The EAS Monte Carlo Simulation Code *CORSIKA*

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COsmic Ray SImulations for KASCADE

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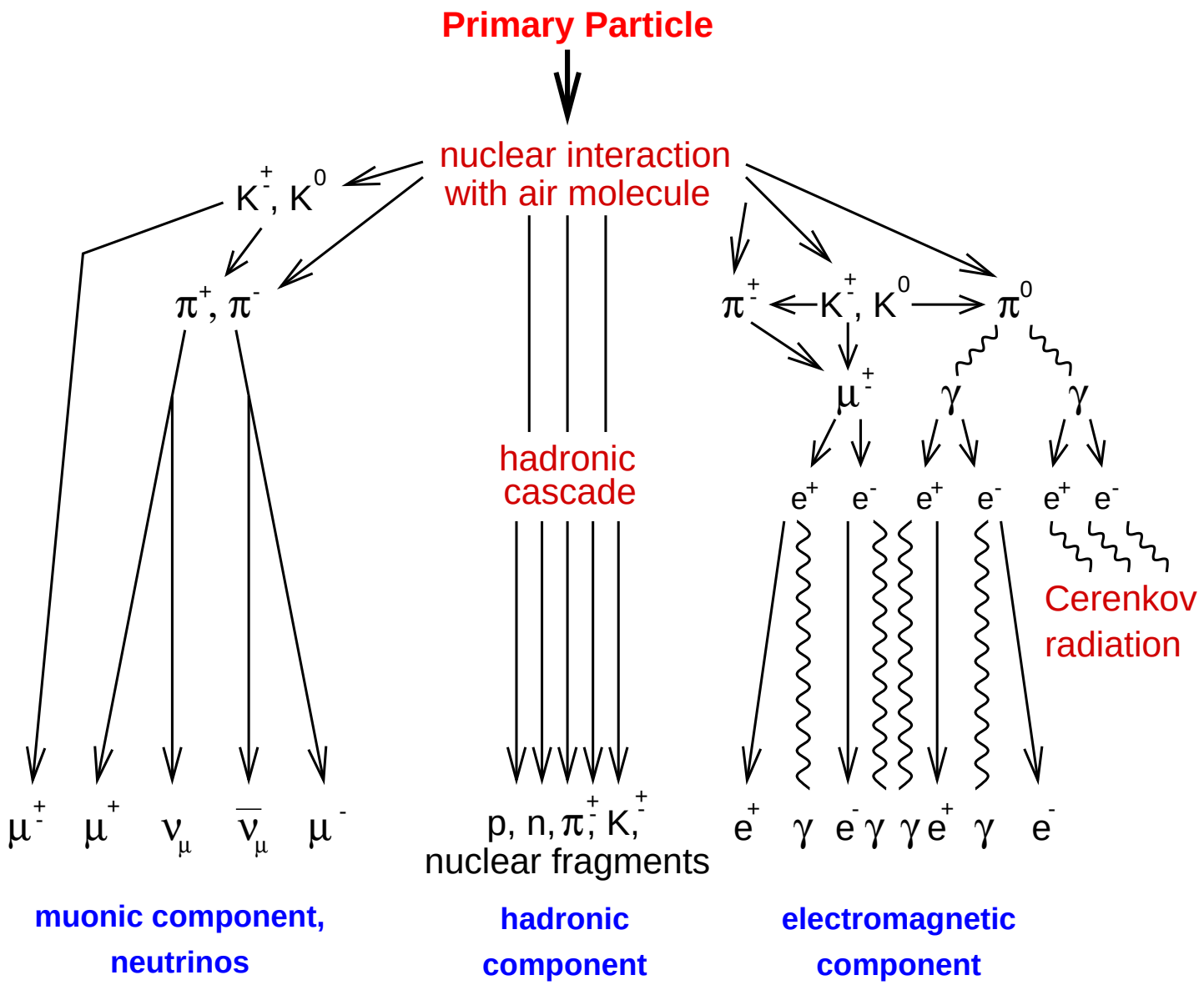
EAS Development

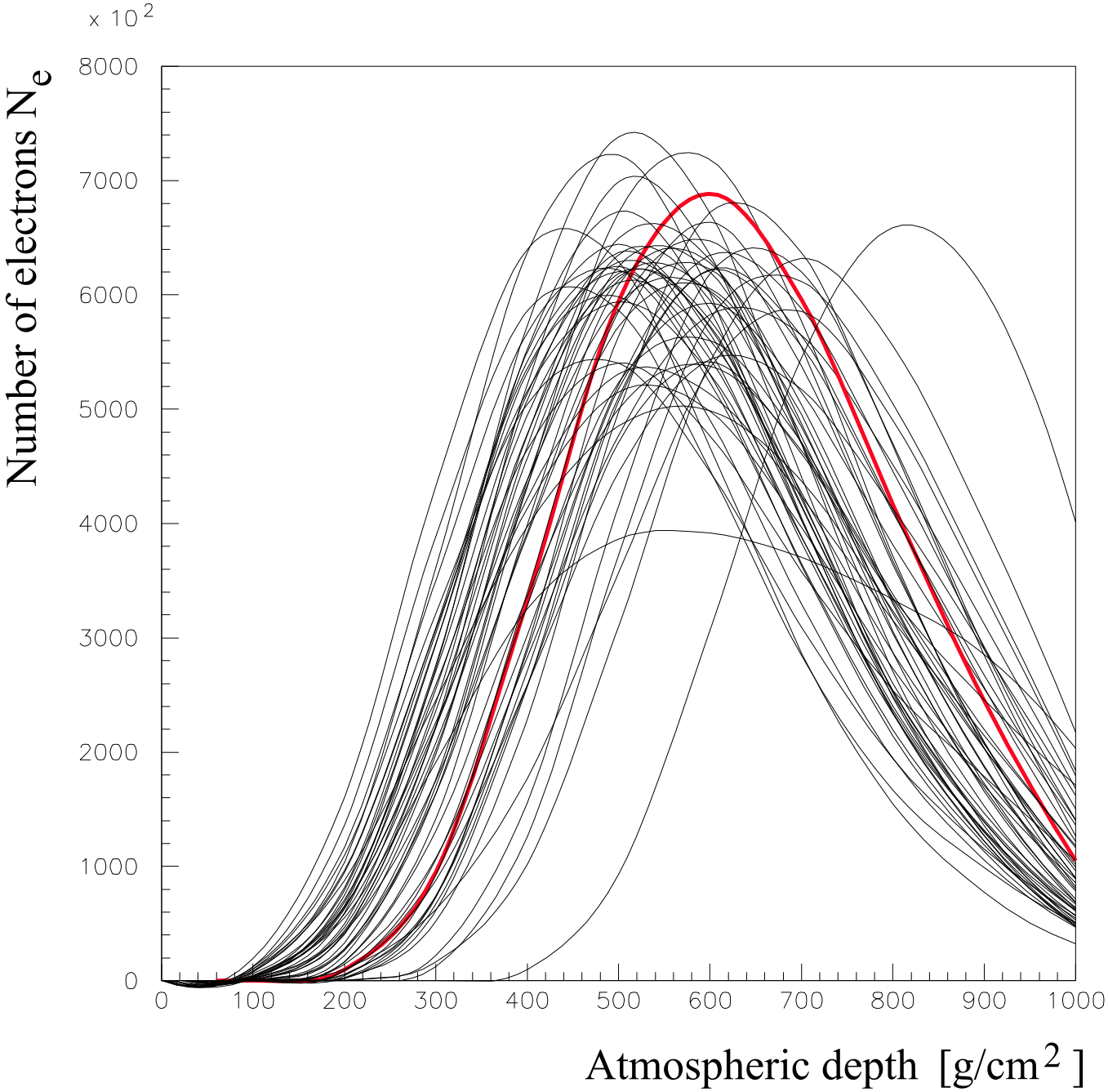


Development of Extensive Air Shower

(schematic)

Why Monte Carlo Simulations?

Shower development is a stochastic random process. Details cannot be described by parametric functions or analytical expressions.



Longitudinal development of 50 extensive air showers.

Proton primary, $E = 10^{15}\ eV$, vertical incidence, $E_{cut} = 3\ MeV$, CORSIKA & QGSJET. The red shower produces an electron number at ground level closest to the average.

Monte Carlo Simulation of EAS

1. **environment:**
   - **atmosphere**
   - **magnetic field**
2. **particle type, energy, direction**
3. **particle range estimation:**
   - **cross-section σ**
   - **life time τ**
4. **particle transport:**
   - **ionization energy loss dE/dx**
   - **multiple scattering**
   - **deflection by Earth magnetic field**
   - **particle reaches detector or cut**
5. **particle interaction: production of secondaries**

   5.1. high-energy hadronic interaction:
   - **DPMJET II.55**
   - **HDPM**
   - **NEXUS 2**
   - **QGSJET 01**
   - **SIBYLL 2.1**
   - **VENUS 4.12**

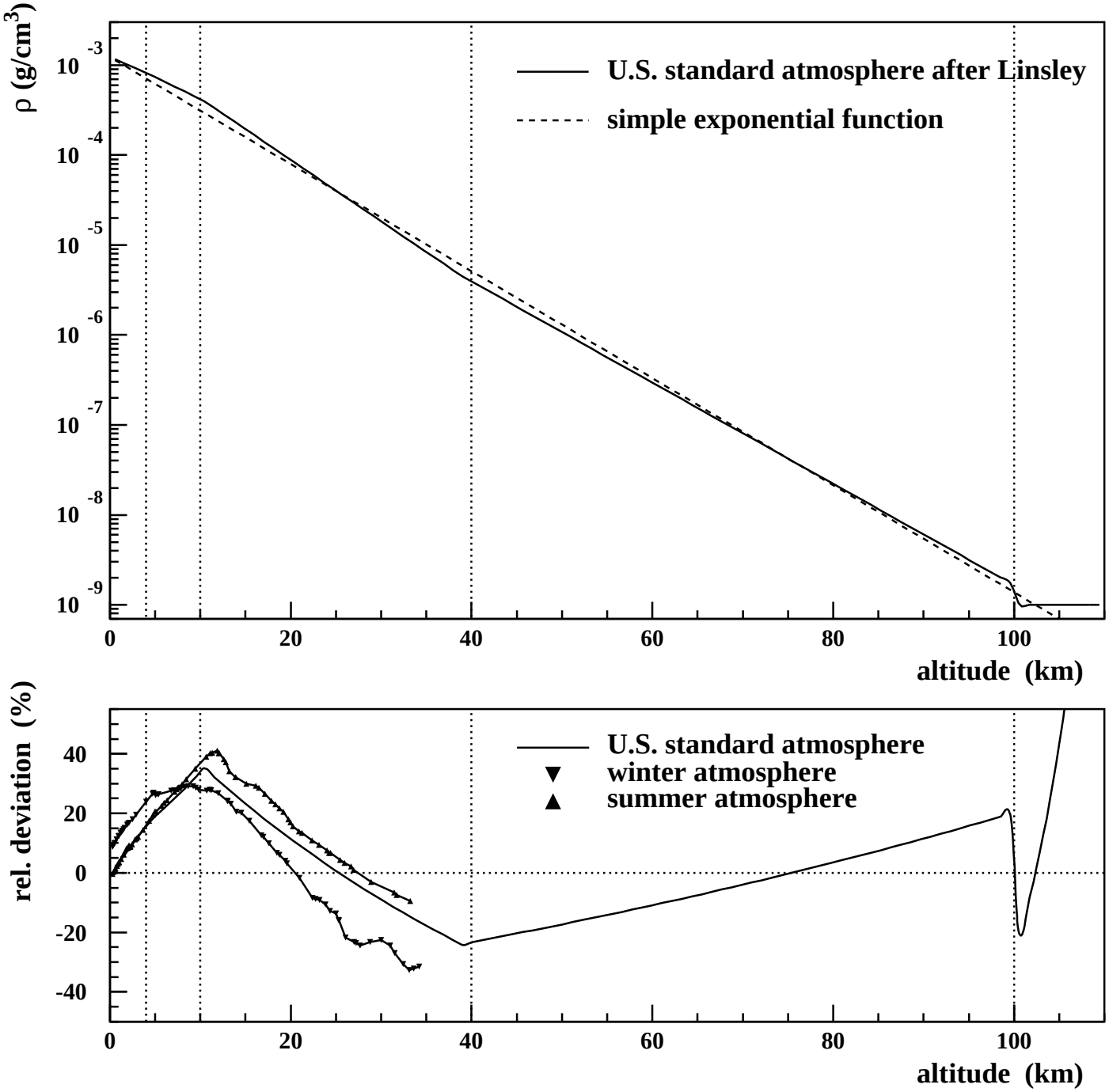
   5.2. low-energy hadronic interaction:
   - **GHEISHA**
   - **UrQMD**

   5.3. decay of particles

   5.4. electromagnetic interaction:
   - **EGS4**
   - **NKG**
6. **store secondary particles**

