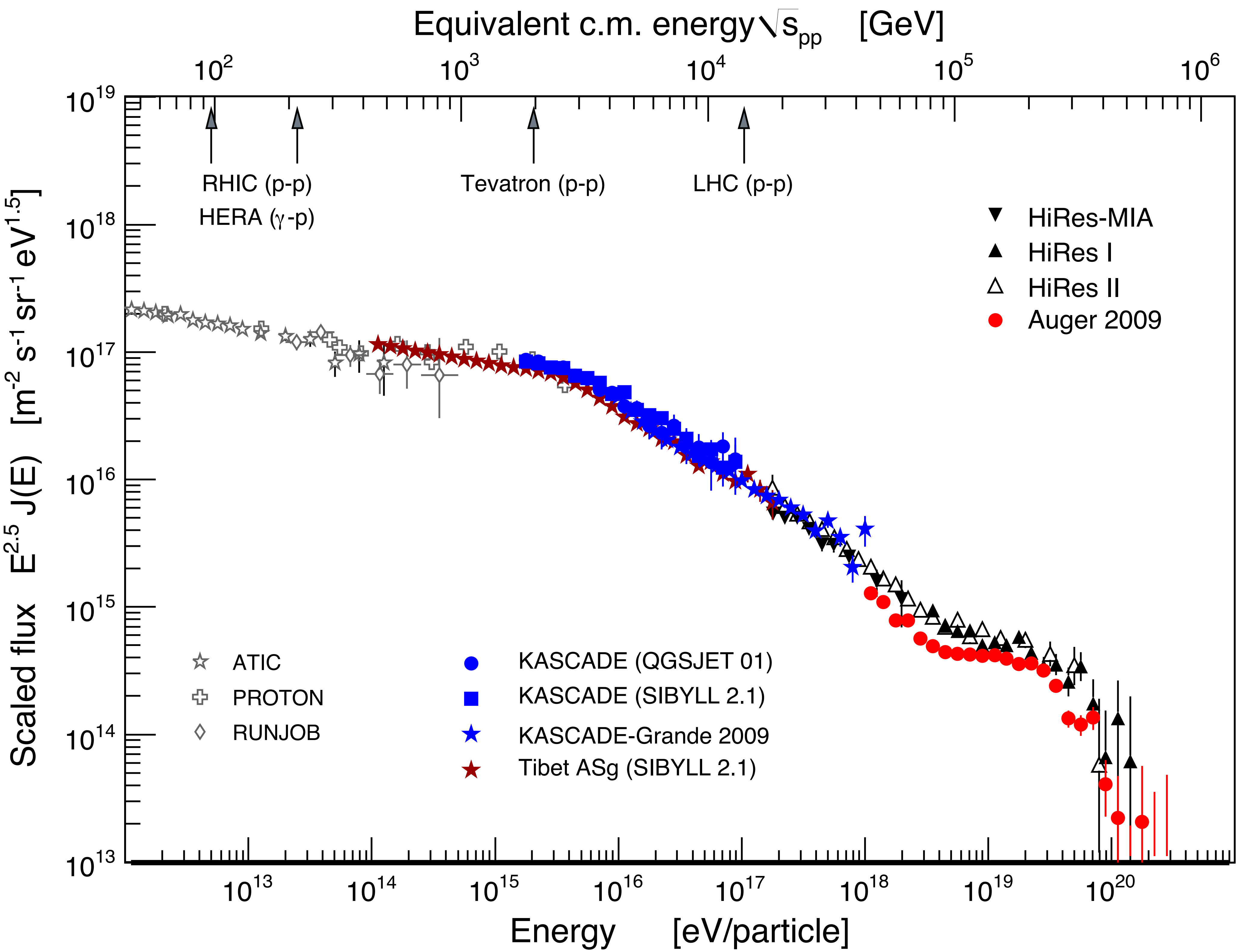
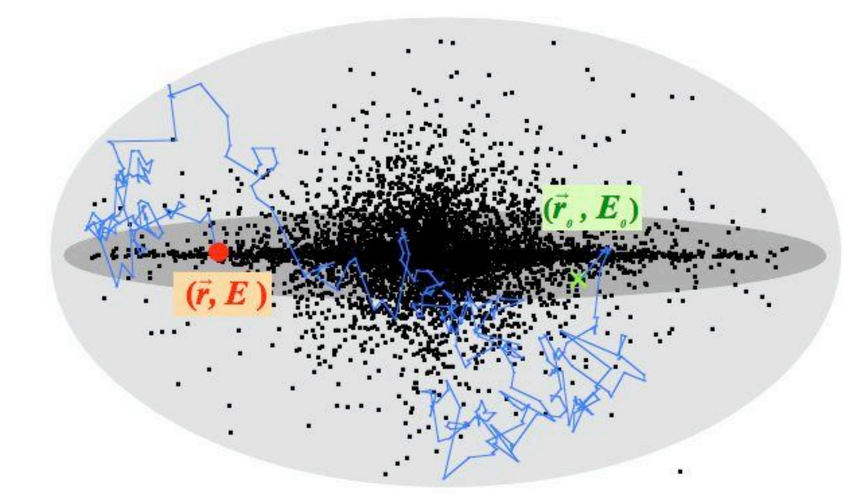
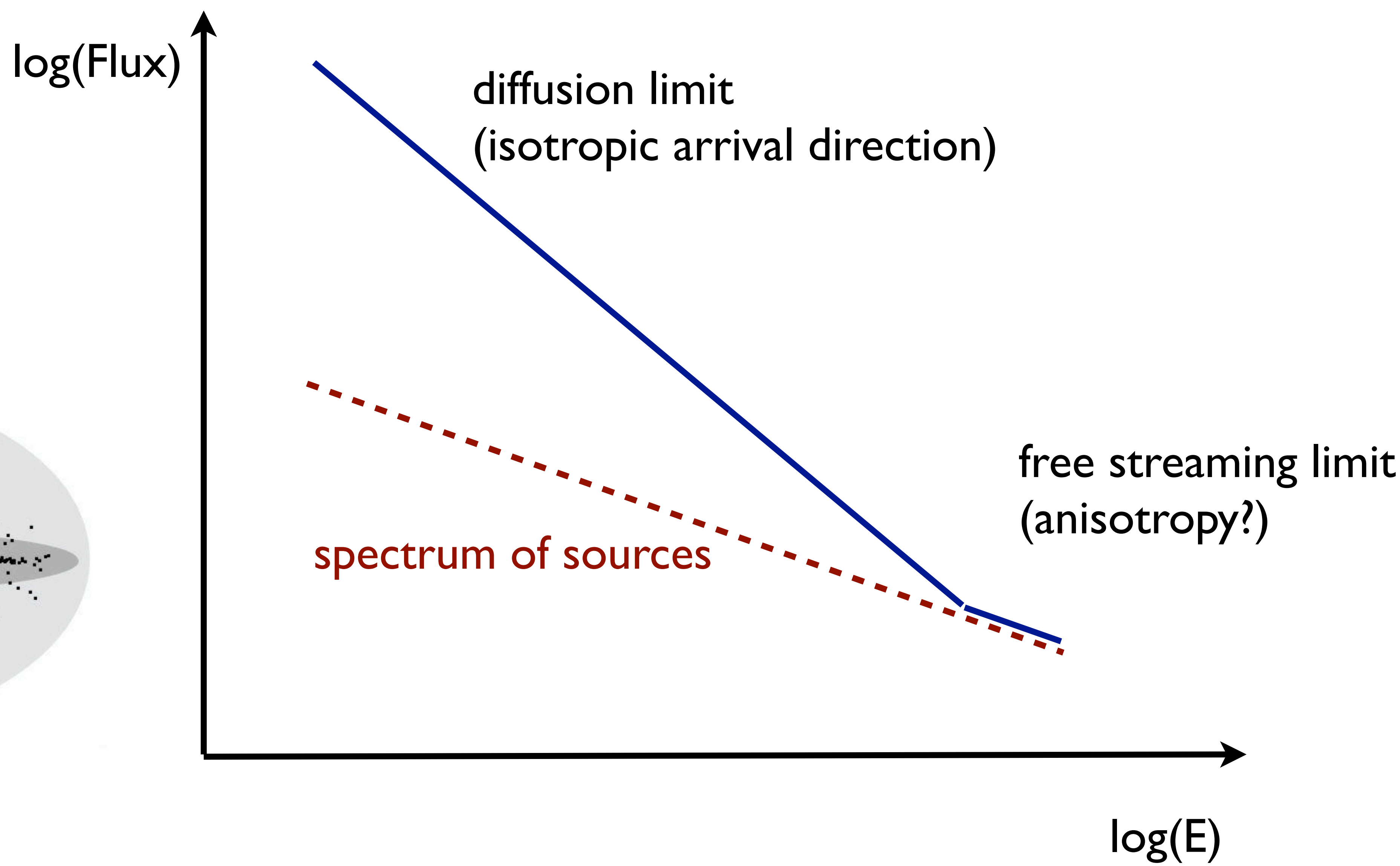
KASCADE Ne-Nμ Analysis

Ralph Engel (as a substitute for Andreas Haungs), for the KASCADE Collaboration
Karlsruhe Institute of Technology (KIT)


Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2009
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) [m^{-2} s^{-1} sr^{-1} $eV^{1.5}$]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy [eV/particle]

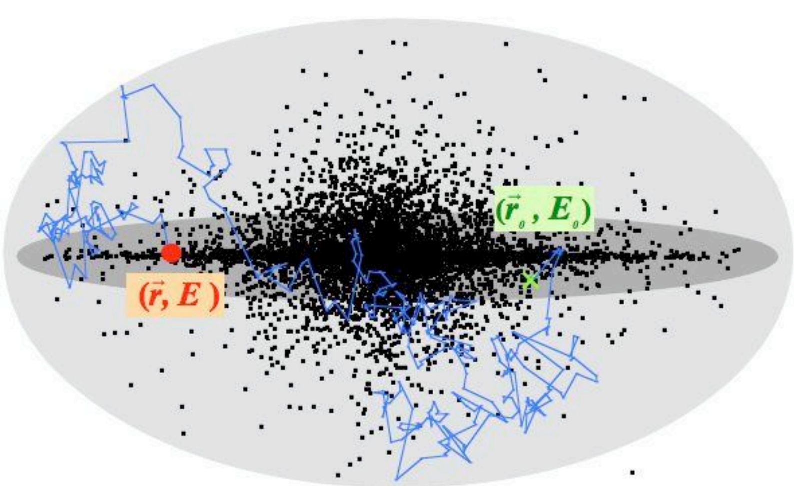
Magnetic fields: Confinement in the Galaxy

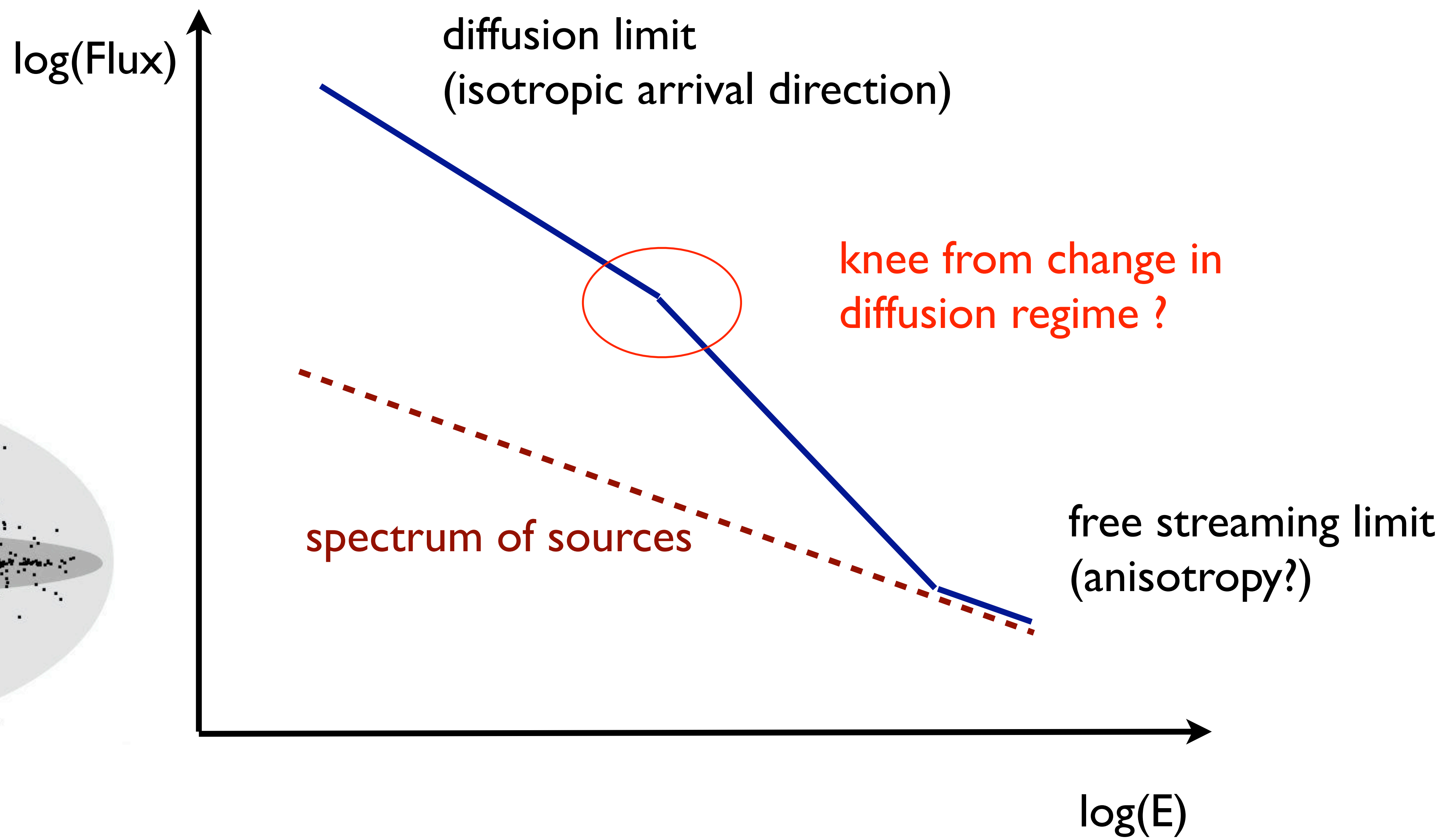




Observed spectrum softer than injection spectrum

Knee due to diffusion / escape from Glaxy





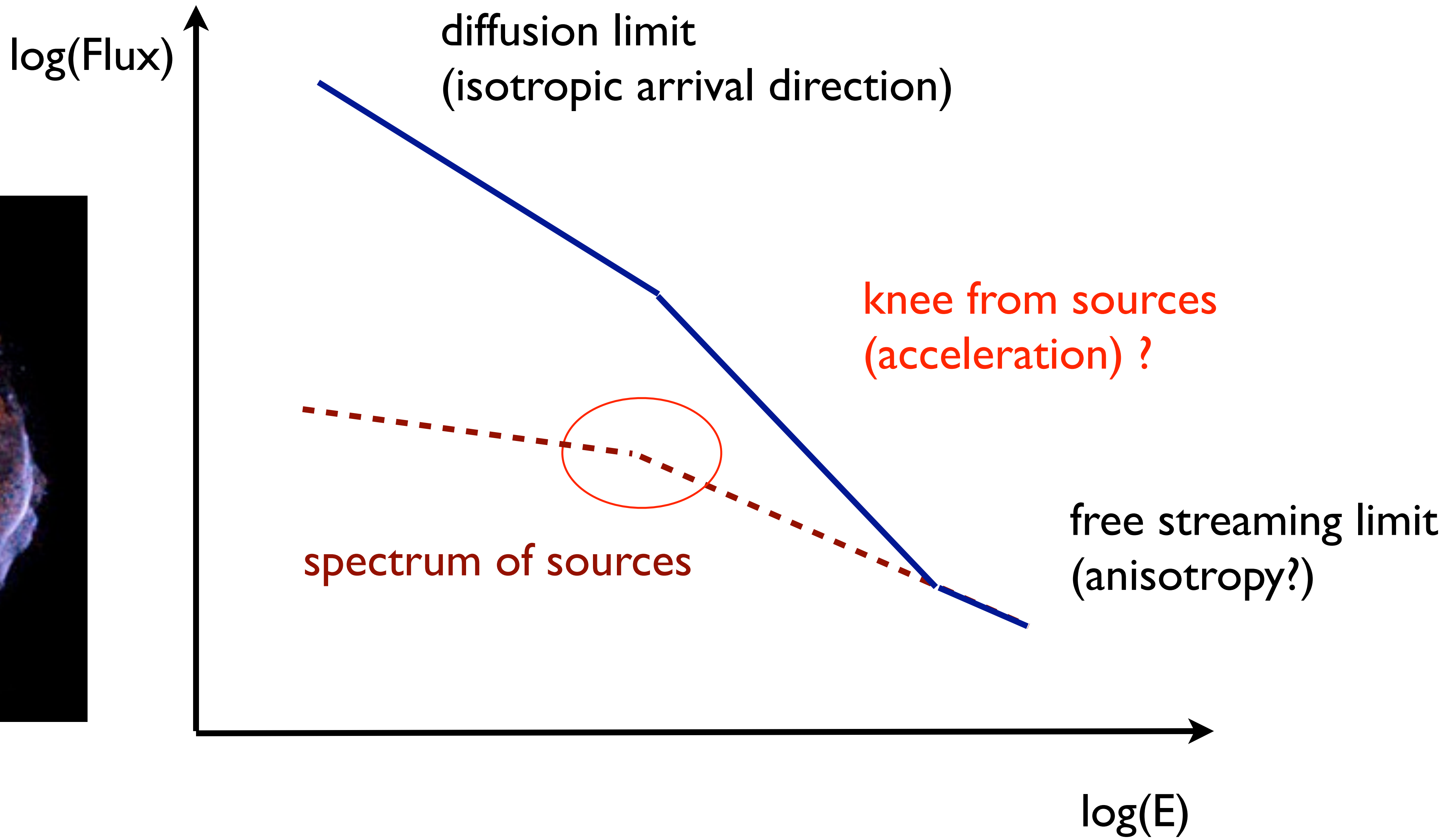
Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

Knee due to features of acceleration processes

SN remnant 1006

Distance ~ 2.2 kpc

20 pc



Acceleration: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

Exotic models for knee interpretation

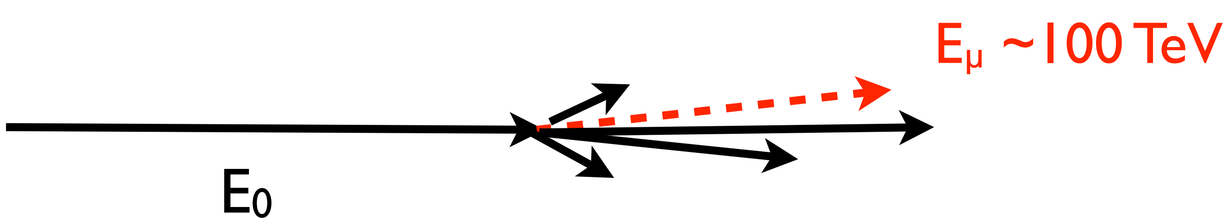
The knee and unusual events at PeV energies

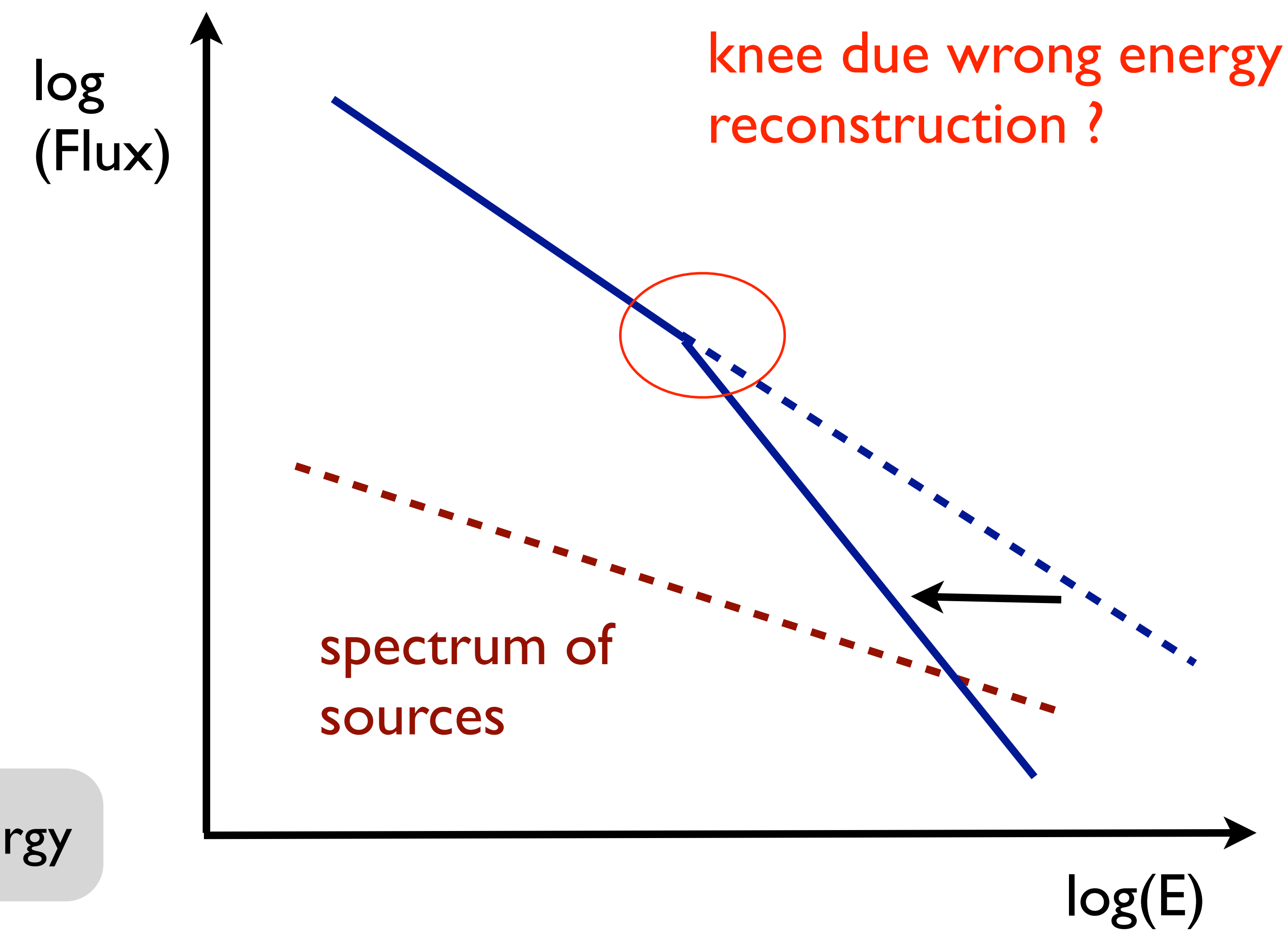
A.A.Petrukhin[a]

[a]Experimental Complex NEVOD, Moscow Engineering Physics Institute,
Kashirskoe shosse, 31, Moscow 115409, Russia

Nuclear Physics B (Proc. Suppl.) 151 (2006) 57–60

The appearance of the knee in EAS energy spectrum in the atmosphere in PeV energy interval and observation of various types of unusual events approximately at same energies are considered as evidence for new physics. Some ideas about possible new physical processes at PeV energies are described. Perspectives to check these ideas and their consequences for experiments at higher energies are discussed.





