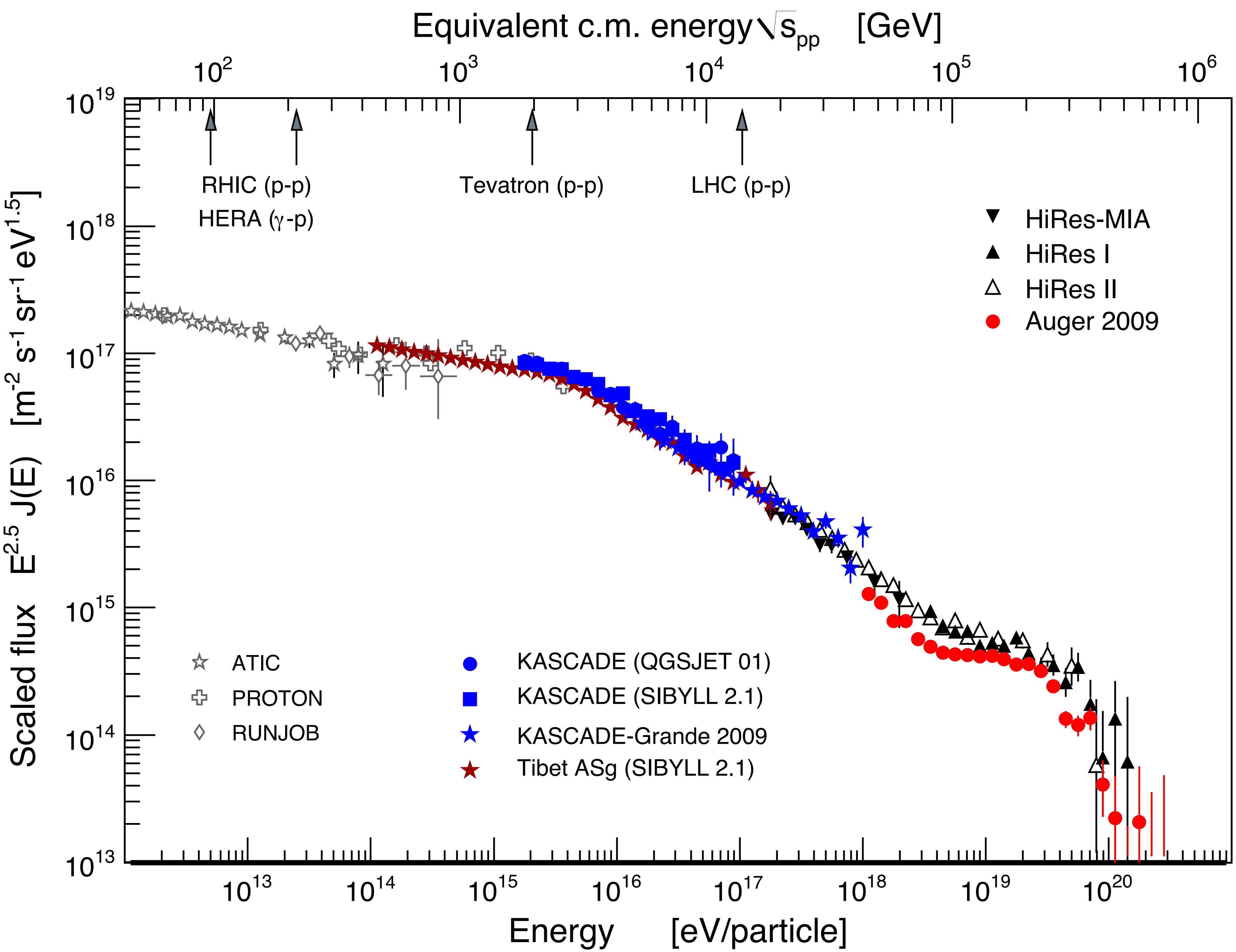
Status of Air Shower Simulations

Ralph Engel,
for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

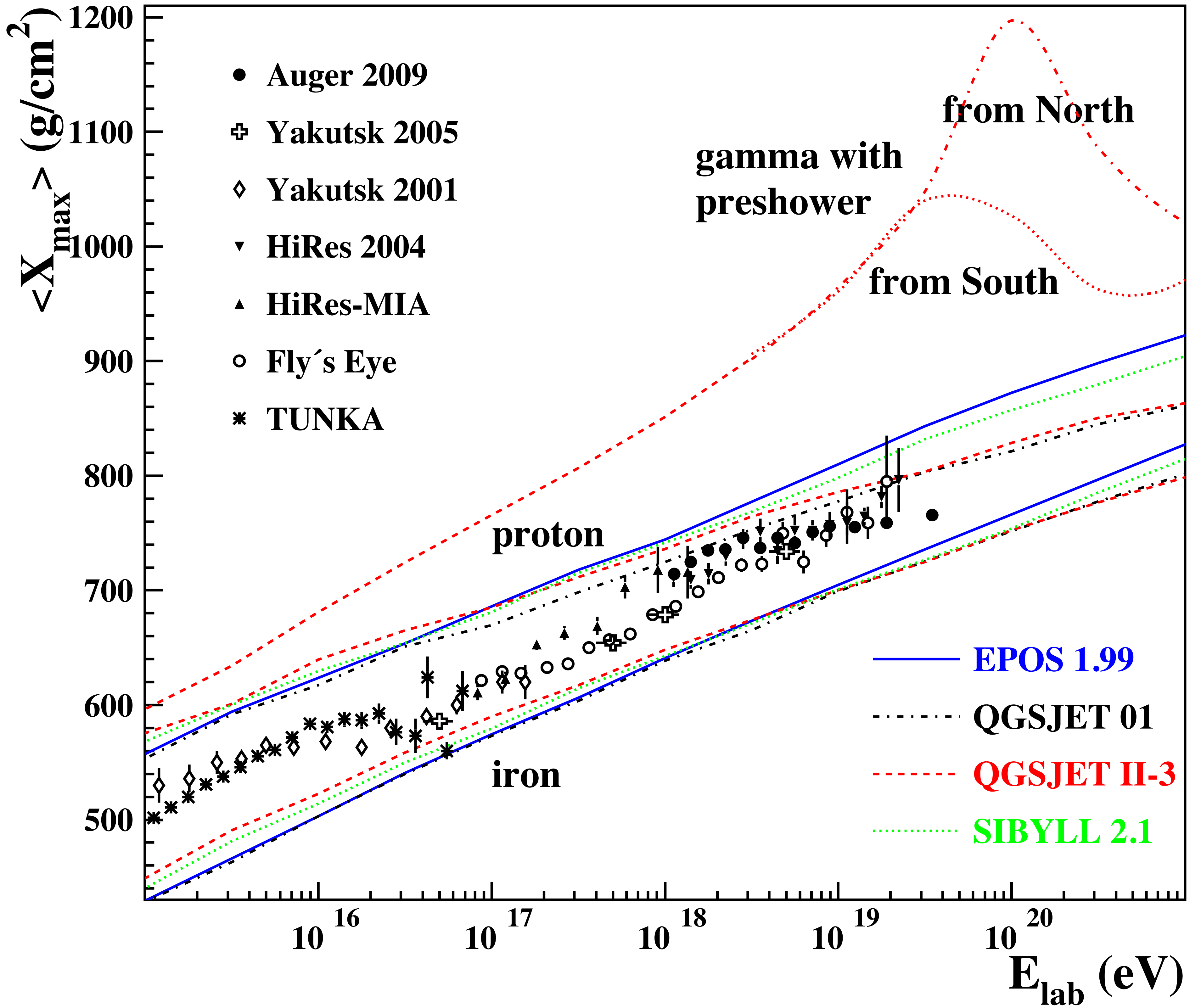
Karlsruhe Institute of Technology

Success: all-particle flux



Composition based on mean Xmax

(Heck, 2010)

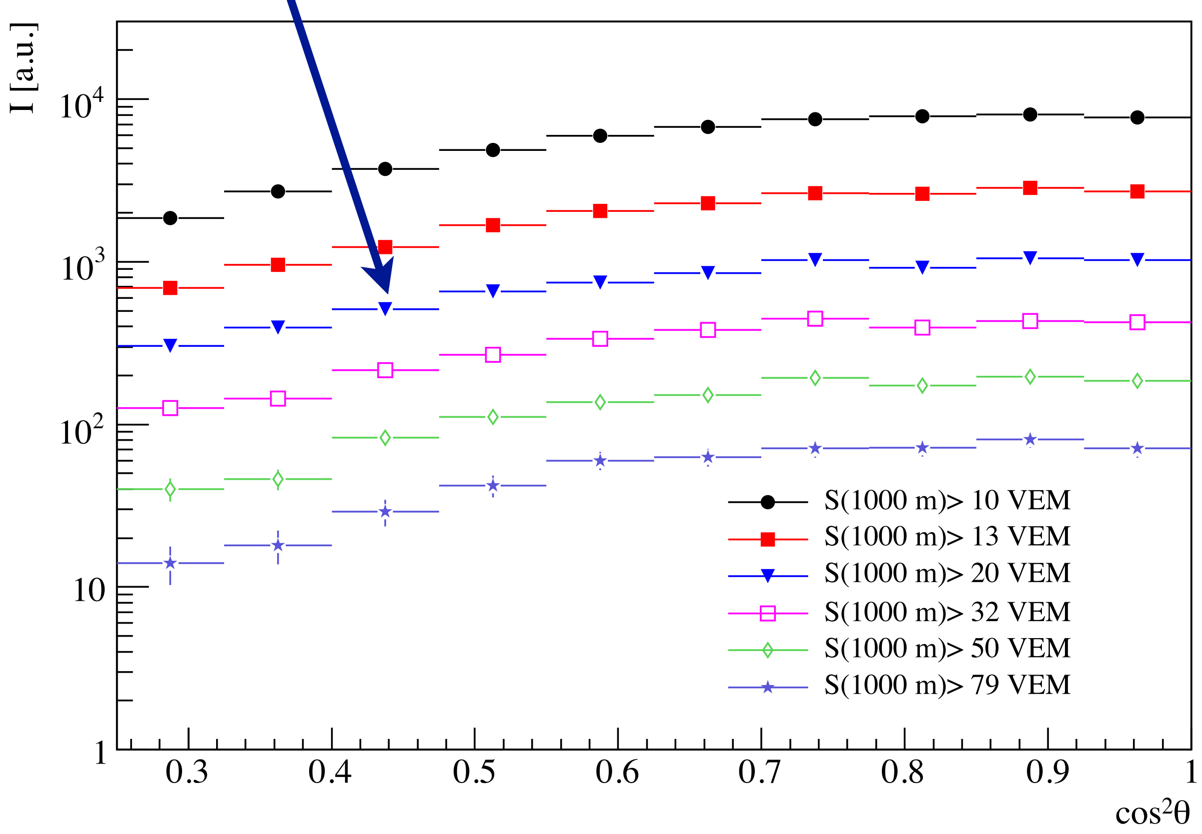


Constant intensity cut method

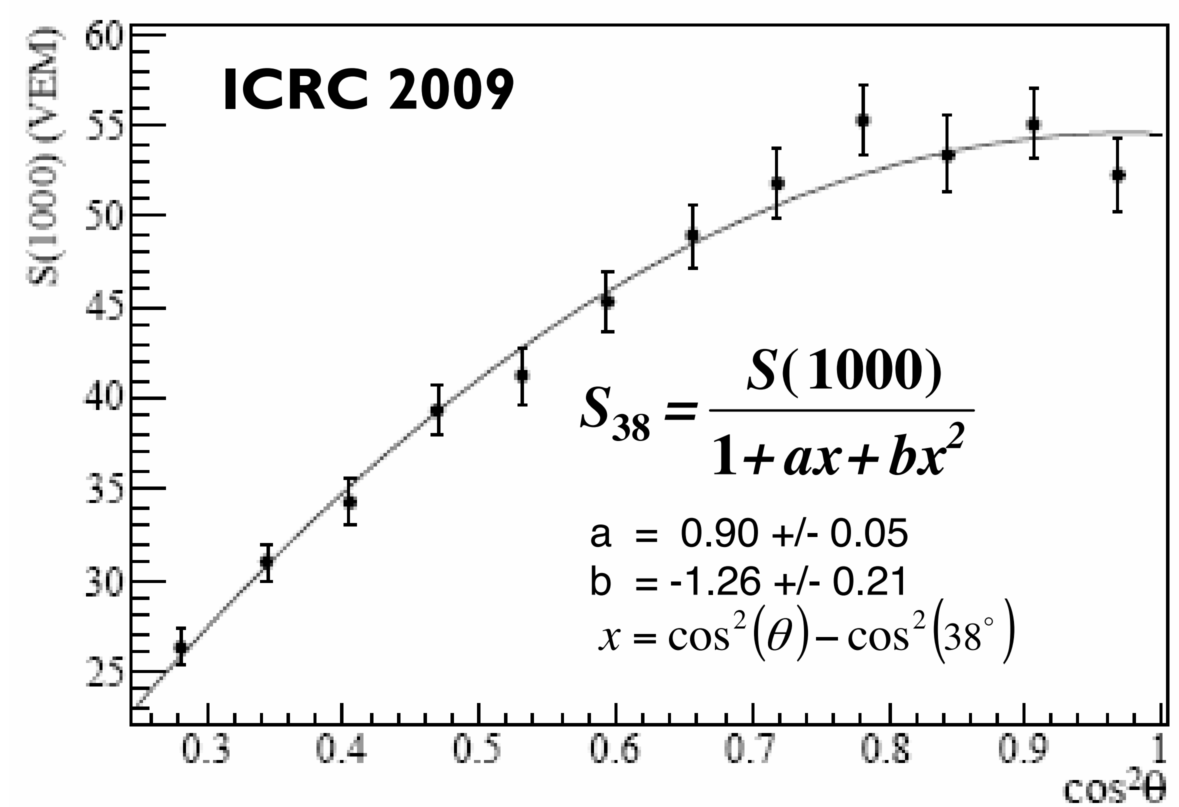
$$N_{\mathrm{ev}} = \int_{\mathrm{angle}} \int_{\mathrm{area}} \int_{\mathrm{time}} \Phi(E,\theta,\varphi) \sin\theta \,\mathrm{d}\theta \,\mathrm{d}\varphi \cos\theta \,\mathrm{d}A \,\mathrm{d}t$$

$$\left.\frac{\mathrm{d}N_{\mathrm{ev}}}{\mathrm{d}\sin^2\theta}\right|_{S(1000)>S_{38} f(\theta)} = \mathrm{const.}$$

