Status of Air Shower Simulations

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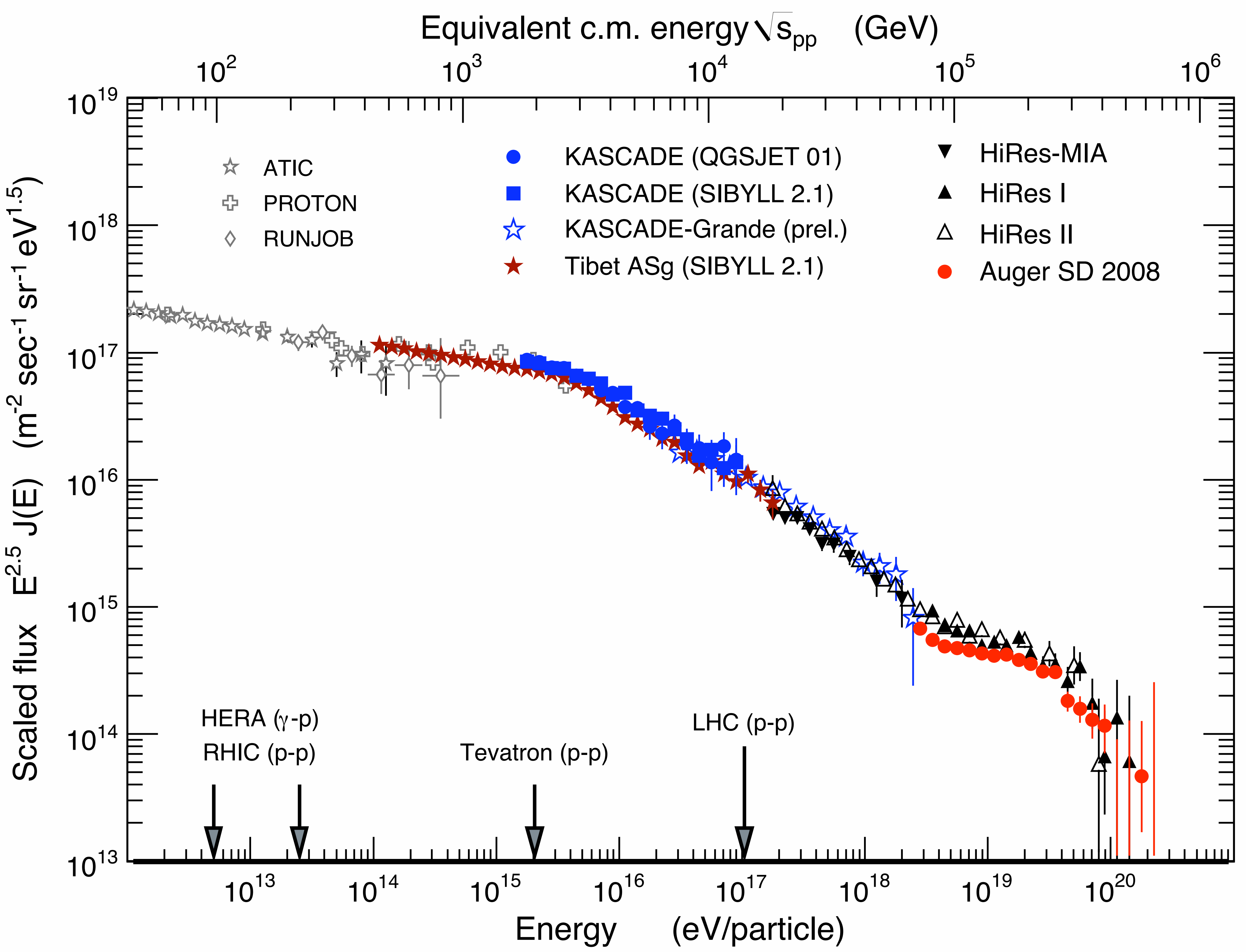
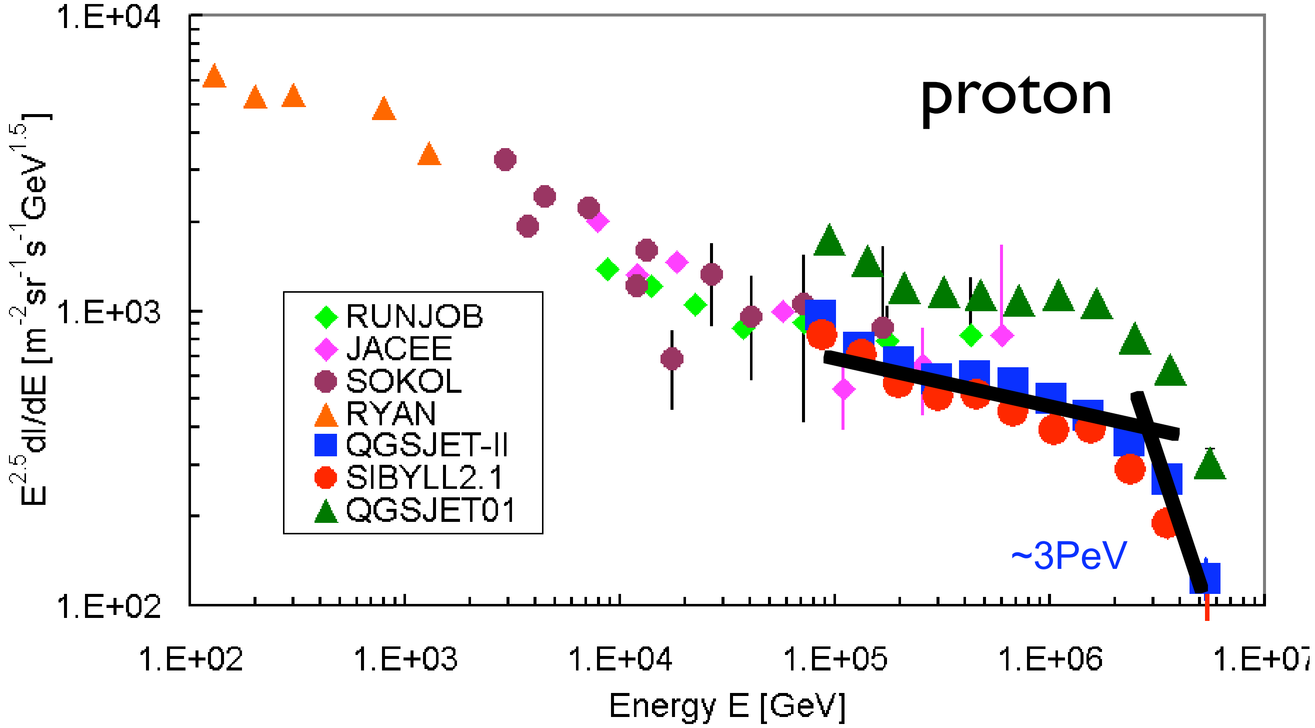
Outline

- Successes of modern air shower simulation
- Tests of air shower with Auger
- Relation to other air shower data
- Implications of Auger observations

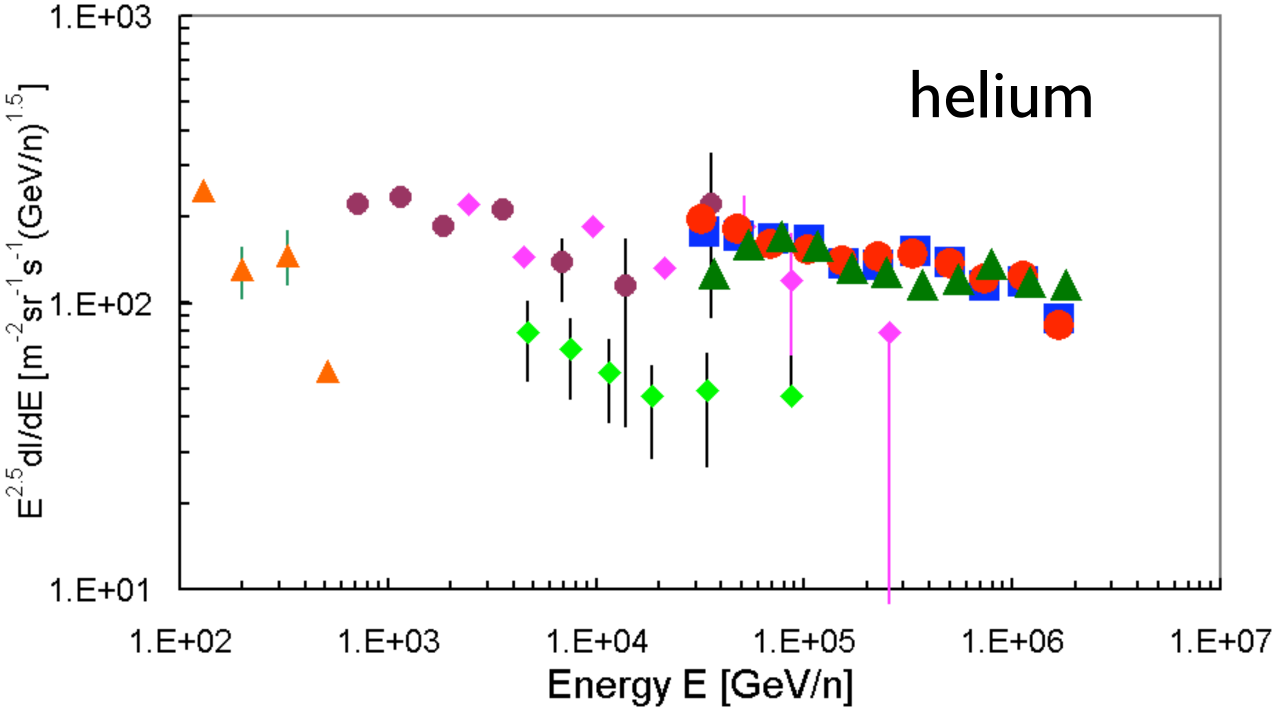
Success: all-particle flux

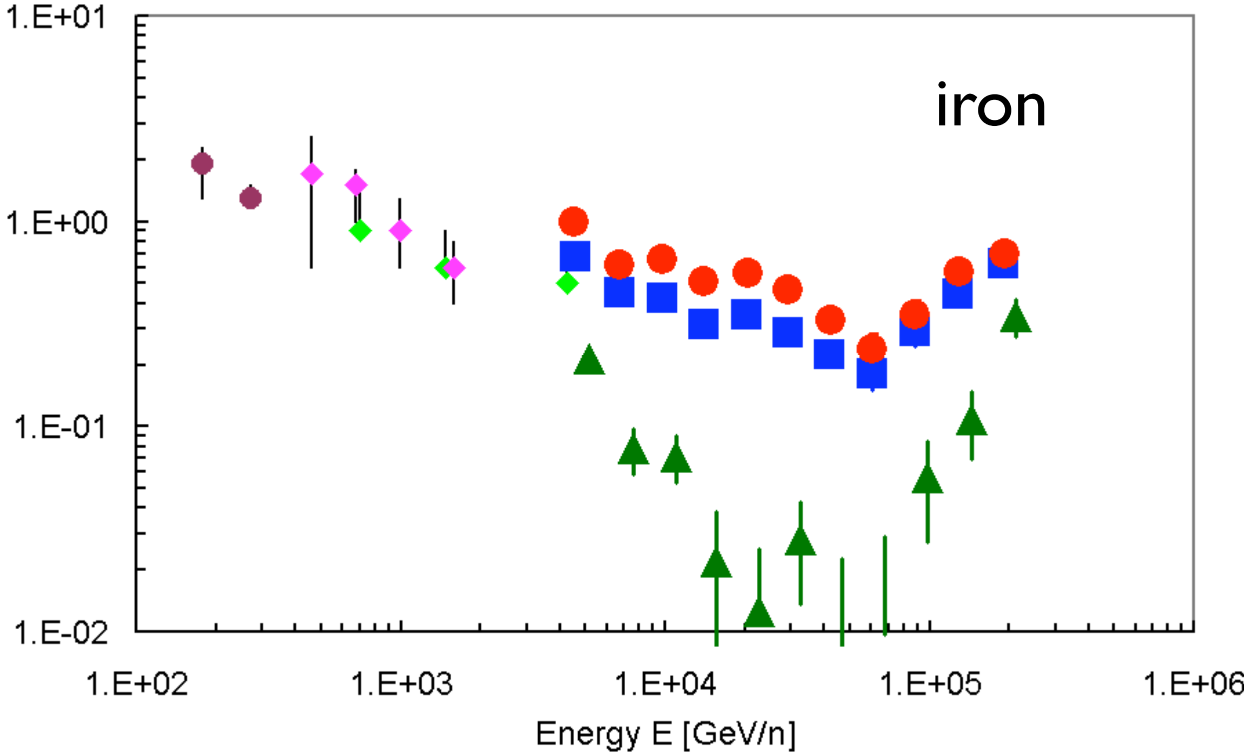


Success: GRAPES-3 element fluxes



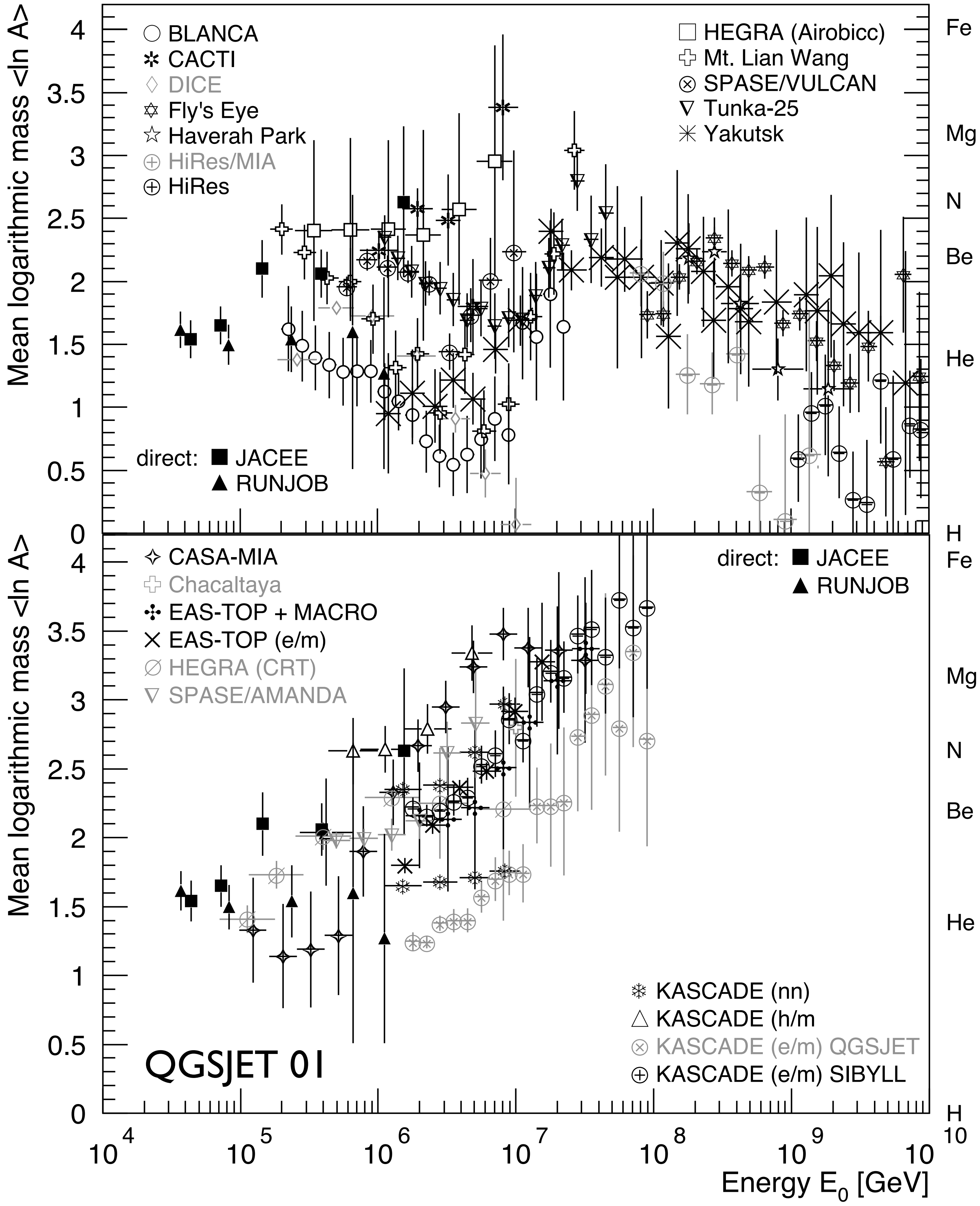
Assessment of models by relation to direct measurements





(H.Tanaka et al., S.Tonwar et al.)

Failure: composition at high energy



Cherenkov and fluorescence light

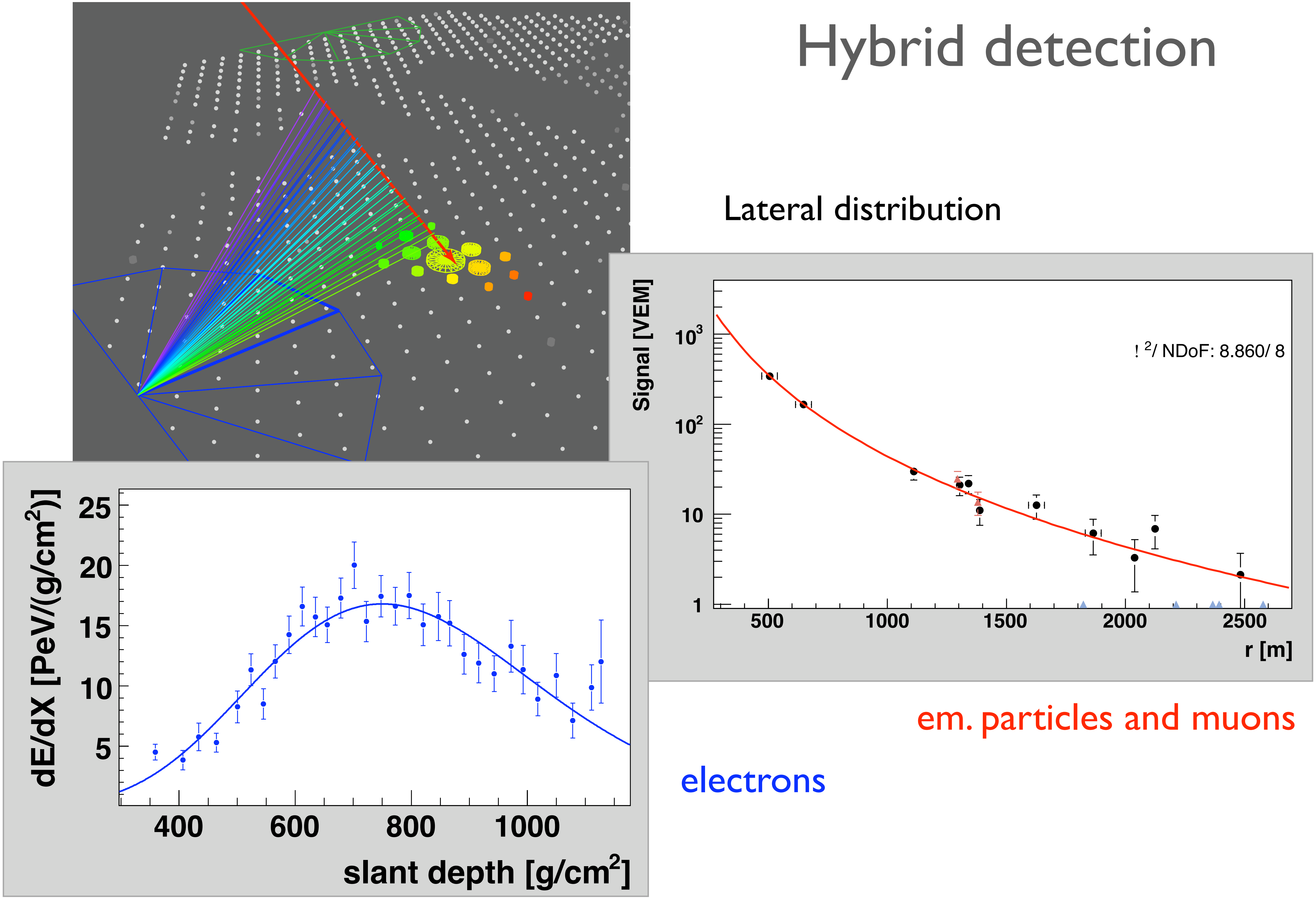
Electrons and muons

(Hörandel, 2007)

Pierre Auger Observatory (cloudy day)

Hybrid detection

Lateral distribution

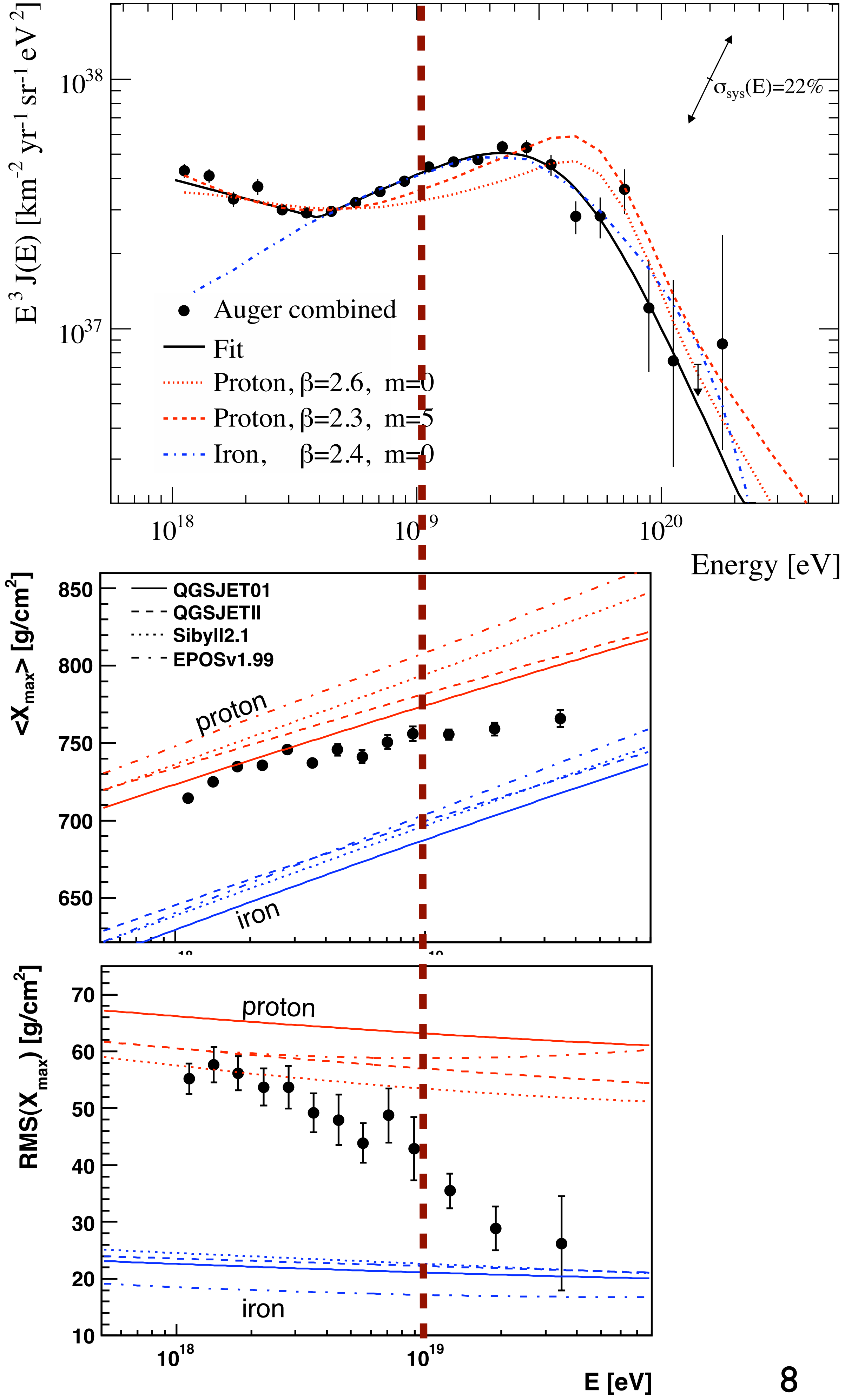


em. particles and muons

electrons

Shower longitudinal profile

Analysis methods



Universality method

em. component universal

muonic contribution: part of signal

Time trace analysis

jump method (muon counting)

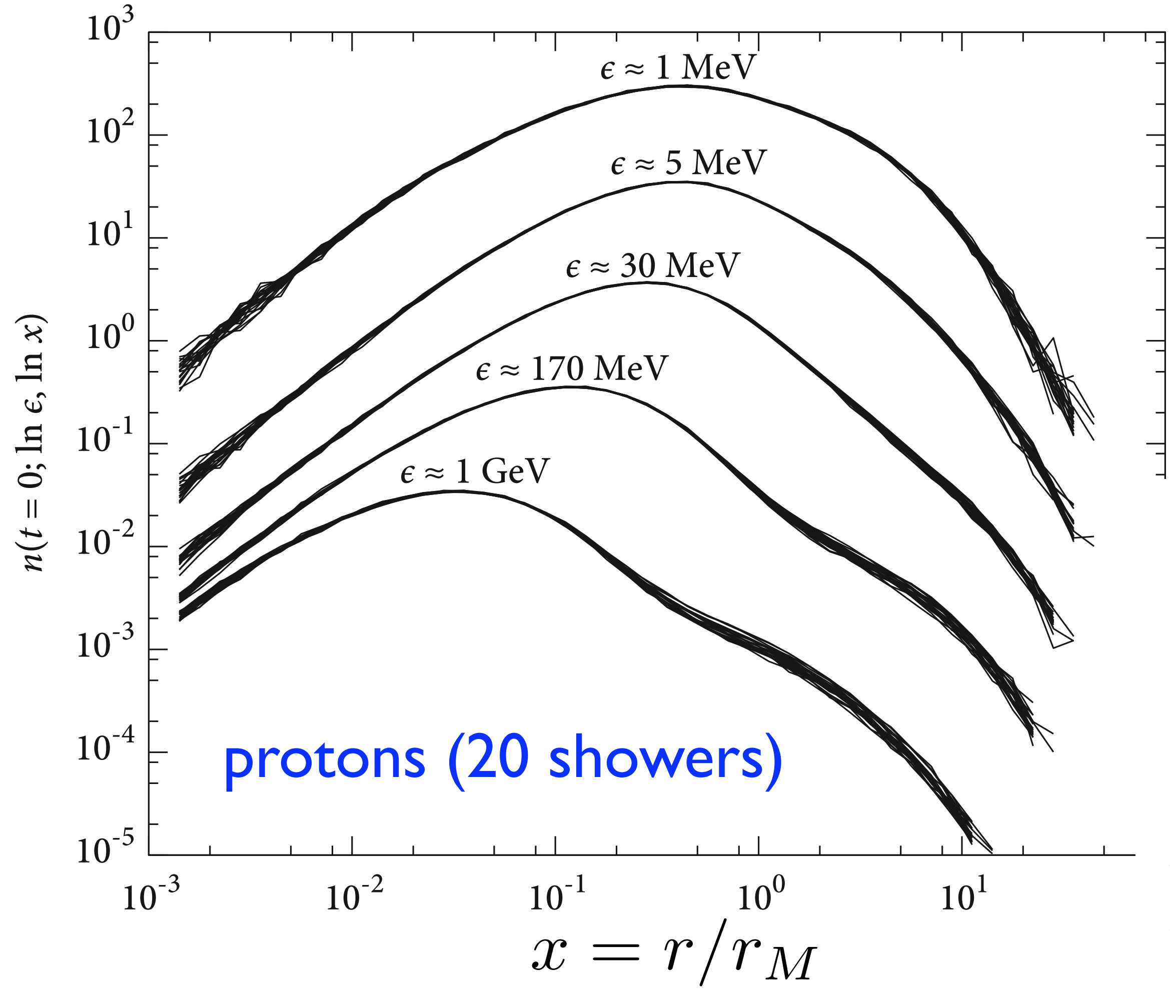
smoothing method (em. component)

