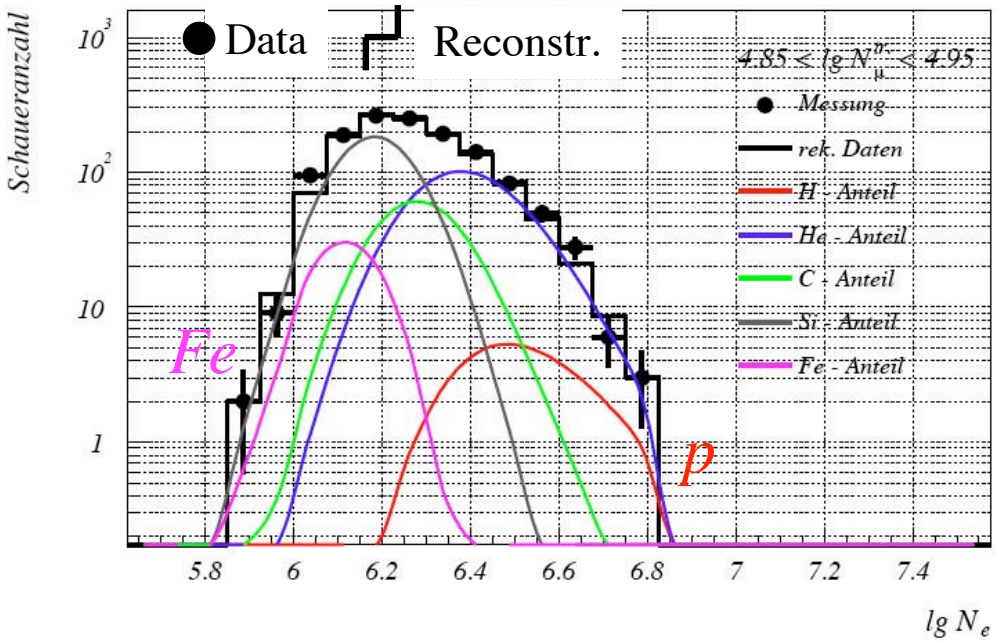


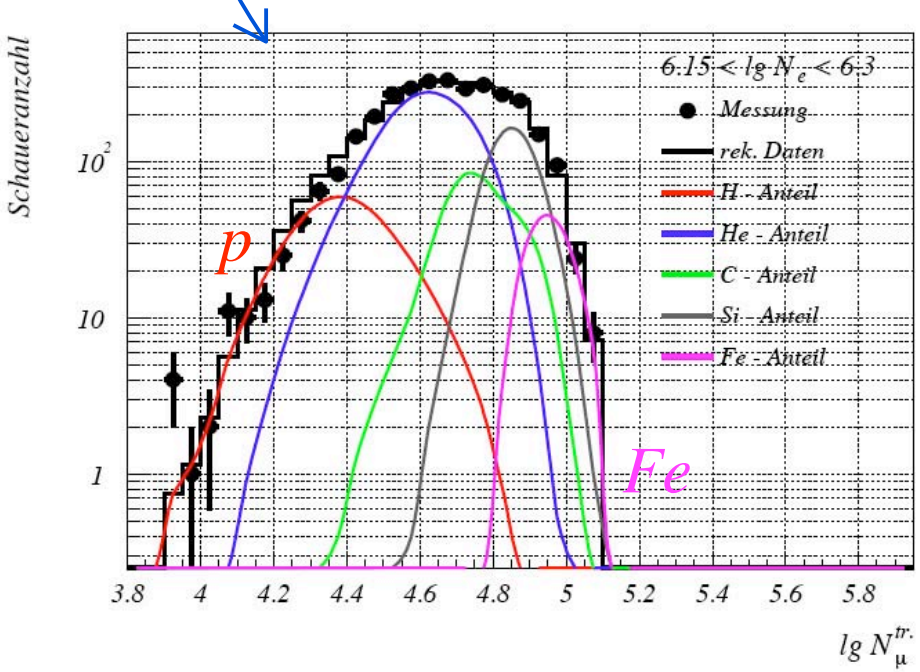


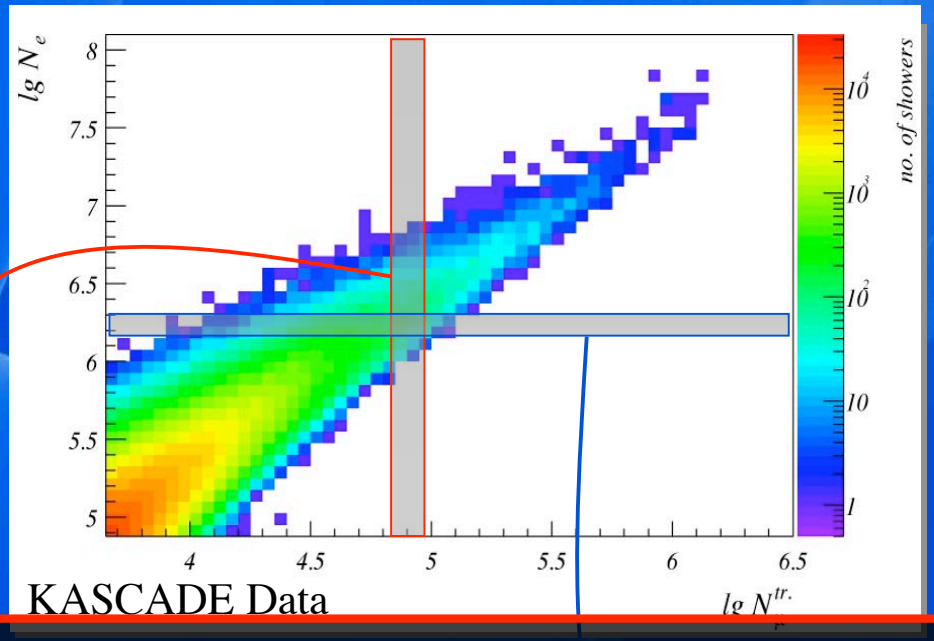


QGSJet

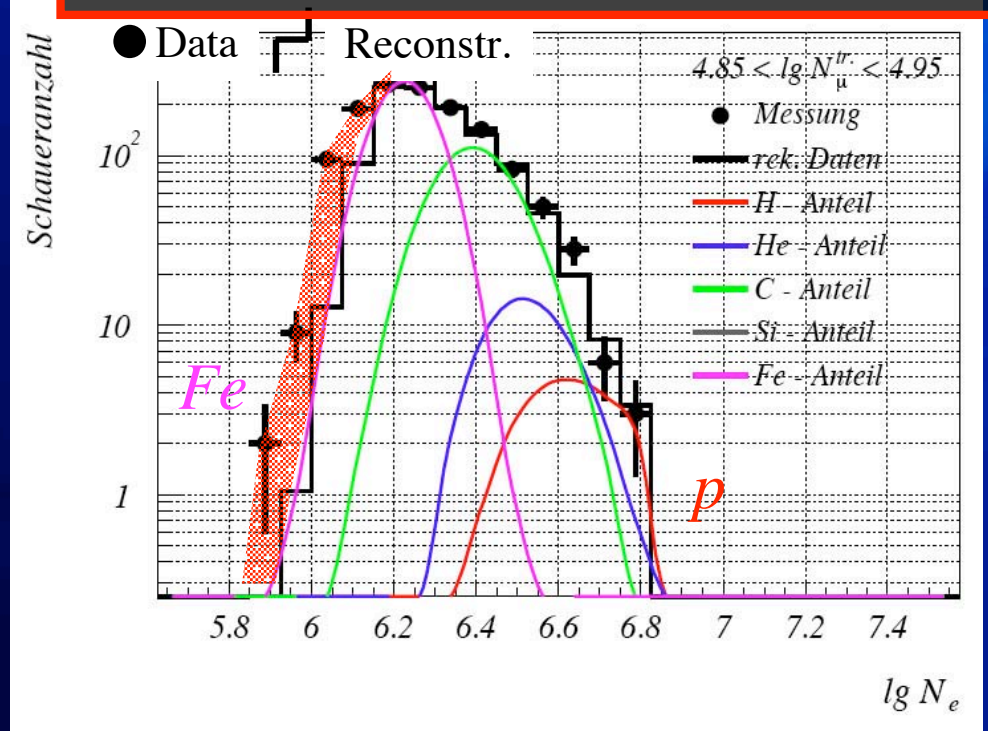

lg N_e
no. of showers
KASCADE Data
lg $N_\mu^{tr.}$

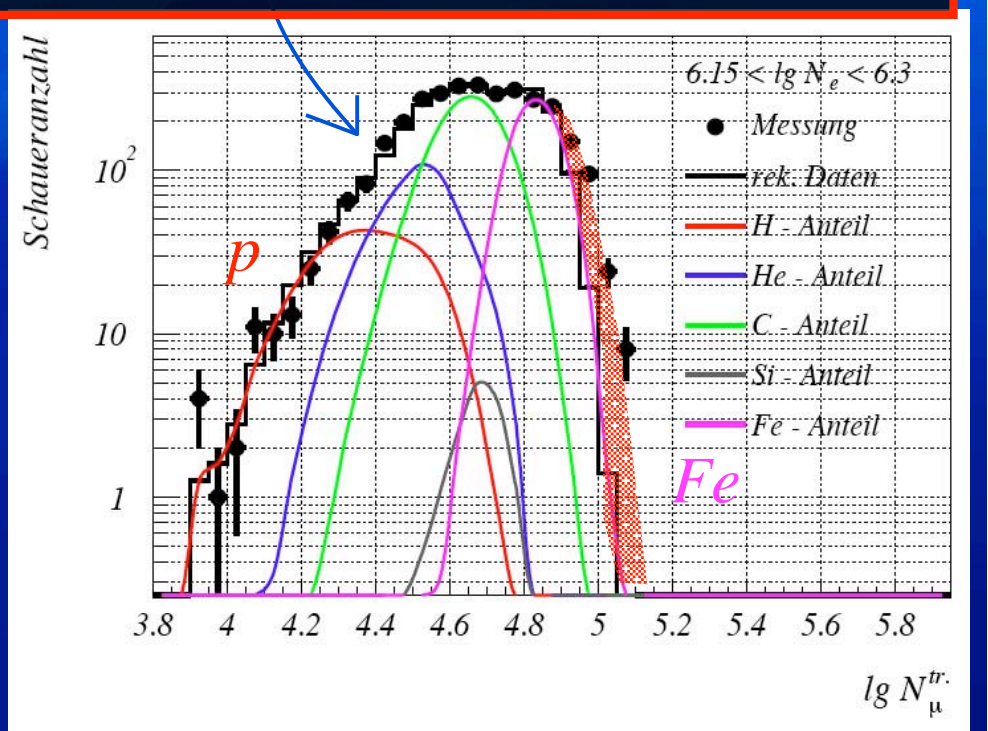

Data
Reconstr.
$4.85 < lg N_\mu^{tr.} < 4.95$
Messung
rek. Daten
H - Anteil
He - Anteil
C - Anteil
Si - Anteil
Fe - Anteil
Fe
p
Schaueranzahl
lg N_e


$6.15 < lg N_e < 6.3$
Messung
rek. Daten
H - Anteil
He - Anteil
C - Anteil
Si - Anteil
Fe - Anteil
p
Fe
Schaueranzahl
lg $N_\mu^{tr.}$

