Status of Air Shower Simulations: particle production theory

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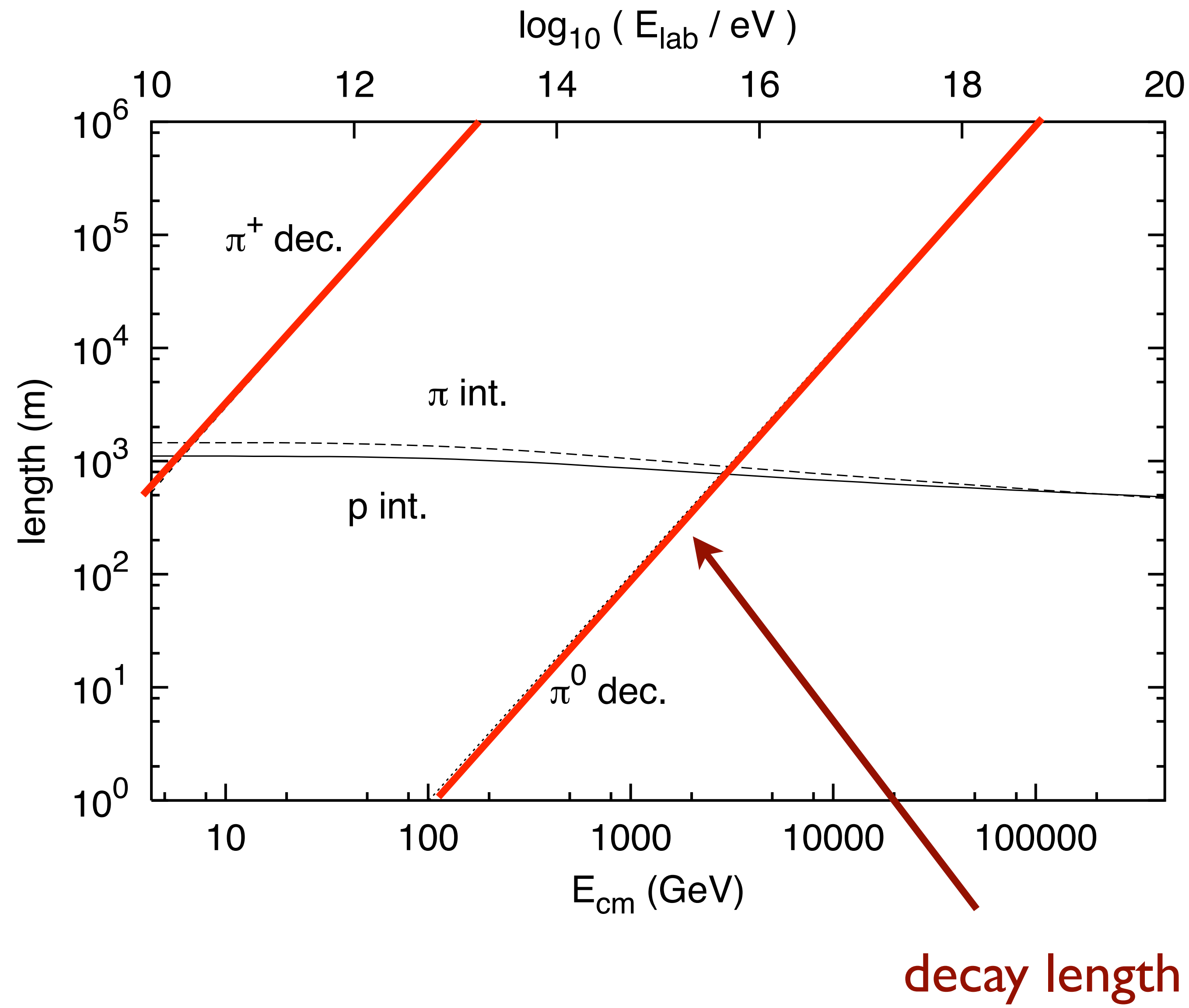
Air showers – decay vs. interaction

