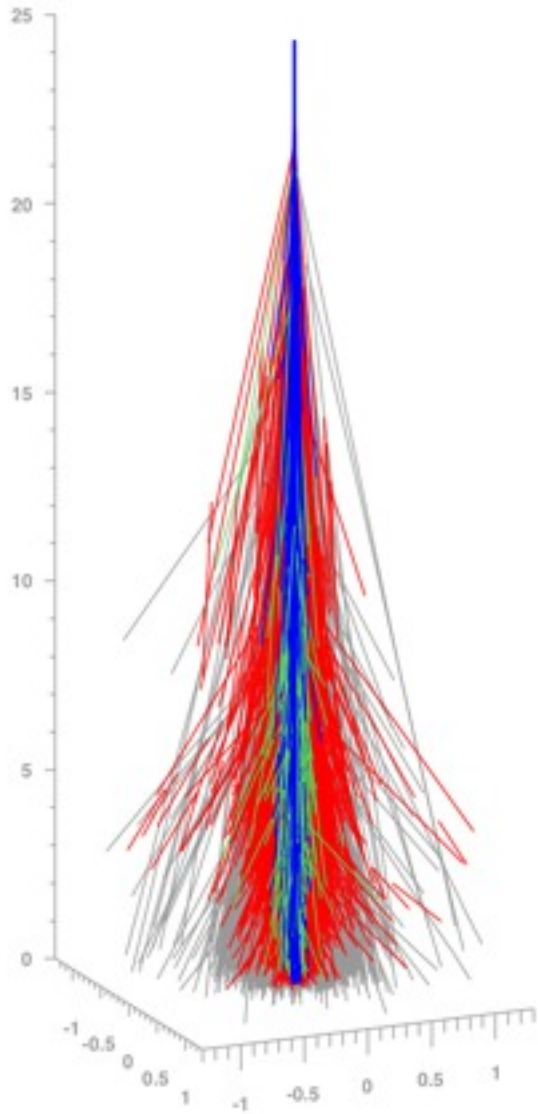
Air Showers and Hadronic Interactions (1/3)



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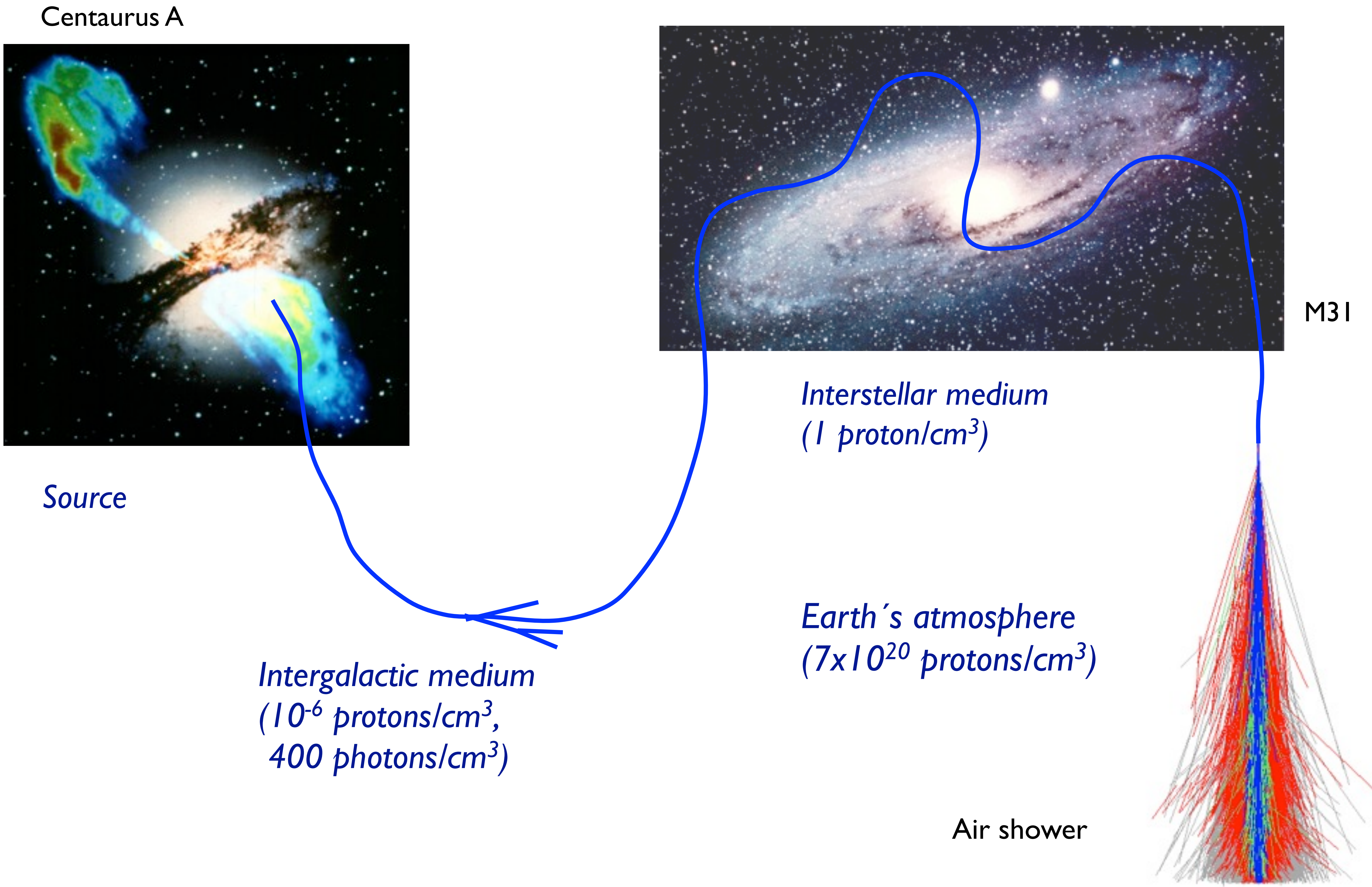
Part 1: Introduction to air shower physics

Particle interactions and cascades



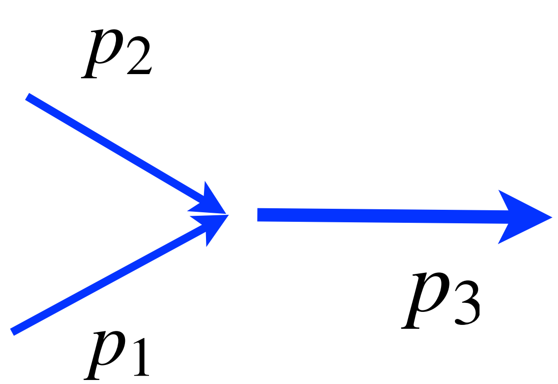
Four-momentum kinematics

Calculation with four-momenta (c=1) $p = (E, \vec{p})$

$$p_1 \cdot p_2 = E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2$$

$$p^2 = E^2 - \vec{p}^2 = m^2$$

Resonance production



Energy-momentum conservation

$$p_1 + p_2 = p_3$$

Mass of produced resonance

$$p_3^2 = m_3^2 = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$$= p_1^2 + 2p_1 \cdot p_2 + p_2^2 = m_1^2 + m_2^2 + 2E_1 E_2 - 2\vec{p}_1 \cdot \vec{p}_2$$

Laboratory and center-of-mass system

Mass of produced resonance, valid in any reference system

$$p_3^2 = m_3^2 = (p_1 + p_2)^2$$

Lab system:

$$p_1 = (E_1, \vec{p}_1) \qquad p_2 = (m_2, \vec{0})$$

$$\boxed{m_3^2 = 2m_2E_1 + m_1^2 + m_2^2}$$

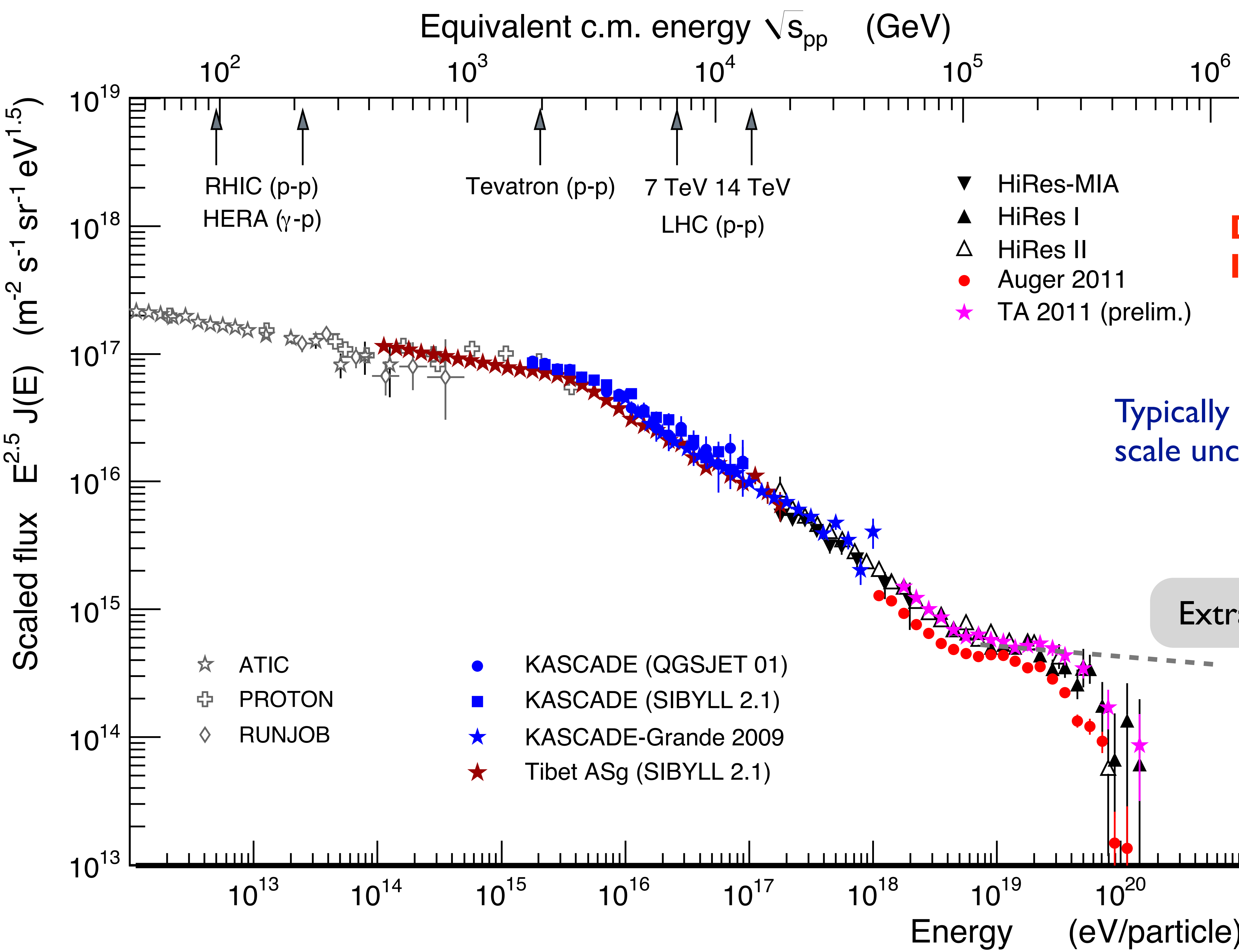
Center-of-mass system (CMS, *):

$$\vec{p}_1^{\star} = -\vec{p}_2^{\star}$$

$$\boxed{m_3^2 = (E_1^{\star} + E_2^{\star})^2}$$

CMS energy: $\boxed{E_{\mathrm{cm}} = \sqrt{s} = E_1^{\star} + E_2^{\star}}$

Cosmic ray flux and CMS energy



Data from ICRC 2011

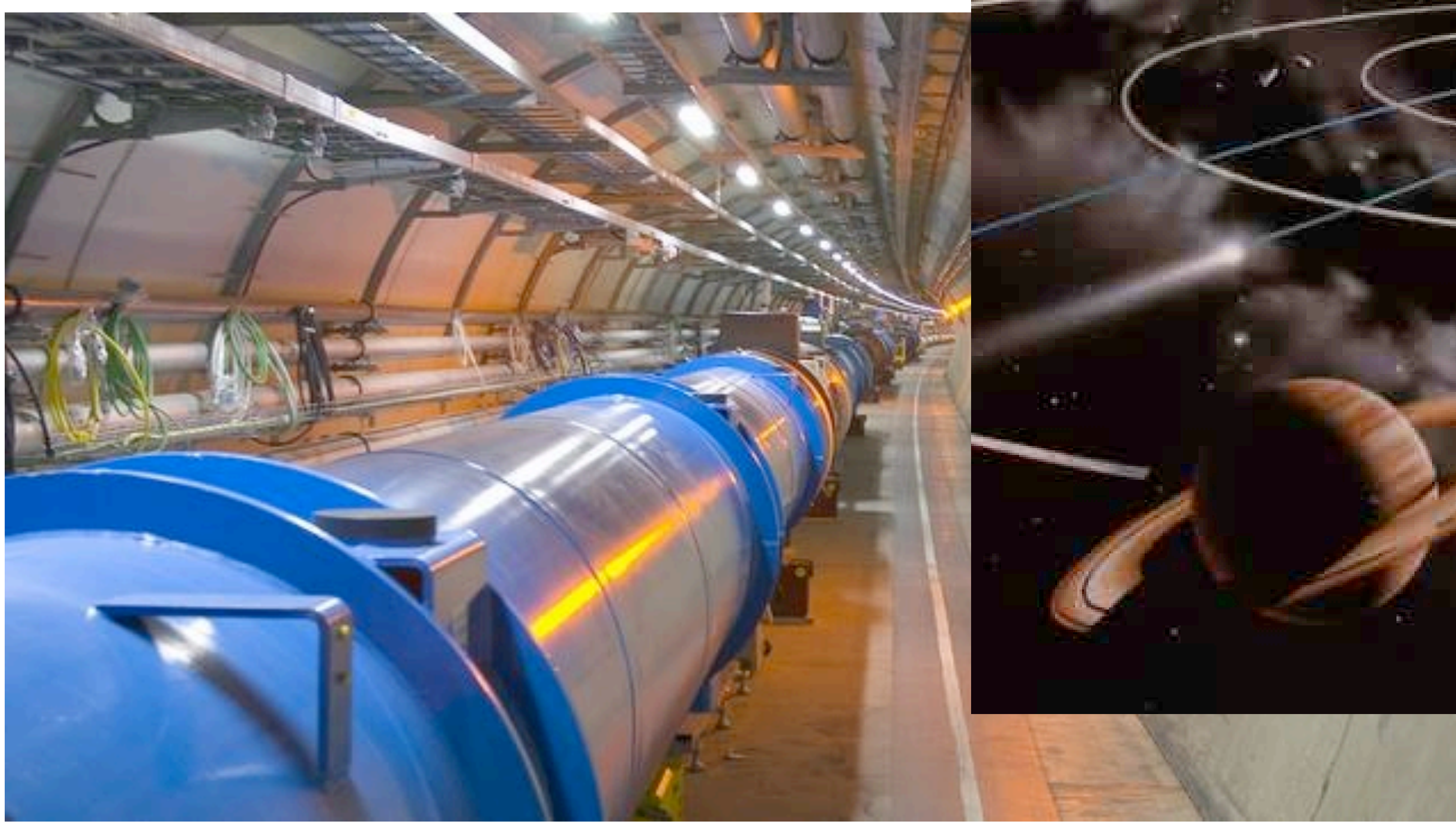
Typically 20% energy scale uncertainty

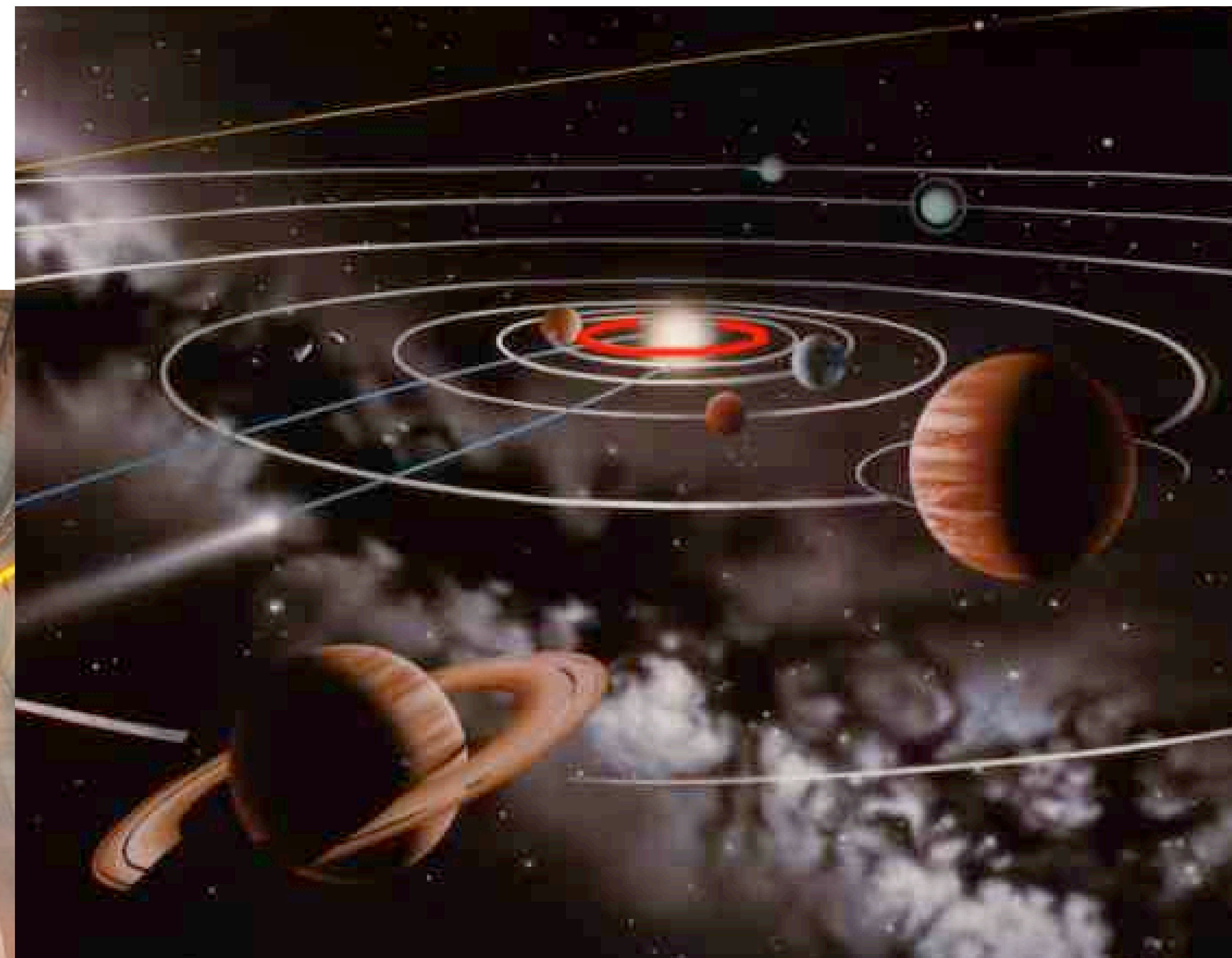
Extrapolated flux

Ultra-high energy: 10^{20} eV

Need accelerator of size of Mercury´s orbit to reach 10^{20} eV with current technology

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets



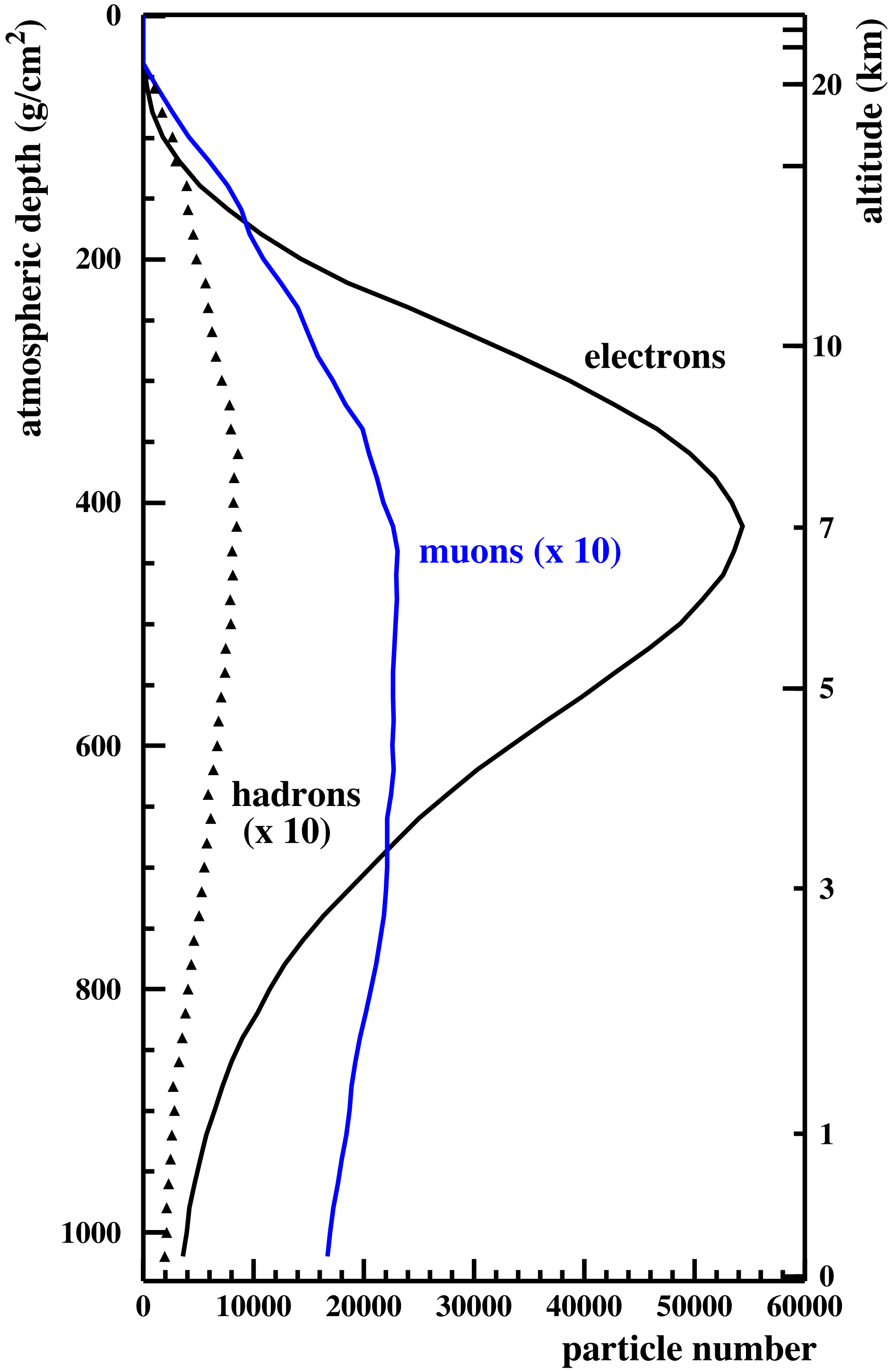


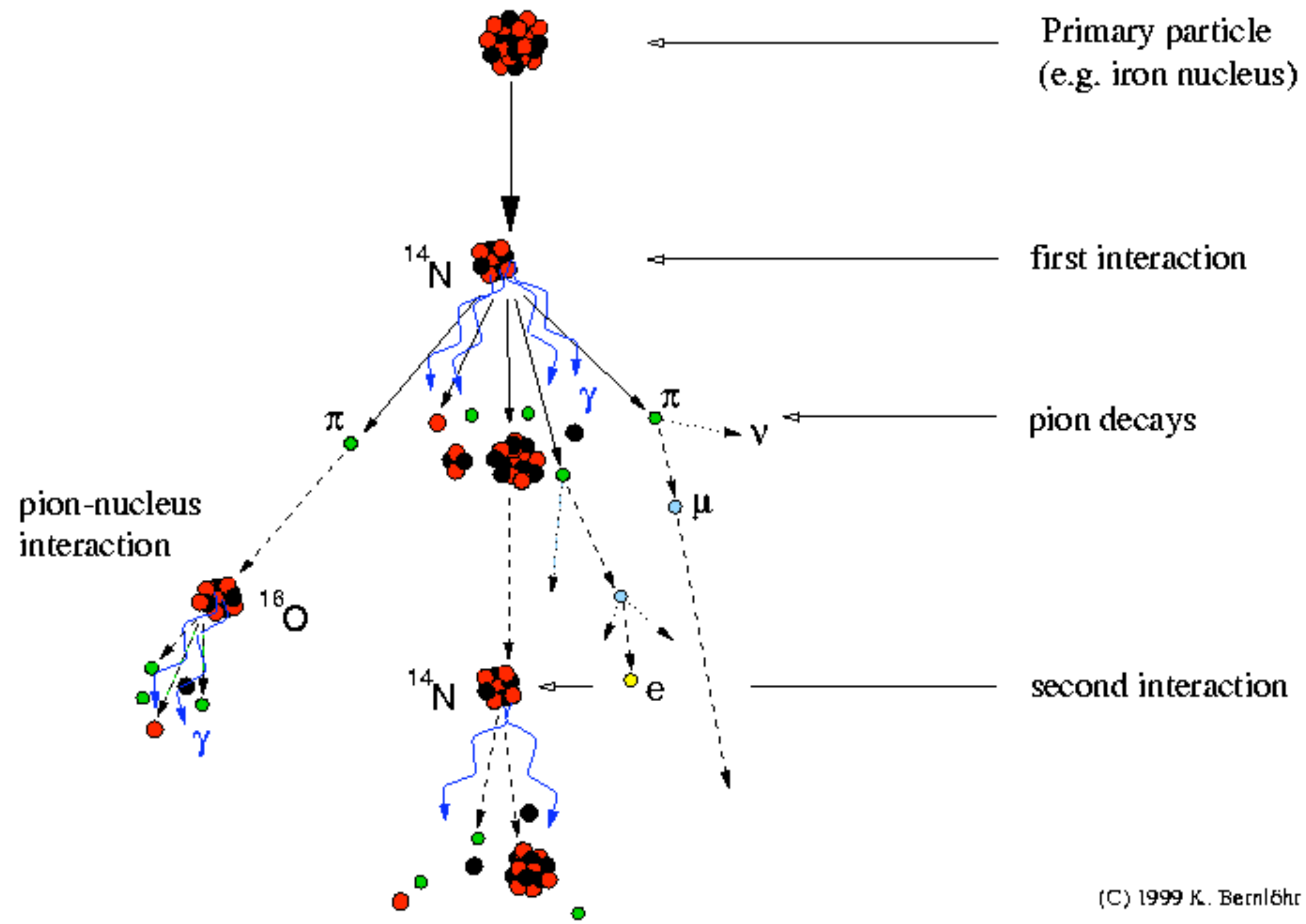
(M. Unger, 2006)

Acceleration time for LHC: 815 years

Extensive air showers

$$\int \rho_{\mathrm{air}}\, \mathrm{d}l = X$$

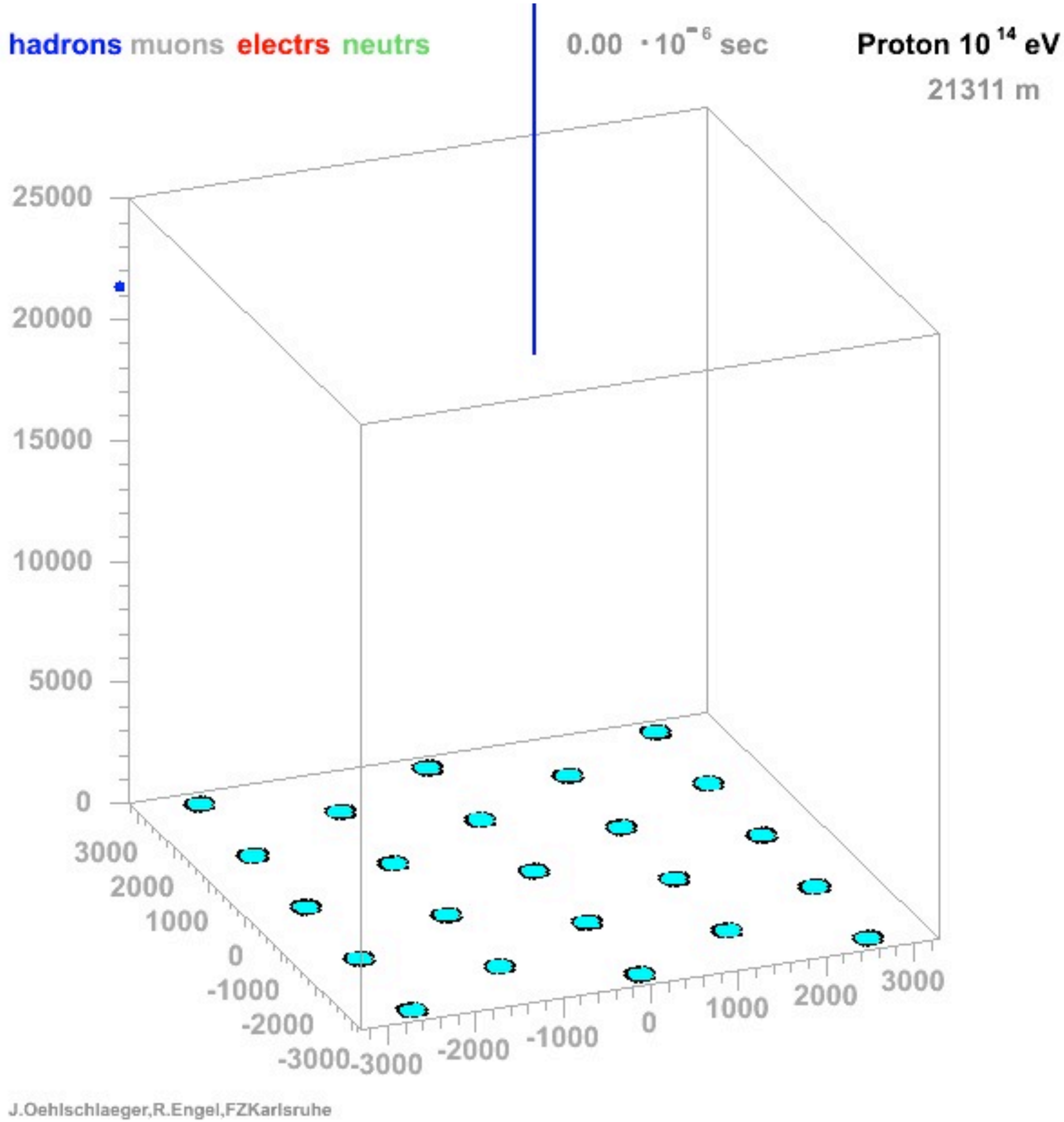




Decay of neutral pions feeds em. shower component

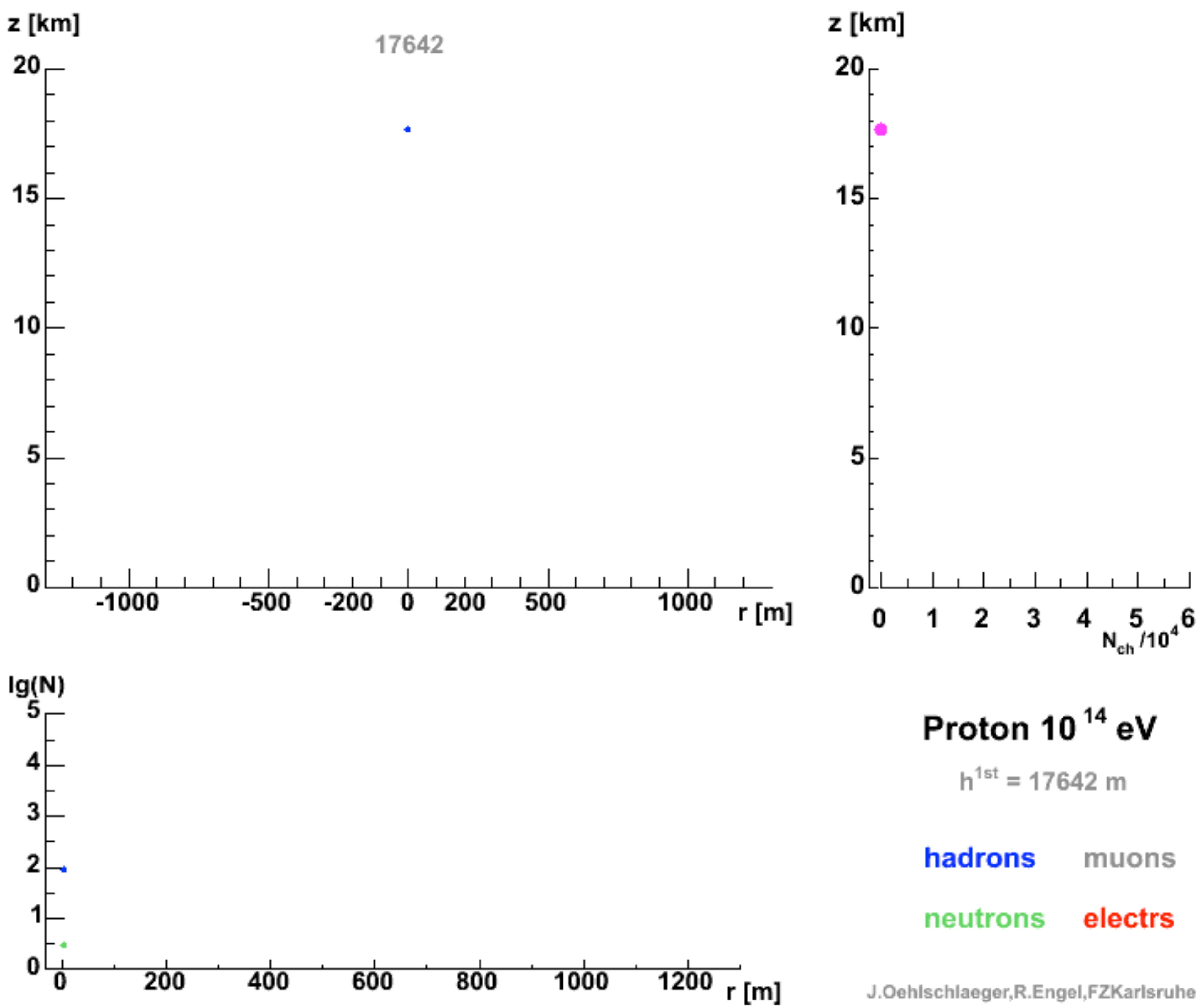
Decay of charged pions (~30 GeV) feeds muonic component

