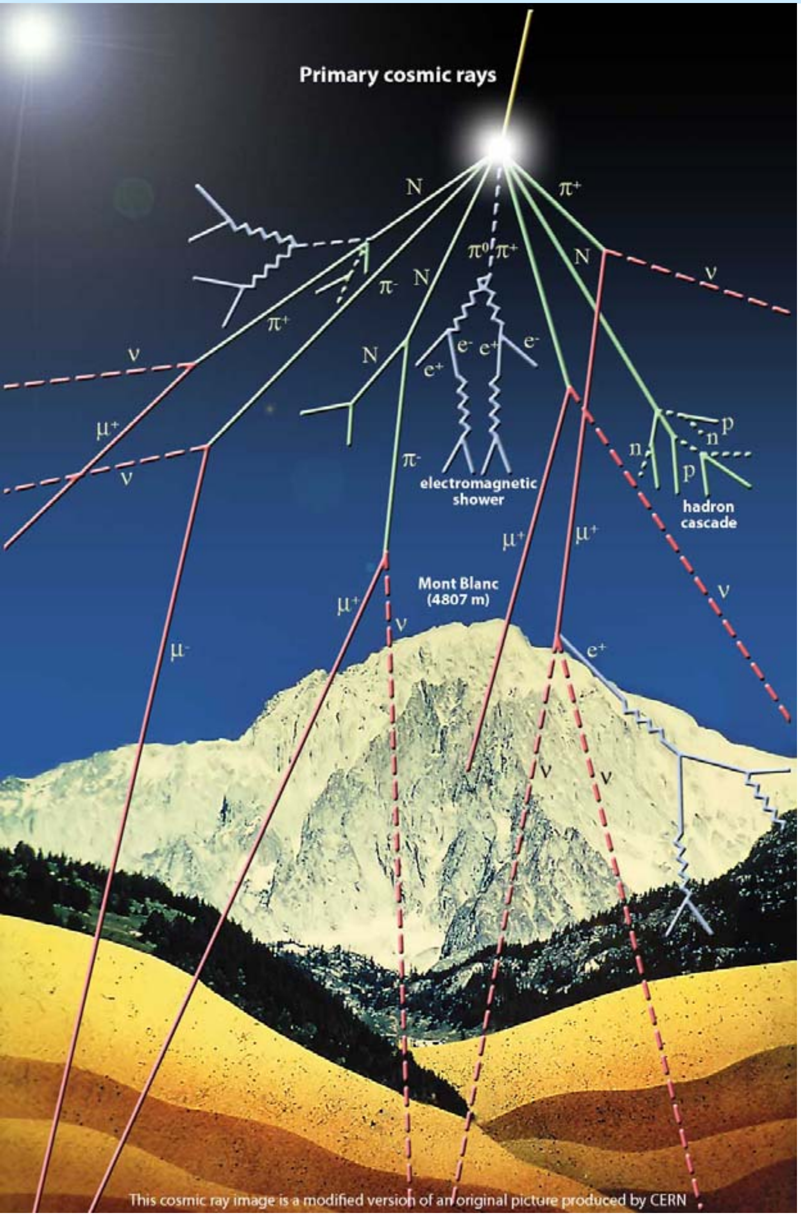
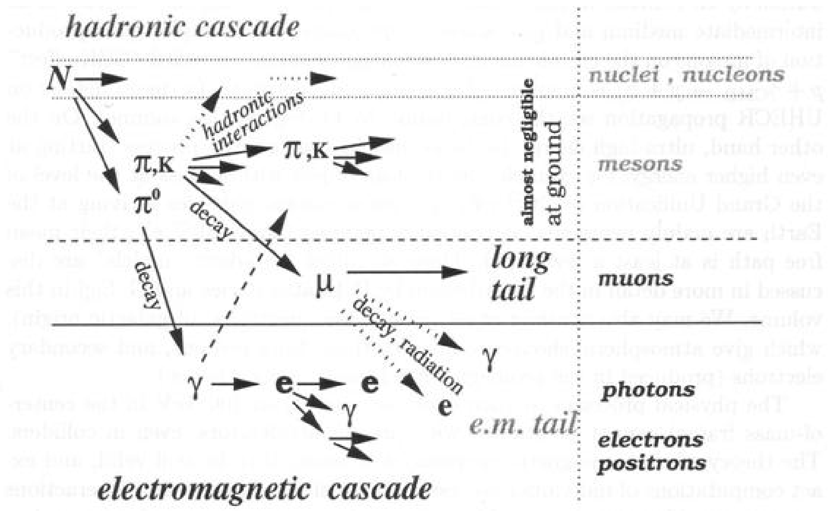
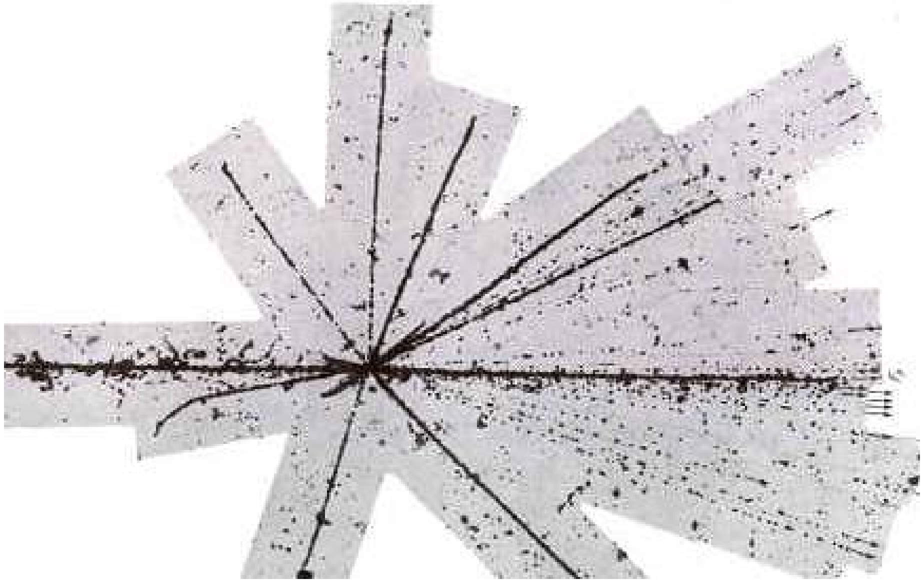
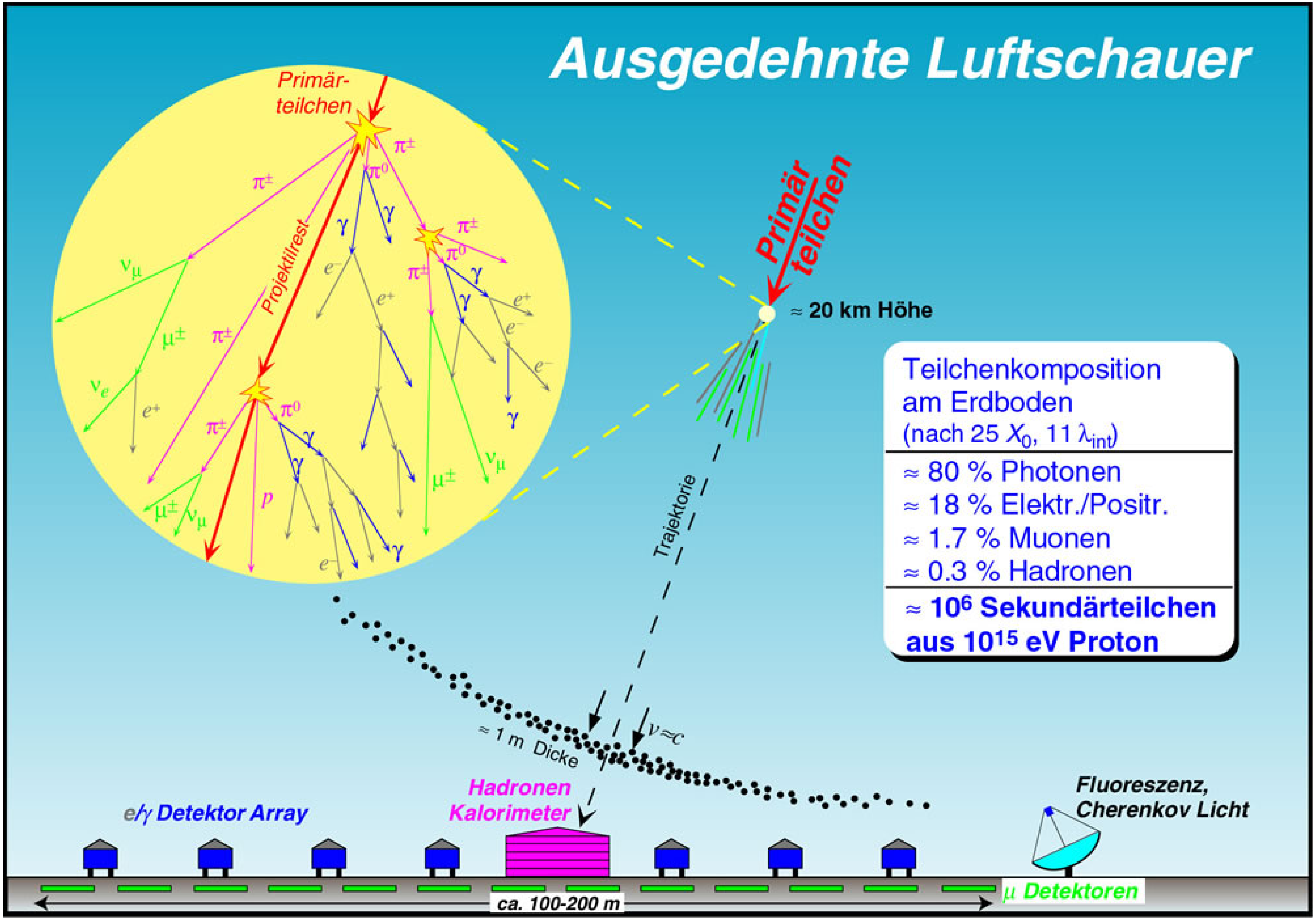
Luftschauer

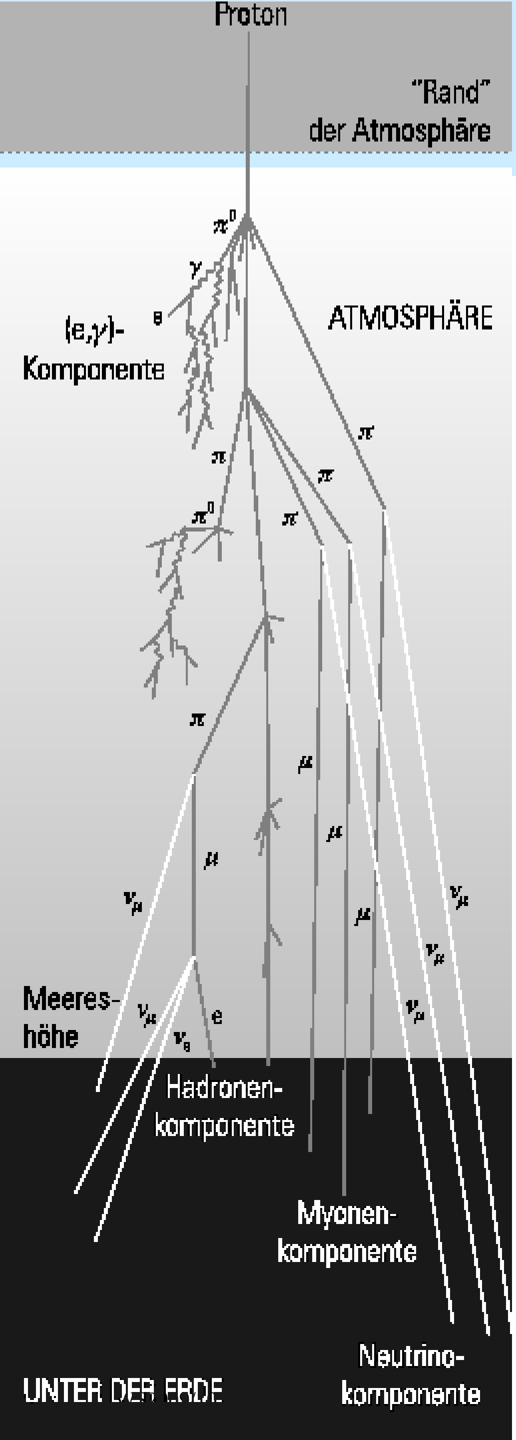






Luftschauernachweis





Luftschauer

Teilchen	Masse [MeV/c²]	Lebensdauer [s]	J^P
p	938.27	$> 10^{31-33}$ a	$\frac{1}{2}^+$
n	939.57	885.7	$\frac{1}{2}^+$
$\pi^\pm$	139.57	$2.6 \cdot 10^{-8}$	0^-
π^0	134.98	$8.4 \cdot 10^{-17}$	0^-
$e^\pm$	0.51		$\frac{1}{2}$
$\mu^\pm$	105.66	$2.2 \cdot 10^{-6}$	$\frac{1}{2}$
$\nu_e,\ \nu_\mu$	≈ 0	∞ (?)	$\frac{1}{2}$

Atmospheric depth and interaction length

atmospheric depth:

$$\rho(h) = \rho_0 e^{-h/H}$$

$$x(h) = X \cdot e^{-h/H}, \quad \text{mit } H \approx 6.5\,\text{km}$$

$$X = 1030\,\text{gcm}^{-2}$$

interaction length:

$$\lambda_I = \frac{1}{n \cdot \sigma} \qquad n = \frac{\rho \cdot N_A}{A} \qquad \lambda'_I = \lambda_I \cdot \rho = \frac{A}{N_A \cdot \sigma}$$

first interaction:

$$x(h) = \lambda'_I = x(h) = X \cdot e^{-h/H} \quad \Longrightarrow \quad h = H \cdot \ln \frac{X}{\lambda'_I} \approx 16\,\text{km}$$

Passage of particles through matter (PDG review)

27. PASSAGE OF PARTICLES THROUGH MATTE

Revised April 2006 by H. Bichsel (University of Washington), D.E. Groom (LBNL), ar
S.R. Klein (LBNL).

27.1. Notation

Table 27.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

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 particle 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	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha)$	$28.816\sqrt{\rho\langle Z/A\rangle}$ eV$^{(a)}$
N_c	Electron density	(units of r_e)$^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	$(716.408$ g cm$^{-2})^{-1}$ for $A = 1$ g mol^{-1}
X_0	Radiation length	g cm^{-2}
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\ m_ec^2$	21.2052 MeV
R_M	Molière radius	g cm^{-2}

$^{(a)}$ For ρ in g cm^{-3}.