Comparison at sea level

$$\lambda_{\text{int}} = \frac{\langle m \rangle}{\sigma_{\text{ine}}}$$



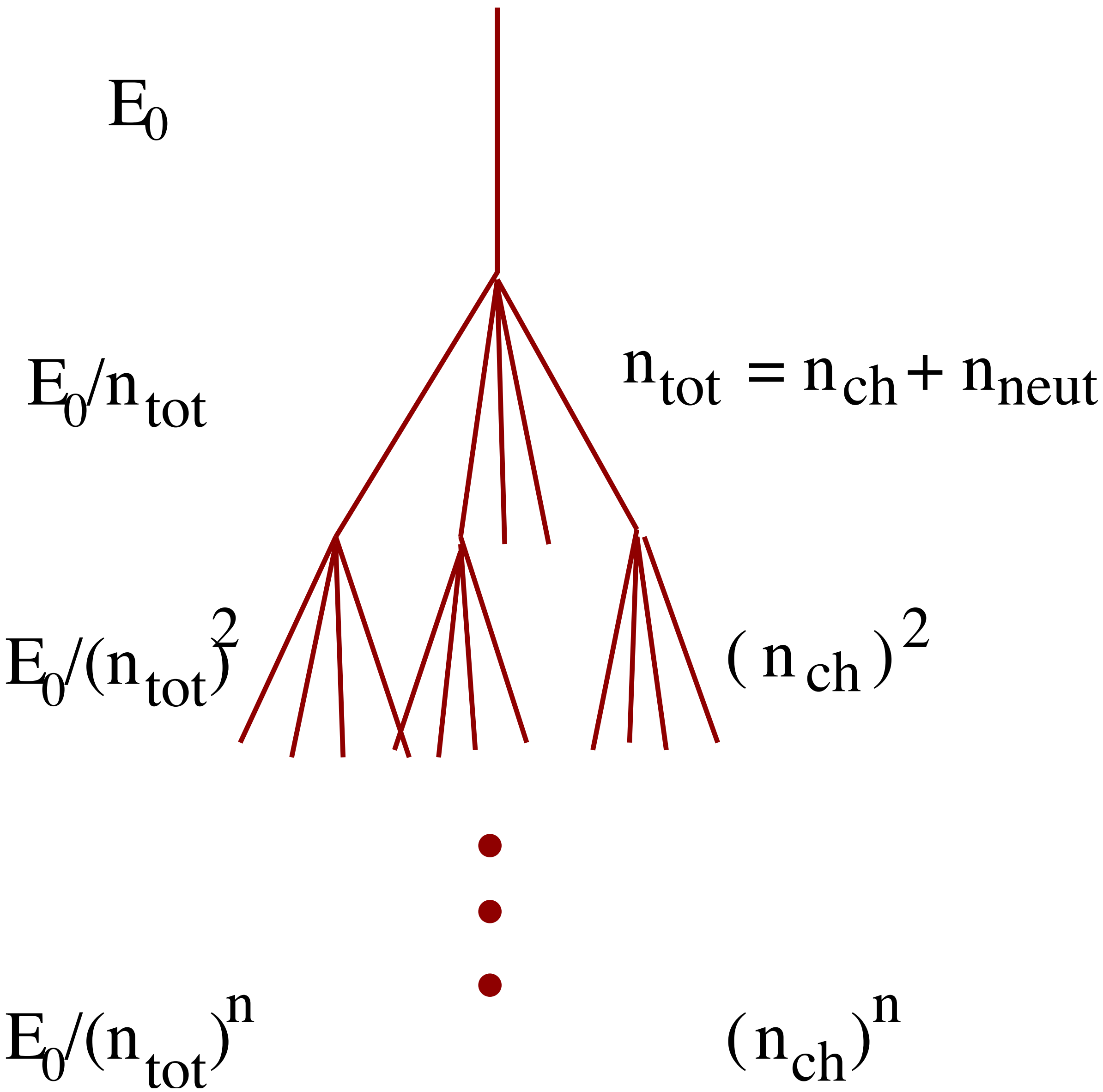
$$c\tau_{\pi^\pm} = 7.8\,\text{m}$$

$$c\tau_{\pi^0} = 25.1\,\text{nm}$$

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

$$\pi^0 \longrightarrow \gamma\gamma$$

Muon production in hadronic showers



Primary particle proton

π^0 decay immediately

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

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

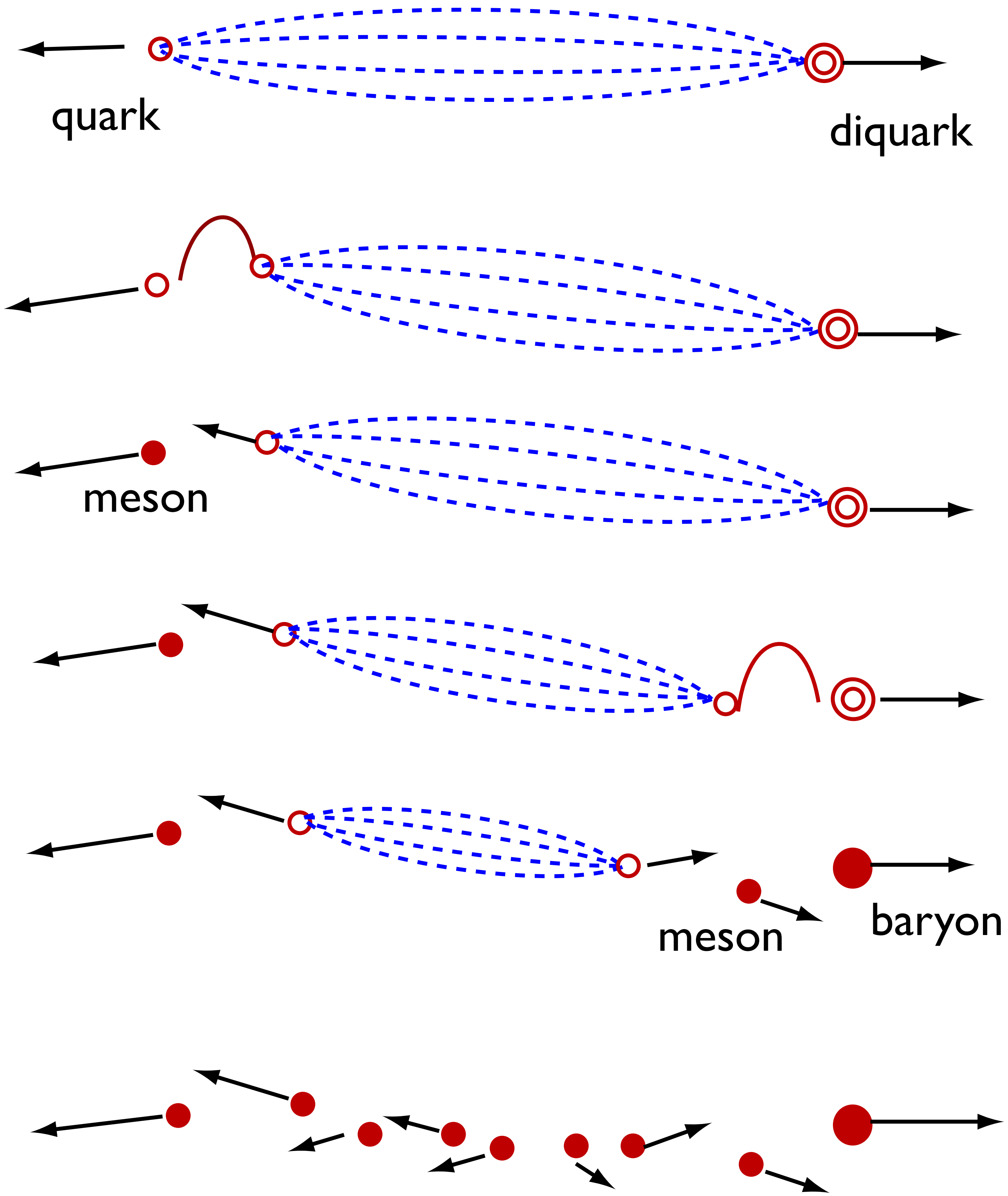
$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

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

(Matthews, Astropart. Phys. 22, 2005)

