Impact of Uncertainties in Hadron Production on Air-Shower Predictions

T. Pierog, R. Engel and D. Heck

Introduction :

- Spectrum
- Observables

Phenomenology of Air-Showers :

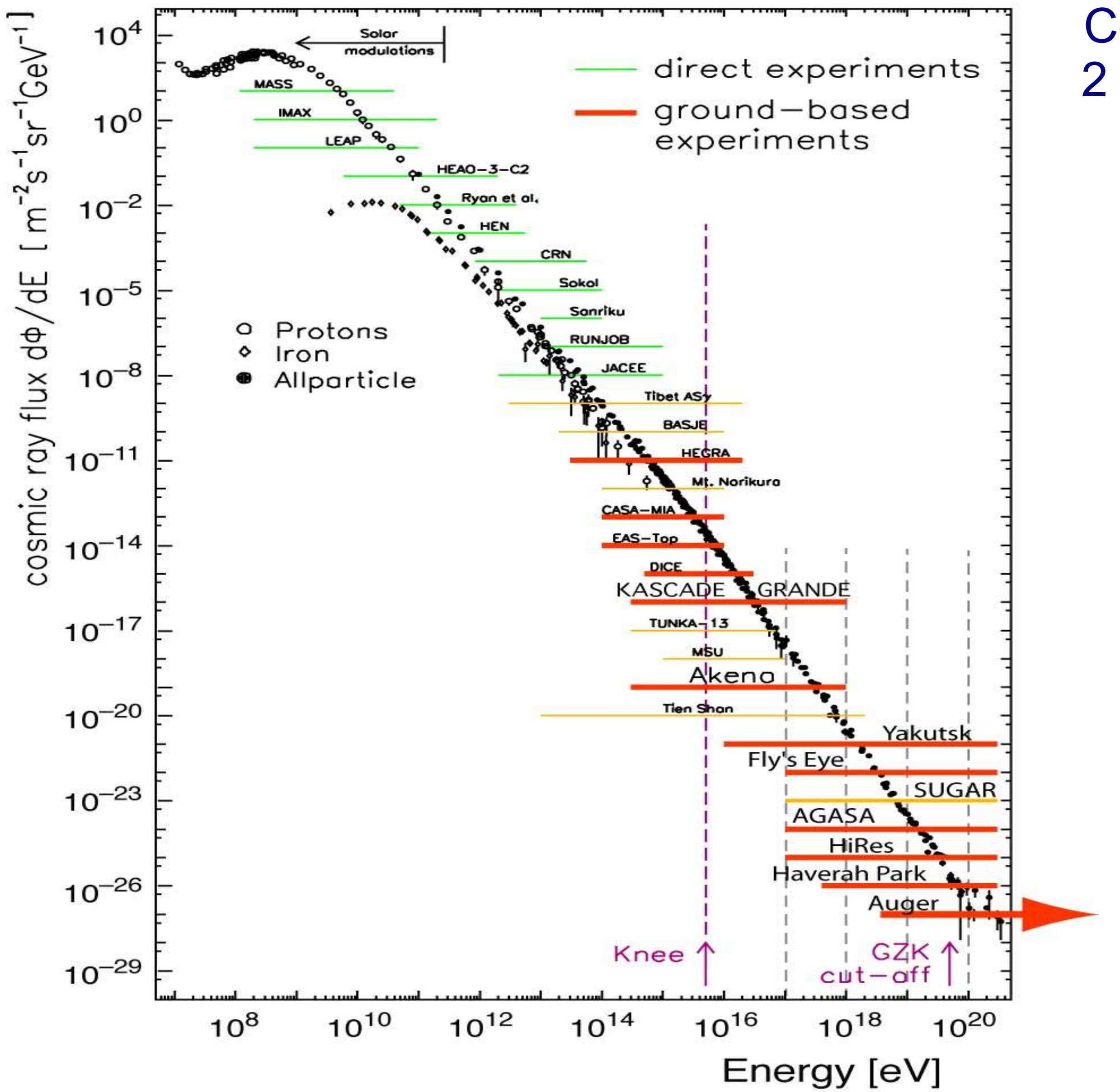
- em. shower
- muons
- from hadr. to em.

Applications :

- $\langle X_{max} \rangle$
- LDF
- N_μ vs N_e

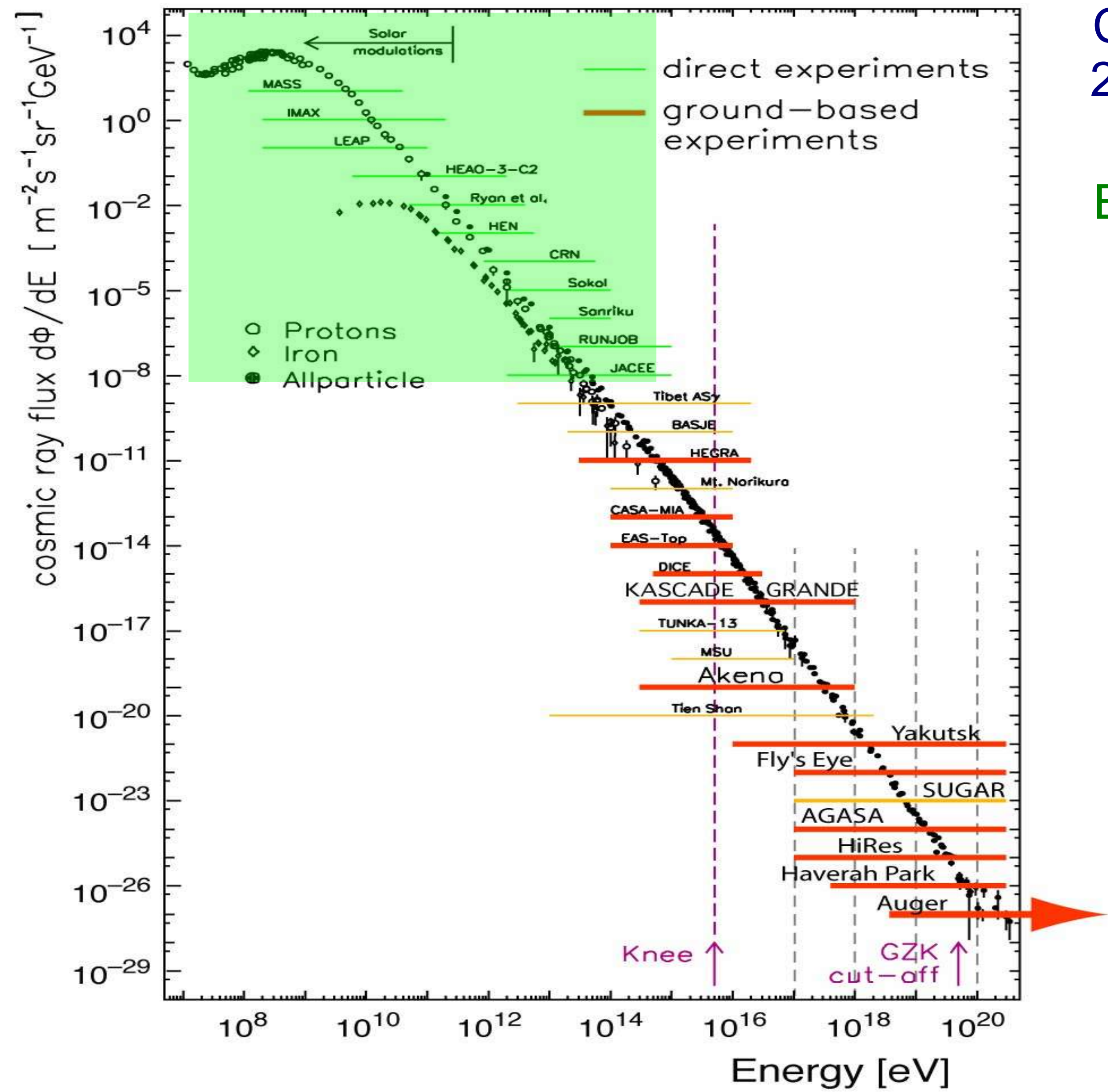
September 9th 2005

Cosmic Ray Spectrum



Cosmic ray spectrum explored by 2 different ways :

Cosmic Ray Spectrum

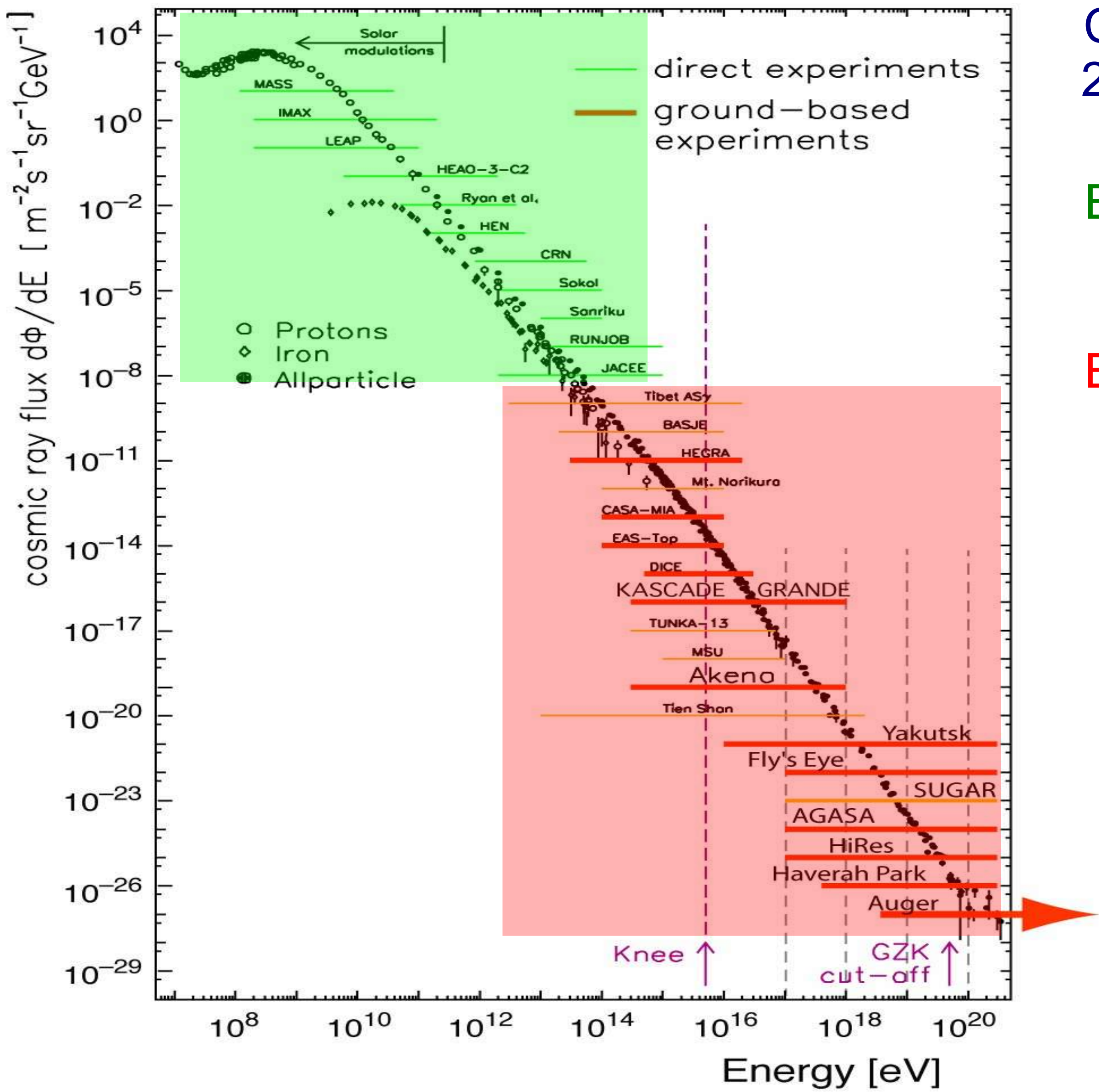


Cosmic ray spectrum explored by 2 different ways :