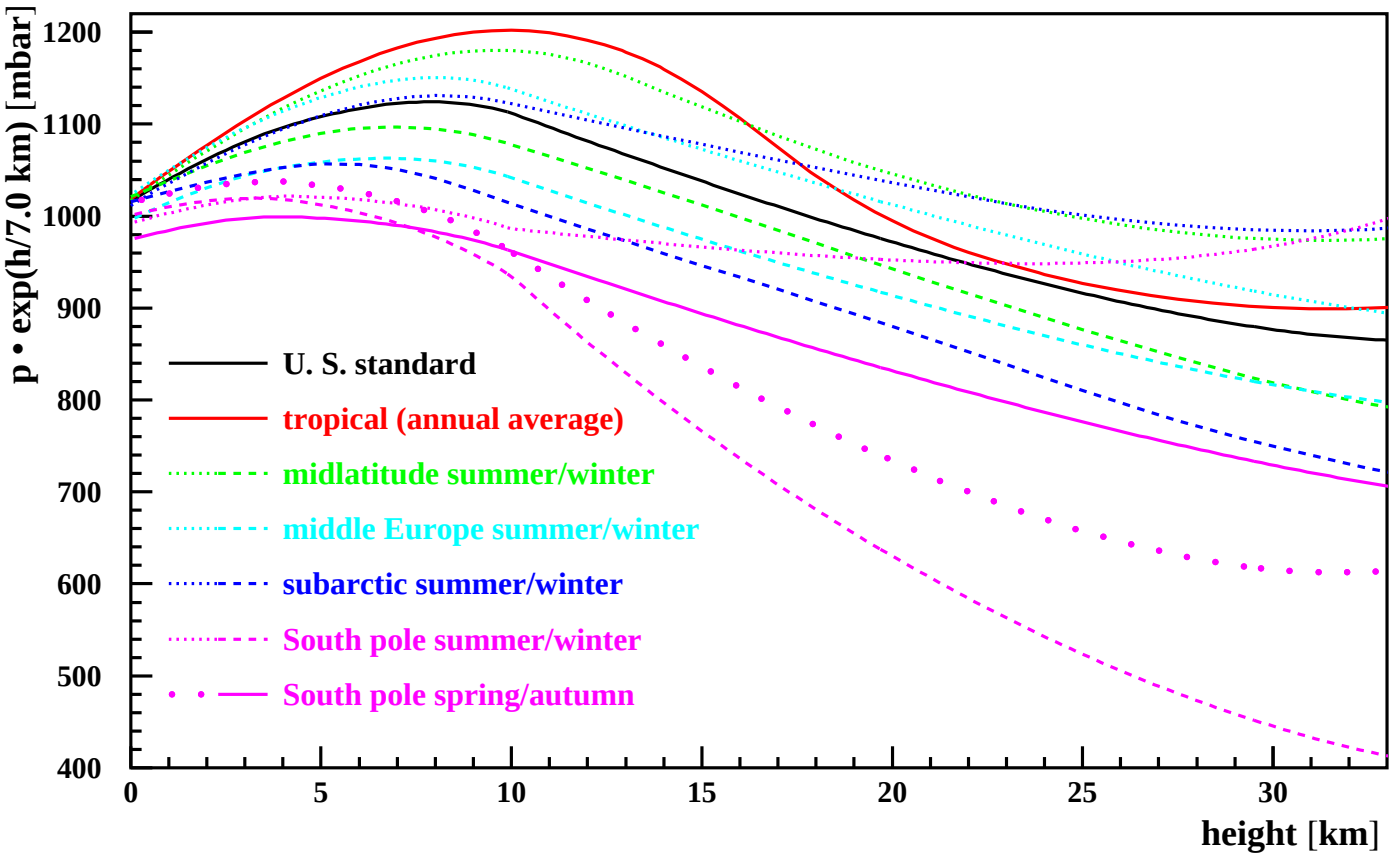
Atmosphere

Density of atmosphere as function of altitude



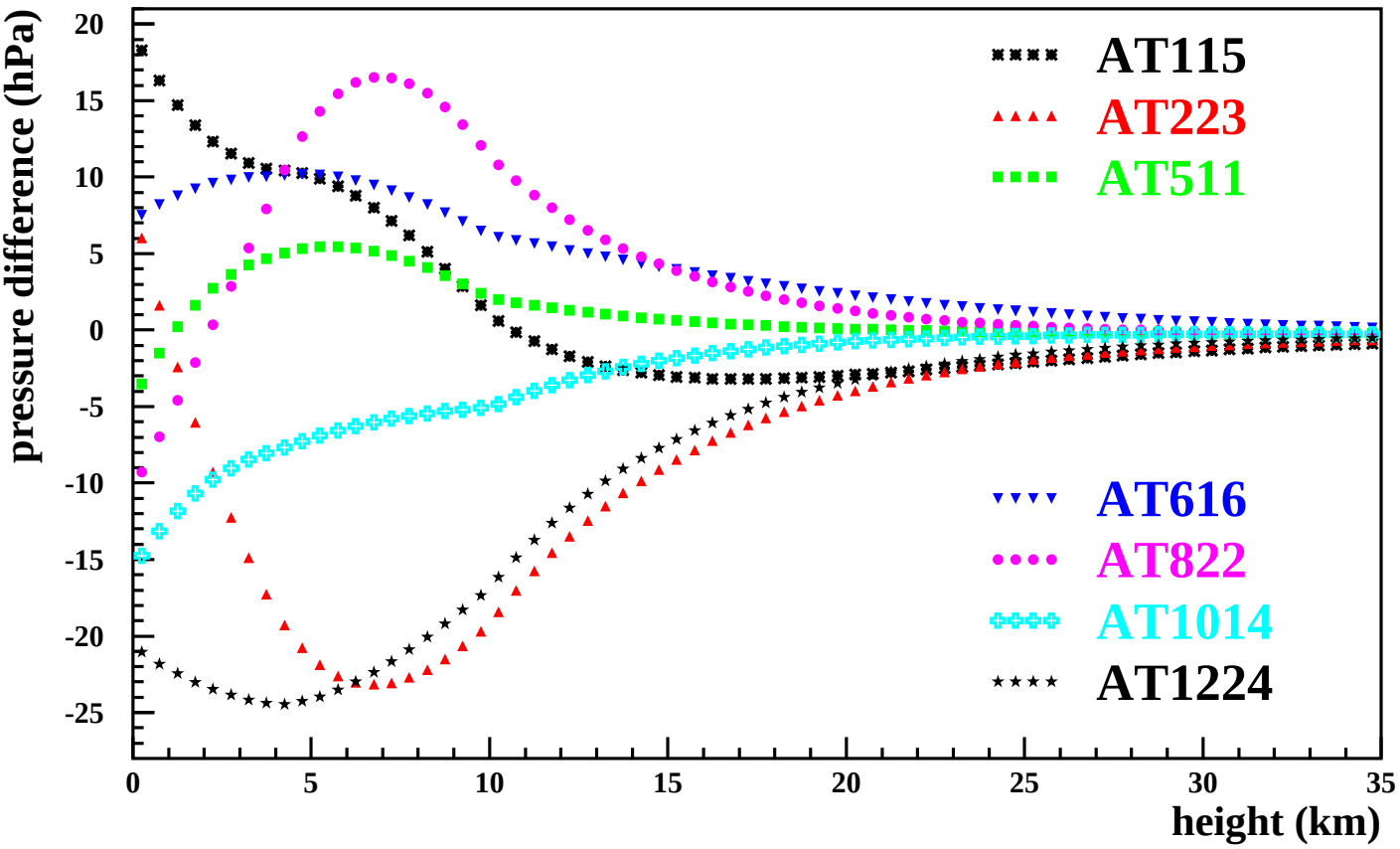
Relative deviation from simple exponential function

Different Atmosphere Parametrisations



Atmospheric profiles for MODTRAN atmospheres.

Atmosphere at Different Seasons



Fits to baloon measurements above Stuttgart (Germany).

Measurements performed by Deutscher Wetterdienst in 1993.

Particles in CORSIKA

Identification	Particle	Identification	Particle
1	γ	51	ρ°
2	e^+	52	ρ^+
3	e^-	53	ρ^-
		54	Δ^{++}
5	μ^+	55	Δ^+
6	μ^-	56	Δ°
7	π°	57	Δ^-
8	π^+	58	$\overline{\Delta}^{--}$
9	π^-	59	$\overline{\Delta}^-$
10	K_L°	60	$\overline{\Delta}^\circ$
11	K^+	61	$\overline{\Delta}^+$
12	K^-	62	$K^{*\circ}$
13	n	63	K^{*+}
14	p	64	K^{*-}
15	$\overline{p}$	65	$\overline{K}^{*\circ}$
16	K_S°	66	ν_e
17	η	67	$\overline{\nu}_e$
18	Λ	68	ν_μ
19	Σ^+	69	$\overline{\nu}_\mu$
20	Σ°		
21	Σ^-	71	$\eta \rightarrow \gamma\gamma$
22	Ξ°	72	$\eta \rightarrow 3\pi^\circ$
23	Ξ^-	73	$\eta \rightarrow \pi^+\pi^-\pi^\circ$
24	Ω^-	74	$\eta \rightarrow \pi^+\pi^-\gamma$
25	$\overline{n}$	75	μ^+ add. info.
26	$\overline{\Lambda}$	76	μ^- add. info.
27	$\overline{\Sigma}^-$		
28	$\overline{\Sigma}^\circ$		
29	$\overline{\Sigma}^+$		
30	$\overline{\Xi}^\circ$		
31	$\overline{\Xi}^+$		
32	$\overline{\Omega}^+$		
50	ω		

$A \times 100 + Z$	nucleus of Z protons and $A - Z$ neutrons ($A \leq 59$)
9900	Cherenkov photons on particle output file

Range of Particle for Interaction

The probability P_{int} to traverse a layer with thickness χ without interaction is

$$P_{int}(\chi) = \frac{1}{\lambda_{int}} e^{-\chi/\lambda_{int}}$$

The individually traversed matter thickness χ is

$$\chi = -ln(RNDM) \cdot \lambda_{int}$$

with random number $0 < RNDM < 1$

The mean free path λ_{int} is given by

$$\lambda_{int} = \frac{\sum_{i=1}^{3} n_i A_i}{\sum_{i=1}^{3} n_i \sigma_{i_{int}}}$$

with A_i = **atomic weight**
and $\sigma_{i_{int}}$ = **(energy dependent) cross-section.**

The atomic fractions n_i (volume fractions) of air are adopted to

N_2	0.7848	(78.084%)
O_2	0.2105	(20.948%)
Ar	0.0047	(0.934%)