Simulation of individual hybrid events

Analysis of data at 10^{19} eV

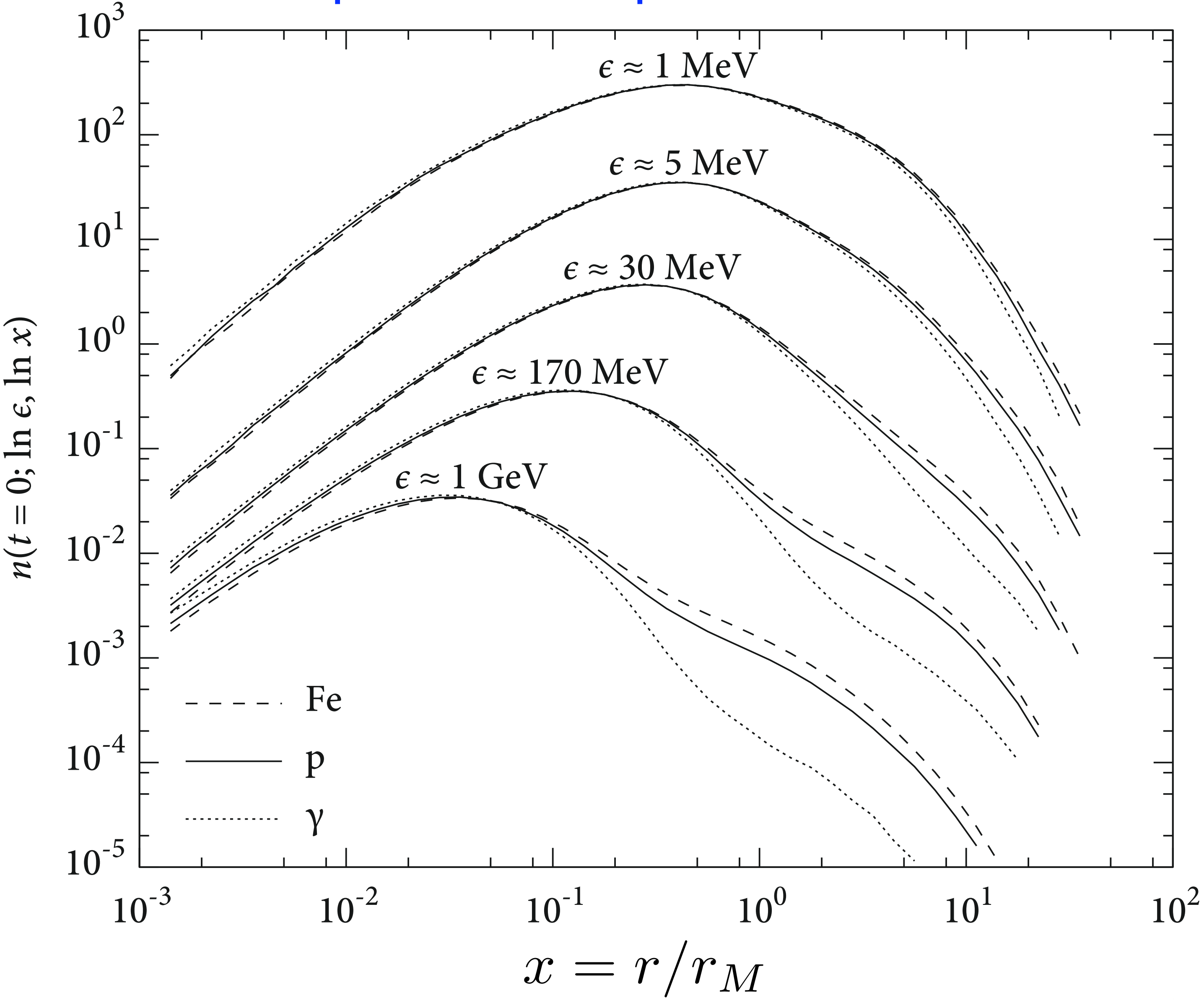
QGSJET II, protons as reference scale

Universality of showers at very high energy (i)



Lateral distribution

protons, iron, photons

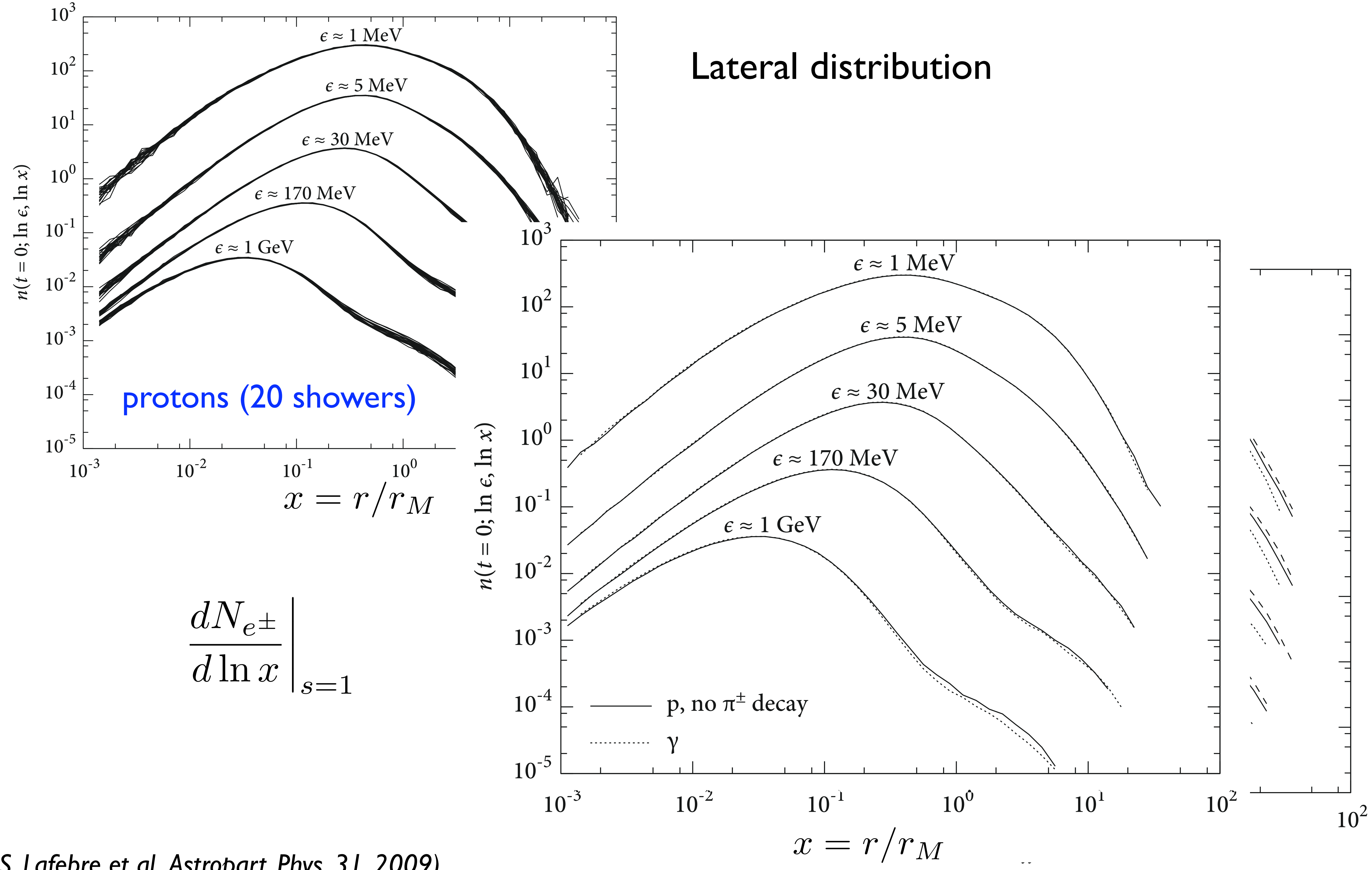


$$\left.\frac{dN_{e^\pm}}{d\ln x}\right|_{s=1}$$

(S. Lafebre et al., Astropart. Phys. 31, 2009)

Universality of showers at very high energy (i)

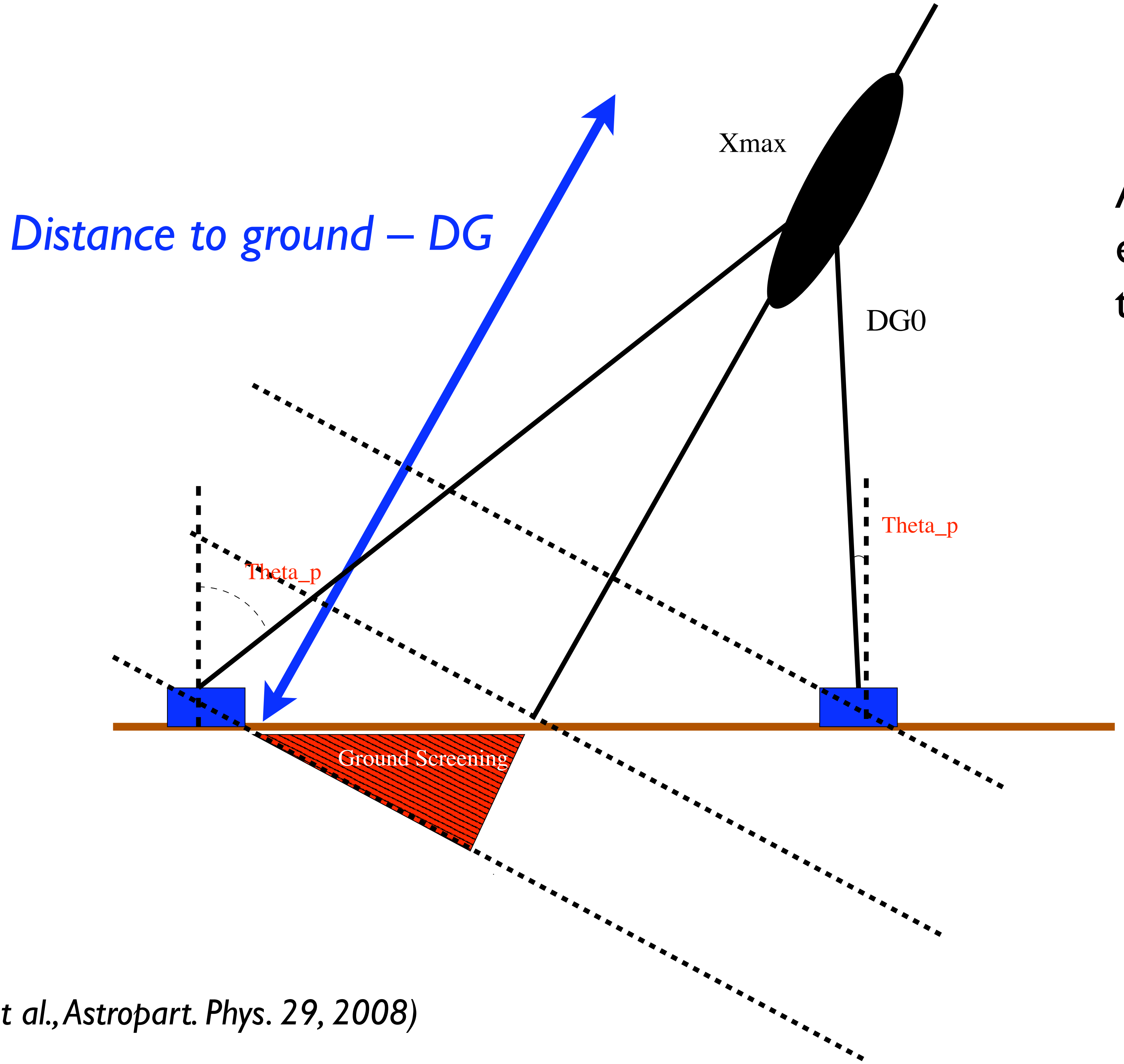
Lateral distribution



$$\left.\frac{dN_{e^\pm}}{d\ln x}\right|_{s=1}$$

(S. Lafebre et al., Astropart. Phys. 31, 2009)

Universality of em. shower component

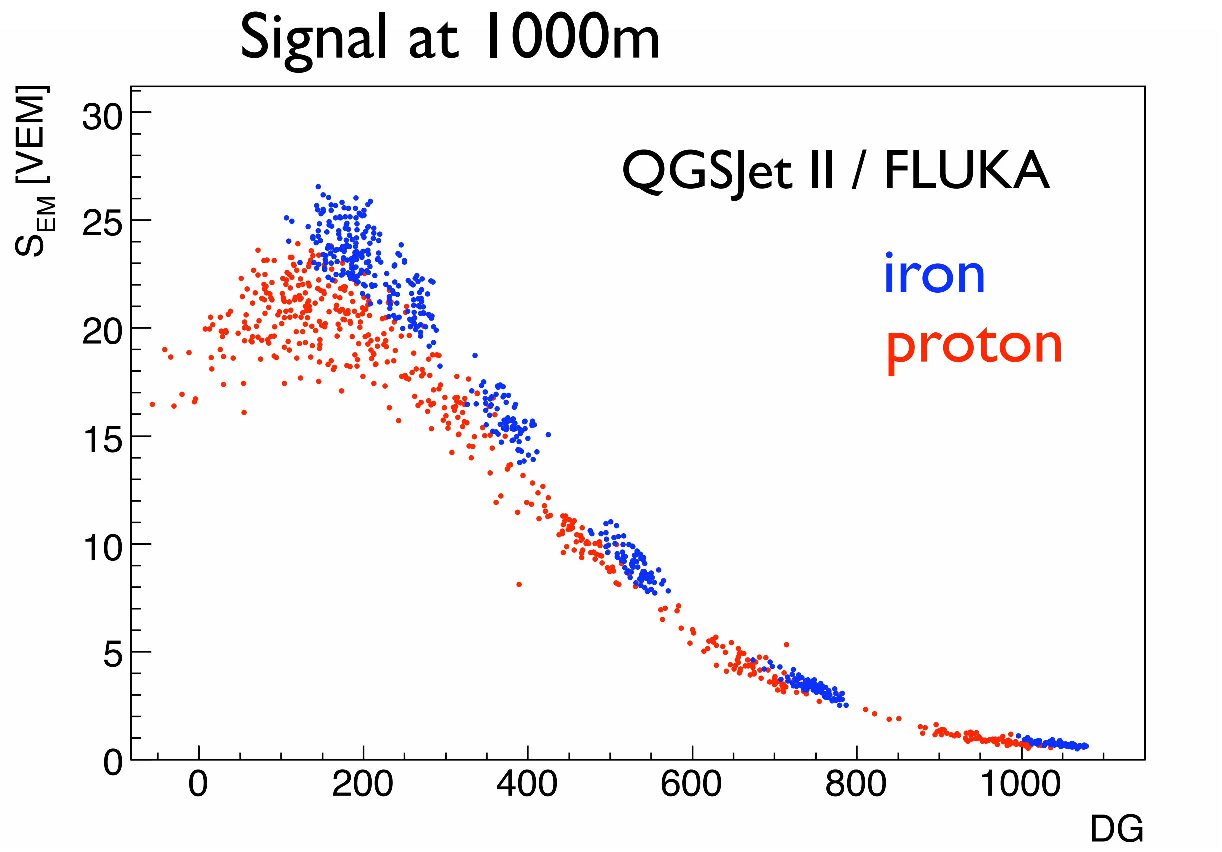


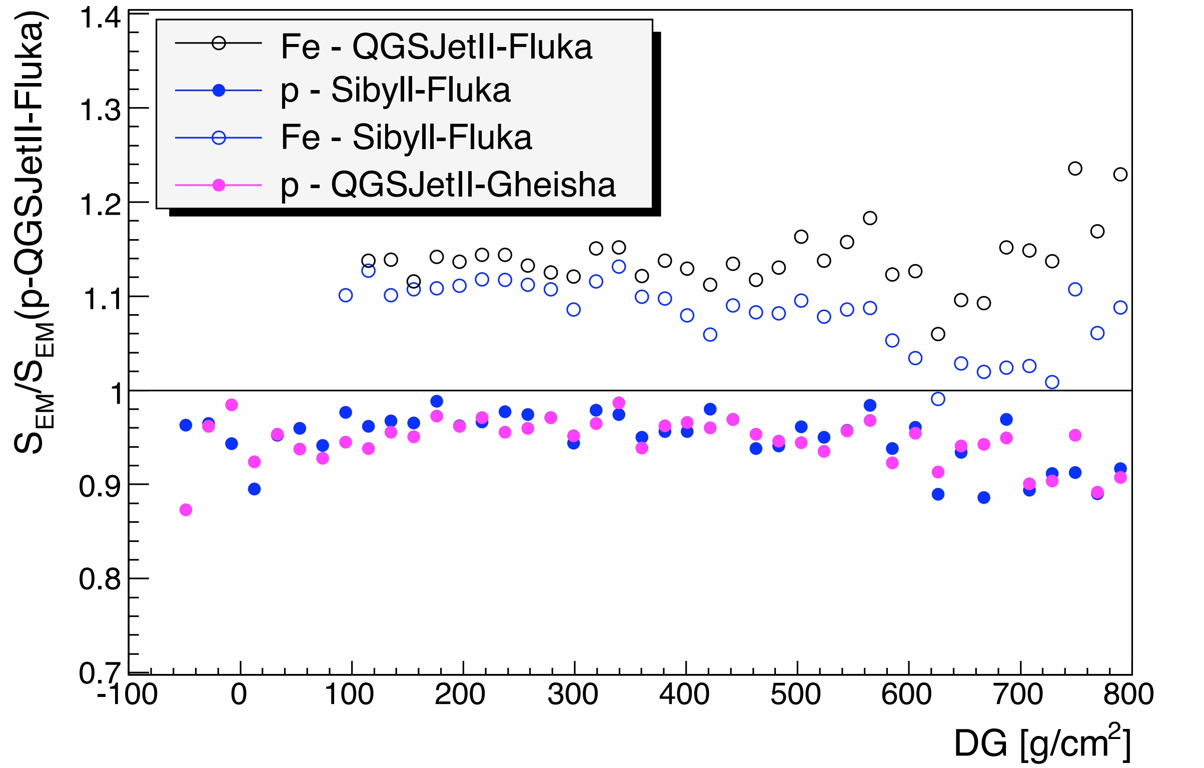
Asymmetries and effective detector area taken into account

Em. particles from muon decay treated separately

(F. Schmidt et al., Astropart. Phys. 29, 2008)

Universality of em. shower component





S_{EM} parametrized as function of distance to ground $DG = X_{\mathrm{det}} - X_{\mathrm{max}}$

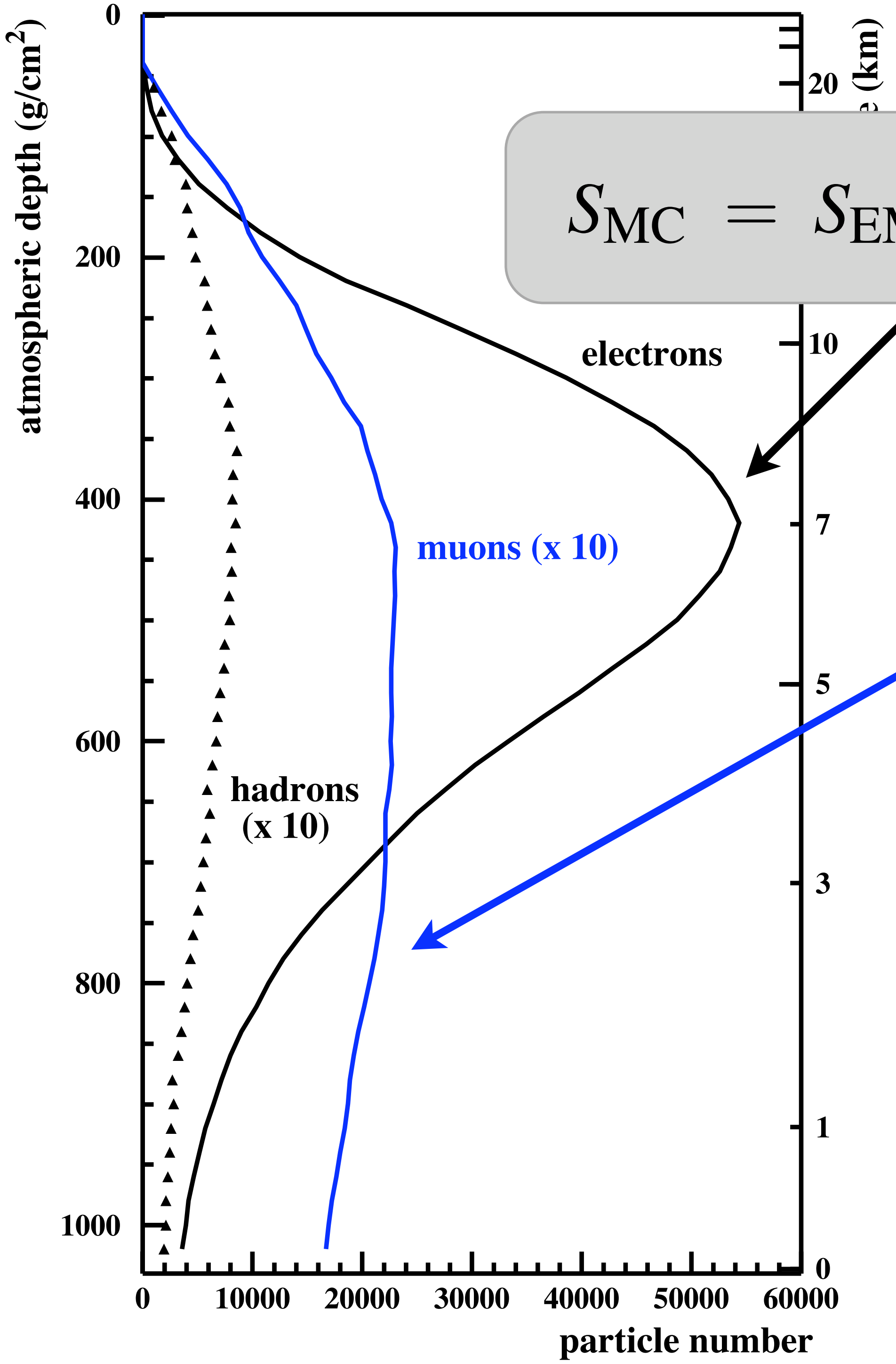
Predicted signal at 1000m:

$$S_{\mathrm{MC}} = S_{\mathrm{EM}}(DG, E) + N_\mu^{\mathrm{rel}} \cdot S_\mu^{\mathrm{QGSII,p}}(DG, 10^{19}\,\mathrm{eV})$$

includes e/m signal from muon decay

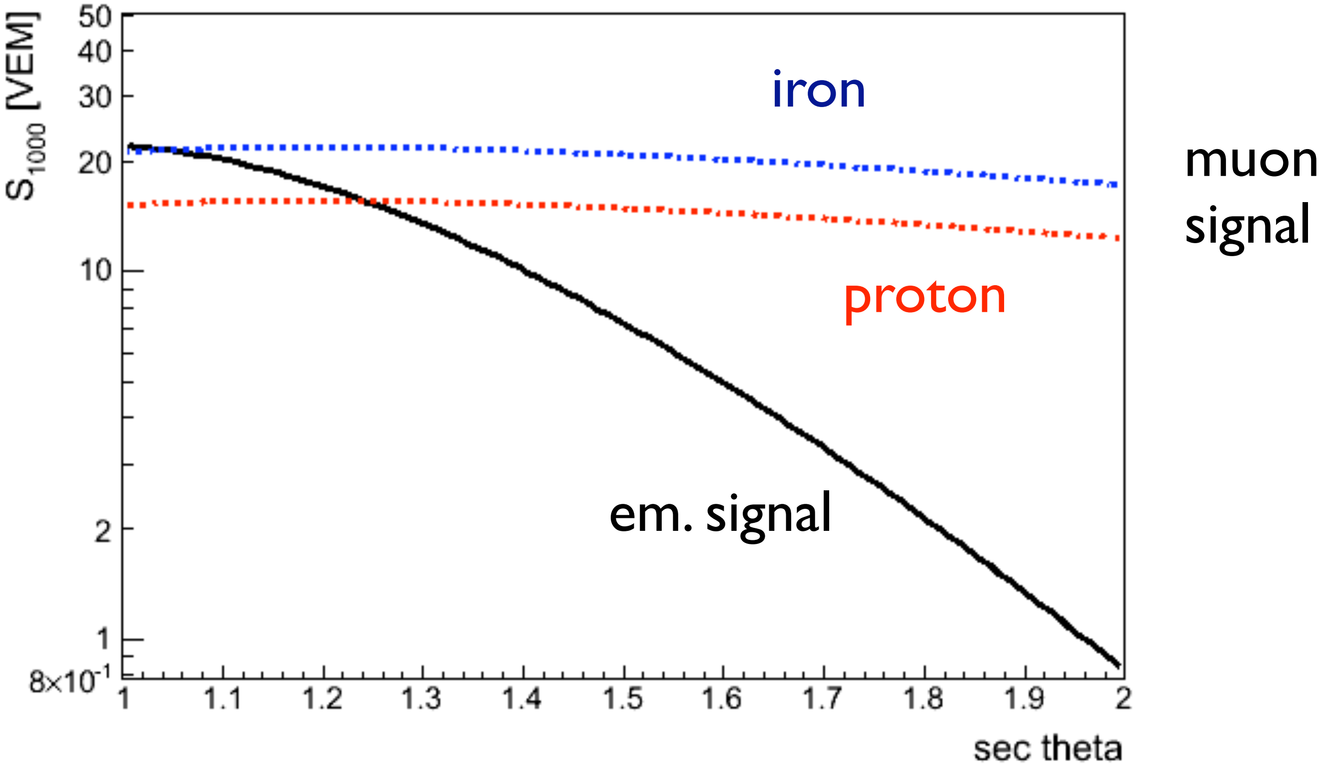
(F. Schmidt et al., Astropart. Phys. 29, 2008)

Prediction of S(1000) for different angles



$$S_{\mathrm{MC}} = S_{\mathrm{EM}}(DG, E) + N_\mu^{\mathrm{rel}} \cdot S_\mu^{\mathrm{QGSII,p}}(DG, 10^{19}\,\mathrm{eV})$$