Shape depends on μ/em ratio

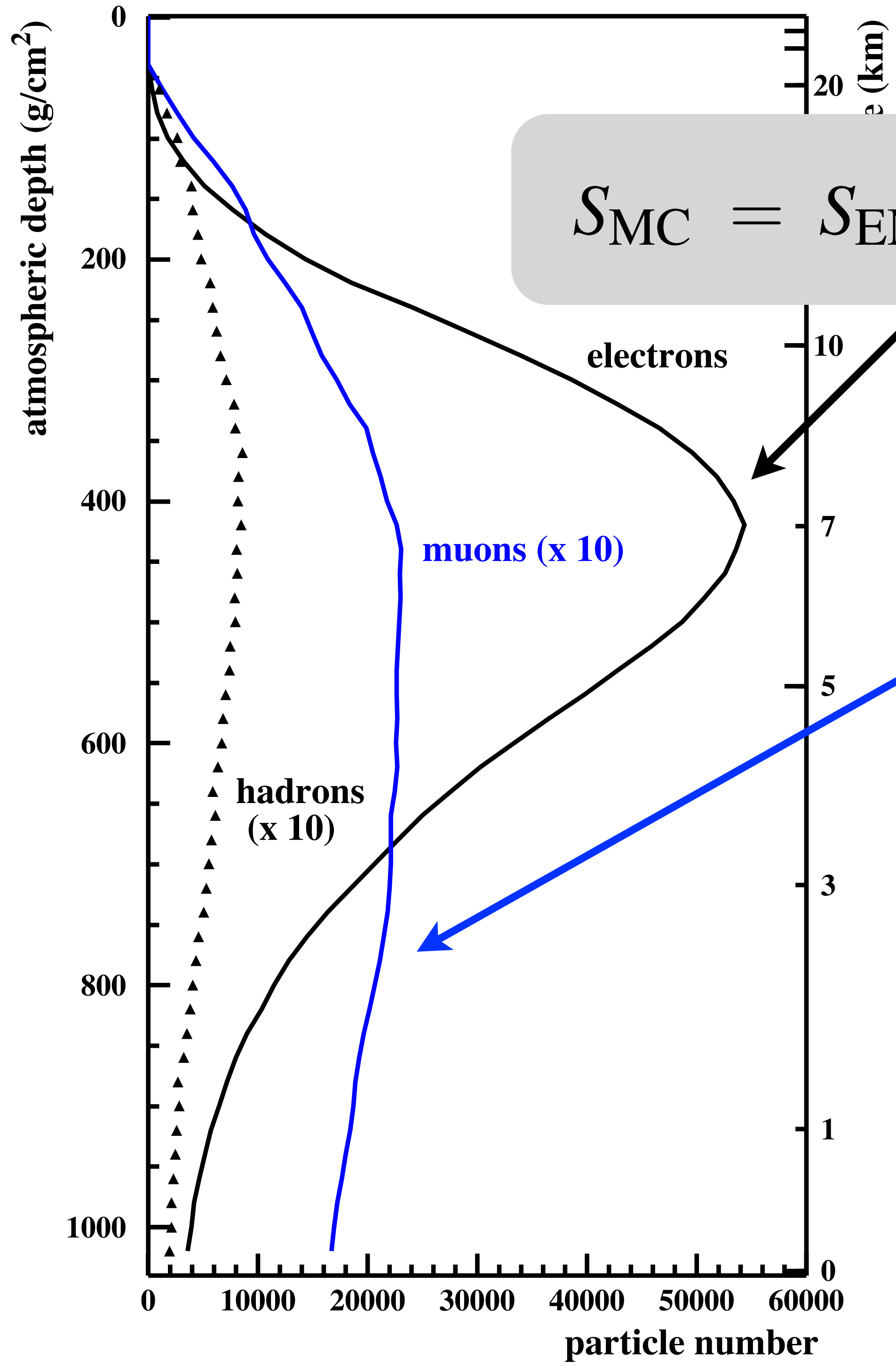


Conversion function independent of S(1000) within statistical uncertainties

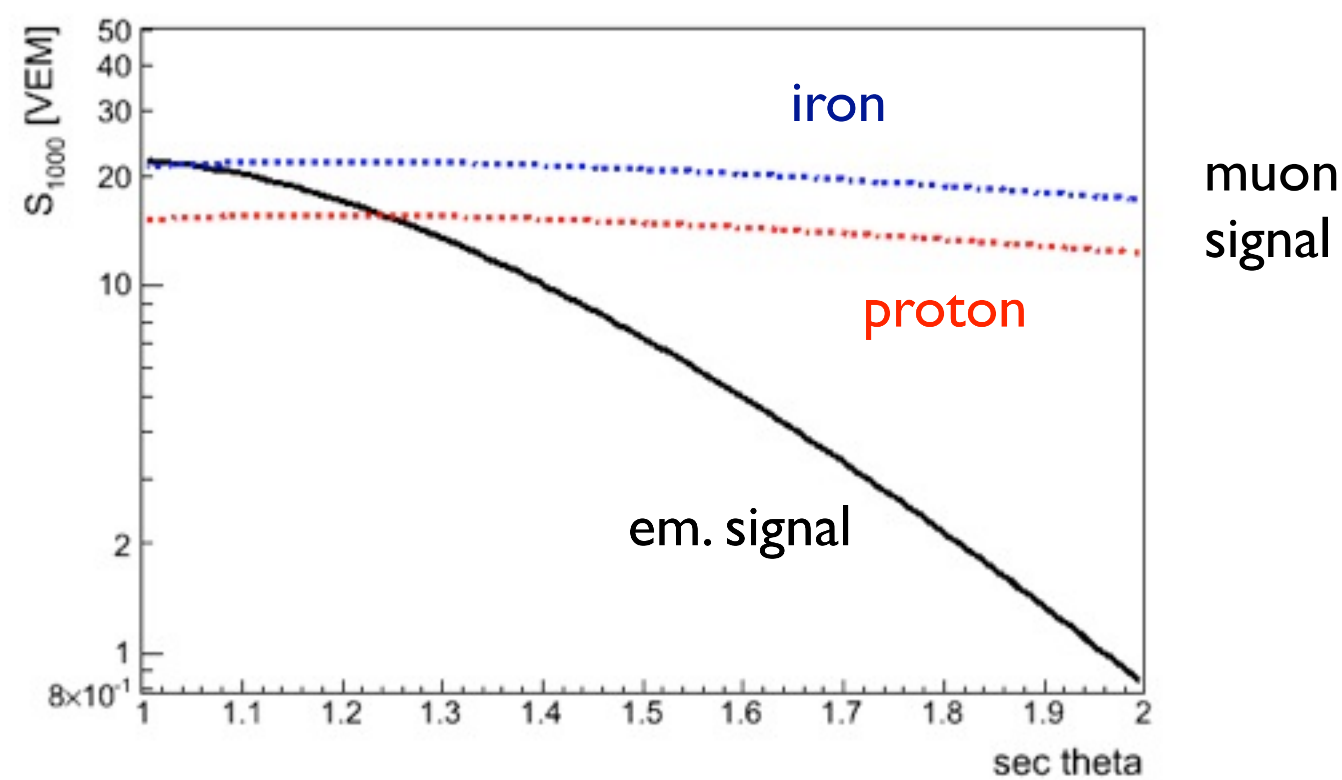


Prediction of S(1000) for different angles

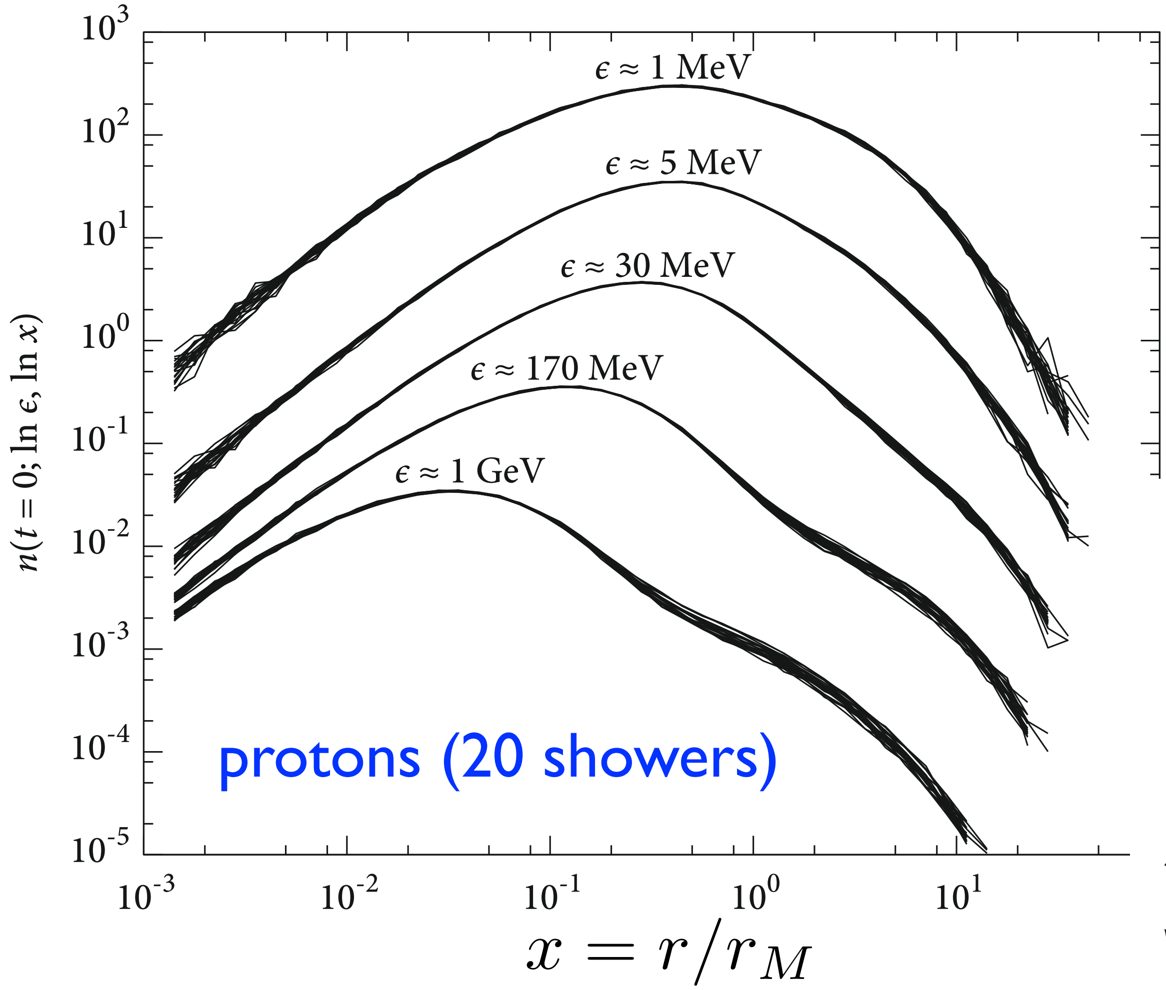
$$S_{\mathrm{MC}} = S_{\mathrm{EM}}(DG, E) + N_\mu^{\mathrm{rel}} \cdot S_\mu^{\mathrm{QGSII,p}}(DG, 10^{19}\,\mathrm{eV})$$



Predicted Auger tank signal

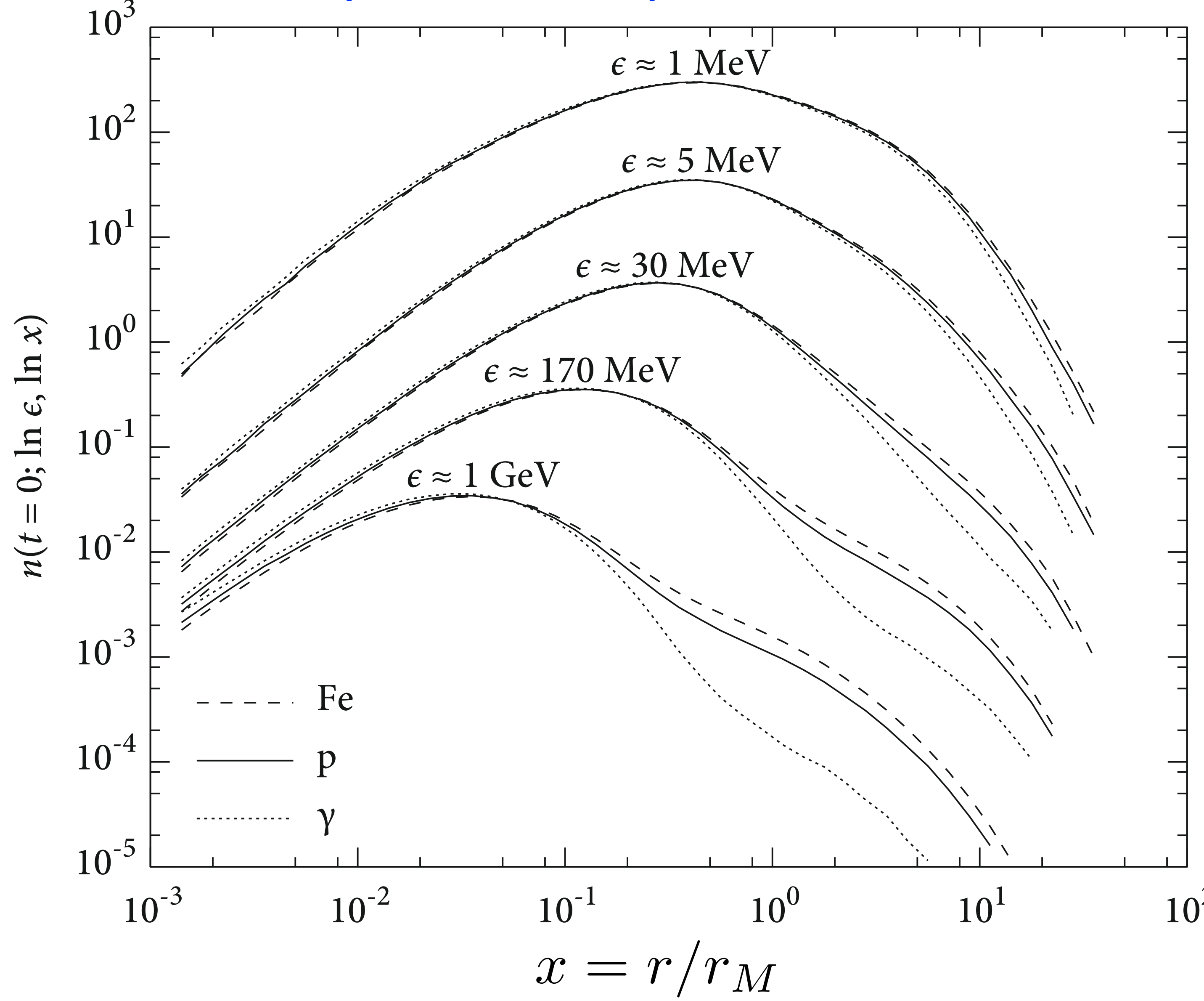


Universality of showers at very high energy (i)



