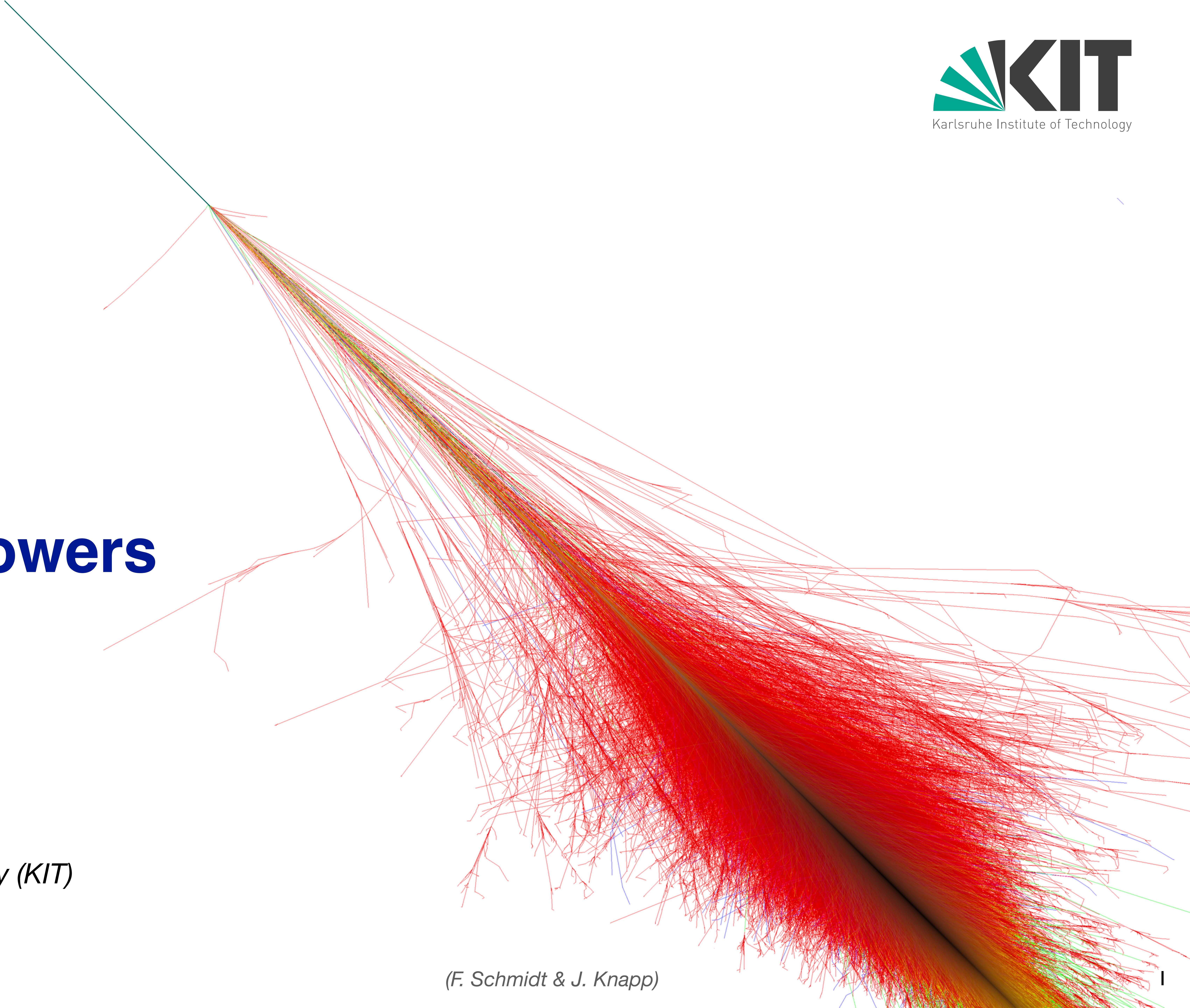
Physics of High-Energy Showers

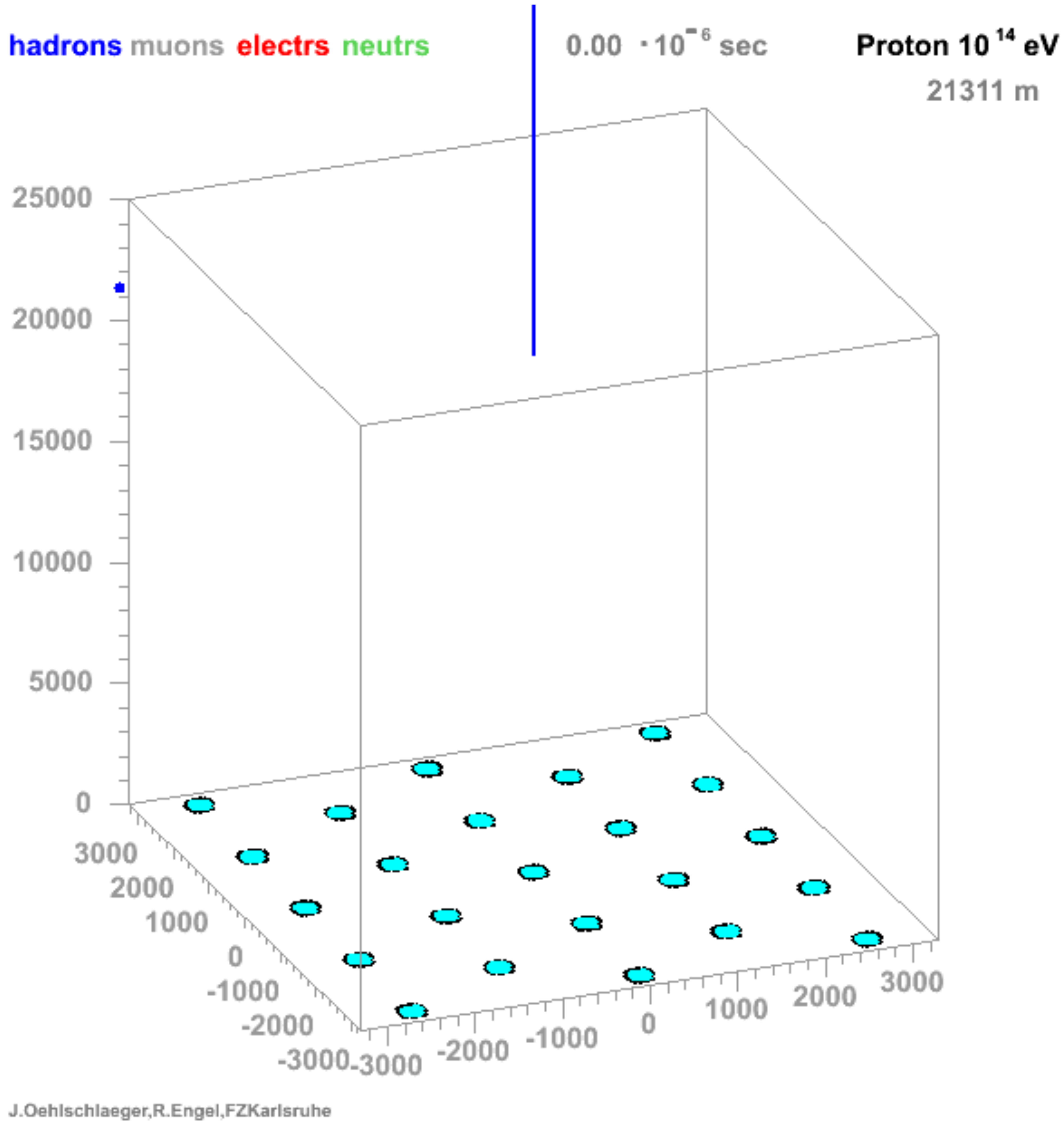
Lecture 1

Ralph Engel

Karlsruhe Institute of Technology (KIT)



(F. Schmidt & J. Knapp)

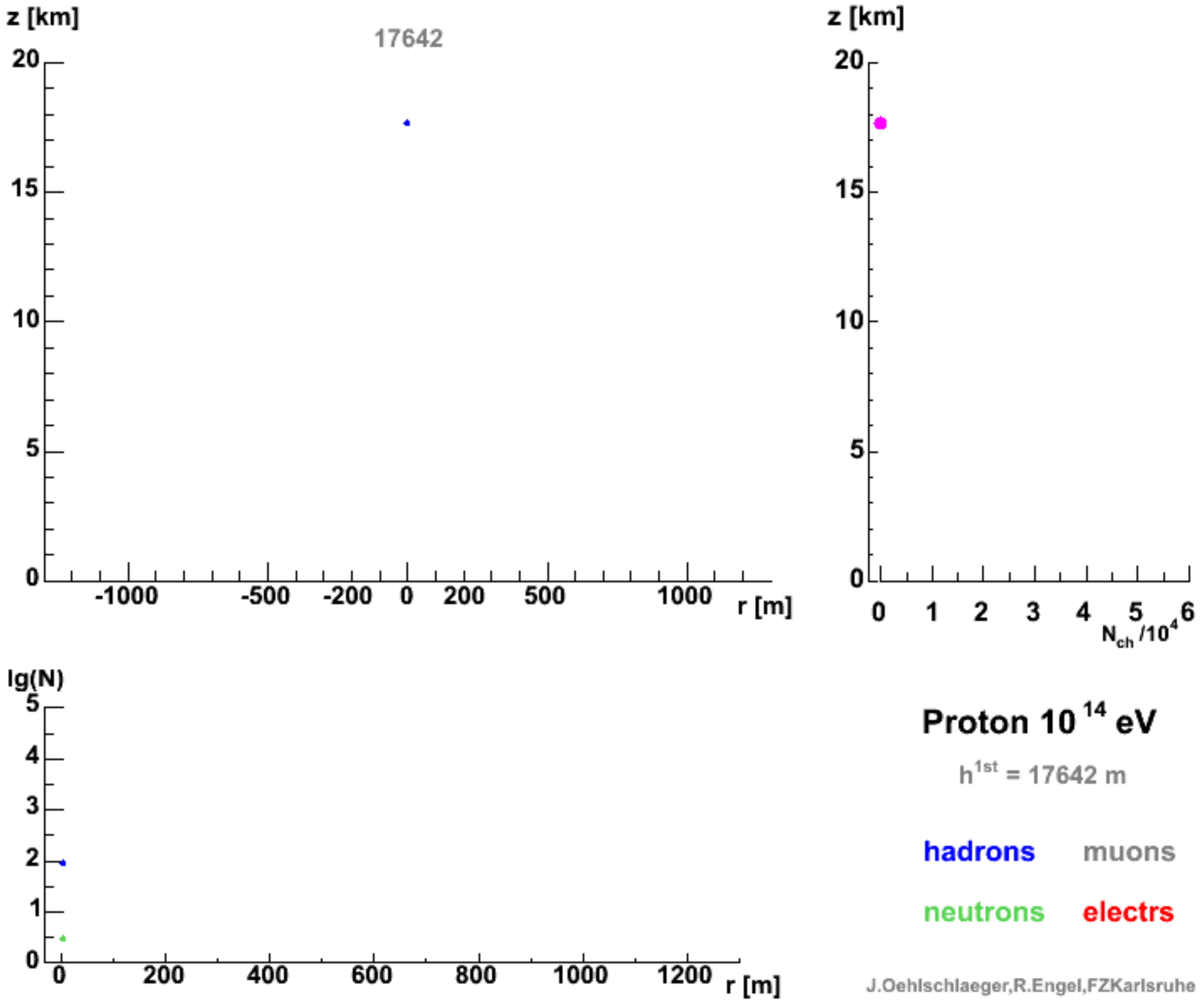


Simulation of shower development (i)

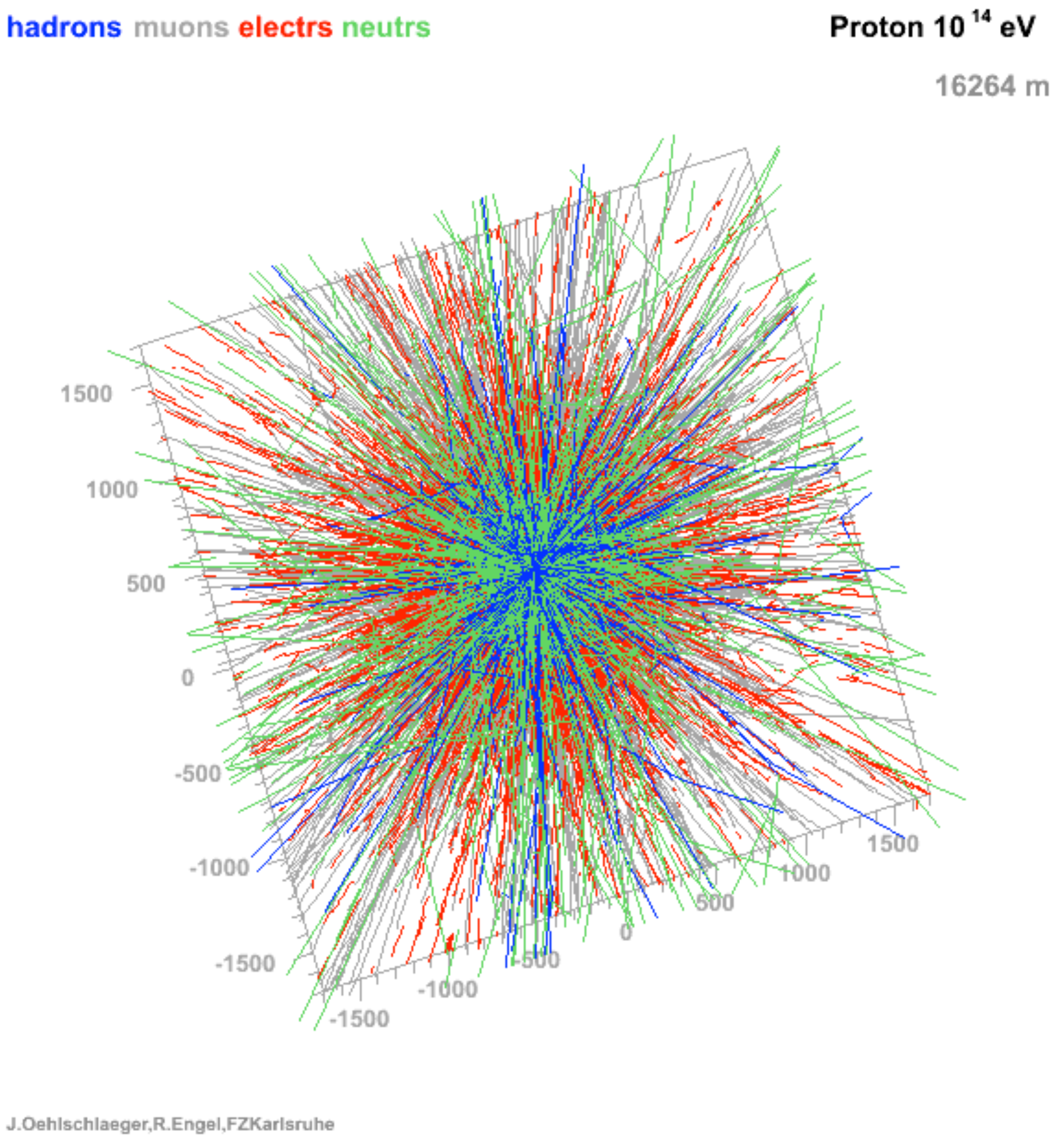
Realistic simulation with CORSIKA

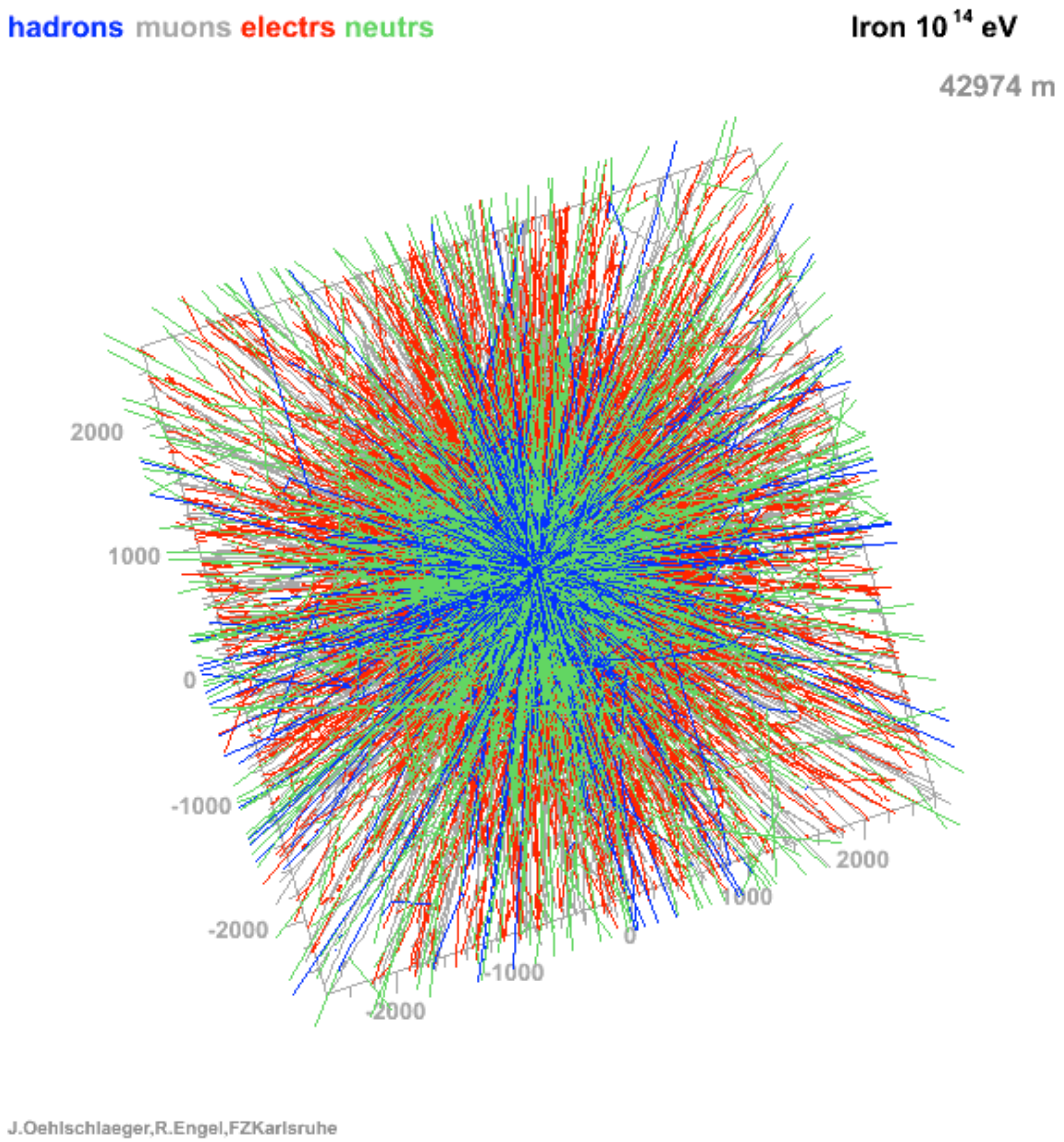
Proton shower of low energy (knee region)

Simulation of shower development (ii)

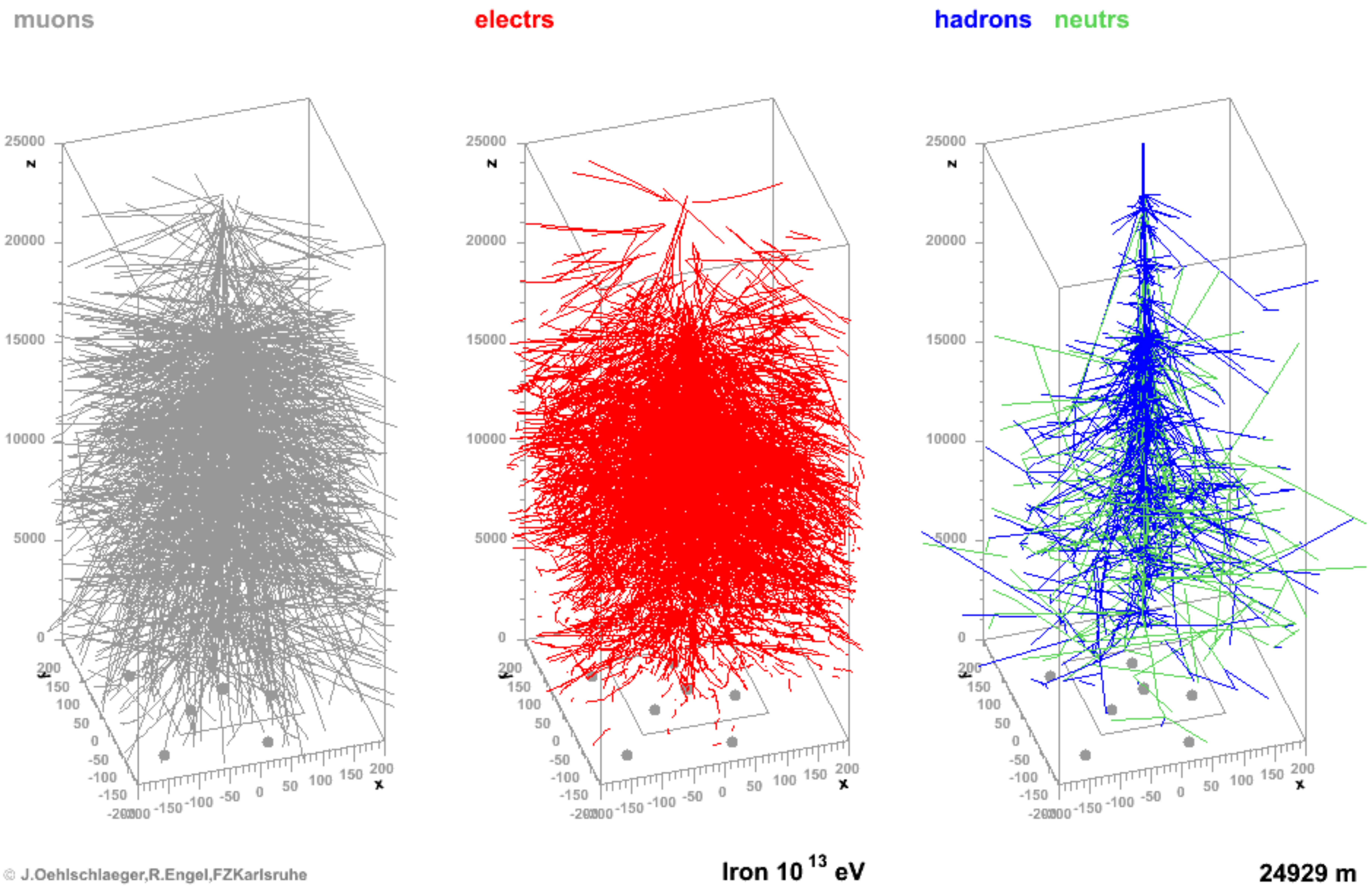


Simulation of air shower tracks (i)

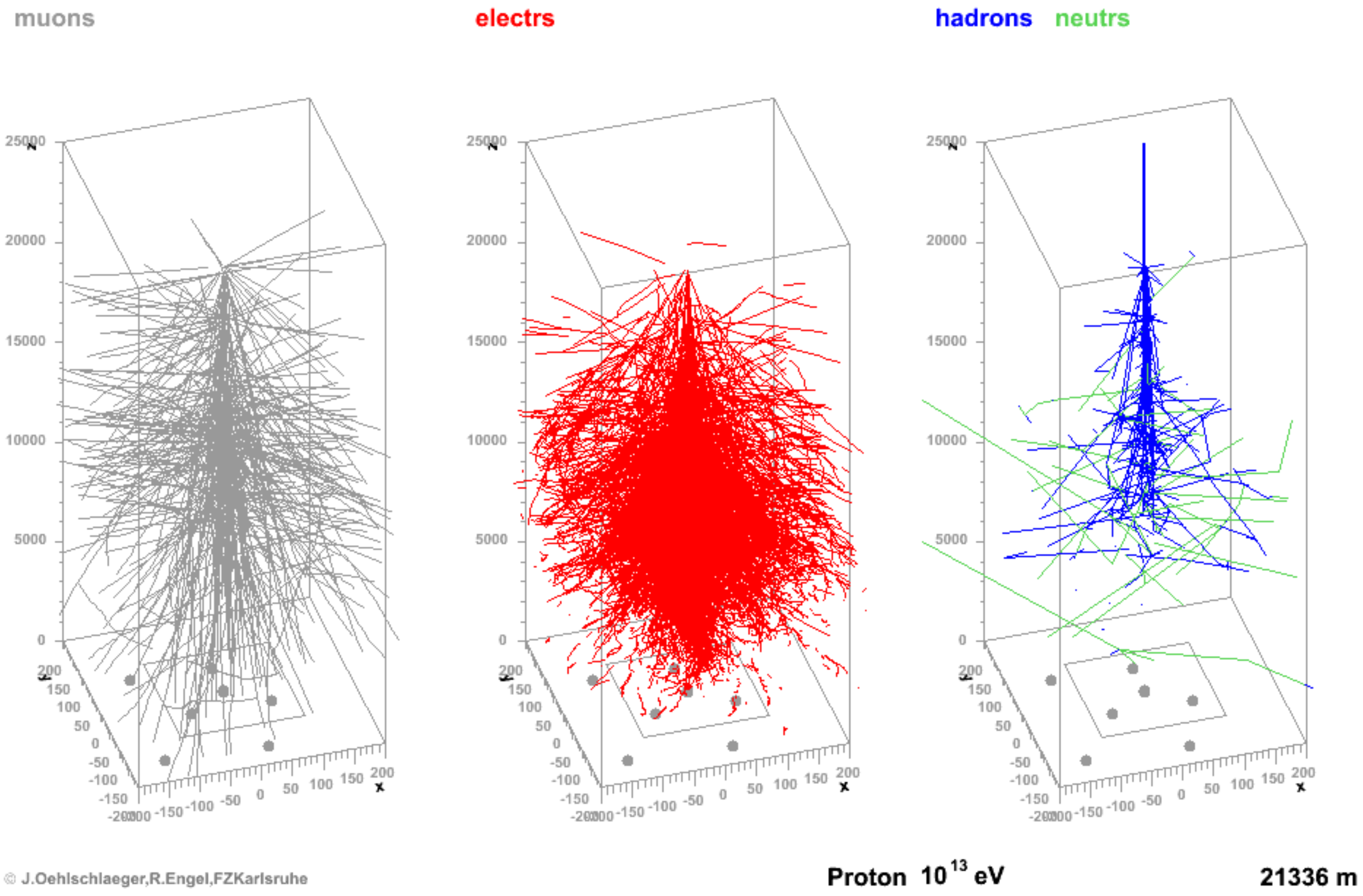




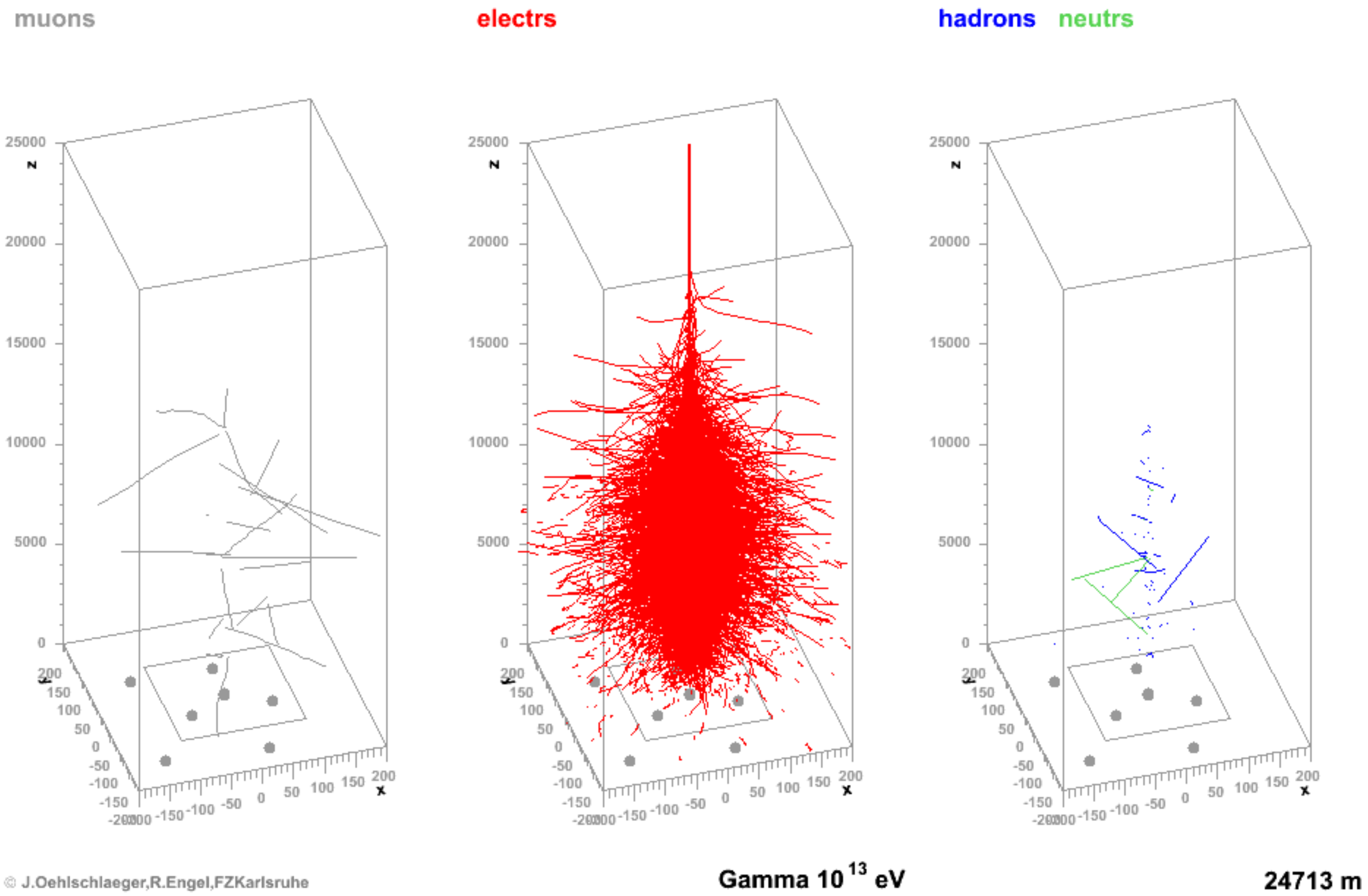
Particles of an iron shower



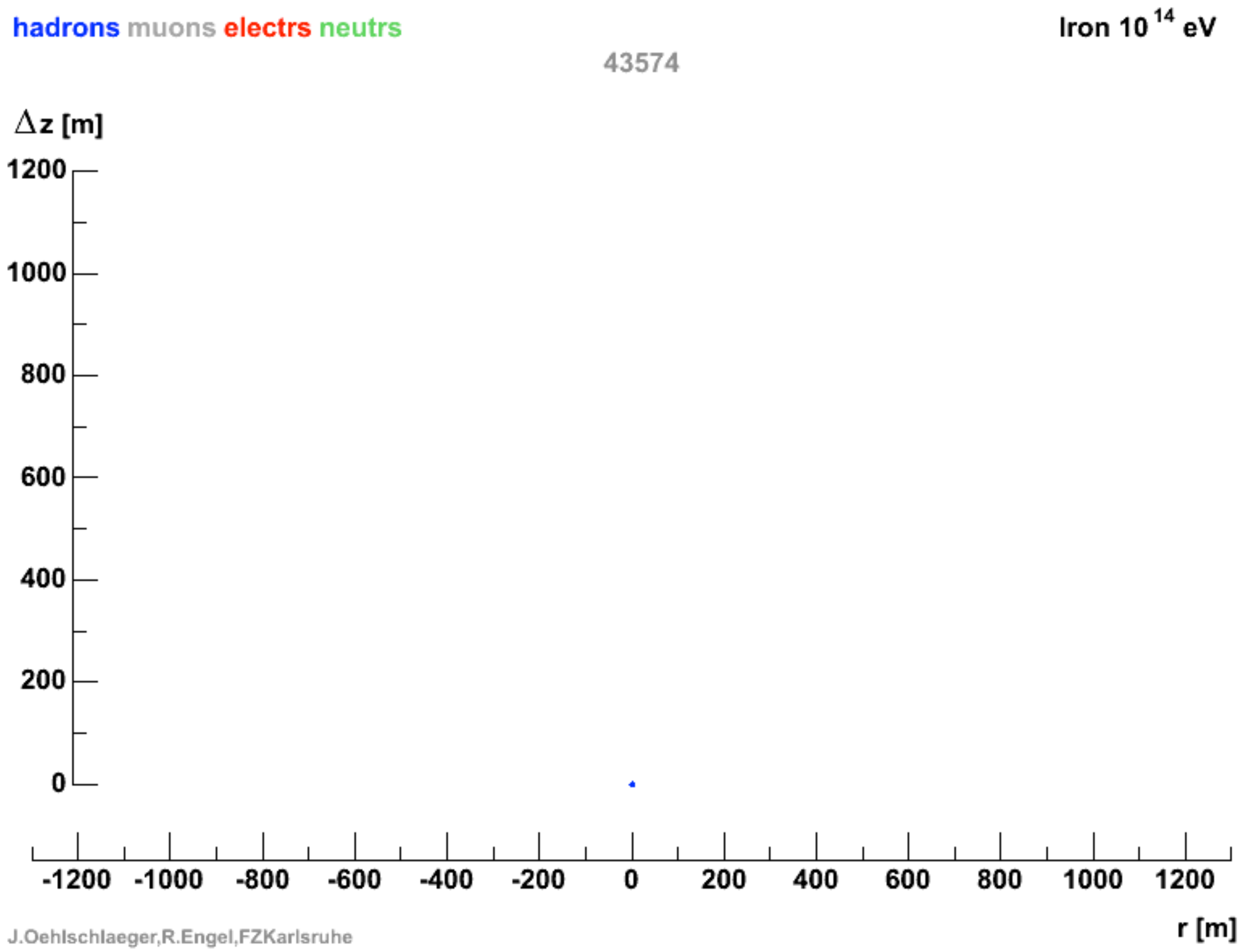
Particles of an proton shower



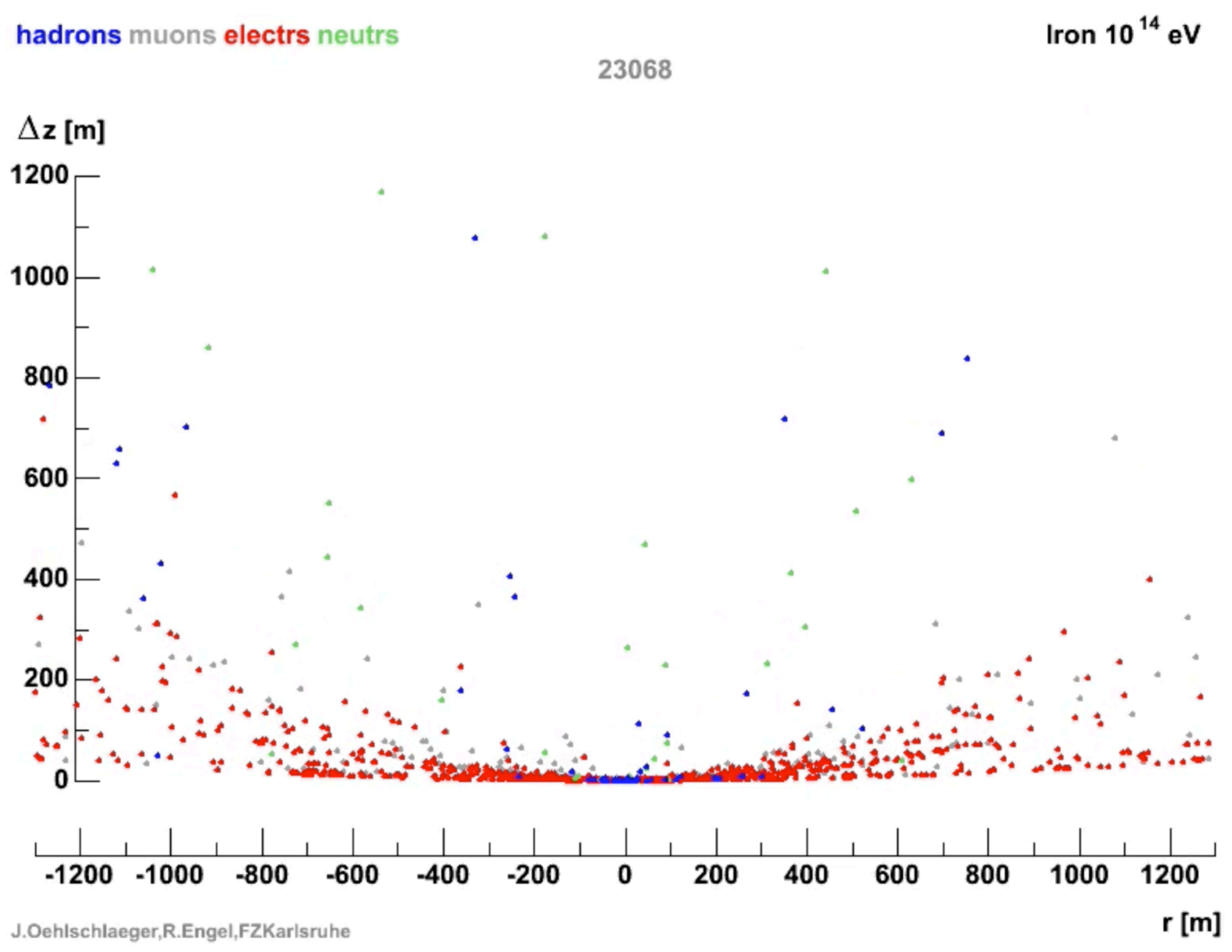
Particles of a gamma-ray shower

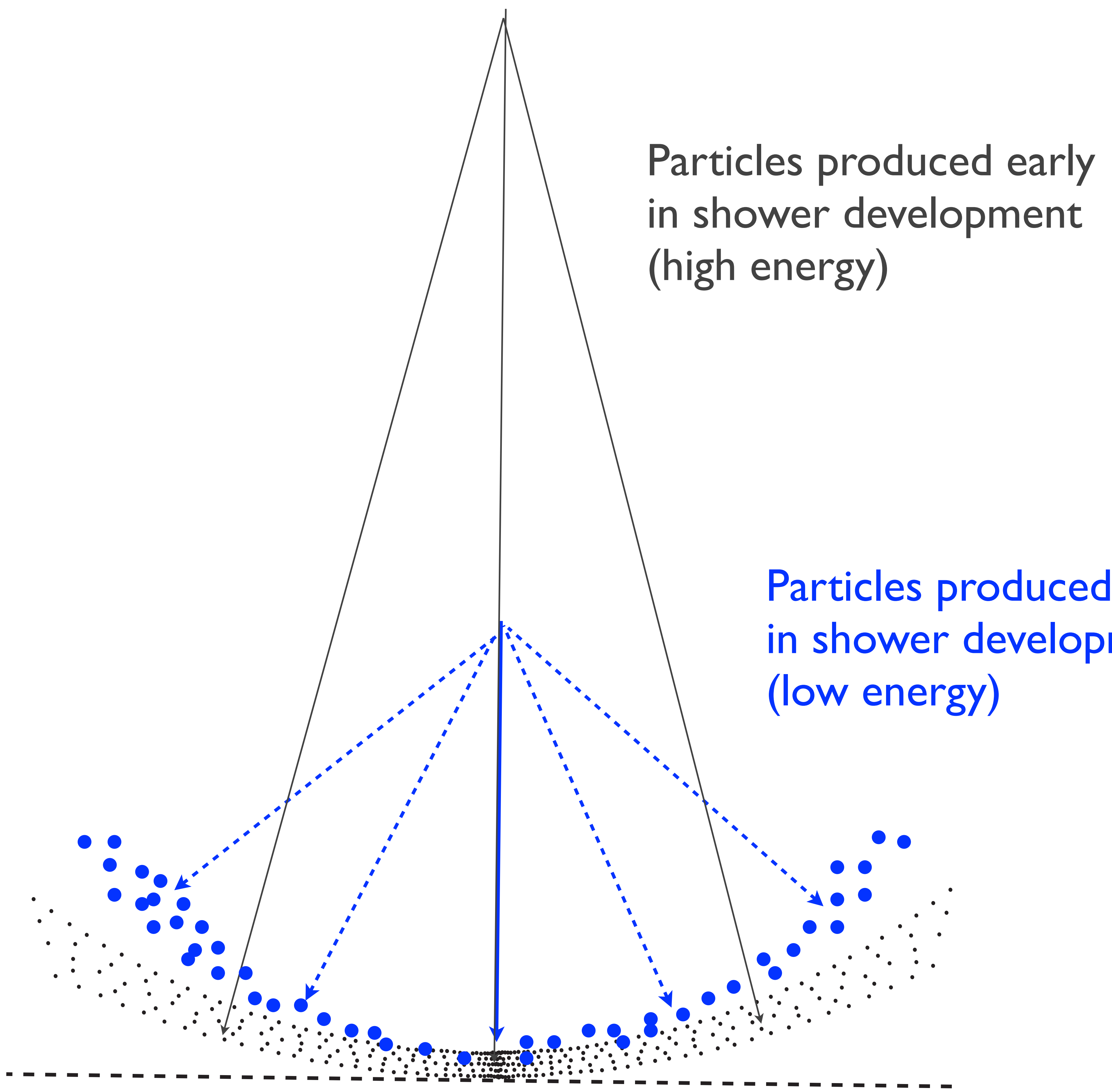


Time structure of shower disk



Time structure of shower disk



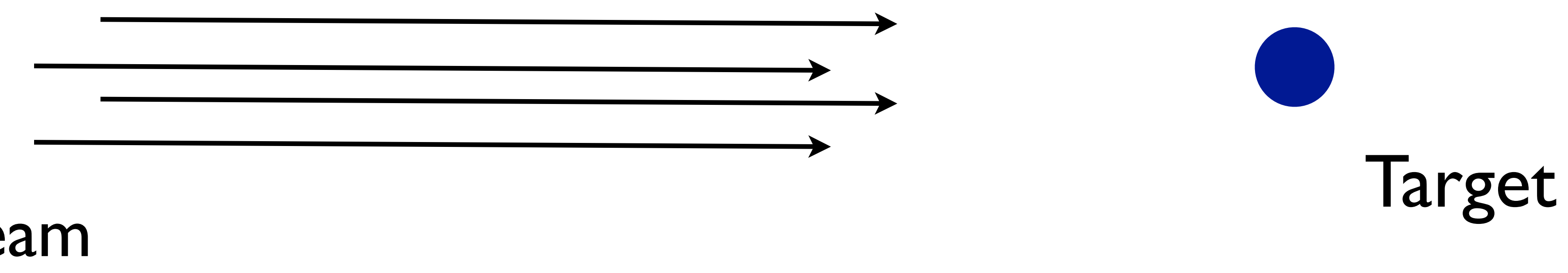


Curvature of shower front
sensitive to early muons

1. Basics

Cross section, interaction rate, interaction length

$$\Phi = \frac{dN_{\text{beam}}}{dA\,dt}$$



Definition

$$\sigma = \frac{1}{\Phi}\frac{\mathrm{d}N_{\text{int}}}{\mathrm{d}t}$$

(Units: 1 barn = 10^{-28} m^2
1 mb = 10^{-27} cm^2)

