

Kern- und Teilchenphysik

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Vorlesung-Website

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Was wollen wir messen?

$$P = (E, \vec{p})$$

el. Signal

Energie: Teilchen stoppen, Ionisation
(E groß: „Schauer“)

Impuls $p = q \beta R$

→ Ortsmessungen!

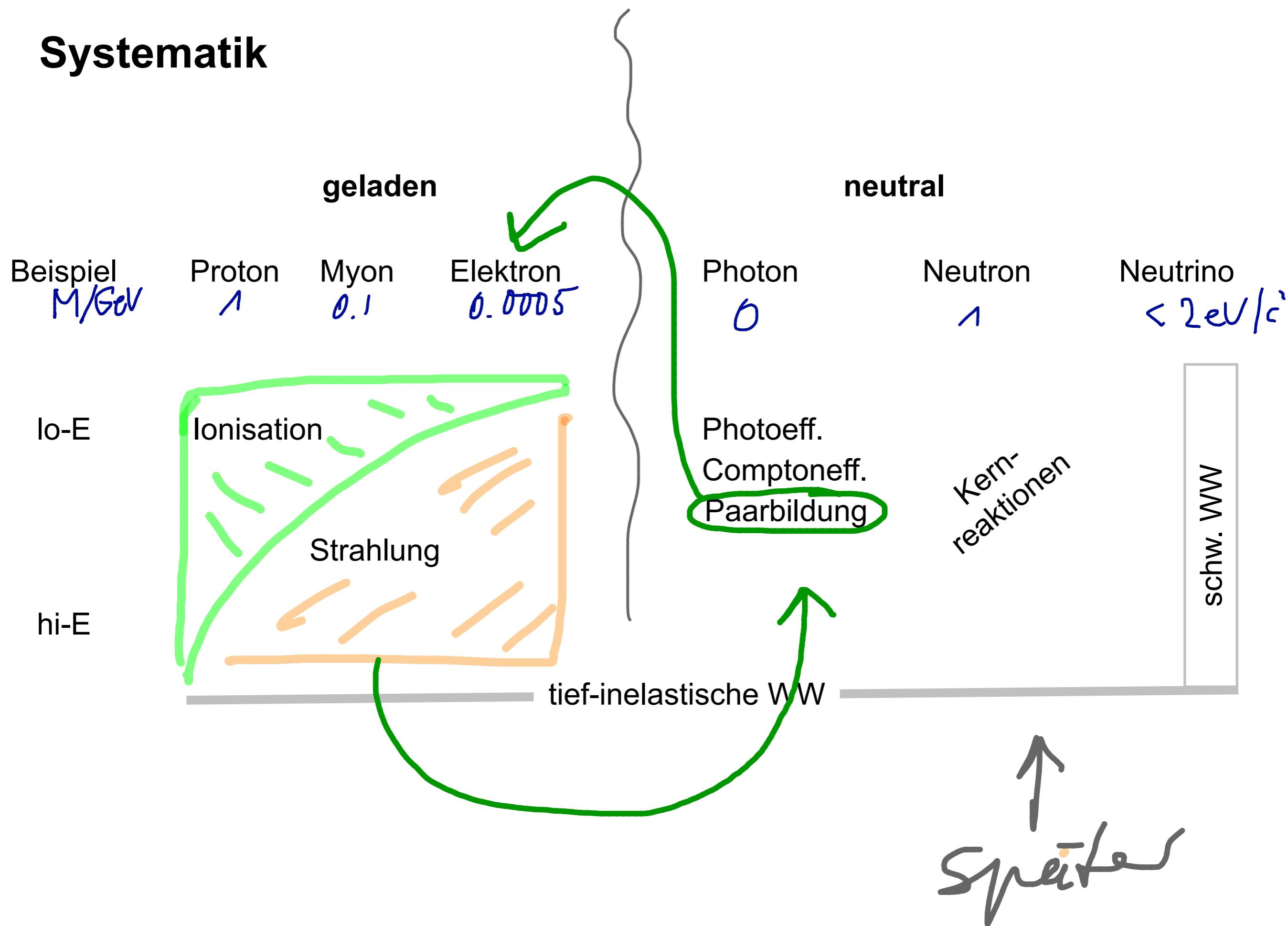
lokalisierte Ionis.

β ← Ionisation, Cherenkov, "TOF"

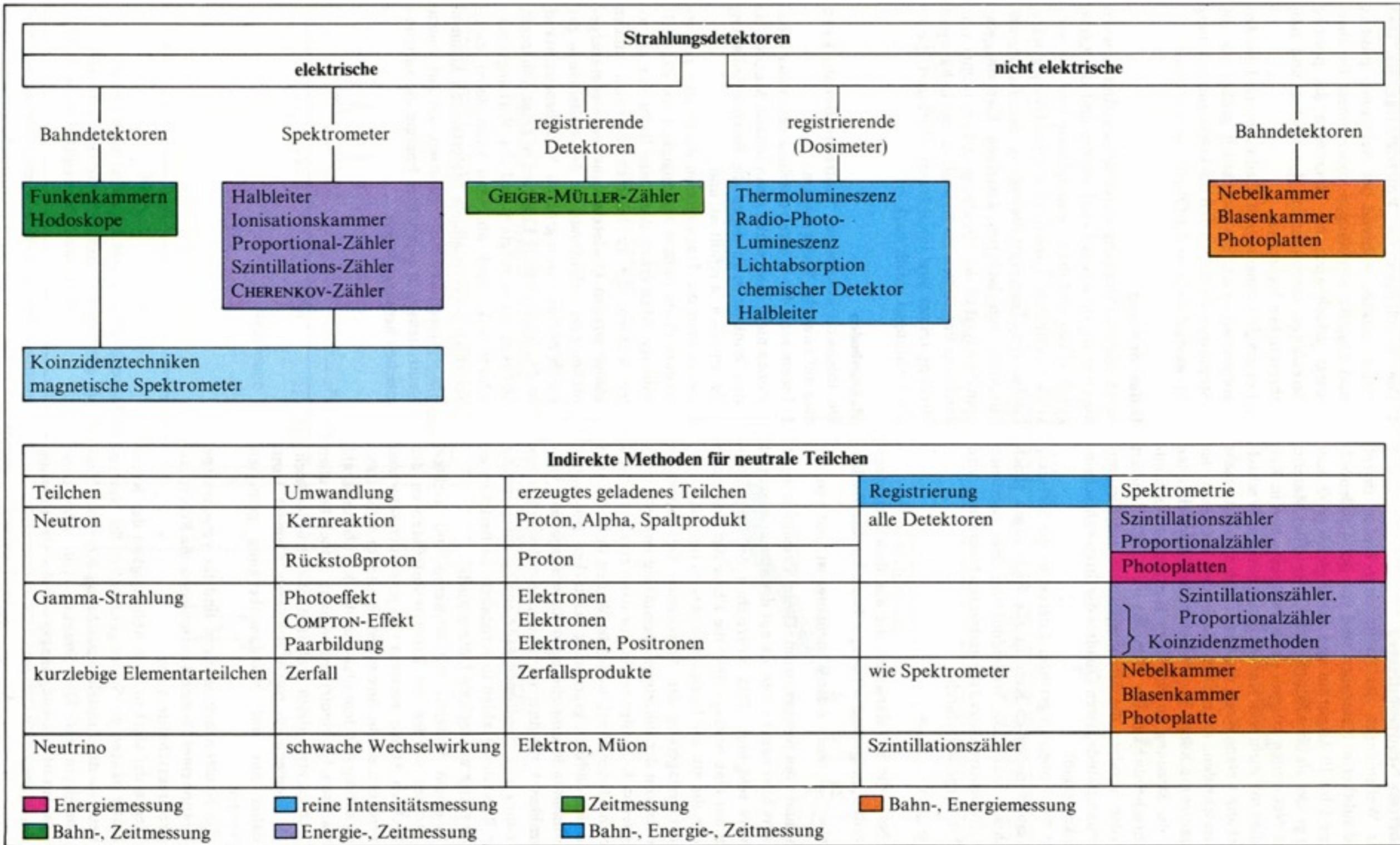
m ← E, p u a Zeit

q ← Ionisation u. a.