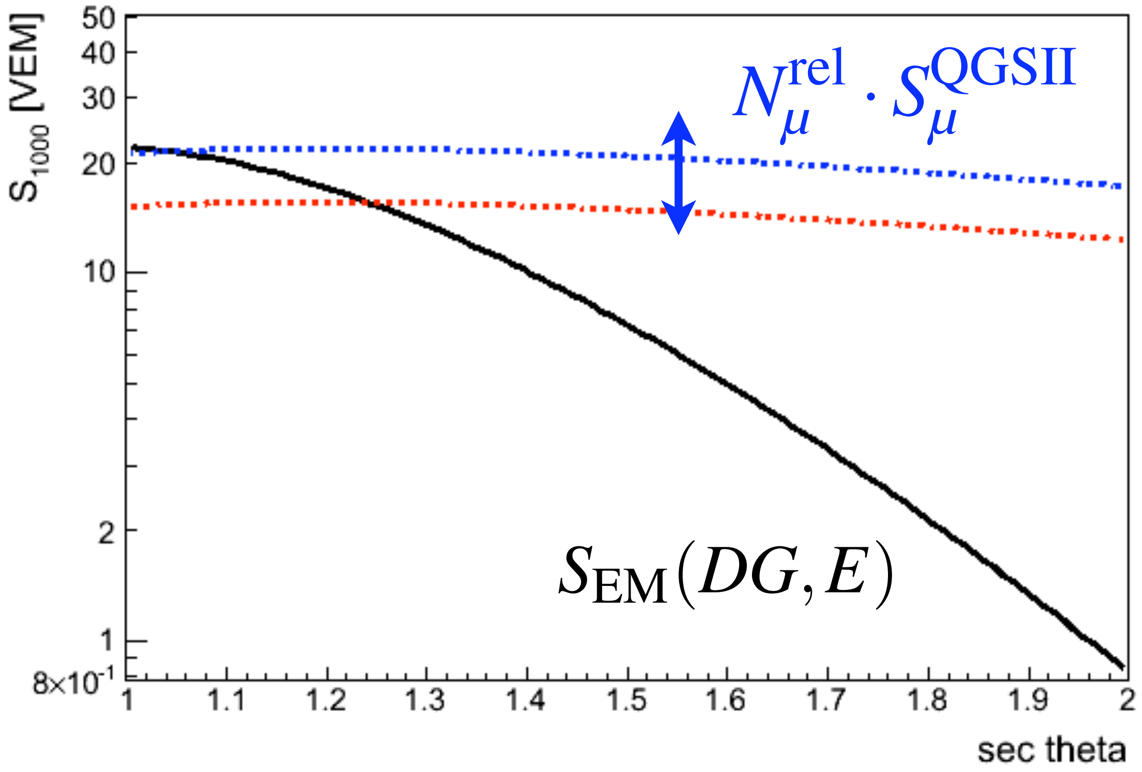
Predicted Auger tank signal

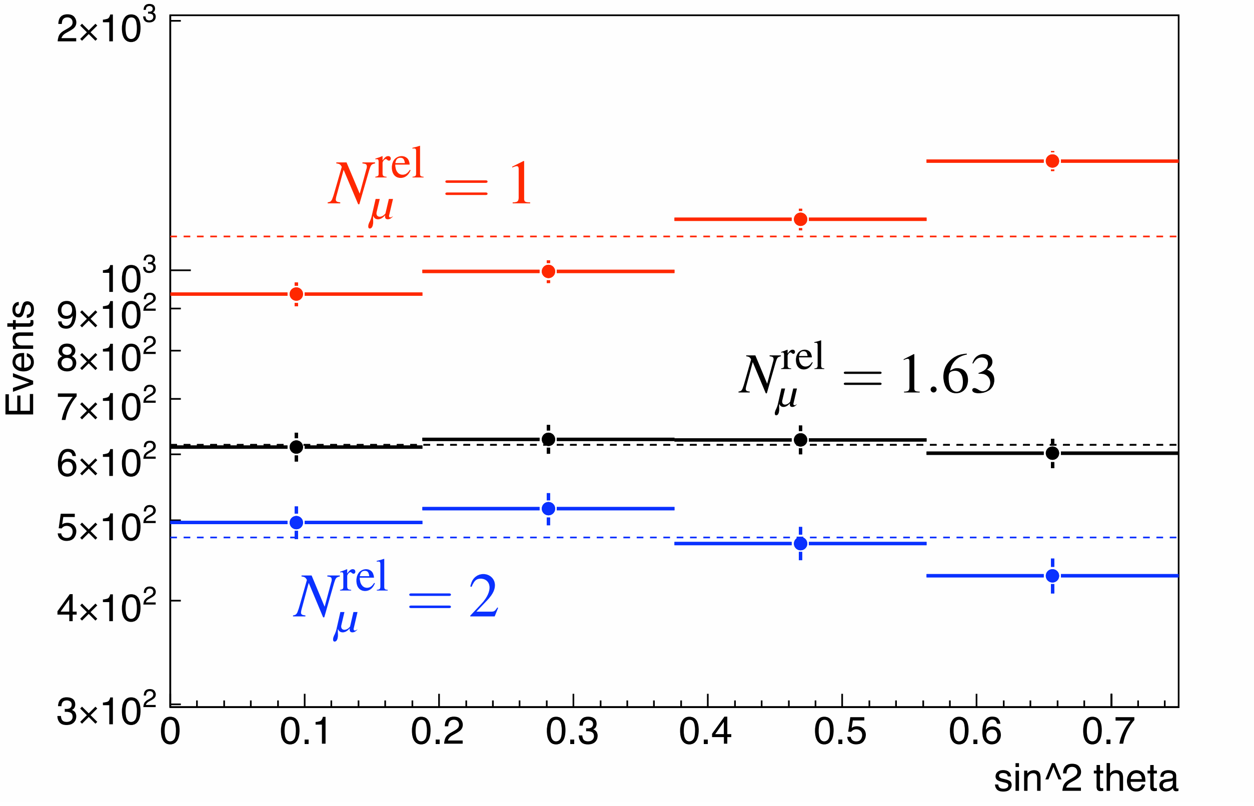


Universality and isotropy

Cosmic ray flux isotropic:

$$\left.\frac{dN_{\mathrm{ev}}}{d\sin^2\theta}\right|_{S(1000)>S_{\mathrm{MC}}(E,\theta,\langle X_{\max}\rangle,N_\mu^{\mathrm{rel}})} = \mathrm{const.}$$





Result accounting for shower fluctuations and detector resolution

$$\boxed{N_\mu^{\mathrm{rel}}(10^{19}\,\mathrm{eV}) = 1.53^{+0.09}_{-0.07}(\mathrm{stat.})^{+0.21}_{-0.11}(\mathrm{sys.})}$$

Absolute energy scale from universality

from Auger data: hybrid measurement

$$S_{38}(10^{19}\,\mathrm{eV}) \;=\; S_{\mathrm{EM}}(10^{19}\,\mathrm{eV}, \theta = 38^\circ, \langle X_{\mathrm{max}} \rangle) \;+\; N_\mu^{\mathrm{rel}} \cdot S_\mu^{\mathrm{QGSII,p}}(10^{19}\,\mathrm{eV})$$

from Auger data:
const. intensity method

Data: Jan 2004 - Dec 2008

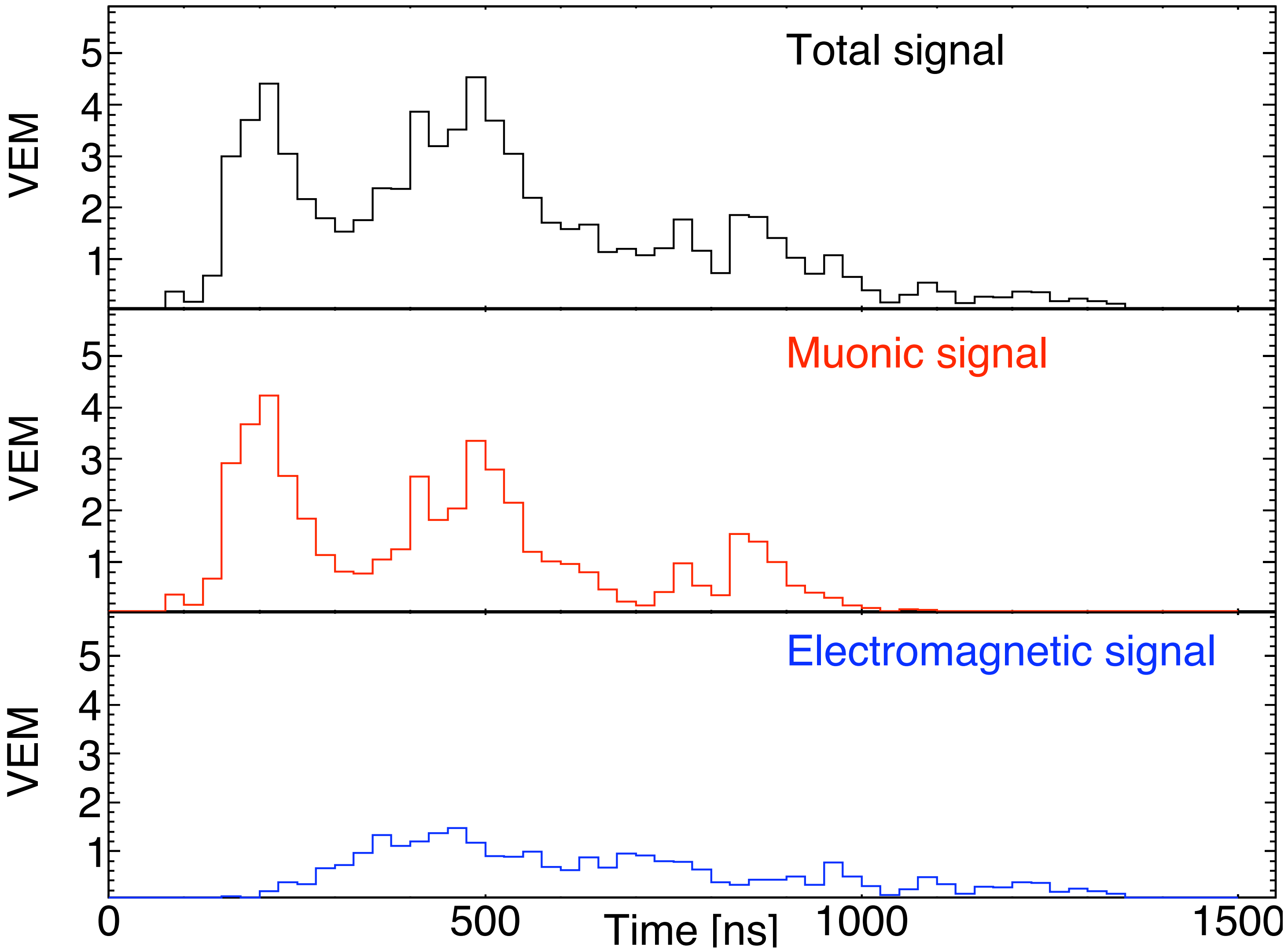
$$\boxed{S_{38}(10^{19}\,\mathrm{eV}) = 38.9^{+1.4}_{-1.2}(\mathrm{stat.})^{+1.6}_{-1.8}(\mathrm{sys.})\ \mathrm{VEM}}$$

Corresponding energy scale

$$\boxed{E' = 1.26^{+0.05}_{-0.04}(\mathrm{sys.}) \times E_{\mathrm{FD}}}$$

(compatible with current uncertainty of fluorescence detector energy scale)

Time structure of tank signal

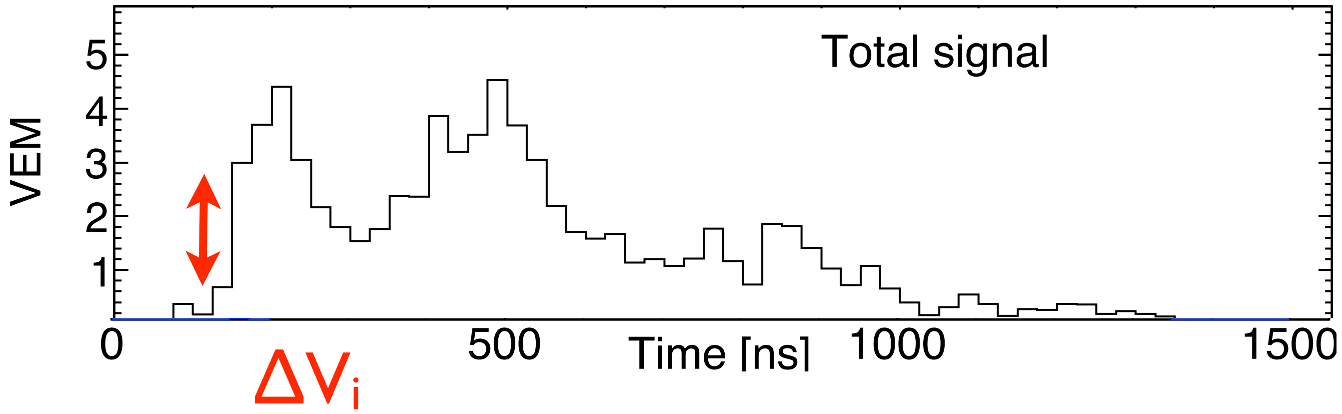


individual muon peaks

smooth signal from em component, peaks from high energy photons possible

Simulated proton shower of E = 10^{19} eV and θ = 45°,

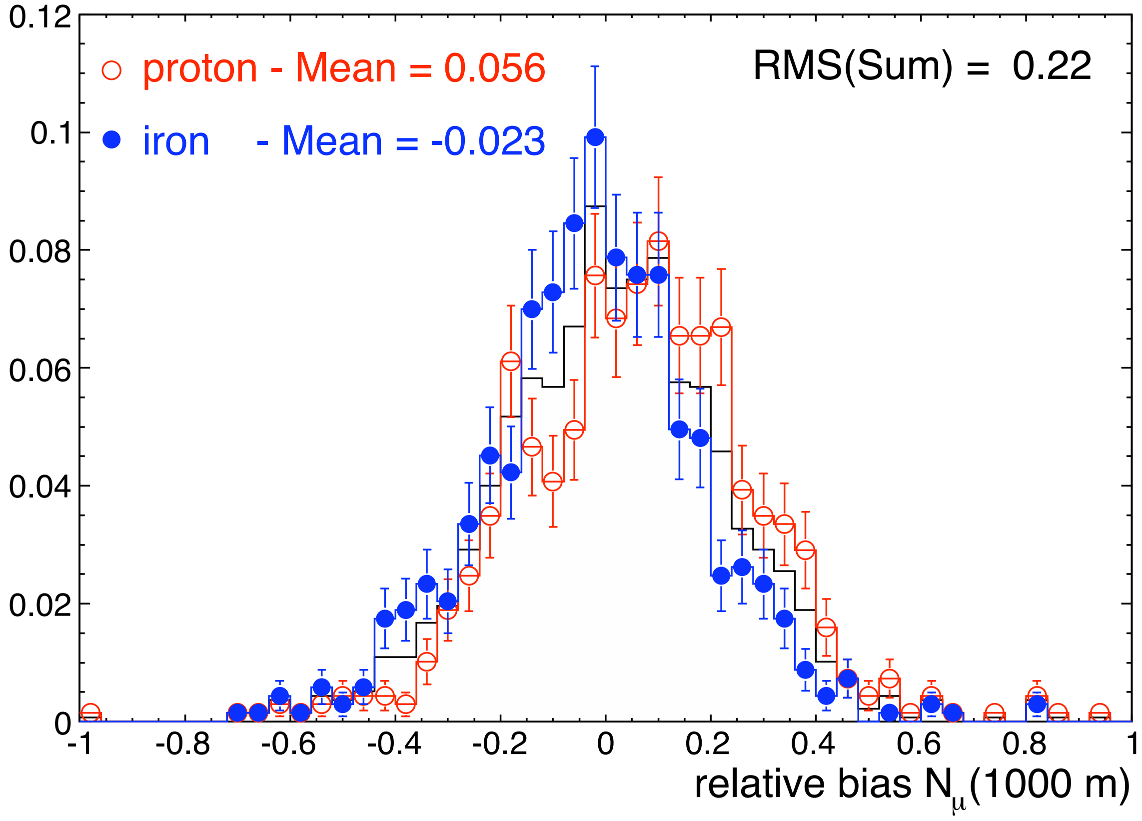
Muon counting with jump method

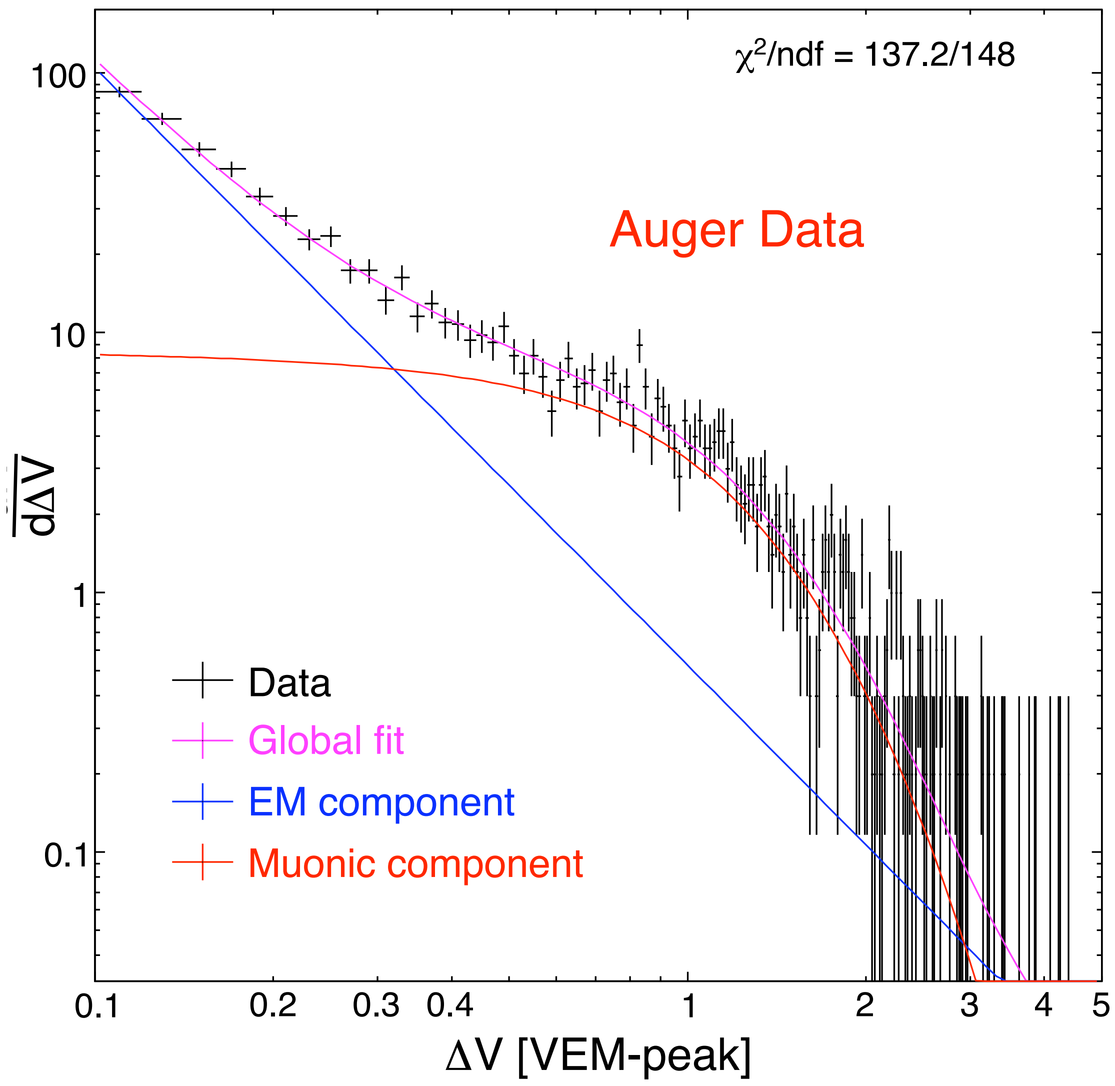


calibration factor

$$N_\mu^{\rm est} = \eta(E,\theta) \times \sum_{\Delta V_i > \Delta V_{\rm th}} \Delta V_i$$