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

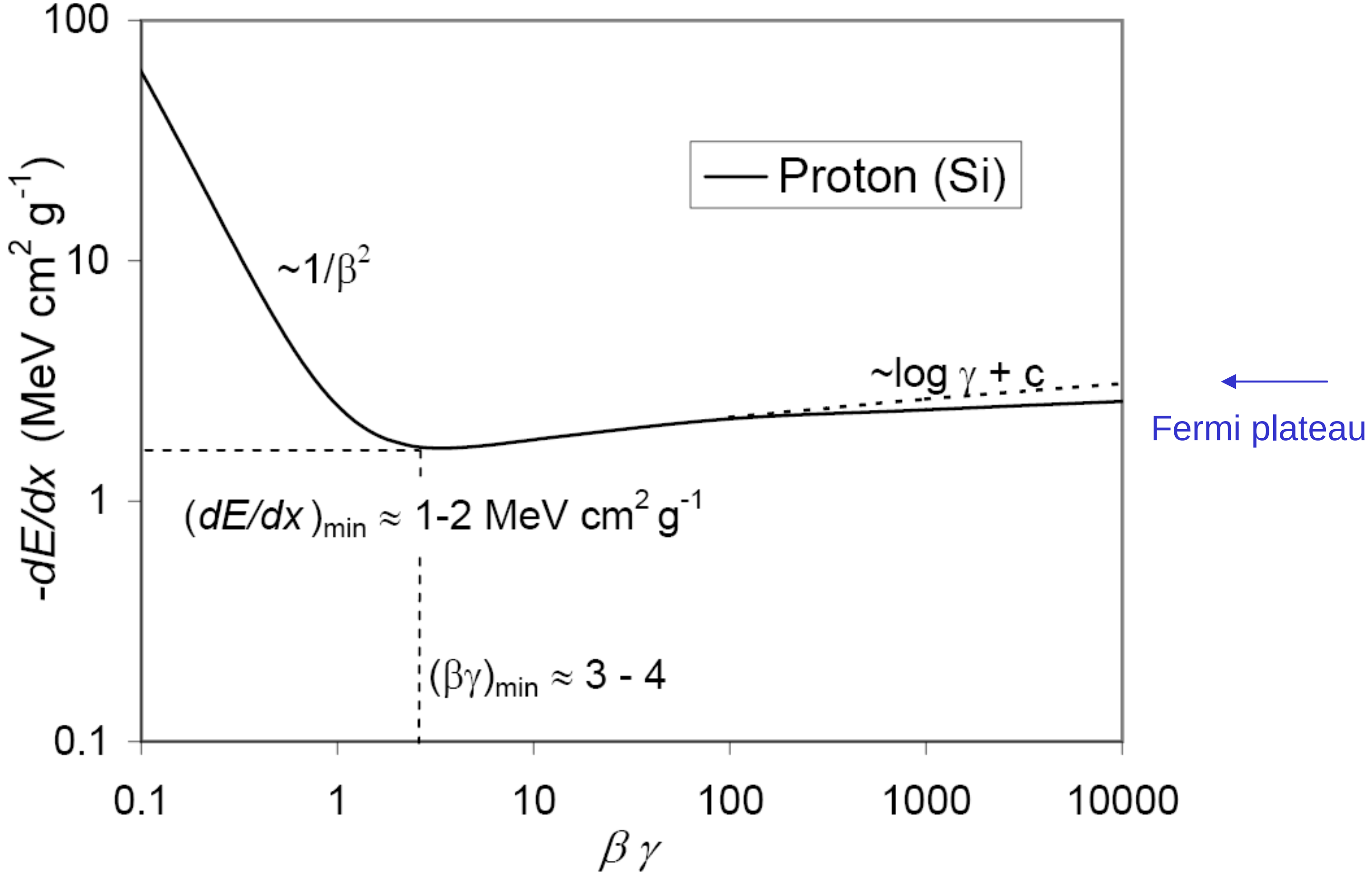
Material	Z	A	$\langle Z/A \rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\|_{\text{min}}$ [b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	X_0 {cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10^6 for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33

Bethe-Bloch-Formula

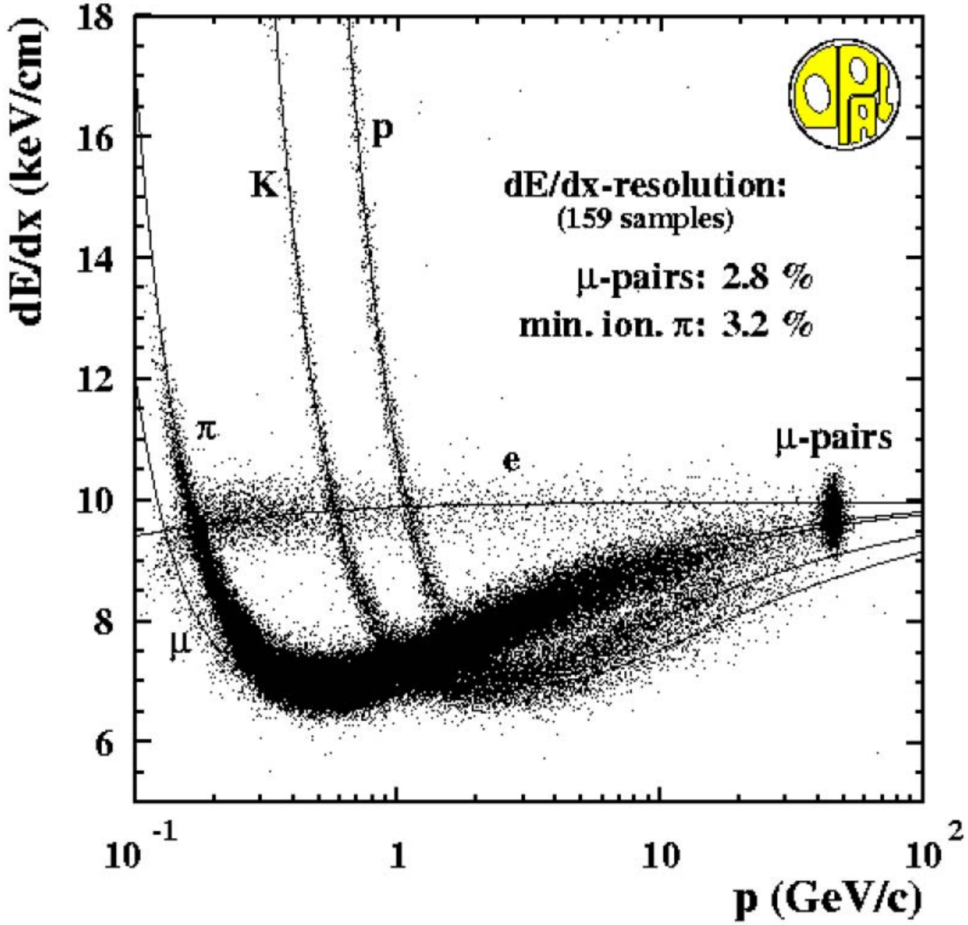
$$-\frac{dE}{dx} = \frac{D \cdot Z \cdot \rho}{A} \cdot \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2\, m_e\, c^2\, \beta^2\, \gamma^2 \Delta T_{max}}{I^2} \right) - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

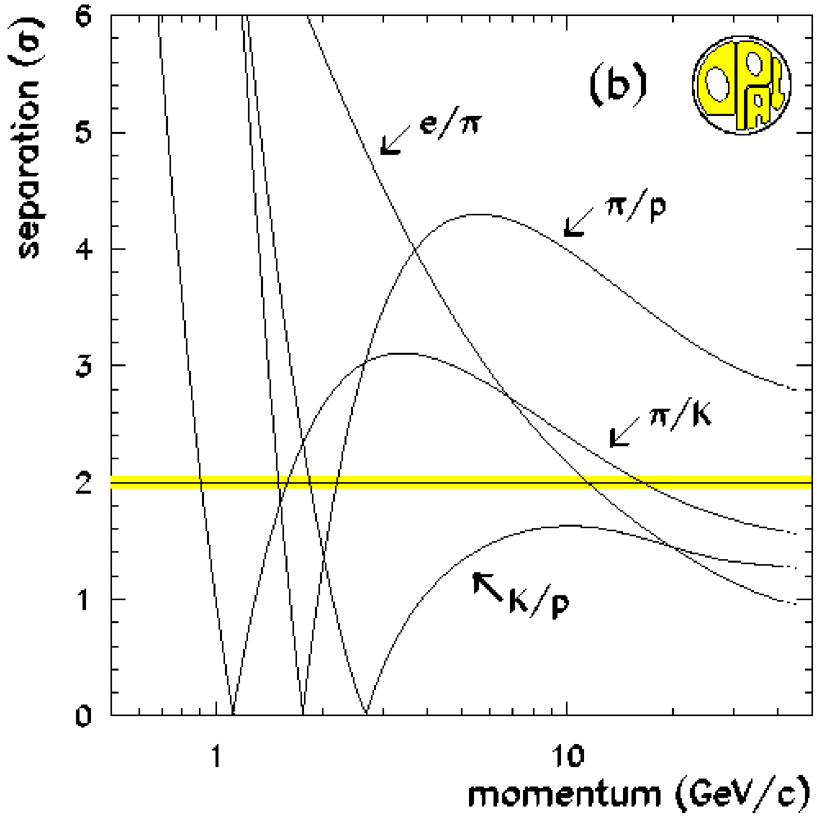
- $D = 4\pi \cdot N_L \cdot r_e^2 \cdot m_e\, c^2 = 0.307$ MeV$\cdot$ cm^2/g (r_e = classical electron radius).
- z, β are charge number and velocity of the particle
- Z, A, ρ are nuclear charge number, atomic mass number and density of the medium.
- I is the mean effective excitation potential of the atoms of the medium. It is roughly:
$$I \approx 16 \cdot Z^{0.9} \text{ eV}. \qquad (1)$$
- ΔT_{max} is the maximal energy transfer to the shell electrons resulting from a central collision.
- δ, C are corrections to this formula: density correction (δ) at large energies and shell corrections (C) at low energies.

dE/dx Characteristics

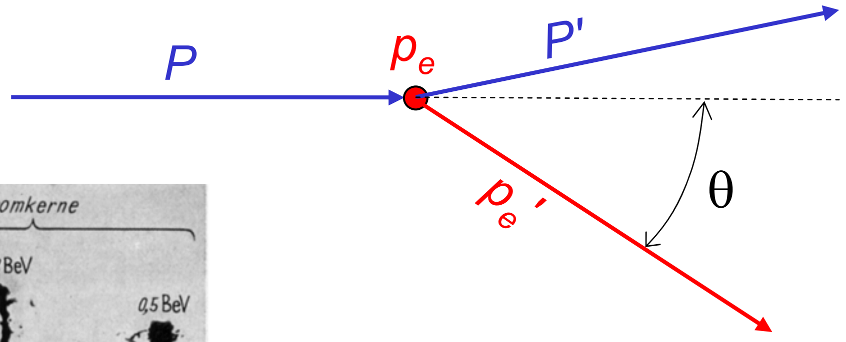


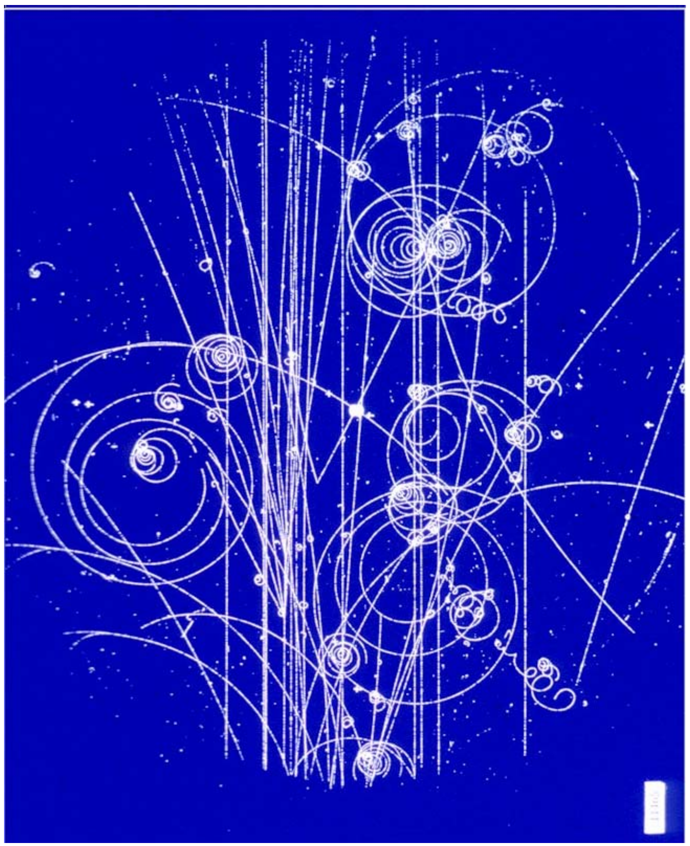
Teilchenidentifikation (dE/dx)