Simulation of shower development (i)

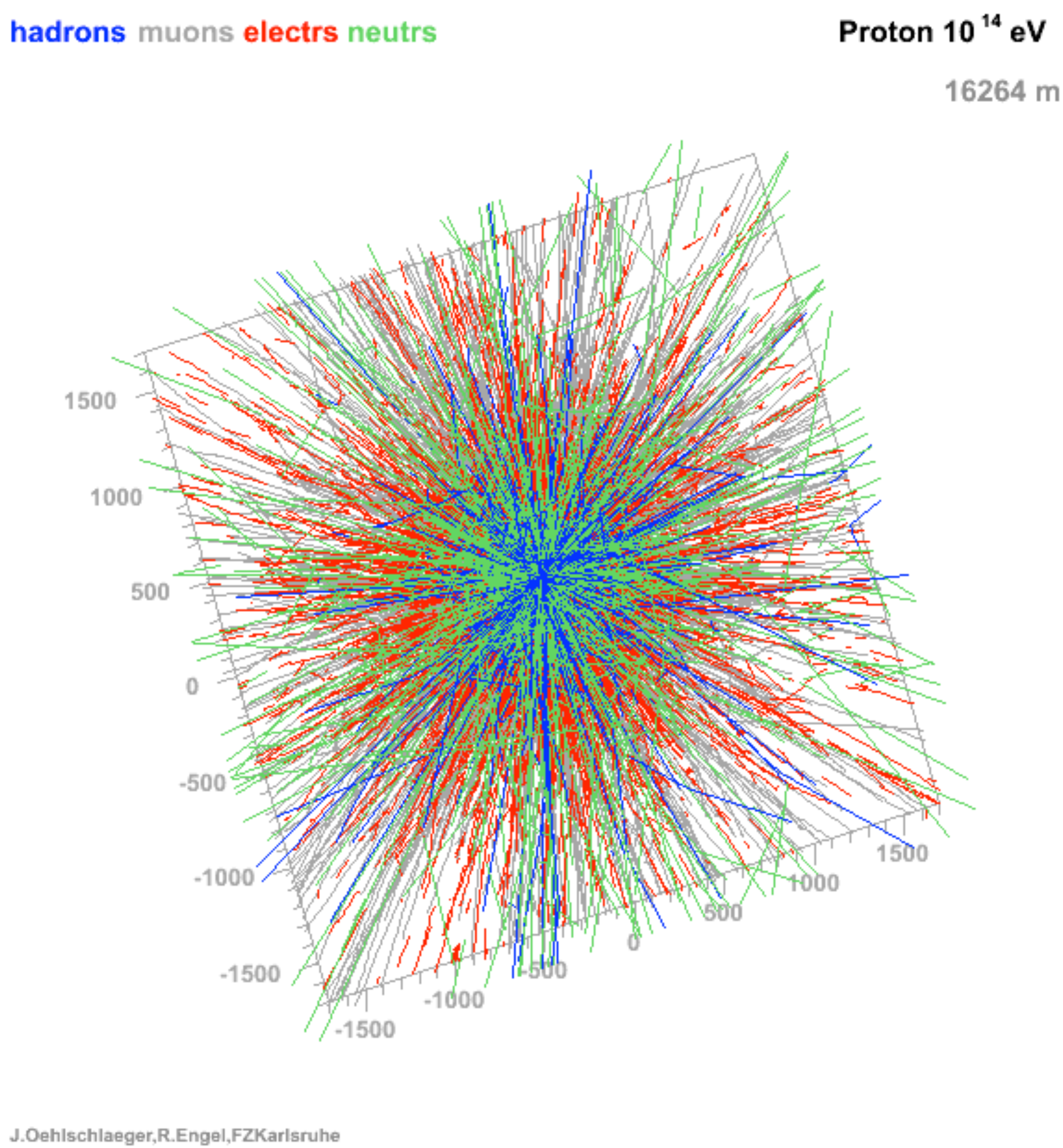


Proton shower of low energy (knee region)

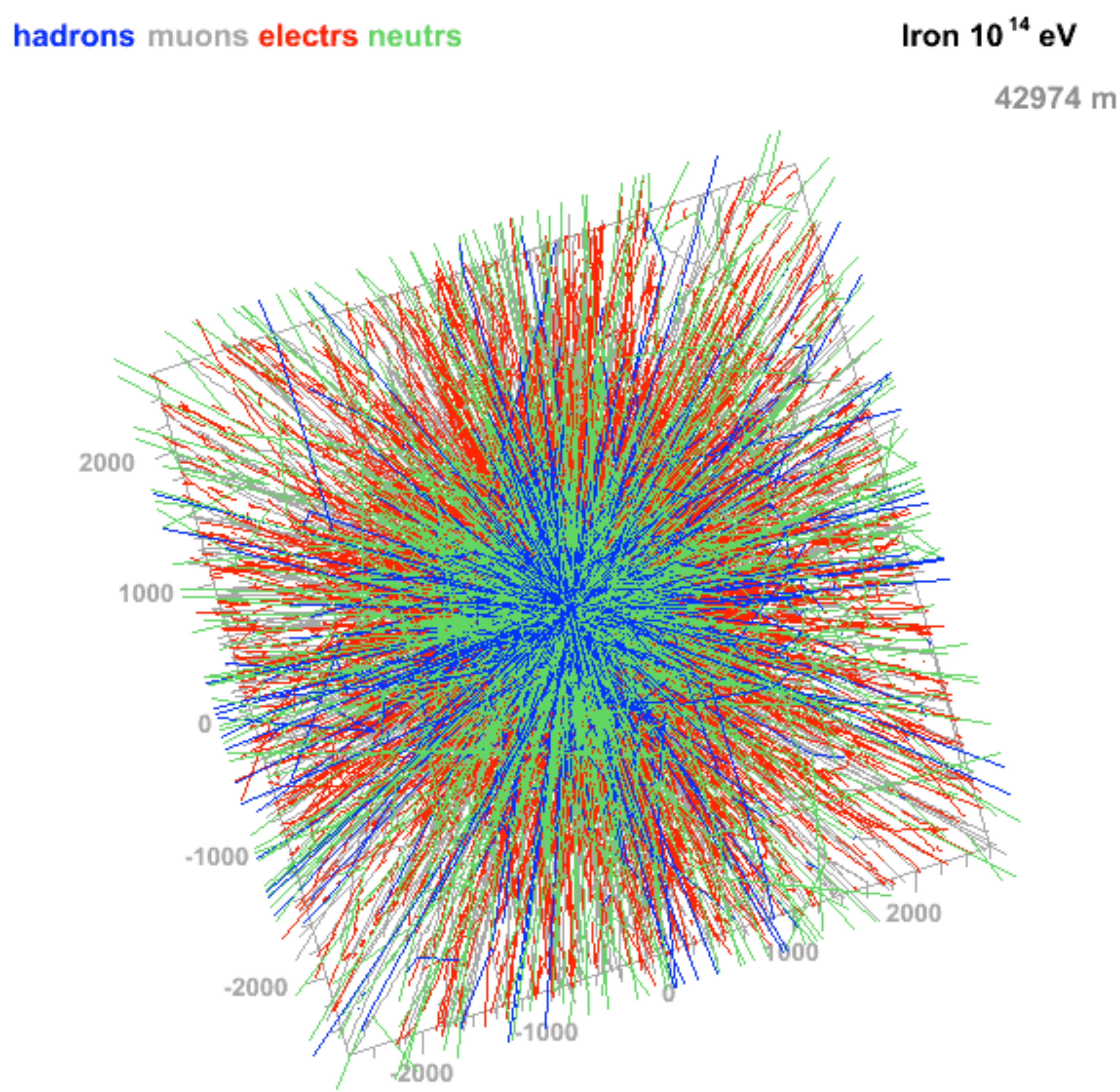
Simulation of shower development (ii)



Simulation of air shower tracks (i)

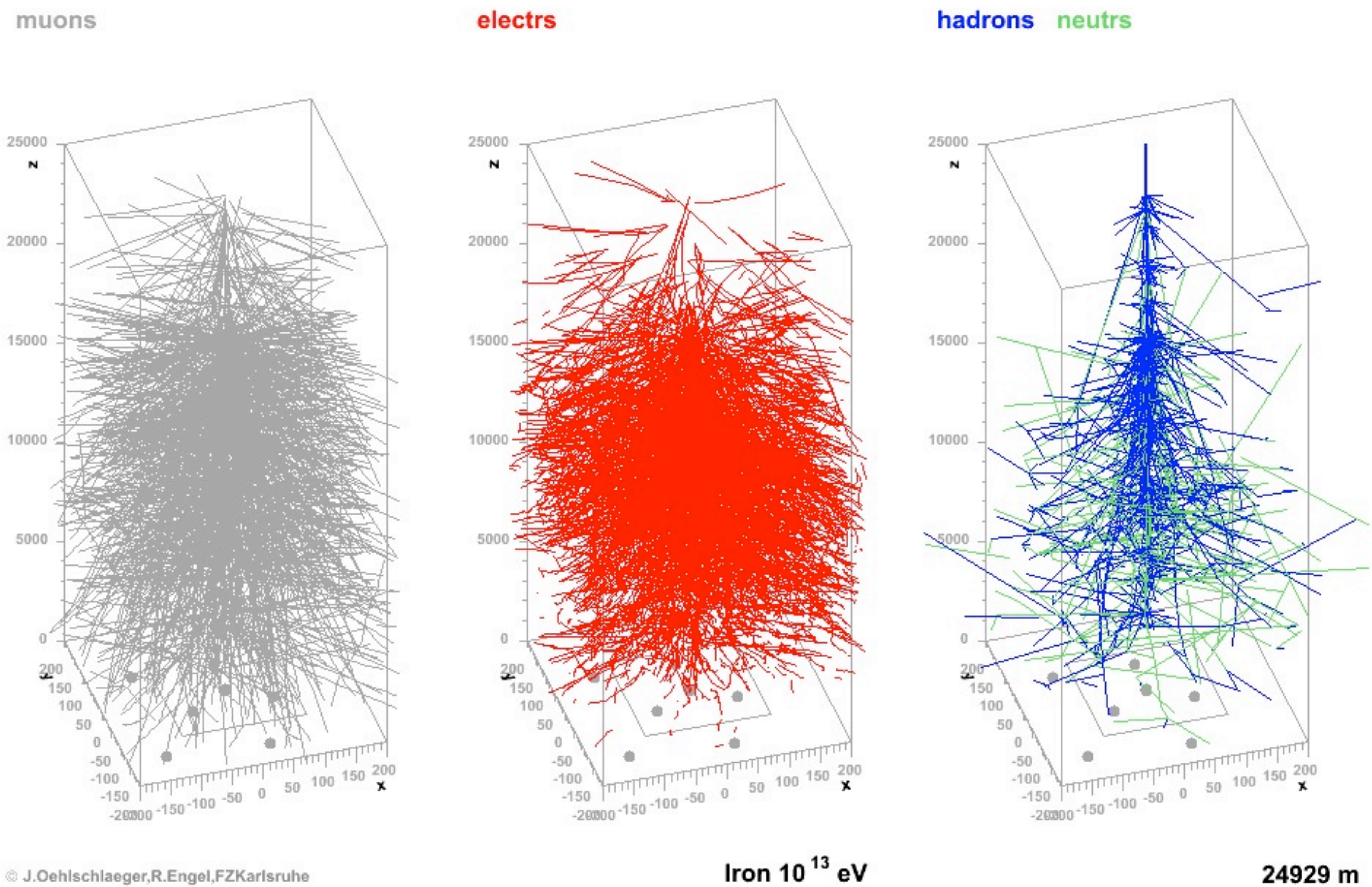


Simulation of air shower tracks (ii)

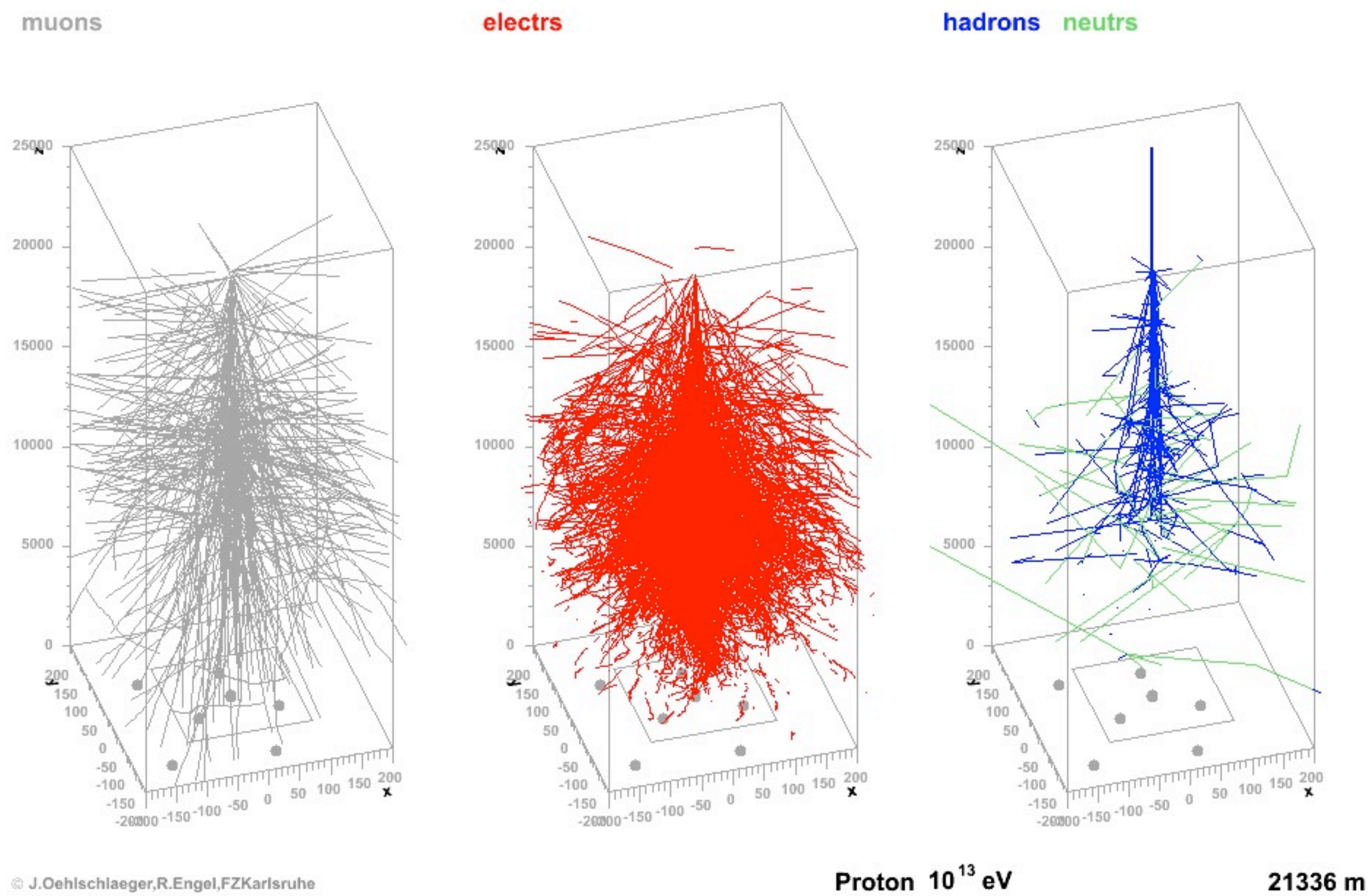


J.Oehlschlaeger,R.Engel,FZKarlsruhe

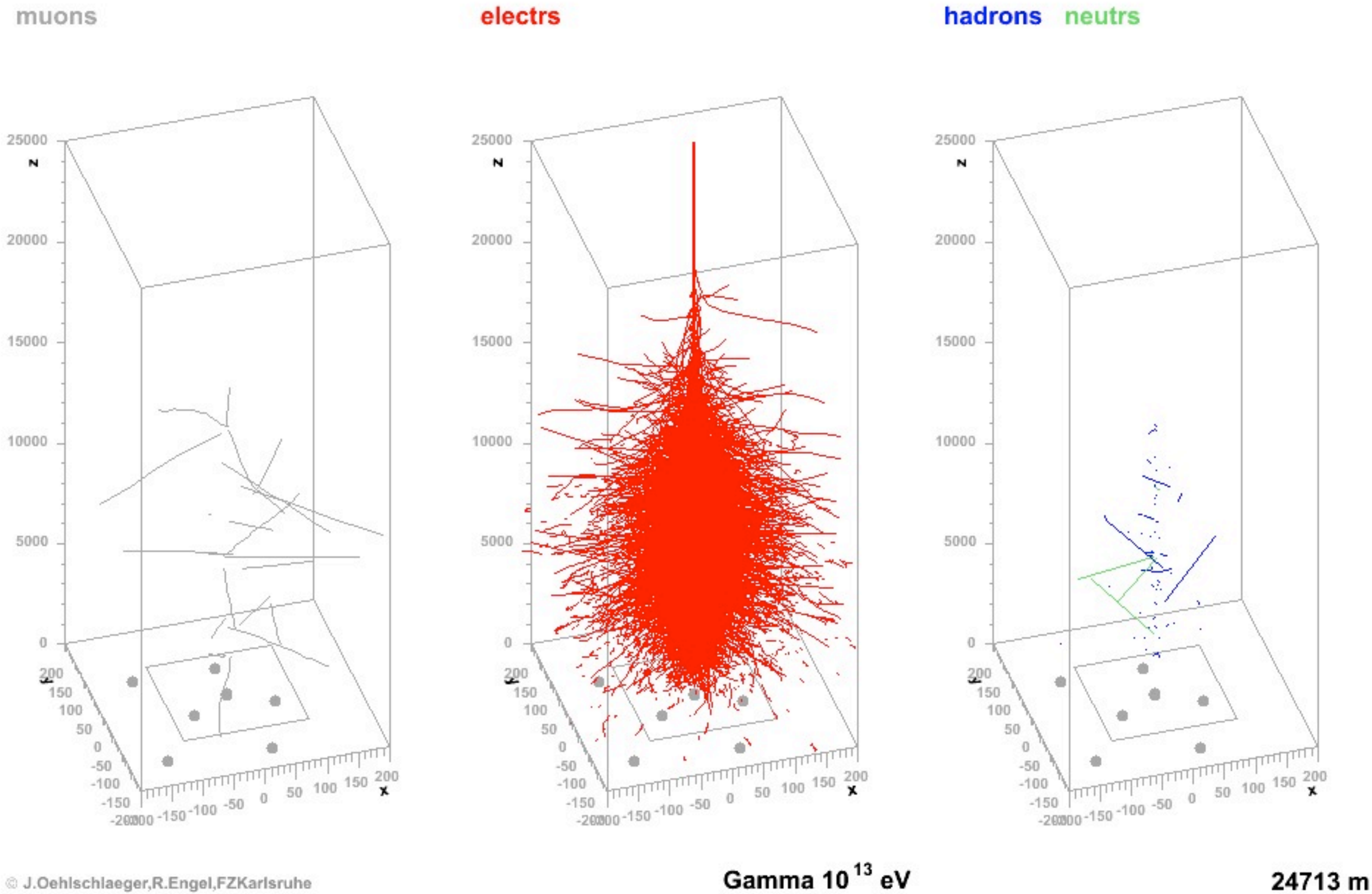
Particles of an iron shower



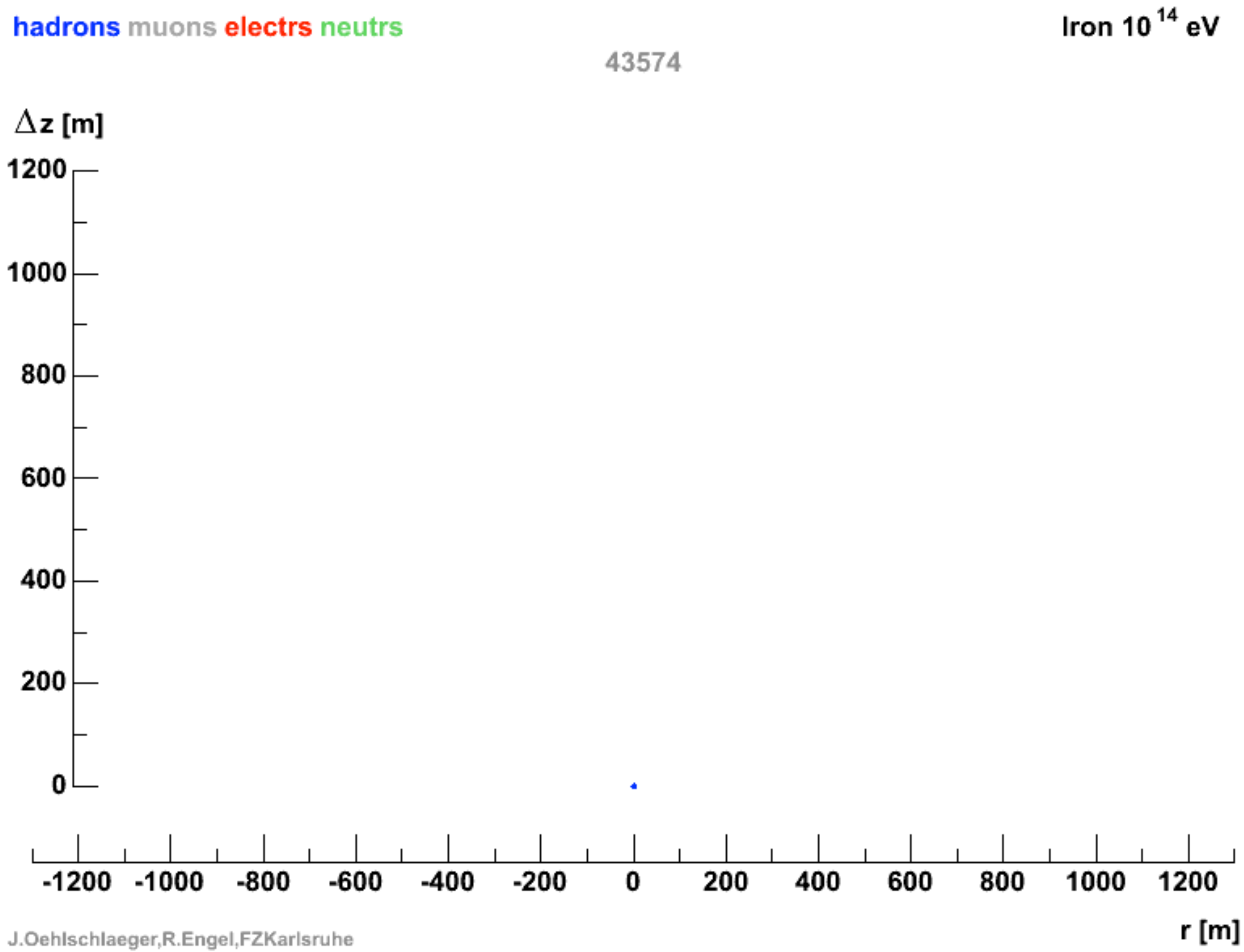
Particles of an proton shower



Particles of a gamma-ray shower

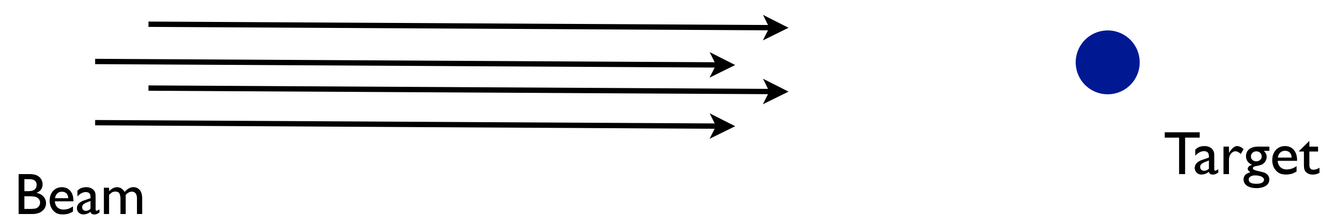


Time structure in shower front



Cross section and interaction rate

Definition



$$\sigma = \frac{1}{\Phi}\frac{dN_{\text{int}}}{dt}$$

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

Interaction rate

Flux of particles on single target

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

$$\frac{dN_{\text{int}}}{dt\,dV} = \frac{\rho_{\text{target}}}{\langle m_{\text{target}}\rangle}\,\sigma\,\Phi$$

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

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

$$\frac{d\Phi}{dX} = -\frac{\sigma}{\langle m_{\text{target}}\rangle}\,\Phi$$

Atmosphere and interaction length

Altitude (km)	Vertical depth (g/cm^2)	Local density (10^{-3} g/cm^3)	Molière unit (m)	Electron Cherenkov threshold (MeV)	Cherenkov angle (°)
40	3	3.8×10^{-3}	2.4×10^4	386	0.076
30	11.8	1.8×10^{-2}	5.1×10^3	176	0.17
20	55.8	8.8×10^{-2}	1.0×10^3	80	0.36
15	123	0.19	478	54	0.54
10	269	0.42	223	37	0.79
5	550	0.74	126	28	1.05
3	715	0.91	102	25	1.17
1.5	862	1.06	88	23	1.26
0.5	974	1.17	79	22	1.33
0	1,032	1.23	76	21	1.36