Systematik



Detektoren Übersicht



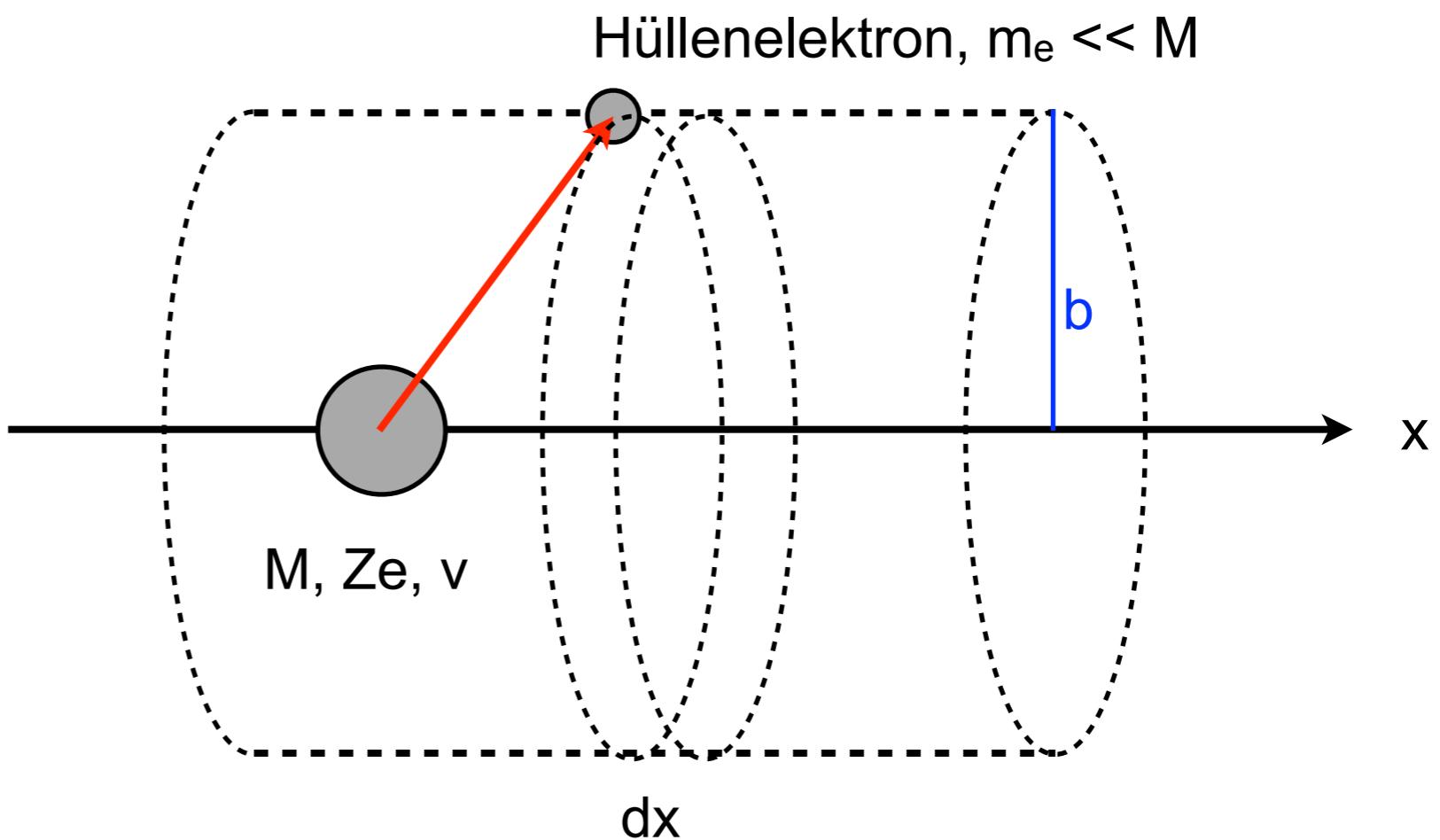
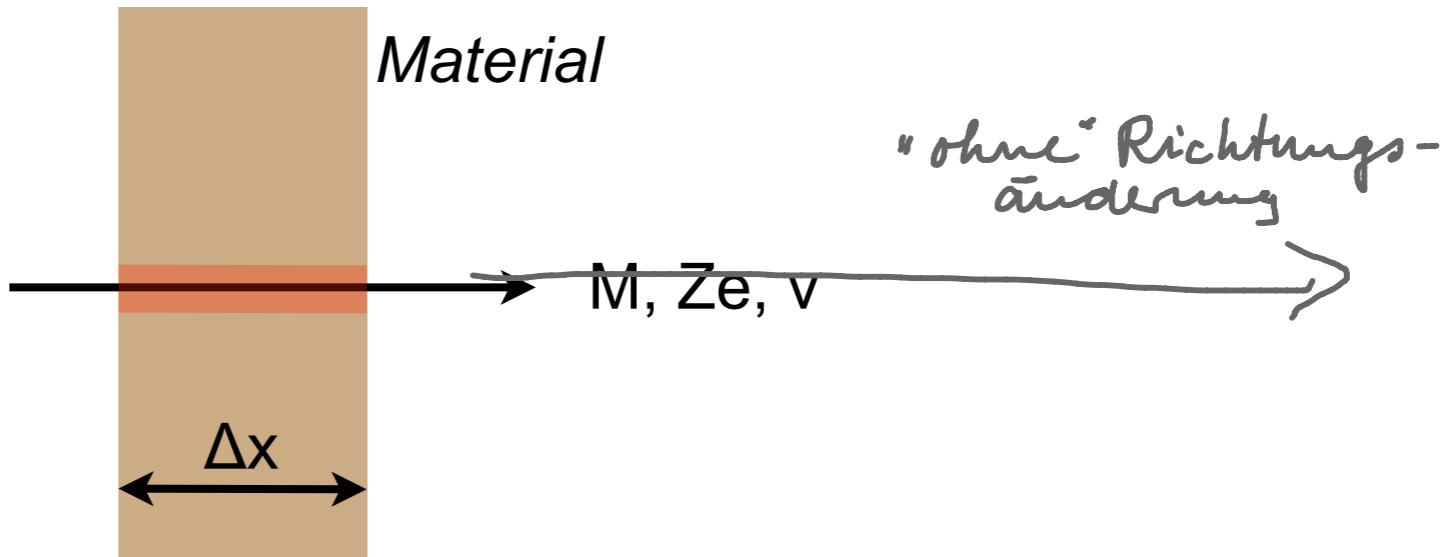
Ionisation: Bethe-Bloch-Gleichung

Impulsübertrag
auf 1 e-
(Gaußscher
Satz)

Energieübertrag
nicht-rel.

Summation
über Elektronen

Integration über
Stoßparameter $\leftarrow b$



Bethe-Bloch-Gleichung: dE/dx

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

$$D = 4\pi \cdot N_A \cdot r_e^2 \cdot m_e c^2 \approx 0.307 \frac{\text{MeV}}{\text{g/cm}^2}$$

z, β Ladungszahl, Geschwindigkeit des Teilchens

Z, A, ρ Kernladungszahl, Massenzahl, Dichte des Mediums

I Effektives Ionisationspotenzial der Medienatome

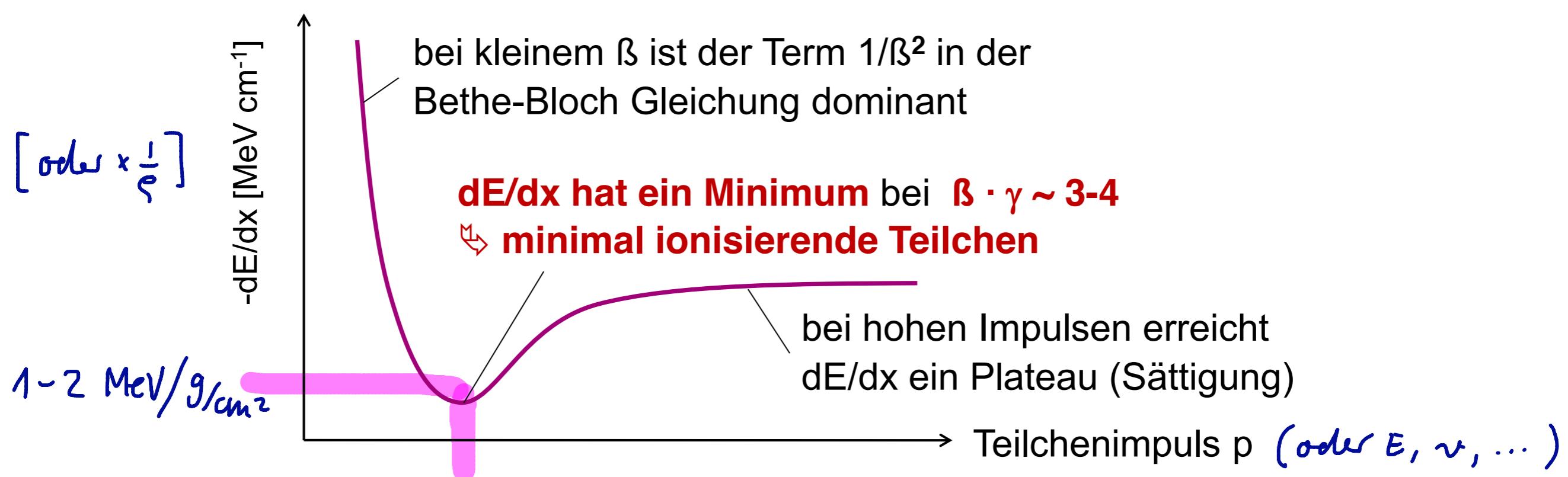
$$I \approx 16 \cdot Z^{0.9} \text{ eV}$$

ΔT_{\max} max. Energieübertrag auf Hüllenelektron
für $M/\gamma \gg m_e$ gilt $\Delta T_{\max} \approx 2m_e c^2 \beta^2 \gamma^2$

δ Dichtekorrekturen bei grossen Energien

C Schalenkorrekturen bei kleinen Energien

■ Vorsicht: Modifikationen nötig für e^+ und e^- !