Range of Particle for Decay

The probability P_D to traverse a path ℓ without decay is

$$P_D(\ell) = \frac{1}{\ell_D} e^{-\ell/\ell_D}$$

The individually traversed path length ℓ is

$$\ell = -ln(RNDM) \cdot \ell_D$$

with random number $0 < RNDM < 1$

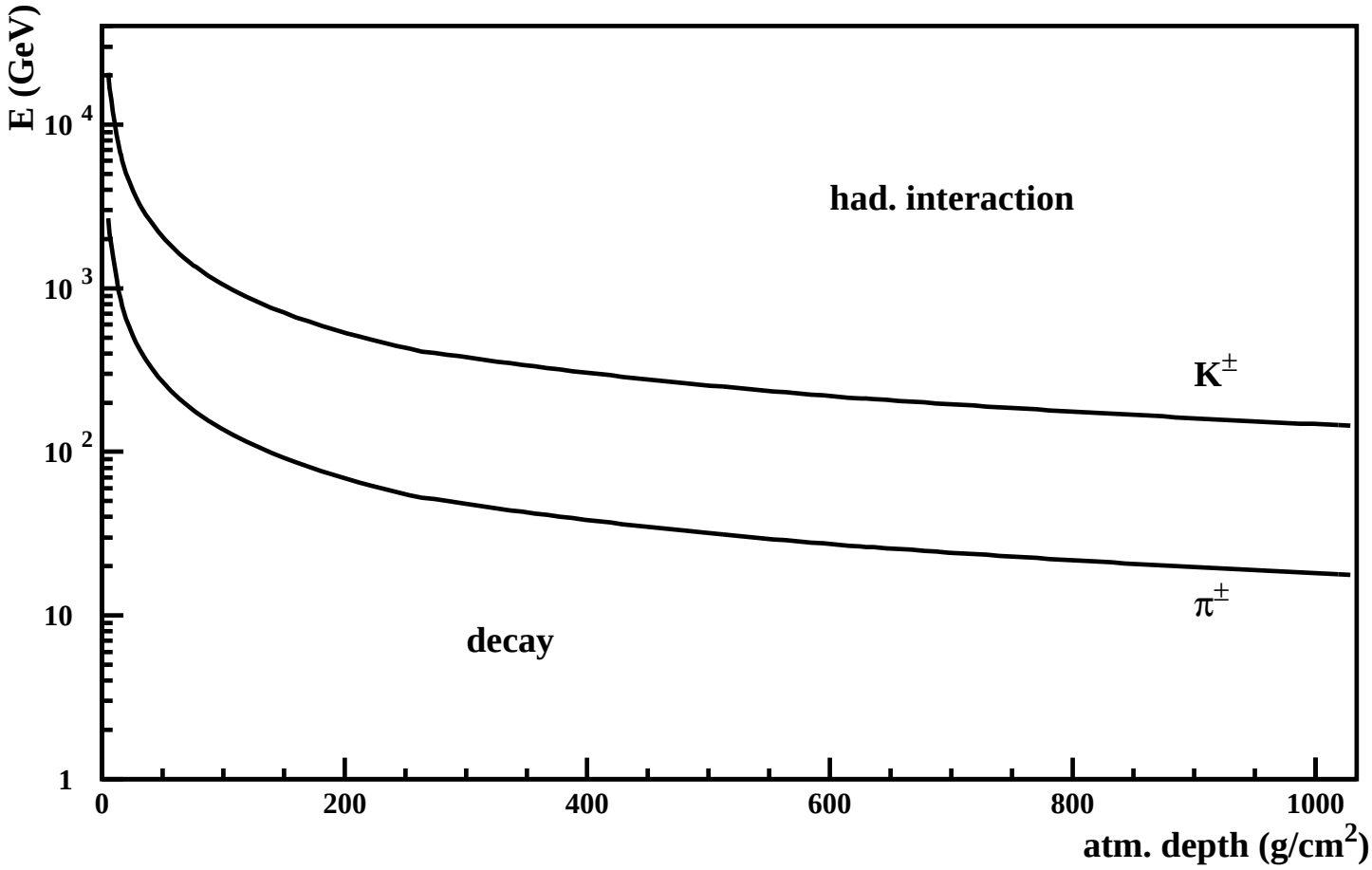
The mean free path ℓ_D is given by

$$\ell_D = c \cdot \tau \cdot \gamma \cdot \beta$$

with

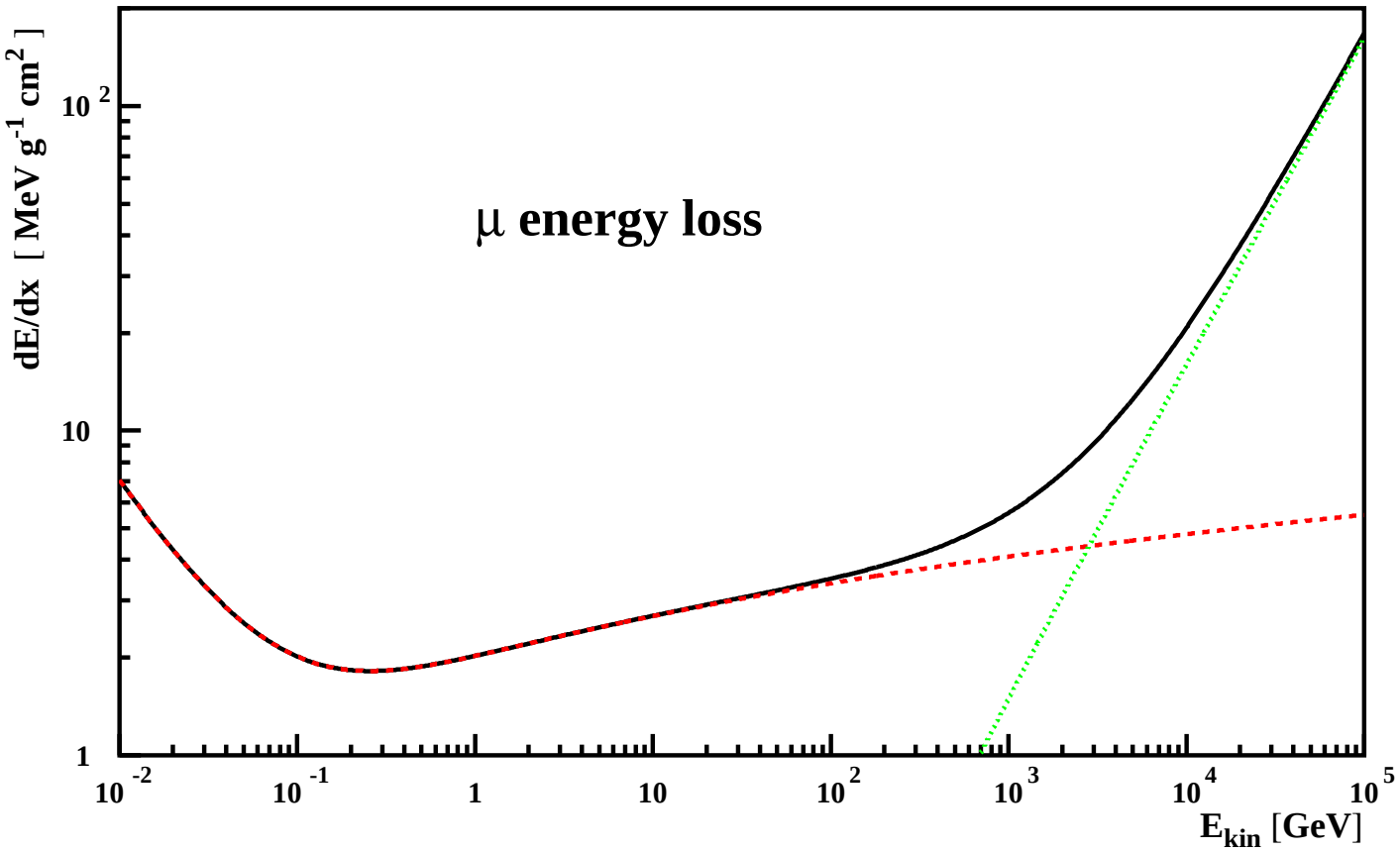
c	=	**vacuum speed of light,**
τ	=	**particle life time at rest,**
γ	=	**particle Lorentz factor and**
β	=	**particle velocity in units of c.**

Fate of Mesons



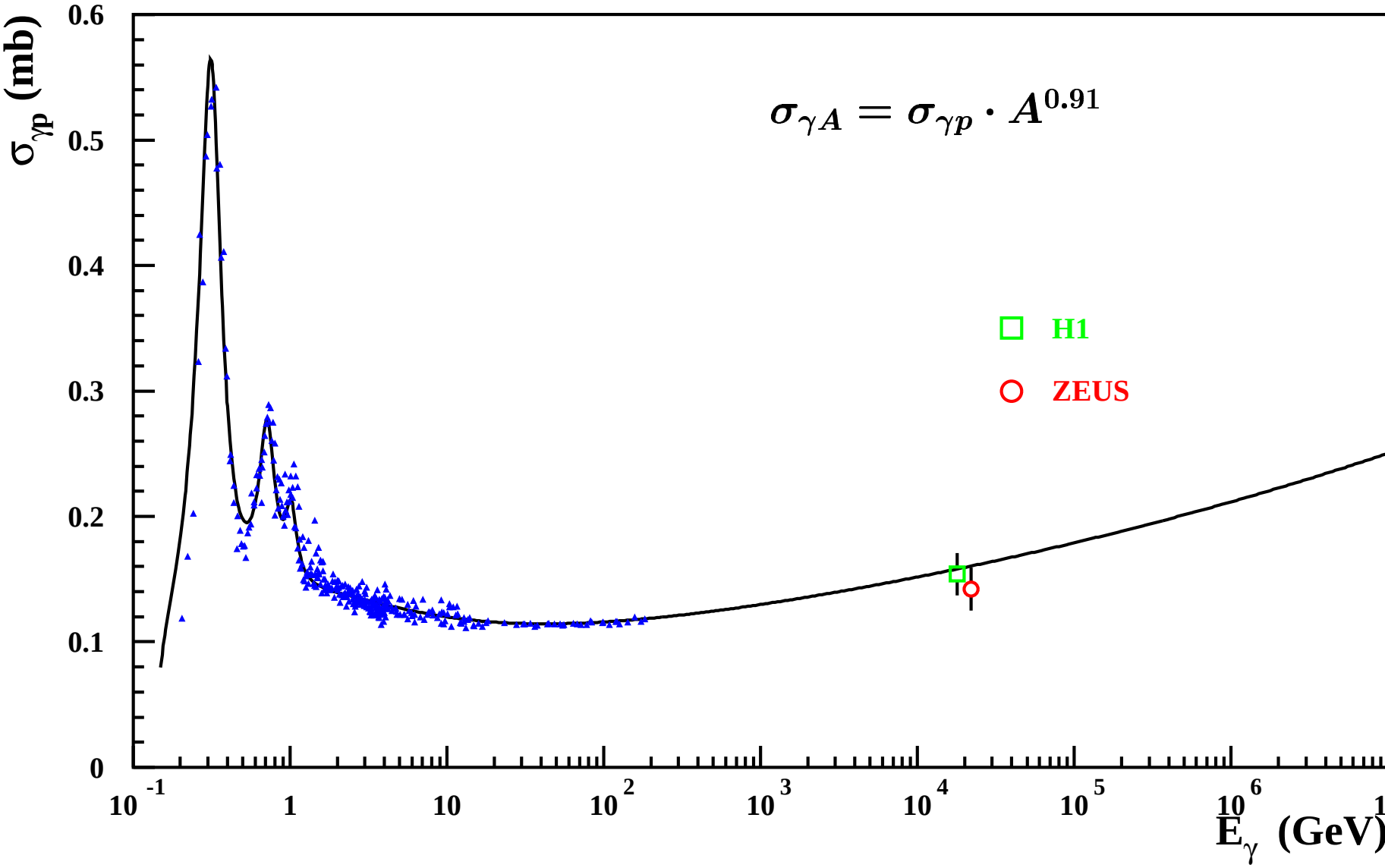
Lines of equal probability for decay and interaction of mesons as function of atmospheric depth and energy.

Ionization Energy Loss



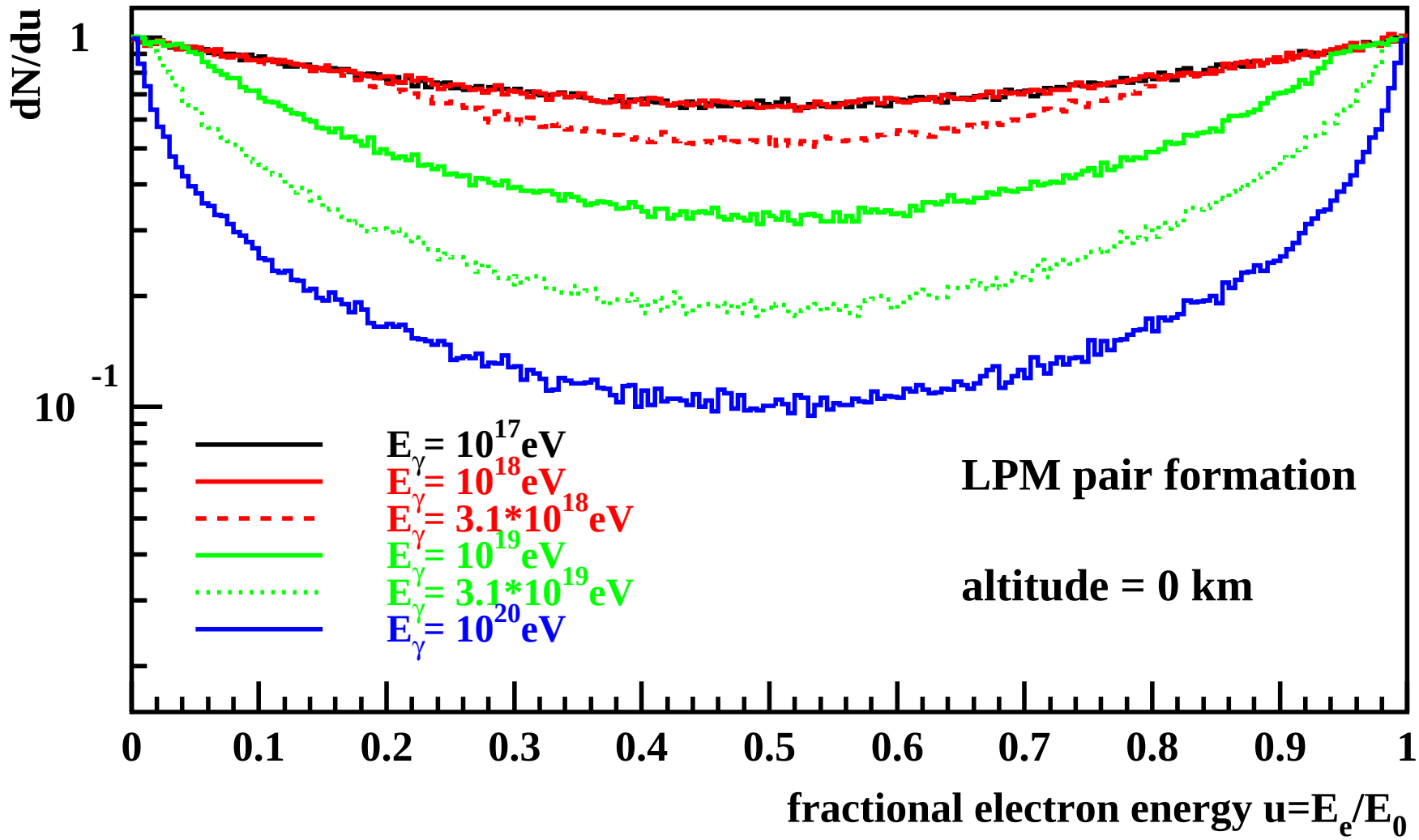
Energy loss of muons in air as function of energy. The contributions from ionization and direct pair production are indicated.

Photoproduction Cross-Section



Photoproduction cross-section of protons as function of photon energy.

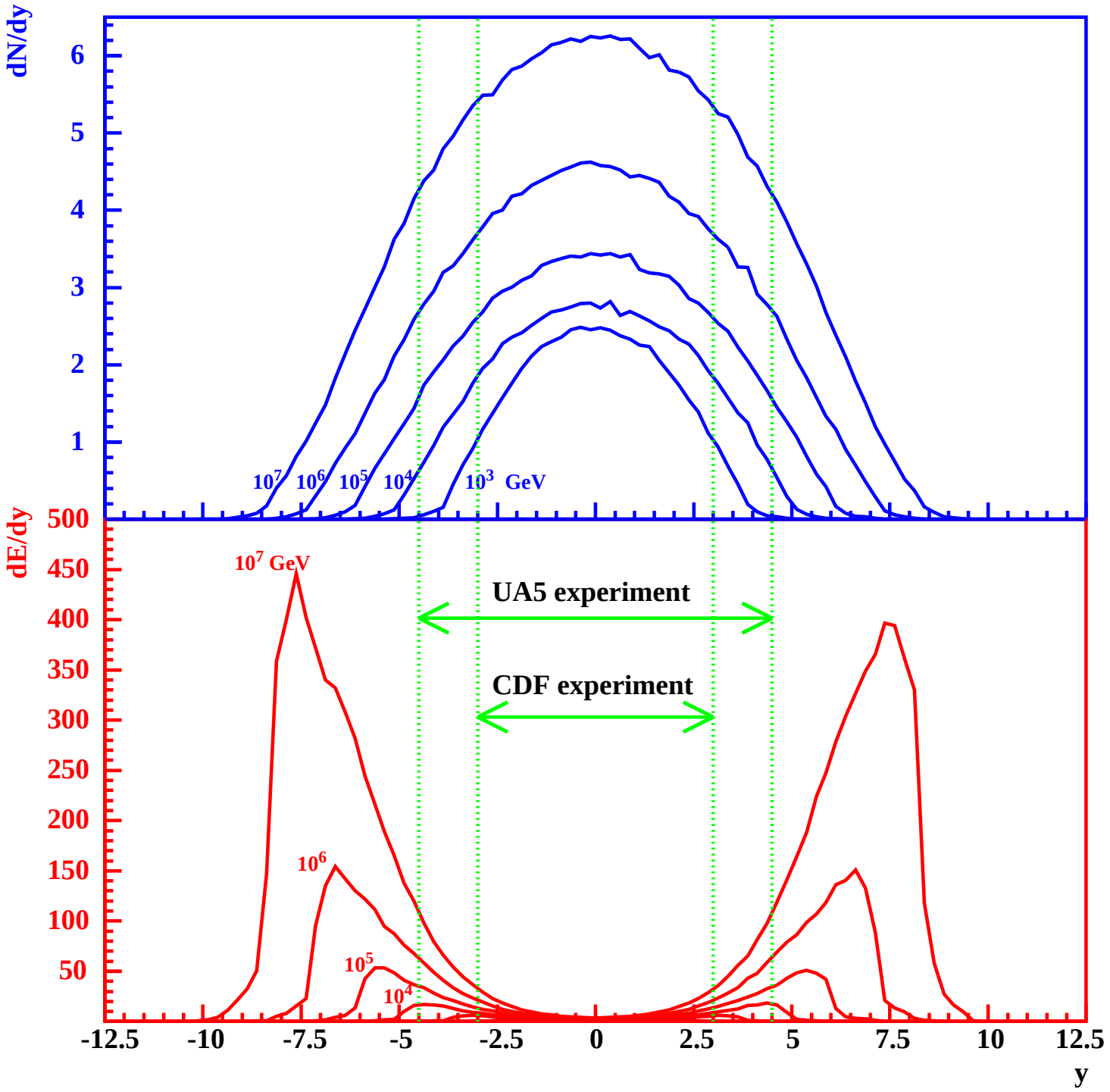
Landau-Pomeranchuk-Migdal-Effect



Suppression of symmetric pair formation by the LPM-effect.