E < 10^{14} eV : large flux

➜ direct detection

Cosmic Ray Spectrum

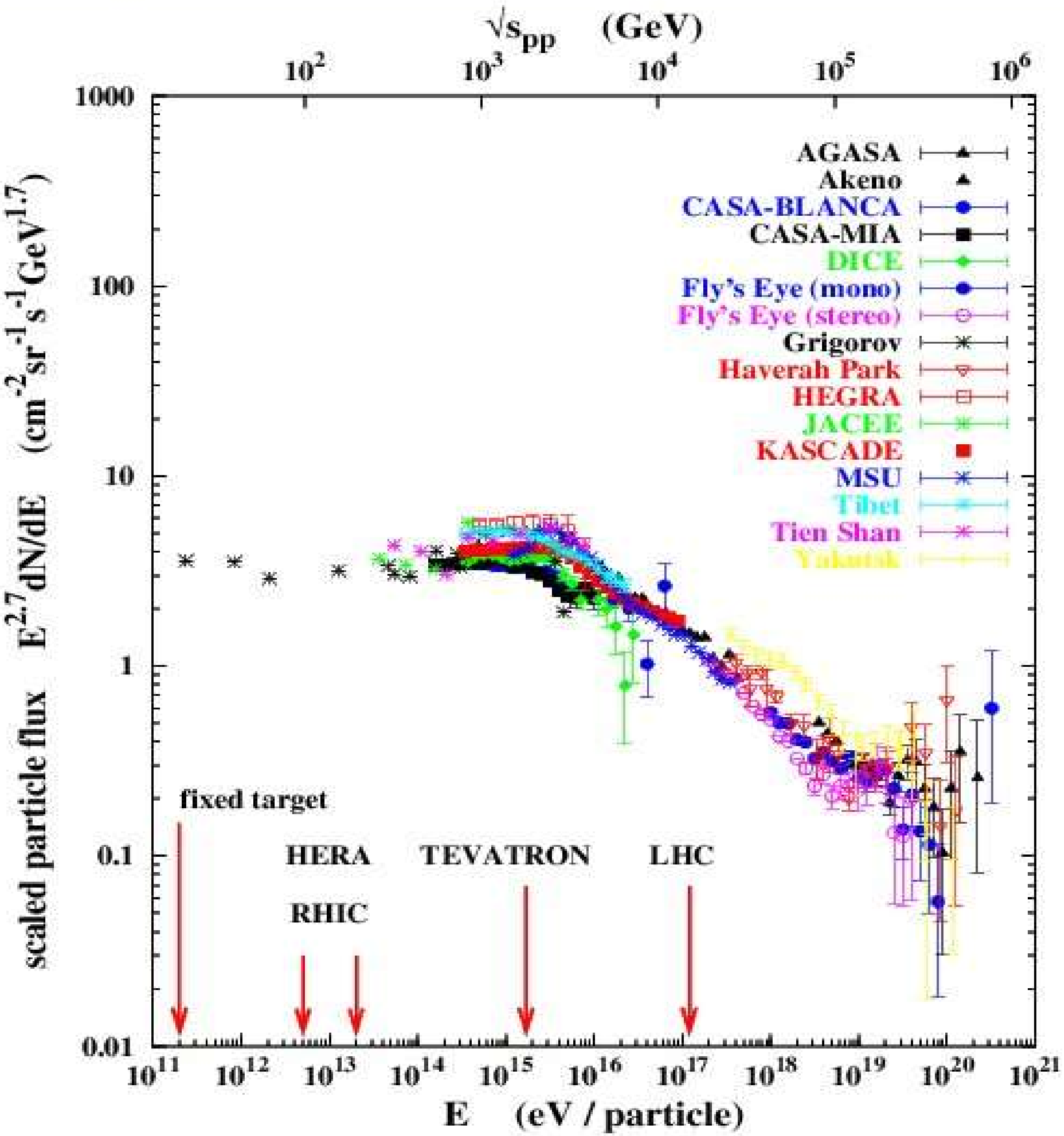


Cosmic ray spectrum explored by 2 different ways :

E < 10^{14} eV : large flux
- direct detection

E > 10^{14} eV : low flux
- indirect detection : air-shower reached ground

Cosmic Ray Spectrum



Cosmic ray spectrum explored by 2 different ways :

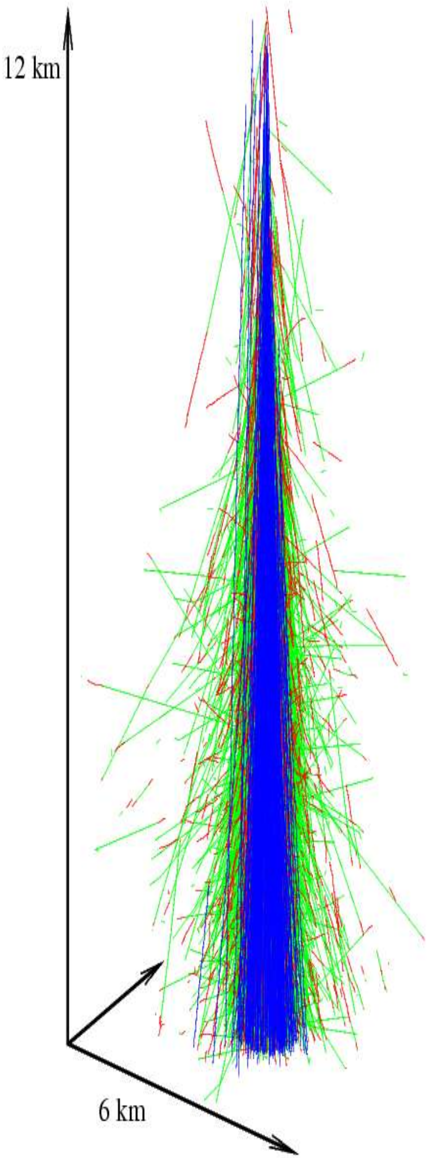
E < 10^{14} eV : large flux
- direct detection

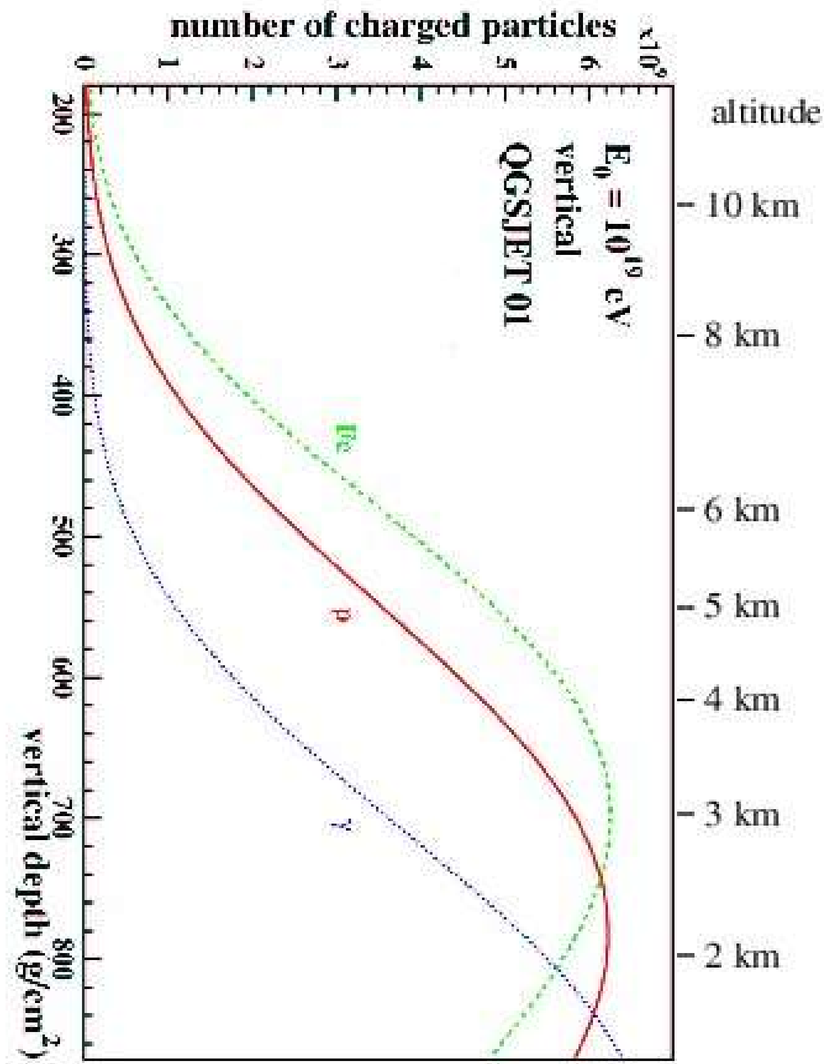
E > 10^{14} eV : low flux
- indirect detection : air-shower reached ground

Air-shower simulations needed to interpret high energy data.

Energy above any collider experiment !

Observables (1)





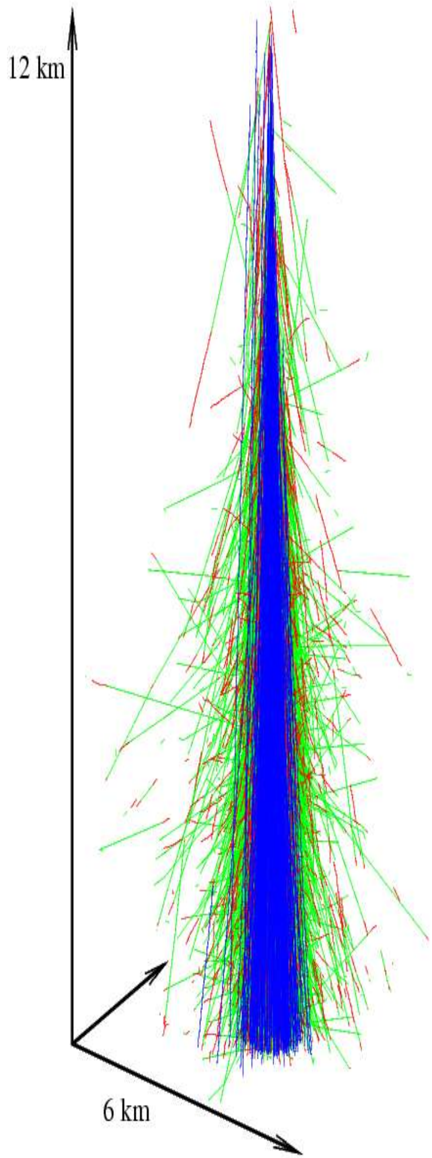
Characteristic energies
($P_{decay} \sim P_{interaction}$) :
$\pi^{\pm}$'s: ~150 GeV
kaons: ~600 GeV
π^0's: ~10^9 GeV

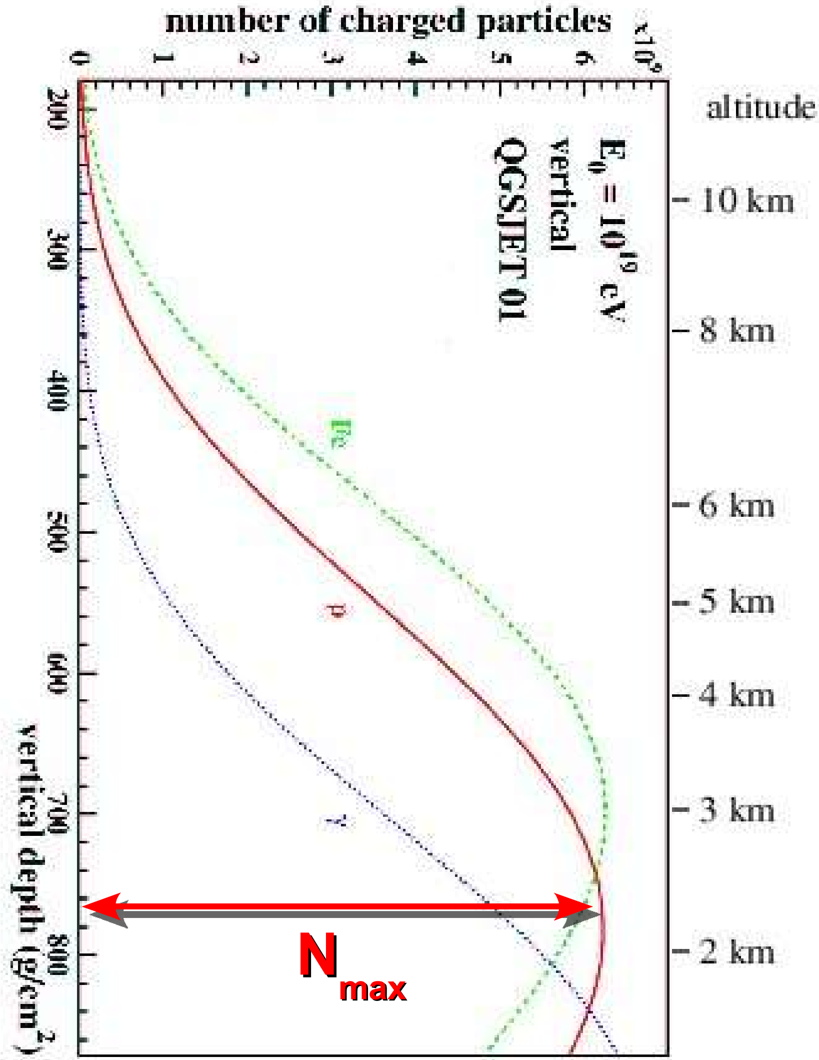
Longitudinal development of air-showers :

number of particles (or energy deposited by charged part.) projected on the axis

Main characteristics :

Observables (1)





Characteristic energies
(P_{decay} ~ $P_{interaction}$) :
$\pi^{\pm}$'s: ~150 GeV
kaons: ~600 GeV
π^0's: ~10^9 GeV

Longitudinal development of air-showers :

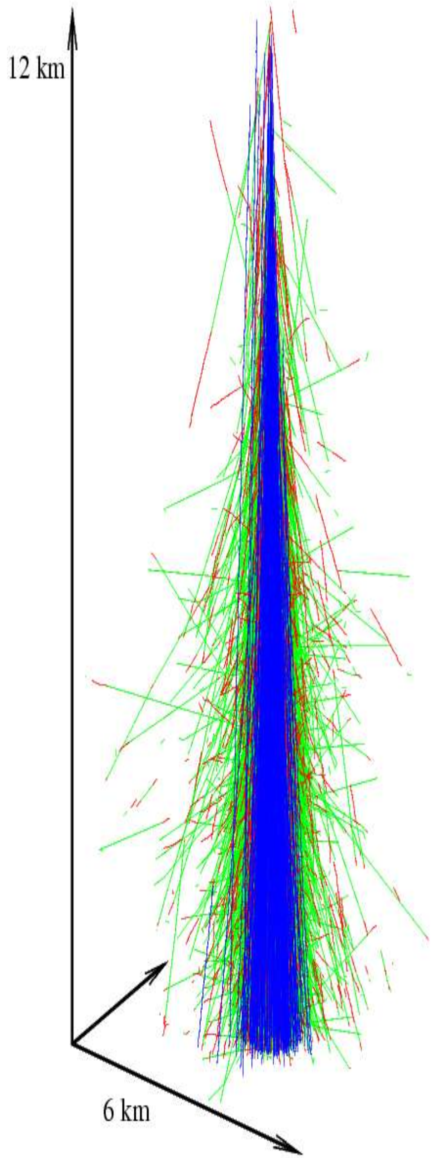
number of particles (or energy deposited by charged part.) projected on the axis