dE/dx

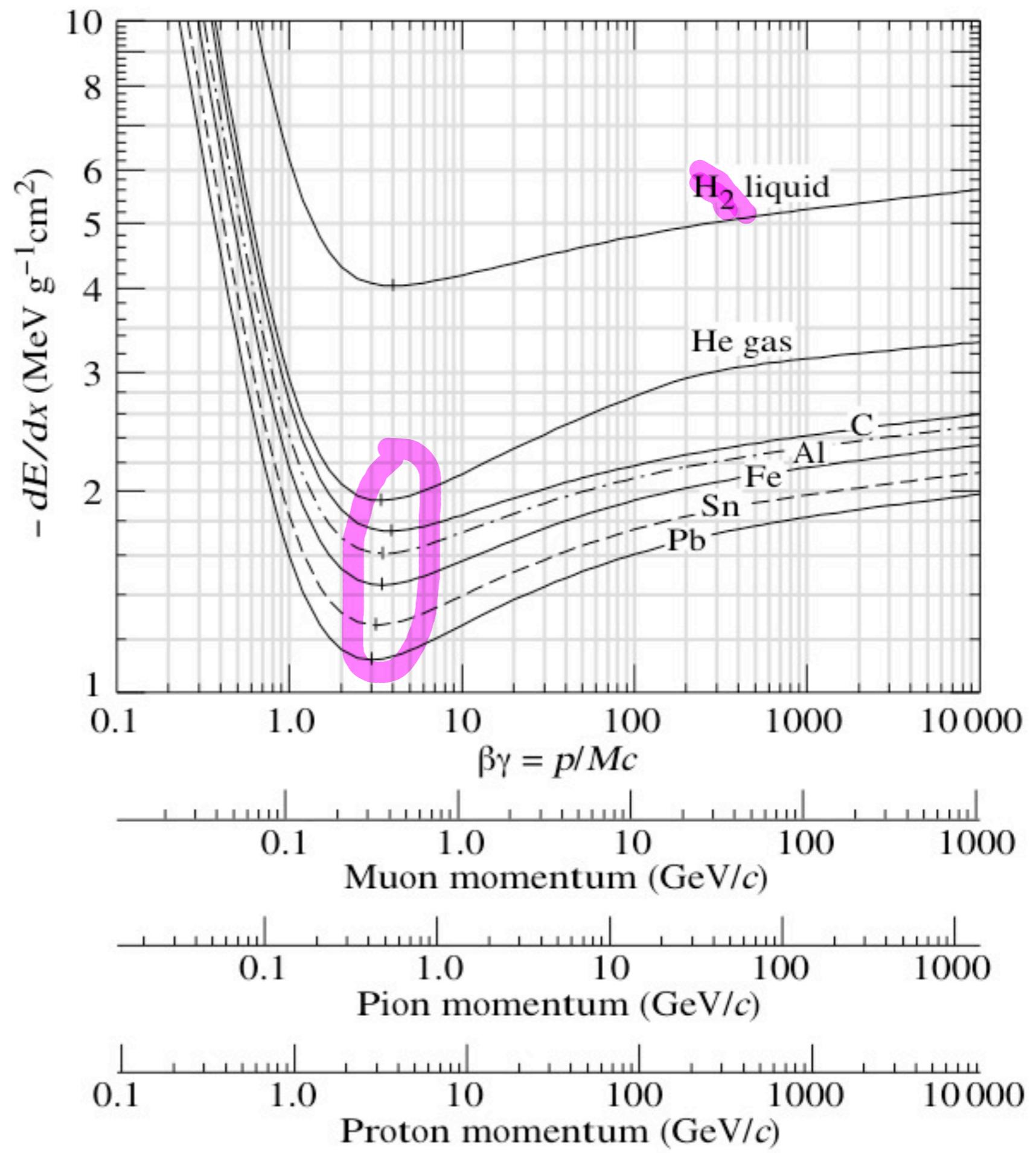


Figure 27.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma > 1000$, and at lower momenta for muons in higher-Z absorbers.

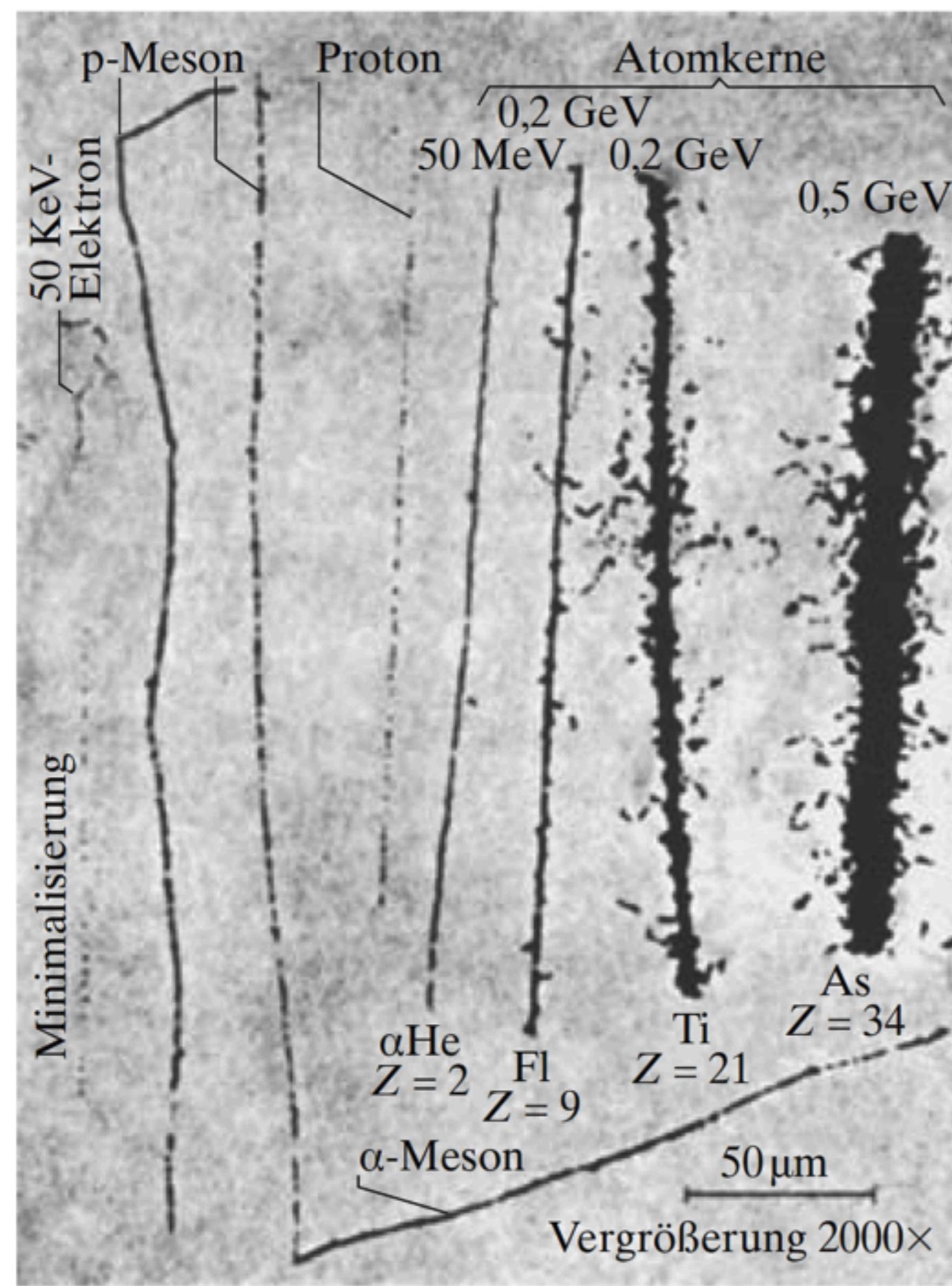
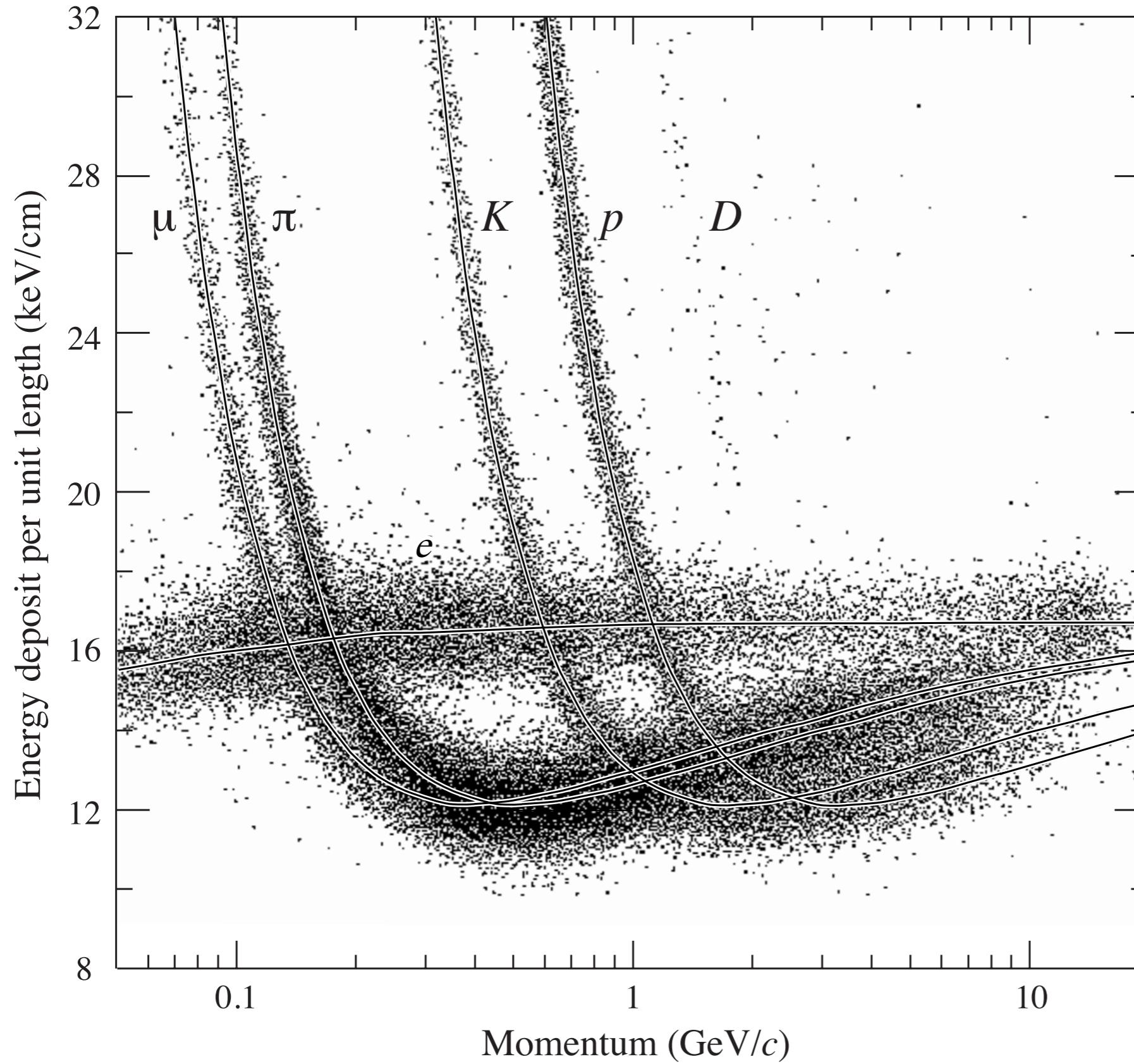