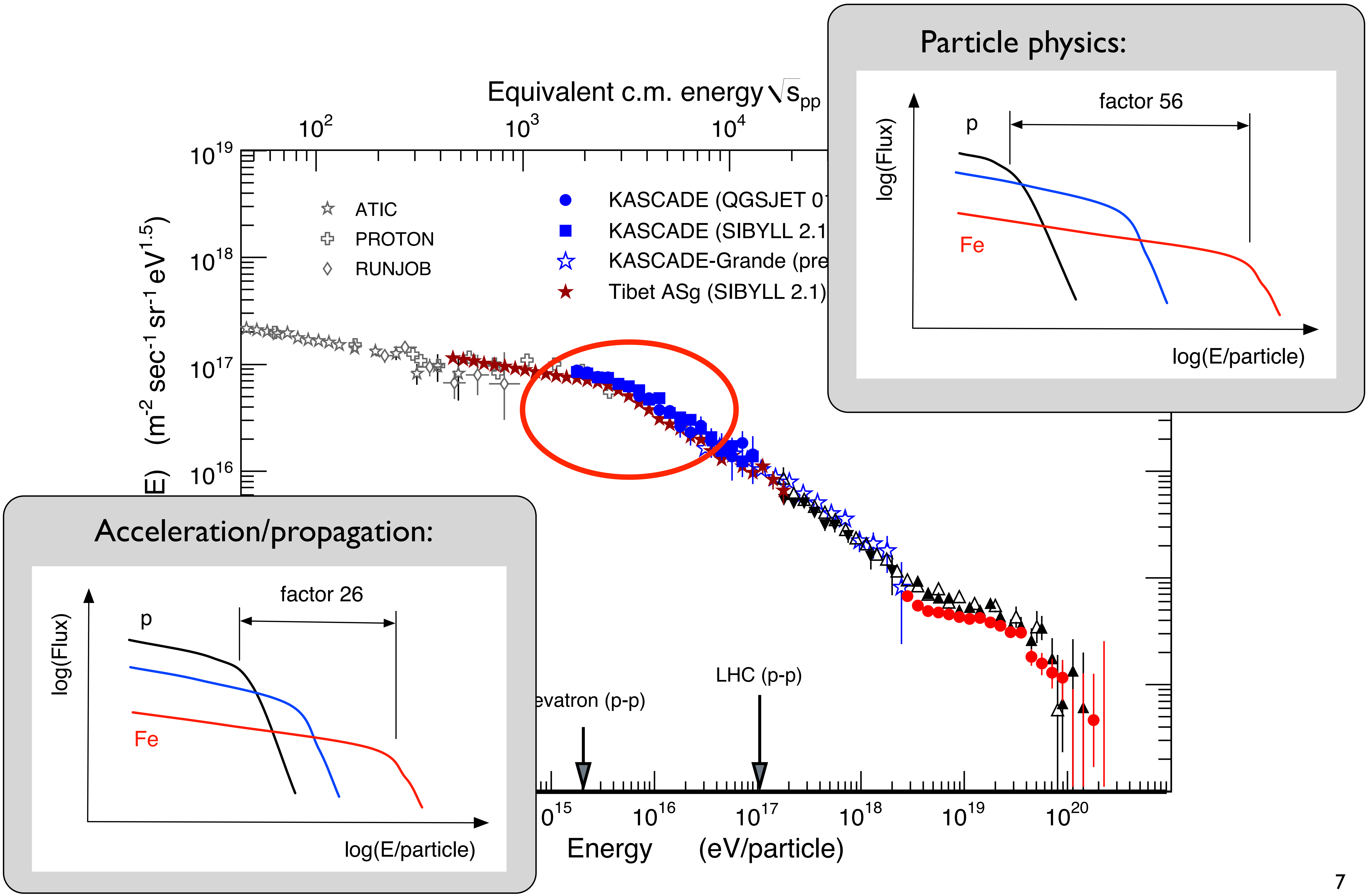
New physics, the cosmic ray spectrum knee, and *pp* cross section measurements

Aparna Dixit[1], Pankaj Jain[2], Douglas W. McKay[3], and Parama Mukherjee[4]

December 7, 2009

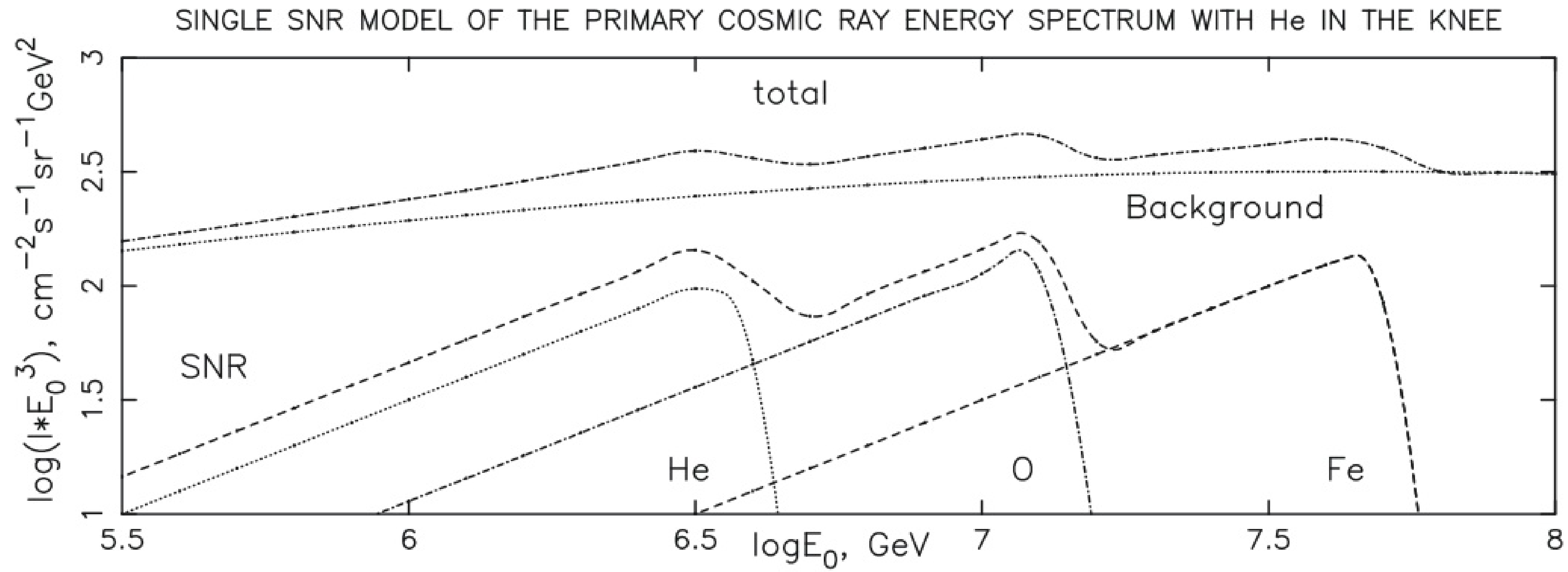
New physics: scaling with nucleon-nucleon cms energy

Limiting scenarios for origin and physics of the knee



Alternative scenarios for origin of knee (i)

Anisotropy likely at some level

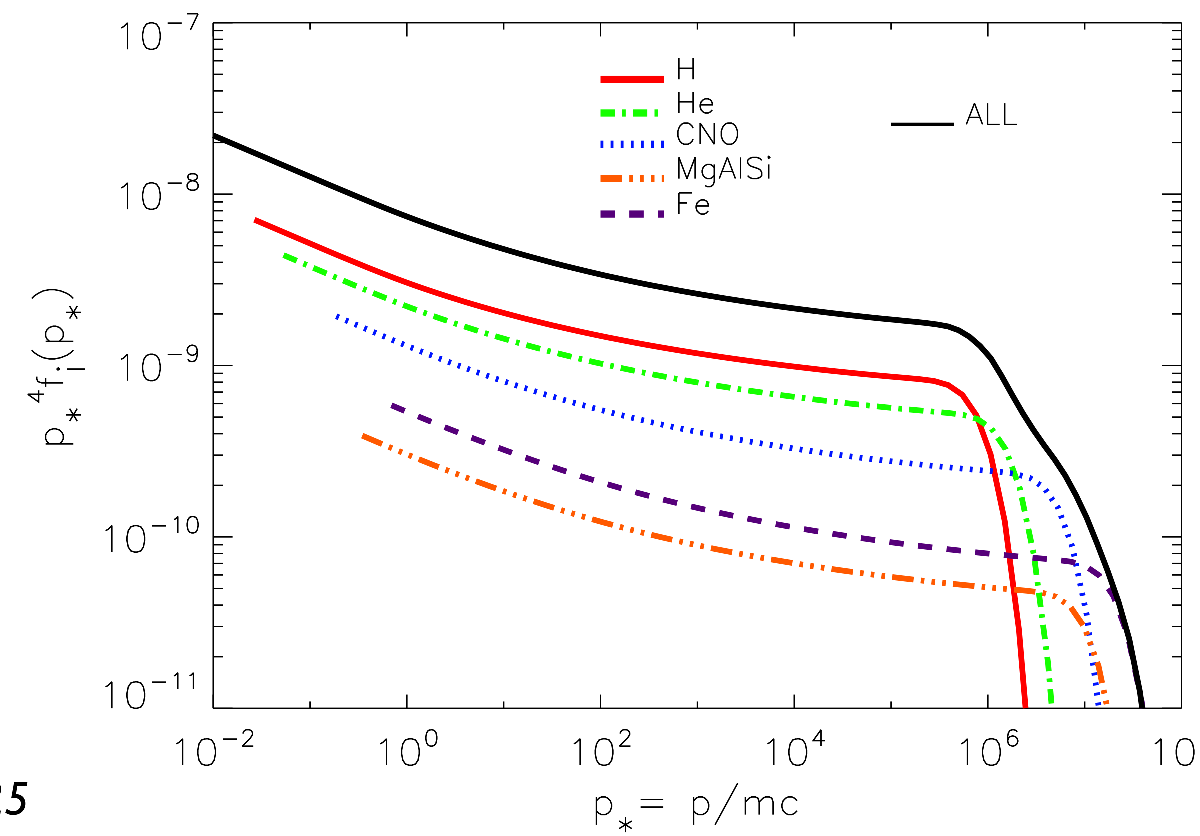


Erlykin & Wolfendale, J.Phys.G32:1-8,2006

Non-linear shock acceleration

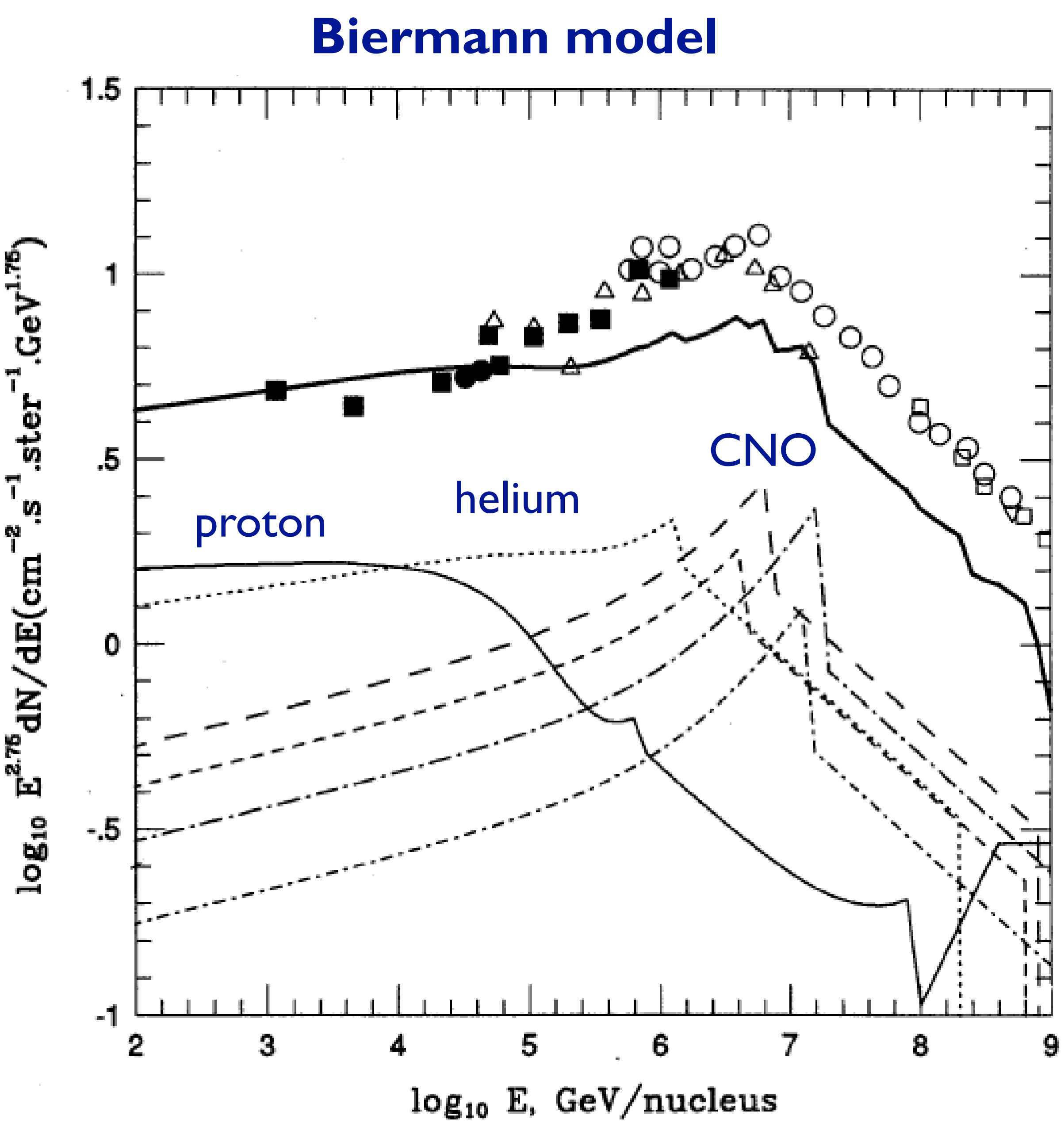
Bell & Lucek, 2001 (several papers)
Berezhko, Völk, ...

Magnetic field amplification, similar end values for different environments

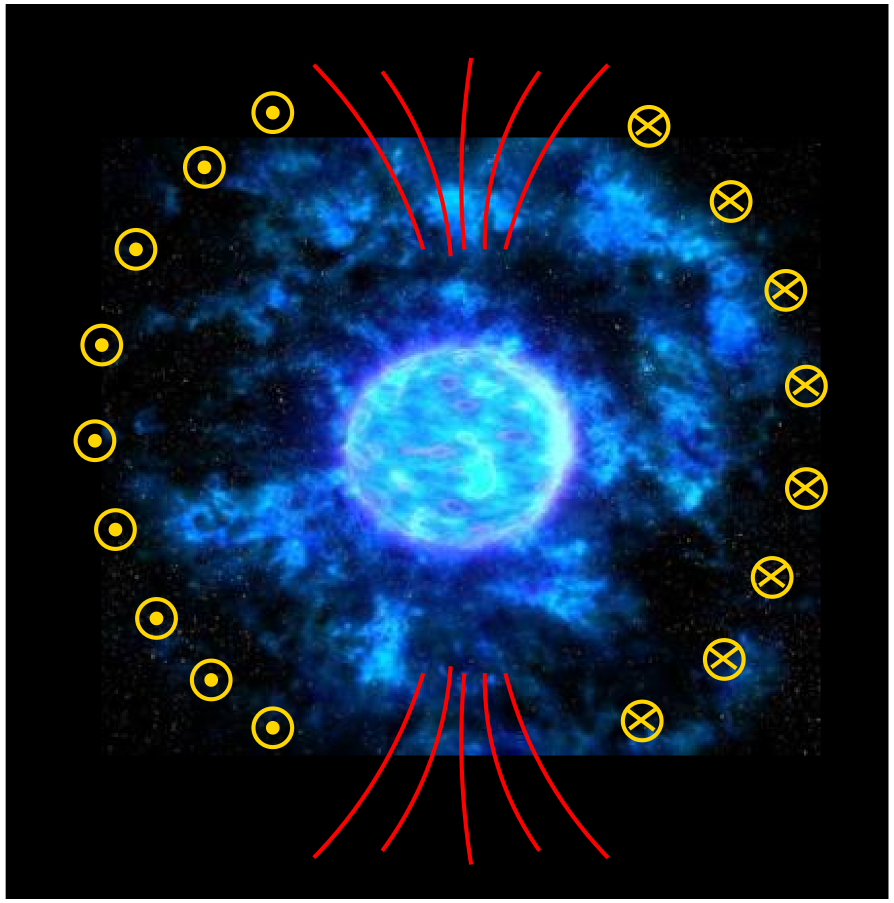


Caprioli, Blasi, Amato, astro-ph/1007.1925

Alternative scenarios for origin of knee (ii)



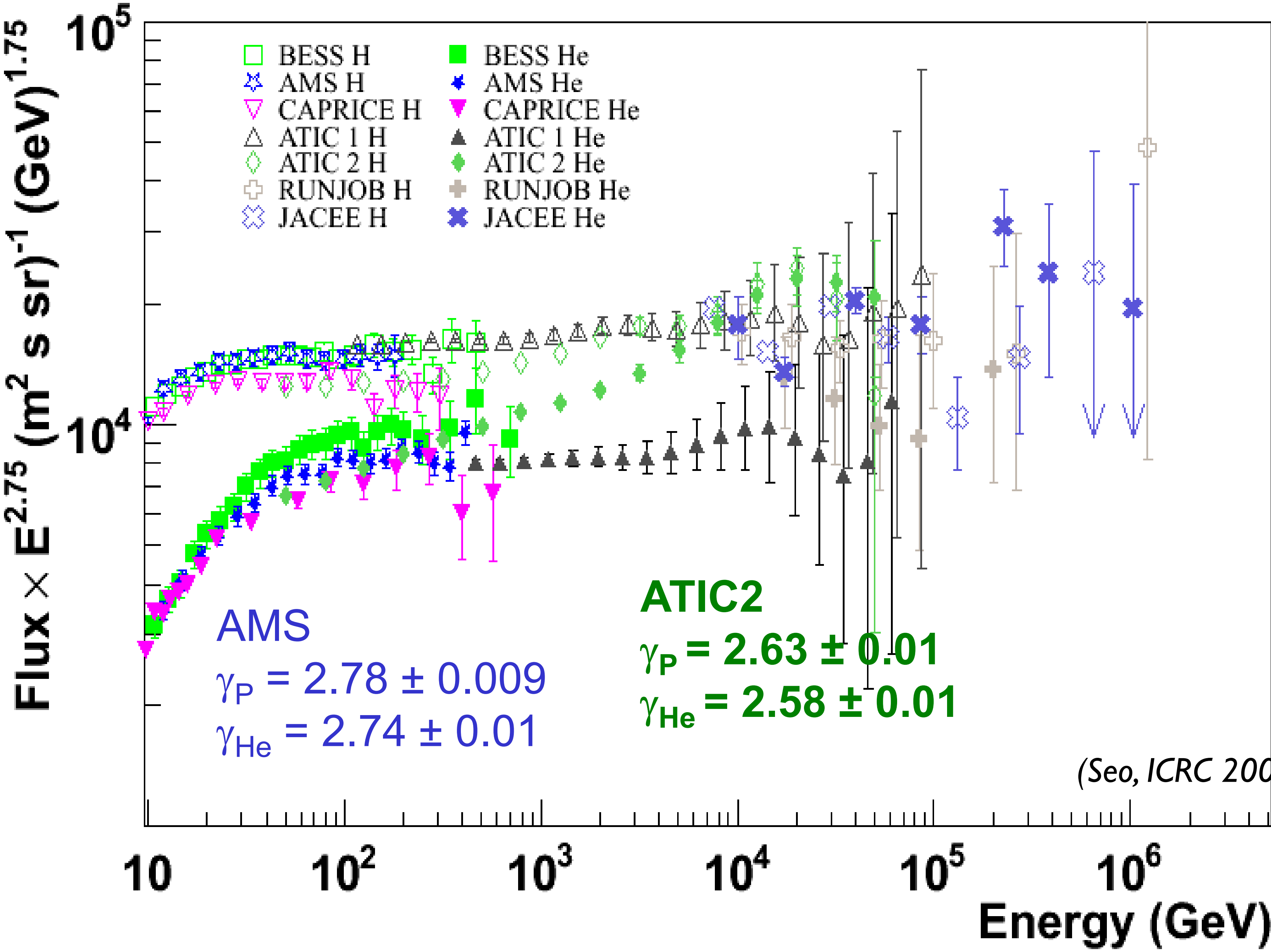
Model with different acceleration scenarios (polar caps and equatorial region) and different types of SNR



(Stanev et al, ApJ 1993)

Update of direct flux measurements

(Seo et al, ICRC 2009)



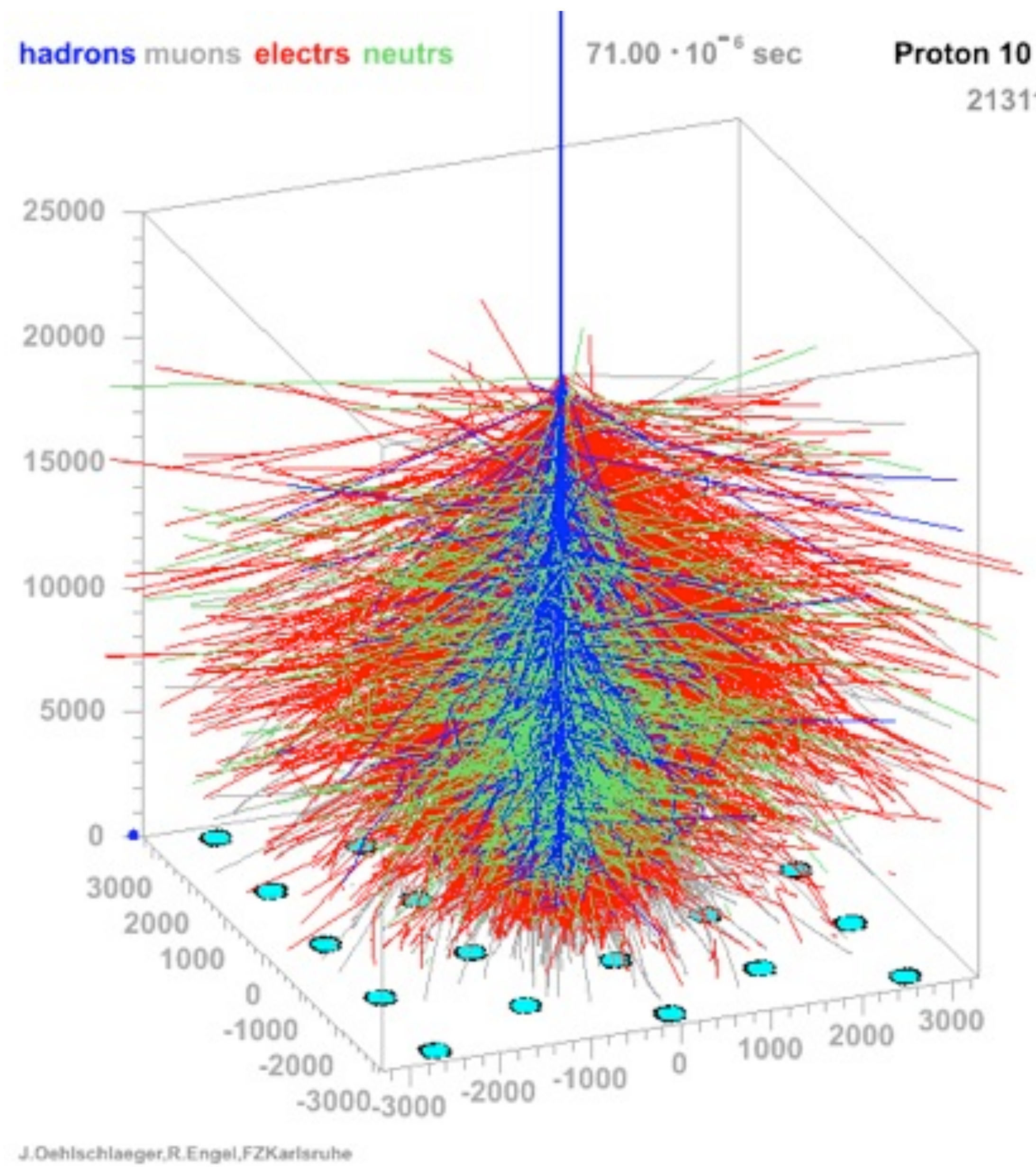
$$I_j \propto E^{-\gamma}$$

JACEE
γ_P = 2.80 ± 0.04
γ_{He} = 2.68+0.04-0.06

RUNJOB
γ_P = 2.78 ± 0.05
(2.74 ± 0.08)
γ_{He} = 2.81 ± 0.06
(2.78 ± 0.2)

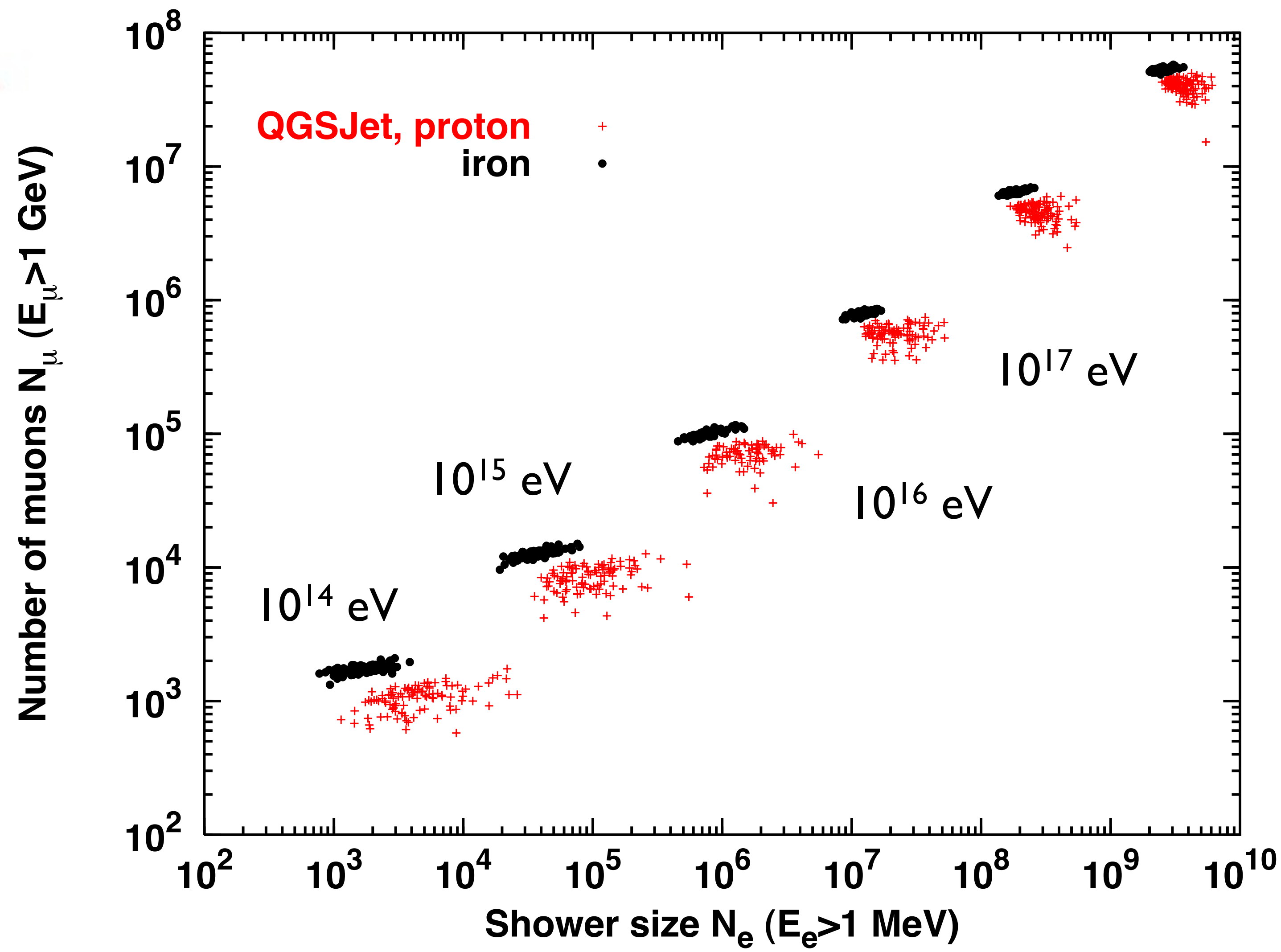
New CREAM data confirm ATIC2
Crossing of helium and proton fluxes observed !