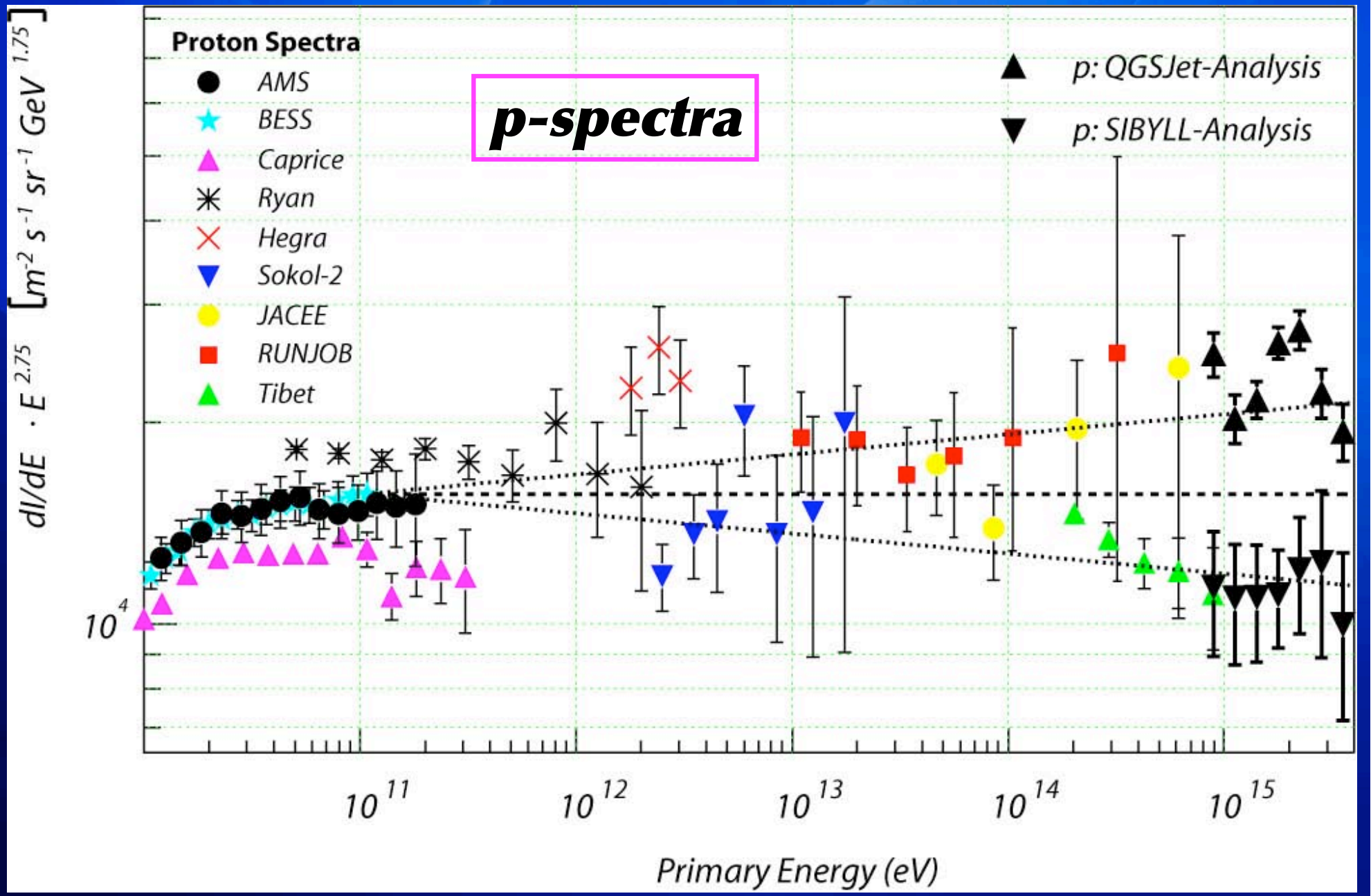


SIBYLL μ-deficit a/o electron excess in SIBYLL

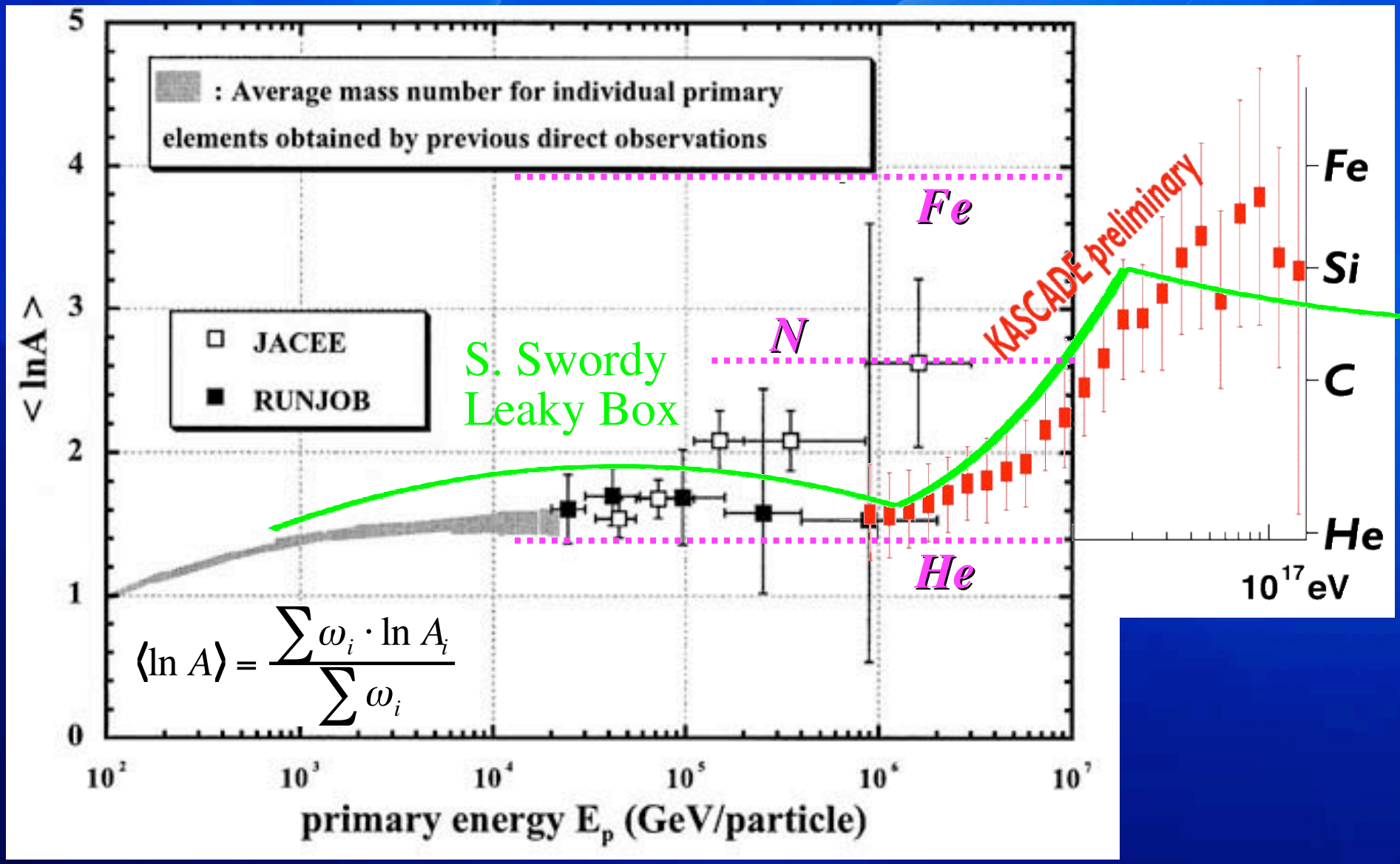




Direct Measurements vs KASCADE-Data

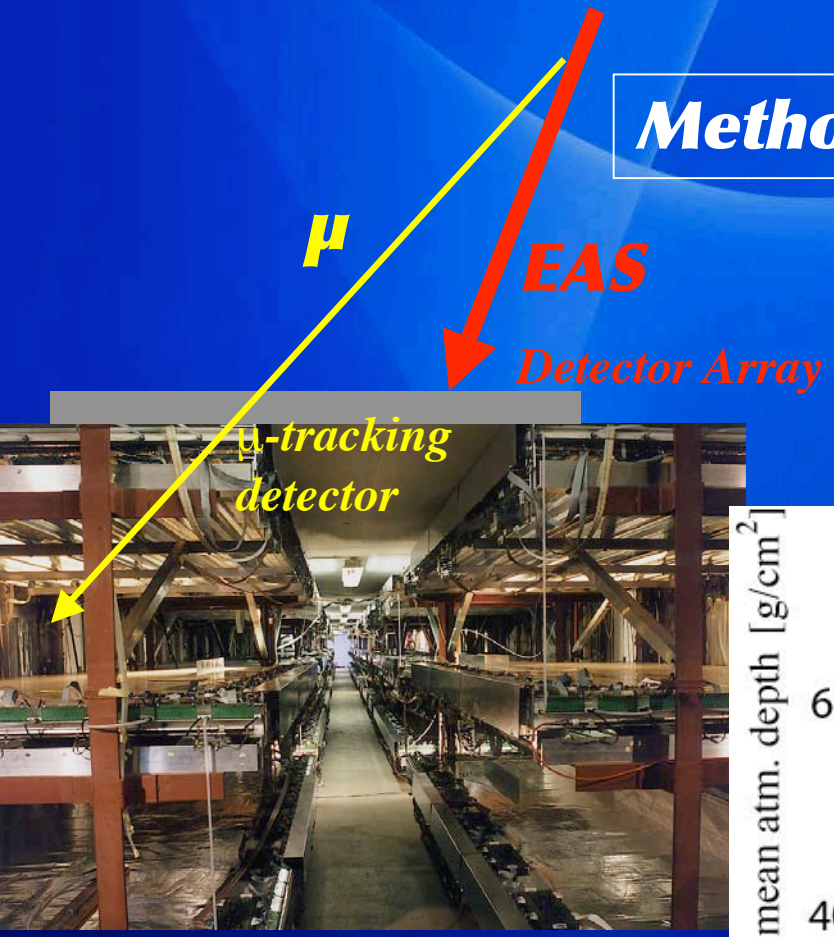


KASCADE vs JACEE & RUNJOB

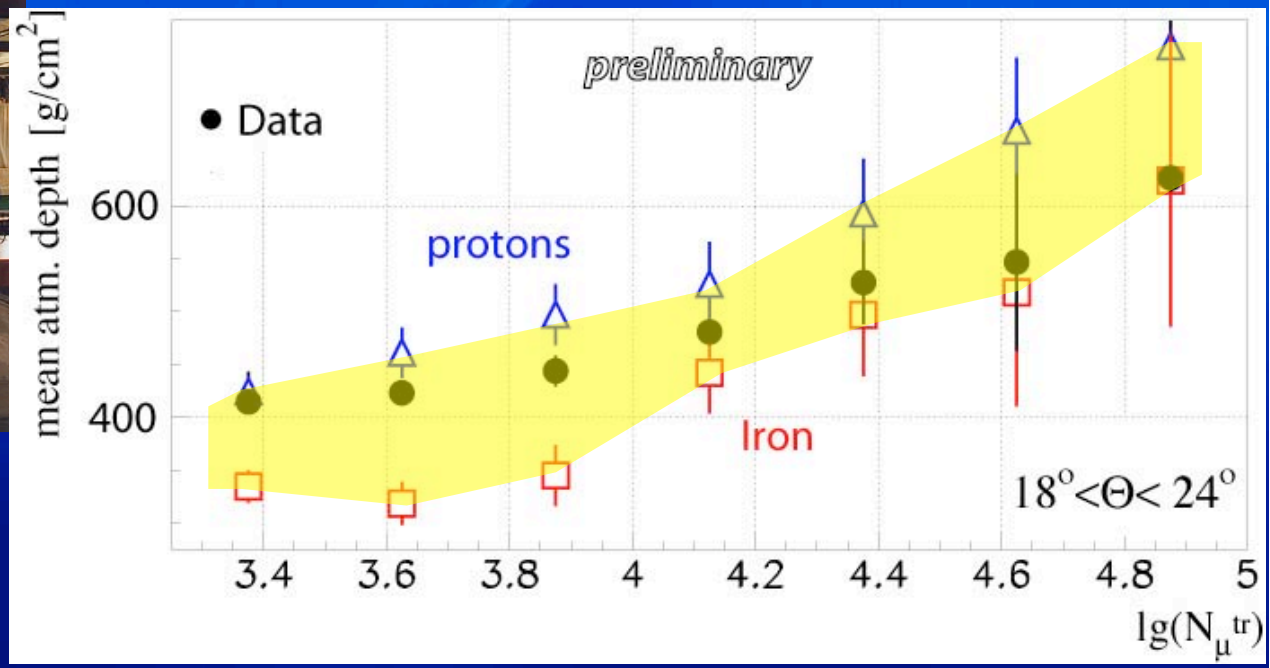


Mass from Muon Production Height

Method of triangulation