Abb. 18.24. Spuren geladener Teilchen in einer elektronenempfindlichen Photoemulsion. (Zusammengestellt von Leprince-Ringuet, aus W. Finkelnburg: *Einführung in die Atomphysik*, 11./12. Aufl. (Springer, Berlin Heidelberg 1976))

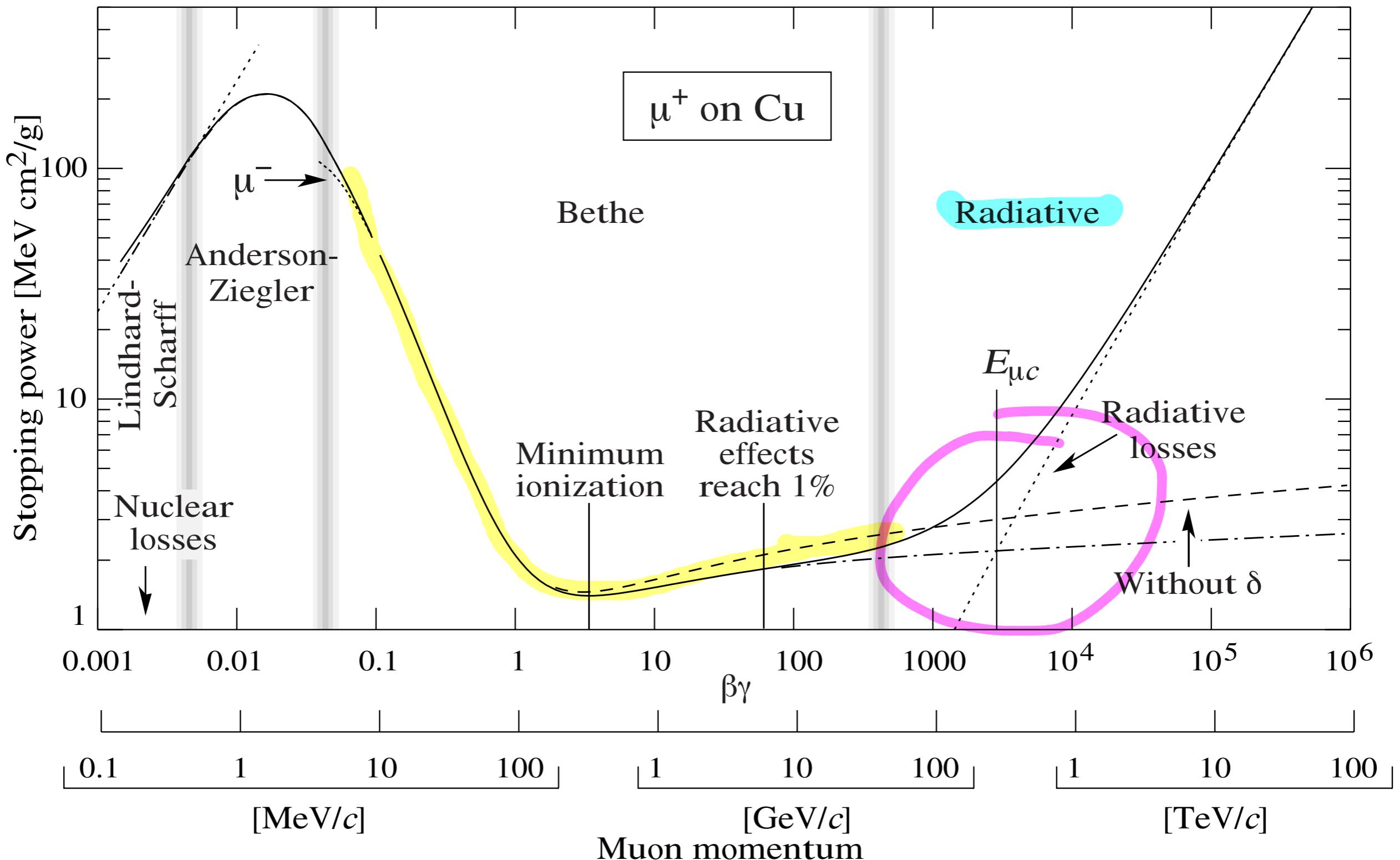
dE/dx in Gas-Detektor



[rpp2010] Figure
28.15: The PEP4/9-
TPC energy deposit
measurements
(185 samples, 8.5 atm
Ar-CH₄ 80:20). The
ionization rate at the
Fermi plateau (at high
 β) is 1.4 times that for
the minimum at
lower β . This ratio
increases to 1.6 at
atmospheric pressure.

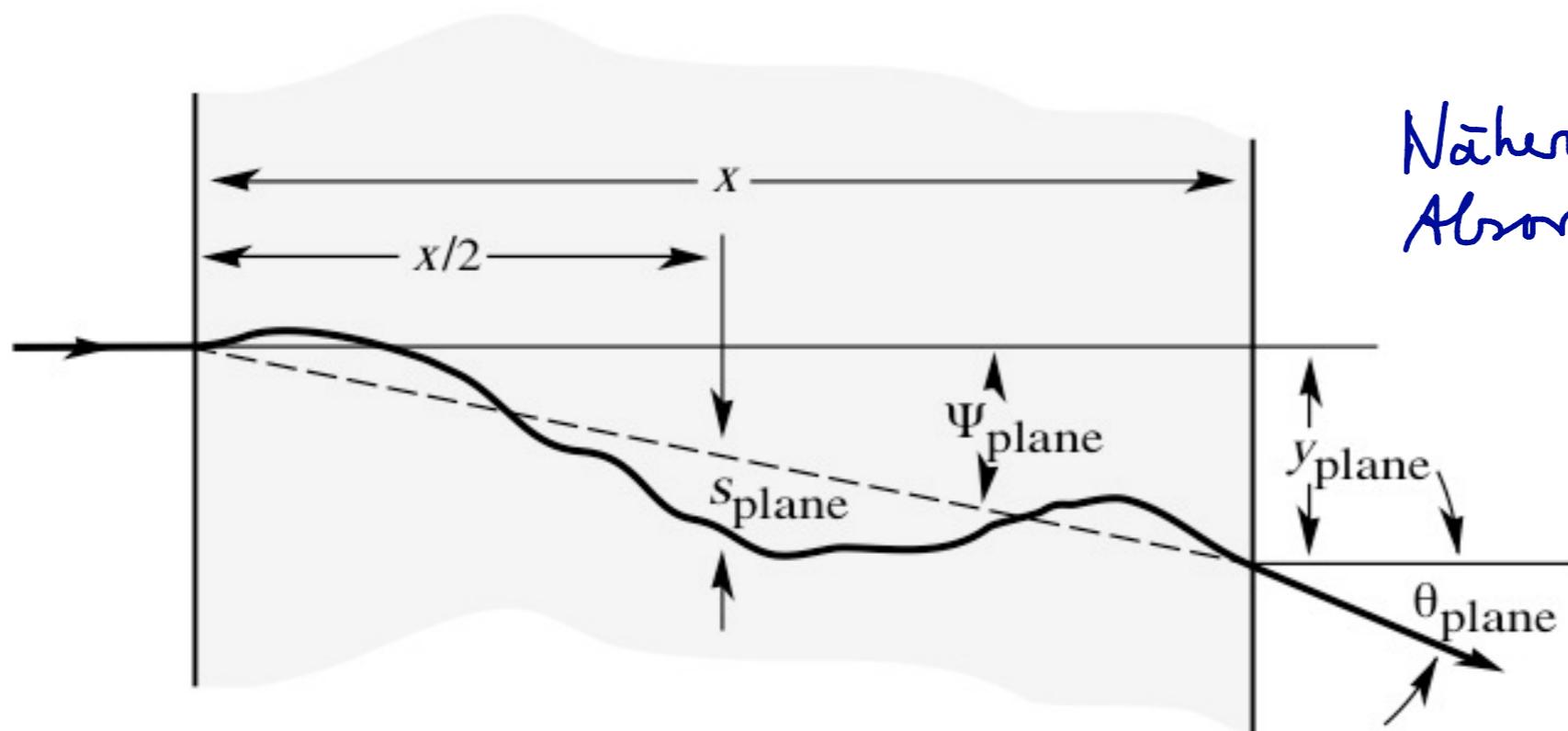
1988:
 $e^+ e^- \rightarrow X$
 $\sim 30 \text{ GeV}$

dE/dx weiter Energiebereich



Coulombstreuung

$\approx N$
 Streuung an e^- : viele kleine Winkel -
 änderungen
 Streuung an Kernen: wenige große Ablenk.