Modification of ratio of neutral to charged pions

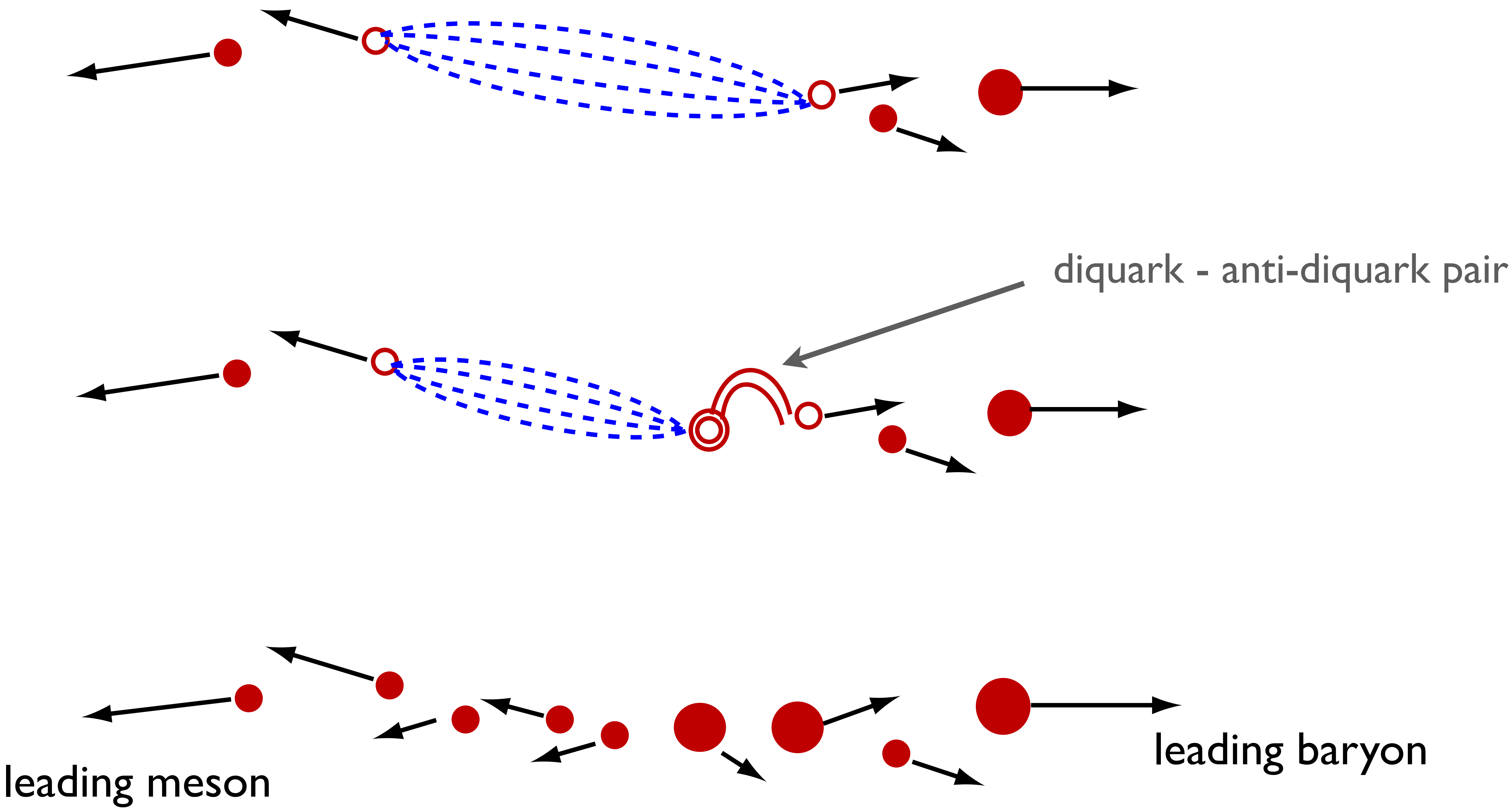


$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\alpha$$

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

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

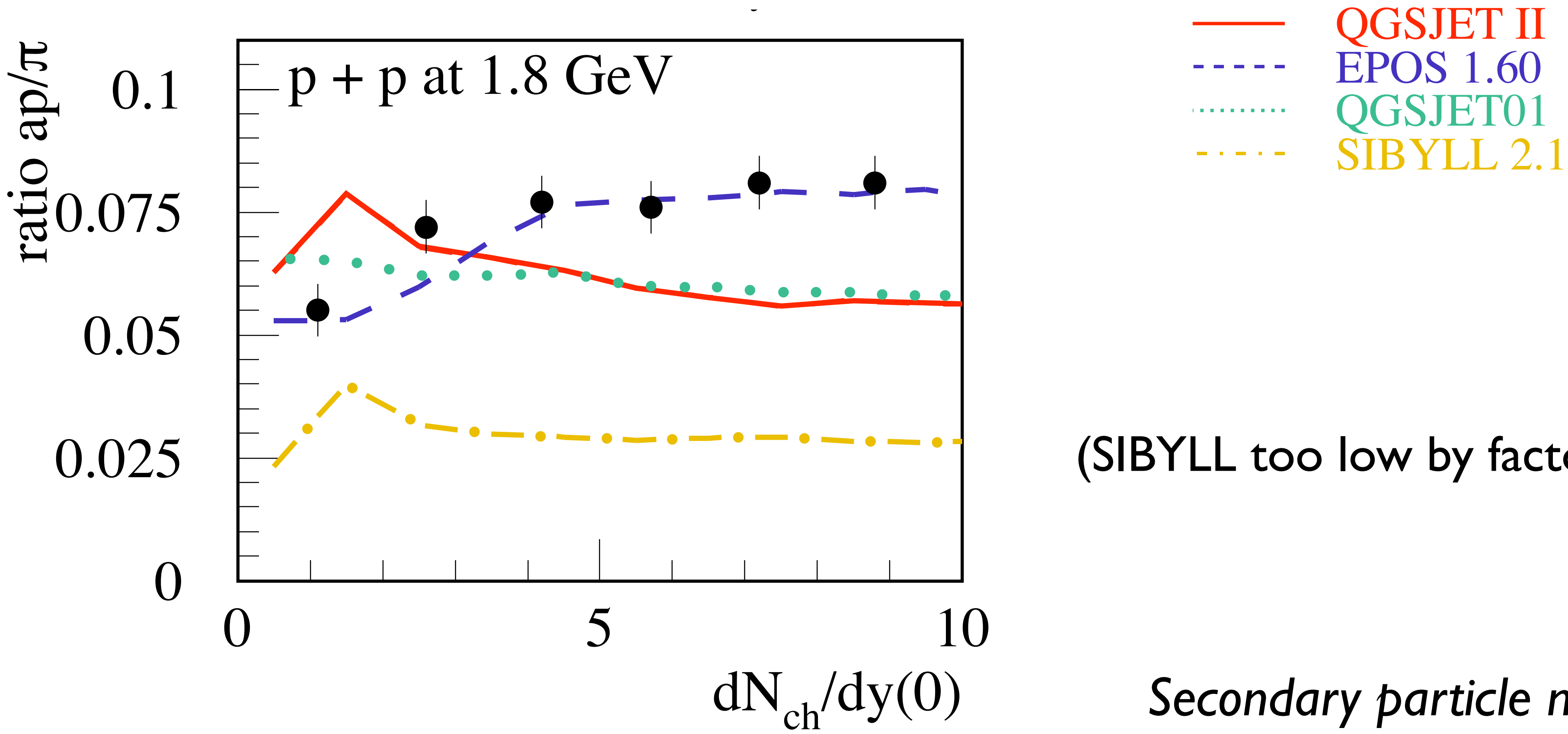
String fragmentation: baryon pairs



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

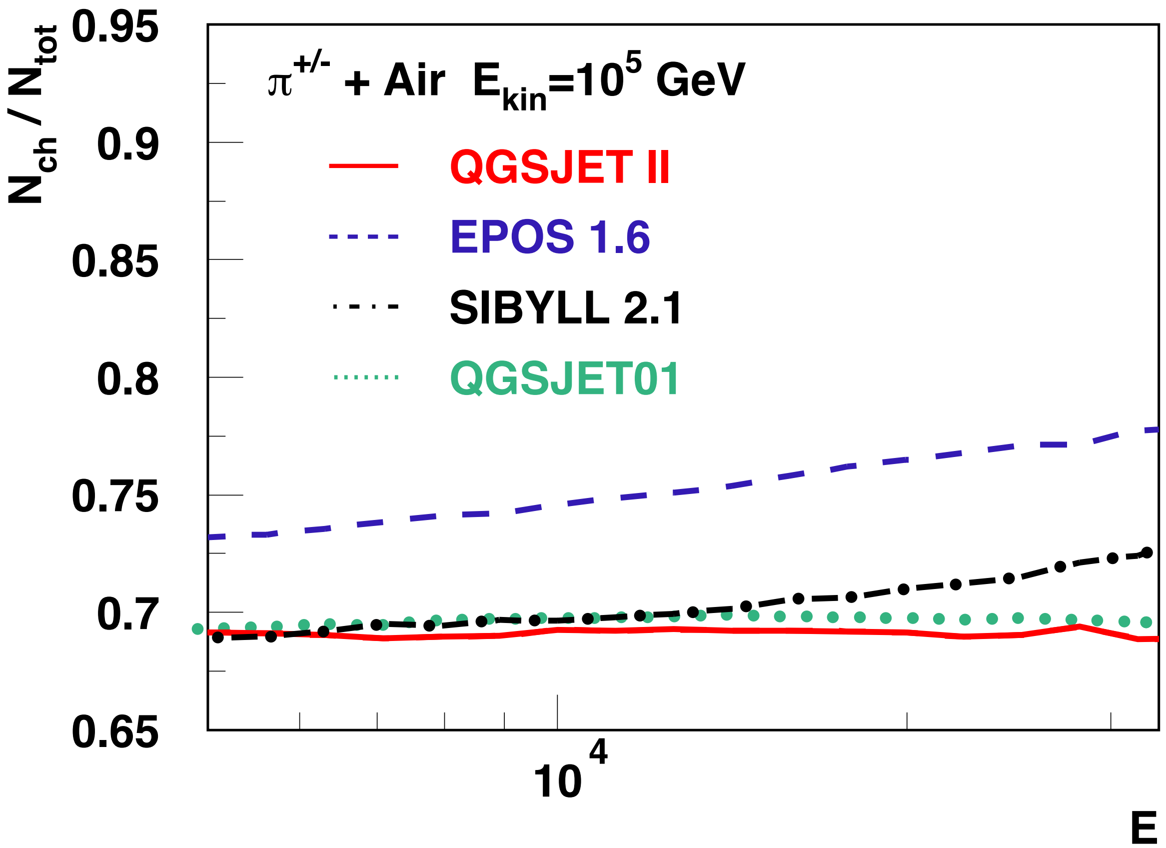
EPOS: modification of fragmentation parameters as function of string density (RHIC data)