US standard atmosphere

Atmospheric depth

$$\int \rho_{\rm air}\, dl = X$$

Interaction length

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

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

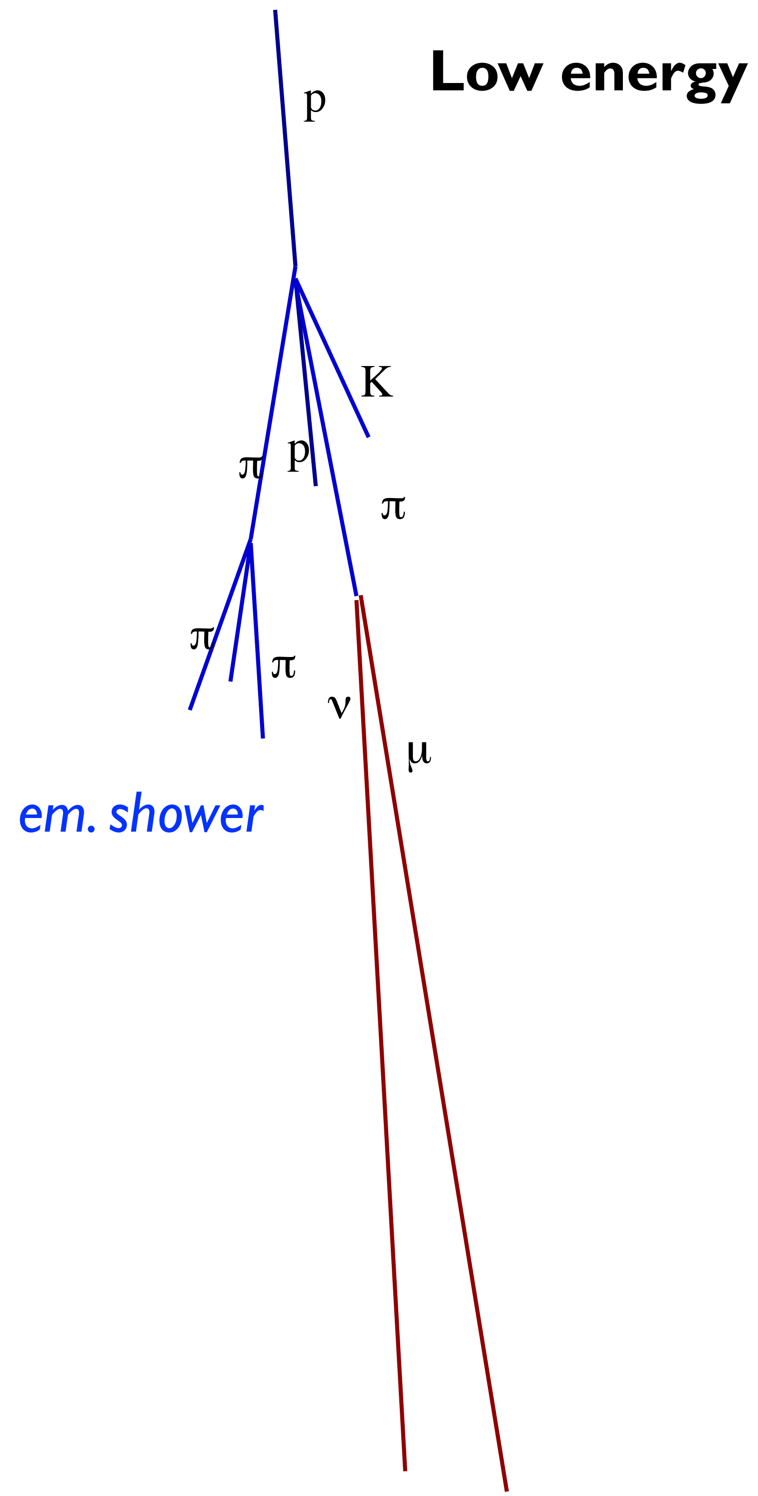
Typical values

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

$$\lambda_p \approx 90\,\mathrm{g/cm^2}$$

$$\lambda_{Fe} \approx 5\,\mathrm{g/cm^2}$$

Hadronic cascades

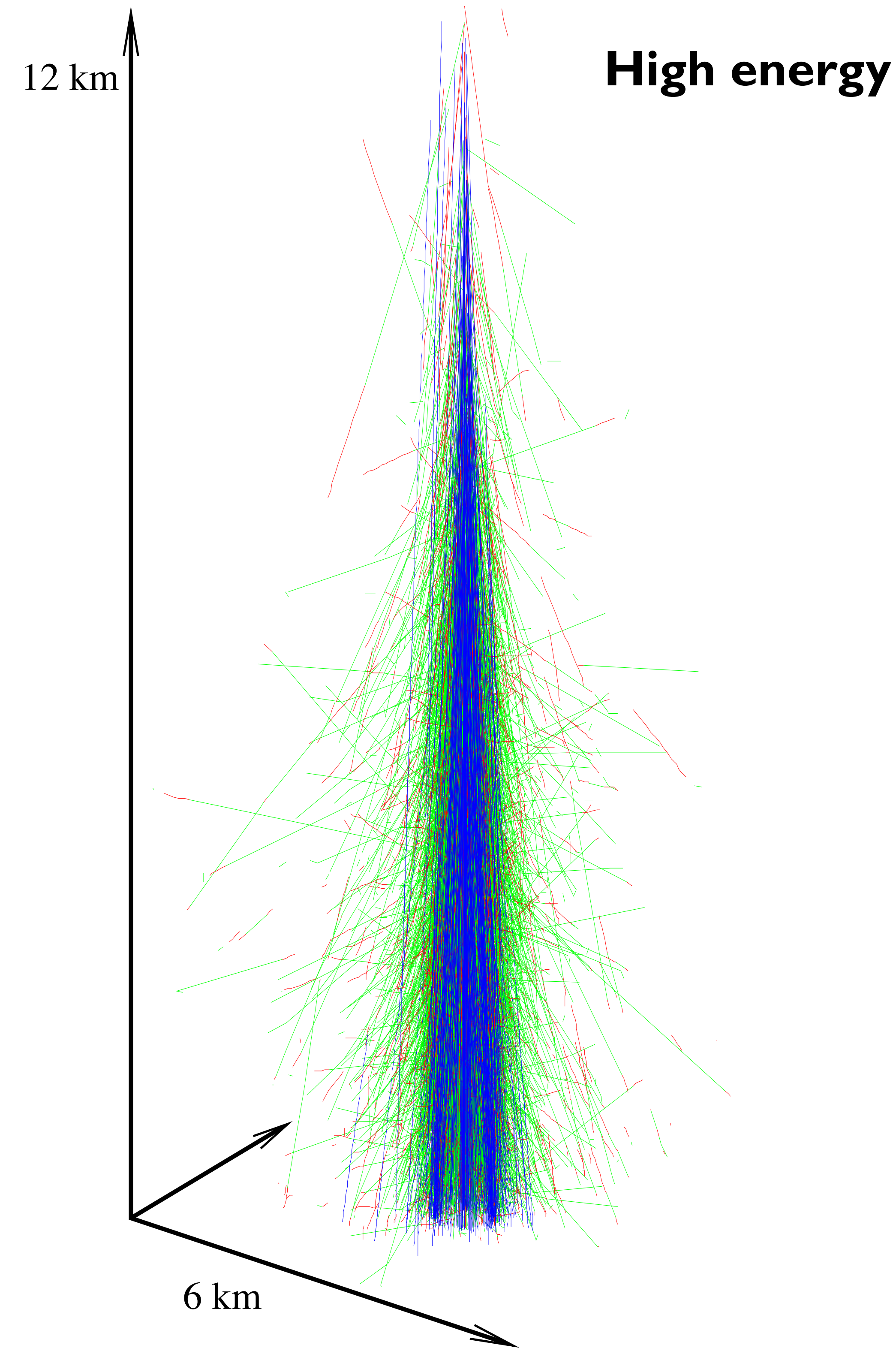


Typical energies above which particles interact

$$E_{\pi^\pm} \sim 30\,\mathrm{GeV}$$

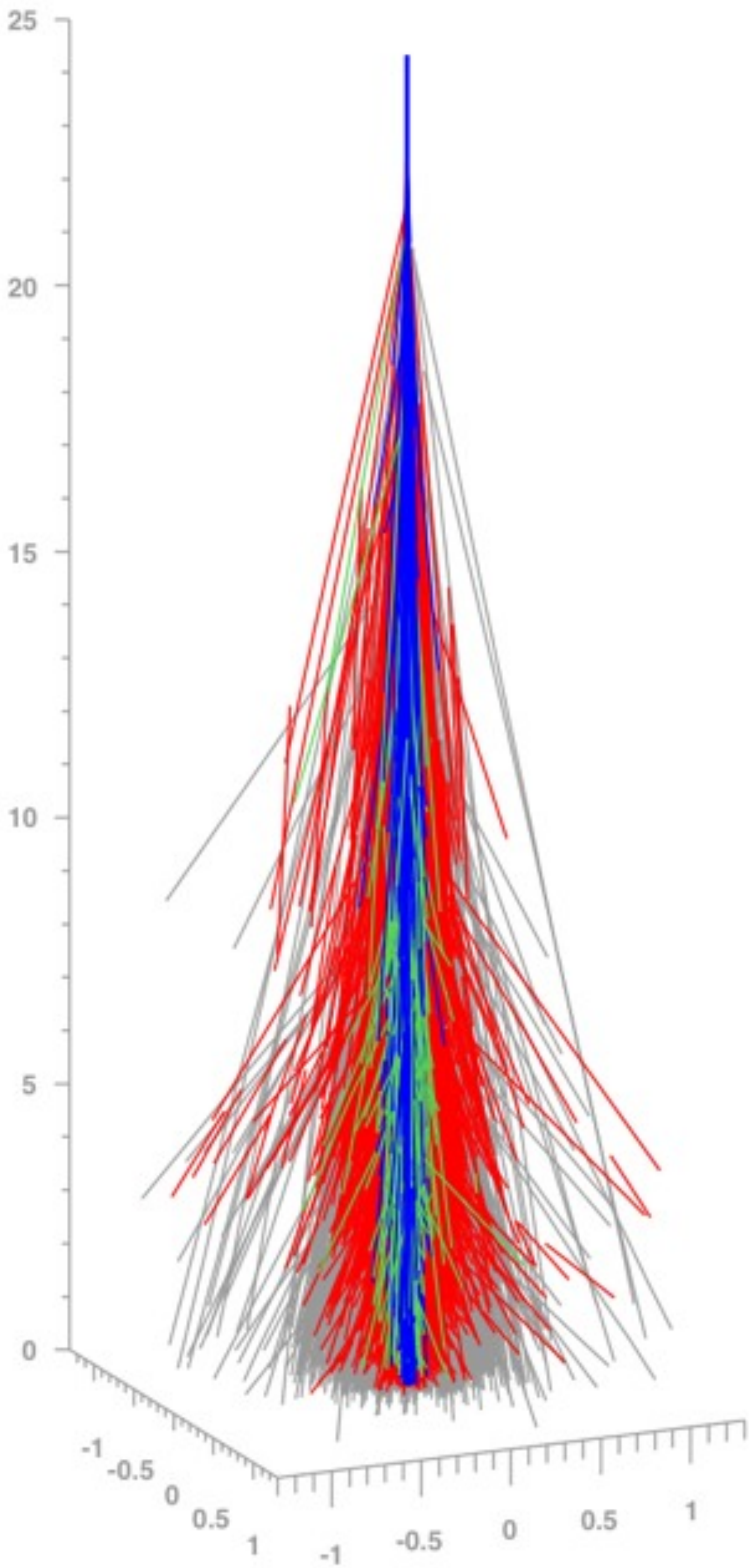
$$E_K \sim 200\,\mathrm{GeV}$$

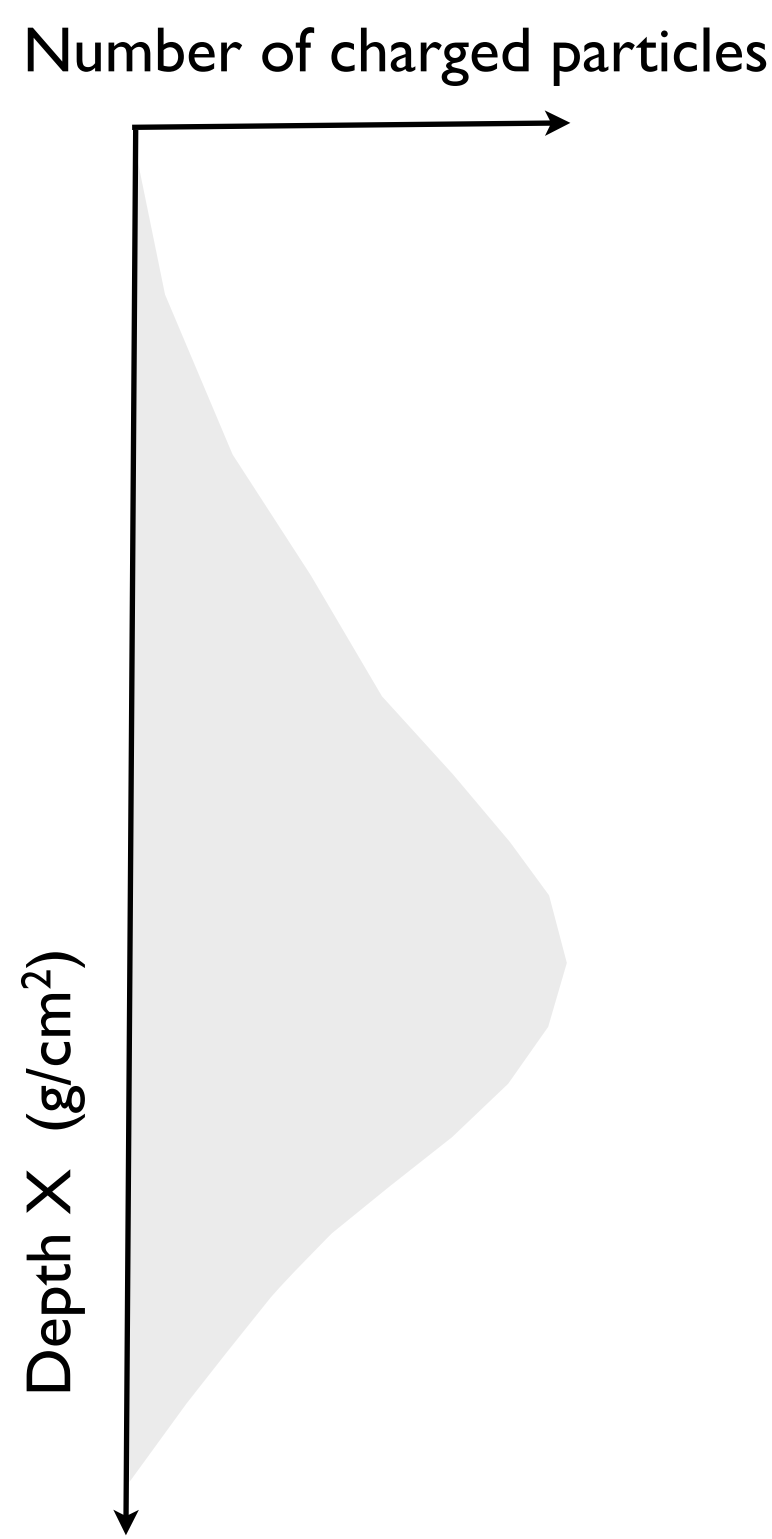
$$E_{\pi^0} \sim 10^{19}\,\mathrm{eV}$$

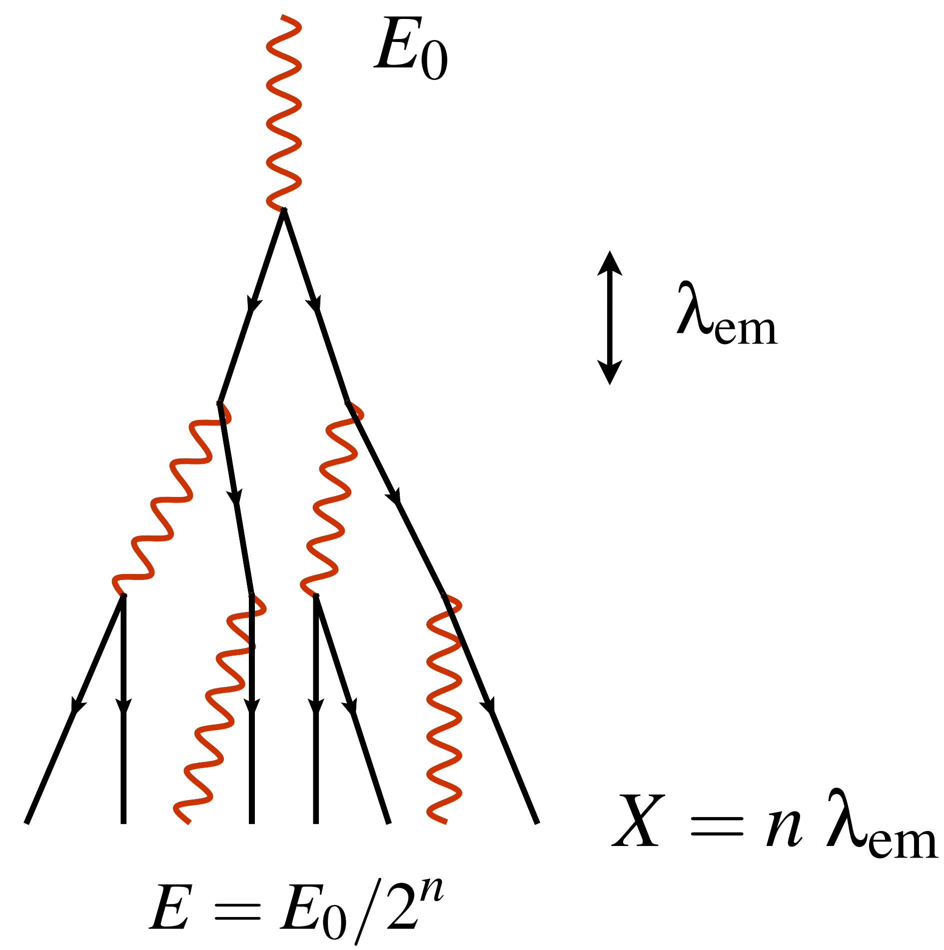


Analytic cascade models of air showers

Electromagnetic showers: Heitler model







Shower maximum: $E = E_c$

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

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

Electromagnetic showers: 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

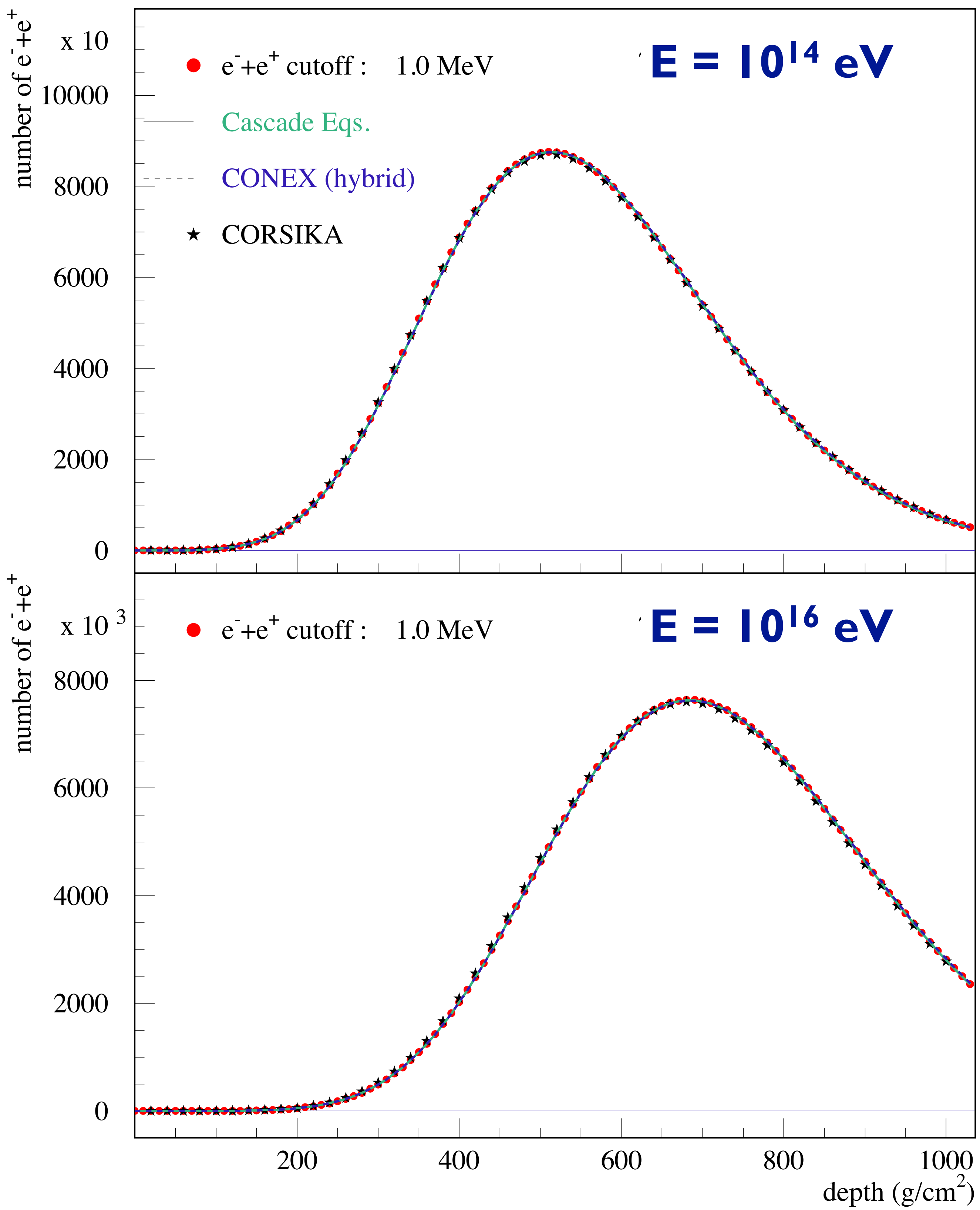
$$\frac{\mathrm{d}\Phi_e(E)}{\mathrm{d}X} = -\frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(E) + \int_E^\infty \frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(\tilde{E})P_{e\to e}(\tilde{E},E)\mathrm{d}\tilde{E}$$

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

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

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

Mean longitudinal shower profile



Calculation with cascade Eqs.

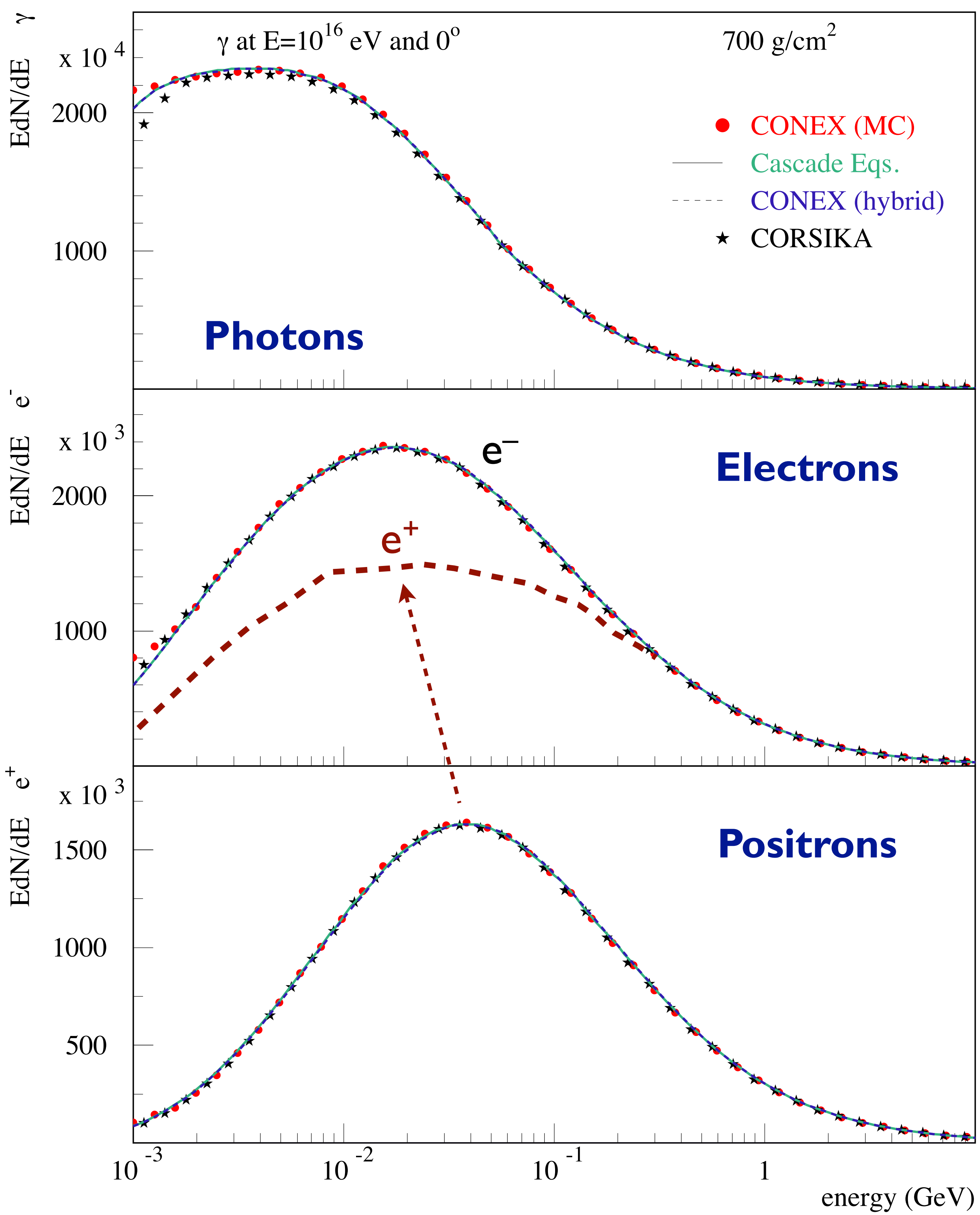
Photons
- Pair production
- Compton scattering

Electrons
- Bremsstrahlung
- Moller scattering

Positrons
- Bremsstrahlung
- Bhabha scattering

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

Energy spectra of secondary particles



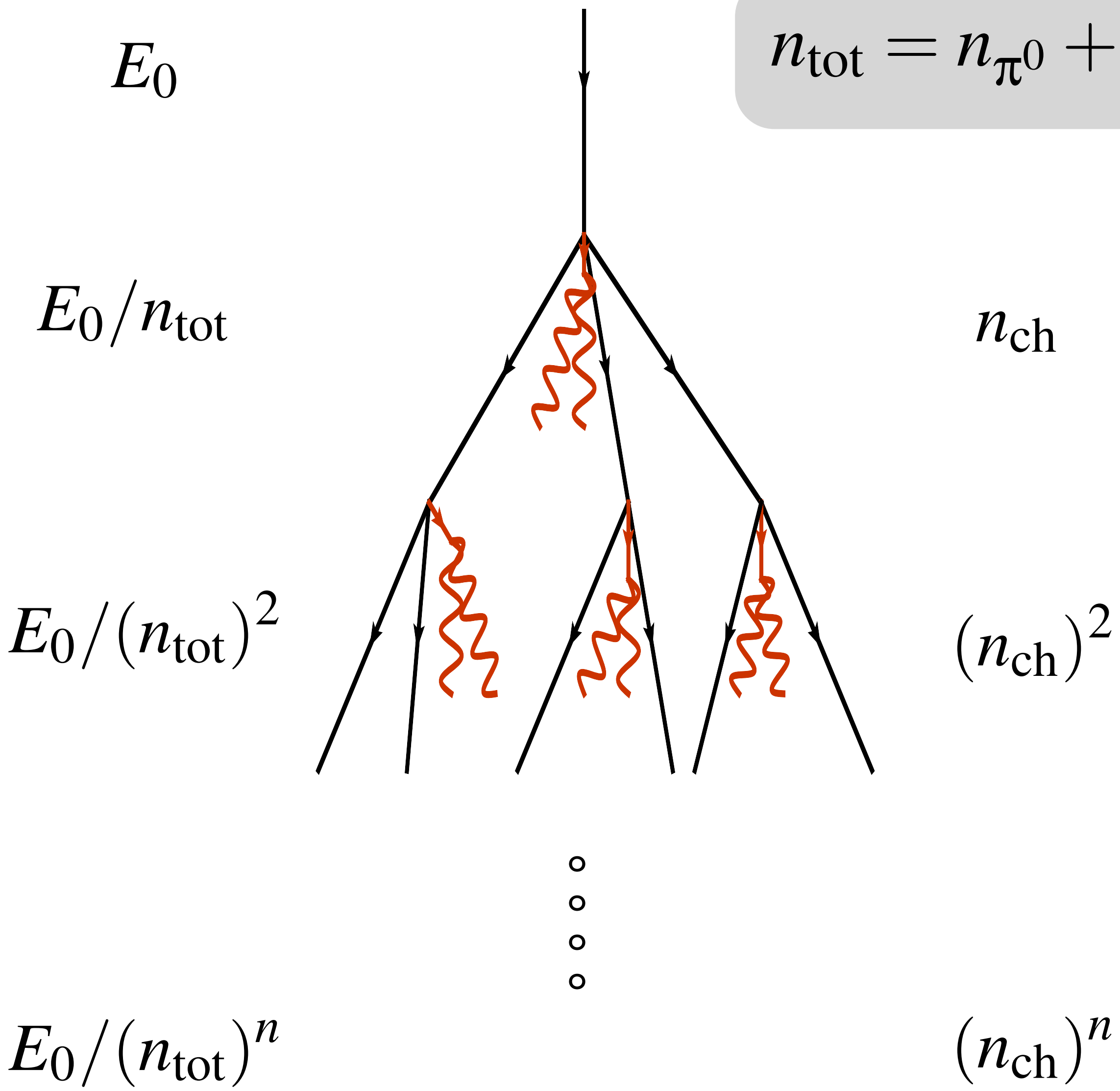
Number of photons divergent

- 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)

Muon production in hadronic showers

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



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new cascades

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

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

Assumptions:

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

(Matthews, Astropart.Phys. 22, 2005)

Superposition model

Proton-induced shower

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

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

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

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

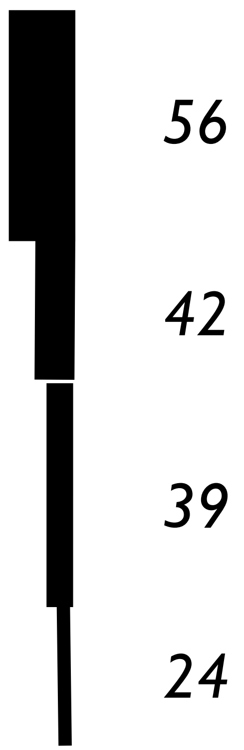
$$N_{\max}^A = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

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

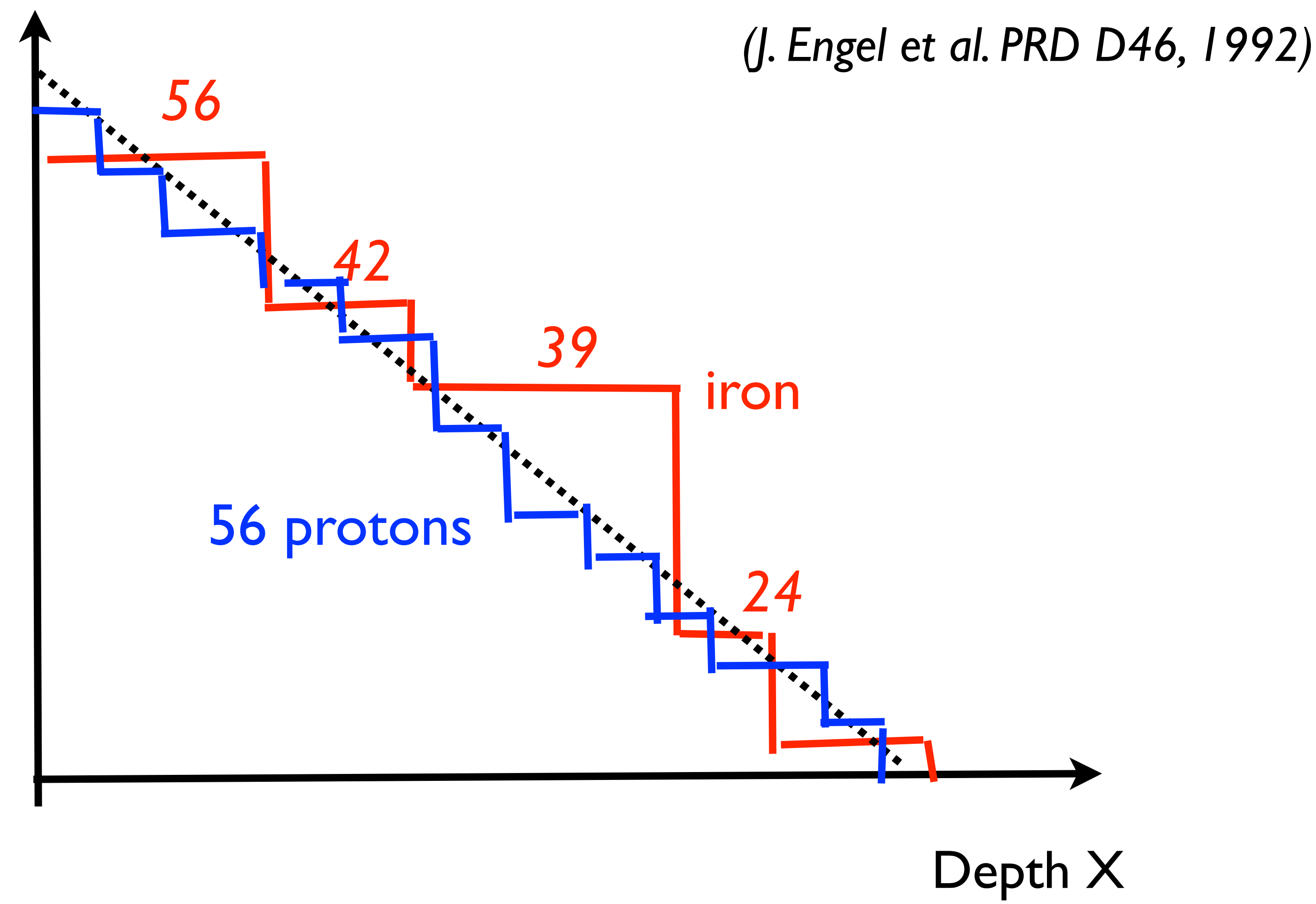
$$N_\mu^A = A\left(\frac{E_0}{AE_{\text{dec}}}\right)^\alpha = A^{1-\alpha} N_\mu$$

