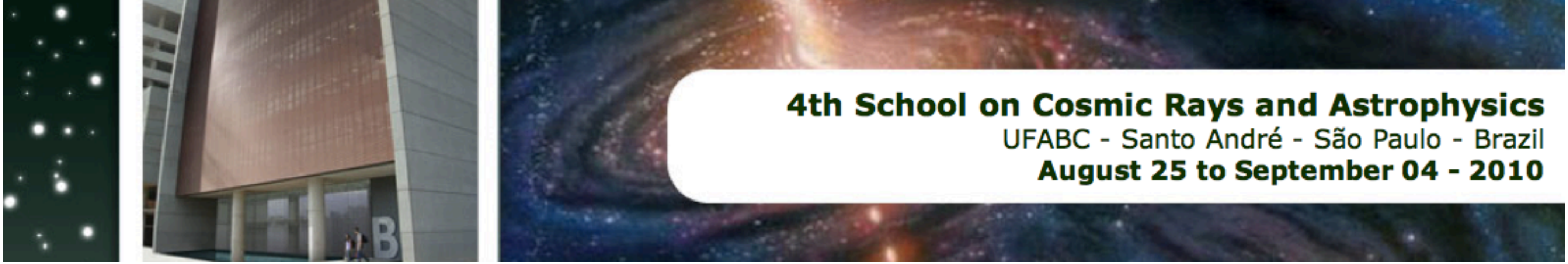
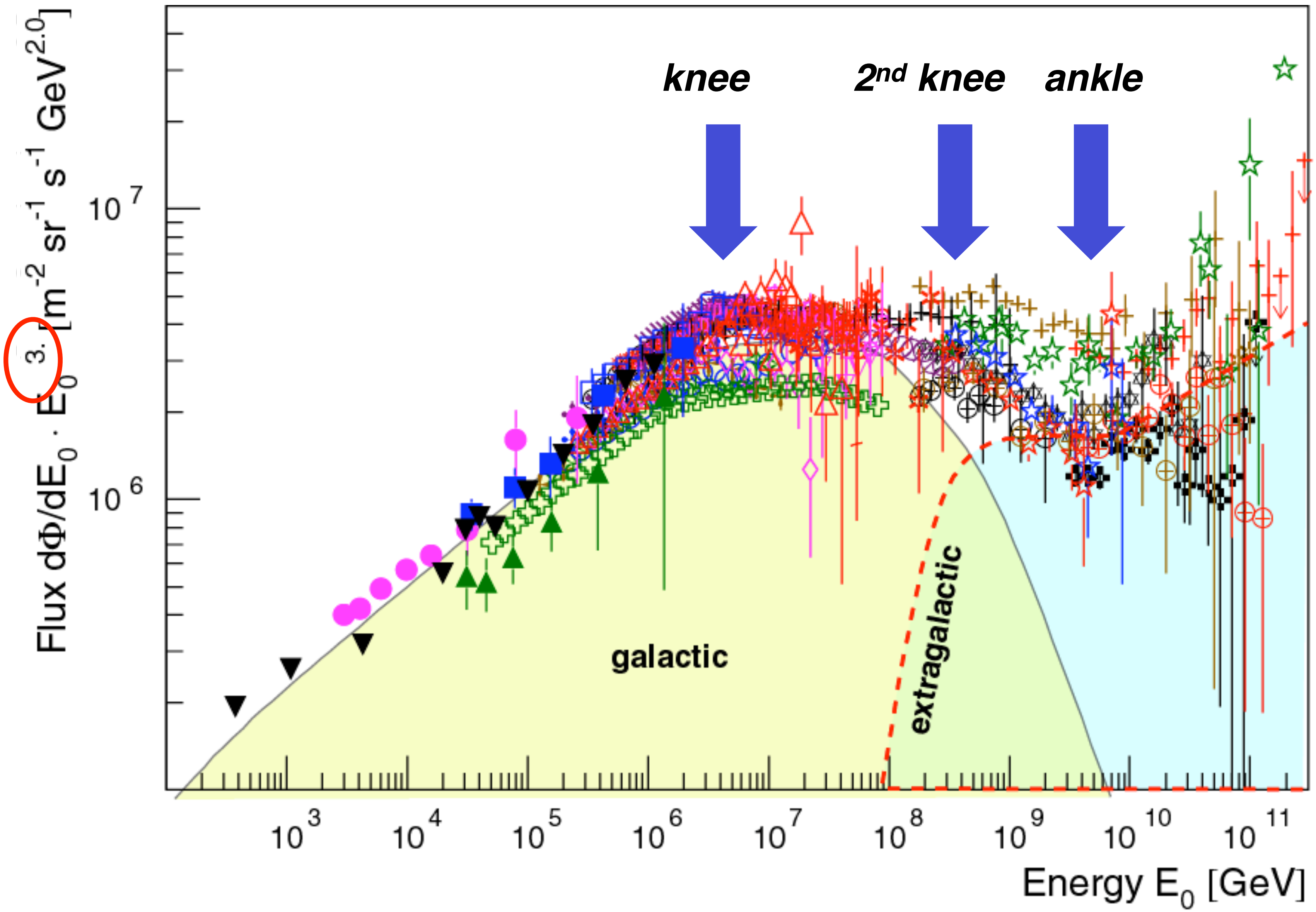


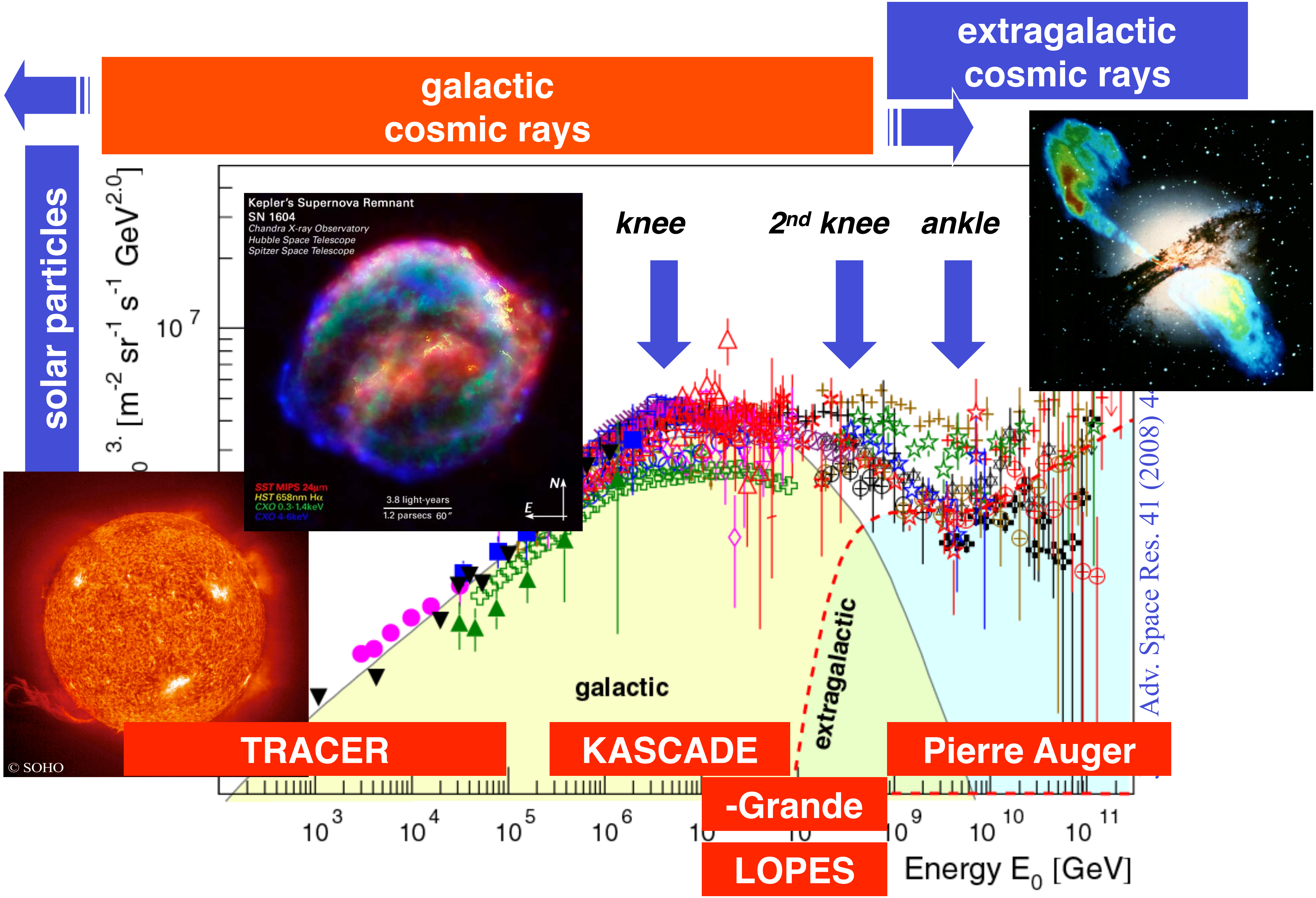
The air shower experiments KASCADE and KASCADE-Grande

Jörg R. Hörandel
Radboud University Nijmegen

IN·DEI·NOMINE·FELICITER

Cosmic-Ray Energy Spectrum



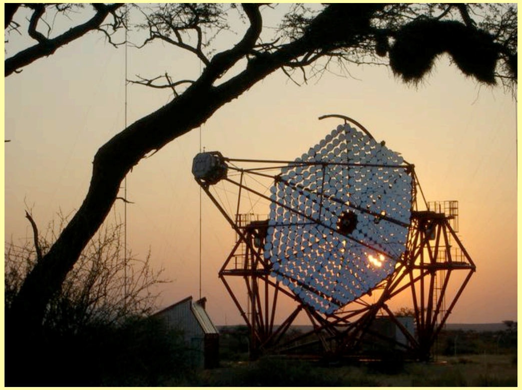


galactic
cosmic rays
extragalactic
cosmic rays
solar particles
Kepler's Supernova Remnant
SN 1604
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope
SST MIPS 24μm
HST 658nm Hα
CXO 0.3-1.4keV
CXO 4-6keV
3.8 light-years
1.2 parsecs 60″
N
E
knee
2nd knee
ankle
galactic
extragalactic
© SOHO
TRACER
KASCADE
-Grande
LOPES
Pierre Auger
Energy E0 [GeV]
Adv. Space Res. 41 (2008) 4

Origin of galactic cosmic rays

explored with complementary approaches

γ-ray astronomy



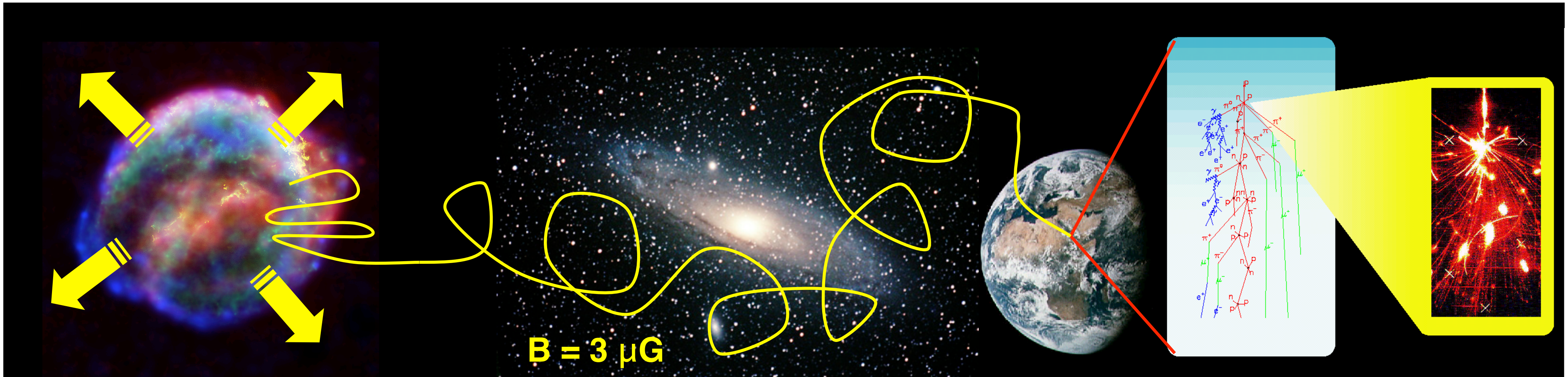
sources
acceleration

direct measurements above the atmosphere

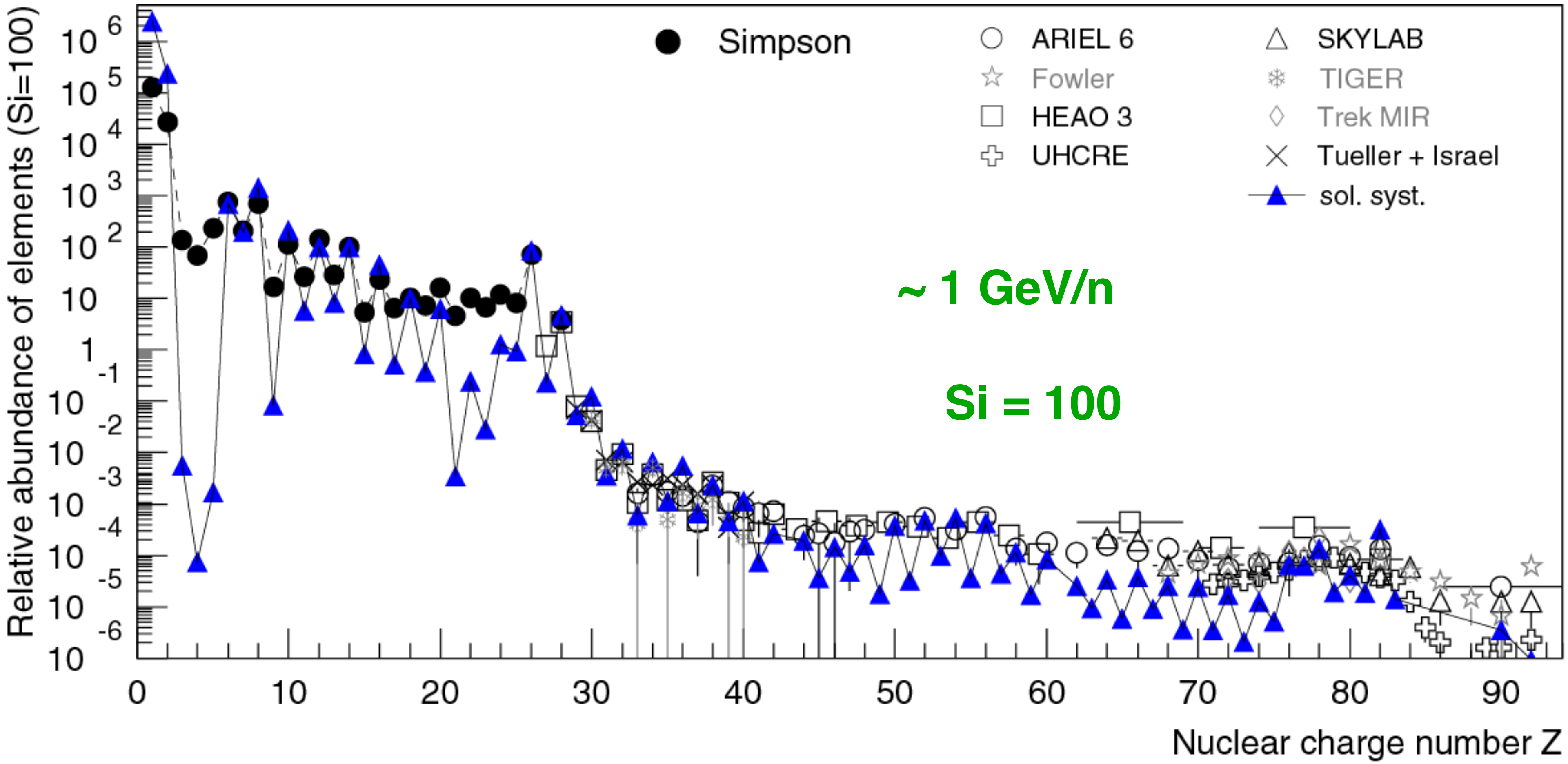
elemental/isotopic composition
propagation in Galaxy

air shower measurements

structures in E-spec.
end of gal. comp.
anisotropy
acceleration., propag.



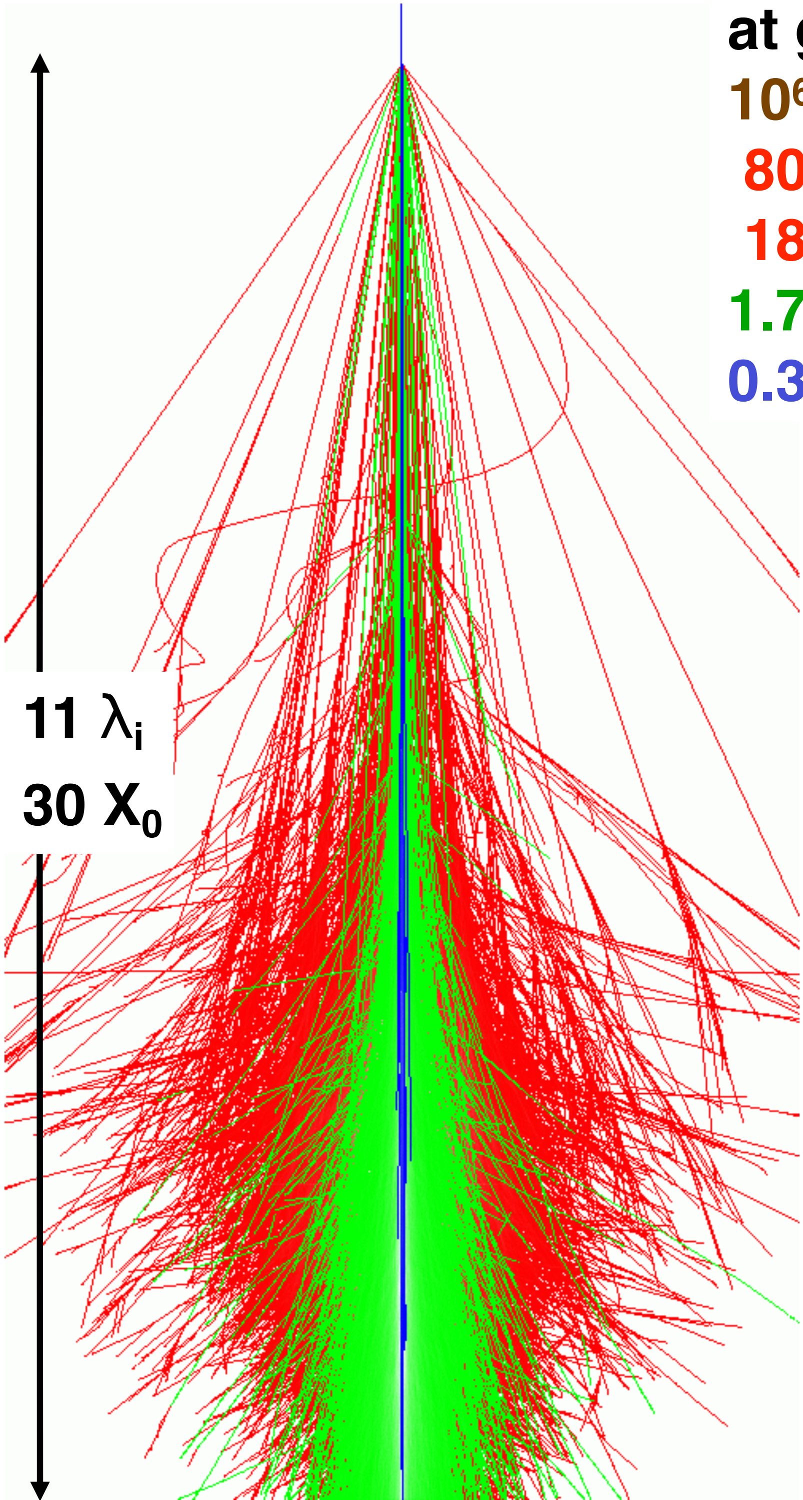
Relative abundance of elements at Earth



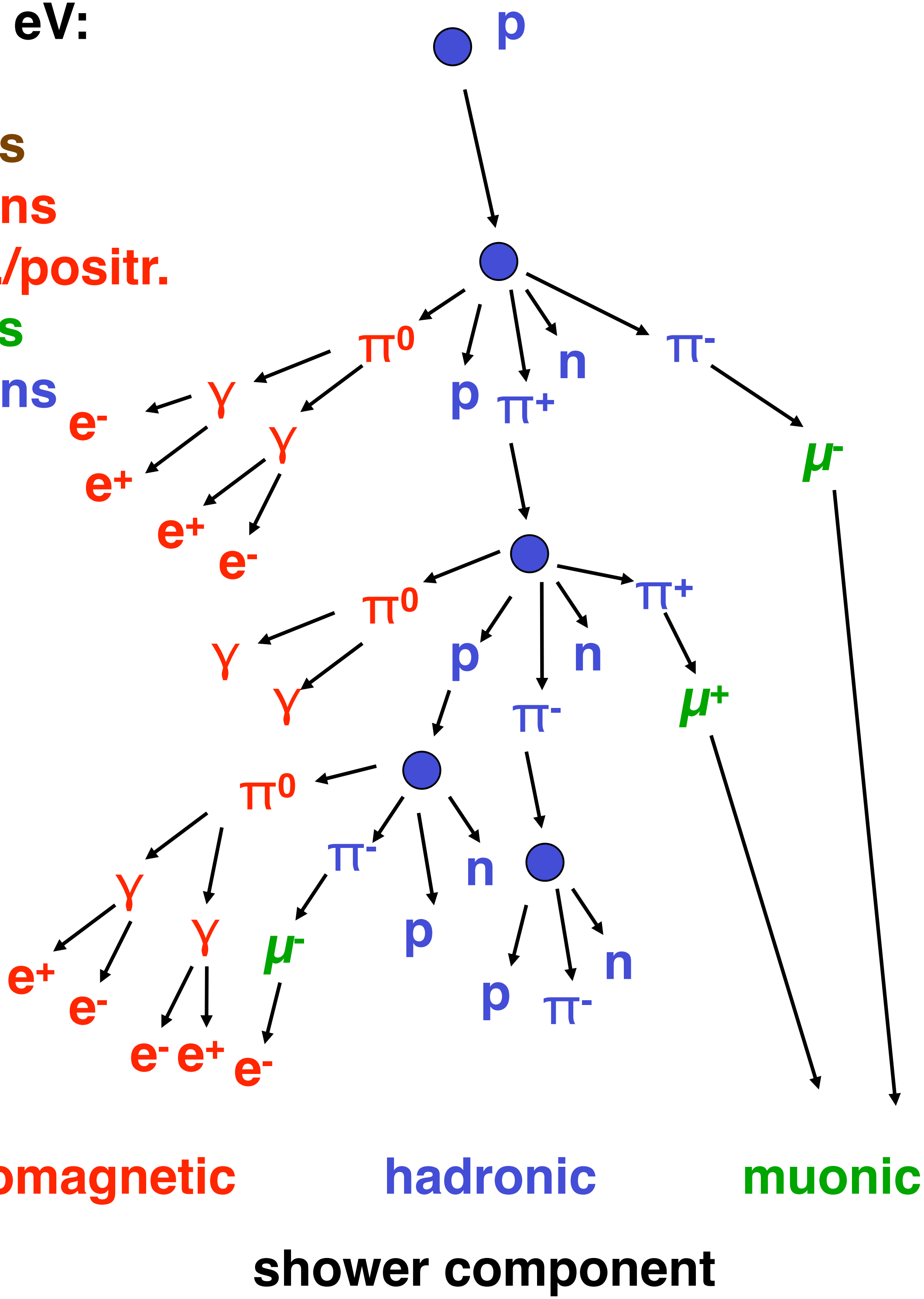
→Cosmic rays are „regular matter“, accelerated to extremely high energies

JRH, Adv. Space Res. 41 (2008) 442

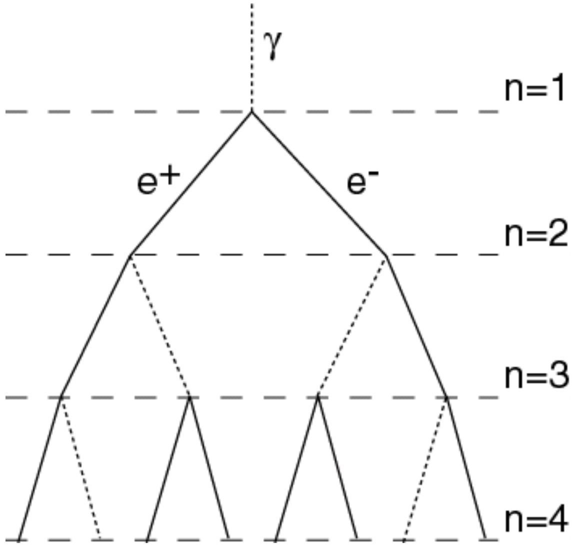
Extensive air showers



Proton 10^{15} eV:
at ground
10^6 particles
80% photons
18% elektr./positr.
1.7% muons
0.3% hadrons



A Heitler Model – Electromagnetic Cascades



pair production $\gamma \rightarrow e^{+}+e^{-}$

bremsstrahlung $e \rightarrow e+\gamma$

splitting length $d=X_0 \ln 2$

radiation length X_0=36.7 g/cm²

after *n* splitting lengths: $x = nX_0 \ln 2$ **and** $N = 2^n = \exp\left(\frac{x}{X_0}\right)$

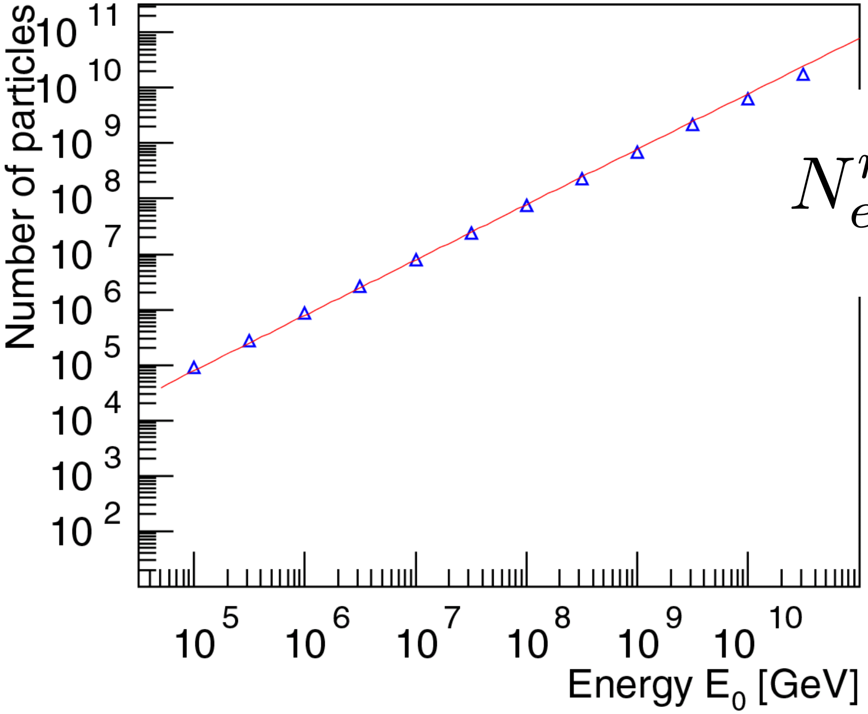
energy per particle $E = E_0/N$ **critical energy** $E_c^e = 85\ \text{MeV}$

number of particles at shower maximum

$$N_{max} = 2^{n_c} = \frac{E_0}{E_c^e} \qquad n_c = \frac{\ln\left(\frac{E_0}{E_c^e}\right)}{\ln 2}$$