Collider Experiments

PARTICLE and ENERGY flow in $p\overline{p}$-interactions.



Most energy in collider experiments escapes undetected !!

Hadronic Interaction Models

Model Version	DPMJET II.55	HDPM	NEXUS 2	QGSJET 01	SIBYLL 2.1	VENUS 4.12
Gribov-Regge	+		+	+	+	+
Minijets	+		+	+	+	
Sec. Interactions			+			+
N-N Interaction	+		+	+		+
Superposition		+			+	
Max. Energy (GeV)	$>10^{11}$	10^8	$2{\cdot}10^8$	$>10^{11}$	$>10^{11}$	$2{\cdot}10^7$
Memory ($Mbyte$)	52	8	101	10	9	21
CPU-time[1] (min)	3.5	1.0	$\approx$100	1.0	0.75	4.5

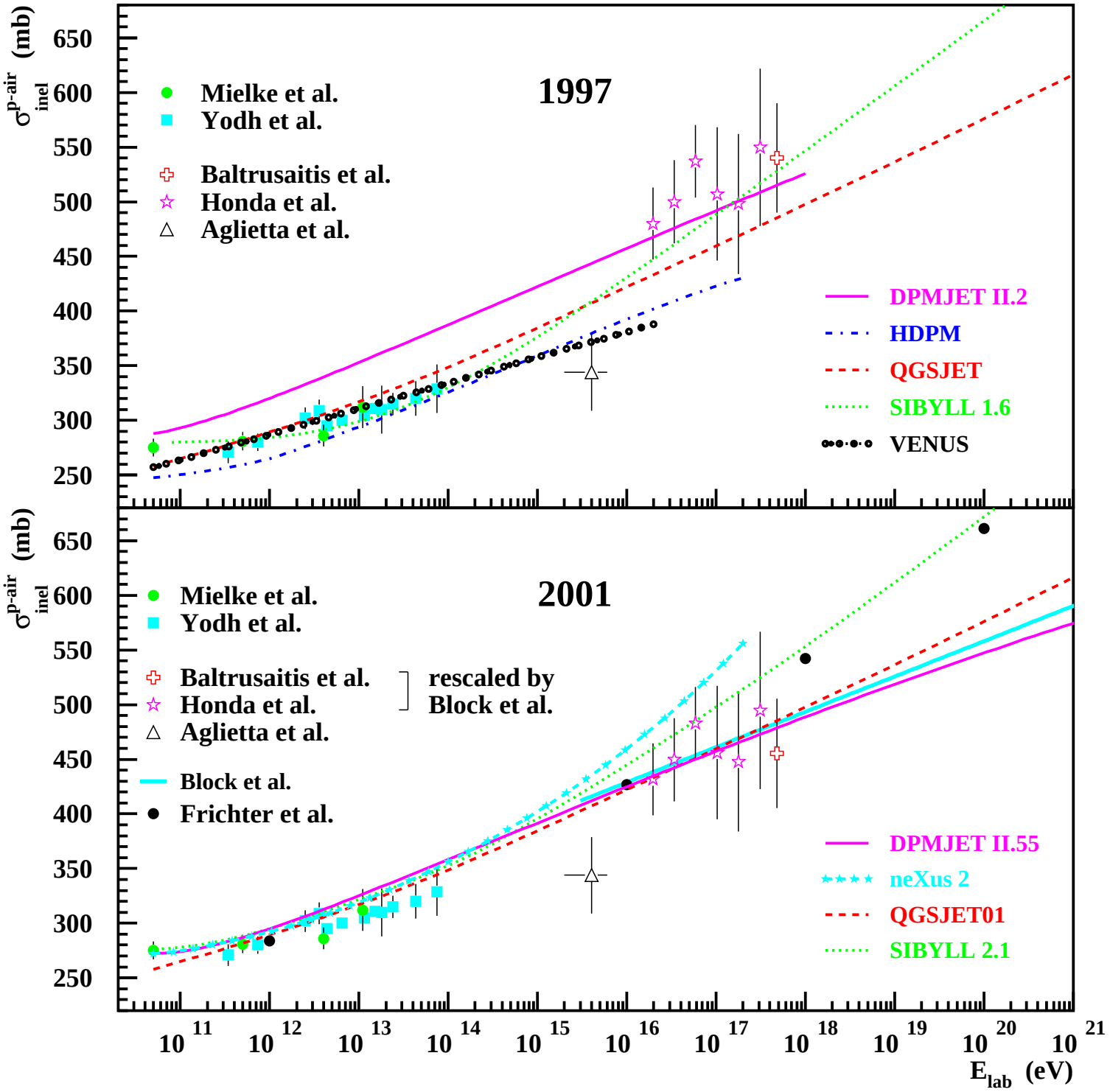
[1] for p, $E_0 = 10^{15}\ eV$, vertical, E_h , $E_\mu \geq 0.3 GeV$, $110\ m$ a.s.l., NKG option, DEC 3000/600 AXP (175 MHz)

Essential features of interaction models.

References to Hadronic Interaction Models

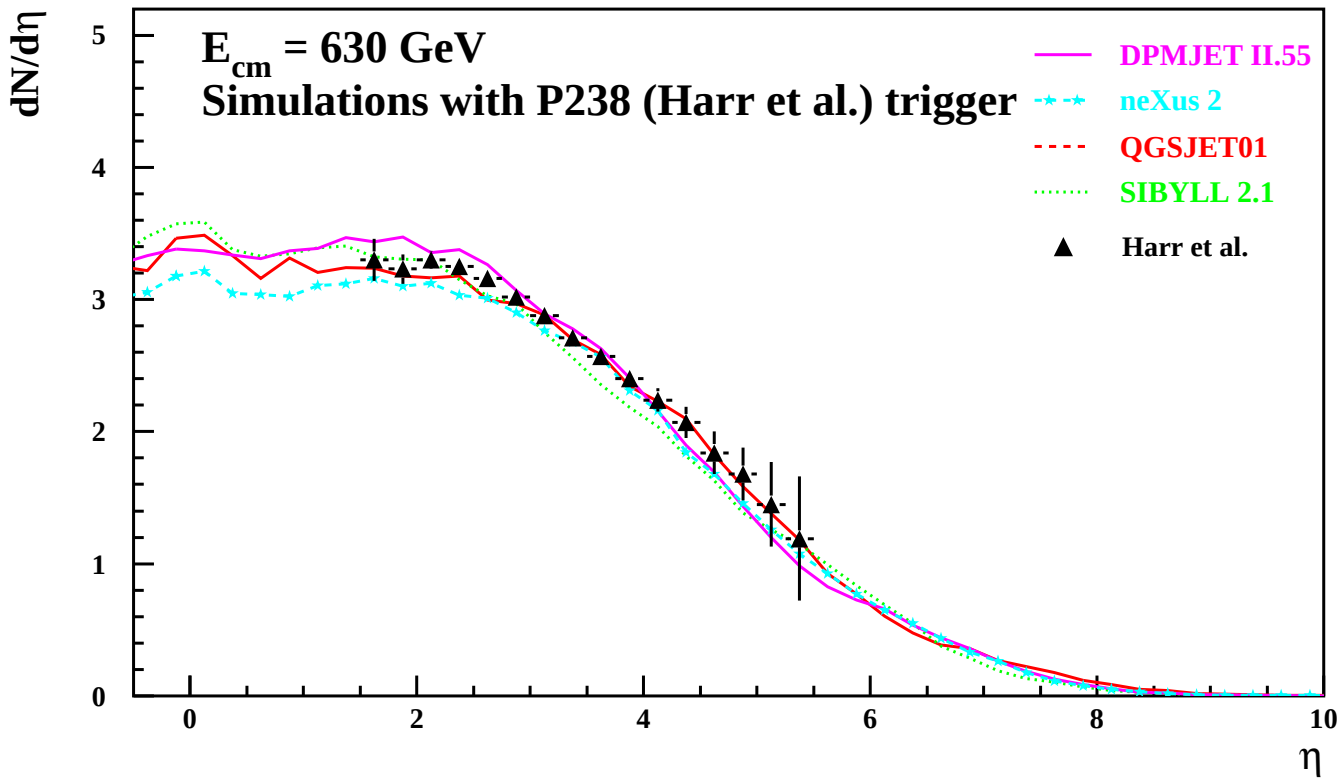
DPMJET	**J. Ranft, Phys. Rev. D51 (1995) 64; preprint $hep\text{-}ph/9911213$ & $hep\text{-}ph/9911232$ (1999)**
HDPM	**J.N. Capdevielle et al., KfK 4998 (1992)**
NEXUS	**H.J. Drescher et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) L91; H.J. Drescher et al., Physics Reports 350 (2001) 93**
QGSJET	**N.N. Kalmykov and S.S. Ostapchenko, Yad. Fiz. 56 (1993) 105; Phys. At. Nucl. 56/3 (1993) 346**
SIBYLL	**R.S. Fletcher, T.K. Gaisser, P. Lipari, T. Stanev, Phys. Rev. D50 (1994) 5 710; J. Engel et al., Phys. Rev. D46 (1992) 5013; R. Engel et al., $Proc.$ 26th $ICRC$, Salt Lake City (USA), 1 (1999) 415**
VENUS	**K. Werner, Physics Reports 232 (1993) 87**
GHEISHA	**H. Fesefeldt, PITHA-85/02 (1985)**
UrQMD	**S.A. Bass et al., Prog. Part. Nucl. Phys. 41 (1998) 225; M. Bleicher et al., J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859**

Cross-Sections



Improvements in inelastic p-air cross-sections.

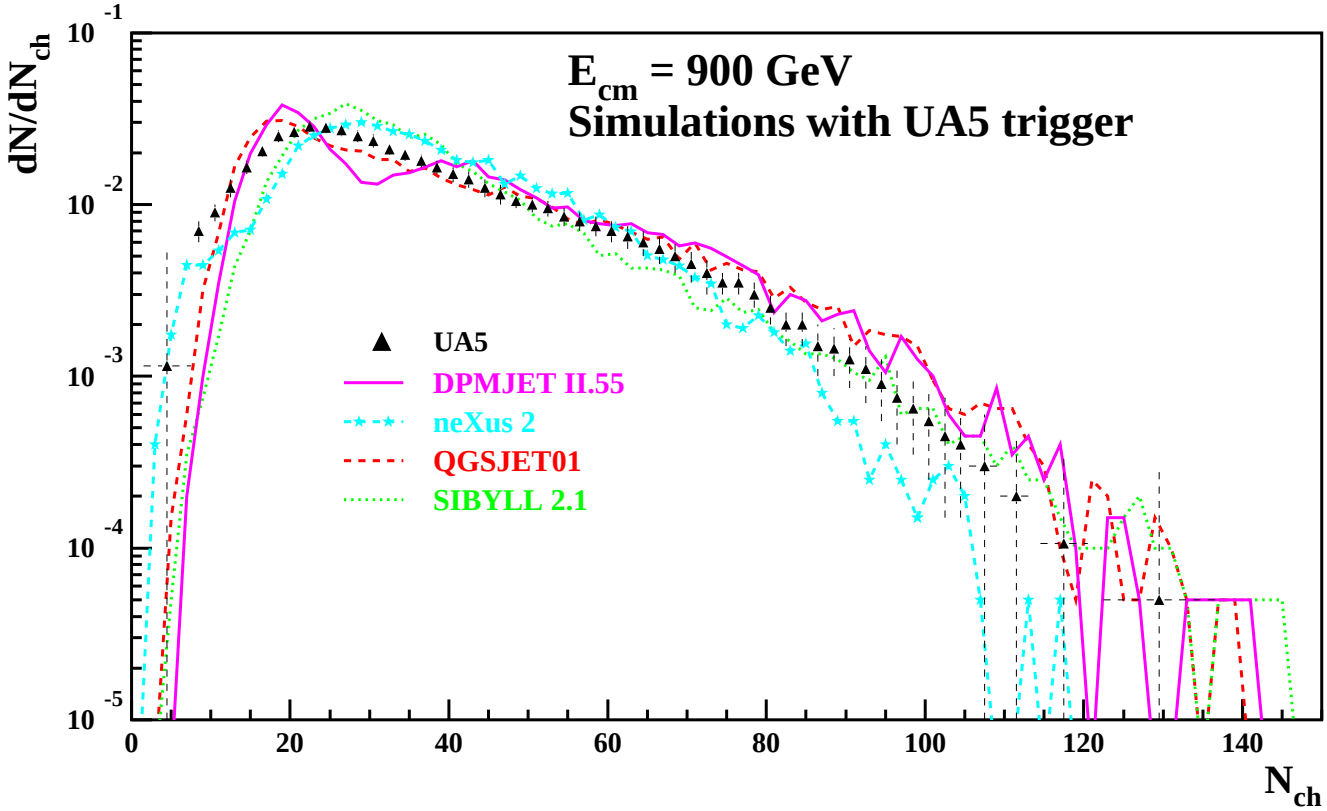
p-$\overline{p}$ Interactions: Pseudorapidity



Pseudorapidity distribution of charged particles for p-$\overline{p}$ collisions at E_{cm} = 630 GeV.

(Simulation with trigger conditions as in P238 experiment.)