Superposition model: correct prediction of mean Xmax

iron nucleus



Number of nucleons without interaction

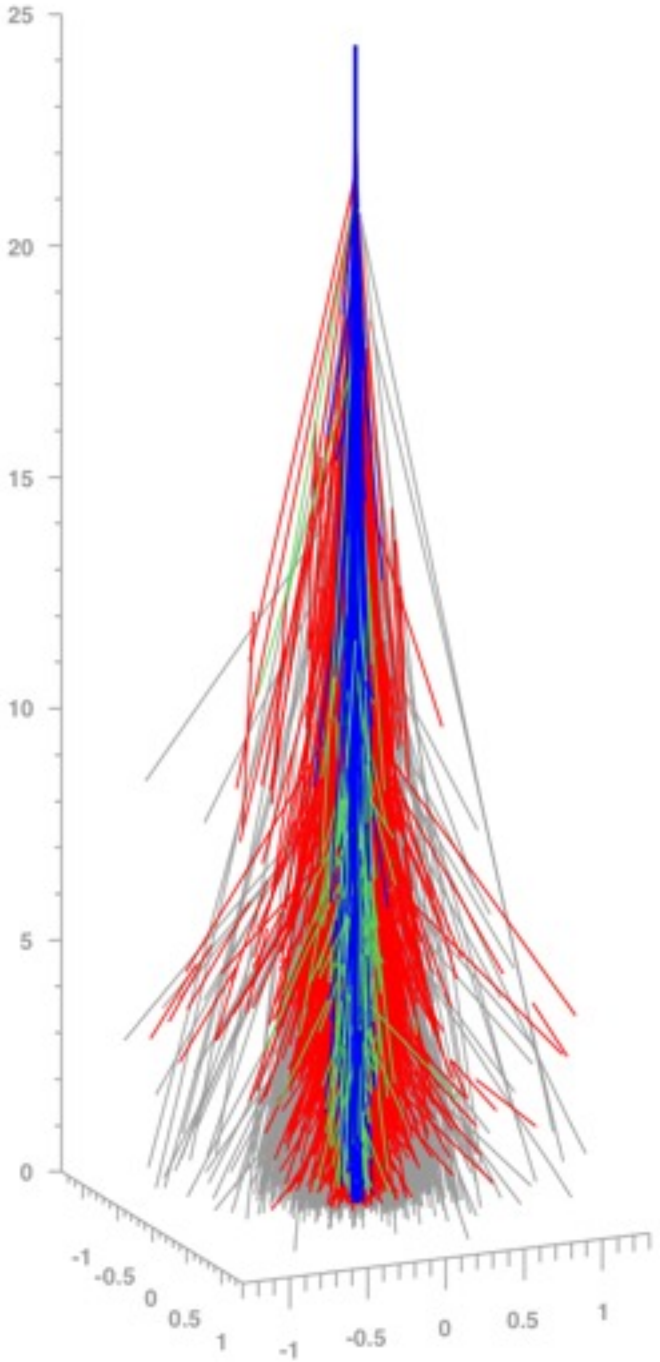


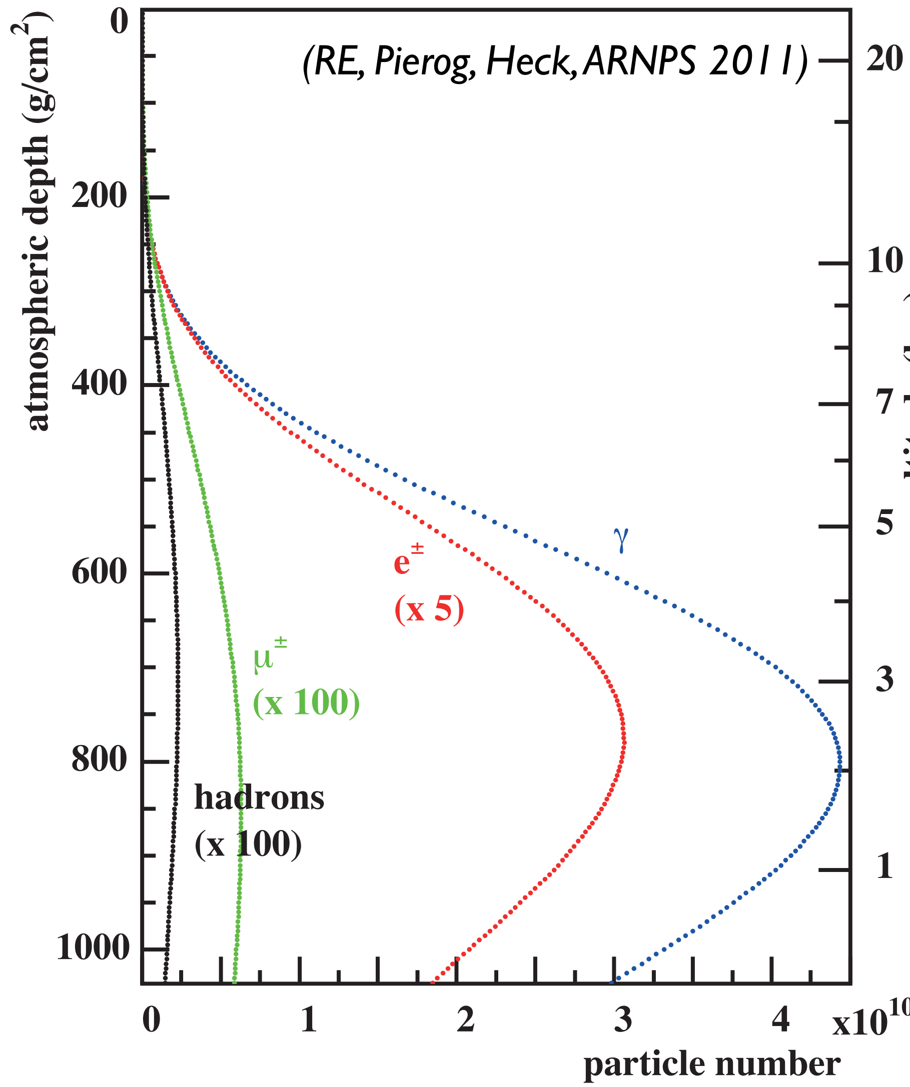
Glauber approximation (unitarity)

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

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

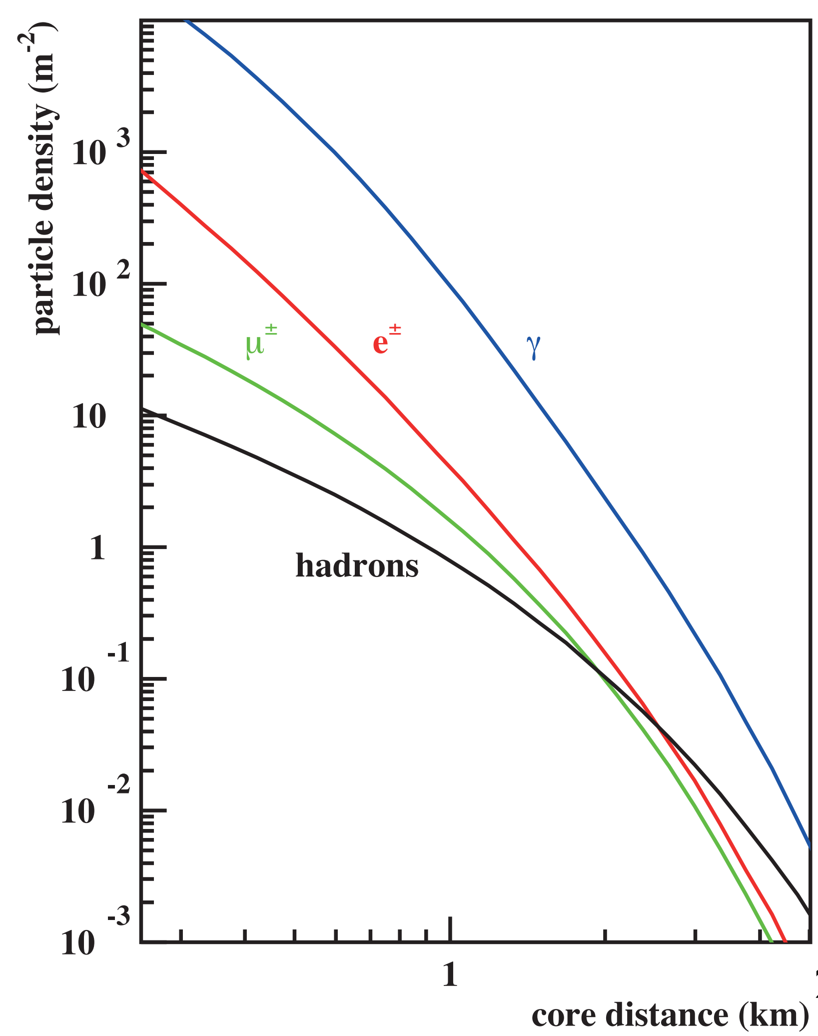
Measured components of air showers





Longitudinal profile:

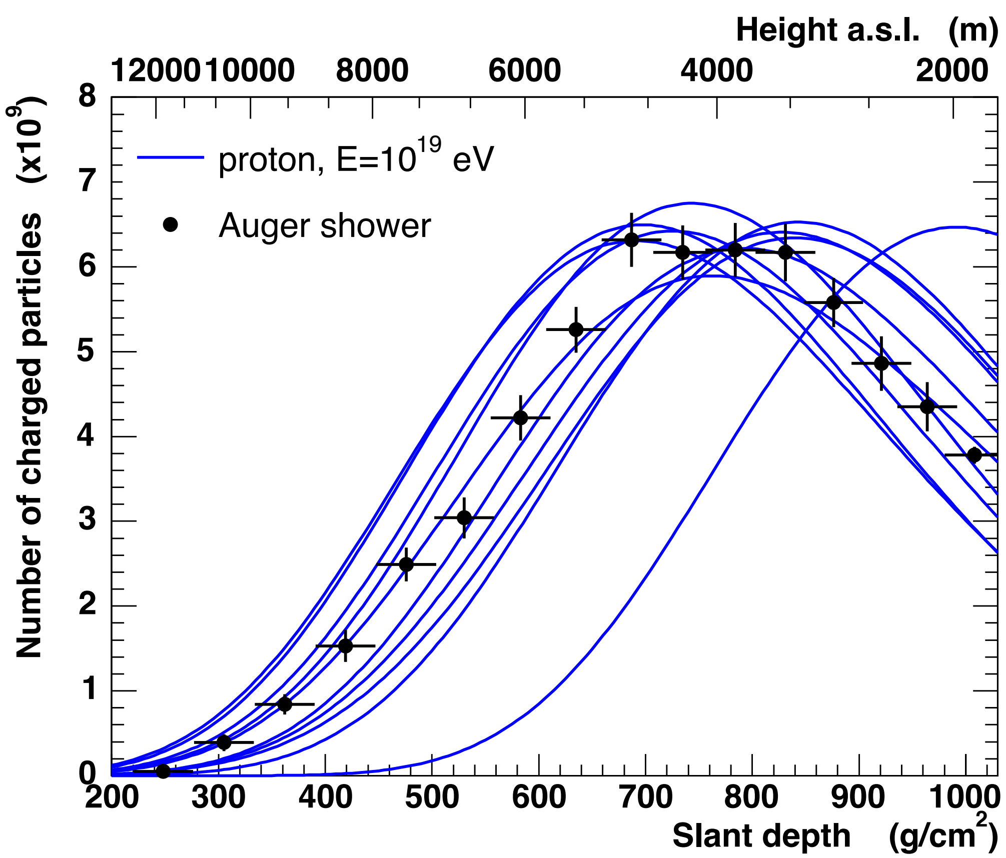
Cherenkov light
Fluorescence light
(bulk of particles measured)

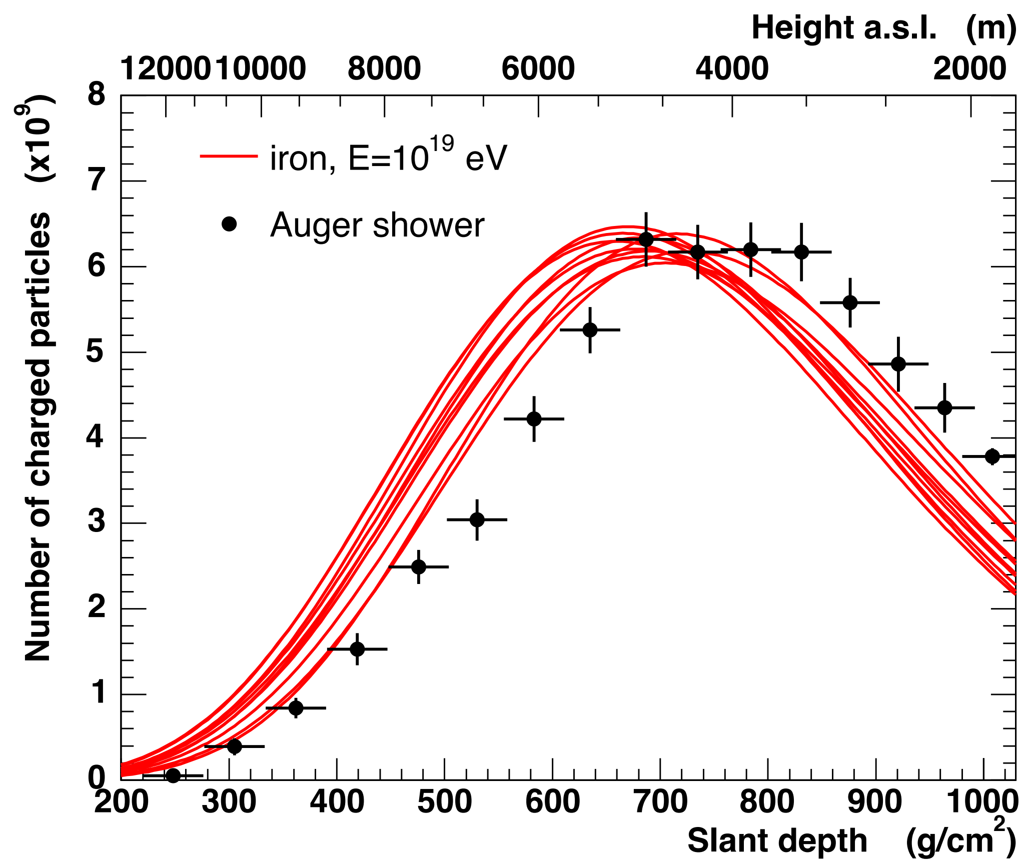


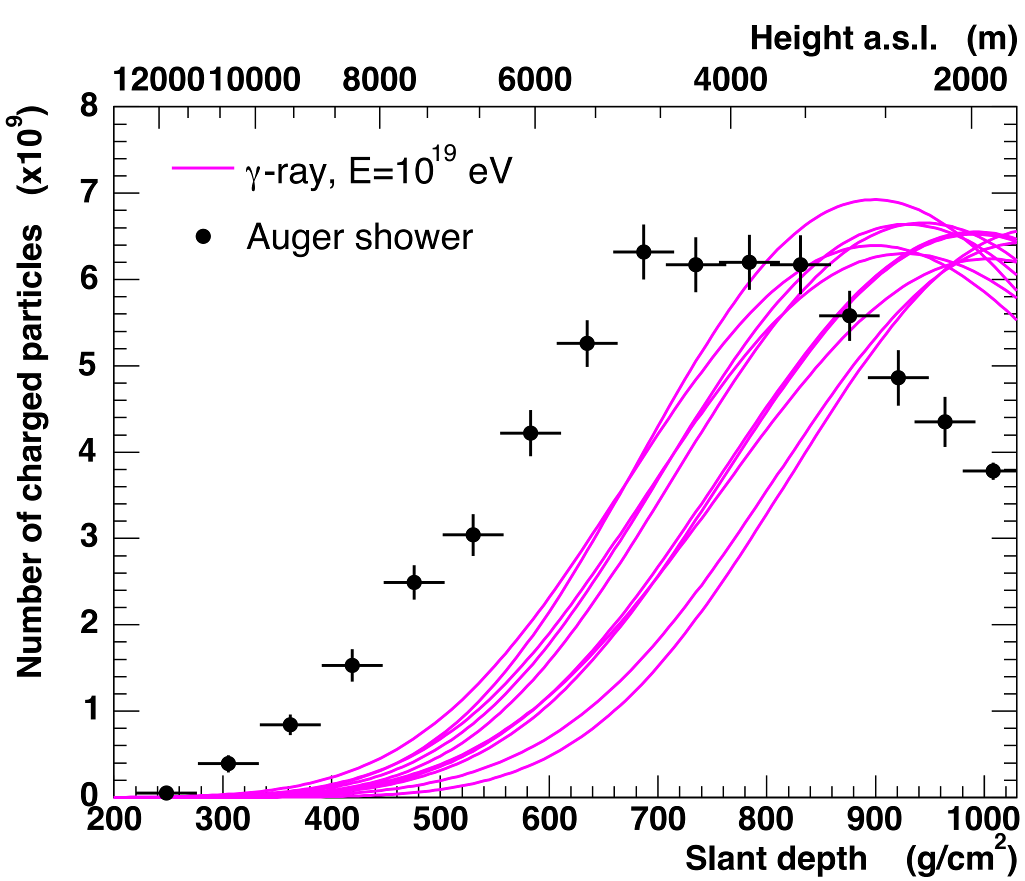
Lateral profiles:

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

Longitudinal shower profile







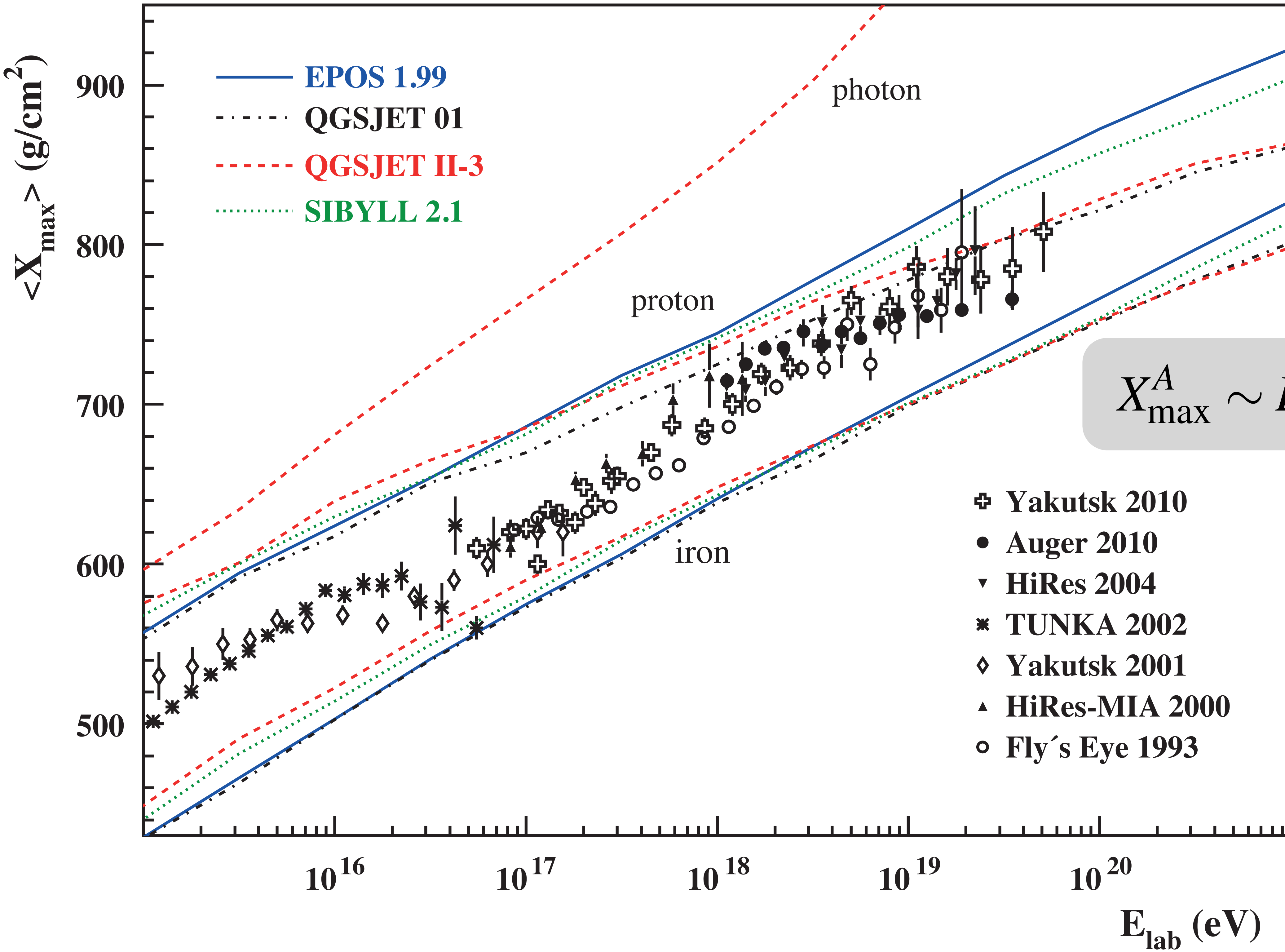
$$N_{\max} = E_0/E_c$$

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

Superposition model:

$$X_{\max}^{A} \sim D_e \ln(E_0/AE_c)$$

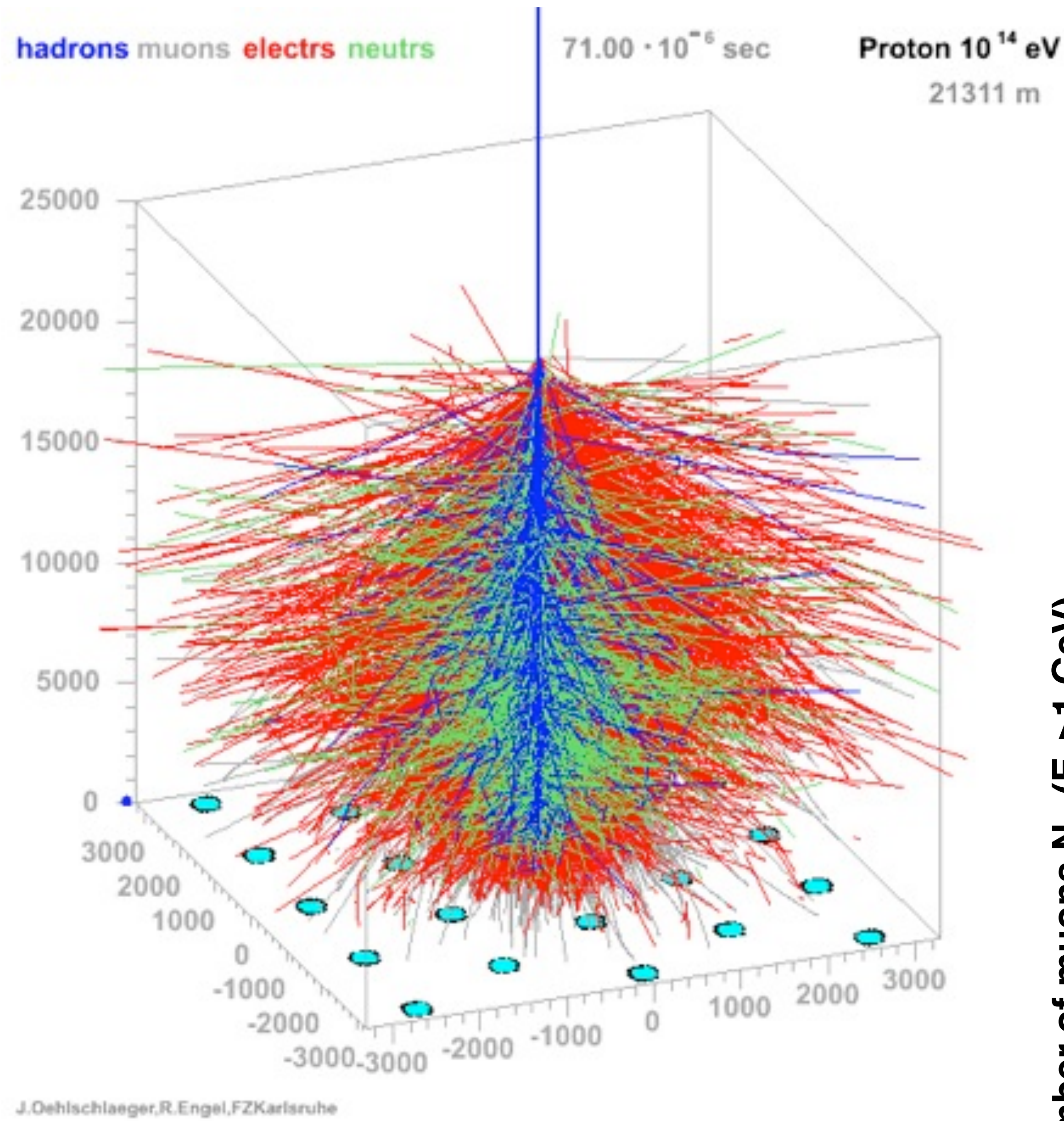
Mean depth of shower maximum



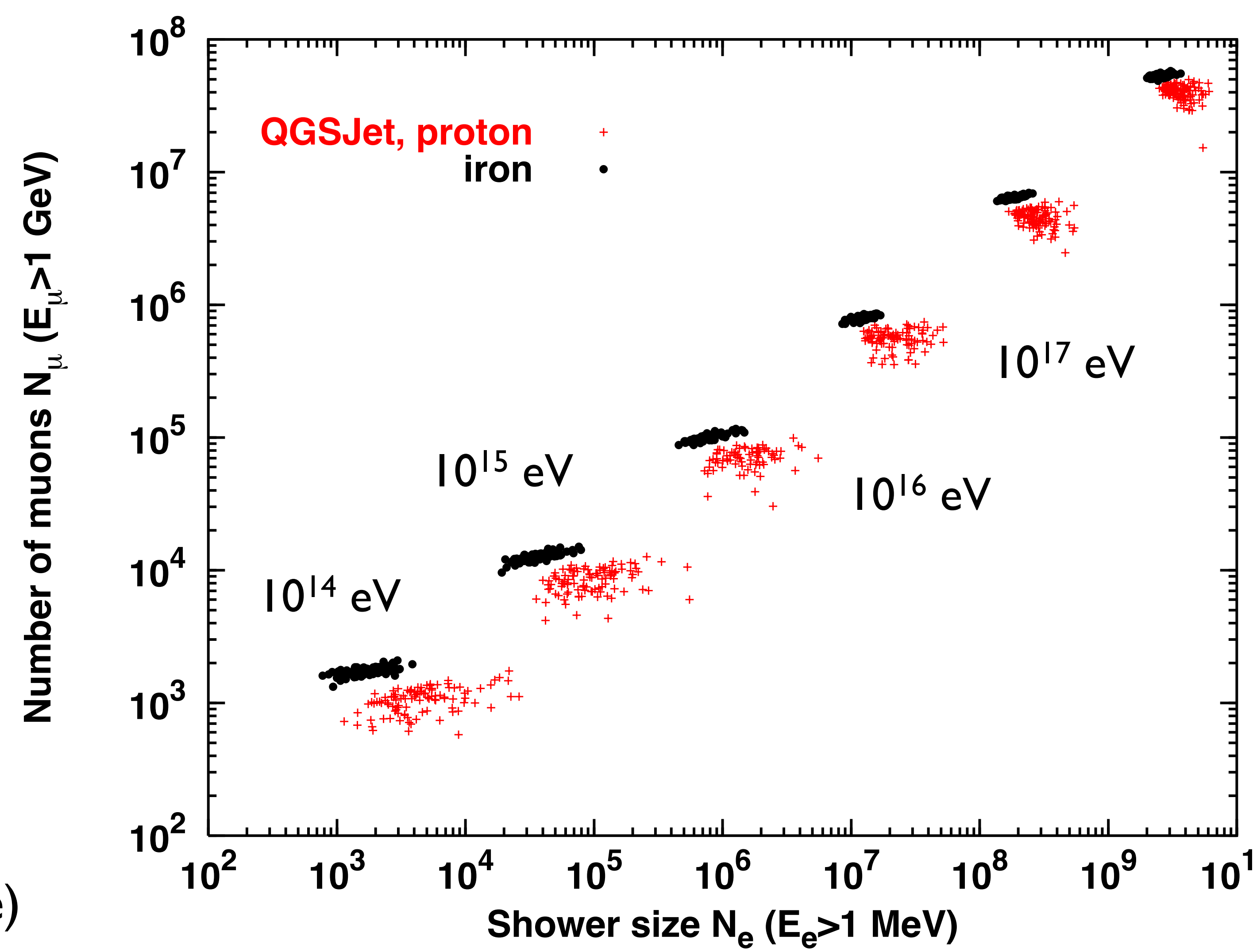
$$X_{\max}^{A} \sim D_e \ln(E_0/AE_c)$$

(RE, Pierog, Heck, ARNPS 2011)

Energy and composition measurement (Ne-Nμ)

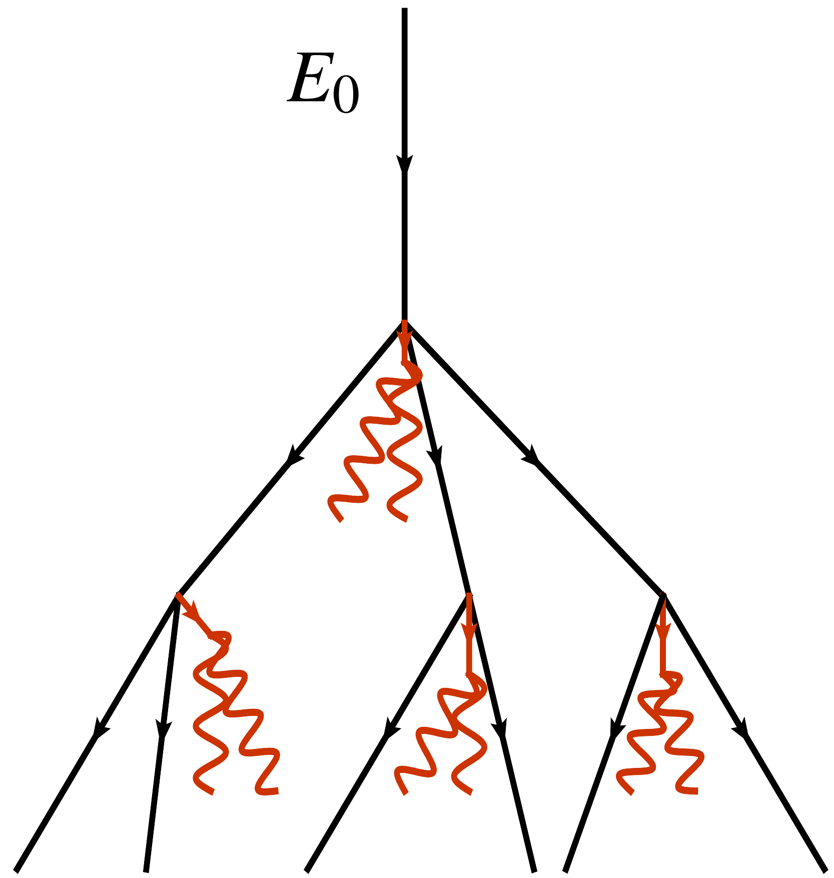


Monte Carlo simulation of showers



Example:
KASCADE and KASCADE-Grande (Karlsruhe)