Air shower ground arrays: Ne-Nμ method

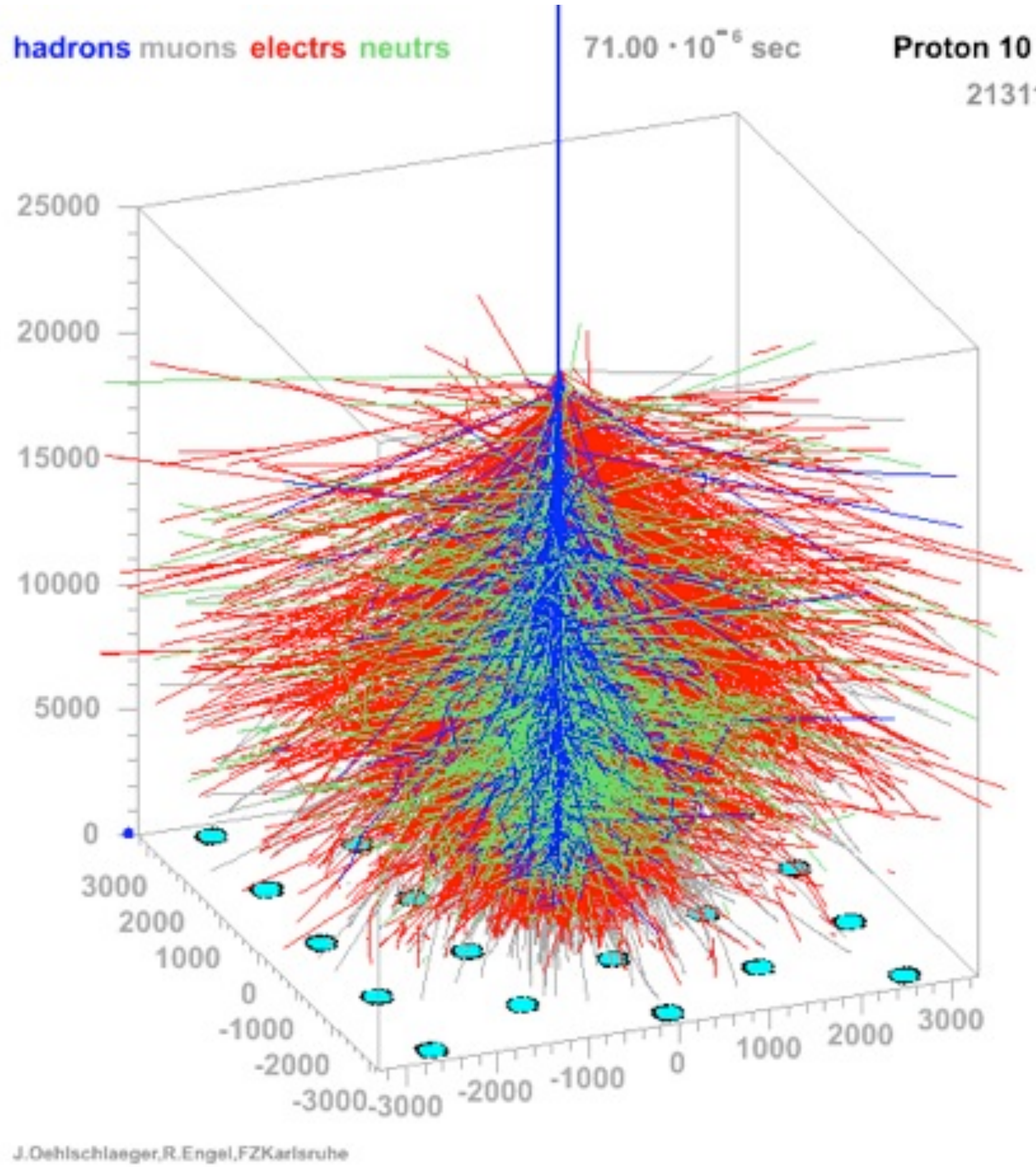


Example:
KASCADE-Grande (Karlsruhe)

Combined energy-composition analysis

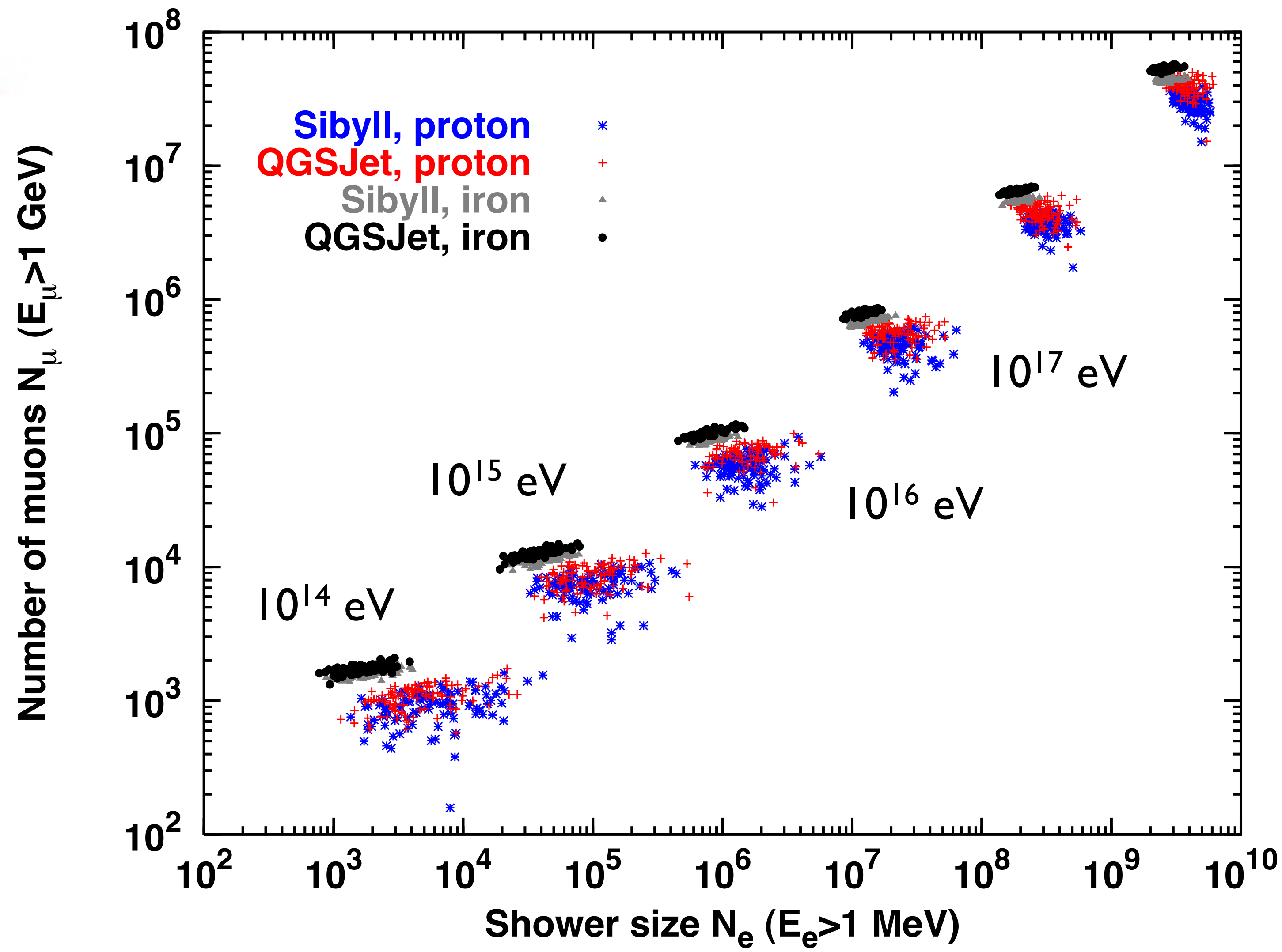


Air shower ground arrays: Ne-Nμ method



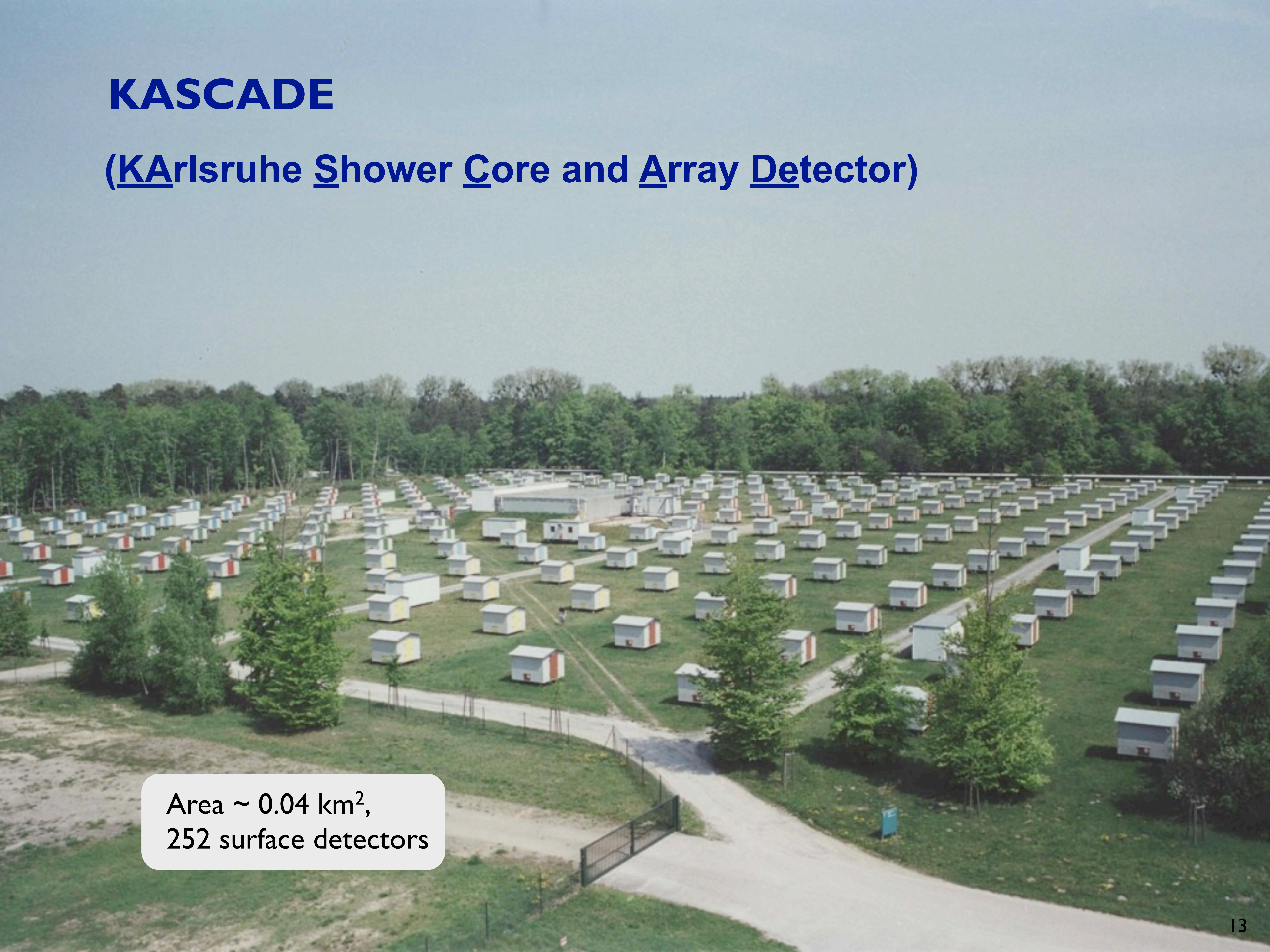
Example:
KASCADE-Grande (Karlsruhe)

Combined energy-composition analysis



KASCADE

(KArlsruhe Shower Core and Array Detector)



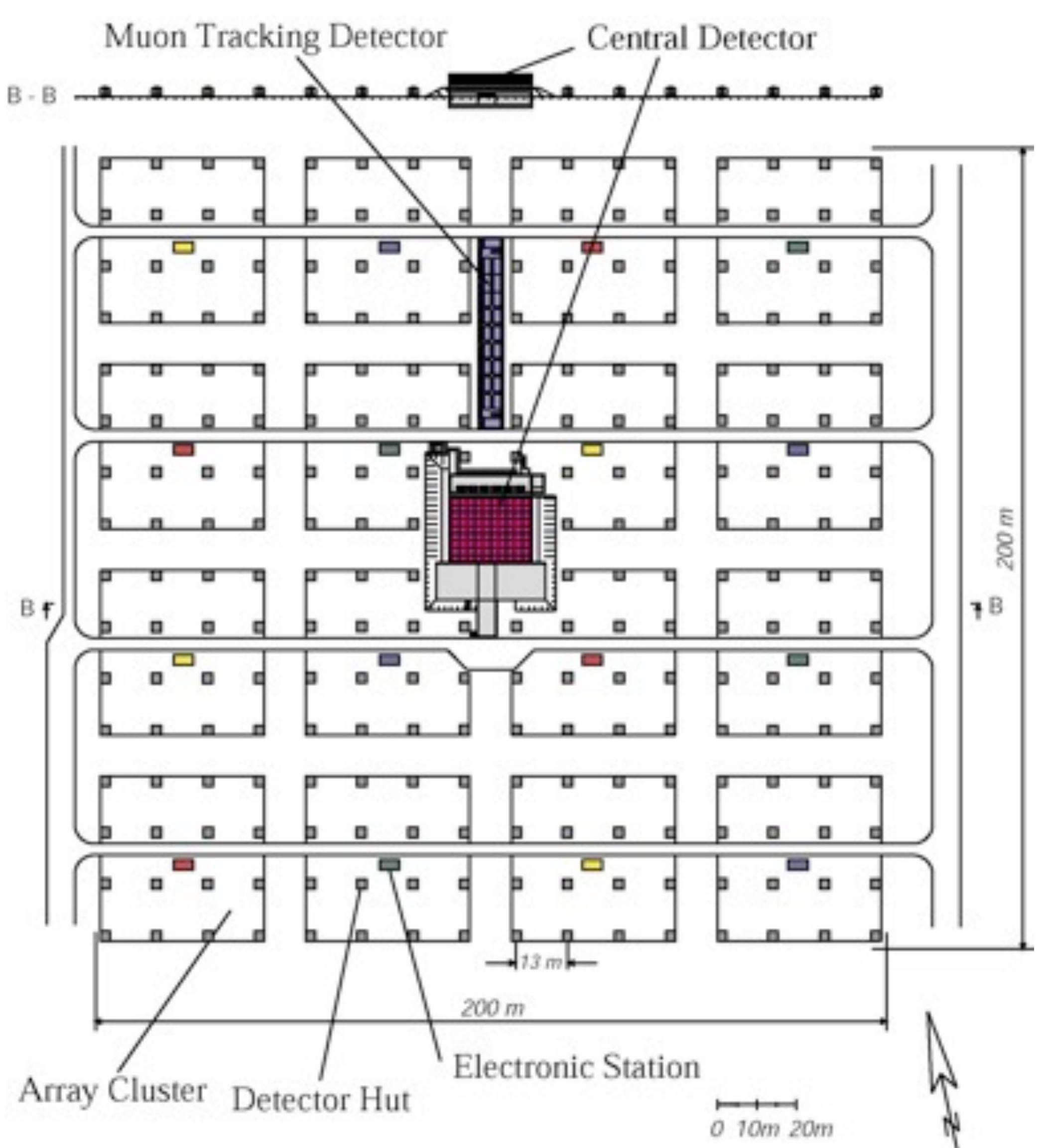
Area ~ 0.04 km^2,
252 surface detectors

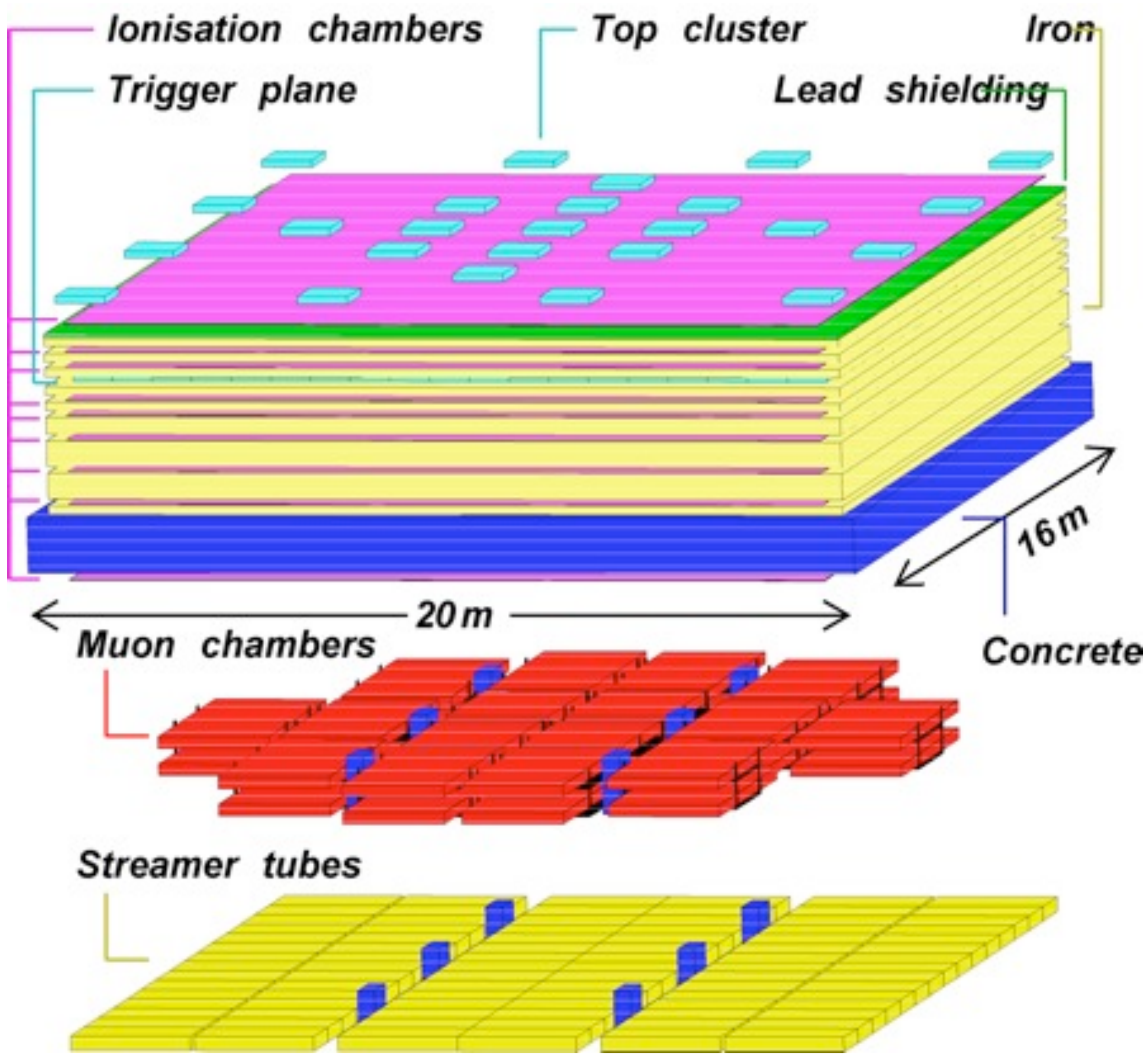

KASCADE in winter
KASCADE: 1997 - 2002
KASCADE-Grande: 2003 - 2009

Overview

Central Detector:
hadron calorimeter
(hadrons, 50 GeV)
trigger plane
(muons, 490 MeV)
muon chambers, LST
(muons, 2.4 GeV)

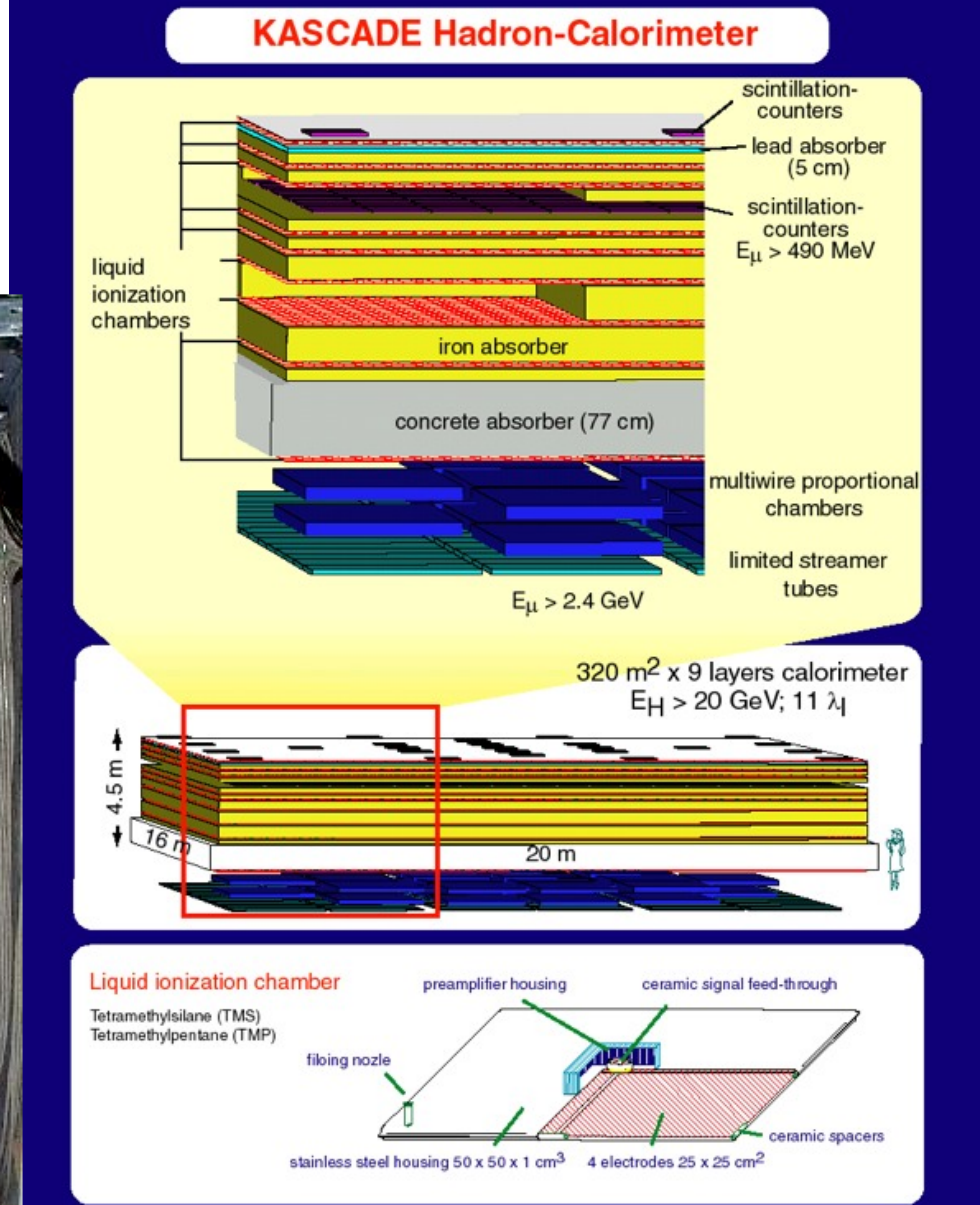
Array:
electrons
muons (230 MeV)
Tunnel:
muon tracking (800 MeV)





Central detector

Hadron calorimeter
320 m^2 x 9 layers



J. Engler et al., NIM A 427 (1999) 528

Muon tunnel

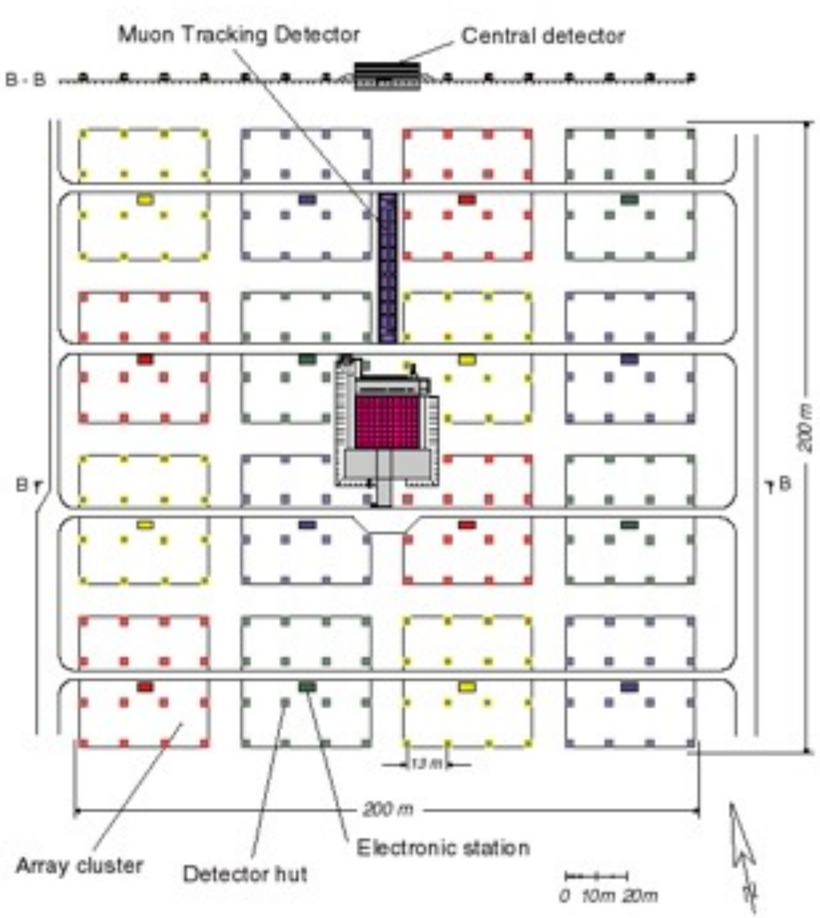
limited streamer tubes
(argon – isobutane)