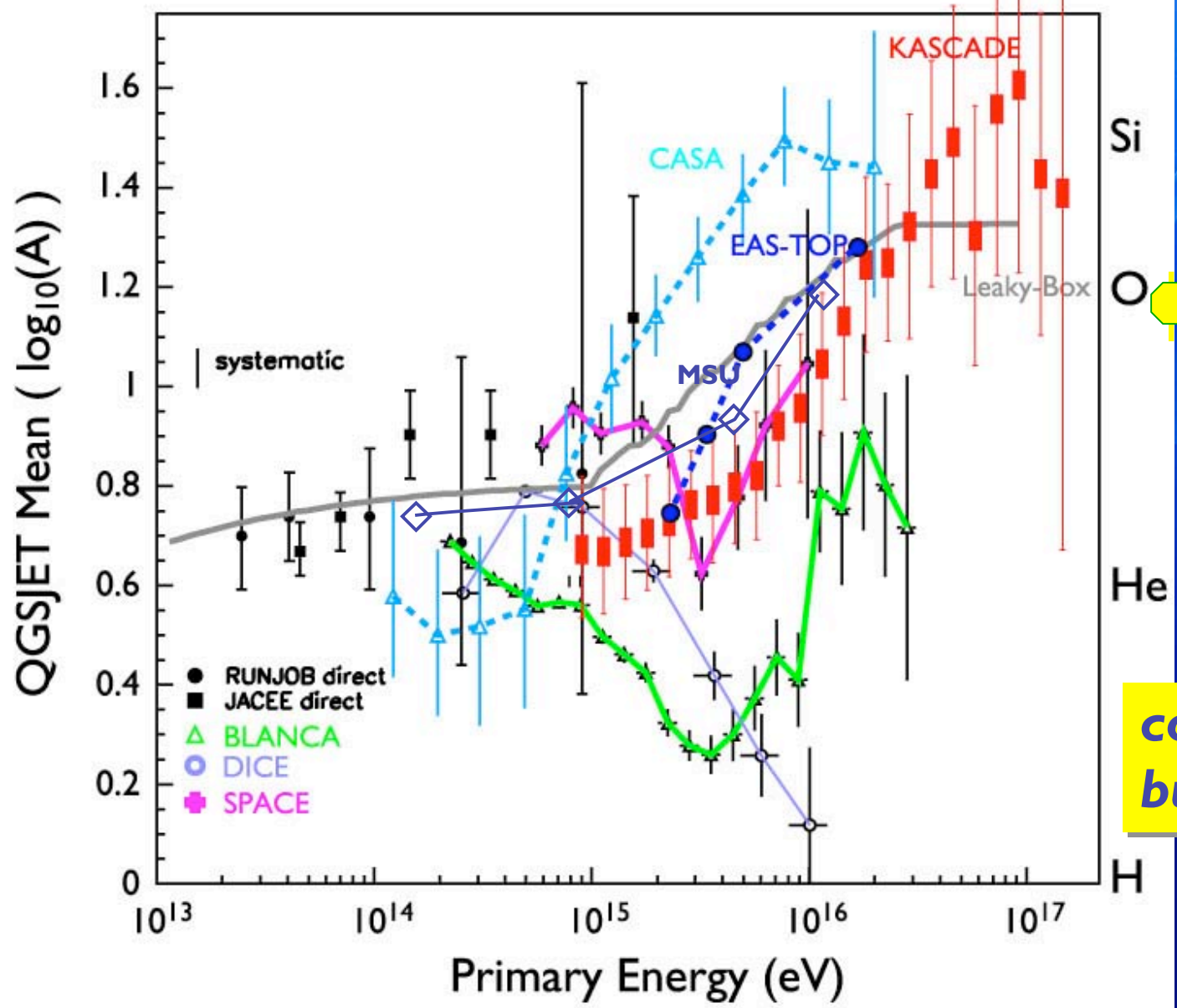
C. Büttner, Doct. Thesis 2003



Light → Heavy

Compilation of InA in Knee Region

S. Swordy et al., APP 2002 in press
H. Ulrich, KASCADE, ICRC 2001
B. Alessandro, EAS-TOP, ICRC 2001
Ave et al., astro-ph/0203150



Ch-Expts
+
KASCADE
+
EAS-TOP
+
CASA-MIA
+
MSU
+
Haverah Park

consistently heavier but systematic shifts

Conclusions so far:

- **Unfolding Method(s) work properly**
- **Spectra of light elements show a distinct knee at ~ 2 PeV**
- **Rigidity dependent knee is favoured, but...**

  ↳ support for astrophysical interpretation of knee

- **Interaction Models still not satisfactory**
- **„Optimal“ Model to describe KASCADE-Data:**