Lateral distribution

protons, iron, photons

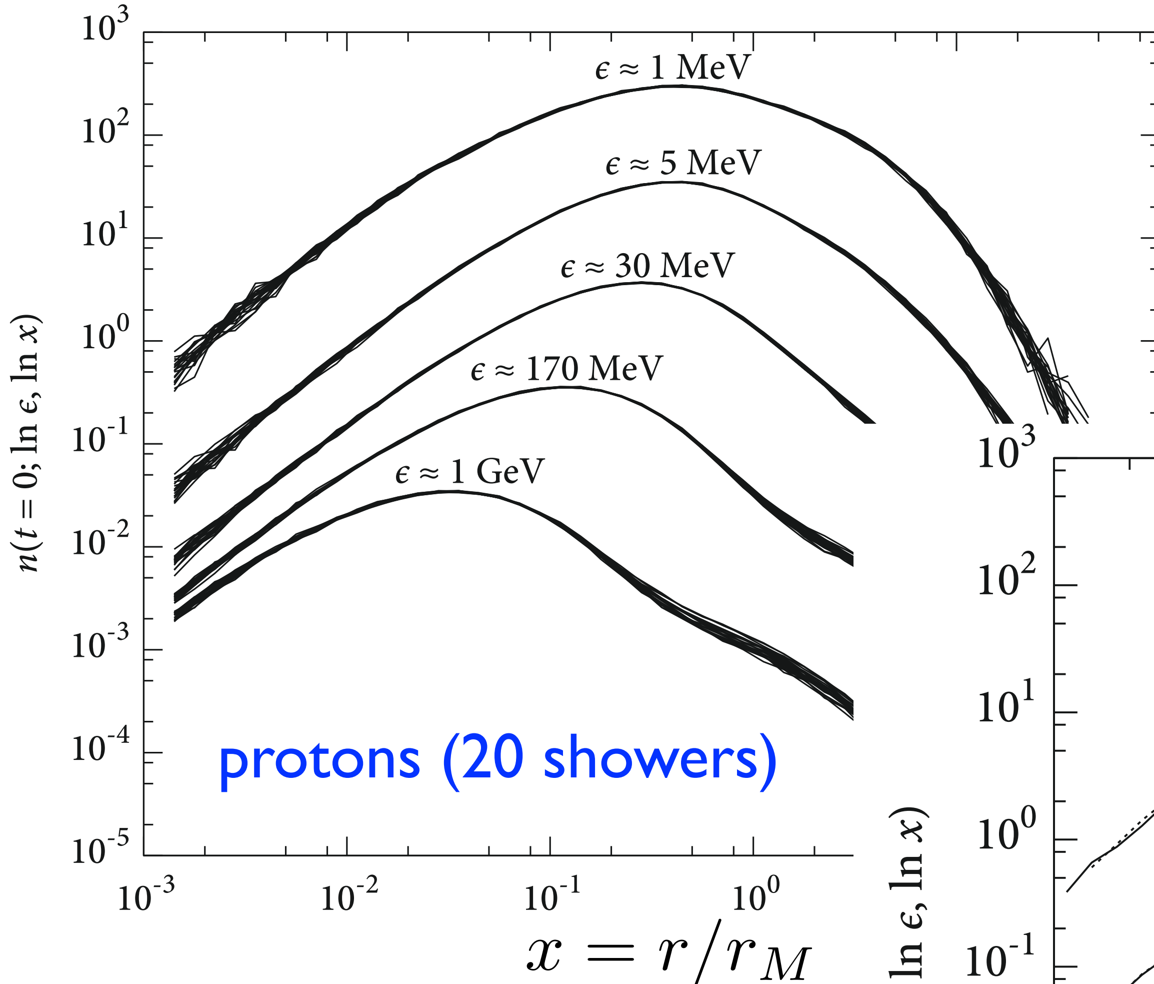


$$\left.\frac{dN_{e^\pm}}{d\ln x}\right|_{s=1}$$

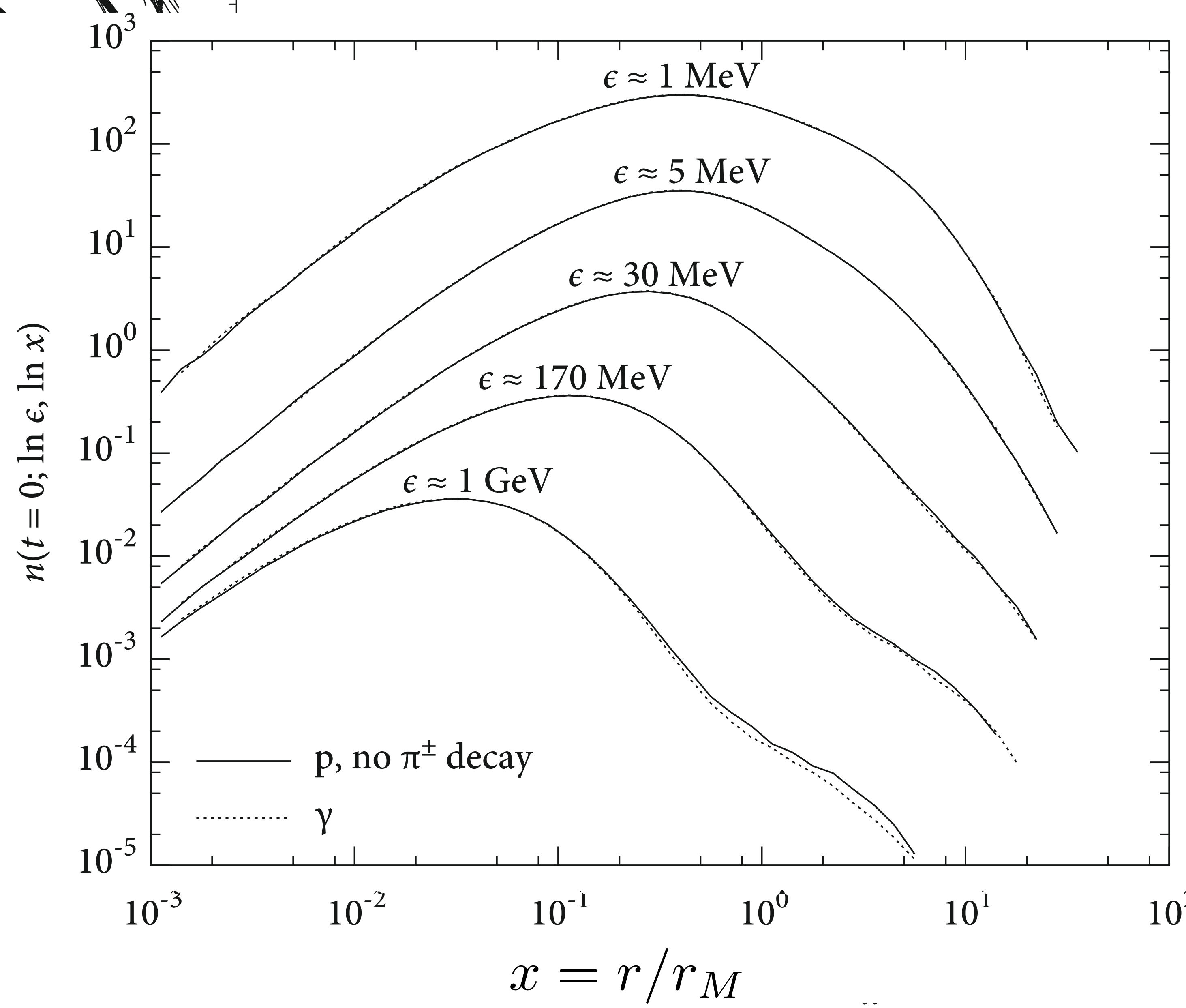
(S. Lafebre et al., Astropart. Phys. 31, 2009)

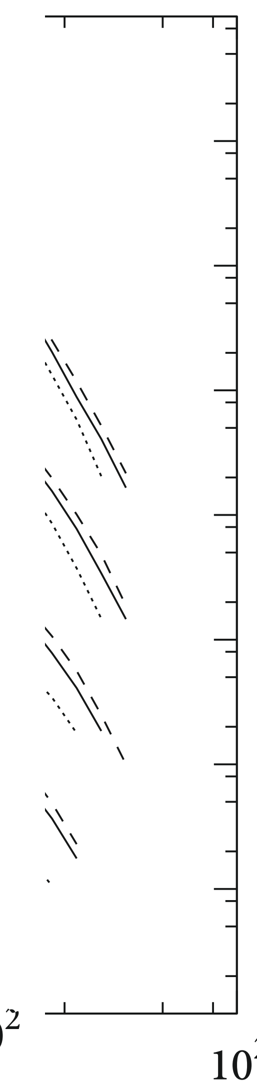
Universality of showers at very high energy (i)

Lateral distribution



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

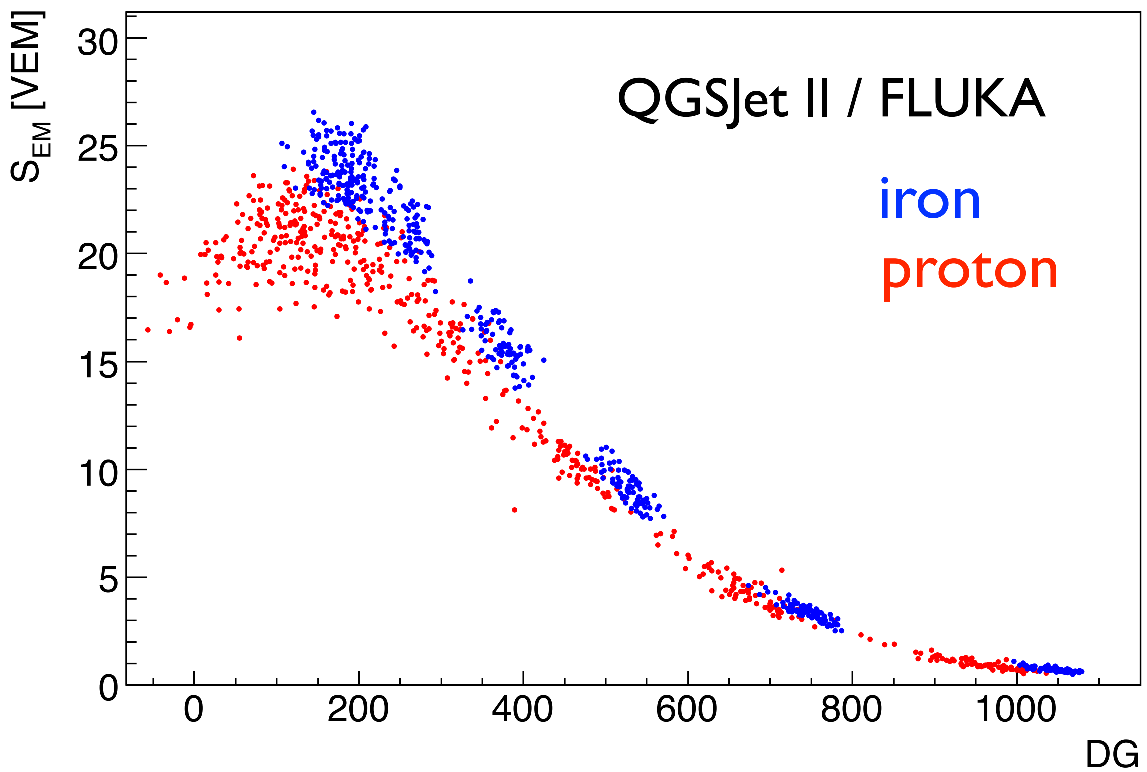


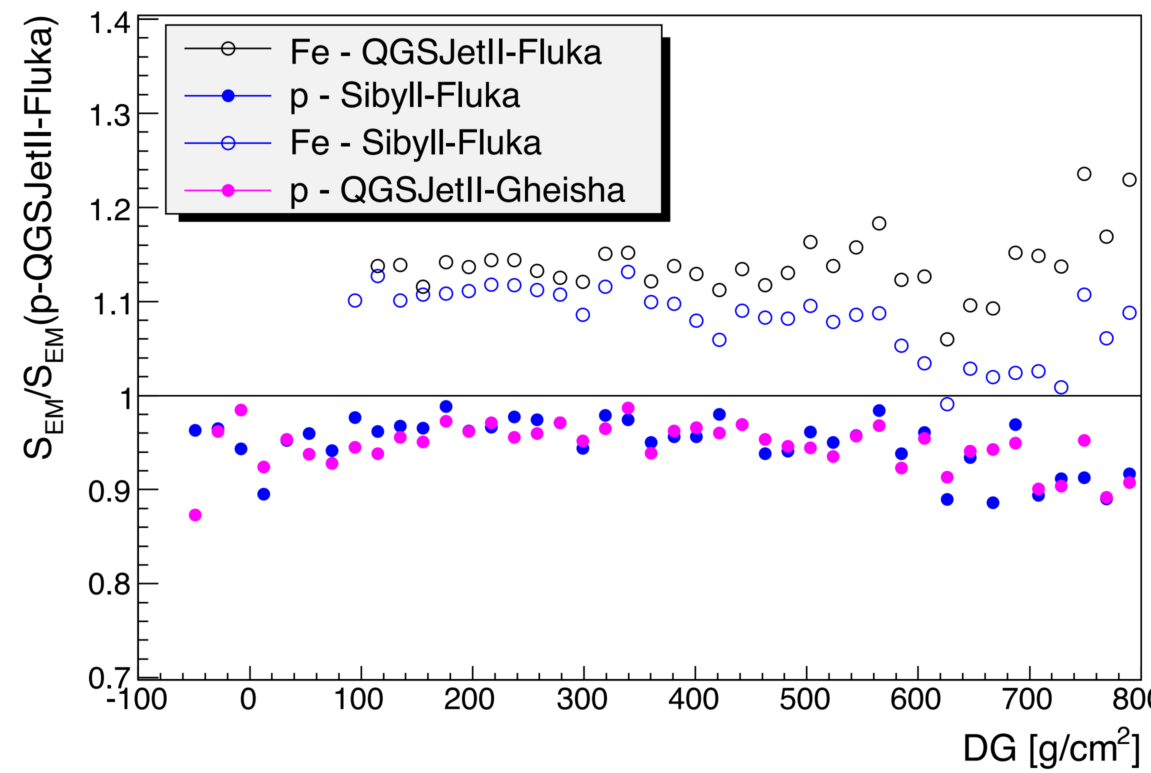


(S. Lafebre et al., Astropart. Phys. 31, 2009)