Flux of particles on single target

Interaction rate

Interaction length

$$\lambda_{\text{int}} = \frac{\langle m_{\text{target}} \rangle}{\sigma}$$

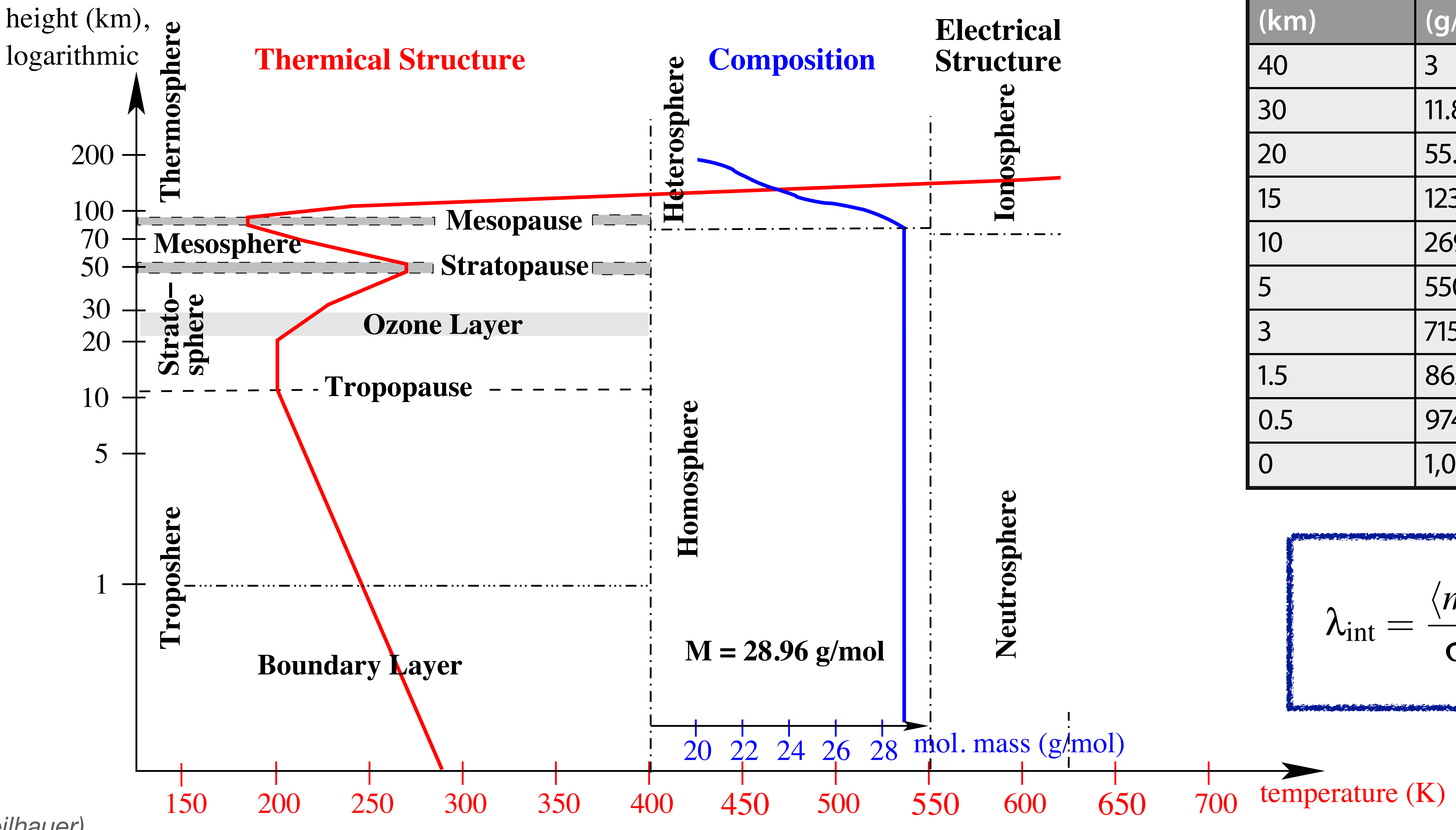
$$\frac{\mathrm{d}N_{\text{int}}}{\mathrm{d}t\,\mathrm{d}V} = \frac{\rho_{\text{target}}}{\langle m_{\text{target}} \rangle}\,\sigma\,\Phi$$

$$dX = \rho_{\text{target}}\,dl$$

$$\frac{dN_{\text{int}}}{dt\,dV} = \frac{dN_{\text{int}}}{dl\,dt\,dA} = -\rho_{\text{target}}\frac{d\Phi}{dX}$$

$$\frac{\mathrm{d}\Phi}{\mathrm{d}X} = -\frac{\sigma}{\langle m_{\text{target}} \rangle}\Phi = -\frac{1}{\lambda_{\text{int}}}\Phi$$

Molecular atmosphere of Earth



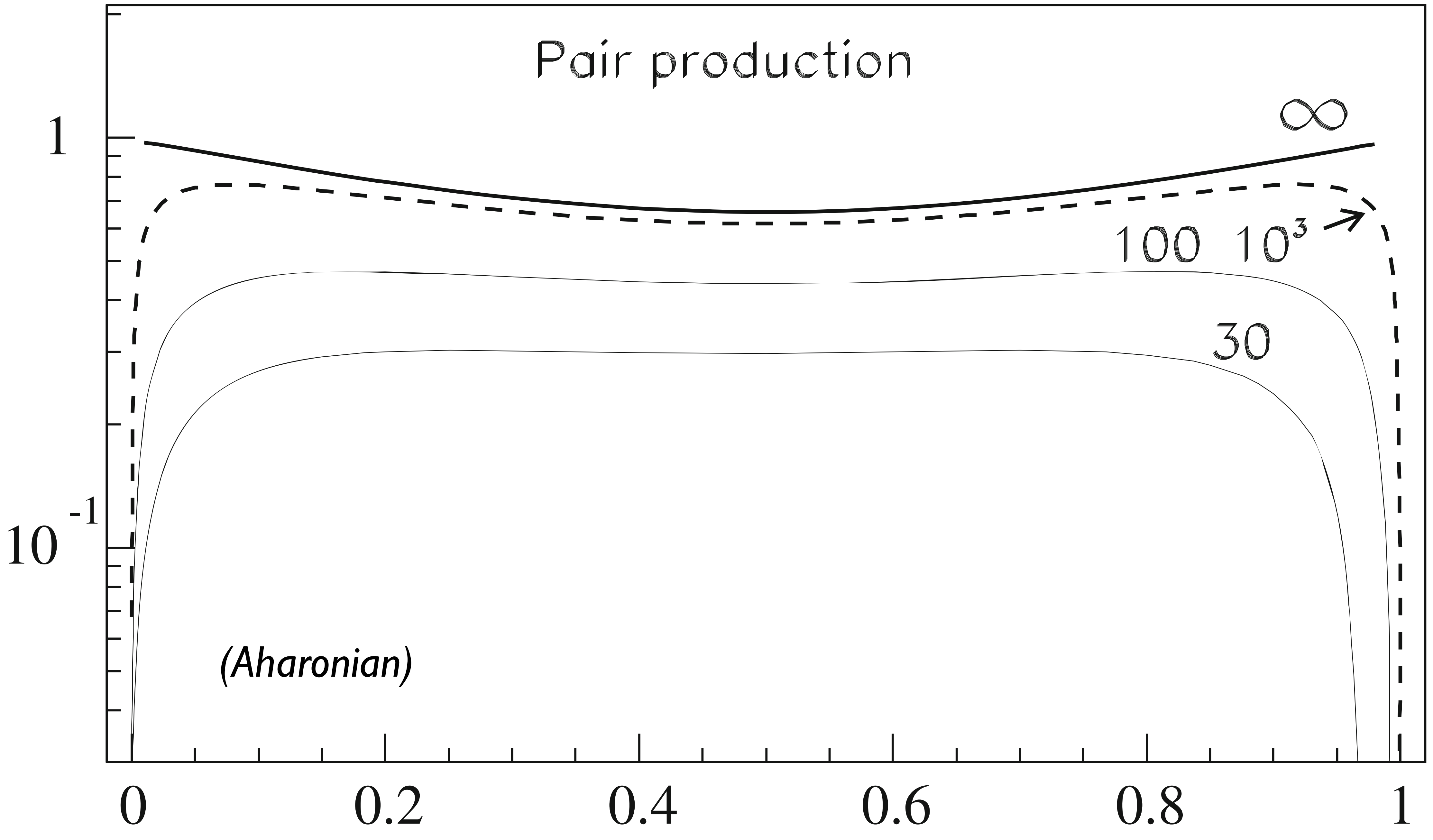
Altitude (km)	Vertical depth (g/cm²)	Local density (10^{-3} g/cm³)
40	3	3.8×10^{-3}
30	11.8	1.8×10^{-2}
20	55.8	8.8×10^{-2}
15	123	0.19
10	269	0.42
5	550	0.74
3	715	0.91
1.5	862	1.06
0.5	974	1.17
0	1,032	1.23

$$\lambda_{\text{int}} = \frac{\langle m_{\text{air}} \rangle}{\sigma_{\text{int}}} = \frac{24160\,\text{mb g/cm}^2}{\sigma_{\text{int}}}$$

(B. Keilhauer)

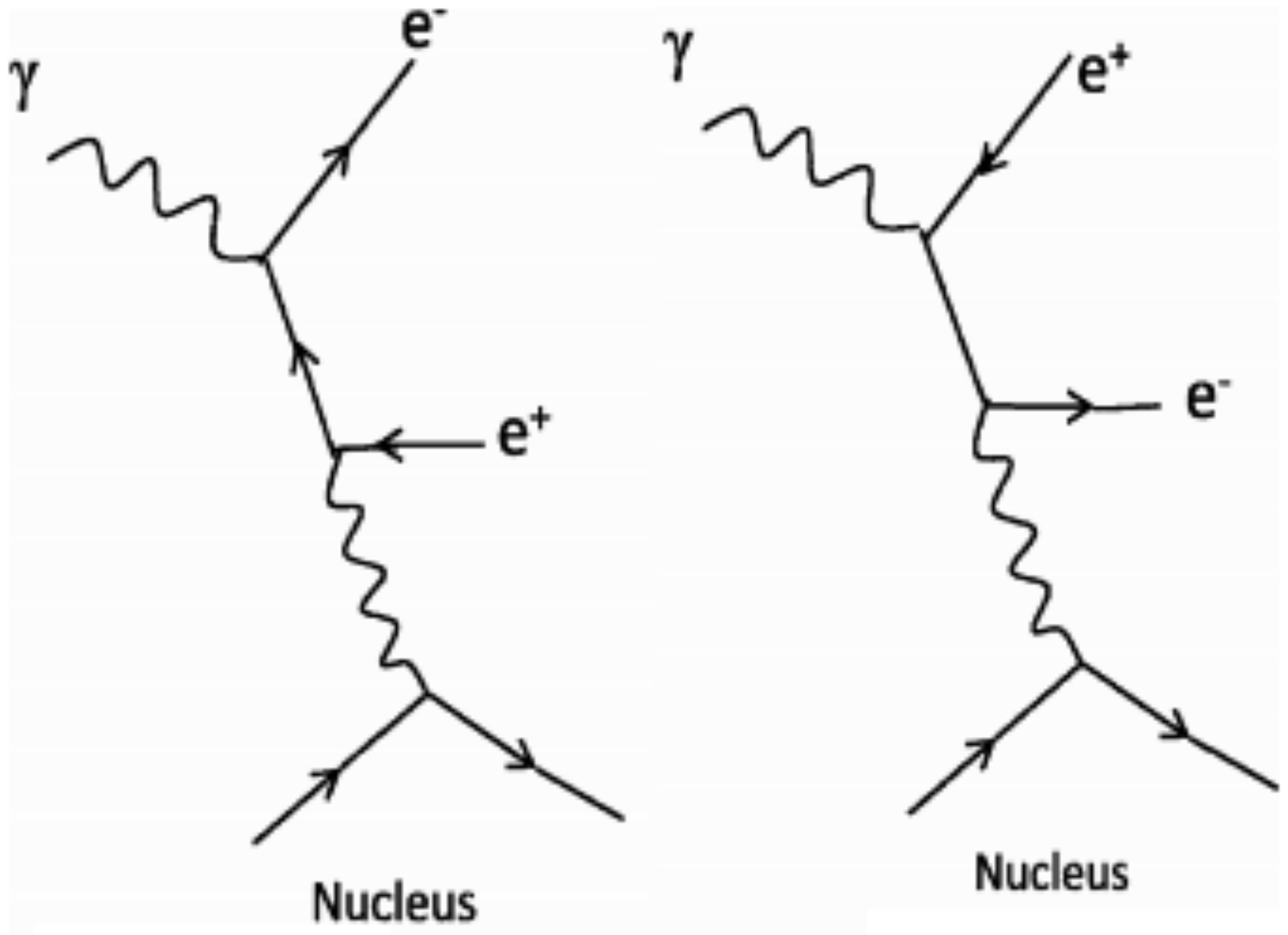
2. Electromagnetic Showers

Bethe-Heitler pair production (i)



E_γ/m_e

$u = E_e/E_\gamma$



QED

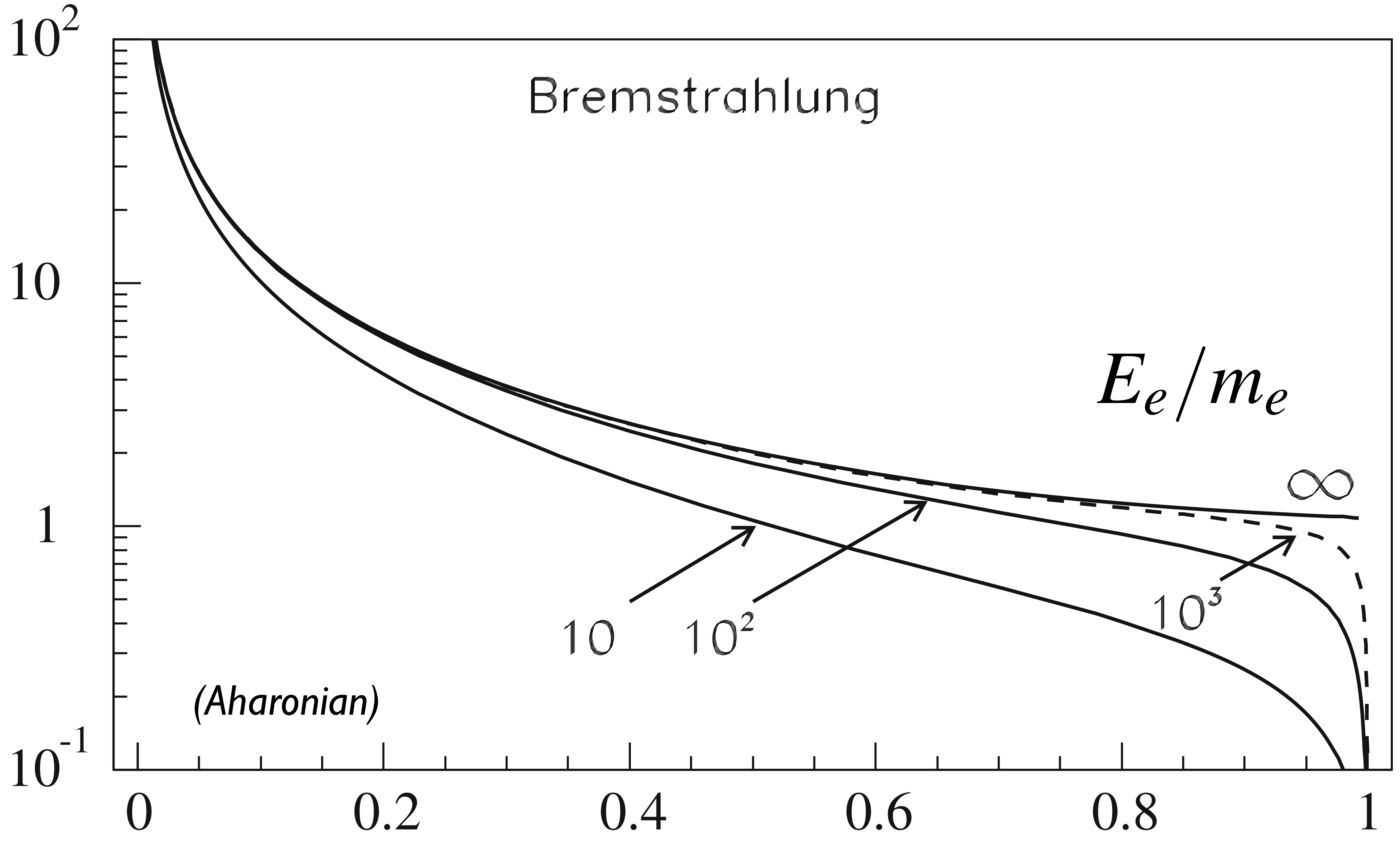
$$\frac{d\sigma_{pair}}{du} = 4\alpha_{em} r_e^2 Z(Z+1)\left\{\left[u^2+(1-u)^2+\frac{2}{3}u(1-u)\right]\ln(183Z^{-1/3})-\frac{1}{9}u(1-u)\right\}$$

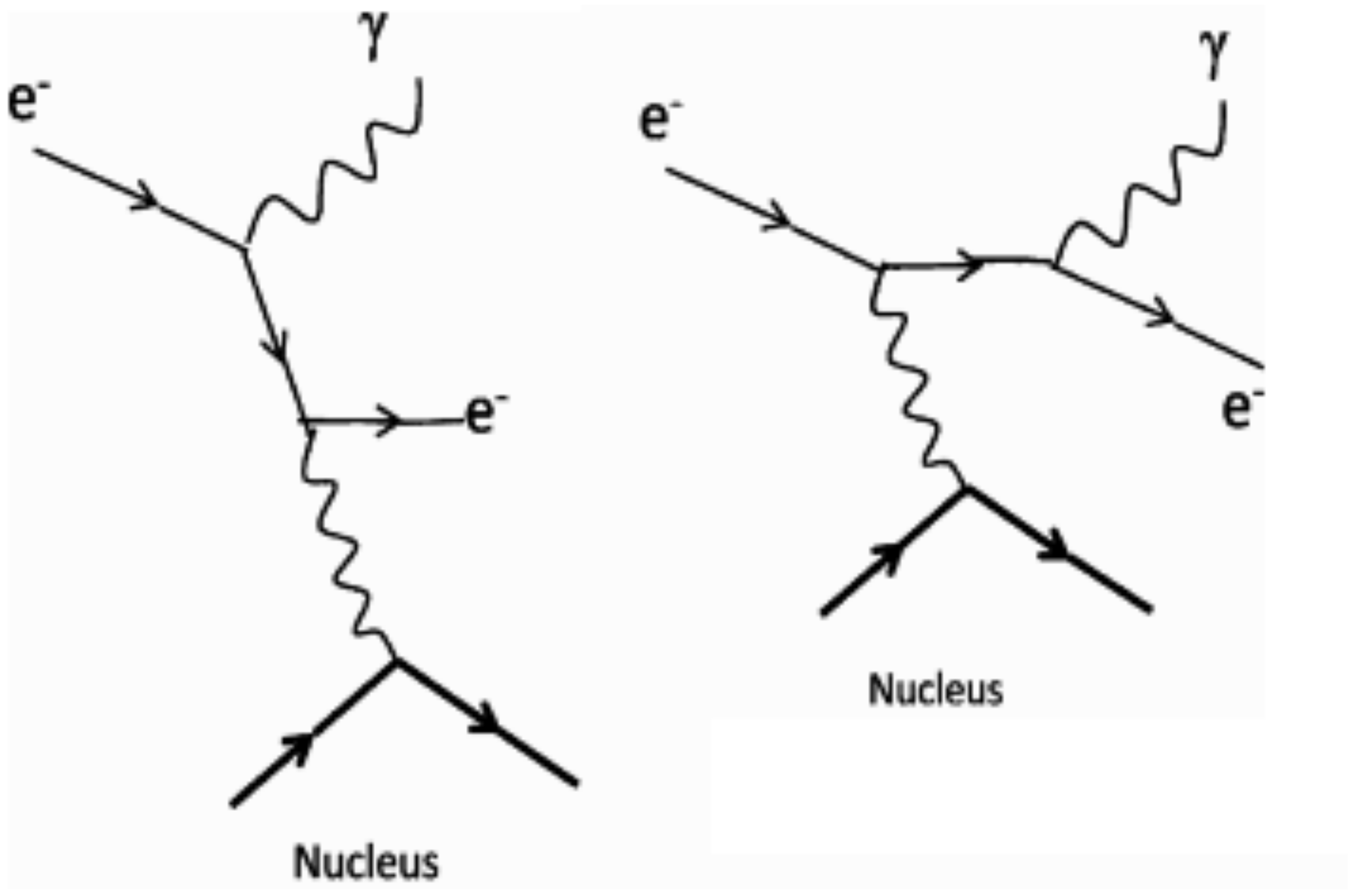
$$\sigma_{pair,tot} = \int \frac{d\sigma_{pair}}{du}\,du = 4\alpha_{em} r_e^2 Z(Z+1)\left[\frac{7}{9}\ln(183Z^{-1/3})-\frac{1}{54}\right]$$

High-energy limit

$$\sigma_{pair,tot} \sim 520\,\text{mb}$$

Electron bremsstrahlung





$$\nu = E_\gamma / E_e$$

QED

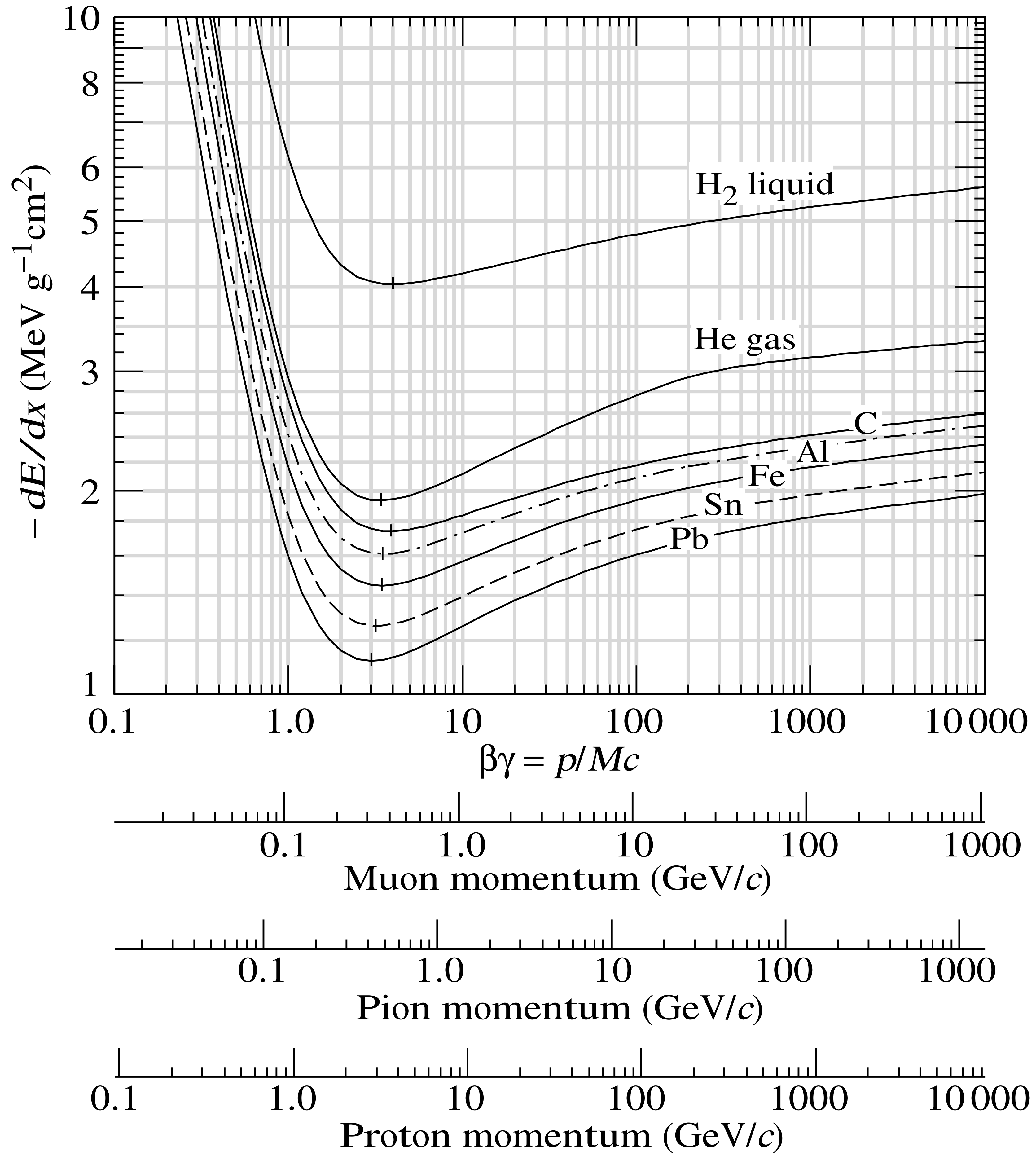
$$\frac{d\sigma_{\rm brem}}{dv} = 4\alpha_{\rm em} r_e^2 Z(Z+1)\frac{1}{v}\left\{\left[1+(1-v^2)-\frac{2}{3}(1-v)\right]\ln(183Z^{-1/3})+\frac{1}{9}(1-v)\right\}$$

$$\sigma_{\rm brem,tot} = \int \frac{d\sigma_{\rm brem}}{dv}\,dv \;\rightarrow\; \infty$$

Cross section divergent (infrared catastrophe)

Ionization energy loss of charged particles

Ionization energy loss: Bethe-Bloch formula



$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	$1/137.035\,999\,11(46)$
M	Incident particle mass	MeV$/c^2$
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times\ c^2$	$0.510\,998\,918(44)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	$2.817\,940\,325(28)$ fm
N_A	Avogadro's number	$6.022\,1415(10) \times 10^{23}$ mol^{-1}
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	g mol^{-1}
K/A	$4\pi N_A r_e^2 m_ec^2/A$	$0.307\,075$ MeV g^{-1} cm^2 for A = 1 g mol^{-1}
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	

Total energy loss of charged particles

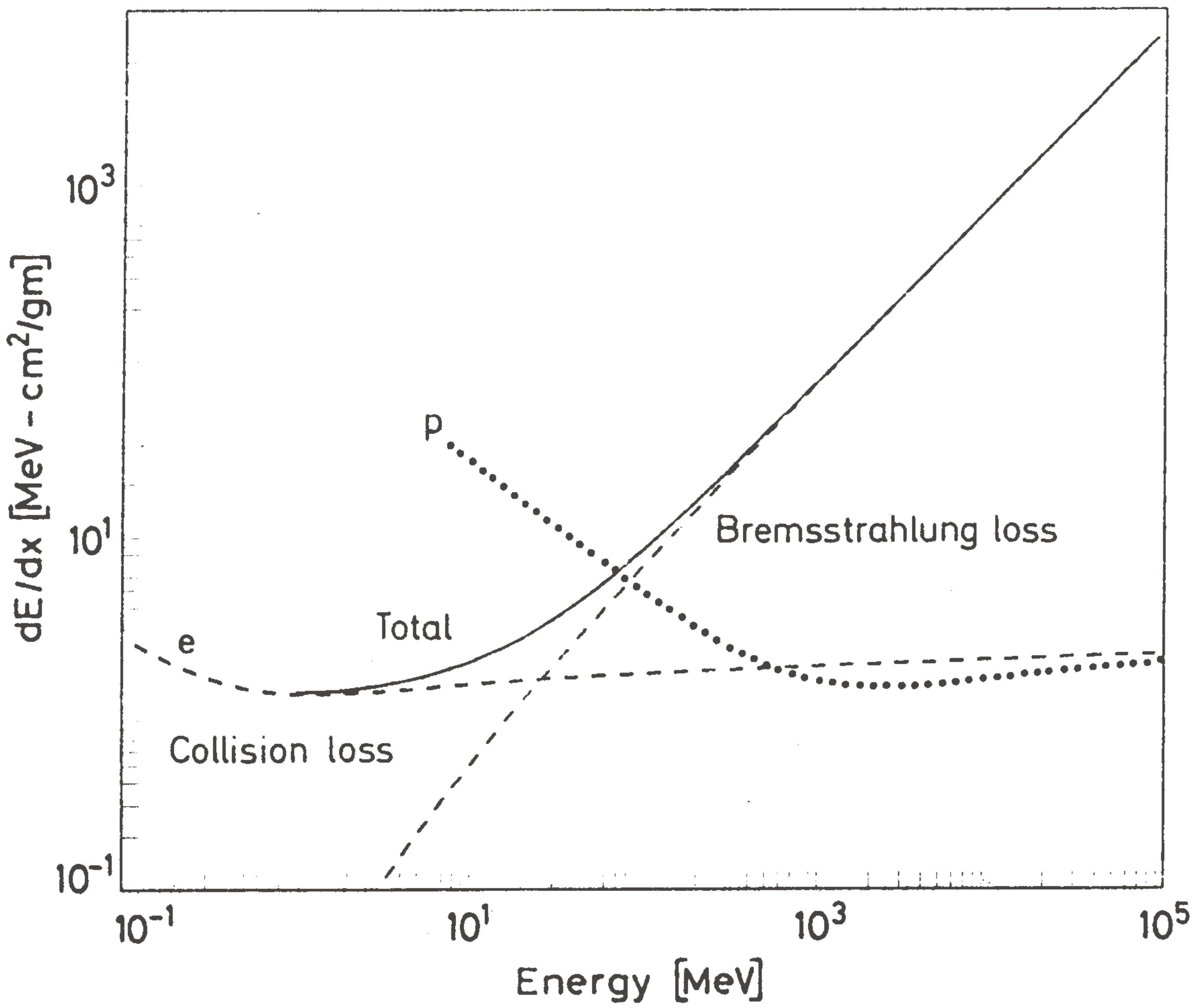
Ionization energy loss: Bethe-Bloch formula

Radiation energy loss: bremsstrahlung

$$\int v \frac{\mathrm{d}\sigma_{\mathrm{brem}}}{\mathrm{d}v}\,\mathrm{d}v = 4\alpha_{\mathrm{em}} r_e^2 Z(Z+1)\left[\ln(183Z^{-1/3}) + \frac{1}{18}\right] = \frac{\langle m_{\mathrm{target}}\rangle}{X_0}$$

Radiation length X_0

$$X_0 \sim 36\,\mathrm{g/cm^2}$$

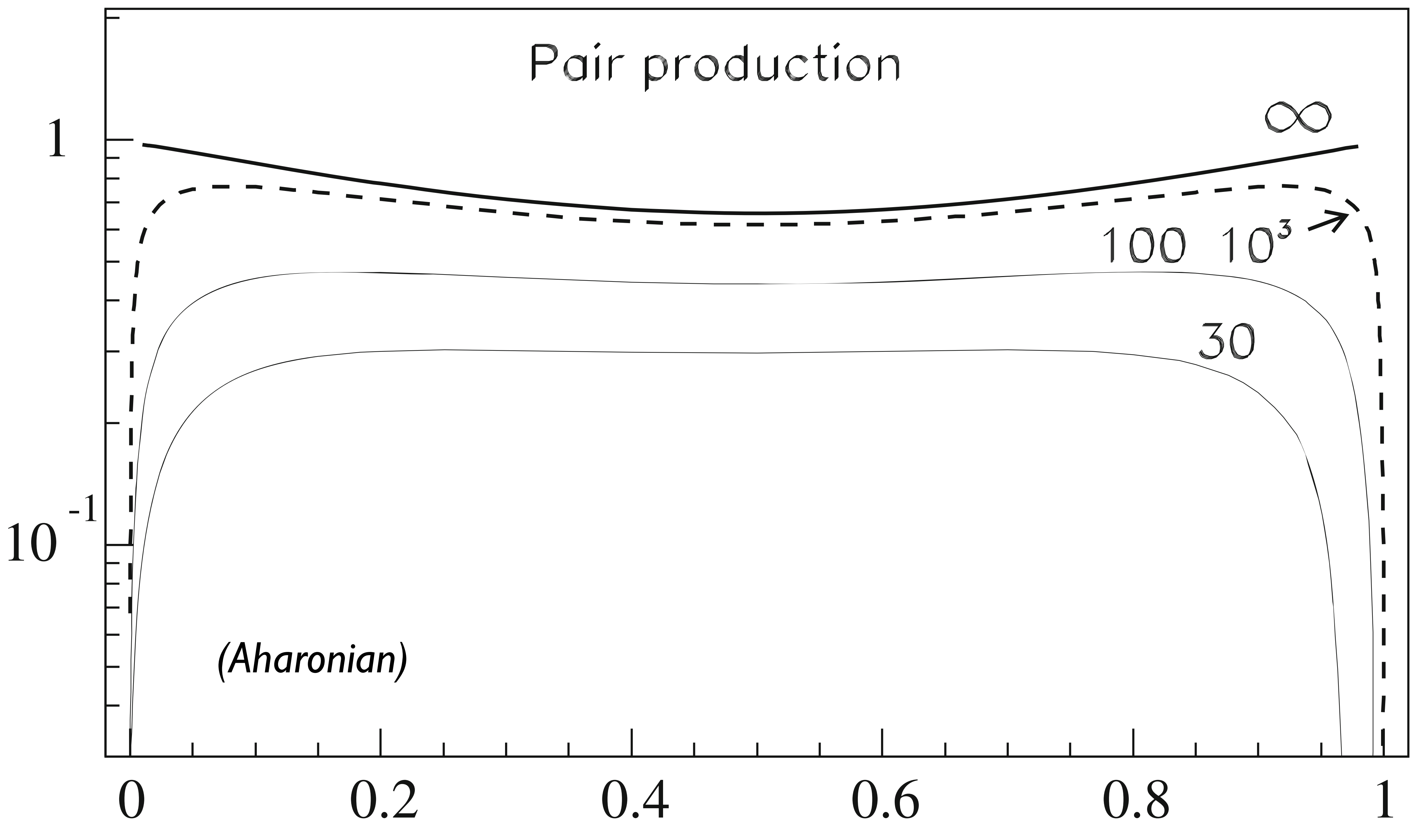


$$\frac{\mathrm{d}E}{\mathrm{d}X} = -\alpha(E) - \frac{E}{X_0}$$

Critical energy E_c defined as energy at which both losses are equal

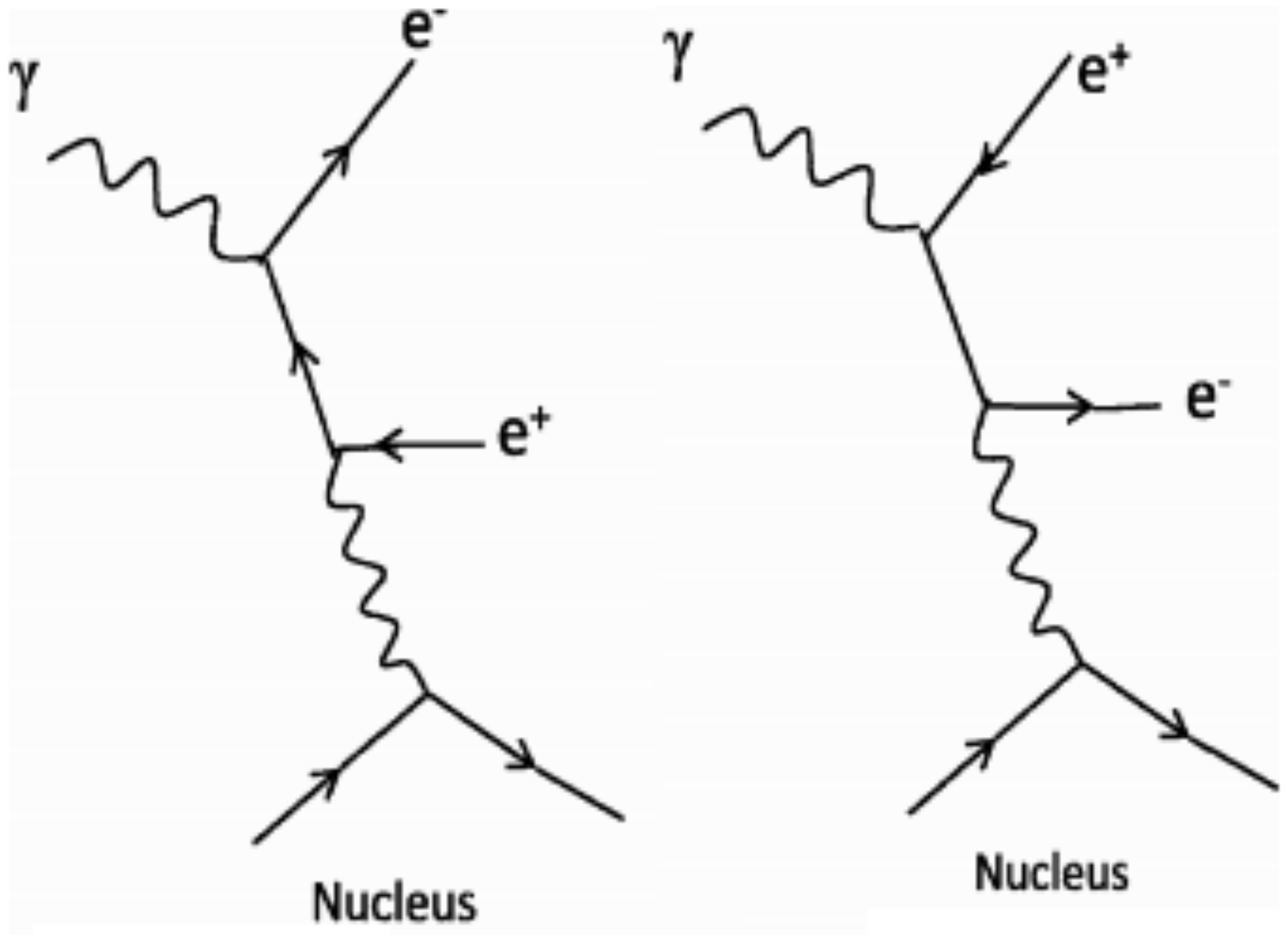
$$E_c = \alpha\, X_0 \sim 85\,\mathrm{MeV}$$

Bethe-Heitler pair production (ii)