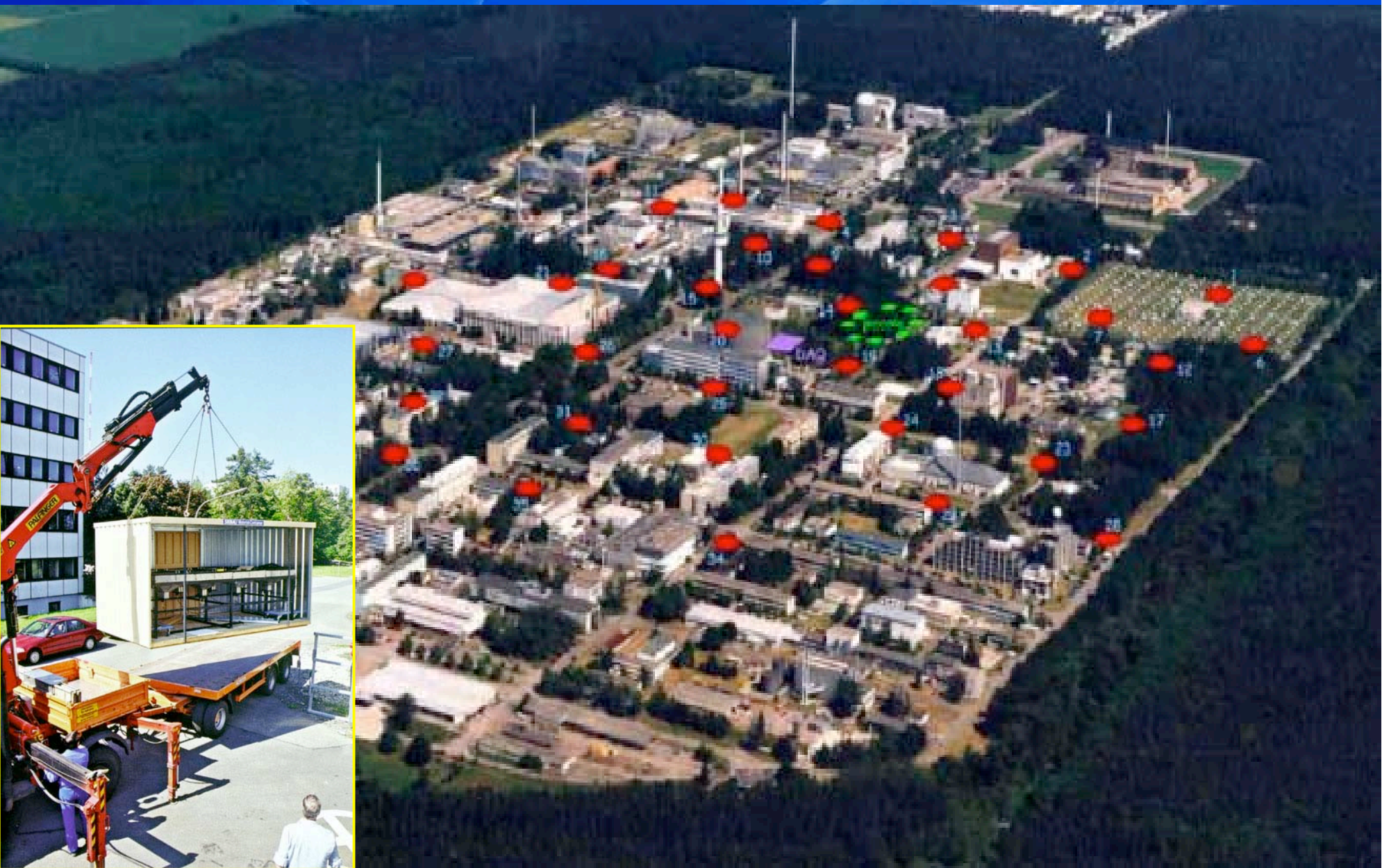
  - Lower N_μ at PeV energies
  - more rapid increase of N_μ towards higher energies

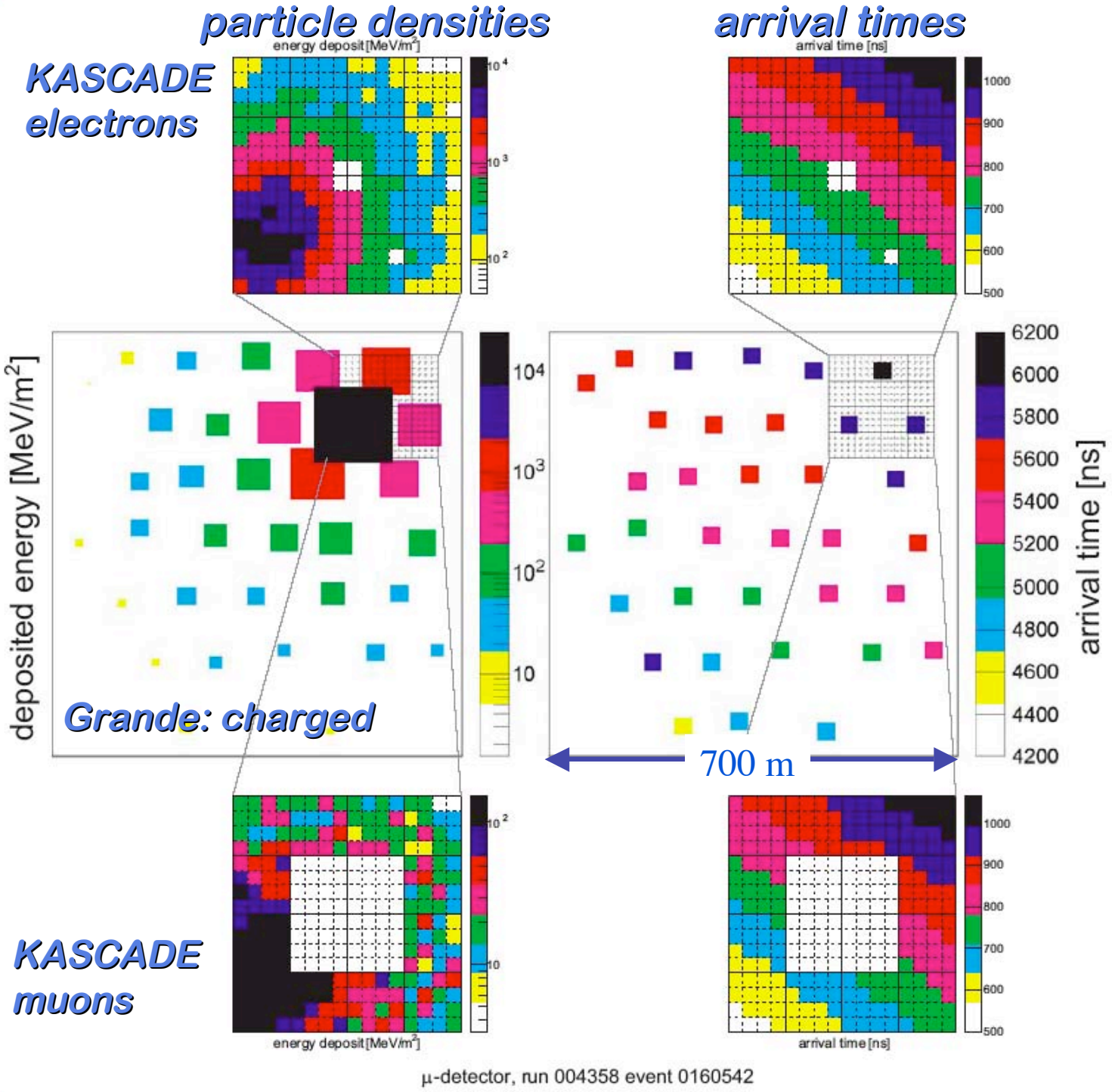
  likewise, but less favoured:

  - Higher N_μ at PeV energies
  - [illegible]

  ↳ clues to better hadronic interaction models

Towards higher Energies: KASCADE-Grande



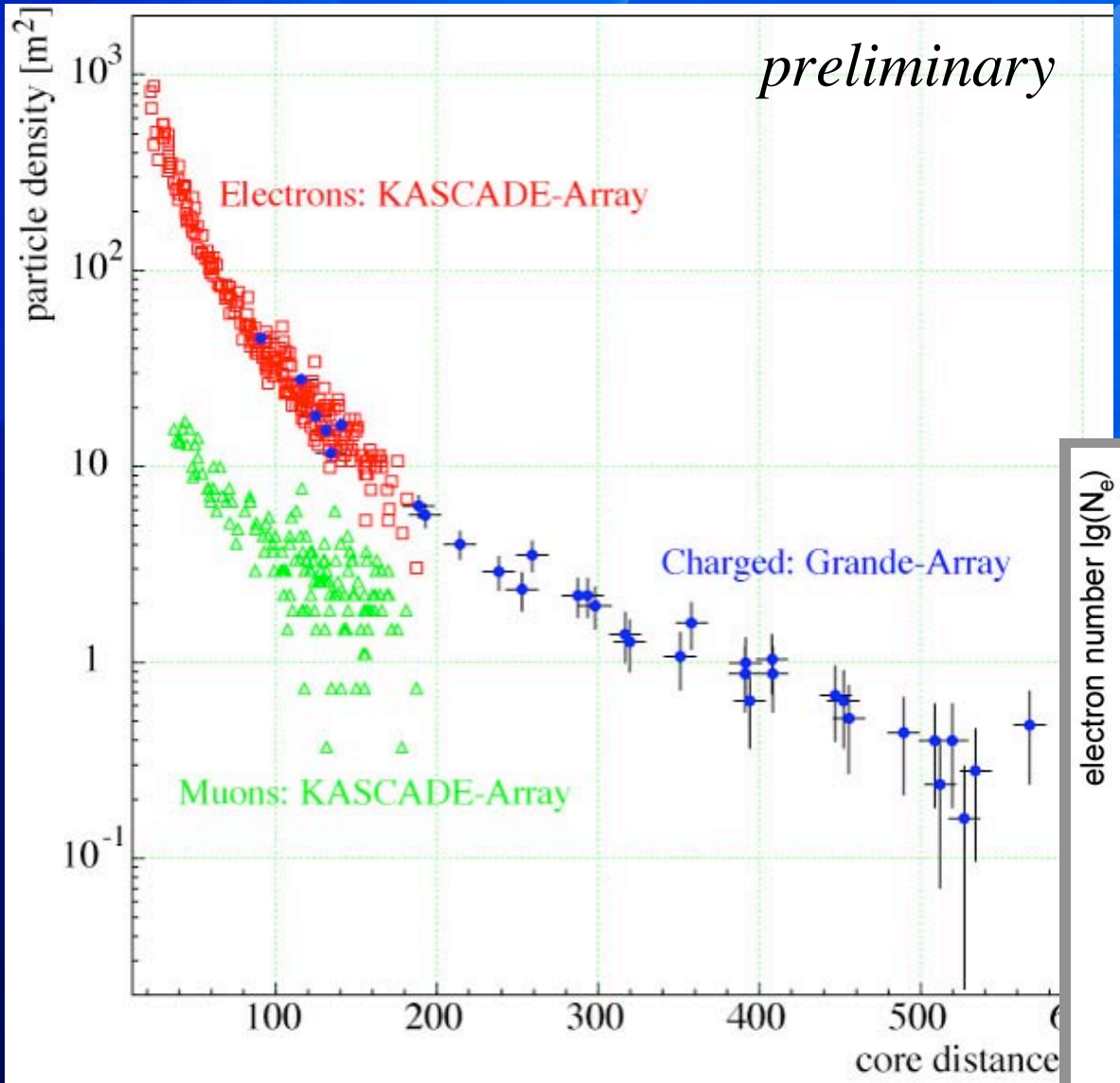


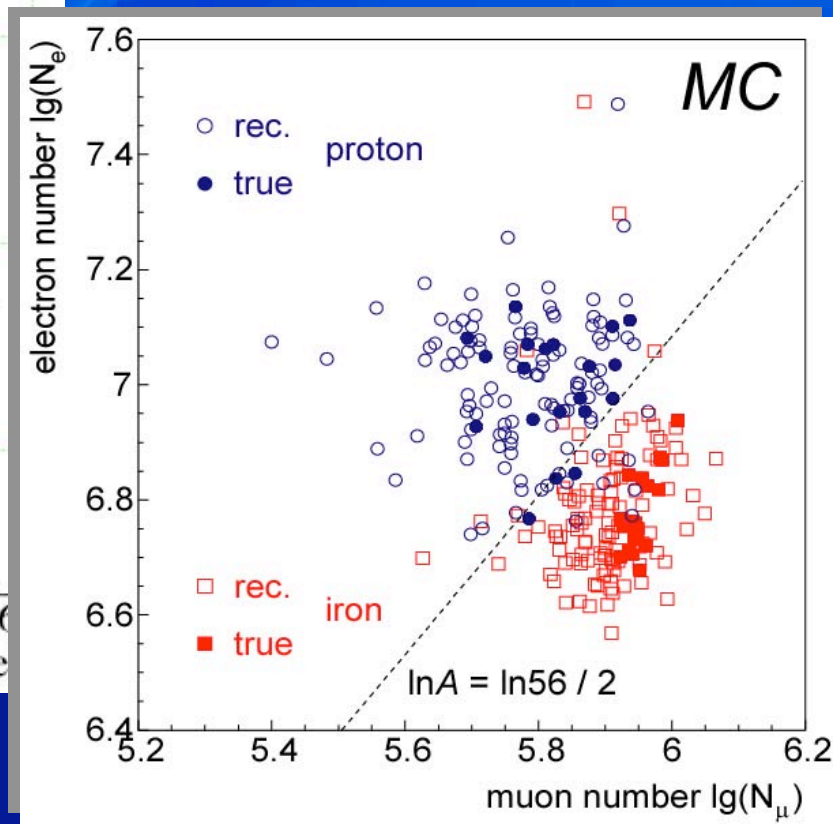
Example of **Joint Event**

251 KASCADE
+
37 Grande Stations

$E > 10^{17}$ eV

Combined Lateral Distribution

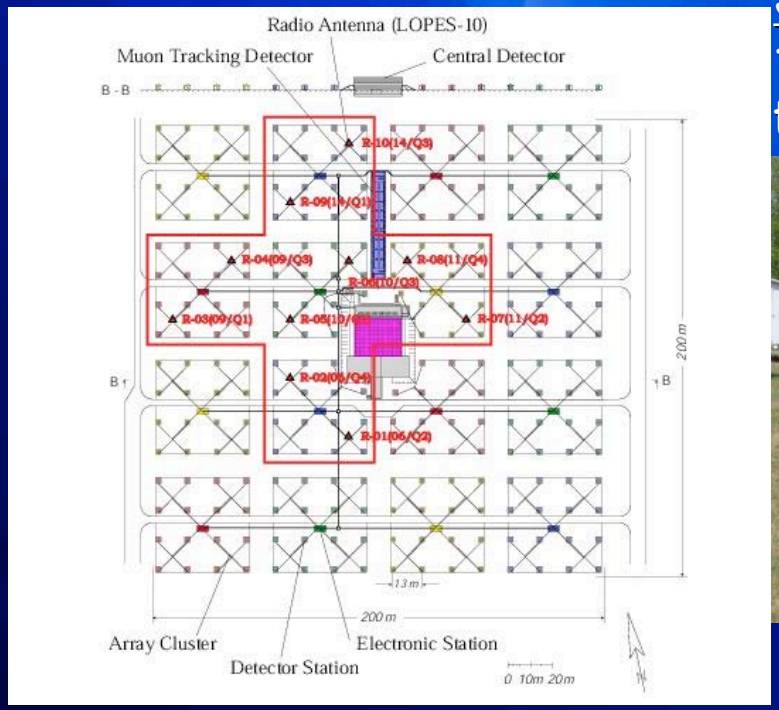




Radio-Observations of EAS

Long standing question:
Are EAS observable by their radio signal ? (30-80 MHz)
➲ **observe EAS at their maximum, 24 hrs a day!**