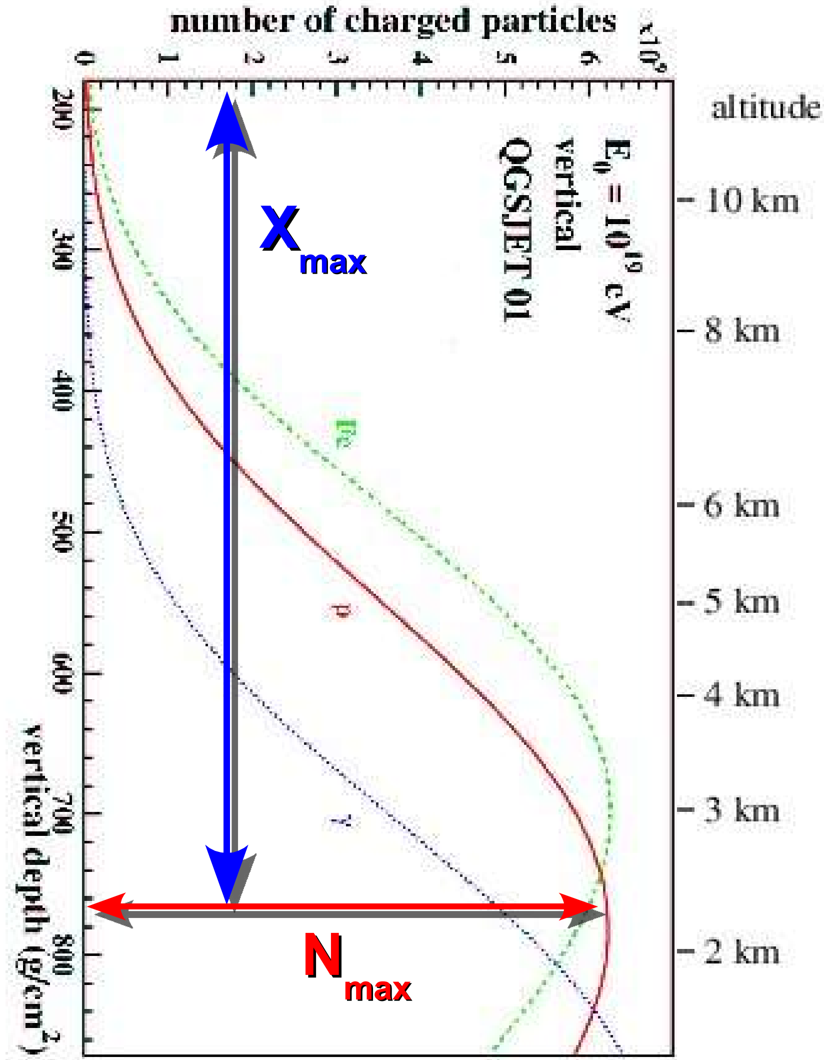
Main characteristics :

- Shower maximum N_{max}

  Mass indepent,
  energy dependent,
  small fluctuations

Observables (1)





Characteristic energies ($P_{decay} \sim P_{interaction}$) :

$\pi^{\pm}$'s: ~150 GeV

kaons: ~600 GeV

π^0's: ~10^9 GeV

Longitudinal development of air-showers :

number of particles (or energy deposited by charged part.) projected on the axis

Main characteristics :

- **Shower maximum N_{max}**

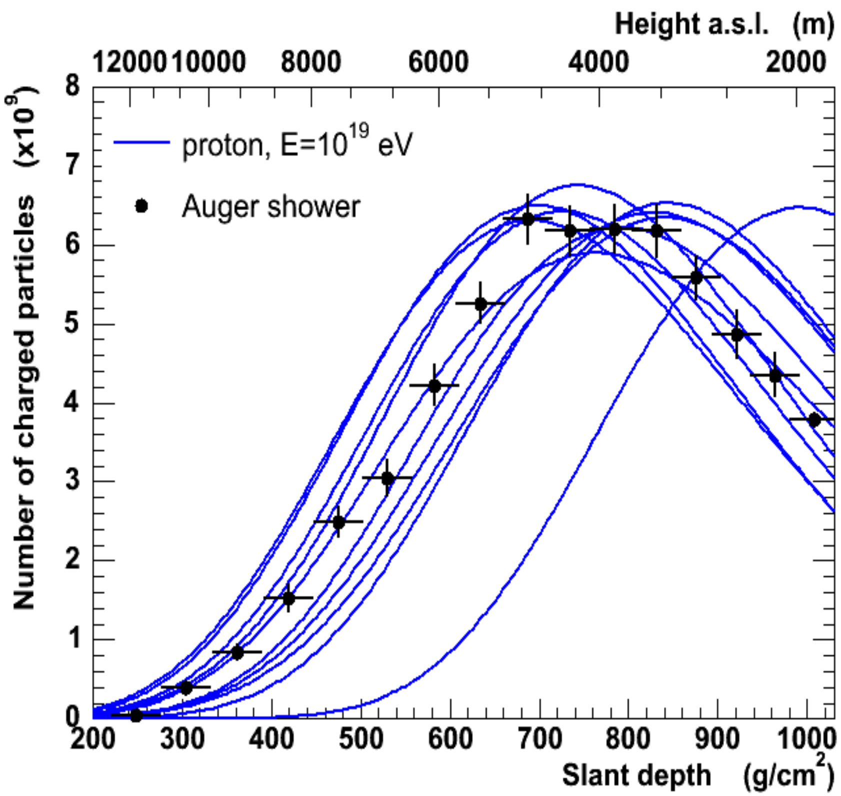
  Mass indepent, energy dependent, small fluctuations

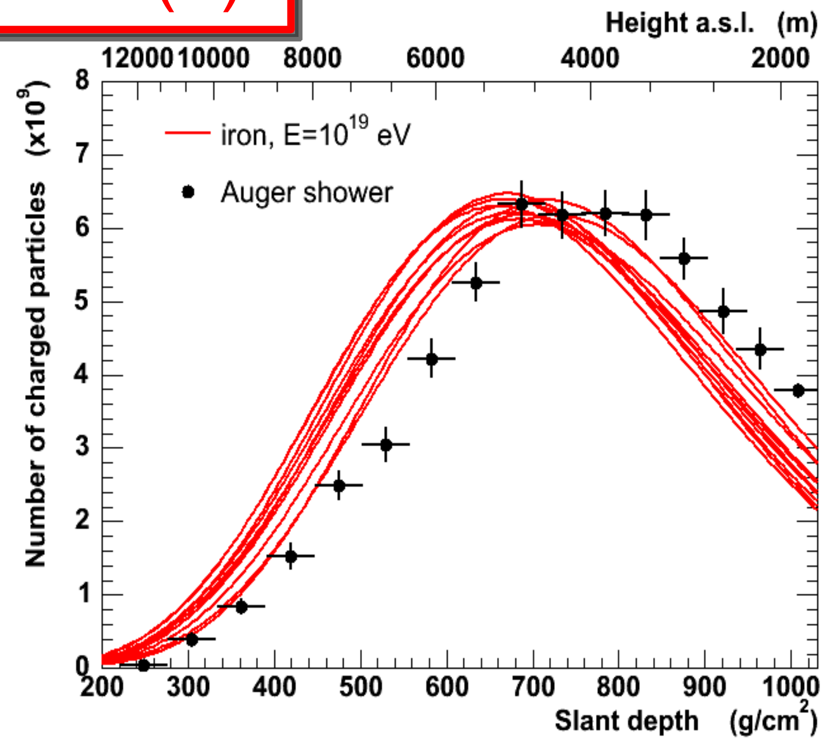
- **Depth of shower maximum X_{max}**

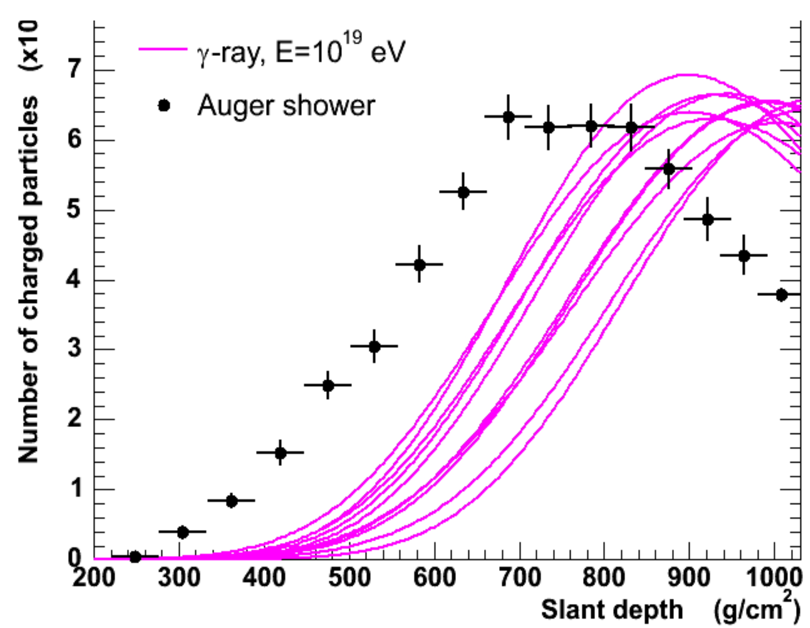
  Mass and energy dependent, large fluctuations

Observables (2)

Detailed MC simulation :
10 showers zenith angle 35°,
QGSJET







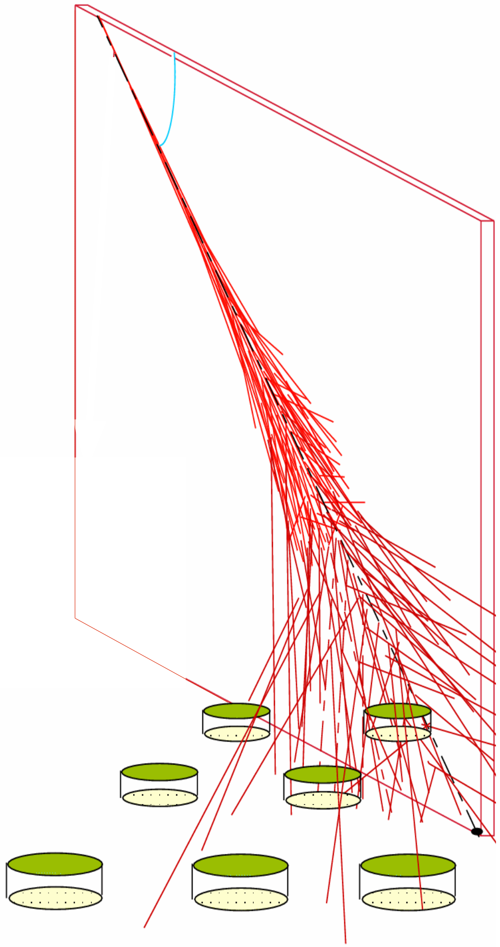
Shower-by-shower fluctuations are very important and mass dependent.

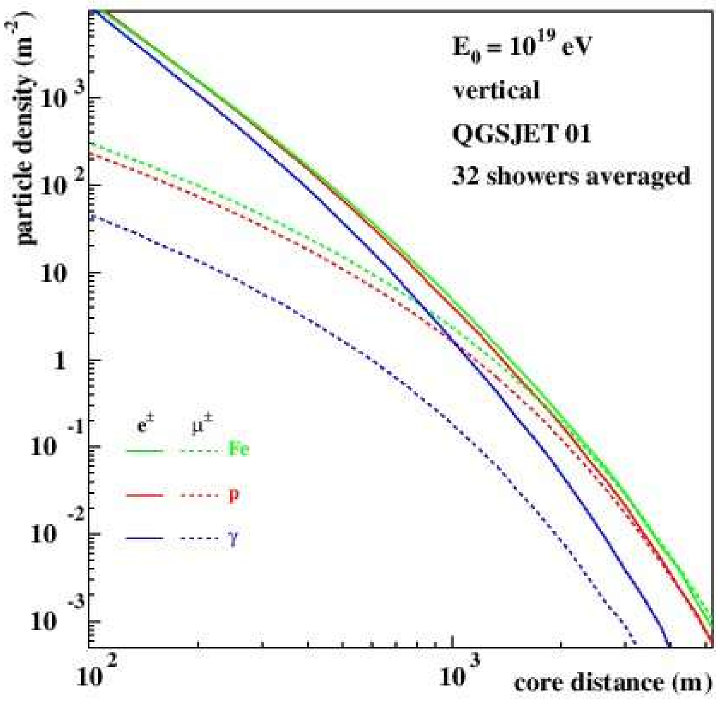
Observables (3)

Particles reaching ground :

most of them at the impact point, but some lateral spread

- Lateral Distribution Function (LDF) used to reconstruct the total number of part.