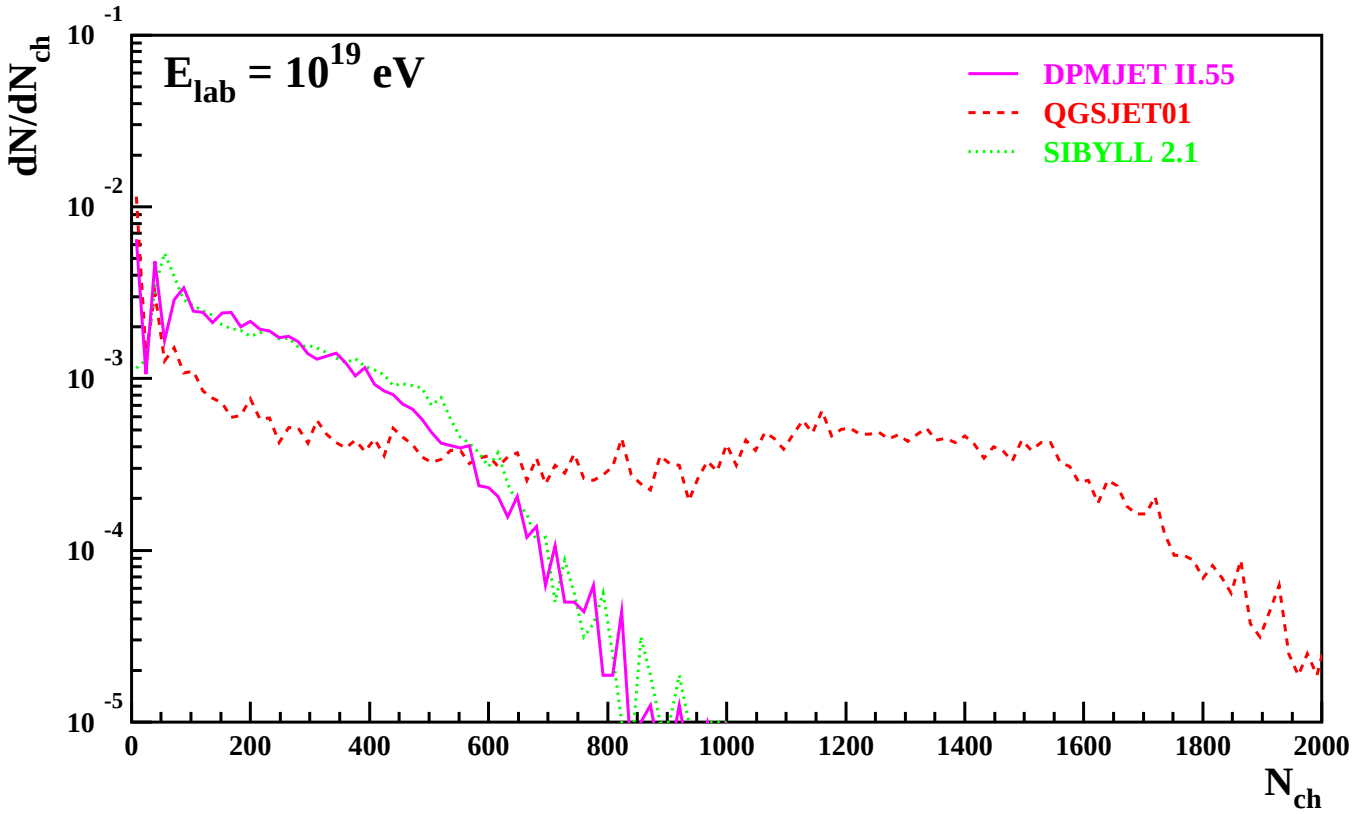
p-$\overline{p}$ Interactions: Multiplicity



Charged particle multiplicity distribution for p-$\overline{p}$ collisions at E_{cm} = 900 GeV.

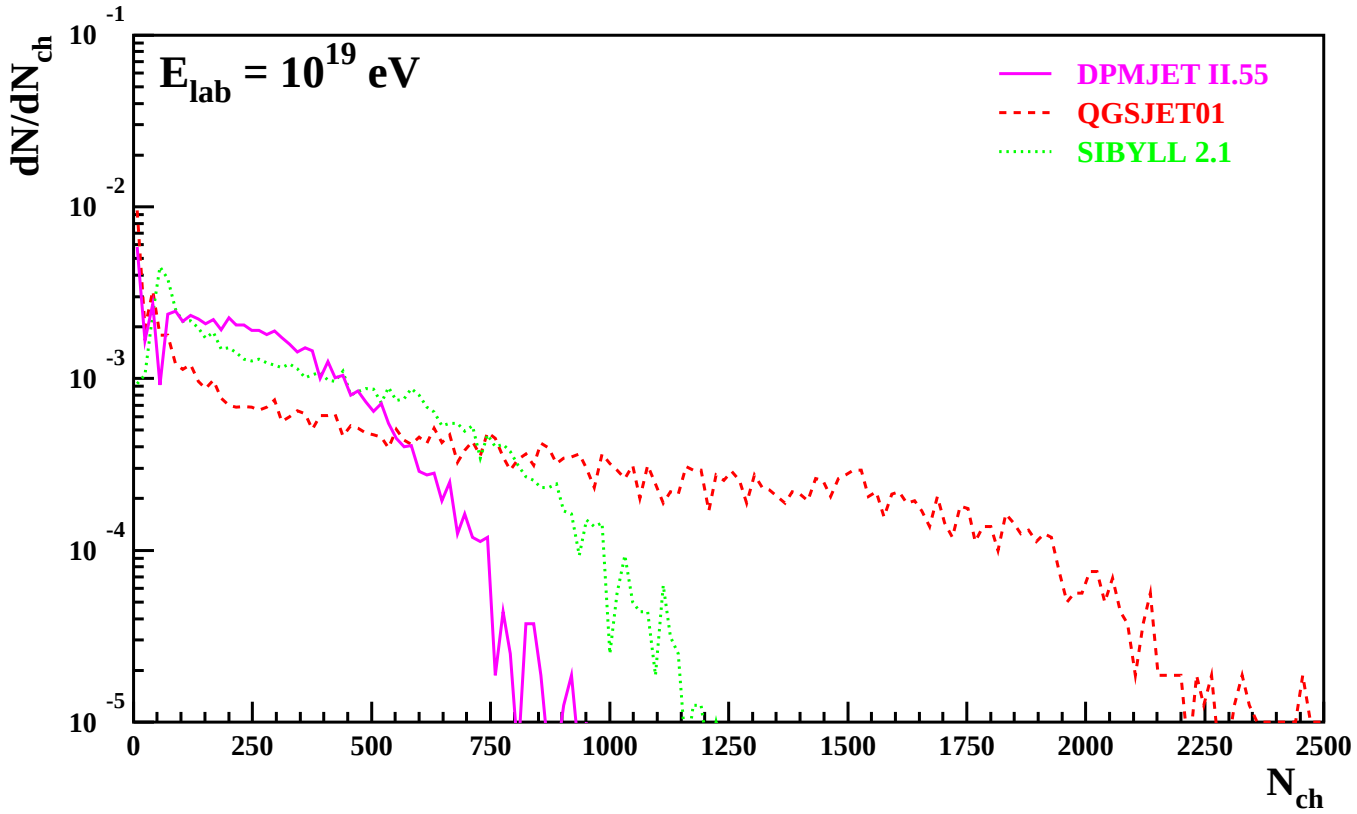
(Simulation with trigger conditions as in UA5 experiment.)

π-^{14}N Interactions: Multiplicity



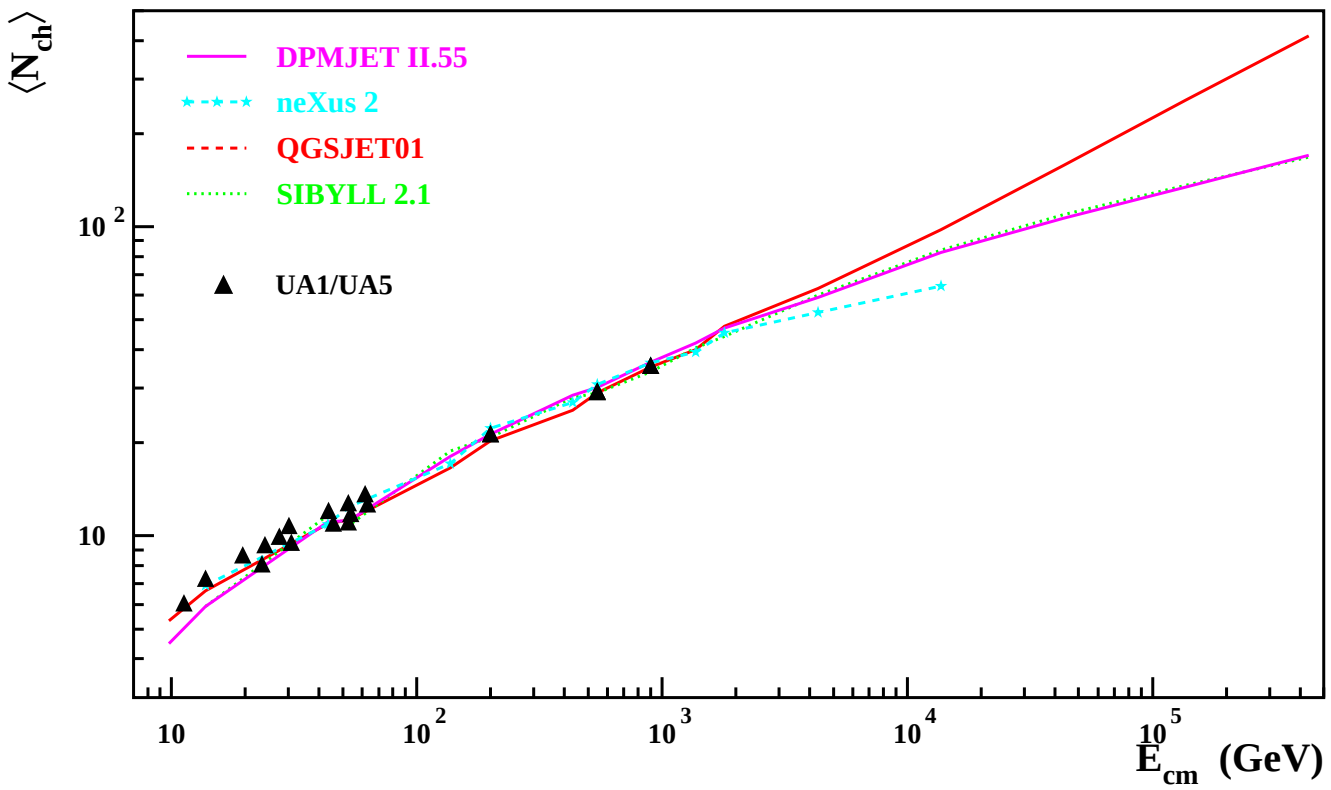
Charged particle multiplicity distribution for π-^{14}N collisions at $E_{lab} = 10^{19}$eV.

p-^{14}N Interactions: Multiplicity



Charged particle multiplicity distribution for p-^{14}N collisions at $E_{lab} = 10^{19}$eV.

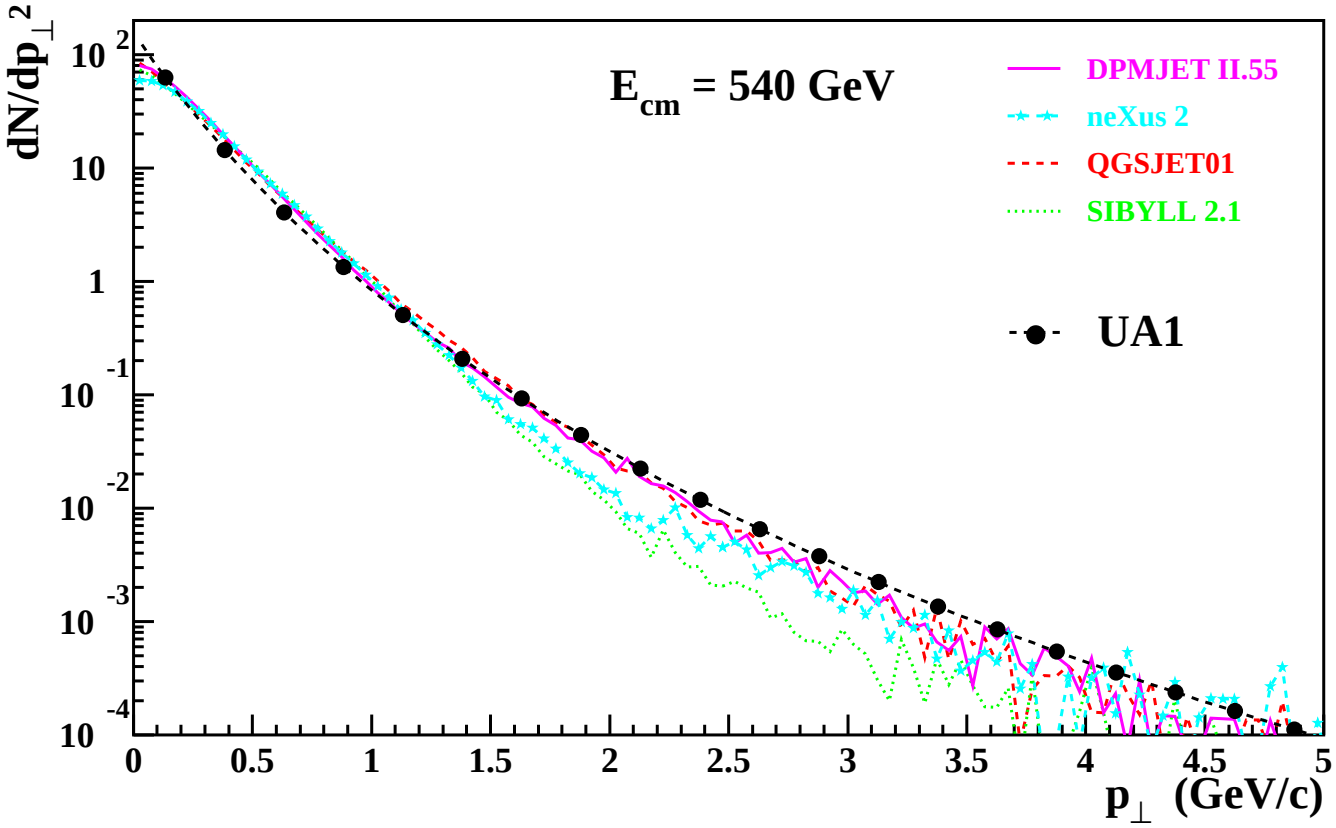
p-$\overline{p}$ Interactions: Multiplicity



Average charged particle multiplicity as function of energy for p-$\overline{p}$ collisions.

(Non-diffractive collisions.)