Universality of em. shower component

Signal at 1000m





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

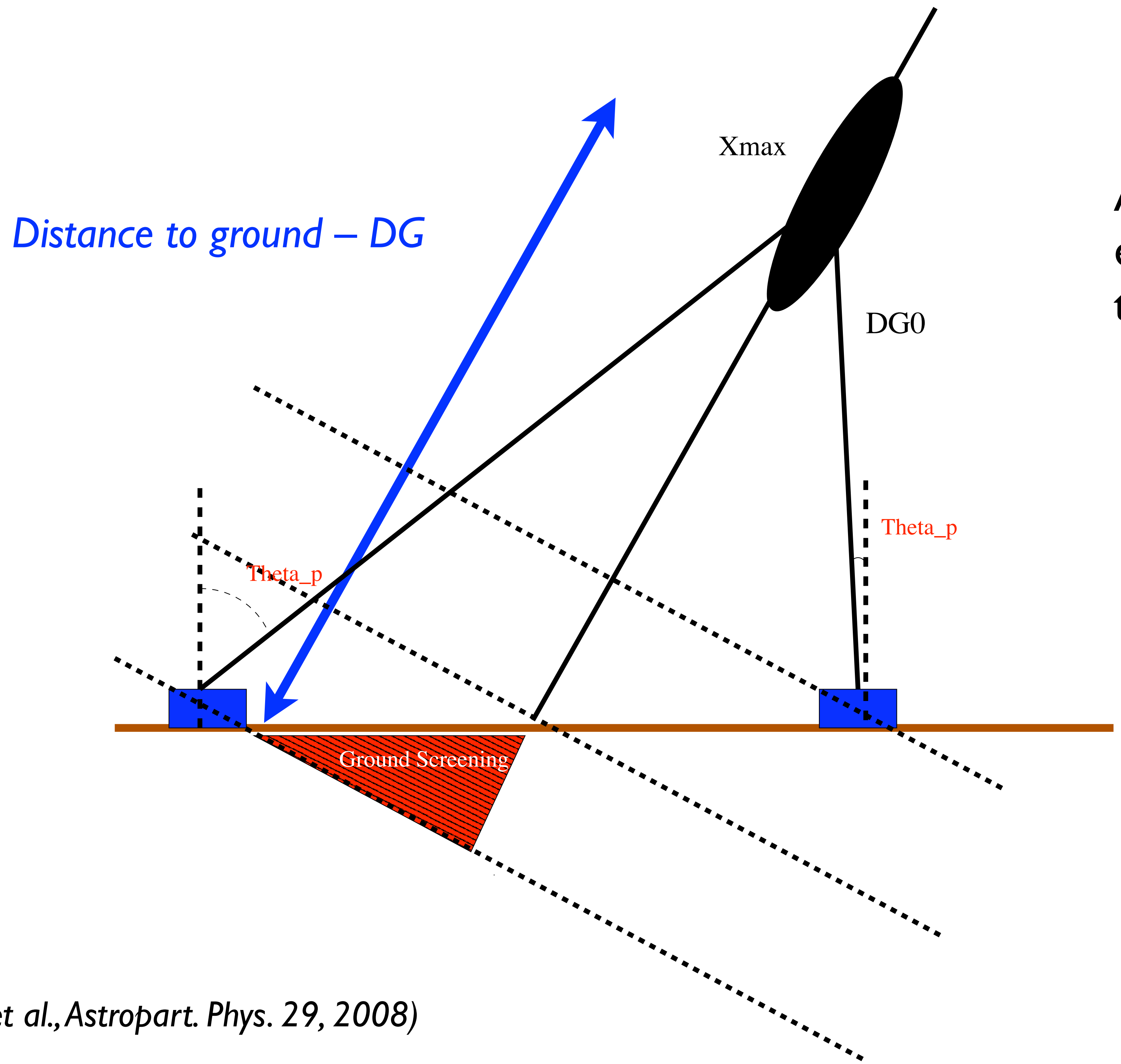
Predicted signal at 1000m:

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

includes e/m signal from muon decay

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

Universality of em. shower component



Asymmetries and effective detector area taken into account

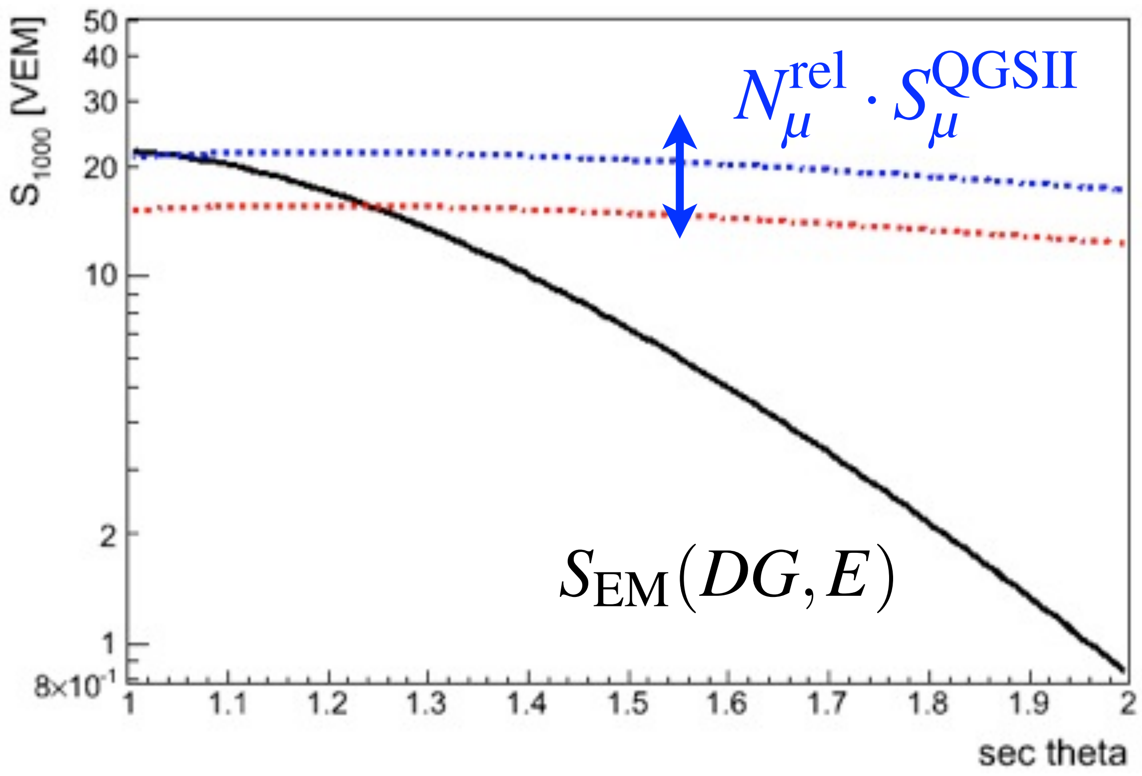
Em. particles from muon decay treated separately

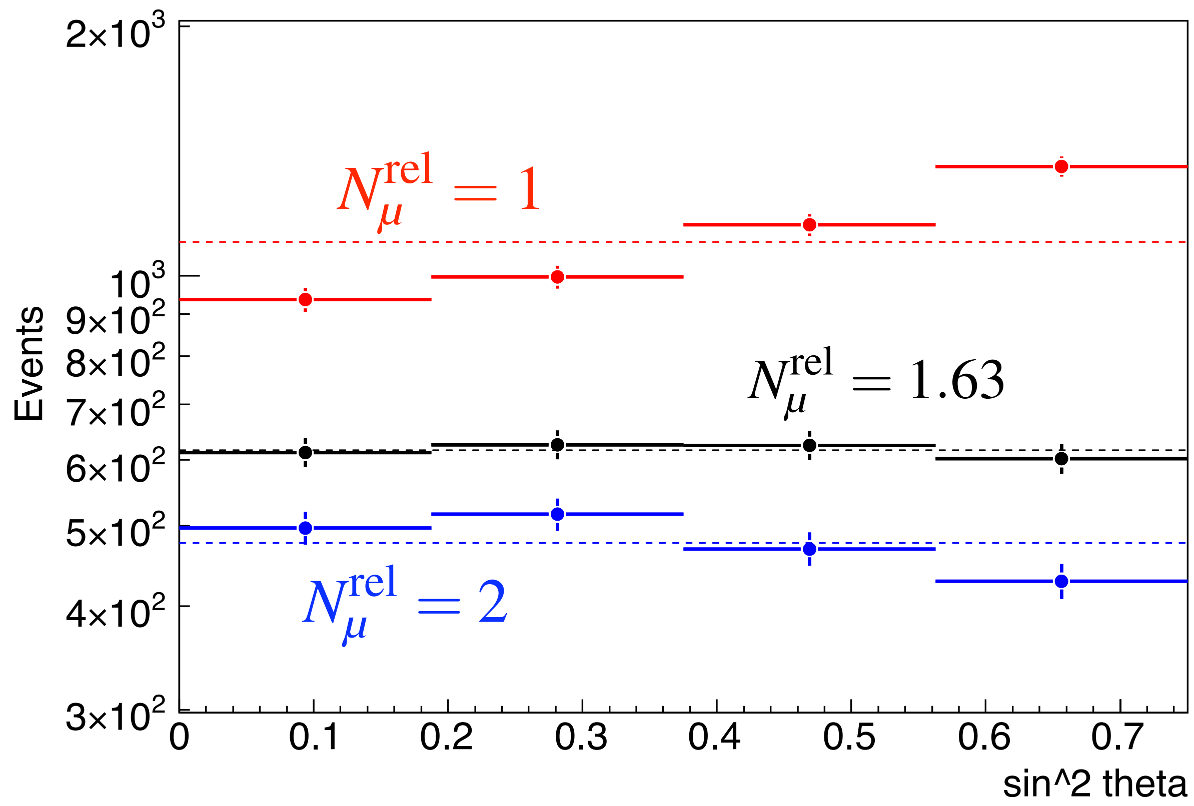
(F. Schmidt et al., Astropart. Phys. 29, 2008)

Dependence of attenuation on muon fraction

Cosmic ray flux isotropic:

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





Result accounting for shower fluctuations and detector resolution

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

Absolute energy scale from universality

from Auger data: hybrid measurement

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

from Auger data:
const. intensity method

Data: Jan 2004 - Dec 2008

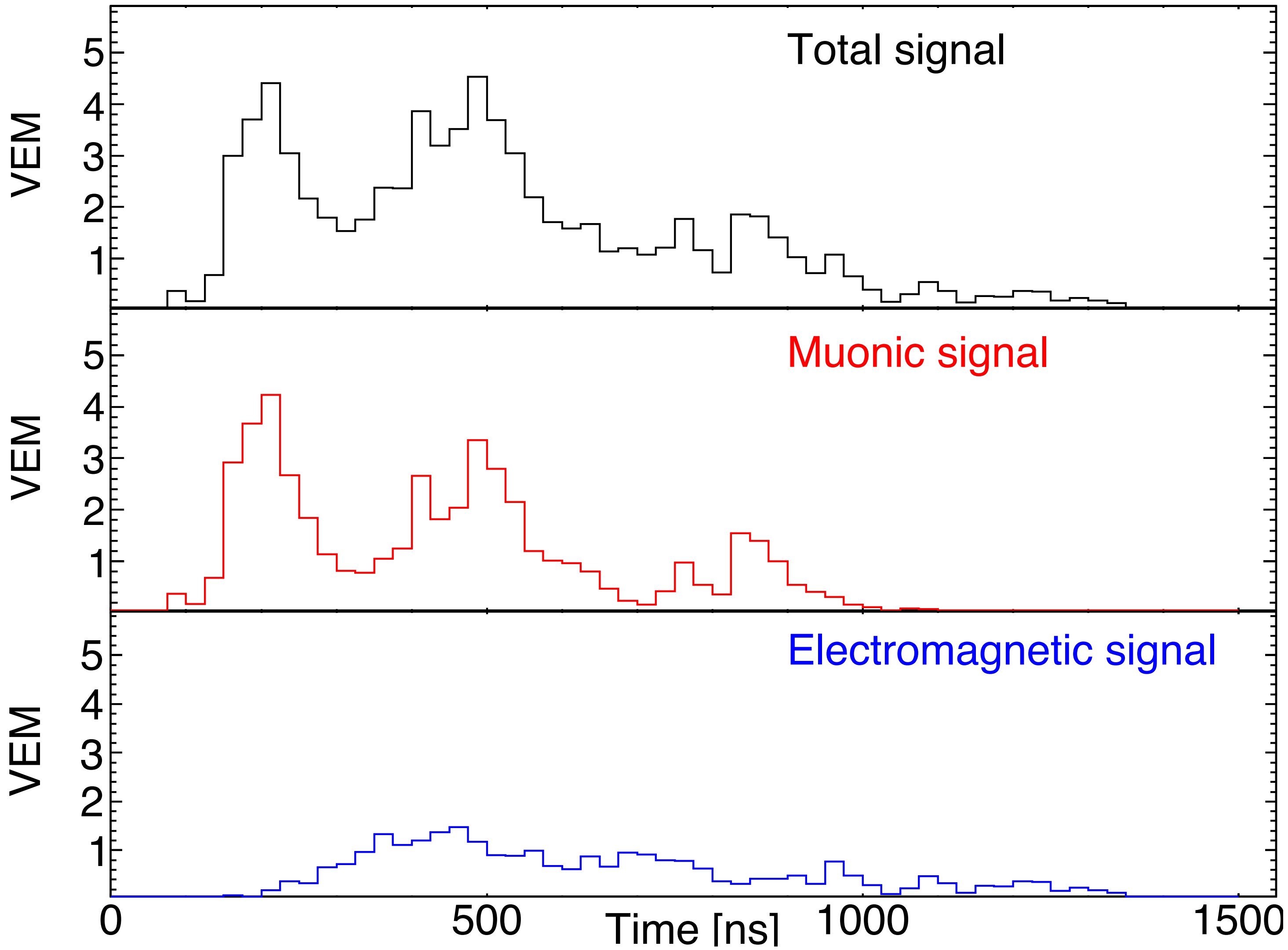
$$S_{38}(10^{19}\,\mathrm{eV}) = 38.9^{+1.4}_{-1.2}(\mathrm{stat.})^{+1.6}_{-1.8}(\mathrm{sys.})\ \mathrm{VEM}$$

Corresponding energy scale

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

(compatible with current uncertainty of fluorescence detector energy scale)