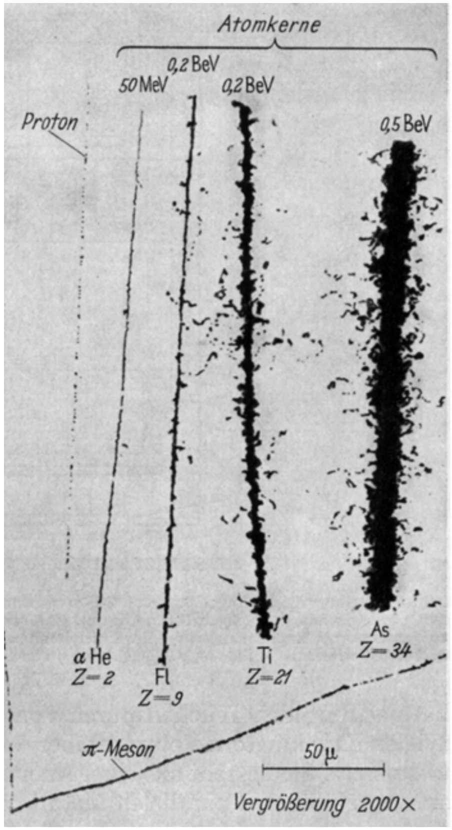


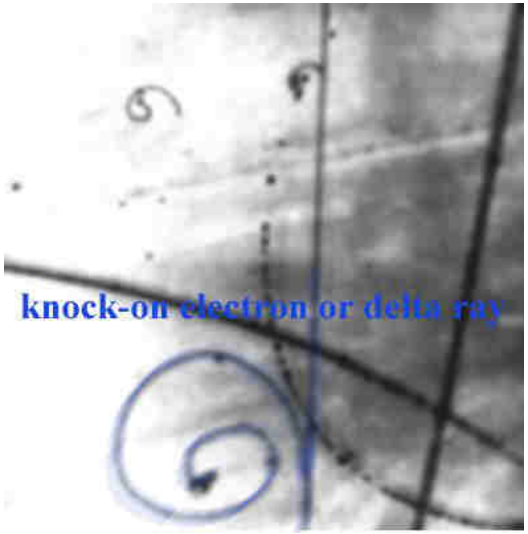


δ-Elektronen

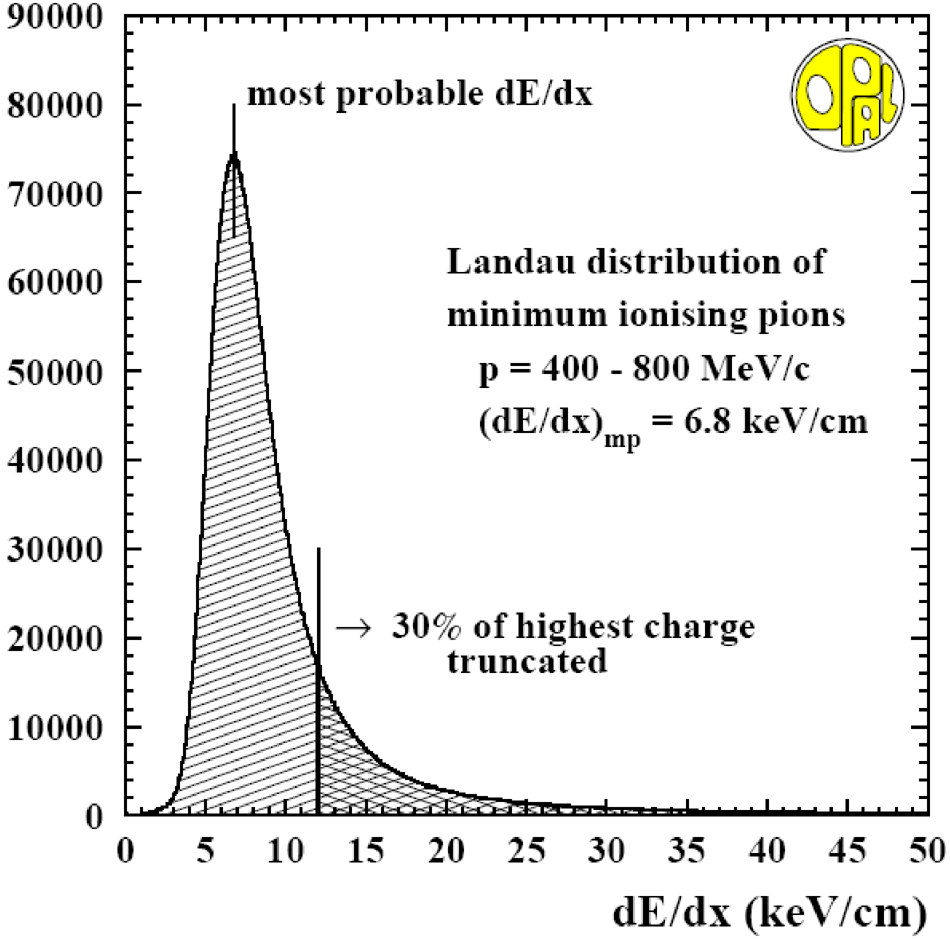


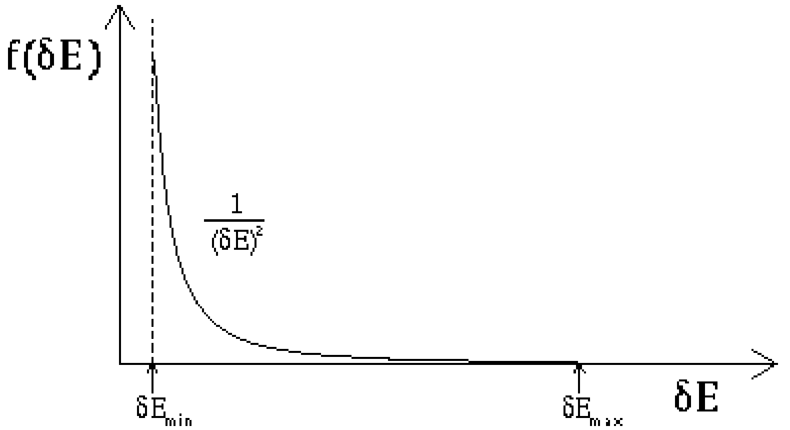






Statistische Fluktuationen (Landau-Verteilung)

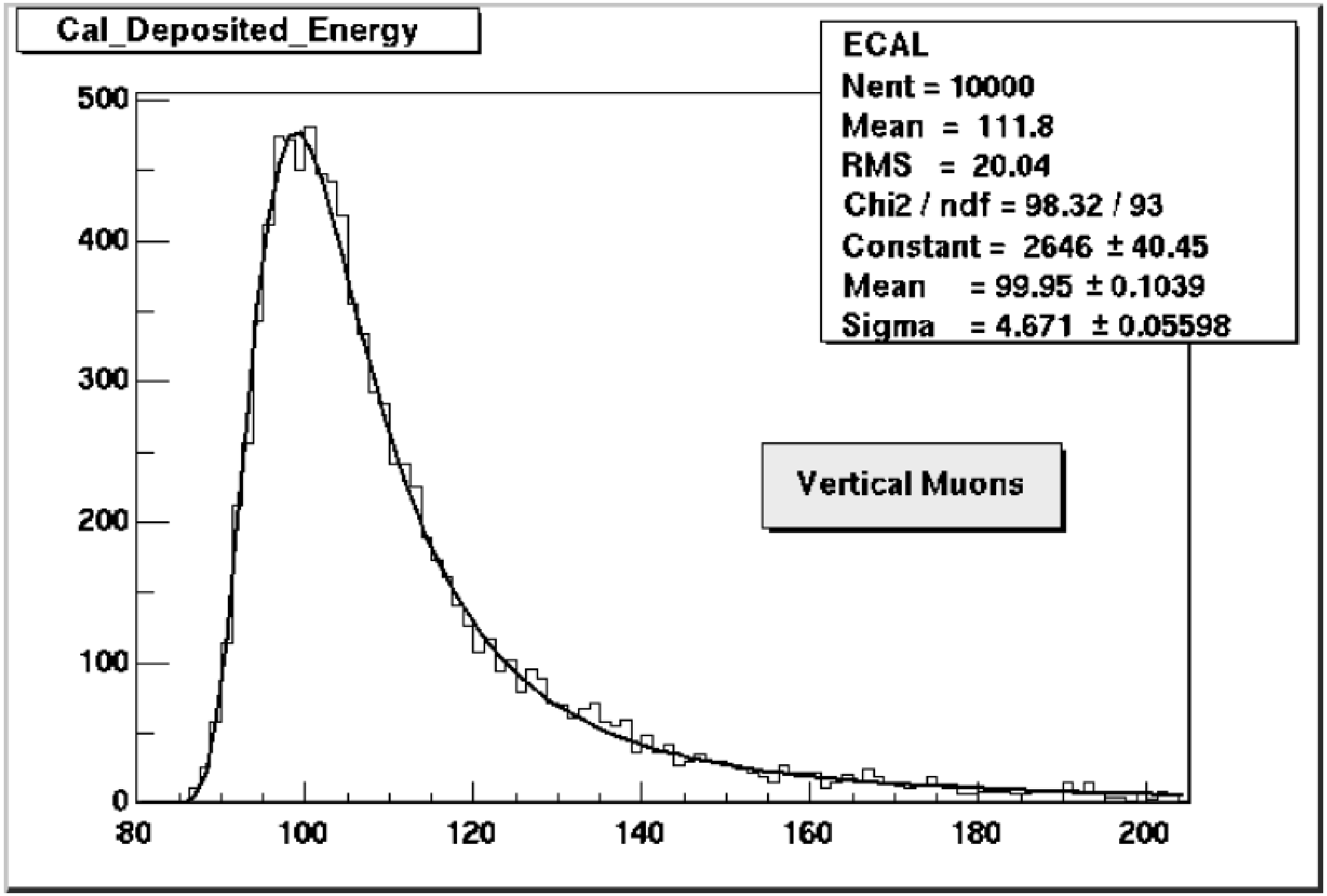




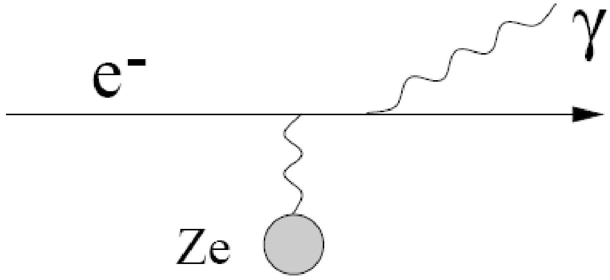
$$\kappa \sim \frac{\langle \Delta E \rangle}{T_{\max}}$$

- κ klein → stark asymmetrisch
- κ groß → symmetrisch, Gauß

Statistical Fluctuations of dE/dx

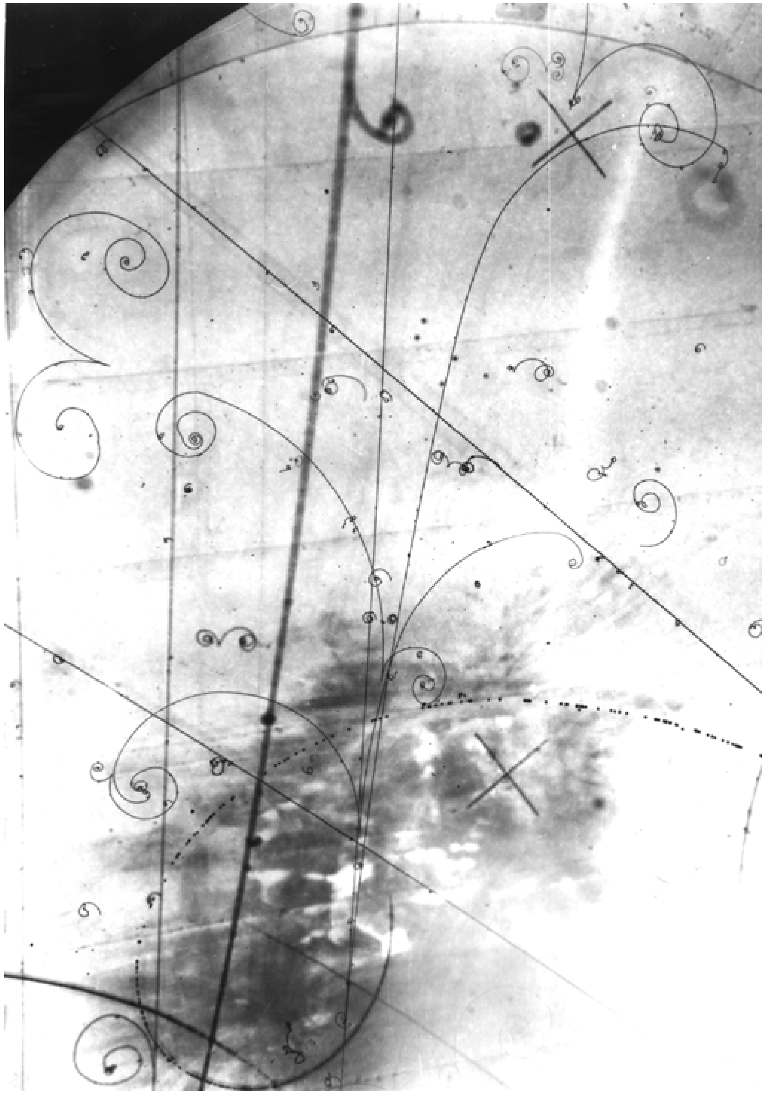


Bremsstrahlung



$$\frac{dE}{E} = -\frac{dx}{x_0} \quad \Rightarrow \quad \left(\frac{dE}{dx}\right)_{rad} = -\frac{E}{x_o}$$

$$E(x) = E_0 \cdot e^{-\frac{x}{x_0}}$$



$$\frac{1}{x_0} = 4\,\alpha\, r_e^2\, Z(Z+1) \cdot \frac{N_L \cdot \rho}{A} \cdot \ln\left(\frac{278}{Z^{1/2}}\right)$$

$$\frac{1}{\rho\, x_0} \sim Z^2$$

Strahlungslängen und kritische Energien

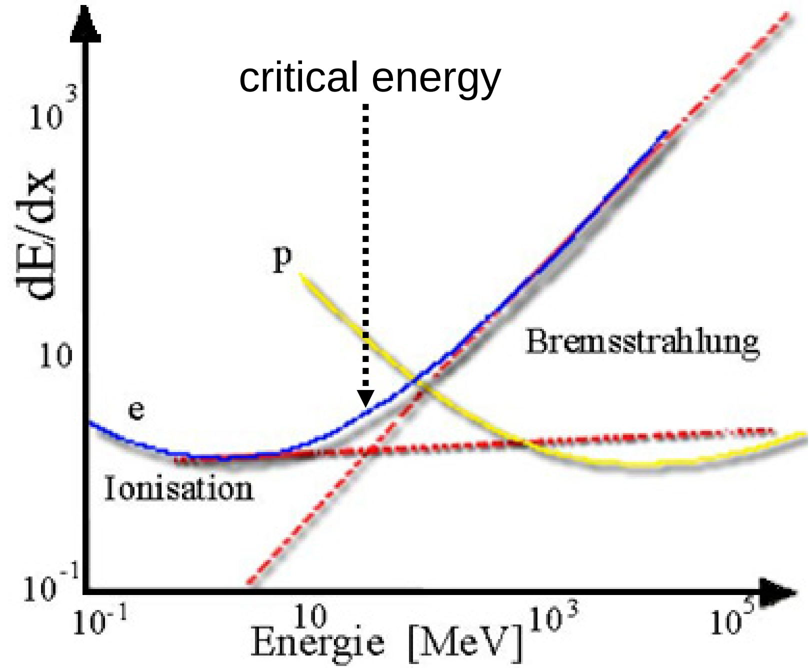
Ionisation:	$\sim Z \cdot \ln E/m$
Bremsstrahlung:	$\sim Z^2 \cdot E/m^2$

Kritische Energie definiert durch:

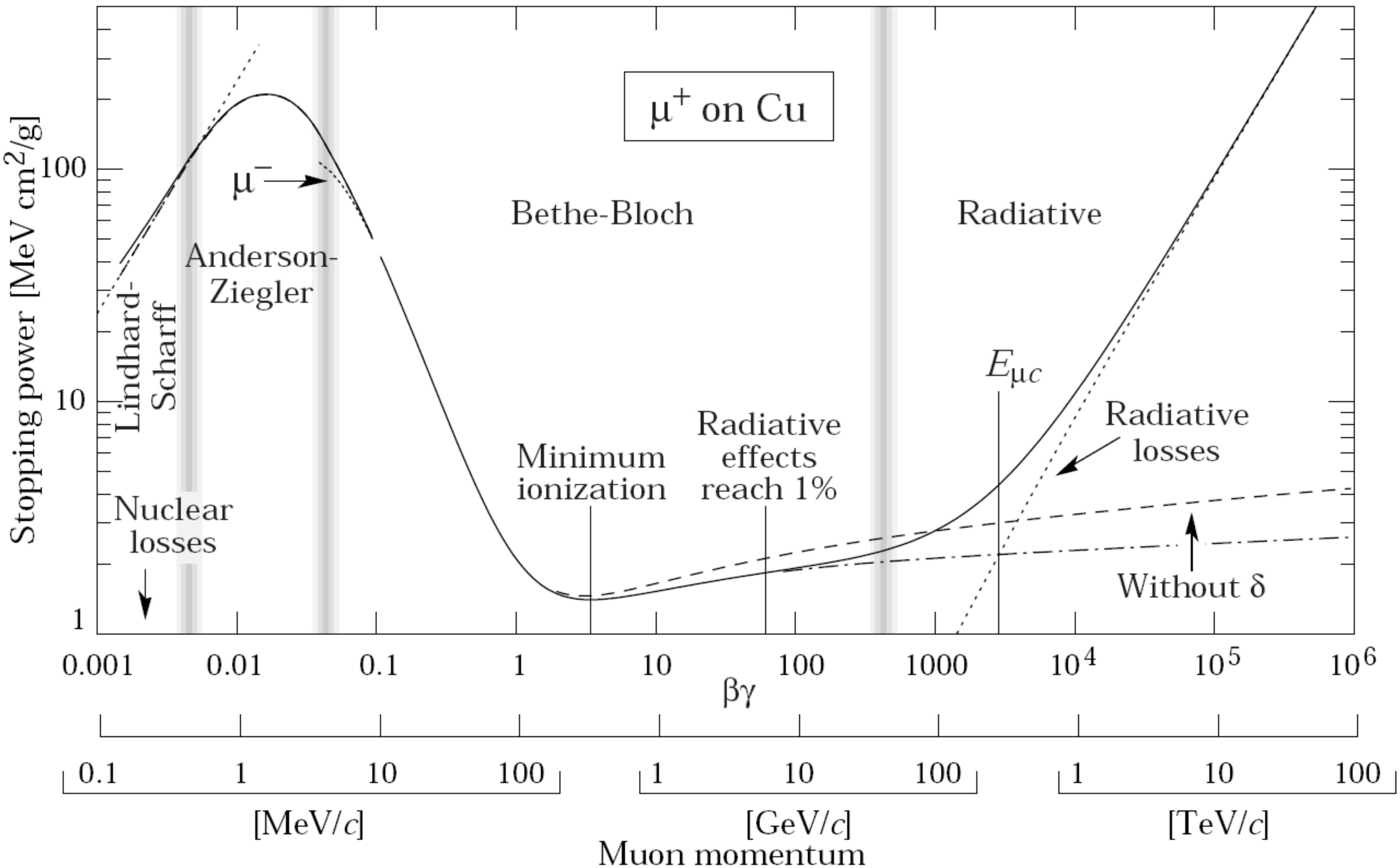
$$\left(\frac{dE}{dx}(E_k)\right)_{rad} = \left(\frac{dE}{dx}(E_k)\right)_{ion}$$

$E_k \sim 1/Z$

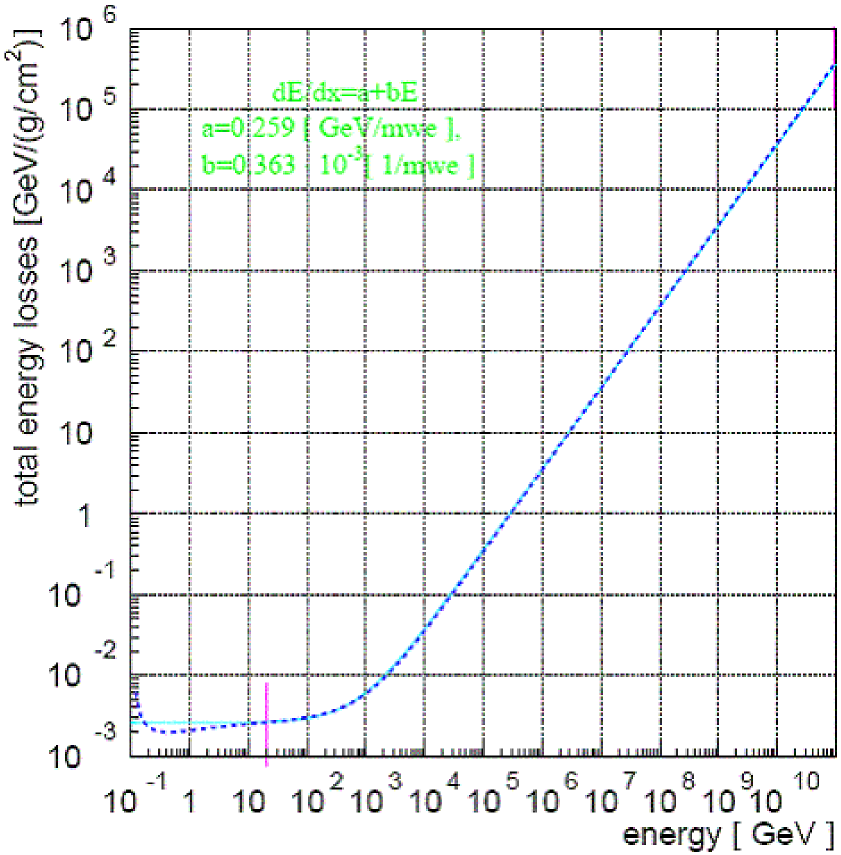
Material	Z	x_0 [mm]	E_k [MeV]	A	λ_a [mm]	λ_a/x_0
H_2O	1, 8	361	92	18	836	2.3
Be	4	353	116	9	407	1.2
C	6	188	84	12	381	2.0
Al	13	89	43	27	394	4.4
Fe	26	17.6	22	56	168	9.5
Cu	29	14.3	20	64	151	10.6
W	74	3.5	8.1	183	96	27.4
Pb	82	5.6	7.3	207	171	30.5
U	92	3.2	6.5	238	105	32.8

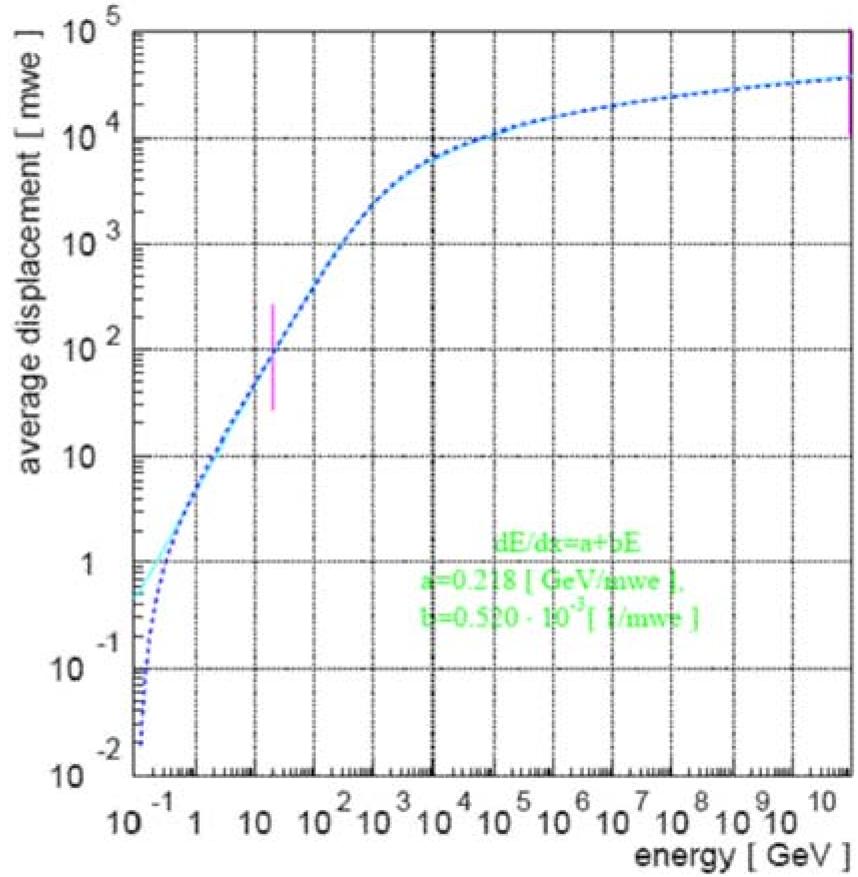


Energieverlust von Myonen

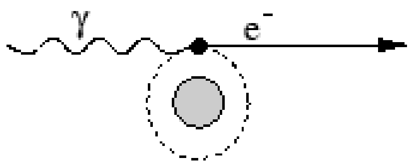


Energieverlust und Reichweite von Myonen

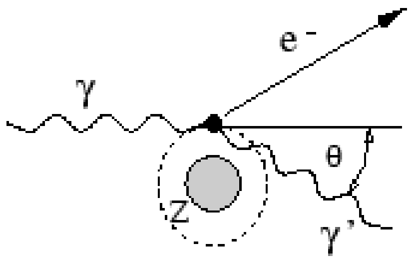




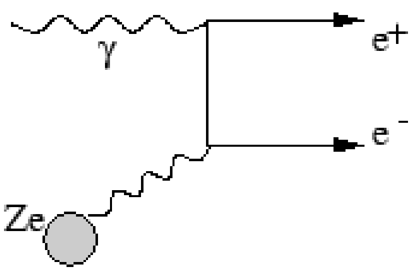
Photoabsorption



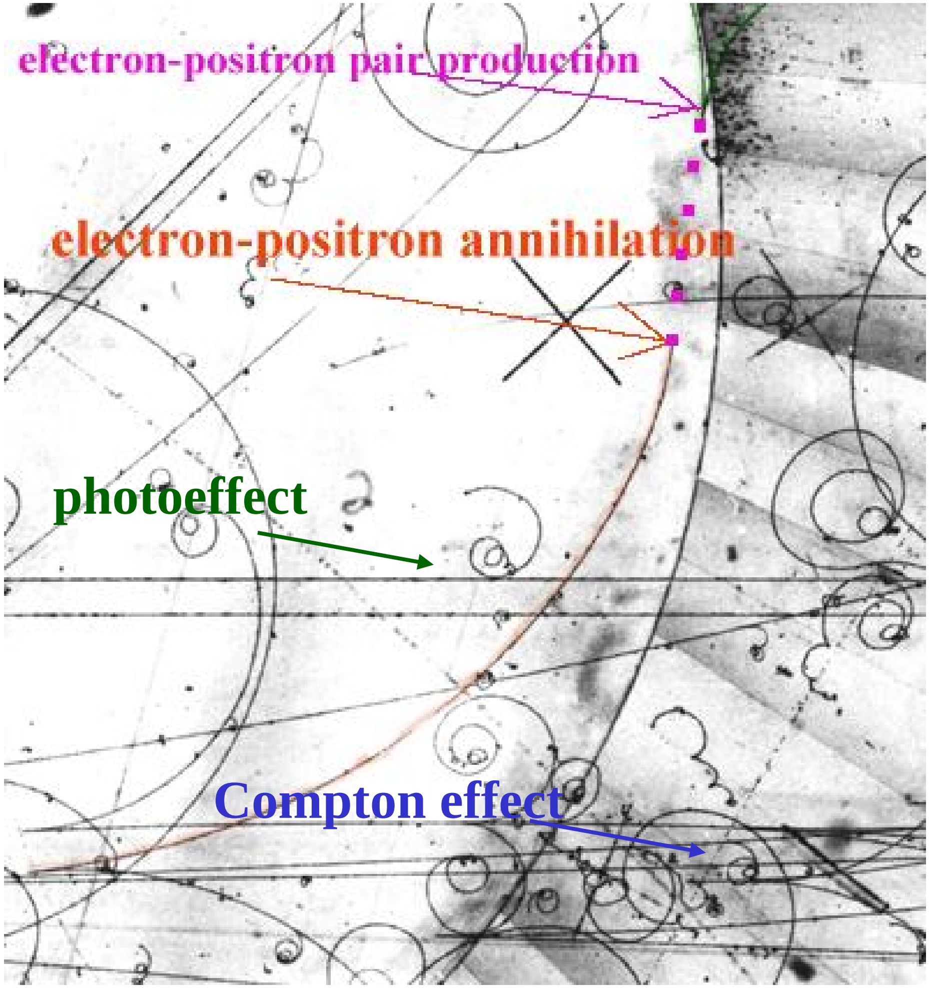
Photoeffekt



Compton-Effekt



Paarproduktion



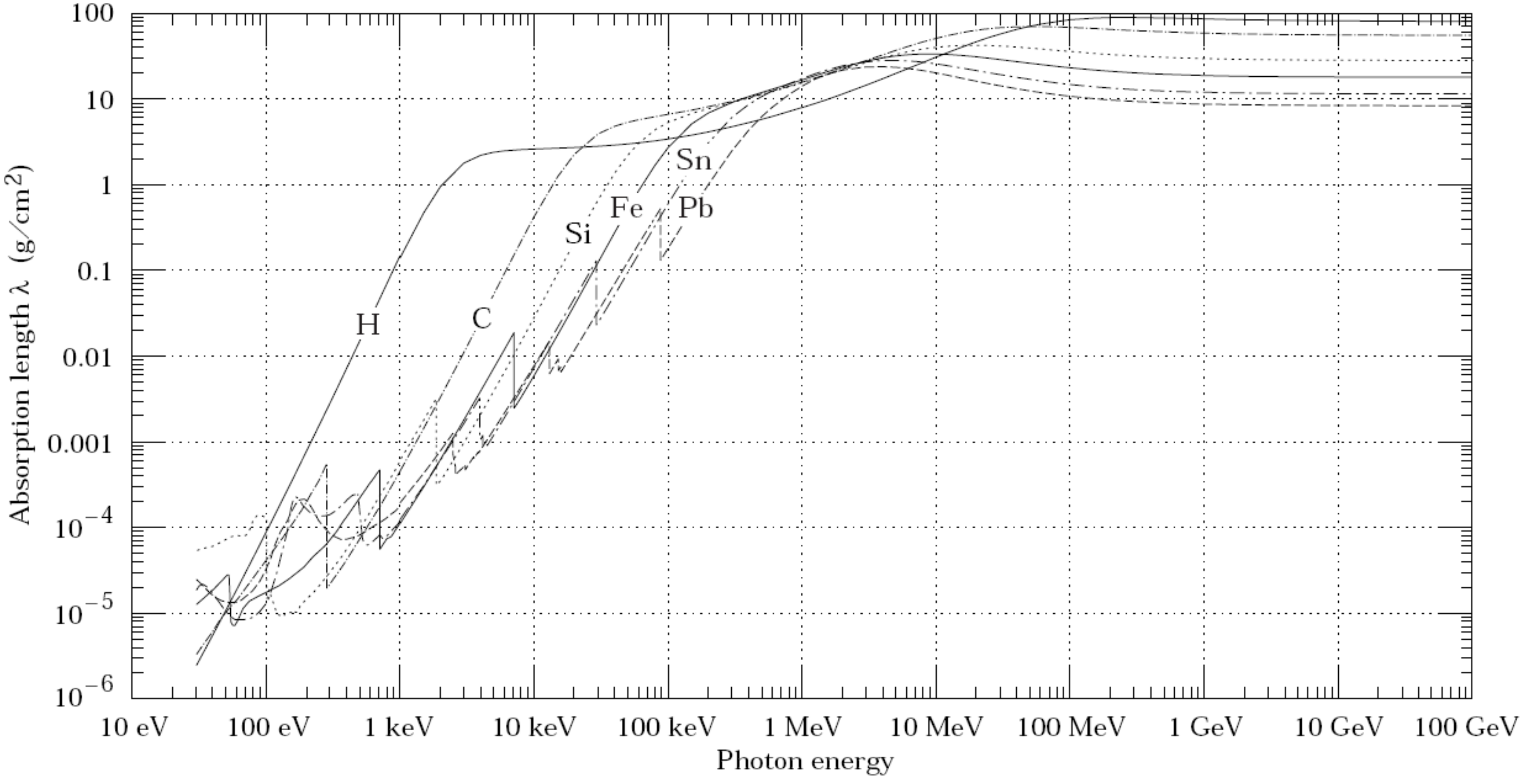
Skala wird durch Thomson-WQ gesetzt (Niederenergie $\gamma\, e^- \rightarrow \gamma\, e^-$):