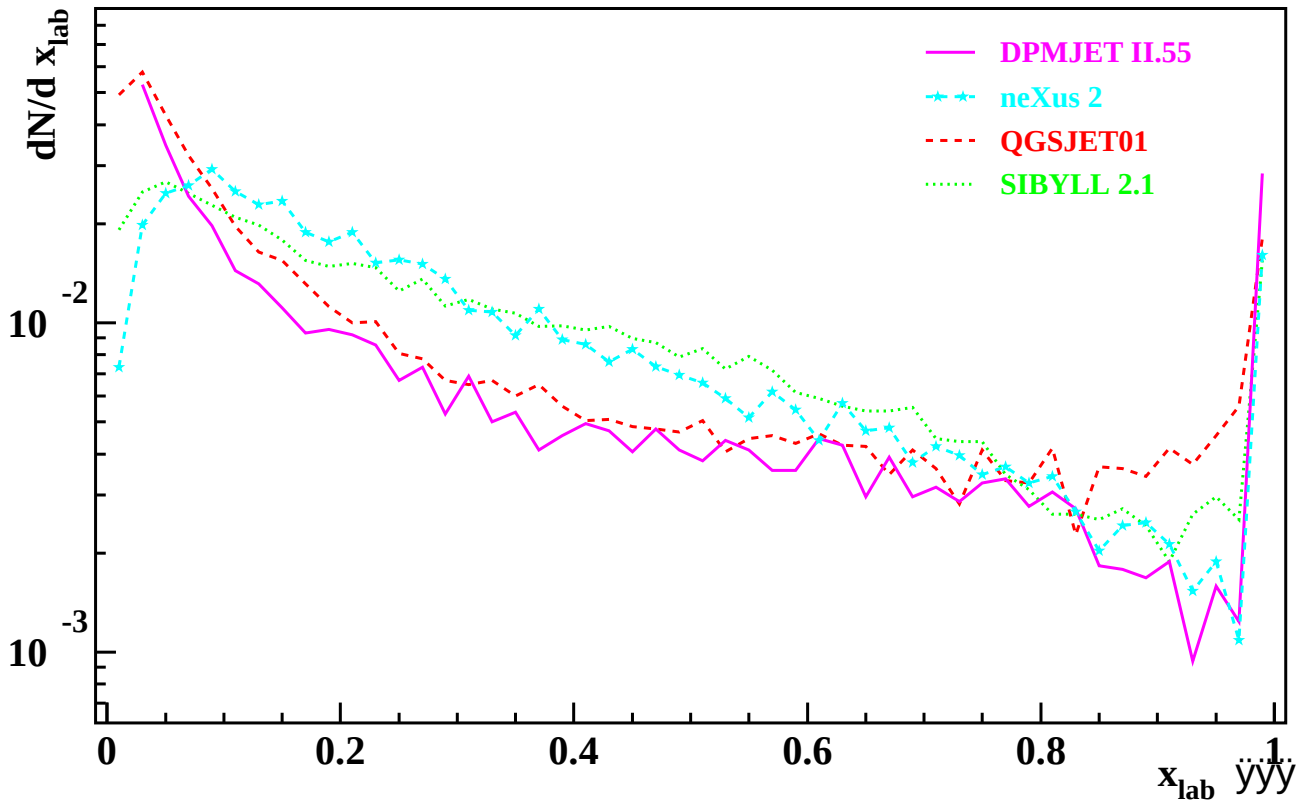
p-$\overline{p}$ Interactions: Transverse Momentum



Transverse momentum distribution of charged particles emerging from p-$\overline{p}$ collisions at E_{cm} = 540 GeV.

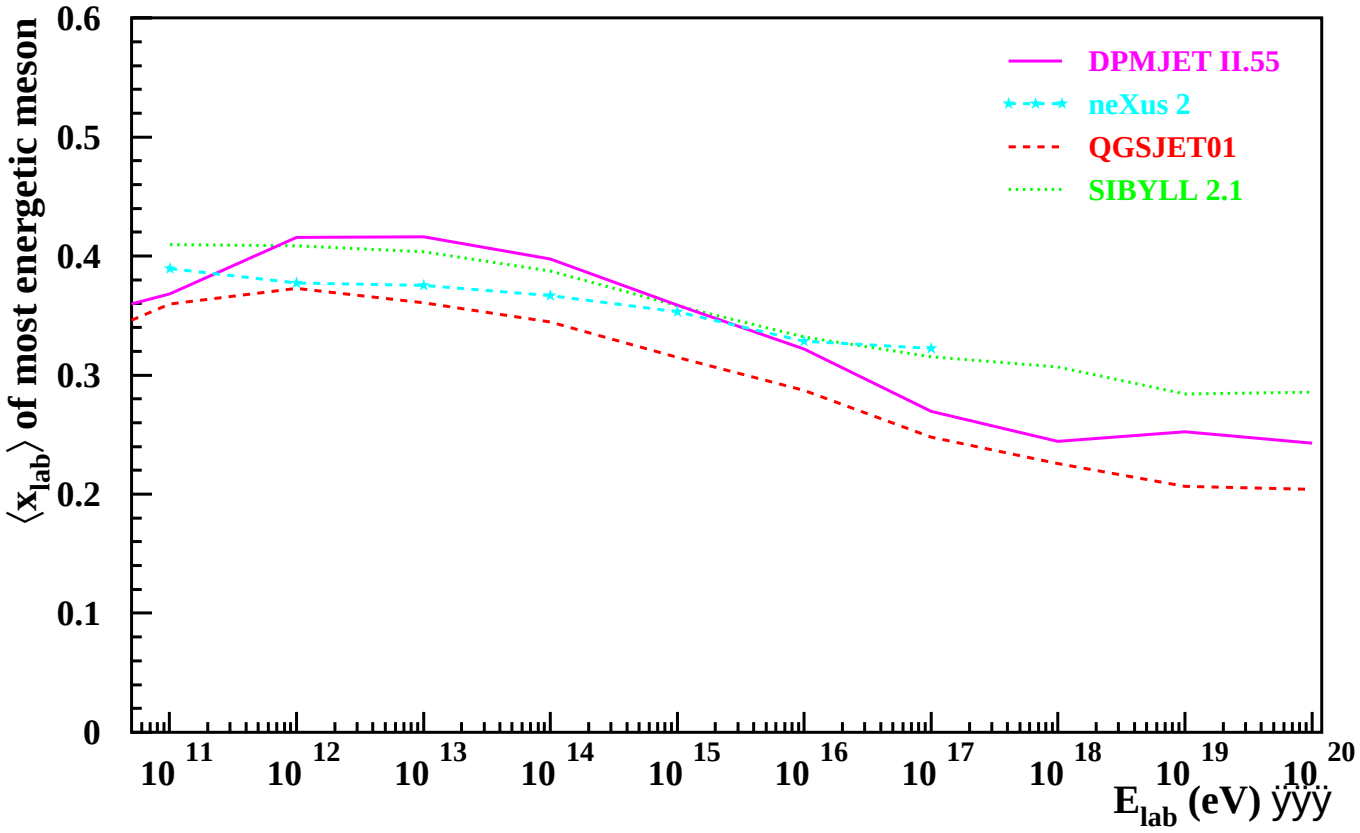
(Non-diffractive collisions.)

p-^{14}N Interactions: Leading Baryon



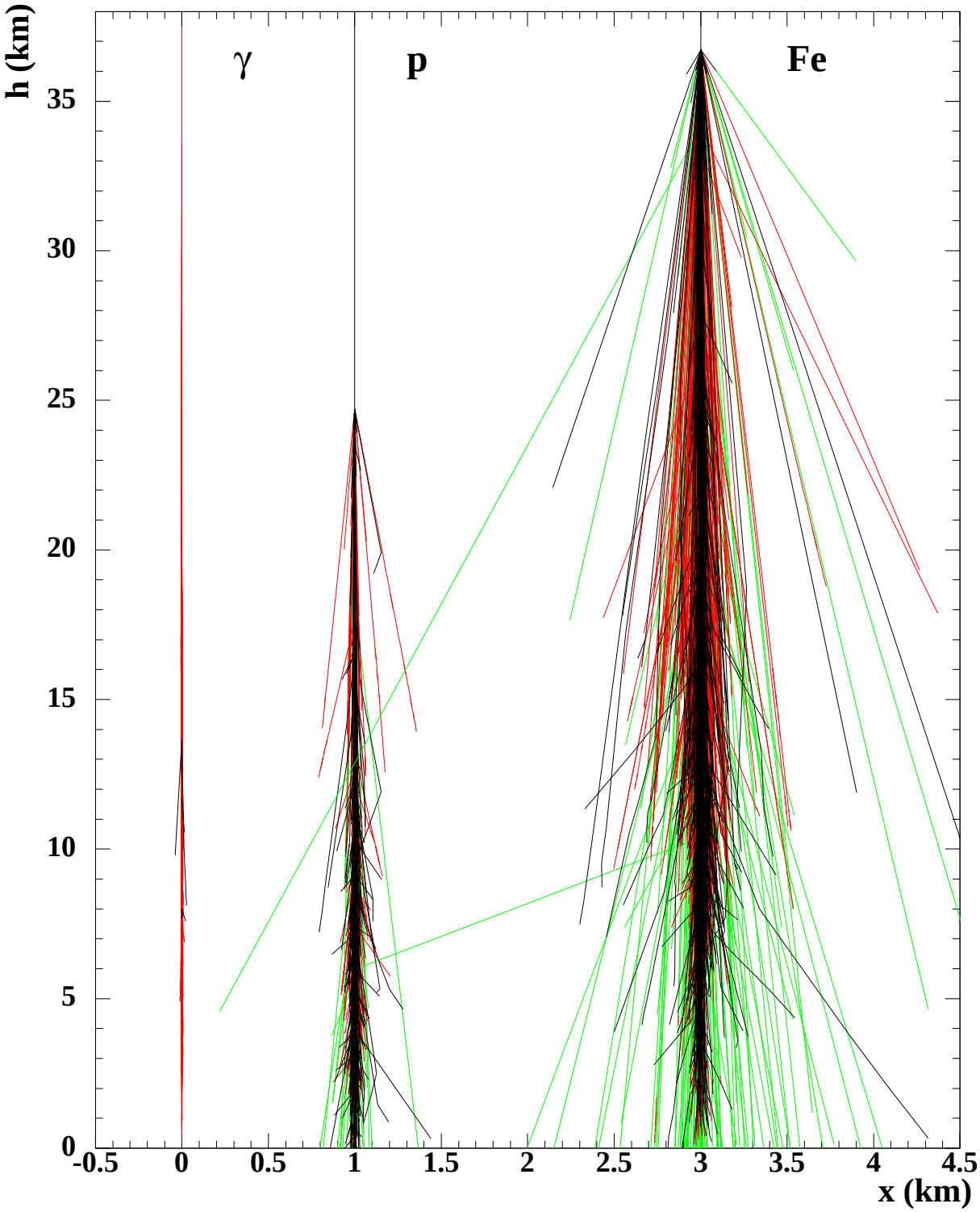
x_{lab} distribution of most energetic baryon for p-^{14}N collisions at $E_{lab} = 10^{16}$ eV.

π-^{14}N Interactions: Elasticity



Average longitudinal momentum fraction carried away by the most energetic meson for π-^{14}N collisions as function of energy.

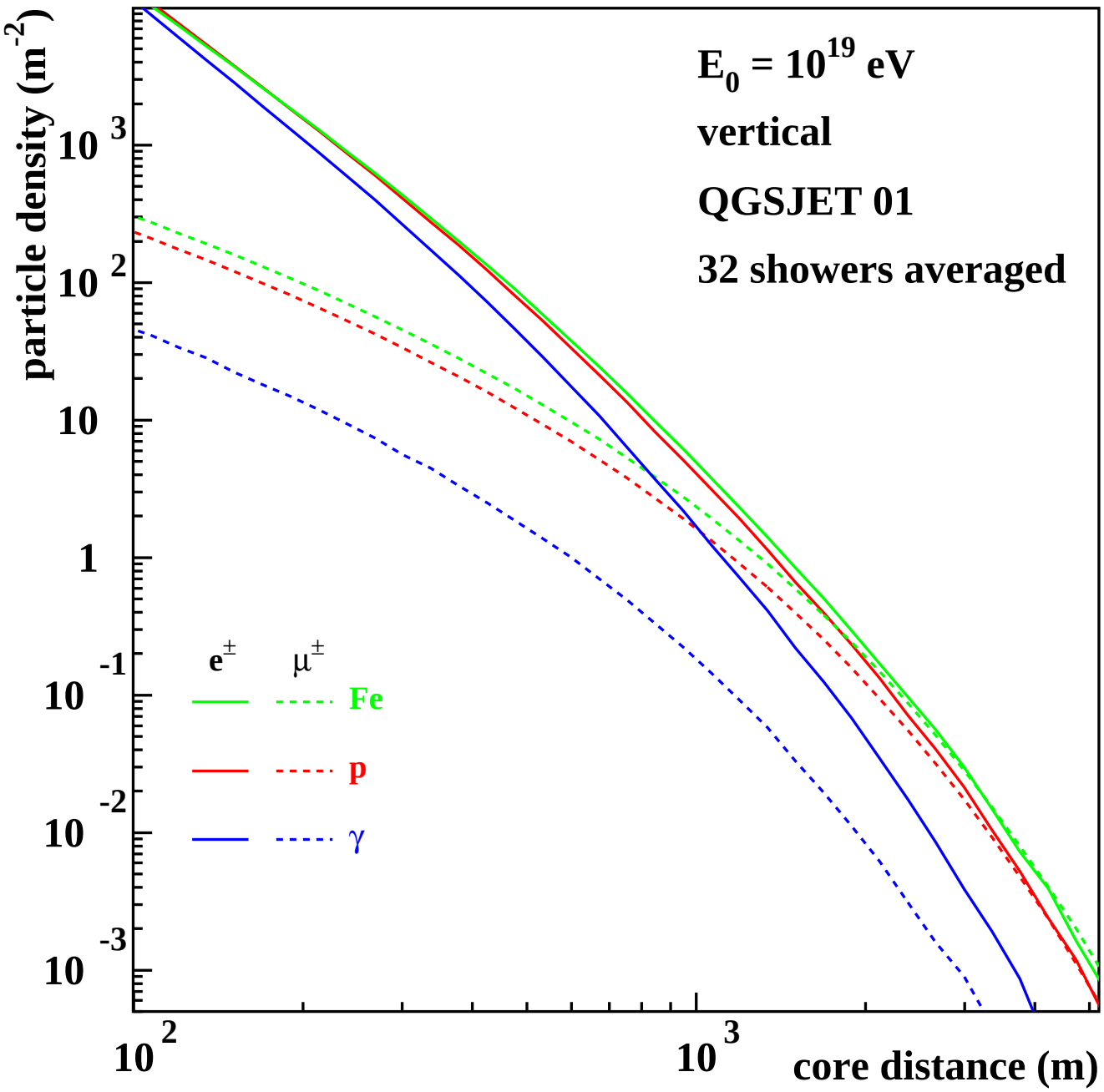
Side View of Showers



Side view of showers induced by different primary particles.