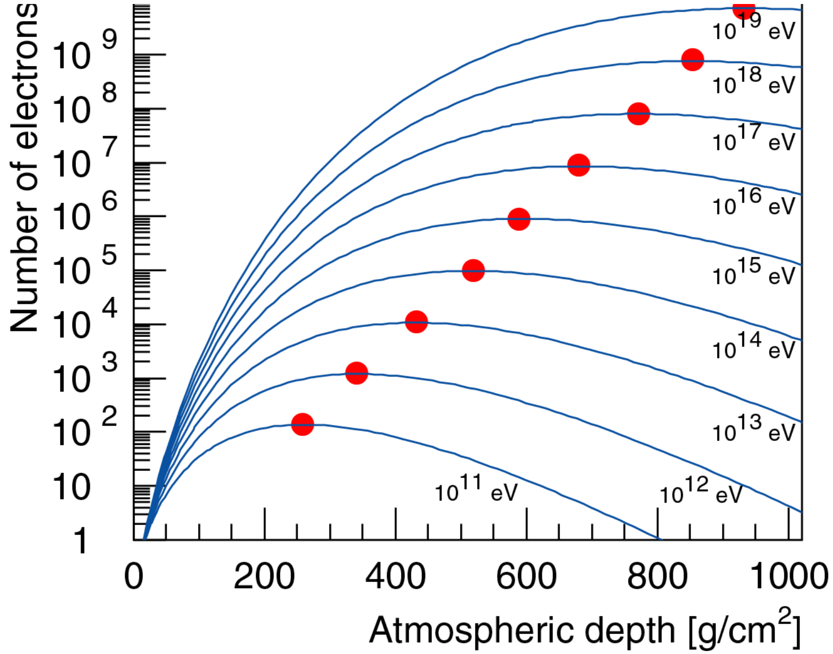
J. Matthews, Astrop. Phys. 22 (2005) 387 JRH, Mod. Phys. Lett. A 22 (2007) 1533

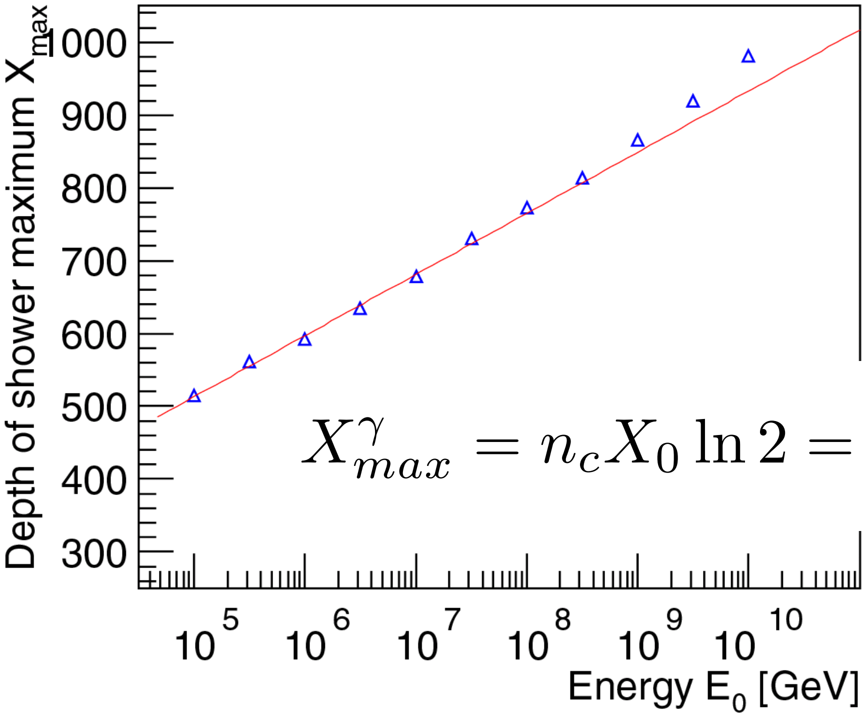
A Heitler Model – Electromagnetic Cascades



number of electrons at shower maximum

$$N_e^{max} = \frac{E_0}{g E_c^e} \approx 9.0 \cdot 10^5 \frac{E_0}{\mathrm{PeV}} \qquad g \approx 13$$



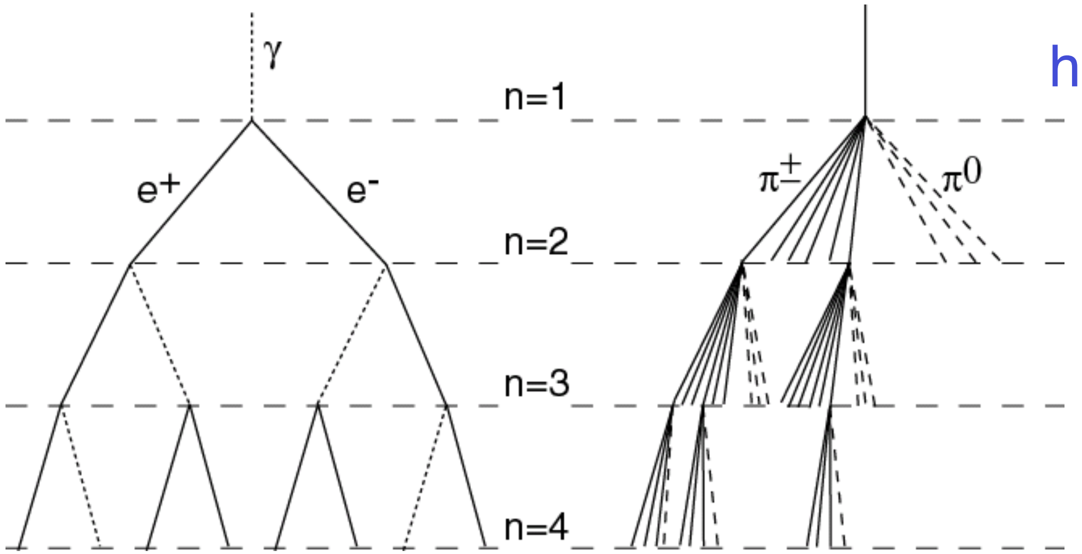


depth of shower maximum

$$X_{max}^{\gamma} = n_c X_0 \ln 2 = X_0 \ln\left(\frac{E_0}{E_c^e}\right) \approx 597 \frac{\mathrm{g}}{\mathrm{cm}^2} + 84 \frac{\mathrm{g}}{\mathrm{cm}^2} \lg\left(\frac{E_0}{\mathrm{PeV}}\right)$$

JRH, Mod. Phys. Lett. A 22 (2007) 1533

A Heitler Model – Hadronic Cascades



hadronic interaction $\pi + A \rightarrow \pi^0 + \pi^+ + \pi^-$

interaction length $\lambda_i^{\pi\text{-air}} \sim 120$ g/cm^2

π → hadronic interaction
→ decay

„critical energy“ $E_c^\pi \sim 20$ GeV

in each interaction $3/2 N_{ch}$ particles: N_{ch} π^{+-} and ½ N_{ch} π^0 $N_{ch} \sim 10$

after *n* interactions $N_\pi = (N_{ch})^n$ $E_\pi = \frac{E_0}{\left(\frac{3}{2}N_{ch}\right)^n}$

after n_c interactions $E_\pi = E_c^\pi$: $n_c = \frac{\ln E_0/E_c^\pi}{\ln \frac{3}{2} N_{ch}} = 0.85 \lg \left(\frac{E_0}{E_c^\pi}\right)$

superposition model

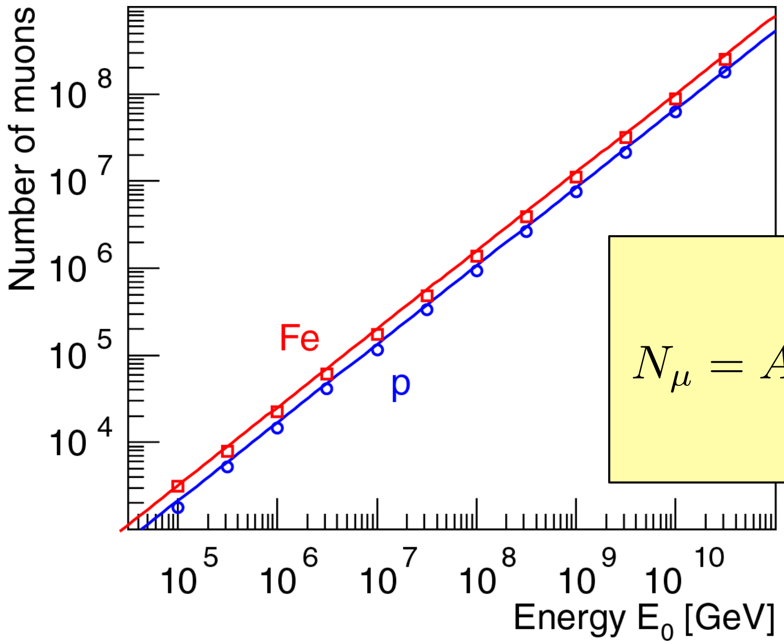
particle (E_0,A) → A proton showers with energy E_0/A

J. Matthews, Astrop. Phys. 22 (2005) 387

JRH, Mod. Phys. Lett. A 22 (2007) 1533

A Heitler Model – N_μ and N_e

Number of muons at shower maximum

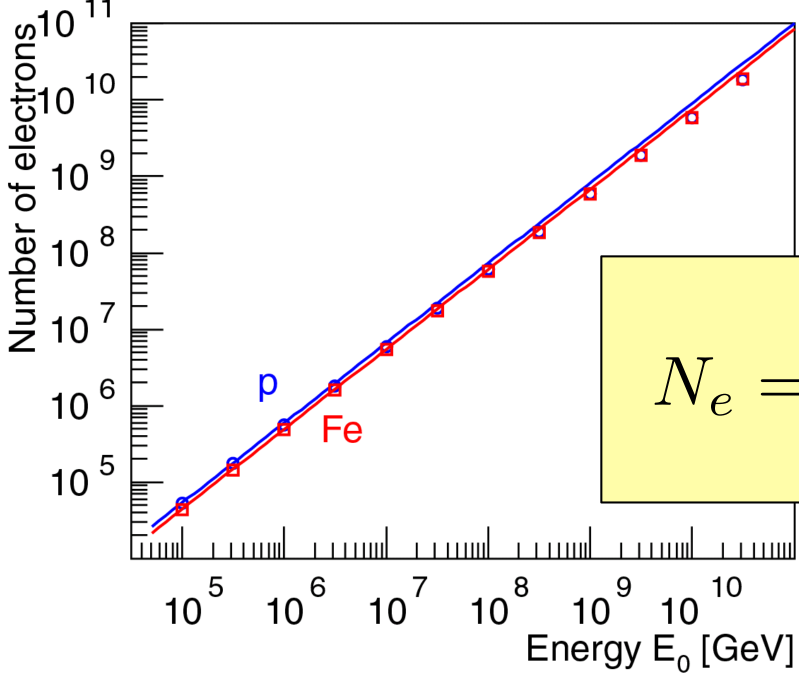


$$N_\mu = N_\pi = (N_{ch})^{n_c}$$

$$\ln N_\mu = n_c \ln N_{ch} = \beta \ln \left(\frac{E_0}{E_c^\pi} \right)$$

$$N_\mu = A \left(\frac{E_0}{A E_c^\pi} \right)^\beta = \left(\frac{E_0}{E_c^\pi} \right)^\beta A^{1-\beta} \approx 1.7 \cdot 10^4 \cdot A^{0.10} \left(\frac{E_0}{1\ \mathrm{PeV}} \right)^{0.90}$$

Number of electrons at shower maximum



$$\frac{E_{em}}{E_0} = \frac{E_0 - N_\mu E_c^\pi}{E_0} = 1 - \left(\frac{E_0}{A E_c^\pi} \right)^{\beta - 1}$$

$$N_e = \frac{E_{em}}{g E_c^e} \approx 6 \cdot 10^5 \cdot A^{-0.046} \left(\frac{E_0}{1\ \mathrm{PeV}} \right)^{1.046}$$

JRH, Mod. Phys. Lett. A 22 (2007) 1533

A Heitler Model – N_μ vs. N_e

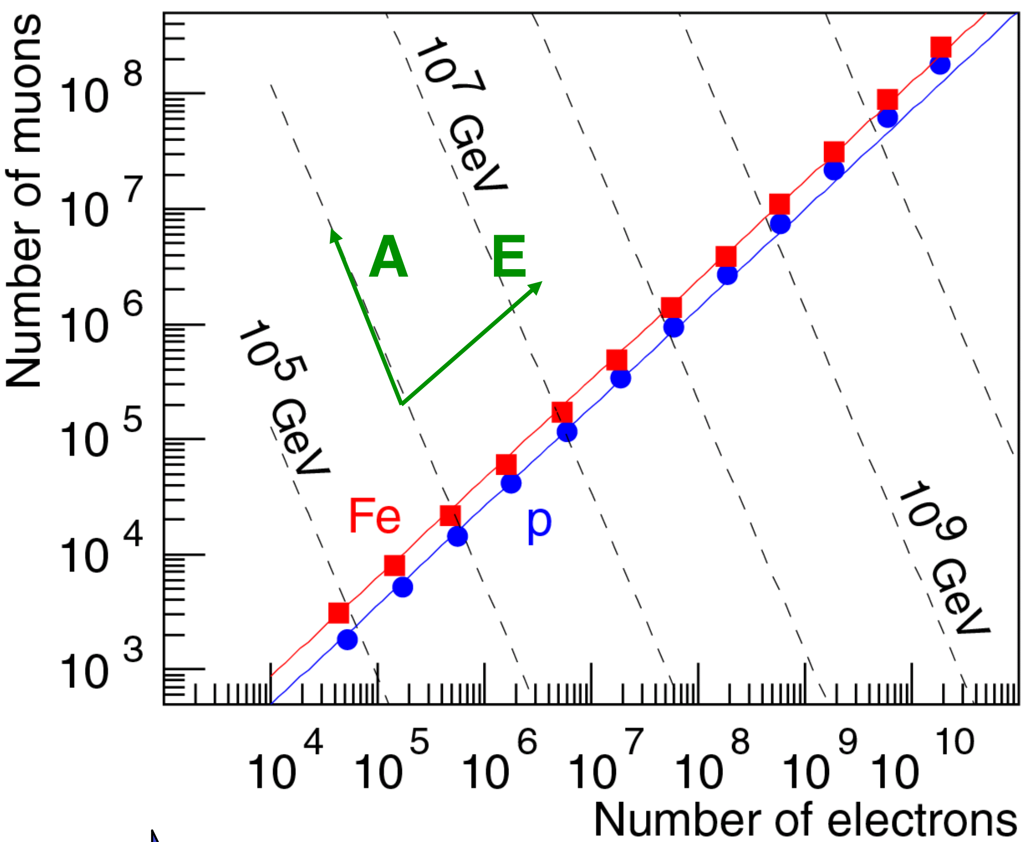
N_e-N_μ plane

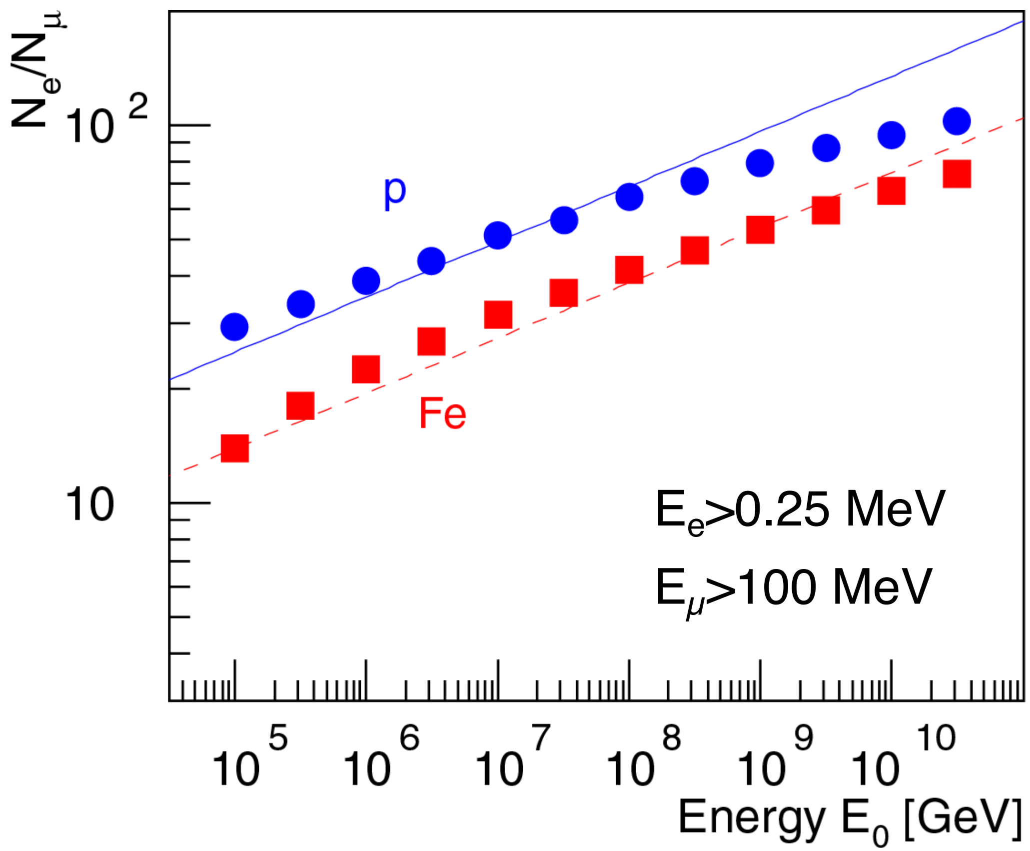
$$N_\mu|_{A=const} \approx 0.18 A^{0.14} N_e^{0.86}$$

$$N_\mu|_{E_0=const} \approx 5.77 \cdot 10^{16} \left(\frac{E_0}{1\ \mathrm{PeV}}\right) N_e^{-2.17}$$

N_e-N_μ ratio

$$\frac{N_e}{N_\mu} \approx 35.1 \cdot \left(\frac{E_0}{A \cdot 1\ \mathrm{PeV}}\right)^{0.15}$$



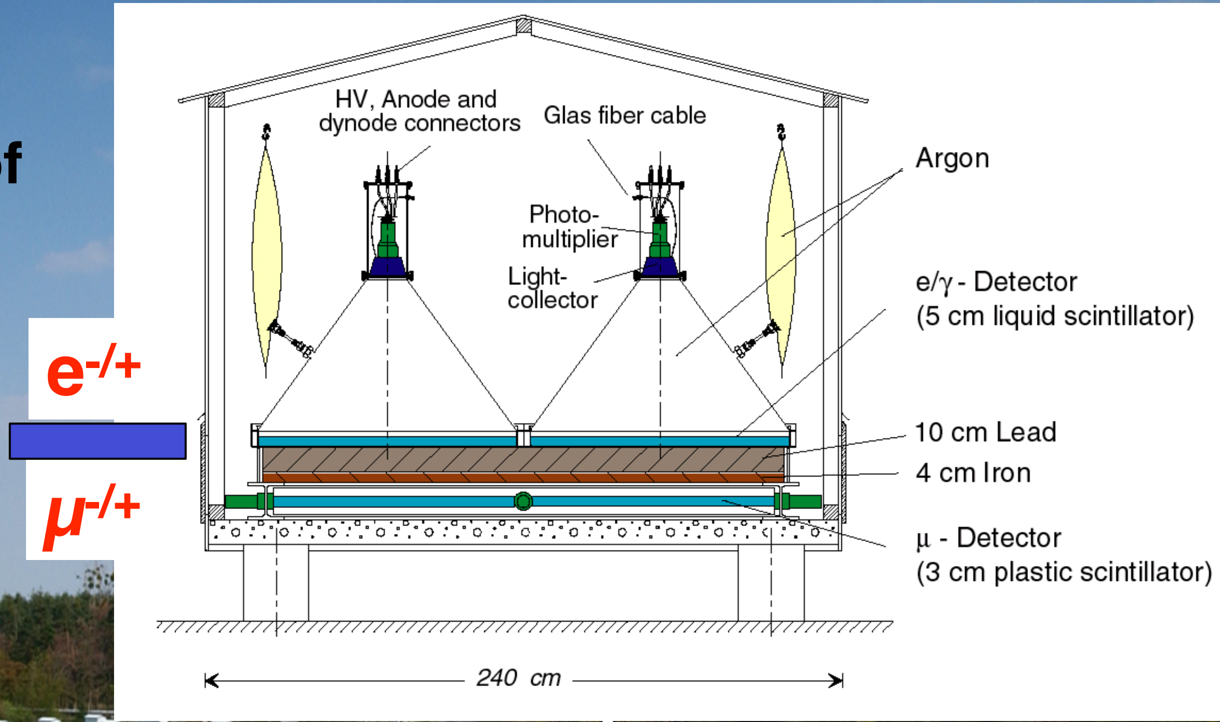


estimator for mass *A* of primary particle

JRH, Mod. Phys. Lett. A 22 (2007) 1533

KArlsruhe Shower Core and Array DEtector

Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components

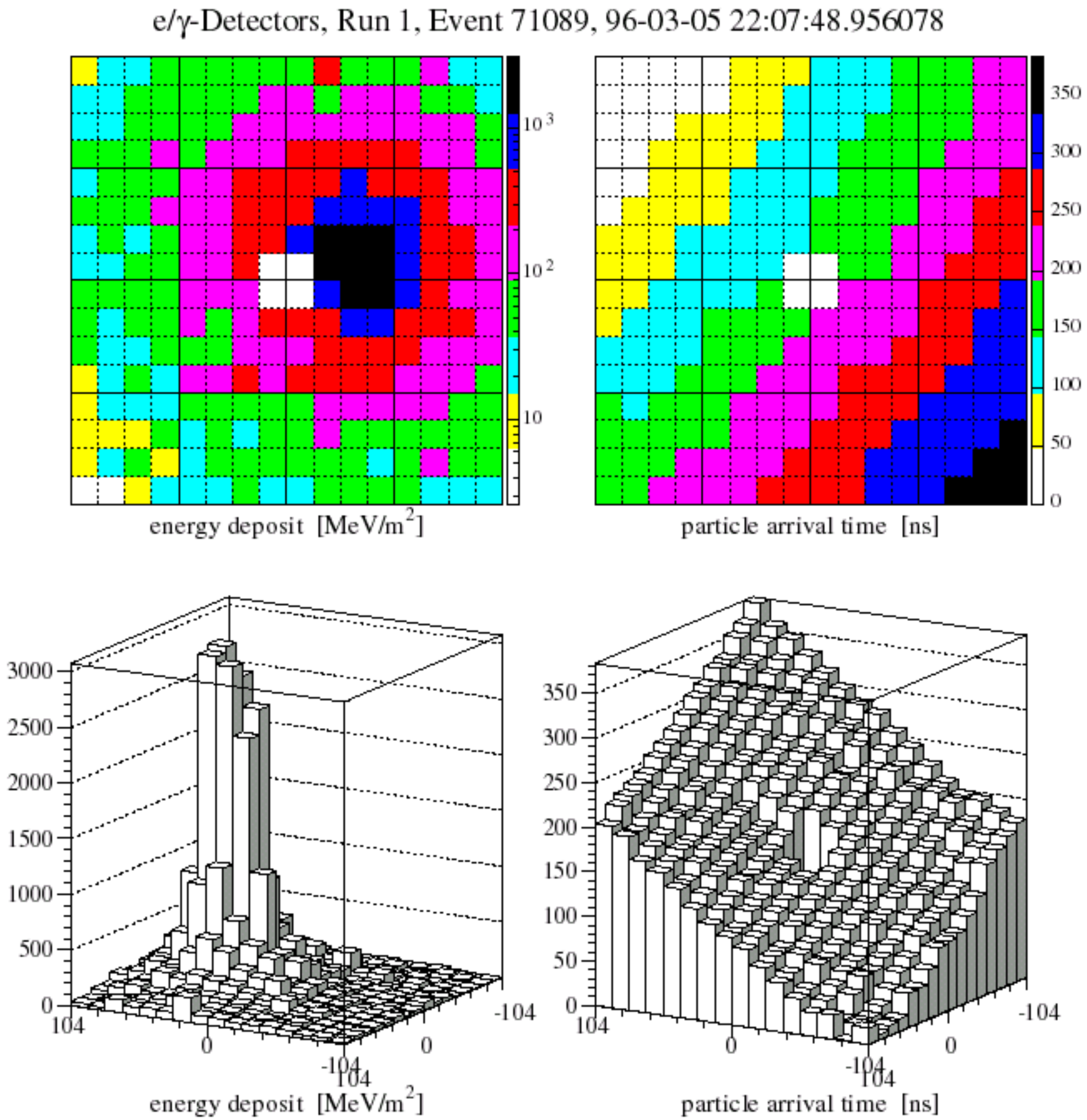


T. Antoni et al, Nucl. Instr. & Meth. A 513 (2004) 490

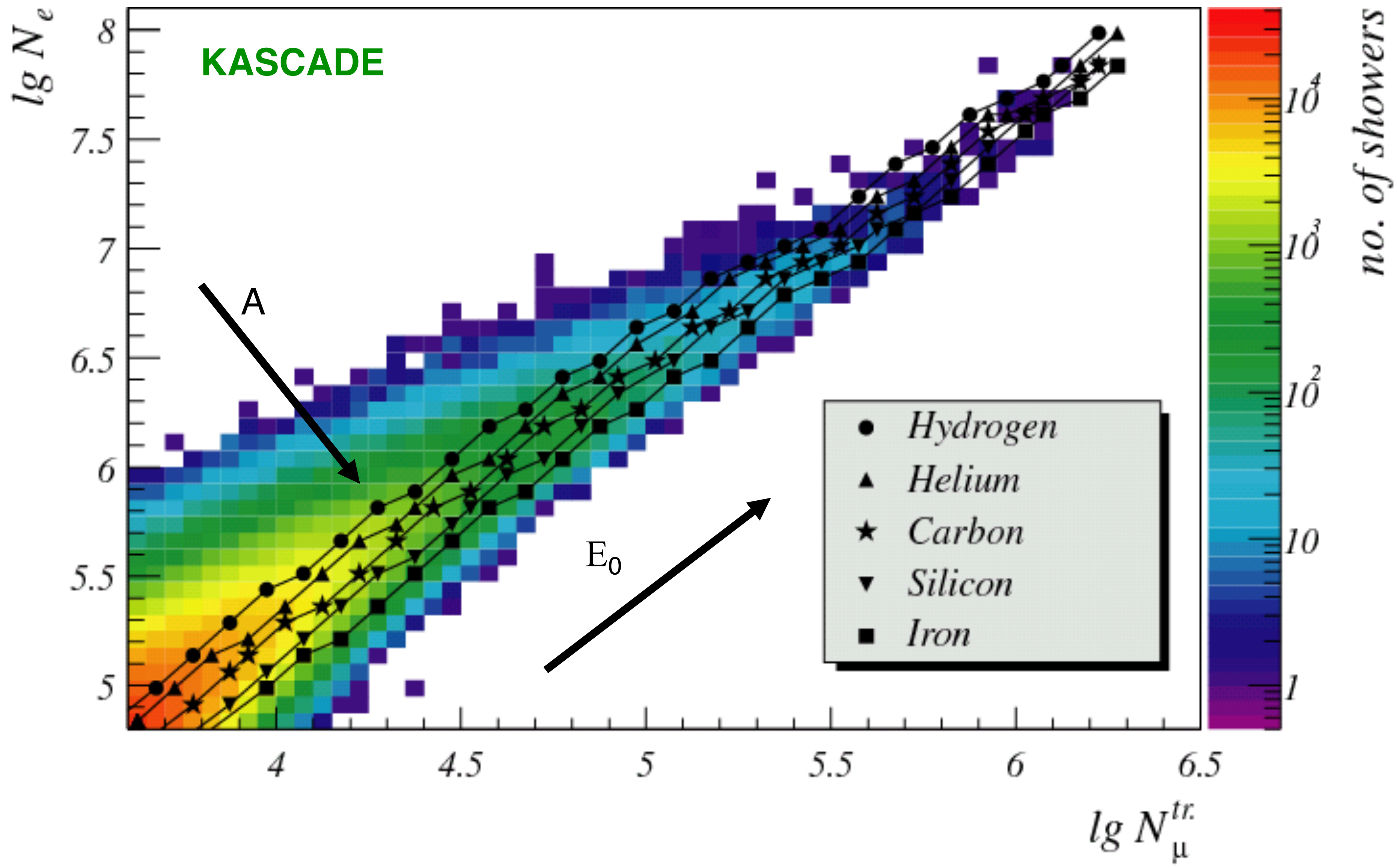
Event reconstruction in the scintillator array

electromagnetic component

shower core	$\Delta r = 2.5 - 5.5$ m
shower direction	$\Delta\alpha = 0.5° - 1.2°$
shower size	$\Delta N_e/N_e = 6 - 12$ %