E_γ/m_e

$u = E_e/E_\gamma$



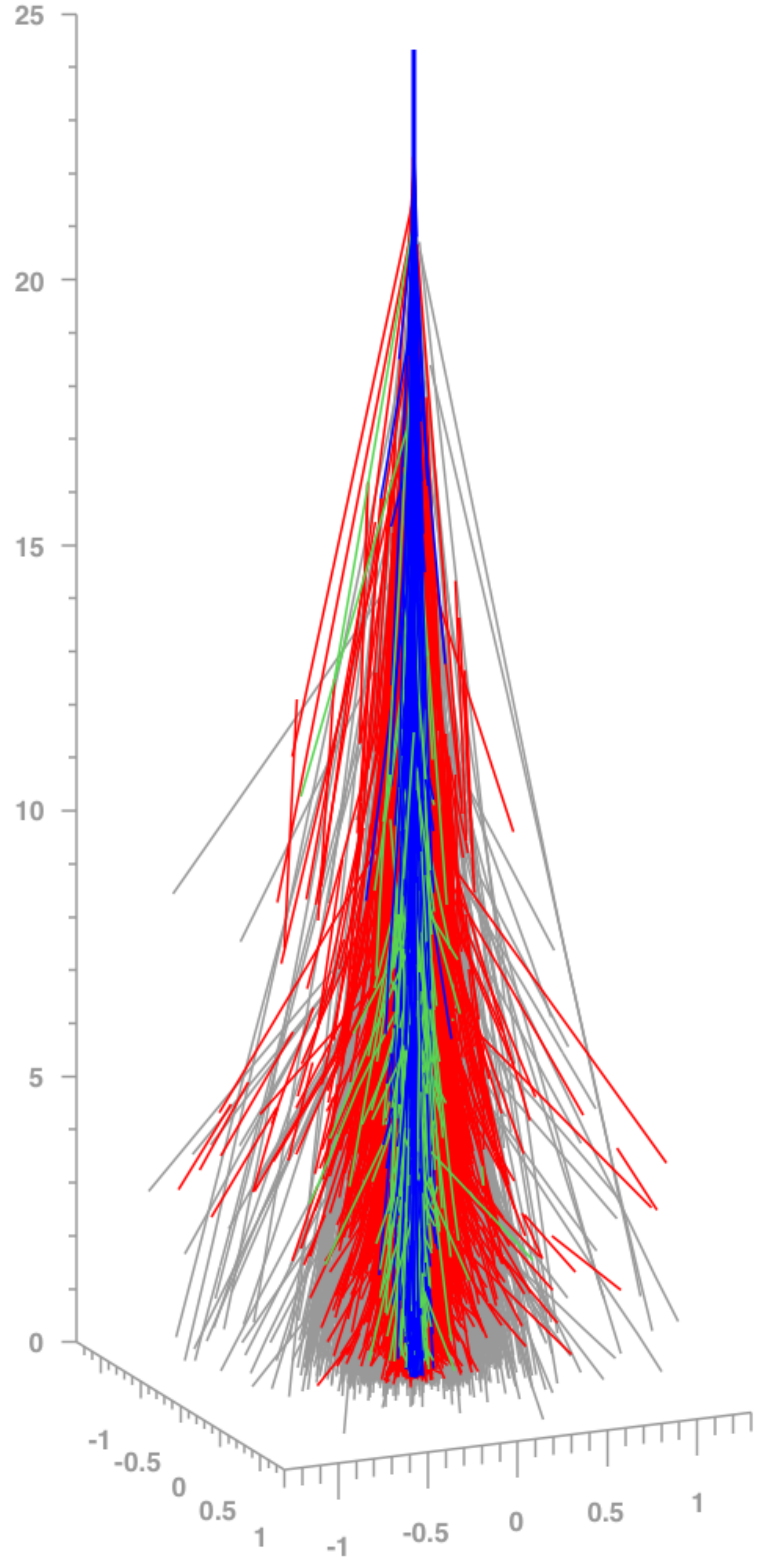
QED

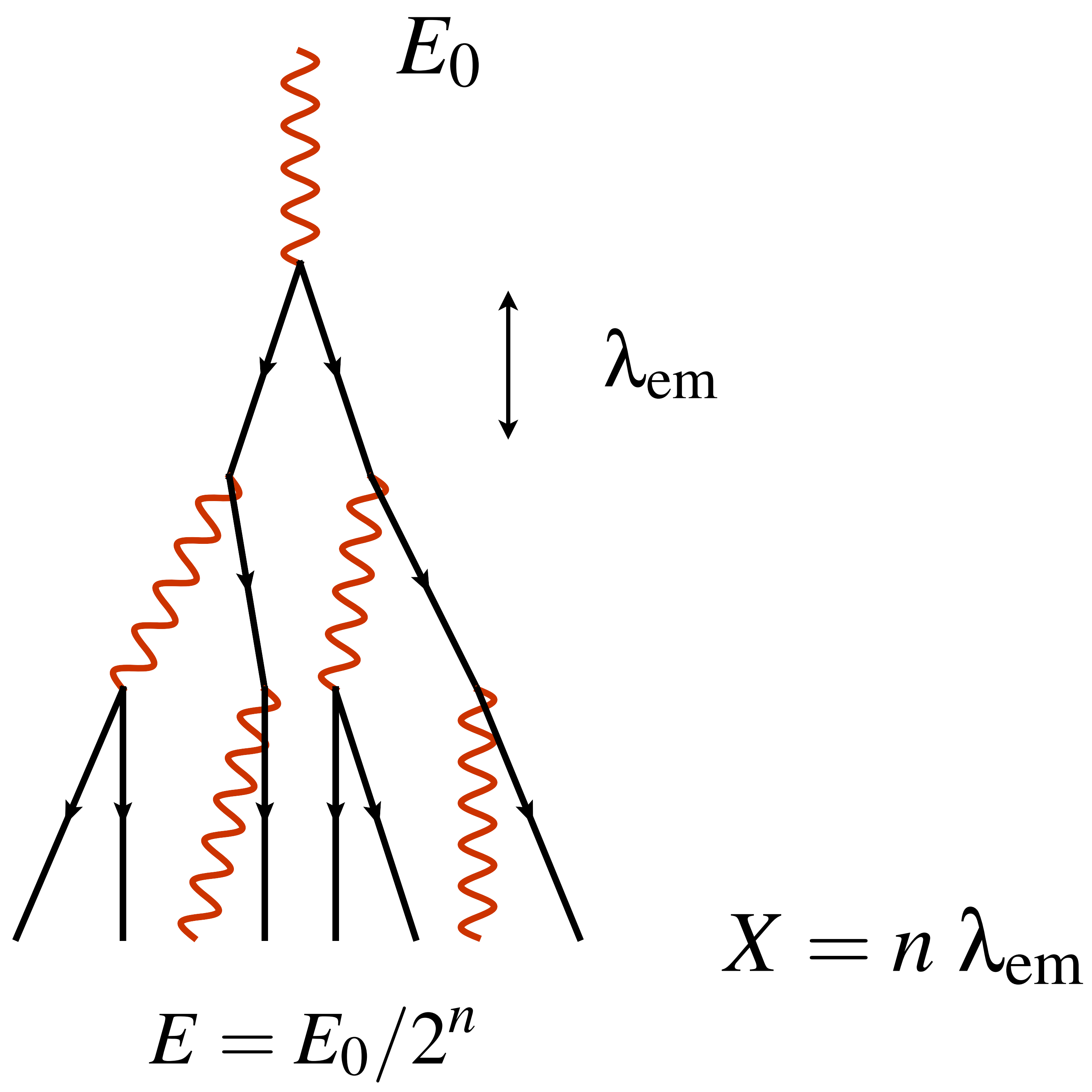
High-energy limit

$$\sigma_{\text{pair,tot}} \sim 520\,\text{mb}$$

$$\lambda_{\text{pair}} = \frac{\langle m_{\text{air}} \rangle}{\sigma_{\text{pair,tot}}} = \frac{9}{7} X_0$$

Qualitative approach: Heitler model





Shower maximum: $E = E_c$

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

$$X_{\max} \sim \lambda_{\text{em}} \ln(E_0/E_c)$$

Cascade equations

Energy loss of electron:

$$\frac{\mathrm{d}E}{\mathrm{d}X} = -\alpha - \frac{E}{X_0}$$

Critical energy: $E_c = \alpha\, X_0 \sim 85\,\mathrm{MeV}$

Radiation length: $X_0 \sim 36\,\mathrm{g/cm^2}$

Cascade equations

$$\frac{\mathrm{d}\Phi_e(E)}{\mathrm{d}X} = -\frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(E) + \int_E^\infty \frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(\tilde{E})P_{e\to e}(\tilde{E},E)\mathrm{d}\tilde{E}$$

$$+ \int_E^\infty \frac{\sigma_\gamma}{\langle m_{\mathrm{air}}\rangle}\Phi_\gamma(\tilde{E})P_{\gamma\to e}(\tilde{E},E)\mathrm{d}\tilde{E} \;+\; \alpha\frac{\partial\Phi_e(E)}{\partial E}$$

$$X_{\mathrm{max}} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad N_{\mathrm{max}} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}}\frac{E_0}{E_c}$$

(Rossi & Greisen, Rev. Mod. Phys. 13 (1940) 240)

Shower age and Greisen formula

Longitudinal profile

$$N_e(X) \approx \frac{0.31}{[\ln E_0/E_c]^{1/2}} \exp\left\{ \frac{X}{X_0} \left(1 - \frac{3}{2}\ln s\right)\right\}$$

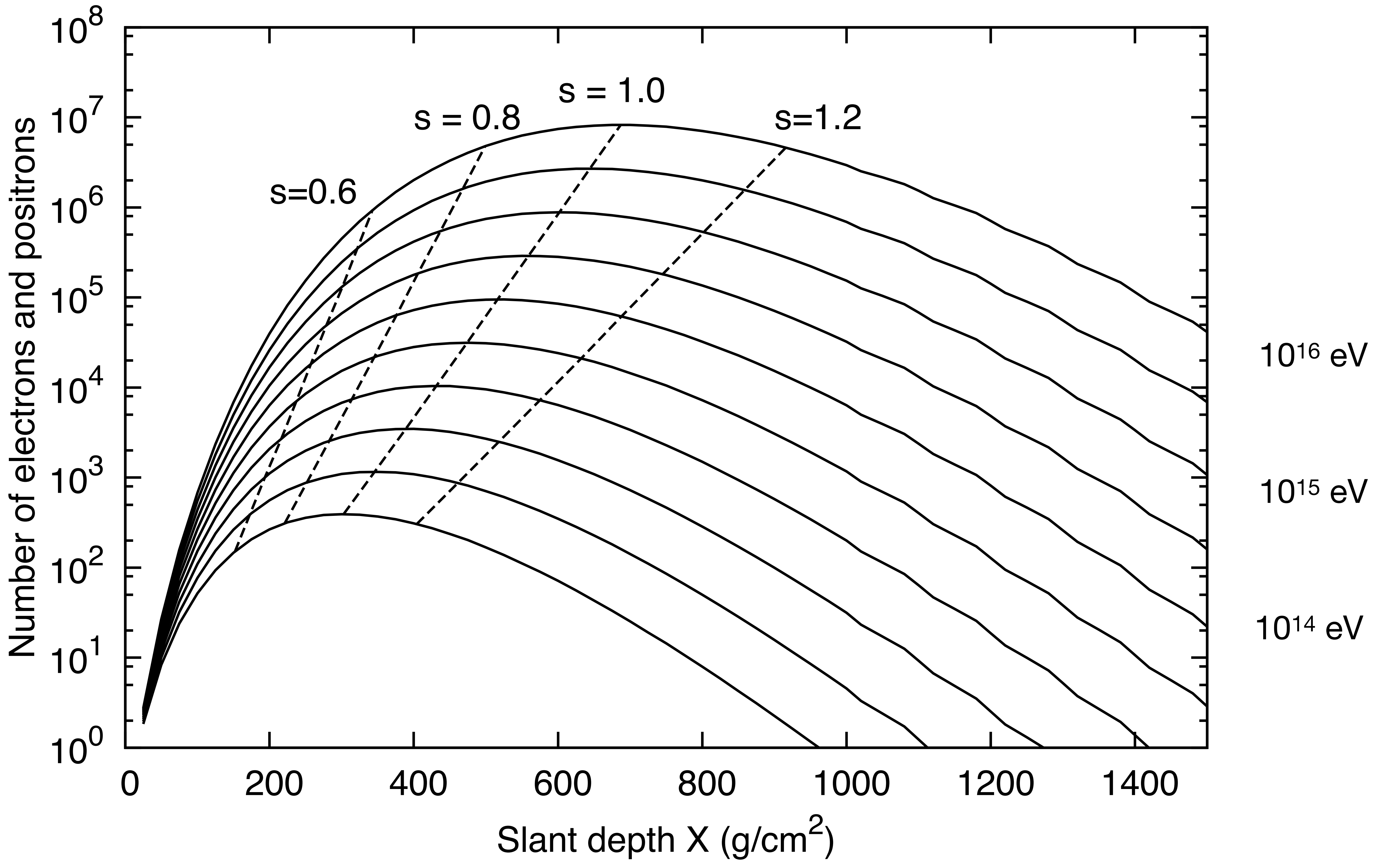
Shower age

$$s = \frac{3X}{X + 2X_{\max}}$$

Energy spectrum particles

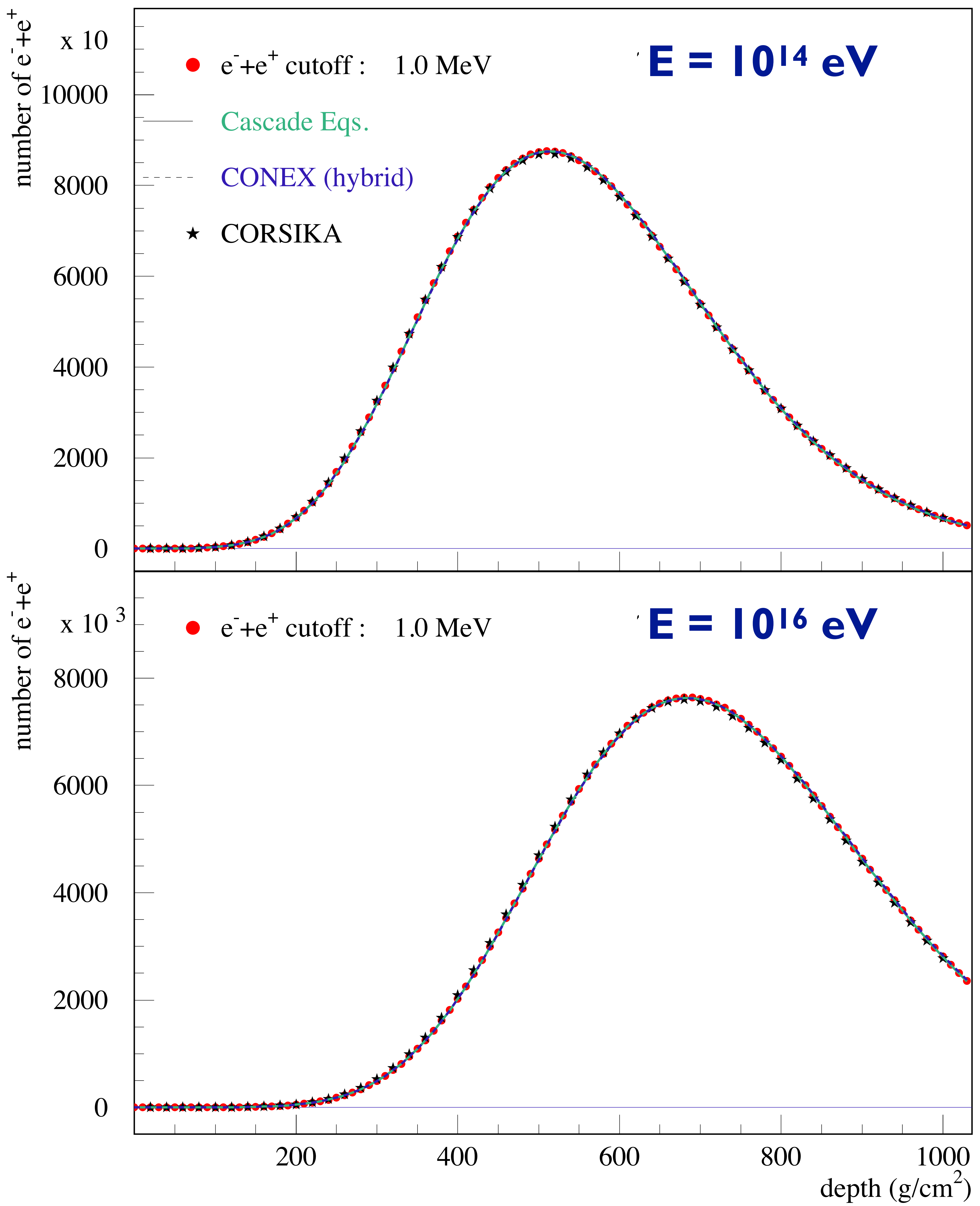
$$\frac{\mathrm{d}N_e}{\mathrm{d}E} \sim \frac{1}{E^{1+s}}$$

Electrons in photon-initiated shower



(Greisen 1956, see also Lipari PRD 2009)

Mean longitudinal shower profile



Calculation with cascade Eqs.

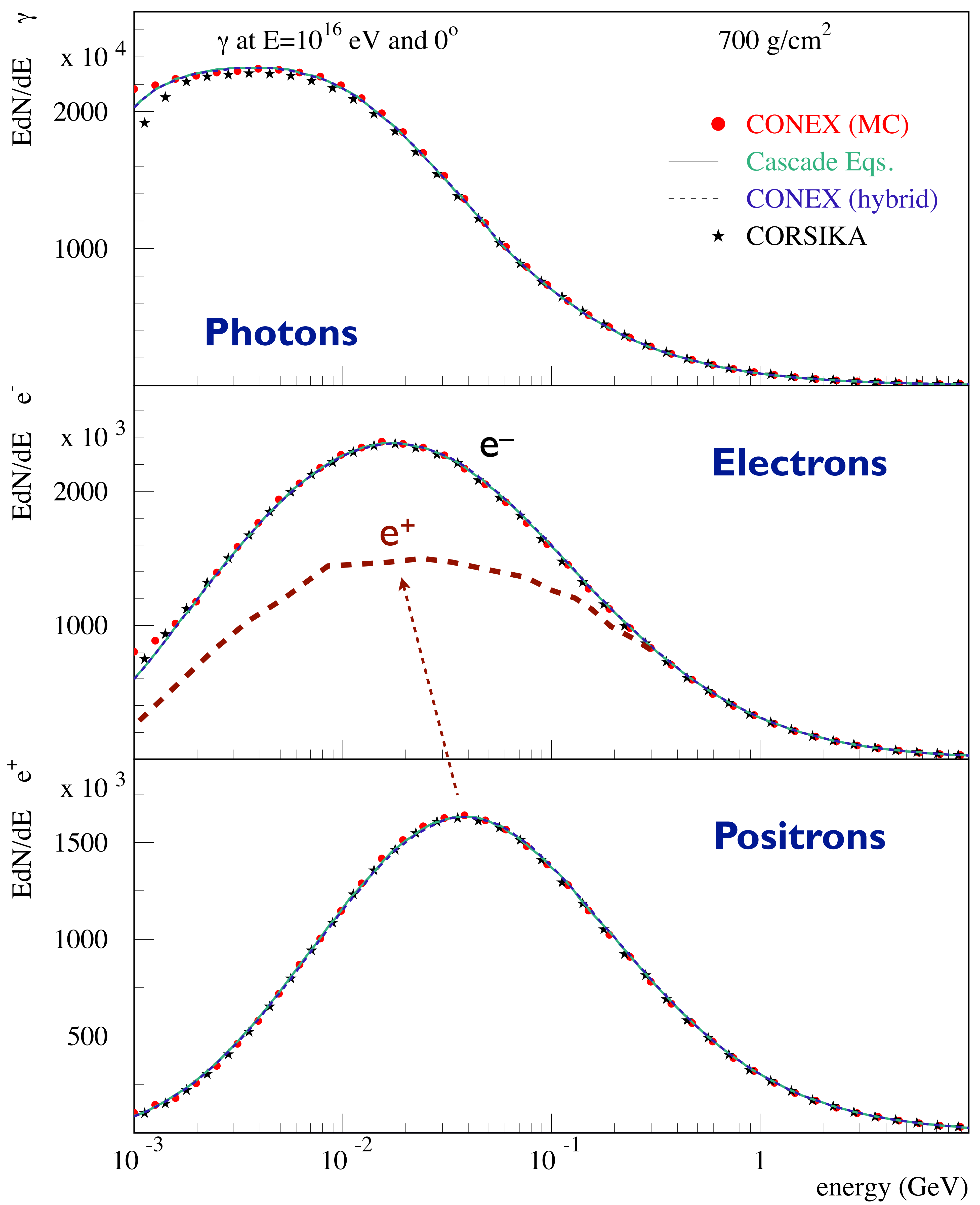
Photons
- Pair production
- Compton scattering

Electrons
- Bremsstrahlung
- Moller scattering

Positrons
- Bremsstrahlung
- Bhabha scattering

(Bergmann et al., Astropart.Phys. 26 (2007) 420)

Energy spectra of secondary particles



Number of photons divergent, energy threshold applied in calculation

- Typical energy of electrons and positrons $E_c \sim 80$ MeV
- Electron excess of 20 - 30%
- Pair production symmetric
- Excess of electrons in target

(Bergmann et al., Astropart.Phys. 26 (2007) 420)

Lateral distribution of shower particles

Coulomb scatting

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{1}{64\pi} \frac{1}{\ln(191 Z^{-1/3})} \left(\frac{E_s}{E}\right)^2 \frac{1}{\sin^4 \theta/2}$$

$$E_s \approx 21\,\mathrm{MeV}$$

Expectation value

$$\int \theta^2 \frac{\mathrm{d}N}{\mathrm{d}\Omega} \mathrm{d}\Omega$$

$$\langle \theta^2 \rangle \sim \left(\frac{E_s}{E}\right)^2$$

$$r_1 = r_M = \left(\frac{E_s}{E_c}\right) \frac{X_0}{\rho_{\mathrm{air}}}$$

Displacement of particle

$$r \sim \left(\frac{E_s}{E}\right) \frac{X_0}{\rho_{\mathrm{air}}}$$

Moliere unit
(78 m at sea level)

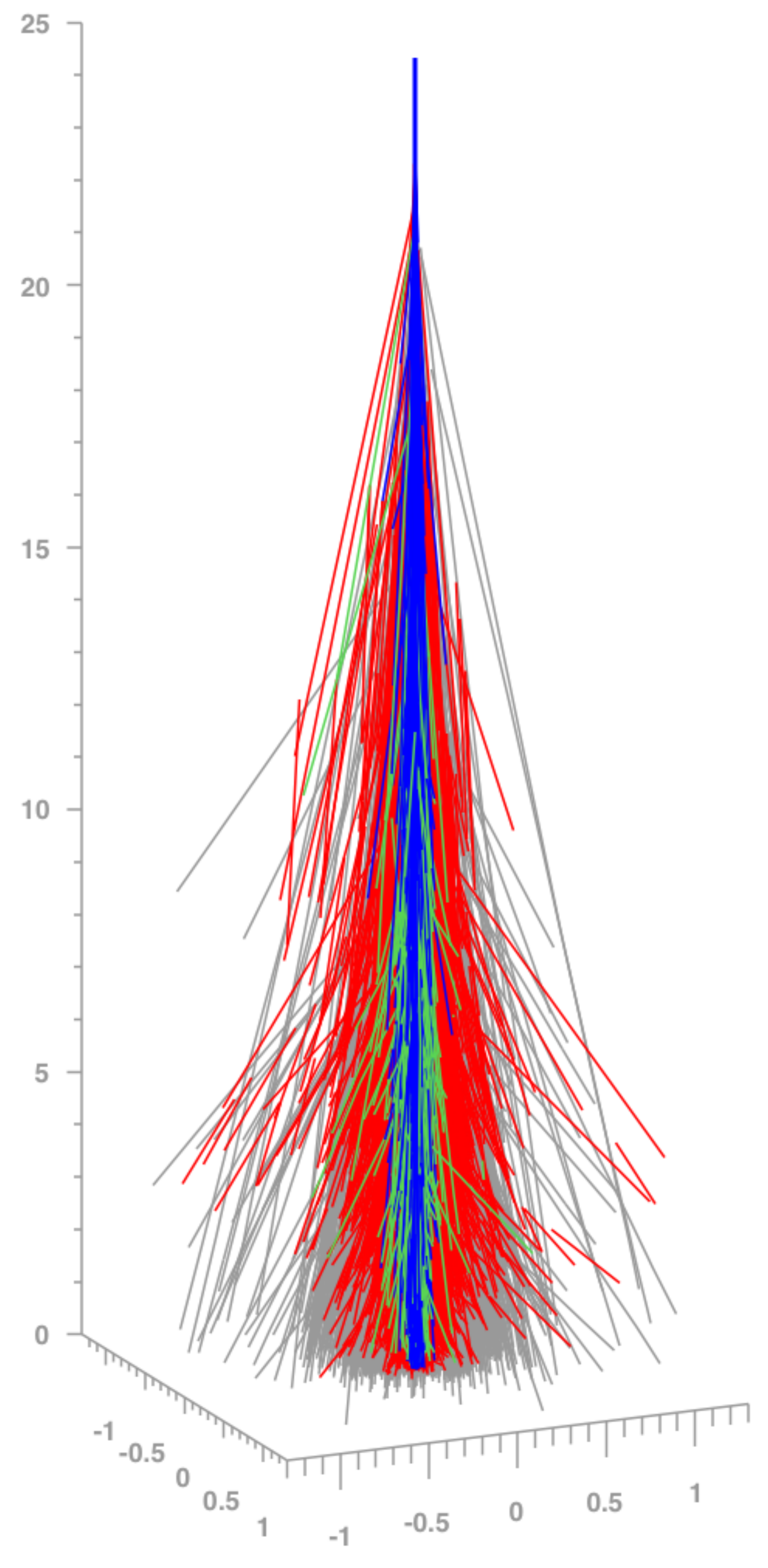
$$\frac{\mathrm{d}N_e}{\mathrm{d}E} \sim \frac{E_c}{E^{1+s}}$$

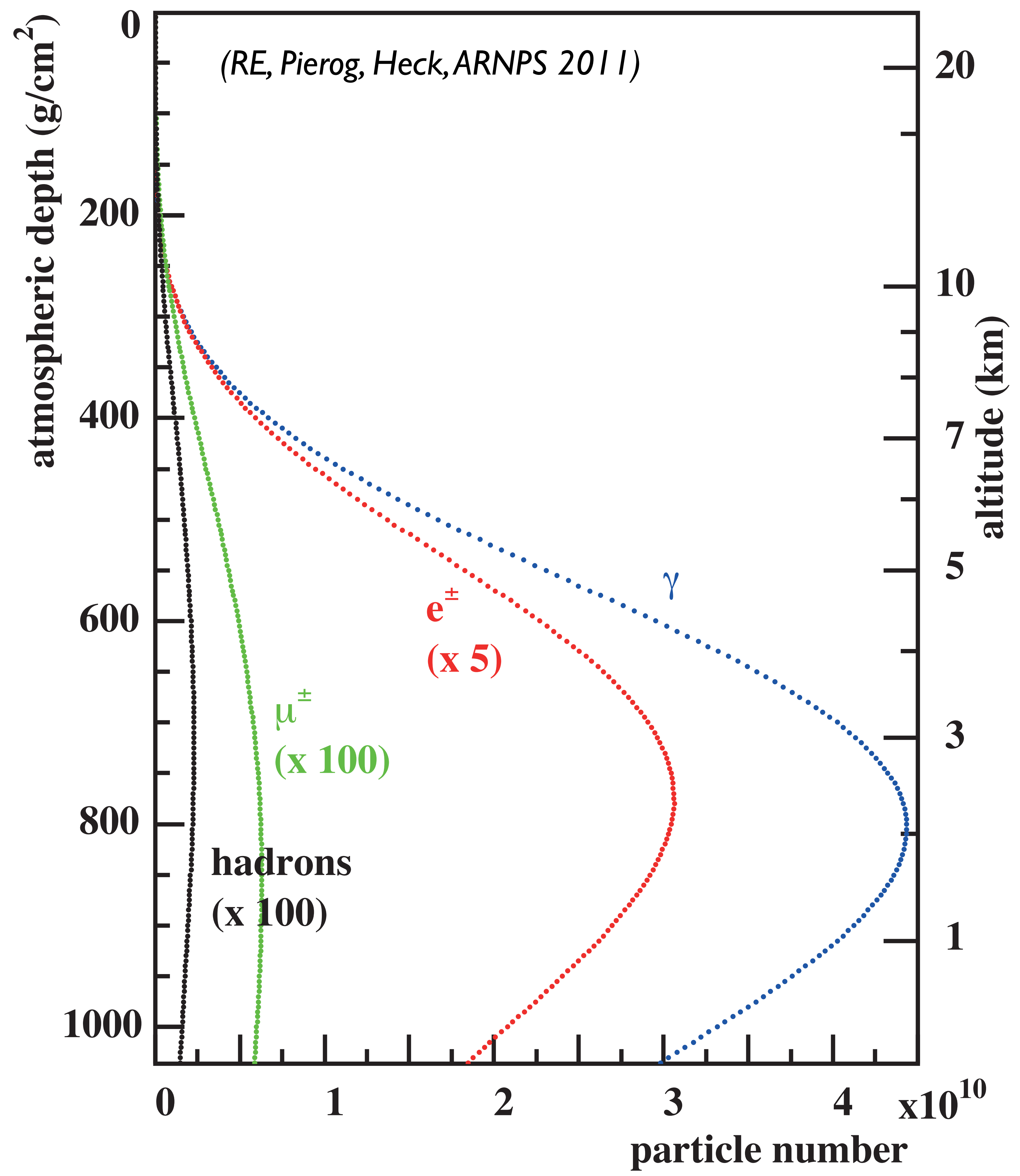
$$\frac{\mathrm{d}N_e}{r\,\mathrm{d}r} \sim \left(\frac{r}{r_1}\right)^{s-2} \left(1 + \frac{r}{r_1}\right)^{s-4.5}$$

Nishimura-Kamata-Greisen (NKG)
lateral distribution function

Hadronic showers

Expectation from simulations



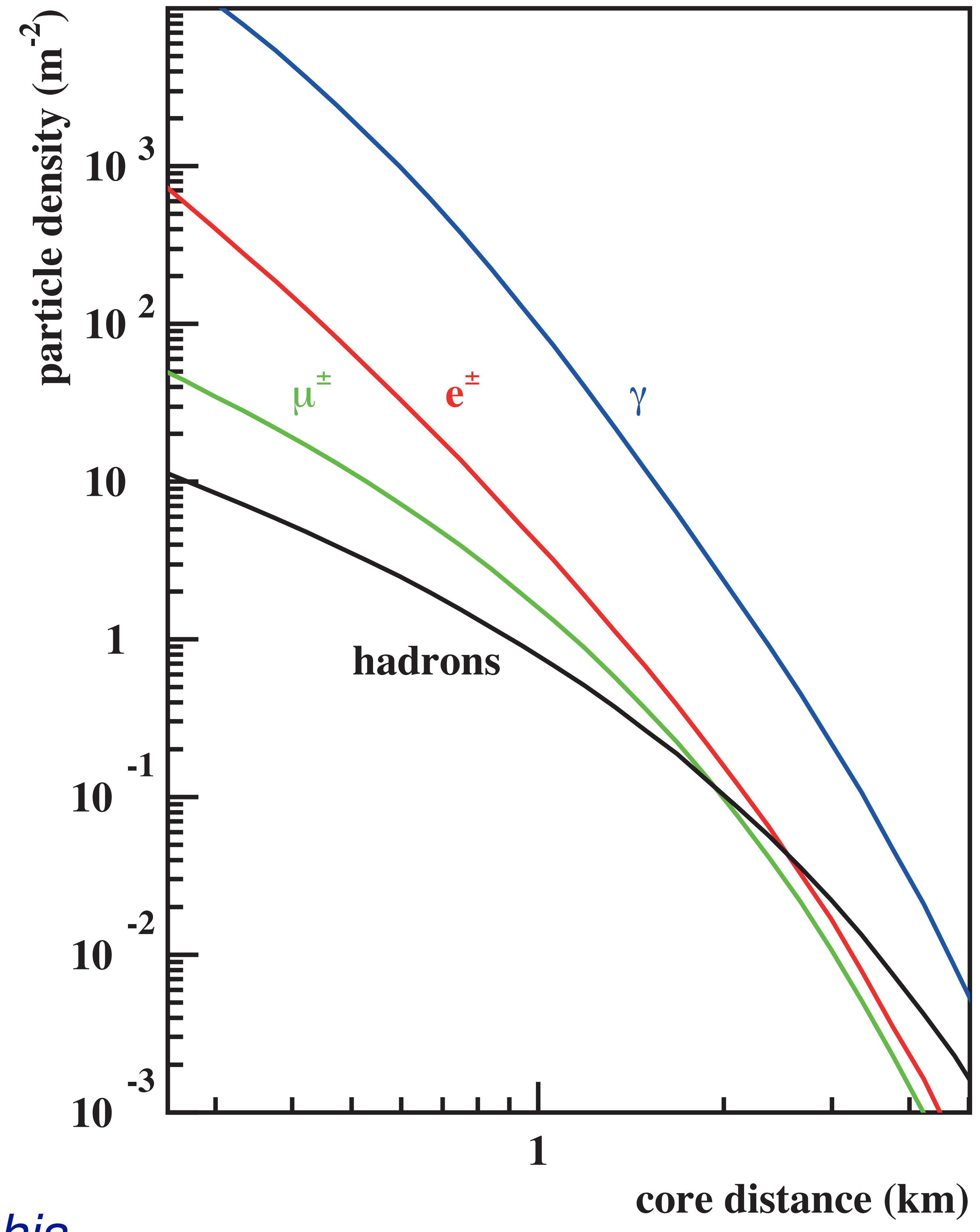


Longitudinal profile:

Cherenkov light
Fluorescence light
(bulk of particles measured)

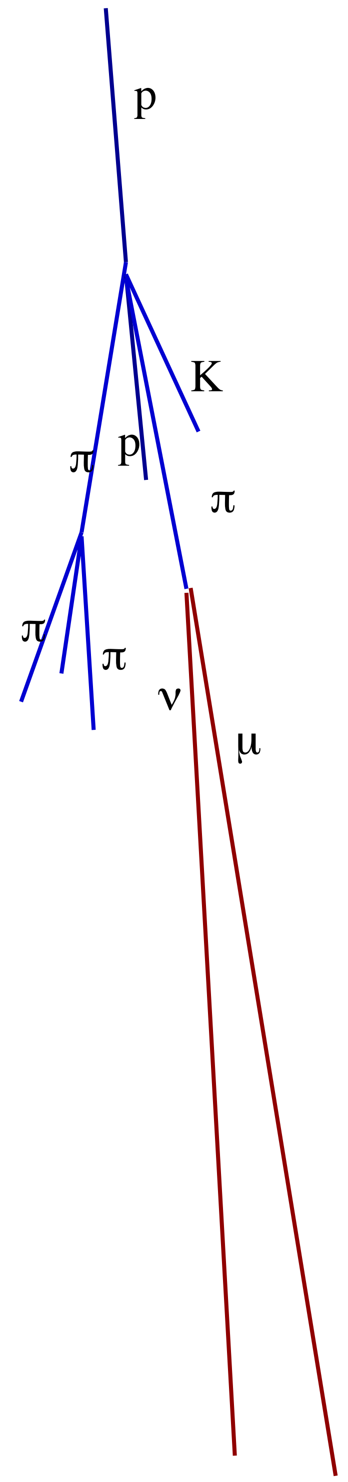
Lateral profiles:

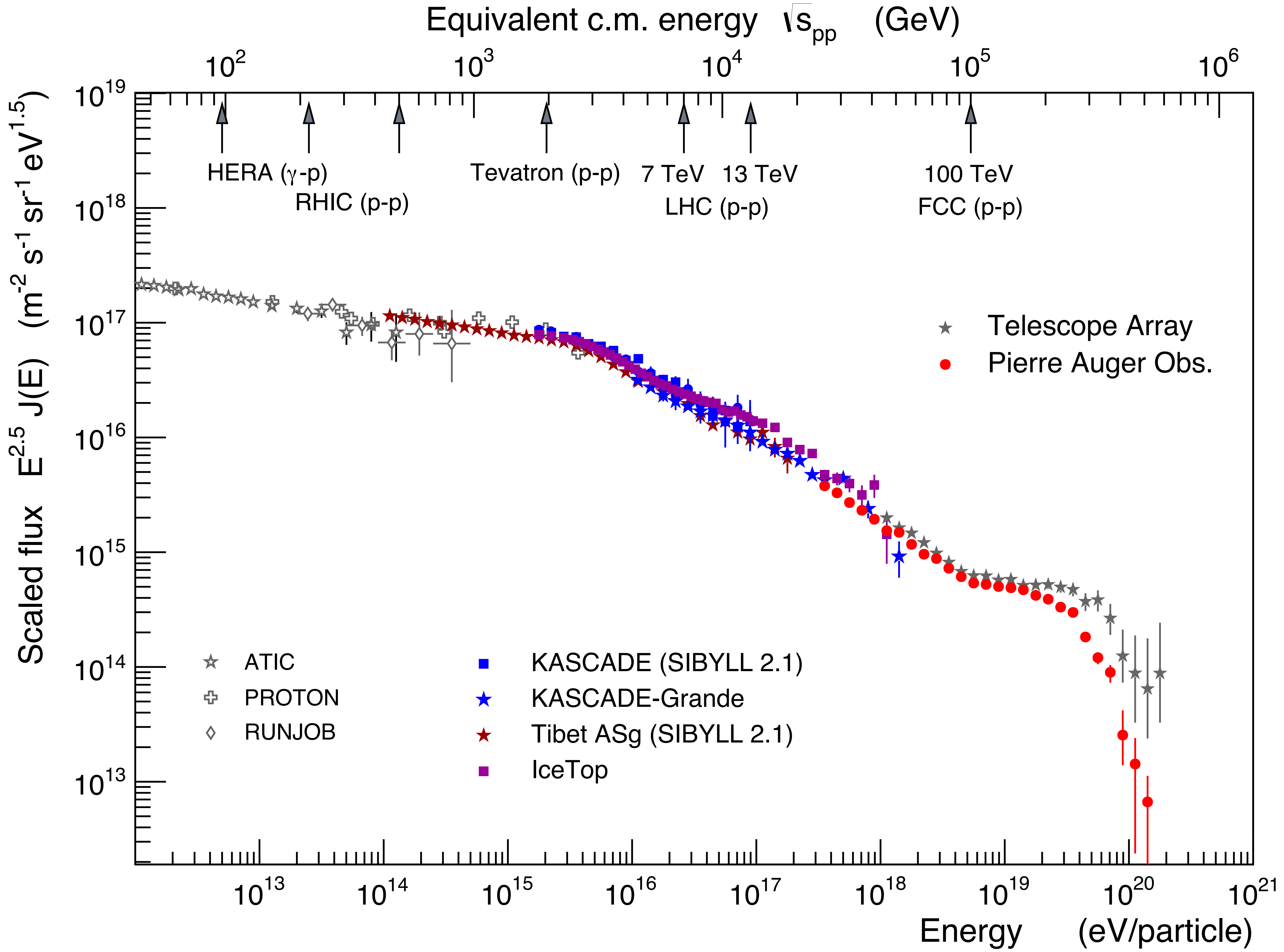
particle detectors at ground
(very small fraction of particles sampled)

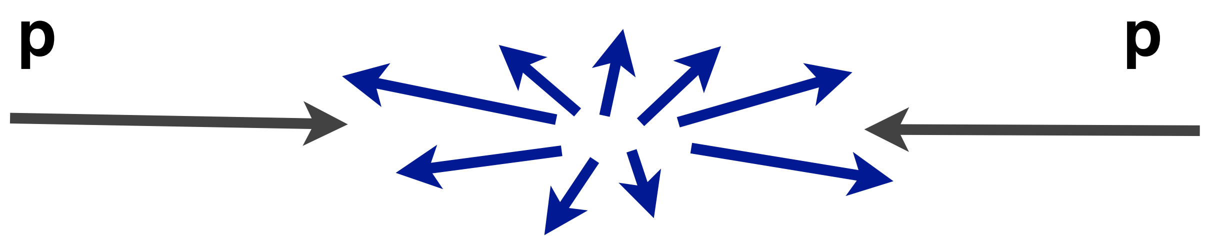


See talk by Piera Ghia

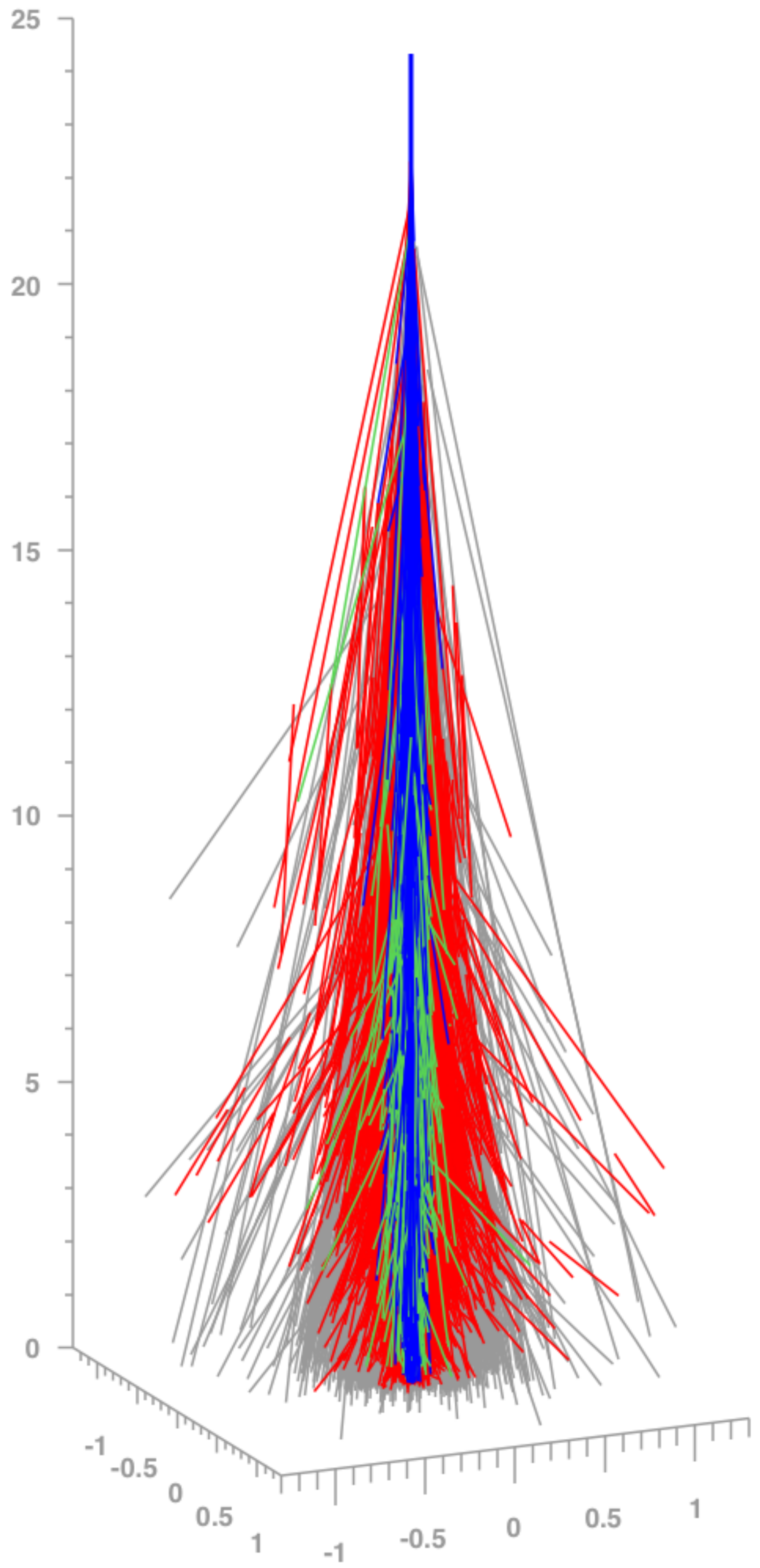
Cosmic ray flux and interaction energies