Näherungen für dicke Absorber ($N \gtrsim 20$)

The nonprojected (space) and projected (plane) angular distributions are given approximately by [33]

$$\frac{1}{2\pi\theta_0^2} \exp\left(-\frac{\theta_{\text{space}}^2}{2\theta_0^2}\right) d\Omega , \quad \left. \right\} \quad (27.15)$$

$$\frac{1}{\sqrt{2\pi}\theta_0} \exp\left(-\frac{\theta_{\text{plane}}^2}{2\theta_0^2}\right) d\theta_{\text{plane}} , \quad \left. \right\} \quad (27.16)$$

+ größere Ablenkungen

Fluktuationen, Landau-Verteilung

Bethe-Bloch $\rightarrow \langle \frac{dE}{dx} \rangle$!

\exists Einzelereignisse mit großen ΔT „S-Elektronen“

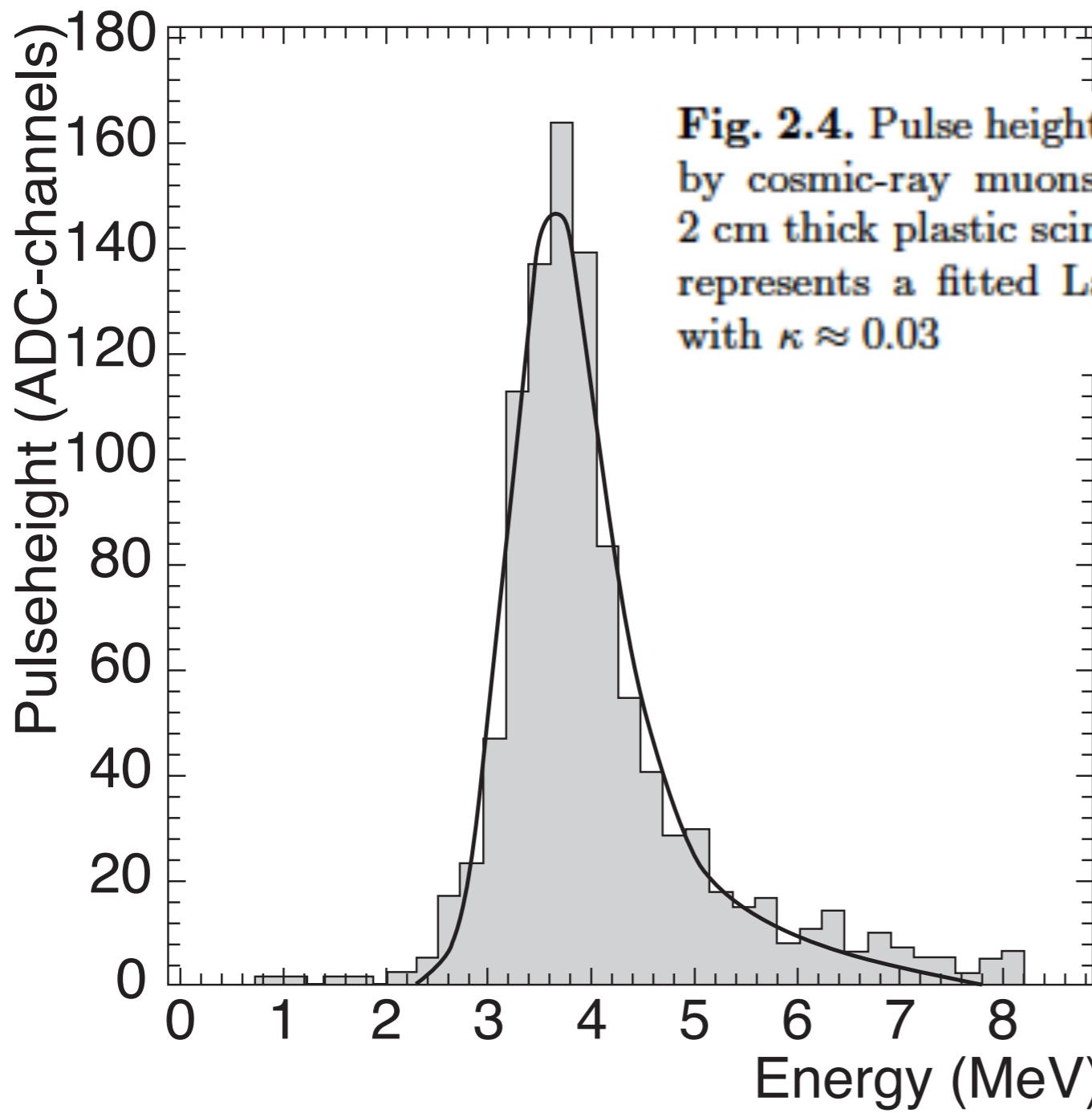
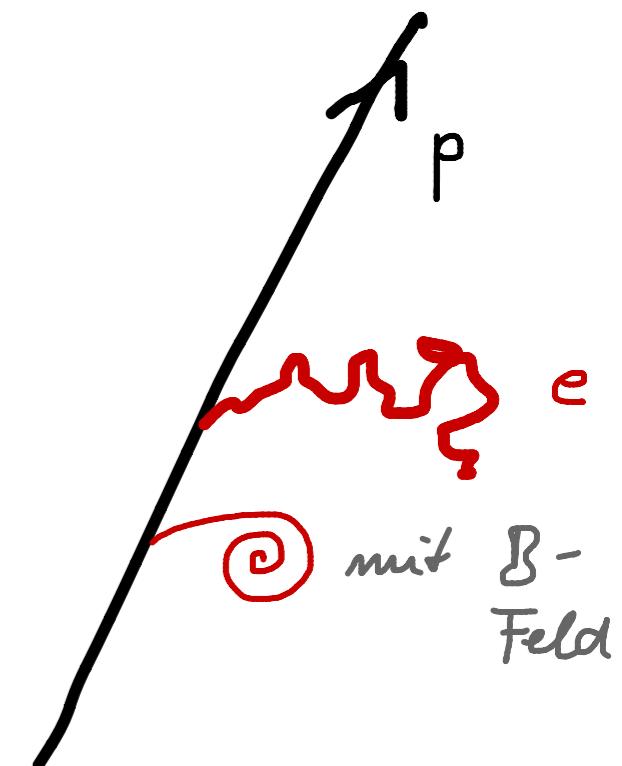


Fig. 2.4. Pulse height spectrum induced by cosmic-ray muons of ~ 1 GeV in a 2 cm thick plastic scintillator. The curve represents a fitted Landau distribution with $\kappa \approx 0.03$

Peakpos < Mittelwert
 $\Delta E_{\text{mp}} < \langle \Delta E \rangle$
dicke Absorber \rightarrow fällt Kurve



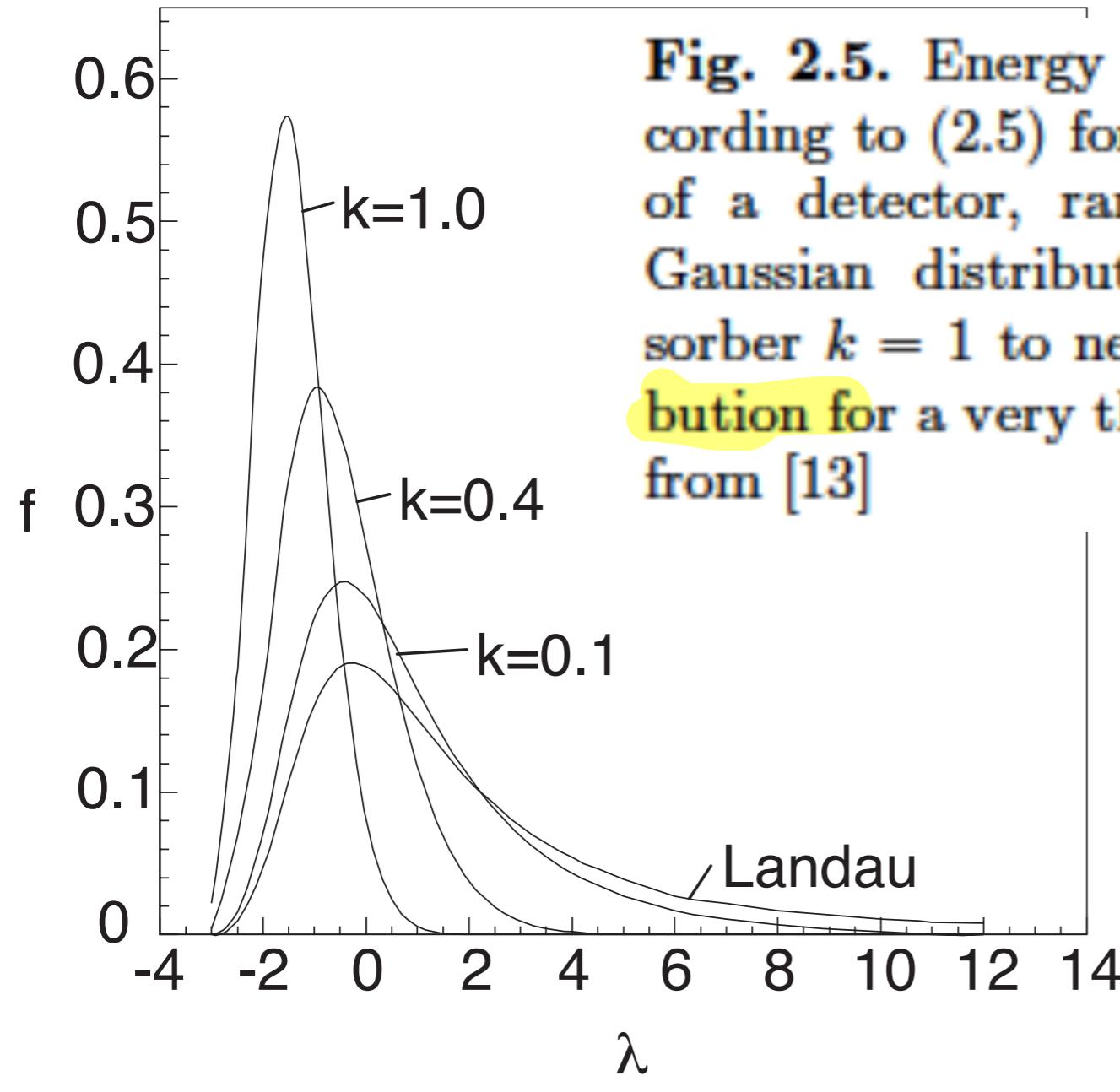


Fig. 2.5. Energy loss distributions according to (2.5) for different thicknesses of a detector, ranging from a nearly Gaussian distribution for a thick absorber $k = 1$ to nearly a Landau distribution for a very thin detector $k = 0.01$, from [13]