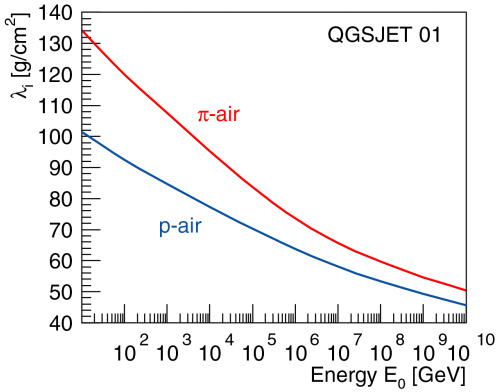
Two dimensional shower size spectrum lg N_e vs. lg N_μ

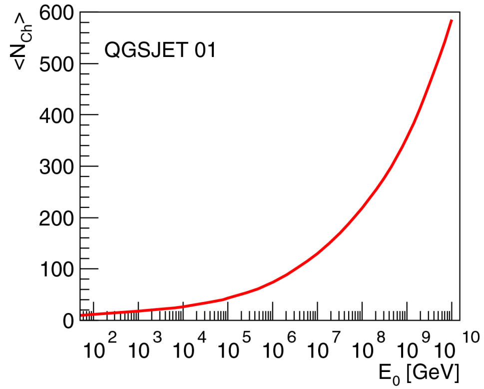


T. Antoni et al., Astropart. Phys. 24 (2005) 1

A Heitler Model – X_{max}

$$X^p_{max} = \lambda_i^{p-air} \ln 2 + X_0 \ln\left(\frac{\kappa E_0}{3 N_{ch} E_c^e}\right)$$



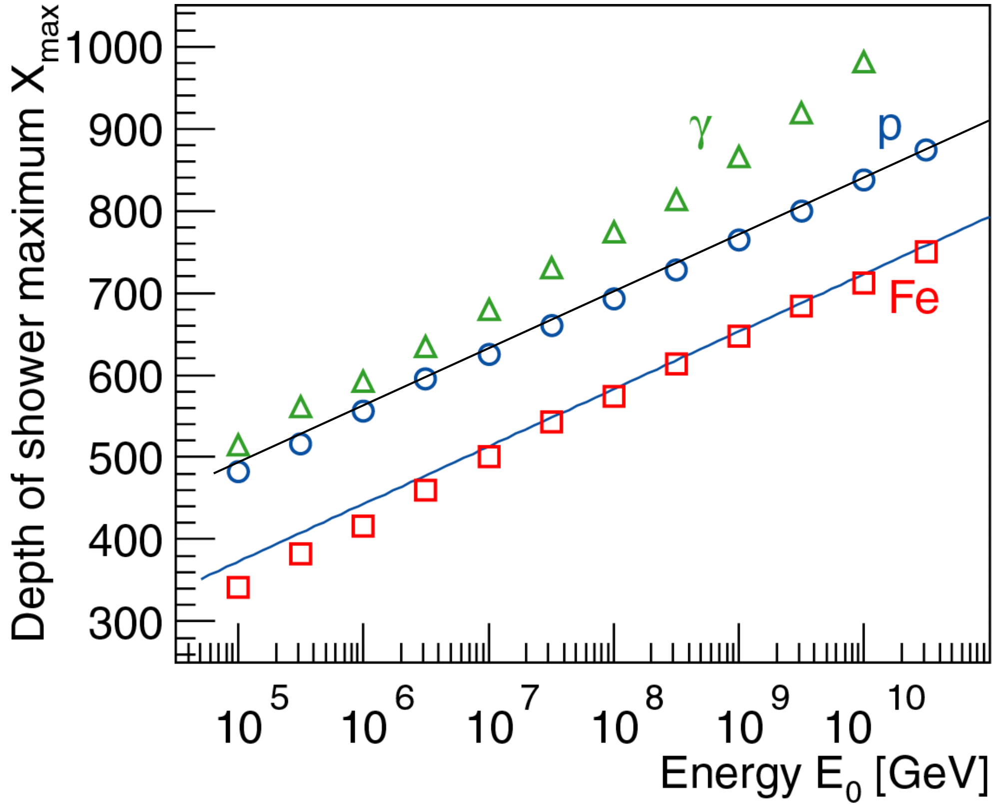


proton air interaction length $\lambda_i^{p-air} = \xi + \zeta \lg \frac{E_0}{\mathrm{PeV}}$

ζ=-4.88 g/cm²

multiplicity of charged particles produced in π-N interactions $N_{ch} = N_0 \left(\frac{E_0}{\mathrm{PeV}}\right)^\eta$ η=0.13

$$X^p_{max} = \xi \ln 2 - X_0 \left(\frac{3 N_0 E_c^e}{\kappa \cdot \mathrm{PeV}}\right) + \Lambda^p \lg\left(\frac{E_0}{\mathrm{PeV}}\right)$$



elongation rate

e/m shower $\Lambda^\gamma = X_0 \ln 10 \approx 84.4 \mathrm{g/cm}^2$

proton shower

$$\Lambda^p = X_0 \ln 10 - \eta X_0 \ln 10 + \zeta \ln 2 \approx 70 \mathrm{g/cm}^2$$

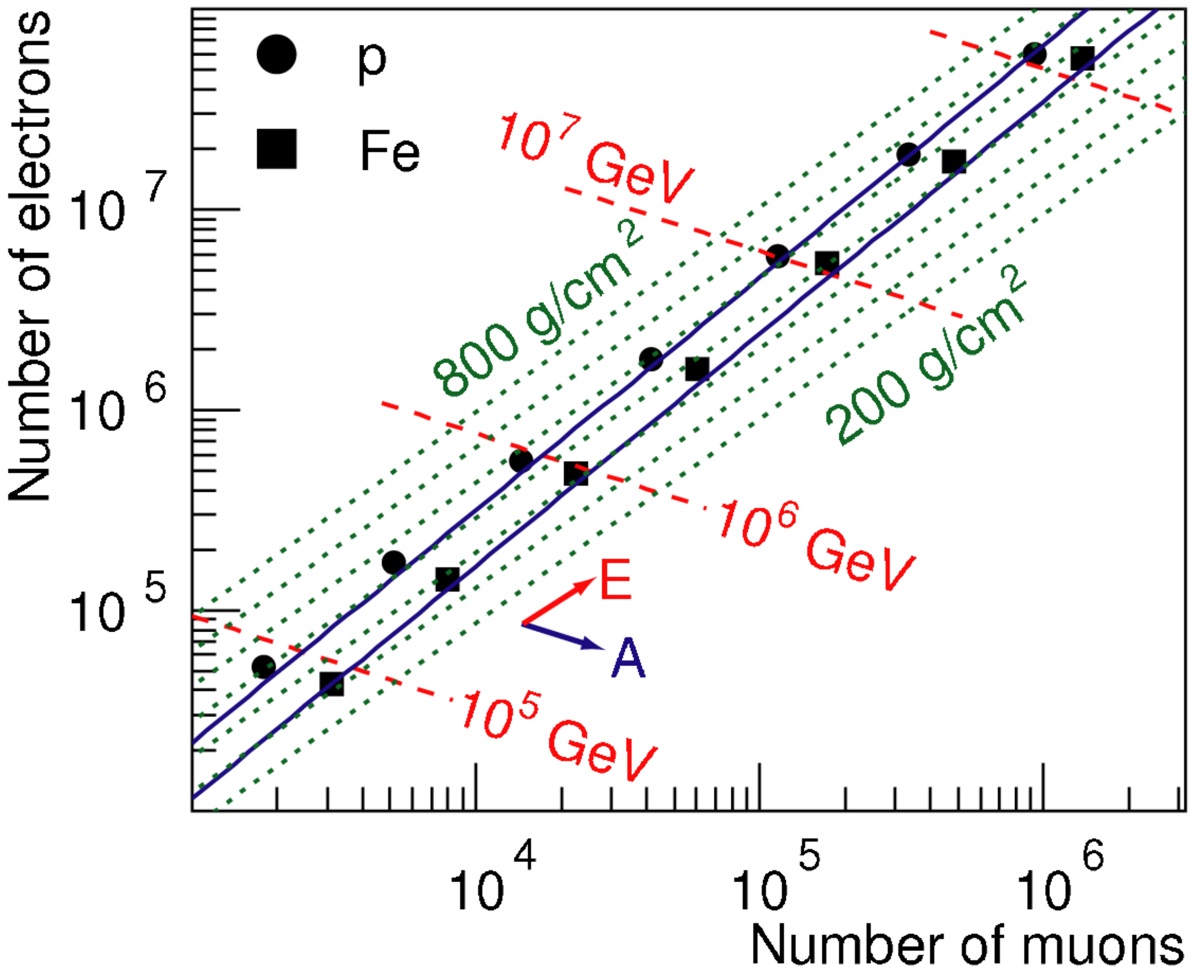
X_{max} for heavy nuclei

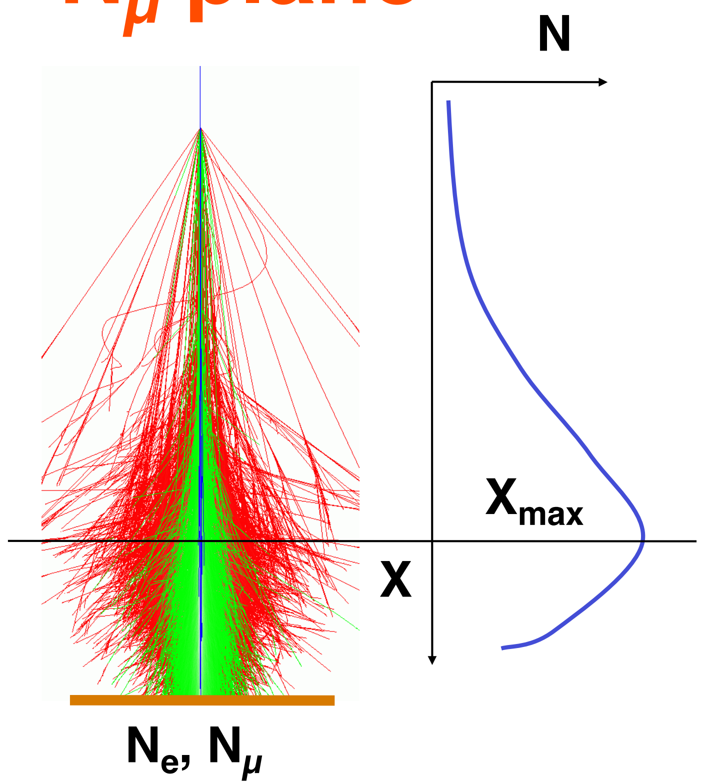
$$X^A_{max} = X^p_{max} - X_0 \ln A$$

estimator for mass *A* of primary particle

JRH, Mod. Phys. Lett. A 22 (2007) 1533

Air showers in the N_e - N_μ plane





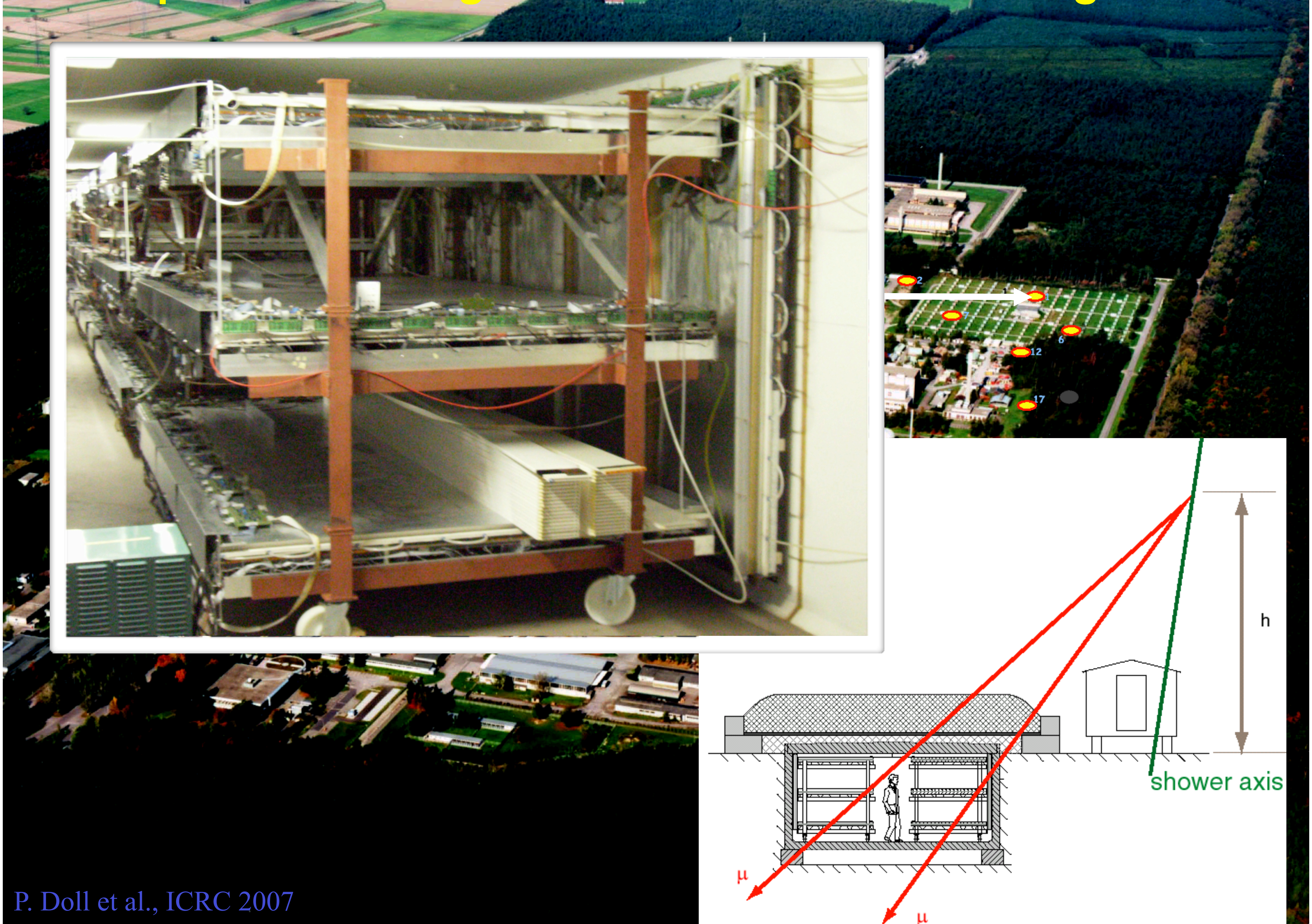
JRH, Nucl. Instr. & Meth. A 588 (2008) 181

energy
$$N_e|_{E_0} = 5.30 \cdot 10^7 (E_0/\mathrm{PeV})^{1.37} N_\mu^{-0.46}$$

mass
$$N_e|_A = 7.24 \cdot A^{-0.16} N_\mu^{1.16}$$

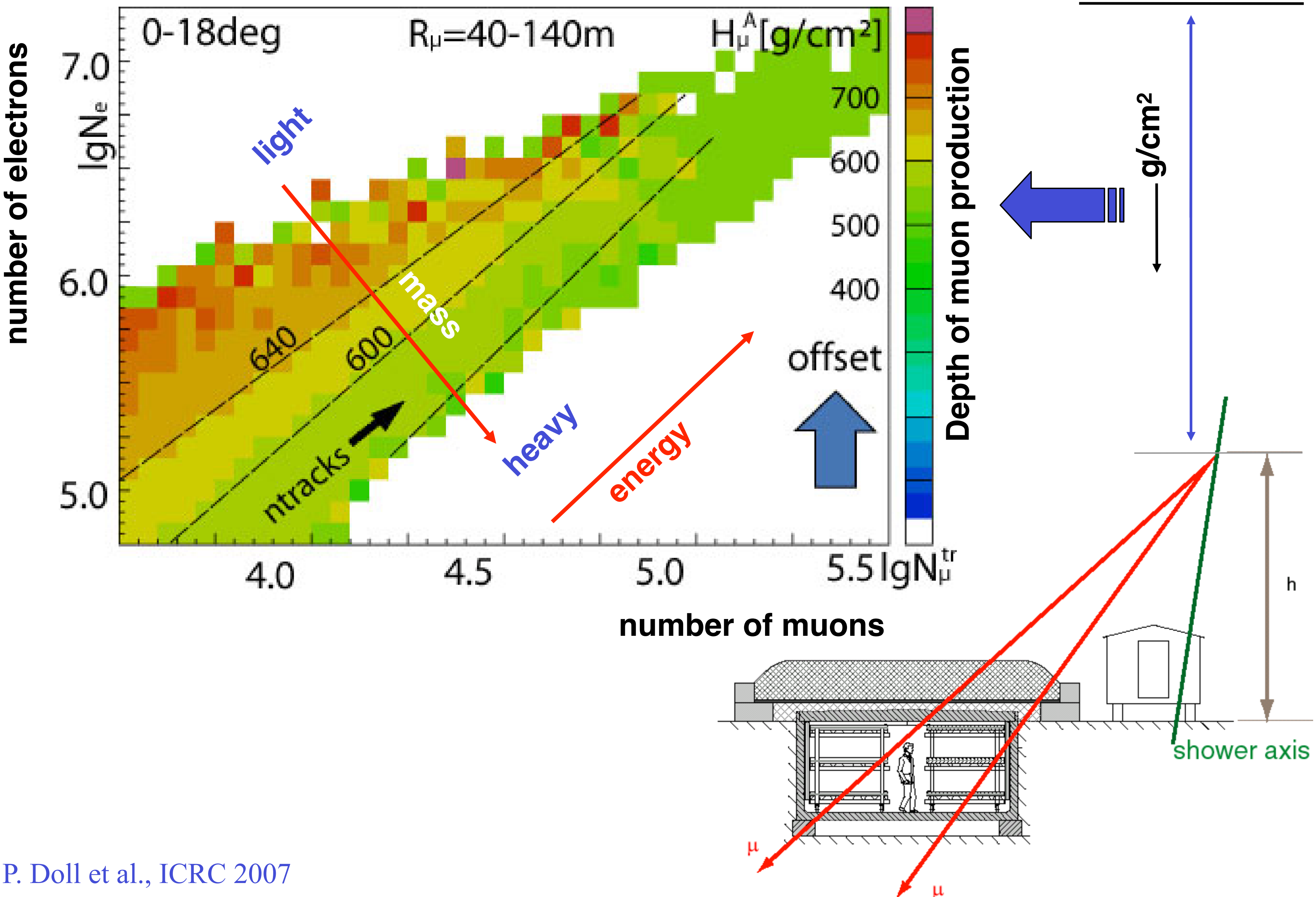
depth of shower maximum
$$N_e|_{X_{max}} = \frac{X_{max} + 287.9\ \mathrm{g/cm}^2}{569.6\ \mathrm{g/cm}^2} + 1.02 N_\mu$$

Muon production height – KASCADE muon tracking detector



P. Doll et al., ICRC 2007

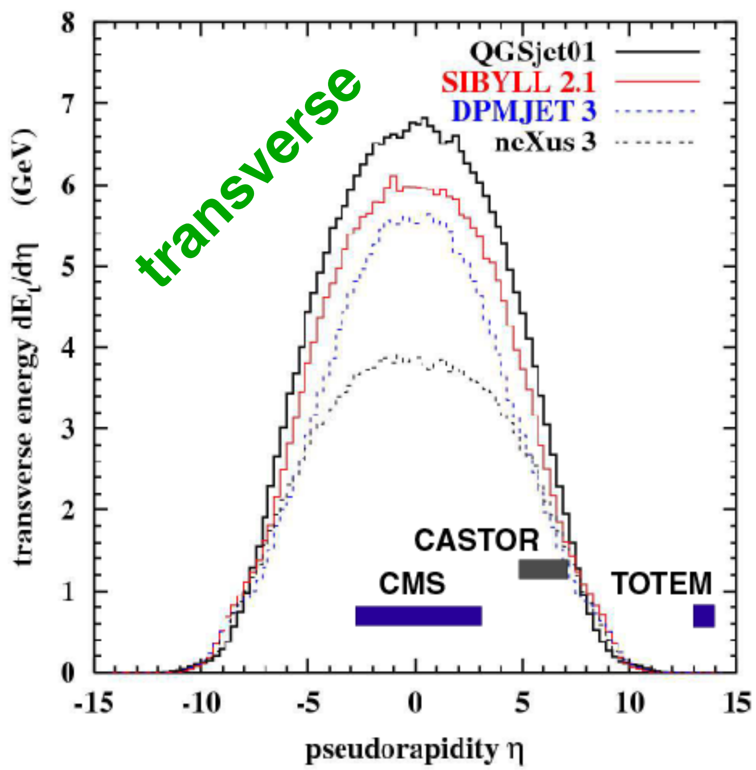
Muon production height – KASCADE muon tracking detector

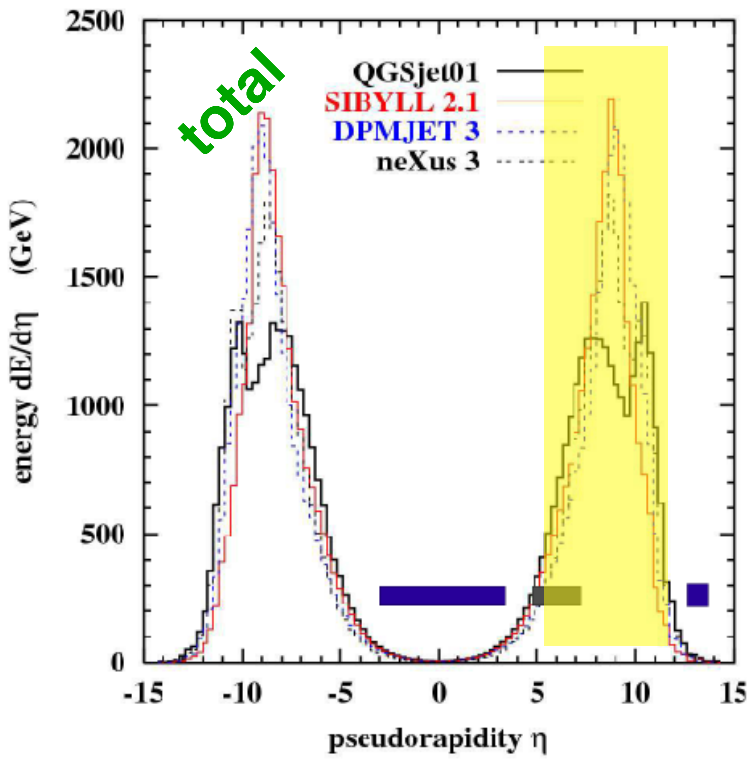


P. Doll et al., ICRC 2007

Hadronic interaction models

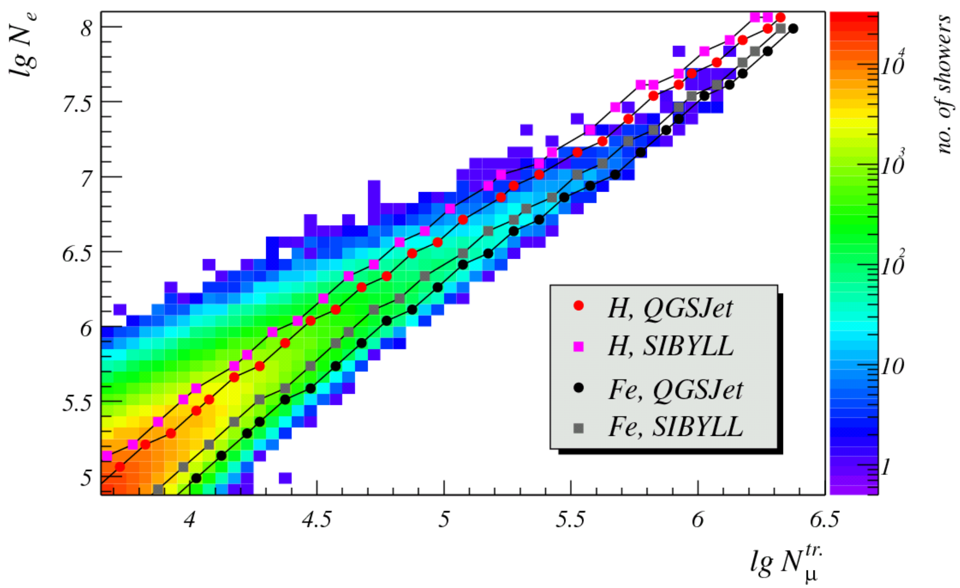
Energy flow in collider experiments





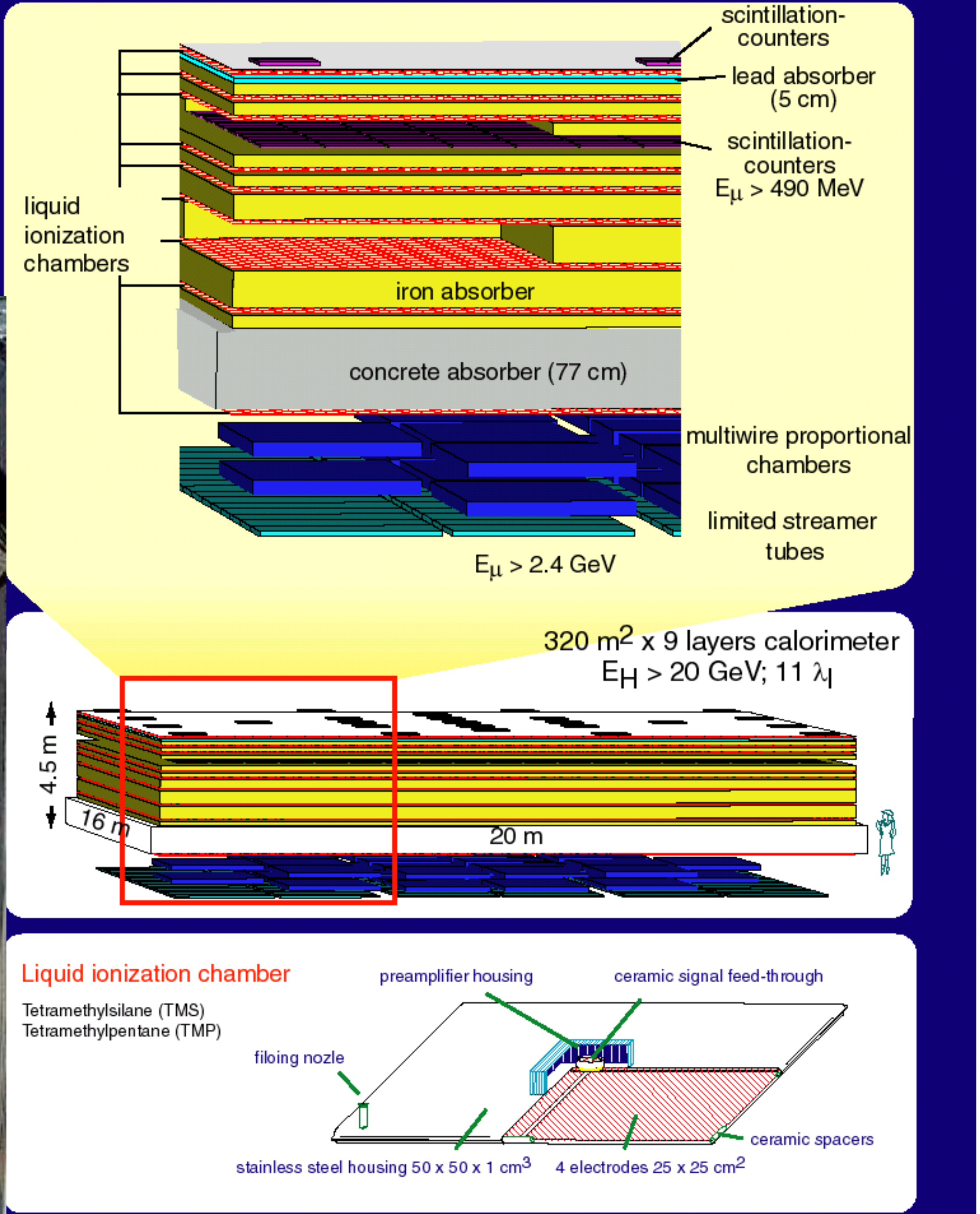
LHC (E_{cms}=17 TeV)
E_{lab}~ 10^{17} eV