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

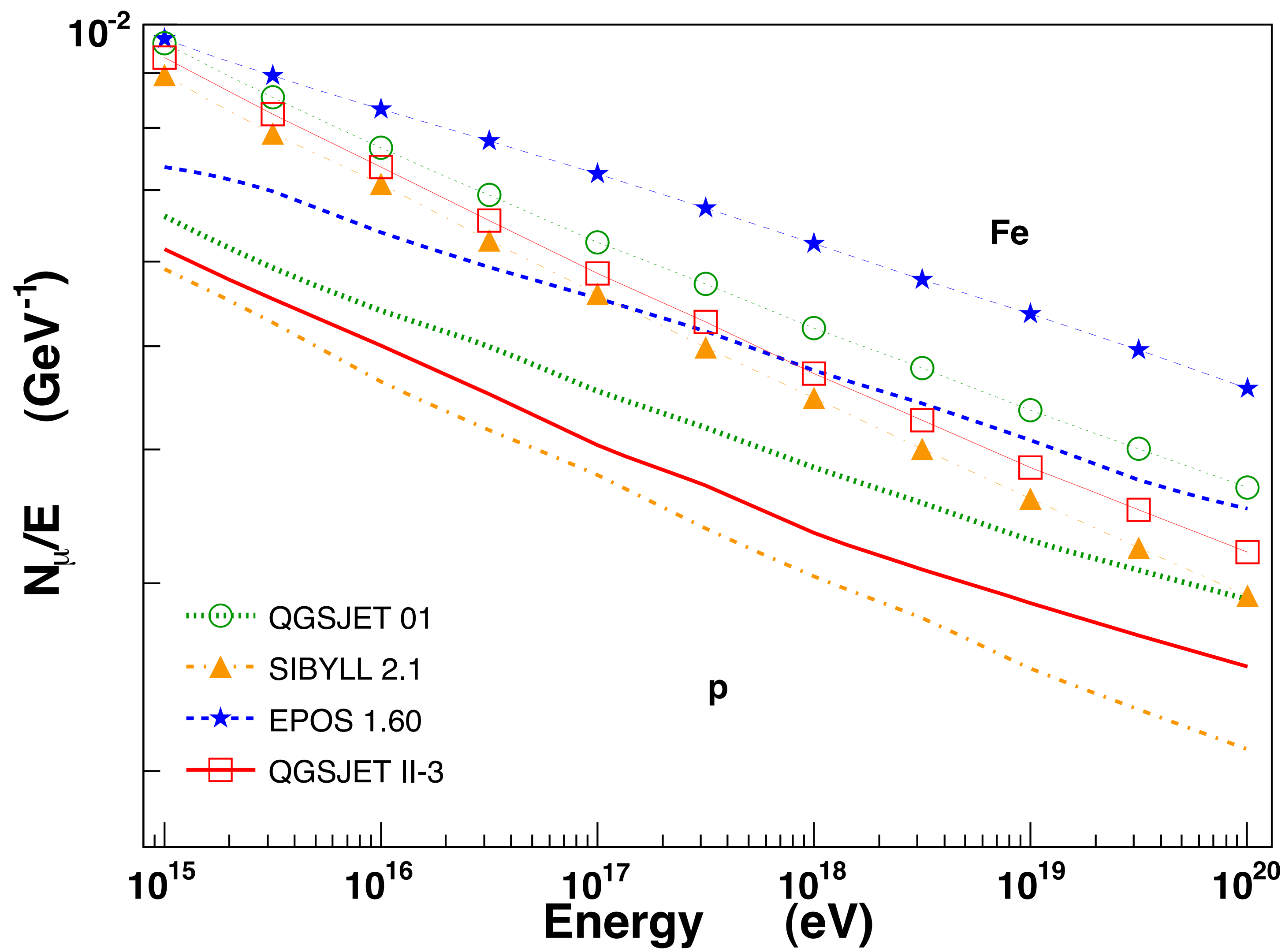
EPOS: Enhancement of baryon pair production

(Grieder, ICRC 1973)