Landau - Variante

$$f(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$

$$\lambda = \frac{\Delta E - E_{mp}}{\xi},$$

$$\xi = kz^2 \frac{Z_M}{A_M} \frac{1}{\beta^2} \rho x, \quad \text{and}$$

$$E_{mp} = \xi \left(\ln \frac{\xi m_e c^2 \beta^2 \gamma^2}{I^2} - \beta^2 \right)$$

Reichweite
für α -Teilchen
in Gas gut
definiert

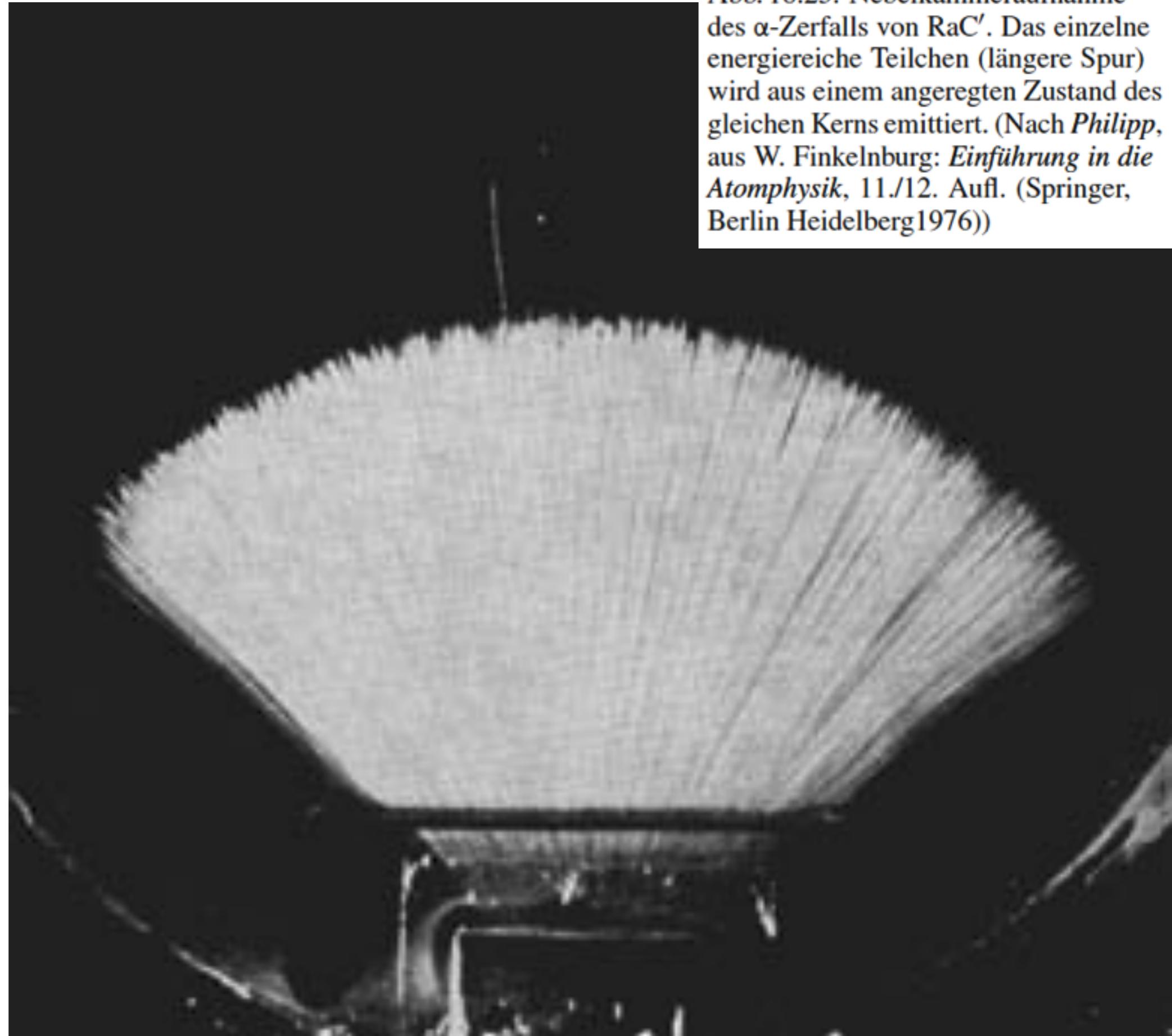
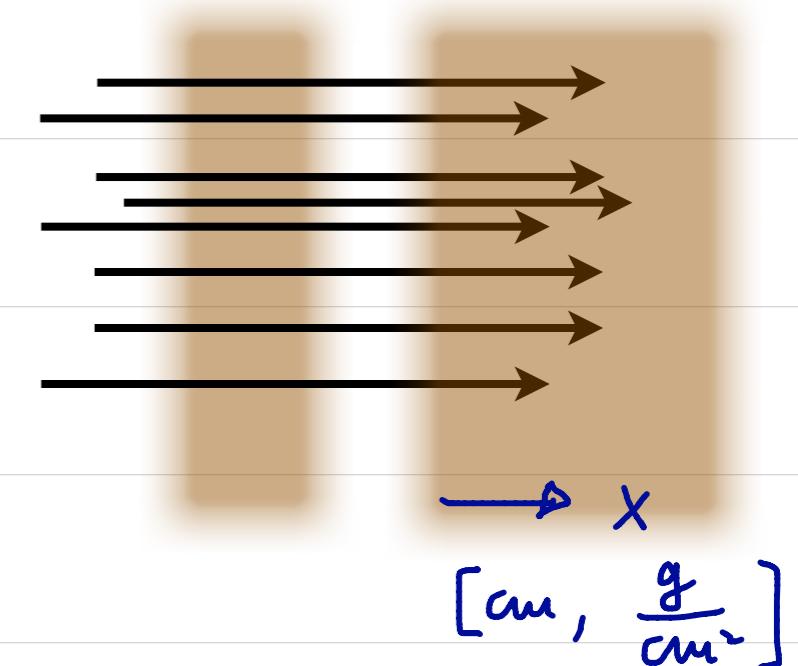
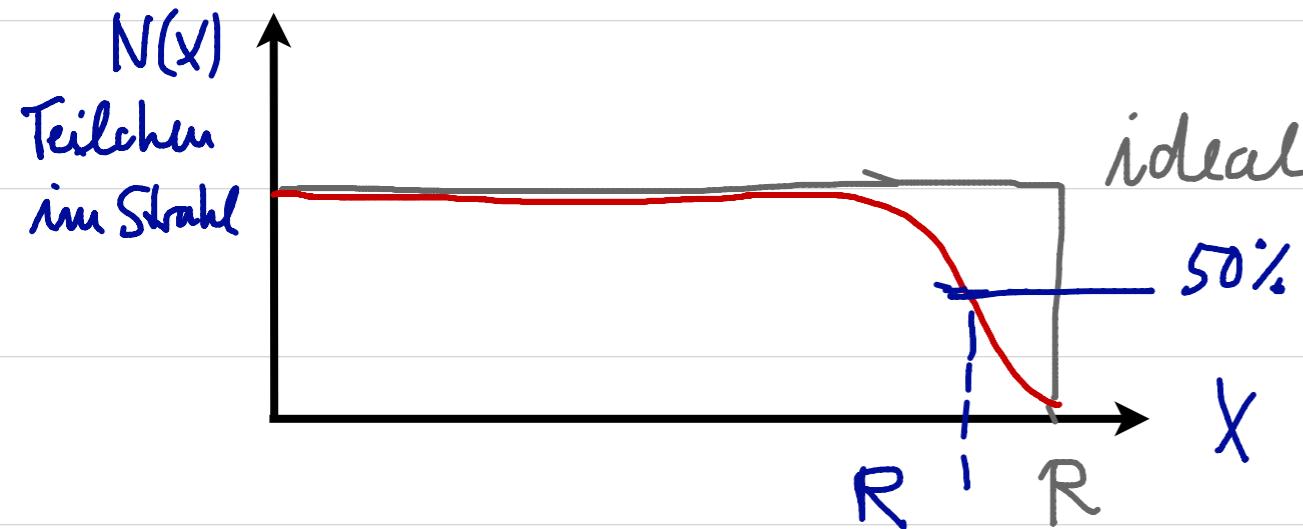
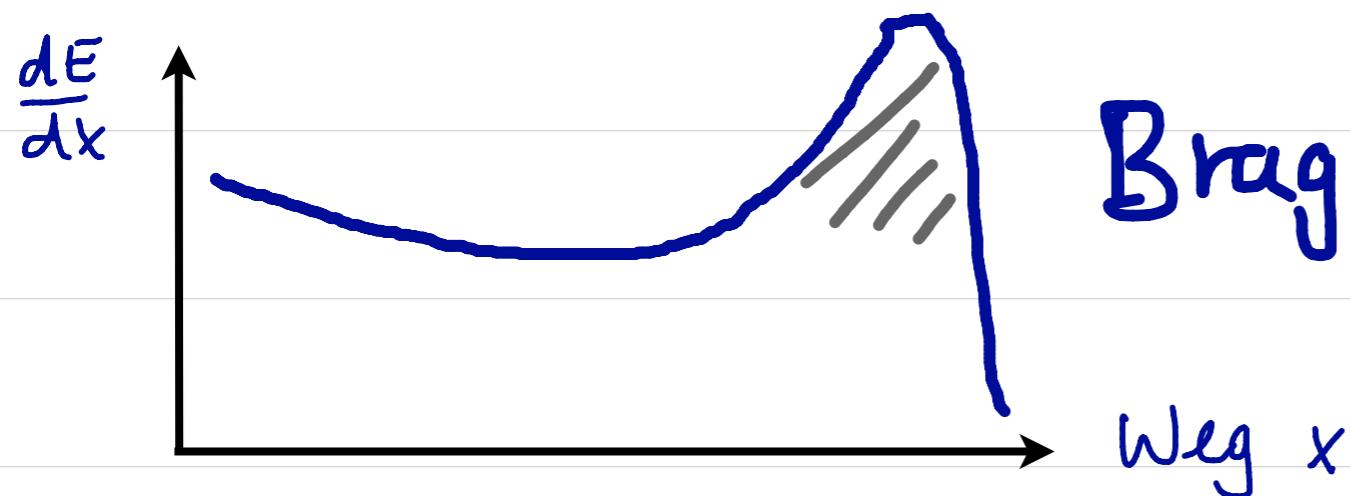
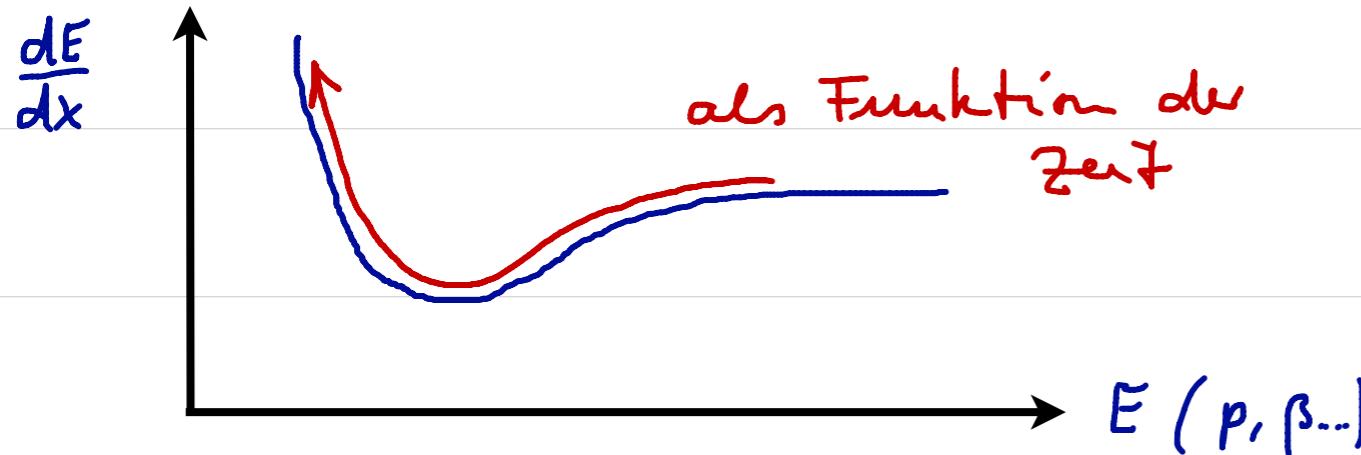