Electromagnetic energy and energy transfer



Hadronic energy

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

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

$$\vdots$$

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

Electromagnetic energy

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

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

$$\vdots$$

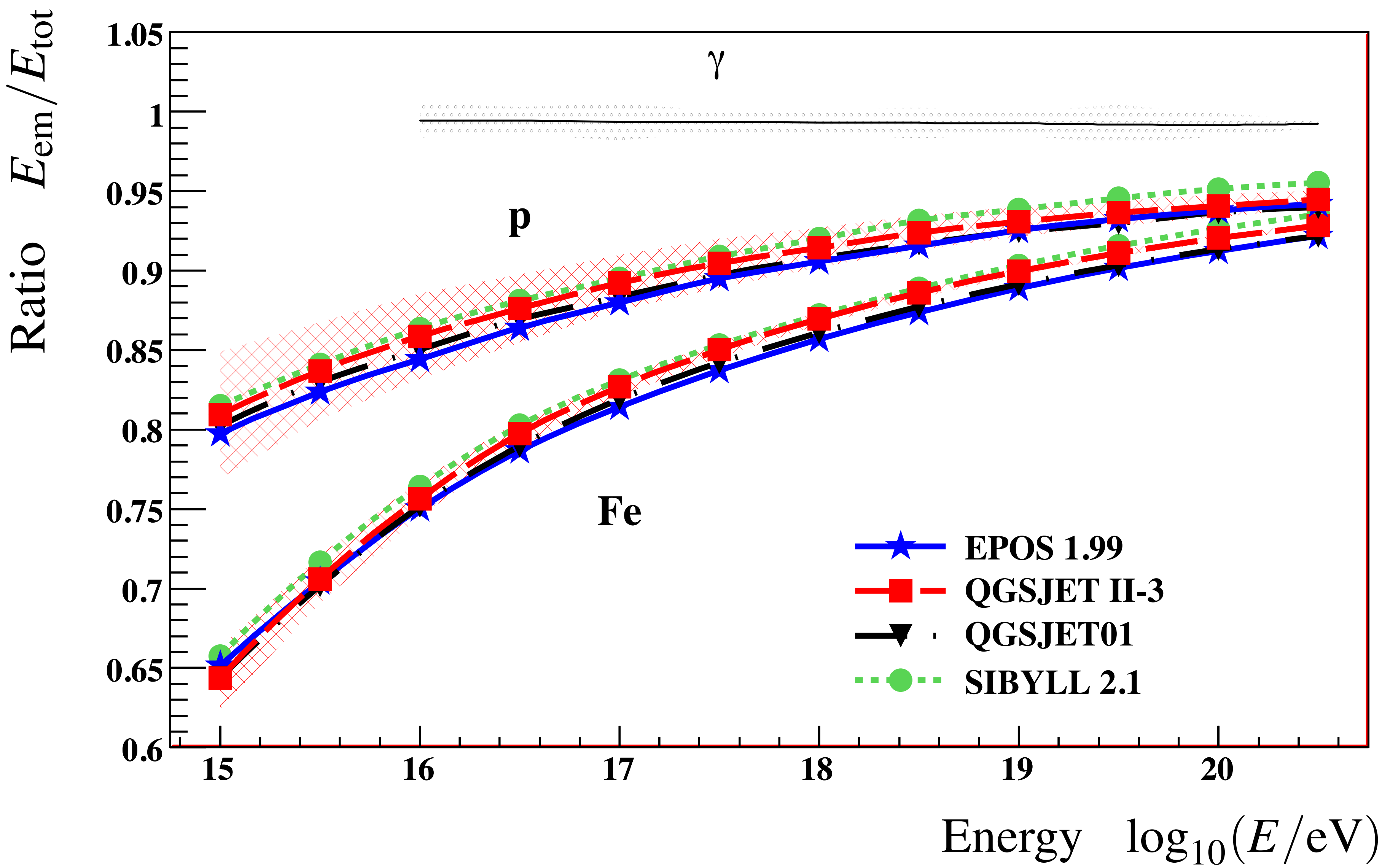
$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

After n generations ...

$$\boxed{\begin{array}{l} n = 5, \quad E_{\text{had}} \sim 12\% \\ n = 6, \quad E_{\text{had}} \sim 8\% \end{array}}$$

Muon multiplicity correlation with missing energy

(RE, Pierog, Heck, ARNPS 2011)

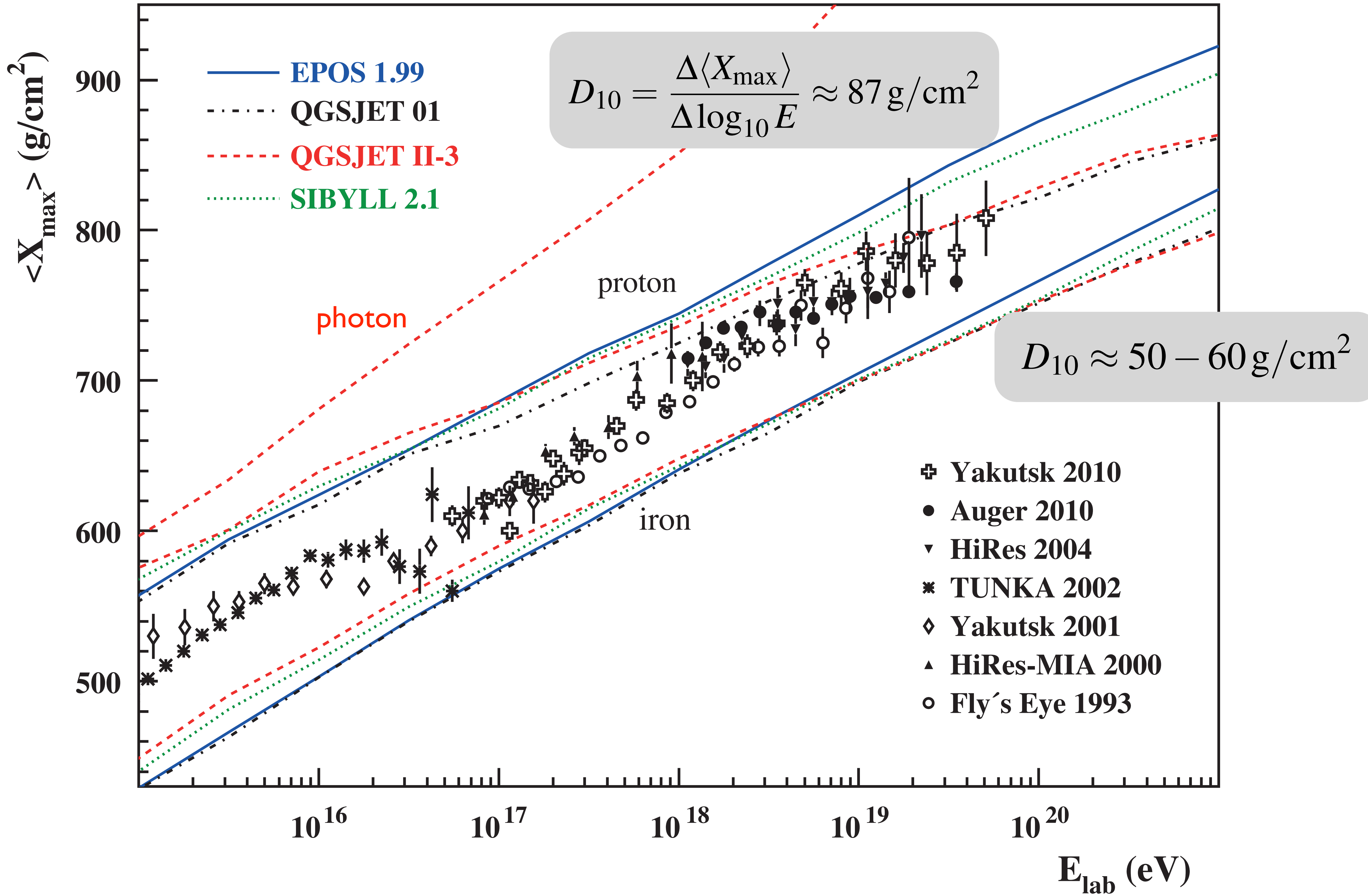


Ratio of em. to total shower energy

Detailed Monte Carlo simulation with CONEX

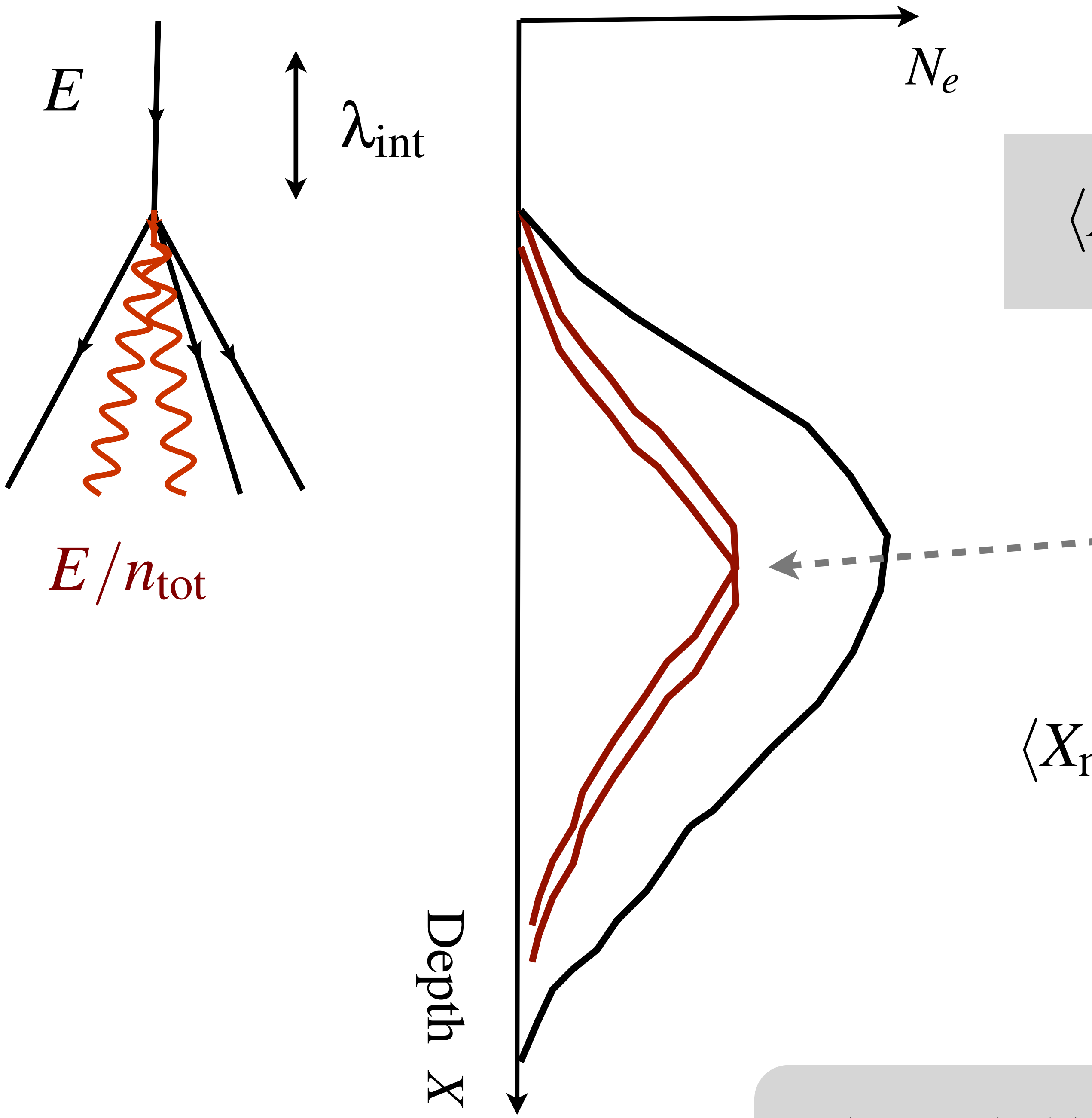
Model dependence of correction to obtain total energy small

Different slopes for em. and hadronic showers



(RE, Pierog, Heck, ARNPS 2011)

Derivation of elongation rate theorem



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

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

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

taking derivative $\log E$

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

Elongation rate of em. shower

Elongation rate theorem

X_0 = 36 g/cm^2

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

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

Summary: Introduction to air showers

Air showers are easy to understand

- Heitler model of em. shower
- Matthews-Heitler model of muon production
- Superposition model (which is better than expected)
- Elongation rate theorem

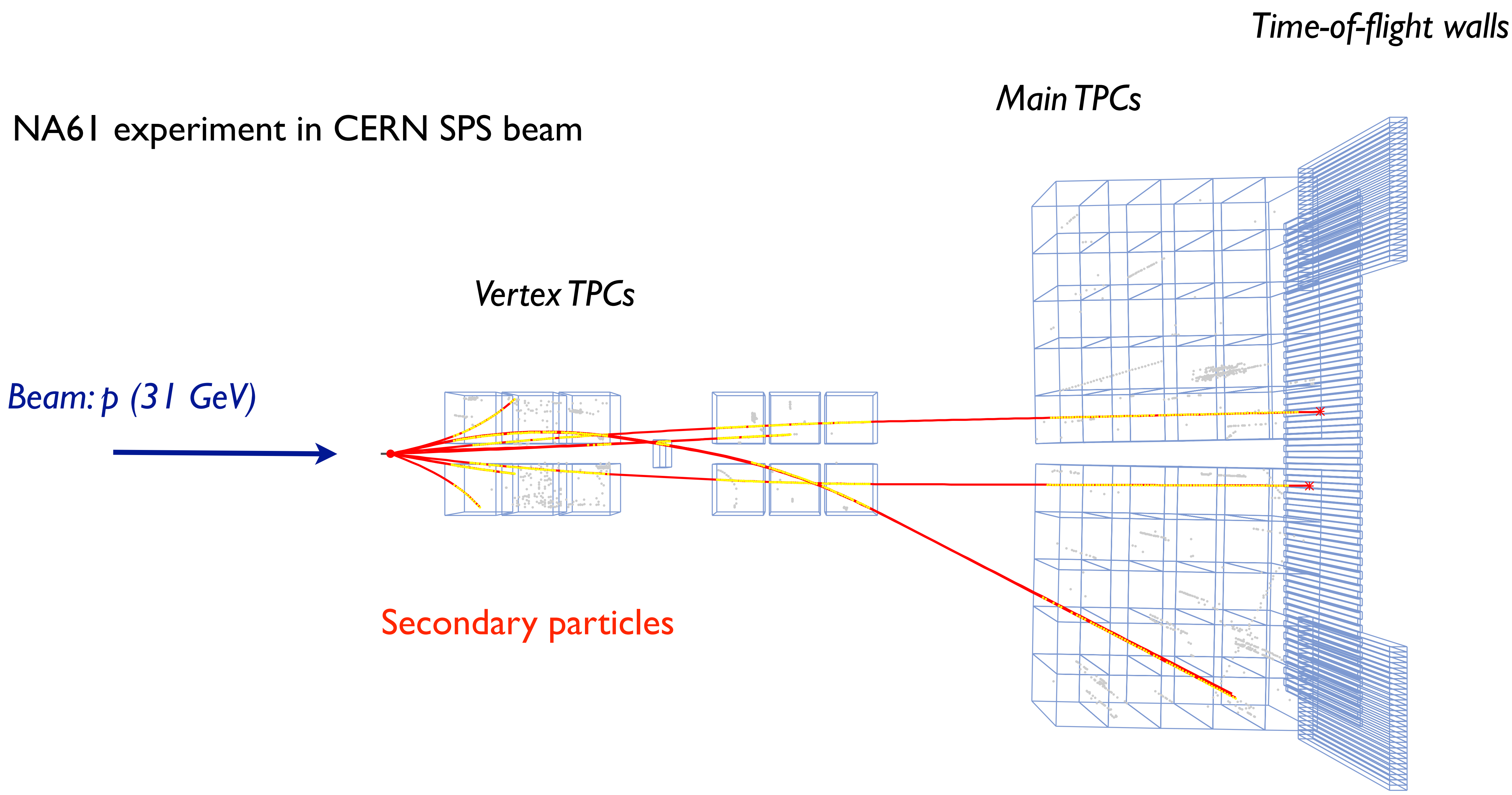
Still to come

- Shower-to-shower fluctuations
- Lateral distribution of particles
- Shower age, universality features
- Model predictions and data interpretation
- Muon discrepancy (help!)

Part 2: Modeling hadronic interactions

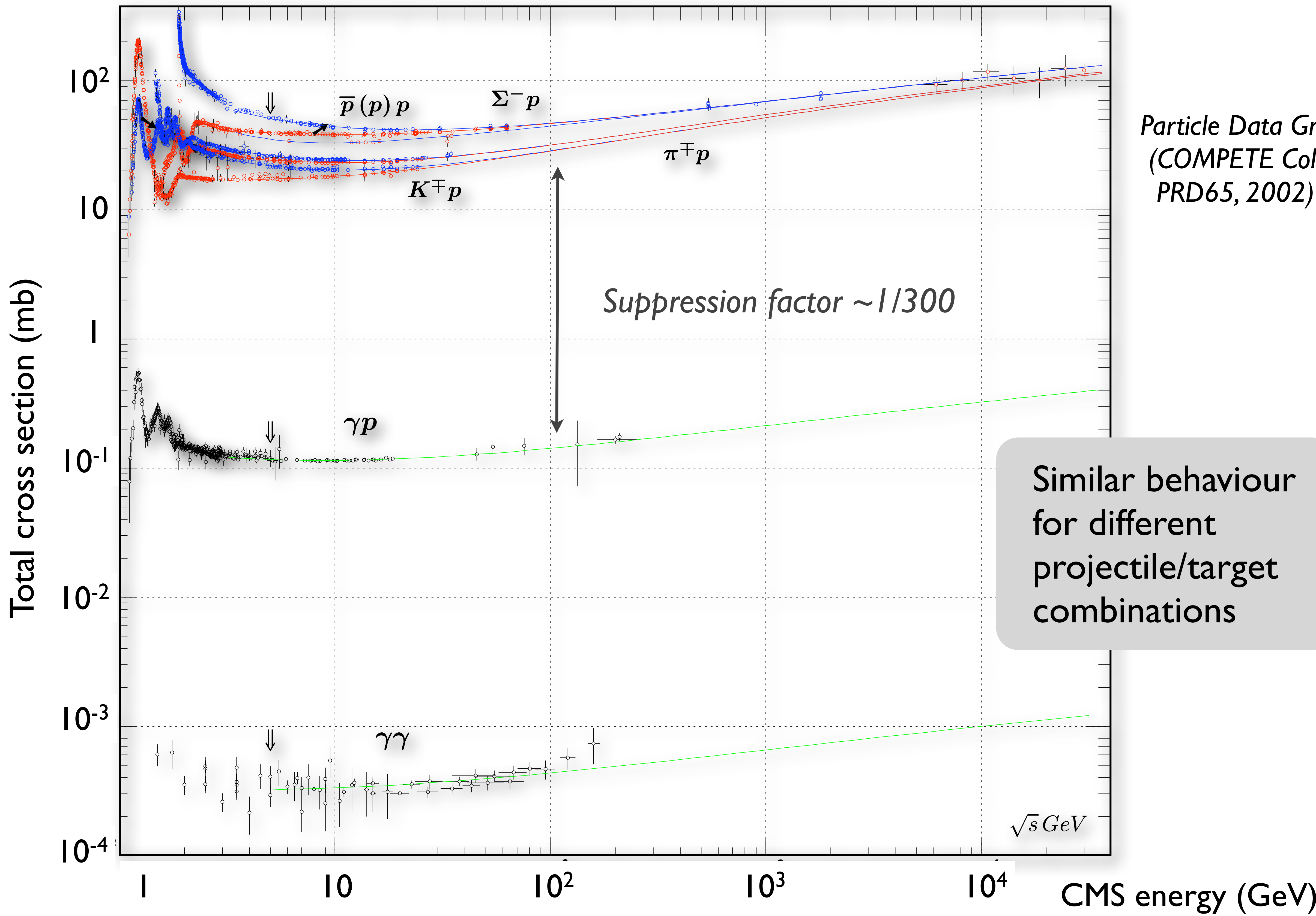
Modeling of hadronic interactions

NA61 experiment in CERN SPS beam



Typical particle multiplicities: 5 to 15 secondaries

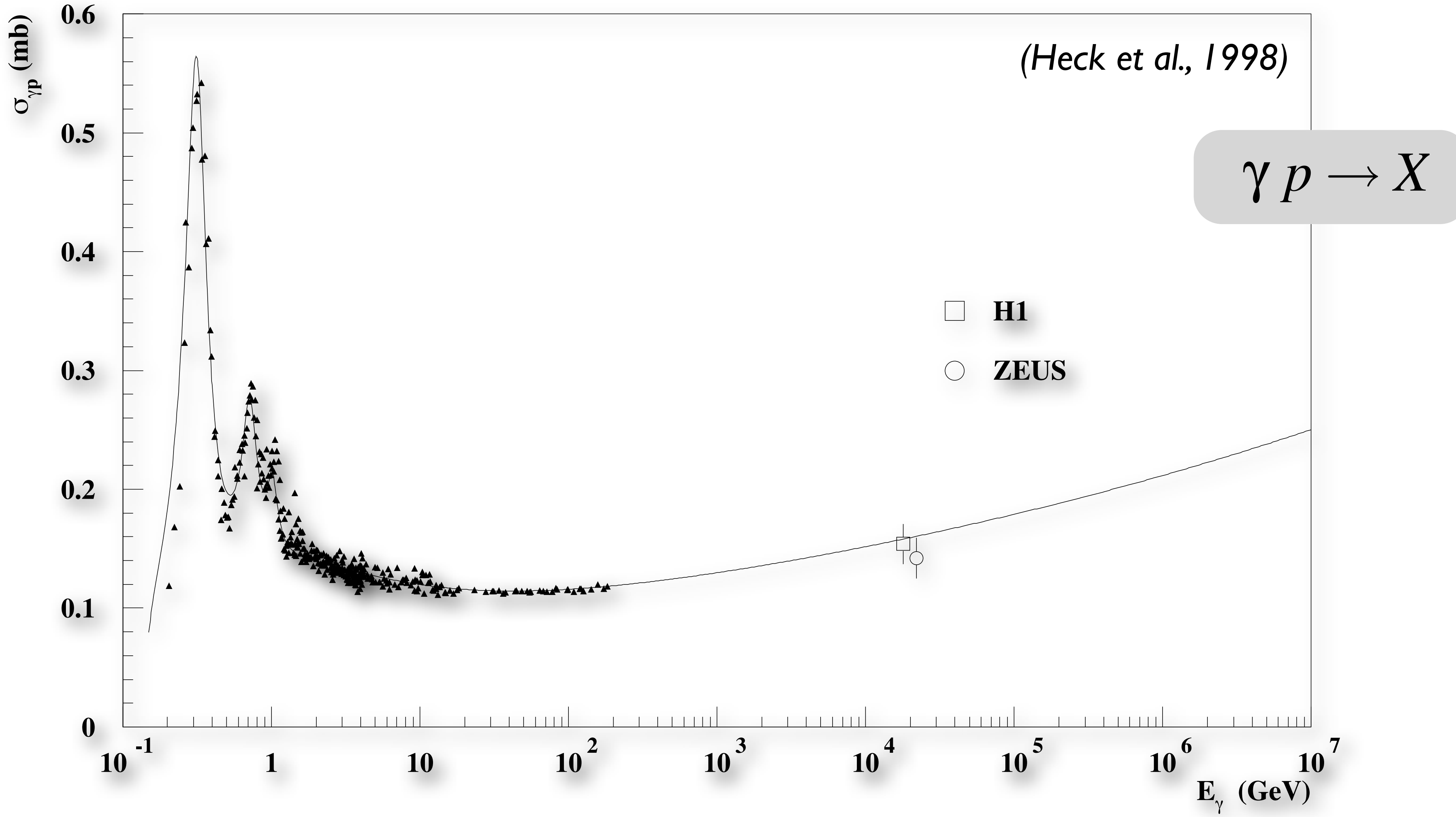
Compilation of total cross sections



Particle Data Group (COMPETE Collab. PRD65, 2002)

Similar behaviour for different projectile/target combinations

Simulation concepts: energy ranges



Resonances (fireball)

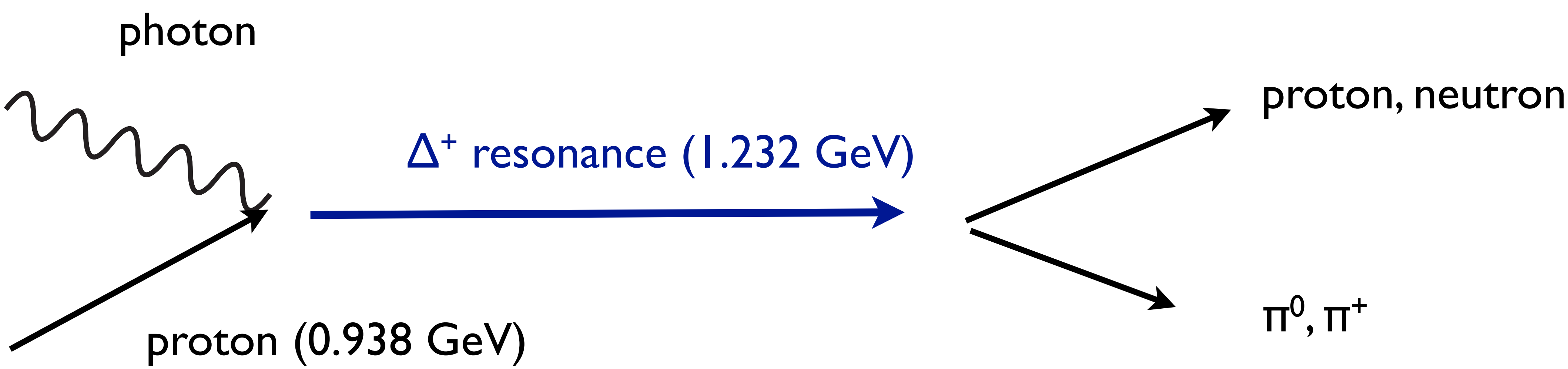
Scaling region (longitudinal phase space)

Minijet region (scaling violation)

???