Time structure of tank signal

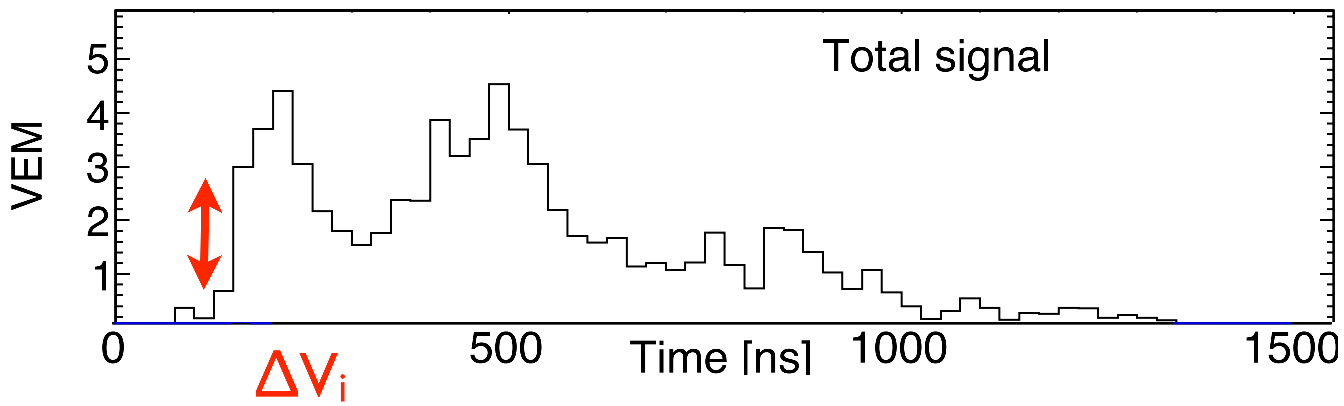


individual muon peaks

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

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

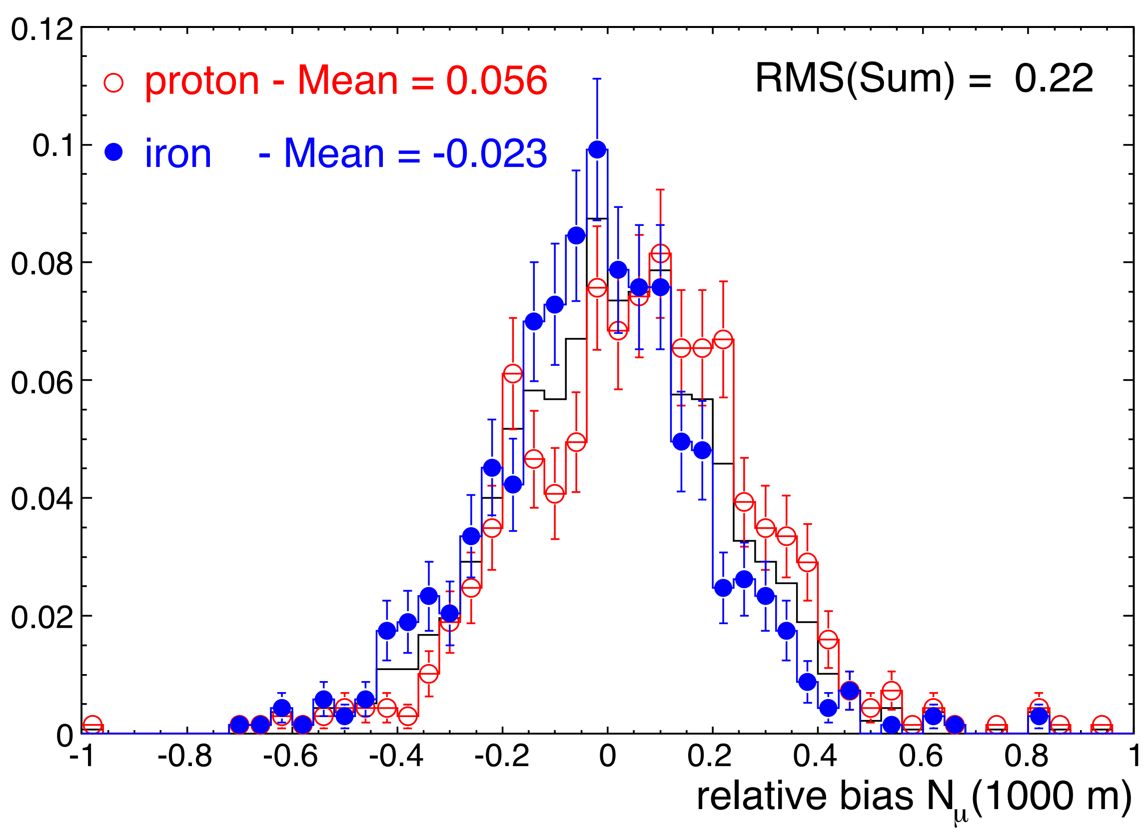
Muon counting with jump method

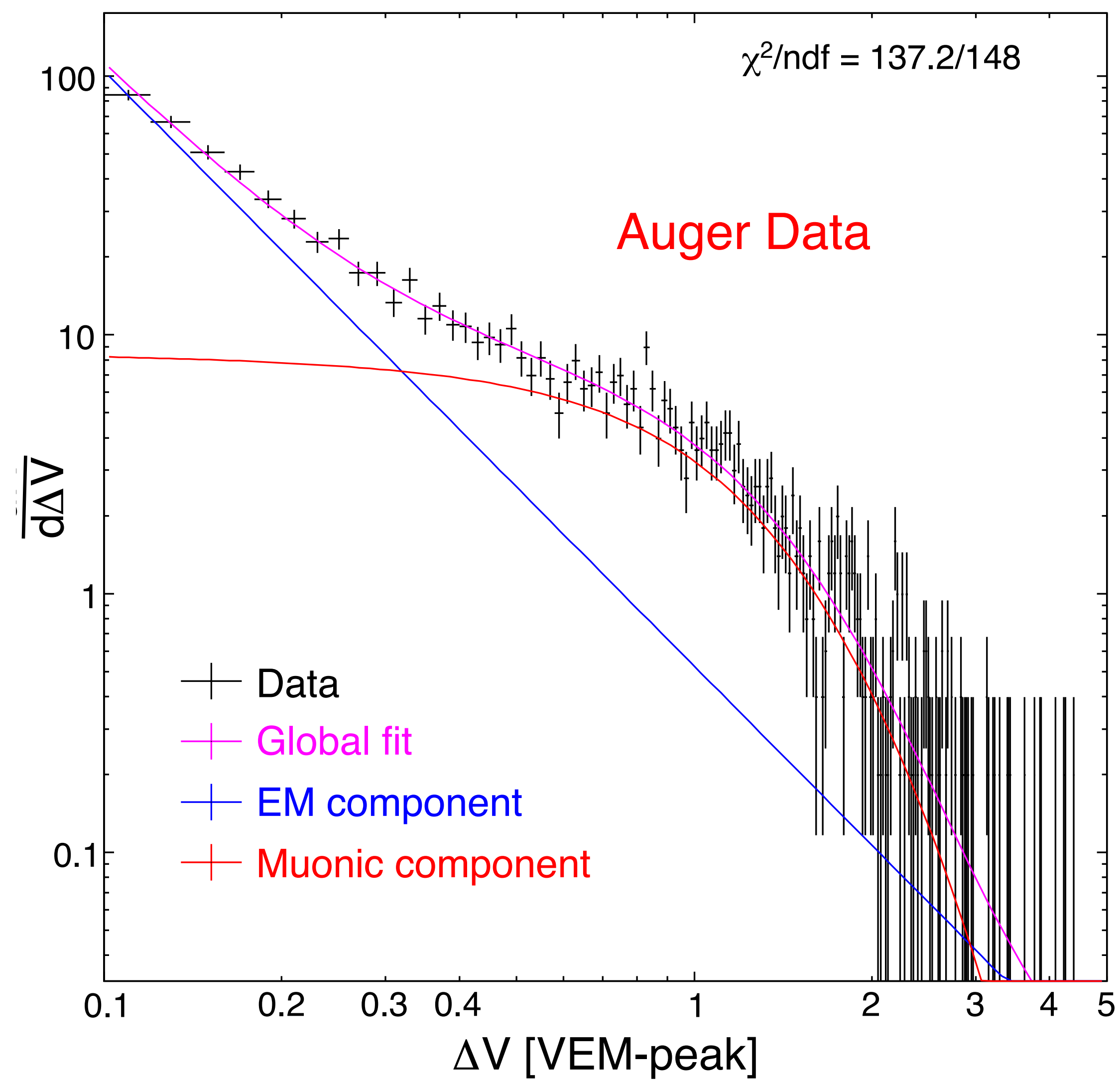


calibration factor

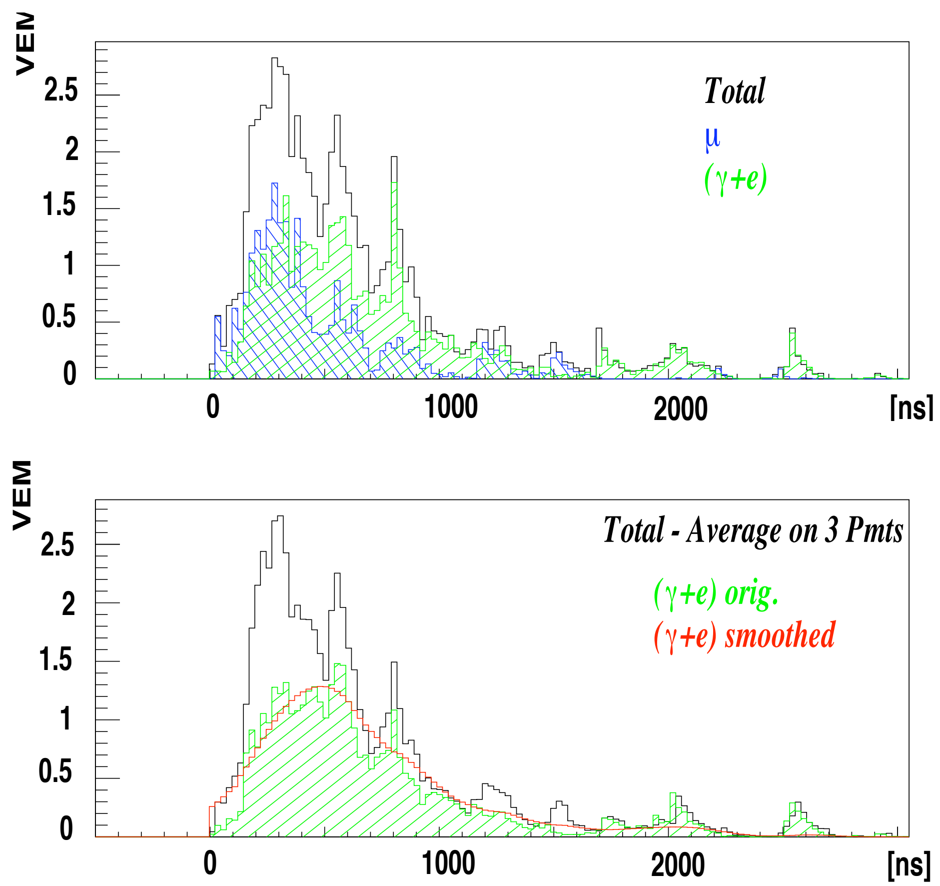
$$N_\mu^{\mathrm{est}} = \eta(E,\theta) \times \sum_{\Delta V_i > \Delta V_{\mathrm{th}}} \Delta V_i$$