Abb. 18.23. Nebelkammeraufnahme des α -Zerfalls von RaC' . Das einzelne energiereiche Teilchen (längere Spur) wird aus einem angeregten Zustand des gleichen Kerns emittiert. (Nach Philipp, aus W. Finkelnburg: *Einführung in die Atomphysik*, 11./12. Aufl. (Springer, Berlin Heidelberg 1976))

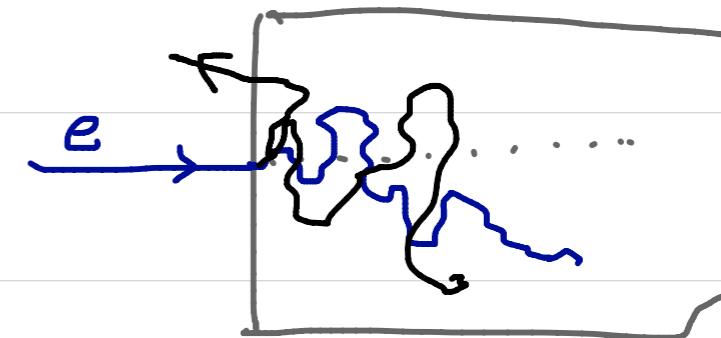
Teilchendurchgang durch Absorber



Reichweite:

$$R = \int_{E_0}^0 \frac{dE}{dE/dx(E)}$$

leichte Teilchen (e^\pm):
Reichweite beim guten
Konzept



Materialeigenschaften

Table 2.1. Energy loss for a minimum-ionising muon dE/dx , density and mean excitation energy $I = I_0 \times Z_M$ for various elements and compounds, for gases see Table 2.5

Element/ Compound	Z_M	Density [g/cm ³]	I [eV]	I_0 [eV]	dE/dx [MeV/gcm ⁻²]
Be	4	1.85	63.7	15.9	1.6
C(graphite)	6	1.8	78	13.0	1.75
Al	13	2.67	166	12.7	1.61
Si	14	2.33	173	12.4	1.66
Fe	26	7.87	286	11.0	1.45
Cu	29	8.96	322	11.1	1.40
Ge	32	5.32	350	11.0	1.37
Sn	50	7.31	488	9.8	1.26
W	74	19.3	727	9.8	1.14
Pb	82	11.3	823	10.0	1.12
Sodium iodide (NaI)	46.5	3.67	452	14.1	1.31
Photograph. Emulsion		3.8			1.31
Plastic Scintillator ¹	5.7	1.03	64.7	11.3	1.94
Lucite, Plexiglas ²		1.19	74		1.93
Polyethylene	5.3	0.94	68	13	2.08
Water	7.5	1.0	75	10	2.0

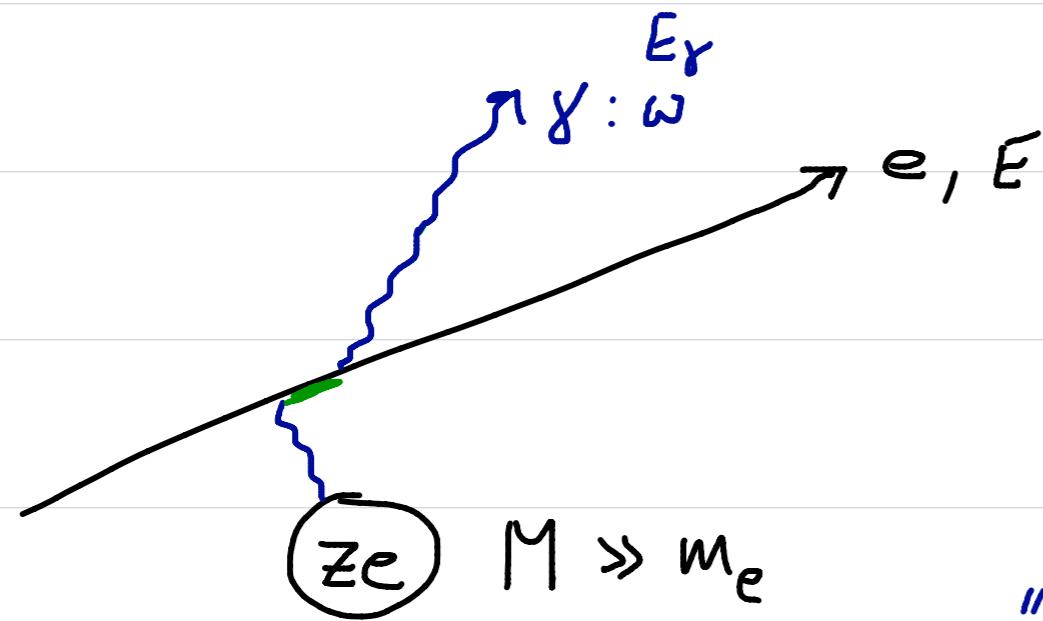
¹ polyvinyltoluene; ² polymethylmethacrylate

Materialeigenschaften

Table 2.2. Radiation lengths X_0 , critical energies ϵ_c , Molière radii ρ_M , threshold energies E_{LPM} and nuclear interaction lengths λ_i for 100 GeV protons in elements and compounds. The densities for gases are given in [g/l] at STP