Particle production in resonance region

Photoproduction of resonances



CMB: Energy threshold not sharp $\quad E_{\gamma,\max} \approx 10^{-3}\mathrm{eV}$

$$E_{p,\Delta} = \frac{m_\Delta^2 - m_p^2}{2E_{\gamma,\max}(1-\cos\theta)} \approx 10^{20}\mathrm{eV}$$

In proton rest frame:

$$E_{\gamma,\mathrm{lab}} \approx 300\ \mathrm{MeV}$$

Decay branching ratio proton:neutron = 2:1

Mean proton energy loss 20%

Decay isotropic up to spin effects

Well-established resonances in photoproduction

Baryon resonances and their physical parameters implemented in SOPHIA (see text). Superscripts $^+$ and ^{0} in the parameters refer to $p\gamma$ and $n\gamma$ excitations, respectively. The maximum cross section, $\sigma_{\max} = 4m_N^2 M^2 \sigma_0/(M^2 - m_N^2)^2$, is also given for reference

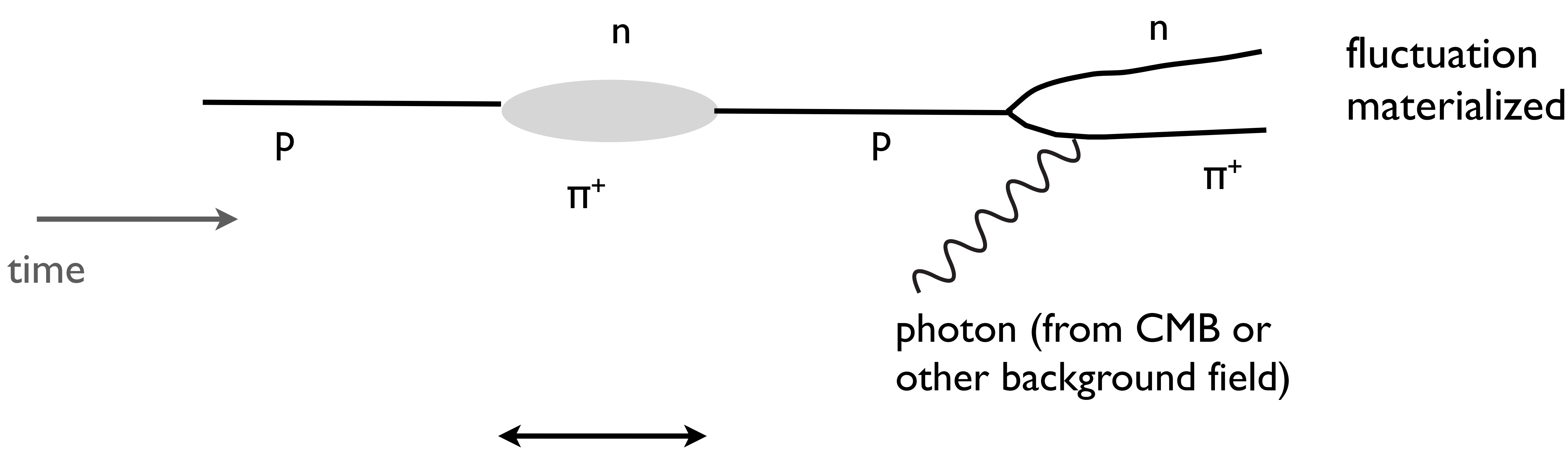
Resonance	M	Γ	$10^3 b_\gamma^+$	σ_0^+	$\sigma_{\max}^+$	$10^3 b_\gamma^0$	σ_0^0	$\sigma_{\max}^0$
$\Delta(1232)$	1.231	0.11	5.6	31.125	411.988	6.1	33.809	452.226
$N(1440)$	1.440	0.35	0.5	1.389	7.124	0.3	0.831	4.292
$N(1520)$	1.515	0.11	4.6	25.567	103.240	4.0	22.170	90.082
$N(1535)$	1.525	0.10	2.5	6.948	27.244	2.5	6.928	27.334
$N(1650)$	1.675	0.16	1.0	2.779	7.408	0.0	0.000	0.000
$N(1675)$	1.675	0.15	0.0	0.000	0.000	0.2	1.663	4.457
$N(1680)$	1.680	0.125	2.1	17.508	46.143	0.0	0.000	0.000
$\Delta(1700)$	1.690	0.29	2.0	11.116	28.644	2.0	11.085	28.714
$\Delta(1905)$	1.895	0.35	0.2	1.667	2.869	0.2	1.663	2.875
$\Delta(1950)$	1.950	0.30	1.0	11.116	17.433	1.0	11.085	17.462

Breit-Wigner resonance cross section

$$\sigma_{\mathrm{bw}}(s; M, \Gamma, J) = \frac{s}{(s - m_N^2)^2} \frac{4\pi b_\gamma (2J+1) s \Gamma^2}{(s - M^2)^2 + s\Gamma^2}$$

Direct pion production

Possible interpretation: p fluctuates from time to time to n and π^+



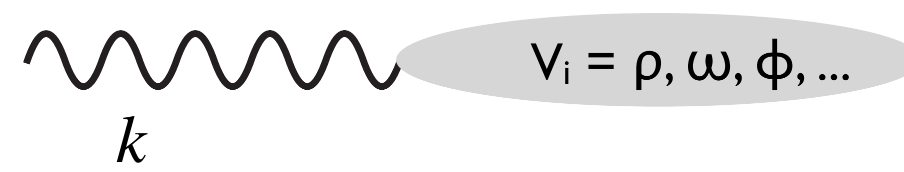
Heisenberg uncertainty relation $\Delta E \Delta t \approx 1$

Energy threshold very low: $E_{\mathrm{cm,min}} = m_\pi + m_p \approx 1.07\ \mathrm{GeV}$

(Δ^+ resonance: 1.232 GeV)

Lifetime of fluctuations

Consider photon with momentum k



Heisenberg uncertainty relation $\Delta E \, \Delta t \approx 1$

Length scale (duration) of hadronic interaction $\Delta t_{\mathrm{int}} < 1\mathrm{fm} \approx 5\mathrm{GeV}^{-1}$

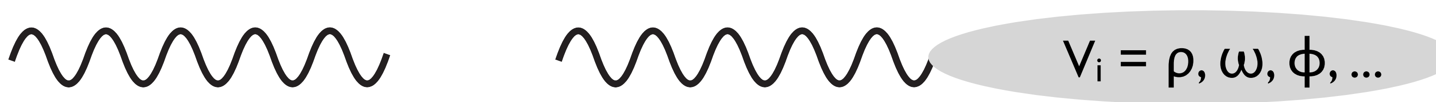
$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{k^2 + m_V^2} - k} = \frac{1}{k(\sqrt{1 + m_V^2/k^2} - 1)} \approx \frac{2k}{m_V^2}$$

Fluctuation long-lived for k > 3 GeV

$$\Delta t \approx \frac{2k}{m_V^2} > \Delta t_{\mathrm{int}}$$

Multiparticle production: vector meson dominance

Photon is considered as superposition of ``bare´´ photon and hadronic fluctuation

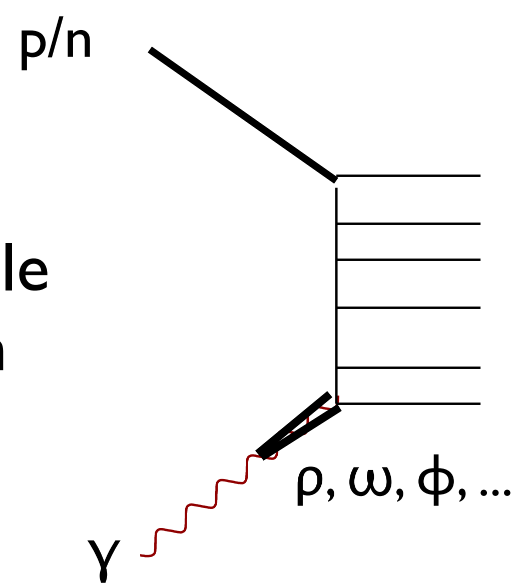


$$|\gamma\rangle = |\gamma_{\mathrm{bare}}\rangle + P_{\mathrm{had}} \sum_i |V_i\rangle$$

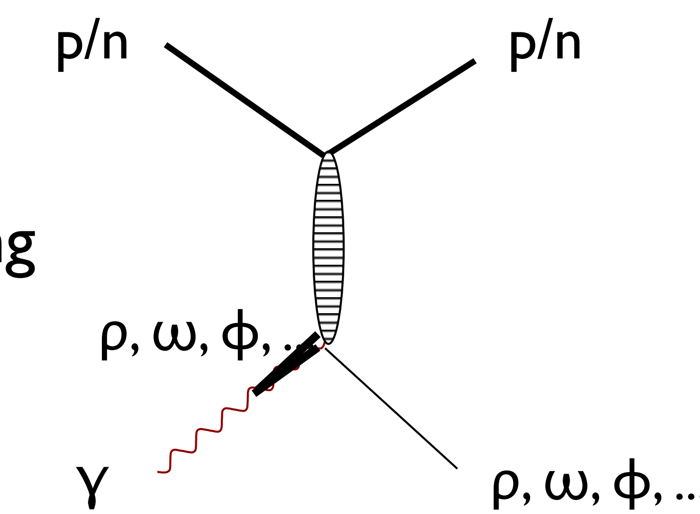
$$P_{\mathrm{had}} \approx \frac{1}{300} \ldots \frac{1}{250}$$

Cross section for hadronic interaction ~1/300 smaller than for pi-p interactions

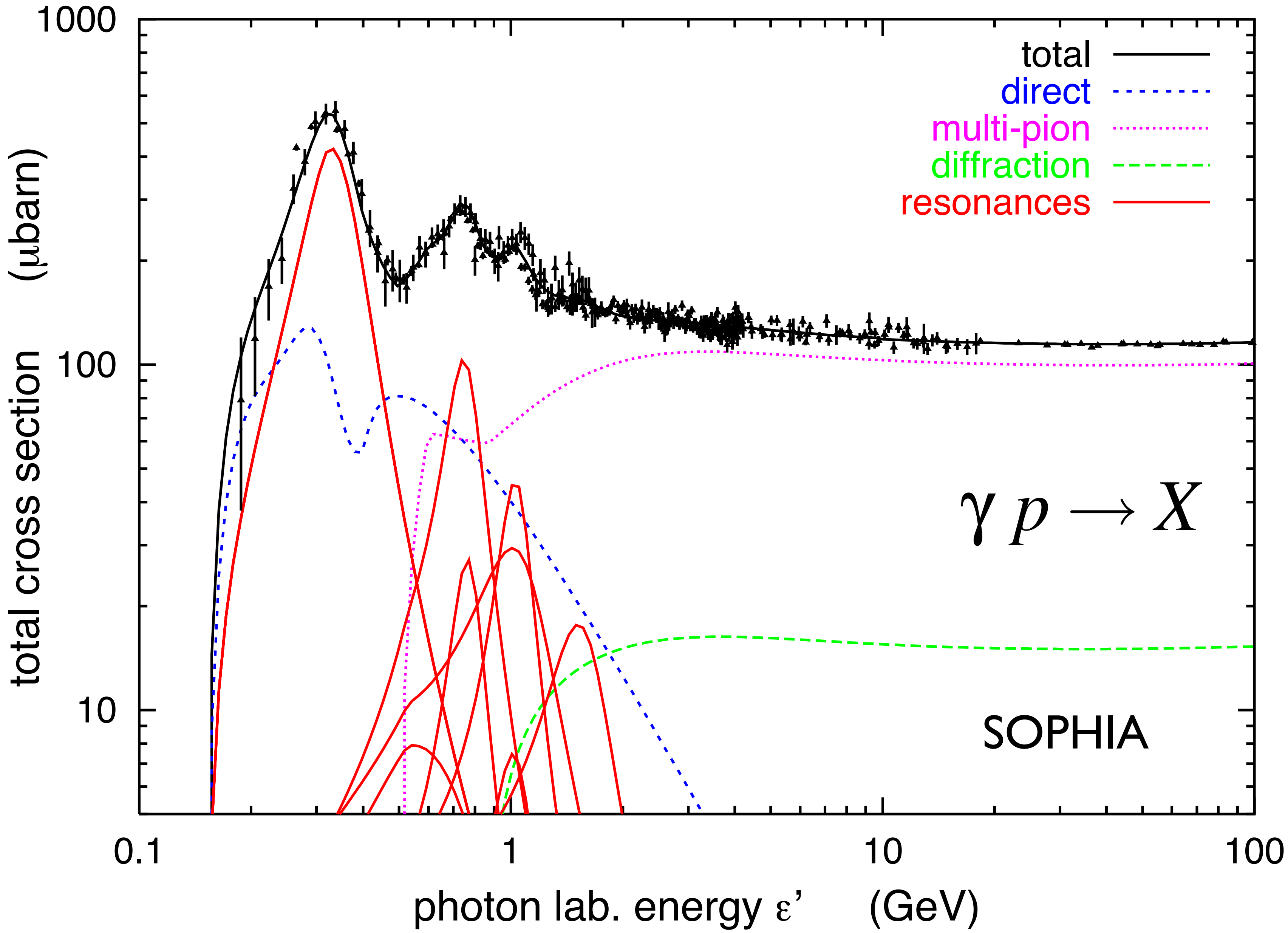
Multiparticle production



Elastic scattering



Putting all together: description of total cross section

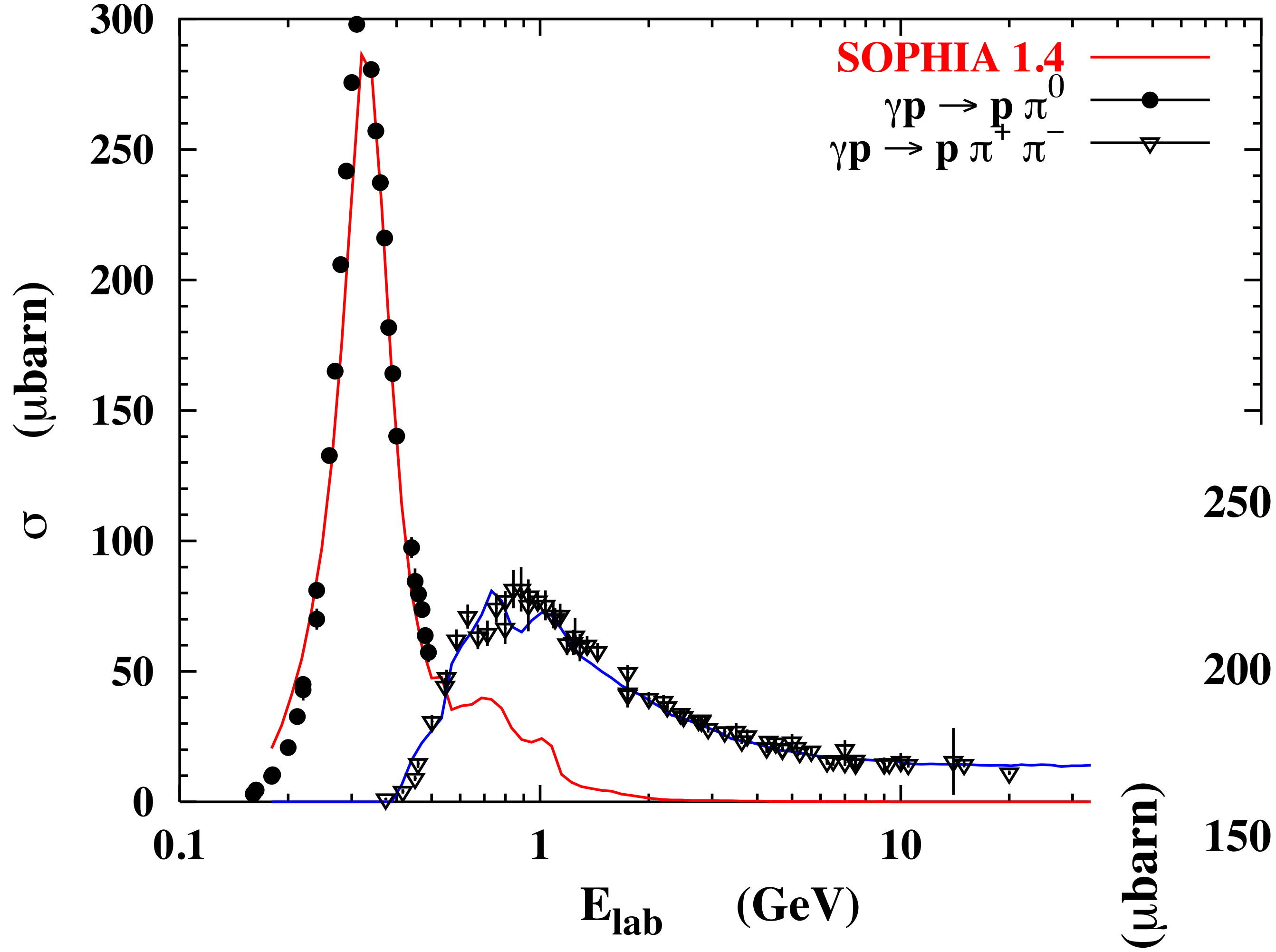


- PDG: 9 resonances, decay channels, angular distributions
- Regge parametrization at higher energy
- Direct contribution: fit to difference to data

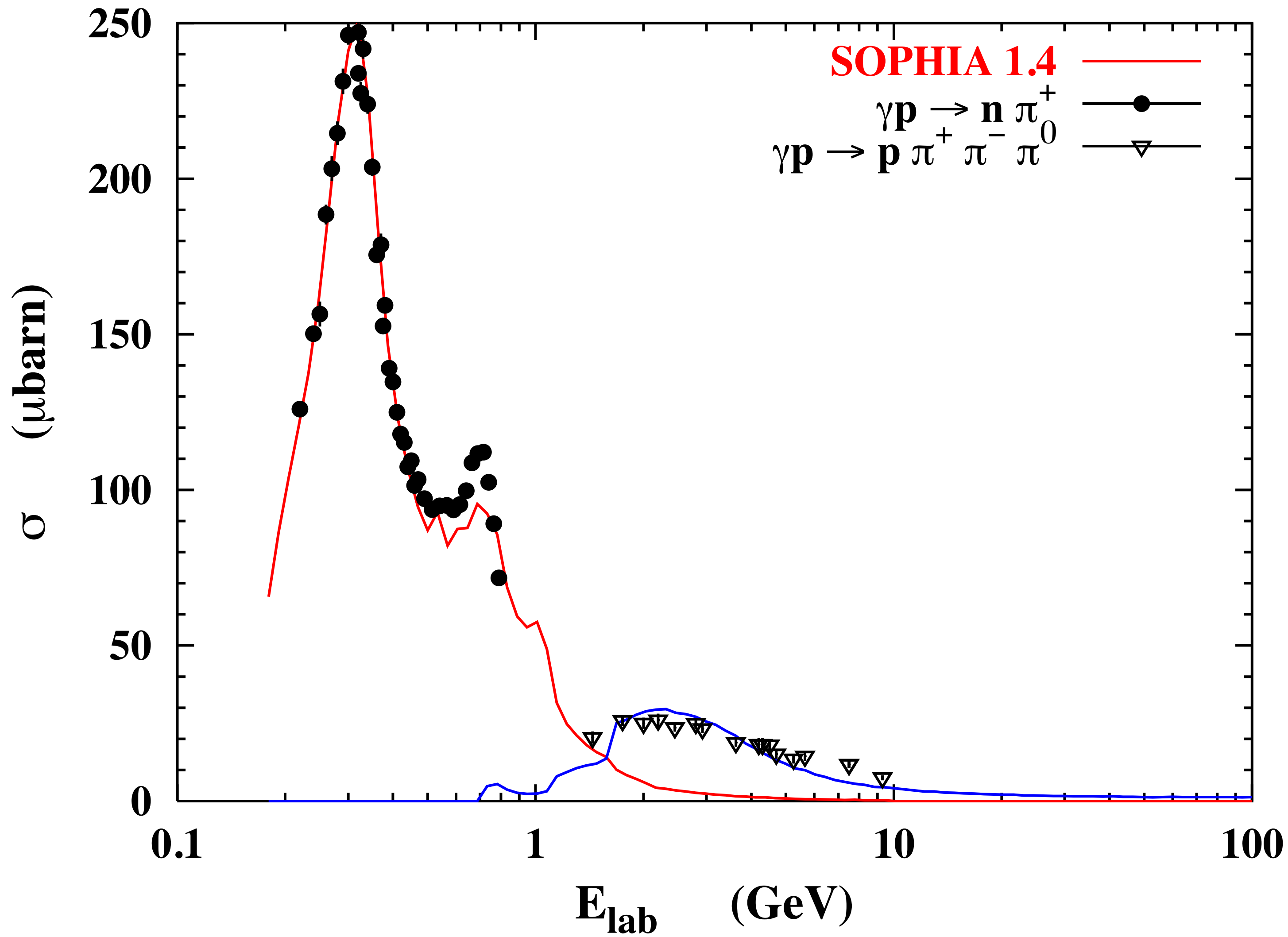
Many measurements available, still approximations necessary

SOPHIA (Mücke et al. CPC124, 2000)

Comparison with measured partial cross sections

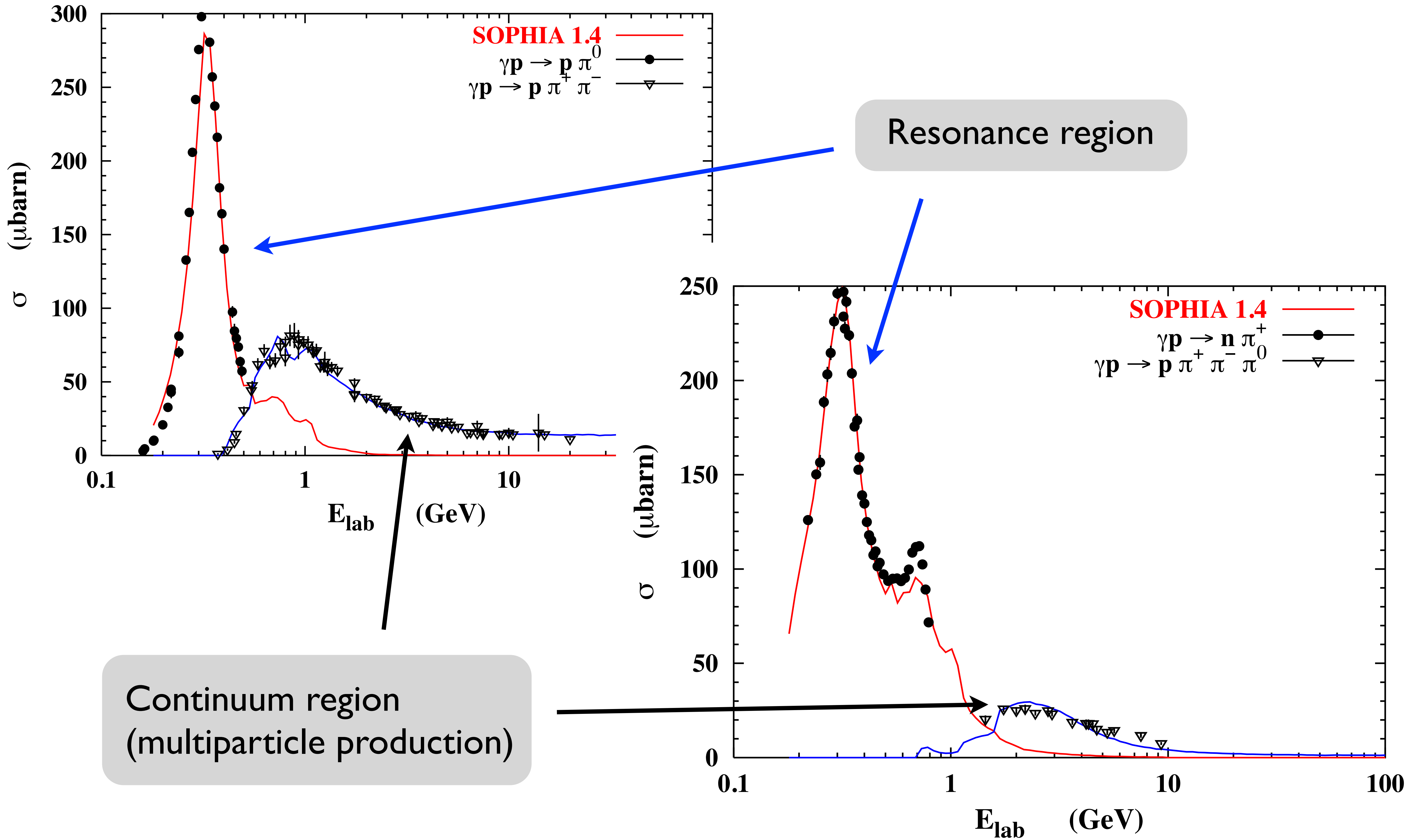


Data from fixed-target experiments



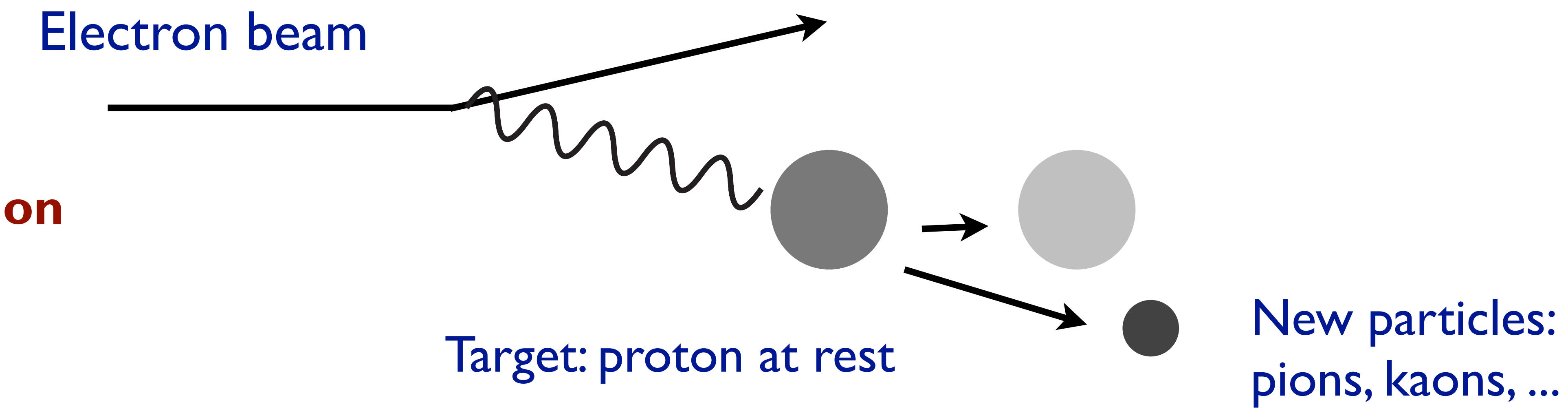
SOPHIA (Mücke et al. CPC124, 2000)

Comparison with measured partial cross sections

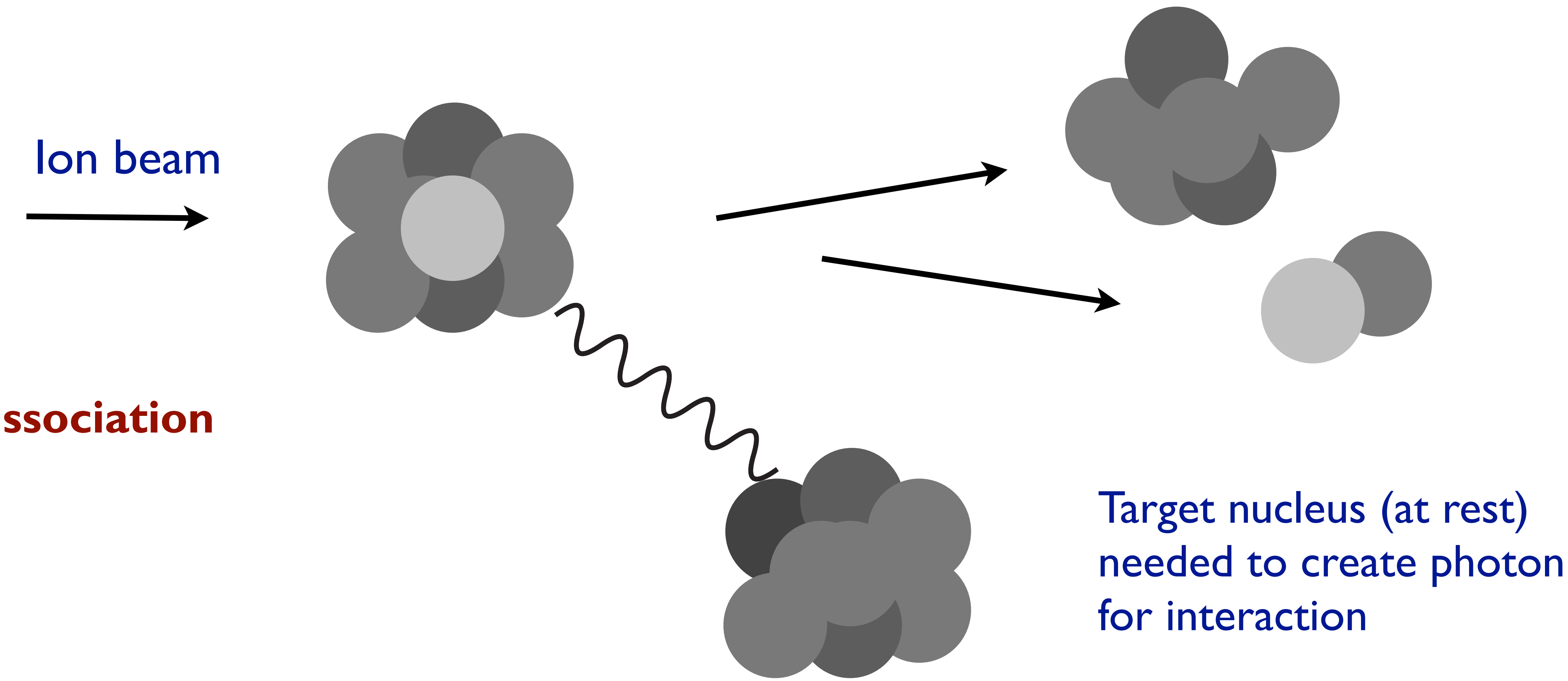


Measurement of nucleus disintegration

Photoproduction



Photodissociation

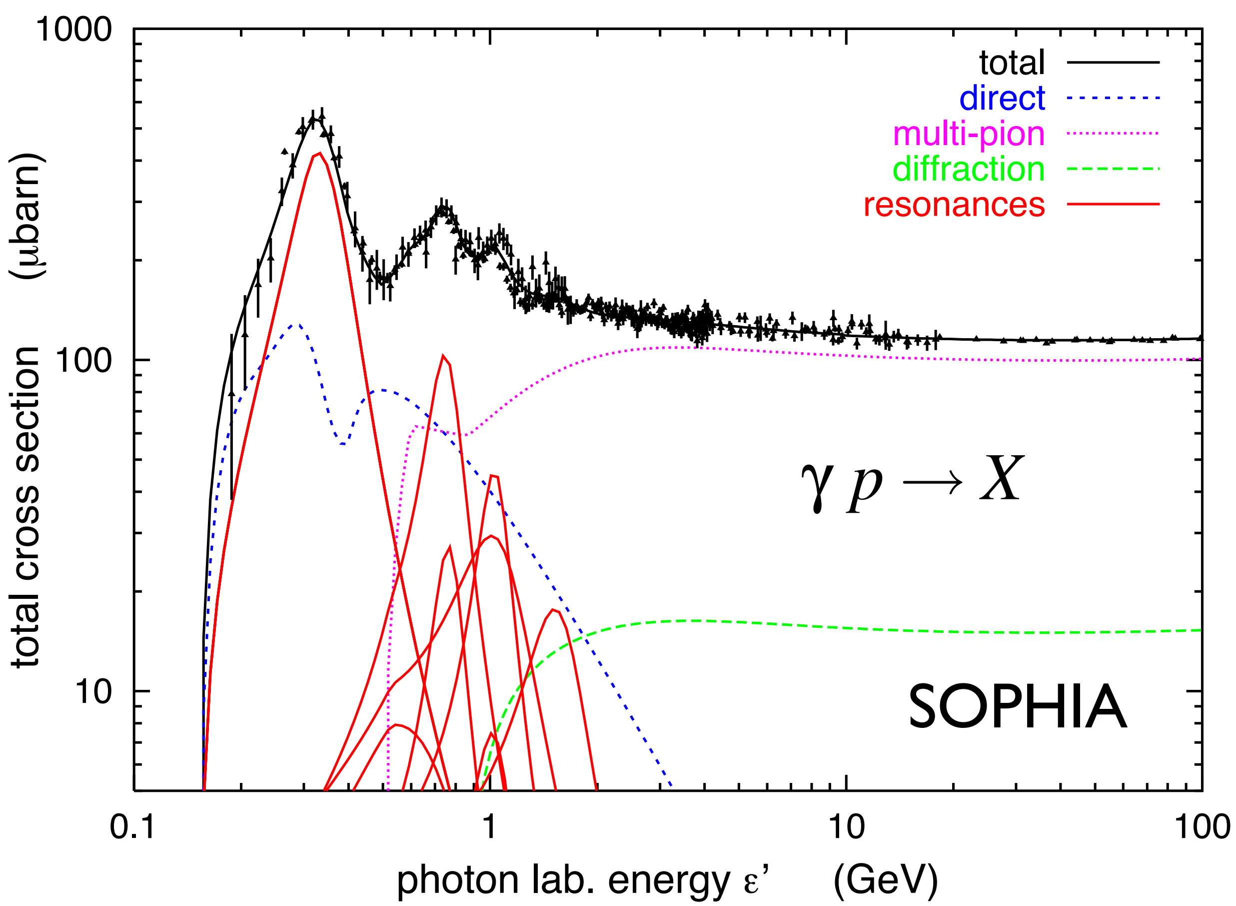


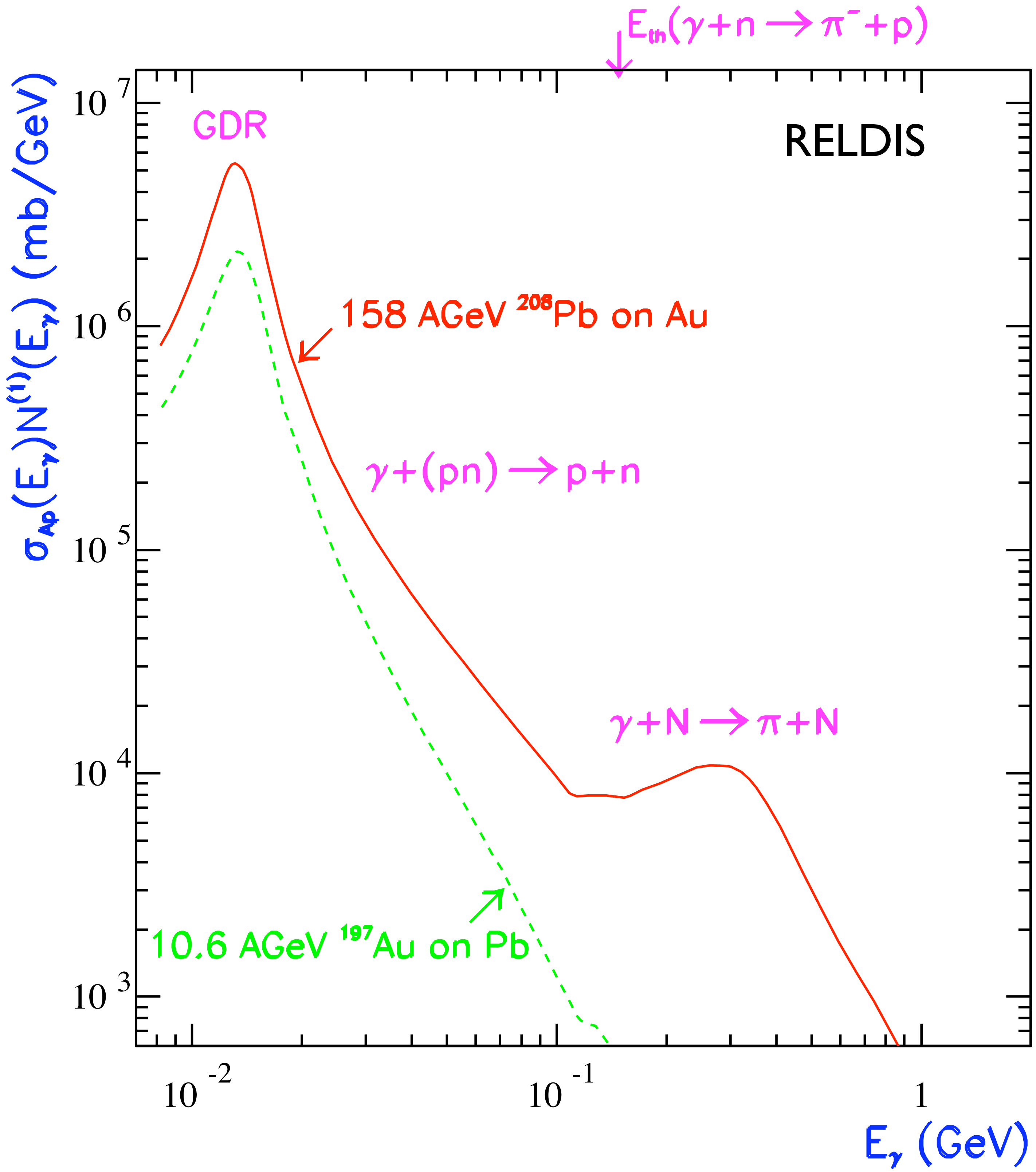
Effective em. dissociation cross section