Problem: energy dependence of α_s
→ different phenomenological approximations to QCD



interpretation of air shower data depends on hadronic interaction model used

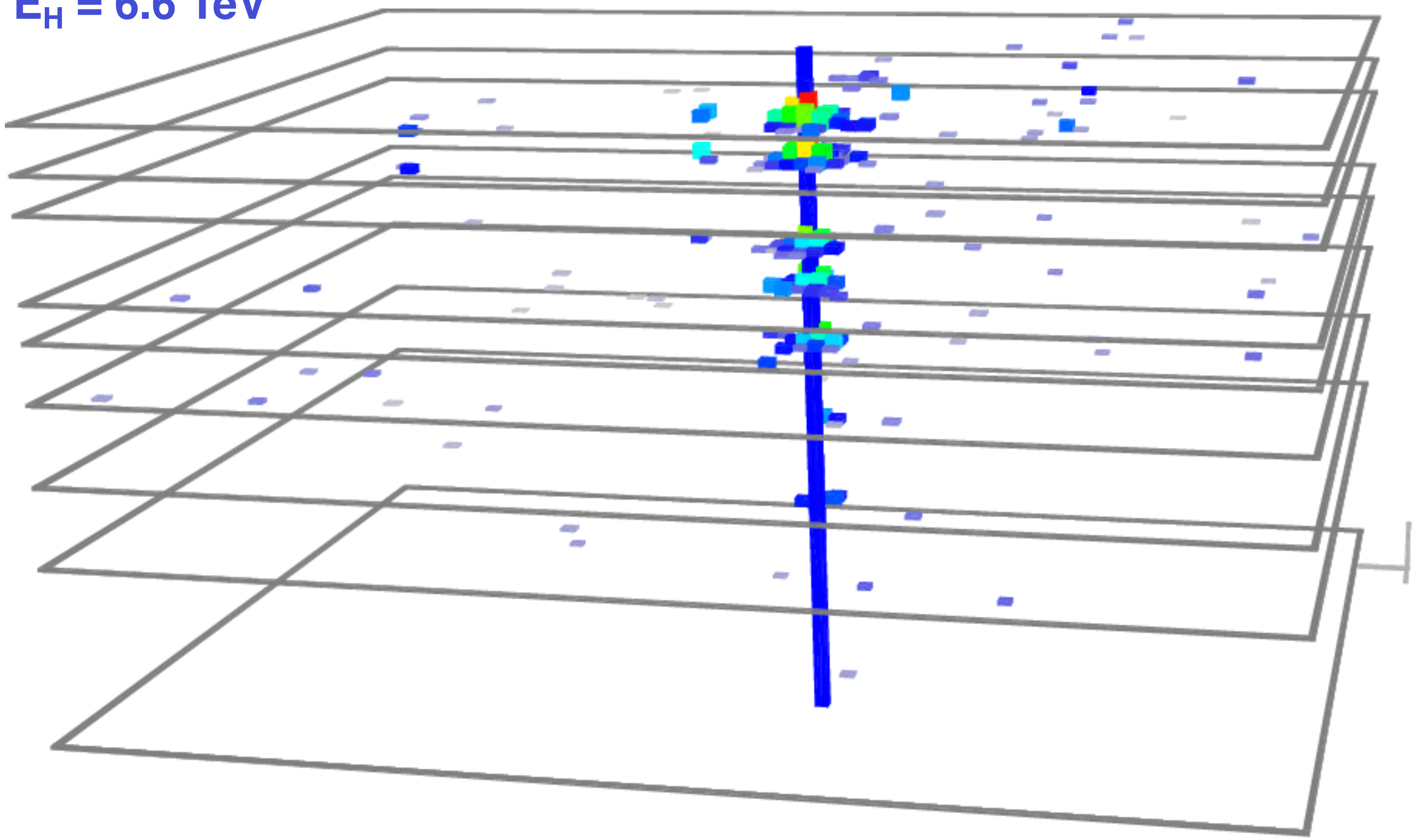
KASCADE Hadron Calorimeter



J. Engler et al., Nucl. Instr. Meth. A 427 (1999) 528

Reconstruction of hadrons

Unaccompanied hadron
E_H = 6.6 TeV



spatial resolution:
$\sigma_x \sim 10 - 12$ cm

angular resolution:
$\sigma_\Theta \sim 1° - 3°$

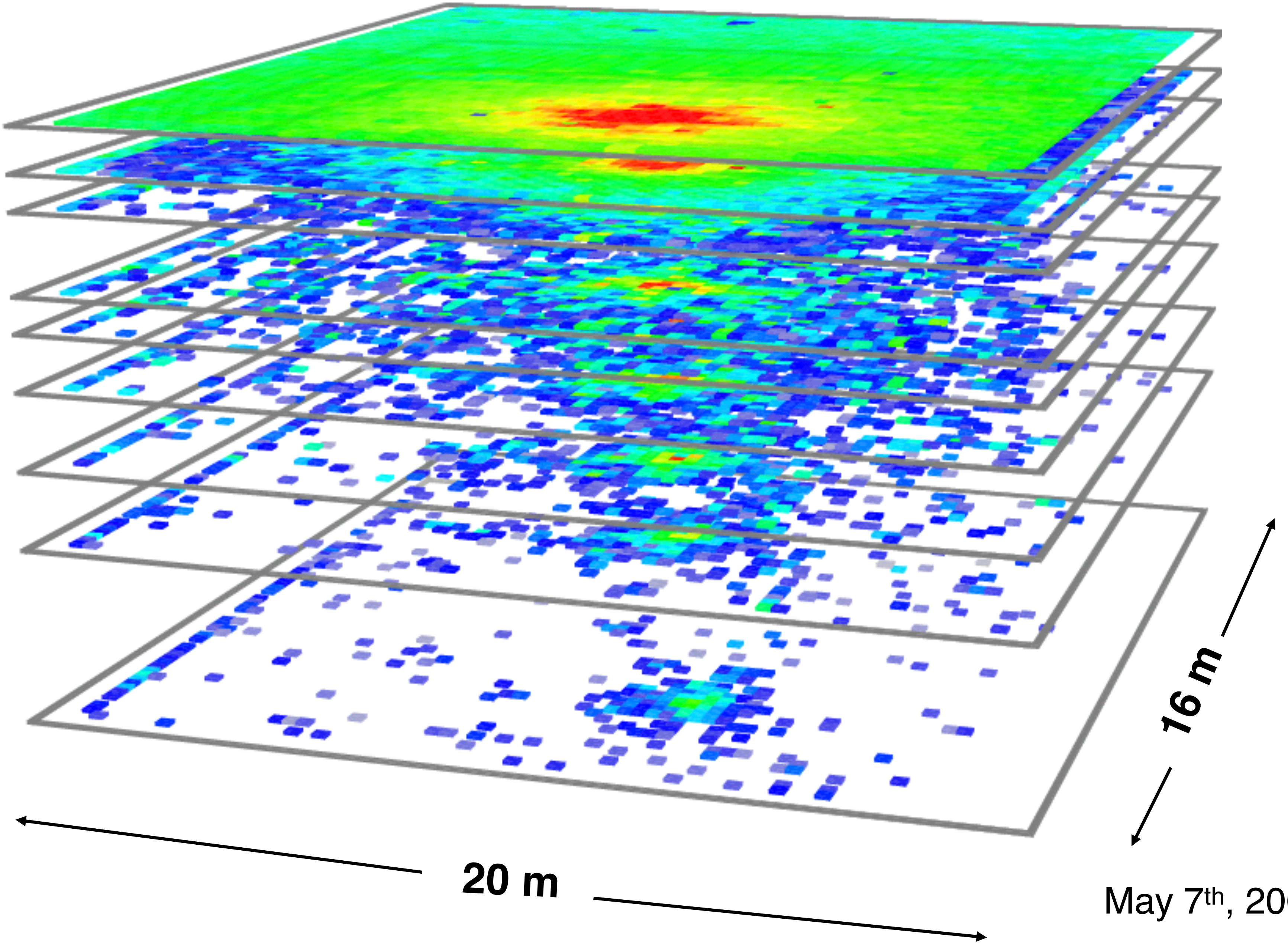
energy resolution:

$$\frac{\sigma(E)}{E}[\%] \approx \frac{250}{\sqrt{E/\mathrm{GeV}}}$$

Hadronic shower core

$E_0 \sim 6$ PeV

Number of reconstructed hadrons $N_h = 143$

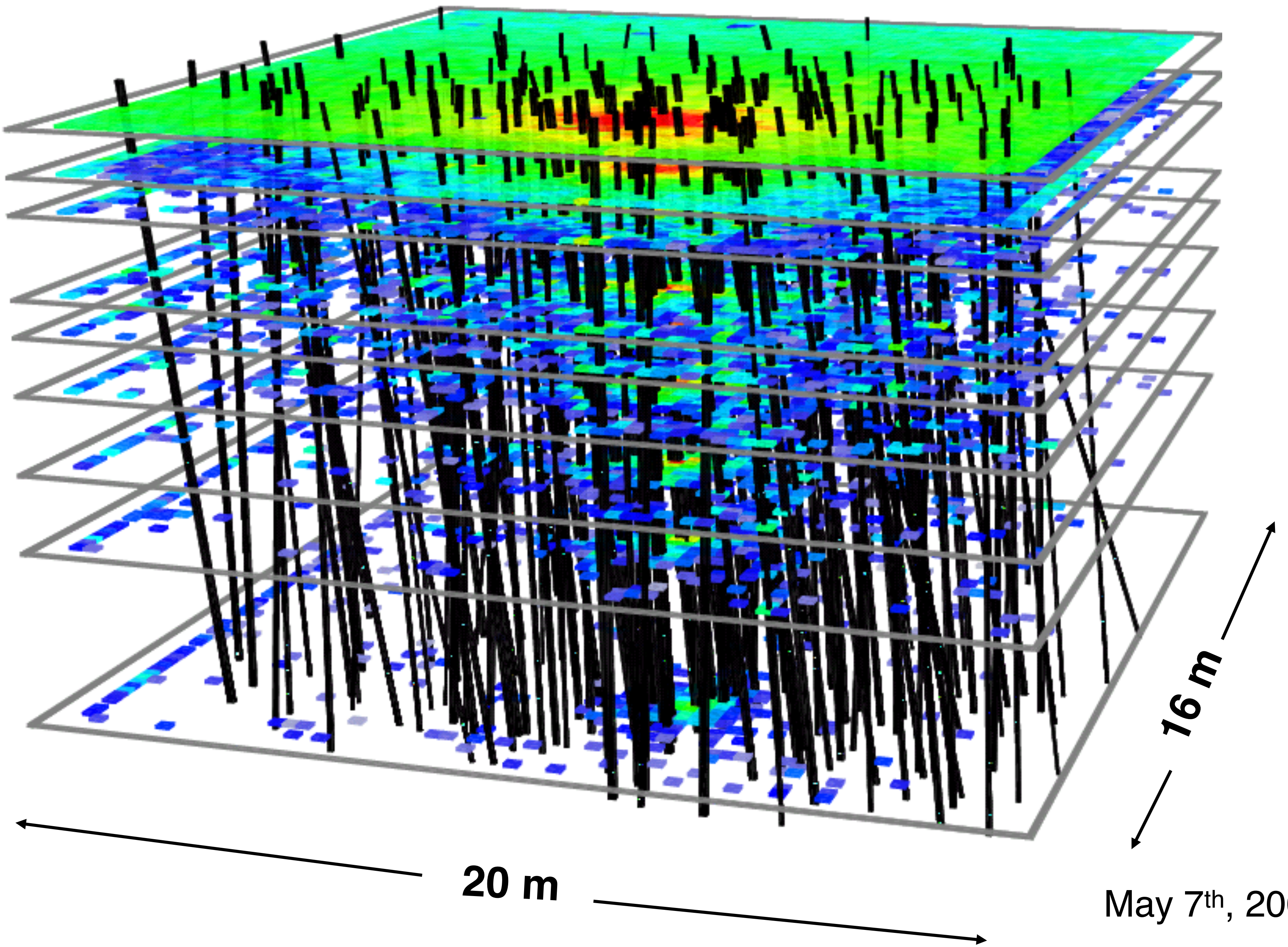


May 7th, 2002 9:45

Hadronic shower core

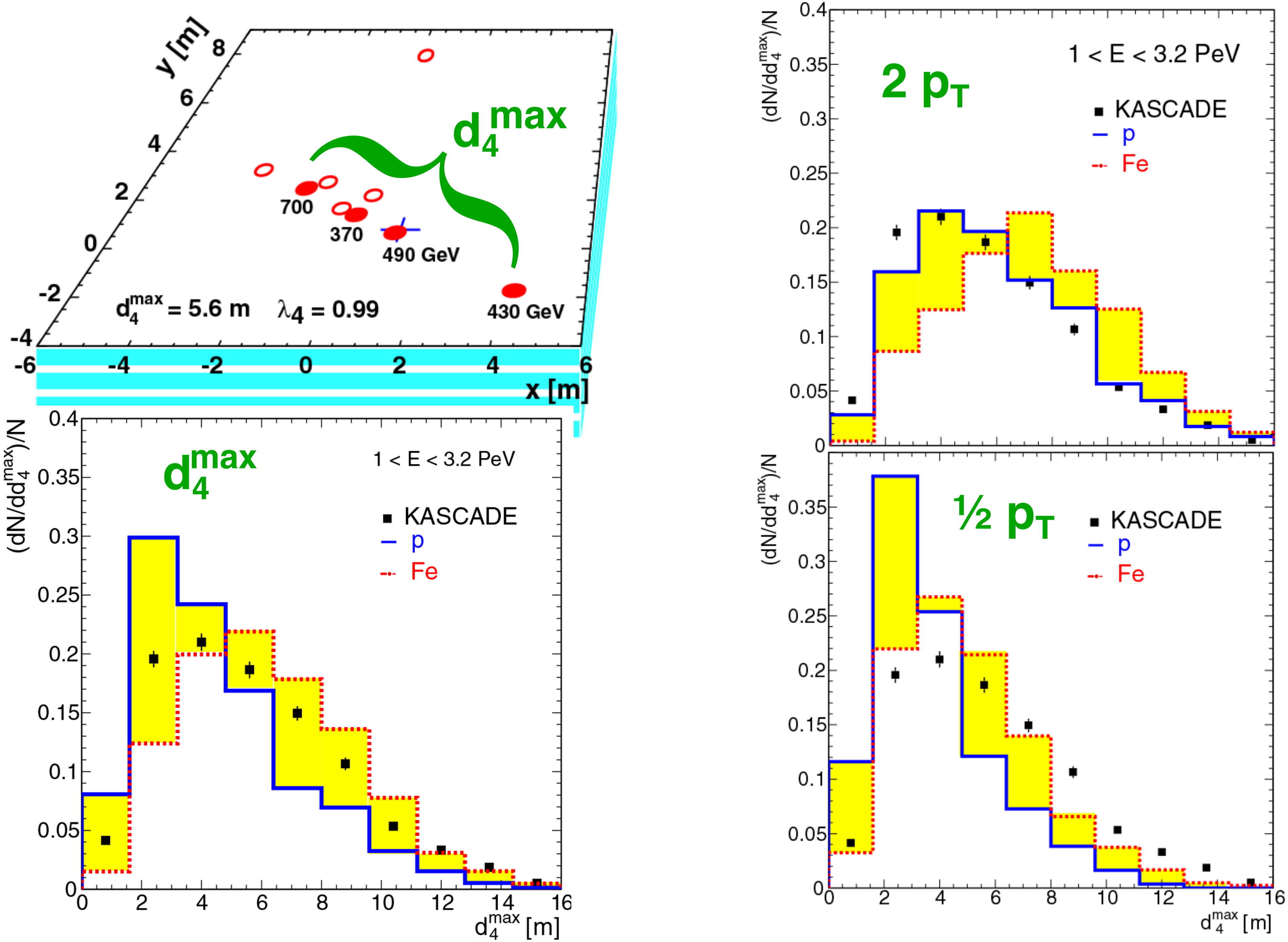
$E_0 \sim 6$ PeV

Number of reconstructed hadrons $N_h = 143$



May 7th, 2002 9:45

Transverse momentum in hadronic interactions

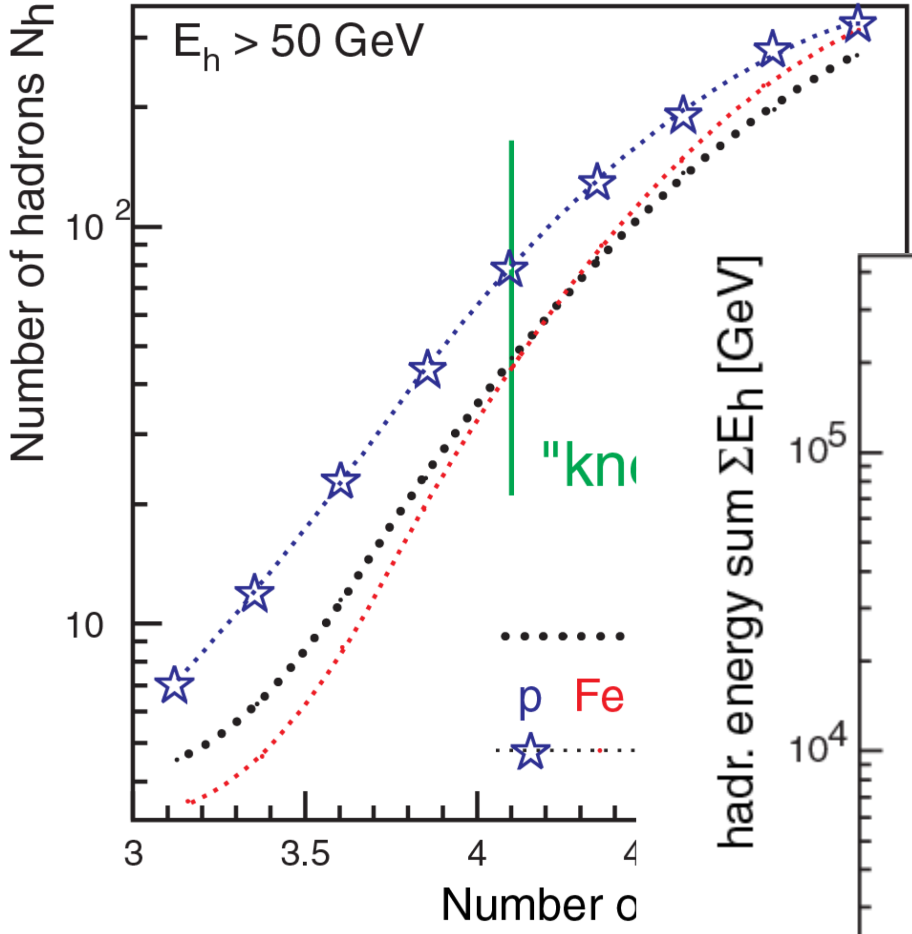


CORSIKA/QGSJET 01

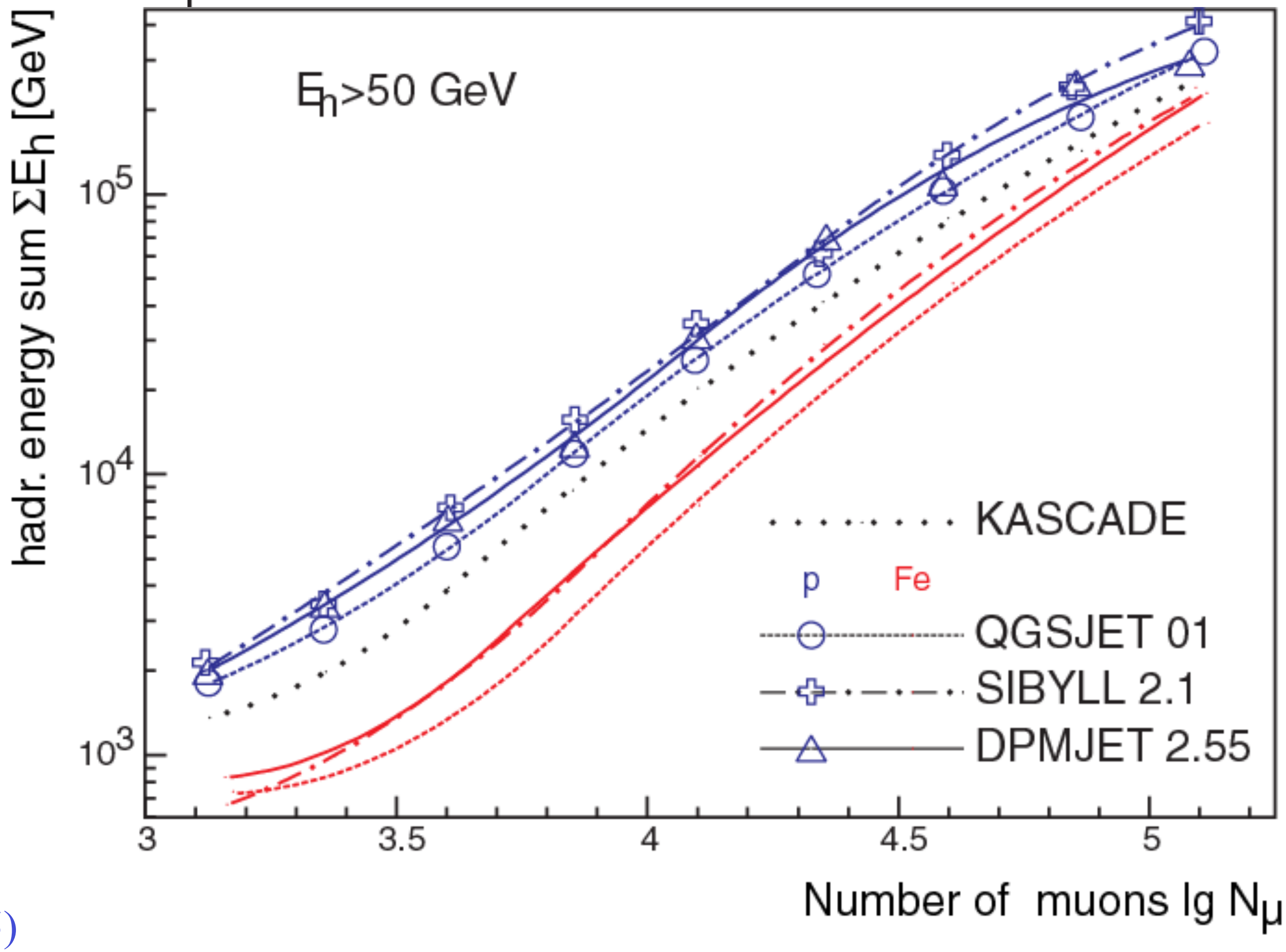
T. Antoni et al., Phys. Rev. D 71 (2005) 072002