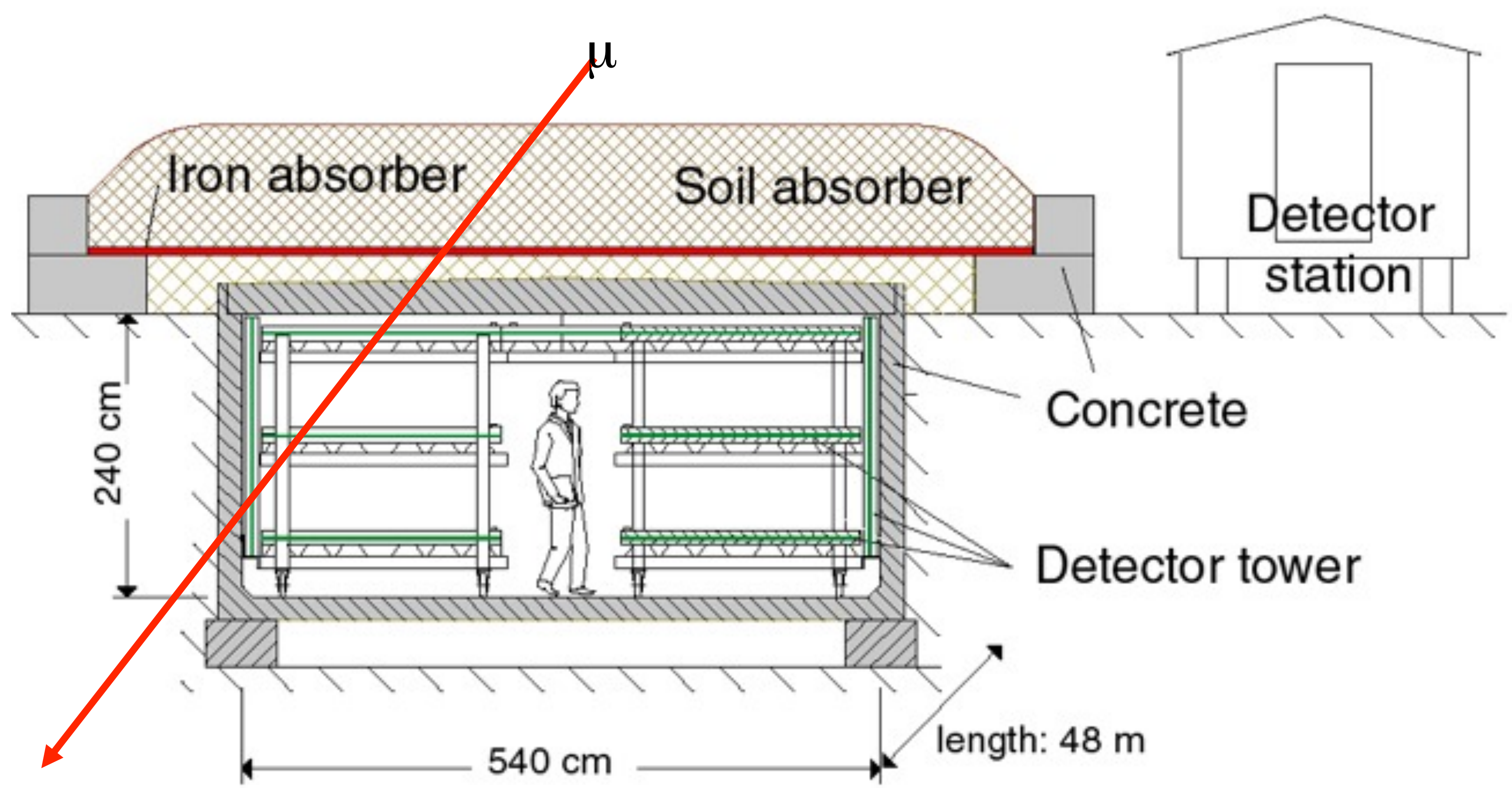
24576 electronic channels

$E_{\mu} > 800$ MeV

144 m^2 x 4 layers

P. Doll et al., NIM A 367 (1995) 120



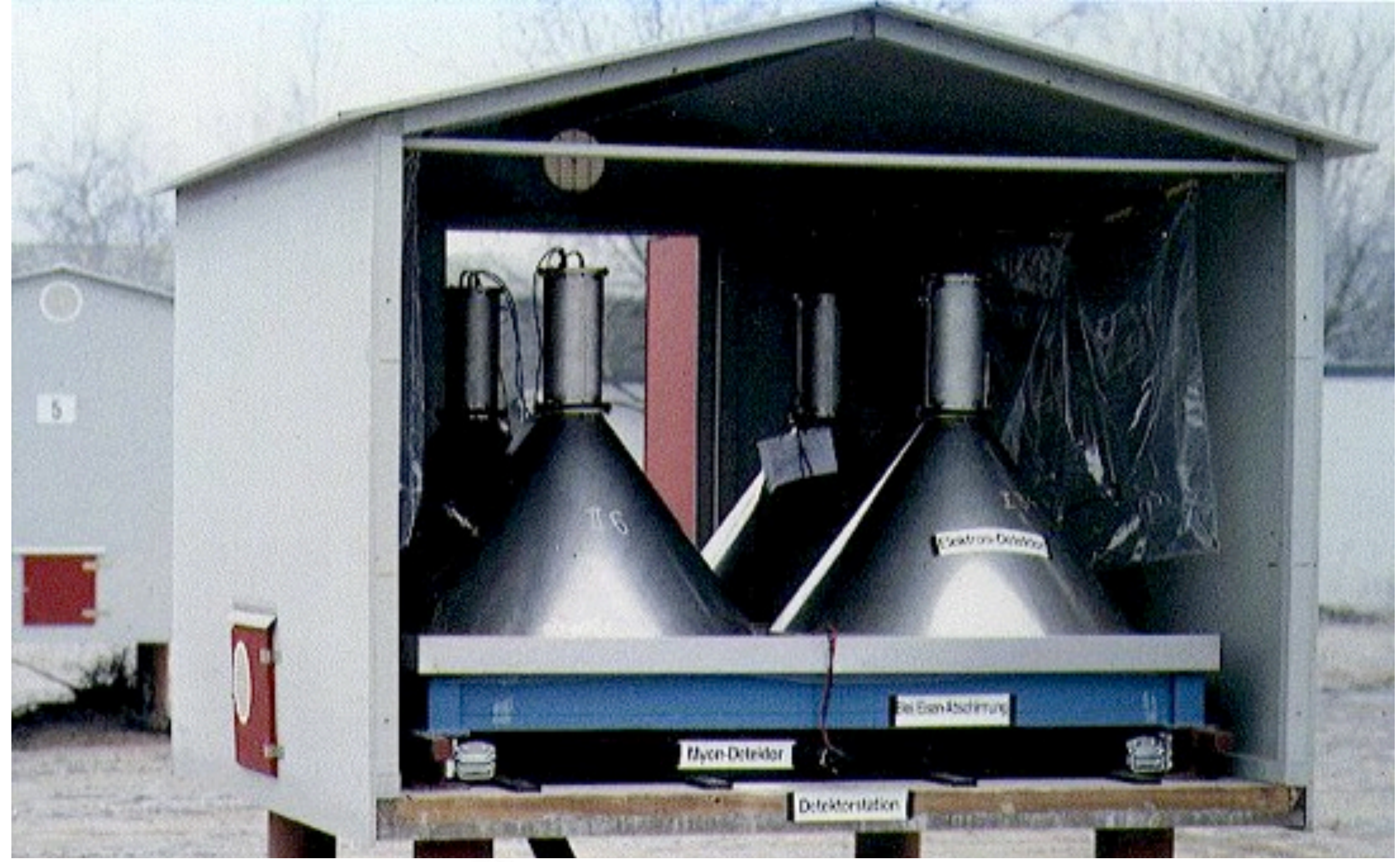


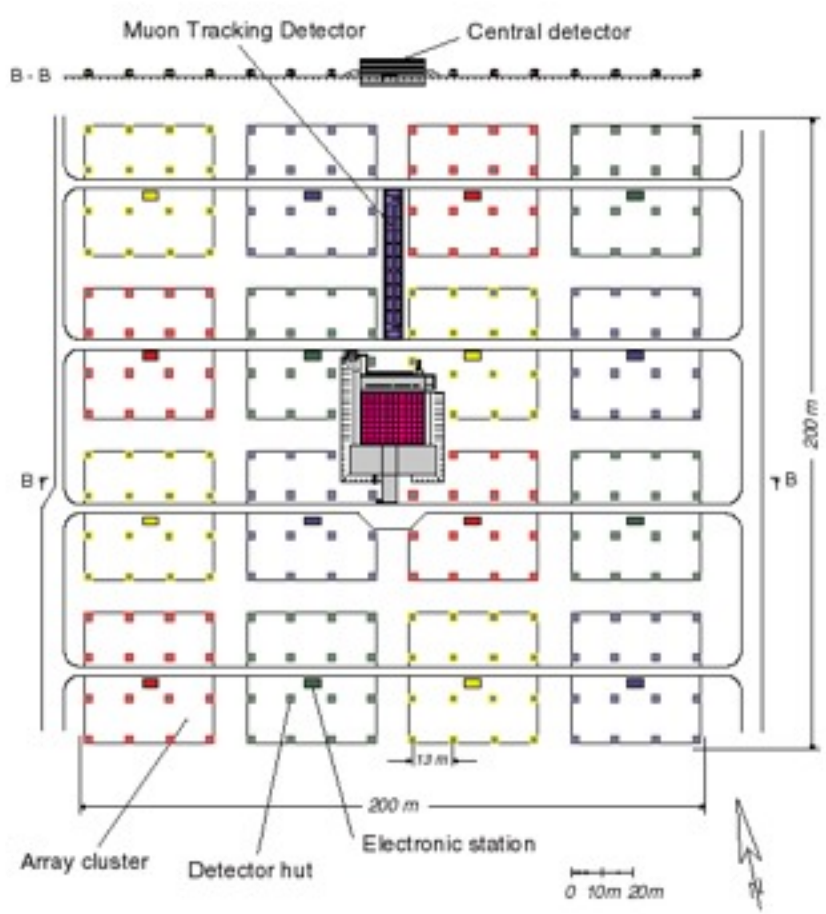
Array detector station

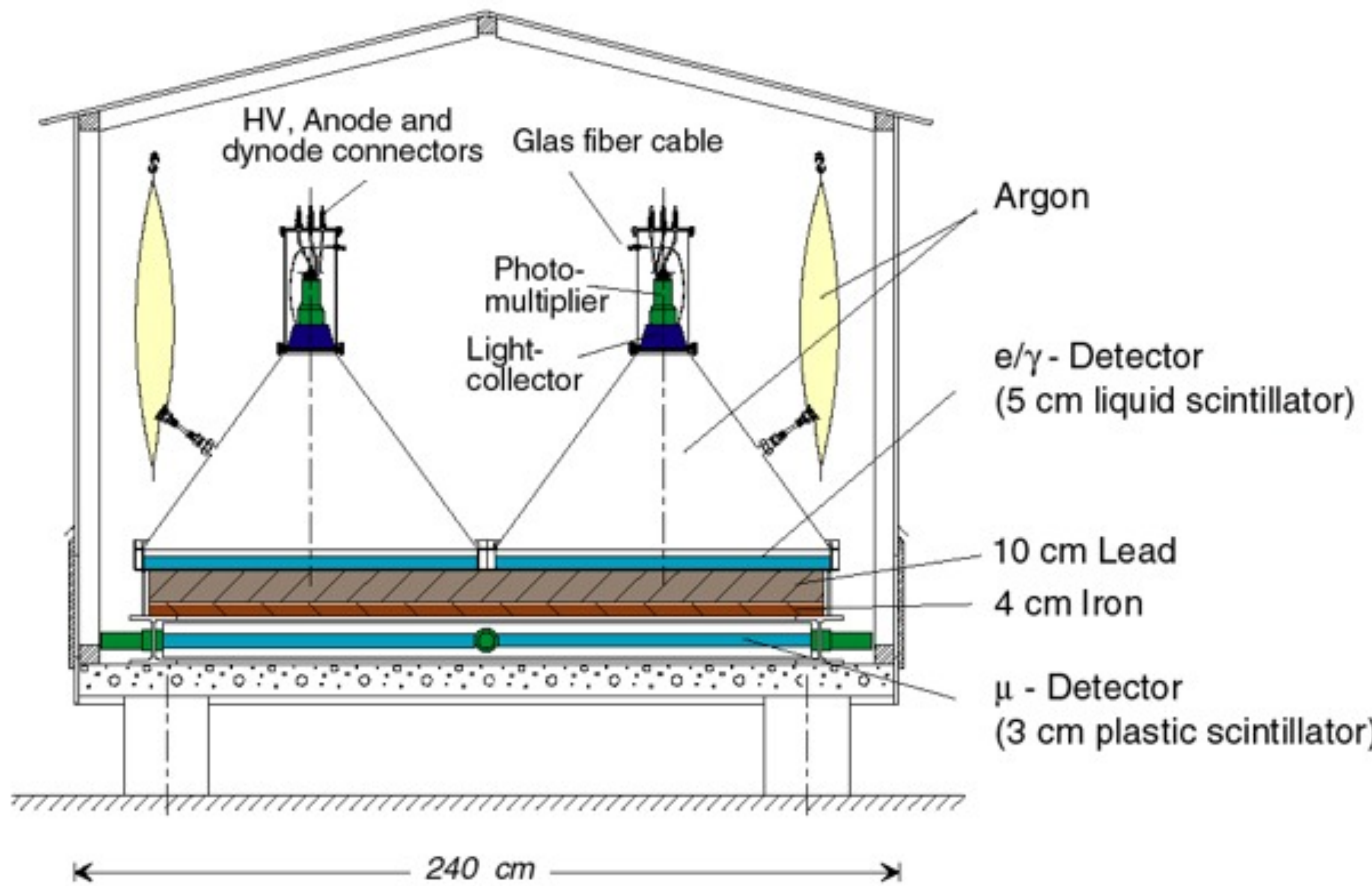
252 Detector stations
200 x 200 m^2 array

e/γ-detectors 490 m^2

μ-detectors 622 m^2

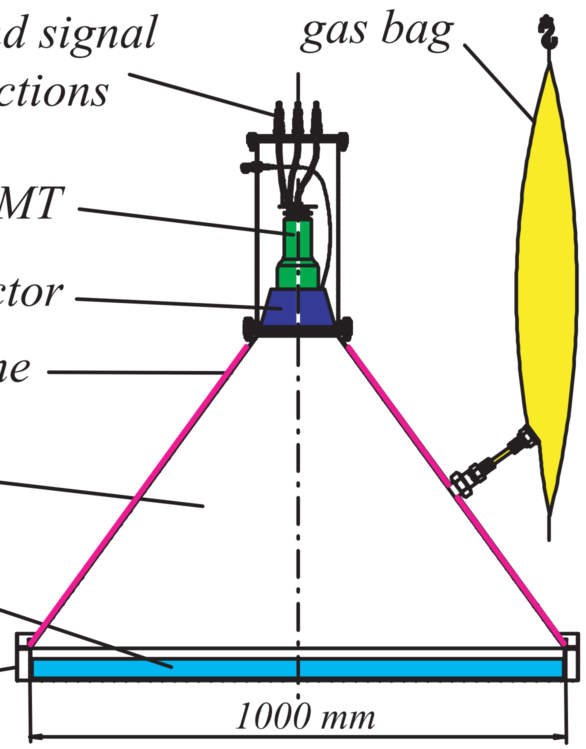


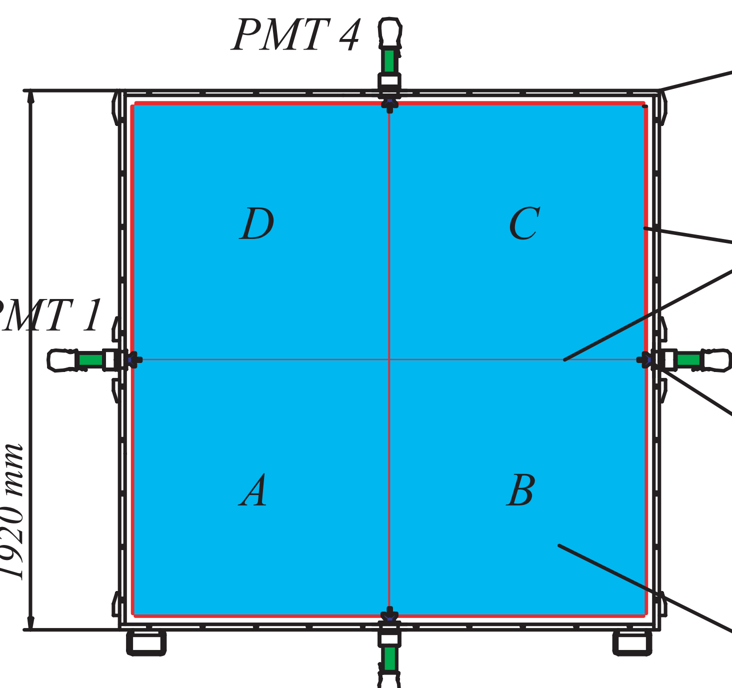




T. Antoni et al., NIM A 513 (2003) 490

Electron and muon detectors





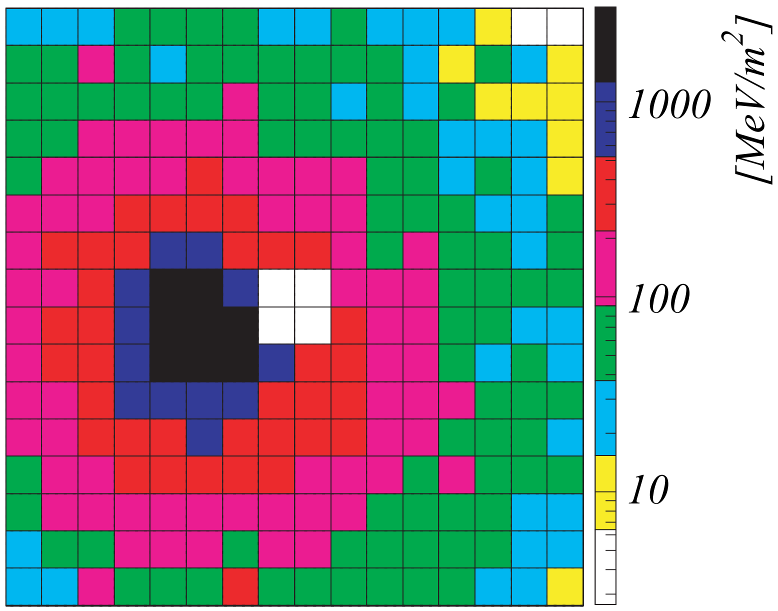
Electron detectors

time resolution 0.77 ns
energy resolution 8%
dynamic range 1/4 ... 2000 m.i.p.

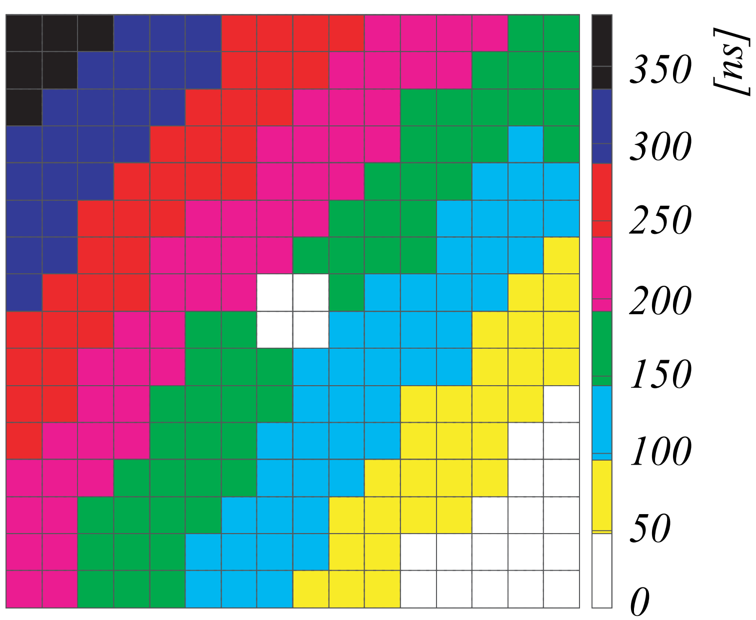
Muon detectors

time resolution 2.9 ns
energy resolution 10%
uniformity better than 2%

Particle density reconstruction in KASCADE

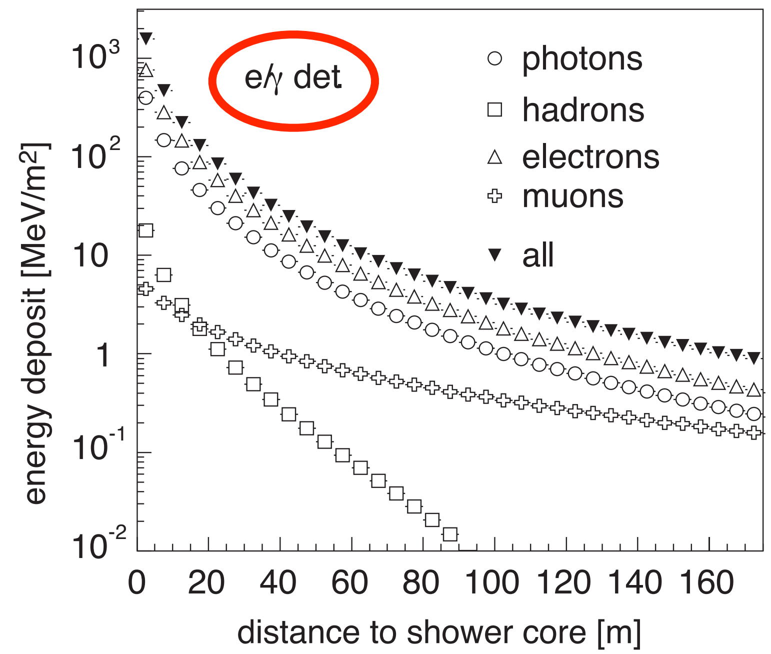


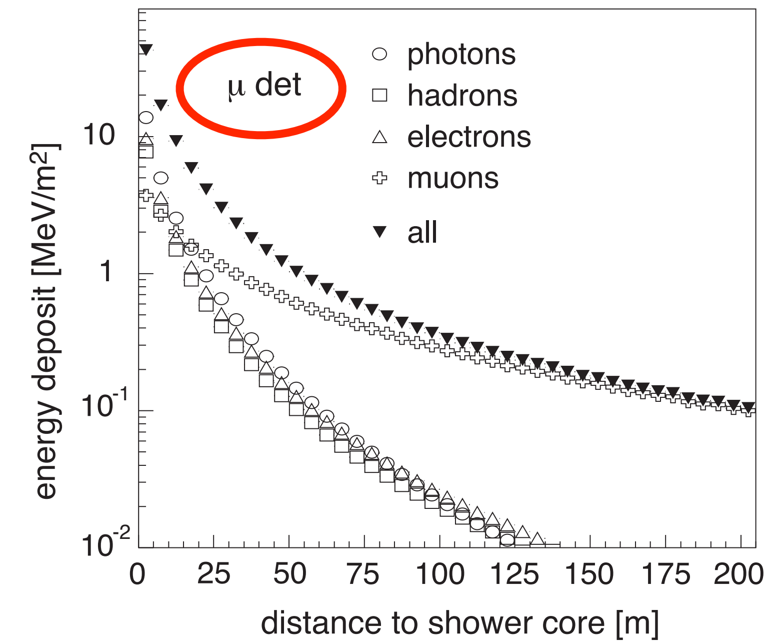
energy deposit



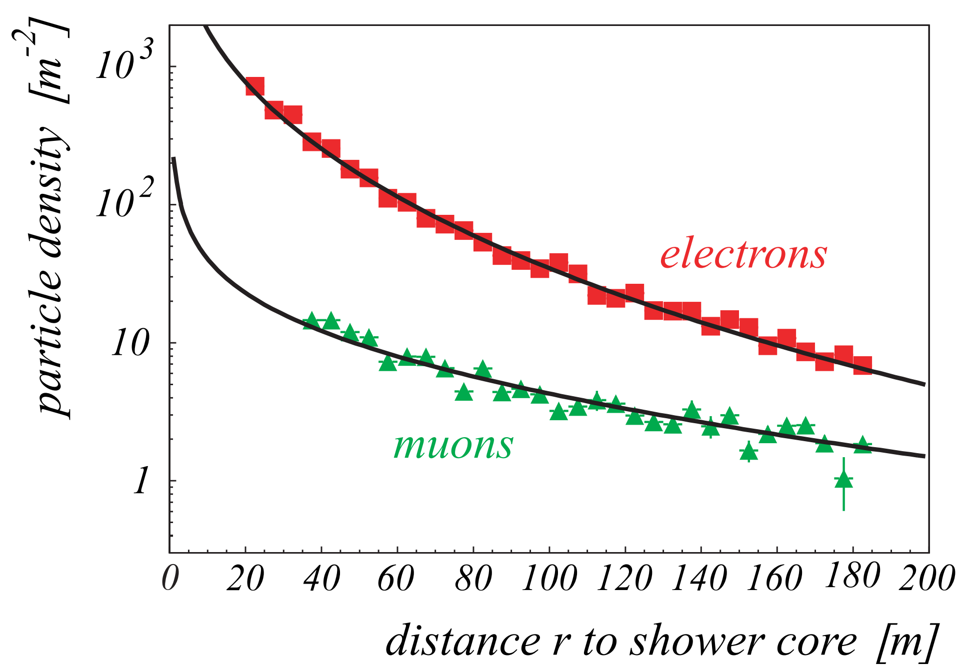
arrival time

Energy deposit





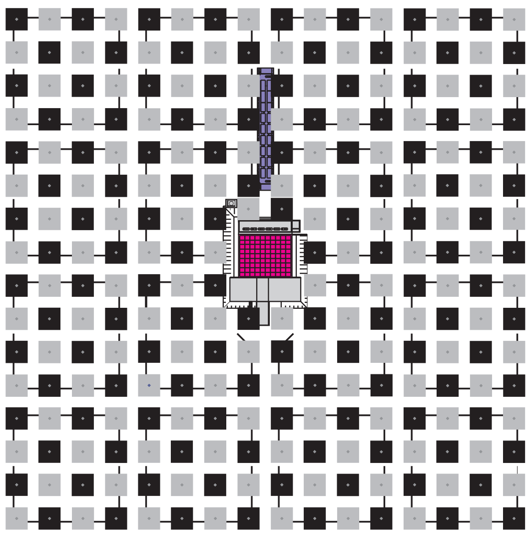
Particle density

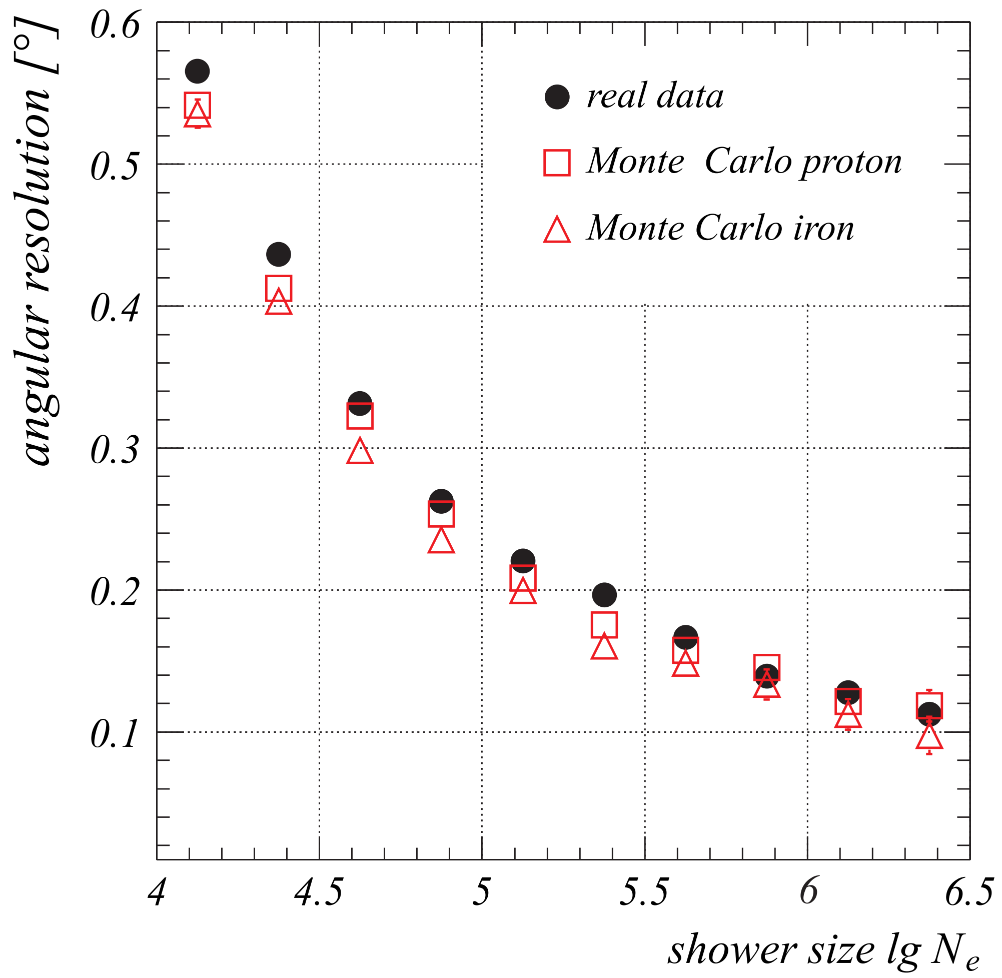


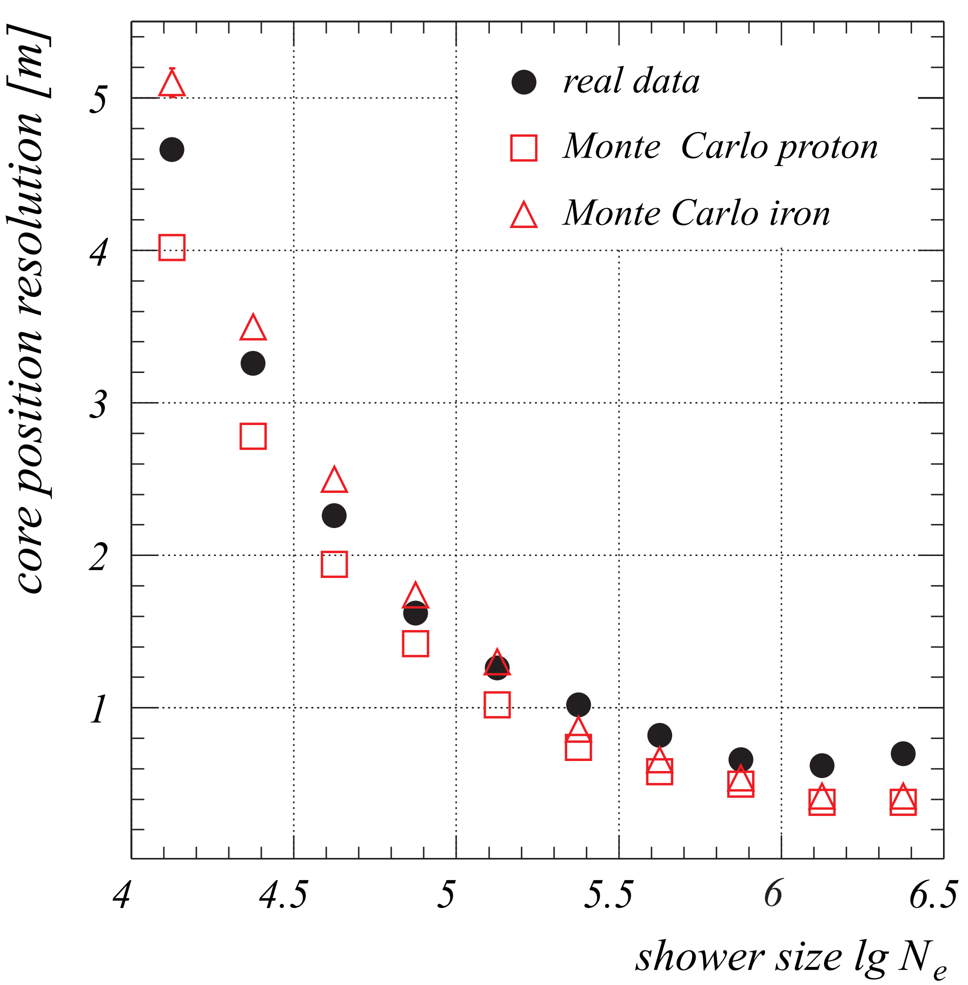
Cross-check of shower reconstruction and simulation