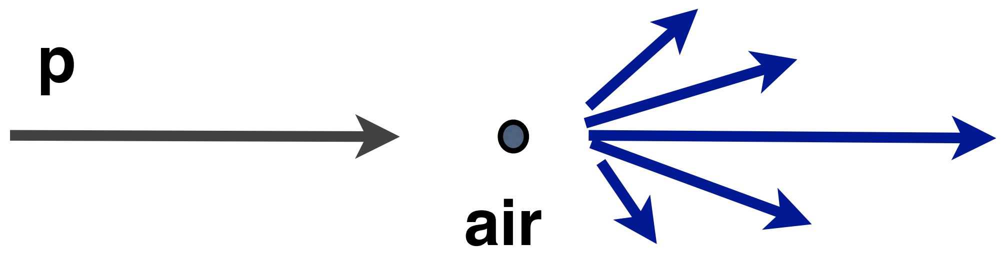




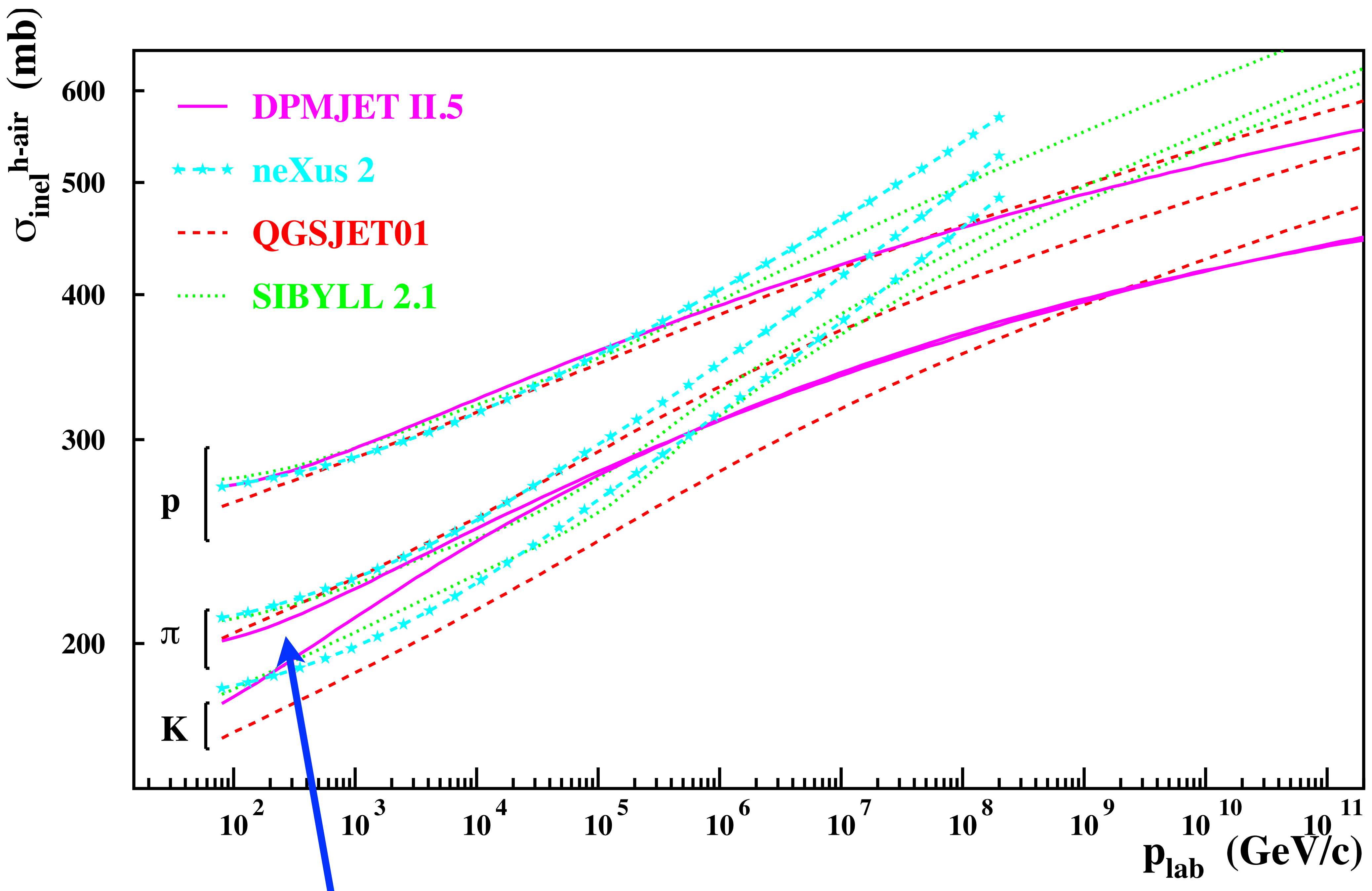
Center-of-mass energy



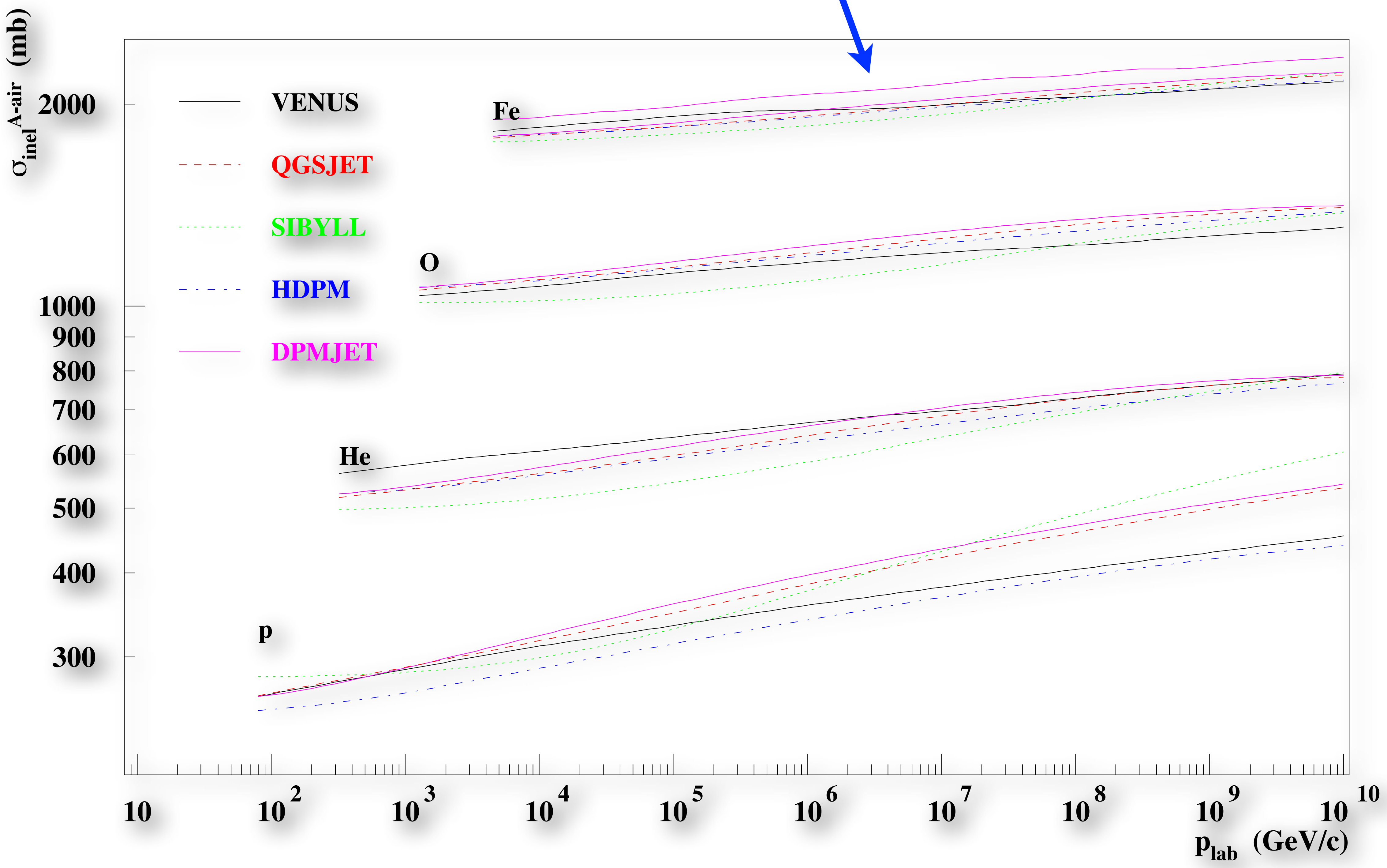
Laboratory energy



Interaction cross sections: mesons and nuclei



Iron nuclei: $\lambda_{int} \sim 12\ \mathrm{g/cm^2}$



Pions: $\lambda_{int} \sim 120\ \mathrm{g/cm^2}$

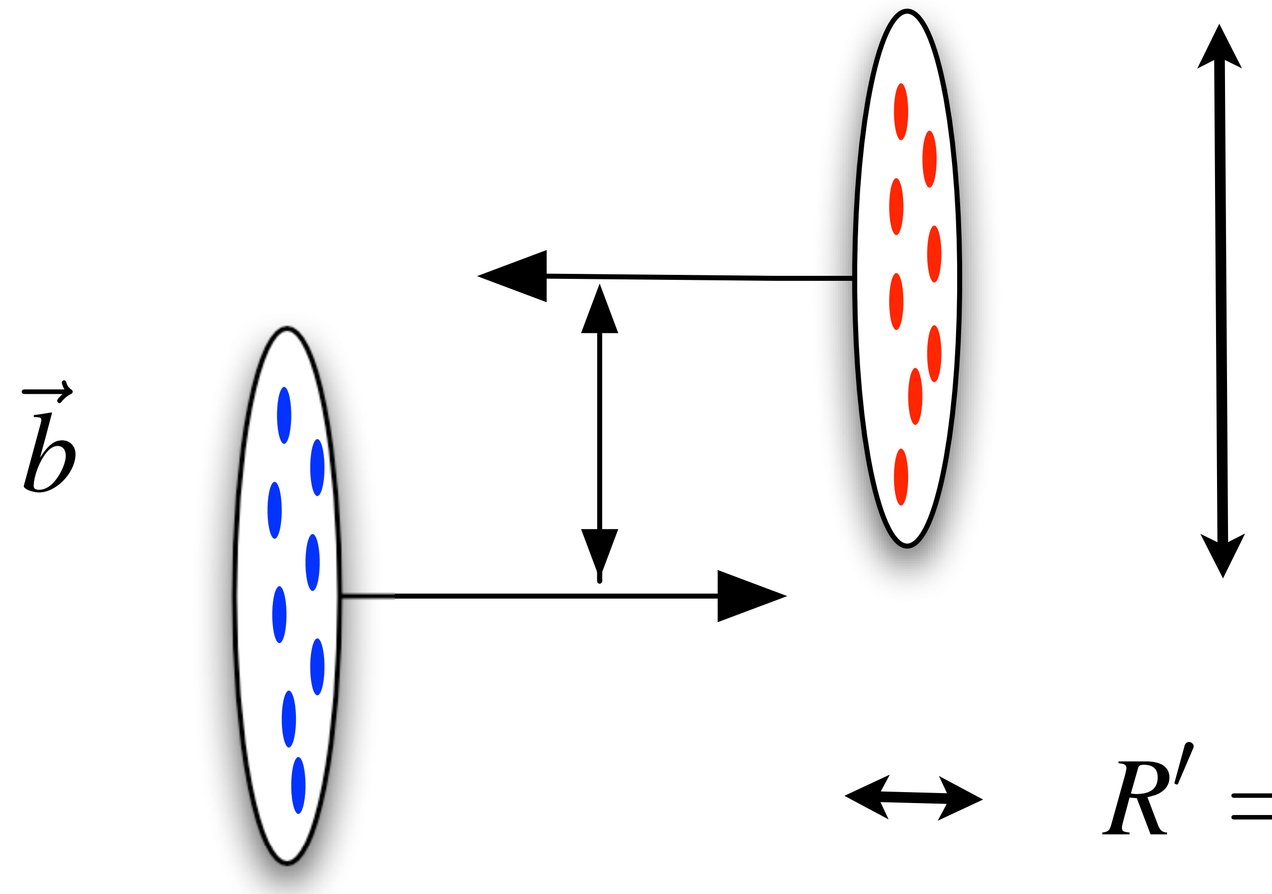
Protons: $\lambda_{int} \sim 75\ \mathrm{g/cm^2}$

Photons: $\lambda_{\gamma,pair} = \frac{9}{7} X_0 \sim 50\ \mathrm{g/cm^2}$

Expectations from uncertainty relation

Assumptions:

- hadrons built up of partons
- partons deflected/liberated in collision process, small momentum
- partons fragment into hadrons (pions, kaons,...) after interaction
- interaction viewed in c.m. system (other systems equally possible)



$$R \approx 1\text{fm} \approx 5\text{GeV}^{-1}$$

$$\leftrightarrow \quad R' = R/\Gamma = R\,\frac{m_p}{E_p}$$

Heisenberg uncertainty relation

$$\Delta x\, \Delta p_x \simeq 1$$

Longitudinal momenta of secondaries

$$\langle p_\parallel \rangle \sim \Delta p_\parallel \approx \frac{1}{R'} \approx \frac{1}{5} E_p$$

$$\Gamma = E_p / m_p$$

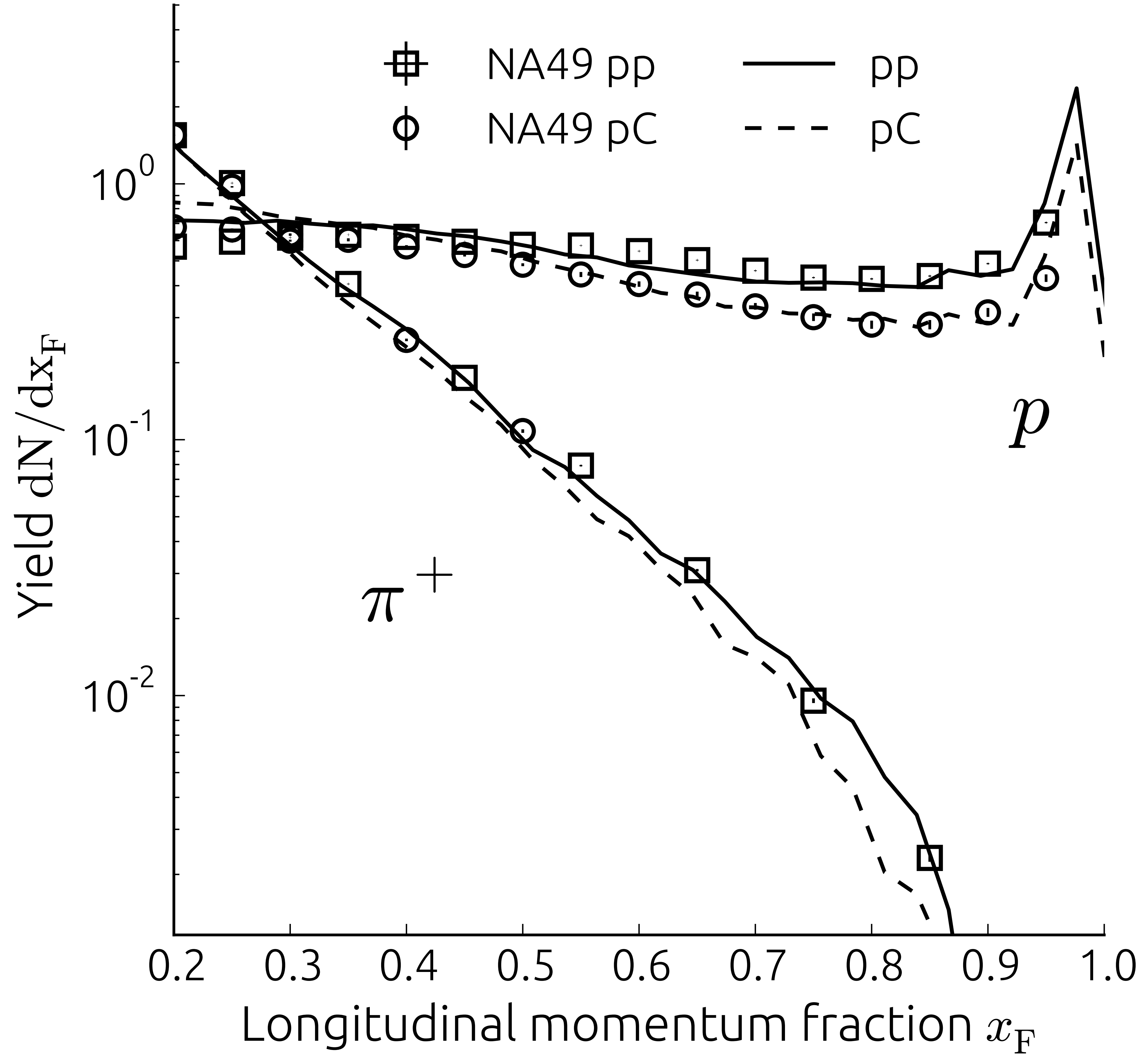
Transverse momenta of secondaries

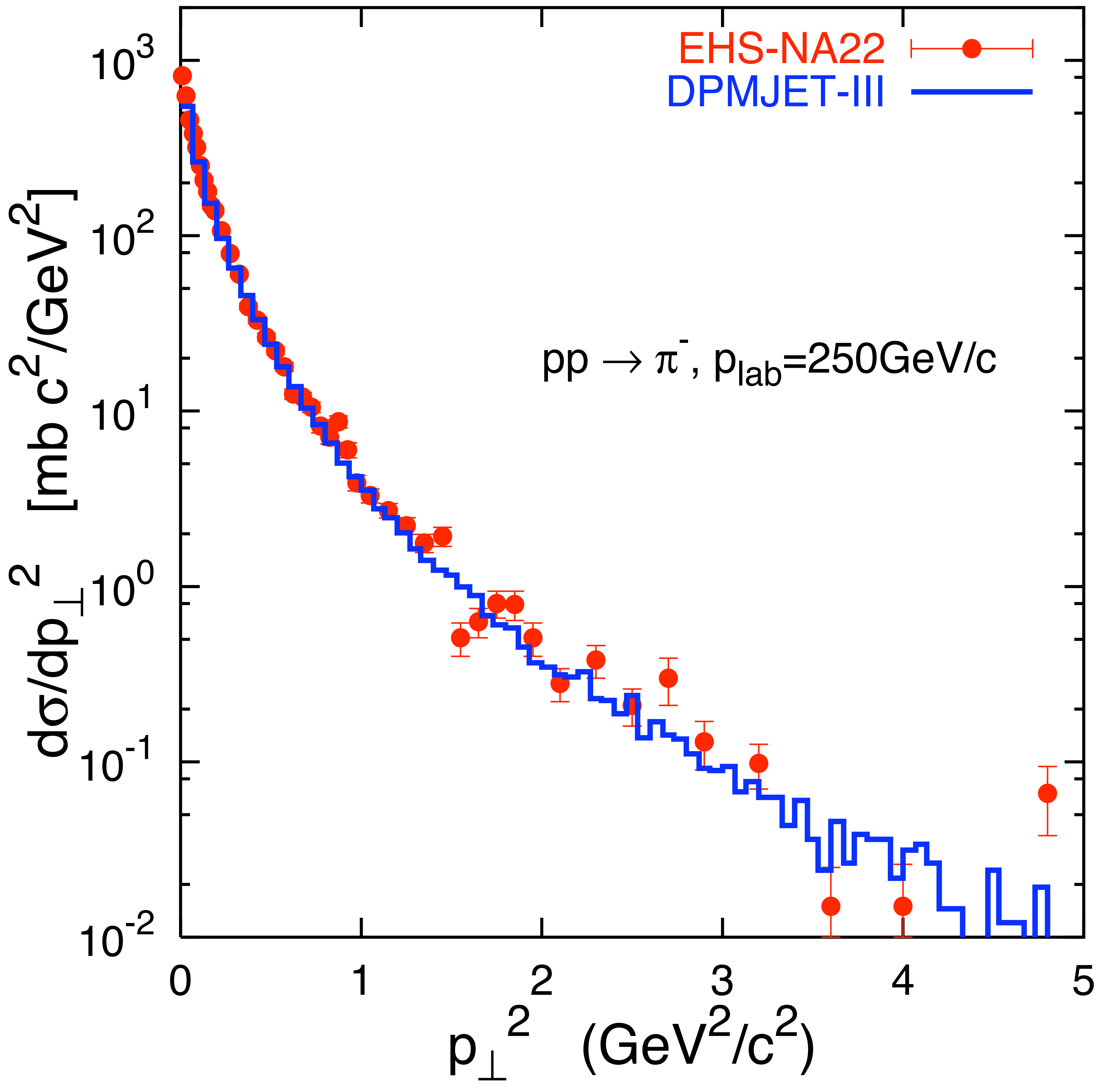
$$\langle p_\perp \rangle \sim \Delta p_\perp \sim \frac{1}{R} \approx 200\,\text{MeV}$$

Typical hadronic final states

Sibyll 2.3rc3b

NA49 p-p and p-C at 158 GeV





Feynman-x $$x_F = \left(\frac{p_\parallel}{p_{\max}}\right)_{\rm CMS}$$

Transverse momentum

(Riehn et al. ICRC 2017)

Secondary particle multiplicities

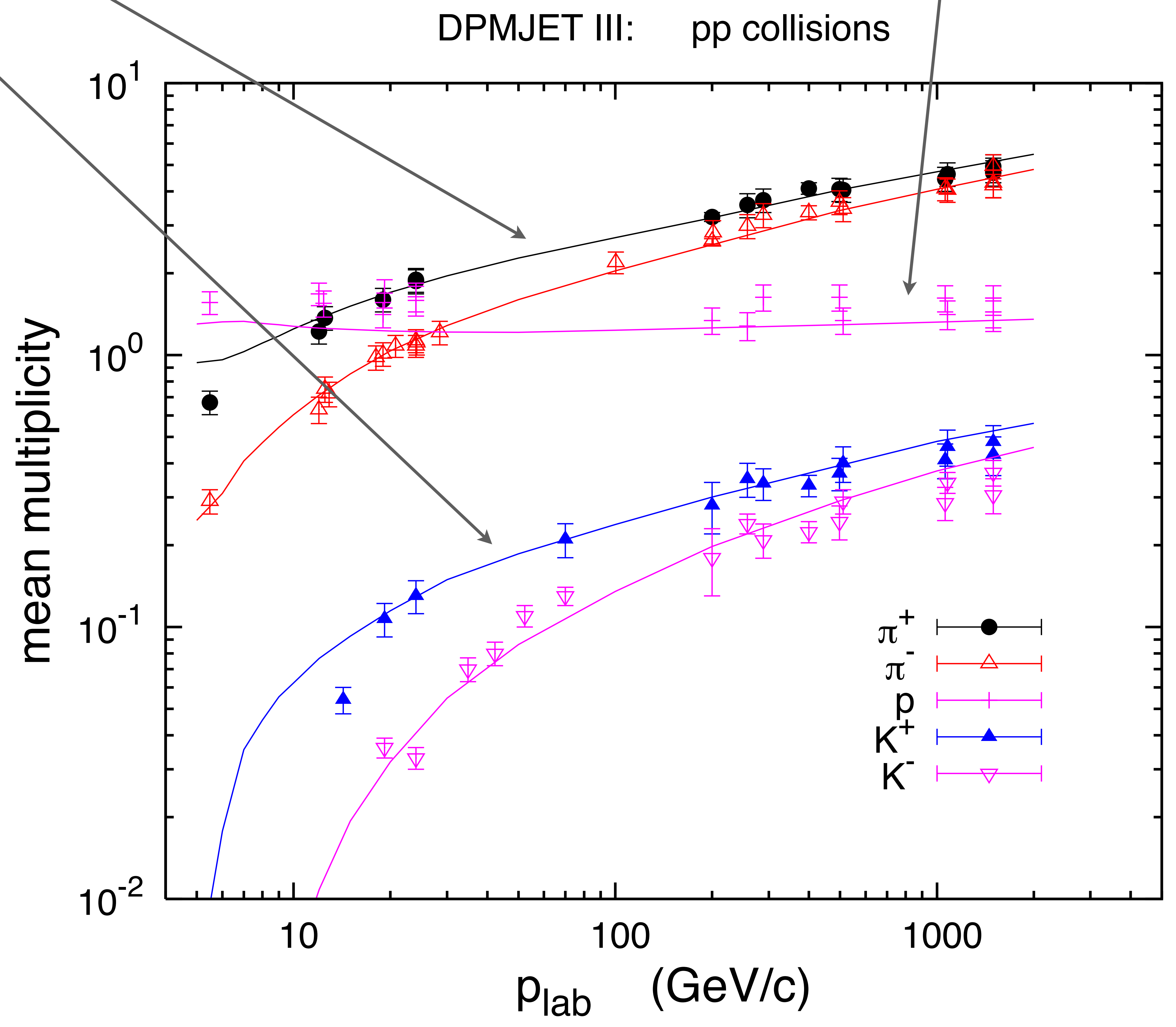
Power-law increase of number of secondary particles

Leading particles (multiplicity const.)

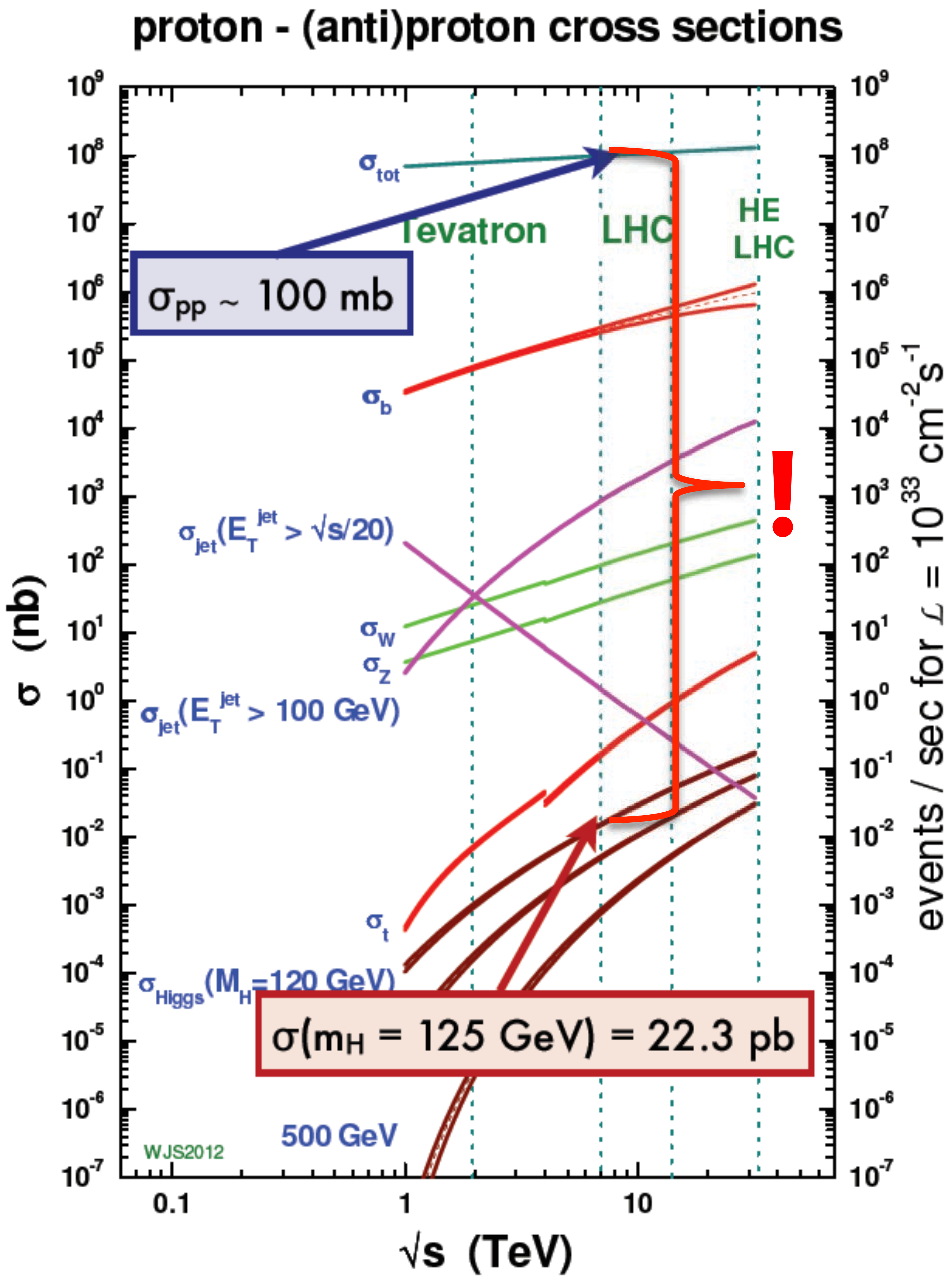
$$n_{\mathrm{ch}} \sim s^{0.1}$$

proton - proton, $E_{lab} = 200\mathrm{GeV}$

	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
K^-	0.18 ± 0.05	0.20
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105



Competing processes of interaction and decay



Interaction length

$$\lambda_{\rm int} = \frac{\langle m_{\rm air}\rangle}{\sigma_{\rm int}}$$

$$\lambda_\pi \approx \lambda_K \approx 120\,{\rm g/cm^2}$$

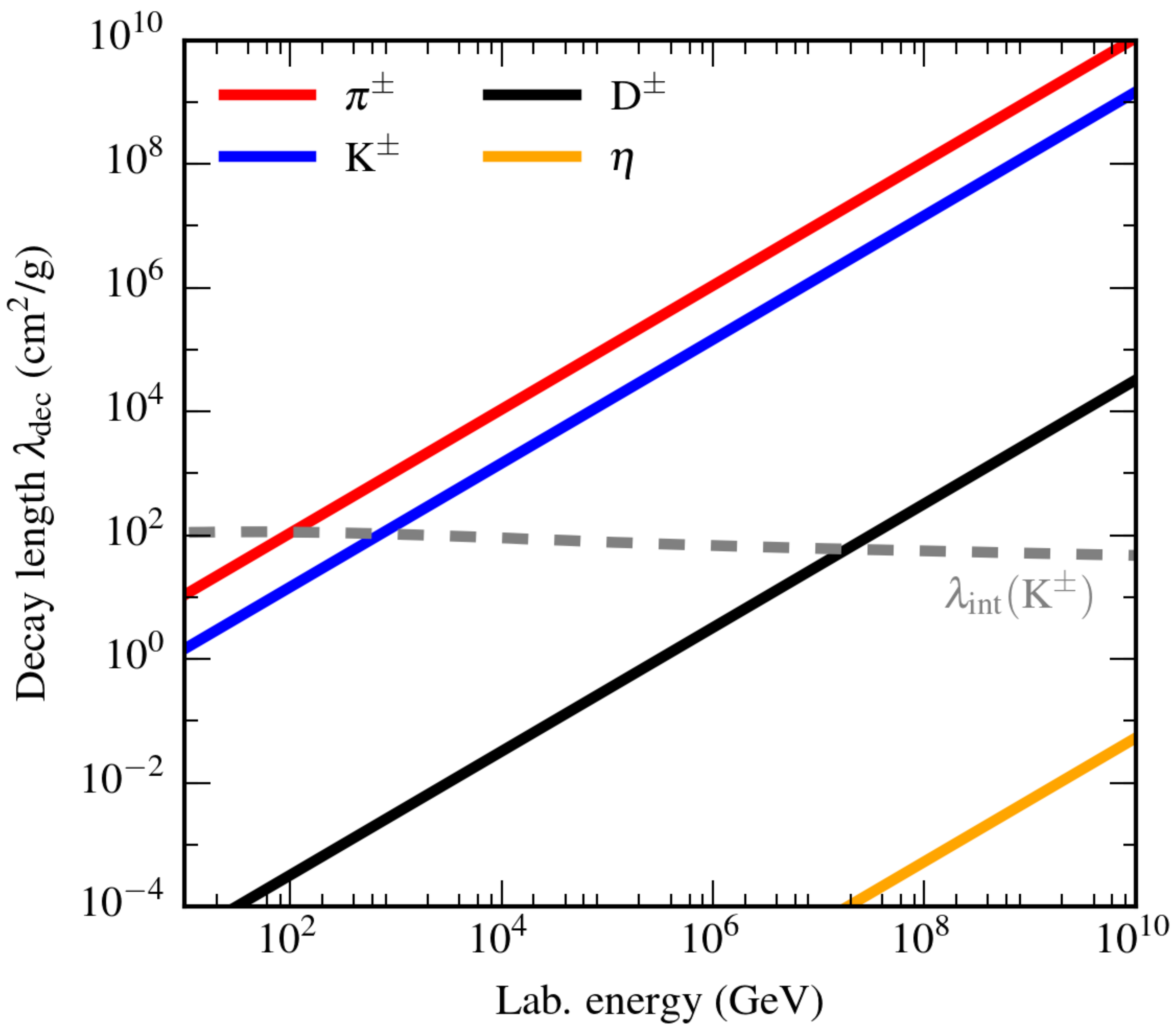
Decay length

$$l_{\rm dec} = \beta c \tau \Gamma \approx c\tau \frac{E}{m}$$

$$\lambda_{\rm dec} = \rho\, l_{\rm dec} \approx c\tau\rho \frac{E}{m}$$

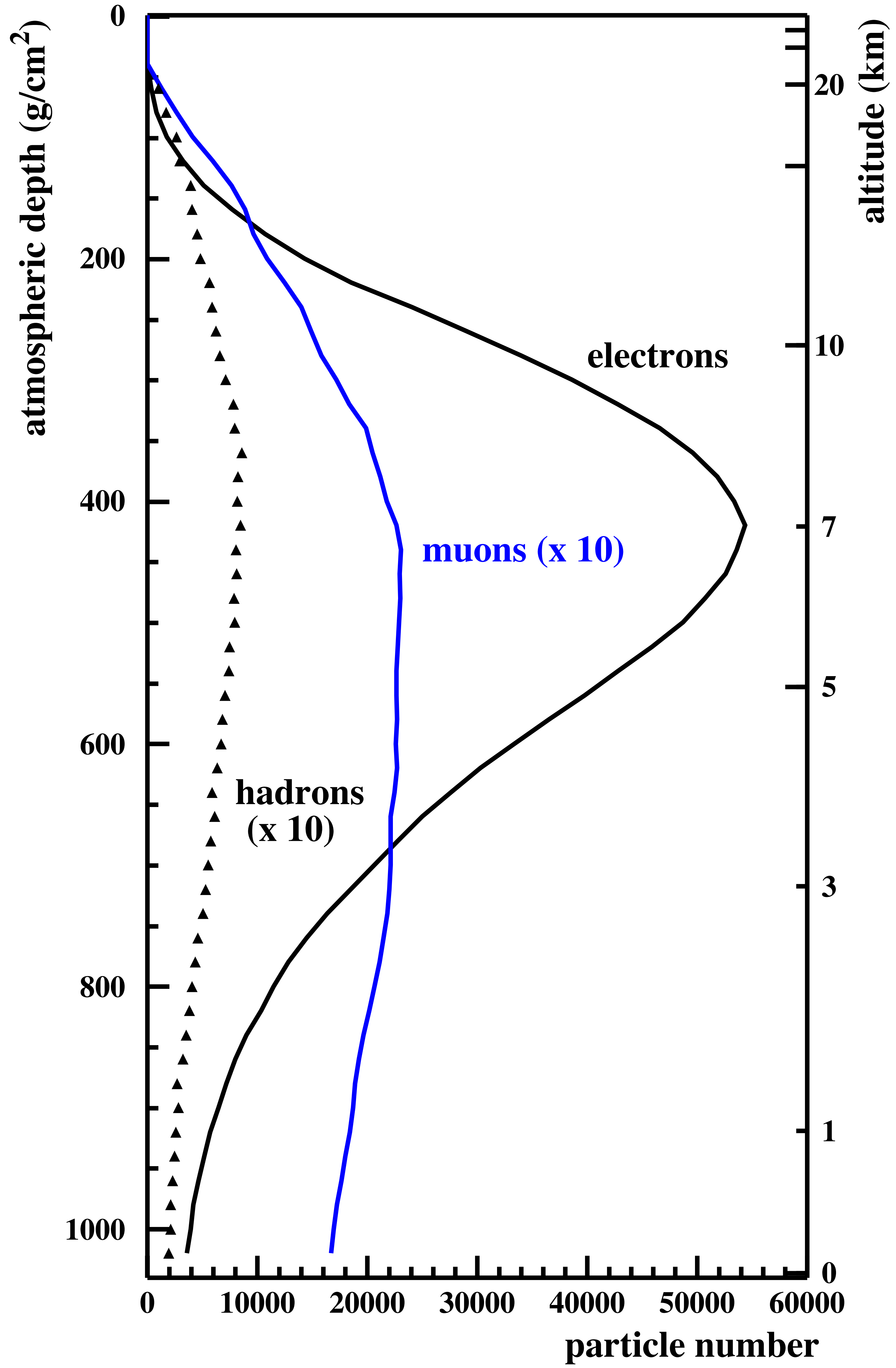
air density

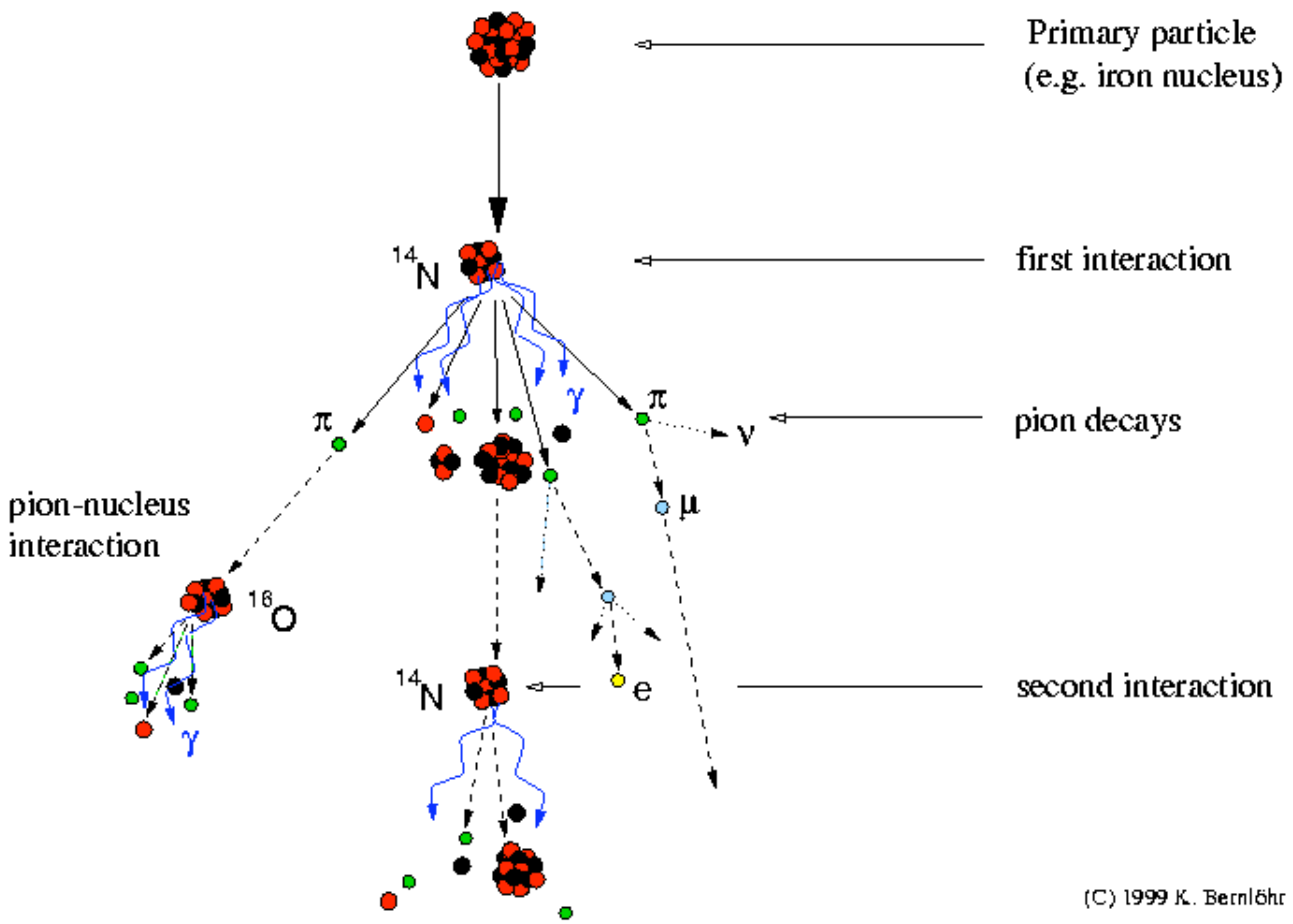
(Fedynitch 2017)