Main contribution:
giant dipole resonance

Dominant emission processes:

- single nucleon
- quasi-deuteron
- alpha particle

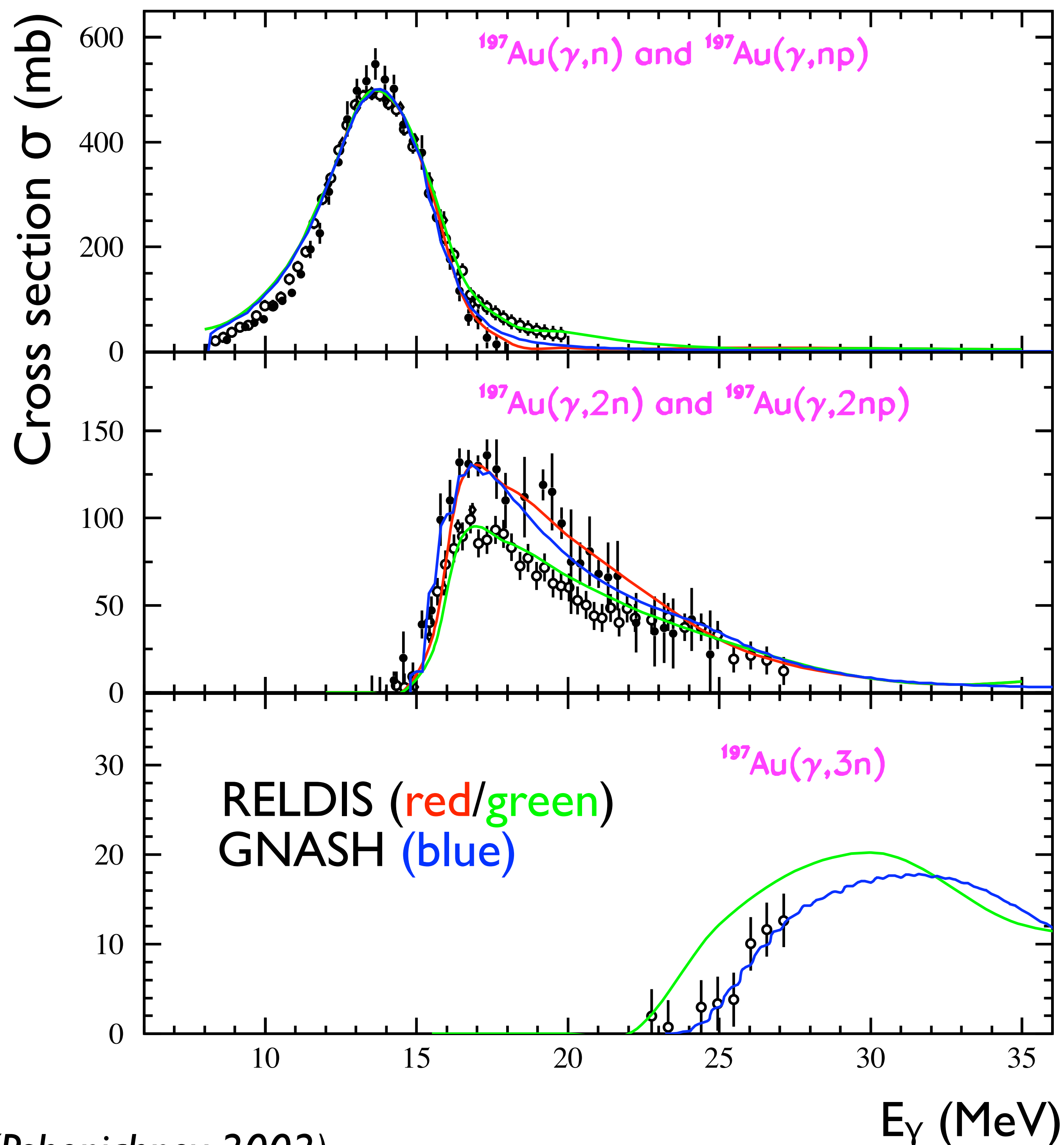




(Pshenichnov 2002)

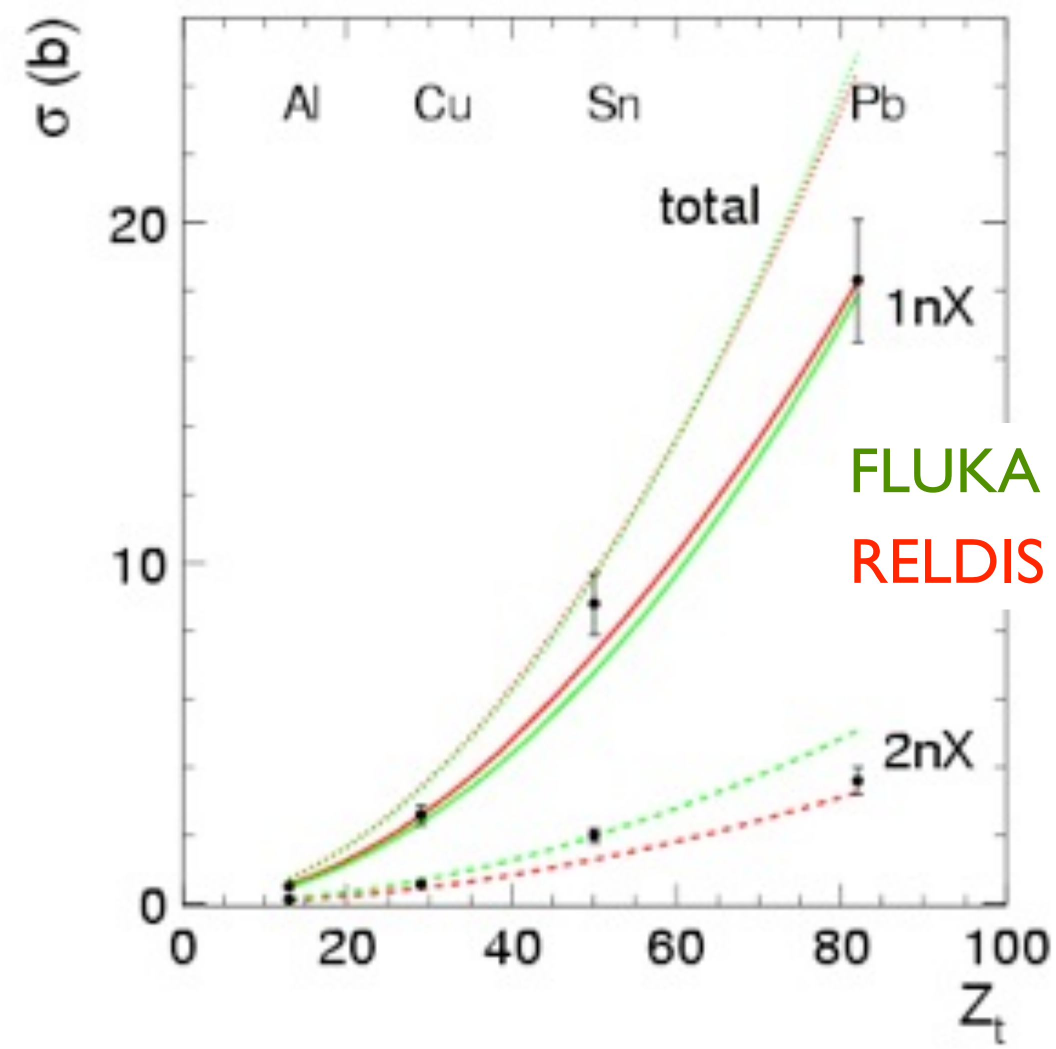
Example: photo-dissociation of nuclei

Saclay & Livermore data



(Pshenichnov 2002)

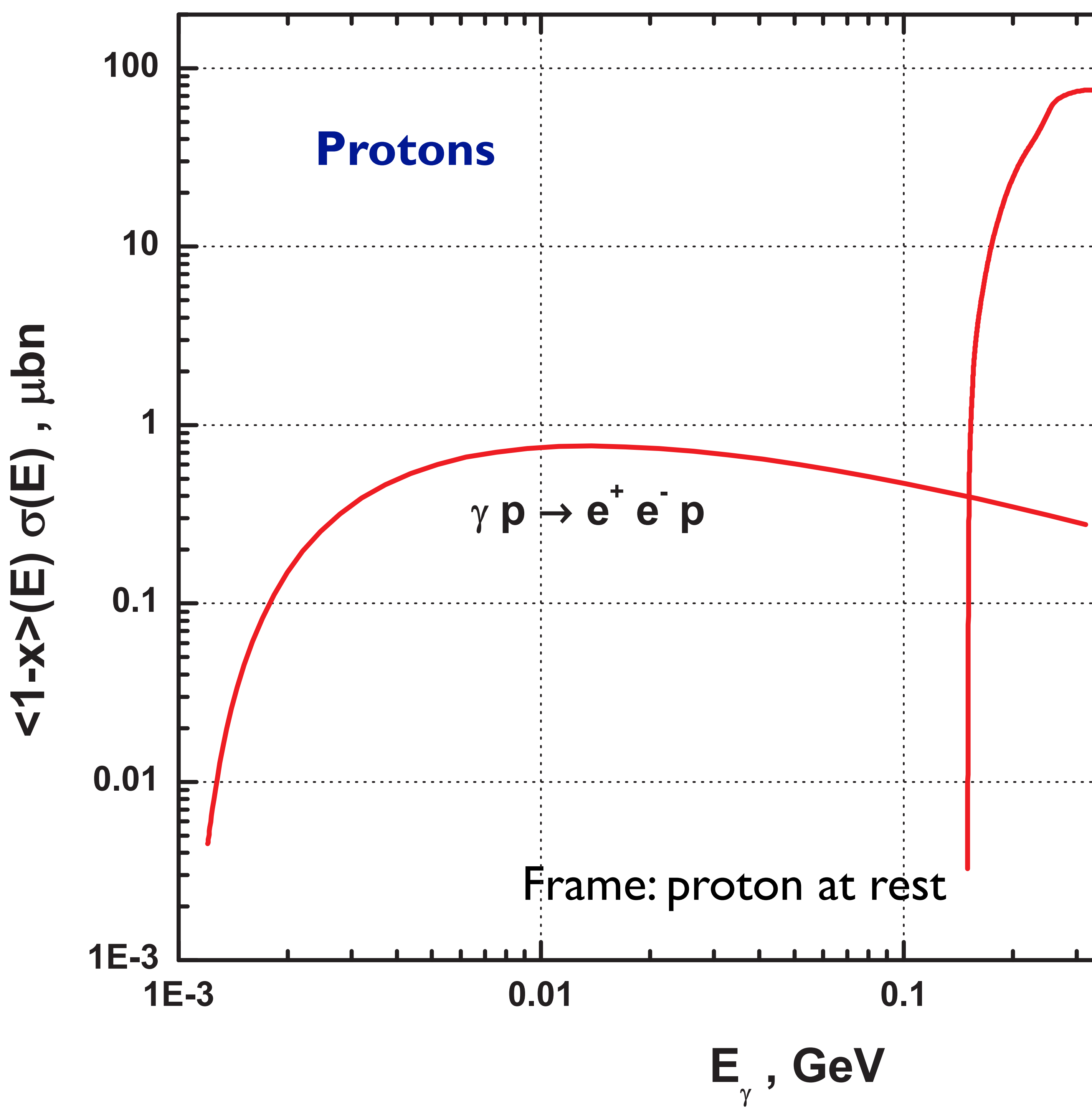
Projectile: 30 AGeV Pb,
different targets

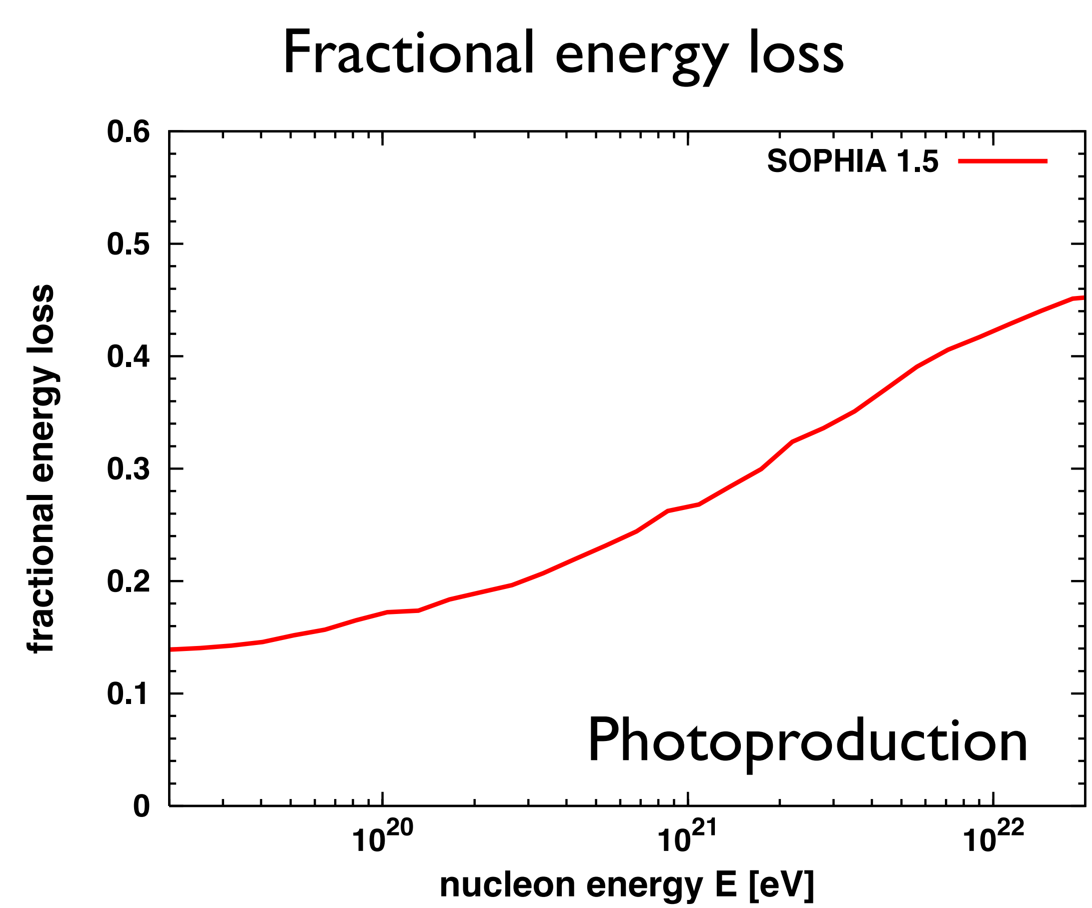


(Smirnov, 2005)

Example: Greisen-Zatsepin-Kuzmin (GZK) effect

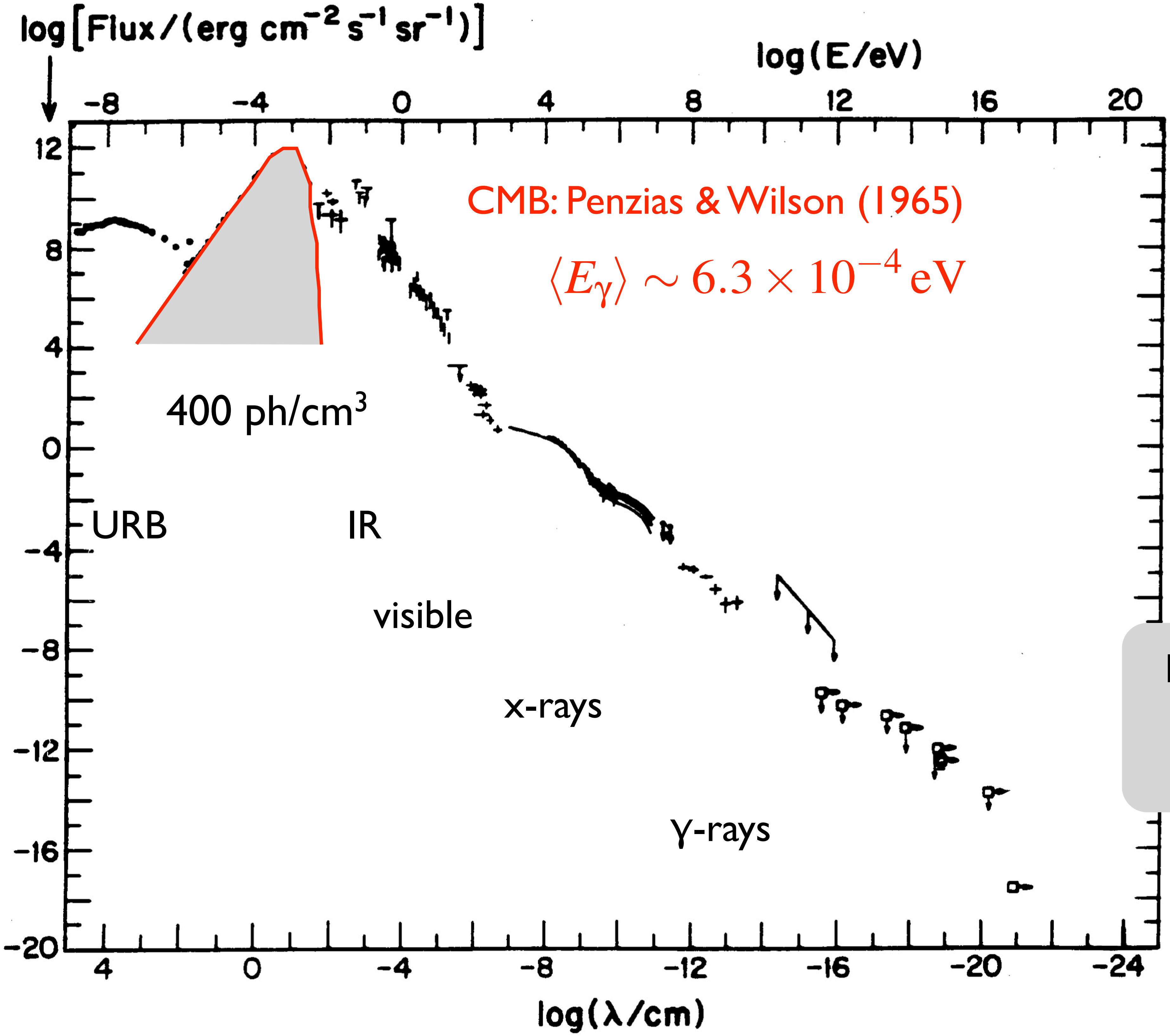
Energy loss times interaction probability





(Berezinsky, 2002)

Radiation fields as possible target



Small interaction probability compensated by large density

In source regions:

- much higher densities
- power-law spectra

Calculation of energy loss length

$$x_{\rm loss}(E) = \frac{E}{dE/dx} = \frac{\lambda(E)}{\kappa(E)}$$

interaction length

inelasticity $\kappa(E) = \frac{\langle \Delta E \rangle}{E}$

$$\frac{1}{\lambda_{\rm ph}(E)} = \frac{1}{8E^2\beta}\int_{\epsilon_{\rm th}}^{\infty} d\epsilon \frac{n(\epsilon)}{\epsilon^2}\int_{s_{\rm min}}^{s_{\rm max}(\epsilon,E)} ds(s - m_p^2c^4)\sigma_{p\gamma}(s)$$

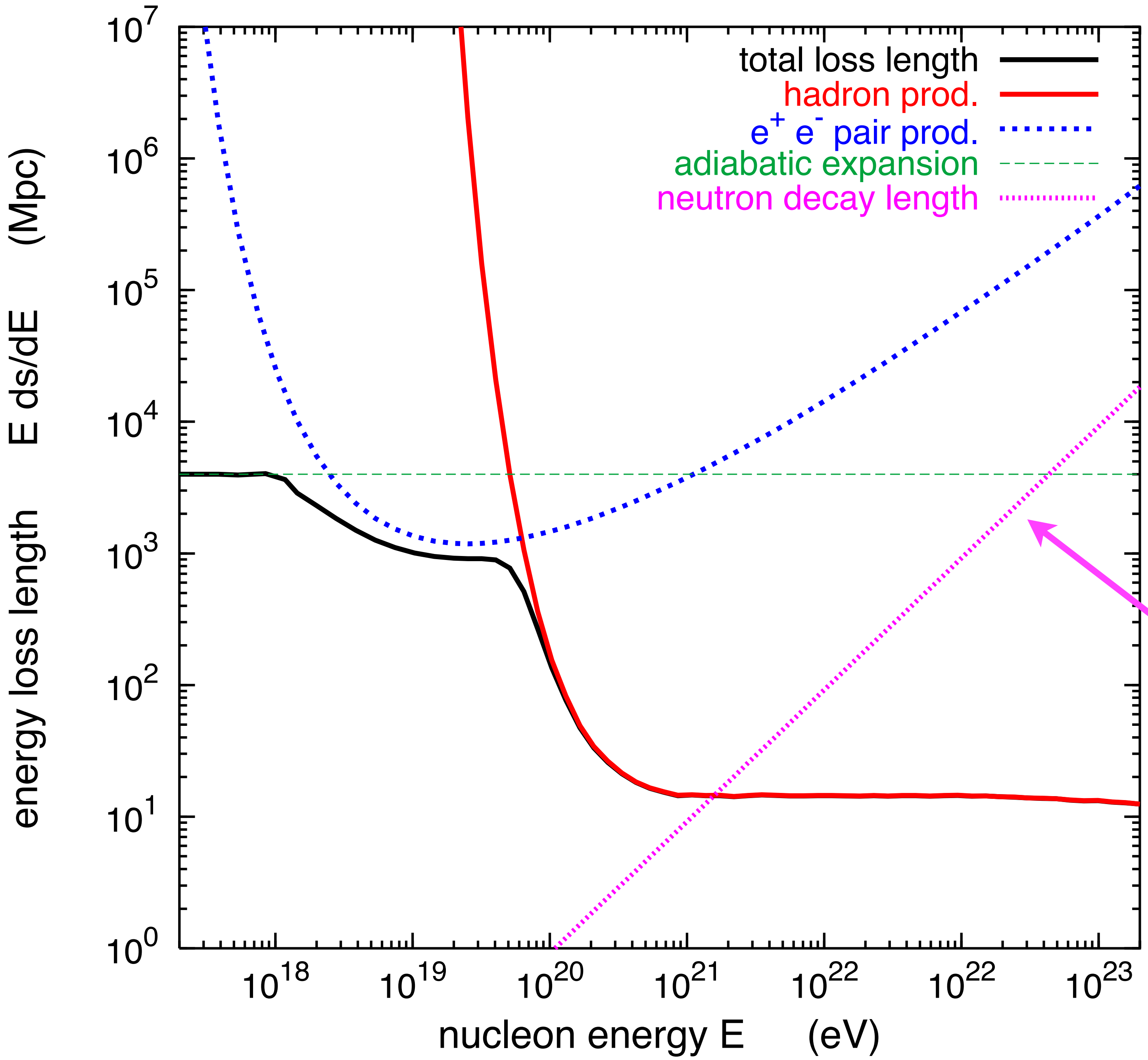
$$s_{\rm min} = (m_p c^2 + m_{\pi^0}c^2)^2 \qquad s_{\rm max}(\epsilon,E) = m_p^2c^4 + 2E\epsilon(1+\beta)$$

$$\epsilon_{\rm th} = \frac{s_{\rm min} - m_p^2c^4}{2E(1+\beta)}, \qquad \beta^2 = 1 - \frac{m_p^2c^4}{E^2}$$

Scaling with redshift:

$$x_{\rm loss}(E,z) = (1+z)^{-3}x_{\rm loss}[(1+z)E, z=0]$$

Energy loss length of nucleons



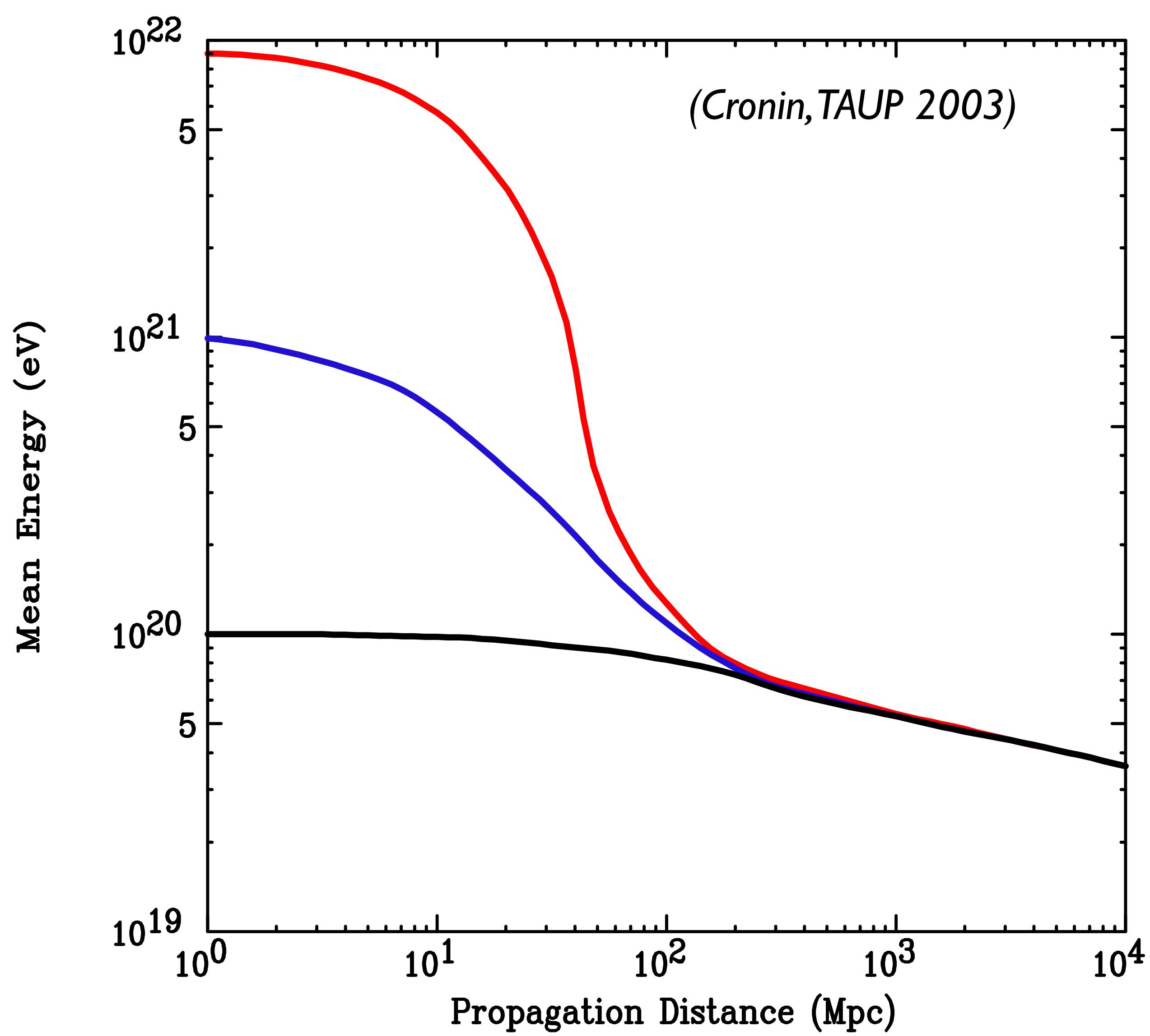
Energy loss length:

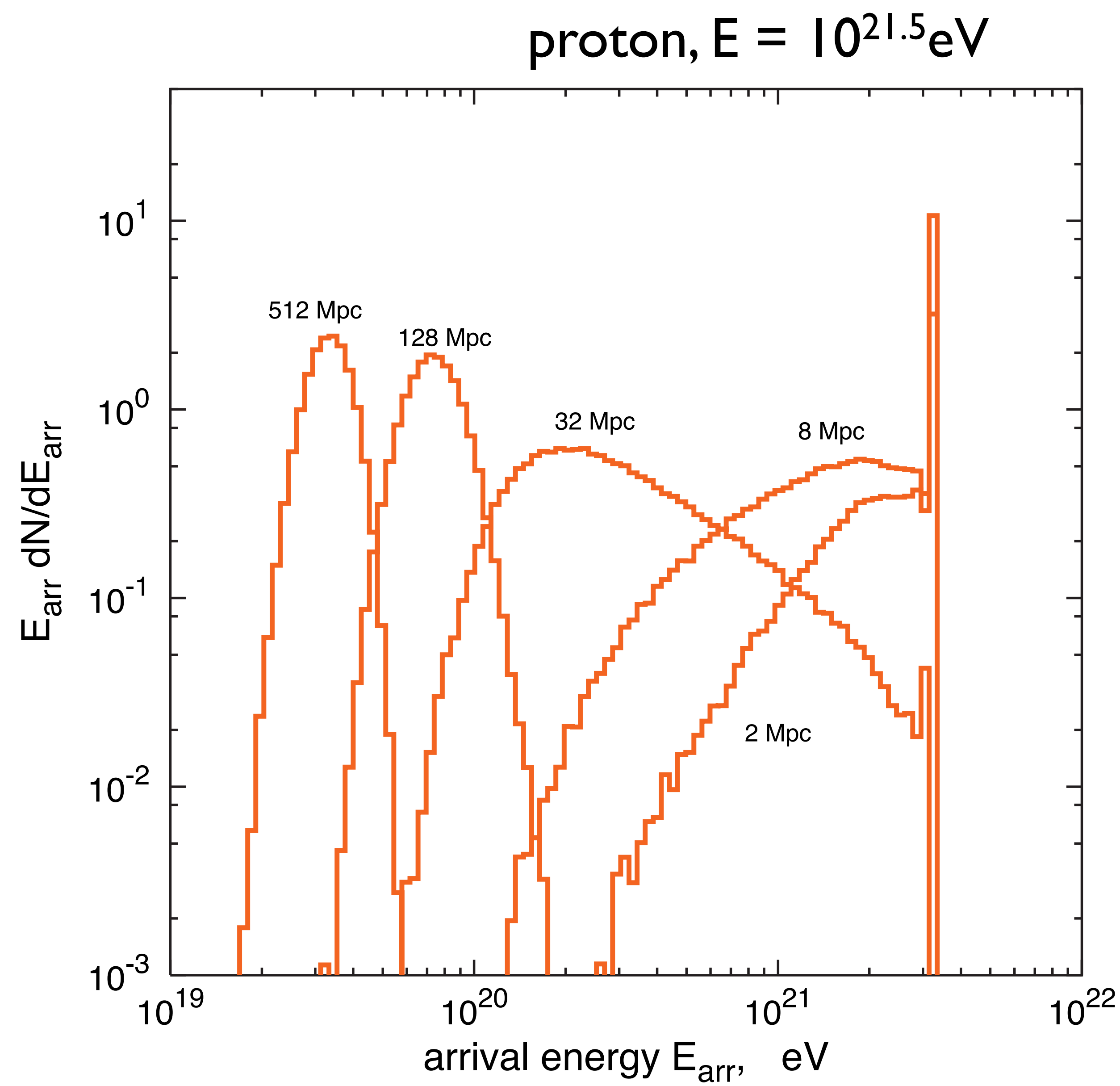
$$\frac{dE}{ds} = -\frac{E}{l_{\mathrm{loss}}}$$

neutron decay length

(Stanev et al., Phys. Rev. D62 (2000) 093005)