Checkerboard analysis

- data reconstruction with every second detector
- simulated data reconstructed same way
- difference between reconstructions



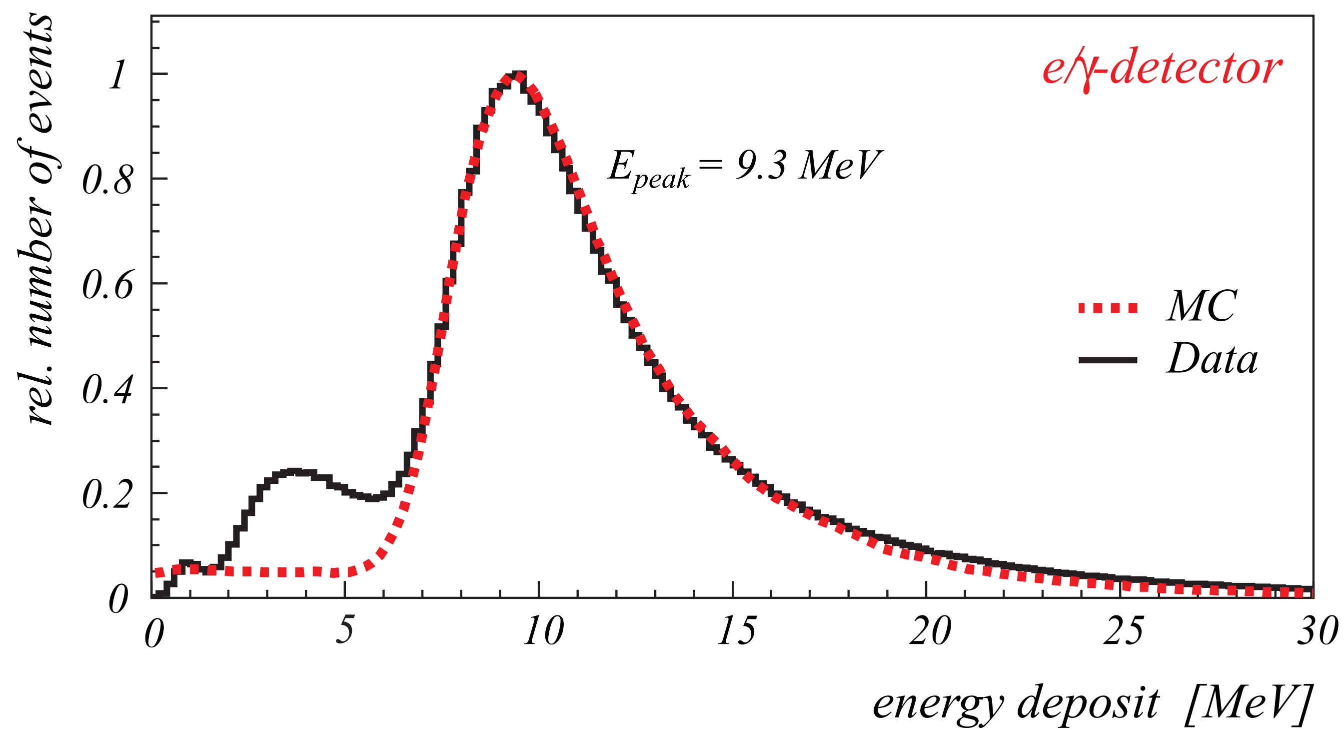


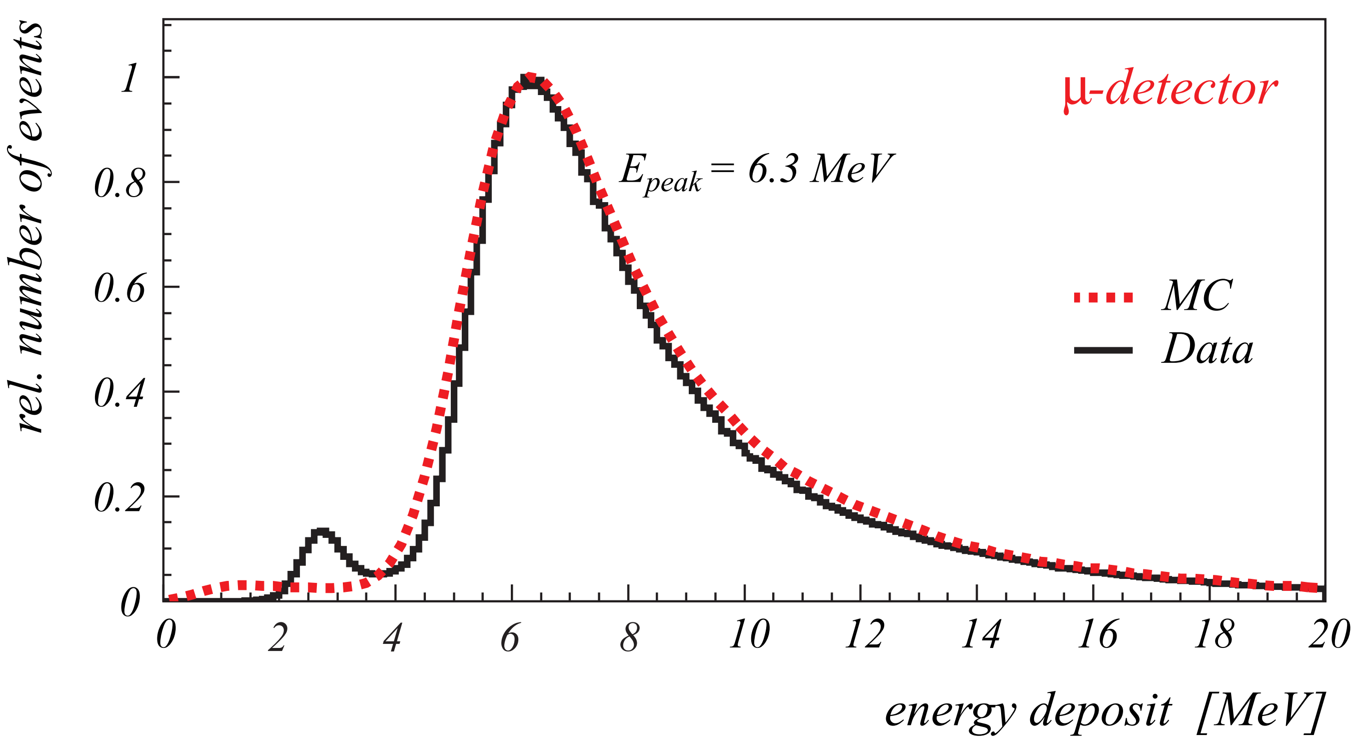


Cross check of detector calibration and simulation

Simulation of inclusive muon flux

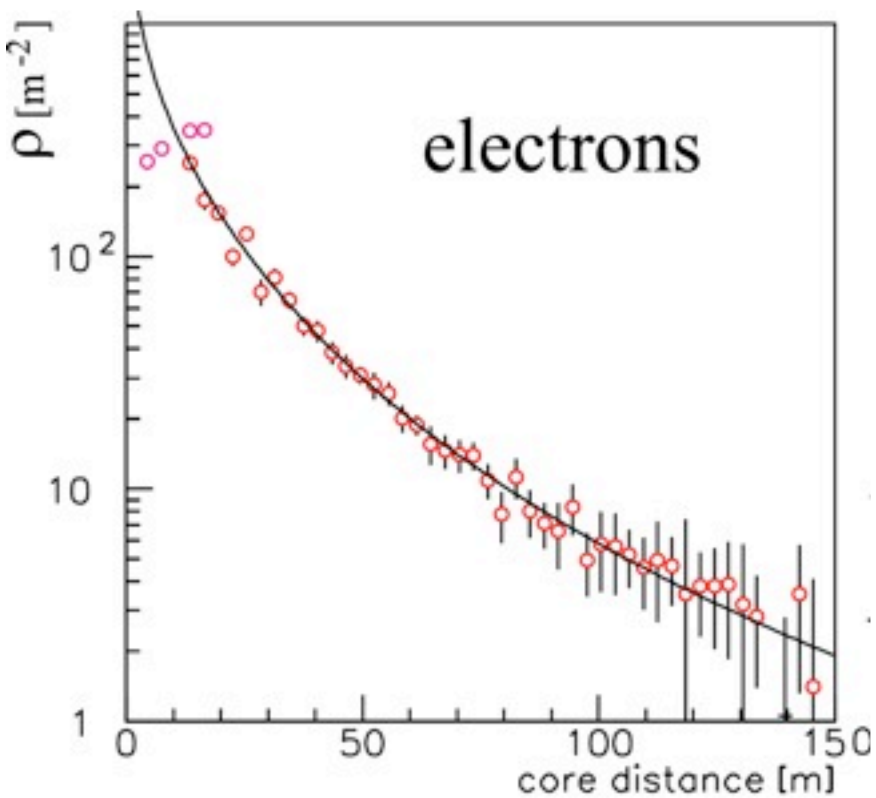
Comparison of muon signal
in data and simulation (no tuning)





Good agreement found

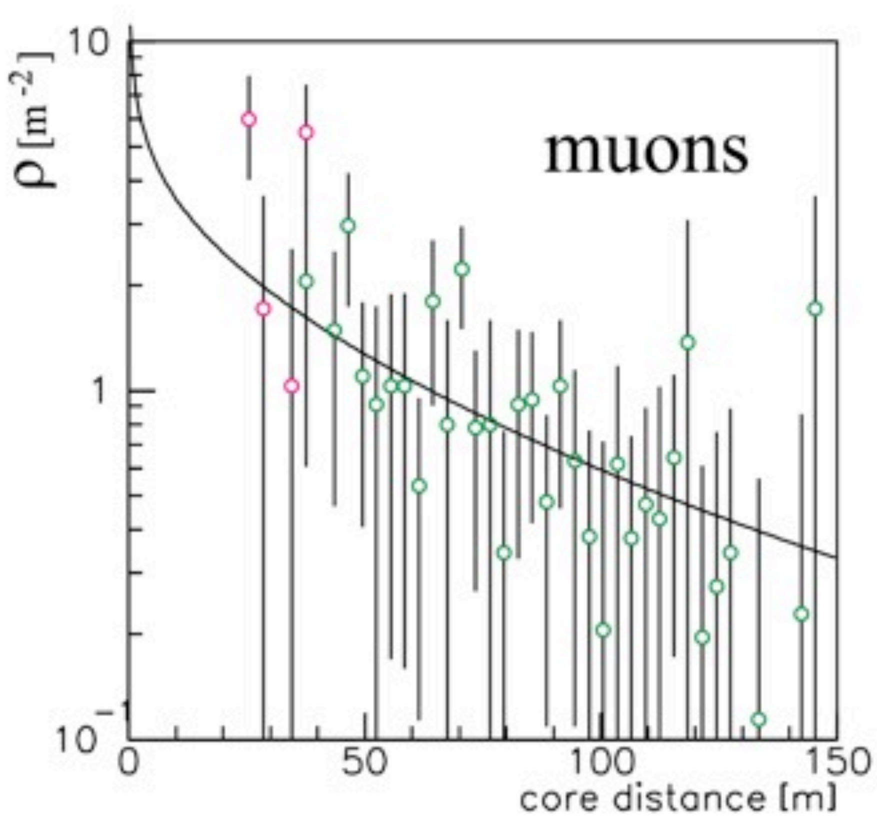
Determination of electron and muon numbers



Modified NKG fit, corrected for E_e > 3 MeV

$$\rho(r) = N_e \cdot c(s) \cdot \left(\frac{r}{r_0}\right)^{s-\alpha} \left(1 + \frac{r}{r_0}\right)^{s-\beta}$$

$$\alpha = 1.5 \qquad \beta = 3.6 \qquad r_0 = 40\,\mathrm{m}$$

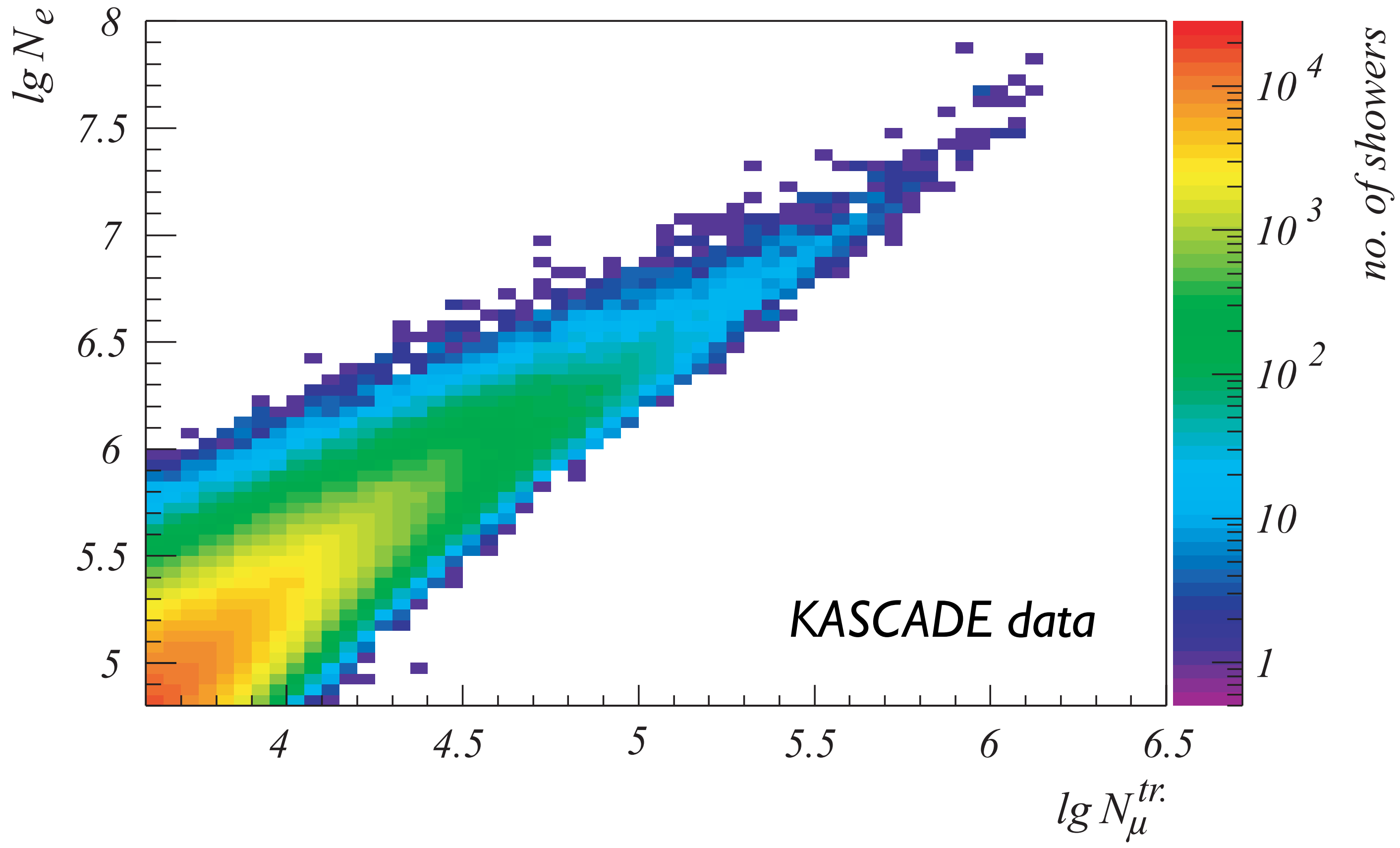


Modified NKG fit, E_μ > 230 MeV

$$\alpha = 1.5 \qquad \beta = 3.7 \qquad r_0 = 420\,\mathrm{m}$$

truncated to 40 - 200m
effective age taken from simulations

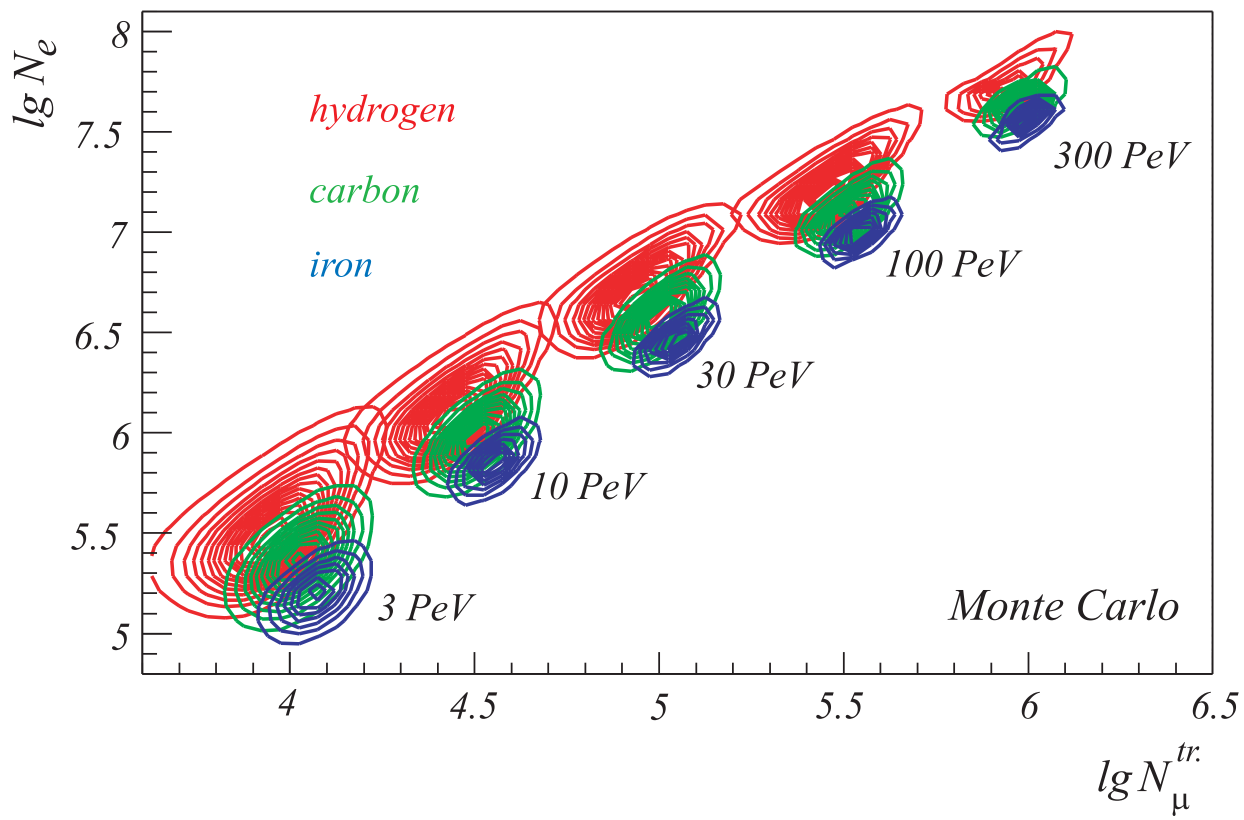
Mass composition as inverse problem (i)



Event selection

- zenith angle θ< 18°
- core R < 91 m from center
- $\lg N_e > 4.8$
- $\lg N_\mu > 3.6$
- reconstruction quality

Mass composition as inverse problem (ii)



Event selection

- zenith angle θ< 18°
- core R < 91 m from center
- $\lg N_e > 4.8$
- $\lg N_\mu > 3.6$
- reconstruction quality

$$N_i = const. \cdot \sum_{A=1}^{N_A} \int_{\theta_1}^{\theta_2} \int_{-\infty}^{+\infty} \frac{dJ_A}{\mathrm{d}\lg E} \times p_A((\lg N_e, \lg N_\mu)_i | \lg E) \times f(\theta) \mathrm{d}\lg E \, \mathrm{d}\theta$$

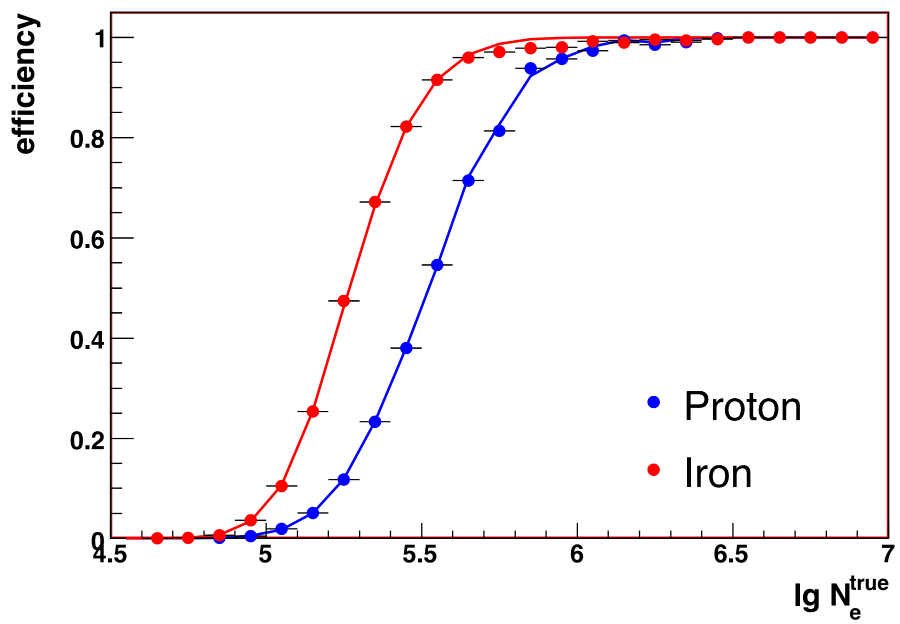
N_i: number of showers in one cell
A: mass number of primary (H, He, C, Si, Fe)
$\frac{dJ_A}{\mathrm{d}\lg E}$: sought-after energy spectrum
p_A: probability to reconstruct sizes $\lg N_e$ and $\lg N_\mu$

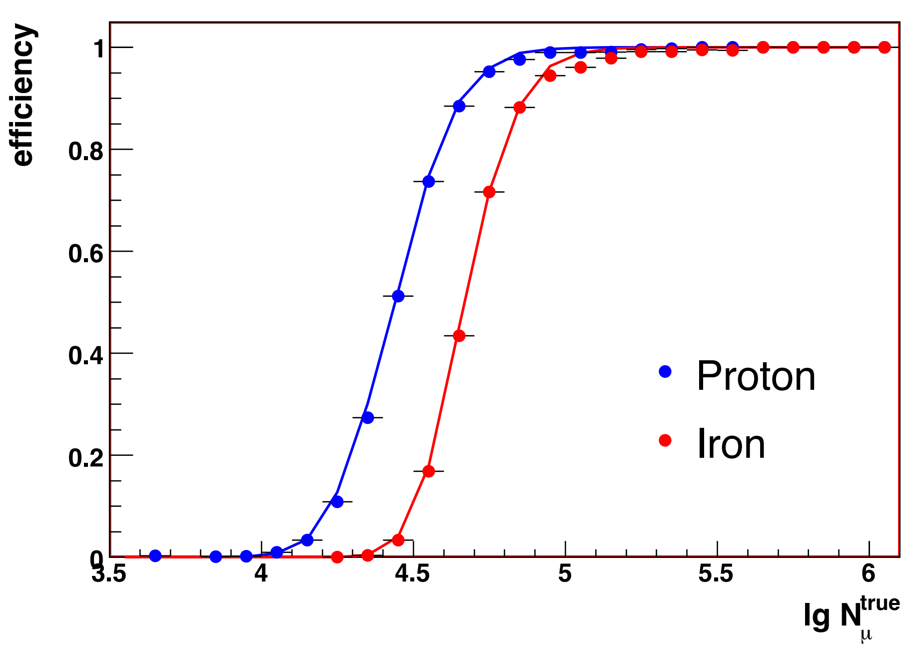
Unfolding done with Gold algorithm

Determination of efficiency and fluctuations

$$N_i = const. \cdot \sum_{A=1}^{N_A} \int_{\theta_1}^{\theta_2} \int_{-\infty}^{+\infty} \frac{dJ_A}{\mathrm{dlg}E} \times p_A((\lg N_e, \lg N_\mu)_i | \lg E) \times f(\theta) \mathrm{dlg}E \, \mathrm{d}\theta$$