Altitude of 8 km

Hadron-induced showers





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

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

$$\pi^+ \longrightarrow \mu^+ \nu_\mu$$

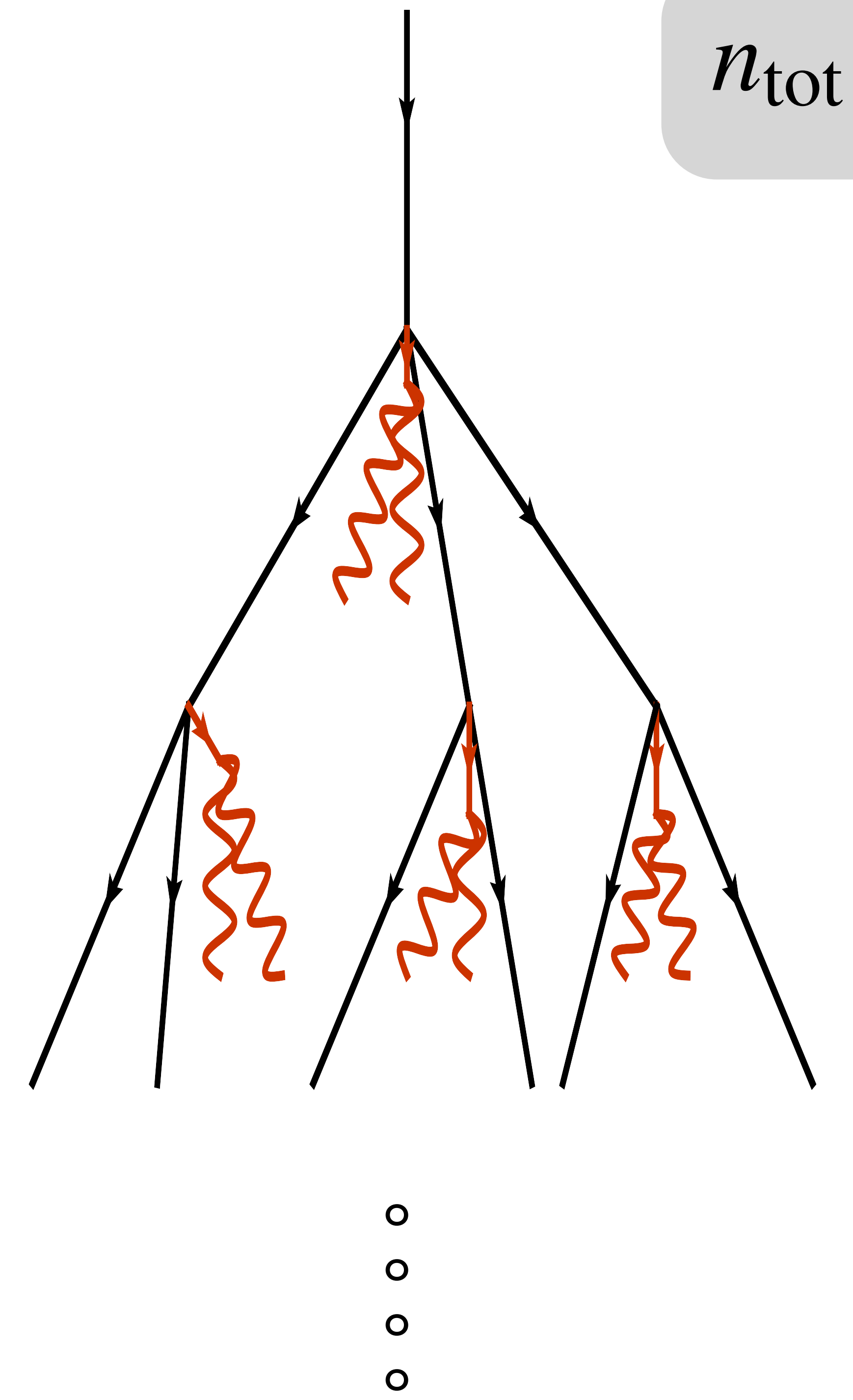
$$\pi^0 \longrightarrow \gamma\gamma$$

Charged pions interact E > 30 GeV

Neutral pions always decay

Qualitative approach: Heitler-Matthews model

$$n_{tot} = n_{\pi^0} + n_{ch}$$



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

Primary particle proton

π^0 decay immediately

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

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

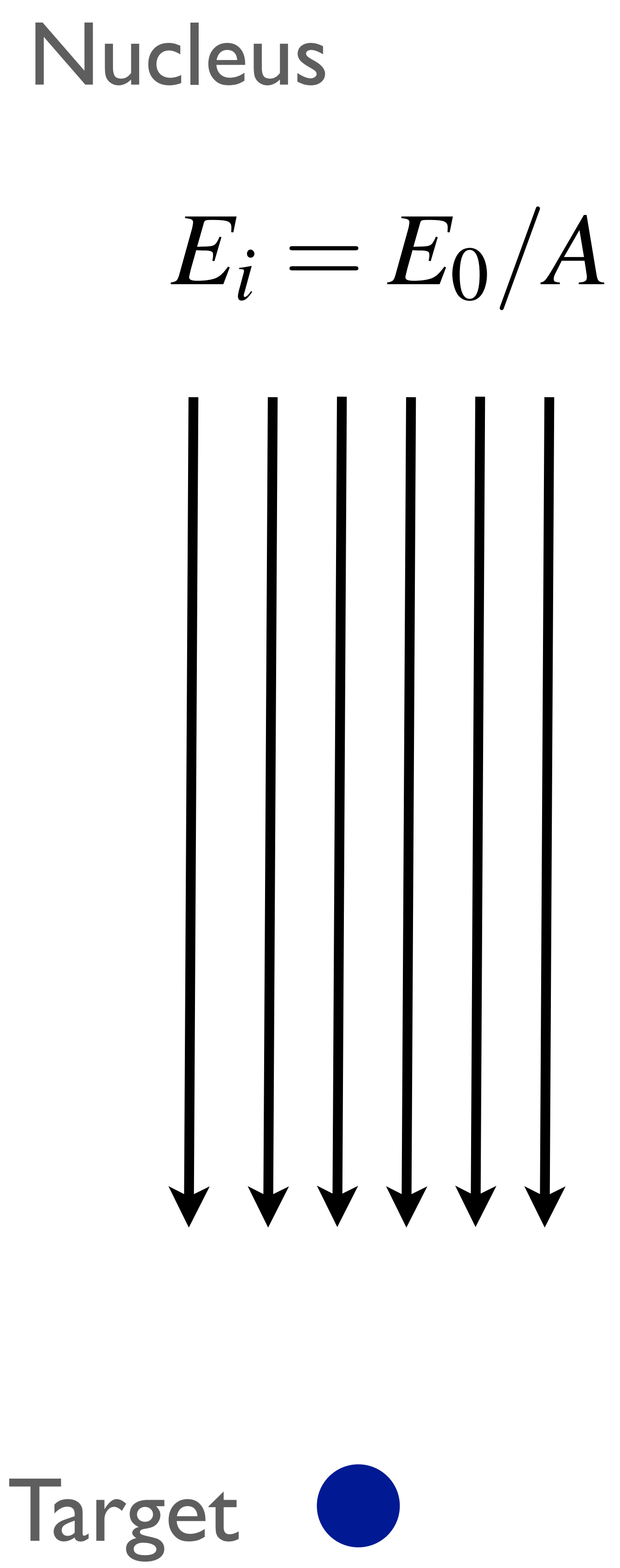
$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Superposition model



Proton-induced shower

$$N_{\max} \sim E_0/E_c$$

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha \qquad \alpha \approx 0.9$$

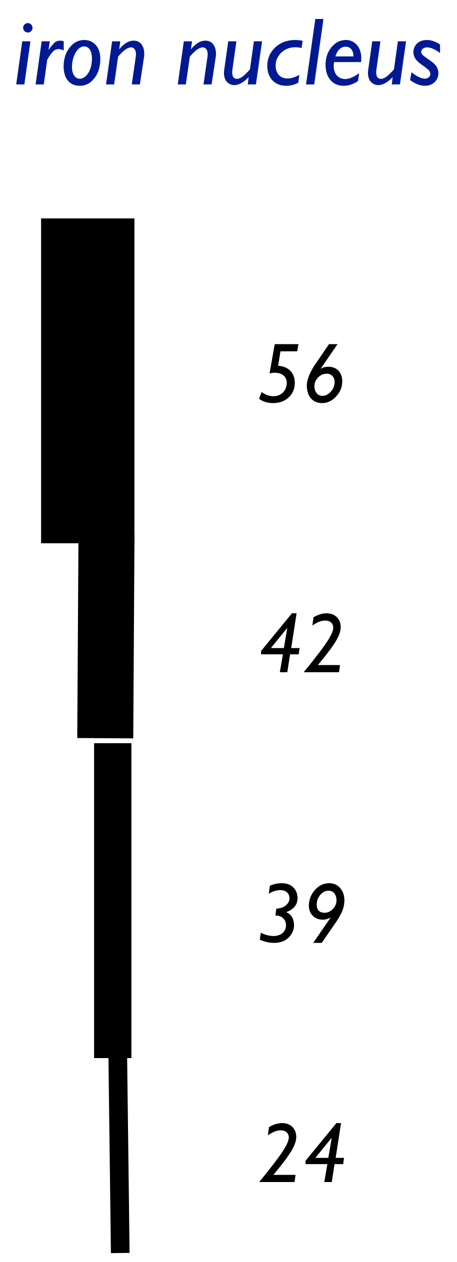
Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

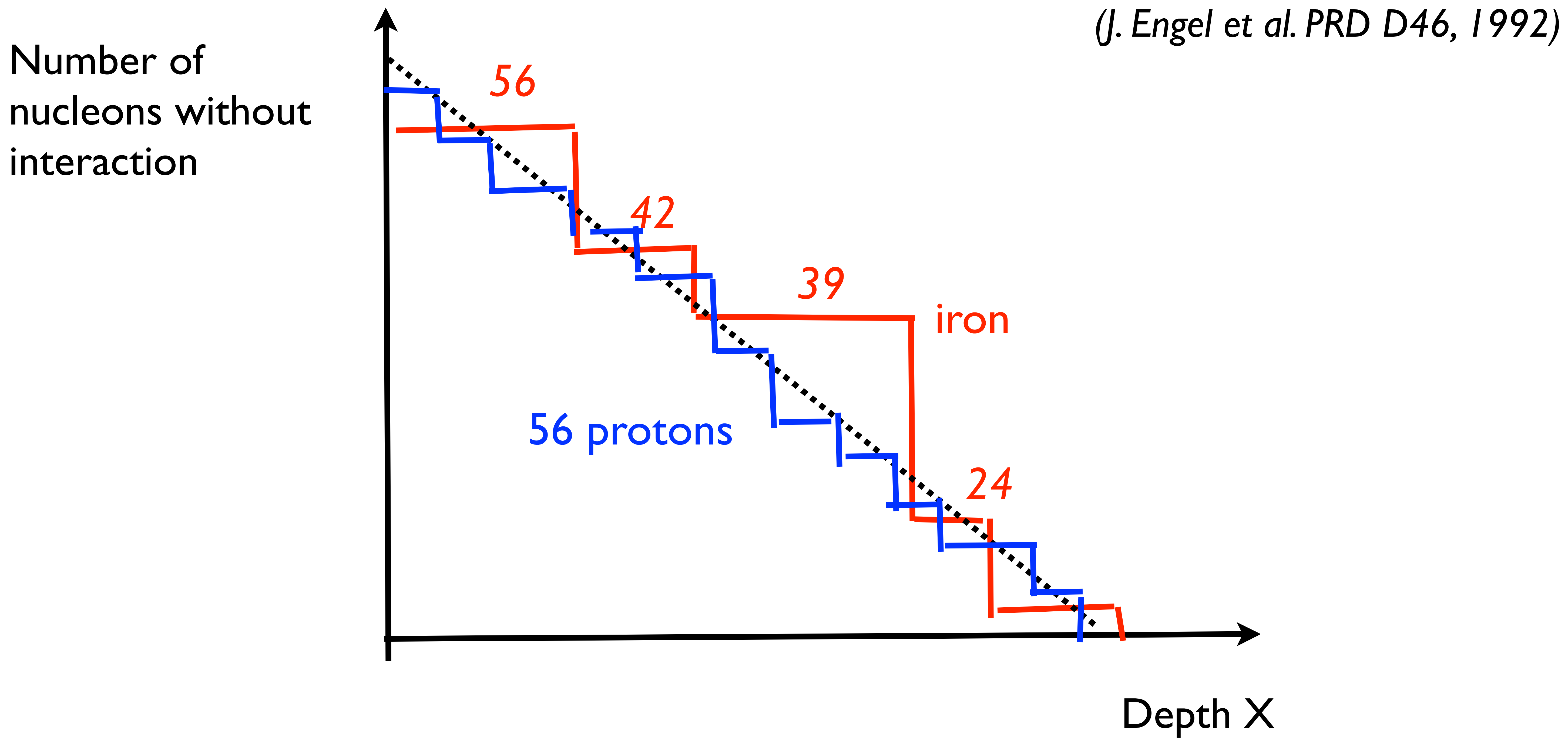
$$N_{\max}^A \sim A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

$$X_{\max}^A \sim \lambda_{\text{eff}} \ln(E_0/A)$$

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

Superposition model: correct prediction of mean Xmax



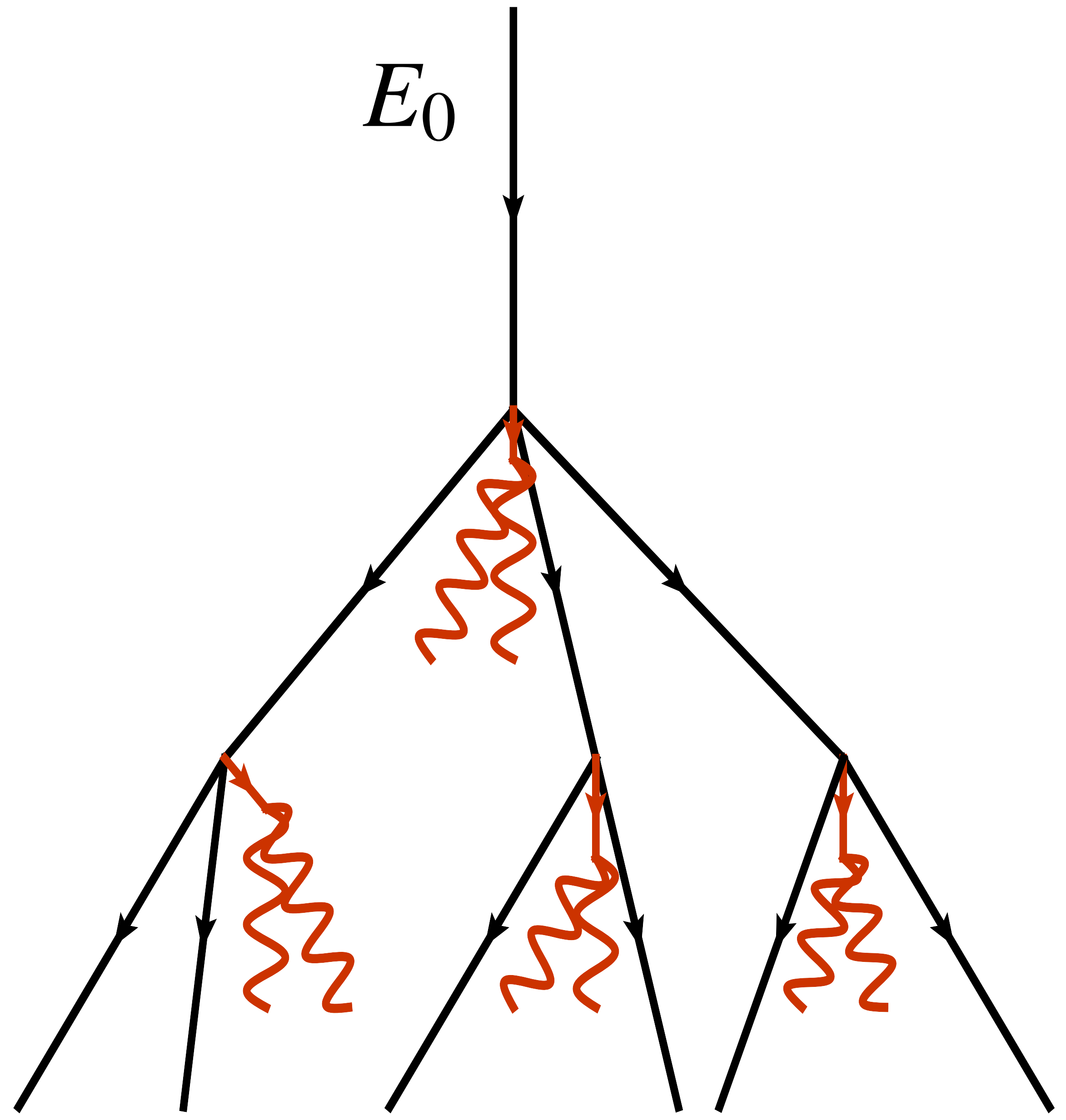


Glauber approximation (unitarity)

$$n_{\text{part}} = \frac{\sigma_{\text{Fe-air}}}{\sigma_{\text{p-air}}}$$

Superposition and semi-superposition models applicable to inclusive (averaged) observables

Electromagnetic energy and energy transfer



Hadronic energy

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

$$\vdots$$

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

Electromagnetic energy

$$\frac{1}{3}E_0$$

$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

$$\vdots$$

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

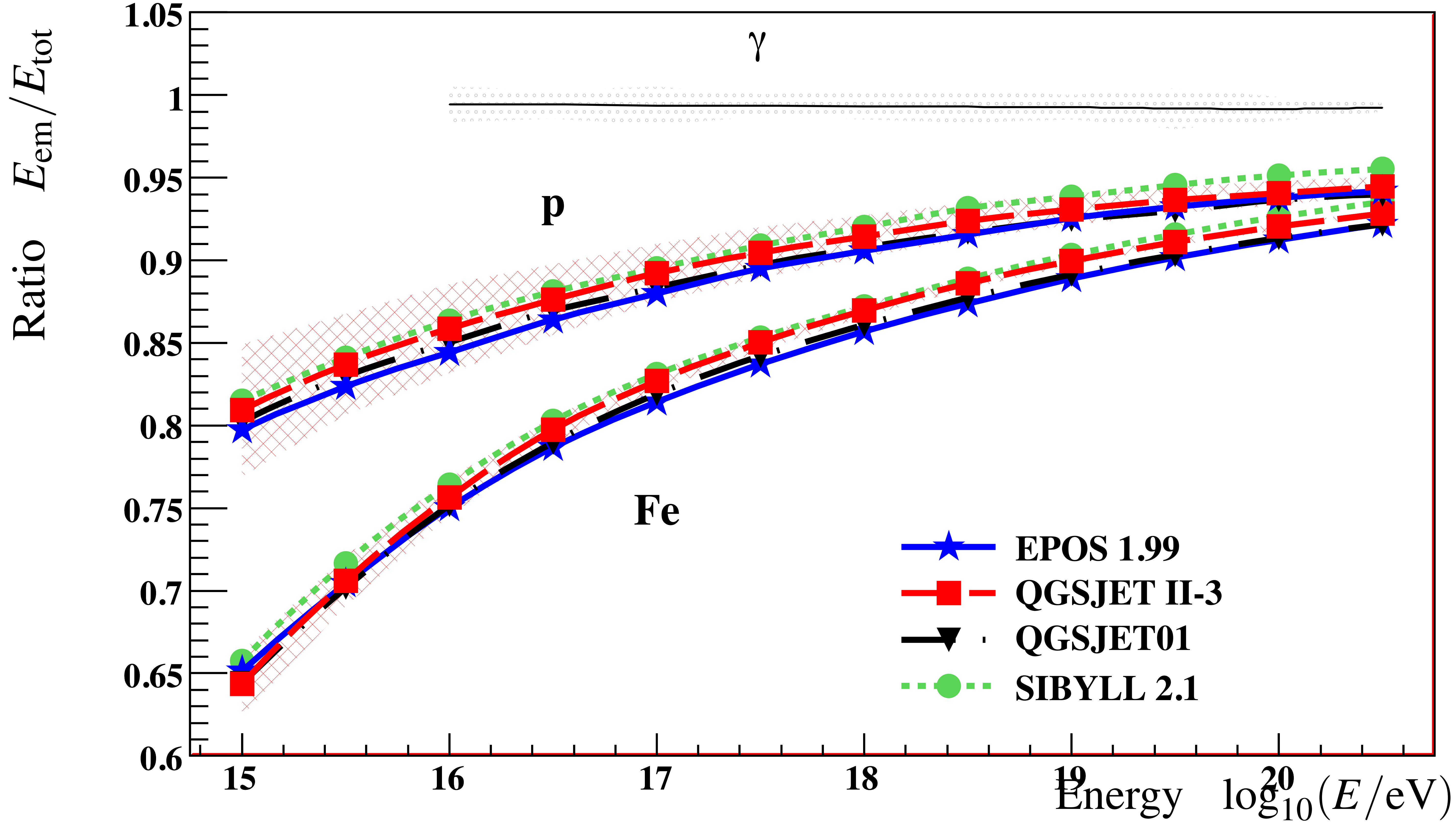
After n generations ...

$n = 5,\ \ E_{\rm had} \sim 12\%$

$n = 6,\ \ E_{\rm had} \sim 8\%$

Energy transferred to electromagnetic component

(RE, Pierog, Heck, ARNPS 2011)



Ratio of em. to total shower energy

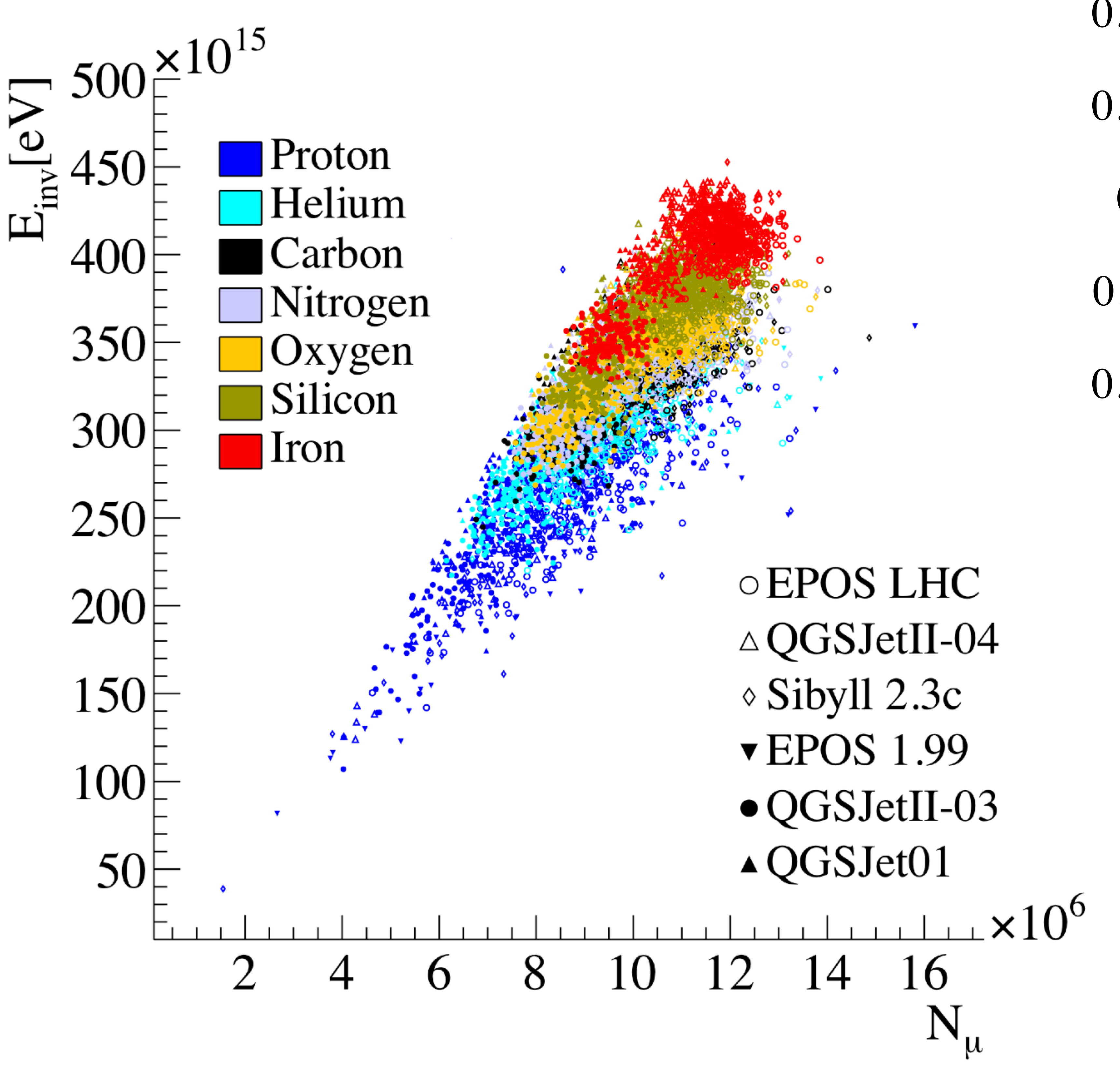
Detailed Monte Carlo simulation with CONEX

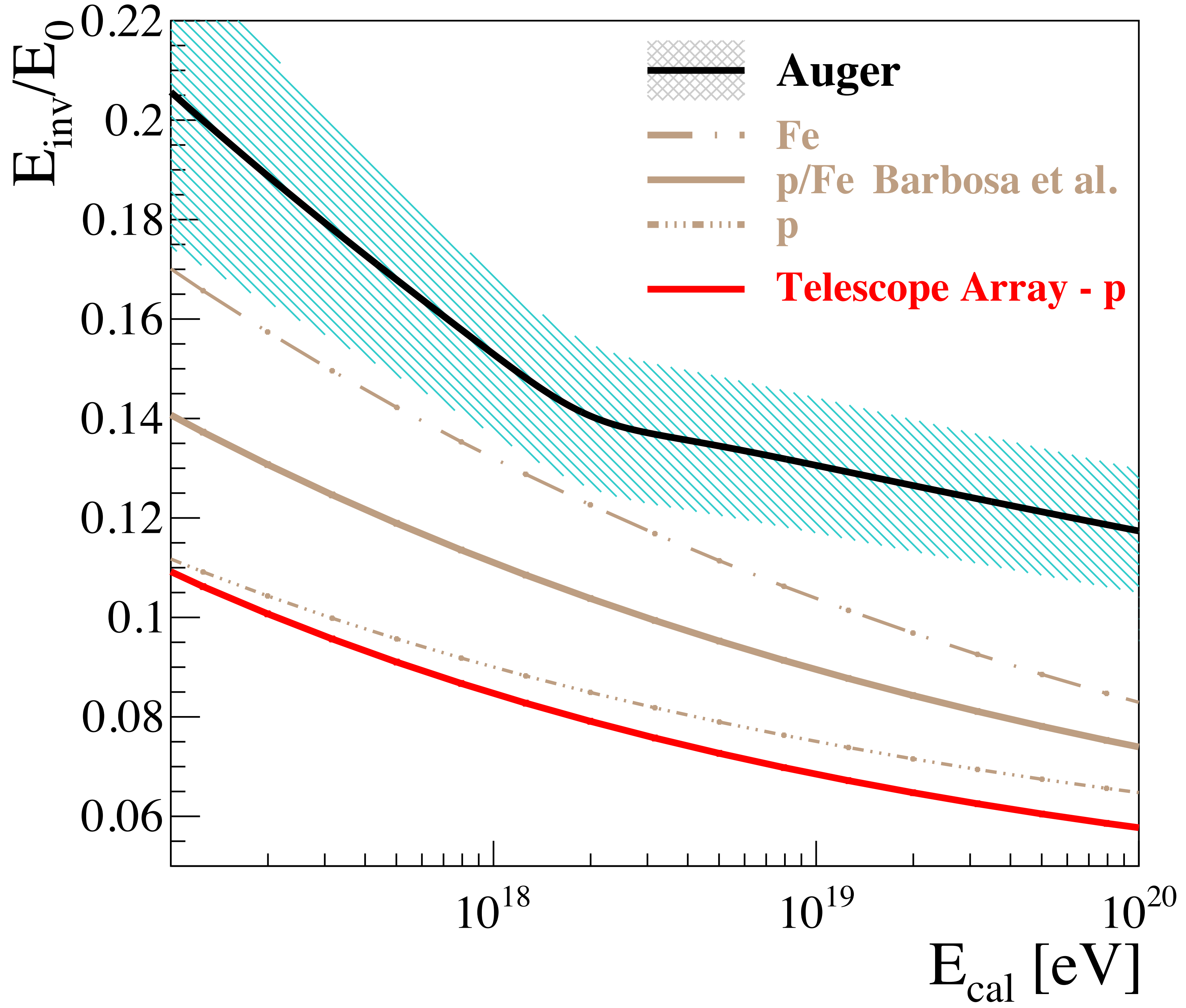
$$E_{\rm inv} = E_{\rm tot} - E_{\rm em}$$

At high energy: model dependence of correction to obtain total energy small

Muons as tracers of the hadronic core

Very good correlation between muon number and invisible energy

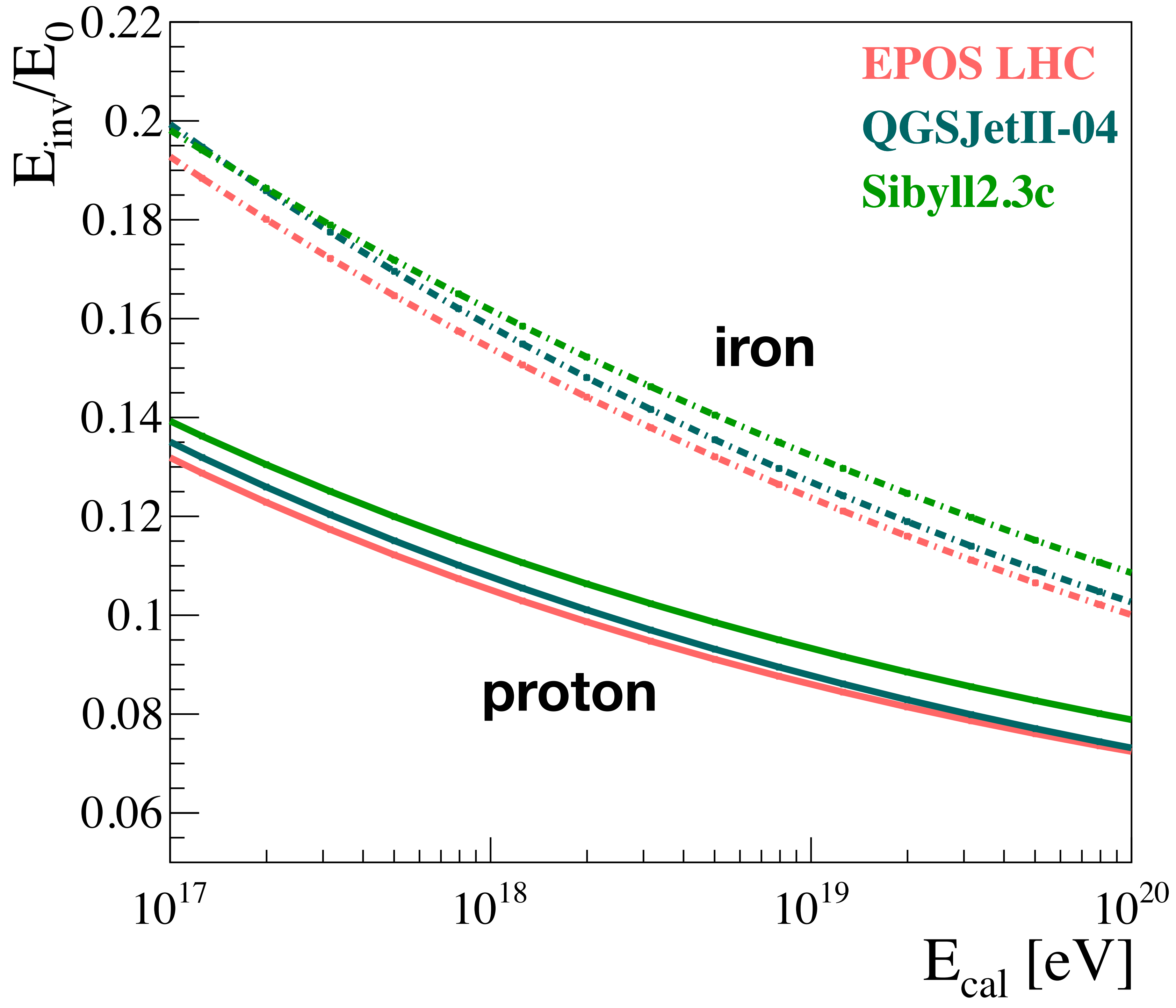




Muon-data based correction for invisible energy used in Auger

$$E_{\rm inv} = E_{\rm tot} - E_{\rm em}$$

Most recent model predictions

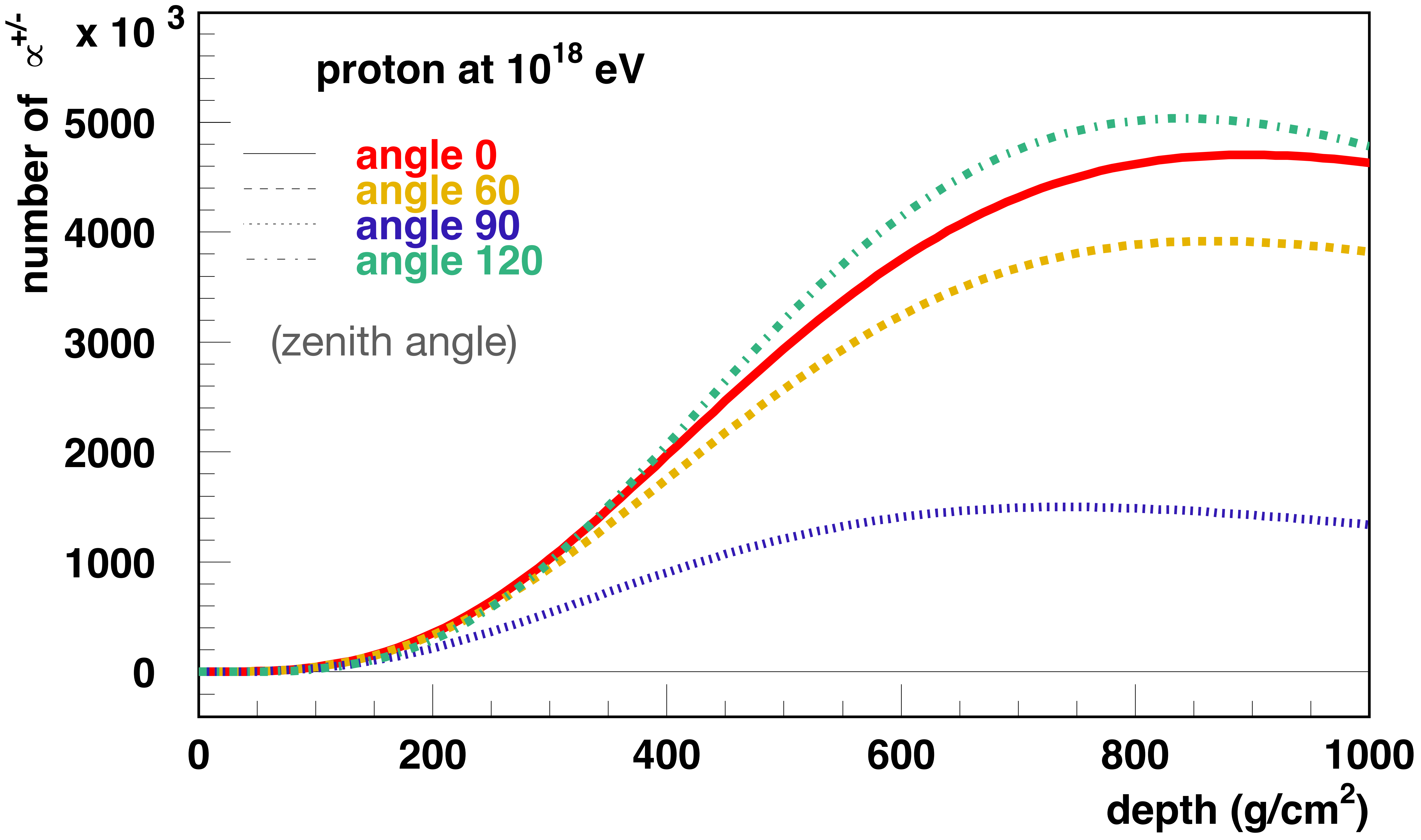


(Auger, PRD 2019)

Effect of air density (number of generations)

(Bergmann et al, APP 26, 2007)

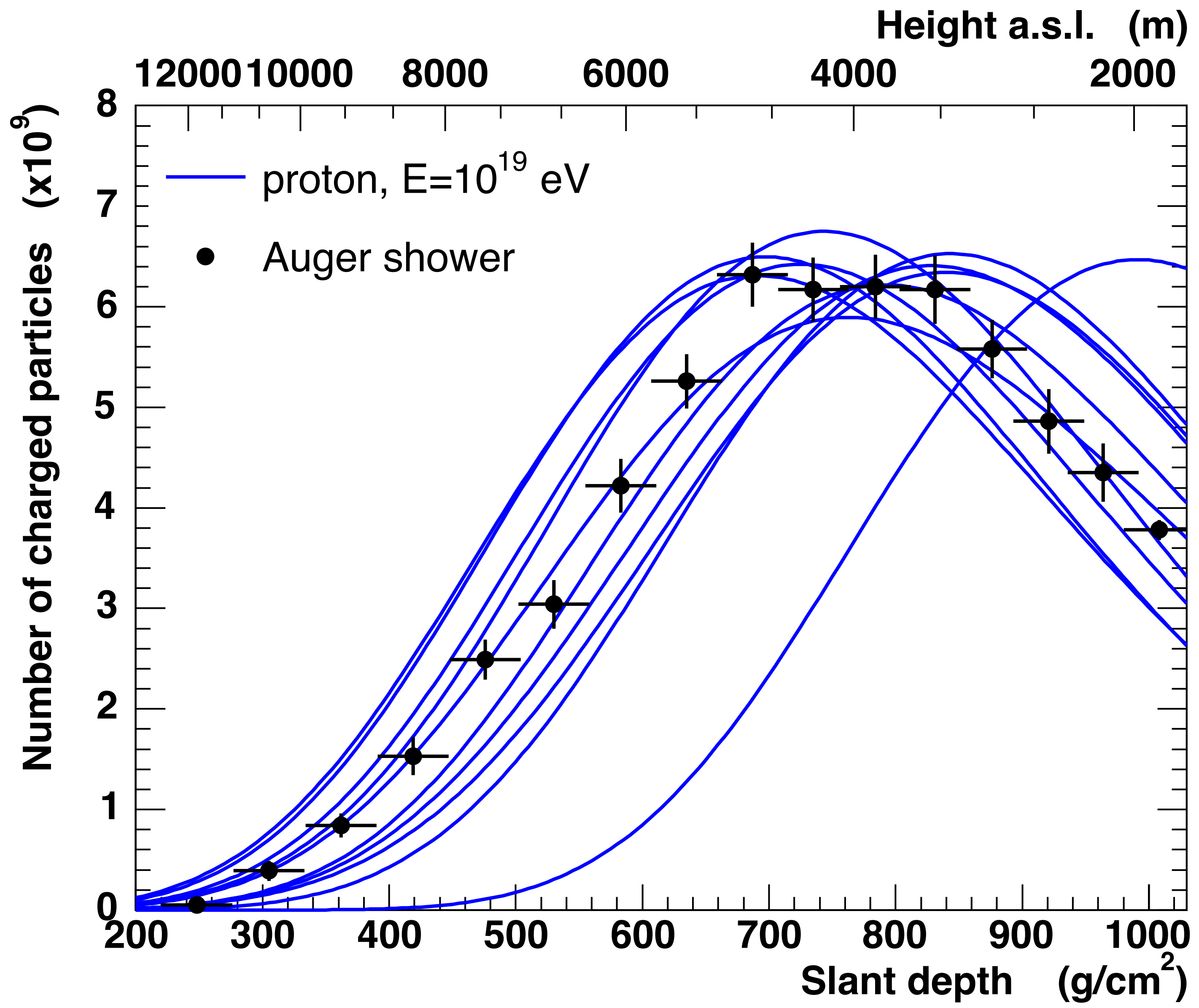
$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\alpha$$