KASCADE: Test of hadronic interaction models

previously



present

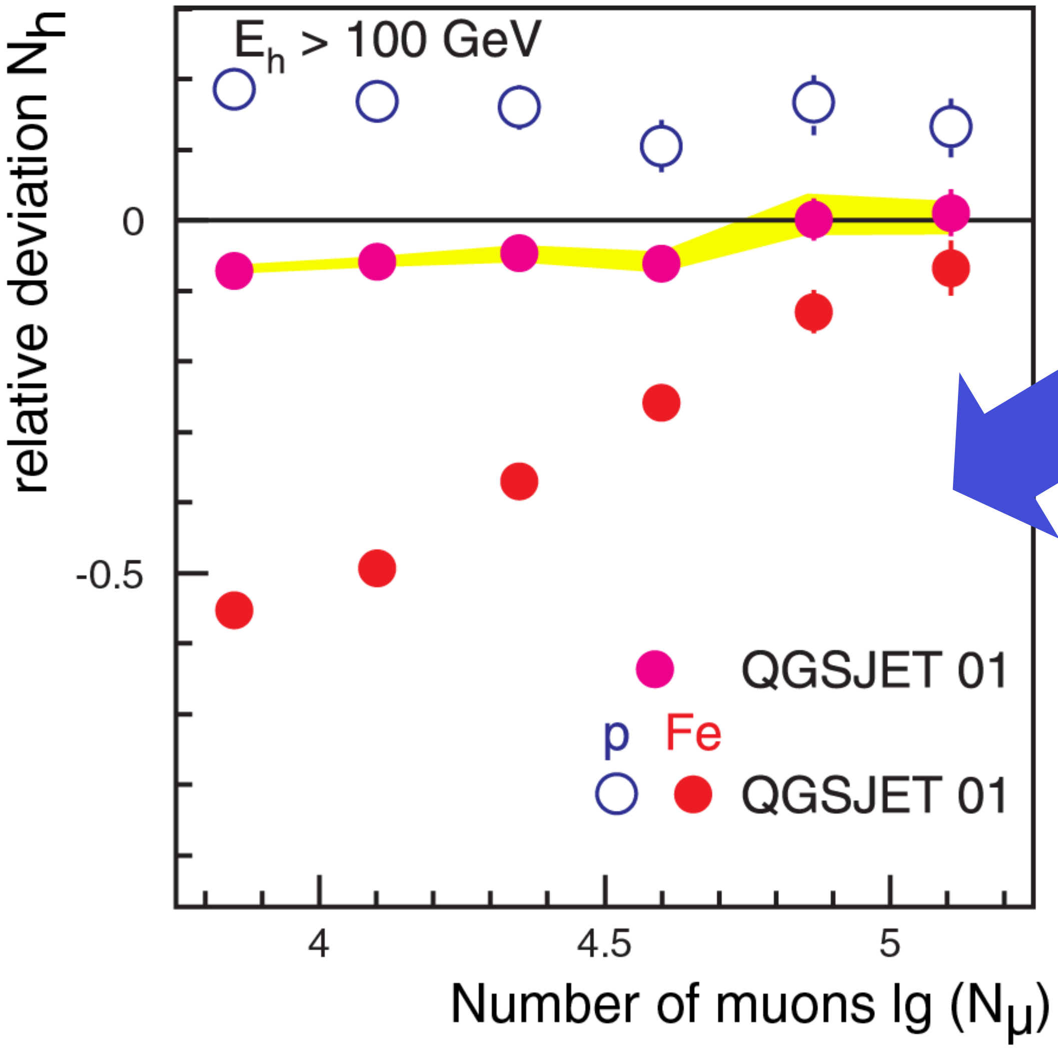


J. Milke et al., 29th ICRC, Pune (2005)

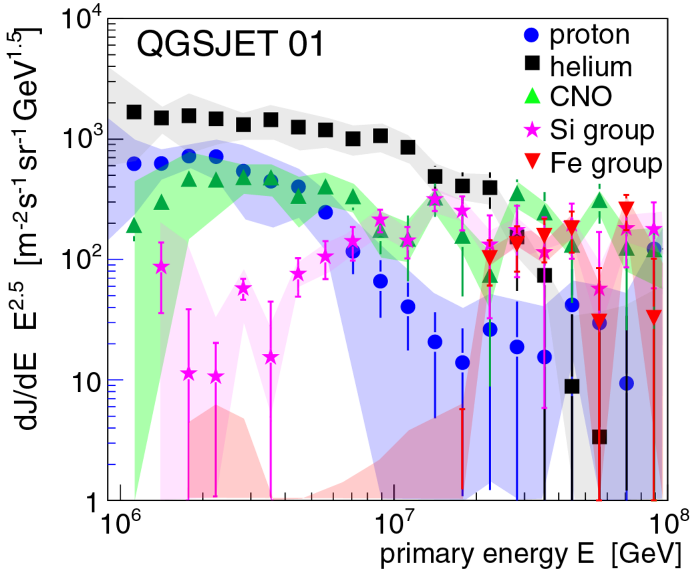
Contemporary models with composition

QGSJET 01

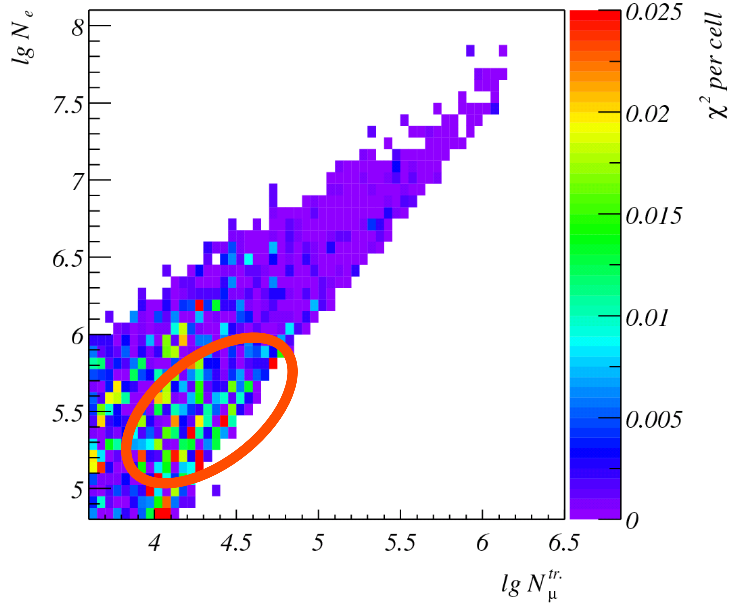
Number of hadrons vs. number of muons



N_e-N_μ analysis



χ^2 distribution



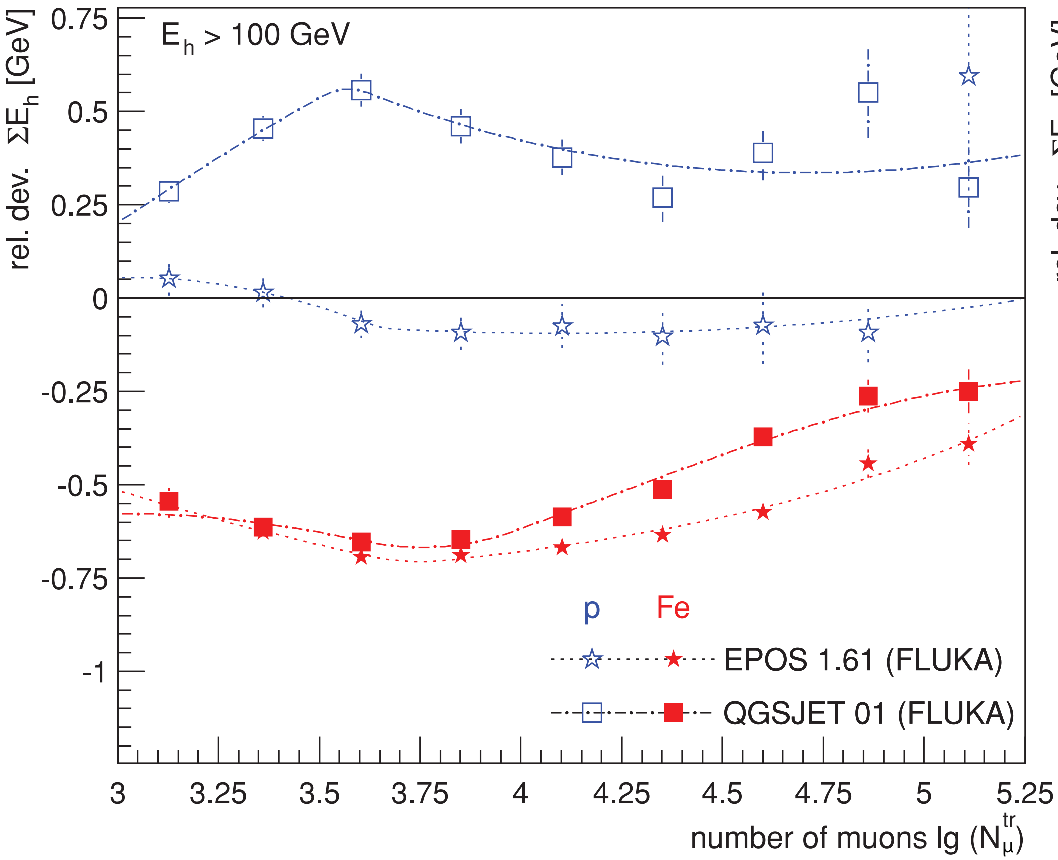
J. Milke et al., 29th ICRC, Pune (2005)

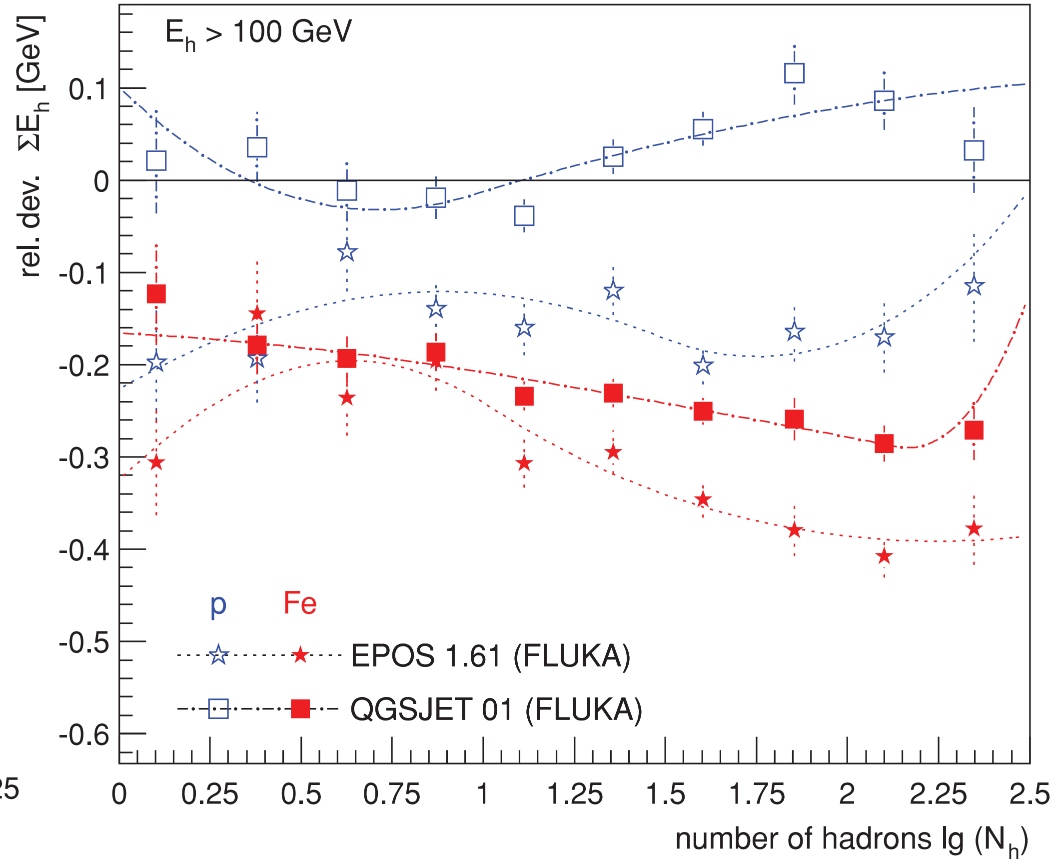
KASCADE – Test of EPOS 1.6

$\Sigma E_h - N_\mu$

$$\frac{X_{sim} - X_{meas}}{X_{meas}}$$

$\Sigma E_h - N_h$





EPOS delivers not enough hadronic energy to the ground

→ energy per hadron too small

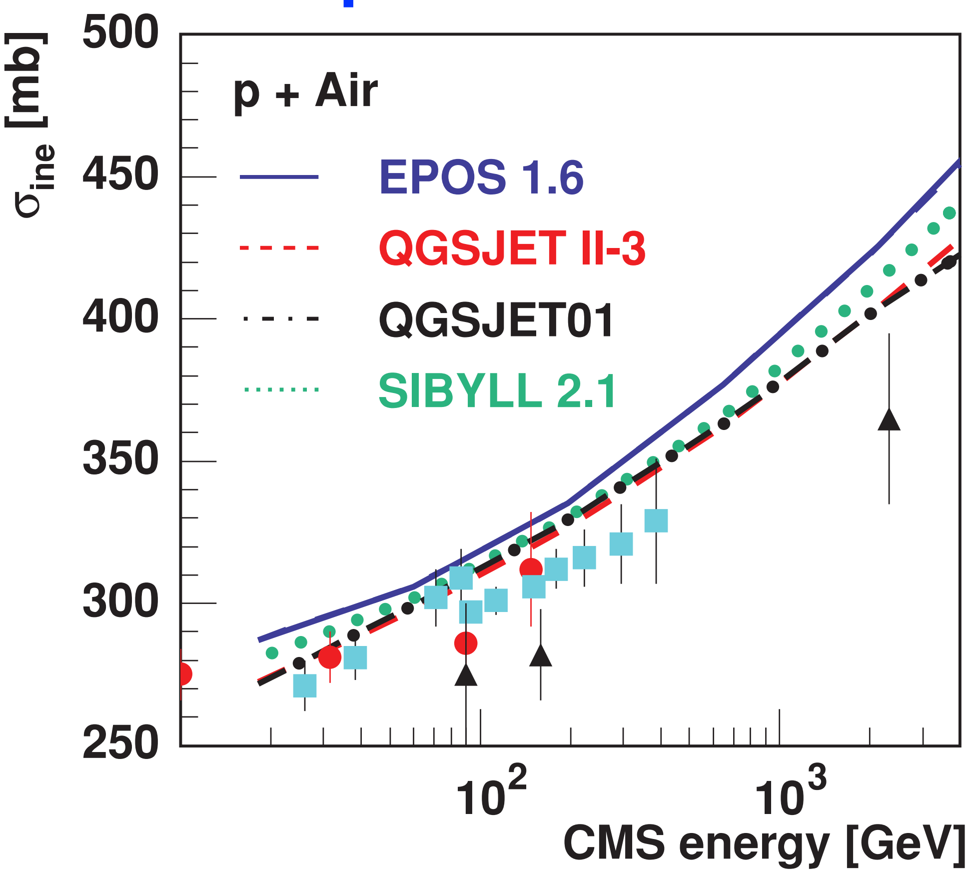
→ EPOS 1.6 is NOT CONSISTENT with KASCADE observations!

W.D. Apel et al., J. Phys. G 36 (2009) 035201

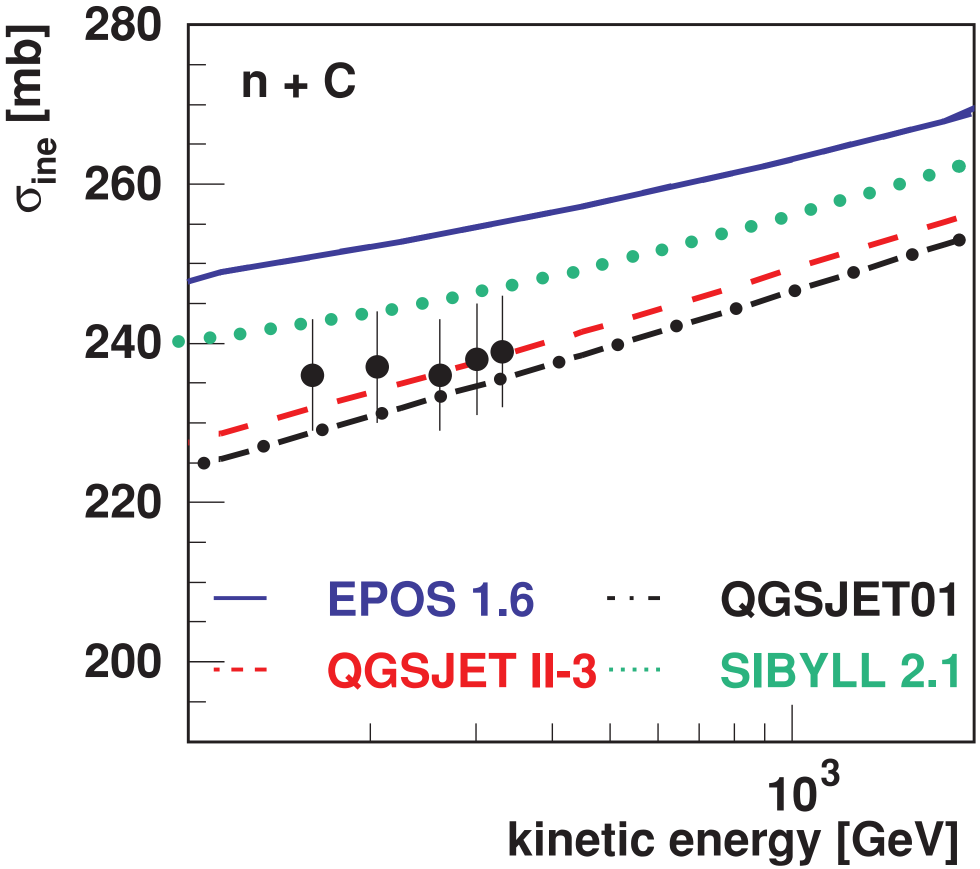
KASCADE – Test of EPOS 1.6

Inelastic cross sections

proton - air



neutron - carbon

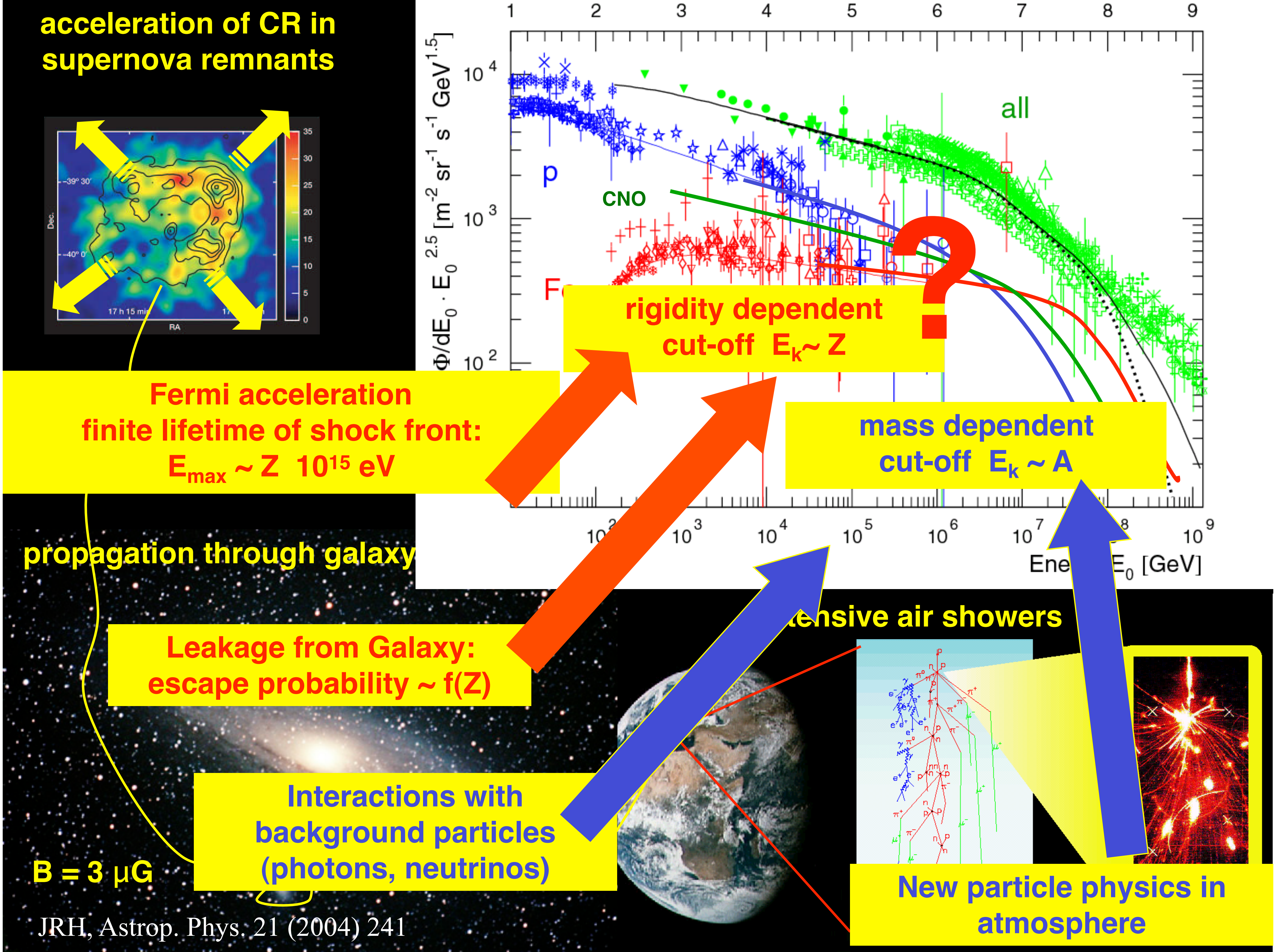


cross sections in EPOS 1.6 too large

→ **new version under preparation**

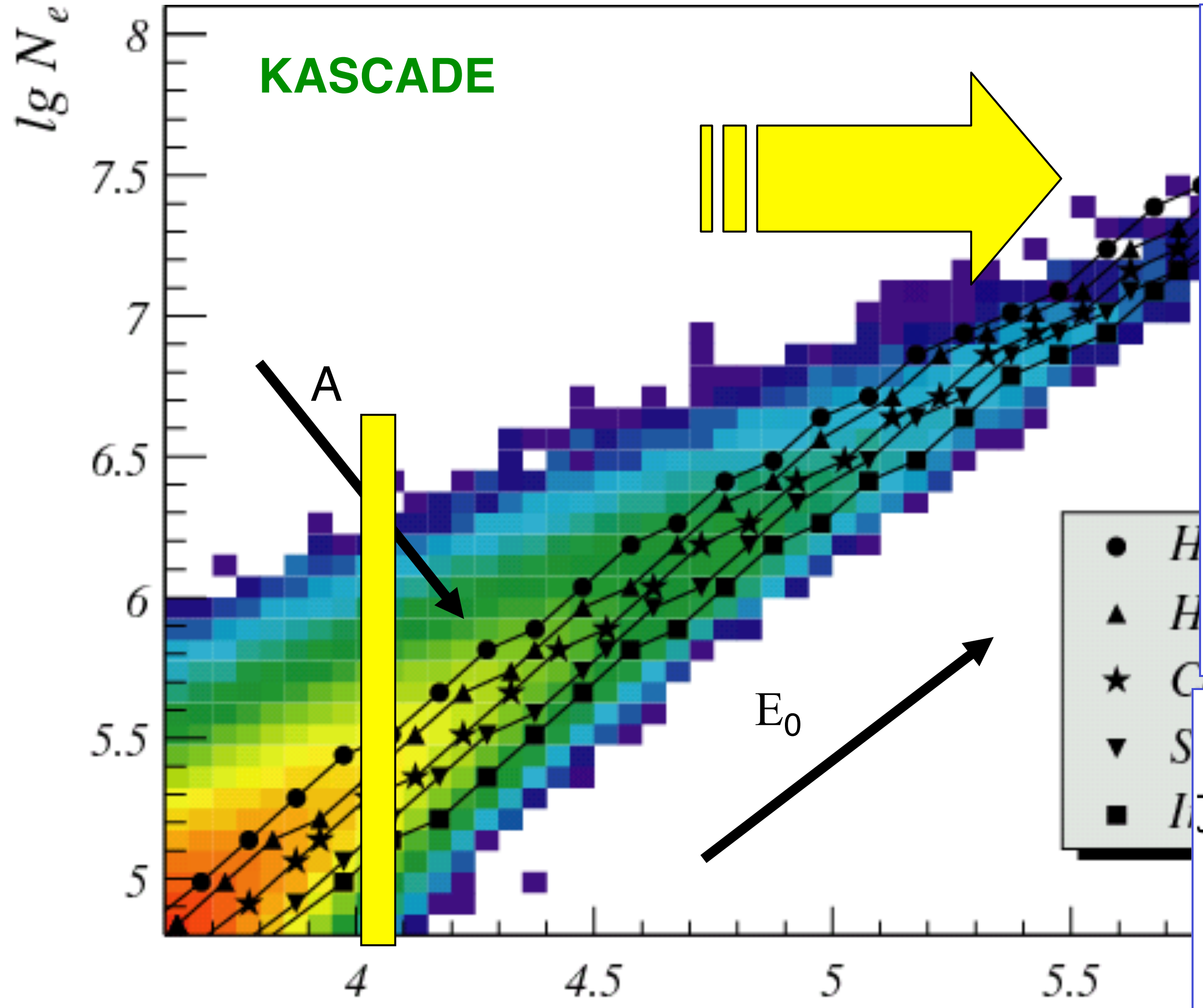
→ **forthcoming studies**

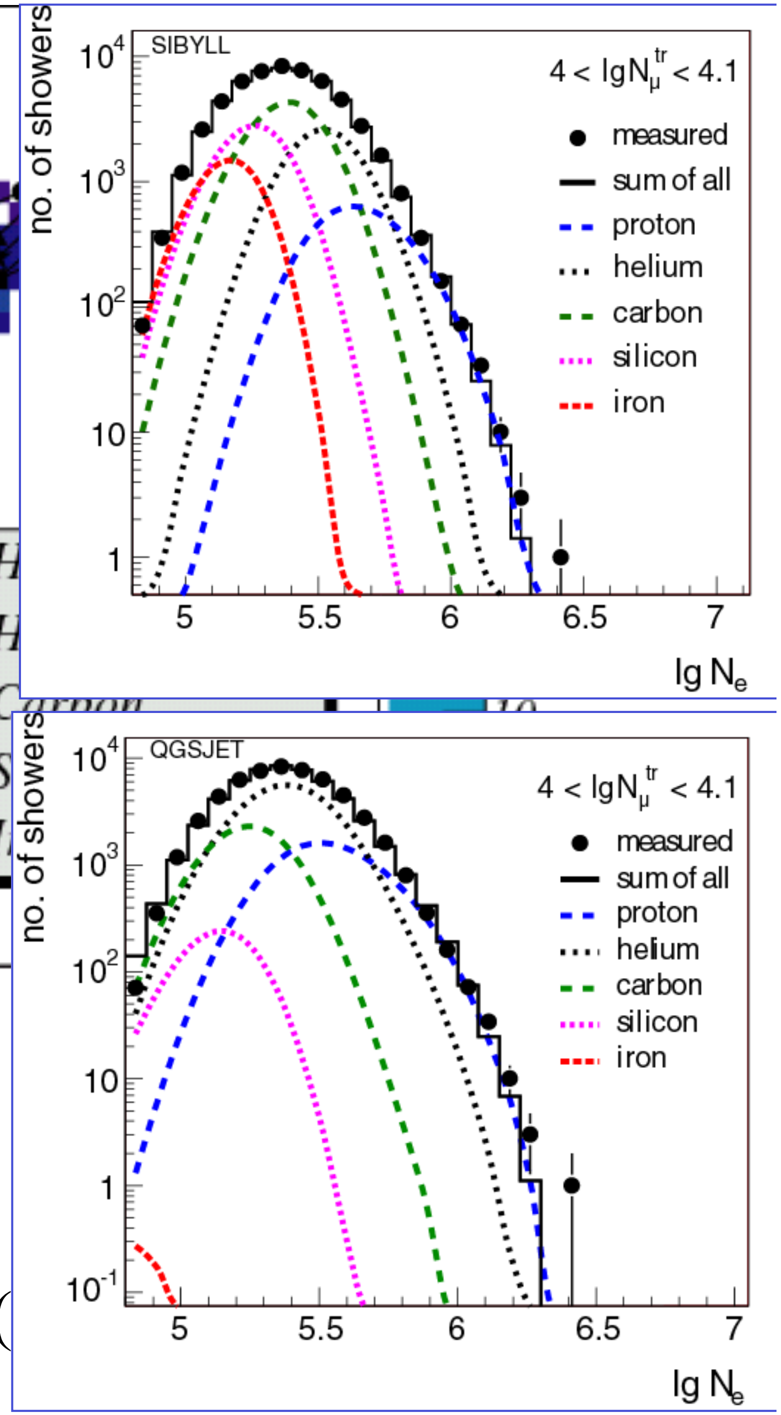
W.D. Apel et al., J. Phys. G 36 (2009) 035201



JRH, Astrop. Phys. 21 (2004) 241

Two dimensional shower size spectrum lg N_e vs. lg N_μ



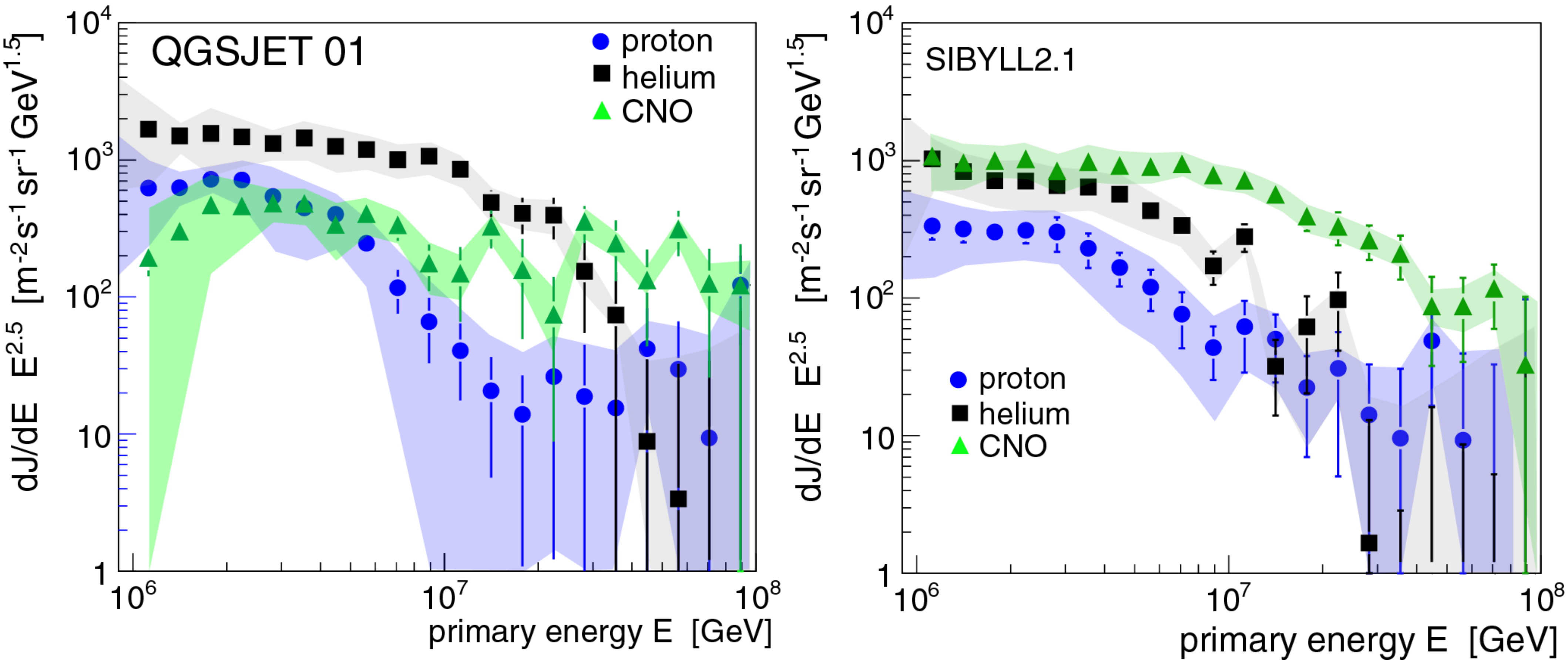


- derive E_0 and A from N_e and N_μ data
- Fredholm integral equations of 1st kind:

$$g_i(\lg N_e, \lg N_\mu) = \int_0^\infty t_i(\lg N_e, \lg N_\mu \mid E)\, p_i($$