MC study of resolution

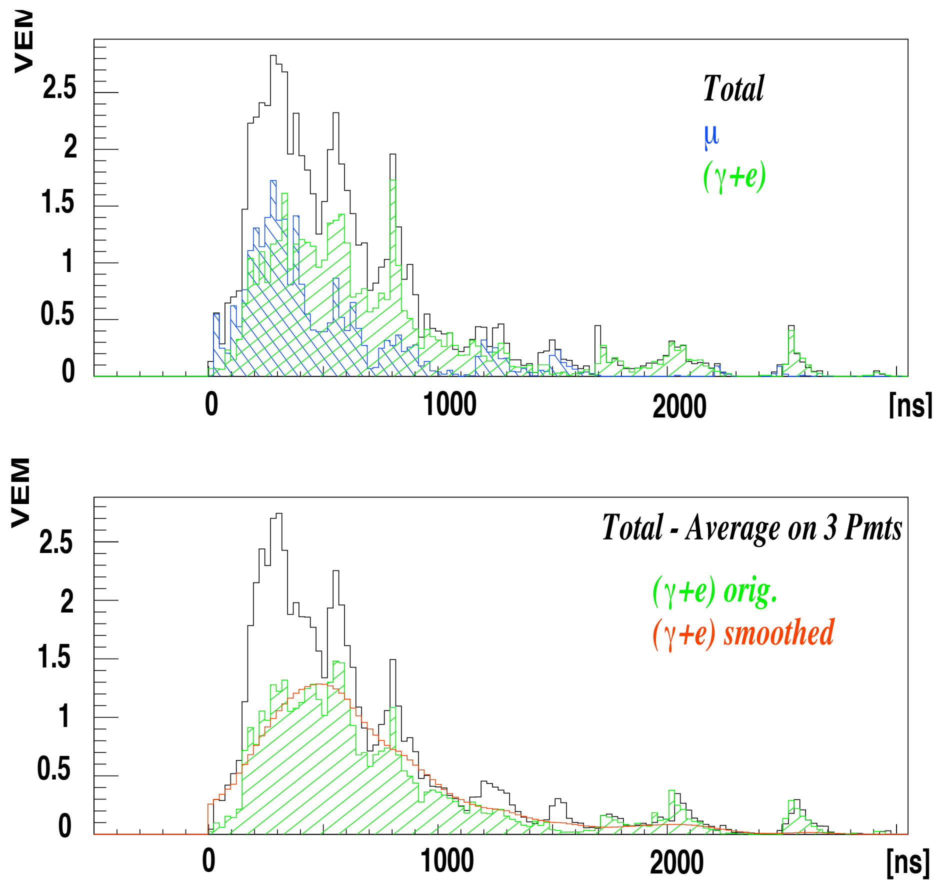




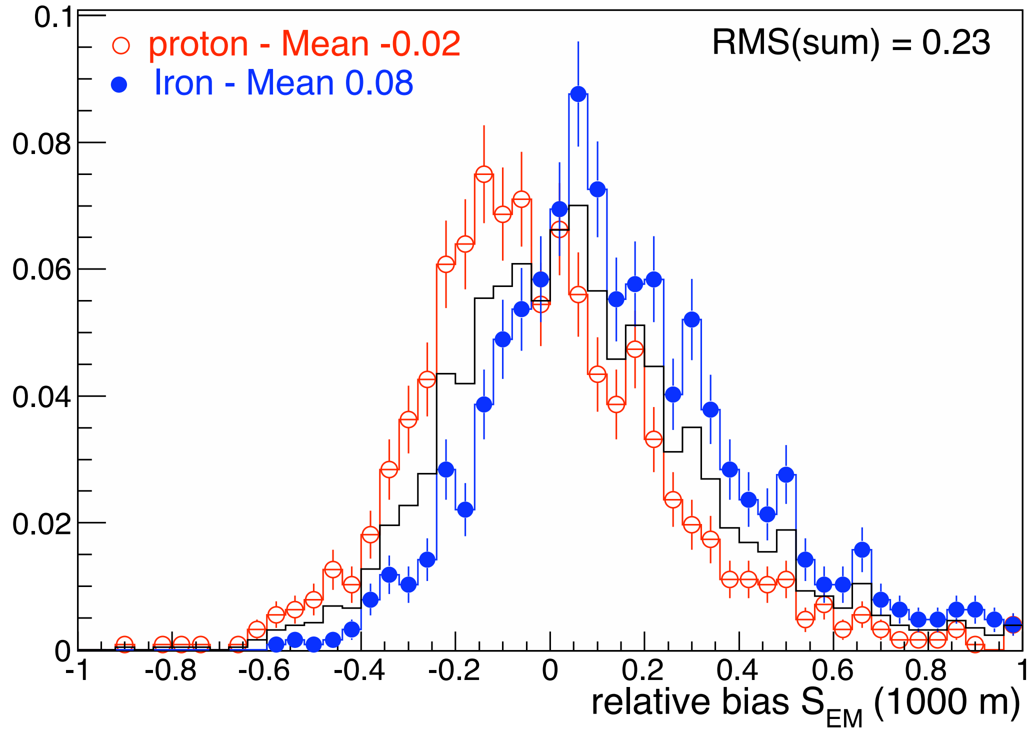
Em. signal from smoothing method

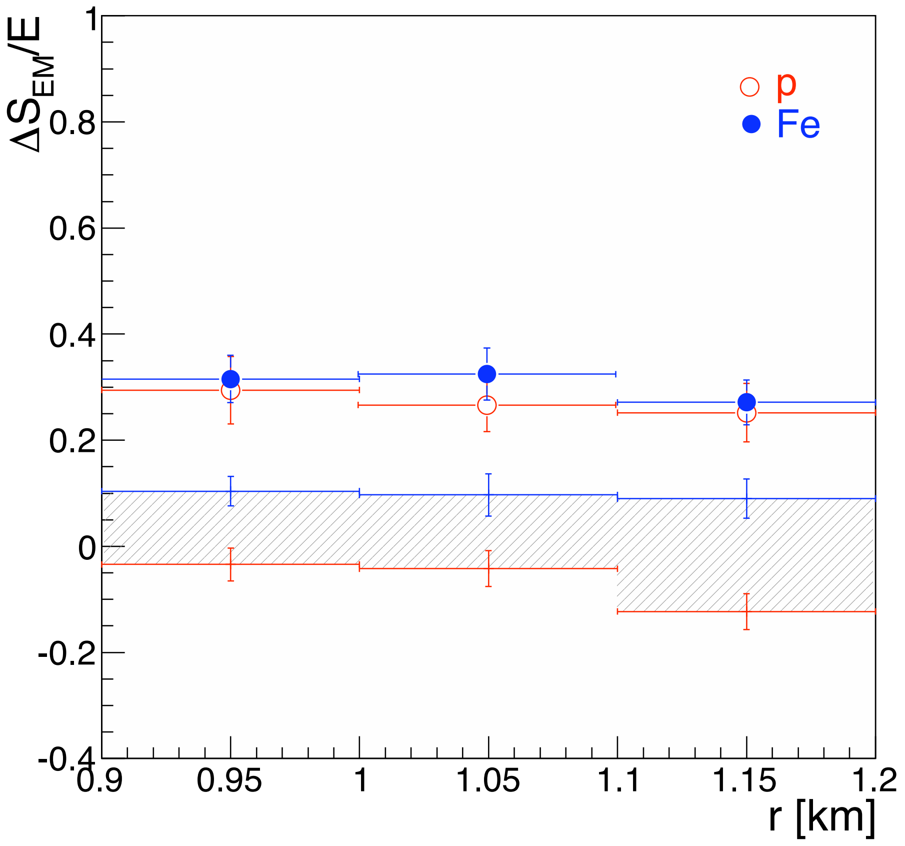
Procedure

- average over 4 bins
- subtract peaks
- repeat procedure 7 times



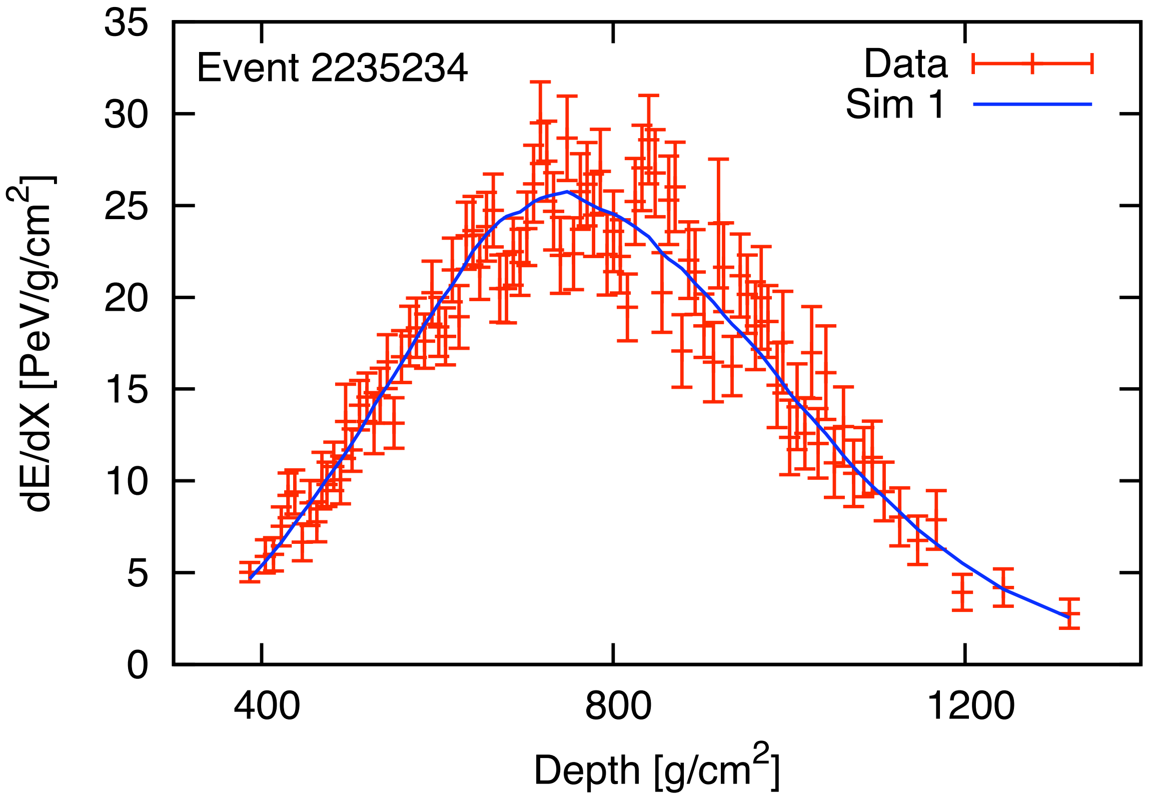
MC study of resolution





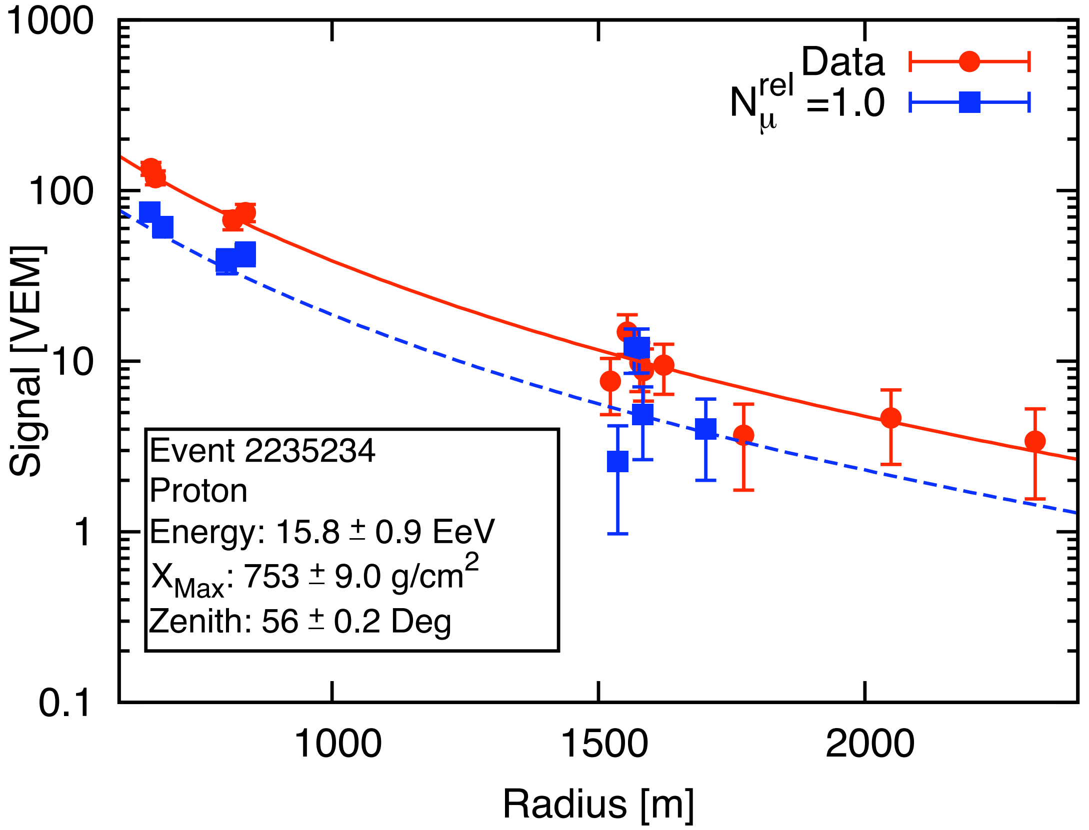
$$E' = 1.29 \pm 0.07(\text{sys.}) \times E_{\text{FD}}$$

Simulation of individual hybrid events



Procedure

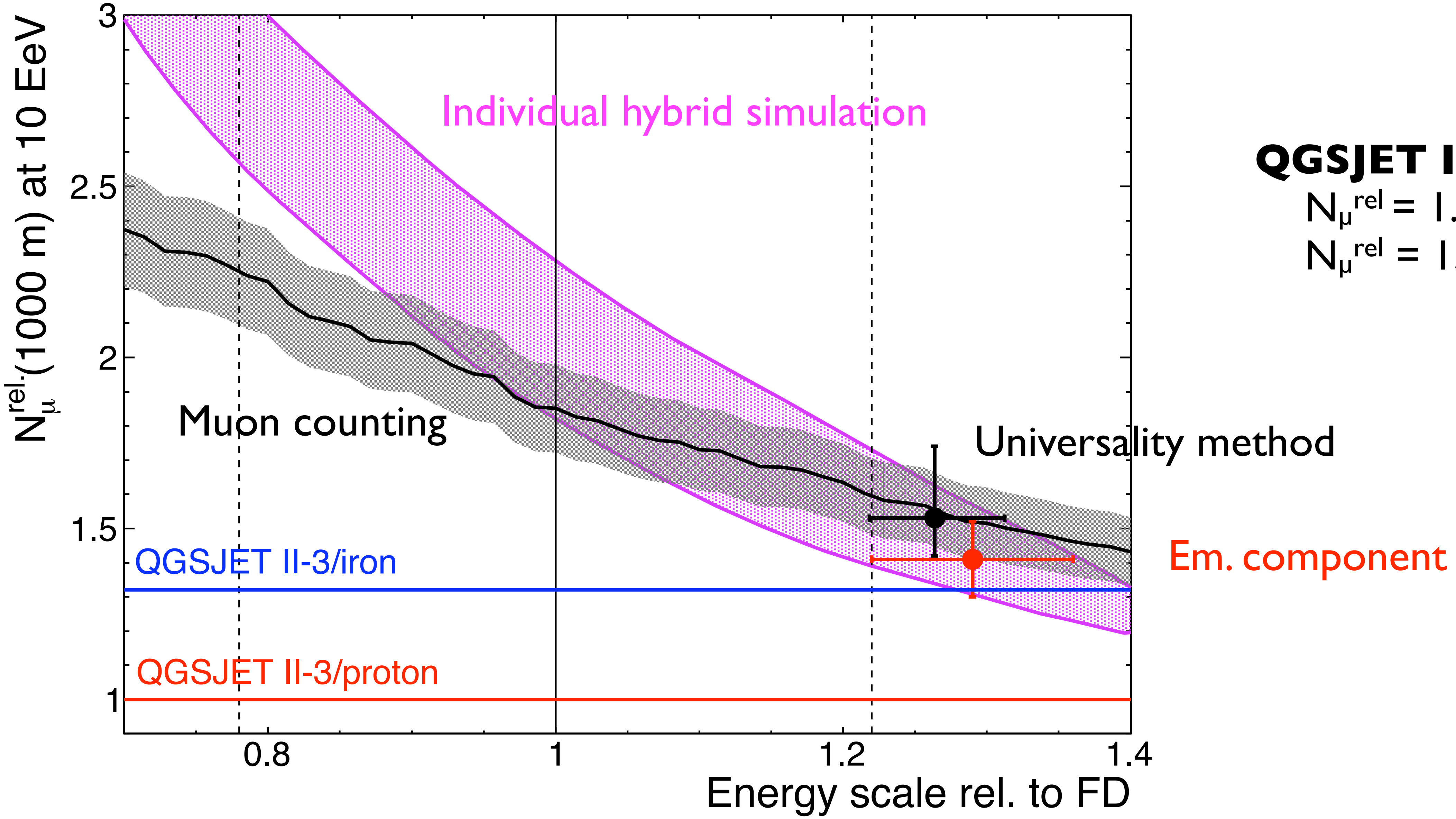
- Simulation of 400 showers with reconstructed geometry
- Proton or iron primaries
- SD simulation for best long. profile
- Reconstruction of hybrid event



Results

- Muon deficit found in both proton and iron like showers
- Showers with same X_{max} show 10-15% variation of S(1000)

Comparison of results



QGSJET II:

N_μ^{rel} = 1.0 (protons)
N_μ^{rel} = 1.32 (iron)

Results of different methods consistent

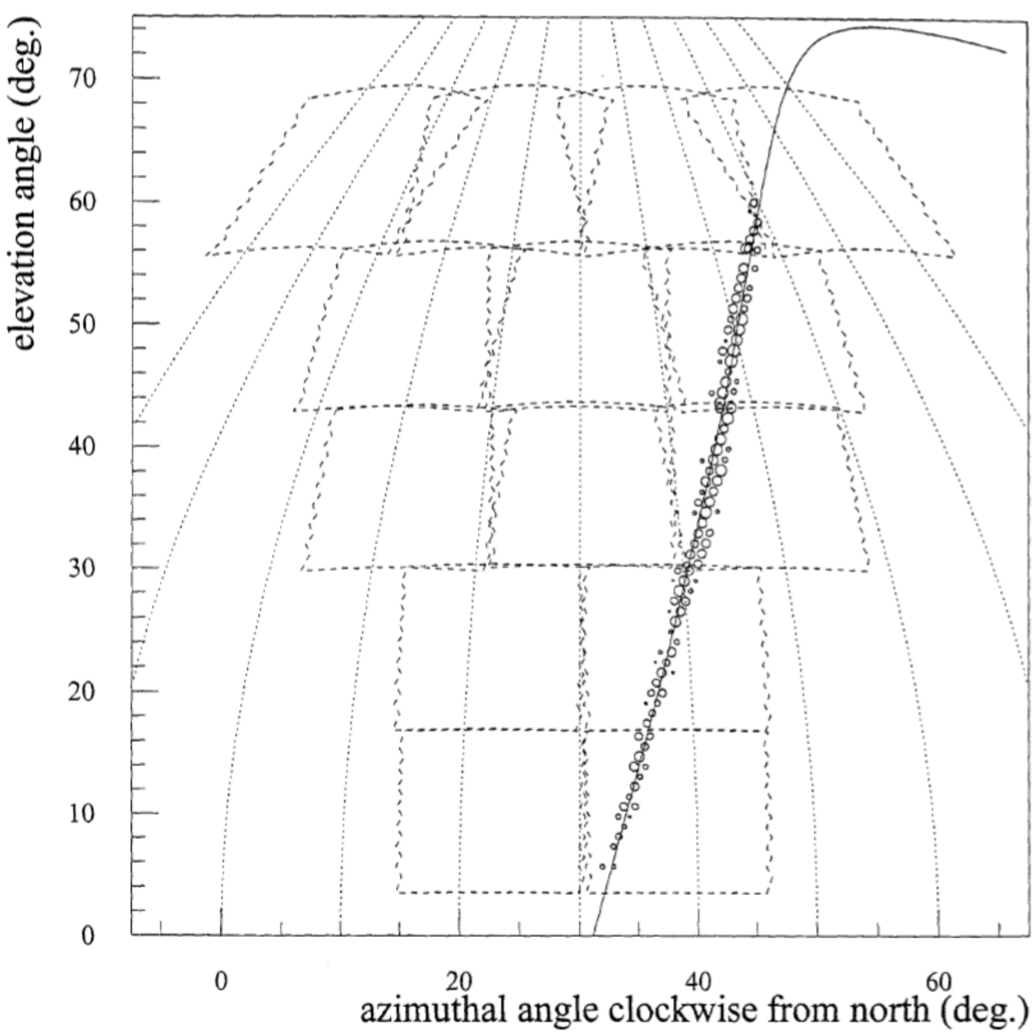
- shift of energy scale expected
- muon deficit in simulation even with shifted energy scale

But: All results depend directly or indirectly on simulation of em. component

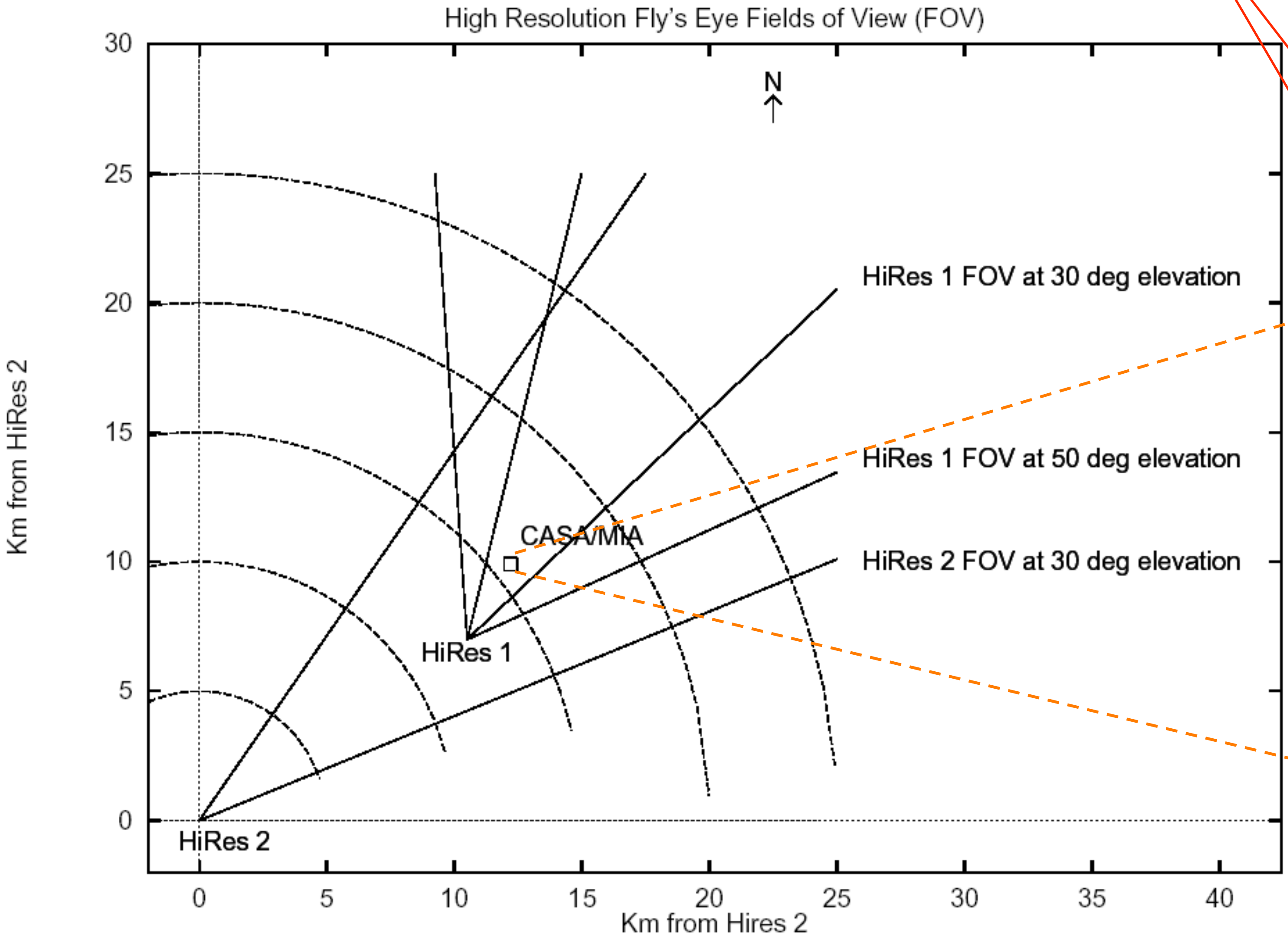
HiRes prototype & MIA

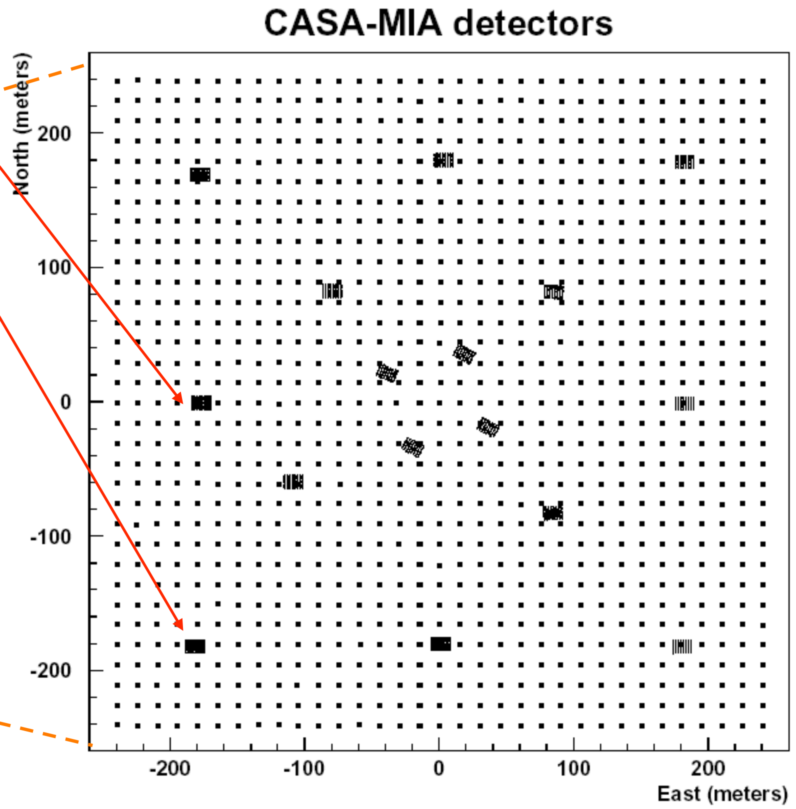
1992-1996: HiRes Prototype

- 14 (HiRes-1) + 4 (HiRes-2) mirror prototype detector operated between 1992 and 1996
- HiRes-1 field of view up to ~70°.
- HiRes-1 operated in hybrid mode with the MIA muon array (16 patches×64 underground scintillation counters each):



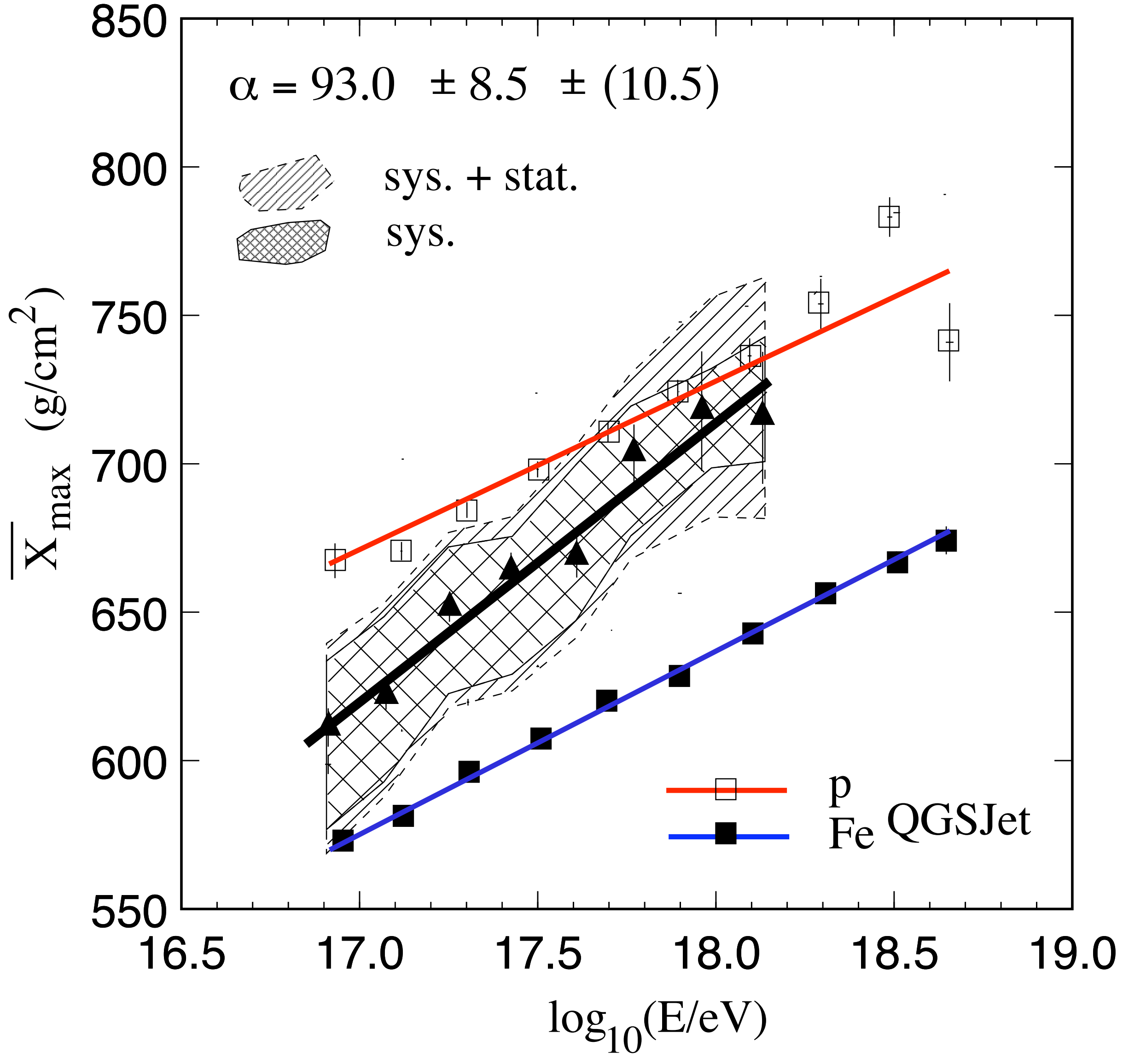
HiRes1 9750.01841315 1995-FEB-01 : 12:26:30.000 000 000



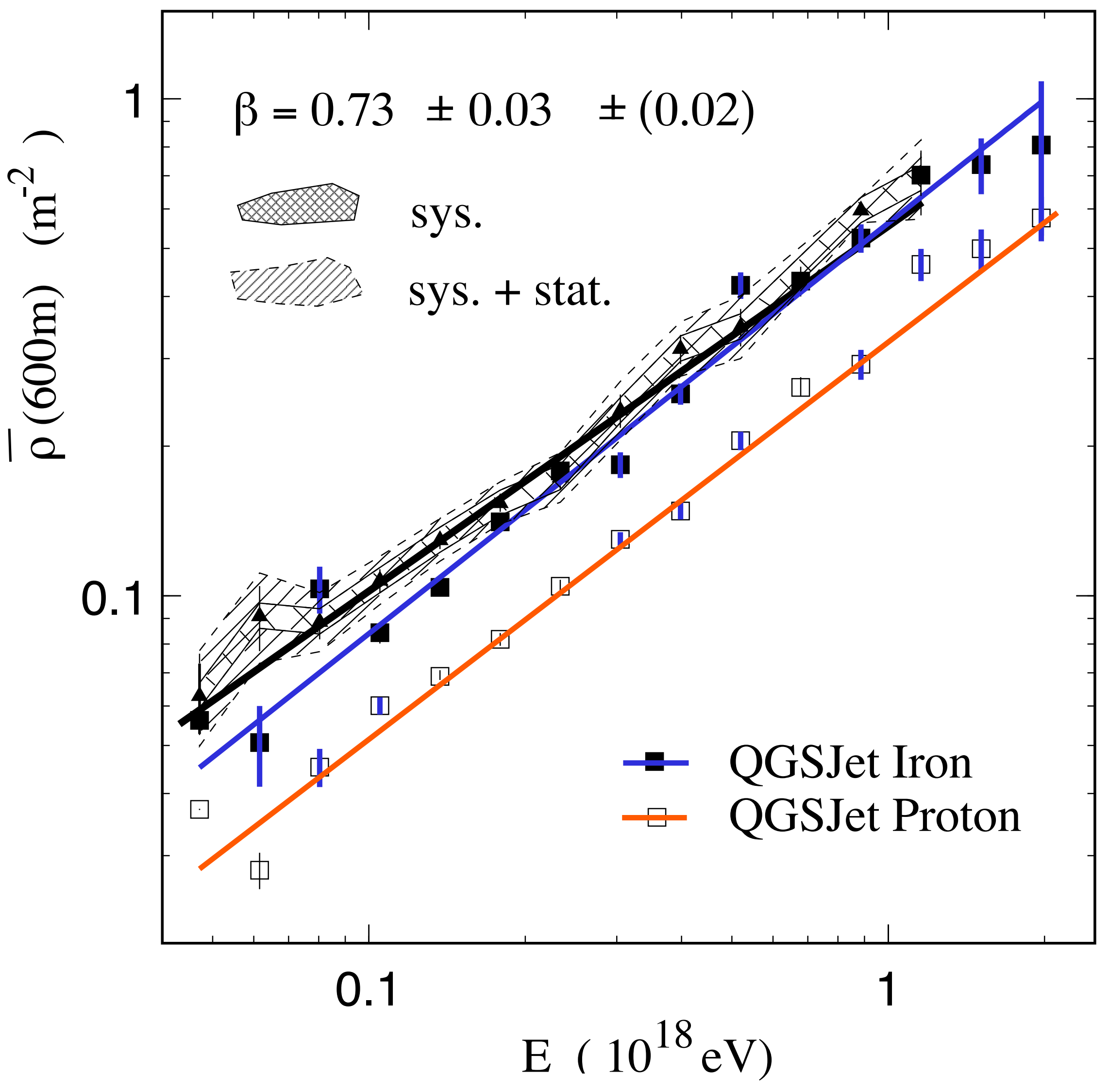


(P. Sokolsky, Seattle 2008)