$$\sigma_{Th} = \frac{8\pi r_e^2}{3} = 0.665\,\mathrm{barn}$$

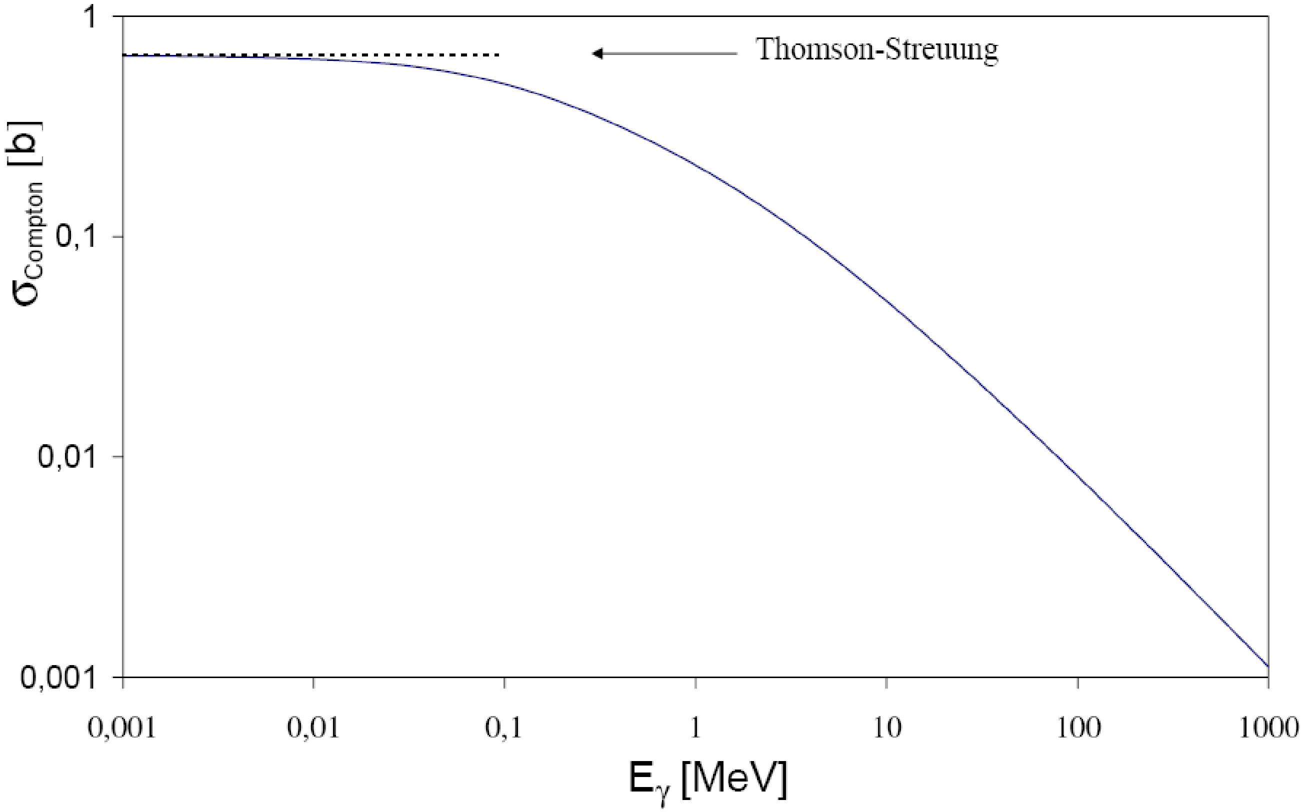
Photon-Absorptionslänge

$$-\frac{1}{N}\frac{dN}{dx} = \mu = \frac{dN_T \cdot \sigma}{dx \cdot F} = \rho\,\frac{N_A}{A}\,\sigma = n \cdot \sigma.$$

$$\lambda = \frac{1}{\mu} = \frac{1}{n \cdot \sigma}$$

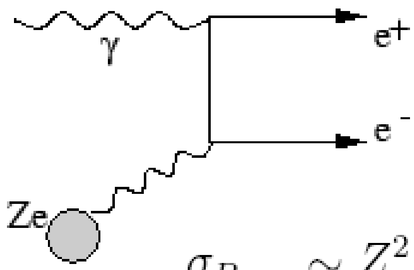


Compton-Effekt



$$\sigma_{Com} = 2\pi r_e^2 Z \left[\frac{1+\epsilon}{\epsilon^2} \left(\frac{2(1+\epsilon)}{1+2\epsilon} - \frac{1}{\epsilon} \ln(1+2\epsilon) \right) + \frac{1}{2\epsilon} \ln(1+2\epsilon) - \frac{1+3\epsilon}{(1+2\epsilon)^2} \right]$$

Paarproduktion

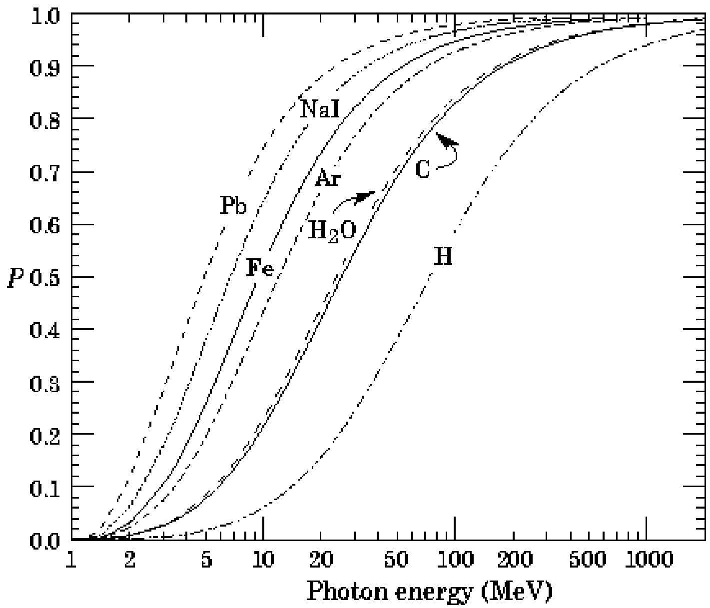


$\sigma_{Paar} \sim Z^2$

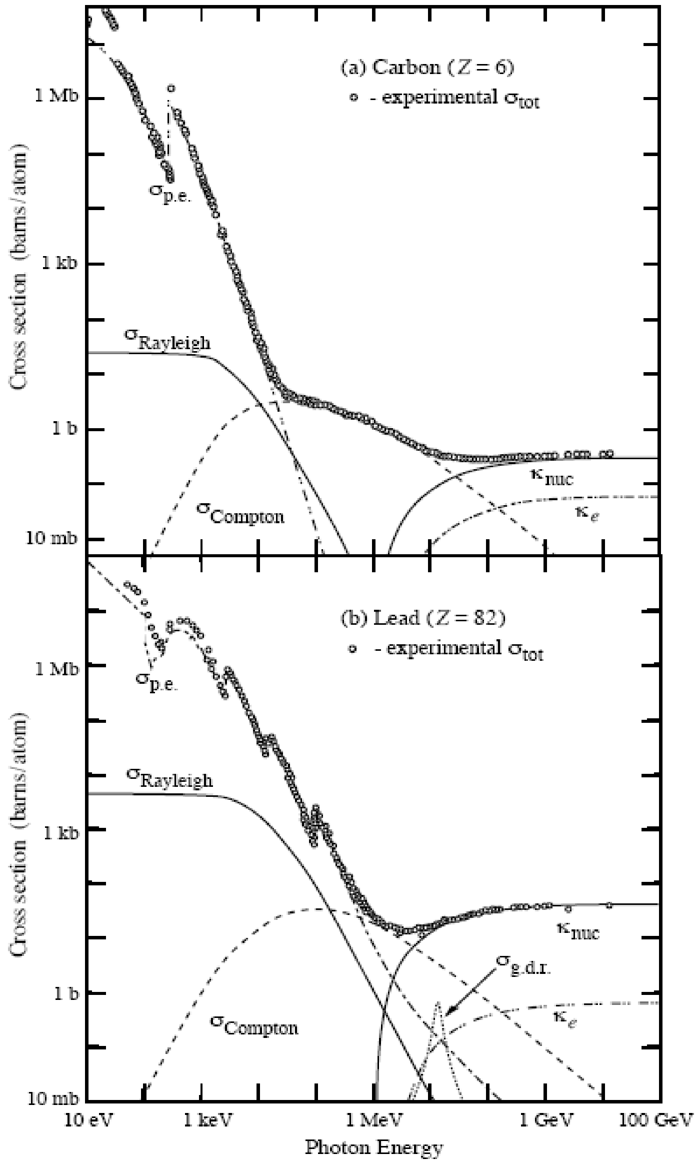
Schwelle: $E_\gamma > 2\, m_e$

Bei hohen Energien: $\sigma_{Paar} = \frac{7}{9} \frac{A}{\rho\, N_L} \frac{1}{x_0}$

$$\lambda_{Paar} = \frac{9}{7} x_0$$



Photon-Absorptionskoeffizient



$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)

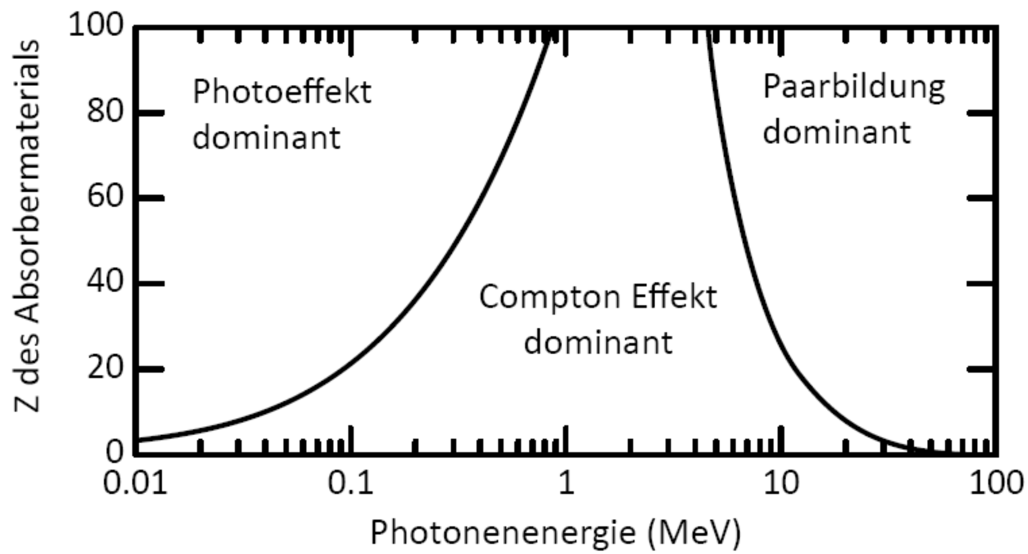
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited

σ_{Compton} = Incoherent scattering (Compton scattering off an electron)

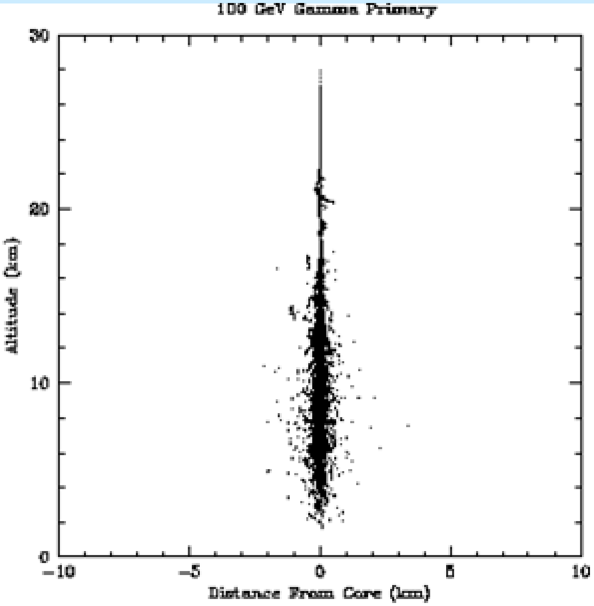
κ_{nuc} = Pair production, nuclear field

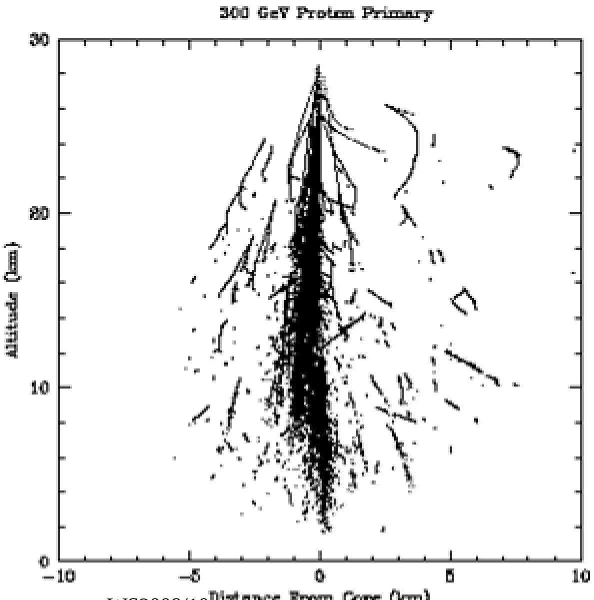
κ_e = Pair production, electron field

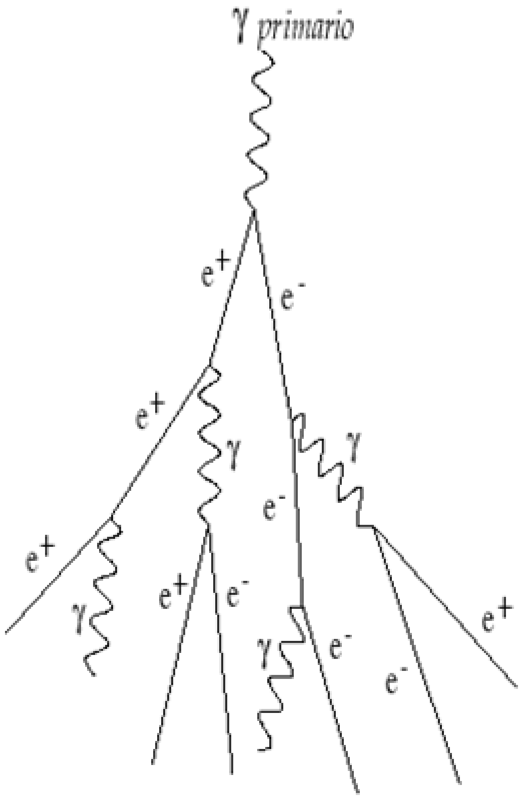
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [46]. In these interactions, the target nucleus is broken up.