T. Antoni et al., Astropart. Phys. 24 (2005) 1

KASCADE: Energy spectra for elemental groups

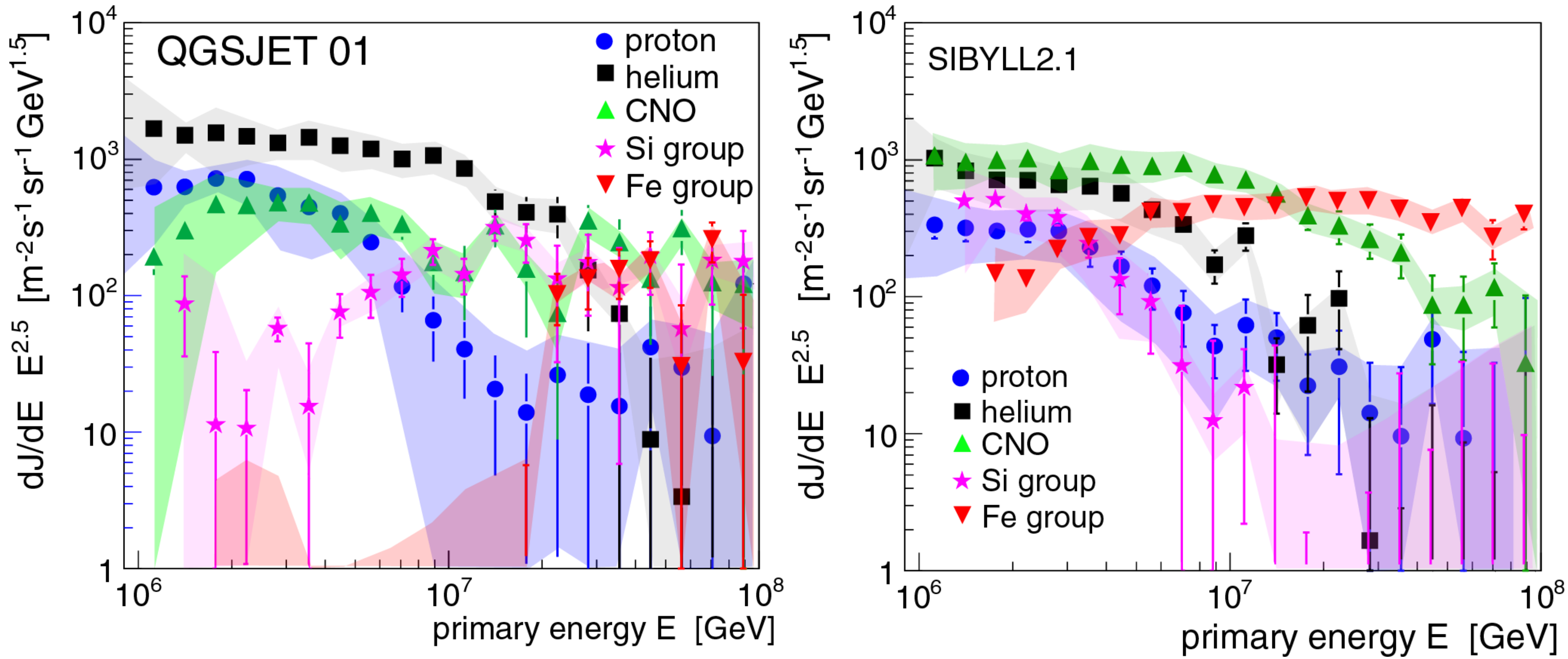


Knee caused by cut-off for light elements

Astrophysical interpretation limited by description of interactions in the atmosphere

T. Antoni et al., Astropart. Phys. 24 (2005) 1

KASCADE: Energy spectra for elemental groups



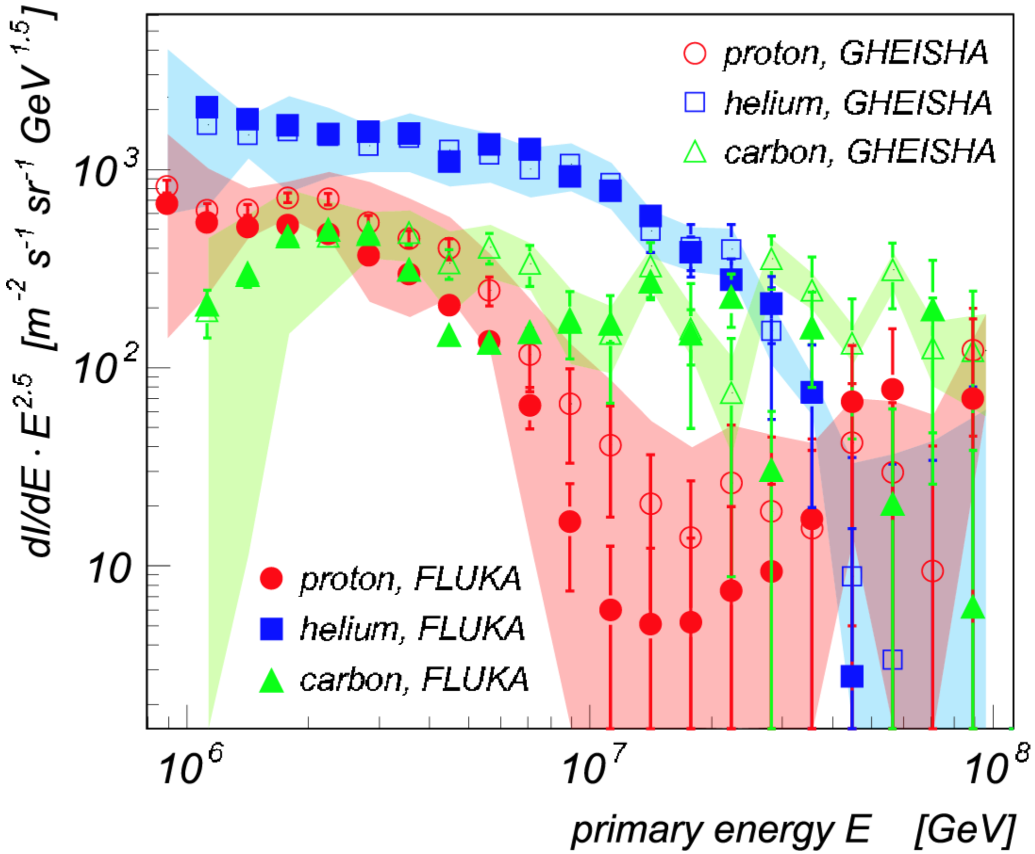
Knee caused by cut-off for light elements

Astrophysical interpretation limited by description of interactions in the atmosphere

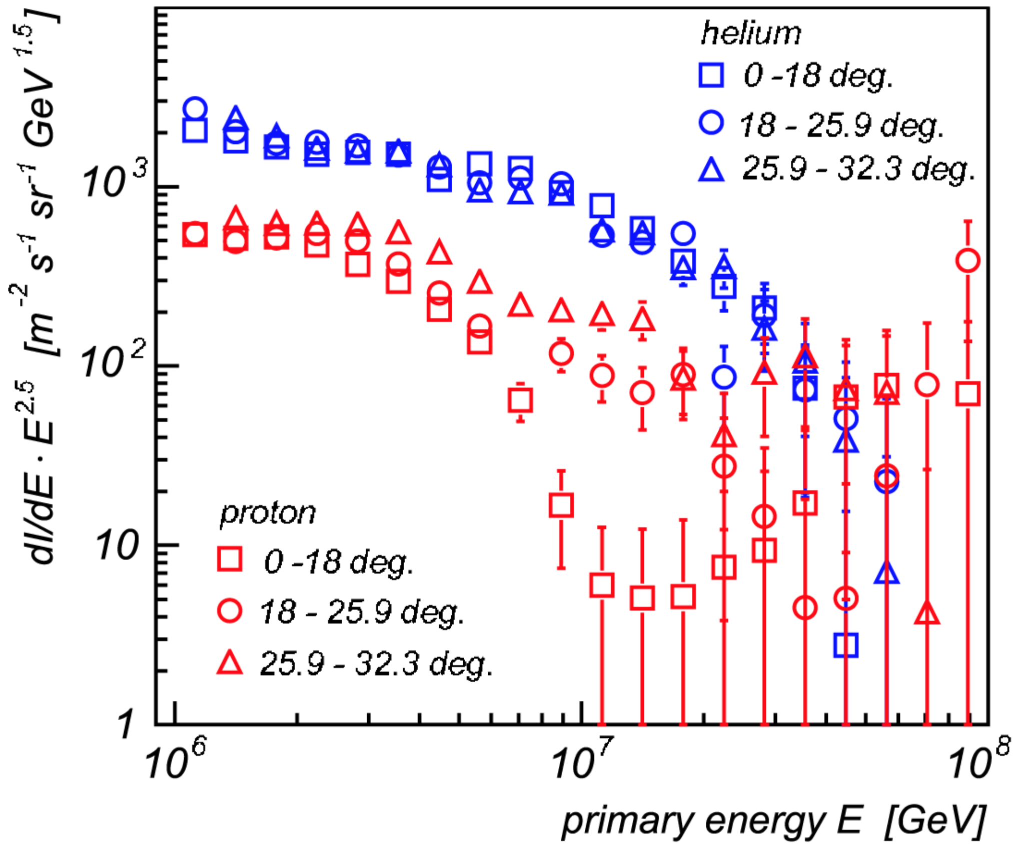
T. Antoni et al., Astropart. Phys. 24 (2005) 1

KASCADE: Energy spectra for elemental groups

Low energy interactions FLUKA ←→ GHEISHA



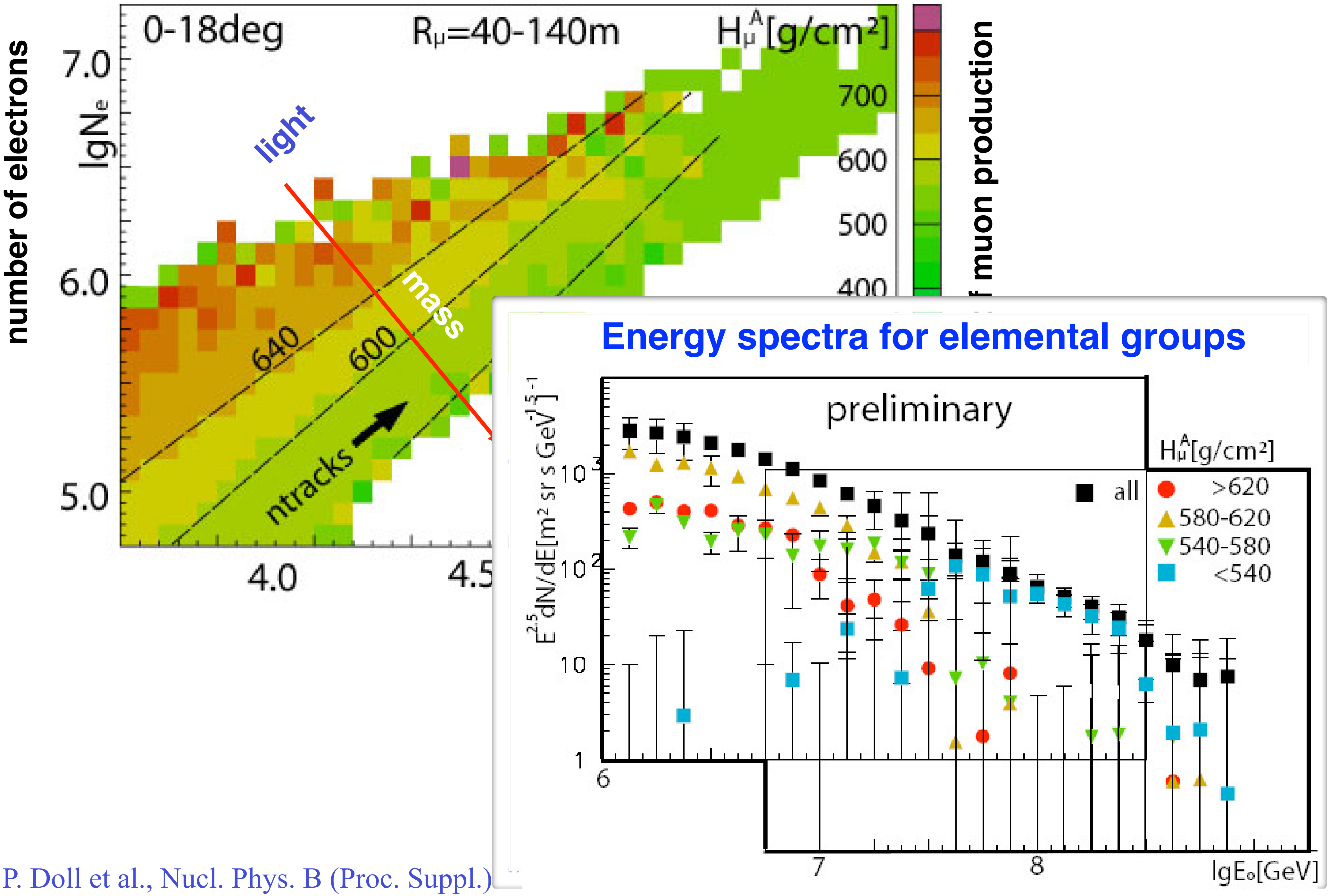
Different zenith angle bins



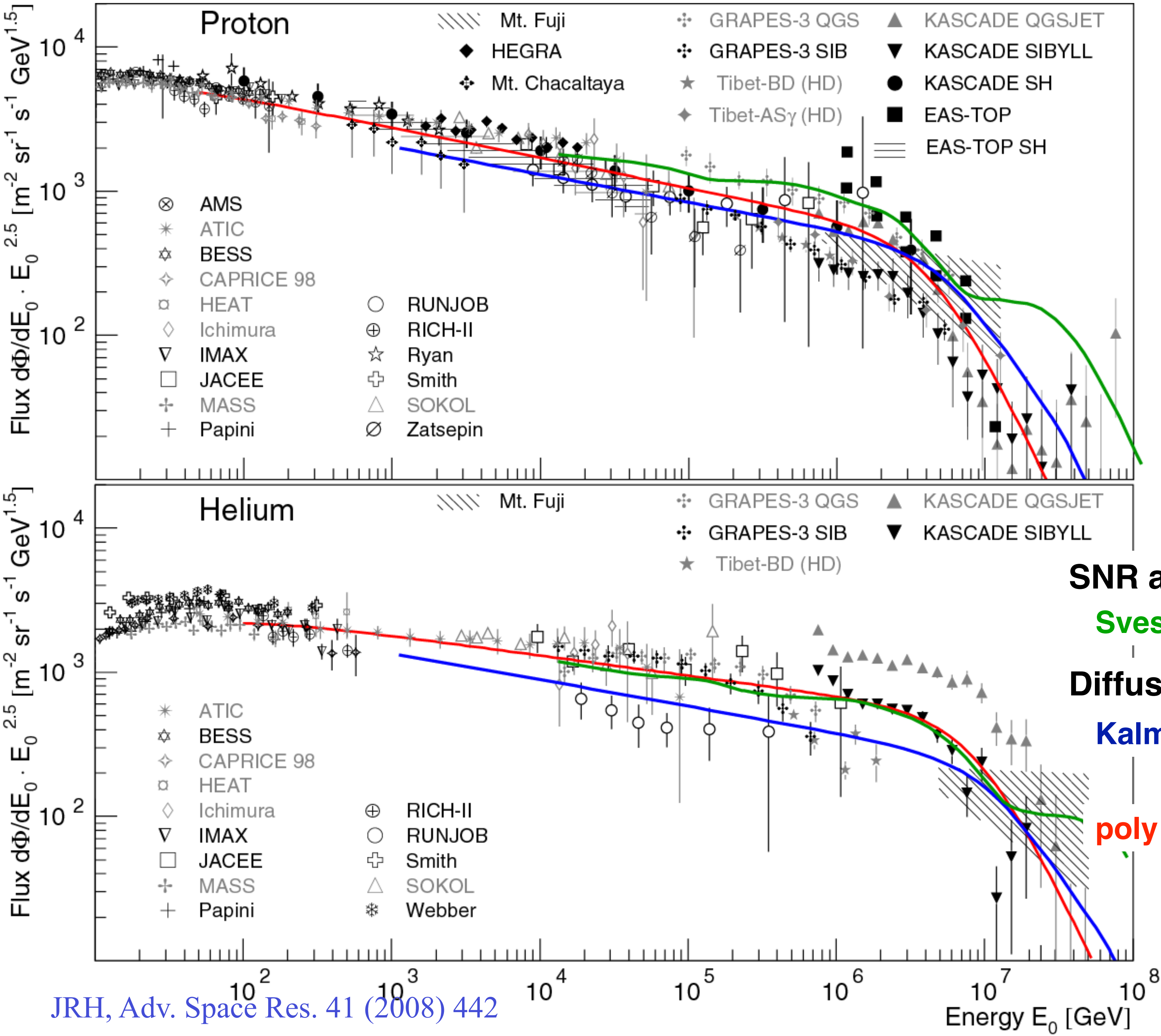
knee in all-particle energy spectrum caused by cut-off of light components

W.D. Apel et al., Astropart. Phys. 31 (2009) 86

Muon production height – KASCADE Muon Tracking Detector



P. Doll et al., Nucl. Phys. B (Proc. Suppl.)



SNR acceleration:

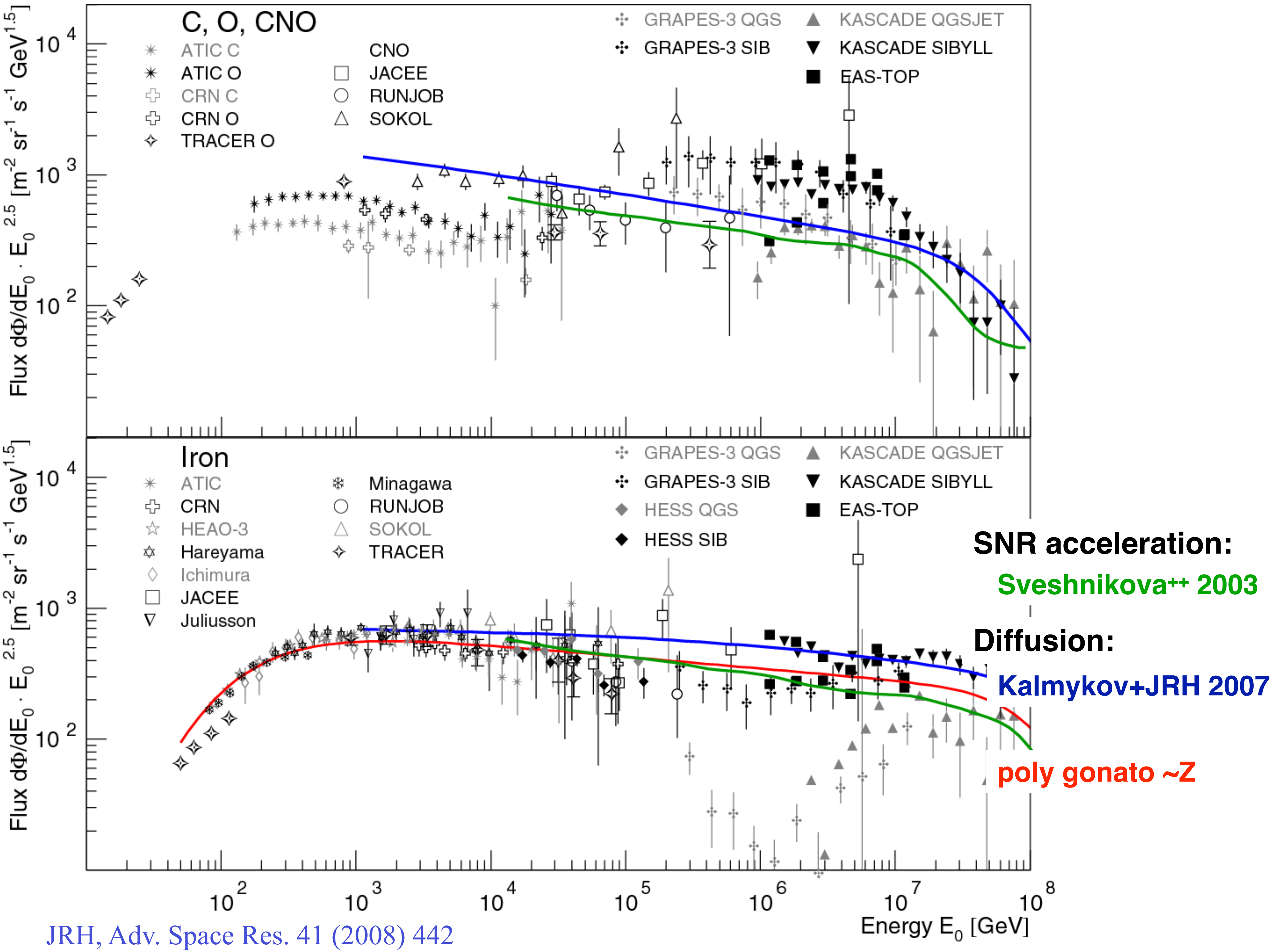
Sveshnikova++ 2003

Diffusion:

Kalmykov+JRH 2007

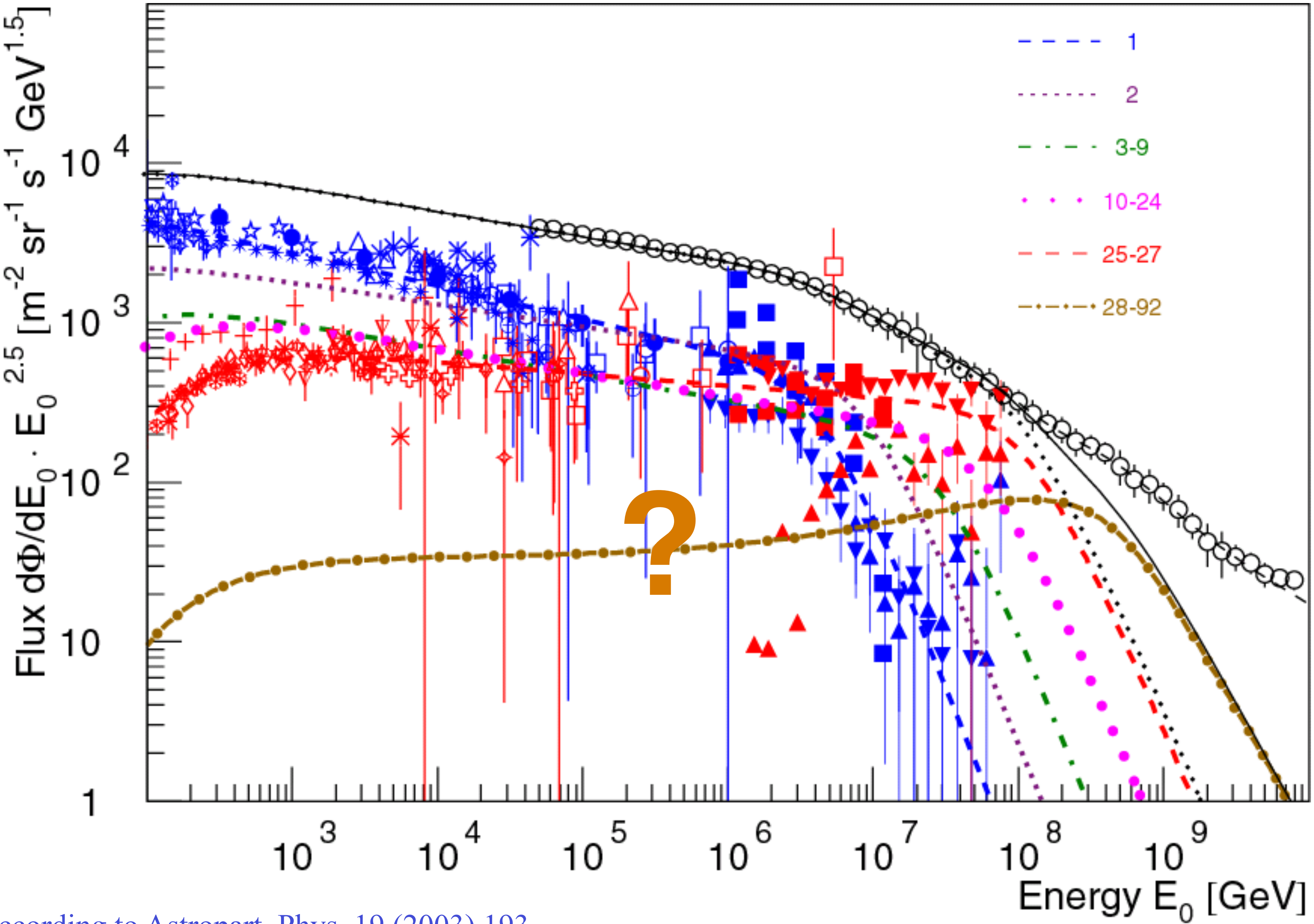
poly gonato ~Z

JRH, Adv. Space Res. 41 (2008) 442



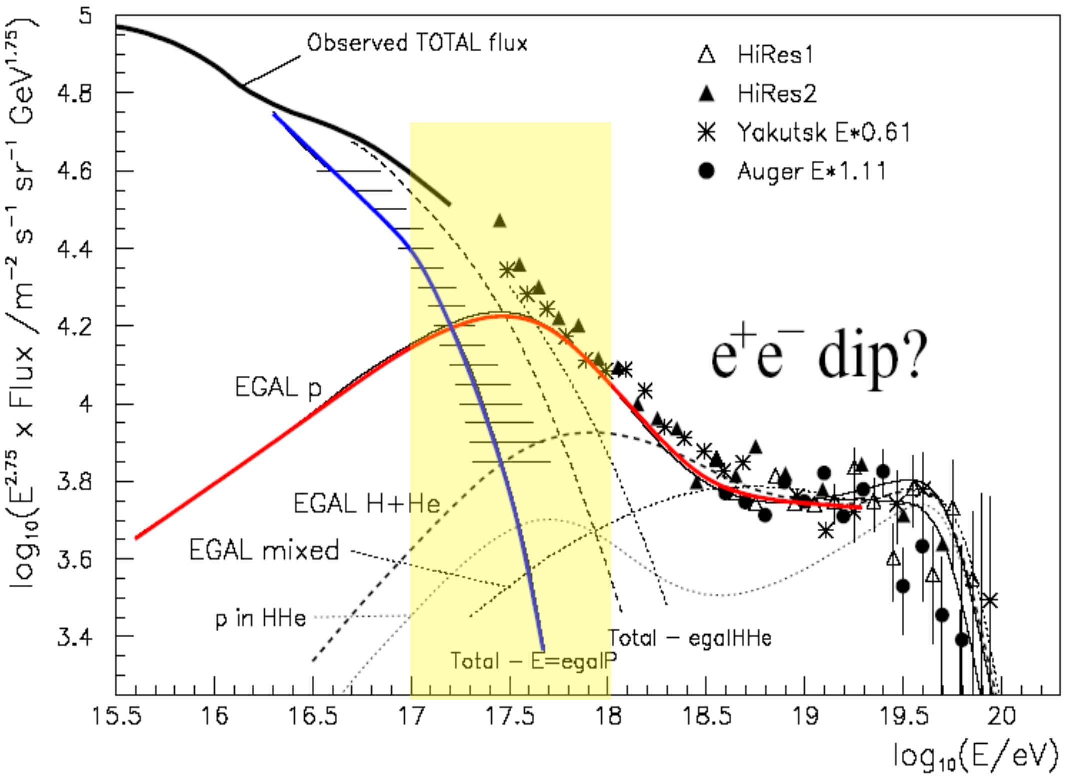
JRH, Adv. Space Res. 41 (2008) 442

Cosmic-ray energy spectrum



according to Astropart. Phys. 19 (2003) 193

Transition to extragalactic CR component

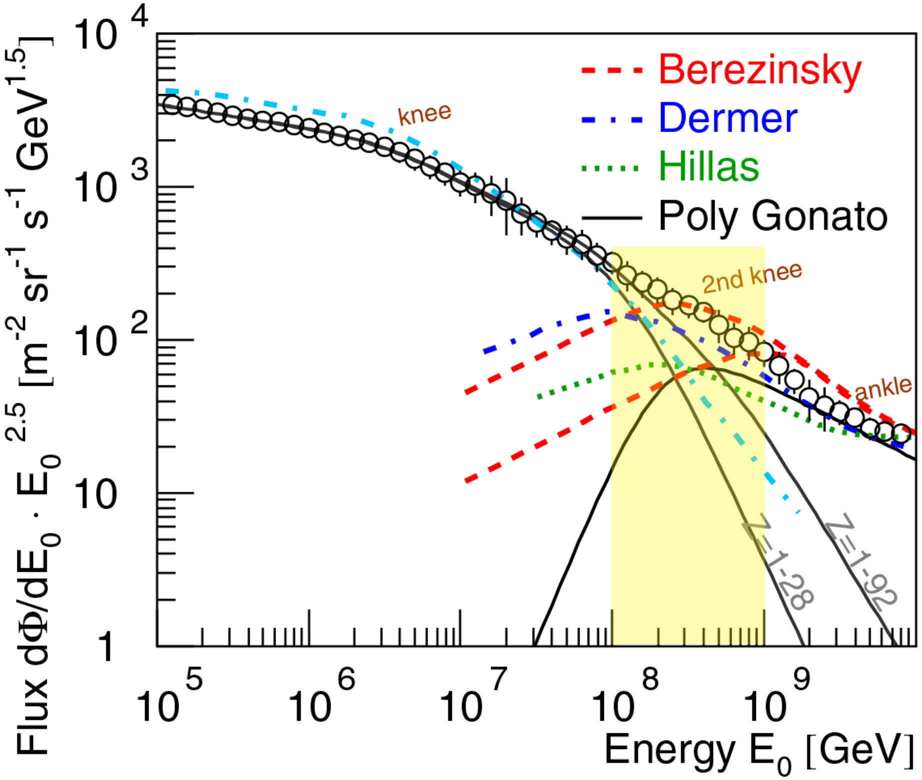


Origin of dip?