MC study of resolution



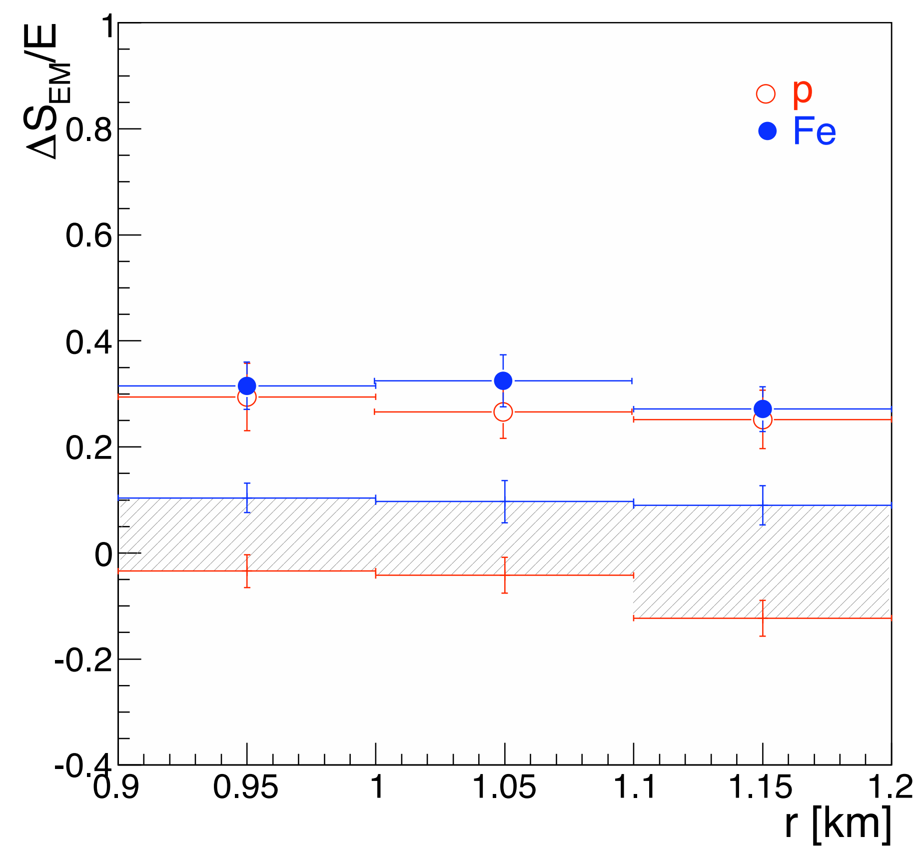


Em. signal from smoothing method

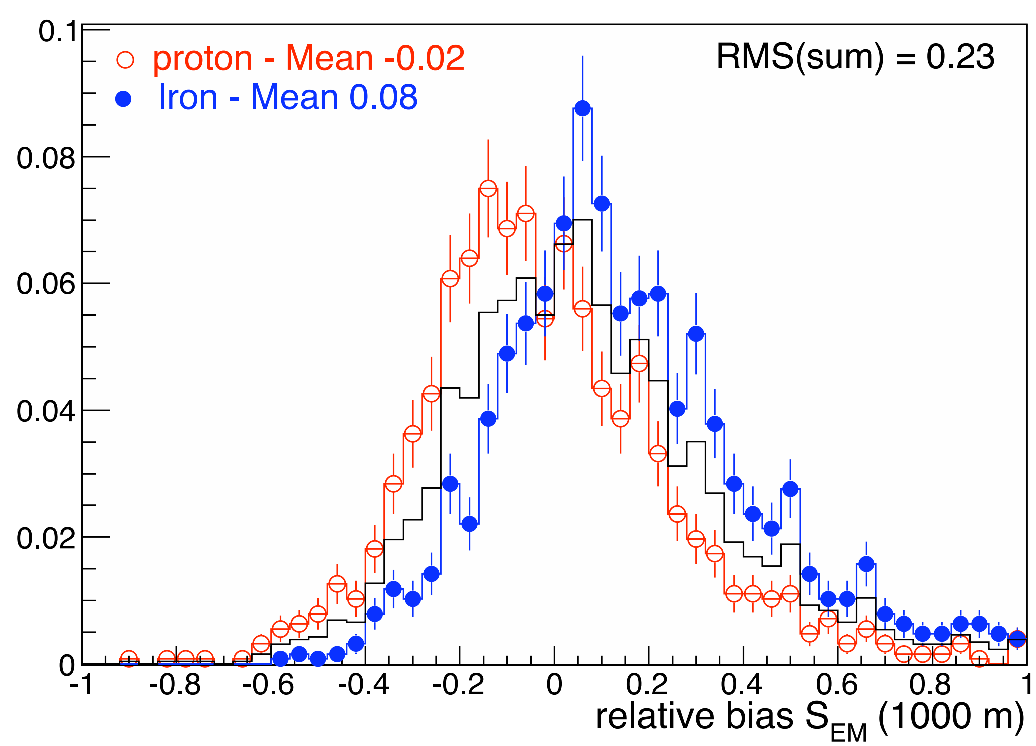


Procedure

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



MC study of resolution



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

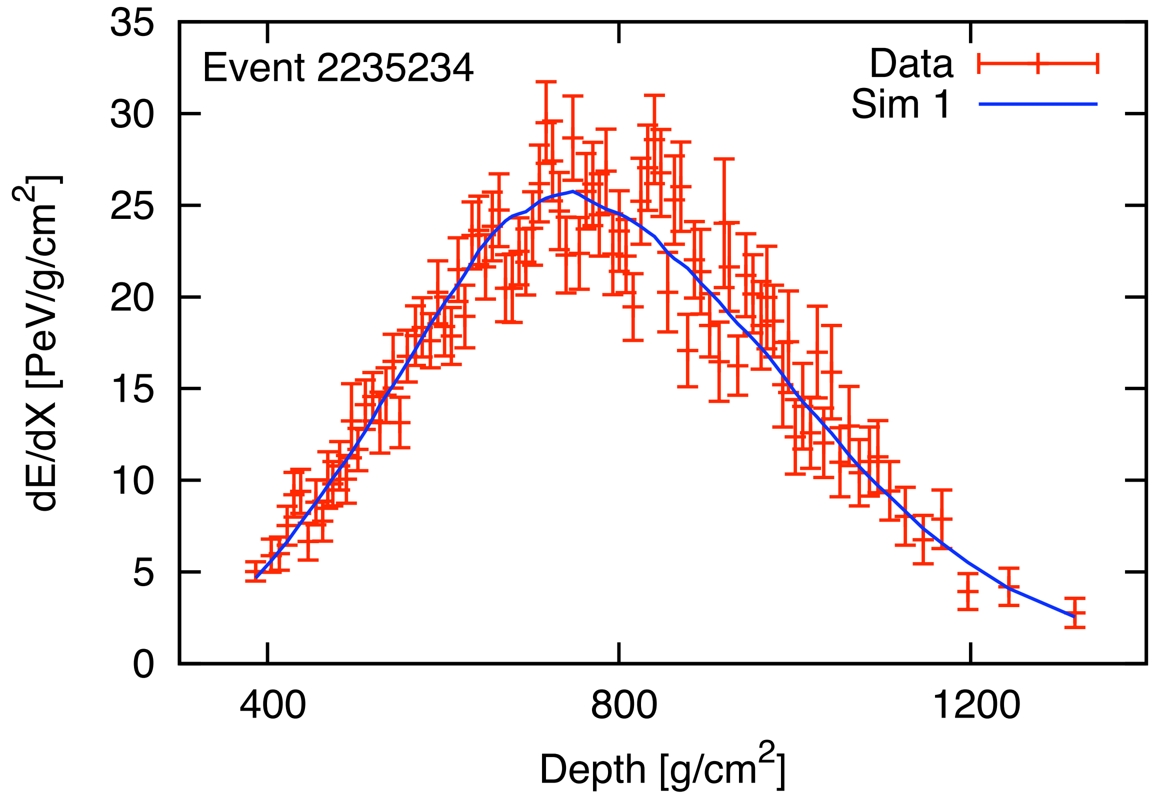
Simulation of individual hybrid events

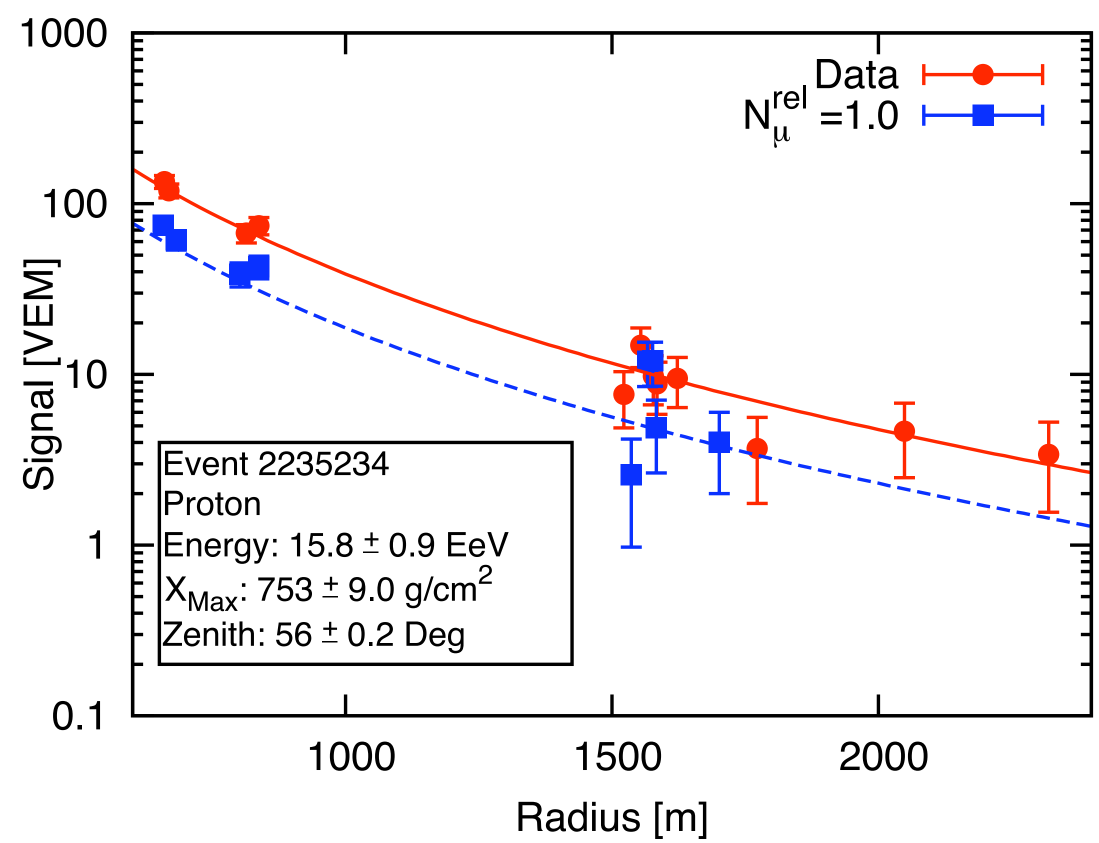
Procedure

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

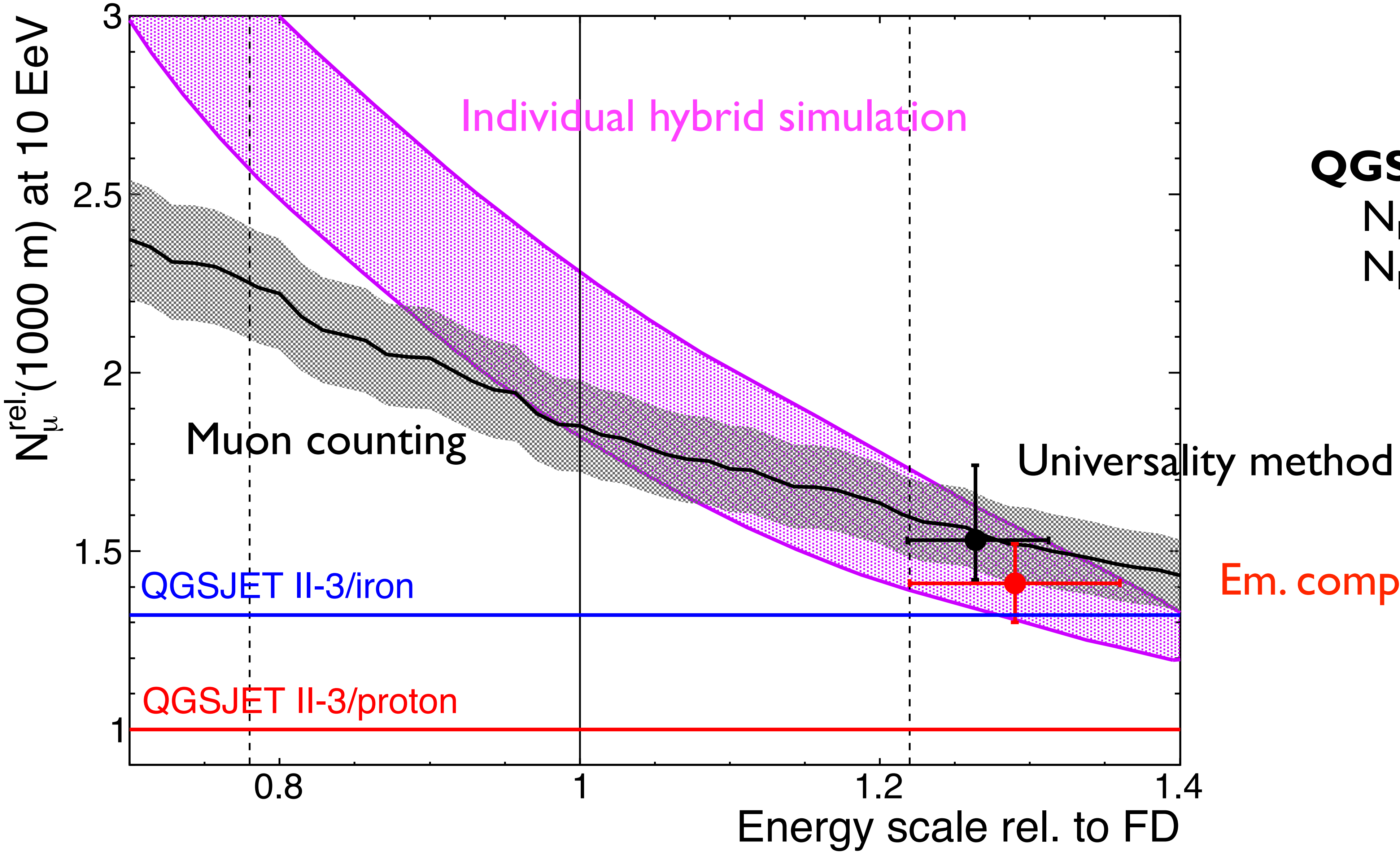
Results

- 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



Em. component

QGSJET II:

N_μ^{rel} = 1.0 (protons)

N_μ^{rel} = 1.32 (iron)

Results of different methods consistent

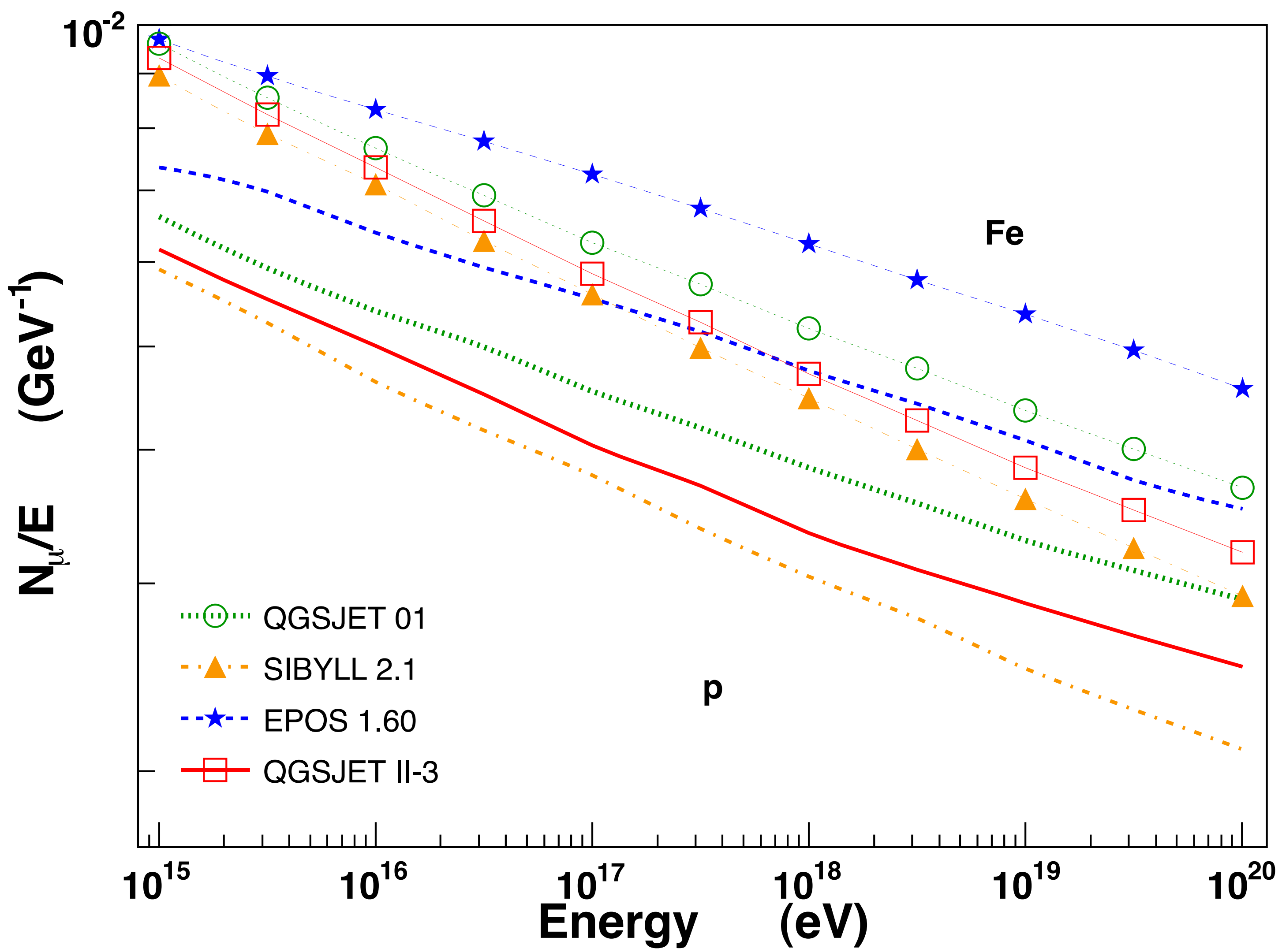
- shift of energy scale expected
- muon deficit in simulation even with shifted energy scale

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

What about EPOS ?