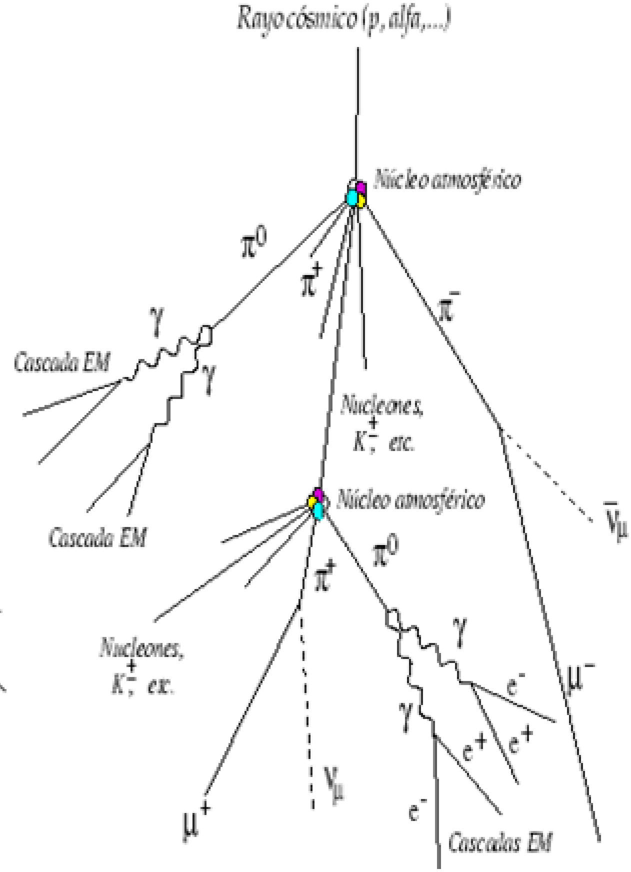


EM und Had. Schauer





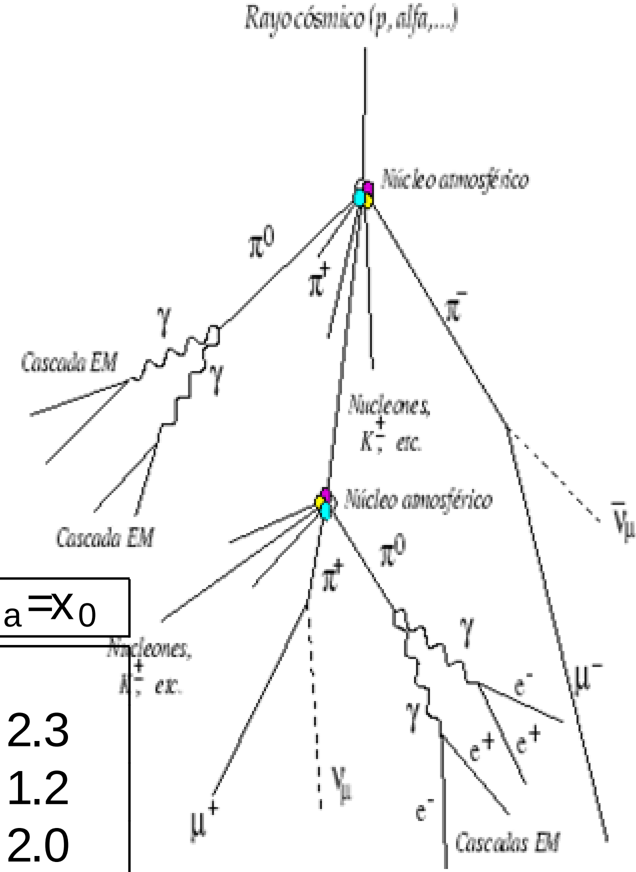




Hadronische WW

$$N(x) = N_0 \, e^{-x/\lambda_a}$$

$$\lambda_a = \frac{A}{N_A \cdot \rho \cdot \sigma_{inel}}$$

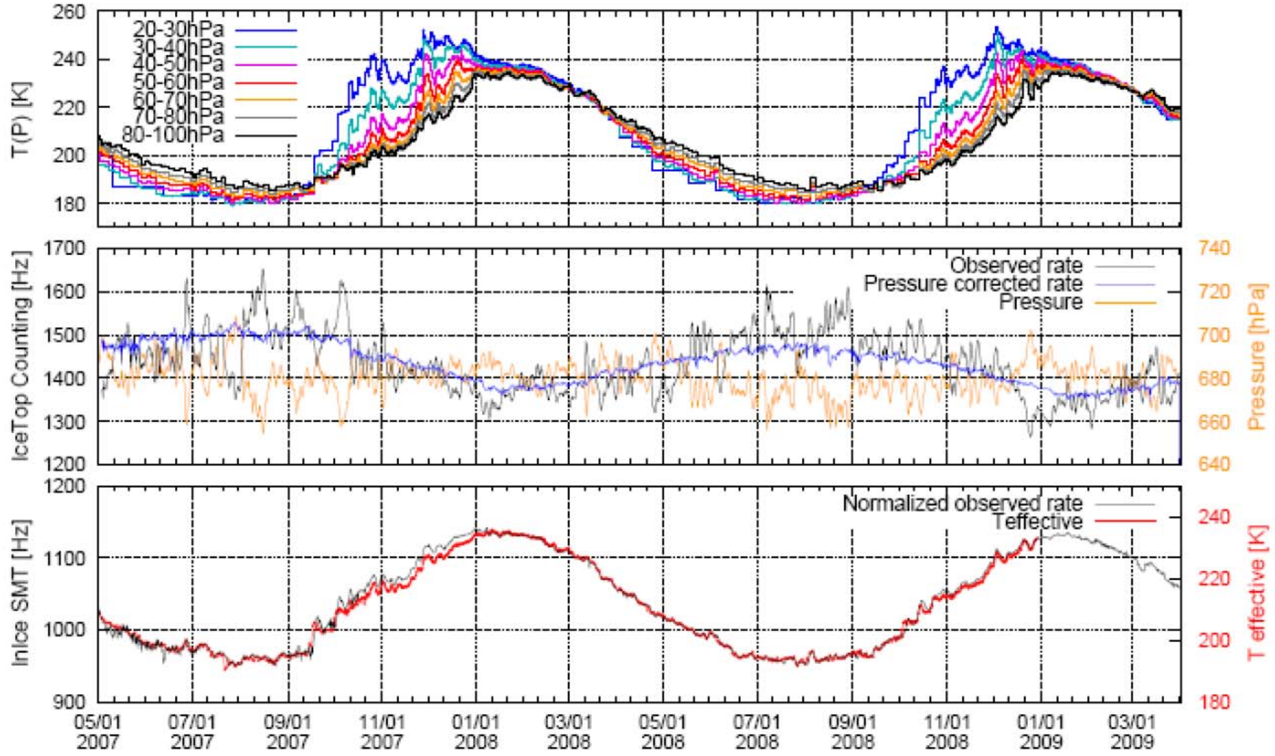


Material	Z	x_0 [mm]	E_k [MeV]	A	¸ a [mm]	¸ a=x_0
H_2O	1, 8	361	92	18	836	2.3
Be	4	353	116	9	407	1.2
C	6	188	84	12	381	2.0
Al	13	89	43	27	394	4.4
Fe	26	17.6	22	56	168	9.5
Cu	29	14.3	20	64	151	10.6
W	74	3.5	8.1	183	96	27.4
Pb	82	5.6	7.3	207	171	30.5
U	92	3.2	6.5	238	105	32.8

Pion-Zerfall vs. Wechselwirkung

e.m. Komponente

Myon. Komponente

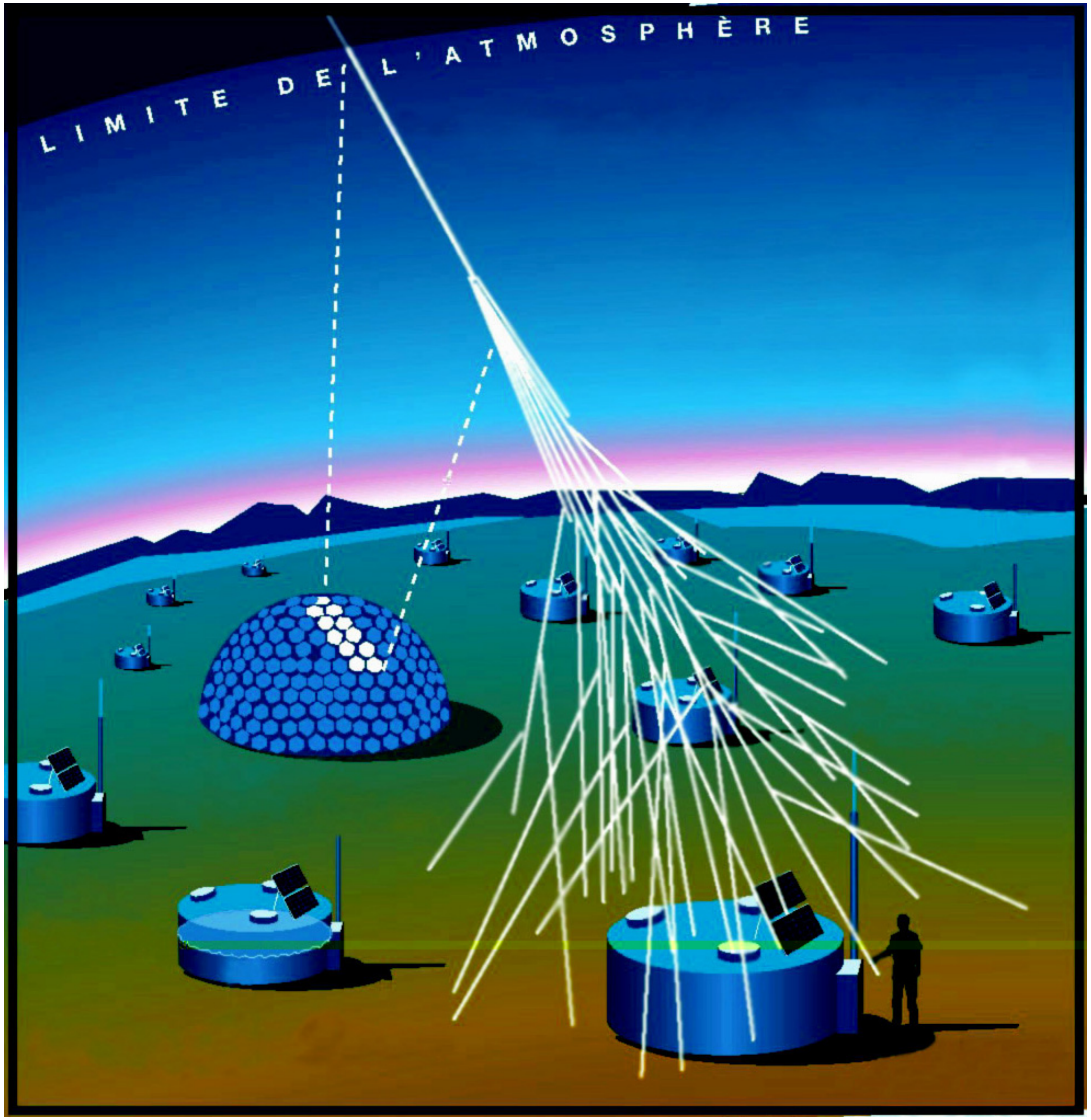


$$\lambda_\tau = \gamma\beta c\tau = \frac{\vec{p}}{m} c\tau$$

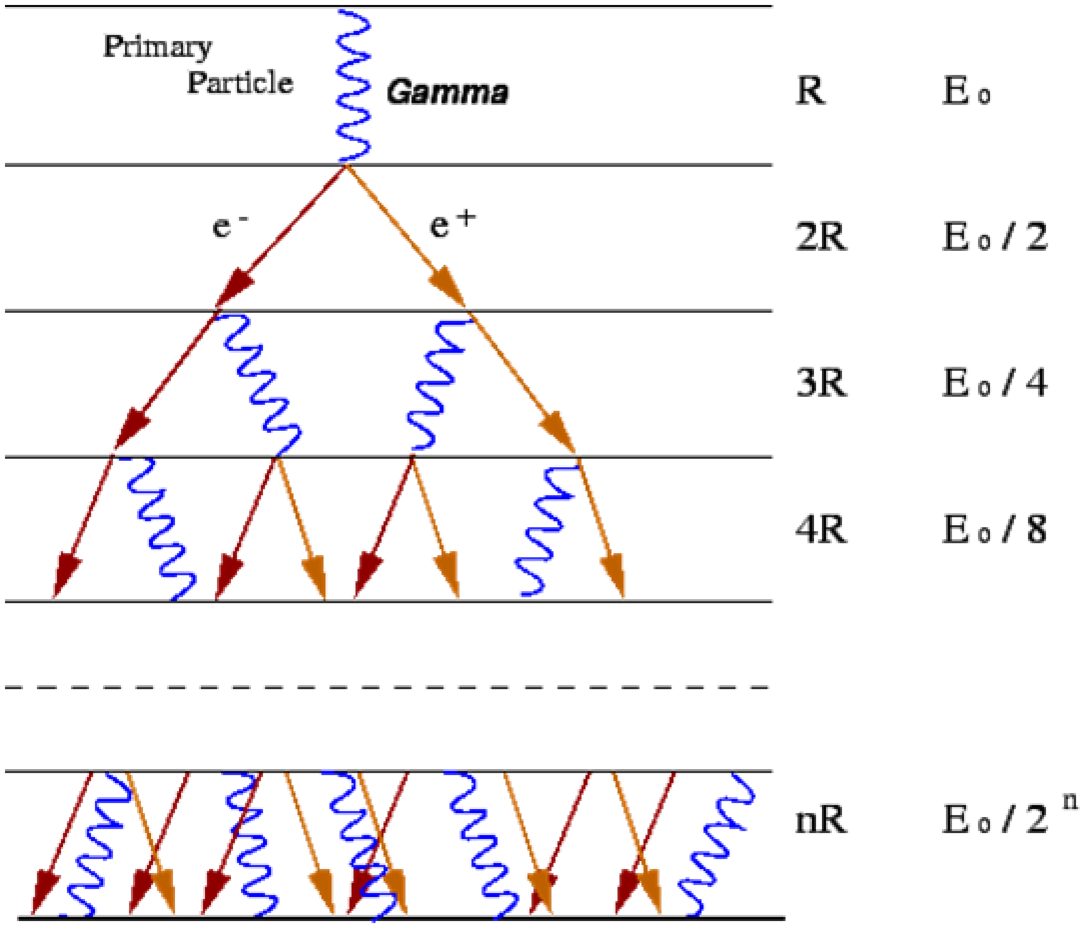
$$\lambda_I = \frac{1}{n\sigma_I} = \frac{A}{\rho N_A \sigma_I}$$