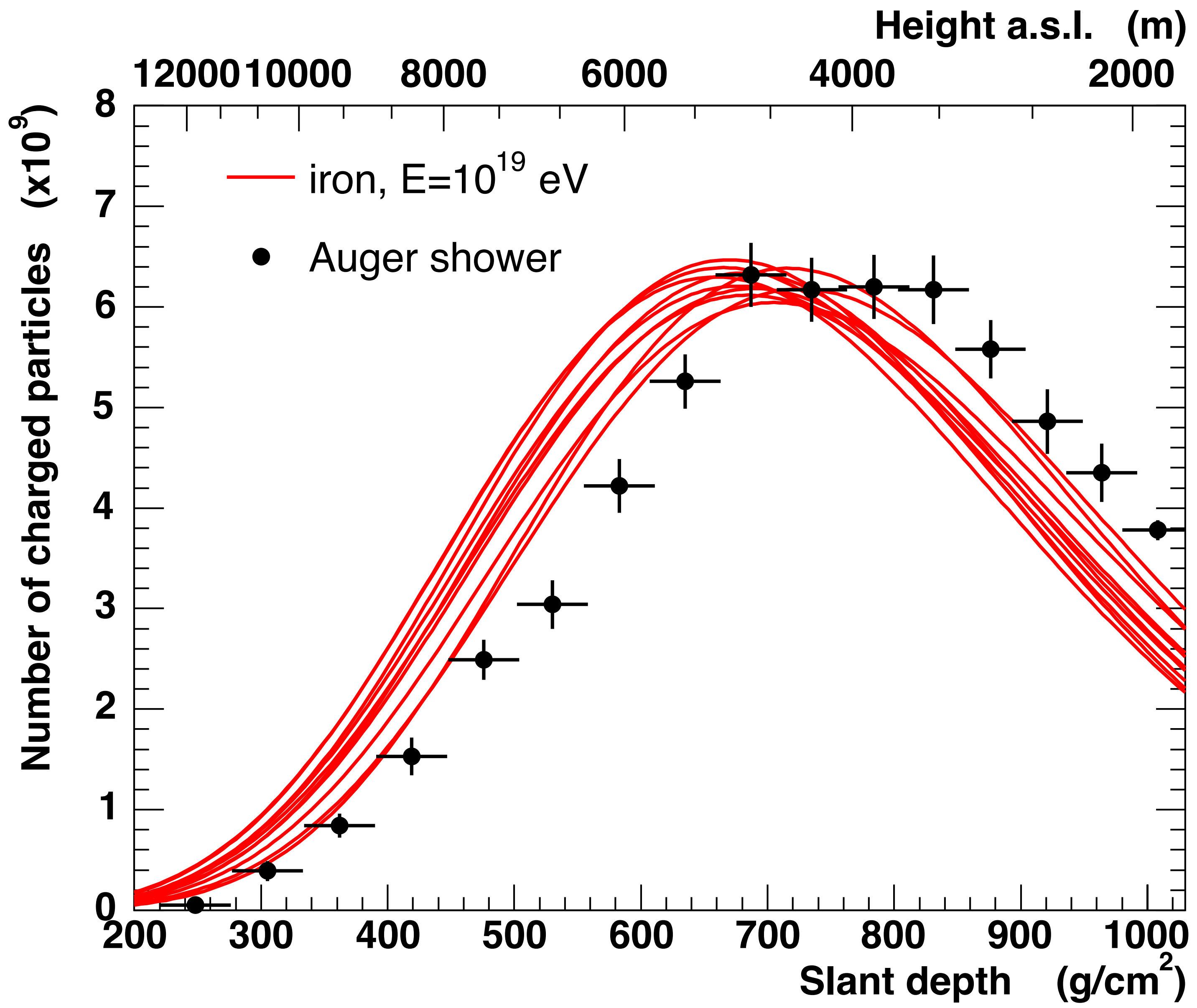


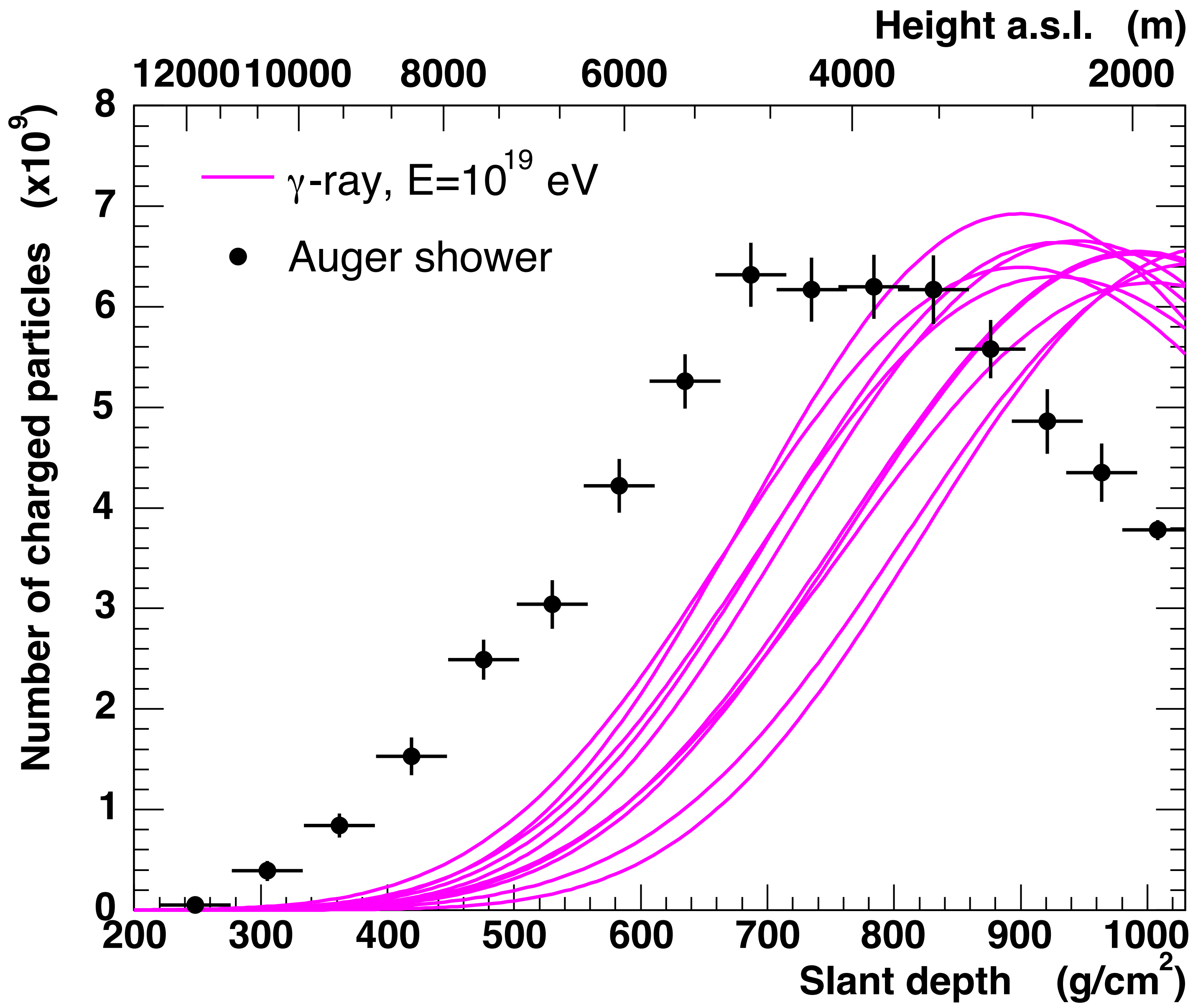
Pion decay energy depends on air density, low density corresponds to large $E_{\rm dec}$

Electromagnetic showers are independent of air density, hadronic showers not

Longitudinal shower profiles: simulations and data







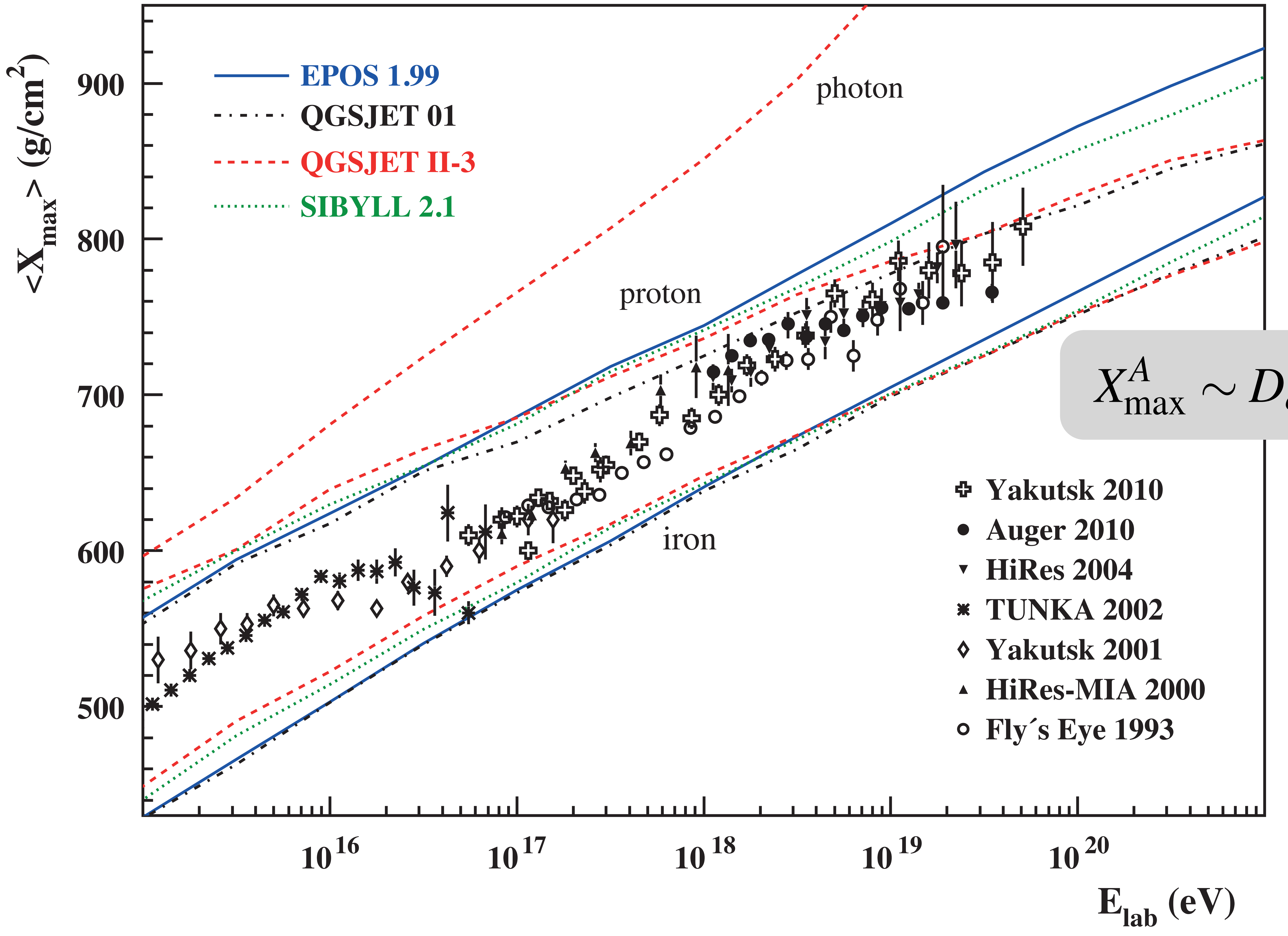
$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim D_{\mathrm{e}} \ln(E_0/E_c)$$

Superposition model:

$$X^A_{\max} \sim D_e \ln(E_0/AE_c)$$

Mean depth of shower maximum



$$X^A_{\max} \sim D_e \ln(E_0/AE_c)$$

Note: old data and model predictions (just for clarity)

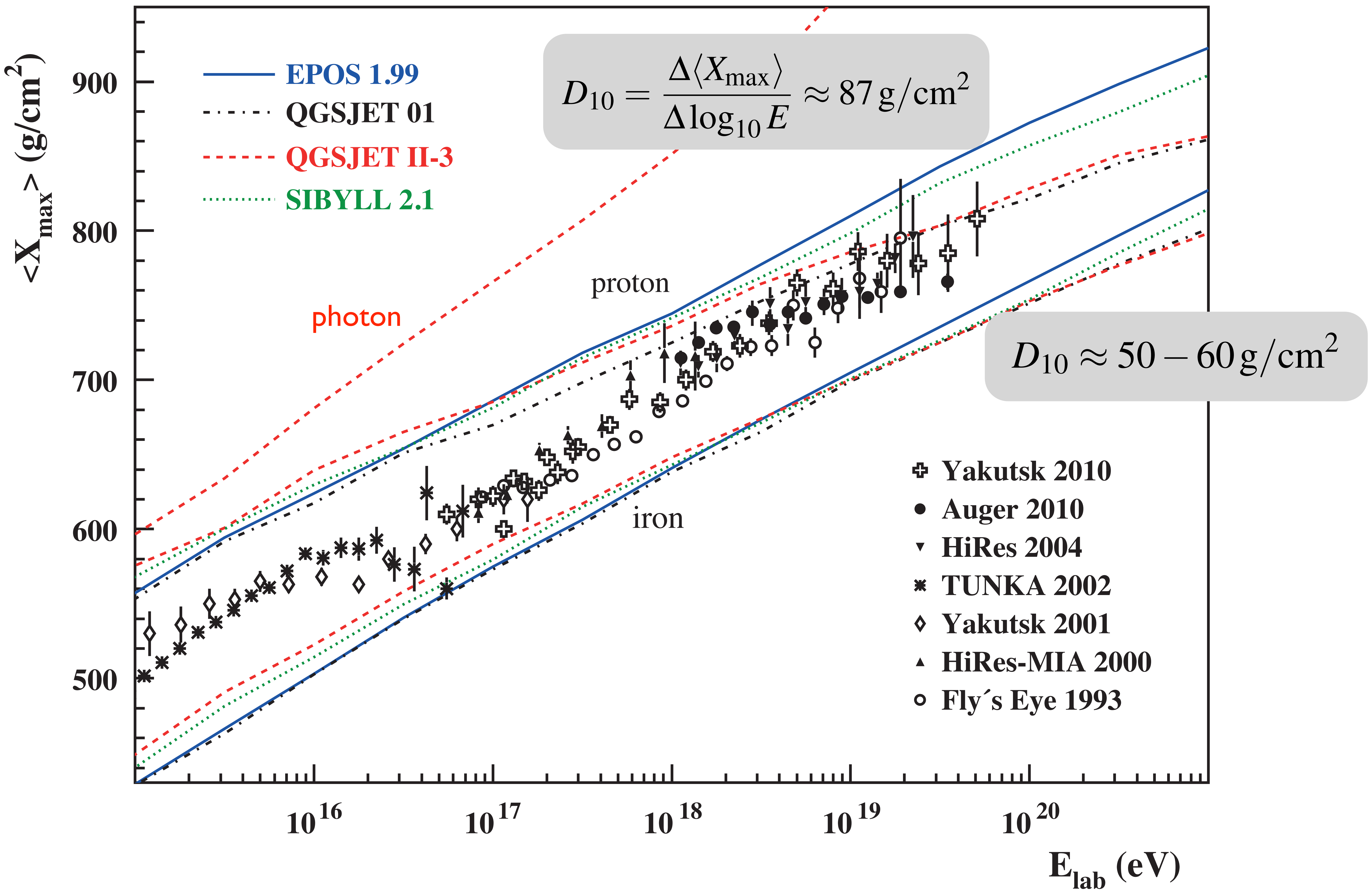
(RE, Pierog, Heck, ARNPS 2011)

Different slopes for em. and hadronic showers

$$D_{10} = \frac{\Delta\langle X_{\max}\rangle}{\Delta \log_{10} E}$$

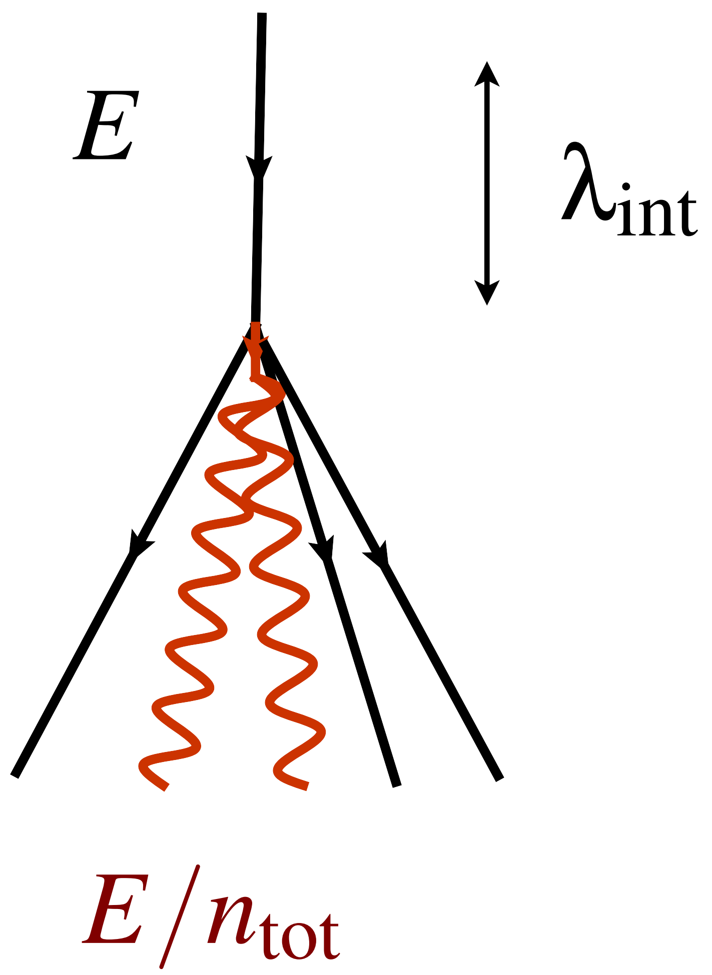
$$D_e = \frac{\Delta\langle X_{\max}\rangle}{\Delta \ln E}$$

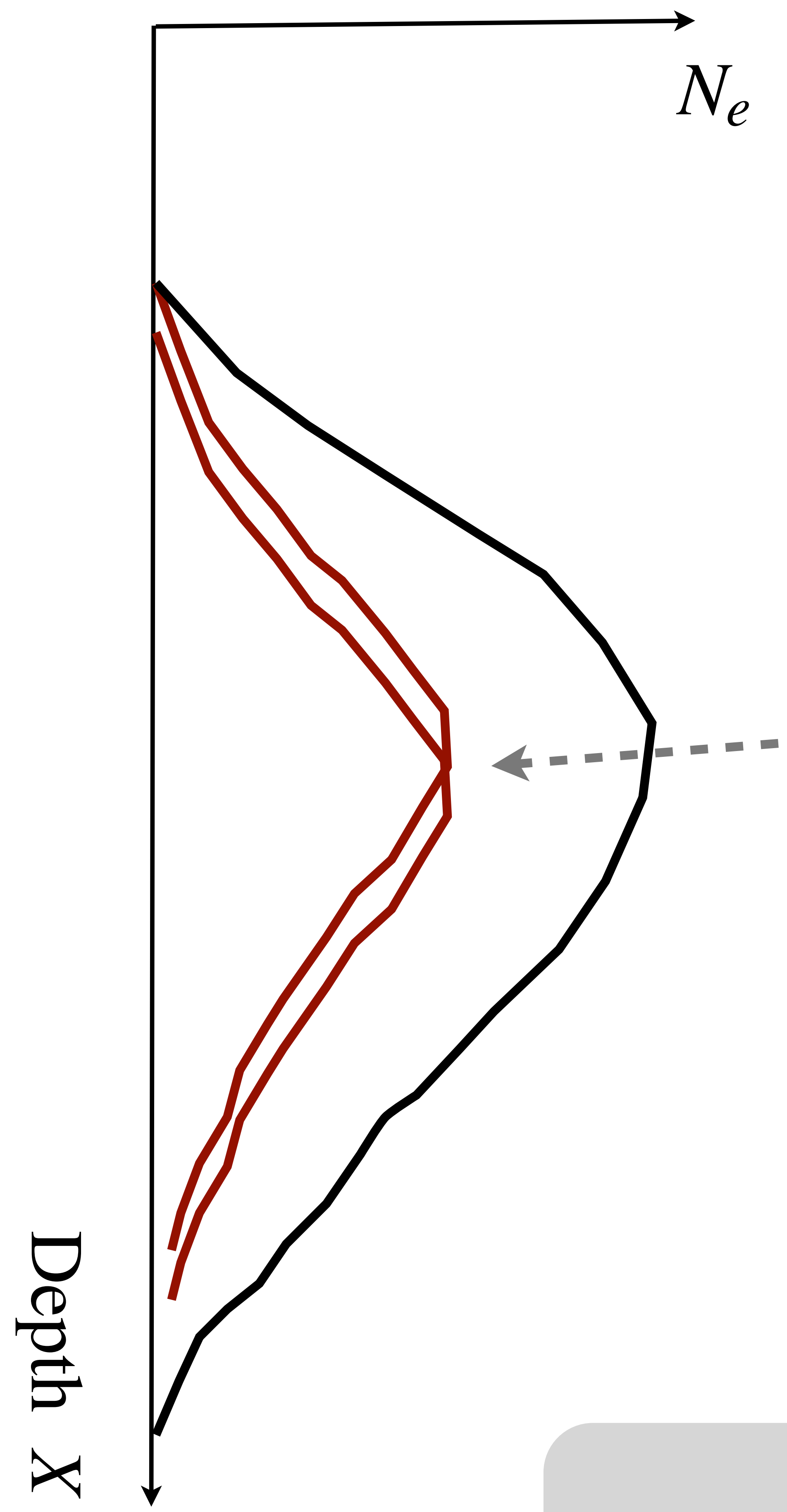
$$D_{10} = \log(10) D_e$$



(RE, Pierog, Heck, ARNPS 2011)

Derivation of elongation rate theorem





$$\langle X_{\rm max}(E)\rangle \;=\; \langle X^{\rm em}_{\rm max}(E/n_{\rm tot})\rangle \;+\; \lambda_{\rm int}$$

em. cascade theory

$$\langle X^{\rm em}_{\rm max}\rangle \sim X_0 \ln(E/n_{\rm tot})$$

$$\langle X_{\rm max}(E)\rangle \;=\; X_0\;\ln(E/n_{\rm tot}) + c \;+\; \lambda_{\rm int}$$

taking derivative $\log E$

$$D_e = \frac{{\rm d}\langle X_{\rm max}(E)\rangle}{{\rm d}\ln E} \;\leq\; X_0 \;-\; X_0 \frac{{\rm d}\ln n_{\rm tot}}{{\rm d}\ln E} \;+\; \frac{{\rm d}\lambda_{\rm int}}{{\rm d}\ln E}$$

Elongation rate of em. shower

Elongation rate theorem

X_0 = 36 g/cm²

$$D_e^{\mathrm{had}} = X_0(1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

$$B_n = \frac{d\ln n_{\mathrm{tot}}}{d\ln E}$$

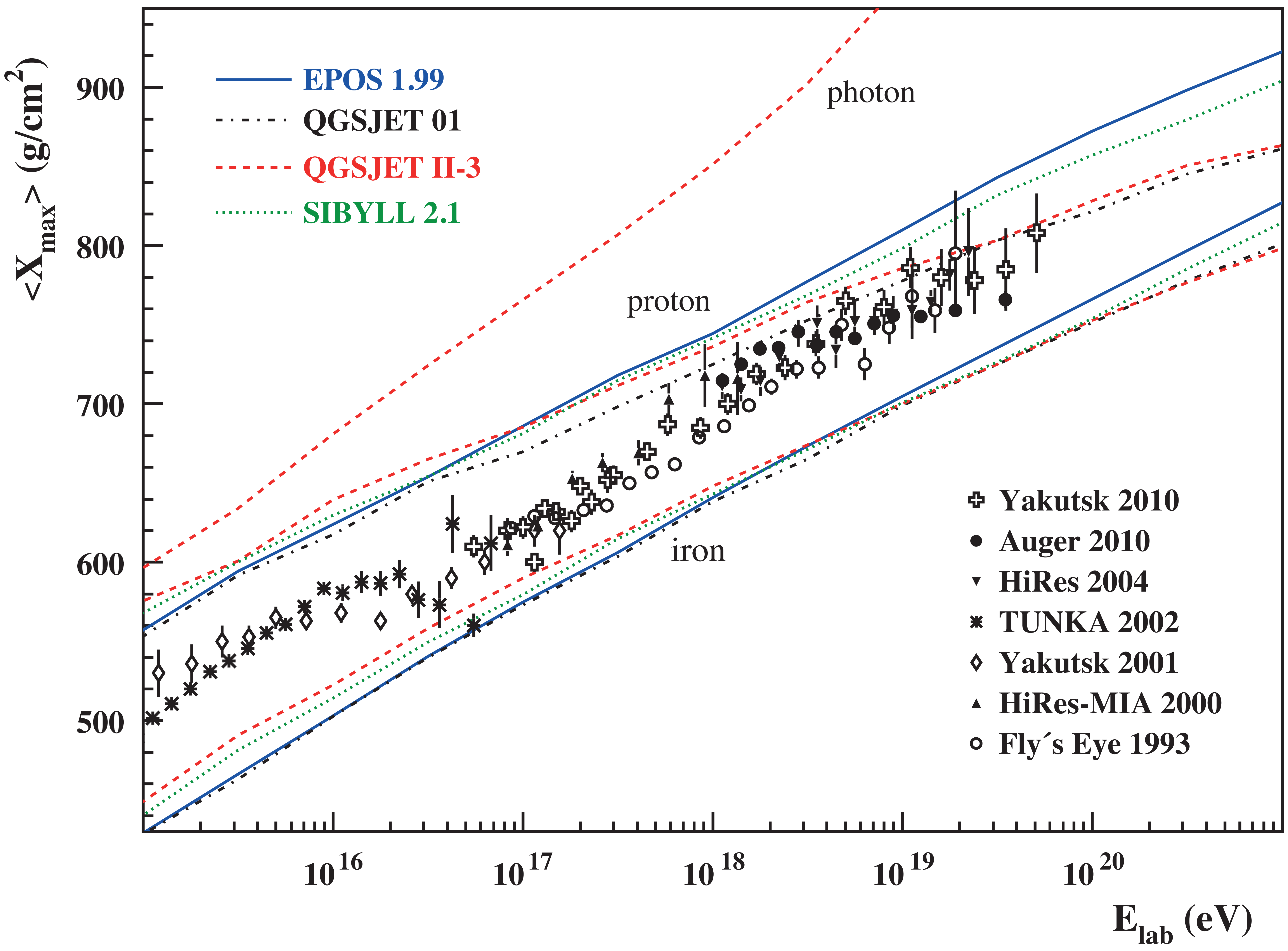
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

$$B_\lambda = -\frac{1}{X_0}\frac{d\lambda_{\mathrm{int}}}{d\ln E}$$

Large if cross section rises rapidly with energy

Note: $D_{10} = \log(10) D_e$

Mean depth of shower maximum



QGSJET predicts very strong scaling violations

(RE, Pierog, Heck, ARNPS 2011)

Elongation rates and model features

Elongation rate theorem

$$D_{10}^{\text{had}} = \ln 10\, X_0 (1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

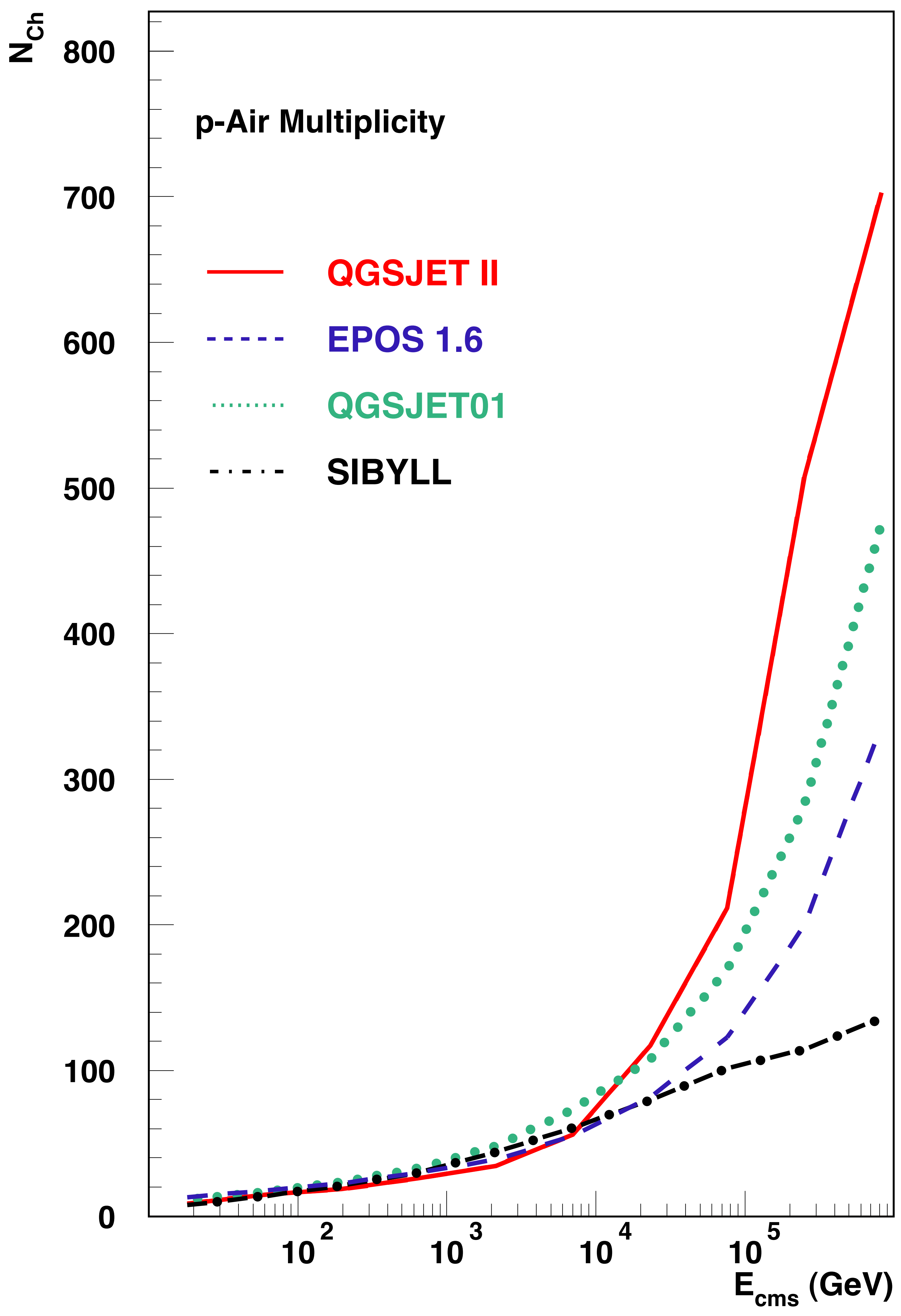
factor ~ 87 g/cm²

$$B_n = \frac{d \ln n_{\text{tot}}}{d \ln E}$$

Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

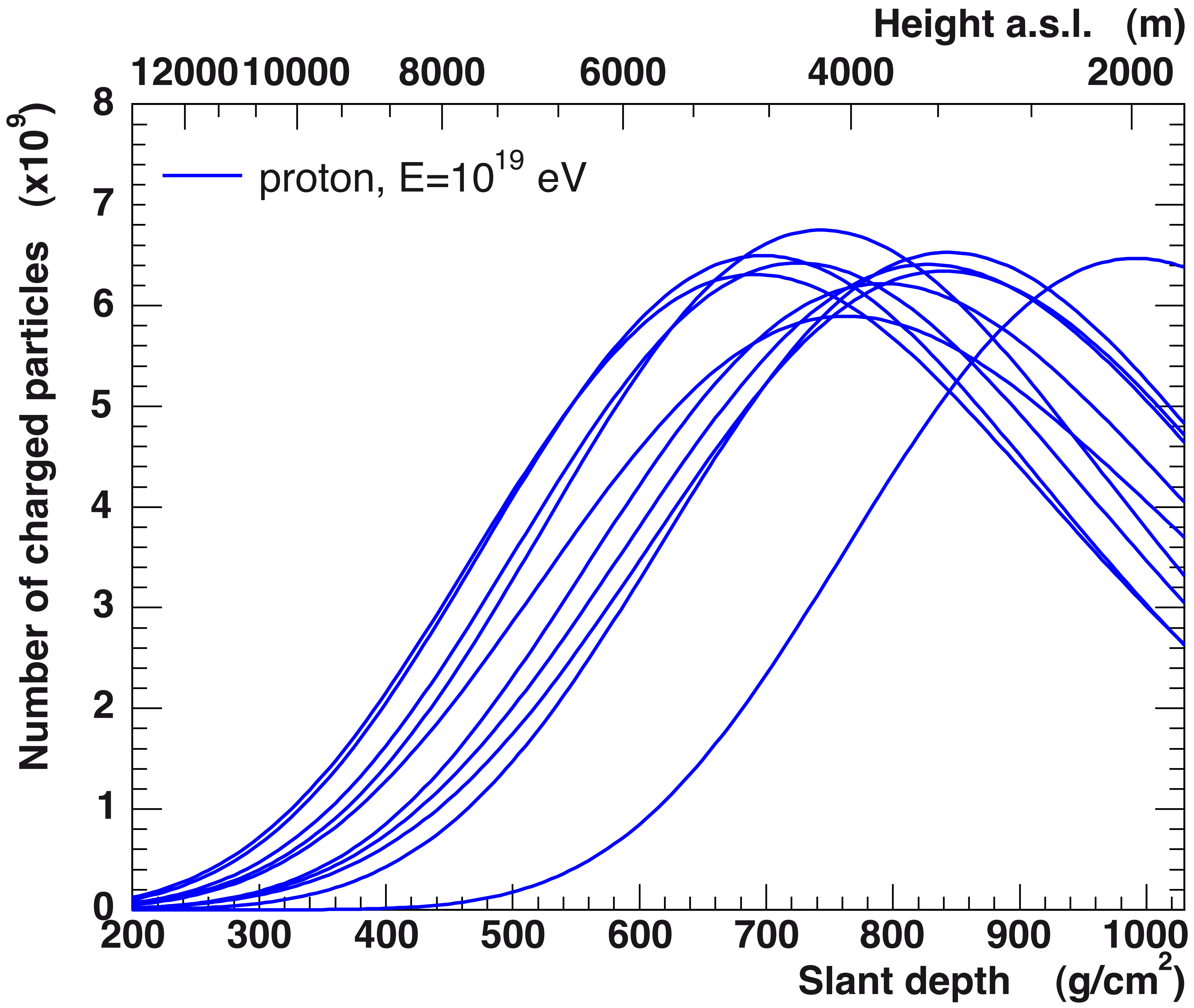
$$B_\lambda = -\frac{1}{X_0} \frac{d\lambda_{\text{int}}}{d \ln E}$$

Large if cross section rises rapidly with energy

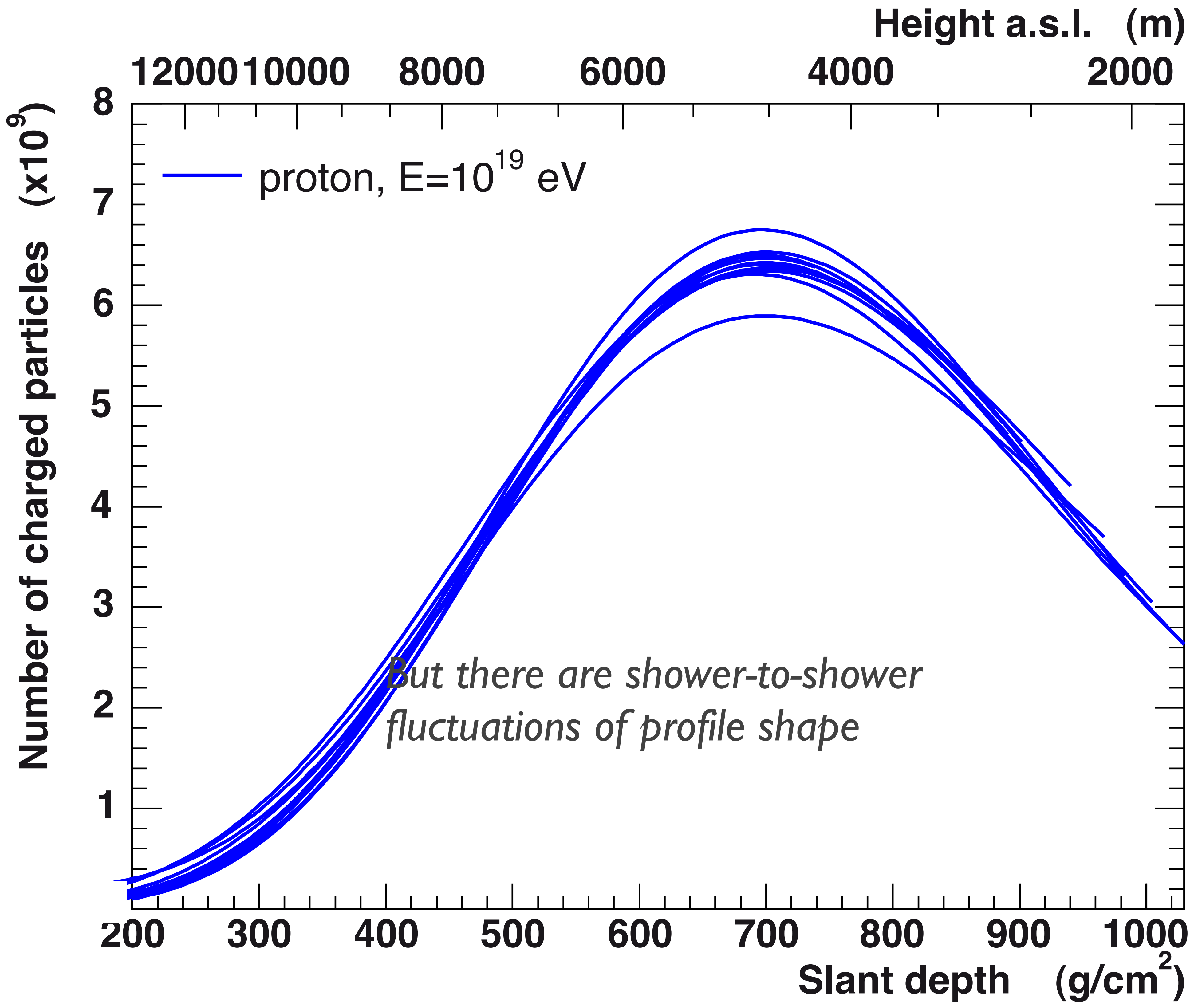


Universality features of high-energy shower profiles

Simulated shower profiles



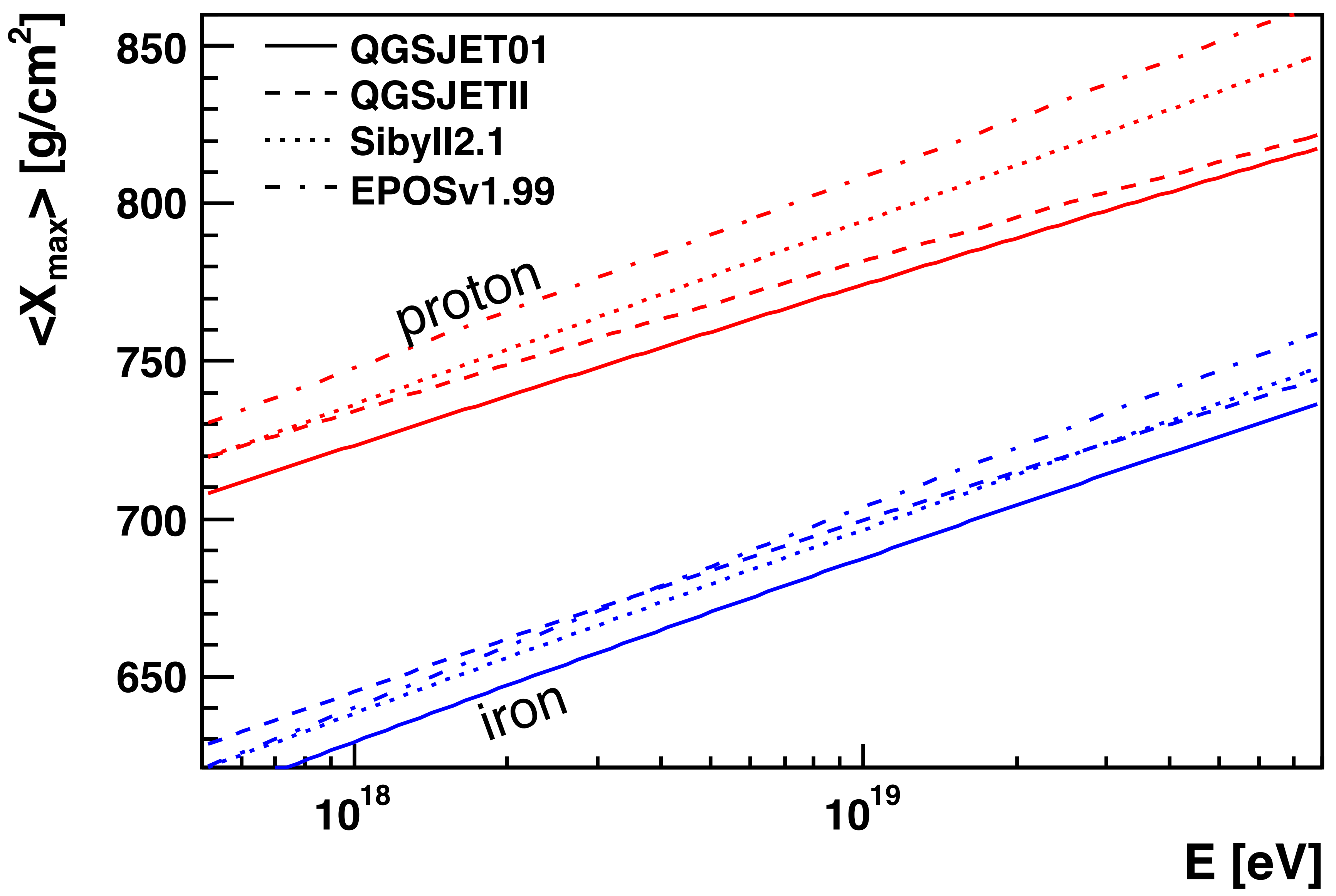
Profiles shifted in depth



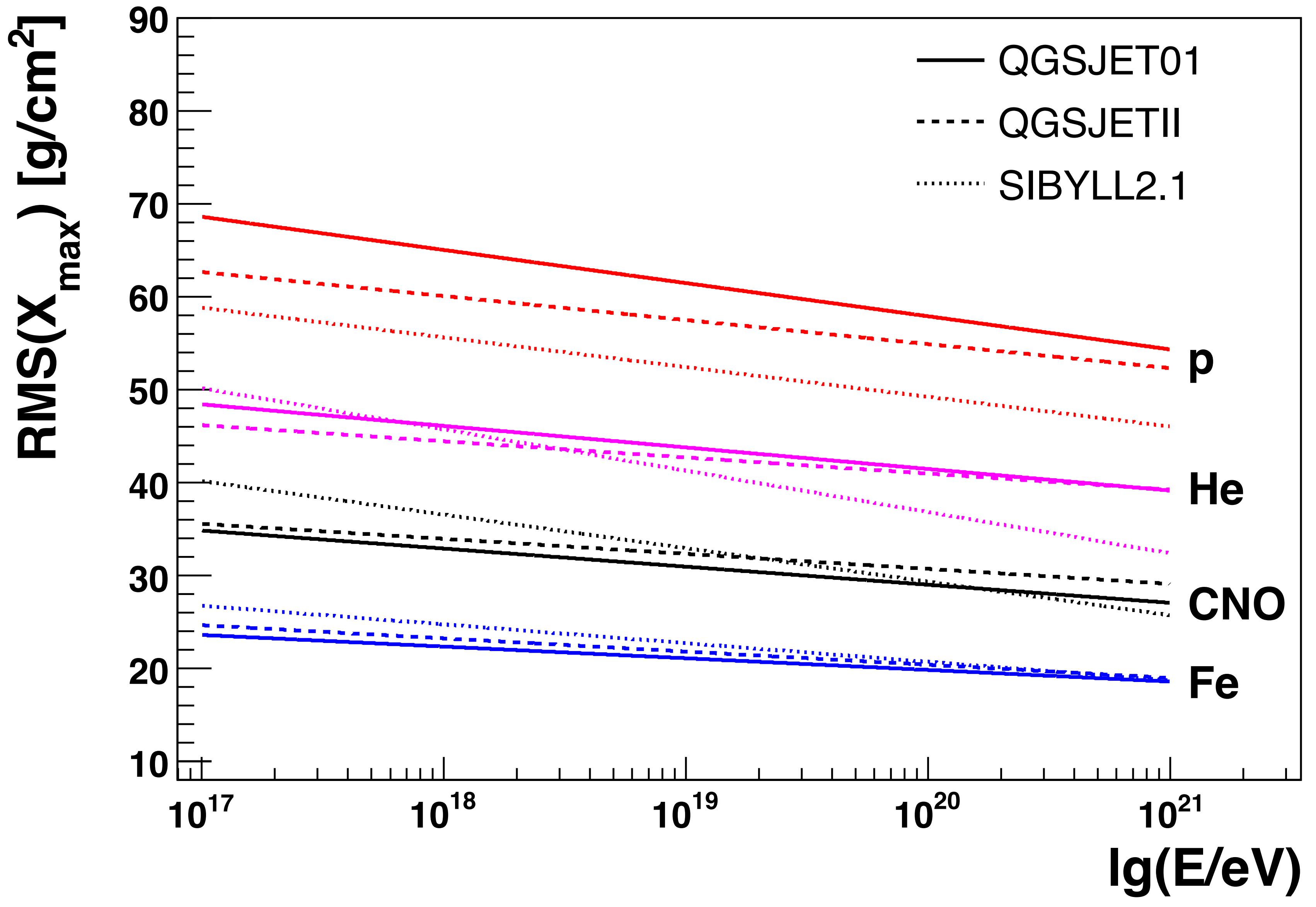
Depth of first interaction X_I and X_{max} strongly correlated, use X_{max} for analysis