- pair production?

$p+\gamma_{3K} \rightarrow p+e^{+}+e^{-}$

Berezinsky astro-ph/0702488

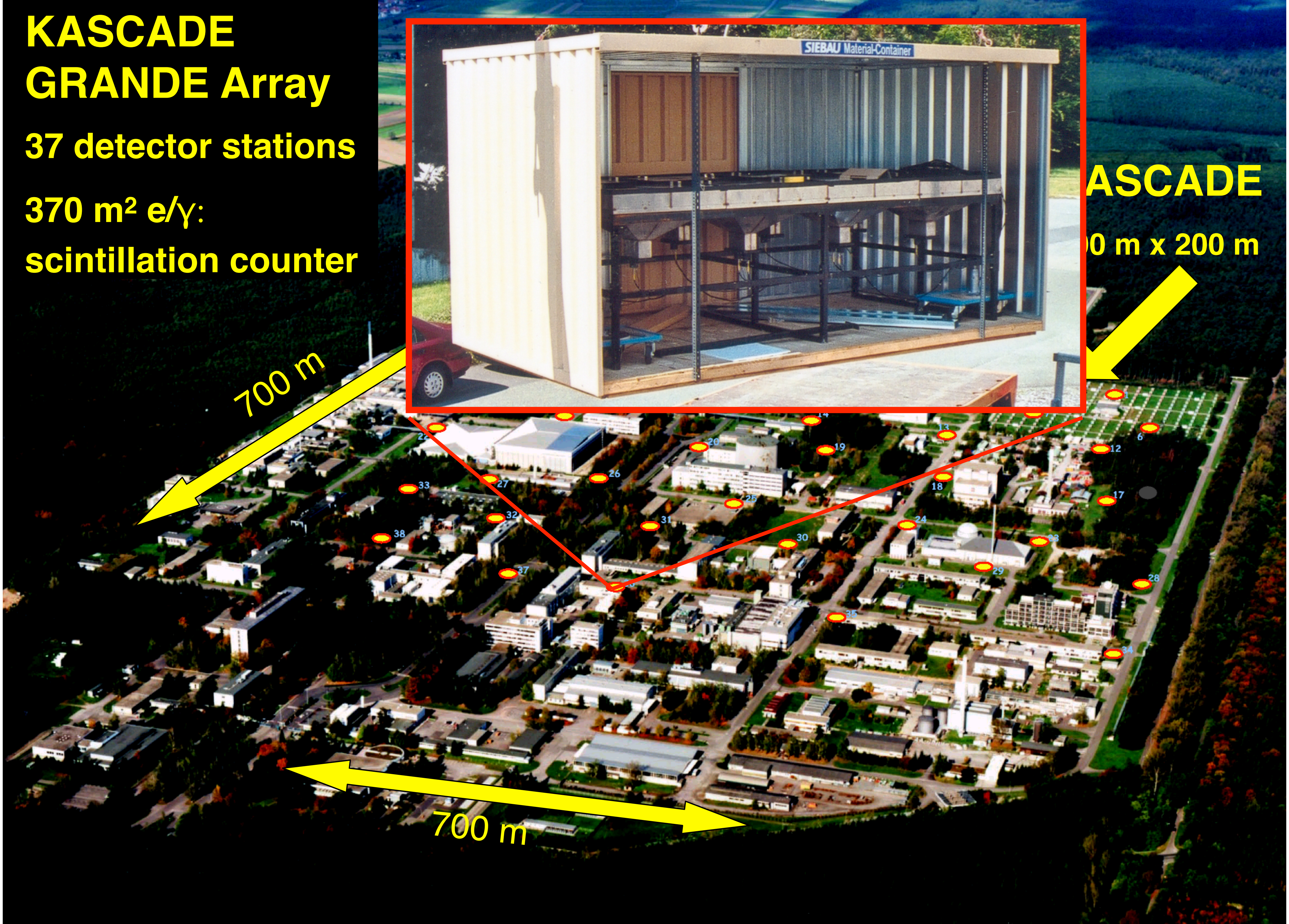


JRH, Adv. Space Res. 41 (2008) 442

KASCADE GRANDE Array

37 detector stations

370 m² e/γ: scintillation counter

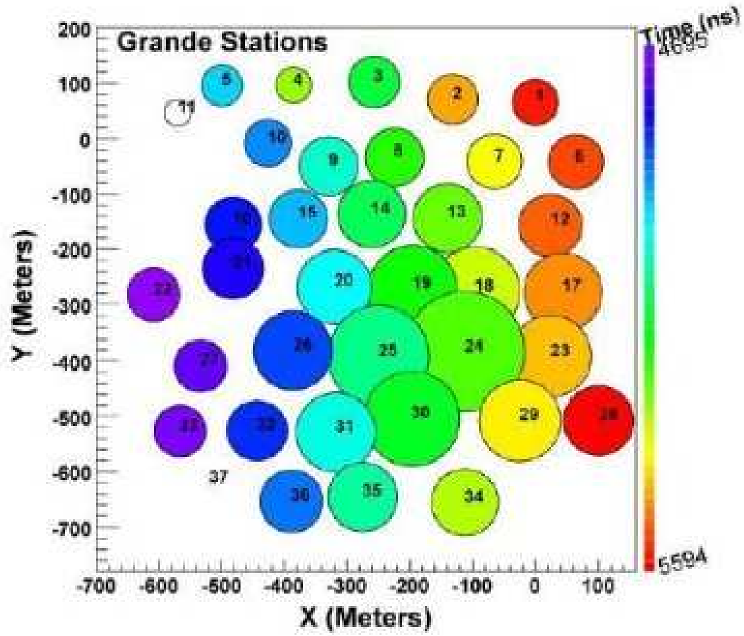


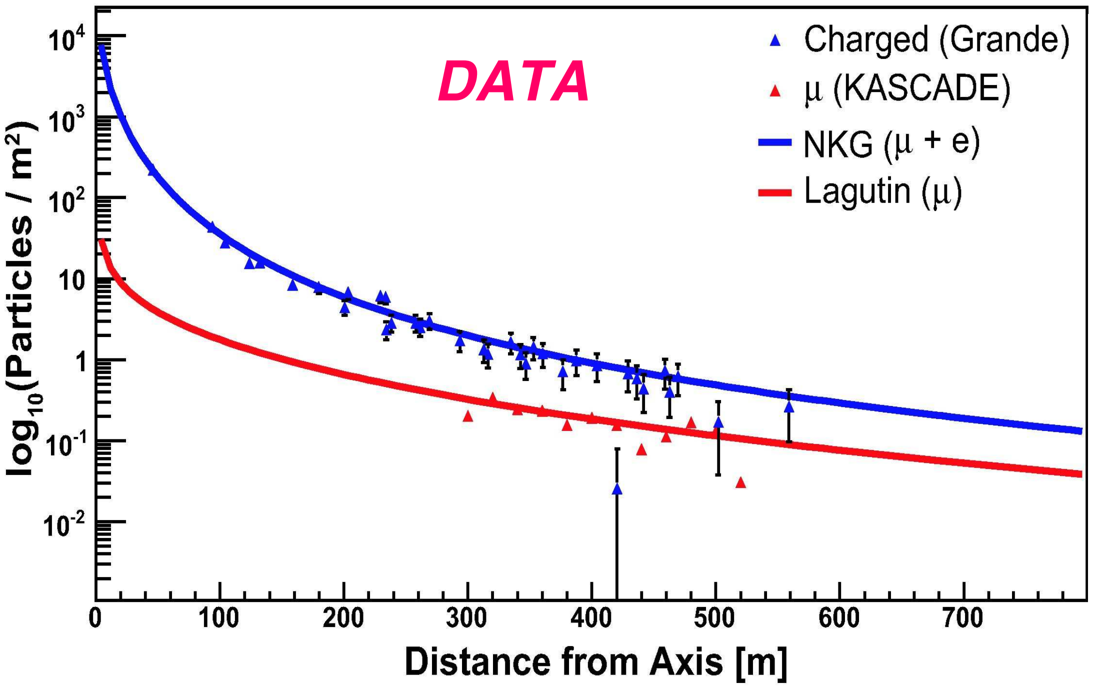
G. Navarra et al., Nucl Instr & Meth A 518 (2004) 207

A standard event

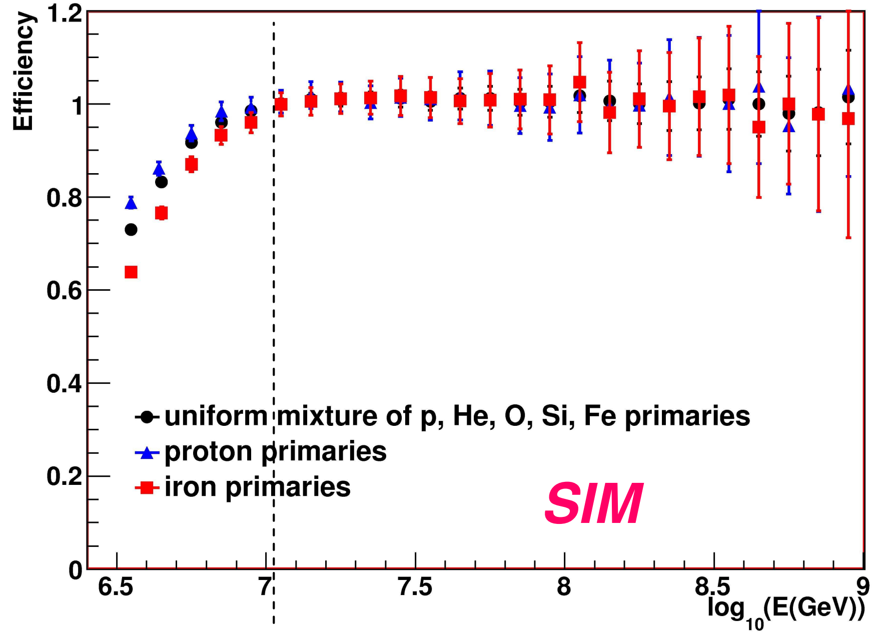
- Recorded on July 8 2005 at 12:11 UTC
- Core: (-155, -401) m
- $\log_{10}(N_{ch}) = 7.0$
- $\log_{10}(N_{\mu}) = 5.7$
- Zenith : 24.2°
- Azimuth: 28.4°

Apel et al. NIMA 620 (2010) 202-216





KASCADE-Grande efficiency

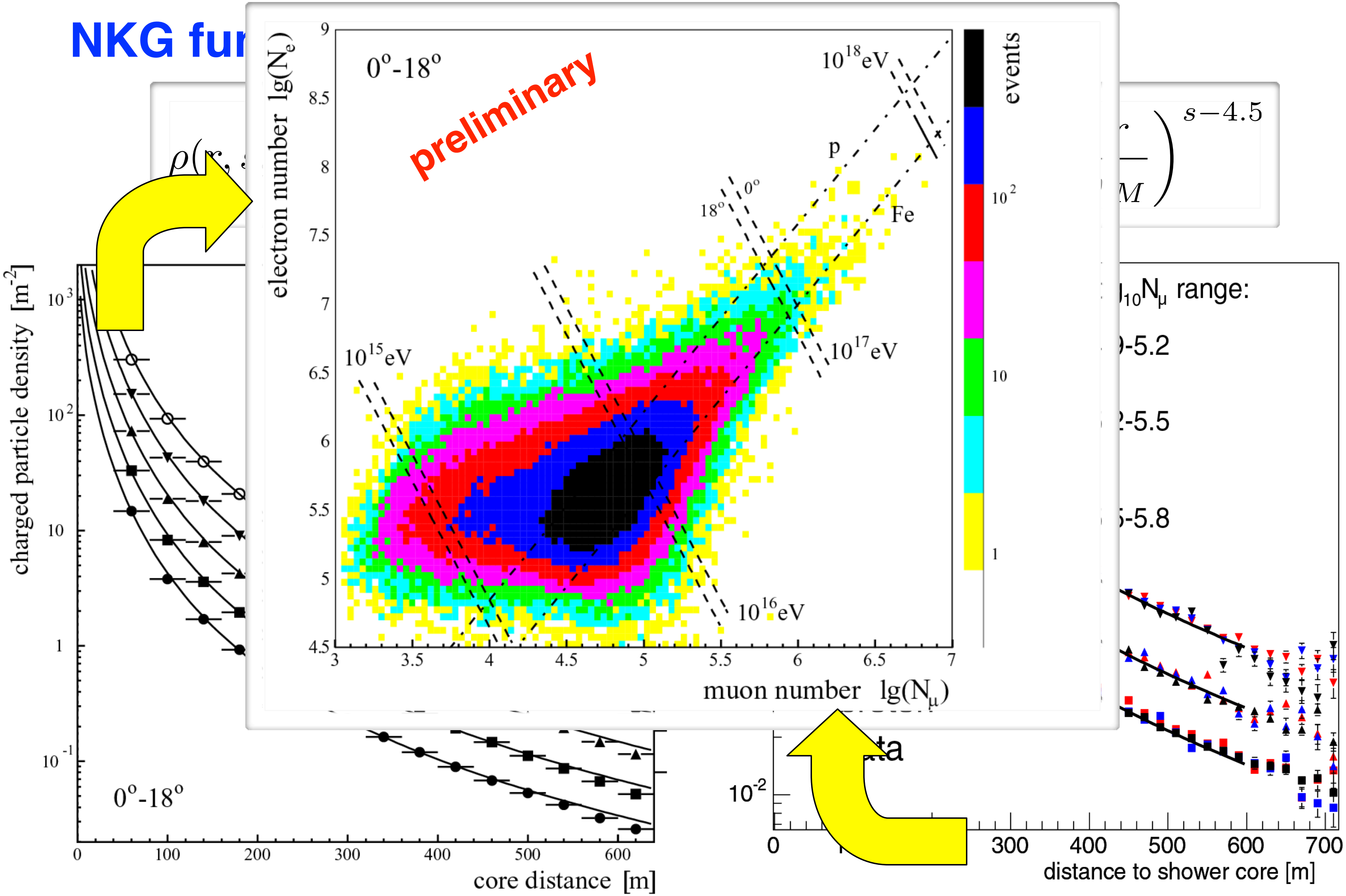


10^{16}eV

M. Bertaina (2010)

KASCADE-Grande – Lateral distributions

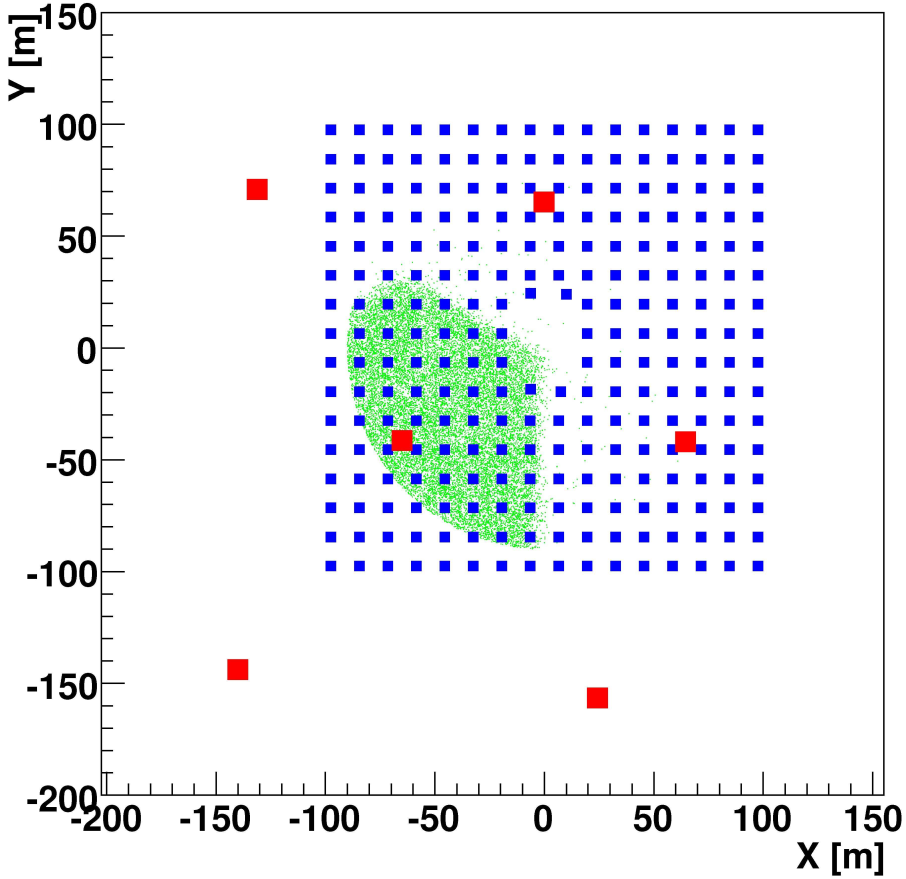
NKG fur

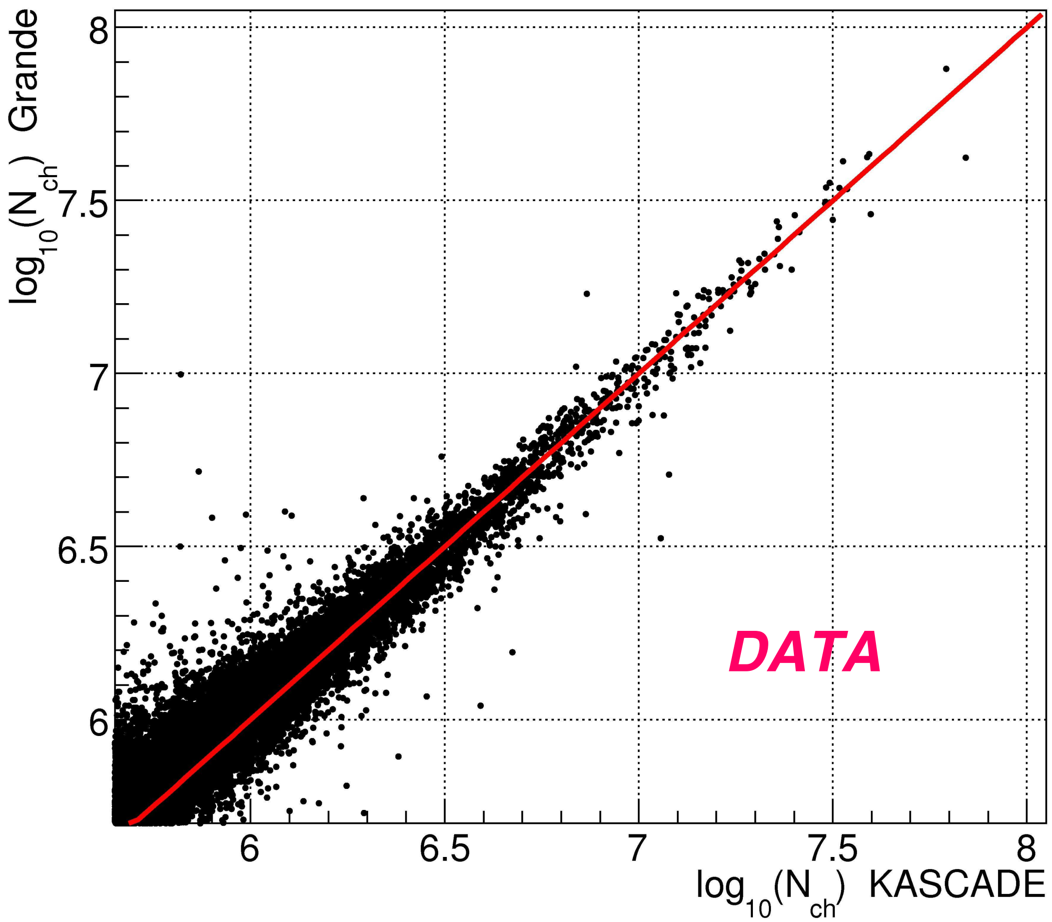


R. Glasstetter et al., Proc. 29th ICRC, Pune 6 (2005) 293

J. v. Buren et al., Proc. 29th ICRC, Pune 6 (2005) 301

Cross-check between KASCADE and Grande





■ KASCADE stations

■ Grande stations

Apel et al. NIMA 620 (2010) 202-216

Reconstruction of the energy spectrum

We use three different methods:

- **N_{ch} as observable**
- **N_{μ} as observable**
- **Combination of N_{ch} and N_{μ} as observables**

↓

- **Cross check of reconstruction procedures**
- **Cross check of systematic uncertainties**
- **Test sensitivity to composition**
- **Cross check of validity of hadronic interaction models**

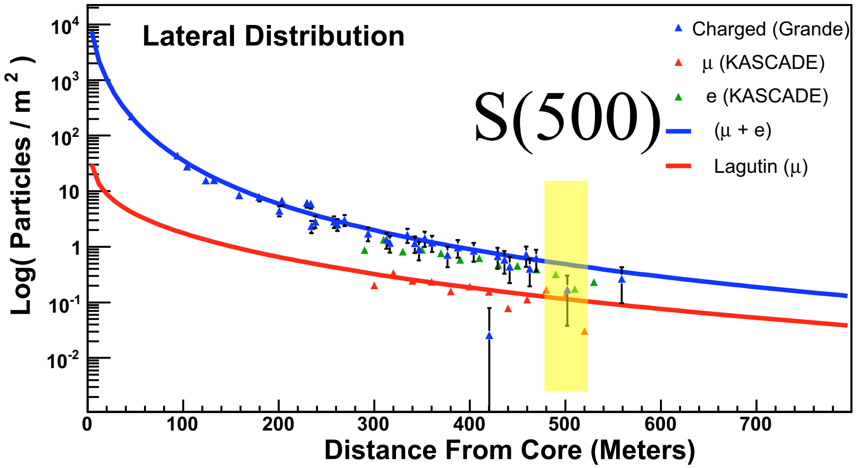
If not explicitly mentioned in the following CORSIKA QGSjetII/FLUKA interaction model is used

***additional method to reconstruct the energy spectrum employs the particle density at 500 m (S500) (see G. Toma's poster on Thursday's morning - Session 4)**

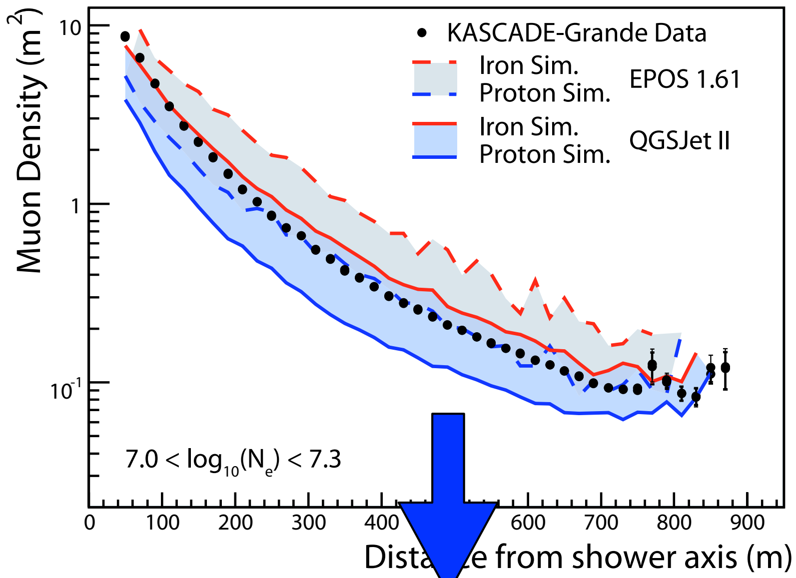
M. Bertaina (2010)