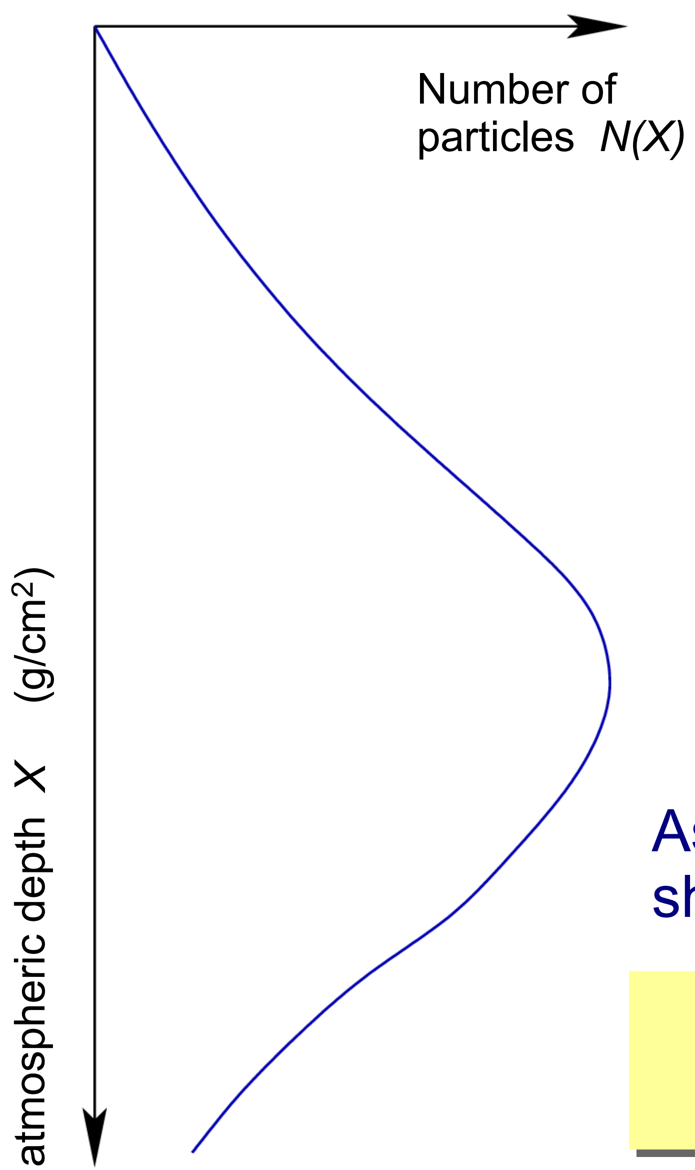


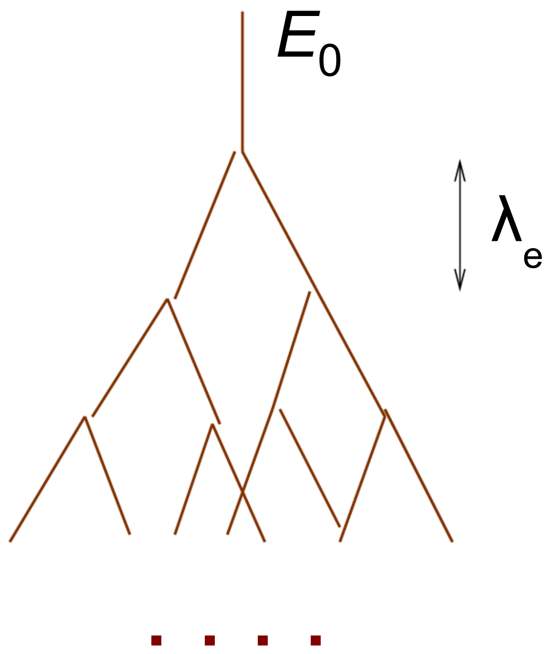
Energy from LDF

Different mass depence of muon's LDF and electron's LDF

Mass from correlation N_{μ} vs N_e

Heitler's Model of EM Showers





Primary particle :
photon

2^n particles after
n interactions

$$n = X/\lambda_e$$

$$N(X) = 2^n = 2^{X/\lambda_e}$$

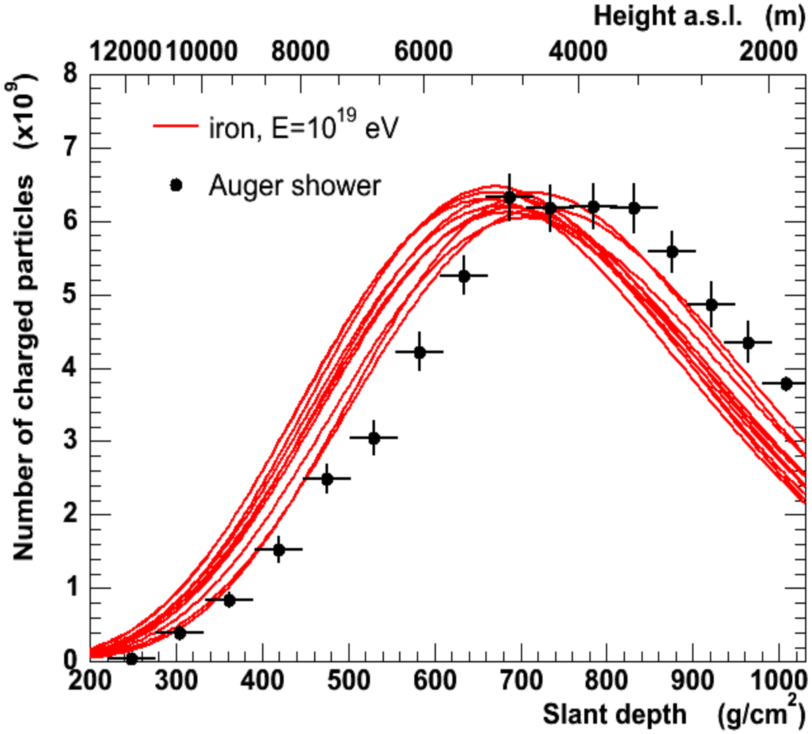
$$E(X) = E_0/2^{X/\lambda_e}$$

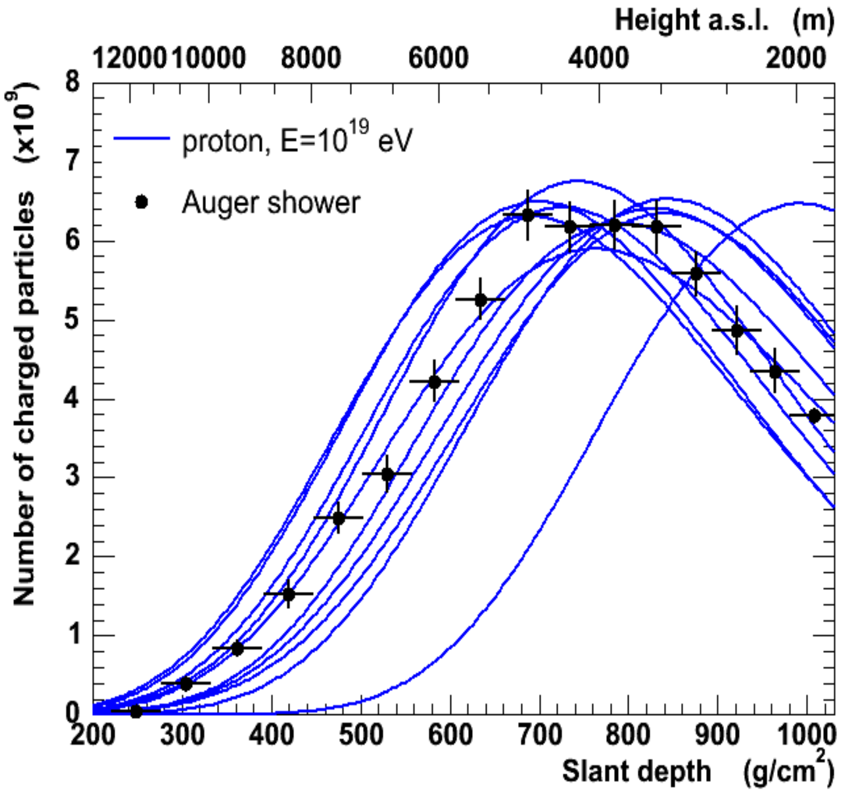
Assumption:
shower maximum reached if $E(X) = E_c$

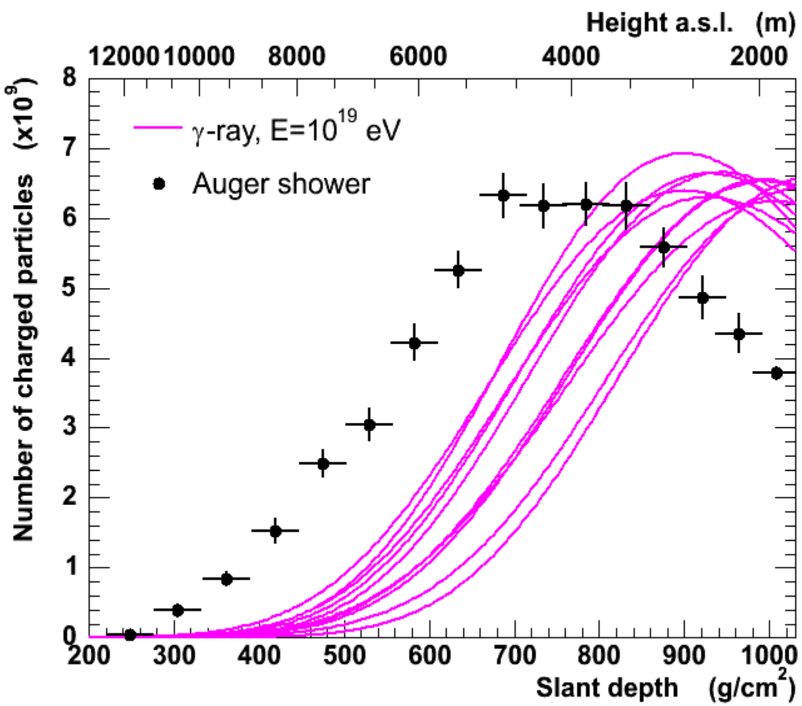
$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

N_{max}

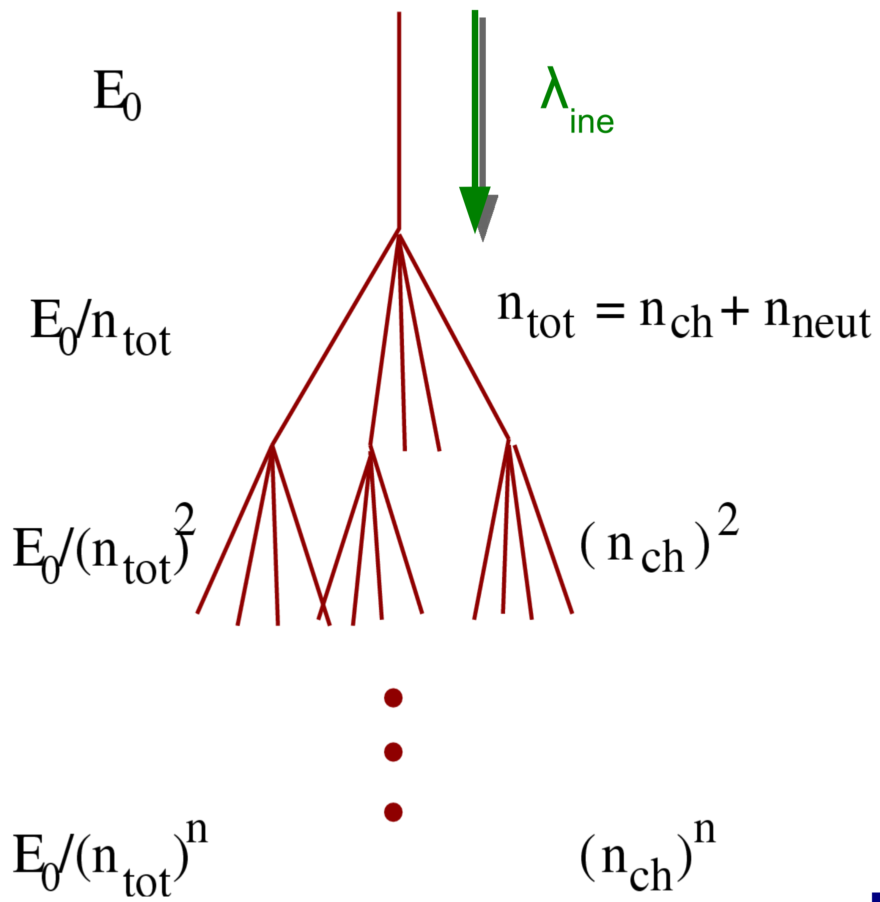
Detailed MC simulation :
10 showers zenith angle 35°,
QGSJET







Muon Component



$$X_{max} \sim \lambda_e \ln\left(E_0/(2\,n_{tot})\right) + \lambda_{ine}$$

Primary particle:
proton

$n_{ch} \sim \pi^{+/-}$

$n_{neut} \sim \pi^0$:
decay immediately $\rightarrow 2\gamma$

Cascade ends with
decay at energy E_{dec}

$$E(X) = E_0/(n_{tot})^n = E_{dec}$$

at this n : $N_\mu = (n_{ch})^n$

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Superposition Model

Proton shower characteristics:

$$N_{max} = E_0 / E_c$$

$$X_{max} = \lambda_e \ln(E_0 / n_{\text{tot}}) + \lambda_{ine}$$

$$N_\mu = \left(\frac{E_0}{E_{dec}} \right)^\alpha ; \alpha = \frac{\ln n_{ch}}{\ln n_{tot}}$$