E_0 = 10^{14} eV; only electrons, muons, and hadrons with energies $>$ 10 GeV are shown (CORSIKA & VENUS).

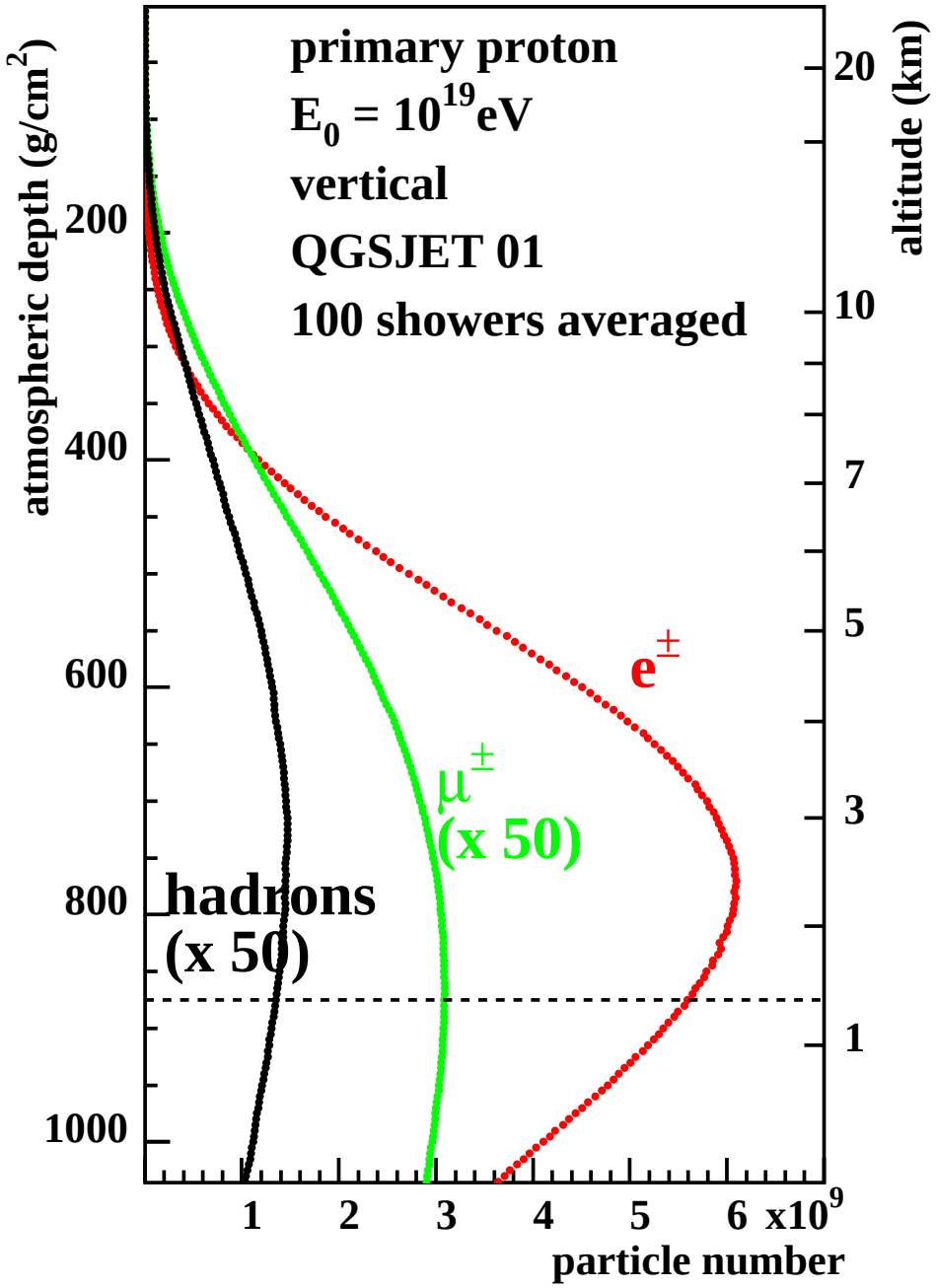
Lateral Distributions of Ground Particles



Lateral particle distributions from showers induced by different primary particles.

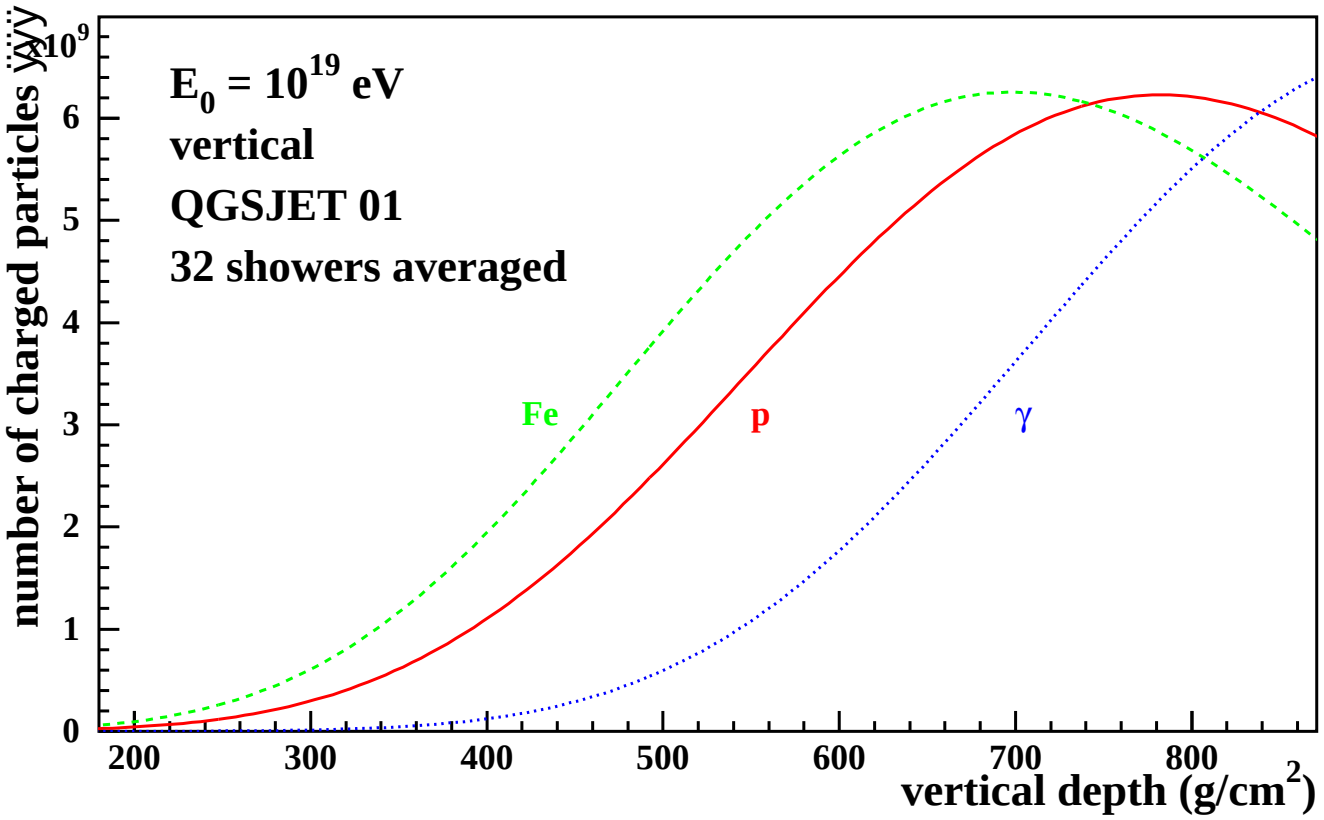
$E_0 = 10^{19}$ eV; detector at 1450 m.

Longitudinal Development of Shower Components



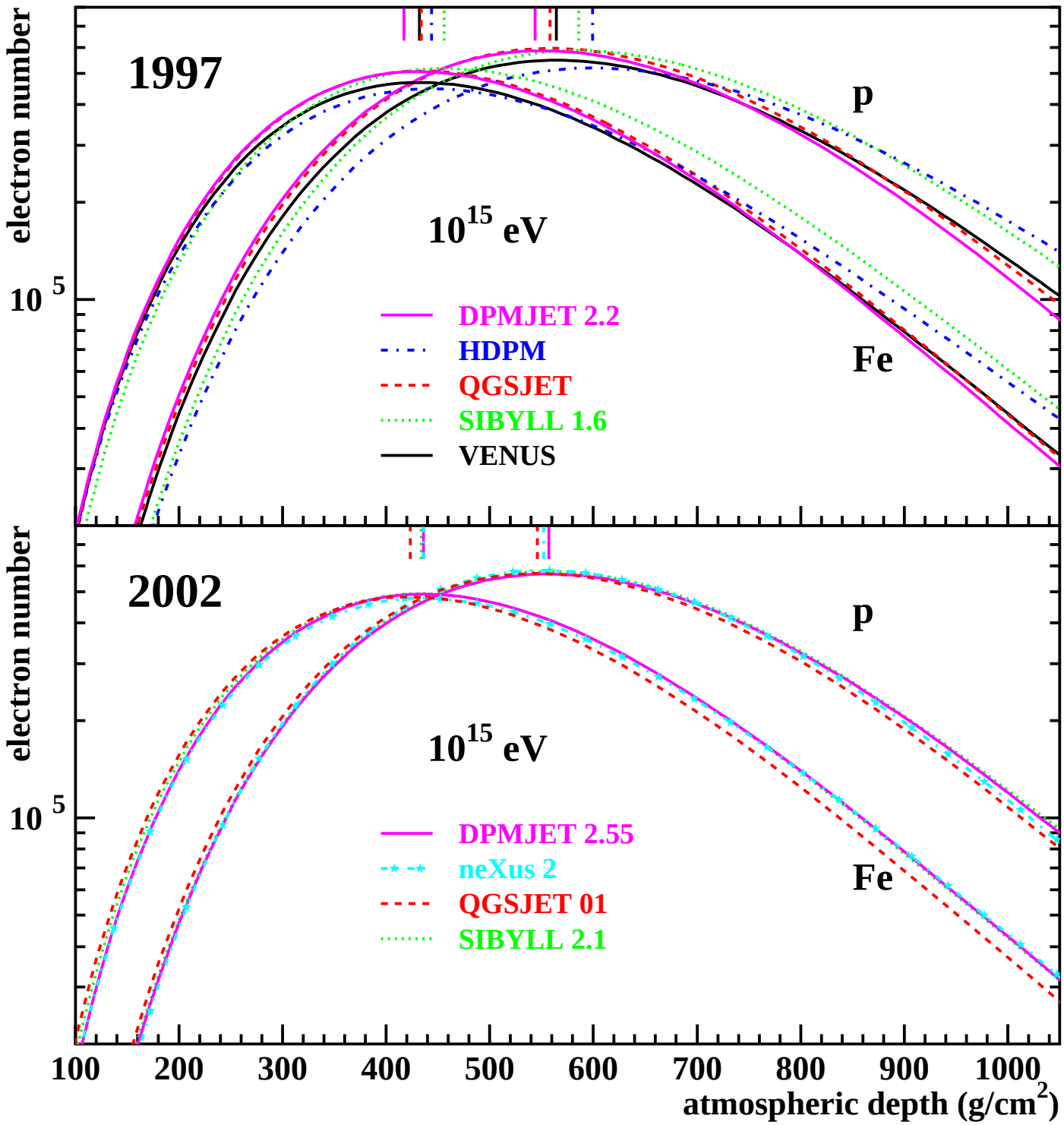
Longitudinal development of electrons, muons and hadrons.

Longitudinal Development of Showers



Longitudinal development of showers induced by different primary particles.