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



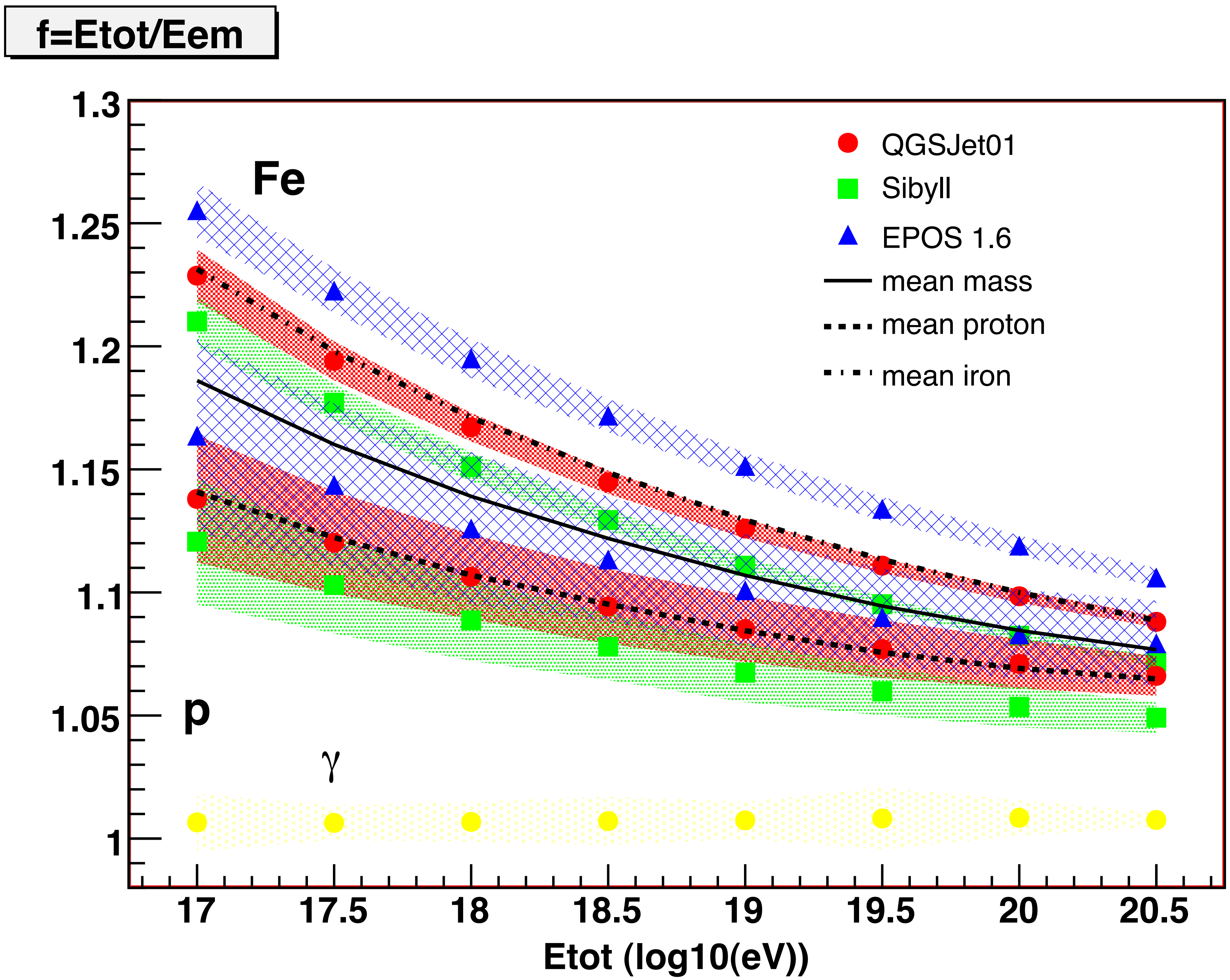
Muon multiplicity re-scaled with energy



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

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

Muon multiplicity correlation with missing energy



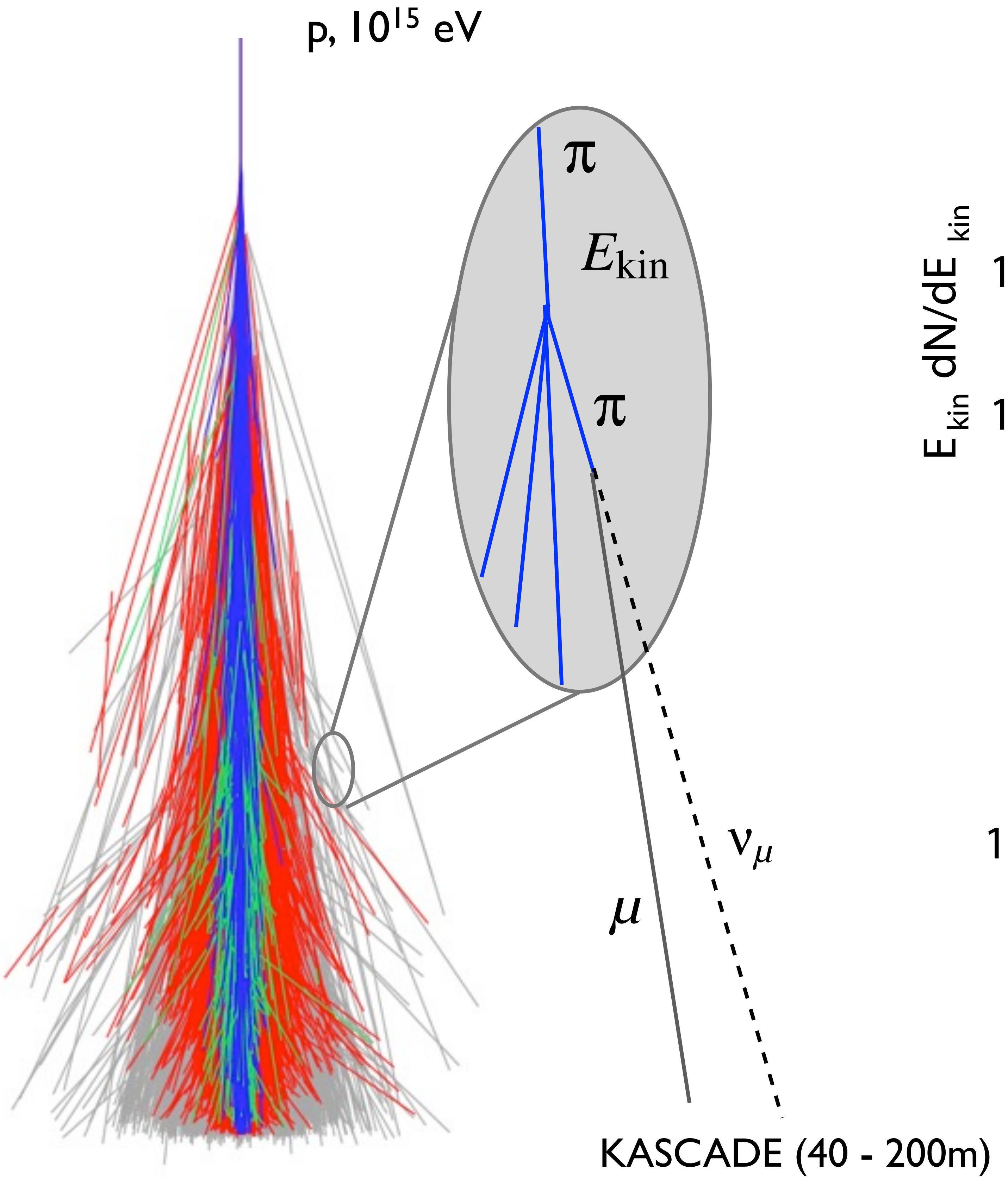
(T. Pierog et al., ICRC 2007)