HiRes-MIA hybrid measurement



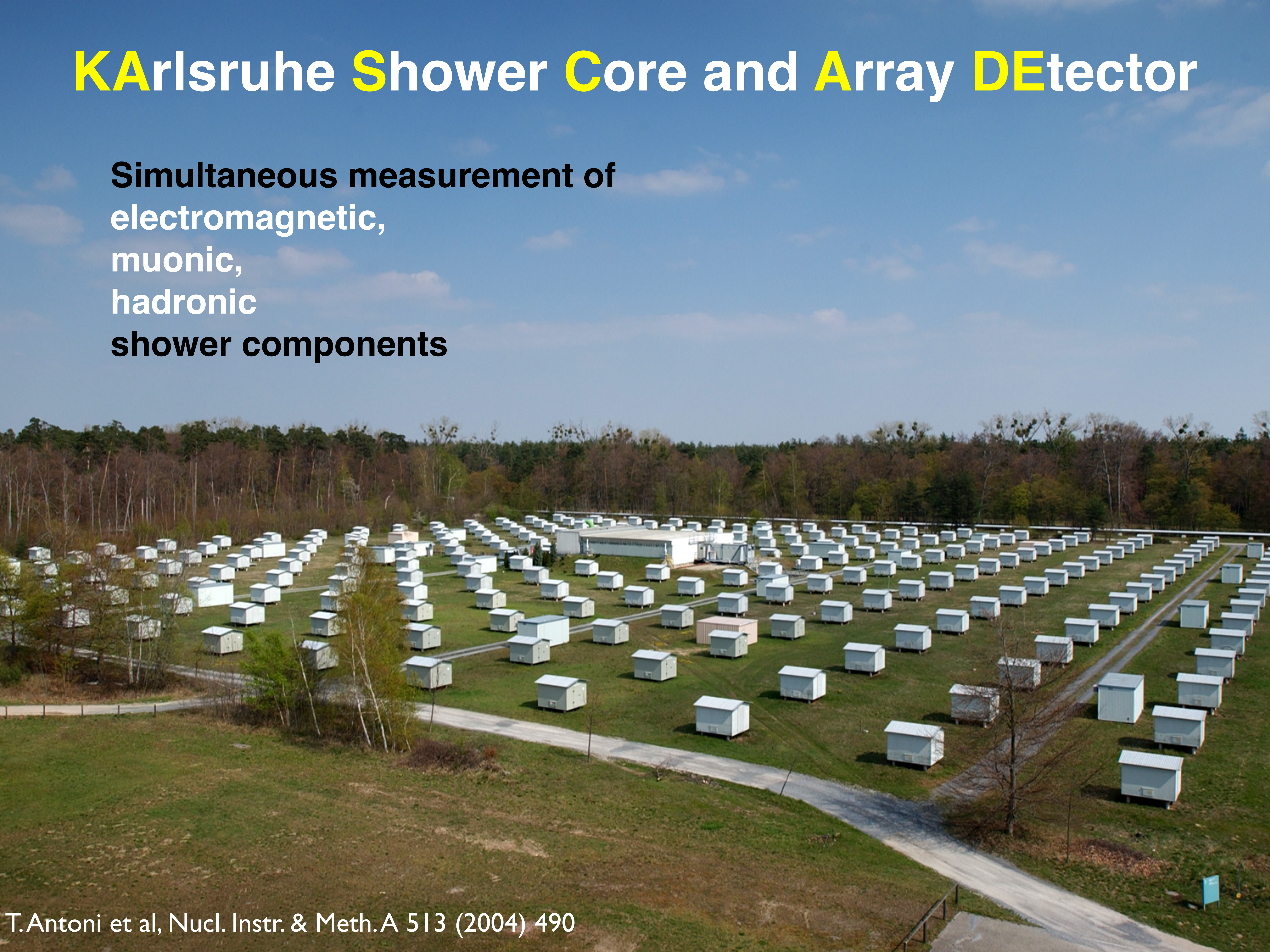
Muon density 600m from core



Analysis with QGSJET98 (very similar to QGSJET01)

HiRes Fly's Eye and MIA Collabs., Phys. Rev. Lett. 84 (2000) 4276

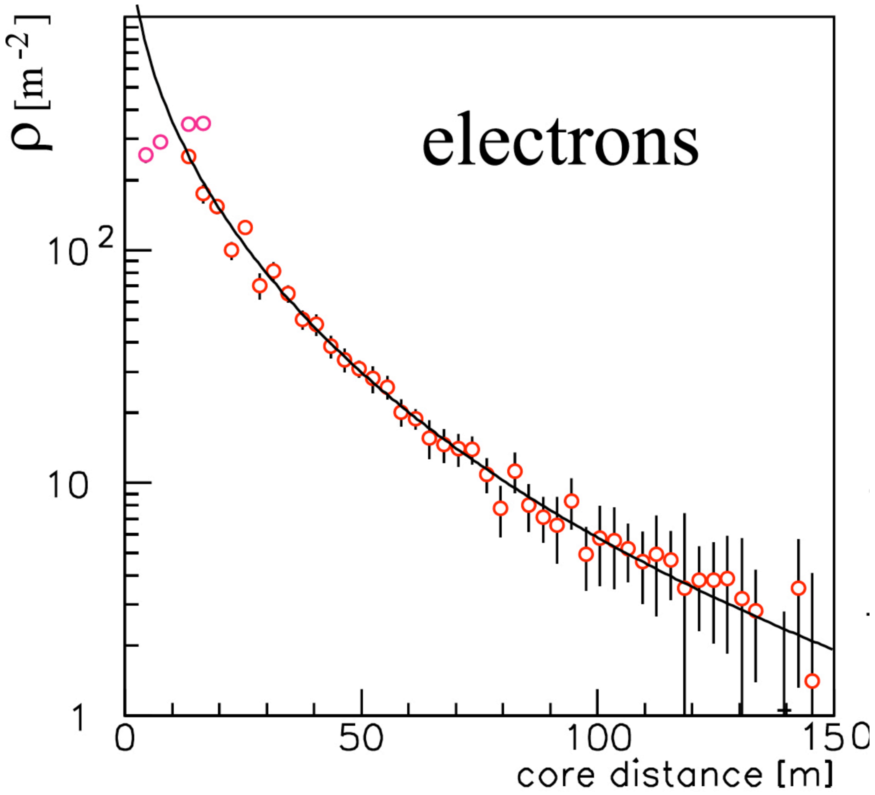
KArlsruhe Shower Core and Array DEtector



Simultaneous measurement of
electromagnetic,
muonic,
hadronic
shower components

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

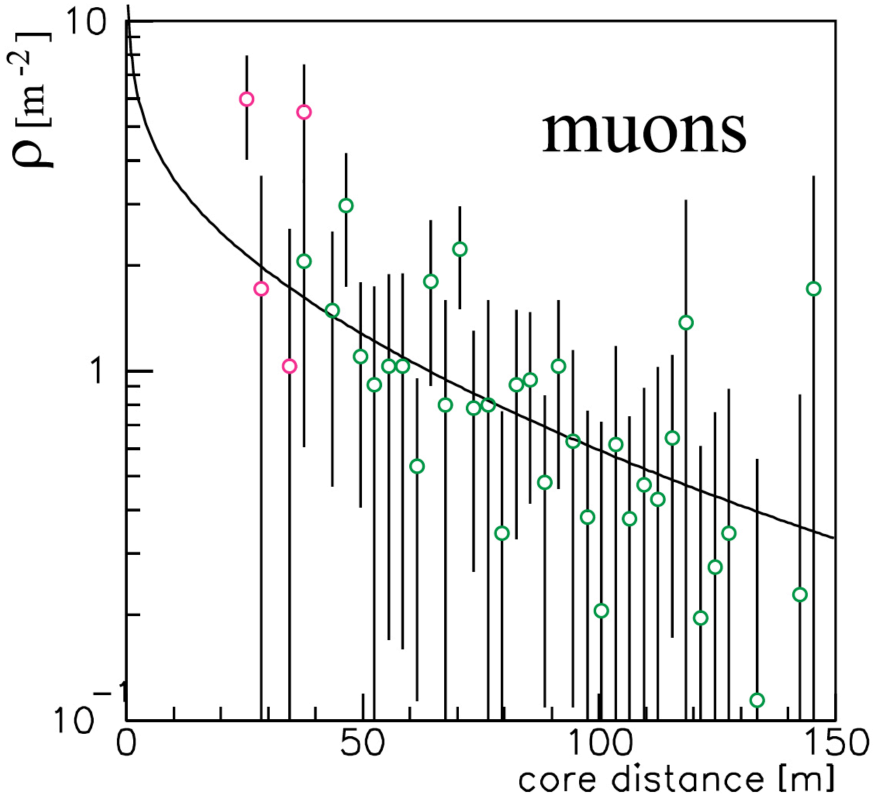
Determination of electron and muon numbers



Modified NKG fit, corrected for E_e > 3 MeV

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

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



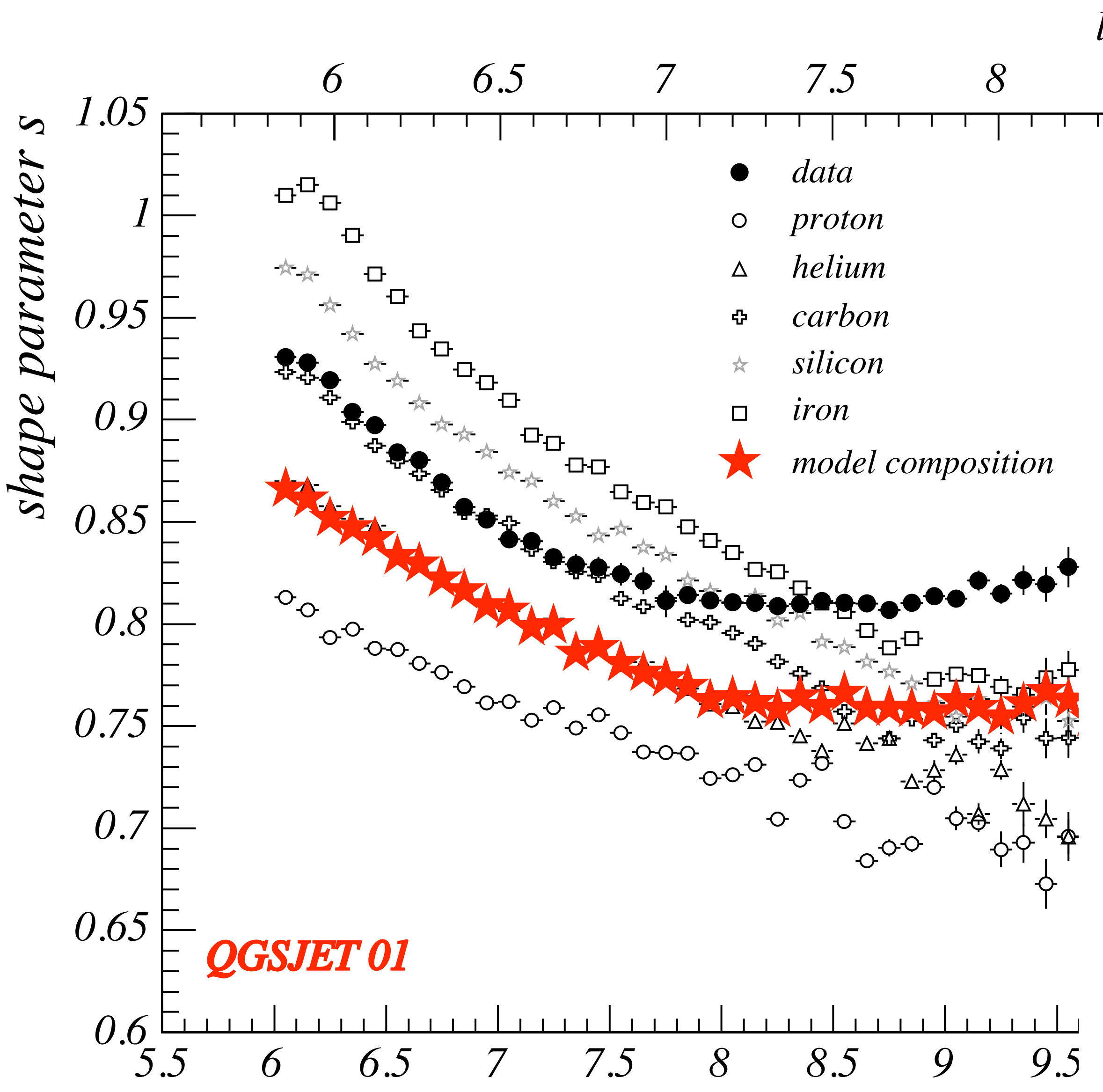
Modified NKG fit, E_μ > 230 MeV

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

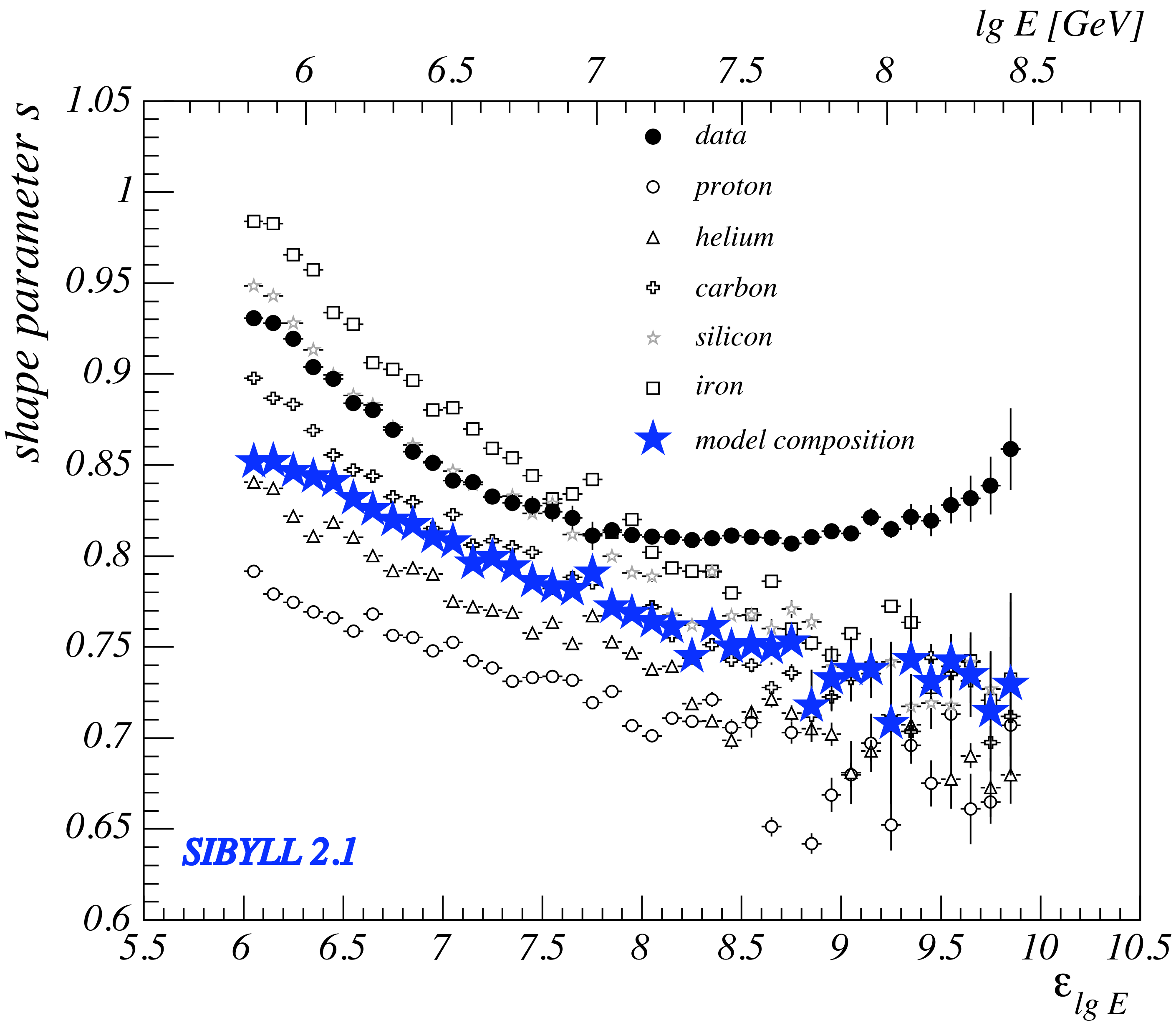
truncated to 40 - 200m
effective age taken from simulations

Slope of lateral distribution at ground

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



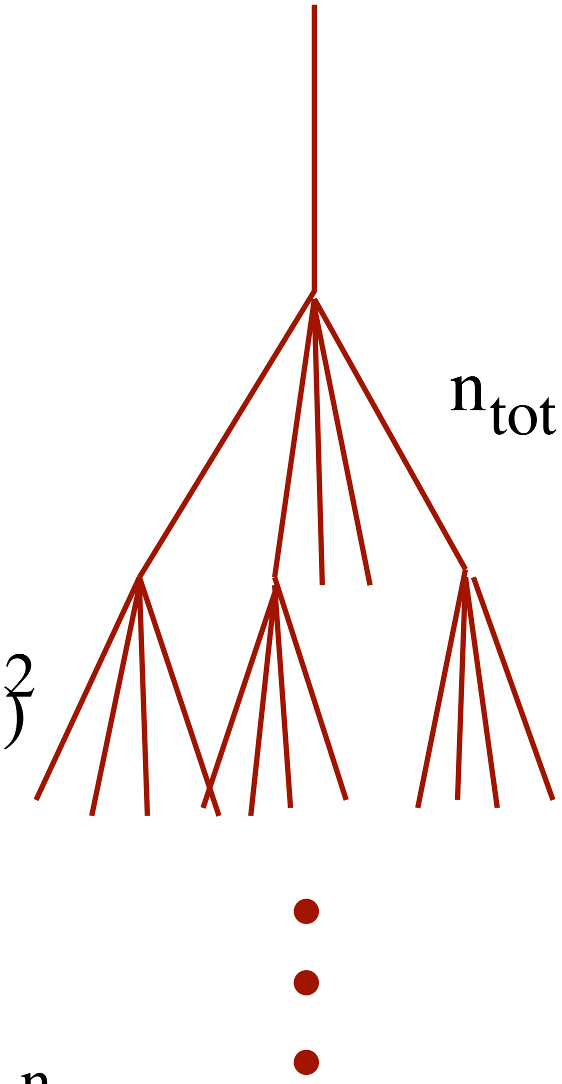
(Apel et al., Astropart. Phys. 24 (2006) 467)



Electron lateral distribution wider than predicted in simulations

Shower simulation: muon deficit?

Muon production in hadronic showers



E_0

E_0/n_{tot} $\quad n_{tot} = n_{ch} + n_{neut}$

$E_0/(n_{tot})^2$ $\quad (n_{ch})^2$

$E_0/(n_{tot})^n$ $\quad (n_{ch})^n$

Primary particle proton

π^0 decay immediately

$\pi^{\pm}$ initiate new cascades

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.82 \ldots 0.95$$

Assumptions:

- cascade stops at $E_{\text{part}} = E_{\text{dec}}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

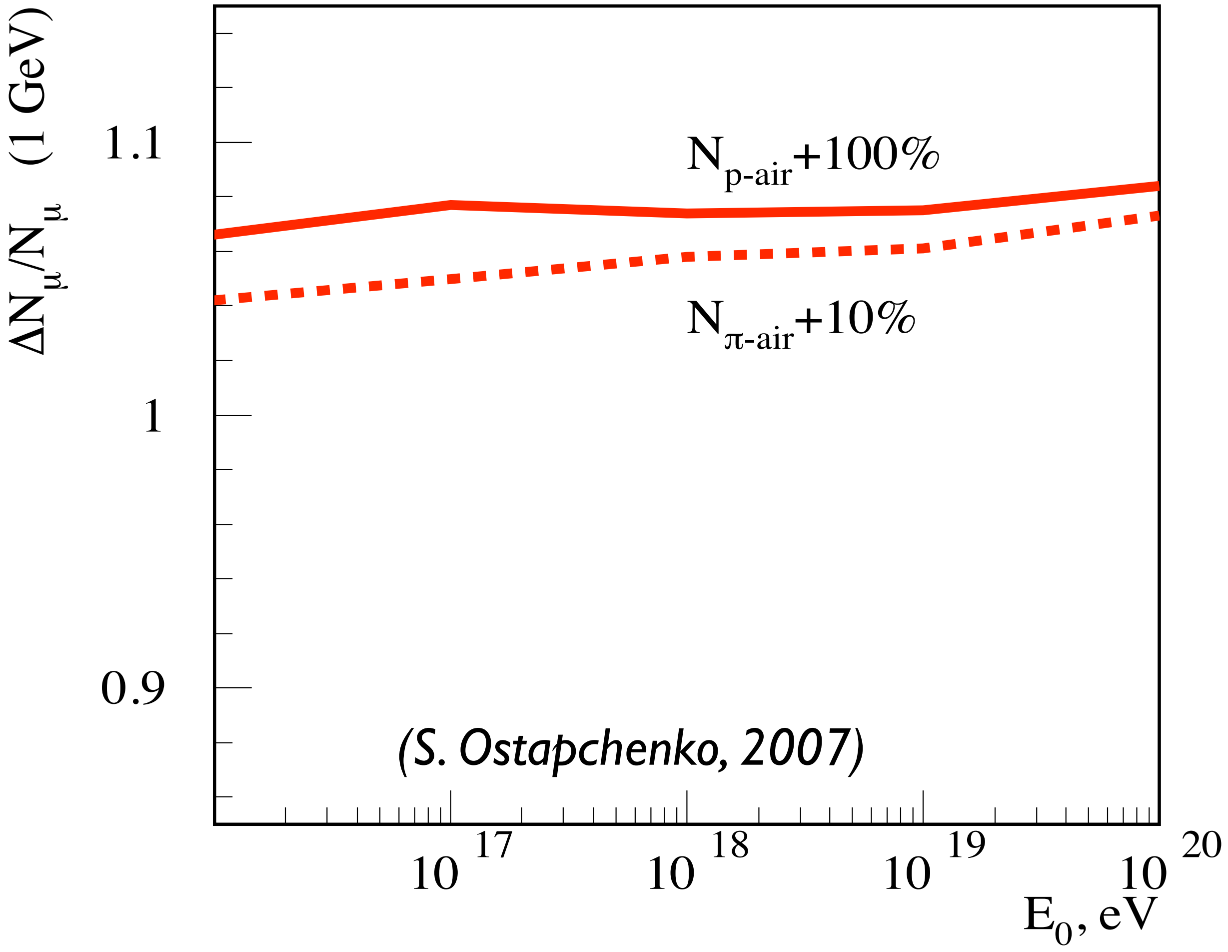
Sensitivity to physics of first interaction

Muon production:

$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\alpha$$

$$N_\mu = n_{\rm ch}^{\rm (first)} \left(\frac{E_0}{n_{\rm tot}^{\rm (first)} E_{\rm dec}}\right)^\alpha = k^{1-\alpha} \left(\frac{E_0}{E_{\rm dec}}\right)^\alpha$$

Muon enhancement

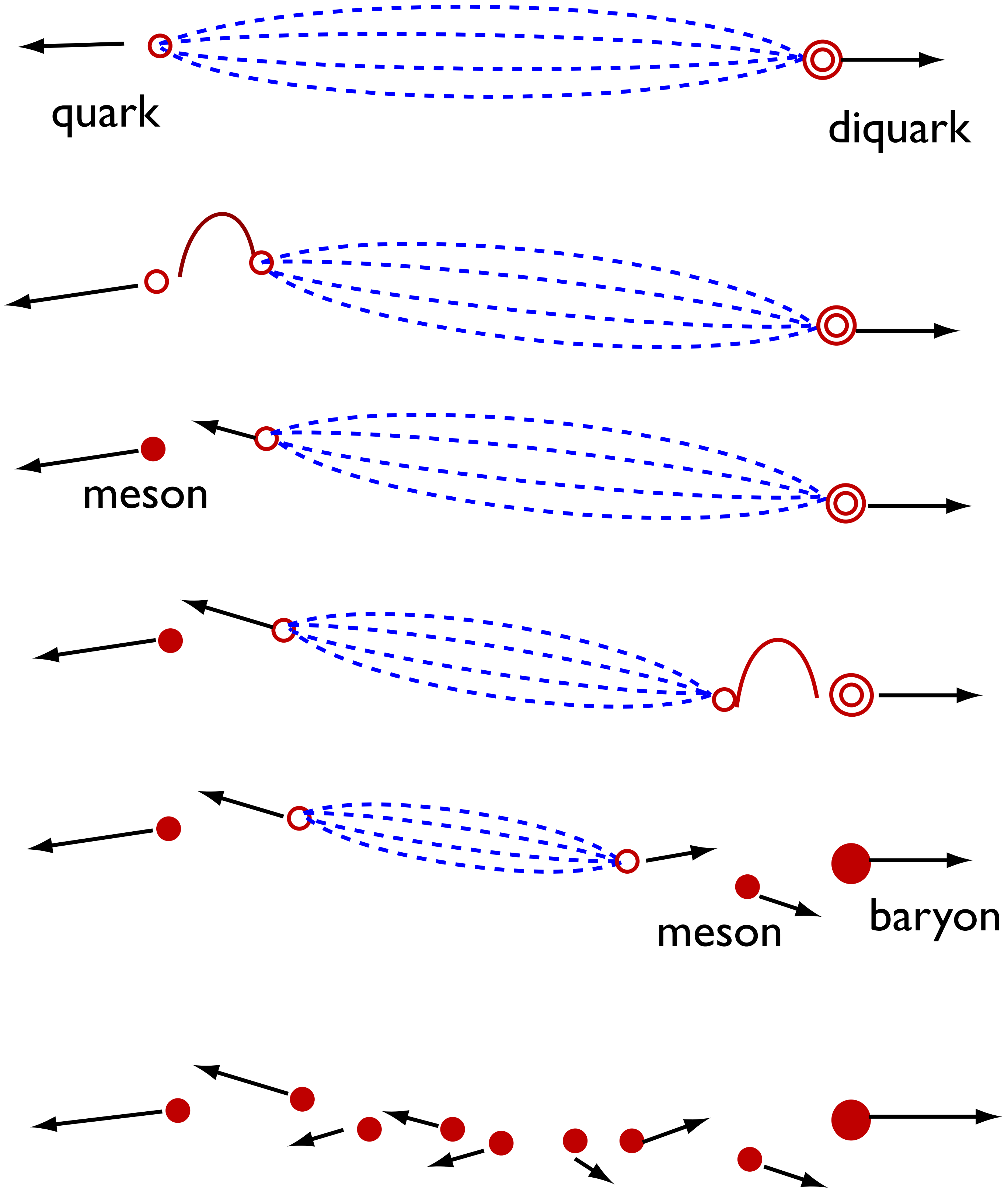


(S. Ostapchenko, 2007)