Hadronic interaction model

- interaction cross section
- mean multiplicity of secondary particles
- ratio of neutral to charged pion / kaon multiplicities

Atmosphere as target and calorimeter

- critical energy
- density : typical pion / kaon decay energy

Assumption:

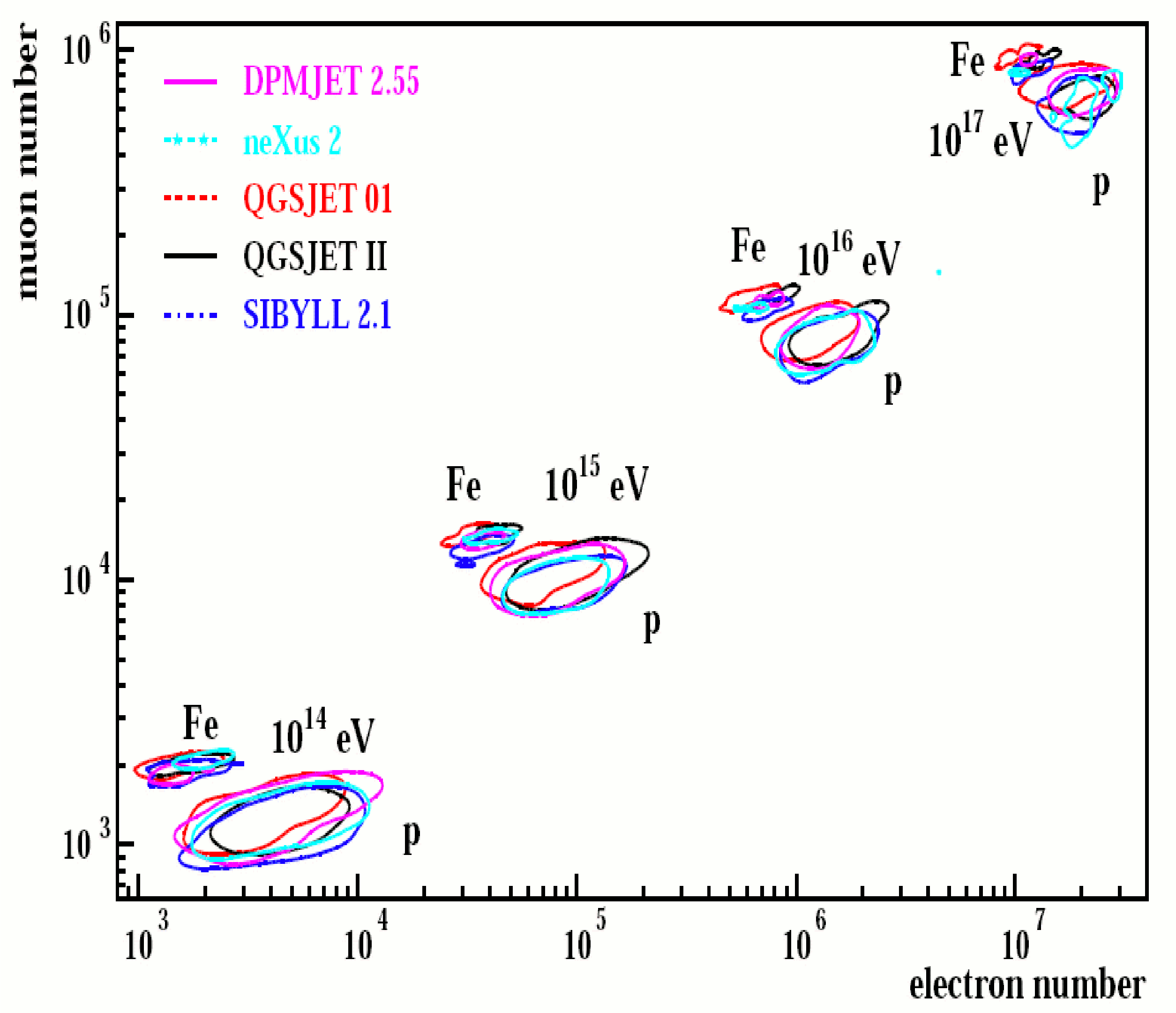
nucleus of mass *A* and energy E_0 acts like *A* independent nucleons with energy $E_n = E_0/A$

$$N_{max}^A = A \; E_n / E_c = E_0 / E_c$$

$$X_{max}^A(E_0) = X_{max}^p(E_0 / A)$$

$$N_\mu^A = A \left(\frac{E_0 / A}{E_{dec}} \right)^\alpha = A^{1-\alpha} N_\mu$$

N_μ and N_e at ground



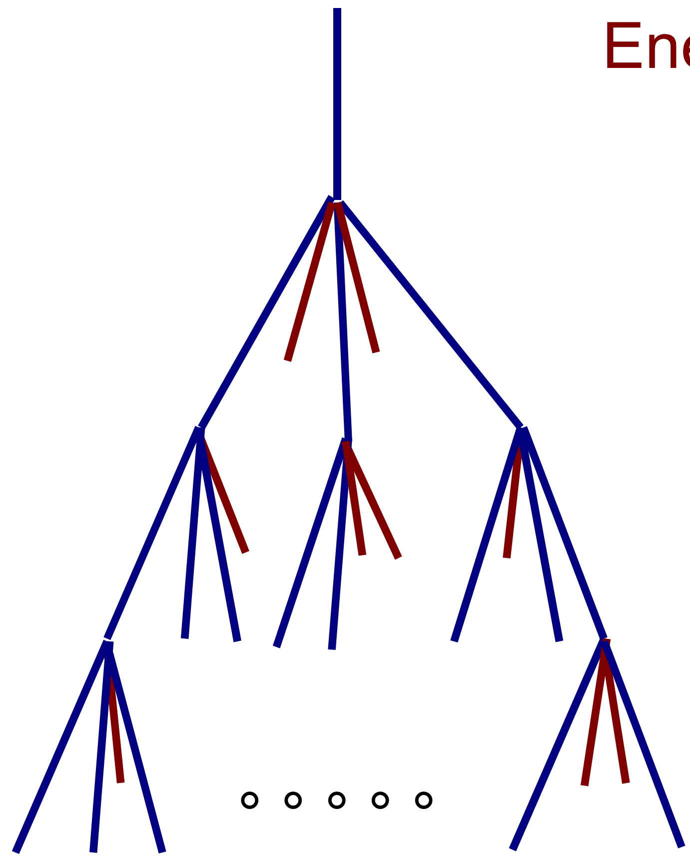
- N_e ~ increases linearly with energy
- Different behaviour with A for N_e and N_μ :
  - N_e decreases with A ($N_e \neq N_{max}$) (X_{max} decrease → older shower)
  - N_μ increases with A (N_μ ~ const. after maximum)

good mass estimator ...

... within a given model !

Energy Transfer

Energy of all hadrons		Energy of all em. particles
E_0		0
$\frac{2}{3}E_0$		$\frac{1}{3}E_0$
$\frac{2}{3}\left(\frac{2}{3}E_0\right)$		$\frac{1}{3}E_0+\frac{1}{3}\left(\frac{2}{3}E_0\right)$



After *n* generations

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0$$

Energy in em. ~ 90 %

(n=5, E_{had}~12%
n=6, E_{had}~8%)

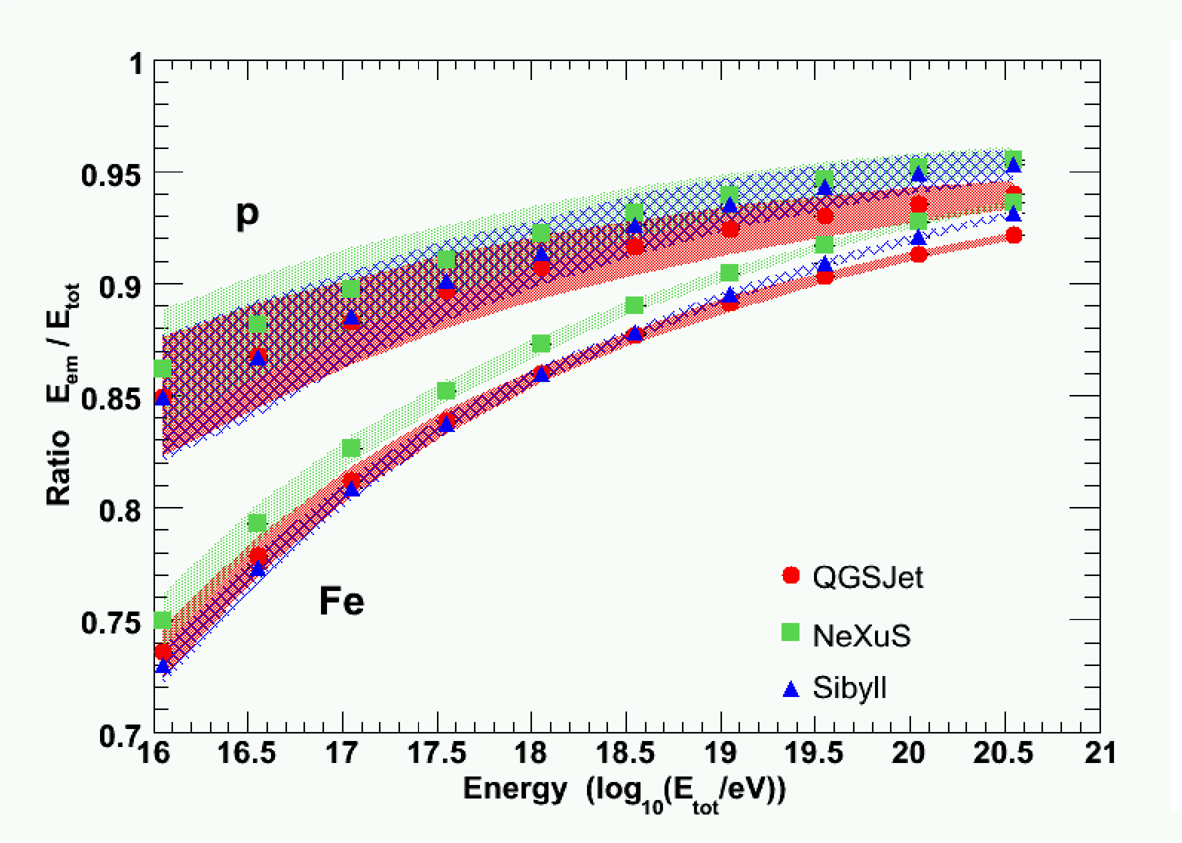
$$E_{\text{em}} = \left[1-\left(\frac{2}{3}\right)^n\right] E_0$$

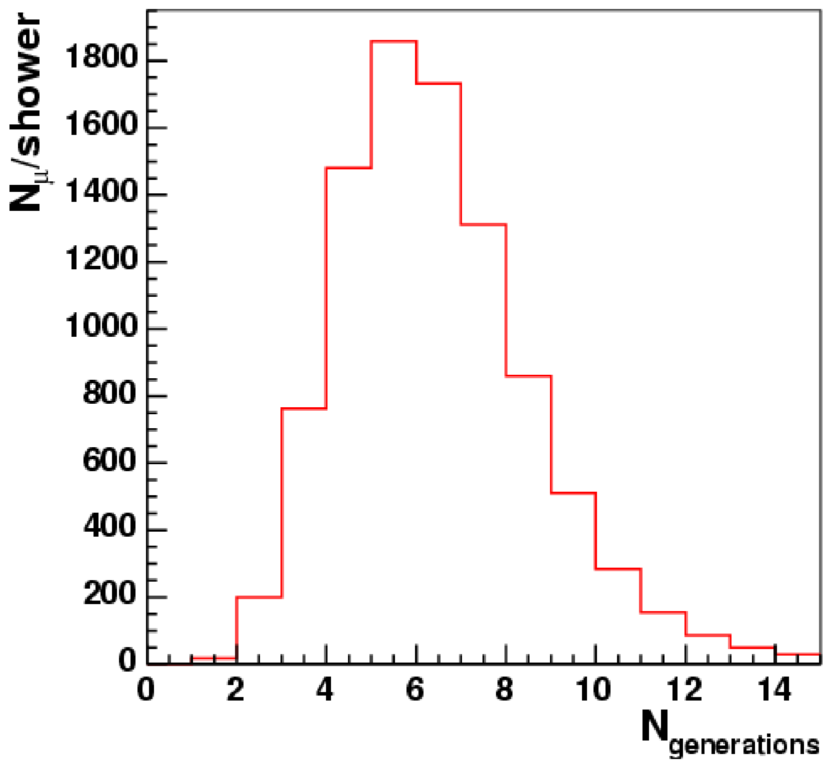
Energy Transfer

From Heitler's model we know :

- ~ 90 % energy in the em. particles
- ~ 5 - 6 hadronic generations

Confirmed by MC simulation and model independent !





Summary on Heitler's Model

Air-shower characteristics controlled by 2 atmospheric parameters and 3 hadronic model dependent parameters :

- hadronic cross section : X_{max}
- mean total multiplicity : X_{max} and number of generations
- ratio charged/total number of particles : muon number

Hadronic interaction MC models disagree on this parameters !