(1 GeV: Zerfallslänge ~ 55 m)

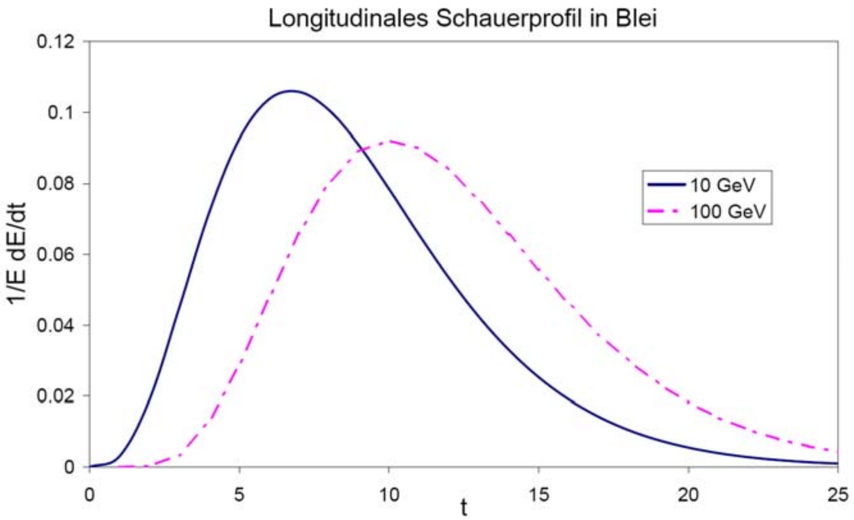
Luftschauer-Detektor



Modell für eine em. Kaskade



Schauerentwicklung



Moliere Radius:

$$R_M = \frac{21.2\,\mathrm{MeV}}{E_k} \cdot x_0$$

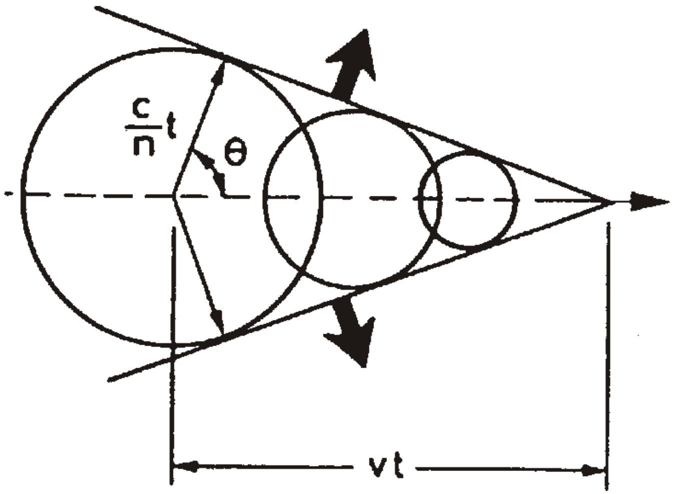
Longo-Formel:

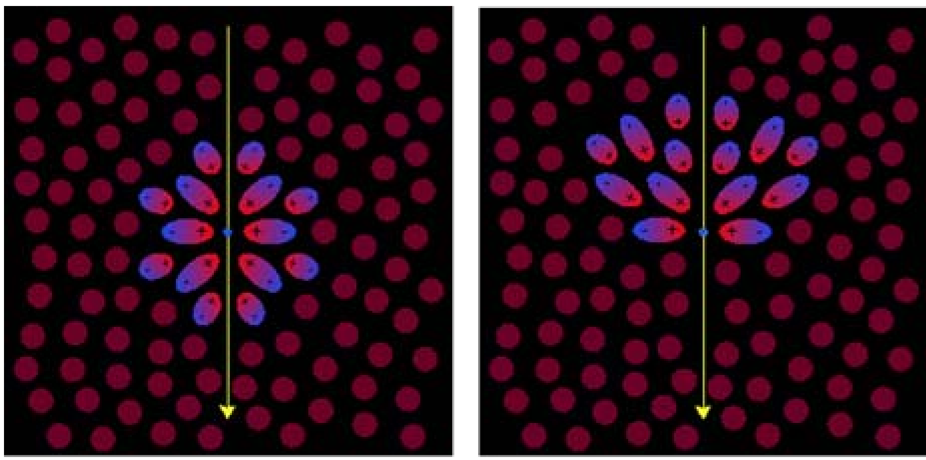
$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} \mathrm{e}^{-bt}$$

$$t_{max} = \frac{\alpha}{b} \qquad t_{max} = \ln \frac{E_0}{E_k} + \begin{cases} -0.5 & \text{(Elektronen)} \\ +0.5 & \text{(Photonen)} \end{cases}$$

$$t^{98\%} \approx t_{max} + 13.6 \pm 2.0$$

Cherenkov Radiation





(a) v < c

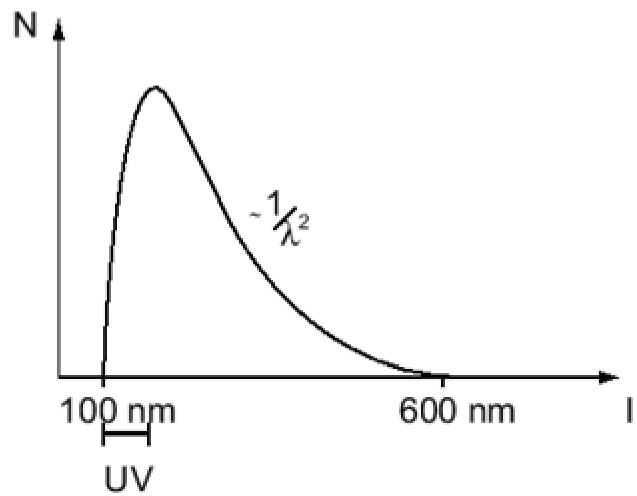
(b) v > c

$$\cos\theta_C = \frac{c/n\cdot\Delta t}{v\cdot\Delta t} = \frac{1}{\beta n}$$

$$\frac{dN}{d\lambda dx} = \frac{2\pi\alpha}{\lambda^2}\sin^2\theta_C$$

$$\text{for } \Delta\lambda = 400 - 700\ \text{nm}:$$

$$\frac{\mathrm{dN}}{\mathrm{dx}} \approx 500\sin^2\theta_C\ \gamma'\mathrm{s/cm}$$



Refractive Indices and Cherenkov Thresholds

Material	$n-1$	β-Schwelle	γ-Schwelle
festes Natrium	3.22	0.24	1.029
Bleisulfit	2.91	0.26	1.034
Diamant	1.42	0.41	1.10
Zinksulfid ($ZnS(Ag)$)	1.37	0.42	1.10
Silberchlorid	1.07	0.48	1.14
Flintglas (SFS1)	0.92	0.52	1.17
Bleifluorid	0.80	0.55	1.20
Clerici-Lösung	0.69	0.59	1.24
Bleiglas	0.67	0.60	1.25
Thalliumformiat-Lösung	0.59	0.63	1.29
Szintillator	0.58	0.63	1.29
Plexiglas	0.48	0.66	1.33
Borsilikatglas	0.47	0.68	1.36
Wasser	0.33	0.75	1.52
Aerogel	0.025 - 0.075	0.93 - 0.976	4.5 - 2.7
Pentan (STP)	$1.7 \cdot 10^{-3}$	0.9983	17.2
CO_2 (STP)	$4.3 \cdot 10^{-4}$	0.9996	34.1
Luft (STP)	$2.93 \cdot 10^{-4}$	0.9997	41.2
H_2 (STP)	$1.4 \cdot 10^{-4}$	0.99986	59.8
He (STP)	$3.3 \cdot 10^{-5}$	0.99997	123

Tabelle 6.2: Cherenkov-Radiatoren [94, 32, 313]. Der Brechungsindex für Gase bezieht sich auf 0°C und 1 atm (STP). Festes Natrium ist für Wellenlängen unterhalb von 2000 Å transparent [373, 209].

$$\cos\theta_C = \frac{1}{\beta n}$$

$$\Rightarrow \cos\theta_C = 1 \text{ for } \beta = \frac{1}{n}$$

threshold

$$\left(\beta < \frac{1}{n} \Rightarrow \cos\theta_C > 1\right)$$

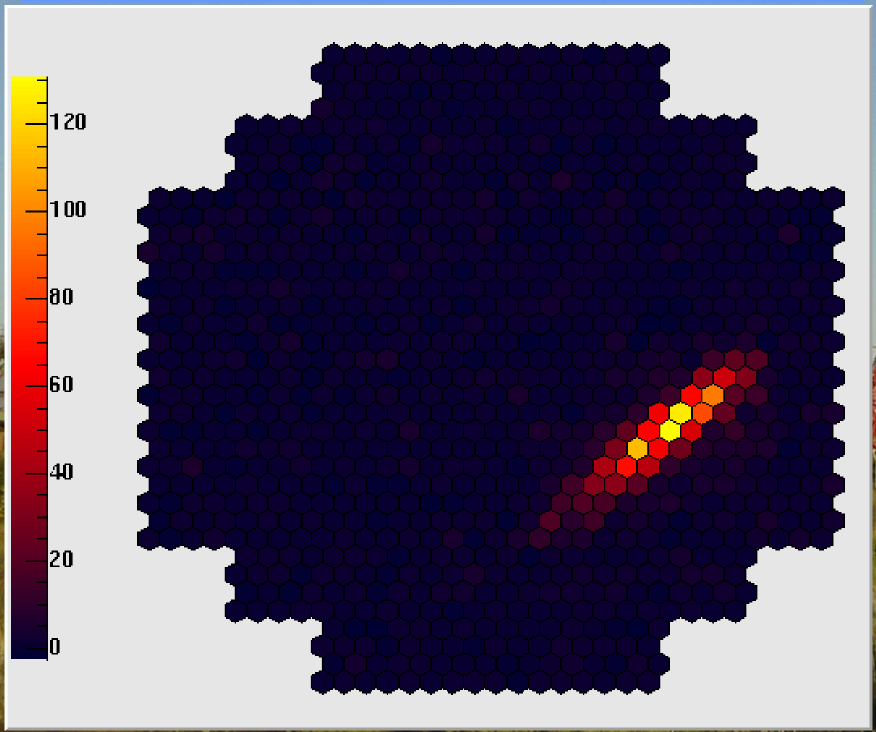
$$\beta = 1 \Rightarrow \cos\theta_C = \frac{1}{n}$$