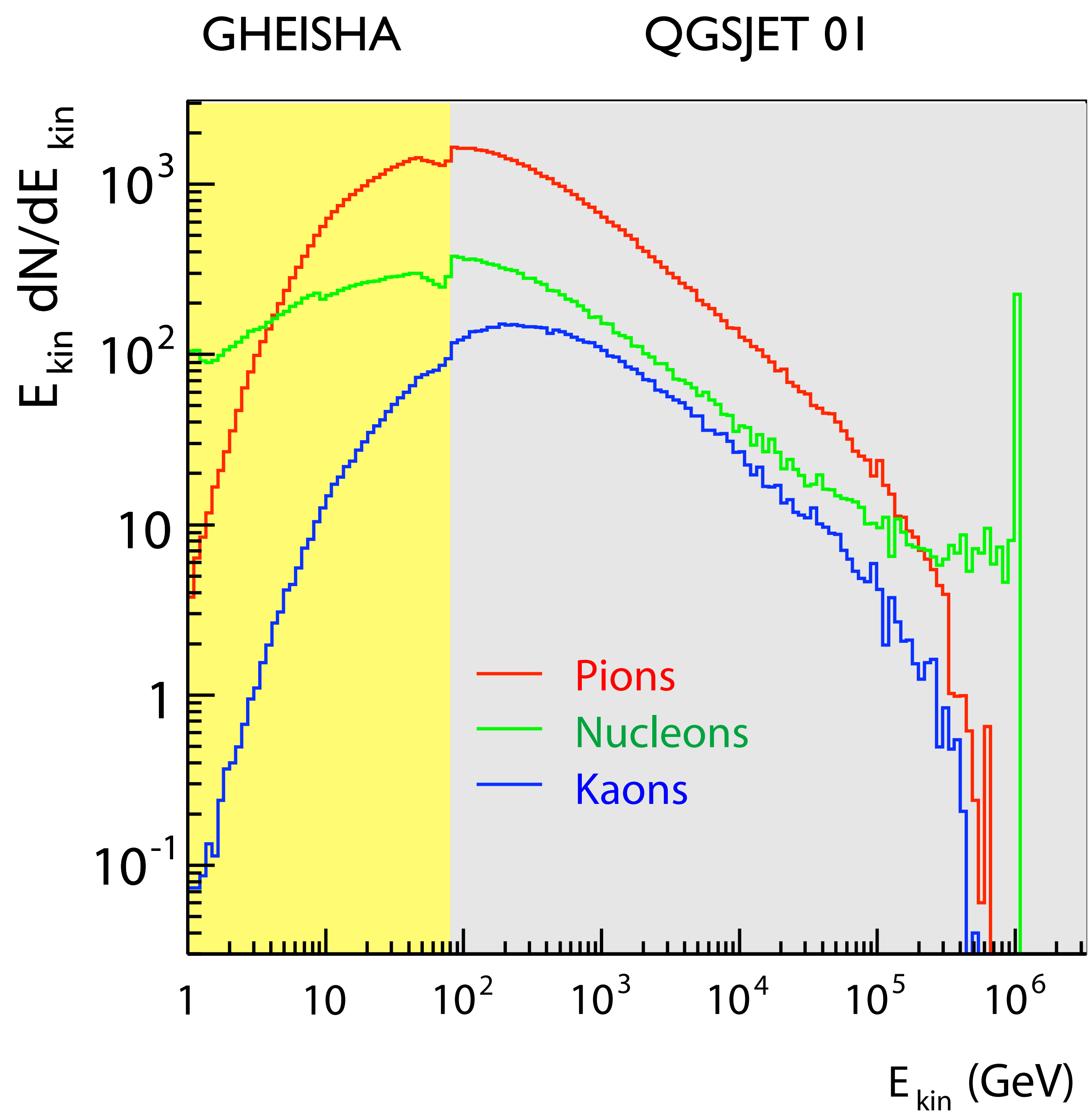
$E = 10^{19.5}$ eV

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

Model dependence of energy correction small

Muon production in air showers



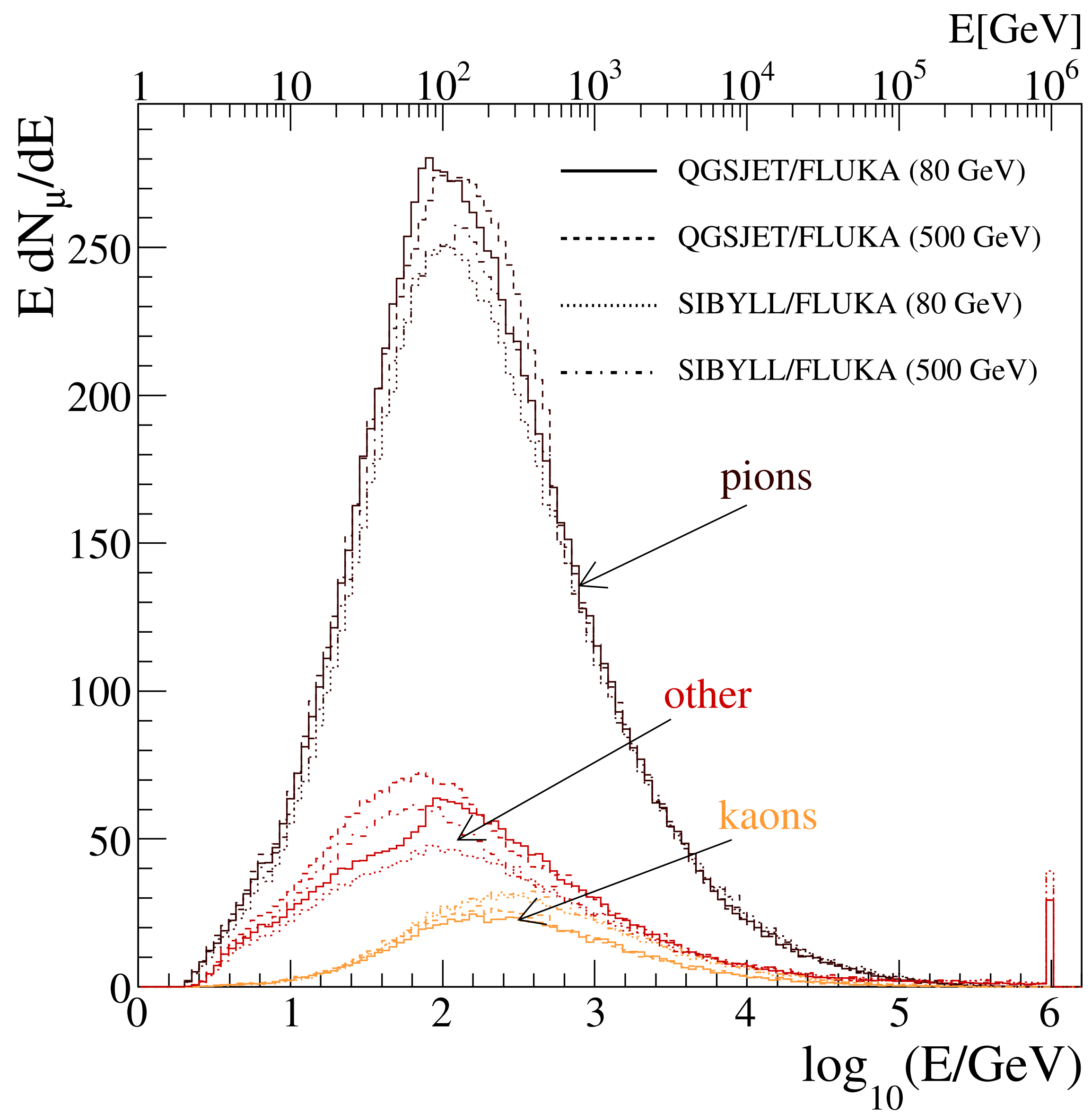


(C. Meurer et al., ICRC 2005, Pune, India)