Efficiencies





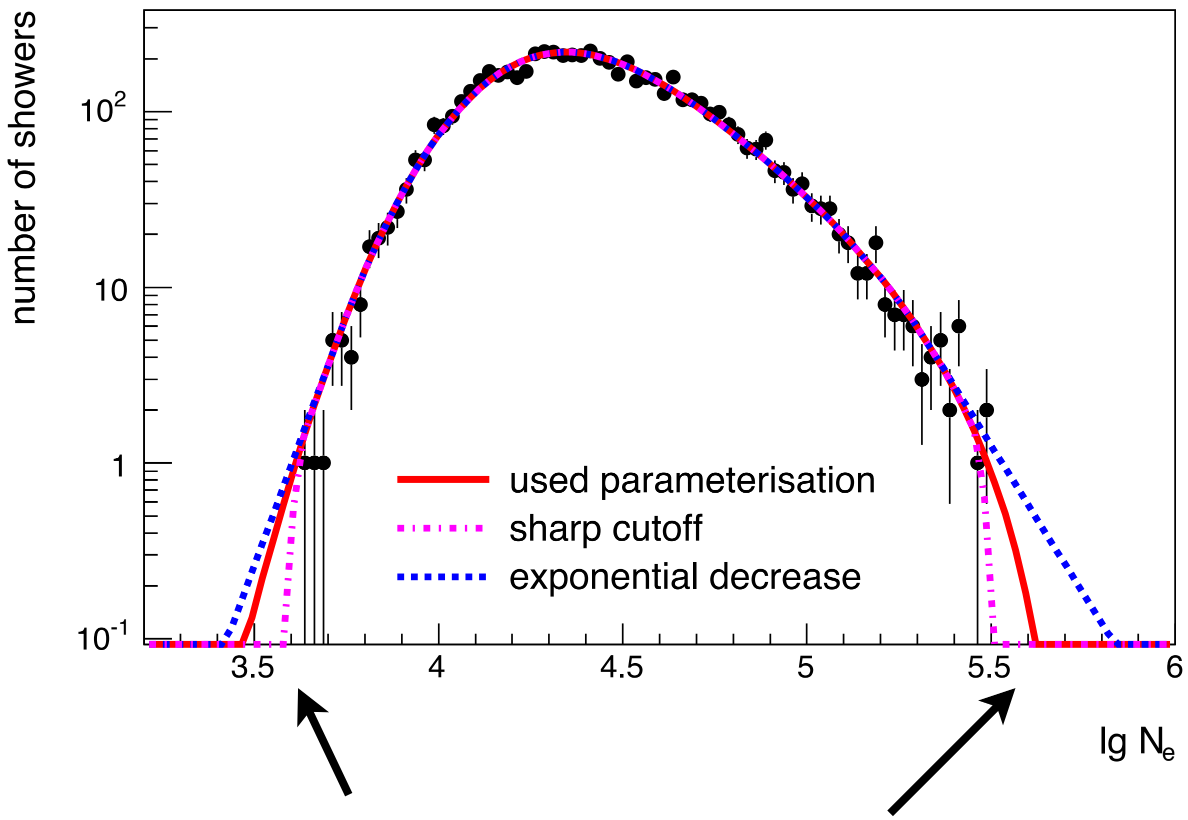
$$p_A = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} s_A \epsilon_A r_A \, \mathrm{dlg} N_e^{true} \mathrm{dlg} N_\mu^{true}$$

s_A: shower fluctuations

ϵ_A: efficiencies

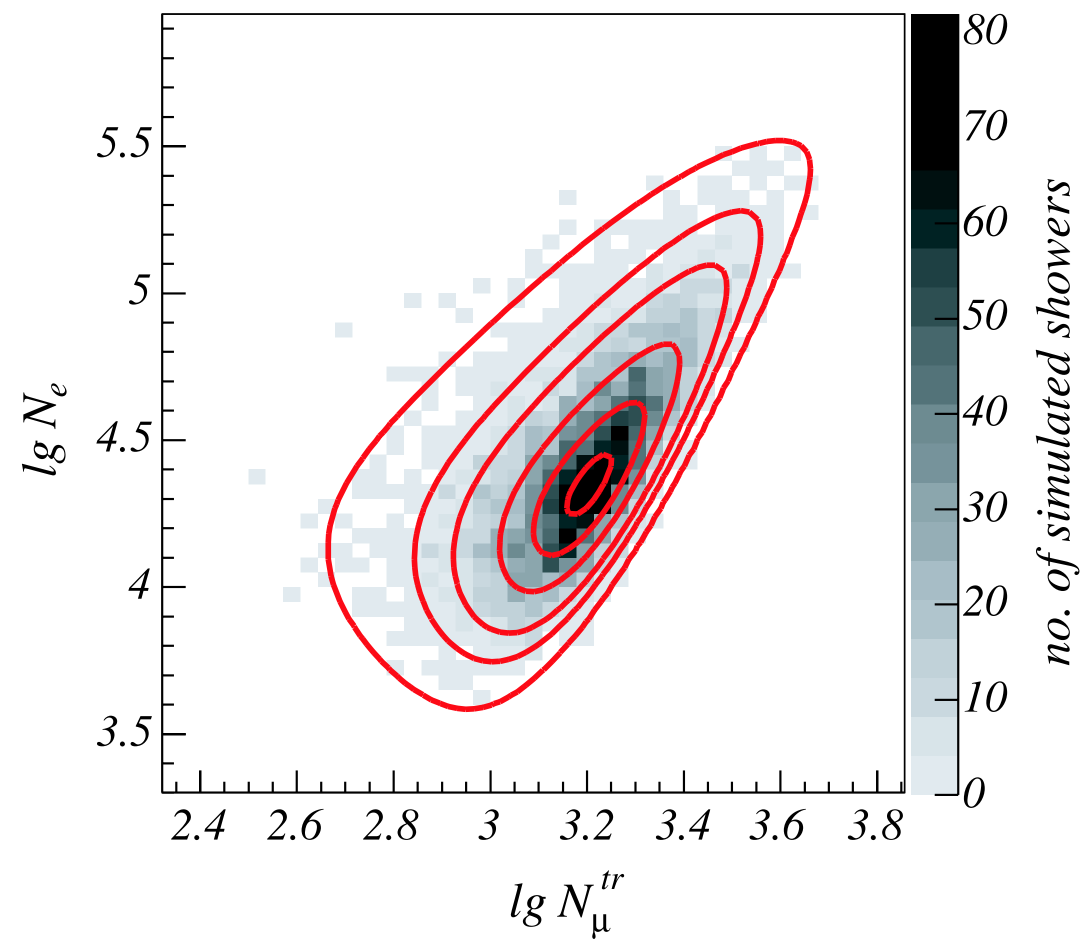
r_A: reconstruction uncertainties

Parametrization of fluctuations



Extrapolation very important for systematic uncertainties

Two-dimensional distribution !

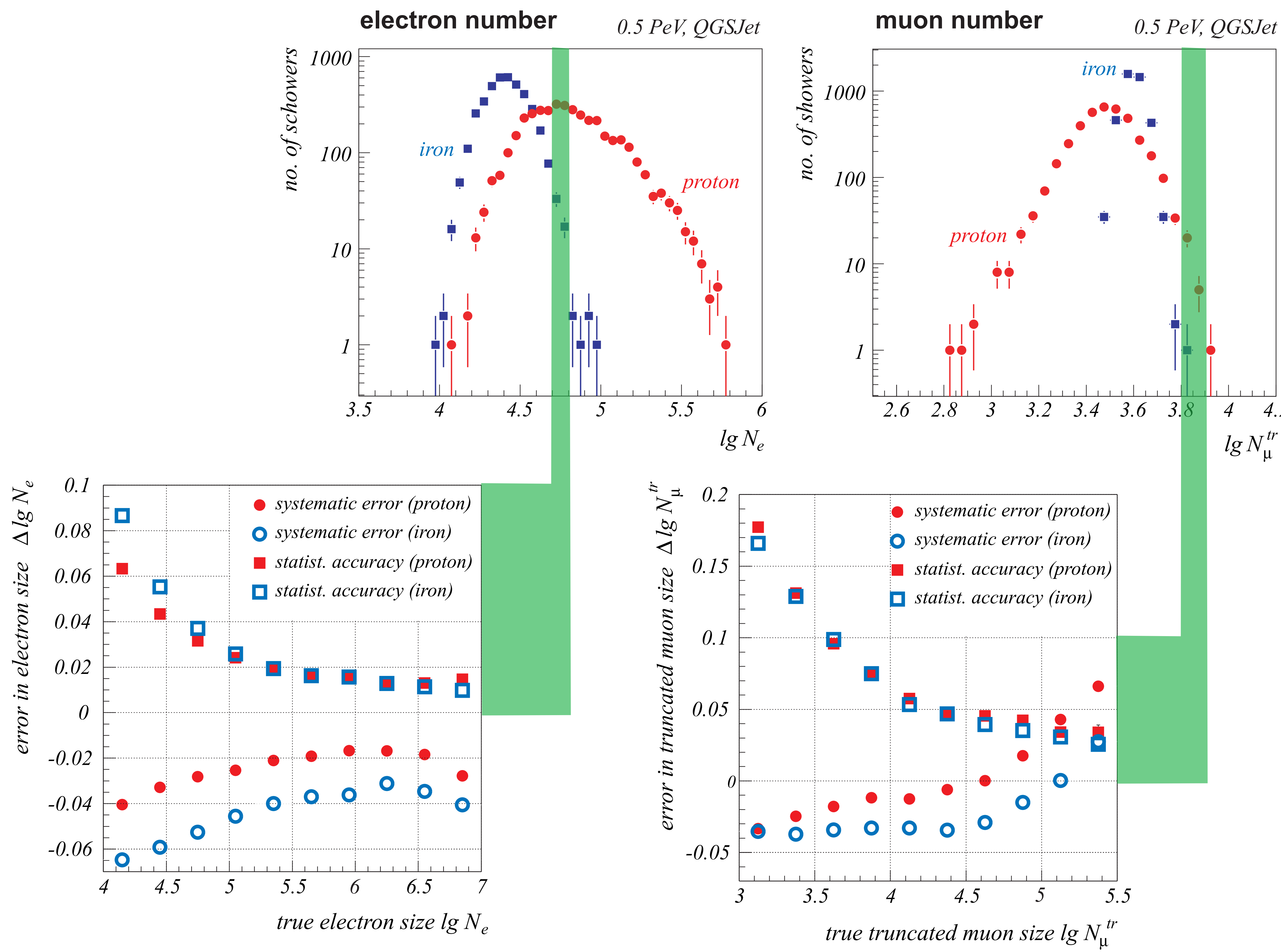


Parametrization of effciency with fully simulated showers (no thinning)

Parametrization of fluctuations

- large statistics simulation, thinned showers
- fixed energies (E = 0.1 0.5, 2, 5, 10, 30, 100, 300, 1000, 3000 PeV)

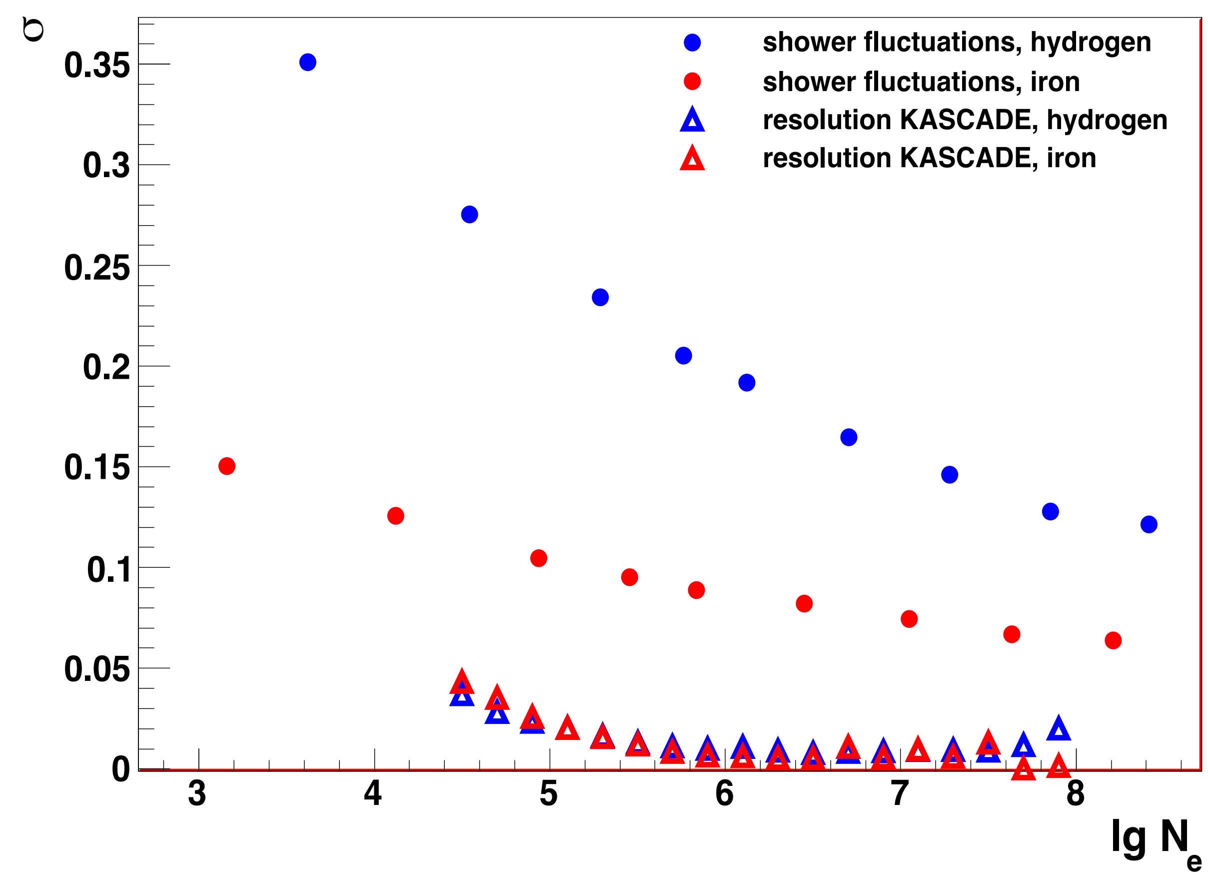
Estimated reconstruction uncertainty



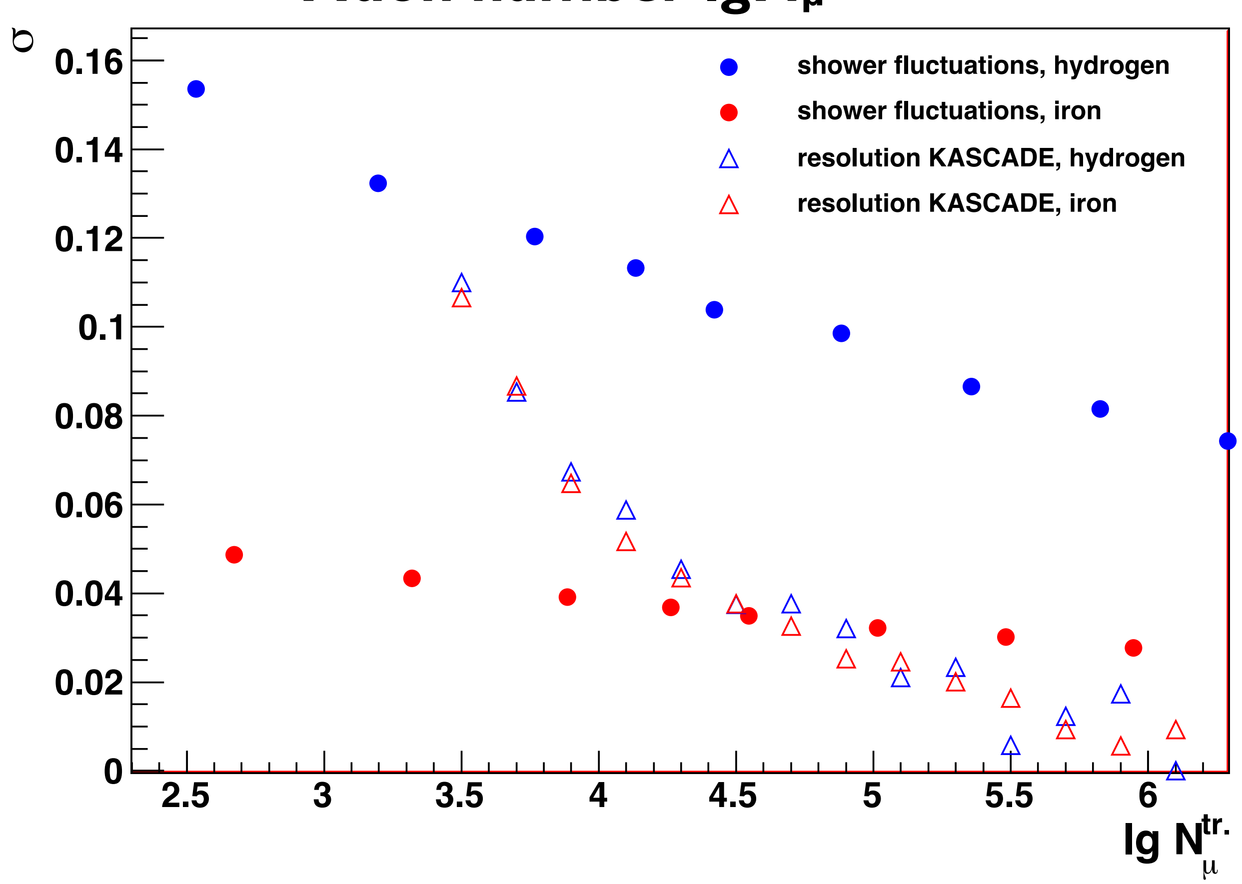
Contributions to overall fluctuations

RMS calculated for quantifying fluctuations, done for comparison only

Electron number lgN_e



Muon number lgN_μ



Electrons: shower-to-shower fluctuations dominating

Muons: both contributions important

KASCADE analysis with QGSJET and SIBYLL

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Astroparticle Physics 24 (2005) 1–25

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KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems

T. Antoni [a], W.D. Apel [b], A.F. Badea [b,1], K. Bekk [b], A. Bercuci [c], J. Blümer [b,a], H. Bozdog [b], I.M. Brancus [c], A. Chilingarian [d], K. Daumiller [b], P. Doll [b], R. Engel [b], J. Engler [b], F. Feßler [b], H.J. Gils [b], R. Glasstetter [a,2], A. Haungs [b], D. Heck [b], J.R. Hörandel [a], K.-H. Kampert [a,b,2], H.O. Klages [b], G. Maier [b,3], H.J. Mathes [b], H.J. Mayer [b], J. Milke [b], M. Müller [b], R. Obenland [b], J. Oehlschläger [b], S. Ostapchenko [b,4], M. Petcu [c], H. Rebel [b], A. Risse [e], M. Risse [b], M. Roth [a], G. Schatz [b], H. Schieler [b], J. Scholz [b], T. Thouw [b], H. Ulrich [b,*], J. van Buren [b], A. Vardanyan [d], A. Weindl [b], J. Wochele [b], J. Zabierowski [e]

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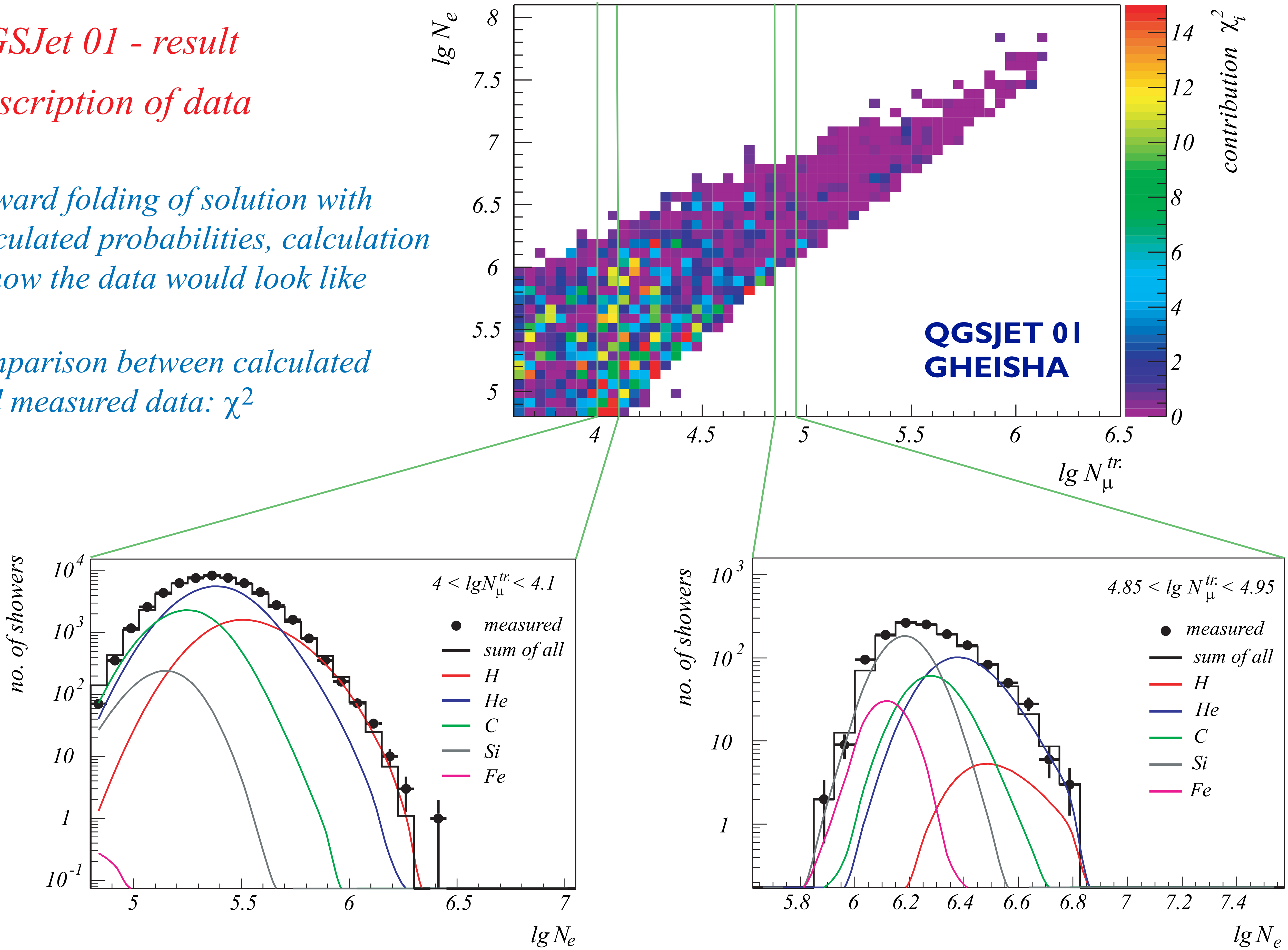
[b] *Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany*
[c] *National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania*
[d] *Cosmic Ray Division, Yerevan Physics Institute, Yerevan 36, Armenia*
[e] *Soltan Institute for Nuclear Studies, 90950 Lodz, Poland*