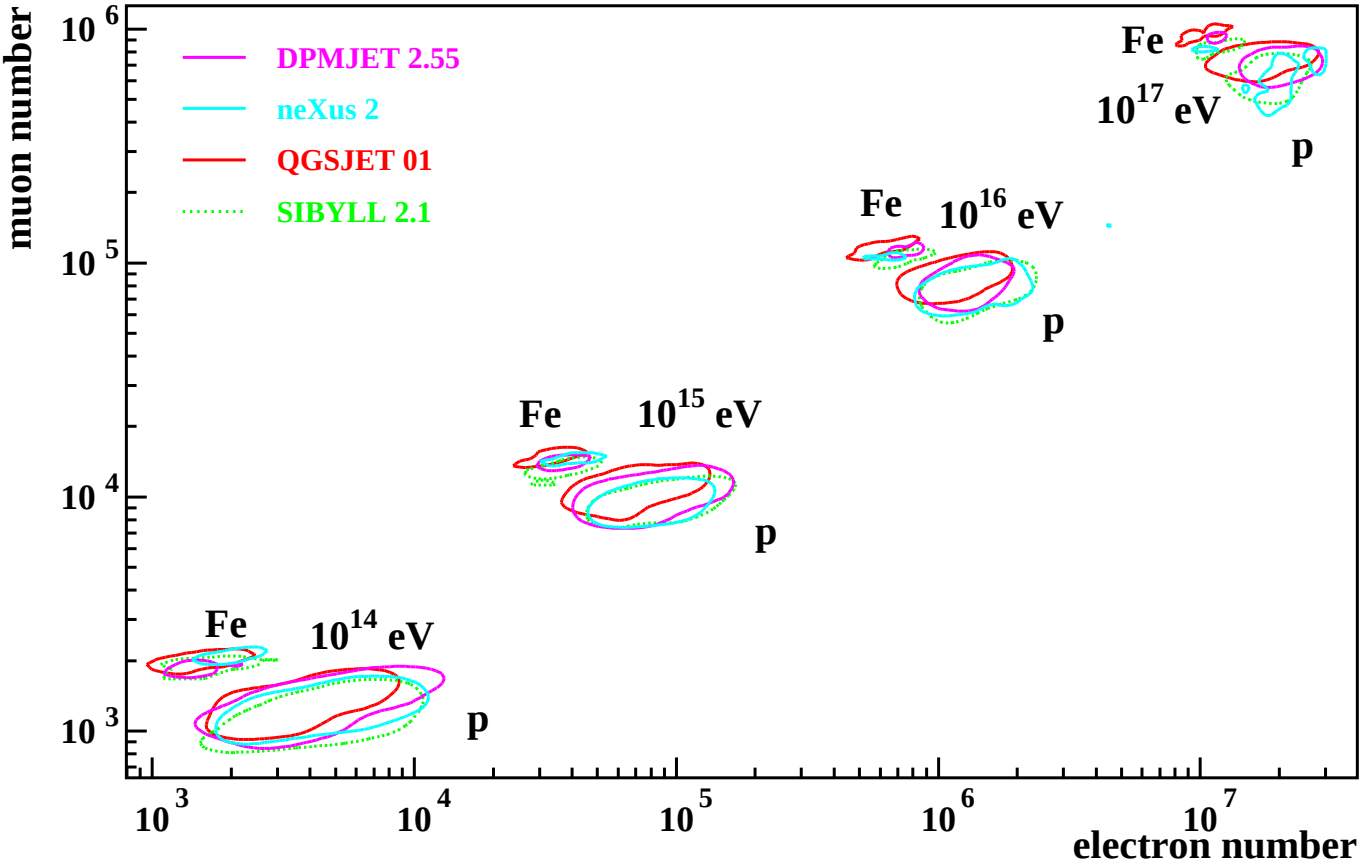
EAS: Longitudinal Development



Improvements in the longitudinal development.

(Vertical incidence, $E_0 = 10^{15}$ eV, $E_e > 3$ MeV.)

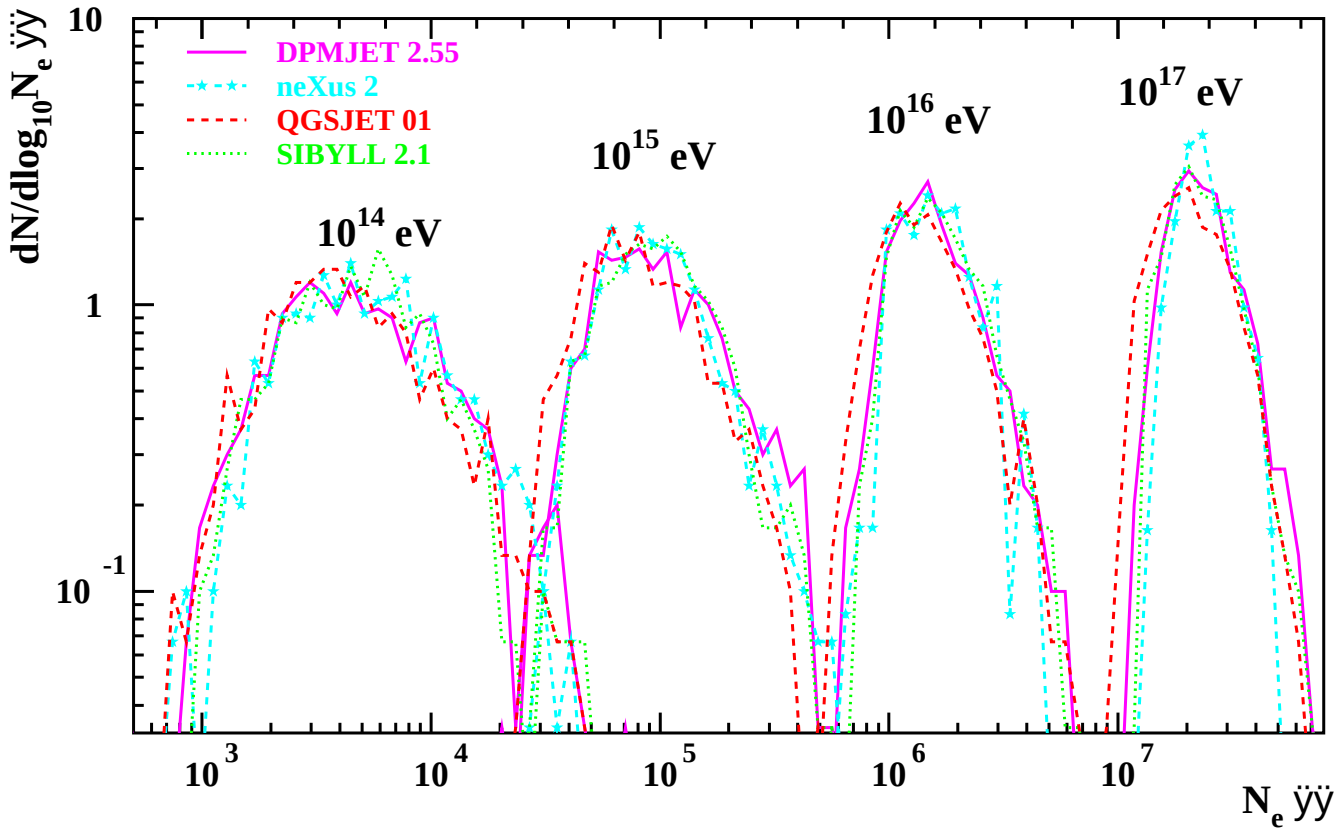
EAS Simulation: N_μ vs. N_e



Muon vs. electron numbers as function of energy and primary particle.

(Vertical incidence, $\varepsilon_{\text{thin}} = 10^{-5}$,
$E_\mu > 0.1$ GeV, $E_e > 0.1$ MeV, 110 m a.s.l.)

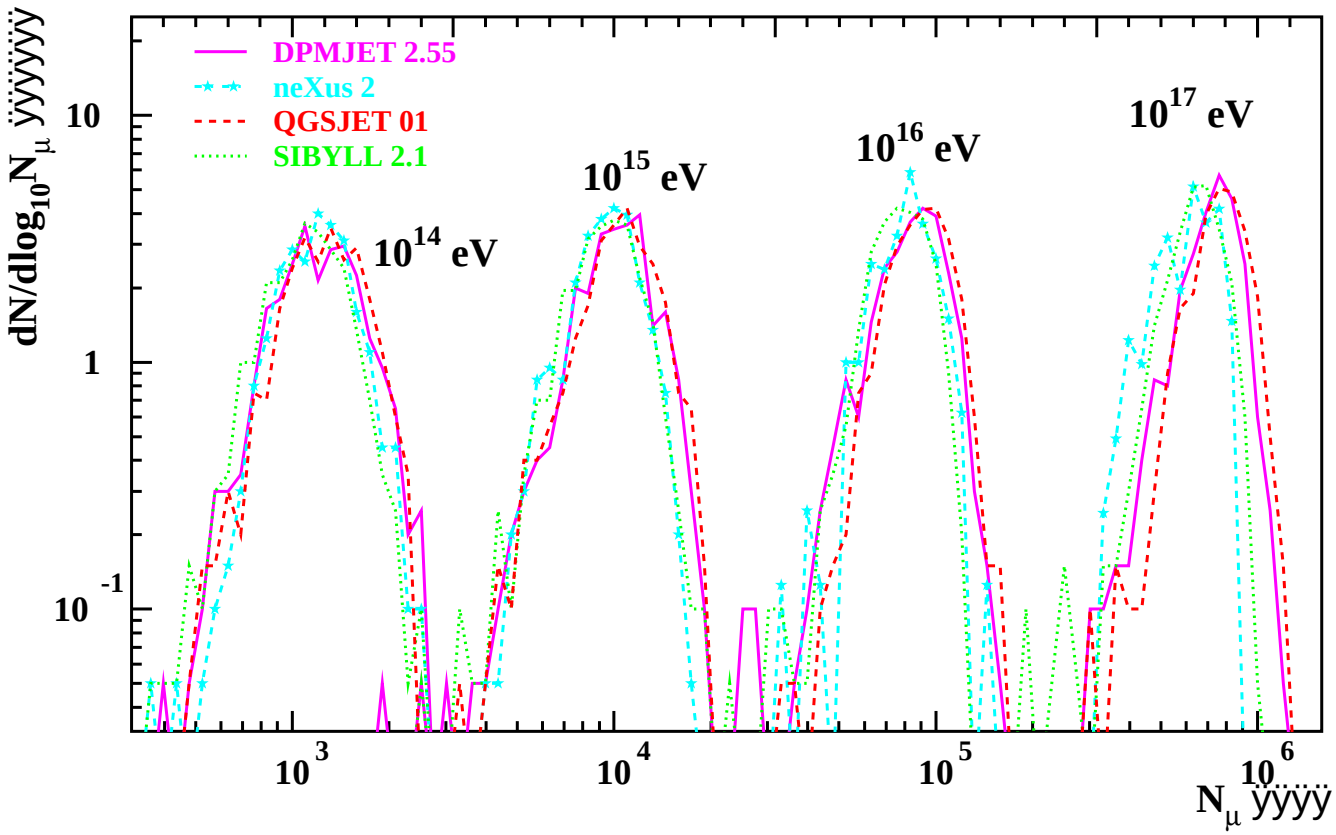
EAS Simulation: N_e



Electron numbers as function of energy.

(Proton, vertical incidence, $\varepsilon_{\text{thin}} = 10^{-5}$,
$E_e > 0.1$ MeV, 110 m a.s.l.)

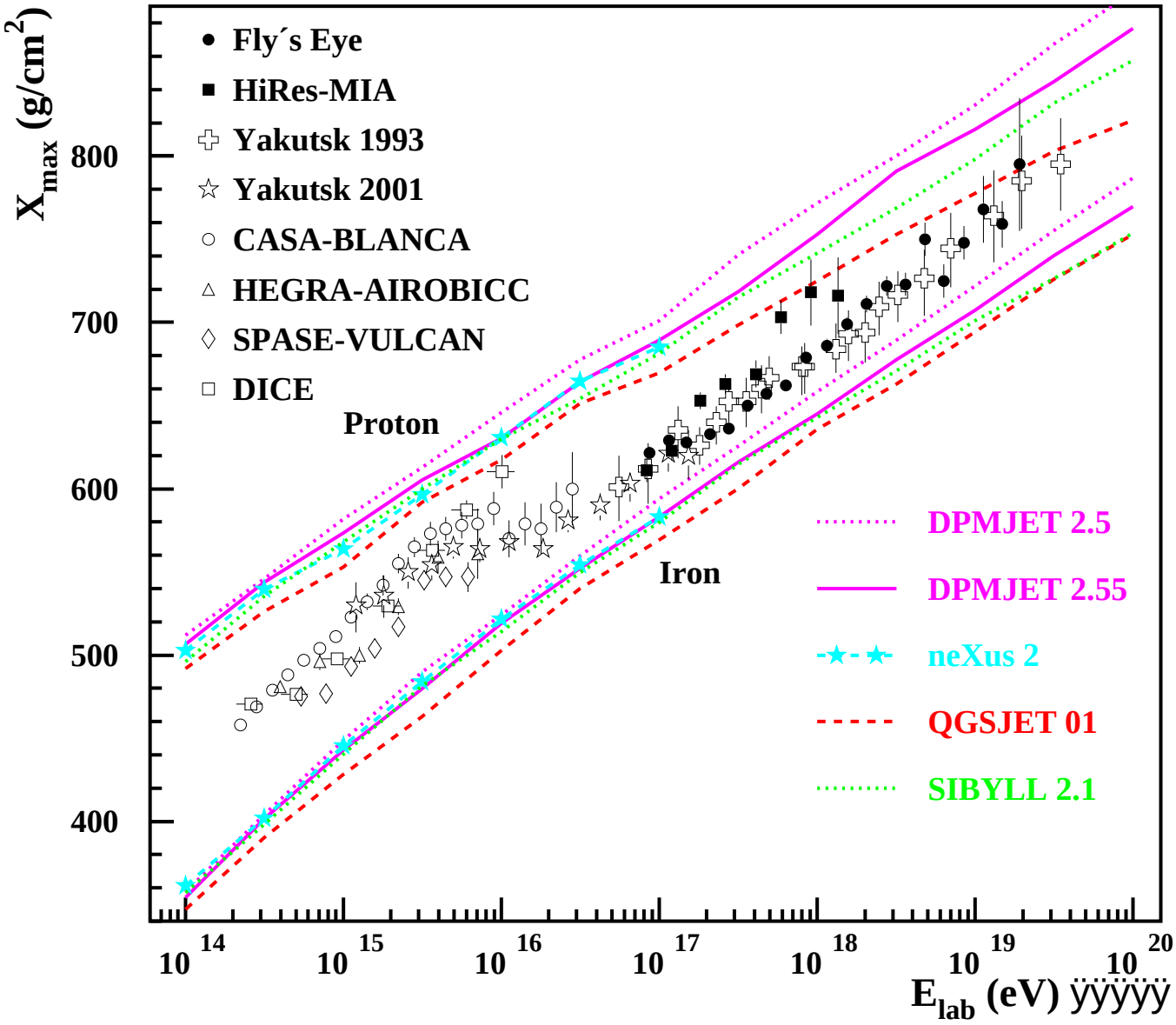
EAS Simulation: N_μ



Muon numbers as function of energy.

(Proton, vertical incidence, $\varepsilon_{\text{thin}} = 10^{-5}$,
$E_\mu > 0.1$ GeV, 110 m a.s.l.)

EAS Simulation: X_{max}



Depth of shower maximum as function of energy and primary particle.

(Vertical incidence, $\varepsilon_{\text{thin}} = 10^{-5}$, $E_e > 0.1$ MeV.)

Options within CORSIKA

Production of Cherenkov radiation

Thin sampling algorithm

Curved Earth atmosphere

Interaction test mode

Generation of neutrinos

External atmospheres

(γ-induced preshower)

(Local energy deposit for fluorescence radiation)

Outlook

- **Hadronic interaction models have significantly converged, but still show differences**

- **Further development is going on:**

  DPMJET 3 is available

  NEXUS 3 is being tested