Hadronic Interaction Models

Realistic Monte-Carlo simulation needs hadronic interaction models

High energy models :

DPMJET II.5 and III (Ranft / Roesler, Engel & Ranft)

NEXUS 2 and 3 (Drescher, Hladik, Ostapchenko, TP & Werner)

QGSJET 01 and II (Kalmykov & Ostapchenko / Ostapchenko)

SIBYLL 2.1 (Engel / Engel, Fletcher, Gaisser, Lipari & Stanev)

Low/intermediate energy models:

GHEISHA (Fesefeldt)

Hillas' splitting algorithm (Hillas)

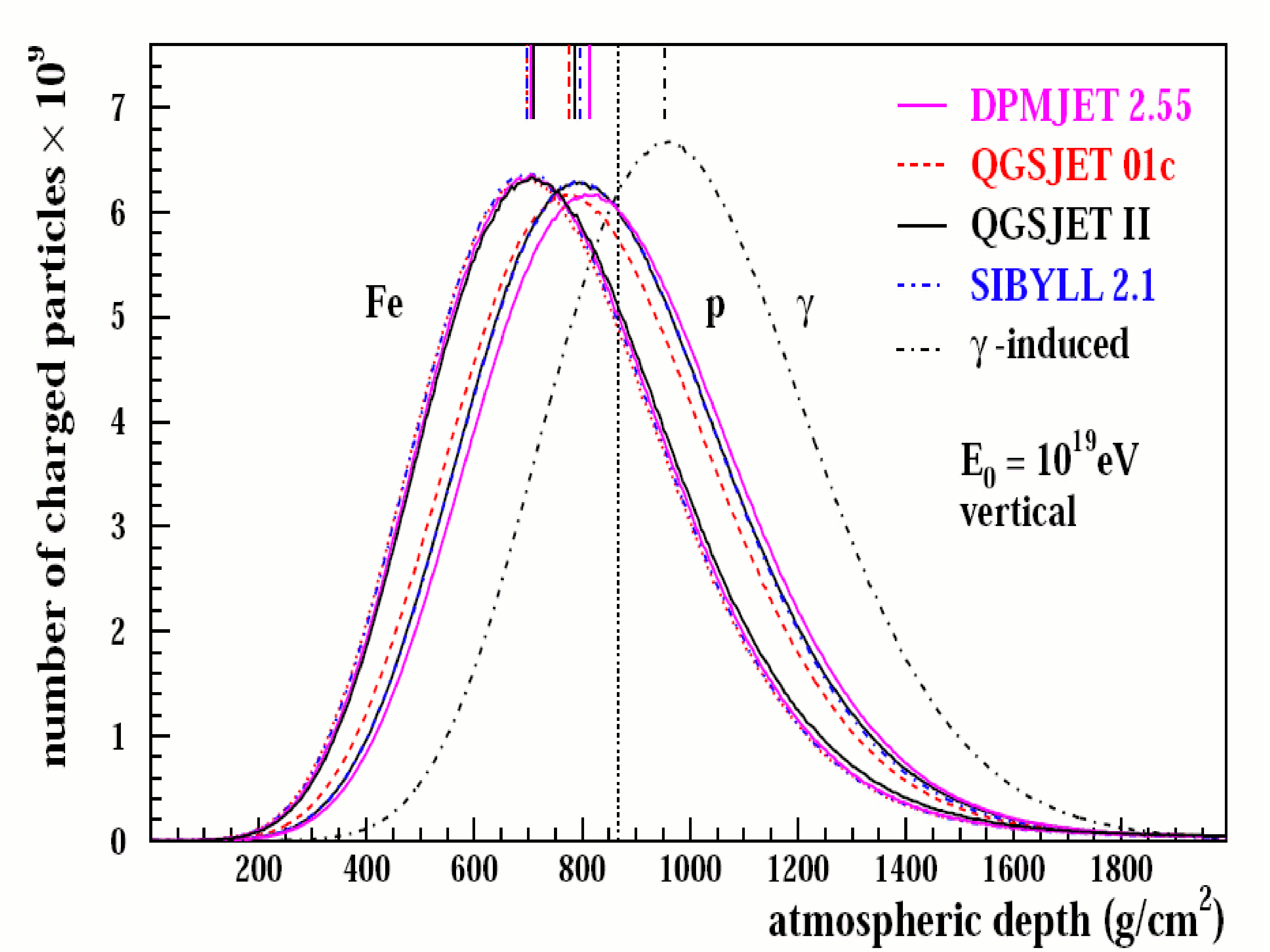
FLUKA (Fasso, Ferrari, Ranft, Roesler & Sala)

UrQMD (Bleicher et al.)

- Gribov-Regge type models
- QCD-inspired minijet production
- Parametrization of data

(see S. Ostapchenko's talk)

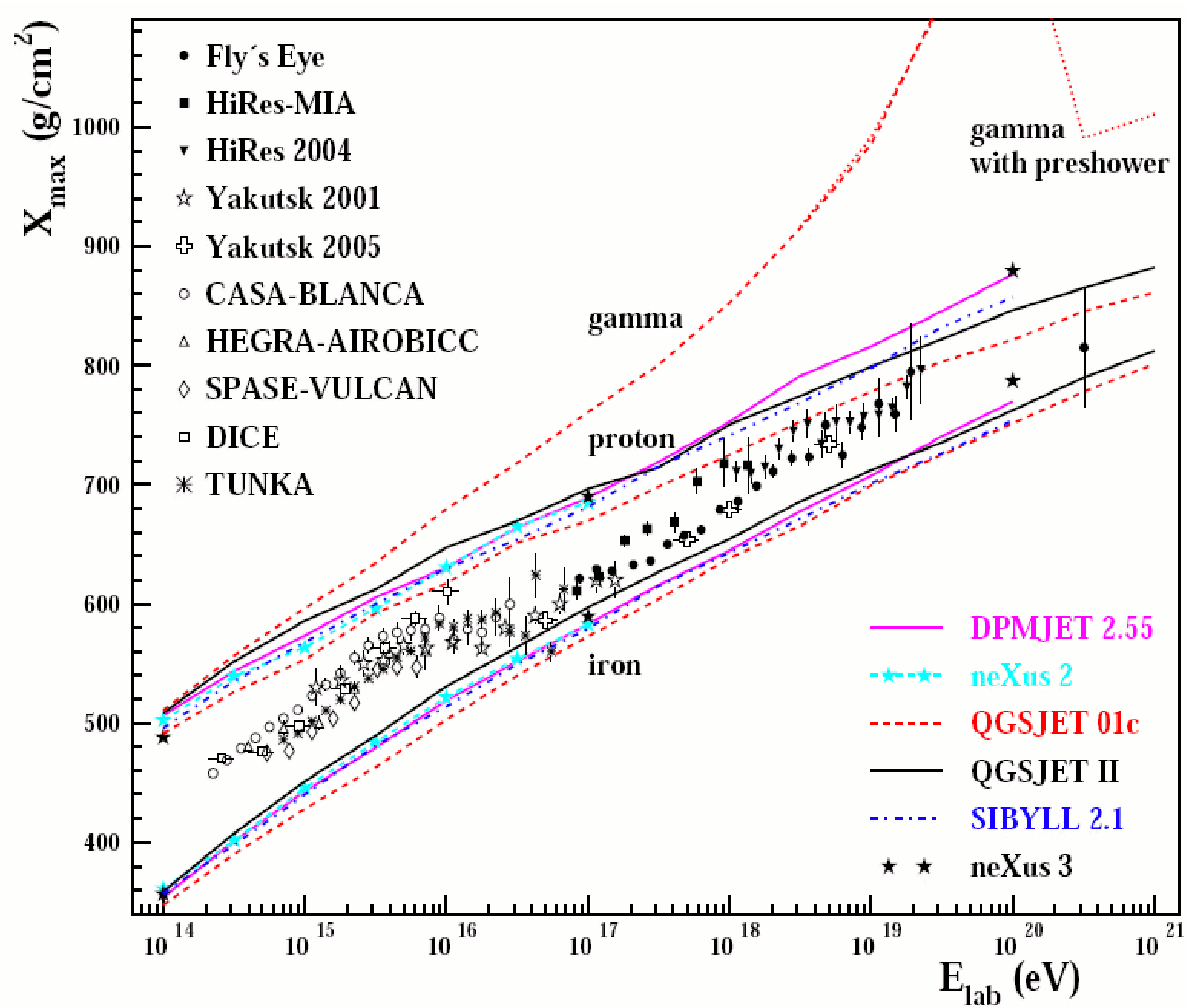
Longitudinal Development



Shape is model-independent (em. processes)

Differences between models appears in X_{max}

Mean Depth of Shower Maximum



Prediction are strongly model dependent at very high energy !

QGSJET 01 : highest n_{tot} and lowest $<X_{max}>$

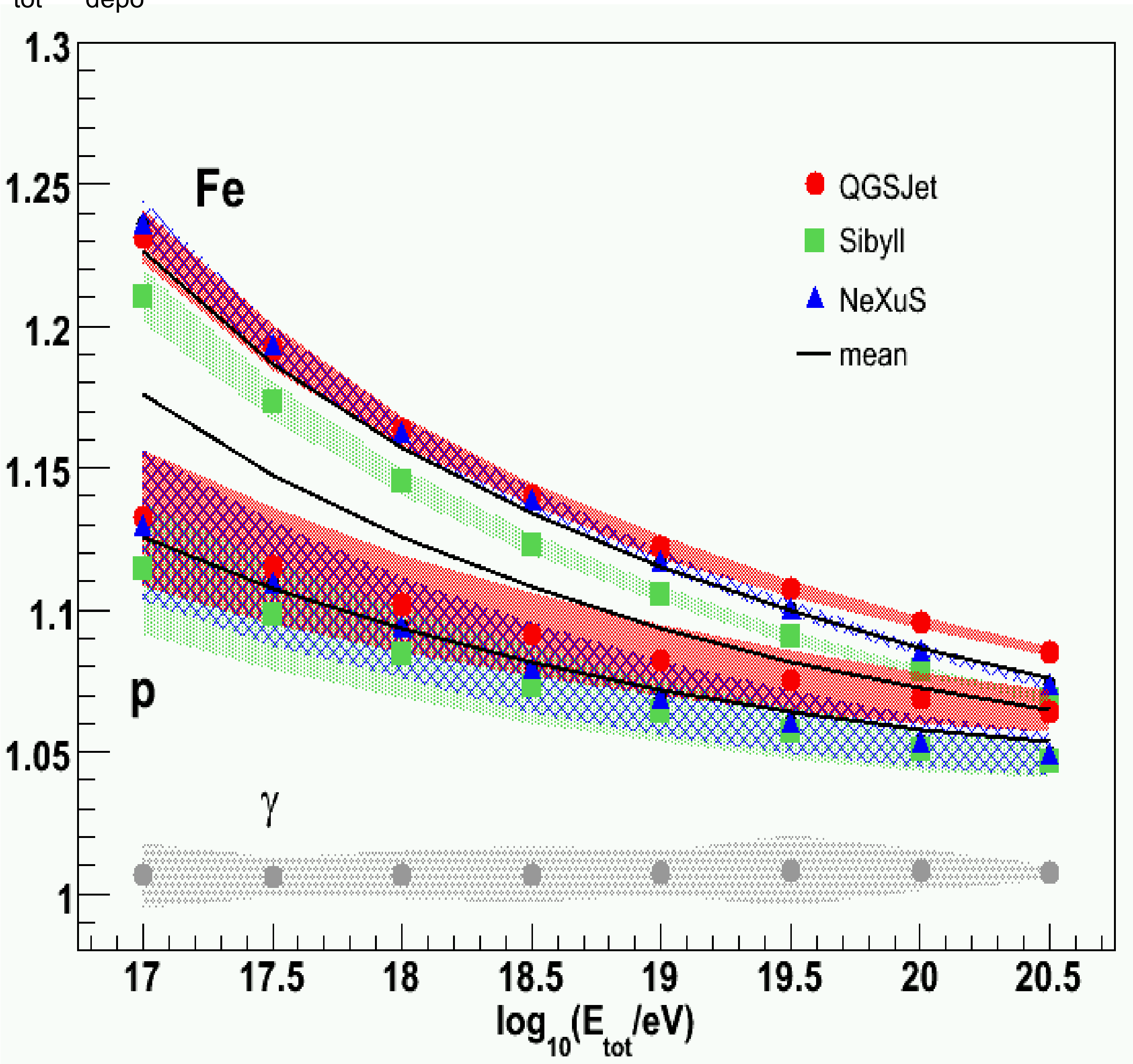
DPMJET : lowest n_{tot} and highest $<X_{max}>$

n_{tot} = multiplicity⊗elasticity

Mass interpretation very difficult ...