Comparison: KASCADE vs. Auger

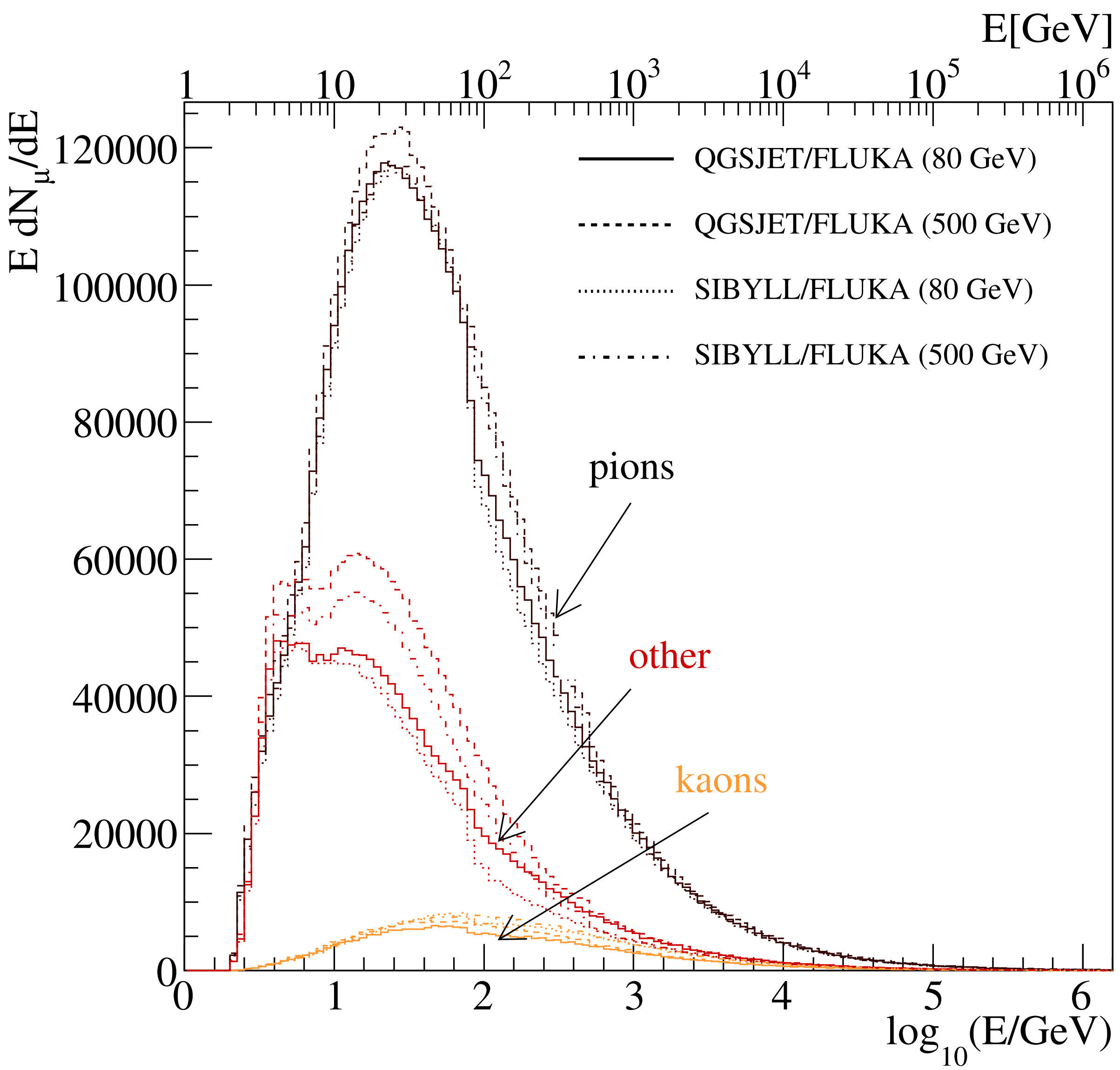
KASCADE

- energy 10^{15} eV, $E_\mu > 250\,\mathrm{MeV}$



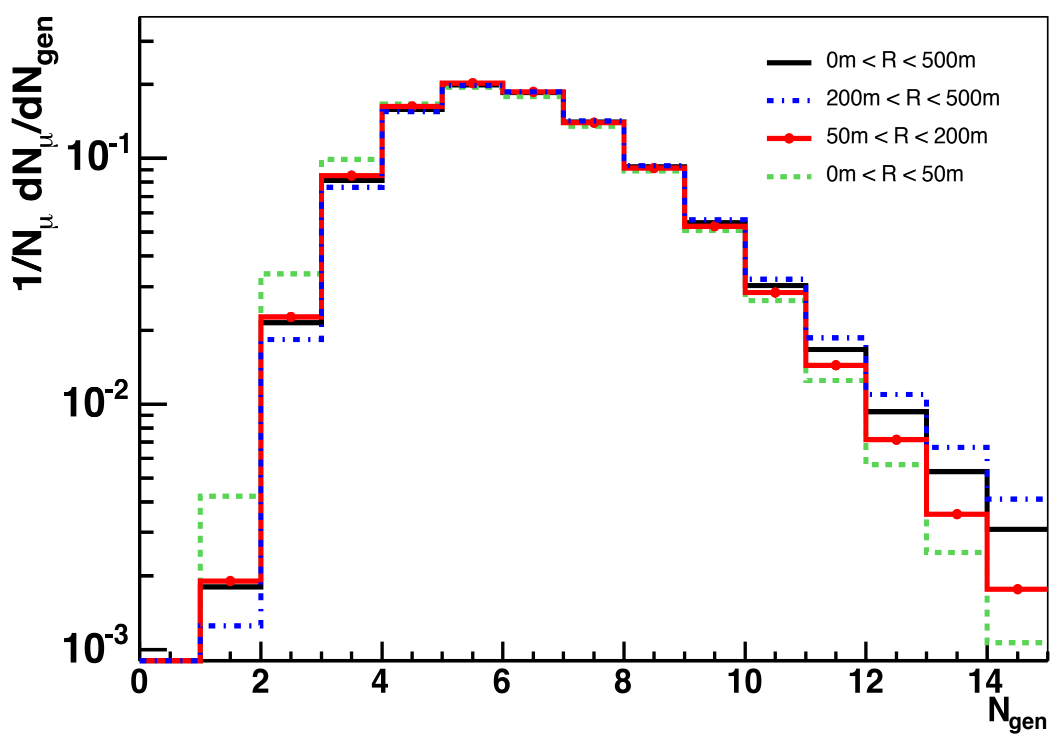
Pierre Auger Observatory

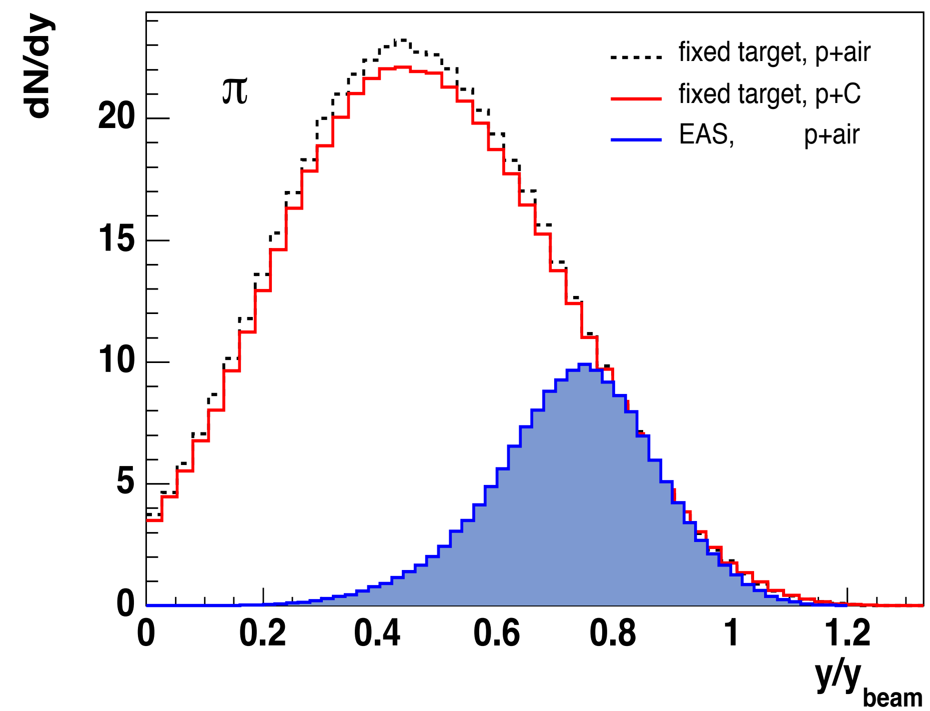
- energy 10^{19} eV, $E_\mu > 150\,\mathrm{MeV}$

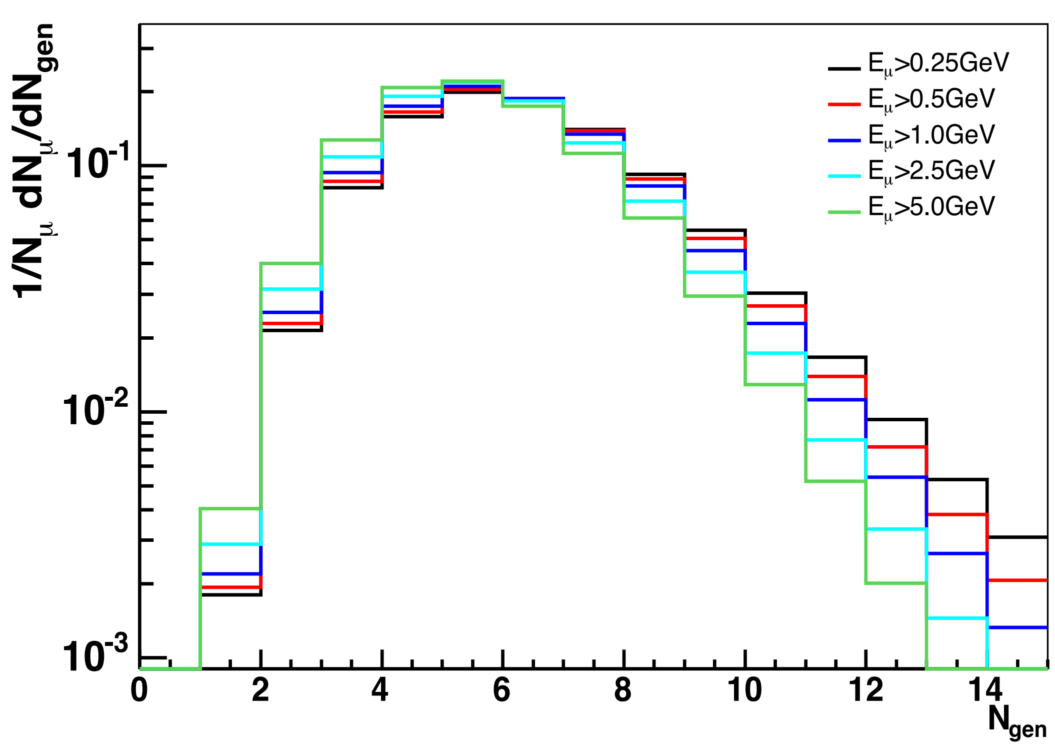


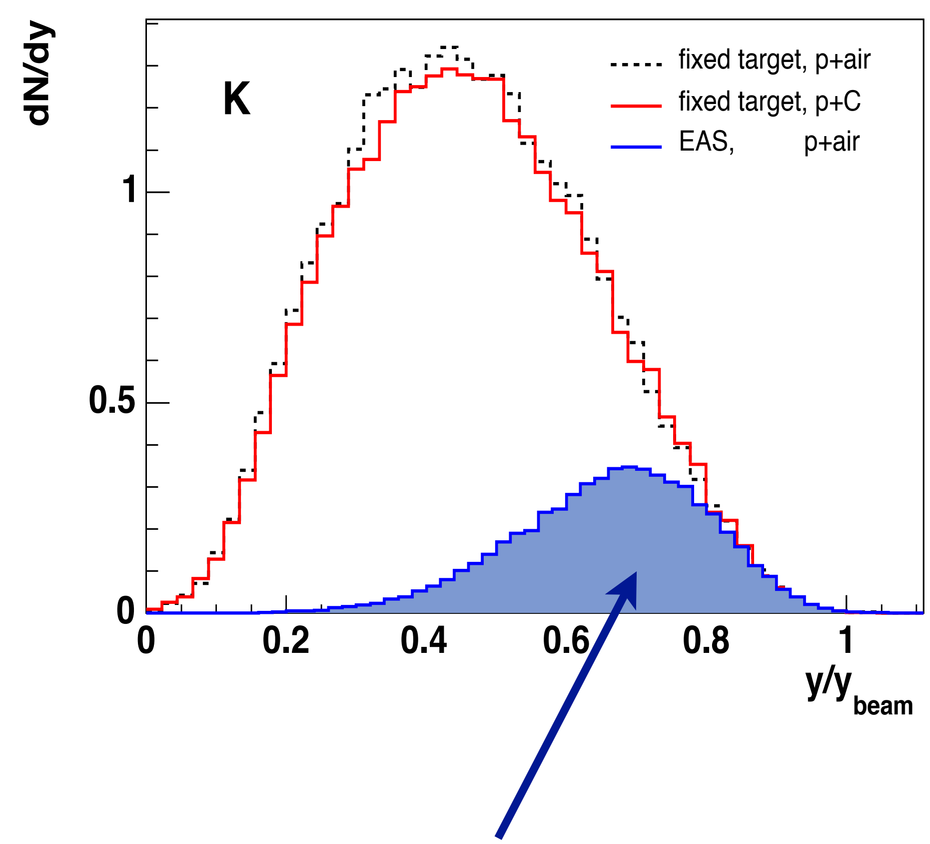
(Maris et al., ICRC 2009)