Multiplicity increase by
factor of 2: 5 -7% more muons,
factor of 10: 25% more muons

Muon number insensitive to changes of high-energy interactions

Modification of ratio of neutral to charged pions

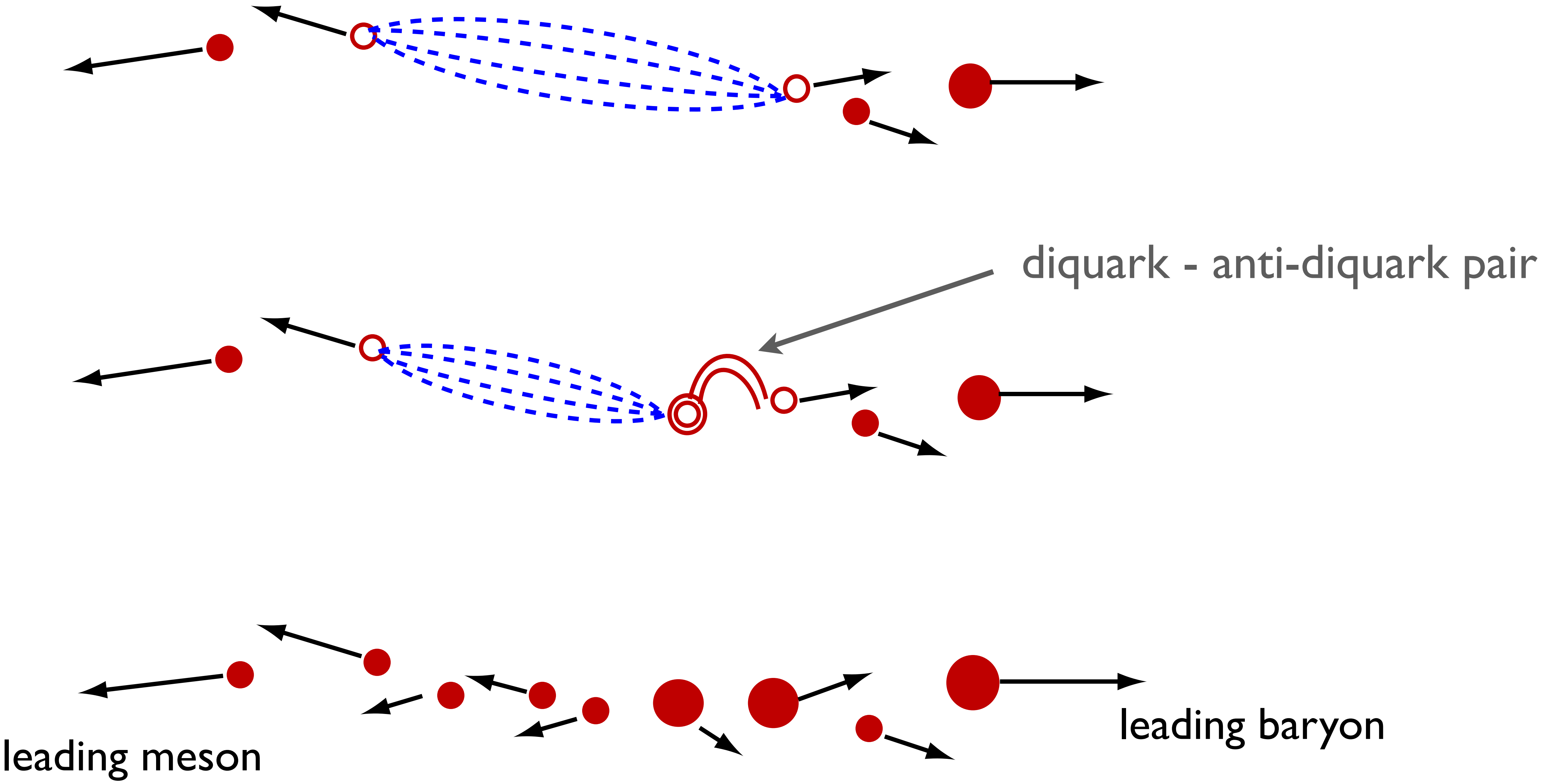


$$N_\mu = \left(\frac{E_0}{E_{\mathrm{dec}}}\right)^{\alpha}$$

$$\alpha = \frac{\ln(n_{\mathrm{ch}})}{\ln(n_{\mathrm{tot}})}$$

Particle ratios:
quark counting and
SU(3) symmetry !

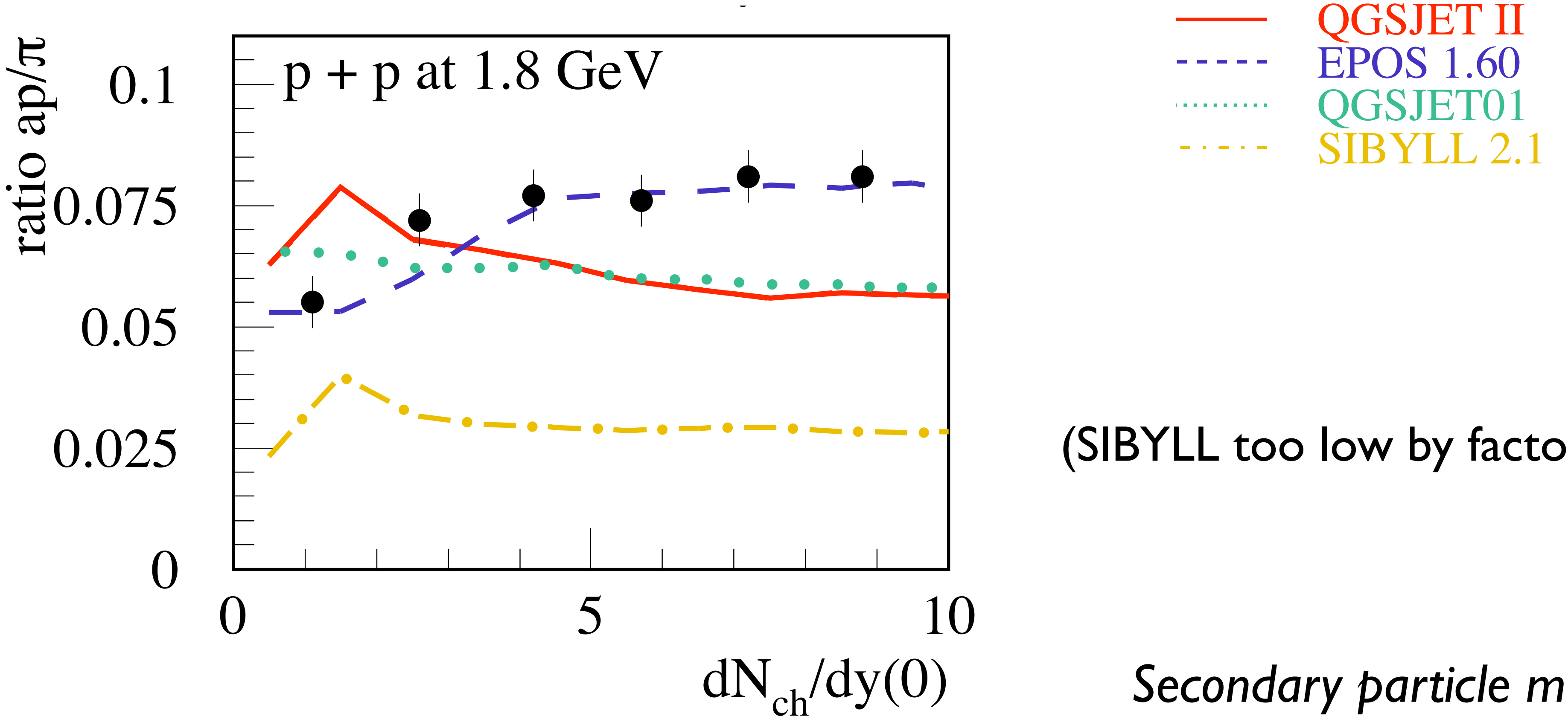
String fragmentation: baryon pairs



baryon anti-baryon pair

Baryon pair-production not understood

Tevatron data (Ecm = 1800 GeV)



(SIBYLL too low by factor ~2)

Secondary particle multiplicity

Two strings of high mass

Many strings of low mass

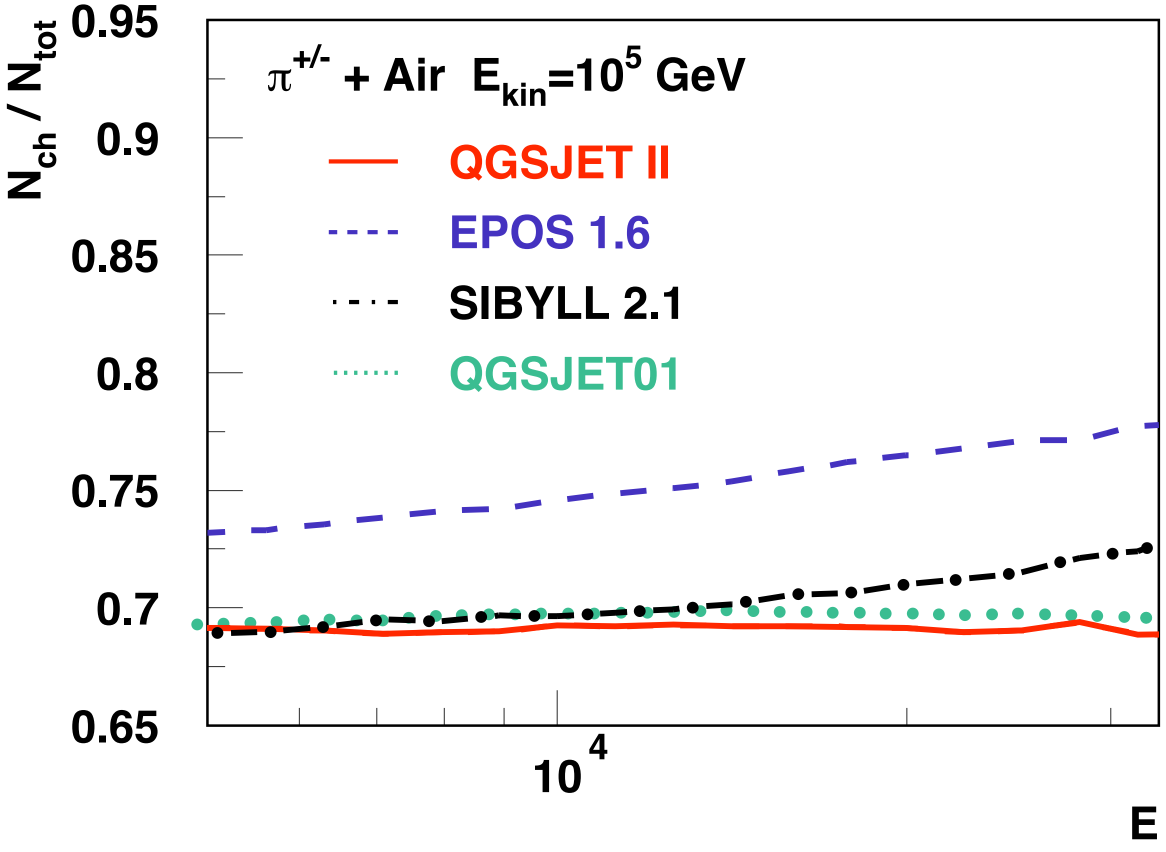
EPOS: modification of fragmentation parameters
as function of string density (RHIC data)

(K.Werner et al., Phys. Rev. C75, 2006)

EPOS: Enhancement of baryon pair production

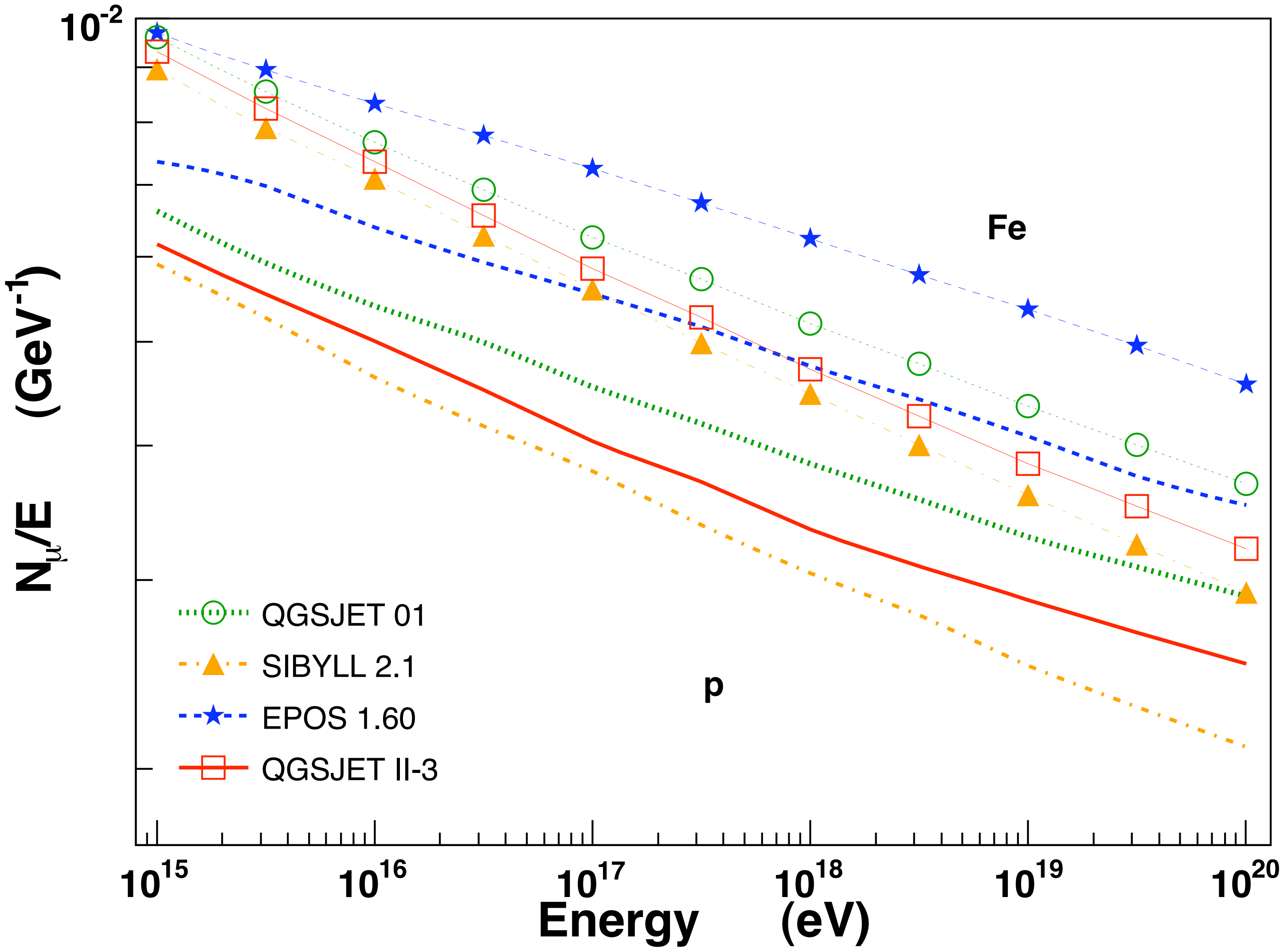
(Grieder, ICRC 1973)

- Small energy fraction, low multiplicity
- Multiplication effect (no decay)
- Large transverse momentum
- Softer muon spectrum



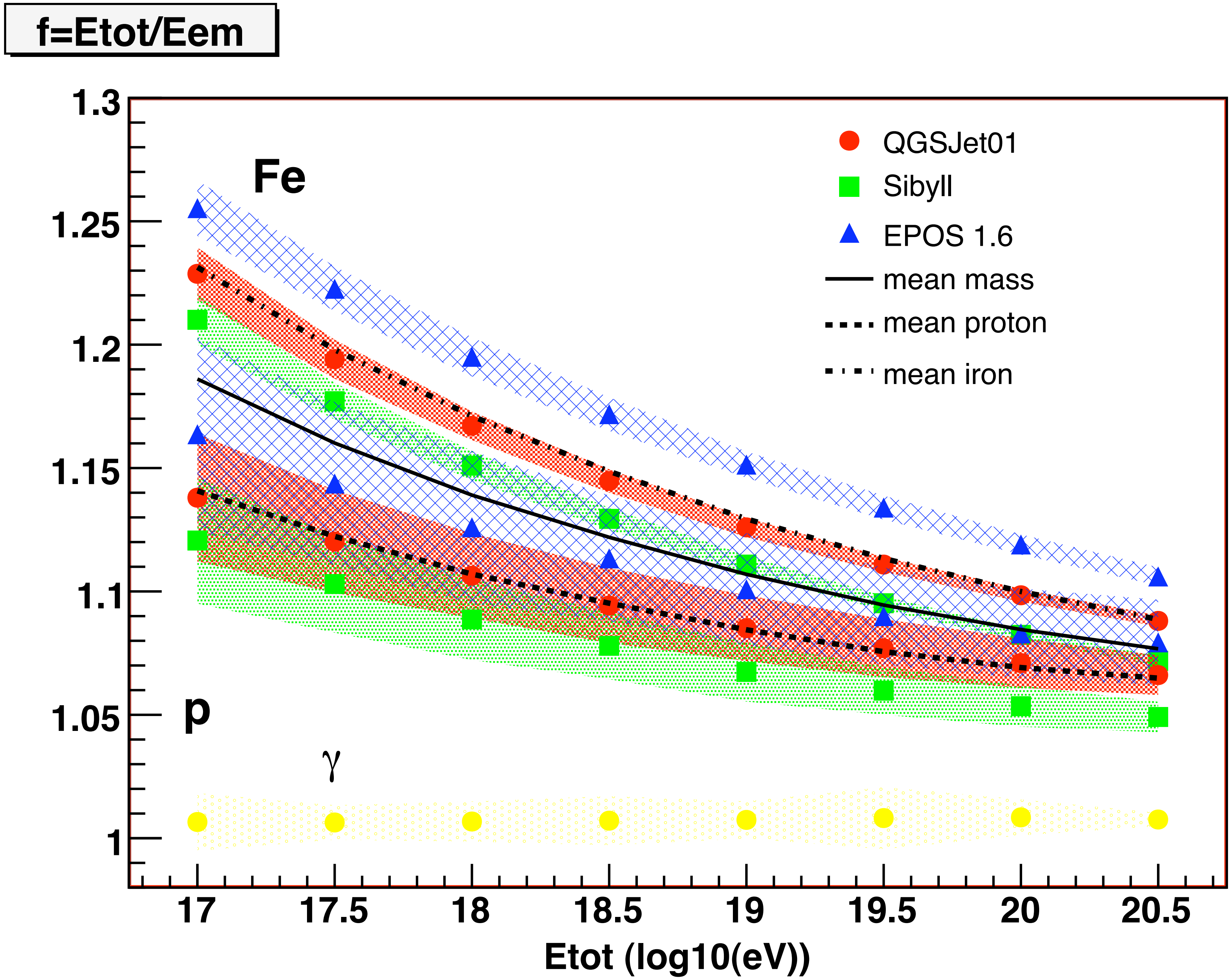
Example: secondary particles in interactions at 10^{14} eV

Muon multiplicity re-scaled with energy



(Pierog, Werner, Phys. Rev. Lett. 101, 2008)

Muon deficit: missing energy correction



(T. Pierog et al., ICRC 2007)

E = $10^{19.5}$ eV

Total energy shift
by not more than 4%,
in extreme case

Model dependence of
energy correction small

New interaction physics?

Fluctuations in Xmax and first interaction point

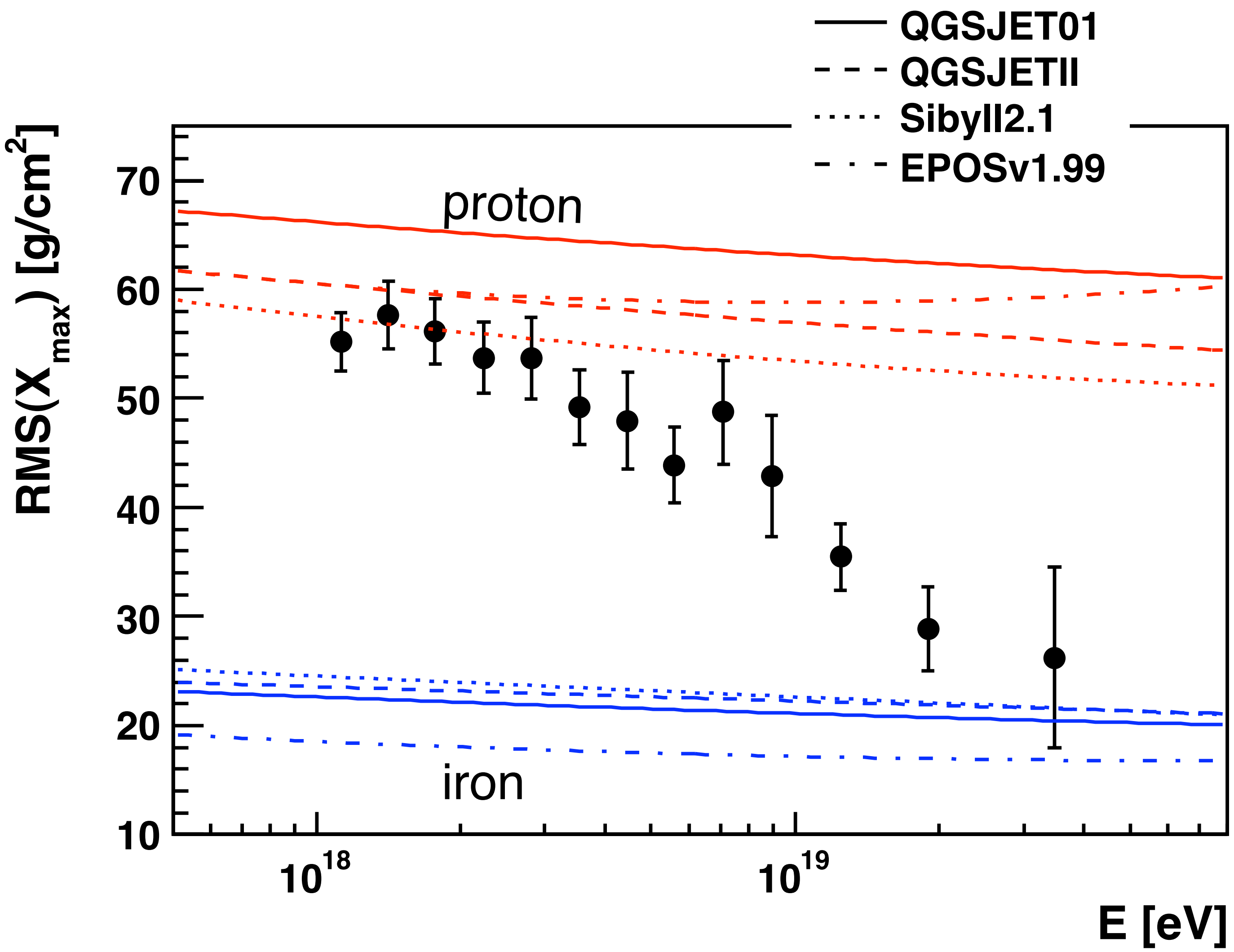
$$\frac{dN}{dX_1} = \frac{1}{\lambda_{\rm int}} \exp\left\{-\frac{X_1}{\lambda_{\rm int}}\right\}$$

$$\langle X_1 \rangle = \lambda_{\rm int}$$

$$\mathrm{RMS}(X_1) = \lambda_{\rm int}$$

$$\lambda_{\rm int} = \frac{24160\ \mathrm{g/cm^2}}{\sigma_{\rm prod}/\mathrm{mb}}$$