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

Muon multiplicity re-scaled with energy

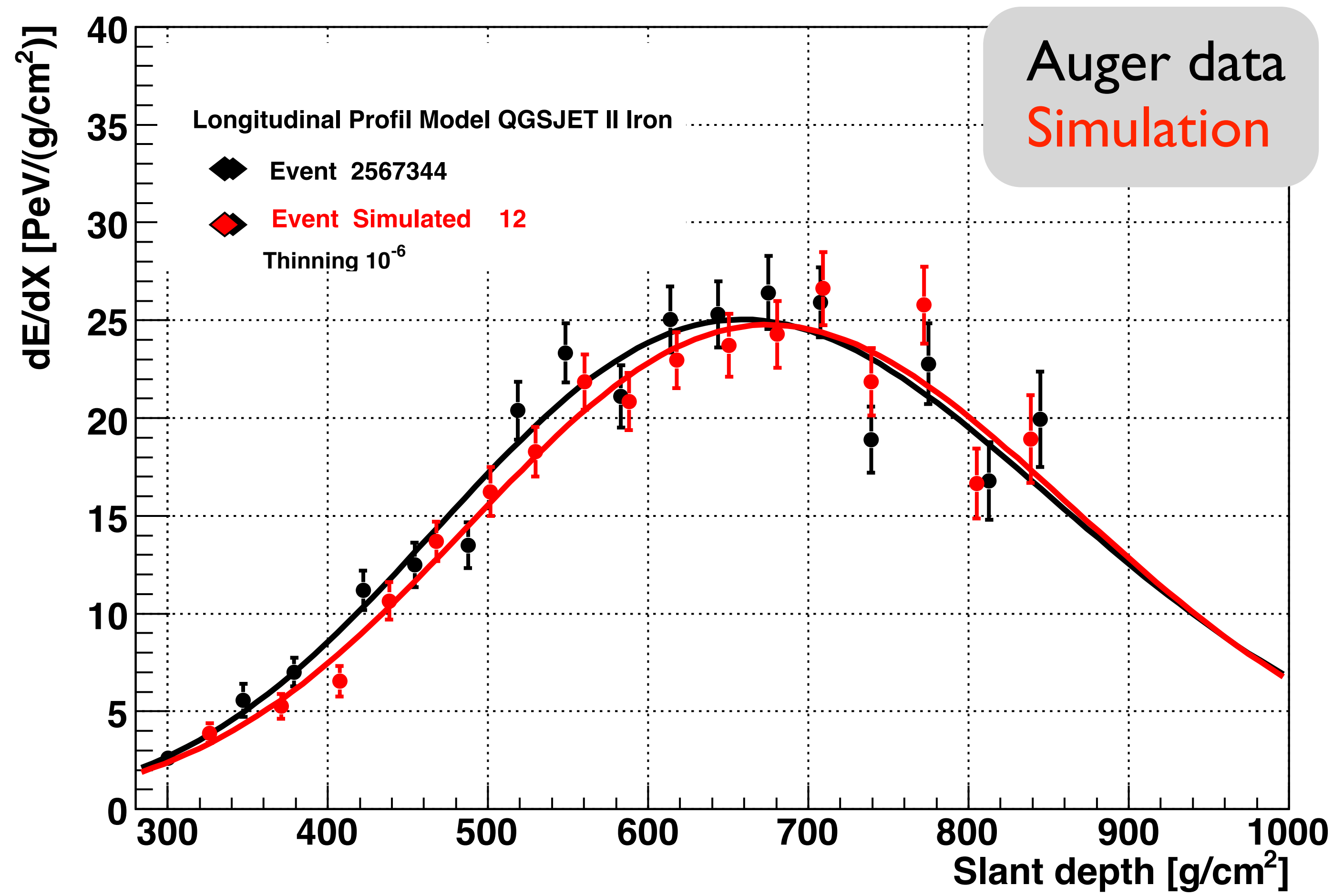


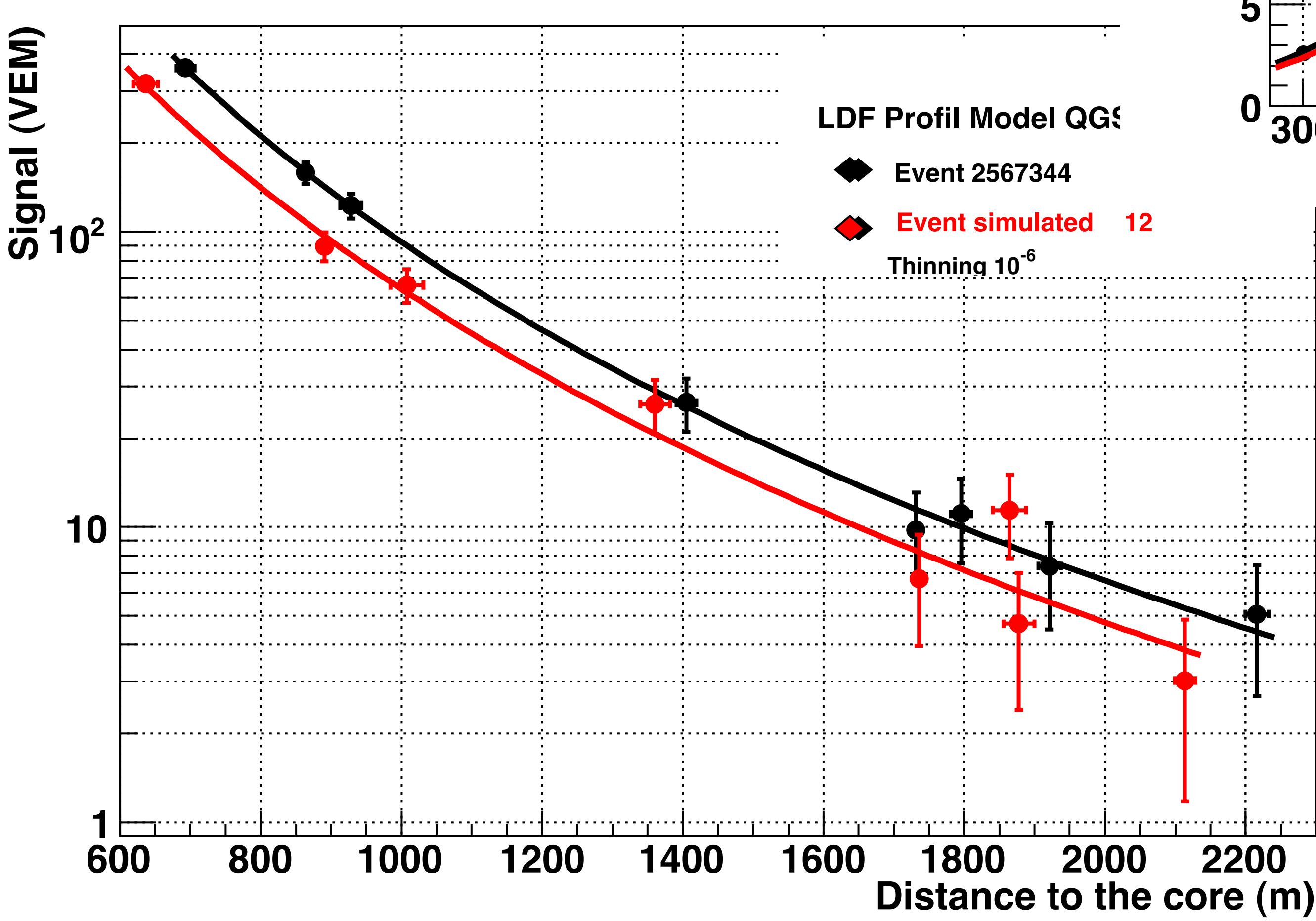
Muon number larger and different energy dependence

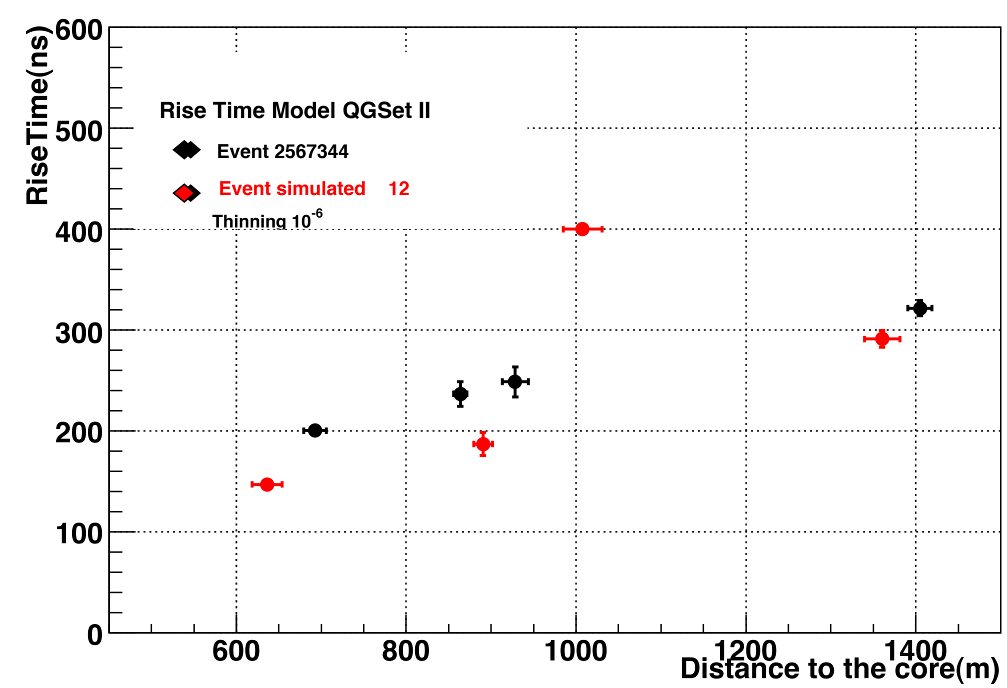
Currently QGSJET II and FLUKA default simulation models in Auger