KASCADE-Grande used as a reference and trigger



Status:
10 antennes in field,
triggered by KASCADE

in Collab. with
H. Falcke et al.

Summary

- **Astrophysics Picture of Knee supported**
- **Interaction Models improved**
  QGSJet best but not optimum
- **More Obervables** to come
- **More Data** to come(KA-Grande)
- **New Techniques** to come(Radio)

Vital Field of Research

KASCADE-Grande Collaboration

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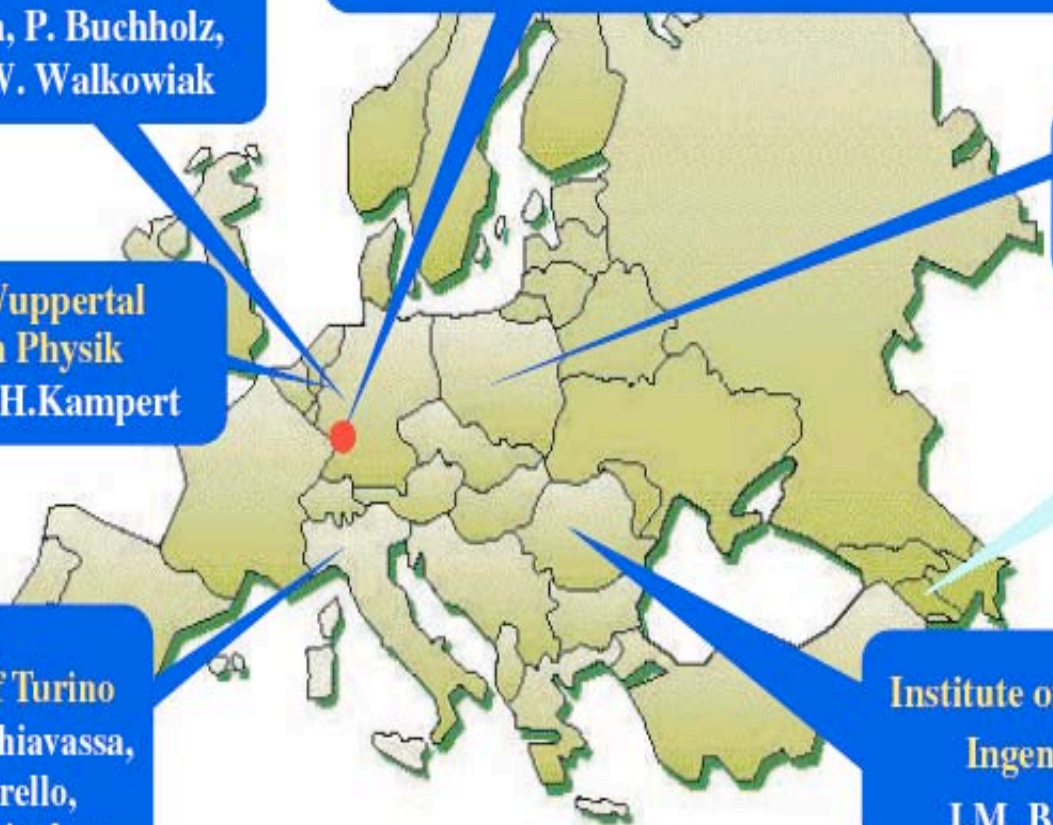

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