Energy Deposit

E_{tot}/E_{depo} Correction factor

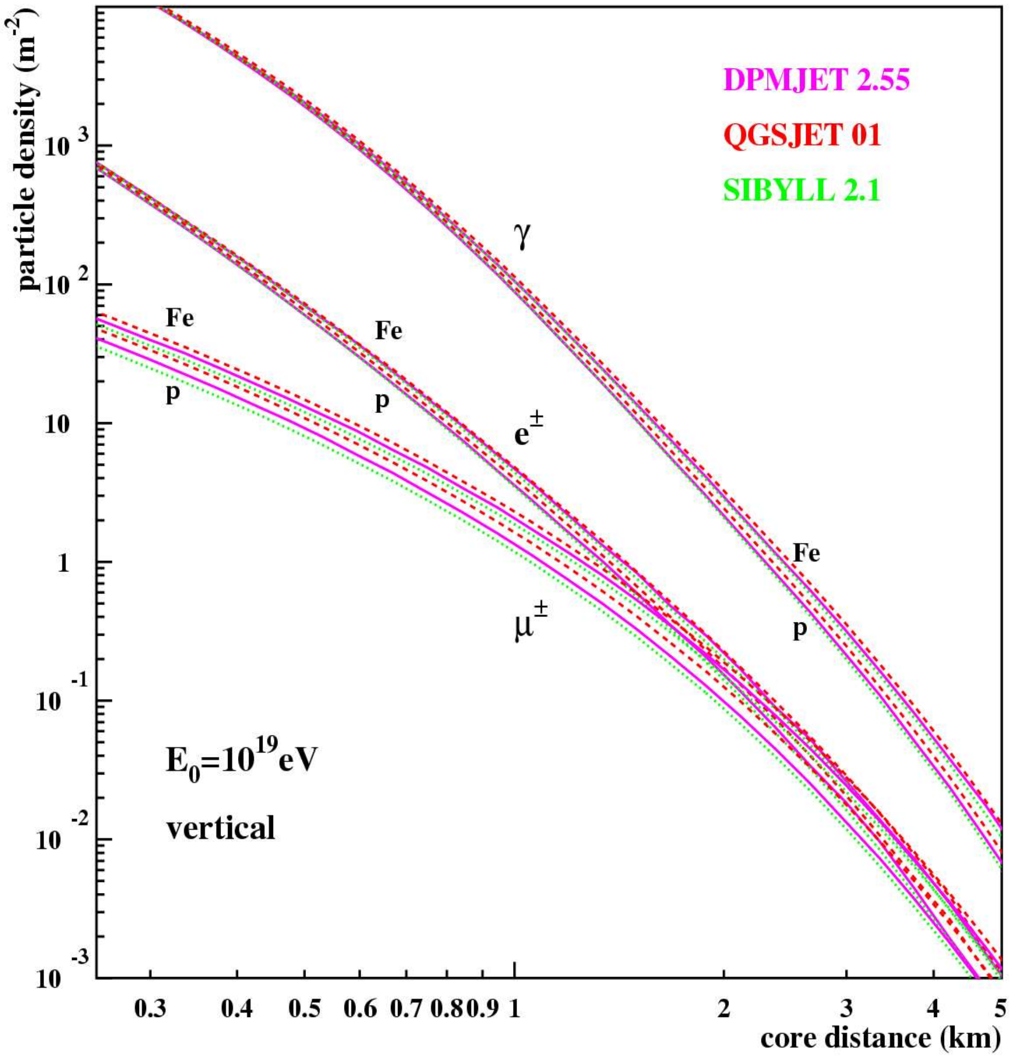


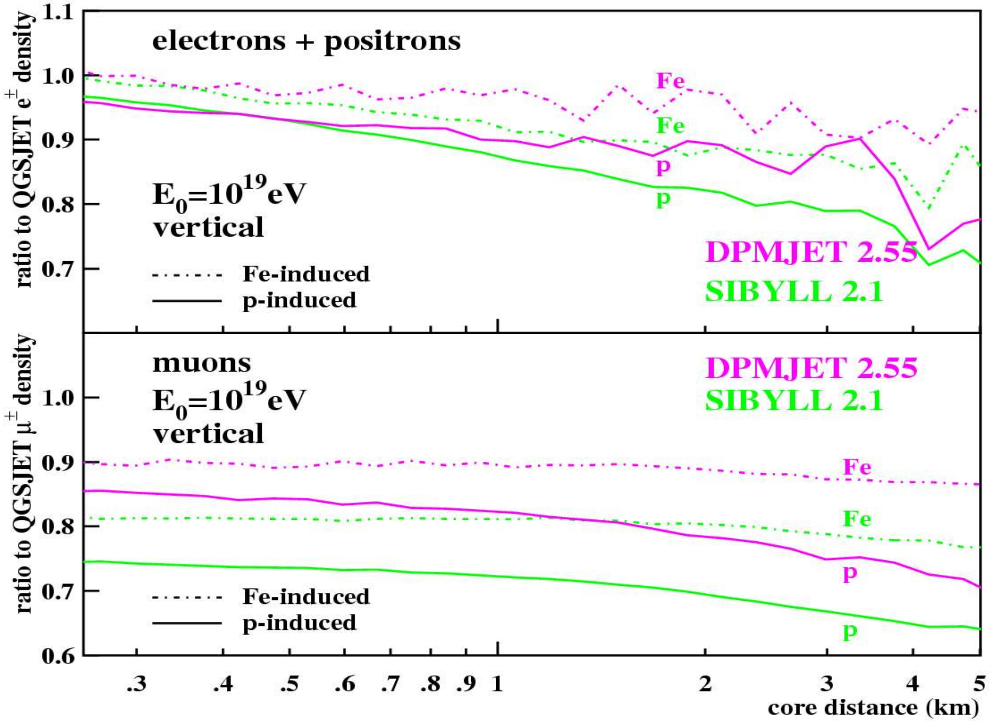
Energy deposit related to fluorescence light emitted : energy estimator

model uncertainties (~2%) lower than uncertainty due to mass (~6%)

Fluorescence light based energy measurement are almost hadronic model independent !

Lateral Distribution Function

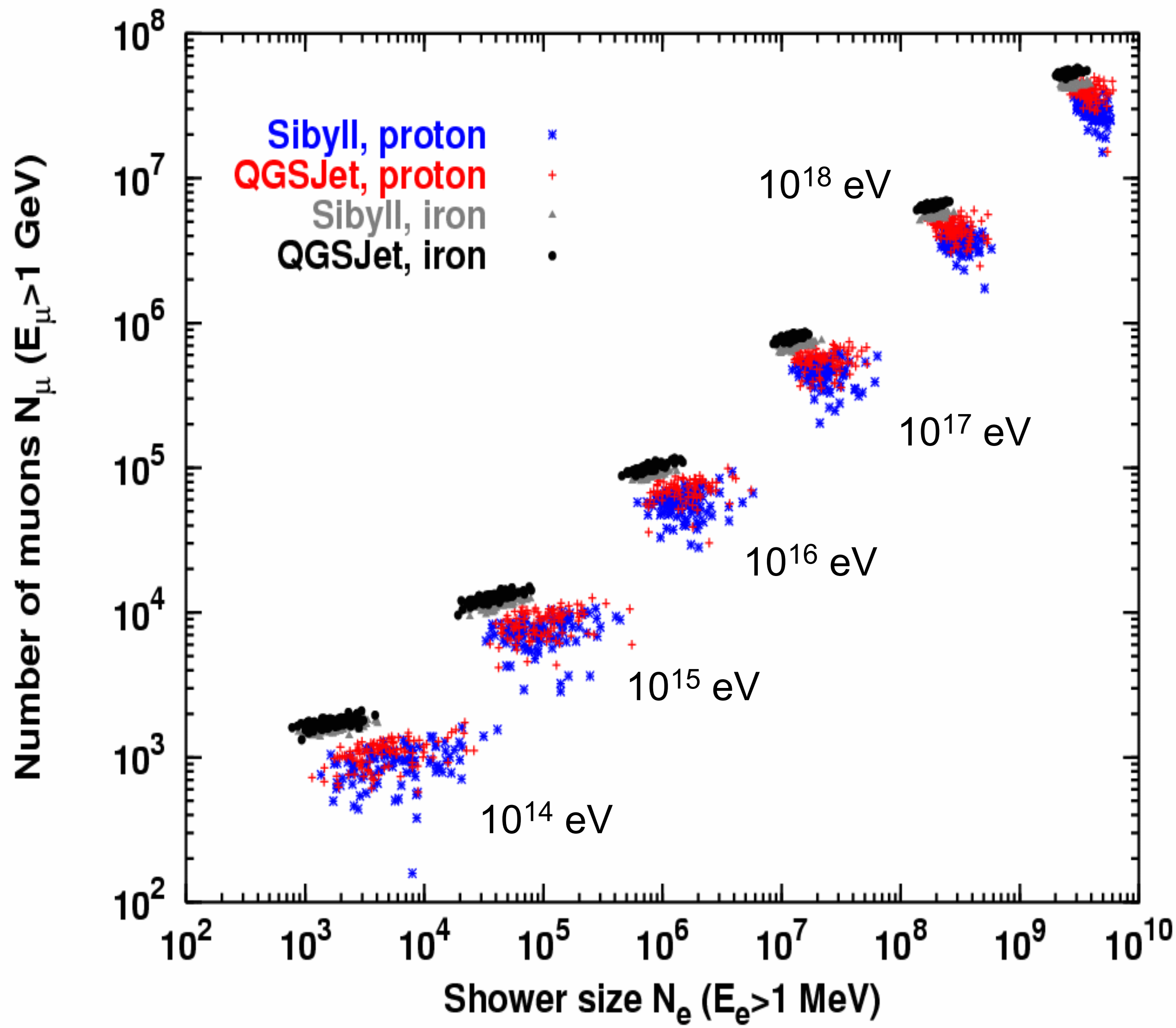




LDF used for energy determination but up to 35 % difference at large distances !

See also Ch. Meurer's talk (dependence on low-energy models)

N_μ vs N_e



From theory, N_e and N_μ do not behave the same : good mass estimator used in many experiment (KASCADE, EAS-TOP, AKENO ...)

but strong model dependence !

Mass analysis based on N_e and N_μ are highly model dependent

(see H. Ulrich (KASCADE) talk)

Conclusion

Air-shower characteristics controlled by features of hadronic multiparticle production :

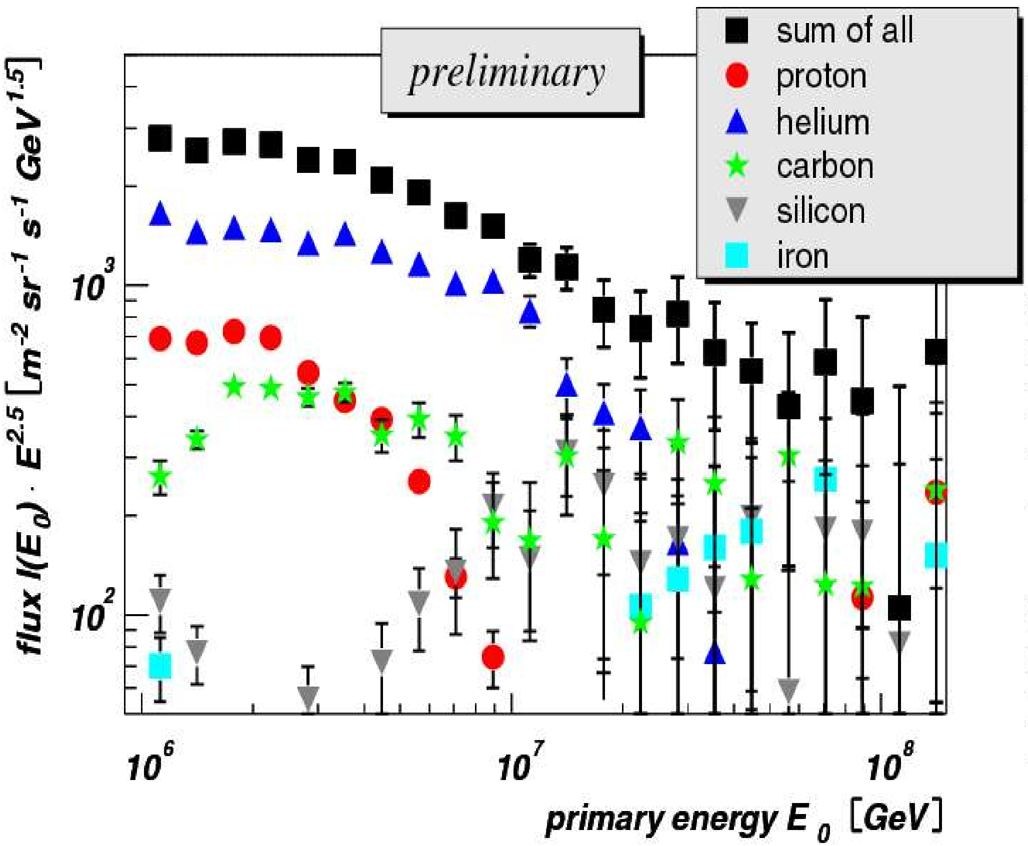
- Hadronic cross section
- Inelasticity
- Diffraction dissociation
- Total multiplicity
- Ratio charged/total number of particles
- .....