Characteristics of hadronic interaction chain









Phase space for muon production

Exotic physics in first few interactions ?

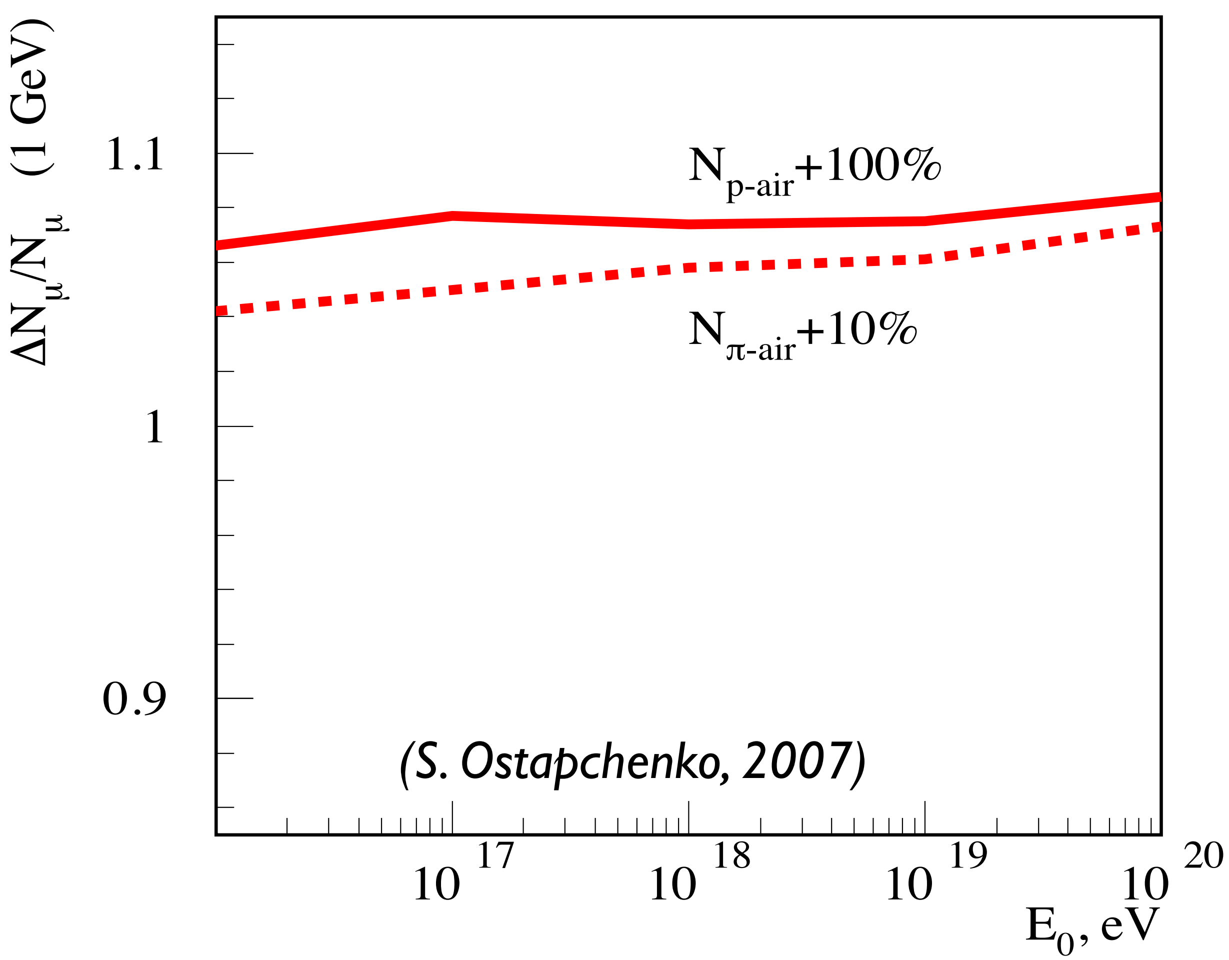
Muon production:

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

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

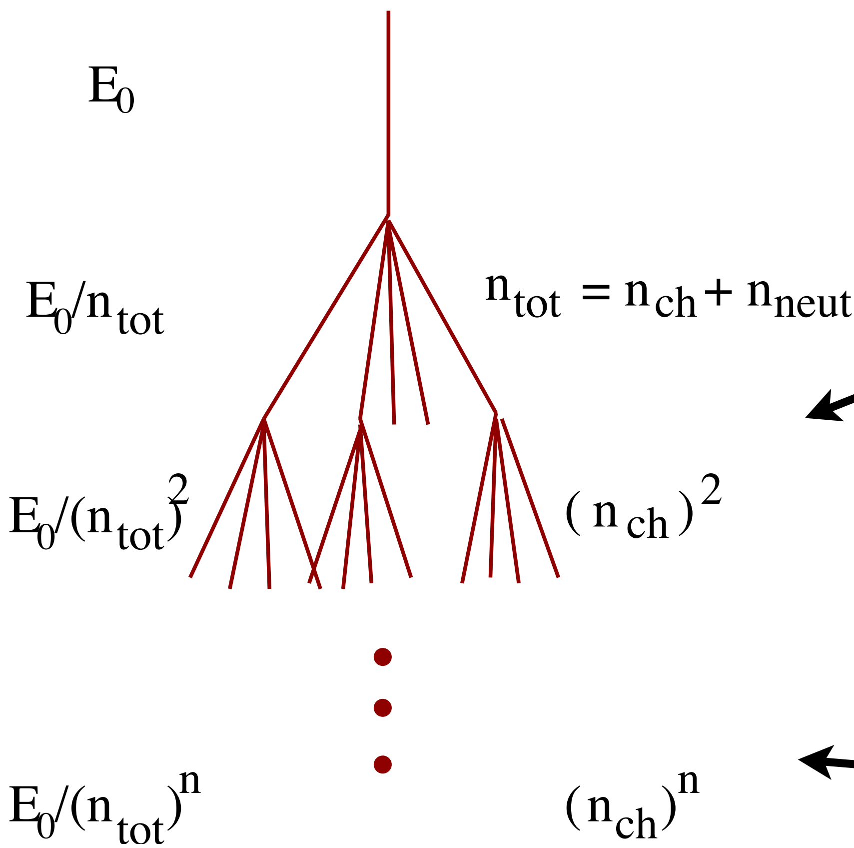
Multiplicity increase by
factor of 2: 5 -7% more muons,
factor of 10: 25% more muons

Muon enhancement



Muon number insensitive to changes of high-energy interactions

Possible application in IceTop/IceCube



High energy muons in IceCube from early interaction generations (measured with energy loss of muon bundles)

Low energy muons in IceTop from late interaction generations (estimated with CIC method and universality)

IceTop/IceCube could distinguish between exotic high energy interaction scenario and low energy interaction effects (antibaryon production?)