largest angle

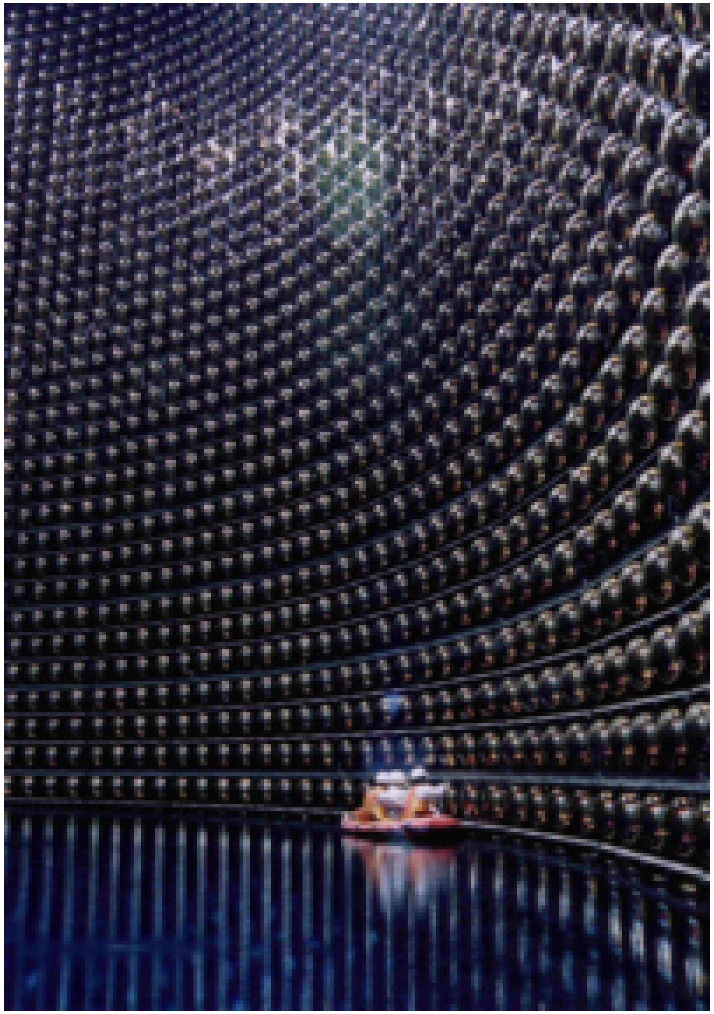
Air Showers from HE γ Rays

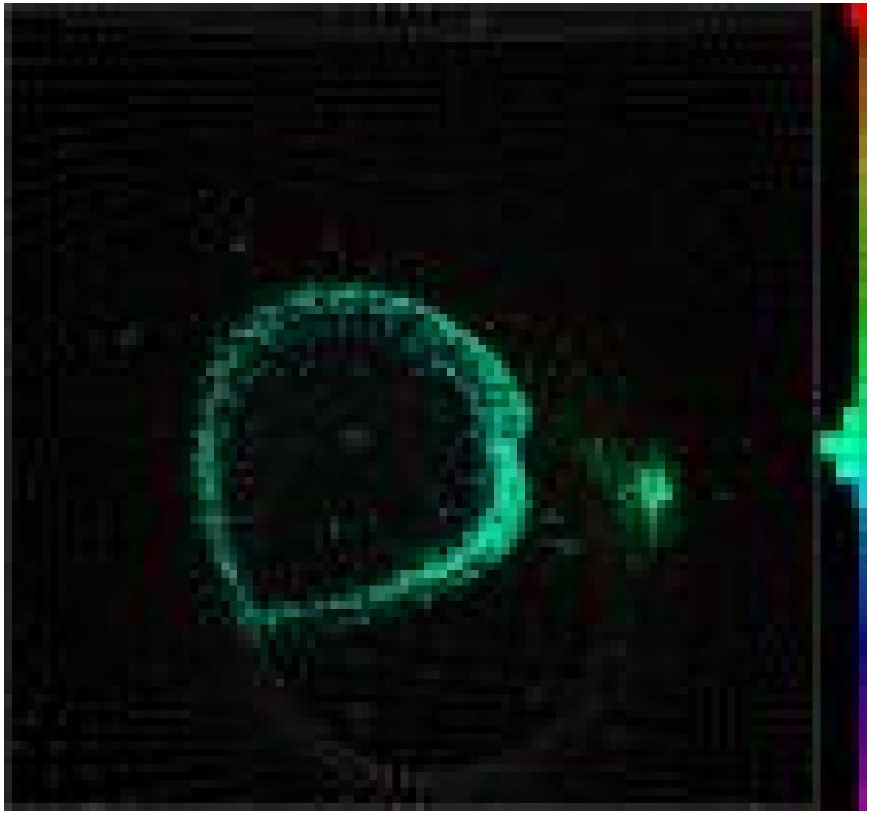
- HESS Telescopes in Namibia

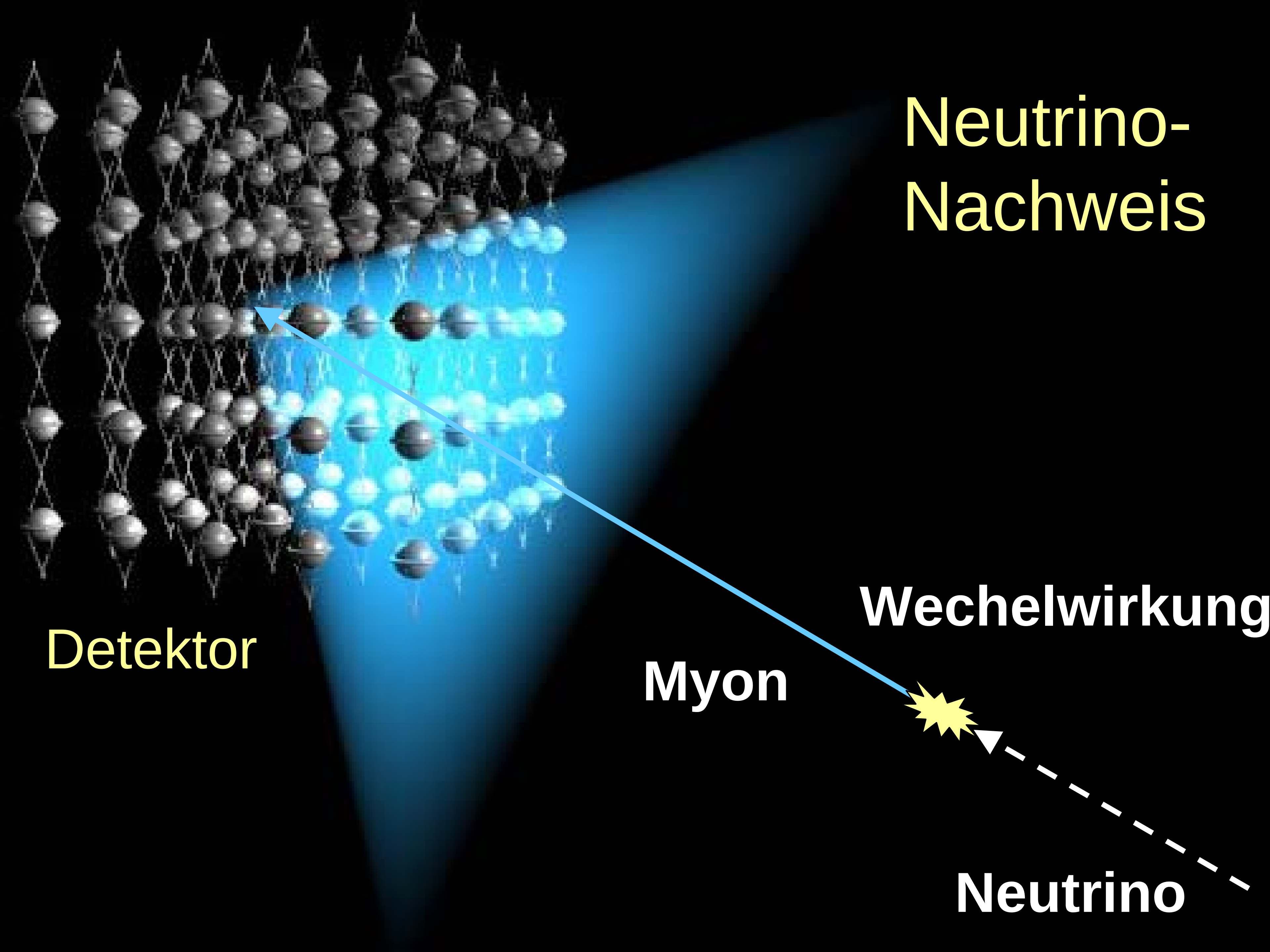
camera in action



Ring Imaging in Water Tanks

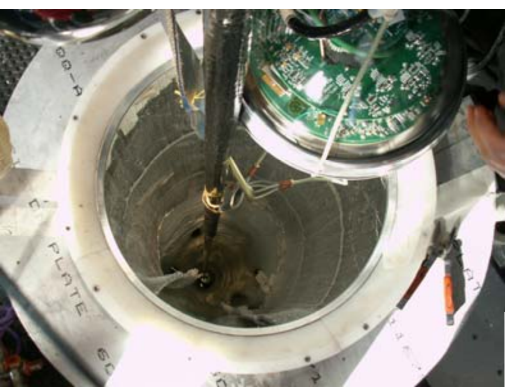


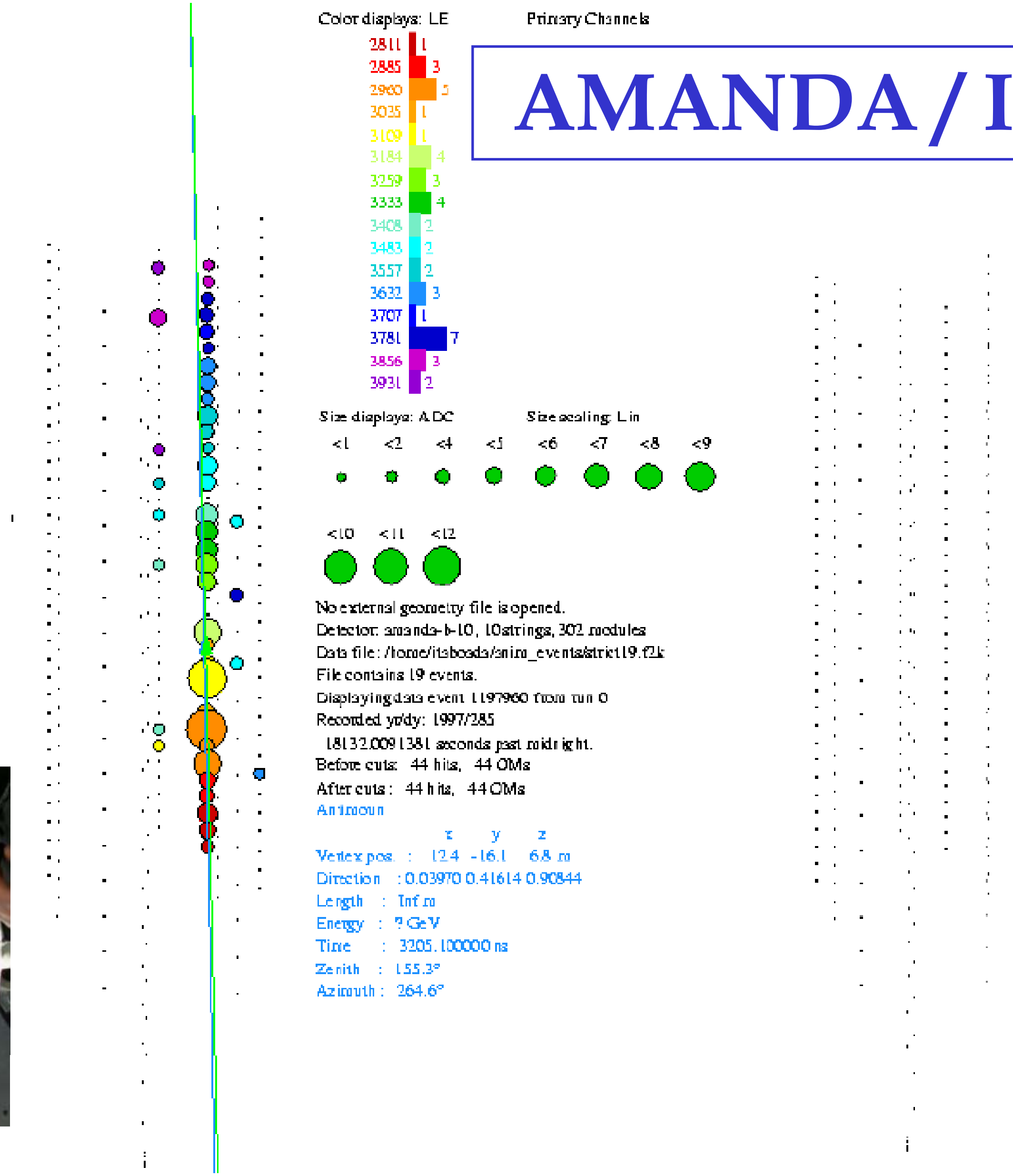




Neutrino-
Nachweis
Detektor
Wechelwirkung
Myon
Neutrino

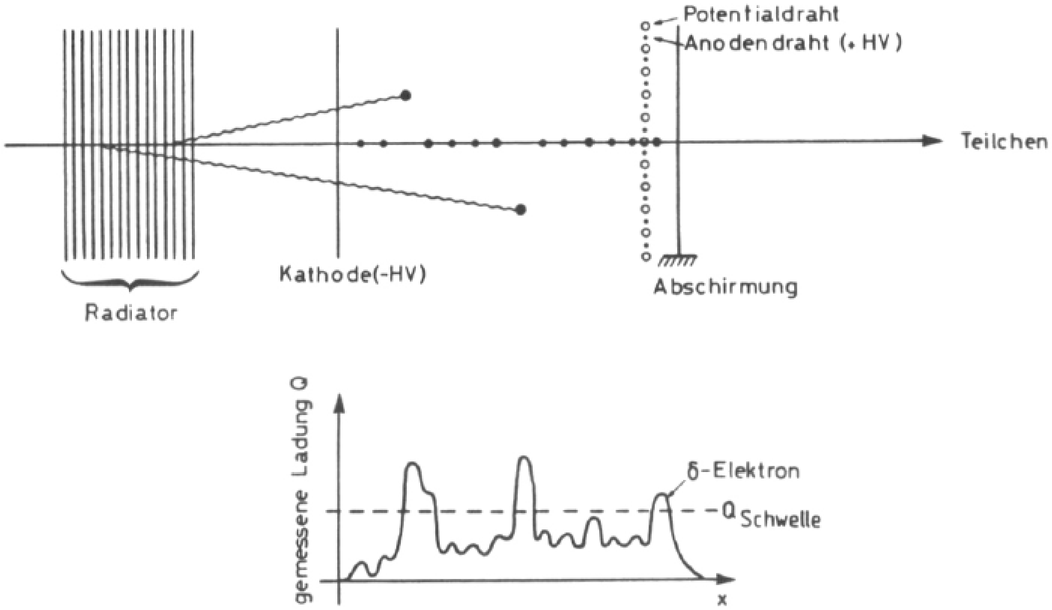
AMANDA / IceCube

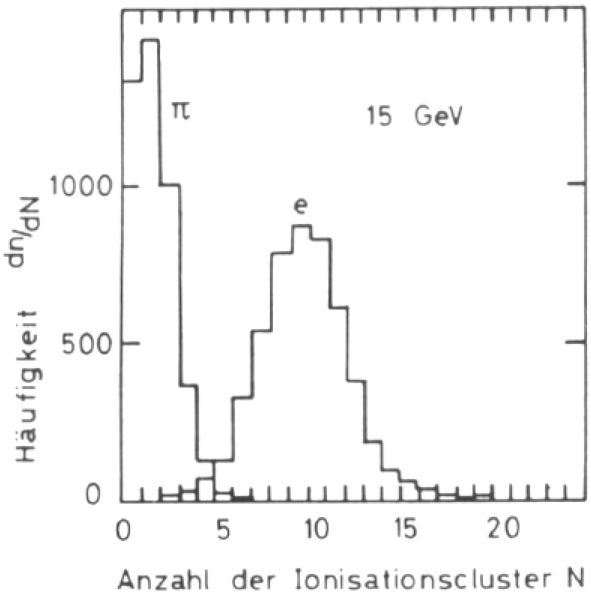




$\nu_\mu + N \rightarrow \mu + X \Rightarrow$ high energy μ above C-threshold in ice

Übergangsstrahlung (TR)



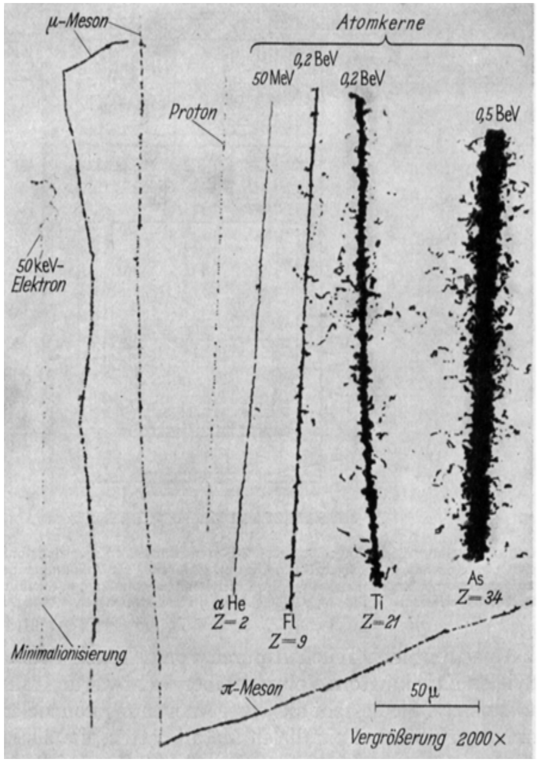


$$I \sim \gamma, \qquad \theta \sim \frac{1}{\gamma}$$

Teilchenidentifikation: Methoden

- Geladene Teilchen: Messe Impuls und Geschwindigkeit $\Rightarrow$ $m = \dfrac{p}{\gamma\beta}$

  - Laufzeitmessung
  - dE/dx-Messung
  - Cerenkov-Strahlung
  - Übergangsstrahlung



- Kinematische Rekonstruktion der Masse
- Elektronen, Photonen: elmag. Schauer
- Myonen: Durchdringungsfähigkeit
- Hadronen: Hadronische Schauer
- Lebensdauermessung bei instabilen Teilchen (schwere Quarks, Leptonen, …)