Implies large (>10 %) uncertainties in :

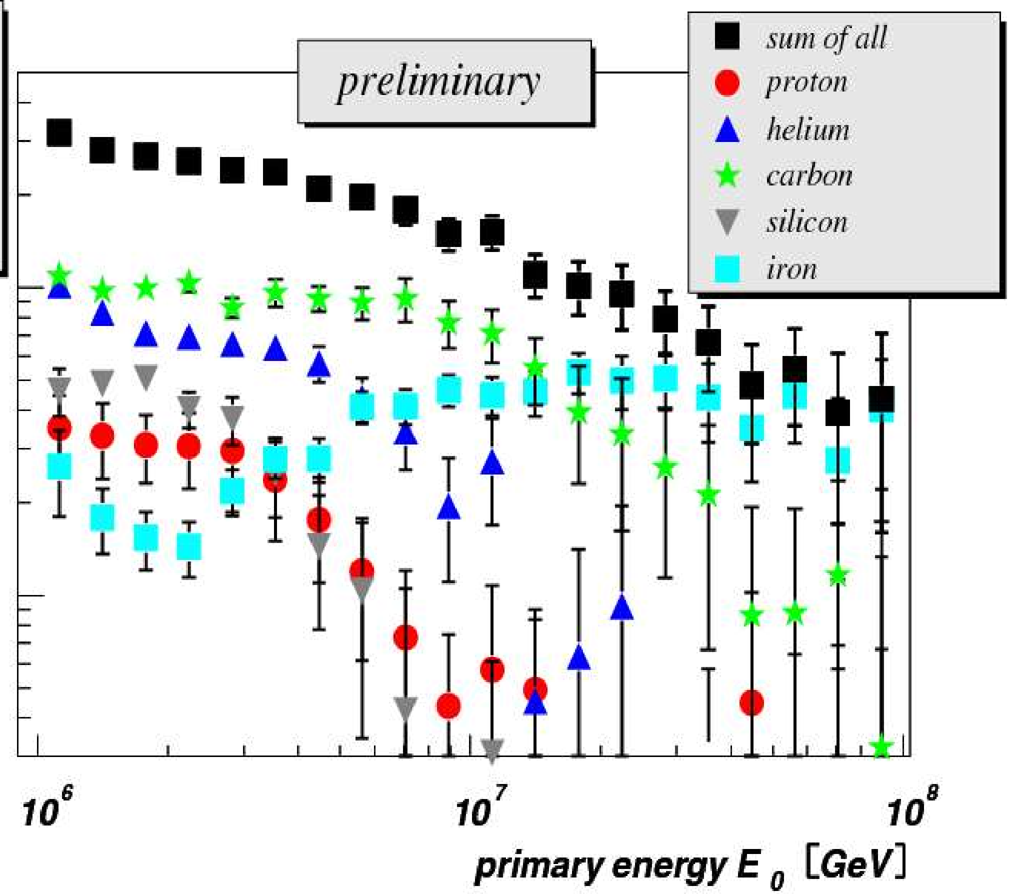
- Energy estimation from surface detectors (LDF)
- Mass estimation from X_{max} or from N_e or N_μ

Only energy estimation from calorimetric measurement are almost MC independent.

Example: KASCADE Composition



QGSJET 01

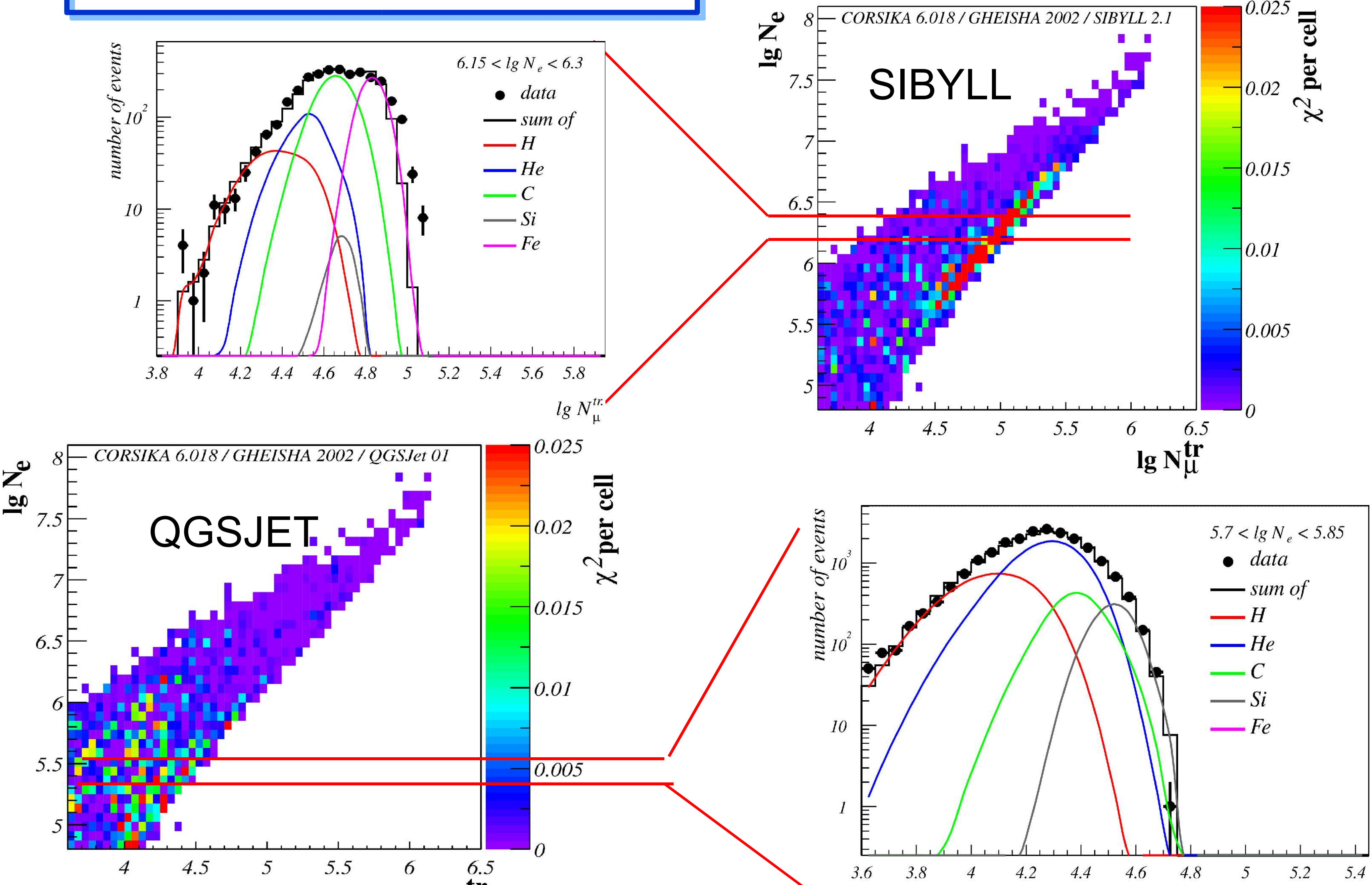


SIBYLL 2.1

KASCADE: high resolution/precision data, analysis limited by model uncertainties

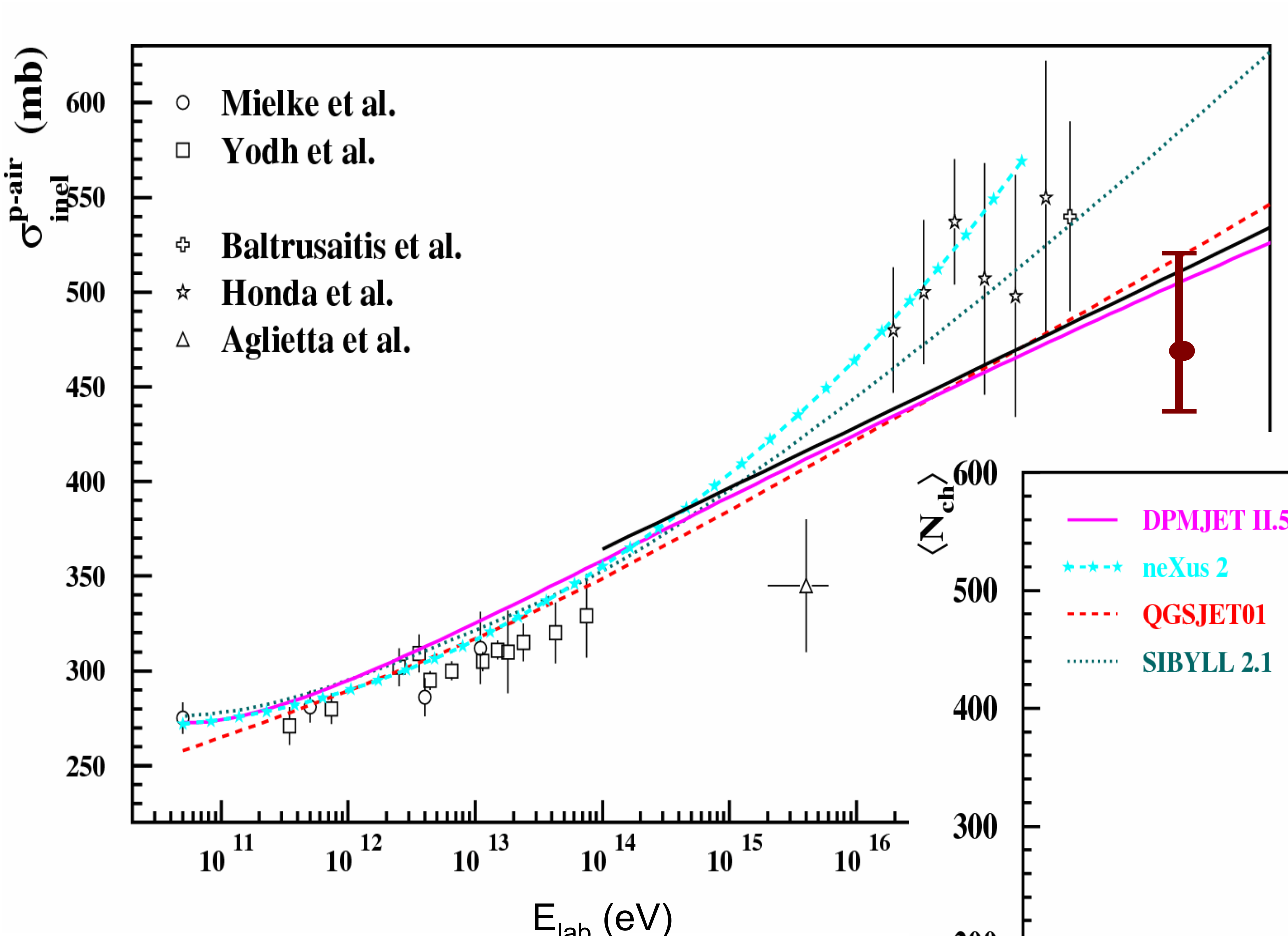
Energy spectra KASCADE:

quality of description of data



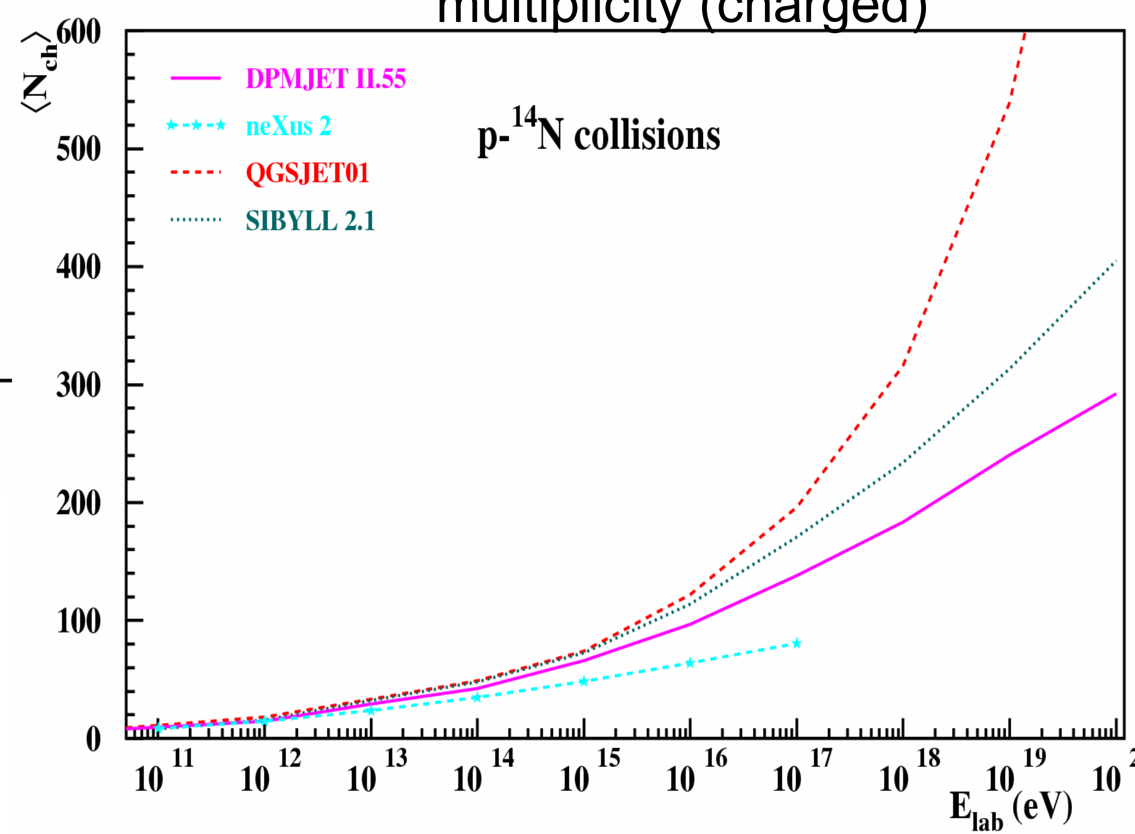
(A. Haungs)

Cross Section and Multiplicity Predictions



Proton-air production cross section

Average secondary particle multiplicity (charged)



QGSJET:
- rapid increase of multiplicity with energy
- smallest elongation rate of all models