Example: QGSJET II, iron

Event 2567344
$\theta = 28°$, $E = 1.4\mathrm{x}10^{19}$ eV
iron-like event

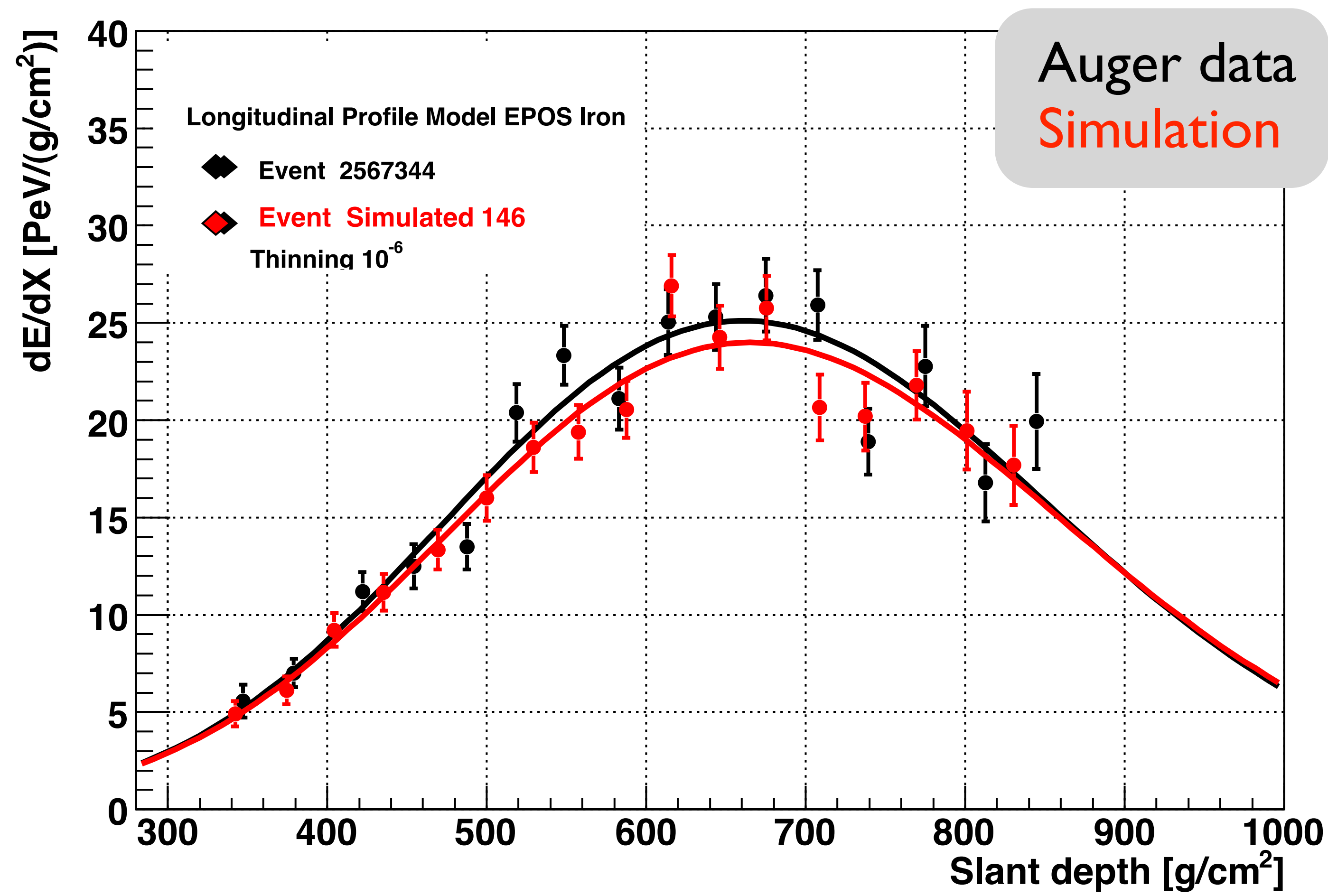


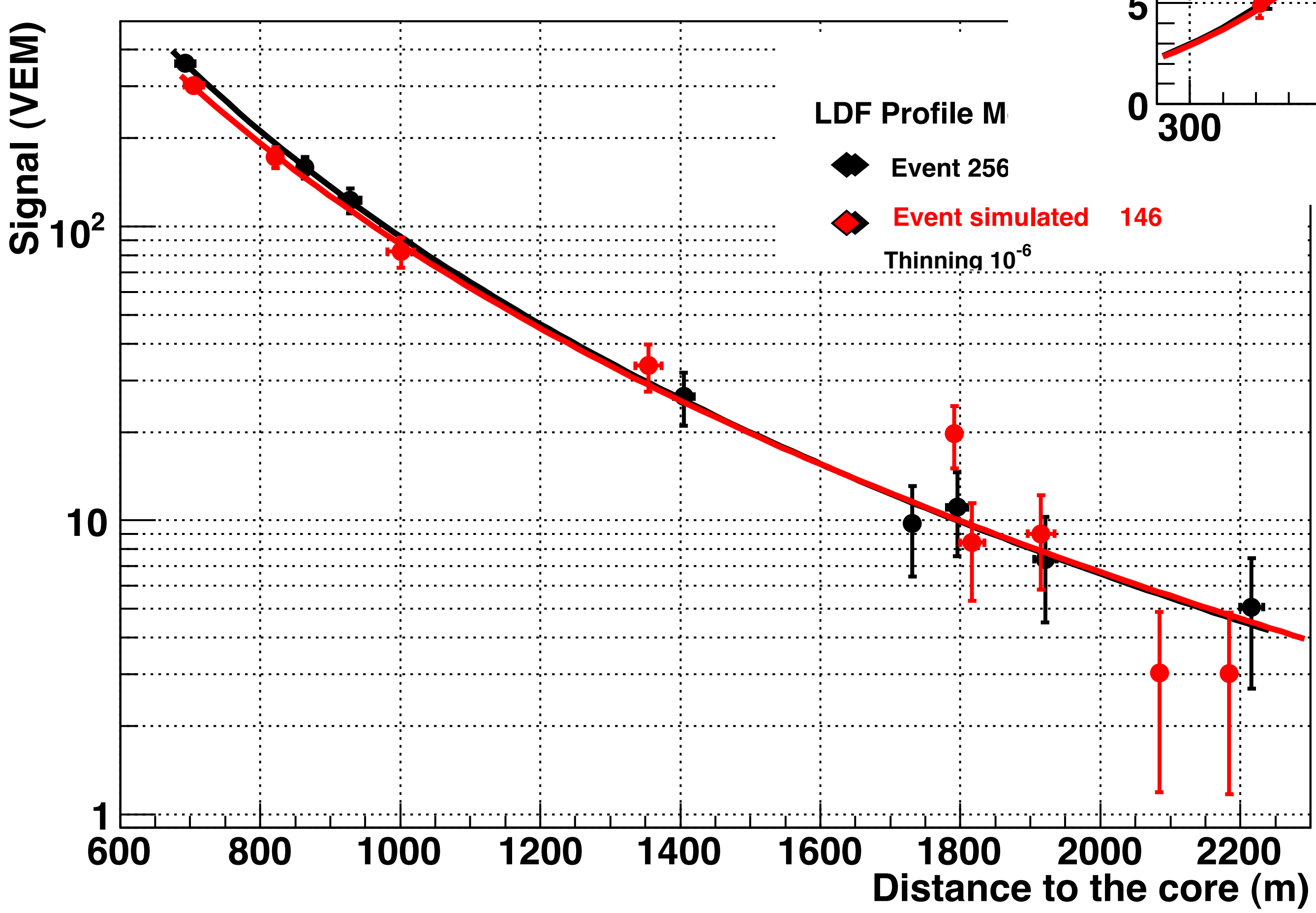


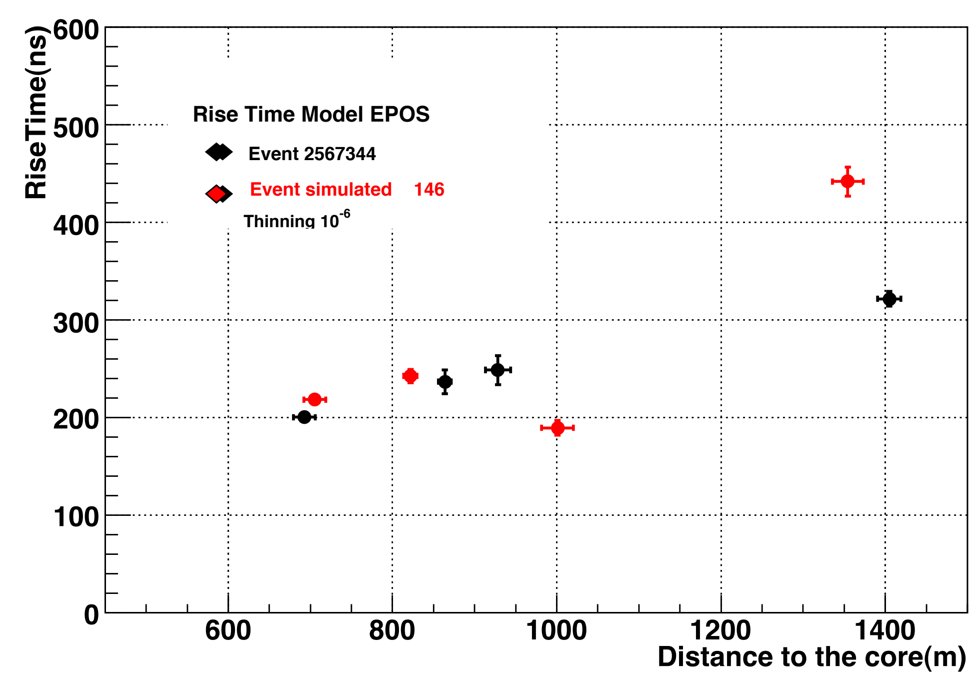


Example: EPOS 1.62, iron

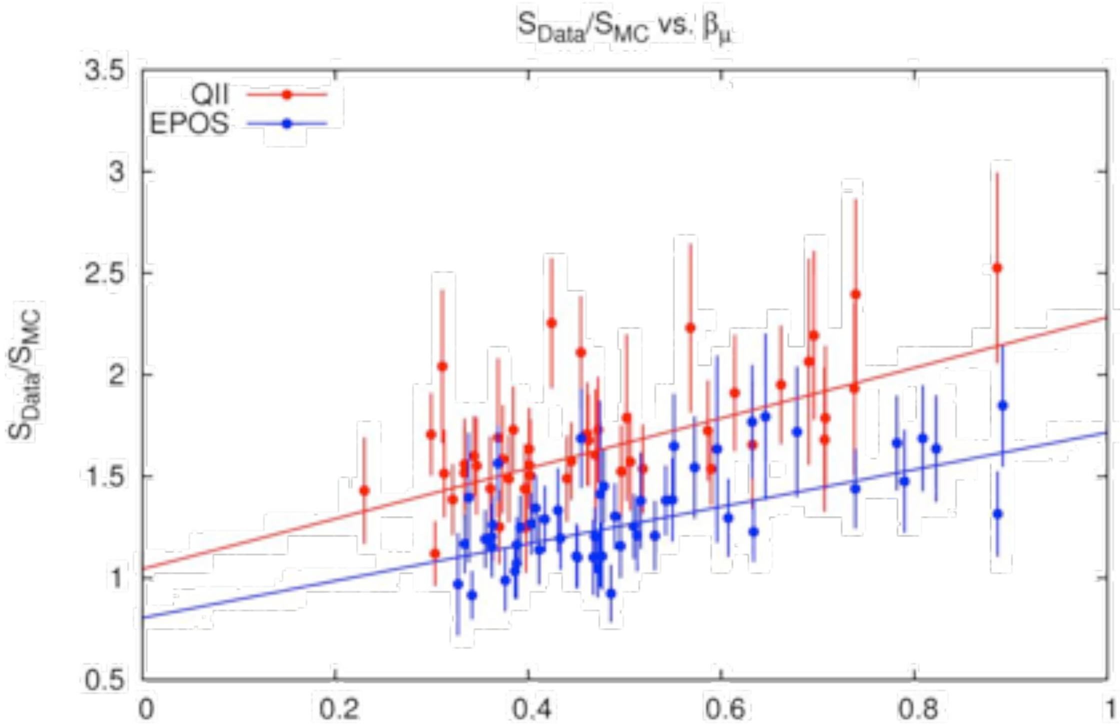
Event 2567344
θ = 28°, E = 1.4x10^{19} eV
iron-like event







Results of simulation of individual hybrid events

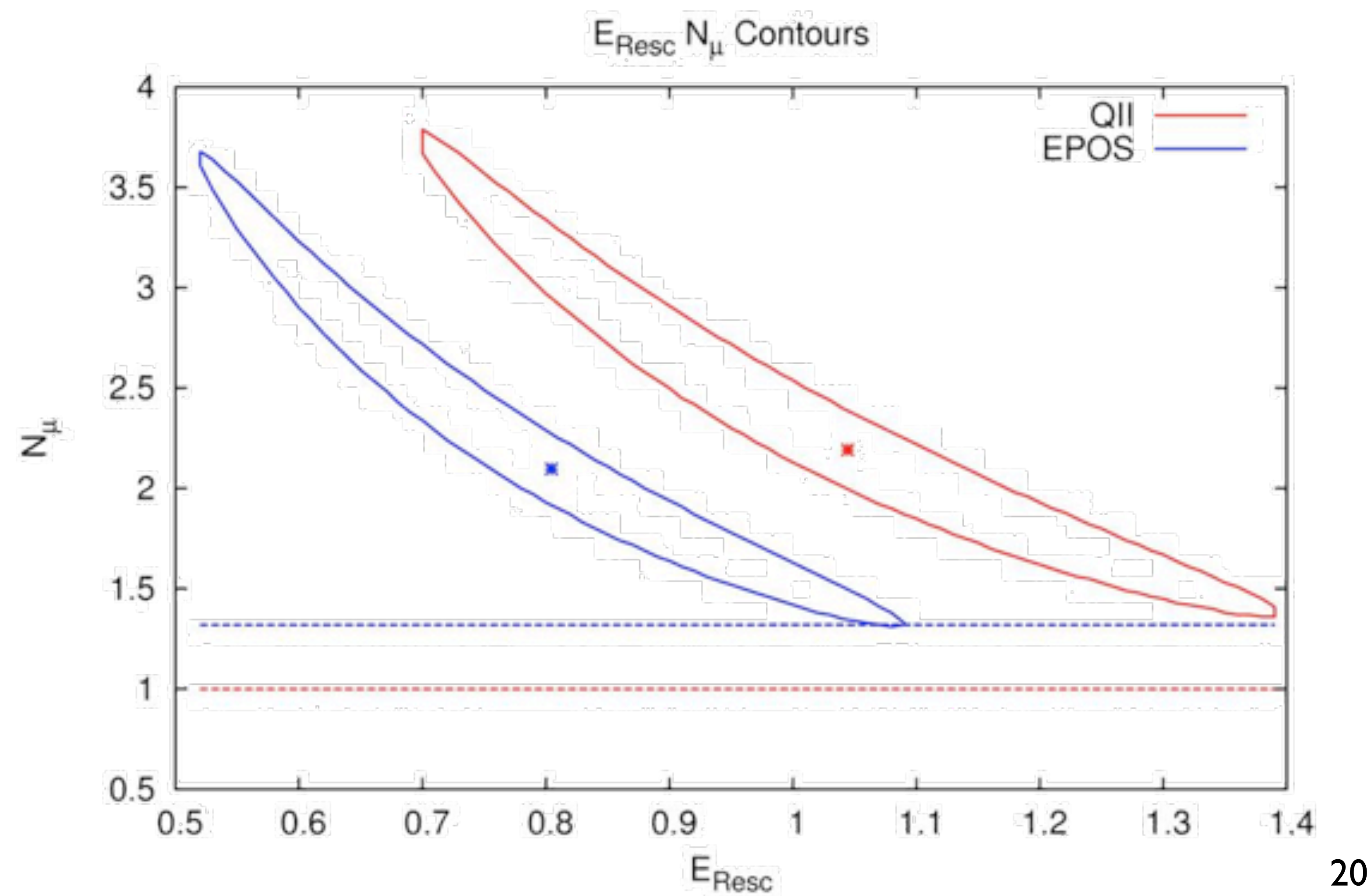


Muon fraction (MC)

Re-scaling of em. and muonic contributions

energy scaling factor $S'_{\rm em} = f_E \cdot S_{\rm em}^{\rm mc}$

muon model scaling factor $S'_\mu = f_\mu \cdot (f_E)^\alpha \cdot S_\mu^{\rm mc}$



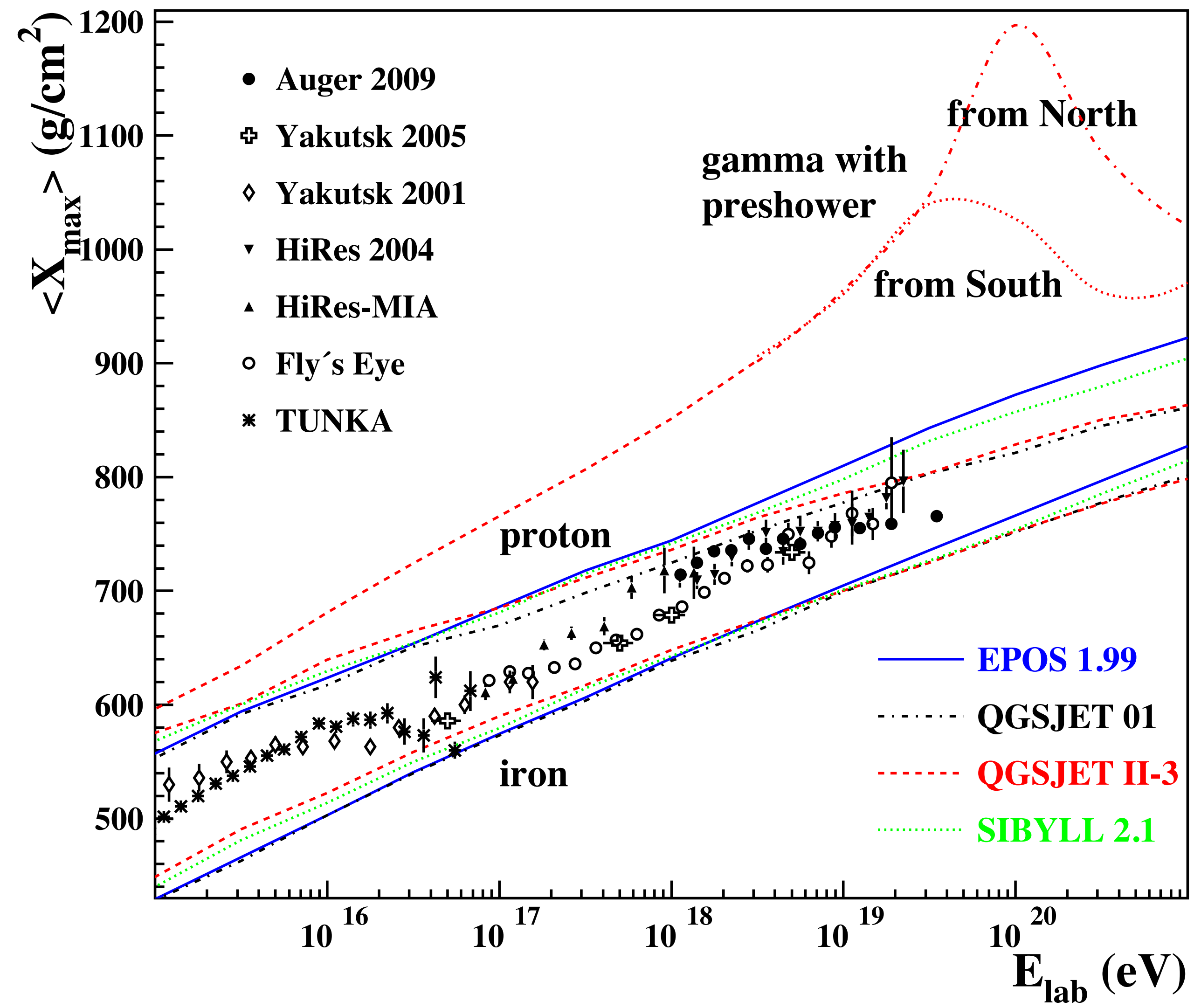
Results of different methods consistent
EPOS 1.99 leads to better description

(Allen et al., Auger, APS 2010)

Possible application in IceCube/IceTop

Similar study could be done:

- Mean Xmax from other experiments
- Universality of shower profiles
- Constant intensity cut analysis
- correction for fluctuations from MC



Model-independent estimate energy scale

(and muon fraction relative to reference model and reference composition)