Applications: mass composition and cross section

Information provided by Xmax fluctuations

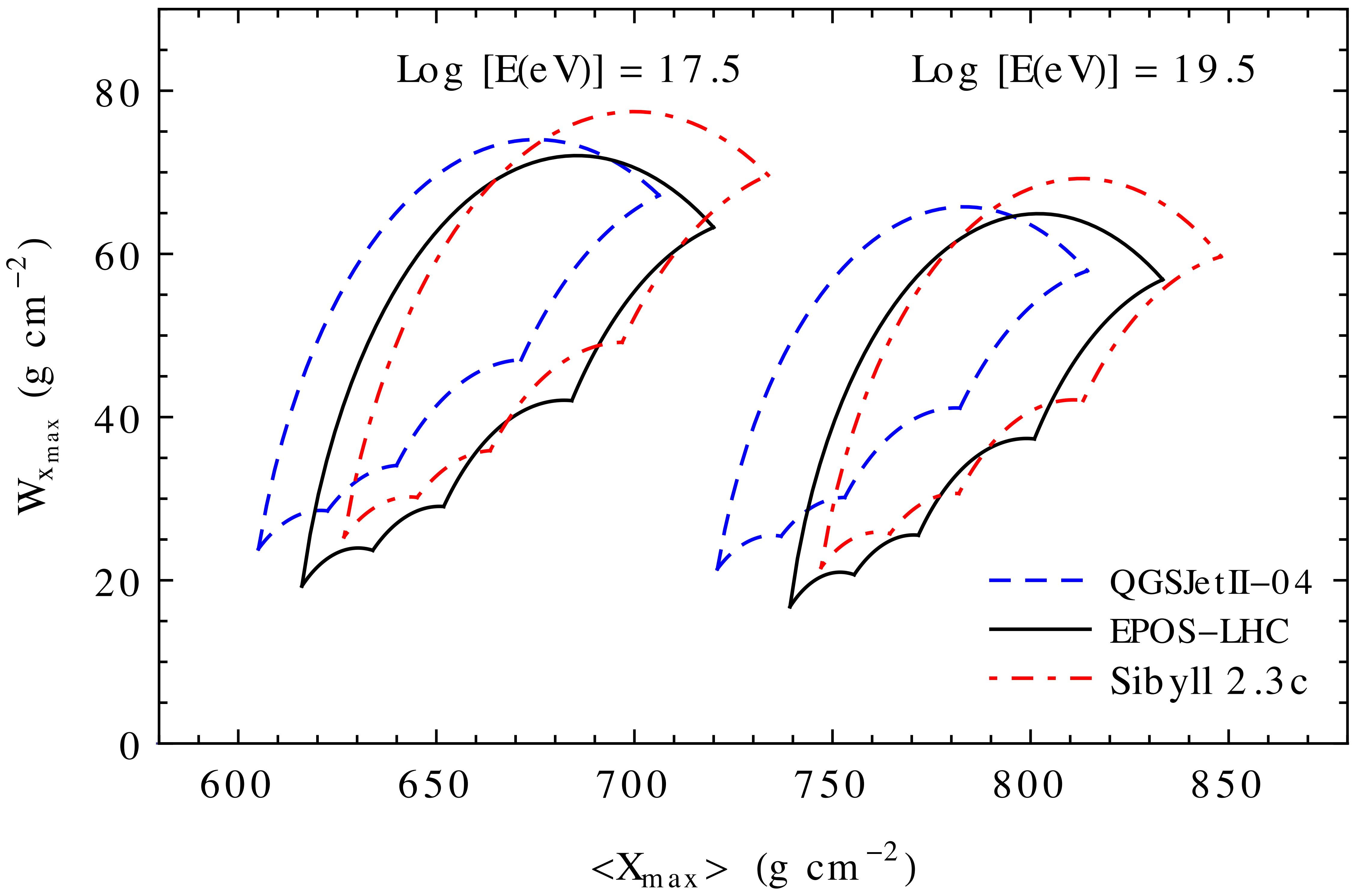


superposition model



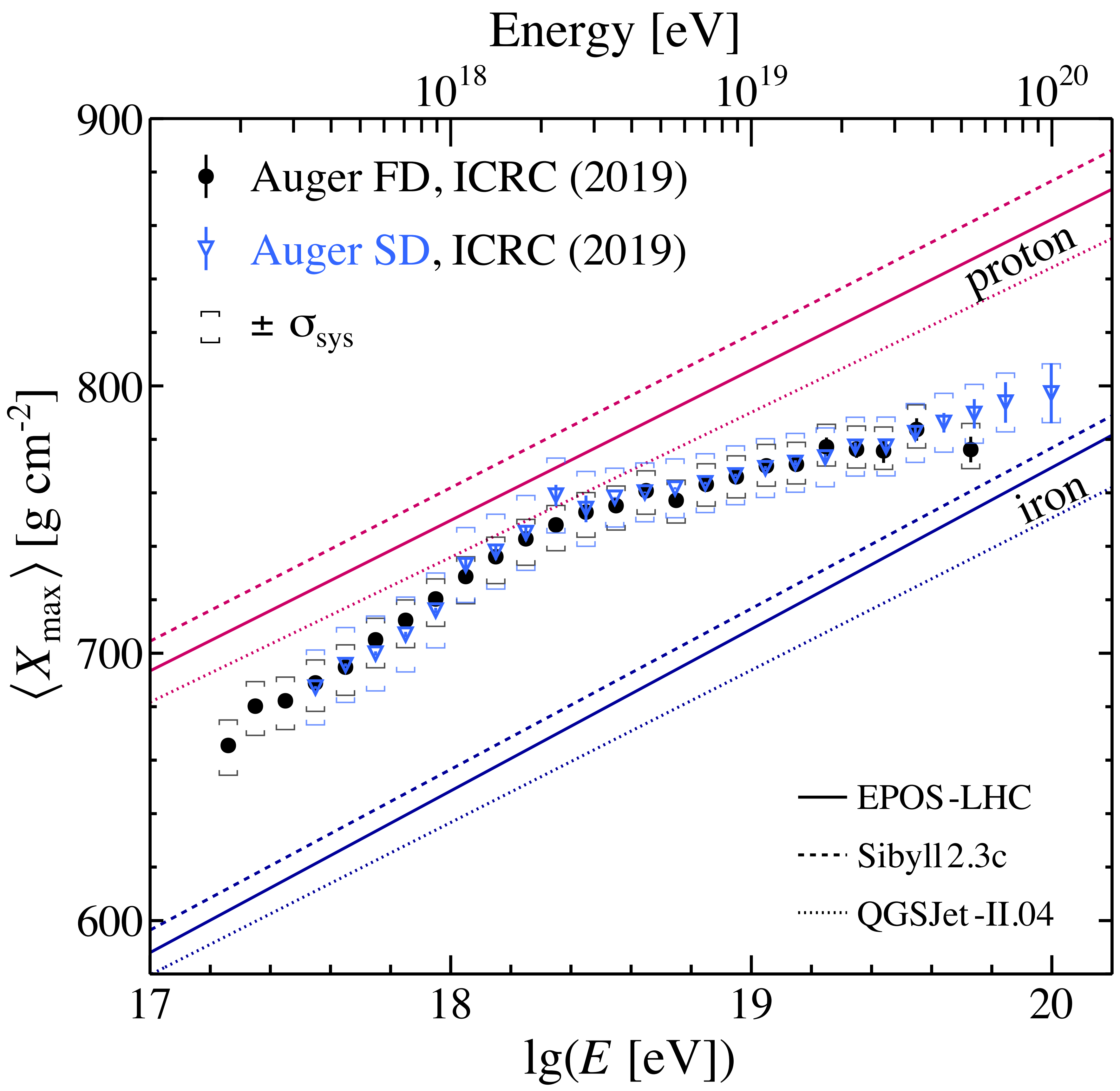
(Unger, Solvay 2018)

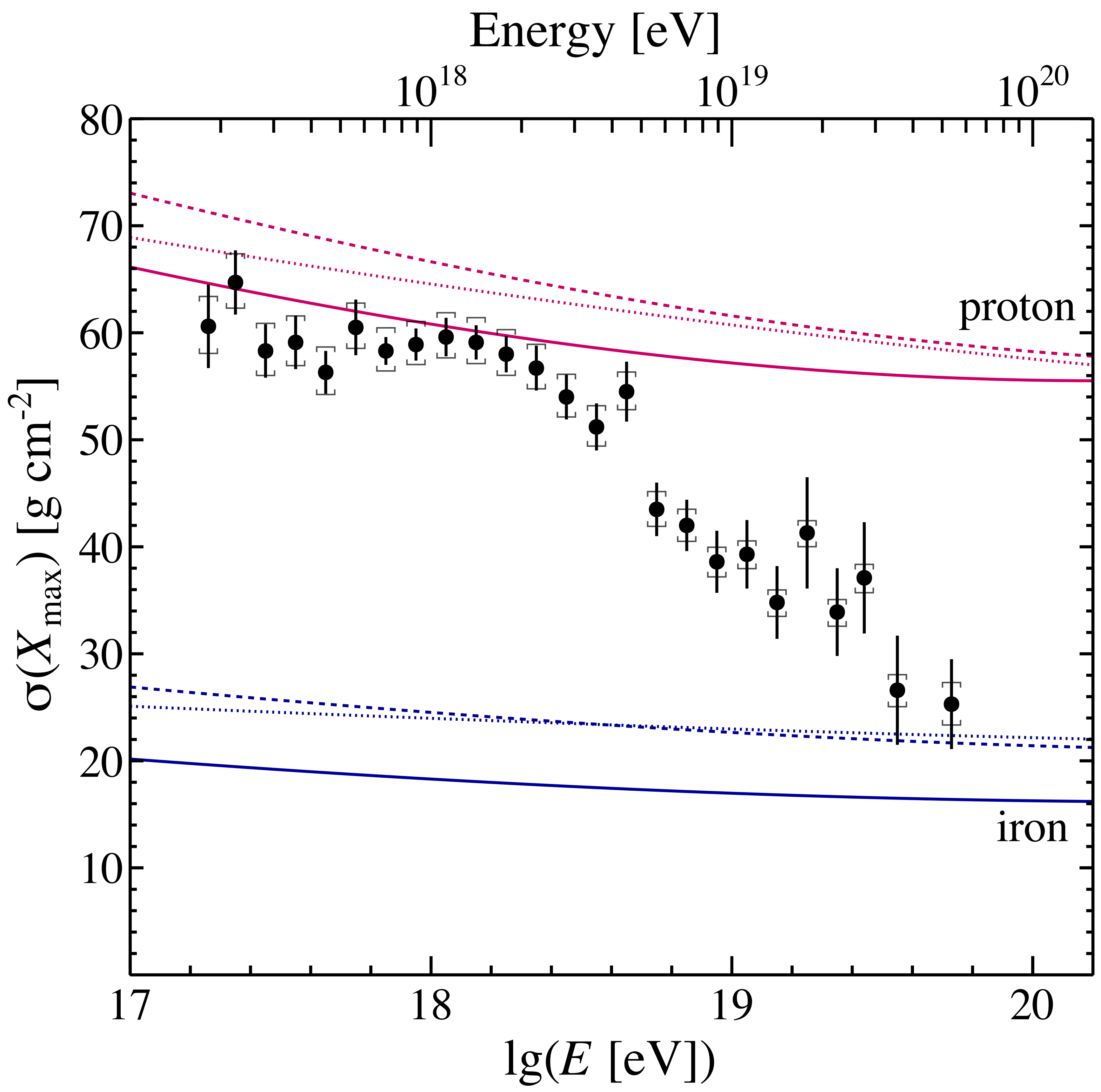
(Lipari, PRD 2021)

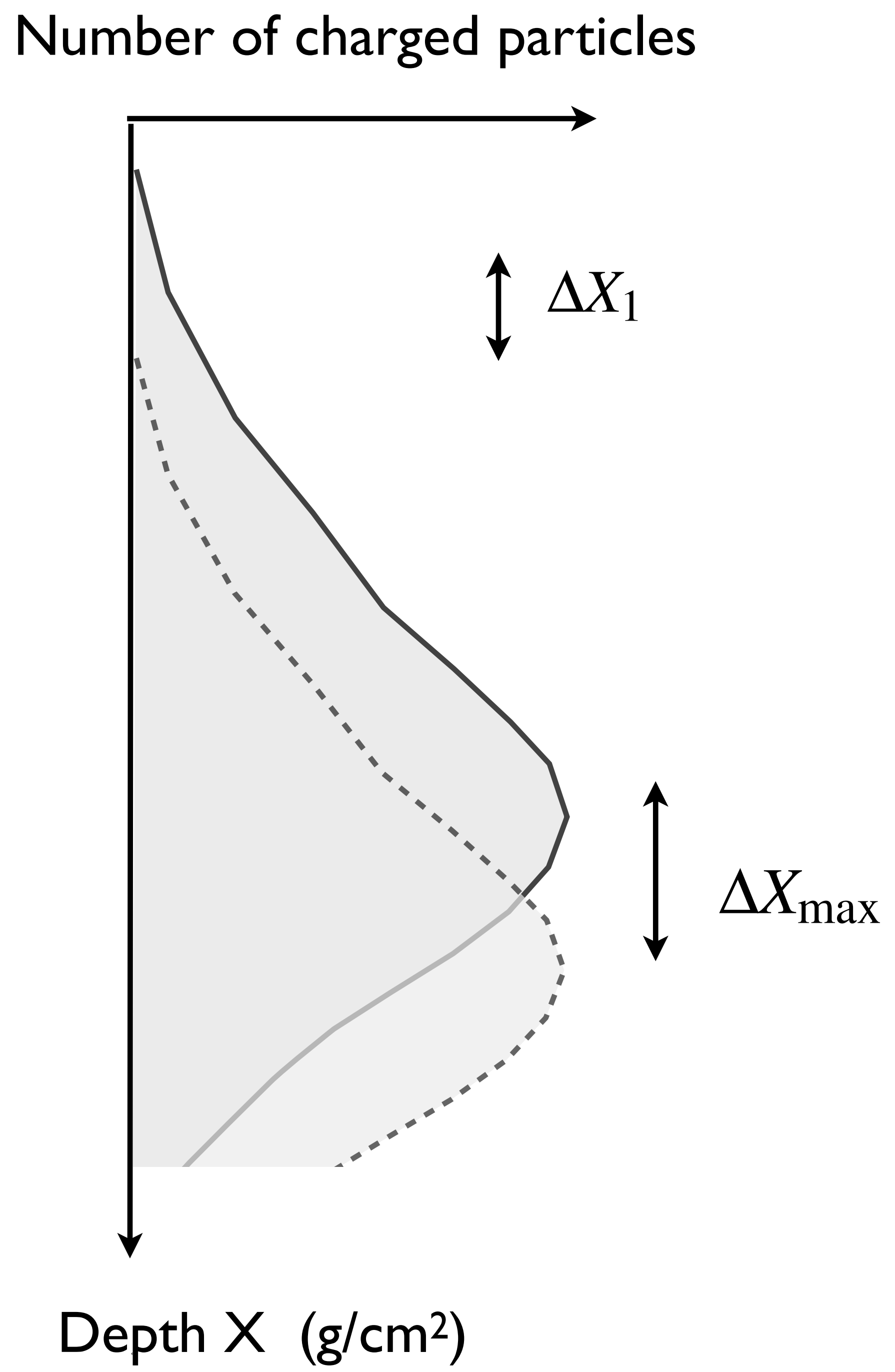


Model dependence of fluctuations seems small (for mixed composition)

Mass composition results – Auger Observatory







$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{X_1,p} \sim 45 - 55\,g/cm^2$$
$$\sigma_{X_1,Fe} \sim 10\,g/cm^2$$

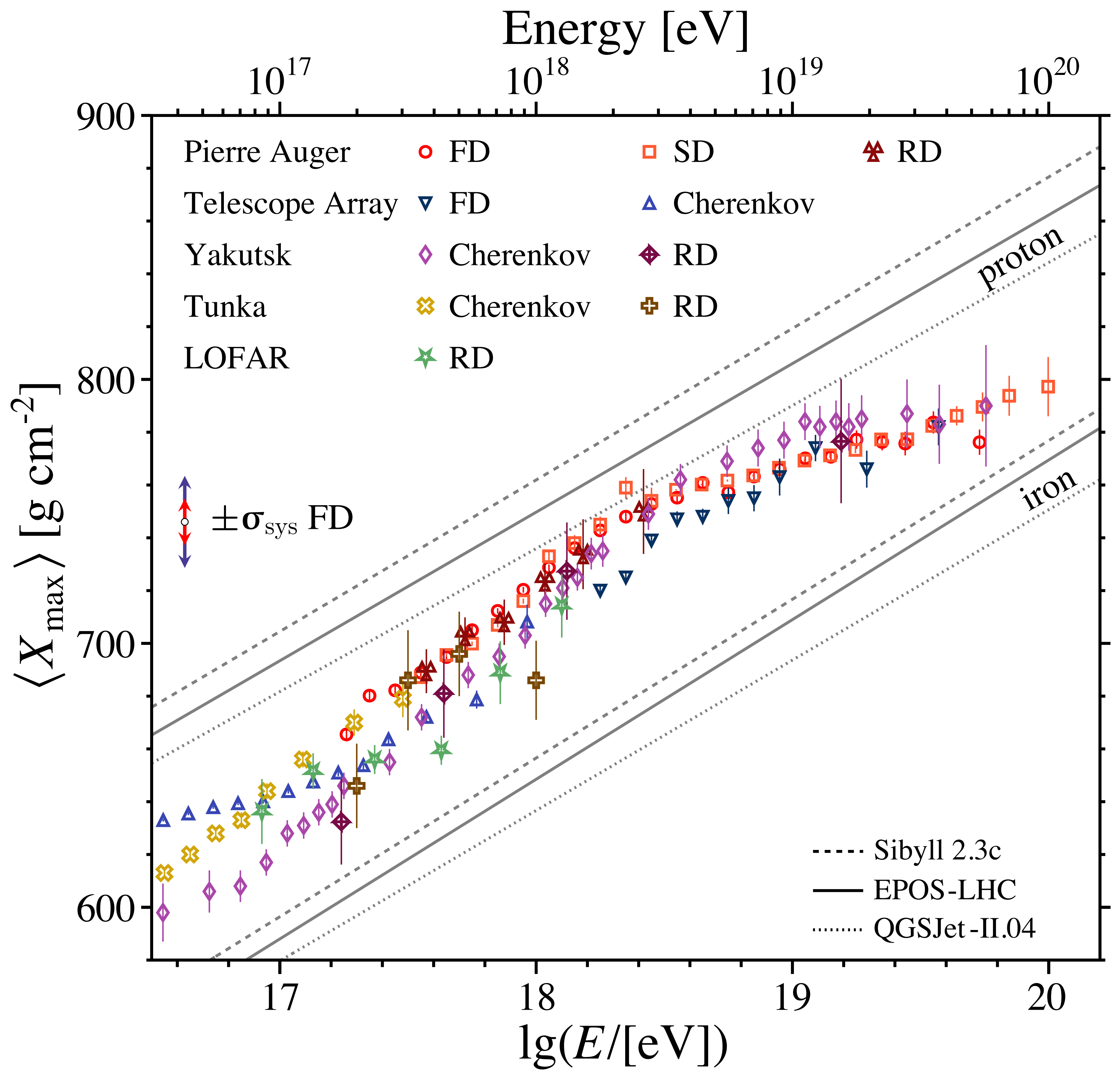
$(E \sim 10^{18}\,eV)$

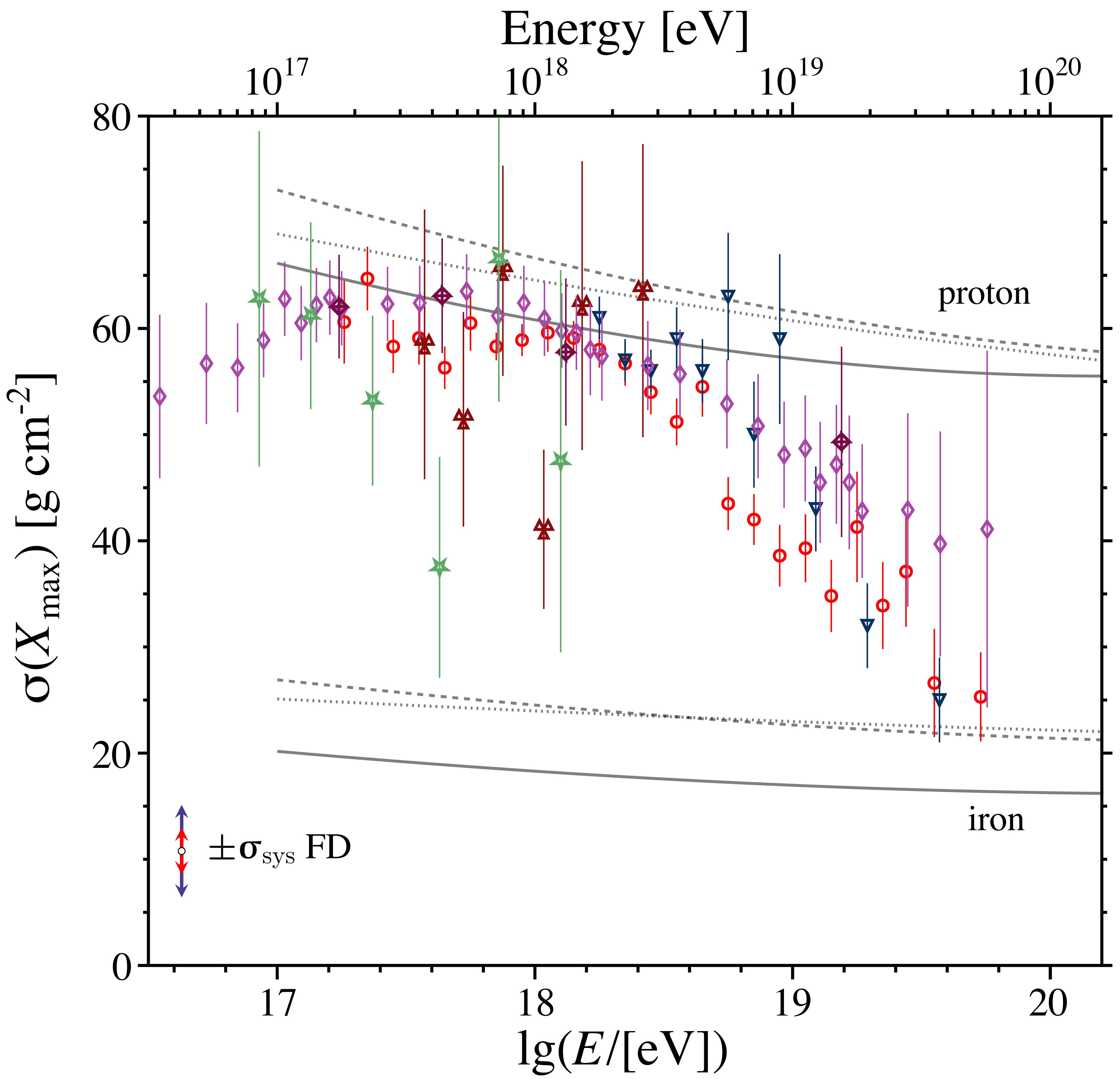
Important: LHC-tuned interaction models used for interpretation

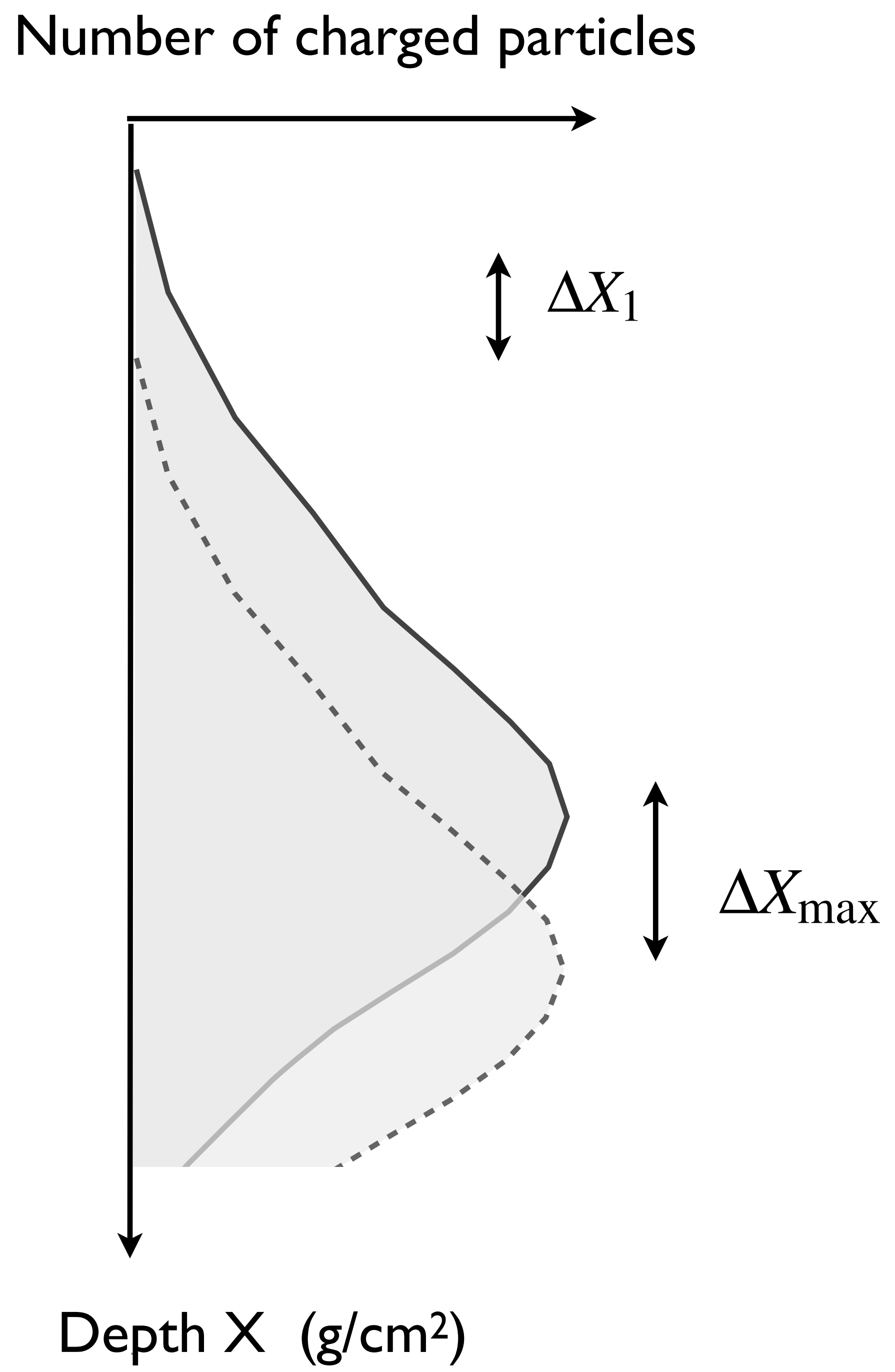
(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019)

(Phys. Rev. D96 (2017), 122003)

Mass composition results – world data







$$\frac{\mathrm{d}P}{\mathrm{d}X_1} = \frac{1}{\lambda_{\mathrm{int}}} e^{-X_1/\lambda_{\mathrm{int}}}$$

$$\sigma_{X_1,\mathrm{p}} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,\mathrm{Fe}} \sim 10\,\mathrm{g/cm^2}$$

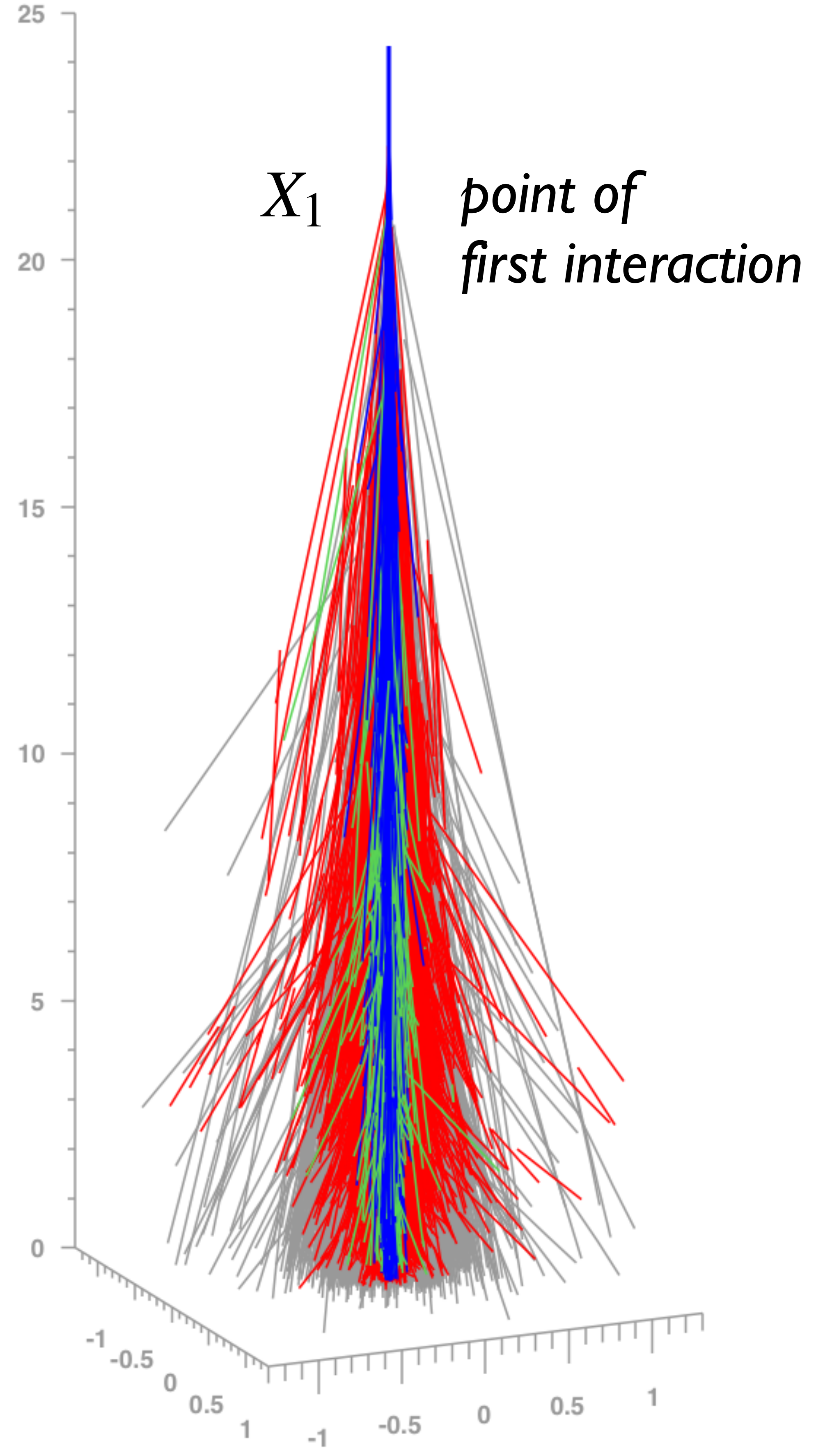
$(E \sim 10^{18}\,\mathrm{eV})$

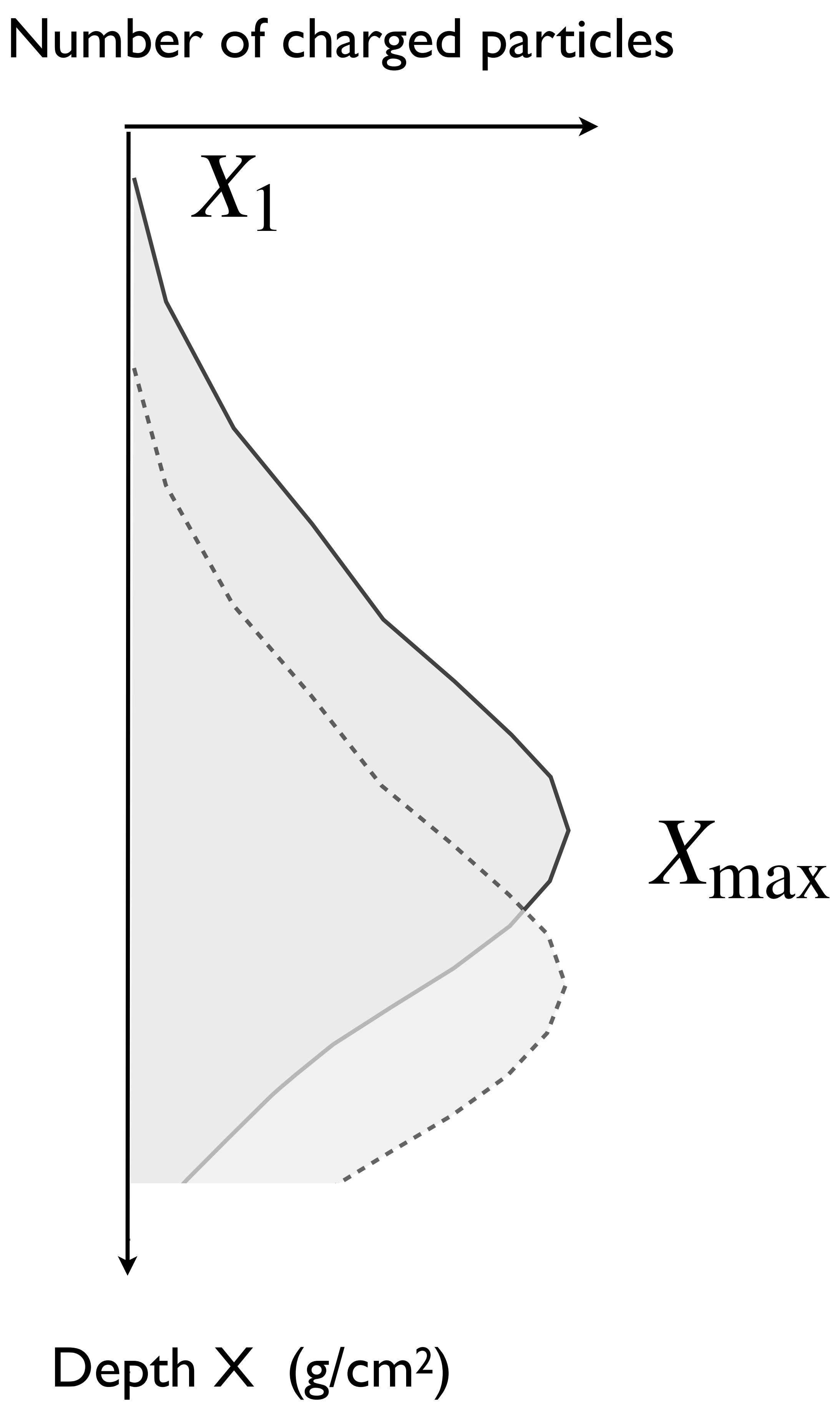
Important: LHC-tuned interaction models used for interpretation

(Snowmass report UHECR composition, 2022)

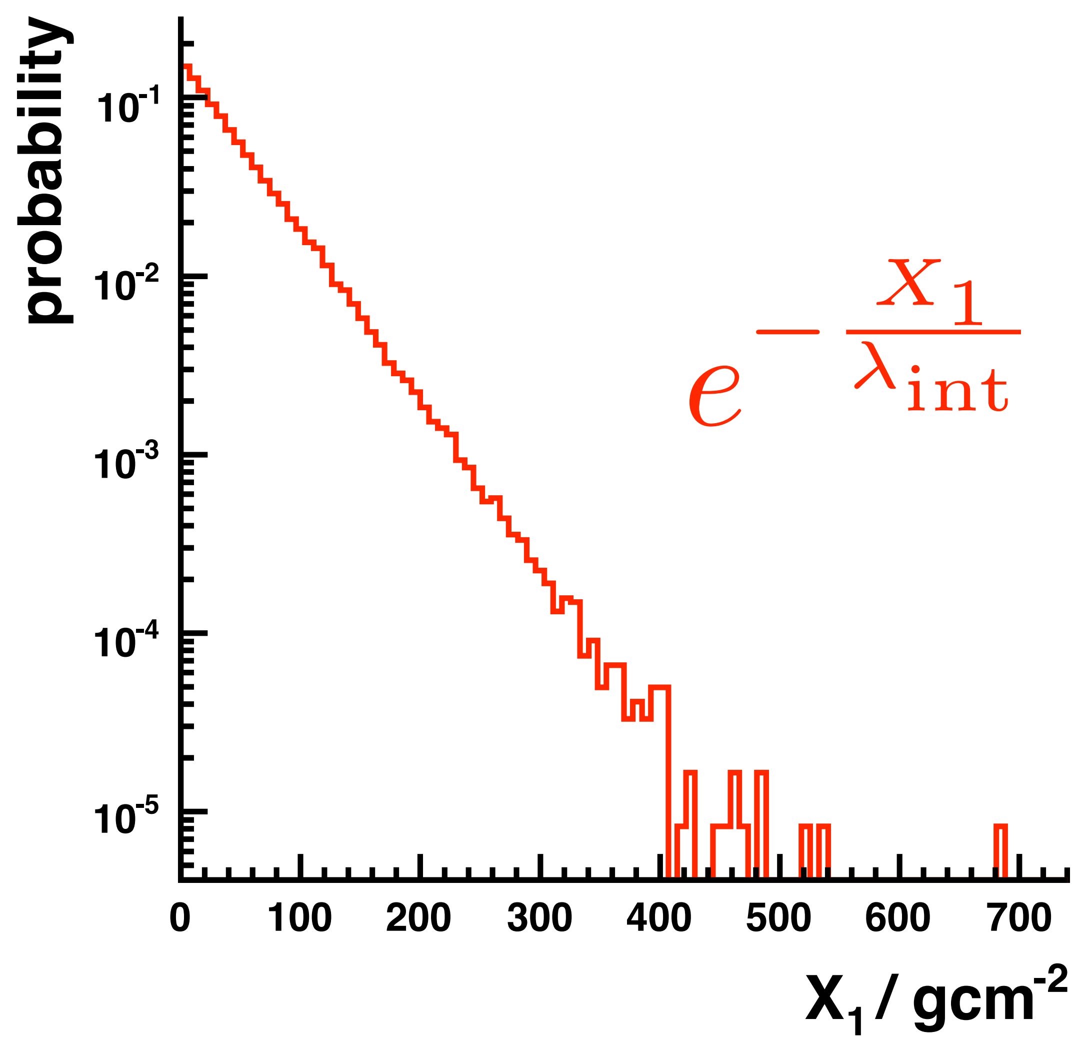
(Phys. Rev. D96 (2017), 122003)

Cross section measurement with air showers





Depth of first interaction



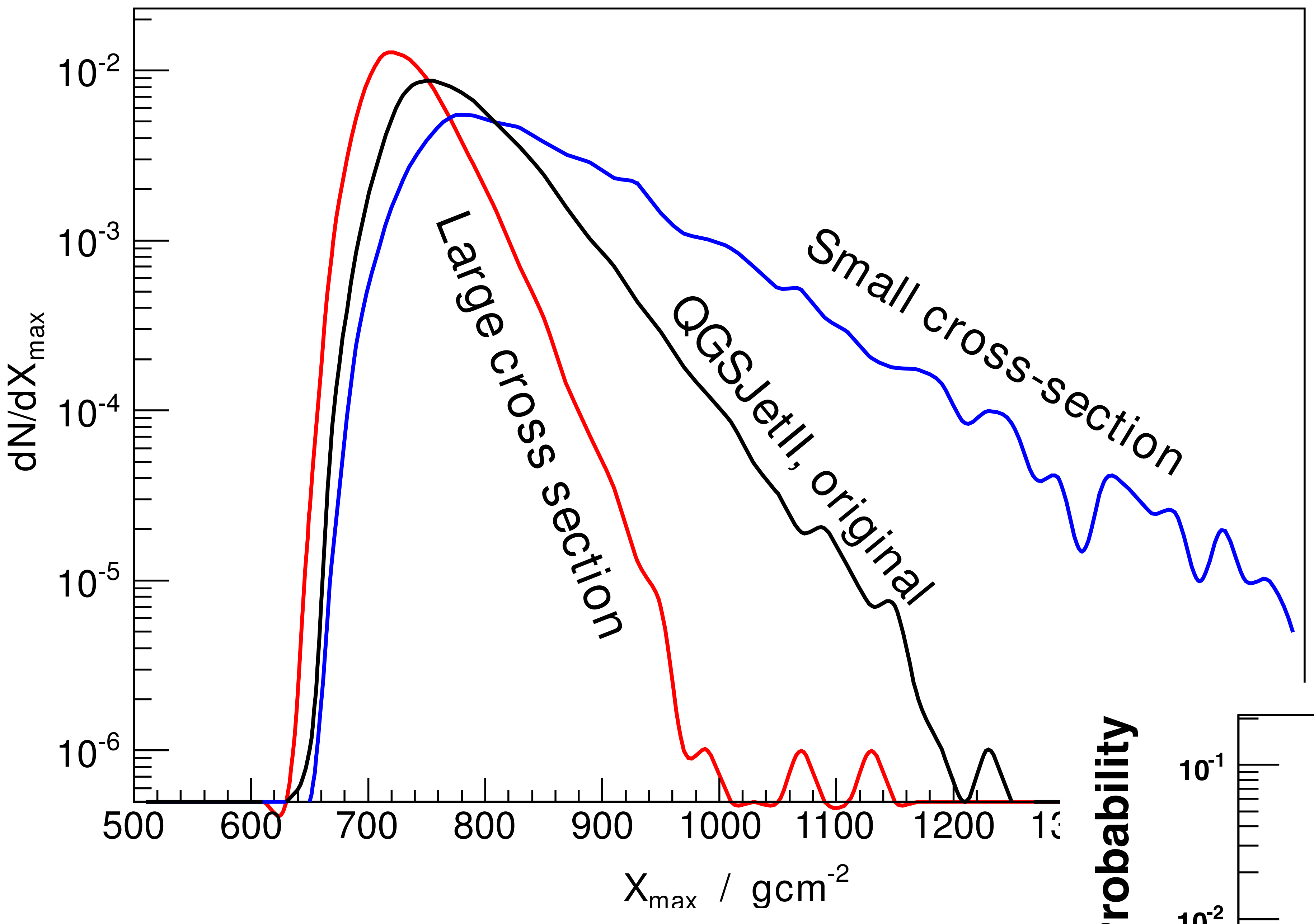
$$\sigma_{\mathrm{prod}} = \frac{\langle m_{\mathrm{air}} \rangle}{\lambda_{\mathrm{int}}}$$

Difficulties

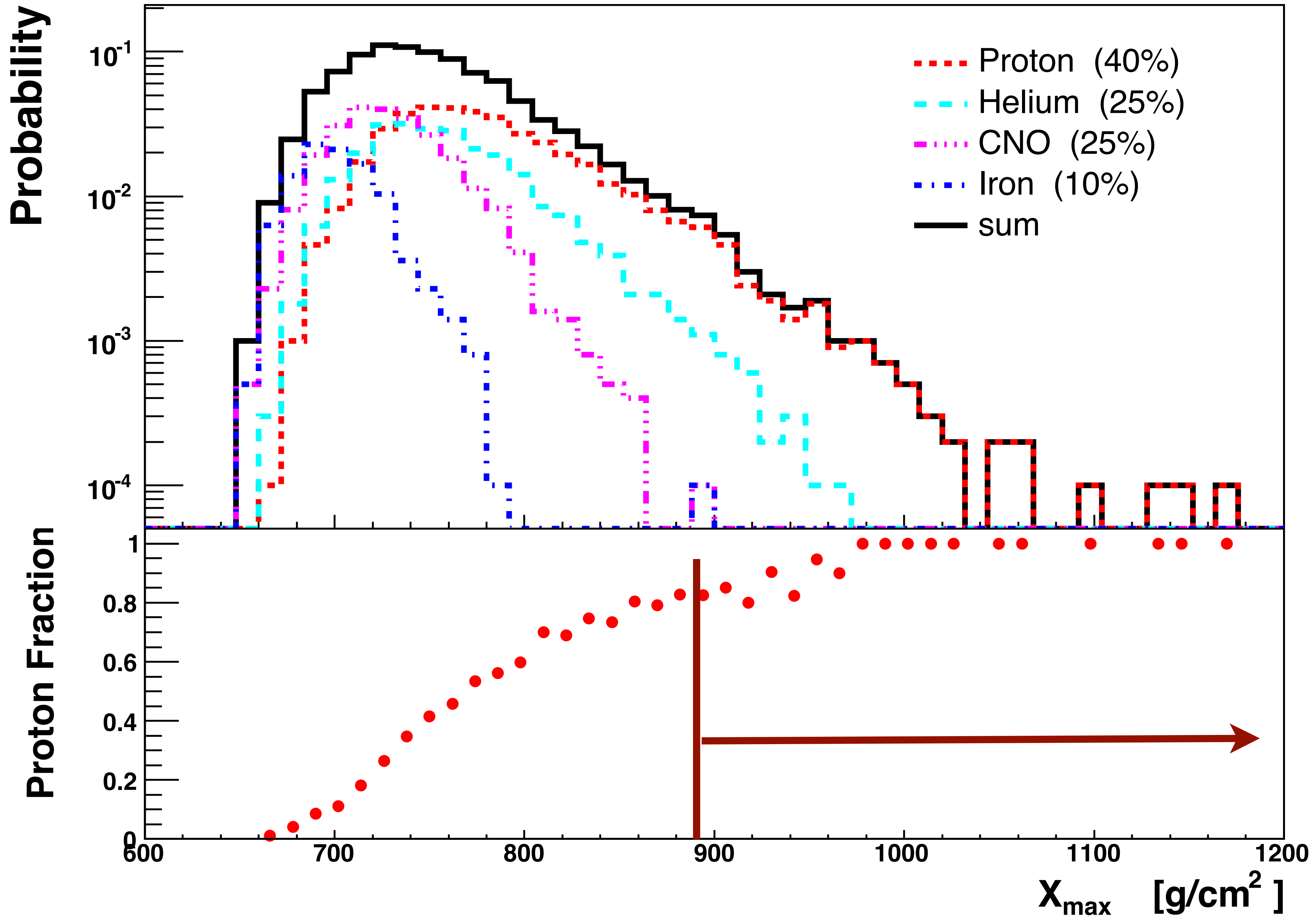
- mass composition (protons?)
- X_1 cannot be measured directly

(R. Ulrich et al. NJP 11, 2009)

Cross section measurement: composition bias?