Protons (500 mb)
cross section: 48 g/cm^2
shower fluctuations: 36 g/cm^2

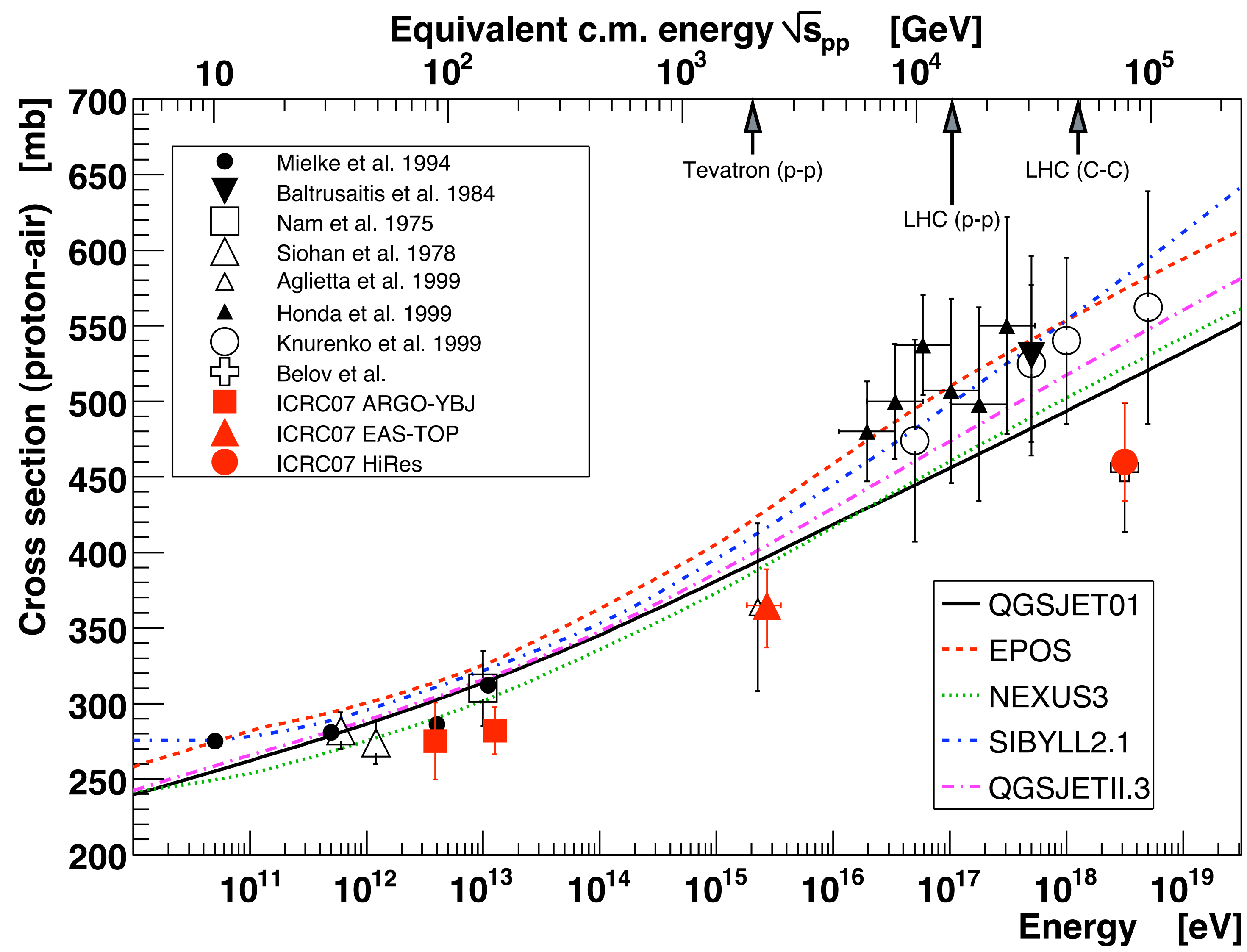


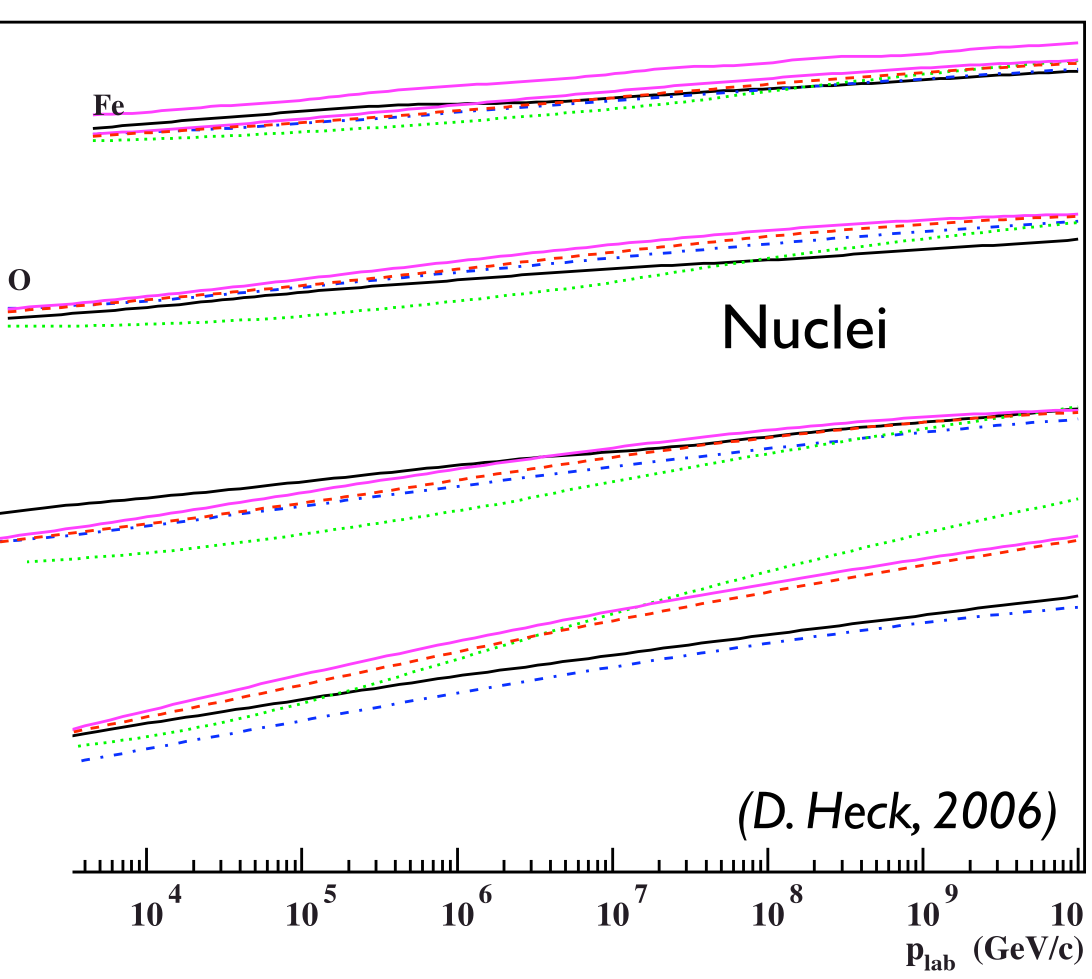
No shower-to-shower fluctuations in addition to depth X$_1$

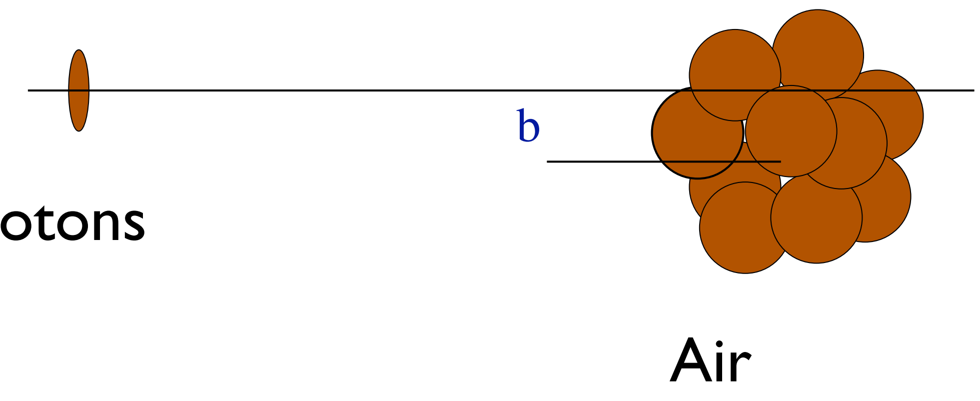
$$\sigma_{\rm prod} \geq 850\mathrm{mb}$$

Summary of cross section data and predictions

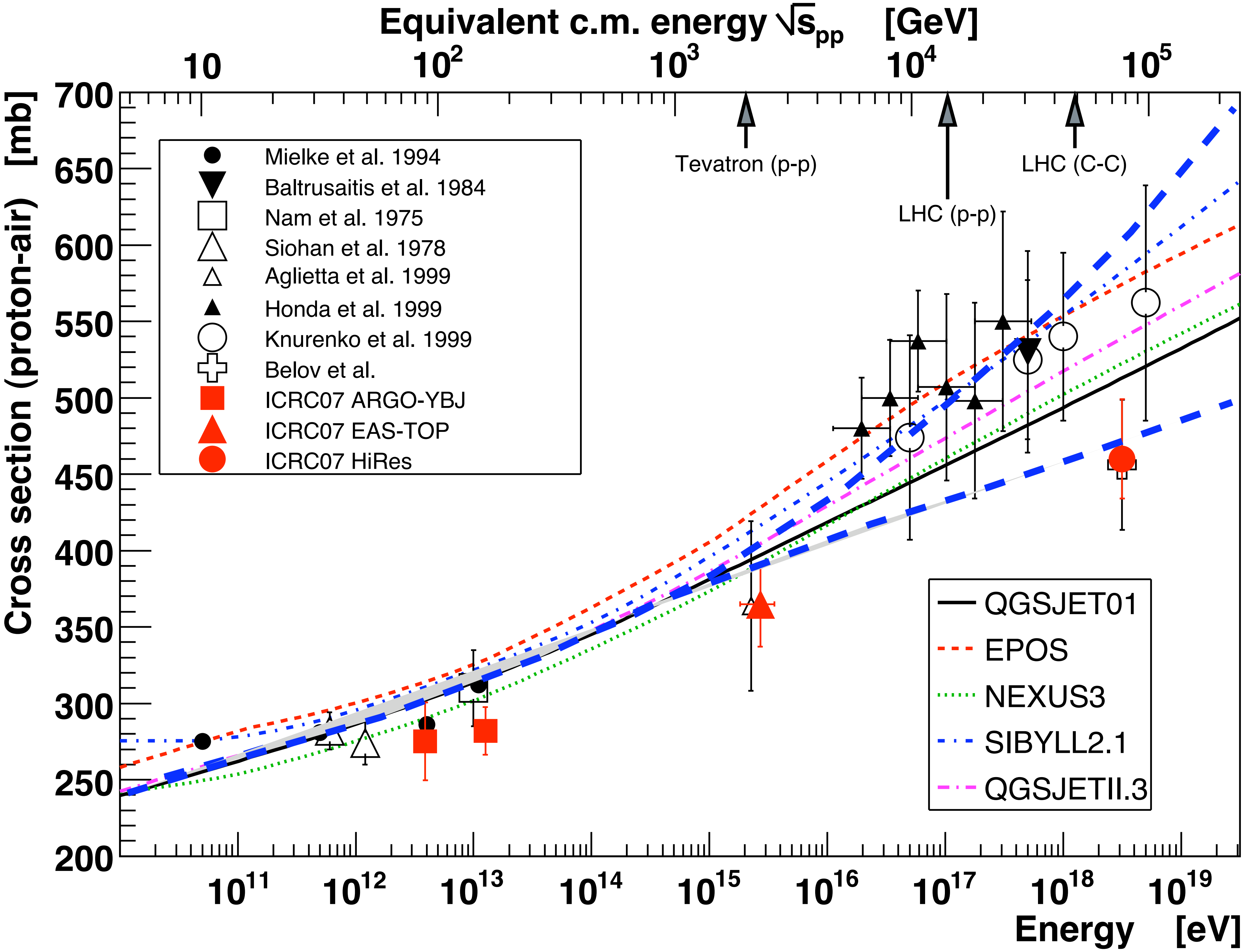
(R. Ulrich, 2007)







More realistic consideration based on SIBYLL



+25%

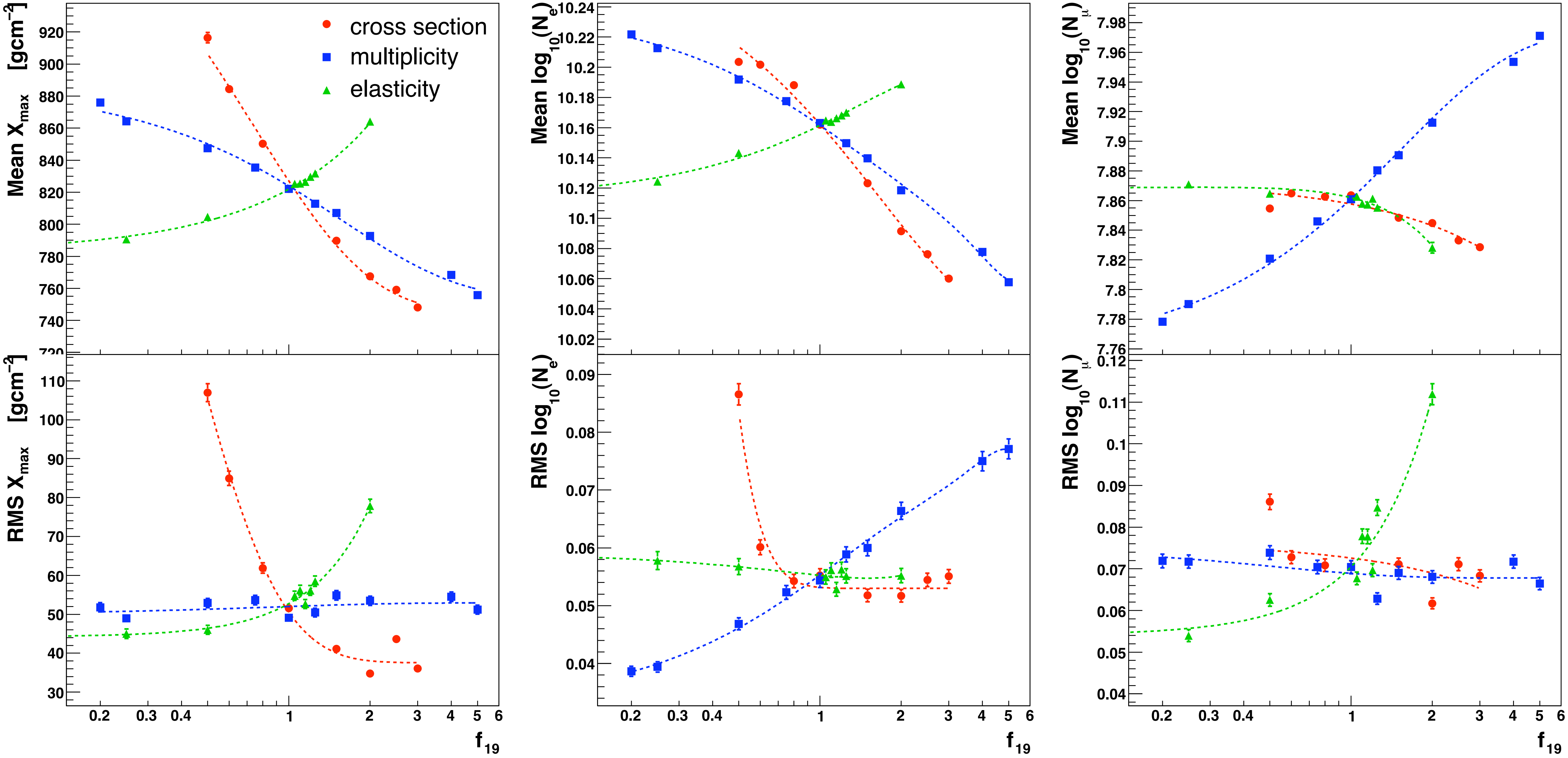
-10%

Interaction model changed phenomenologically

(R. Ulrich et al., astro-ph/0709.1392)

Proton showers (toy model)

$$E_{\mathrm{lab}} = 10^{19.5}\,\mathrm{eV}, \quad \sqrt{s}_{pp} \approx 240\,\mathrm{TeV}$$



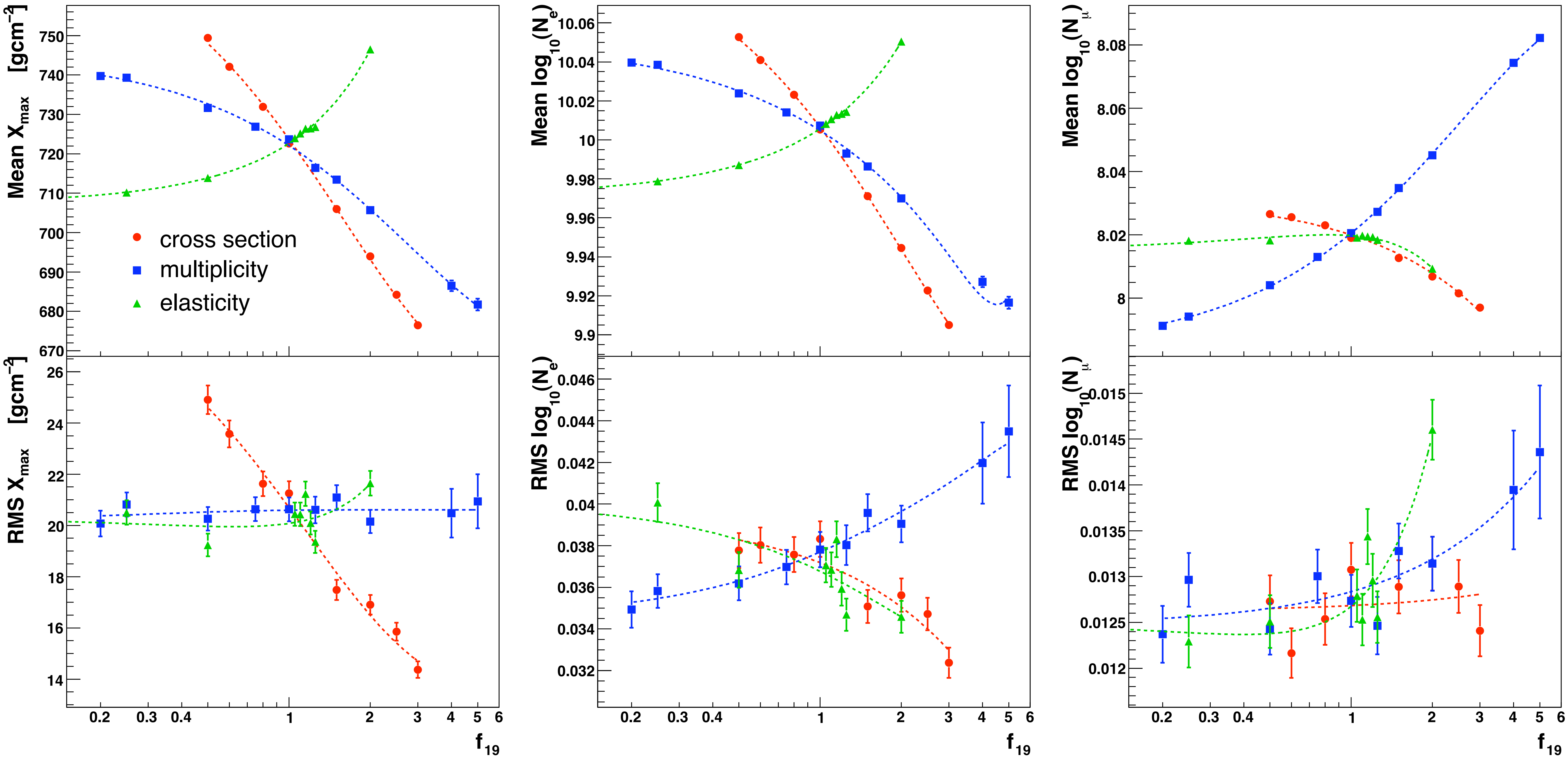
(a) Shower maximum, $X_{\max}$ (b) Electrons, N_{e} (c) Muons, N_{μ}

Scaling factor at 10^{19} eV

(R. Ulrich et al., 0906.0418)

Iron showers (toy model)

$$E_{\mathrm{lab}} = 10^{19.5}\,\mathrm{eV}, \quad \sqrt{s_{pp}} \approx 32\,\mathrm{TeV}$$



(a) Shower maximum, $X_{\max}$

(b) Electrons, N_{e}

(c) Muons, N_{μ}

Scaling factor at 10^{19} eV

(R. Ulrich et al., 0906.0418)

Conclusions

Air shower simulation not reliable for
- energy determination with muon-sensitive detector array
- ground-based composition observables
- hadron distributions at ground

Strong indications for
- deficit in muon production
- energy scale to be shifted up in case of Auger

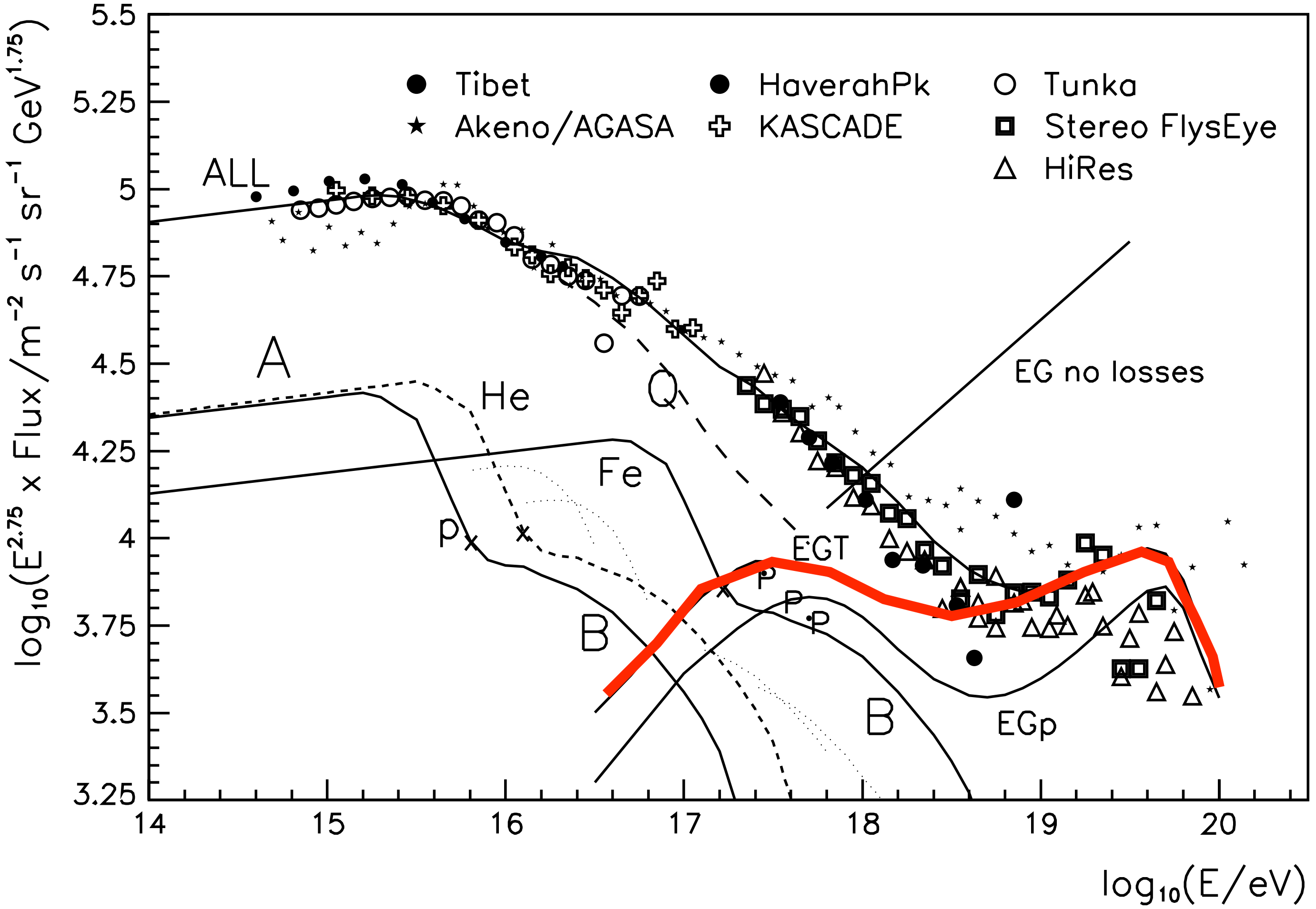
Improvement of data description with EPOS, but no complete explanation found so far

Interpretation of Auger data on Xmax with exotic physics difficult

Data from colliders (LHC!) very important to extrapolate cross section and particle production more reliably

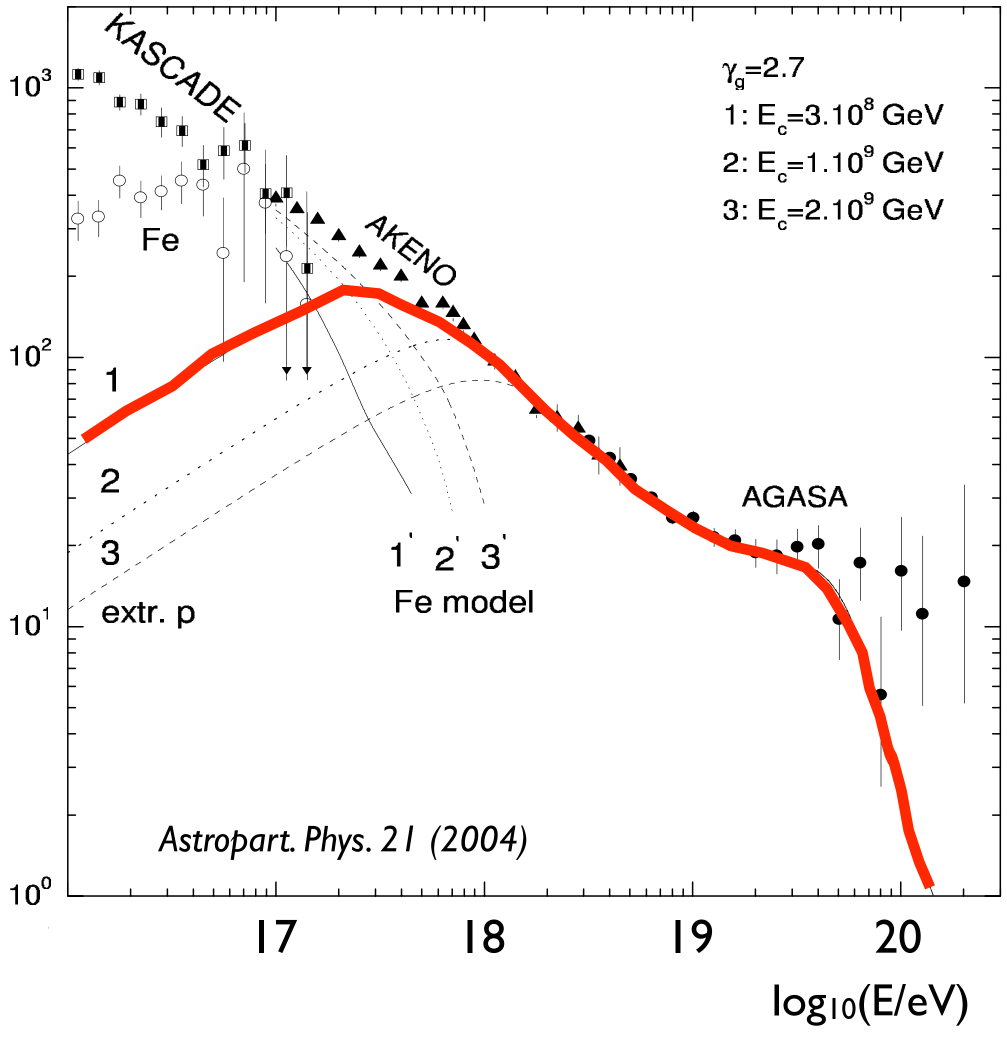
Auger enhancements: physics motivation

J. Phys. G31 (2005)



Berezinsky et al.:

- Ankle is feature due to extragalactic proton propagation
- Injection spectrum **dN/dE ~ $E^{-2.7}$**



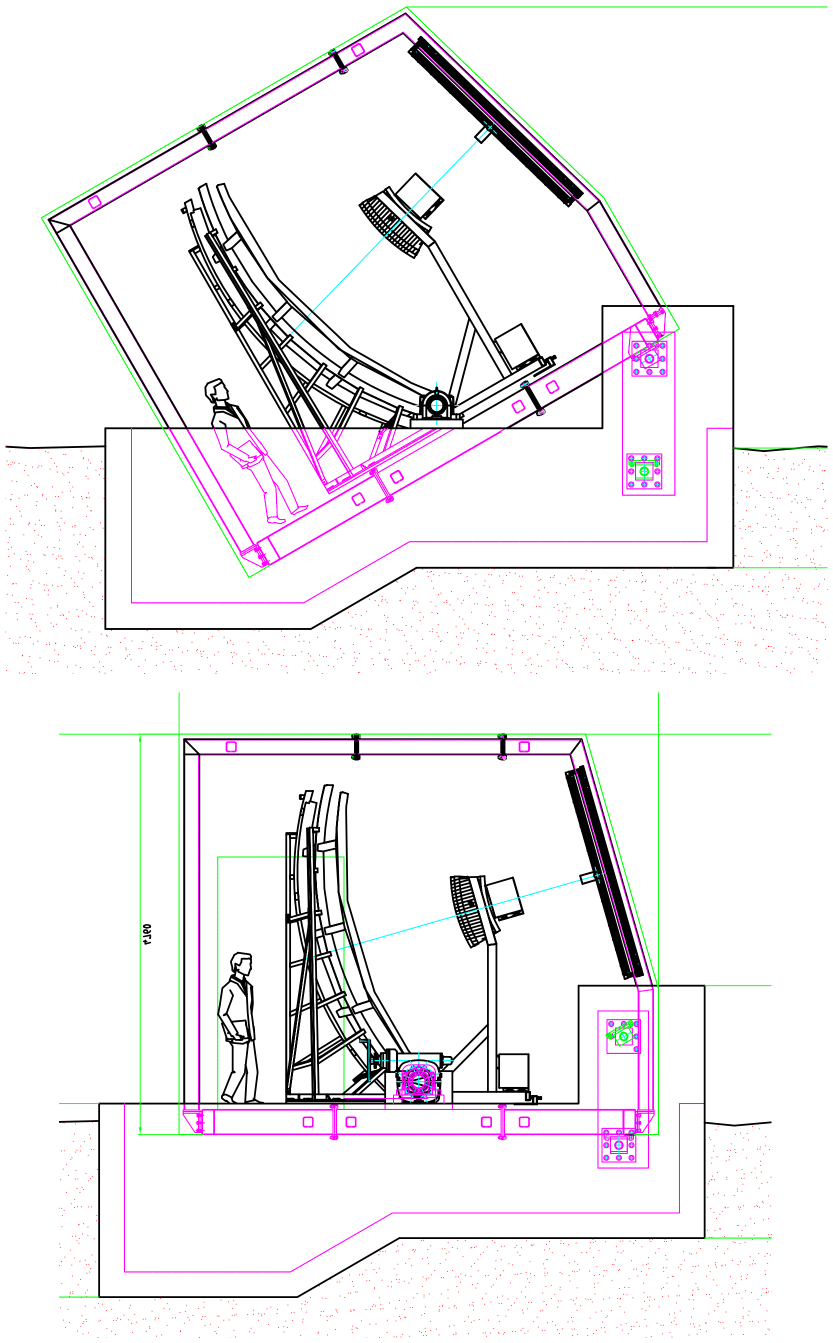
Astropart. Phys. 21 (2004)