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

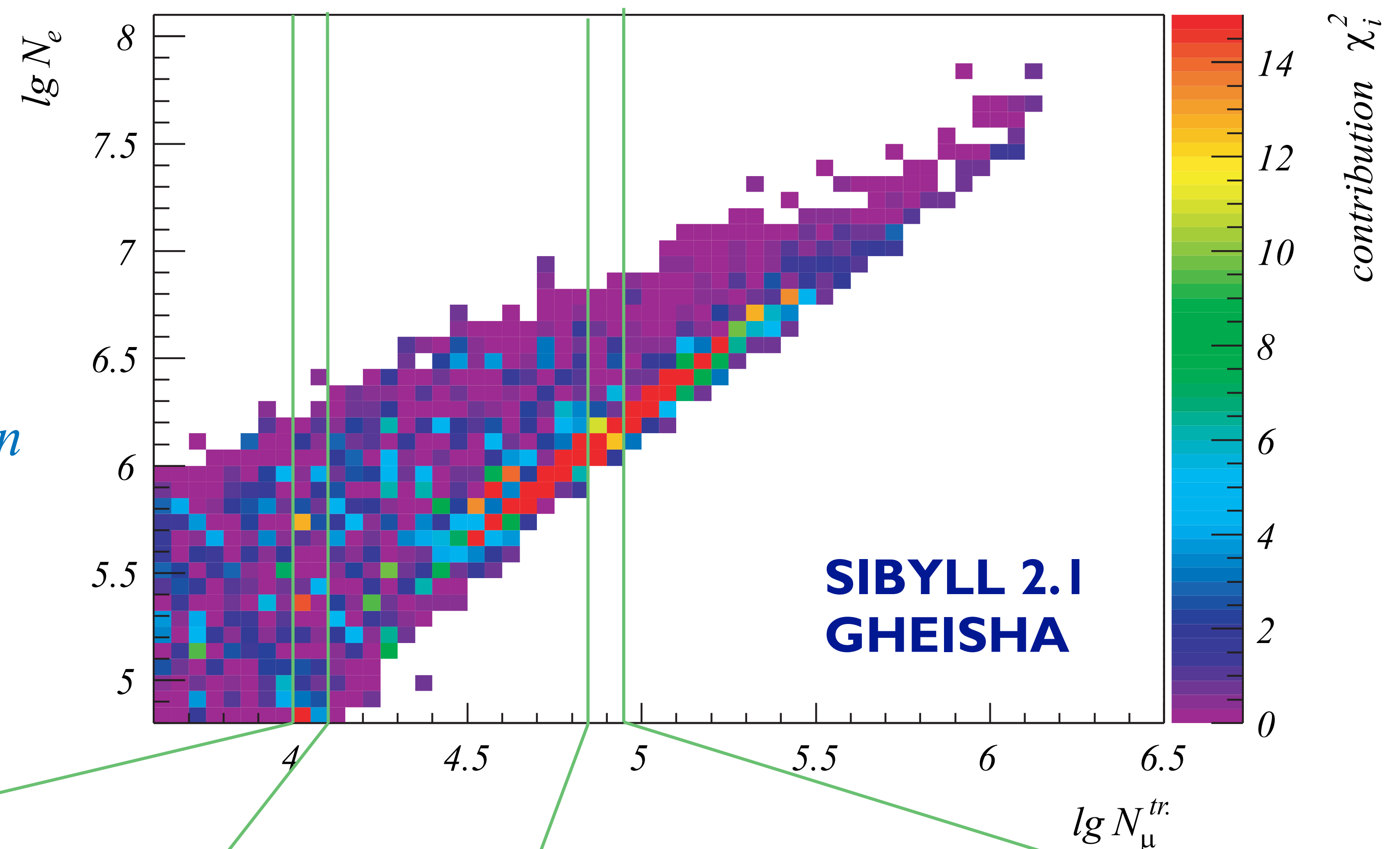


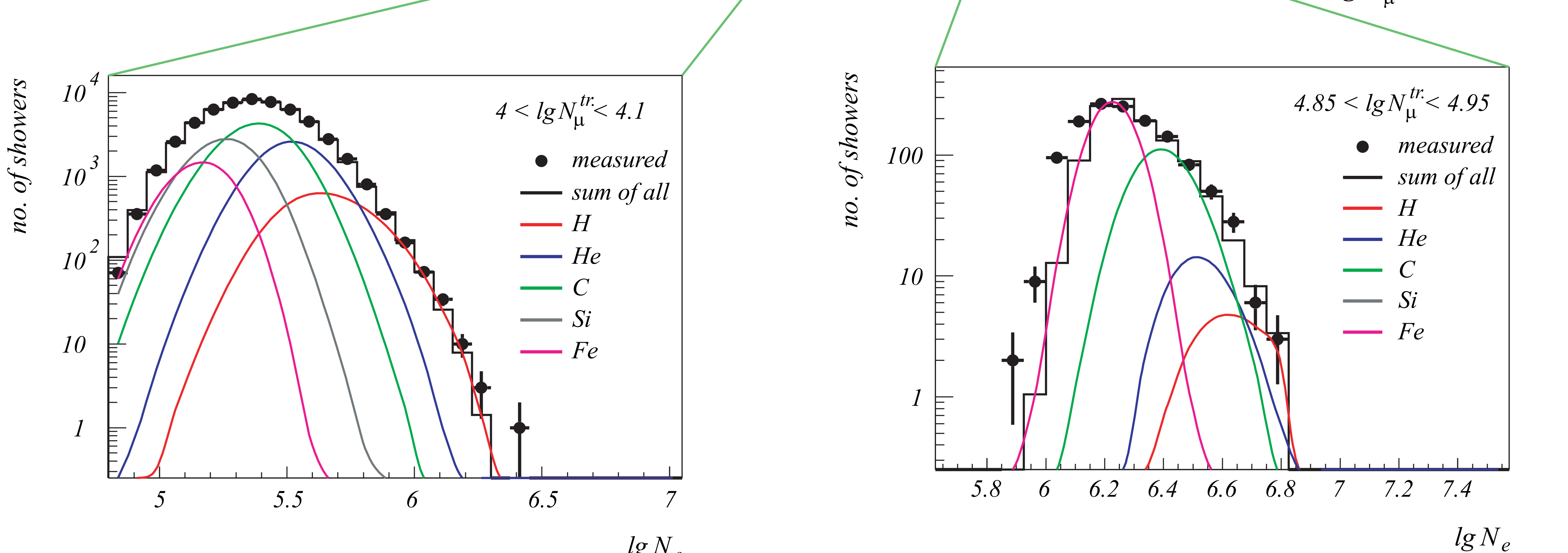
SIBYLL 2.1 - result

Description of data

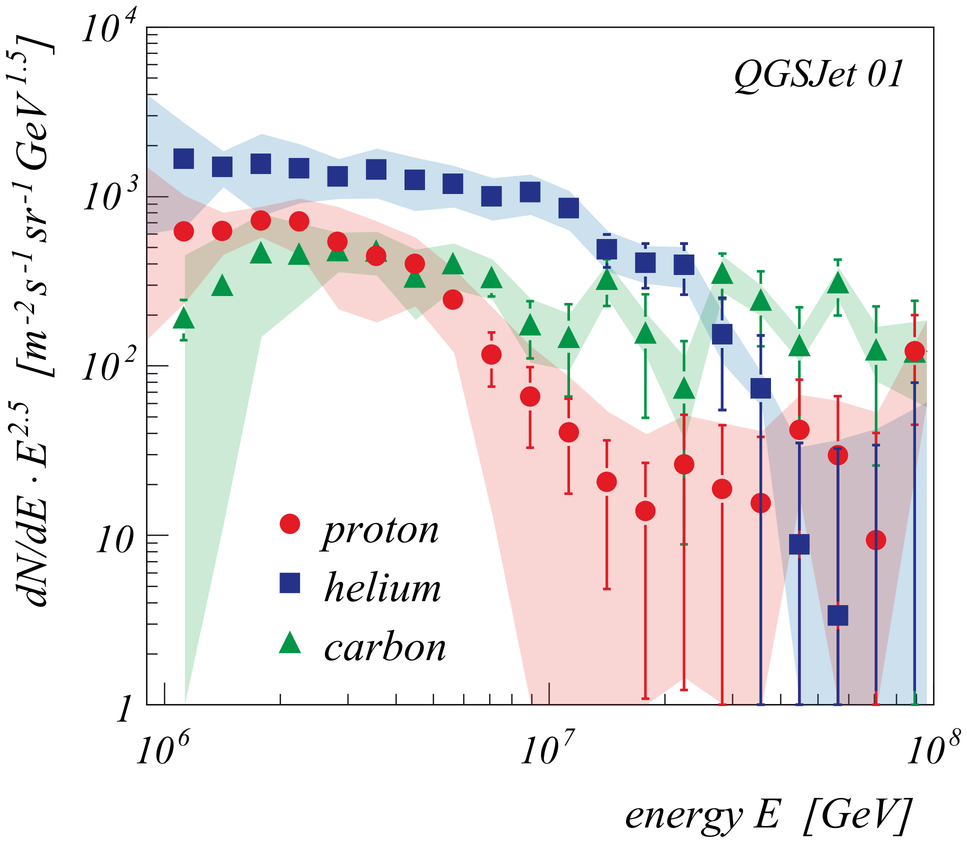
forward folding of solution with calculated probabilities, calculation of how the data would look like

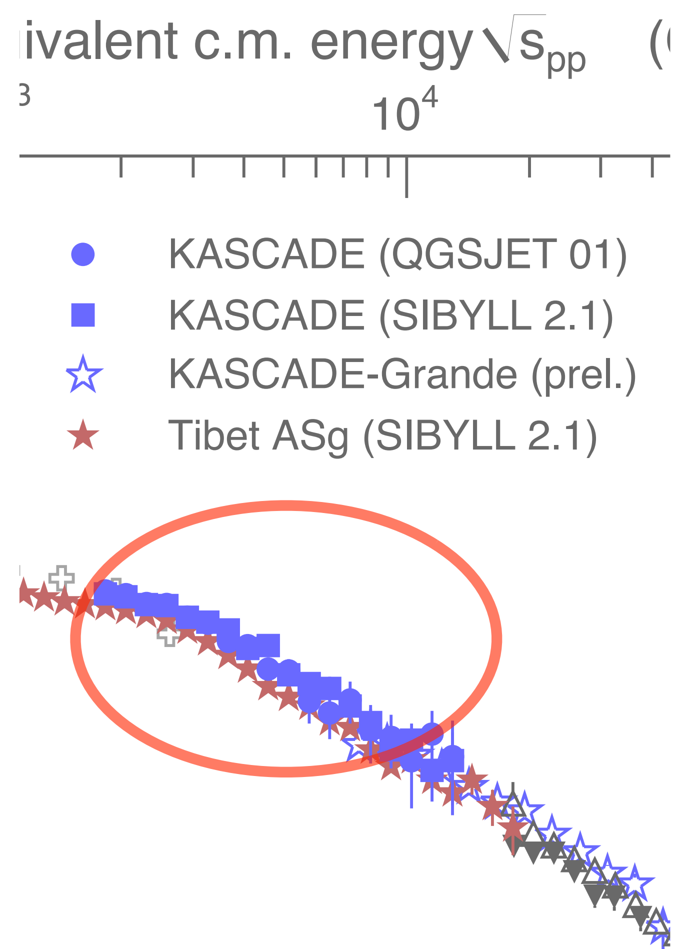
comparison between calculated and measured data: χ^2

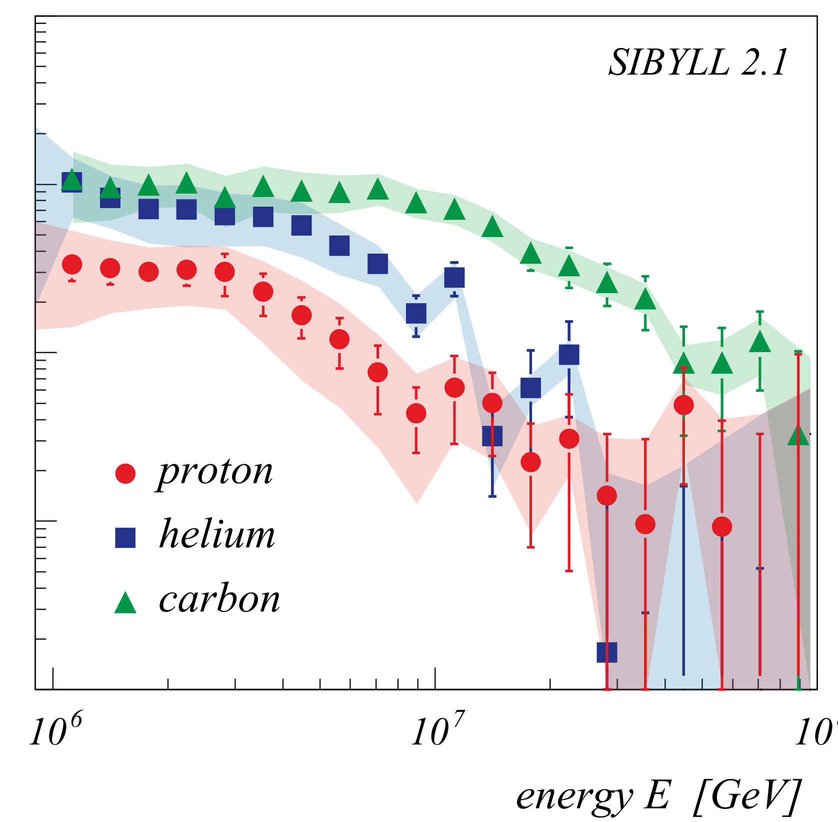


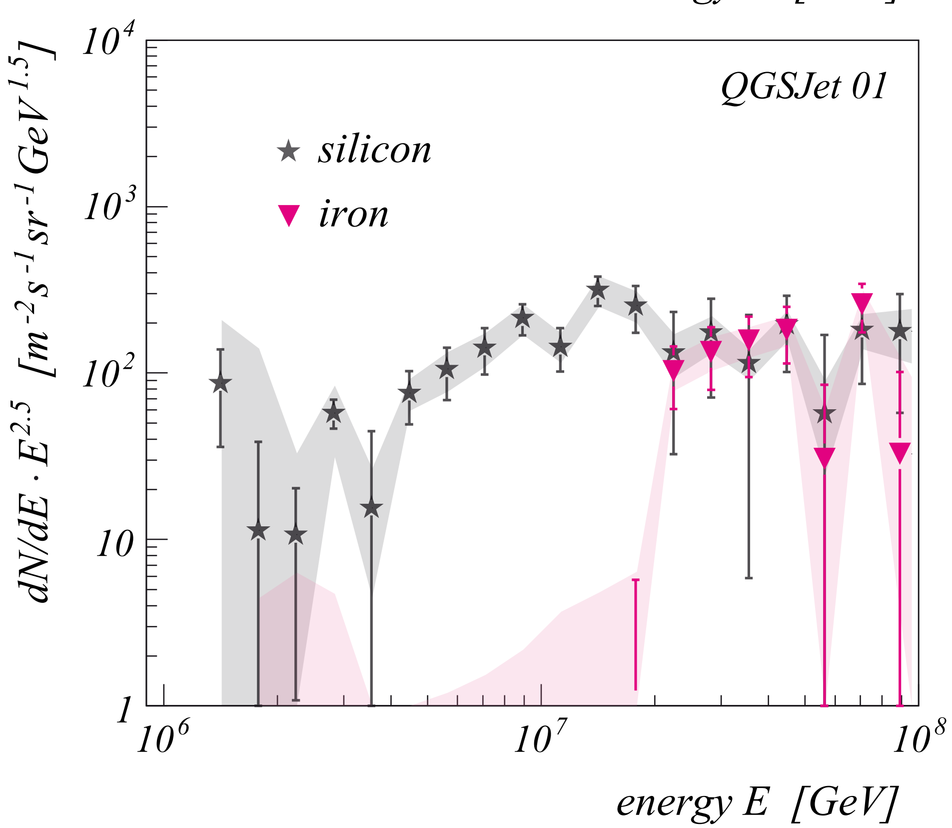


KASCADE: Composition in knee region (2005)

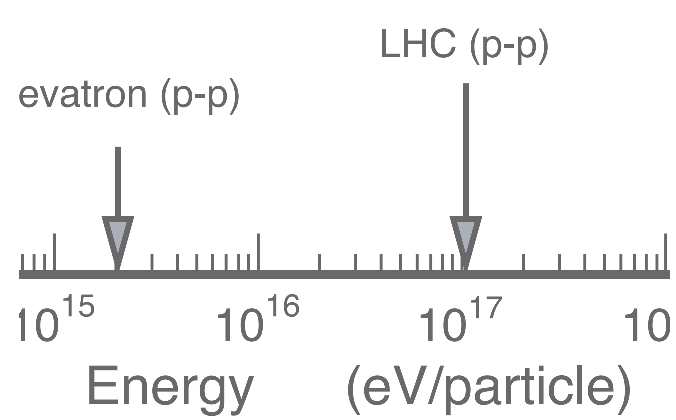


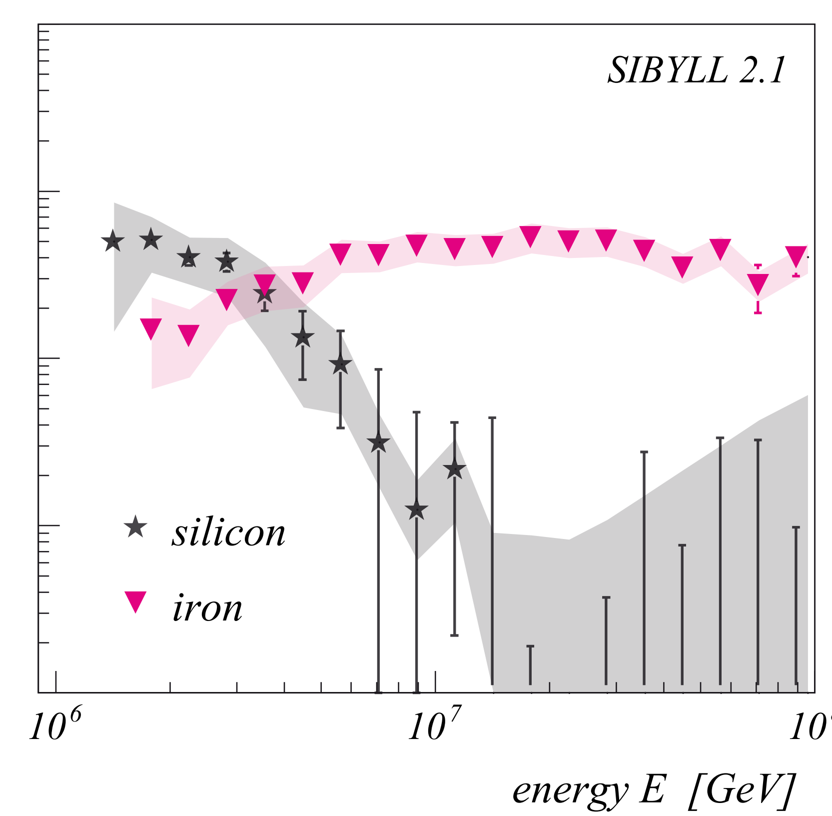






KASCADE Collab.
Astropart. Phys. 24 (2005) 1

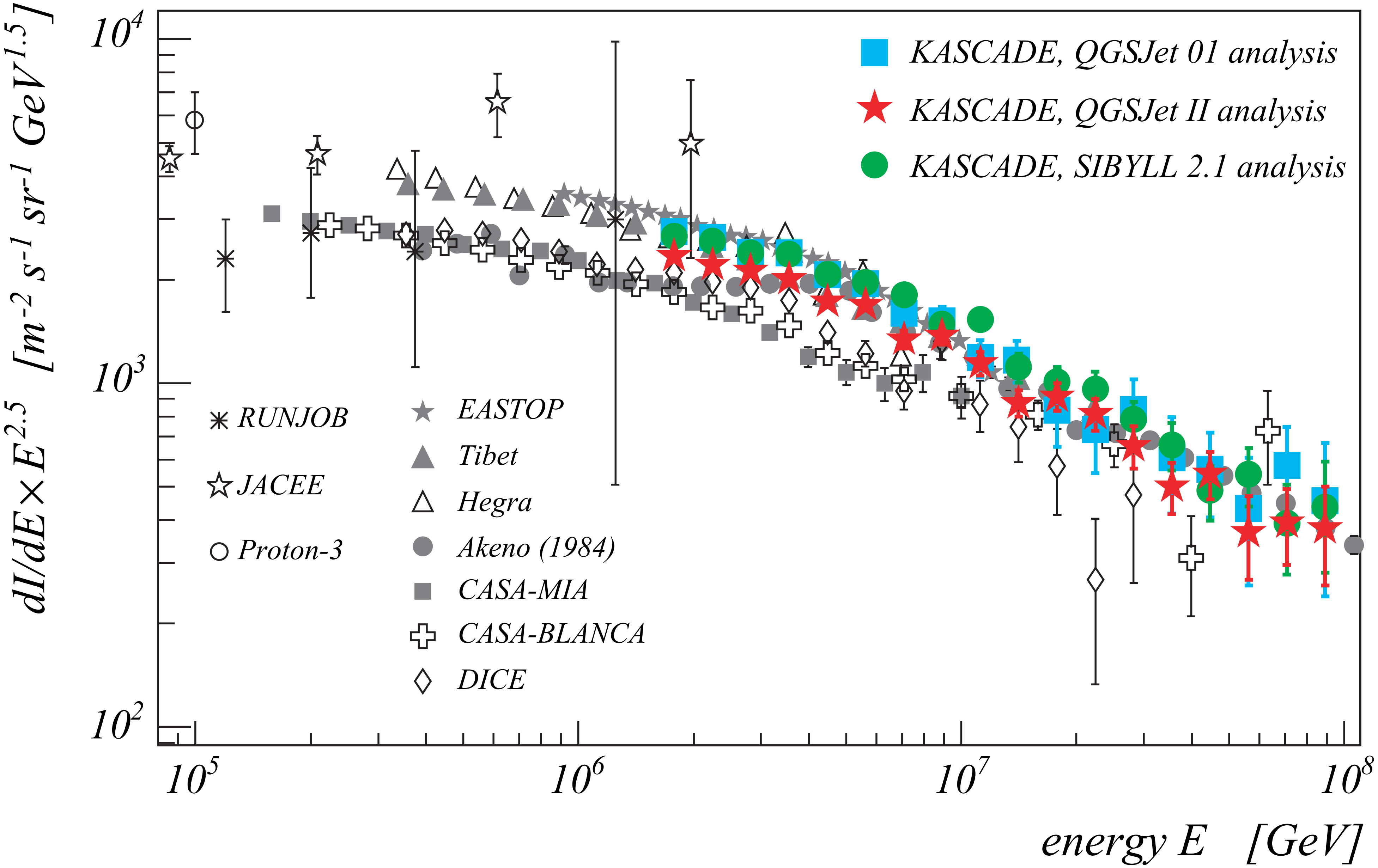




KASCADE all-particle spectrum (2005)

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

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



(Ulrich et al., C2CR 2005)

New analysis of KASCADE data (2010)

- Same analysis methods
- Same unfolding algorithm, but stop criterium optimized
- Higher statistics in data
- New version of CORSIKA
- New low-energy model (E_{lab} < 80 GeV) FLUKA
- New versions of QGSJET and EPOS

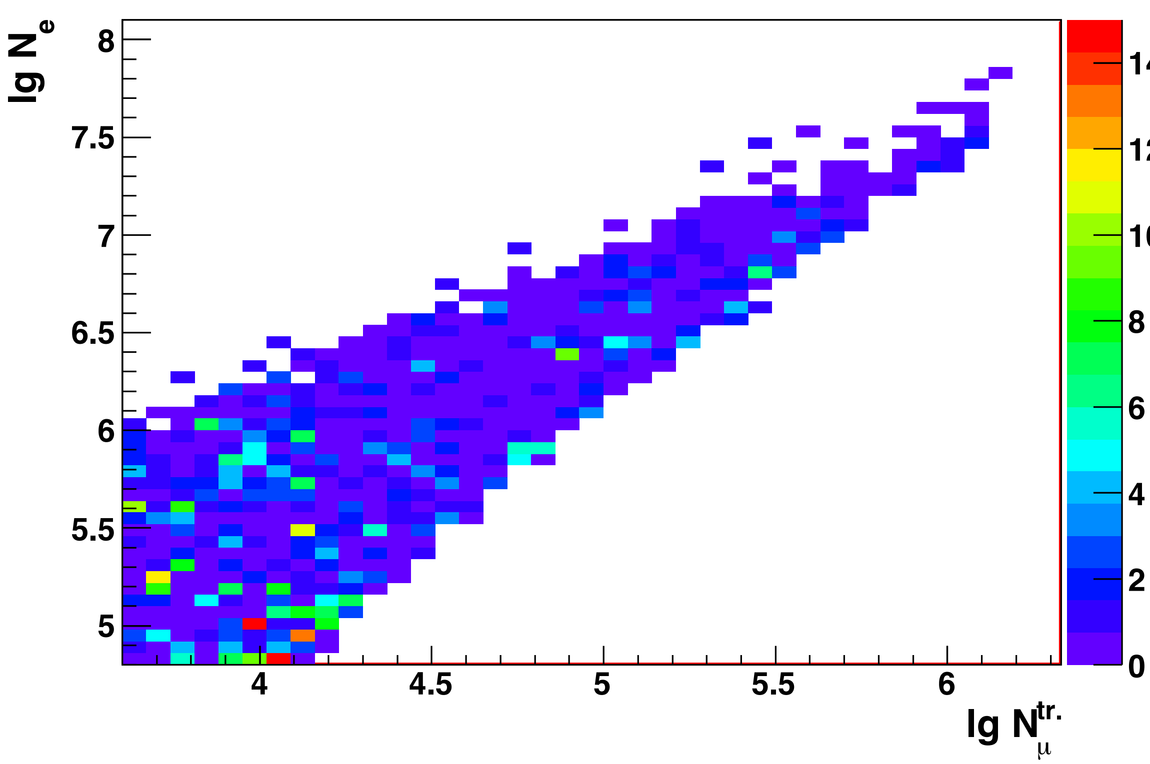
Results preliminary, work in progress

Main contributers

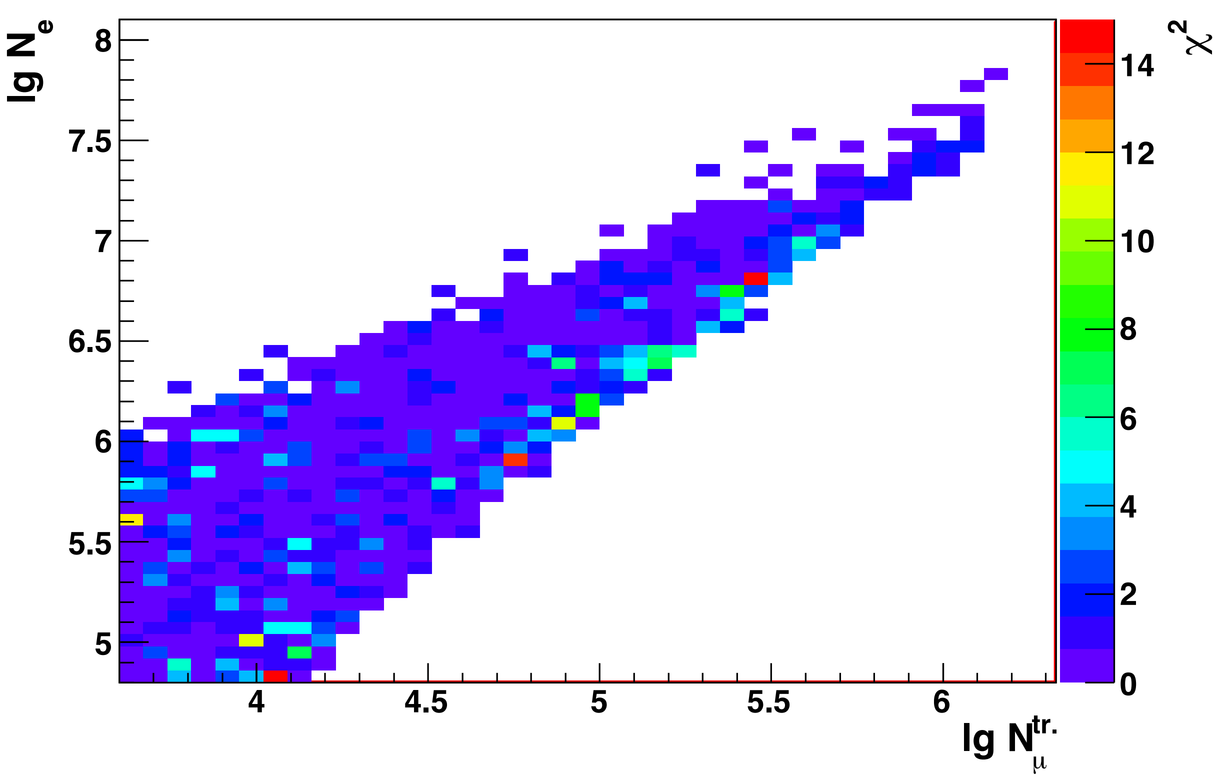
2005: Holger Ulrich, see PhD thesis and Astropat. Phys. 24 (2005) 1
2010: Marcel Finger, PhD thesis in preparation