Simulation for proton showers with different cross sections:
very good sensitivity of tail of distribution

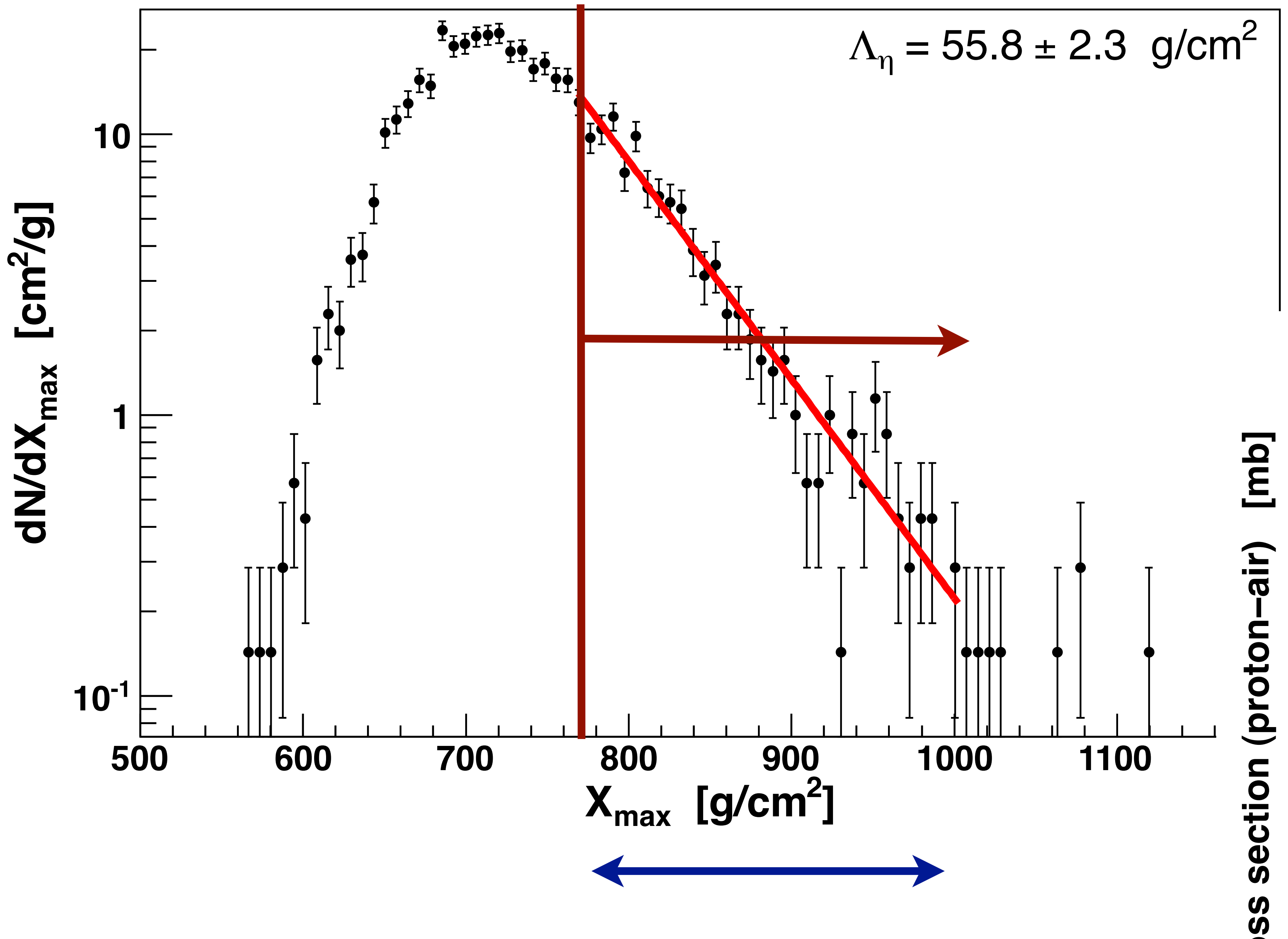


Example of distribution of X_{max} for mixed composition

Only deep showers are used in analysis to enhance proton fraction in data sample

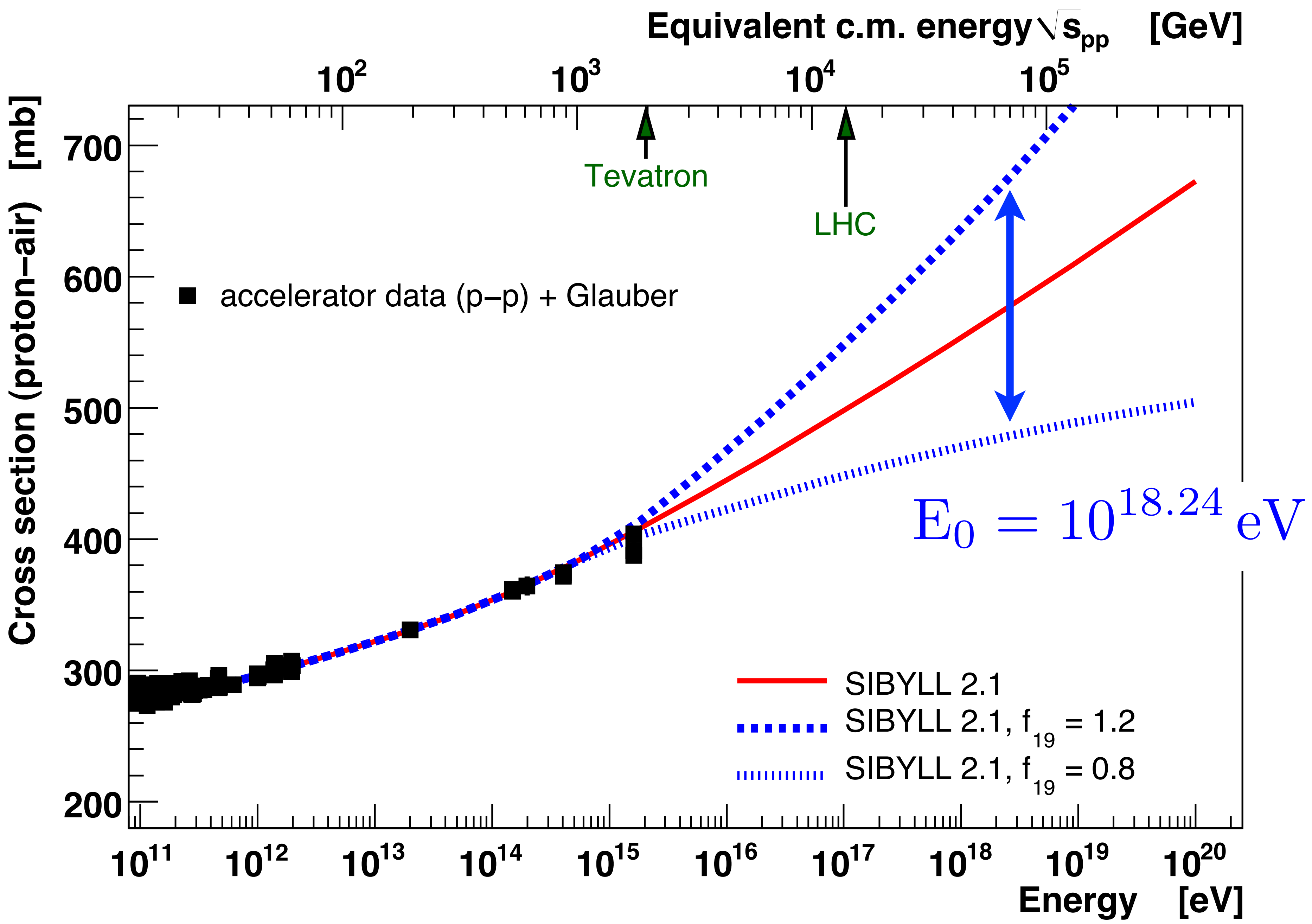
(Pierre Auger Collab. PRL)

Cross section measurement: self-consistency



Depth range of analysis

(Auger Collab. 1107.4804)

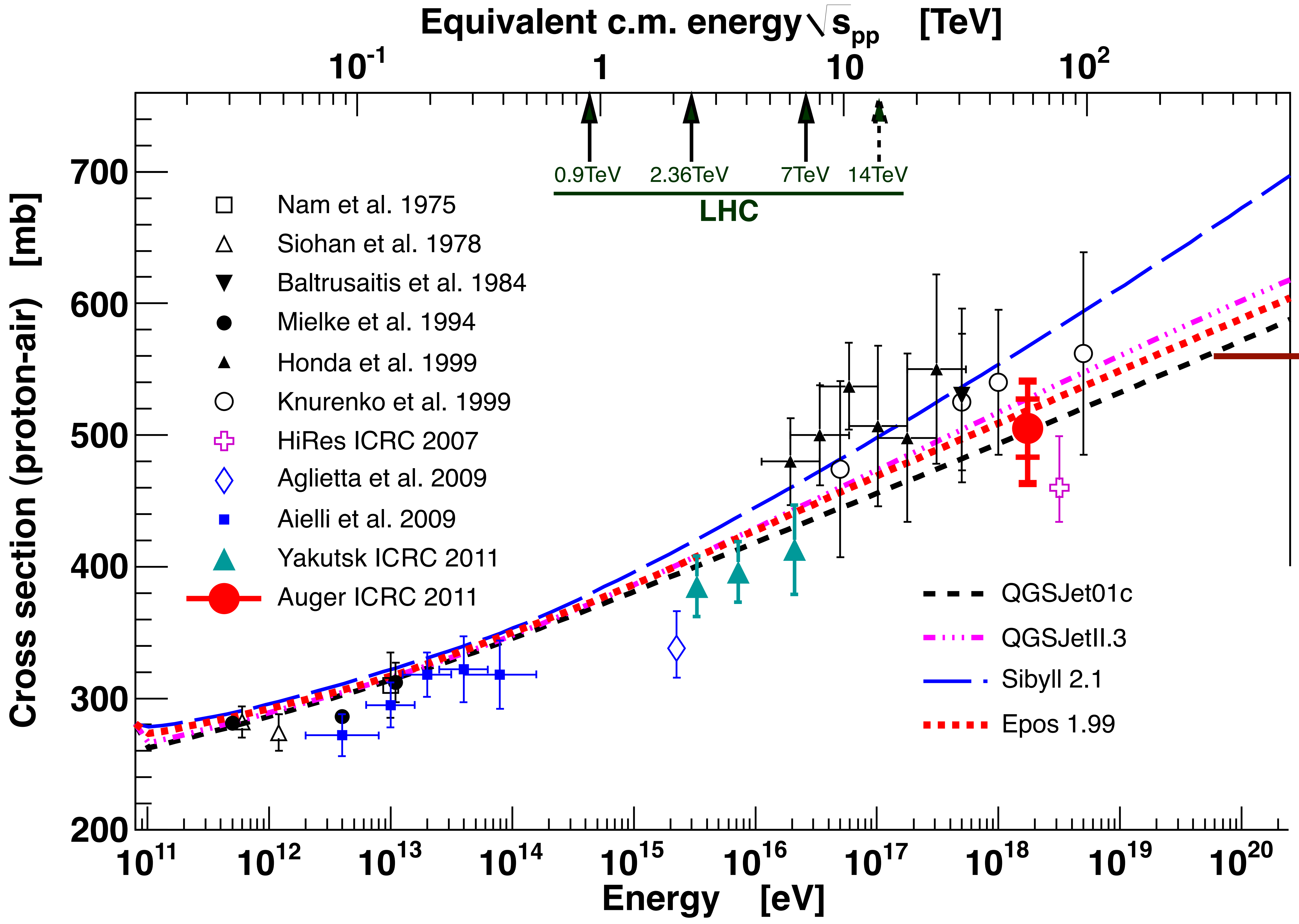


Cross section accepted if simulated slope fits measured slope of X_{max} distribution

Simulation of data sample with different cross sections, interpolation to measured low-energy values

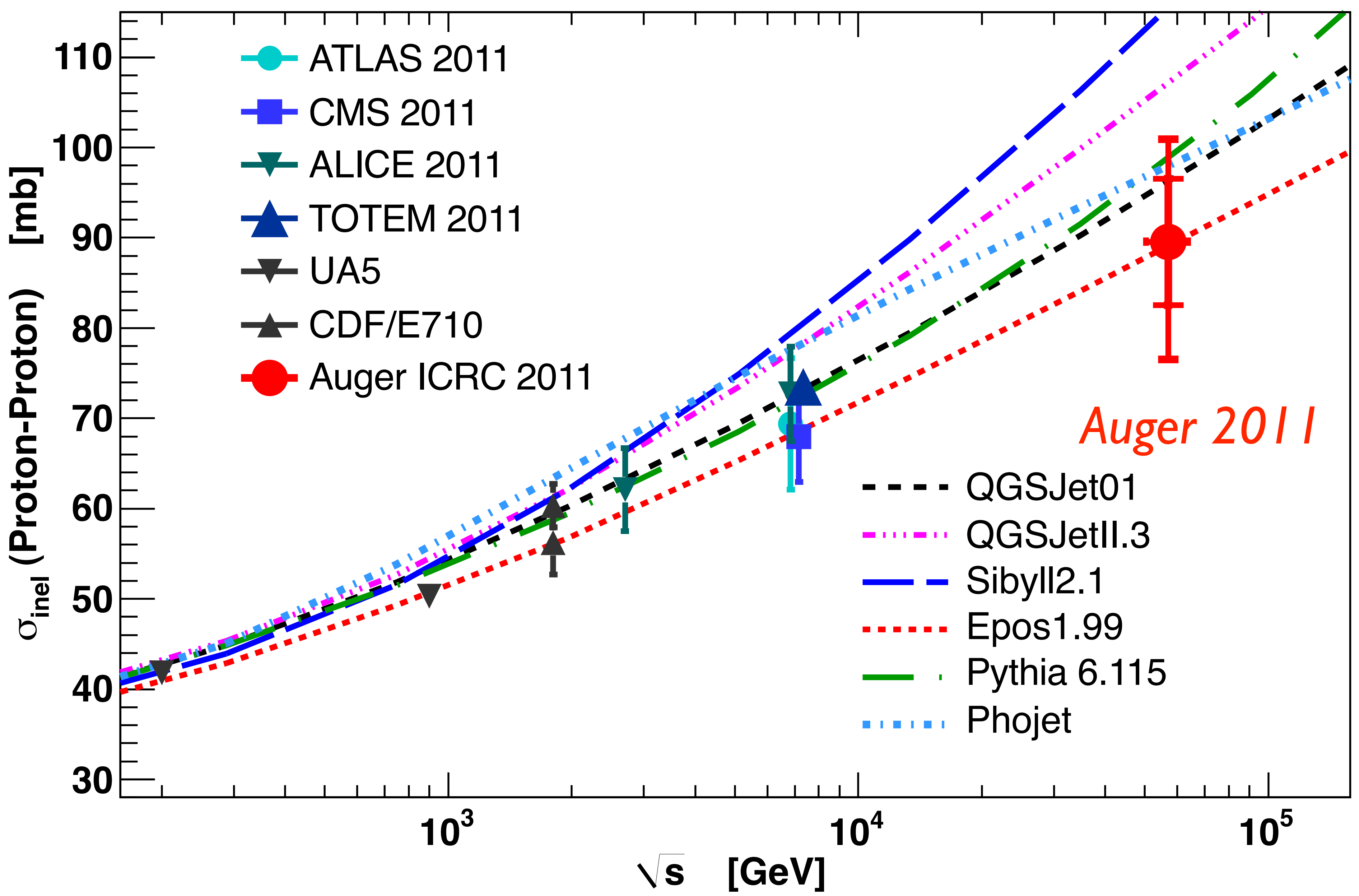
$$\sigma_{p\text{-air}} = \left(505 \ \pm 22_{\rm stat} \ \left({}^{+26}_{-34}\right)_{\rm sys}\right) \ \text{mb}$$

High-energy frontier: proton-air cross section



Conversion from p-air to p-p cross section always model-dependent

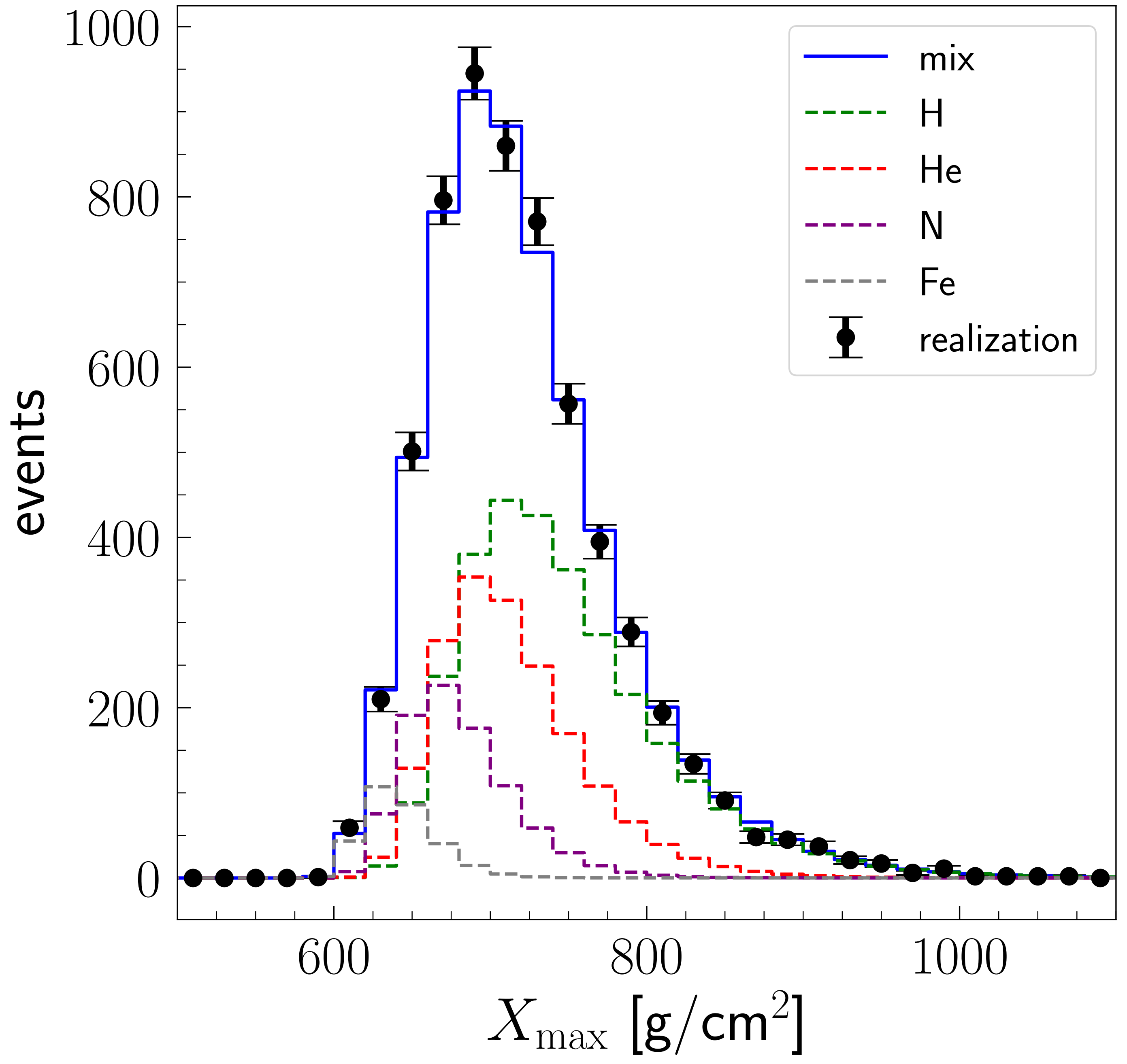
Glauber model



Cross section independent of LHC data,
very good agreement with extrapolated data

(Pierre Auger Collab. 1107.4804, Phys. Rev. Lett. 2012)

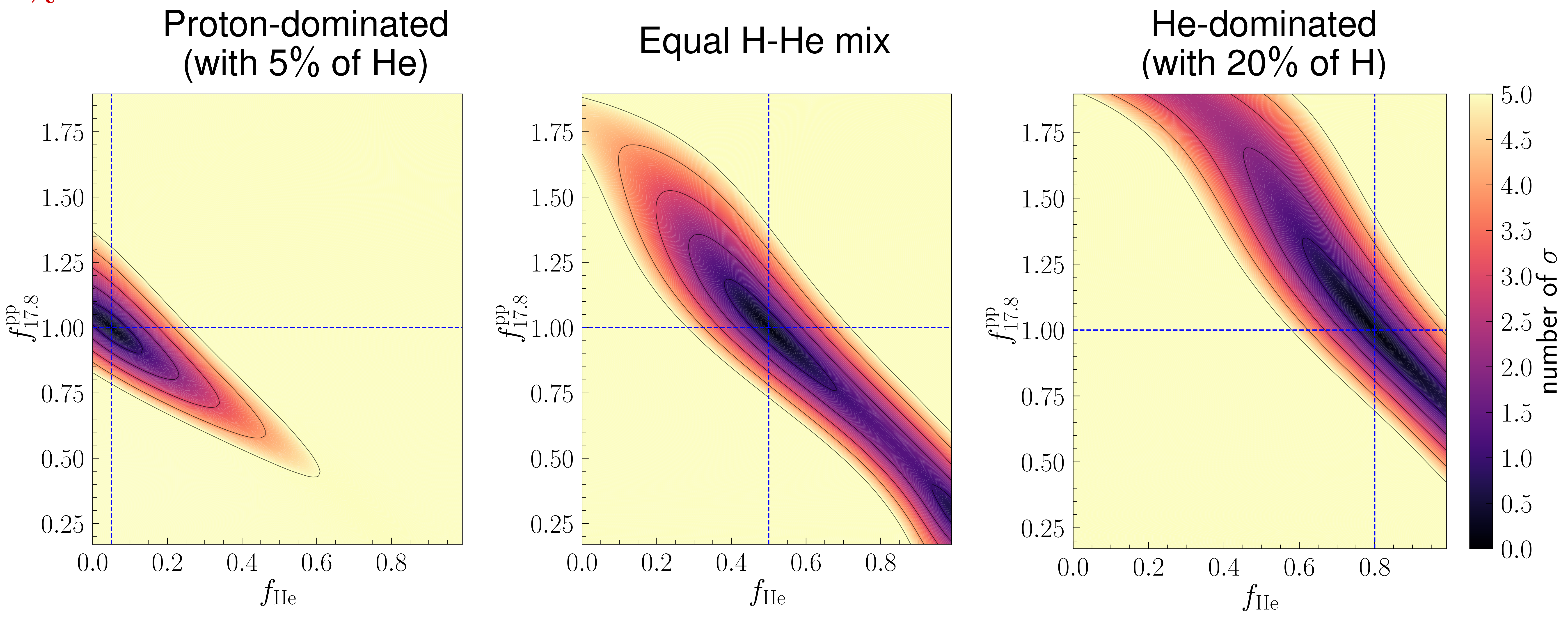
Measurement of composition and cross section?



Analysis of Monte Carlo data set

Olena Tkachenko (ICRC 2021)

χ^2 deviation



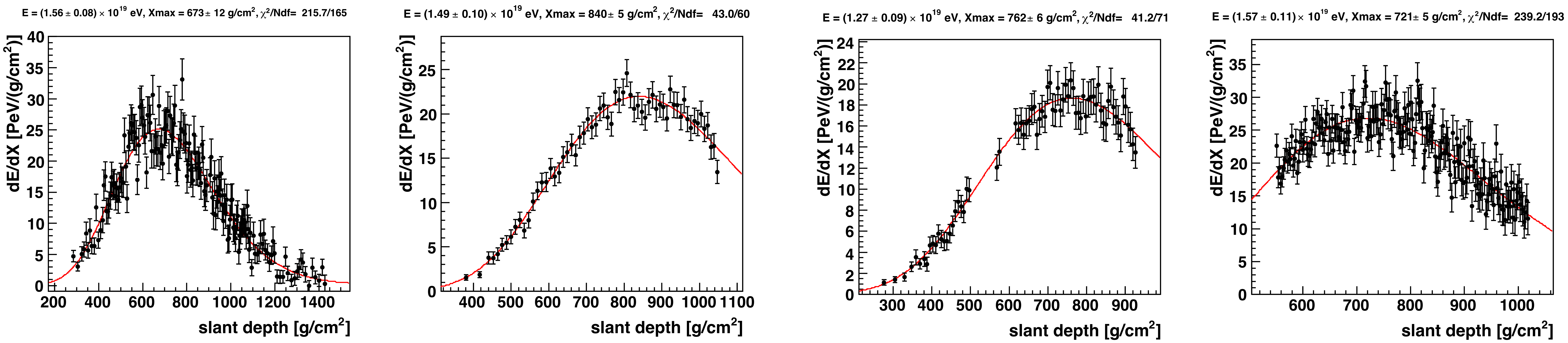
- lg(E/eV) = $10^{17.8}$-$10^{17.9}$ eV
- Model: Sibyll 2.3d

**blue dashed line* shows the simulated He fraction and scaling factor, and colorbar shows the χ^2 deviation in units of sigma.

Consistent analysis, results stable only for large proton fraction

(Lipari, PRD 2021)

Gaisser-Hillas parametrization of shower profile



$$N(X) = N_{\max} \left(\frac{X - X_1}{X_{\max} - X_1} \right)^{(X_{\max} - X_1)/\Lambda} \exp \left(- \frac{X - X_{\max}}{\Lambda} \right)$$

Gaisser & Hillas ICRC 1977

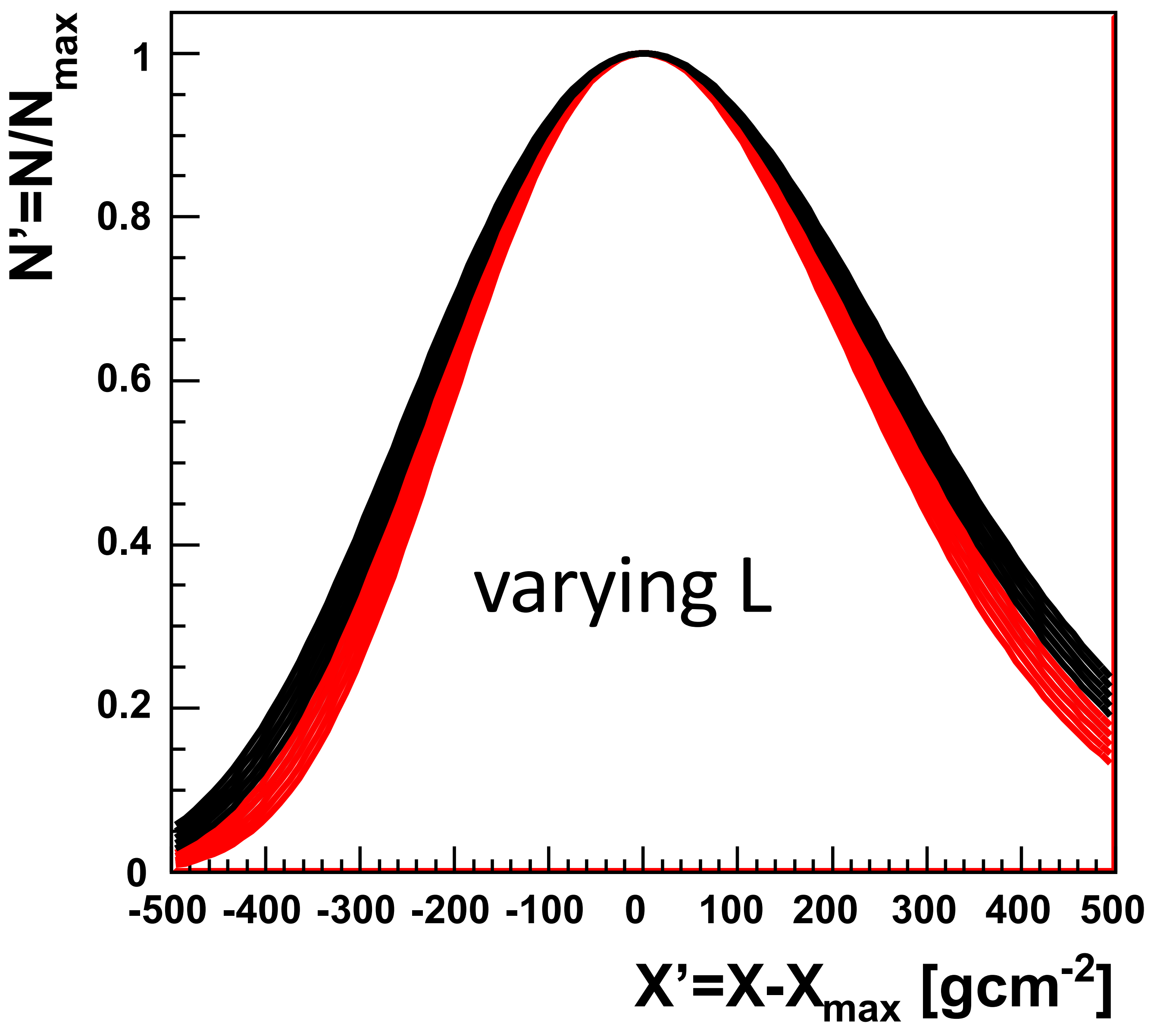
Very good description of individual shower profiles and of mean shower profile (effective parameters)

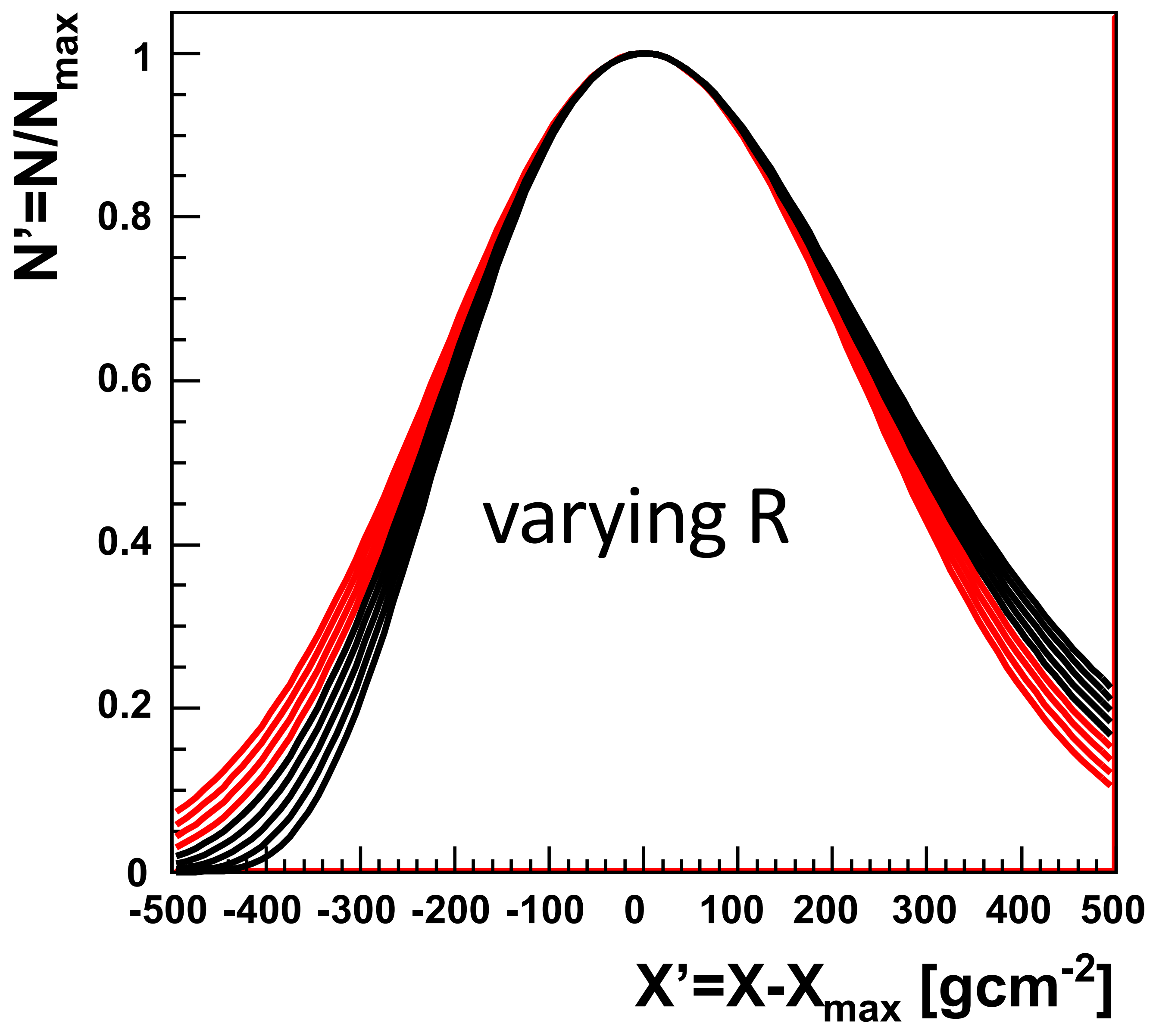
Alternative way of writing GH parametrization

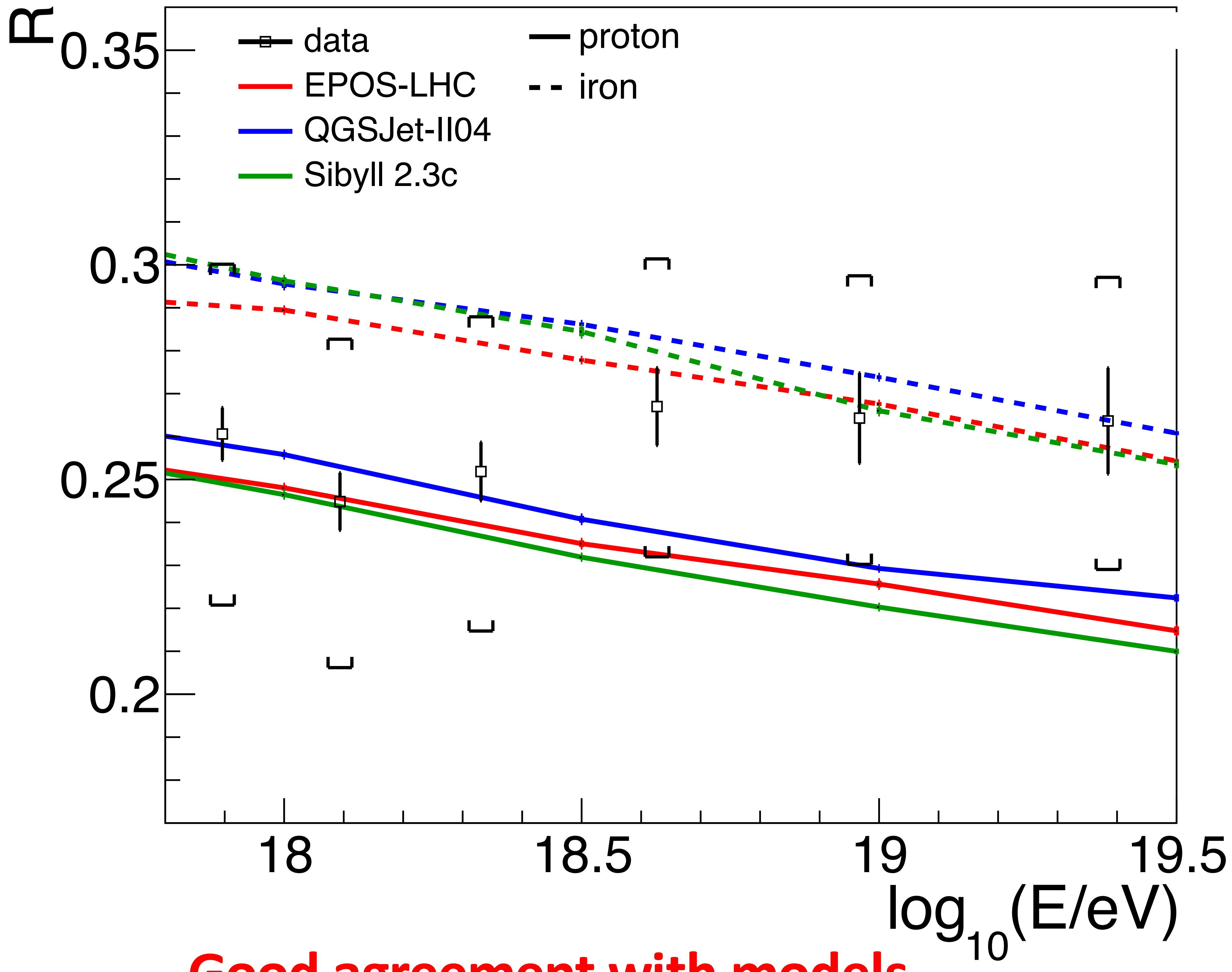
R is sensitive to the injection of **high energy π^0** in the start up of the shower.

$R = \sqrt{\lambda / |X_0'|}, \qquad L = \sqrt{|X_0'| \lambda} \qquad X_0' = X_0 - X_{max}$

$$\frac{dE}{dX} = \left(1 + R\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{RL}\right)$$







Good agreement with models.
Too large systematics for hadronic physics, for the moment.

S. Andringa et al, Astropart.Phys. 34 (2011) 360

Auger JCAP 1903 (2019) 03 018

End of Lecture 1