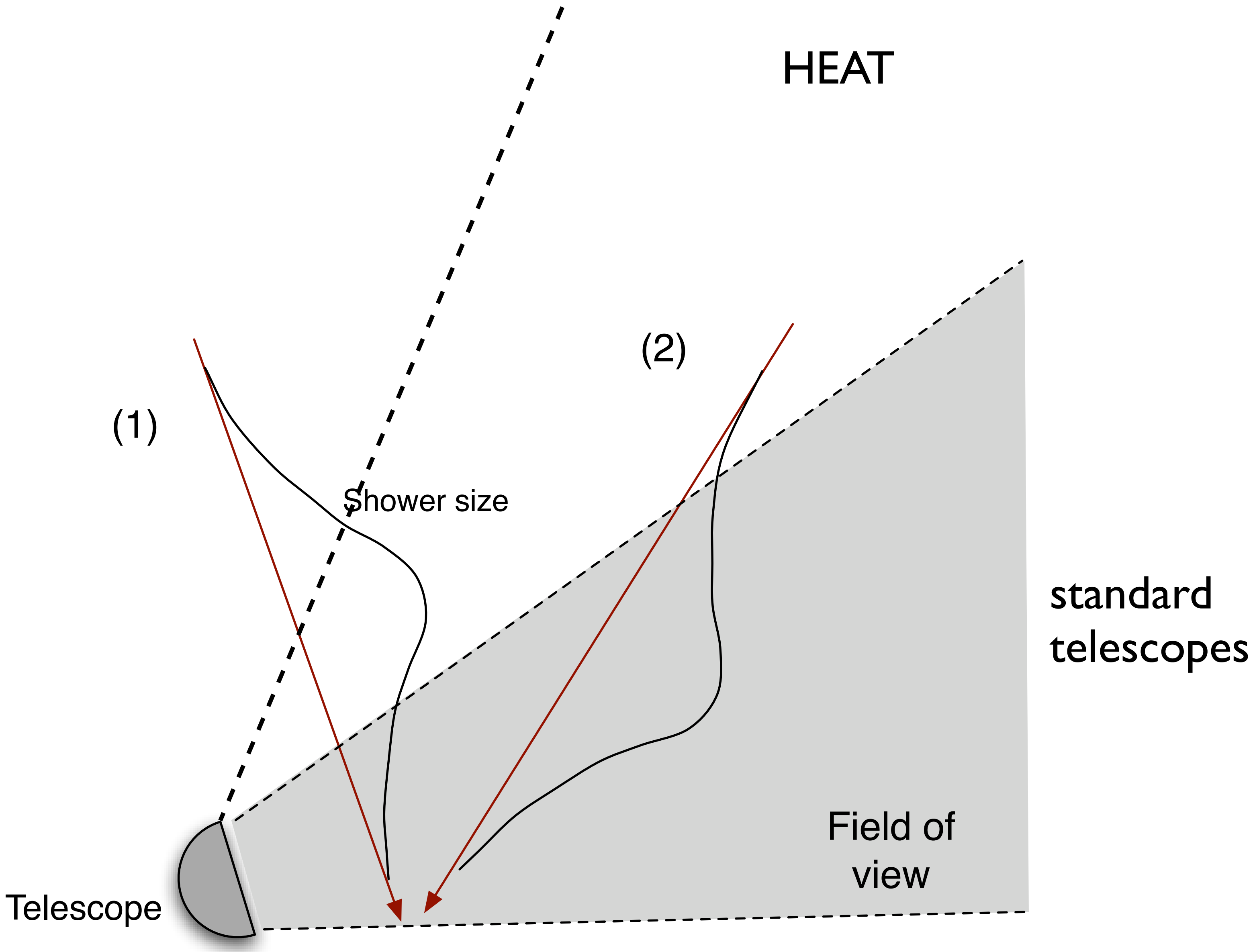
Hillas:

- Ankle is transition galactic to extragalactic cosmic rays
- Injection spectrum **dN/dE ~ $E^{-2.3}$**

Flux very similar, composition different

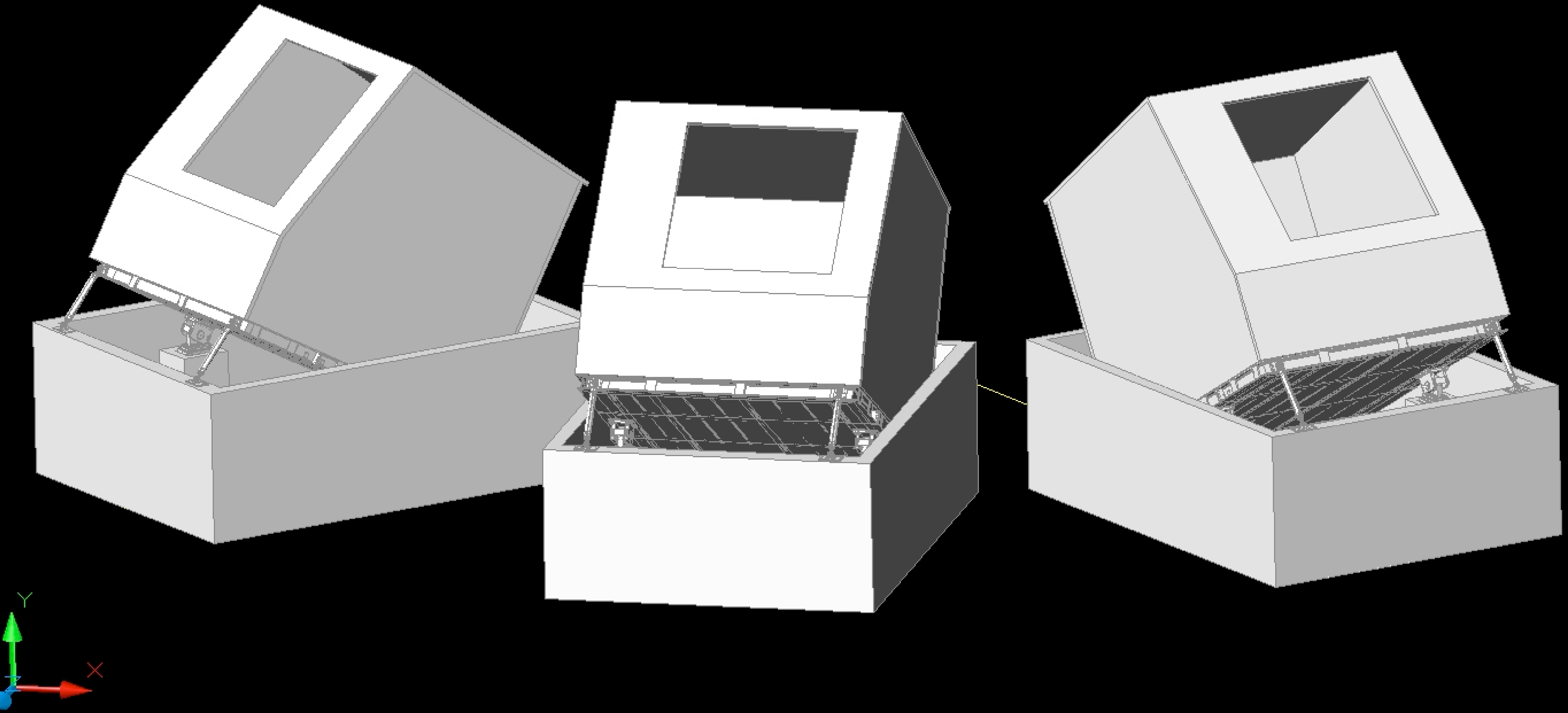
HEAT: High Elevation Auger Telescopes

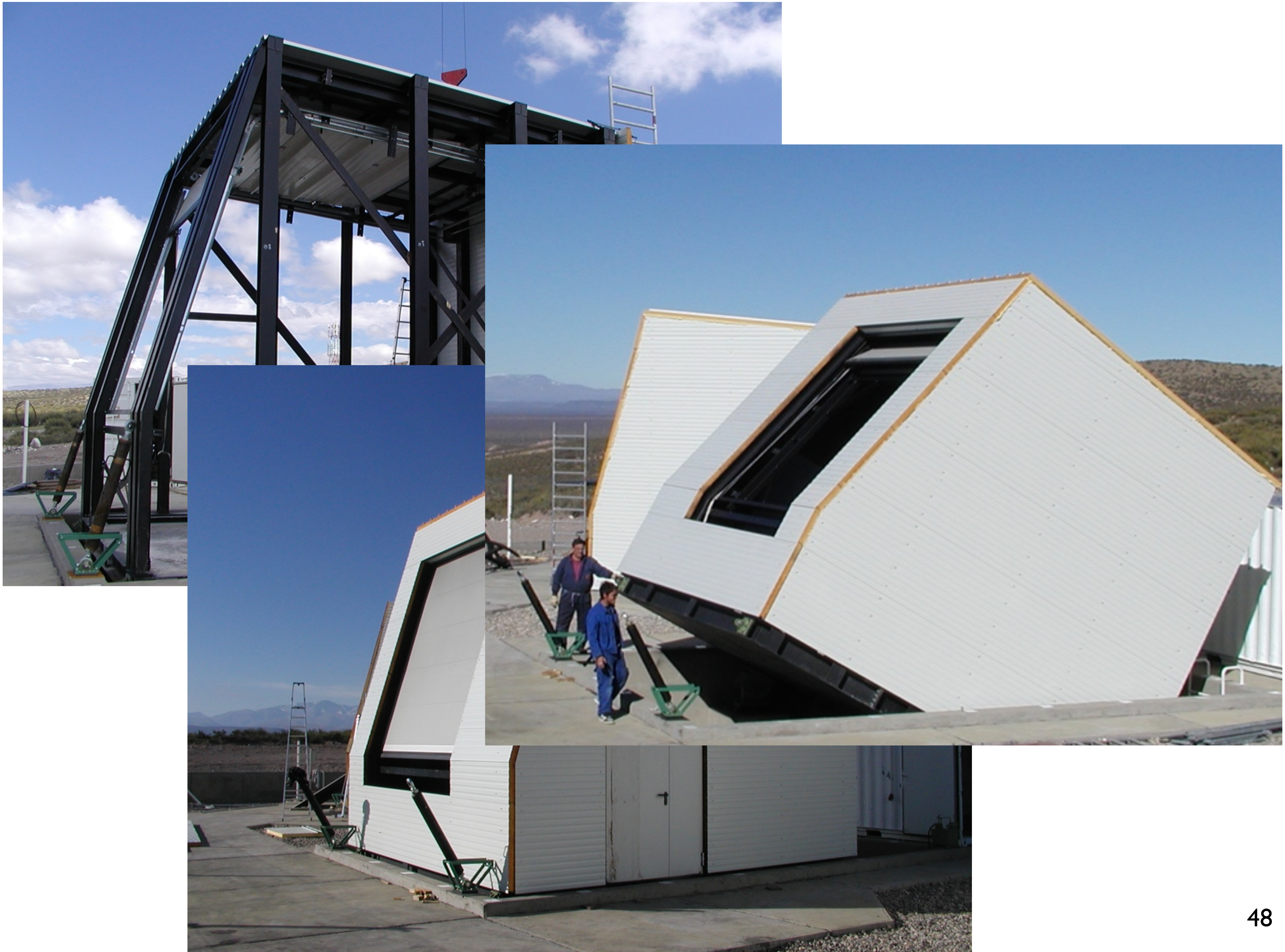


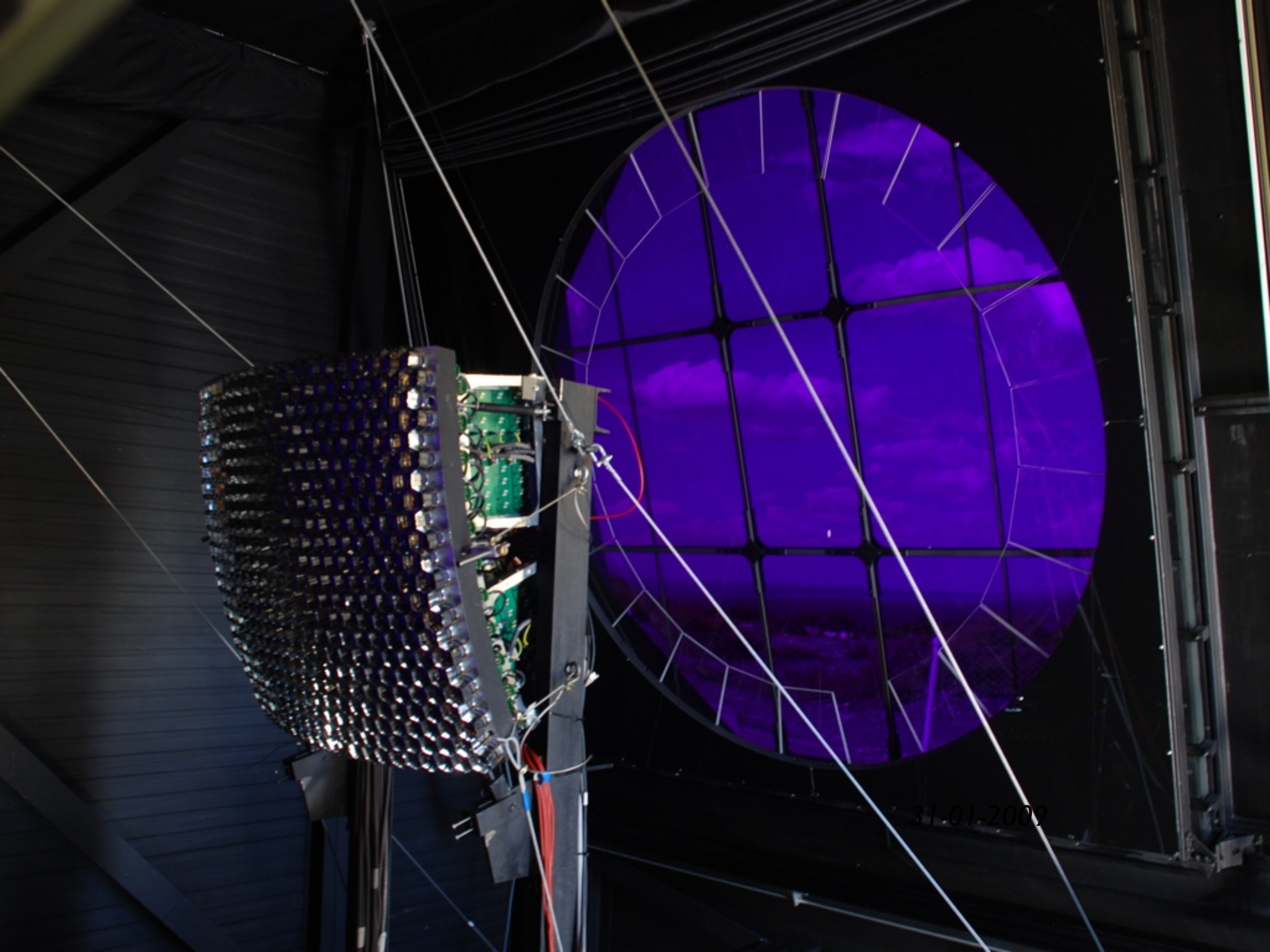


- 3 ``standard´´ Auger telescopes tilted to cover 30 - 60° elevation
- Custom-made metal enclosures
- Also prototype study for northern Auger Observatory

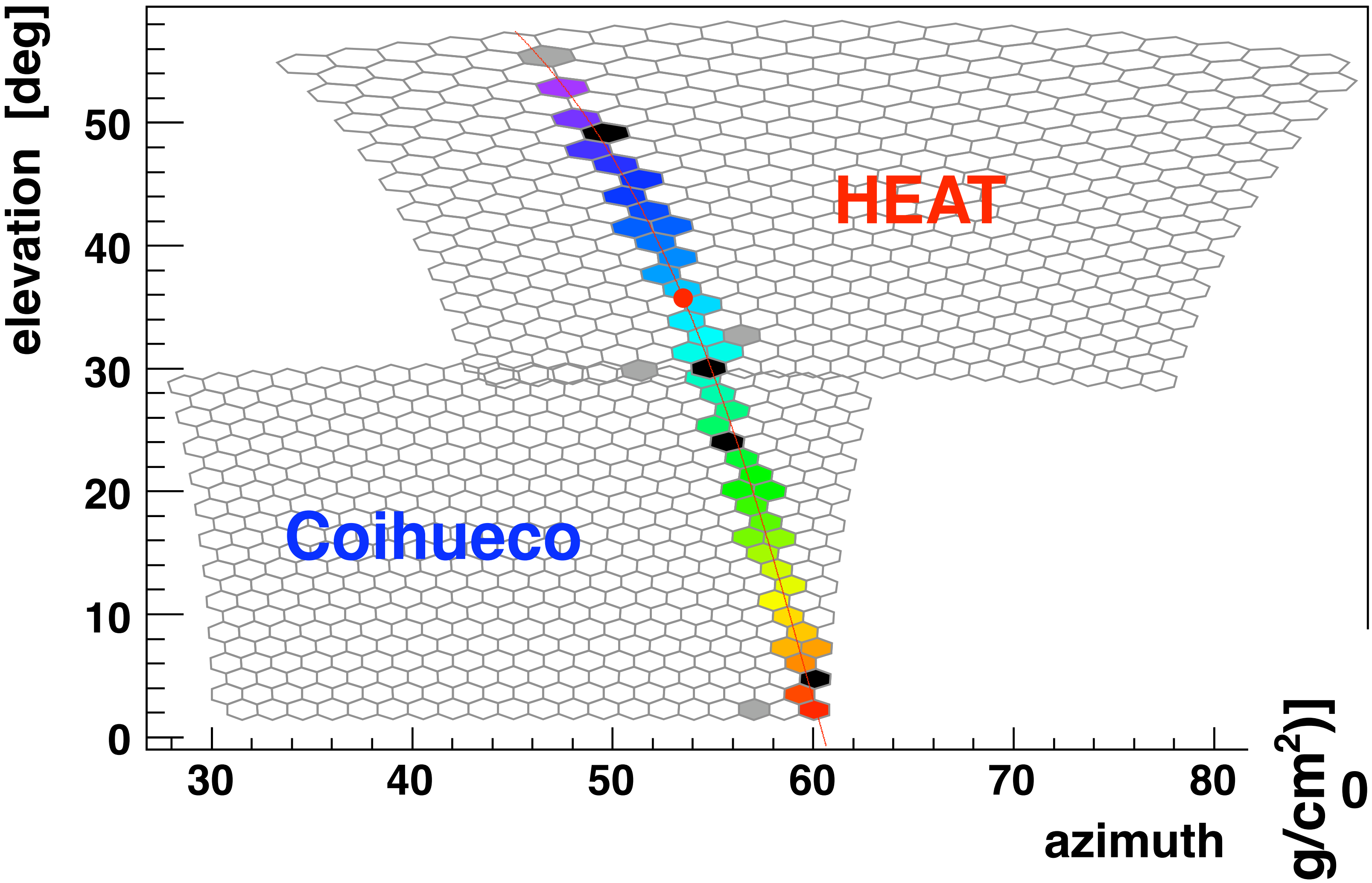
CAD view

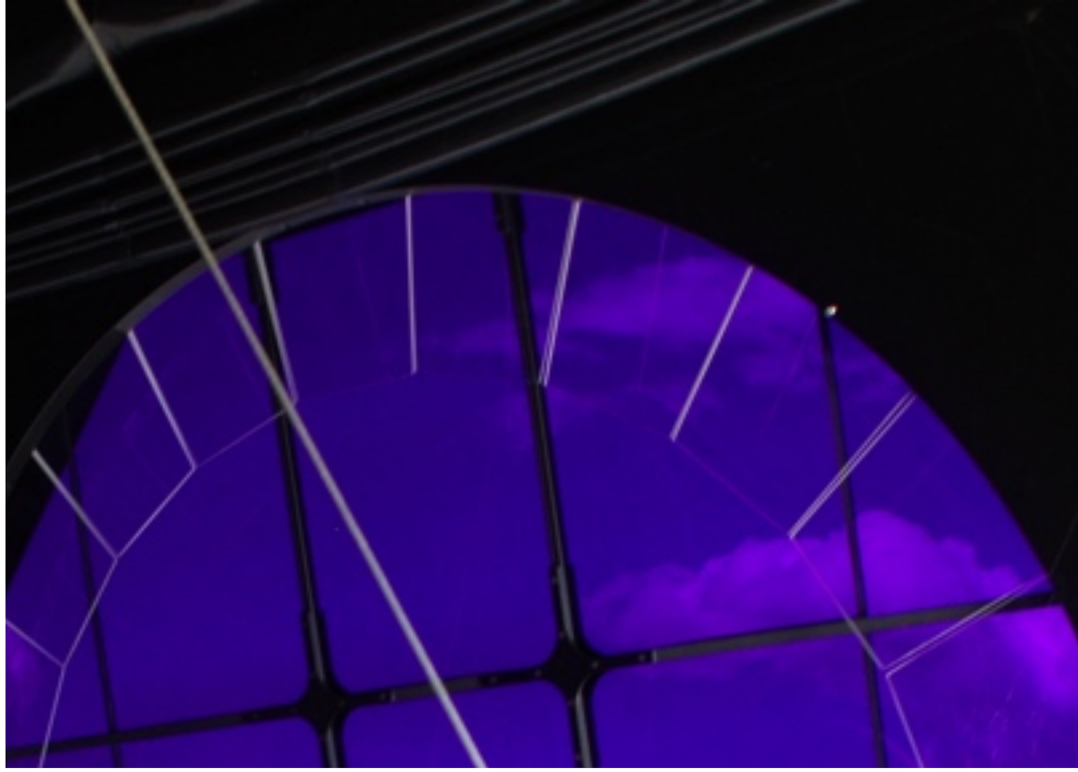




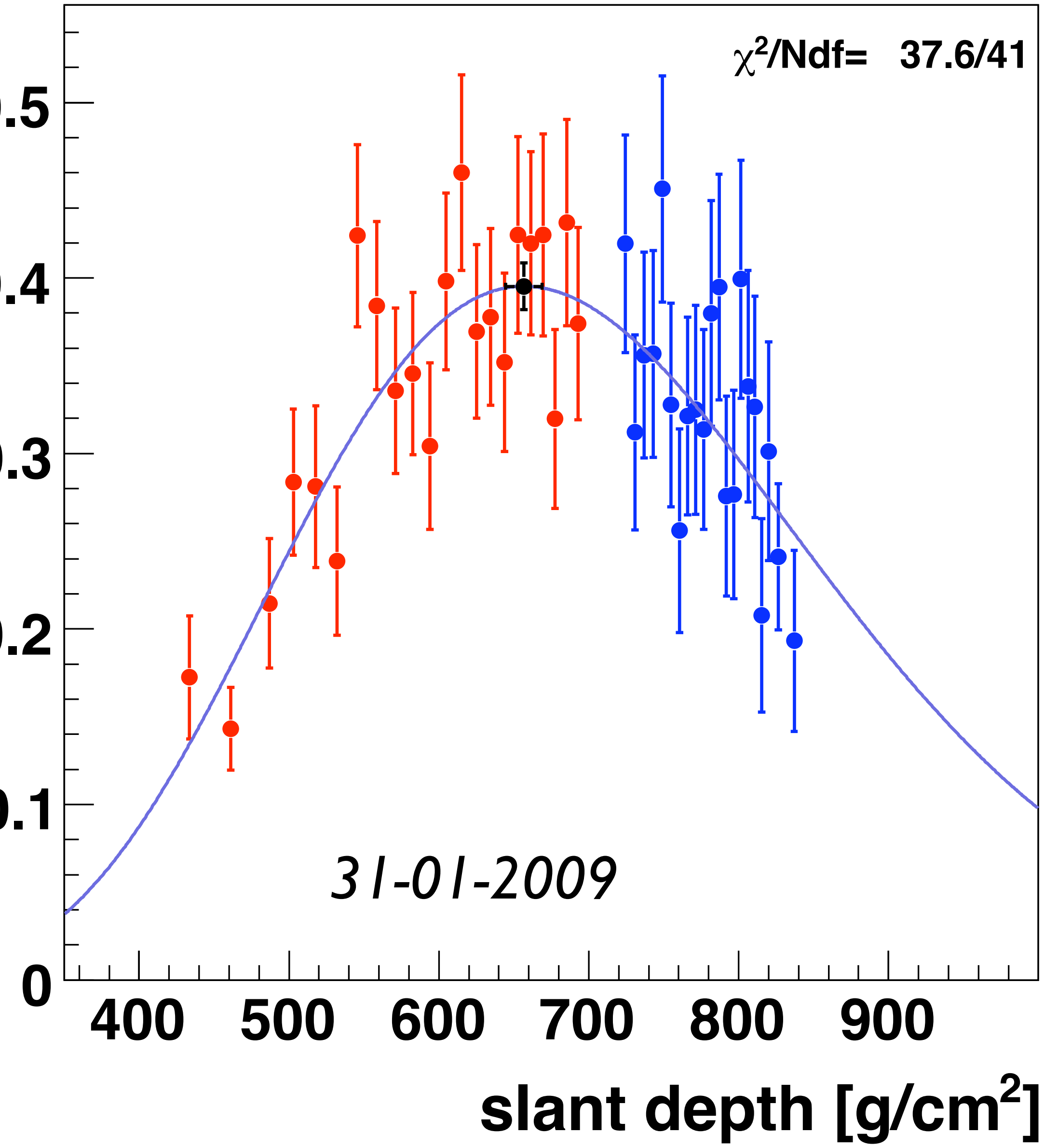


31-01-2009


elevation [deg]
50
40
30
20
10
0
30
40
50
60
70
80
azimuth
HEAT
Coihueco




SDE
SOC
Nightwish


dE/dX [PeV/(g/cm²)]
χ^2/Ndf= 37.6/41
0.5
0.4
0.3
0.2
0.1
0
400
500
600
700
800
900
slant depth [g/cm²]

31-01-2009