KASCADE-Grande first results

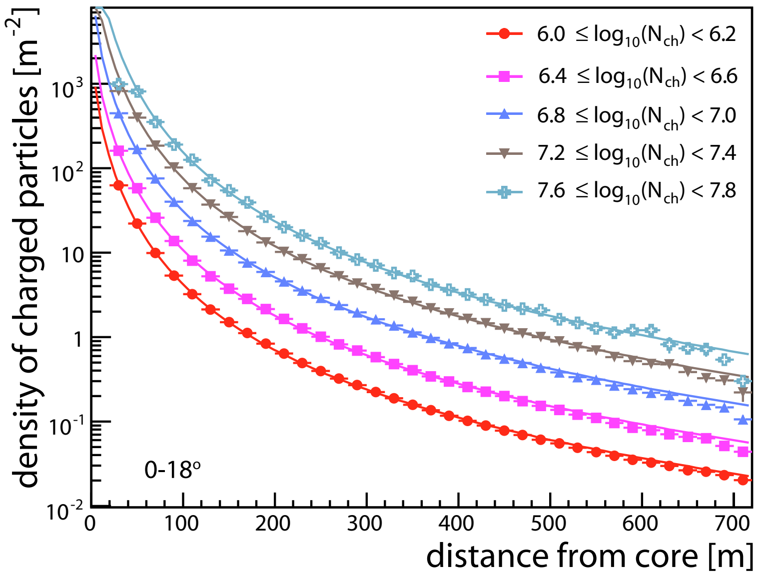
lateral distribution of single event



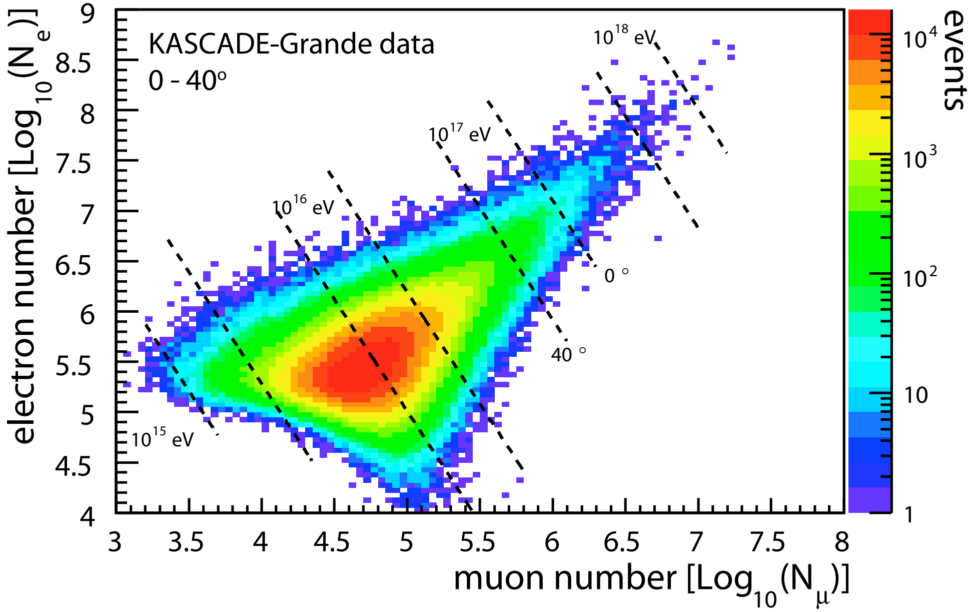
muon lateral density



charged-particle lateral density



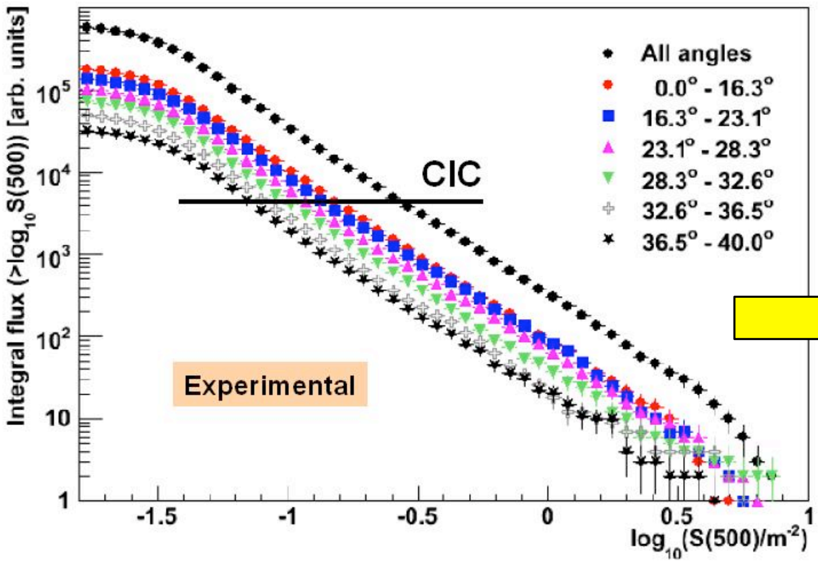
N_e-N_μ correlation

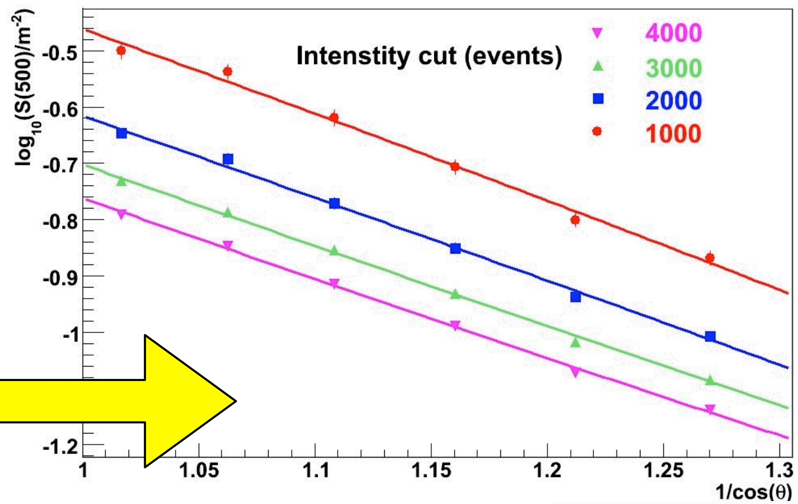


A. Haungs et al., Nucl. Phys. B (Proc. Suppl.) 2009

S(500): charged-particle density 500 m from shower axis

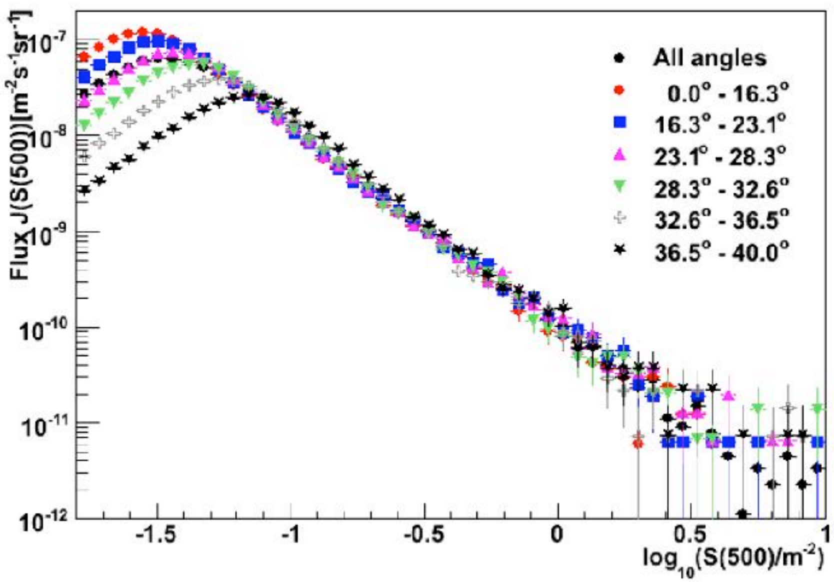
integral S(500) spectrum



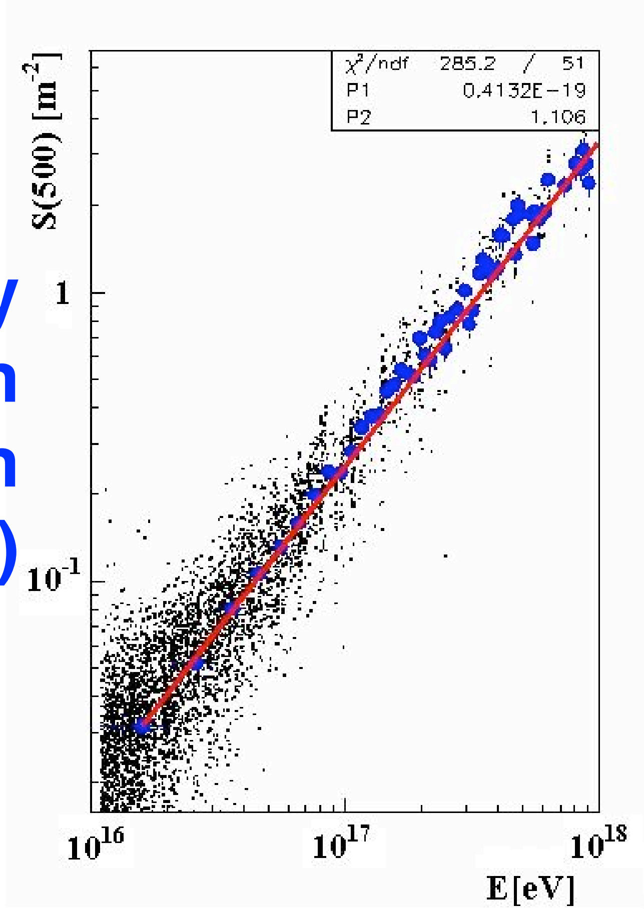


attenuation of S(500) with zenith angle

corrected for attenuation



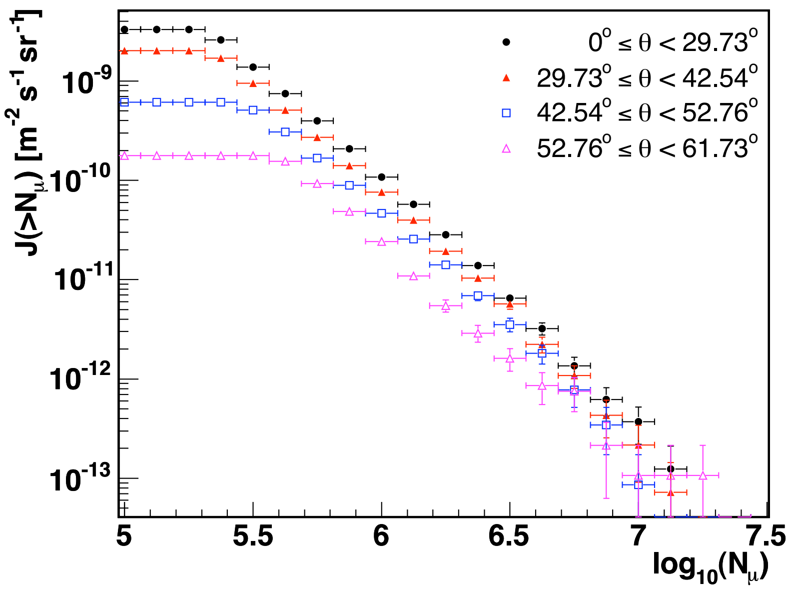
energy calibration (based on simulations)



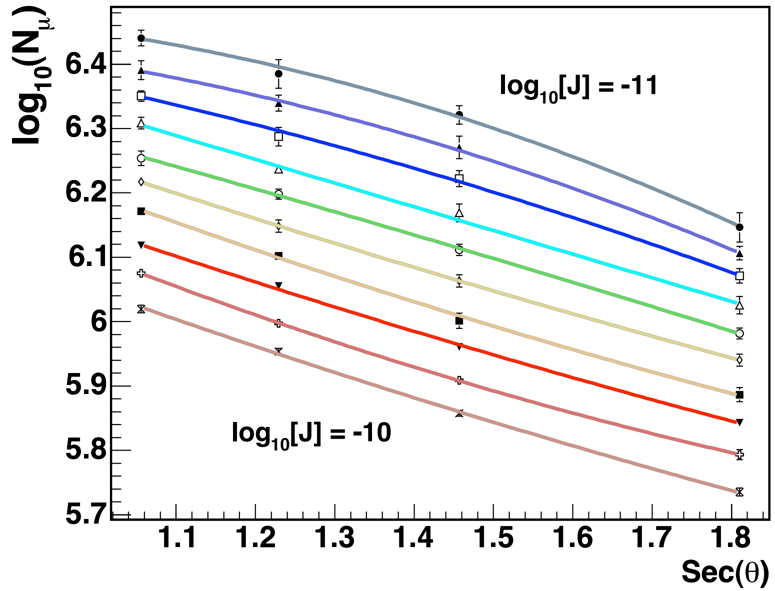
G. Toma et al., Nucl. Phys. B (Proc. Suppl.) 2009

Constant Intensity Cut and Muon Data

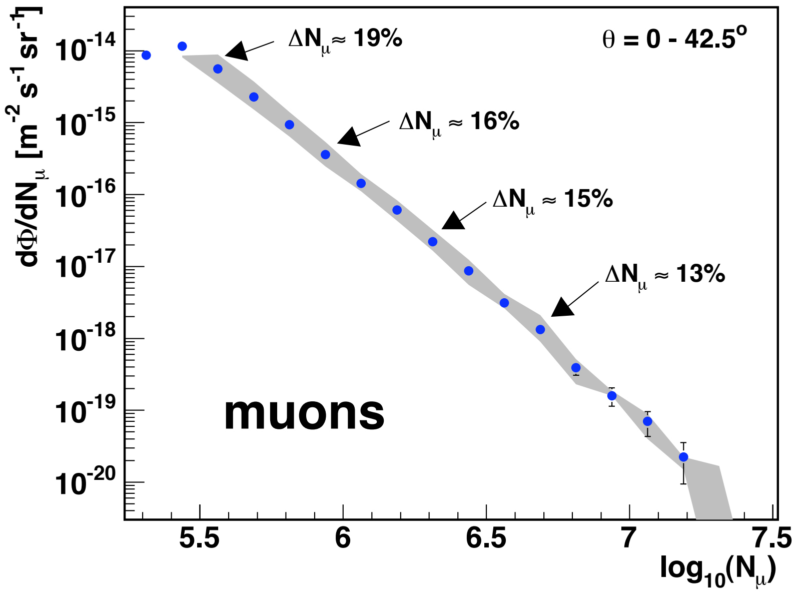
integral muon number spectrum



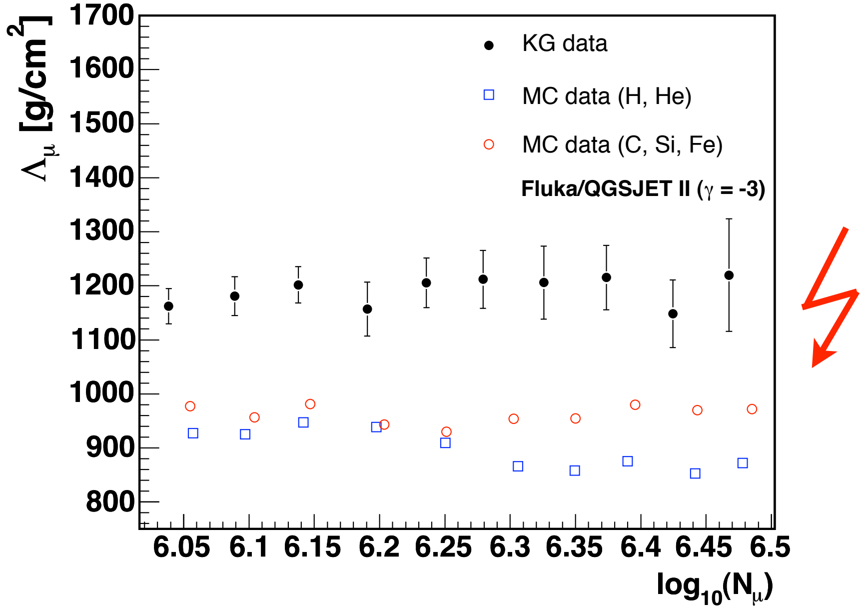
muon attenuation curves



shower size spectrum

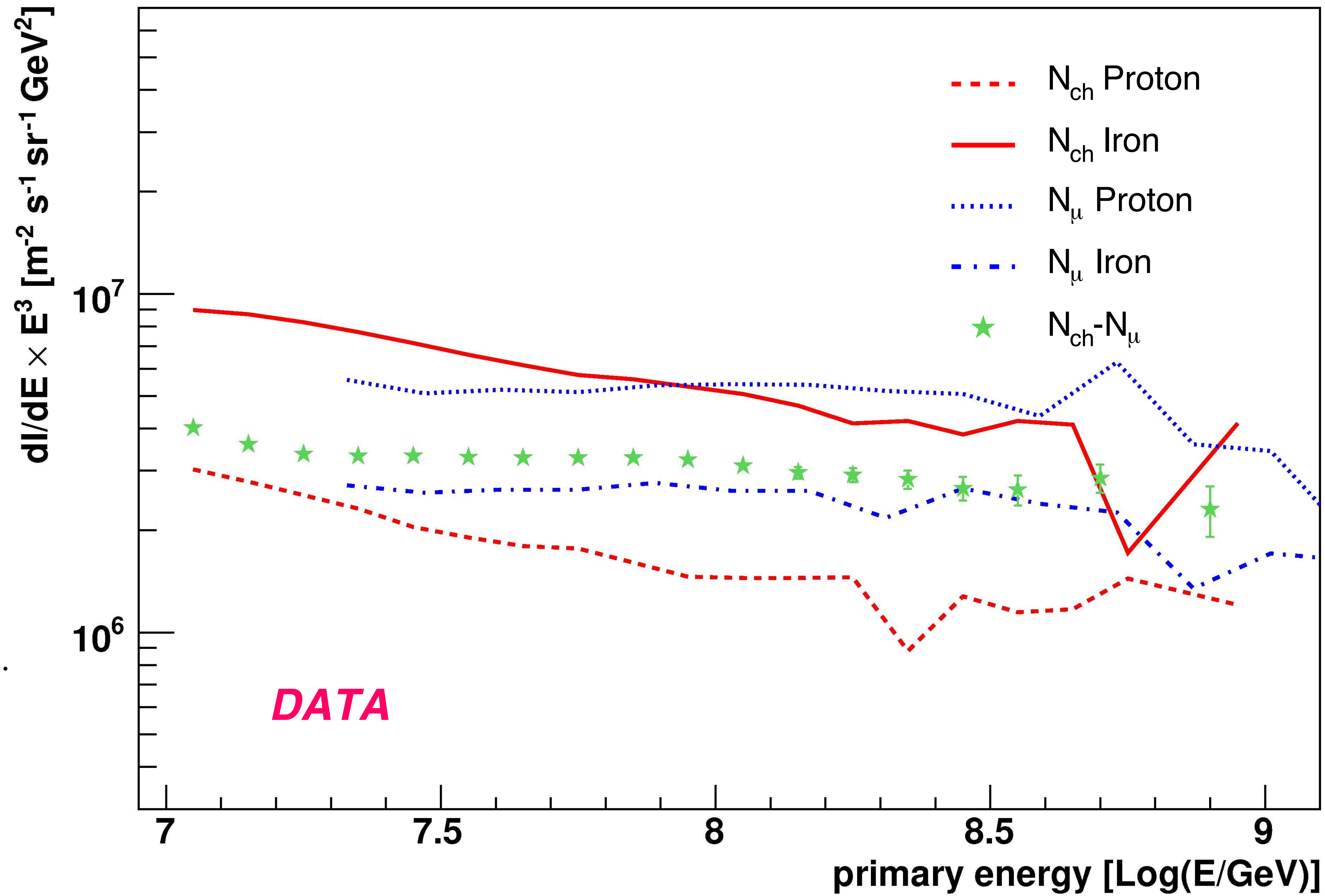


but: attenuation length



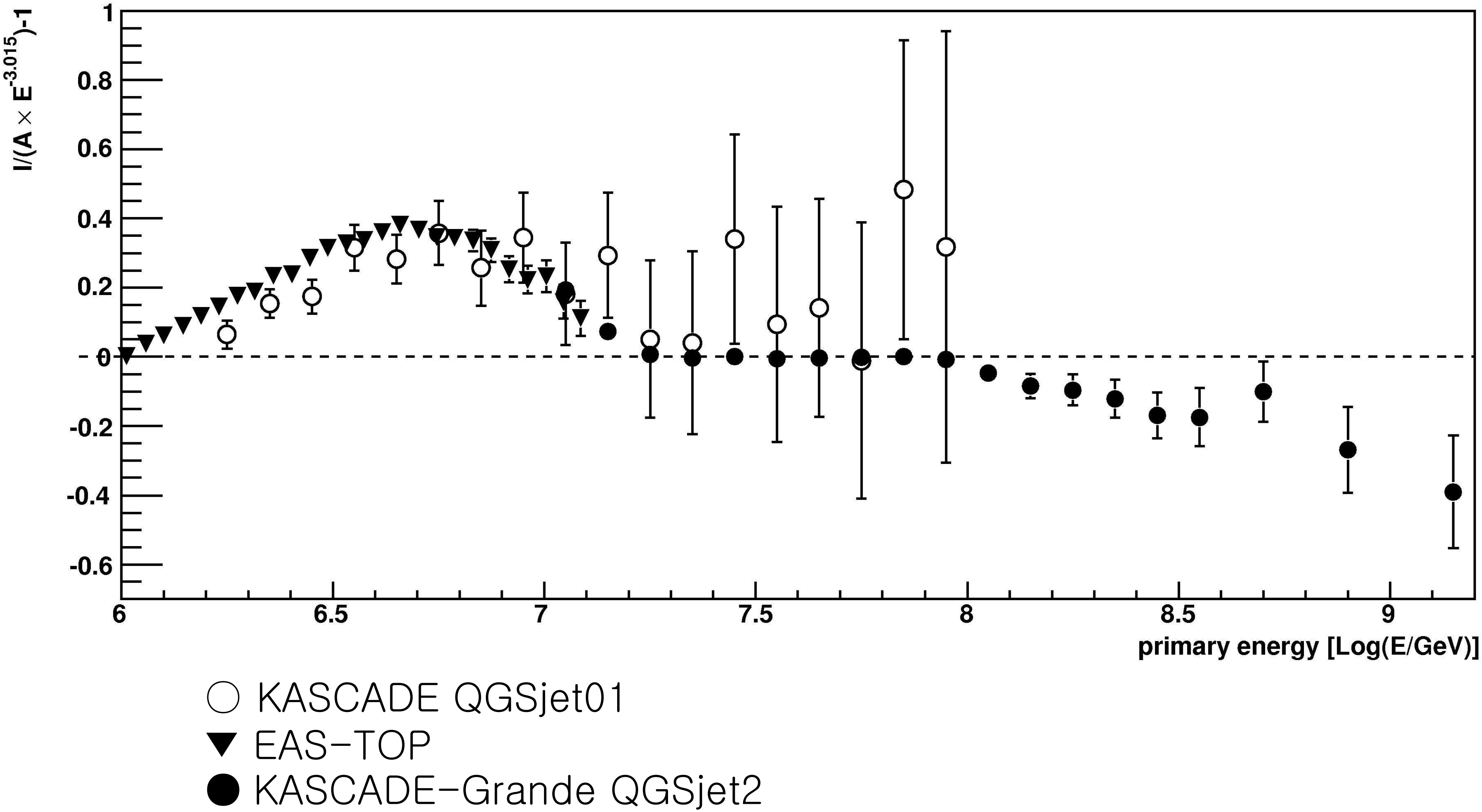
A. Haungs et al., Nucl. Phys. B (Proc. Suppl.) 2009

Comparing the 3 methods (dI/dE x E^3)



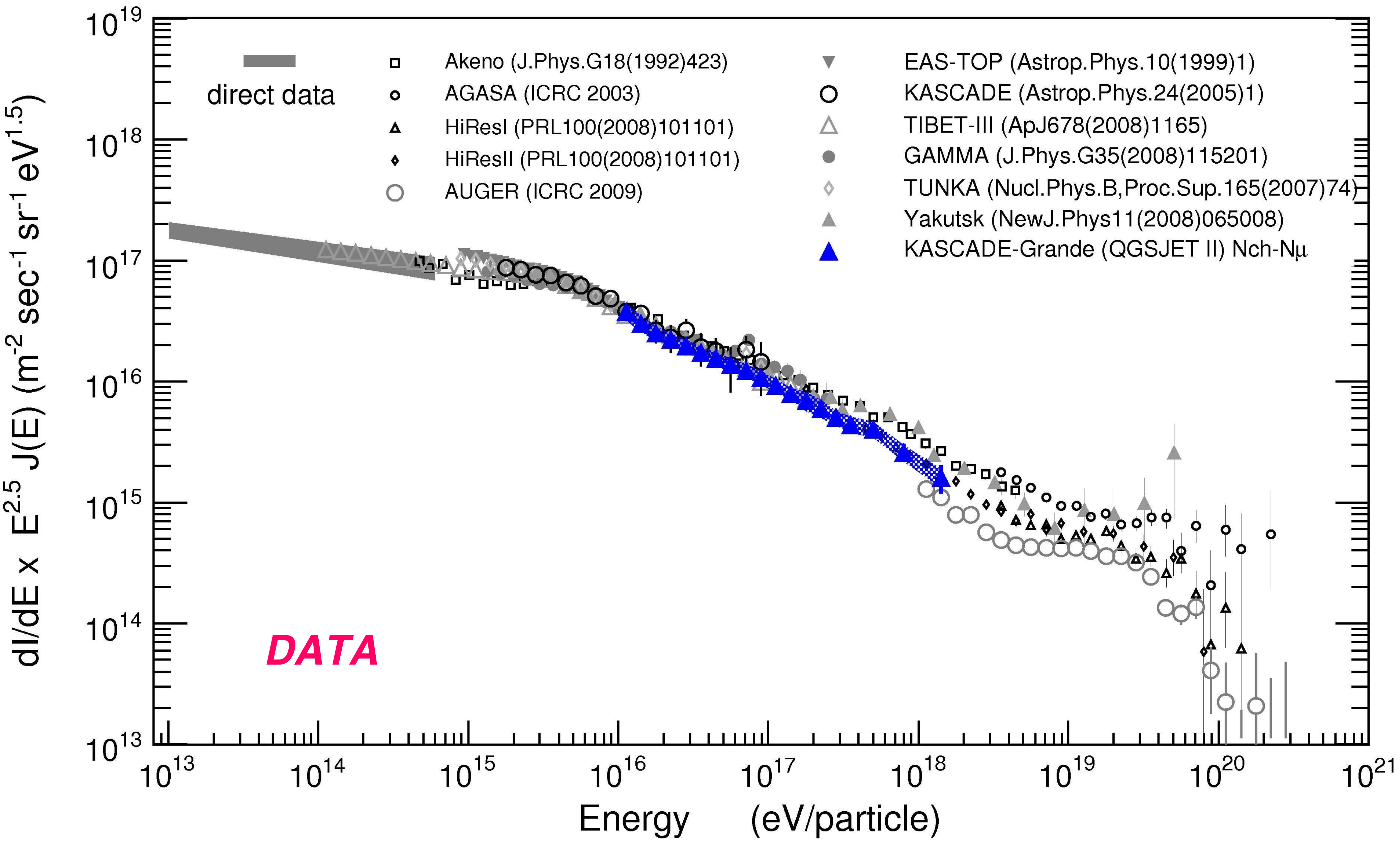
M. Bertaina, ECRS (2010)

Comparison with KASCADE & EAS-TOP



M. Bertaina (2010)

The all-particle energy spectrum



M. Bertaina, ECRS (2010)

The air shower experiments KASCADE and KASCADE-Grande

- Behaviour of light cosmic-ray components at knee confirmed
- Knee caused by cut-off of light nuclei

- Test of hadronic interaction models ongoing
  Improvement of interaction models in progress

- Analysis of KASCADE-Grande successfully ongoing
- All-particle energy spectra have been reconstructed
- Mass reconstruction in progress

- New insight to end of galactic component upcoming...

KASCADE-Grande Collaboration

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http://www-ik.fzk.de/KASCADE-Grande/

*deceased