Mean loss rate vs. full simulation





Hadronic energy loss: stochastic process

(Achterberg 1999, Stanev et al., PRD62, 2000)

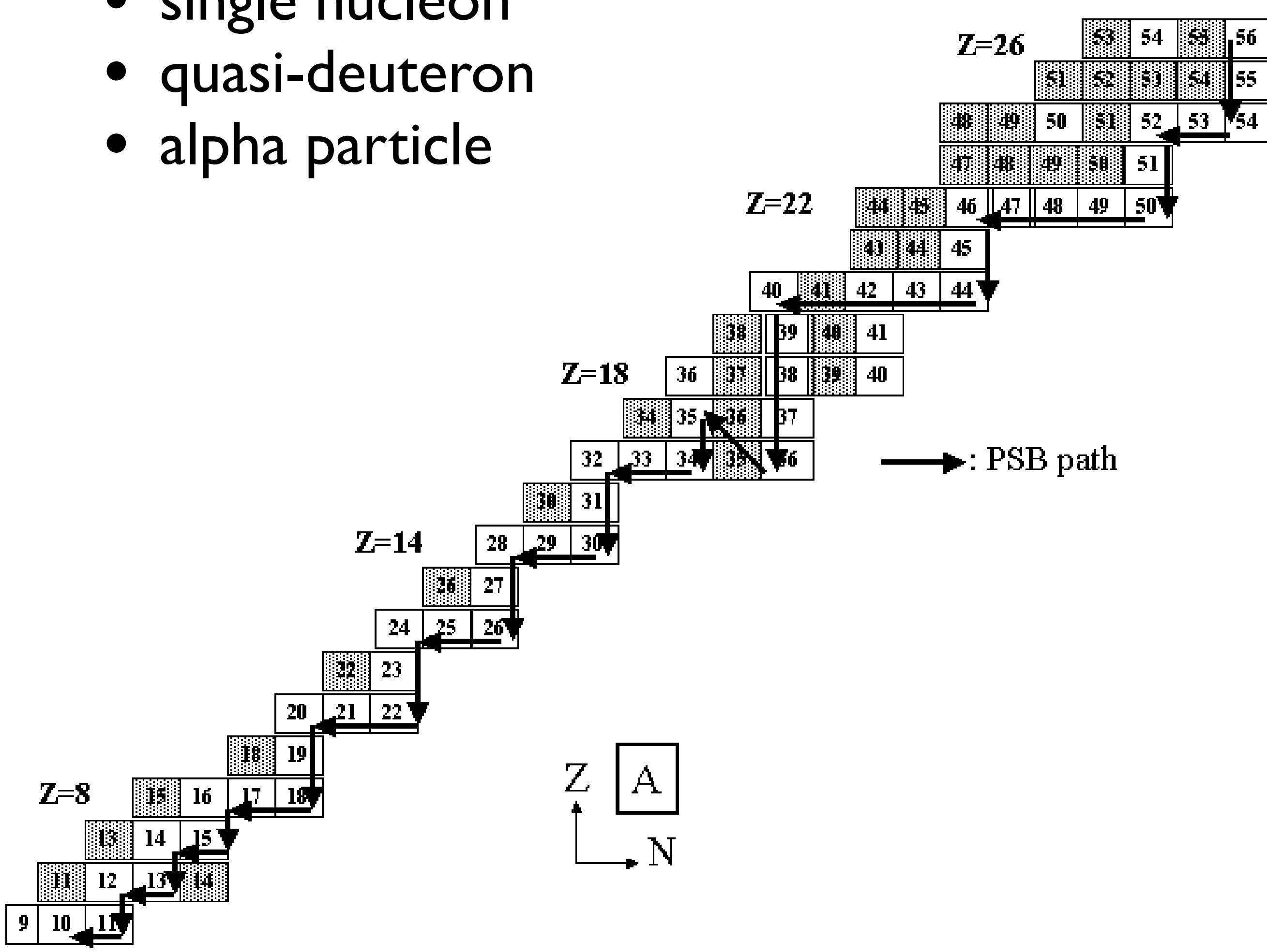
Photodisintegration of nuclei

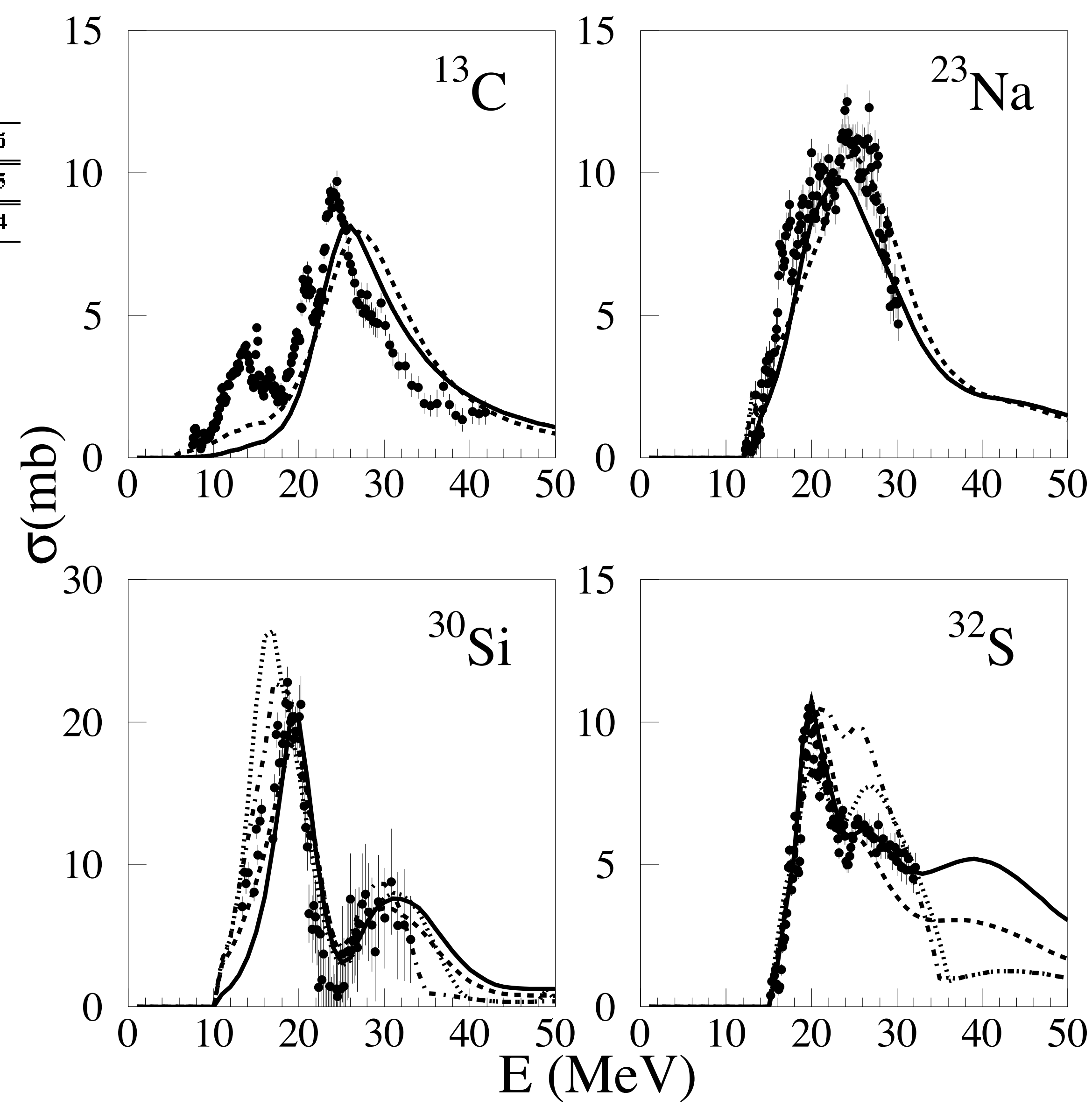
Main contribution:
giant dipole resonance

$$T_{E1}(\varepsilon_\gamma) = \frac{8}{3}\frac{NZ}{A}\frac{e^2}{\hbar c}\frac{1+\chi}{mc^2}\;\frac{\Gamma_{\rm GDR}\,\varepsilon_\gamma^4}{(\varepsilon_\gamma^2 - E_{\rm GDR}^2)^2 + \Gamma_{\rm GDR}^2\,\varepsilon_\gamma^2}$$

Dominant emission processes:

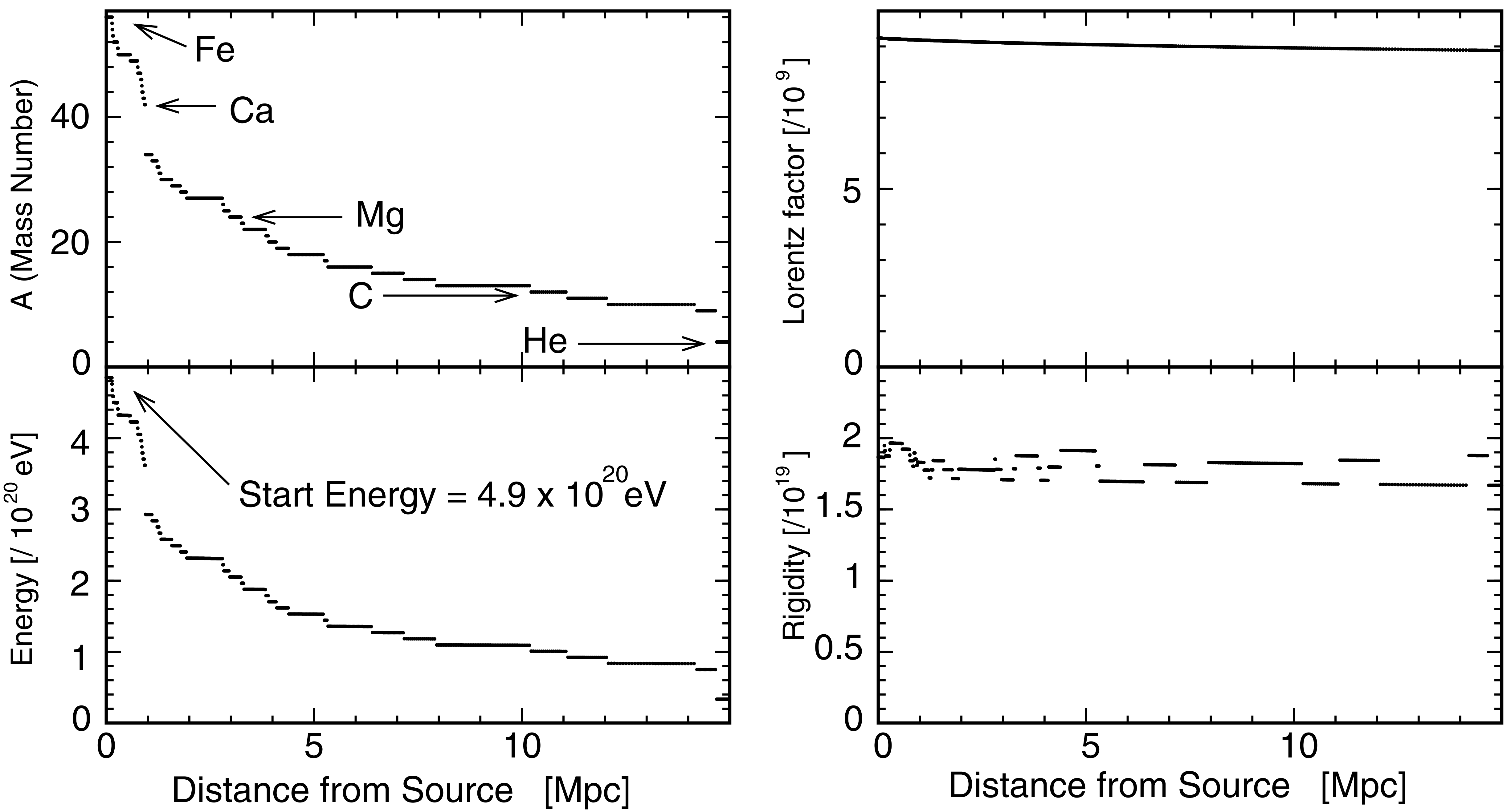
- single nucleon
- quasi-deuteron
- alpha particle





(Khan et al., Astropart. Phys. 23, 2005)

Example of nucleus disintegration path



(Yamamoto et al., APP20, 2004)

Energy considerations for nuclei

Energy of nucleus needed for formation of giant dipole resonance in CMB

Nucleus at rest

13 MeV

$$
\begin{aligned}
s &= (p_\gamma + p_A)^2 \\
&= p_\gamma^2 + p_A^2 + 2(p_\gamma \cdot p_A) \\
&= (Am_p)^2 + 2Am_pE_\gamma
\end{aligned}
$$

Iron: $E_A \sim 3\ 10^{20}$ eV
Helium: $E_A \sim 2\ 10^{19}$ eV

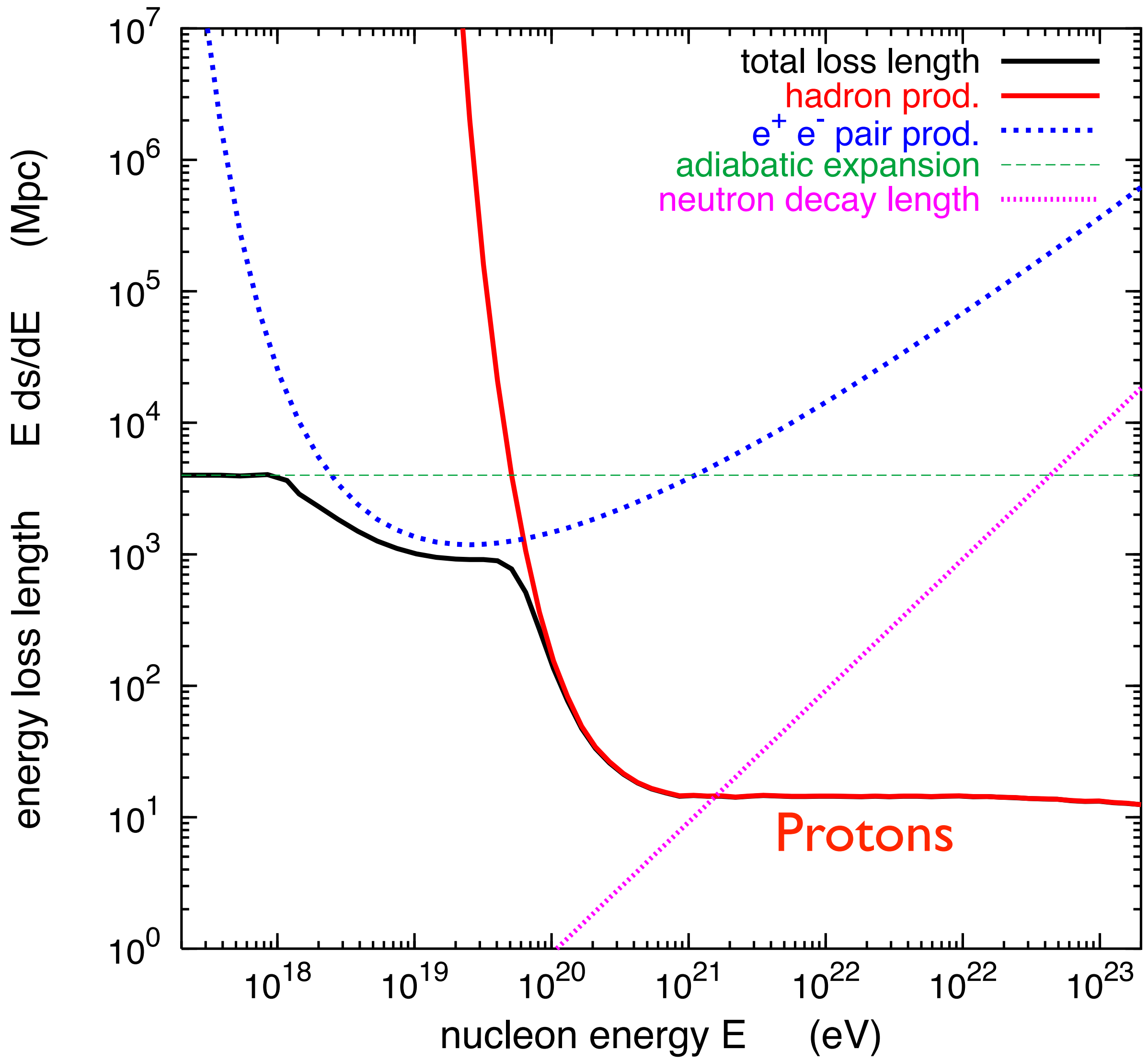
Nucleus with E_A in CMB field

$$s = (Am_p)^2 + 2E_\gamma^{\mathrm{CMB}} E_A (1 - \cos\theta)$$

$$\boxed{E_\gamma^{\mathrm{CMB}} \geq A \frac{m_p E_\gamma}{(1-\cos\theta)E_A}}$$

Light nuclei disintegrate very fast while traveling through CMB

Comparison of energy loss lengths



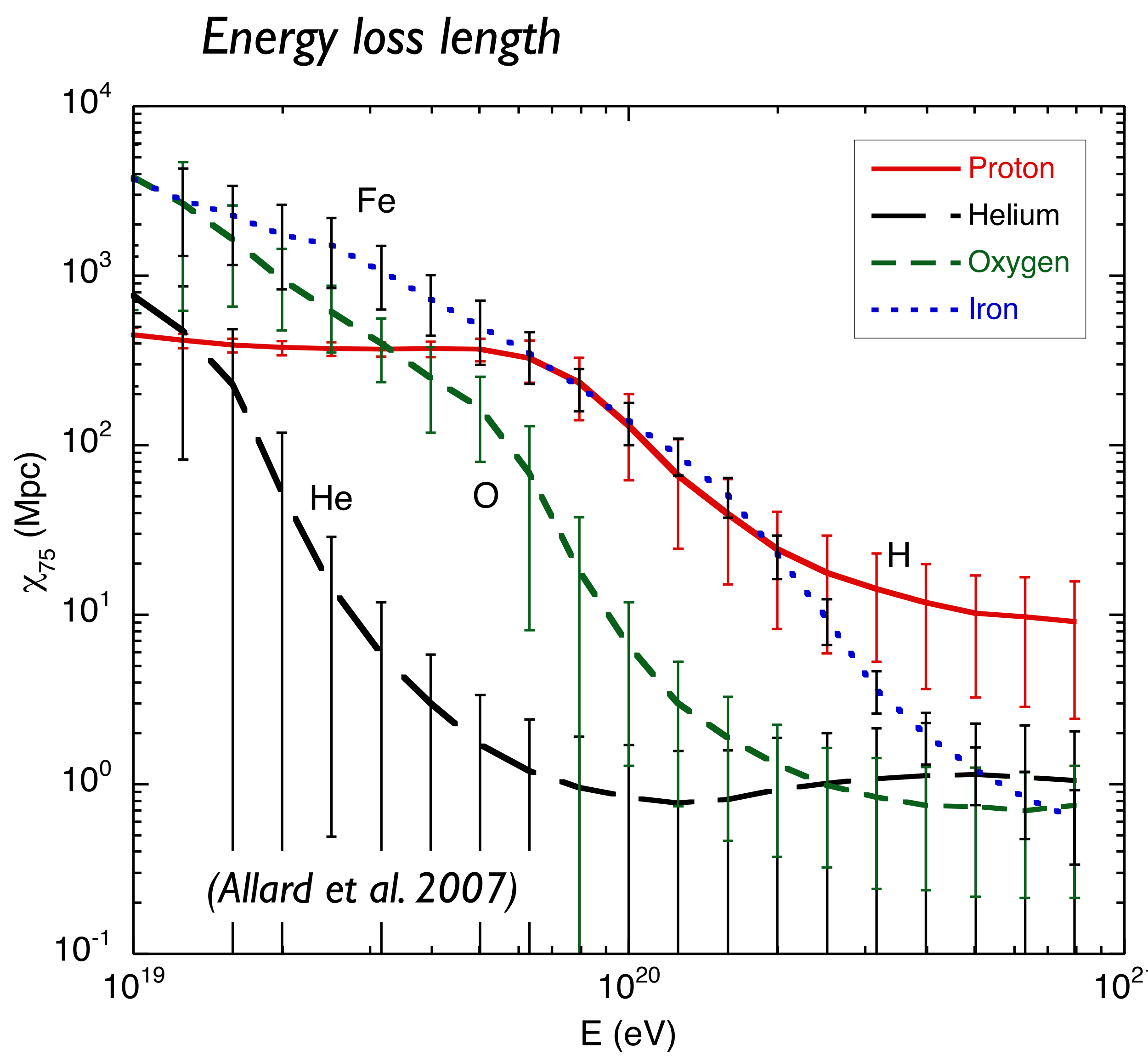


Photo-pion production

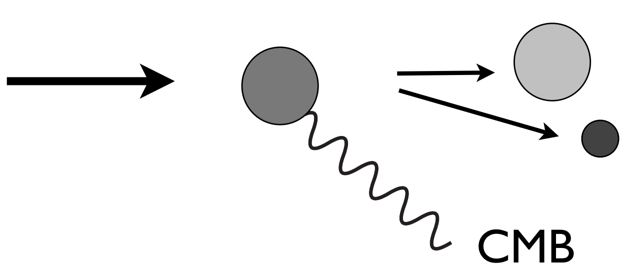
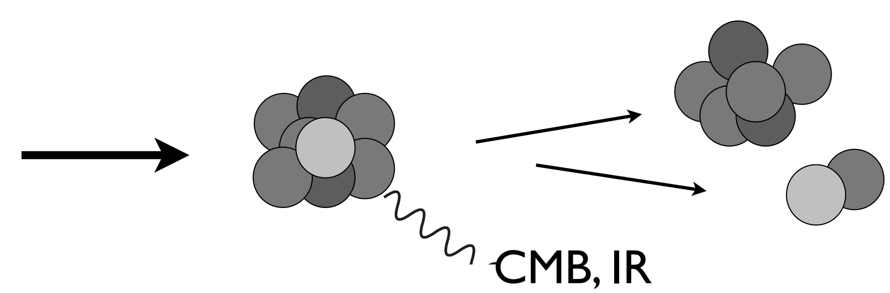


Photo-dissociation (giant dipole resonance)



Summary: Modeling of resonance region

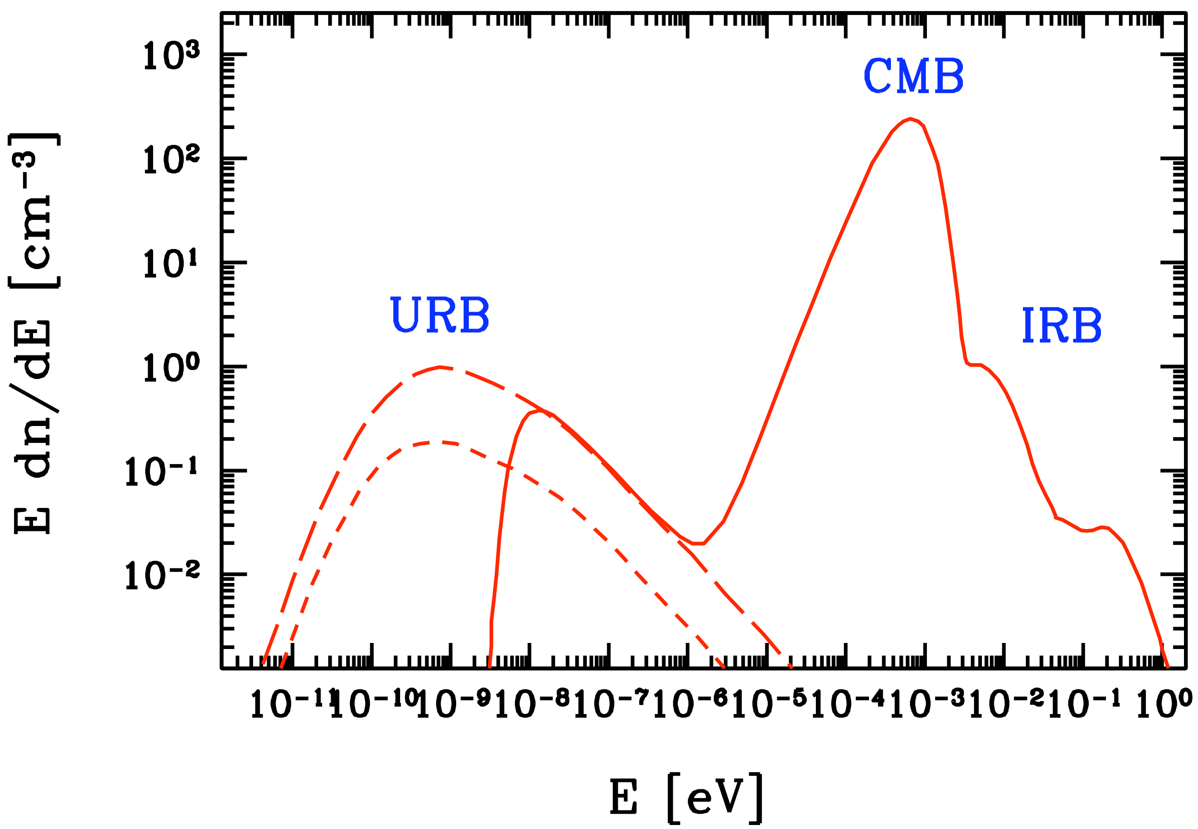
No fundamental problem in resonance region

- Large amount of data exists (still not perfect)
- Careful implementation needed
- Several simulation codes available

Application to GZK processes

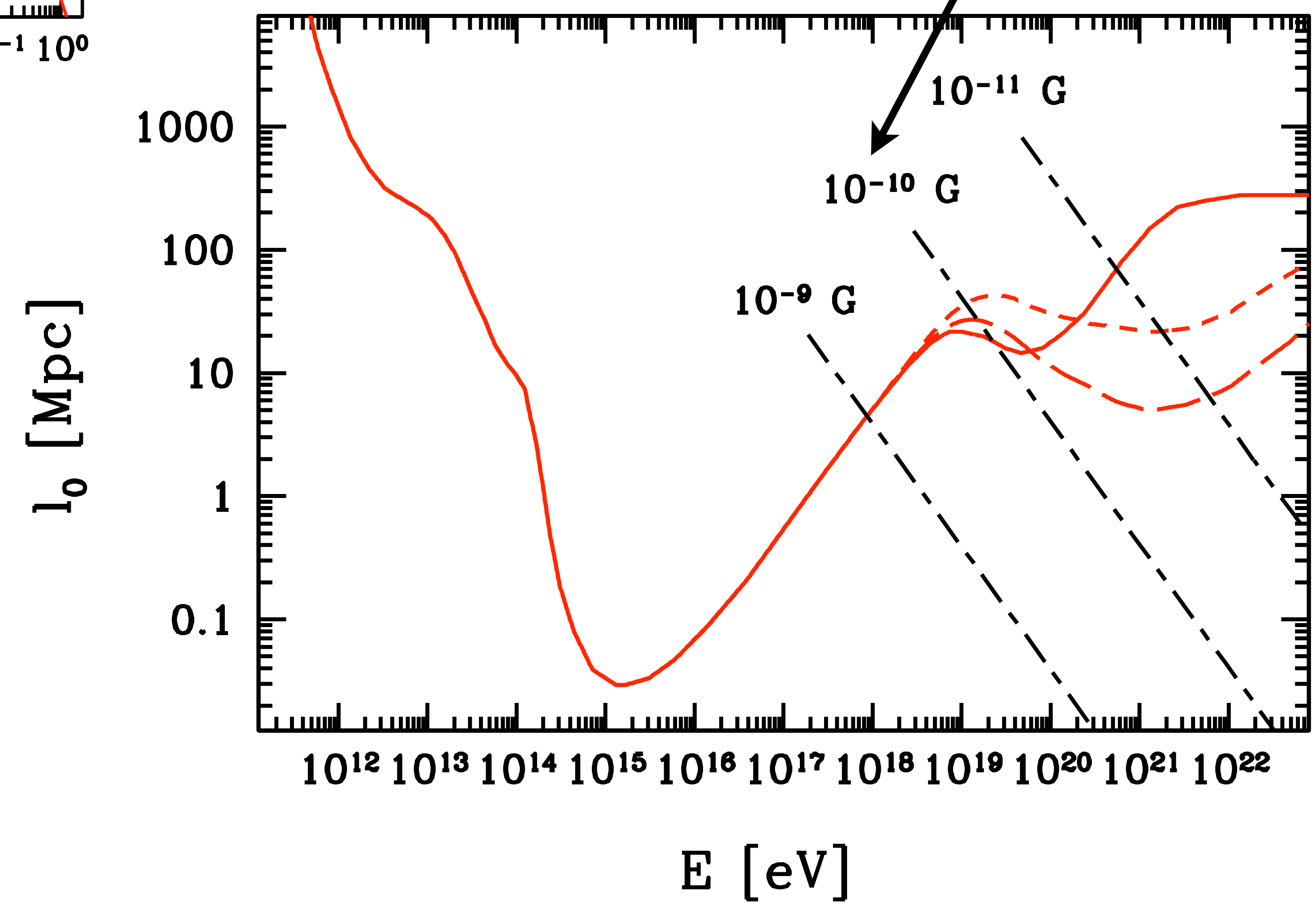
- Processes reasonably well understood
- Remarkable coincidence of energy thresholds
- Light nuclei disintegrate very fast
- Largest uncertainties coming from IR and UR background fields

Energy loss length of photons



Photons:
Bethe-Heitler e^+e^- pair production
with photons of radio background

Synchrotron losses
of electrons



Energy loss length significantly smaller than that of hadrons

(Fodor, Katz & Ringwald, 2002)