KASCADE data vs. QGSJET 01 and QGSJET II

QGSJET01



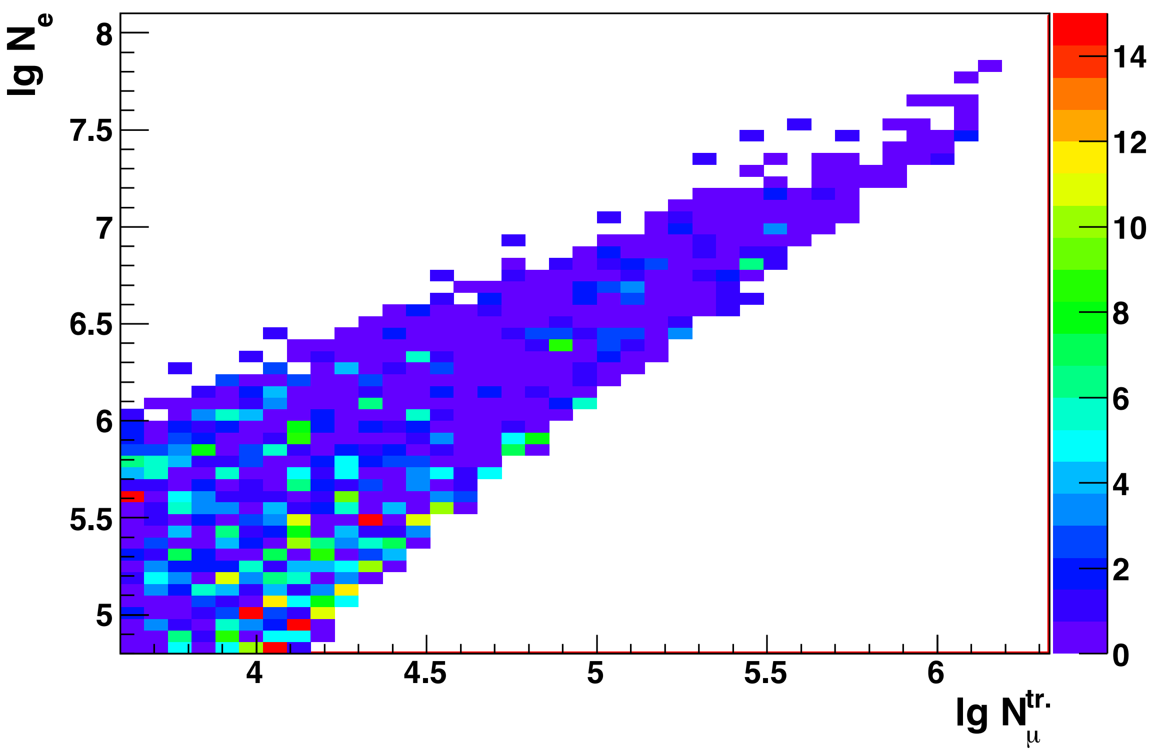
QGSJETII



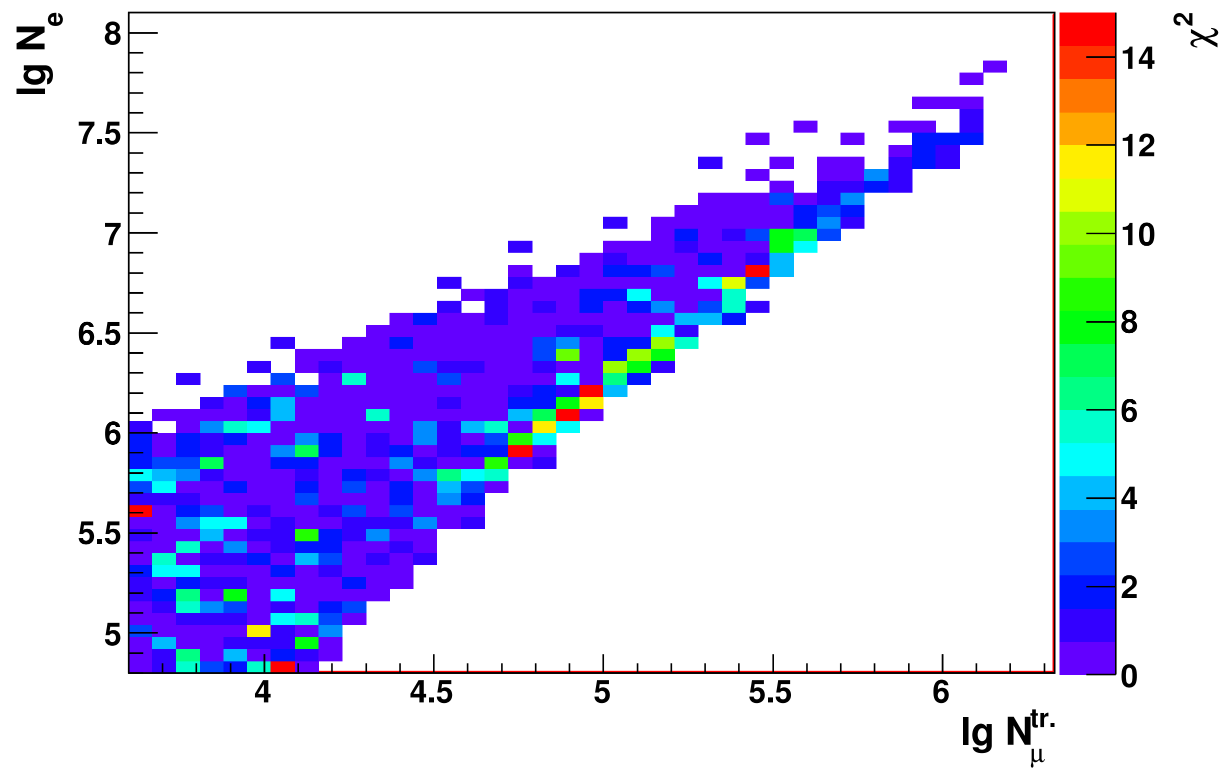
- $\chi_i^2 = \frac{(N_i^{meas.} - N_i^{rec.})^2}{\sigma_i^2}$
- $\chi^2/ndf = 1.29$ for QGSJETII and 1.34 for QGSJET01

KASCADE data vs. EPOS 1.99 and SIBYLL

EPOS1.99



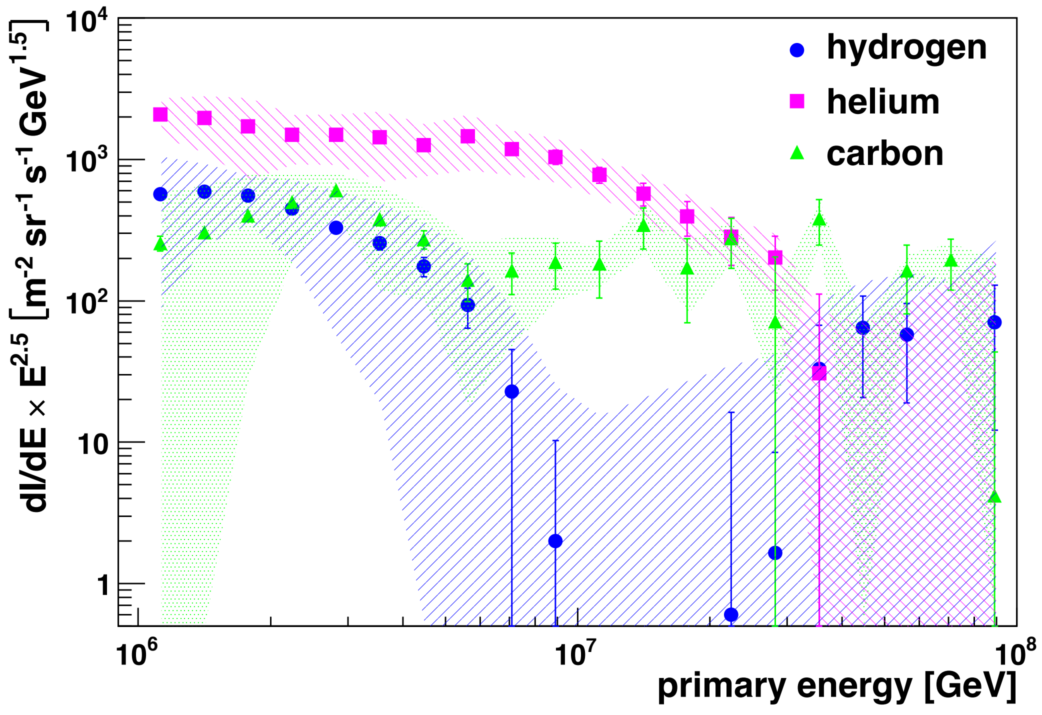
SIBYLL

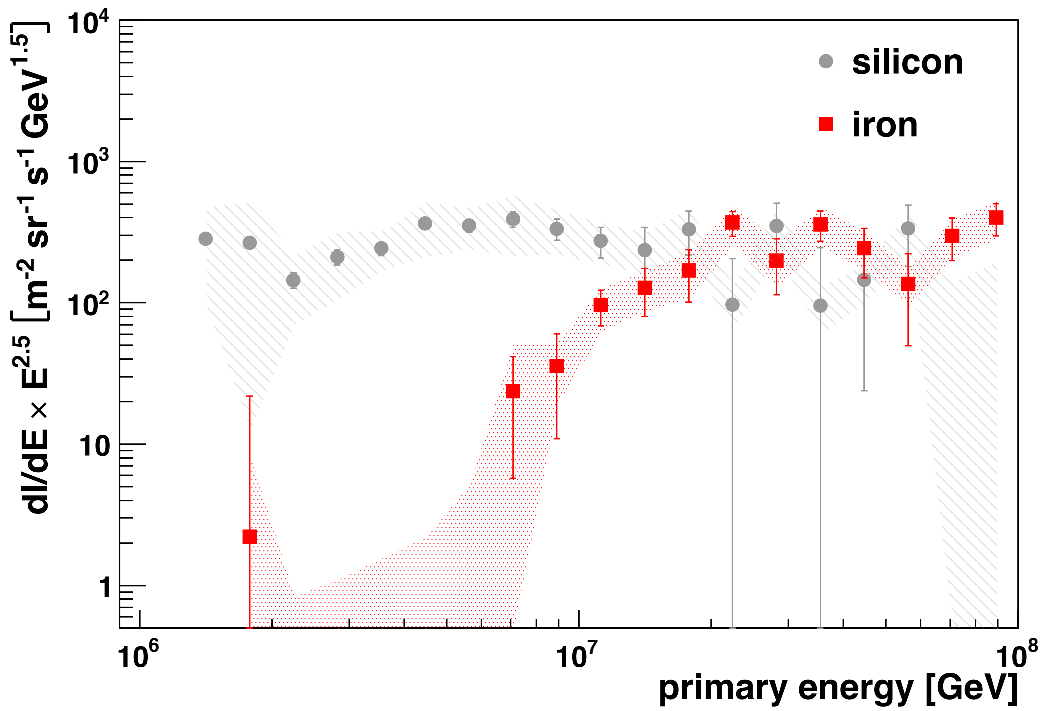


- $\chi_i^2 = \frac{(N_i^{meas.} - N_i^{rec.})^2}{\sigma_i^2}$
- $\chi^2/ndf = 1.79$ for EPOS1.99 and 1.77 for SIBYLL

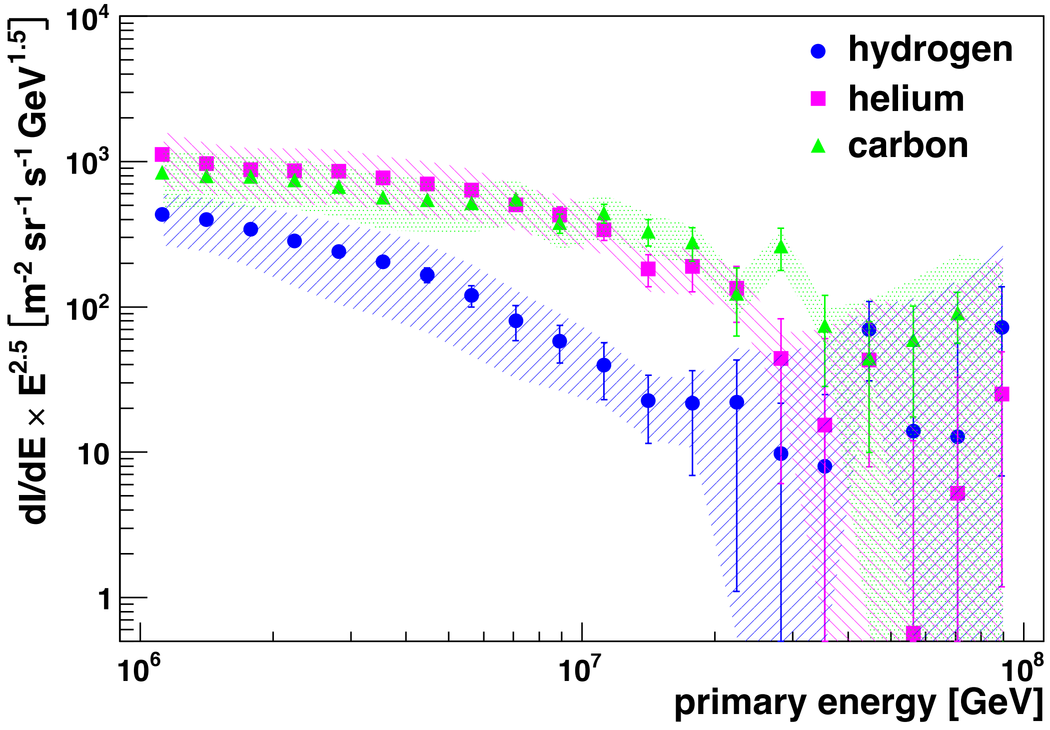
KASCADE: Composition in knee region (2010)

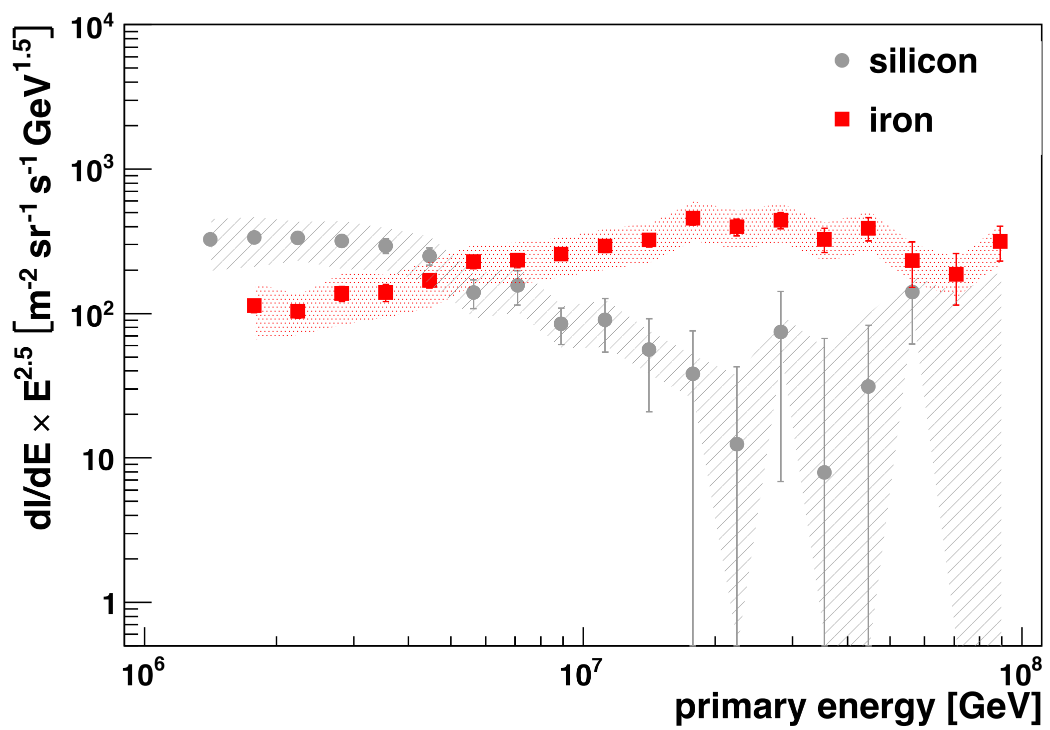
QGSJET 01 / FLUKA





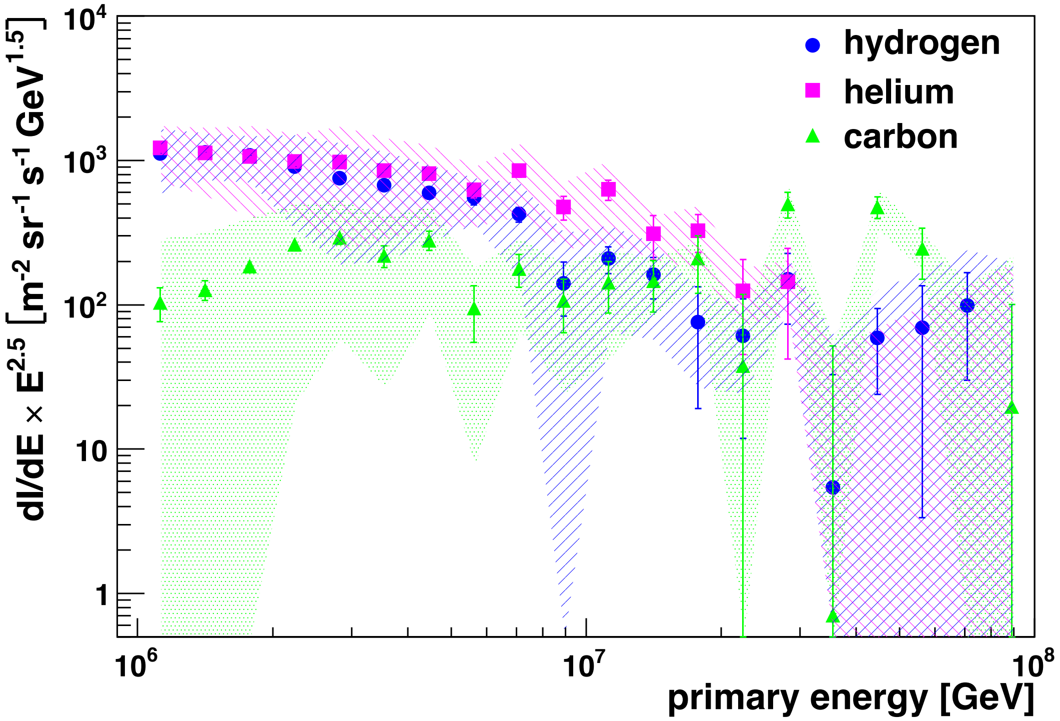
QGSJET II.03 / FLUKA



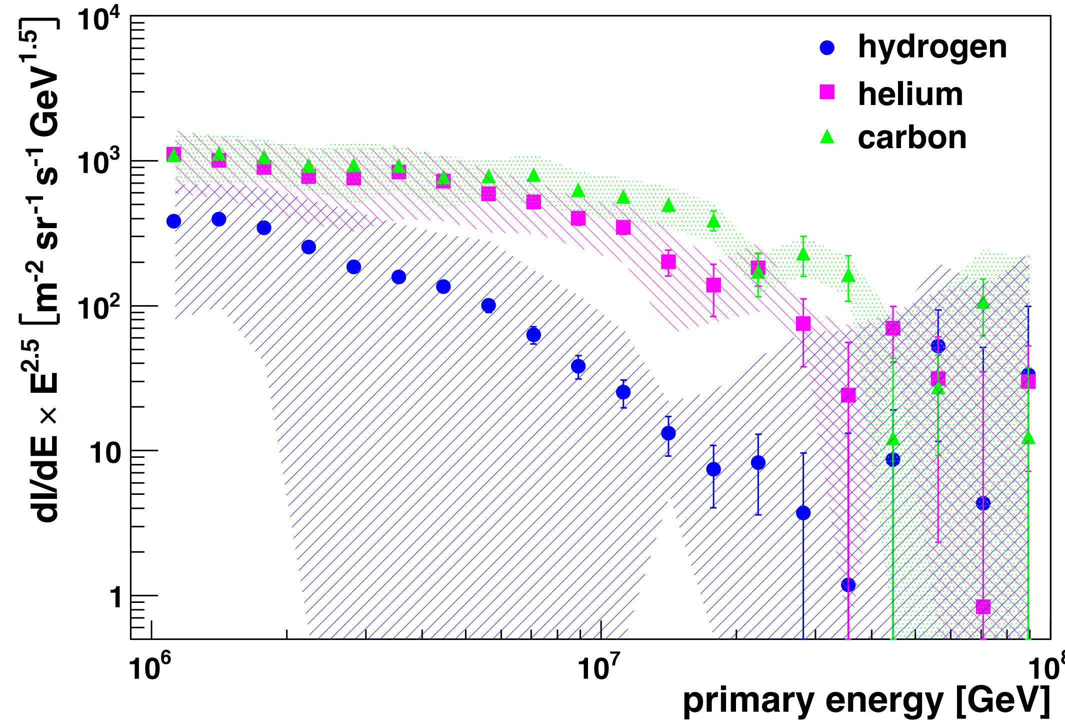


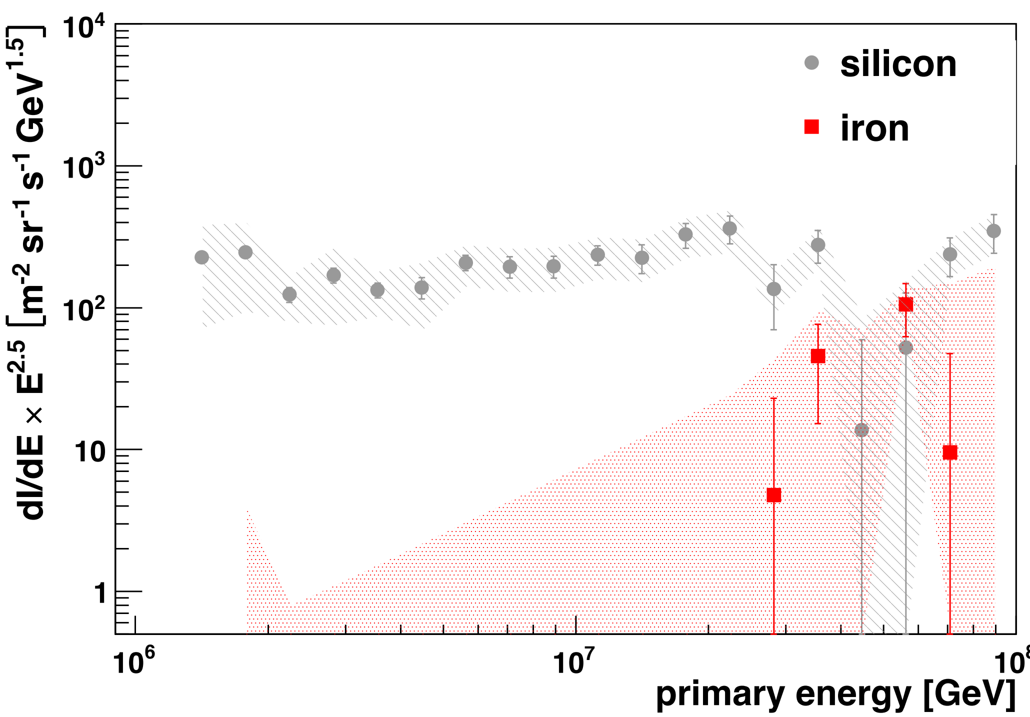
KASCADE: Composition in knee region (2010)

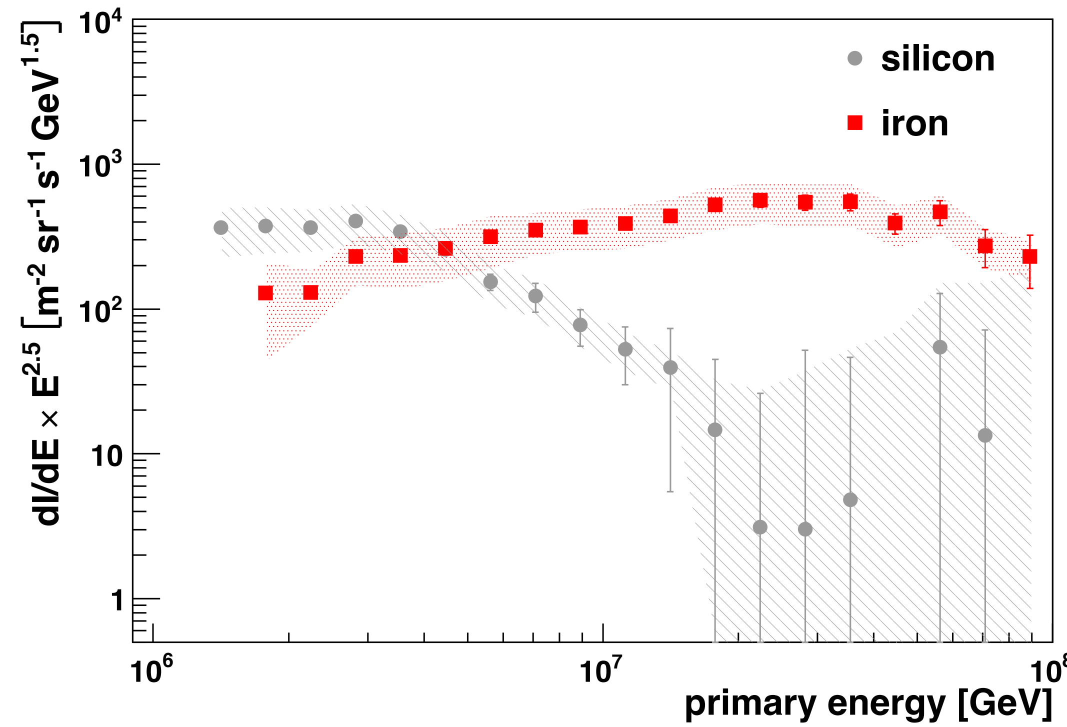
EPOS 1.99 / FLUKA



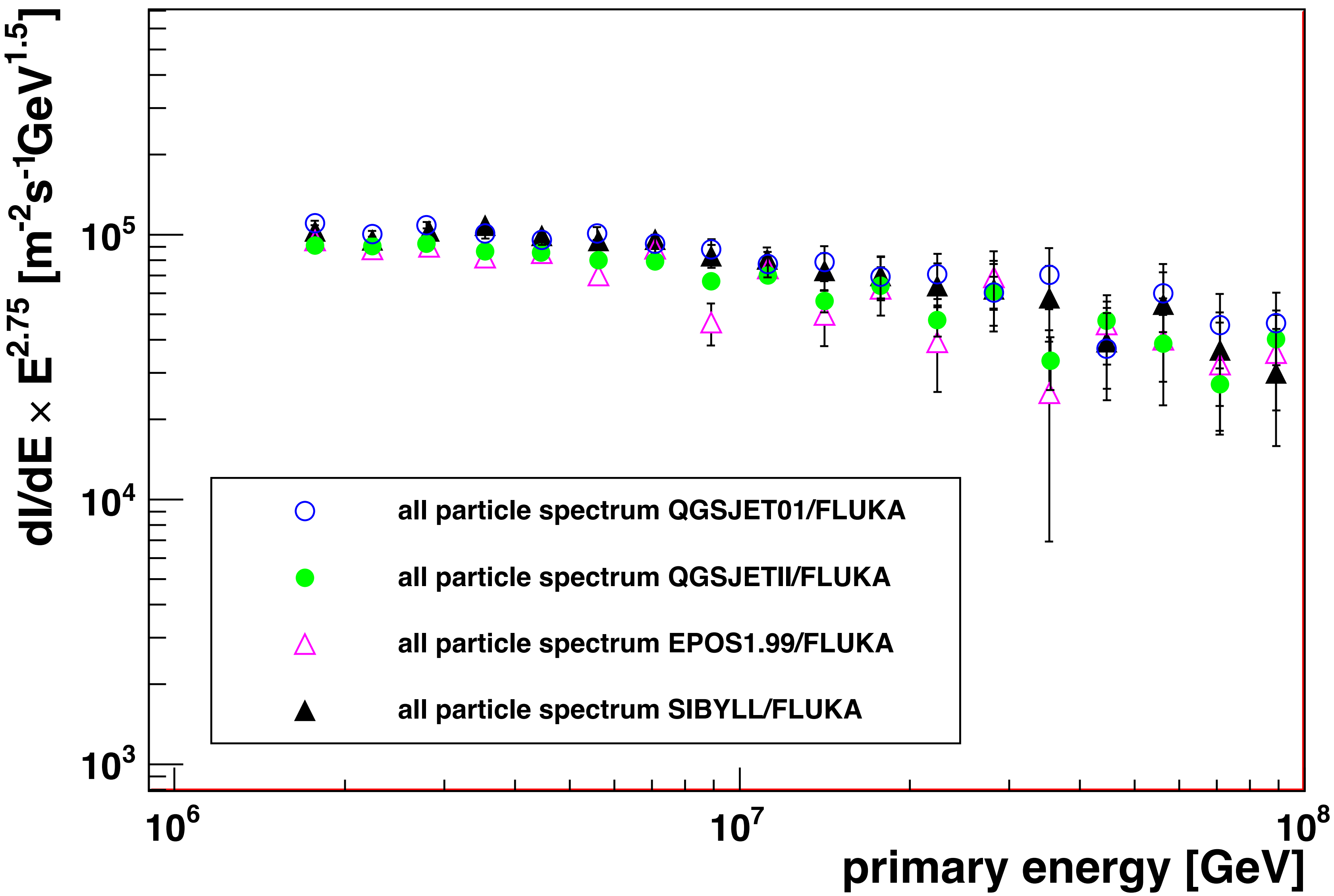
SIBYLL 2.1 / FLUKA







KASCADE all-particle spectrum (2010)



Results preliminary, work in progress

Good agreement between different spectra,
some difference between EPOS and other models found

KASCADE-Grande Collaboration

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June 2010