Material	Z_M	A_M	ρ [g/cm ³]	X_0 [g/cm ²]	X_0 [cm]	ϵ_c [MeV]	ρ_M [cm]	E_{LPM} [TeV]	λ_i [g/cm ²]
H ₂	1	1,01	[0.0899]	62	731000	350	42000	6600	50.8
He	2	4	[0.1786]	94	530000	250	45000	5800	65.1
Air	7.3	14.4	[1.29]	37	30420	86	7400	234000	90.0
C	6	12.01	2.265	43	18.8	82	4.8	151	86.3
H ₂ O	7.5	14.2	1.0	36	36	70	9.2	278	83.6
SiO ₂	11.2	21.7	2.2	27	12	50	4.9	77	97.4
Al	13	27	2.70	24	8.9	40	4.4	68	70.6
Fe	26	55.85	7.87	14	1.76	21	1.7	13.6	82.8
Cu	29	63.55	8.96	13	1.43	19	1.6	11.2	85.6
W	74	183.9	19.3	6.8	0.35	8	0.9	2.7	110.3
Pb	82	207.2	11.35	6.4	0.56	7.4	1.6	4.3	116.2

Bremsstrahlung



Bethe - Heitler 1934

$$N(\omega) d\omega \propto Z^2 \frac{d\omega}{\omega} \quad \uparrow \text{höhe } \gamma\text{-Eru.}$$

$$\text{"WQ"}, \left. \frac{dE}{dx} \right|_{\text{rad}} \propto \frac{E}{m^2} \rightarrow E(x) = E_0 e^{-\frac{x}{X_0}}$$

X_0 Strahlungslänge

Strahlungslänge:

$$X_0 = \frac{716.4 \times A_M}{Z_M(Z_M + 1) \ln(287/\sqrt{Z_M})} \text{ g/cm}^2$$

Material	Z	x_0 [mm]	E_k [MeV]
H ₂ O	1, 8	361	92
Be	4	353	116
C	6	188	84
Al	13	89	43
Fe	26	17.6	22
Cu	29	14.3	20
W	74	3.5	8.1
Pb	82	5.6	7.3
U	92	3.2	6.5

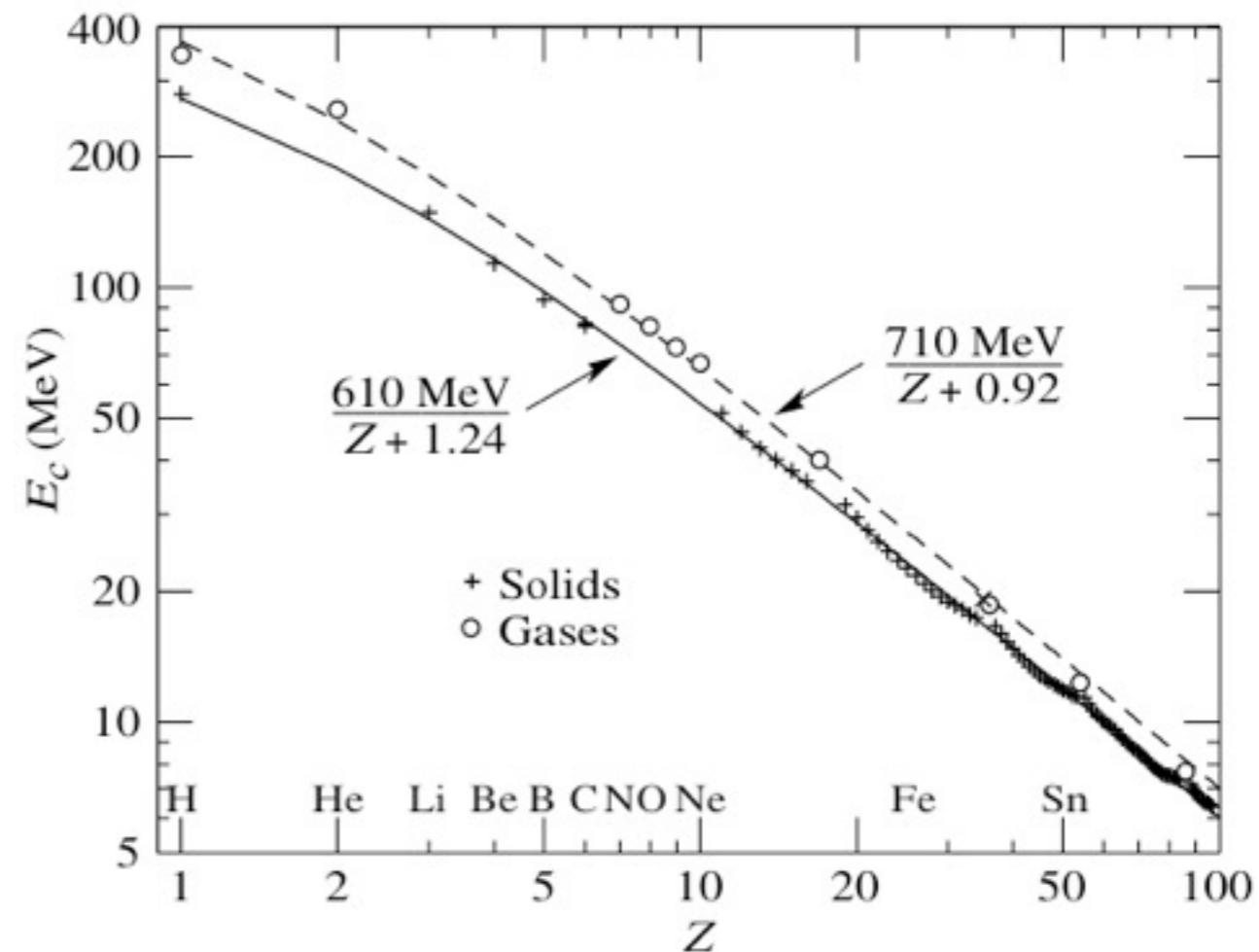
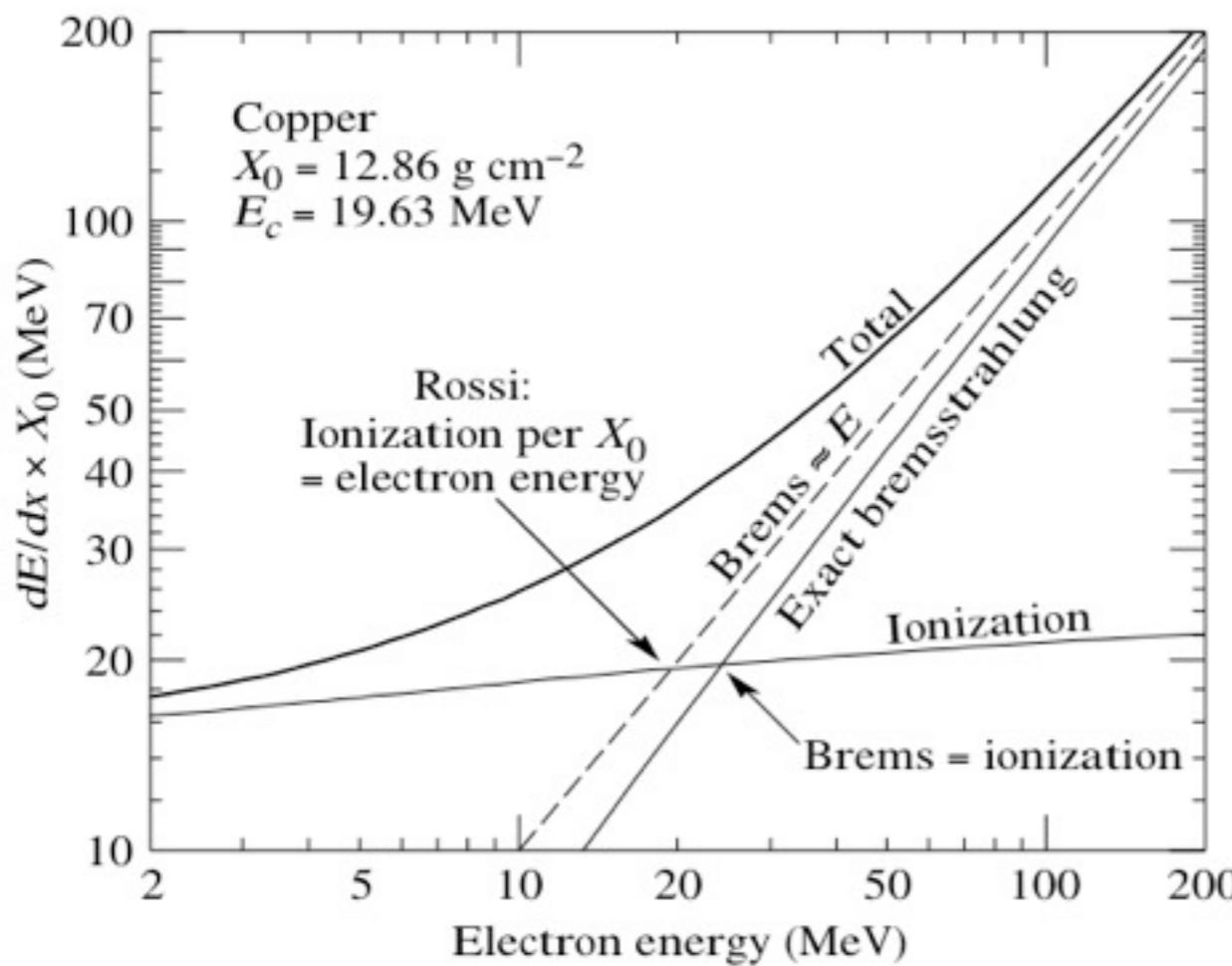
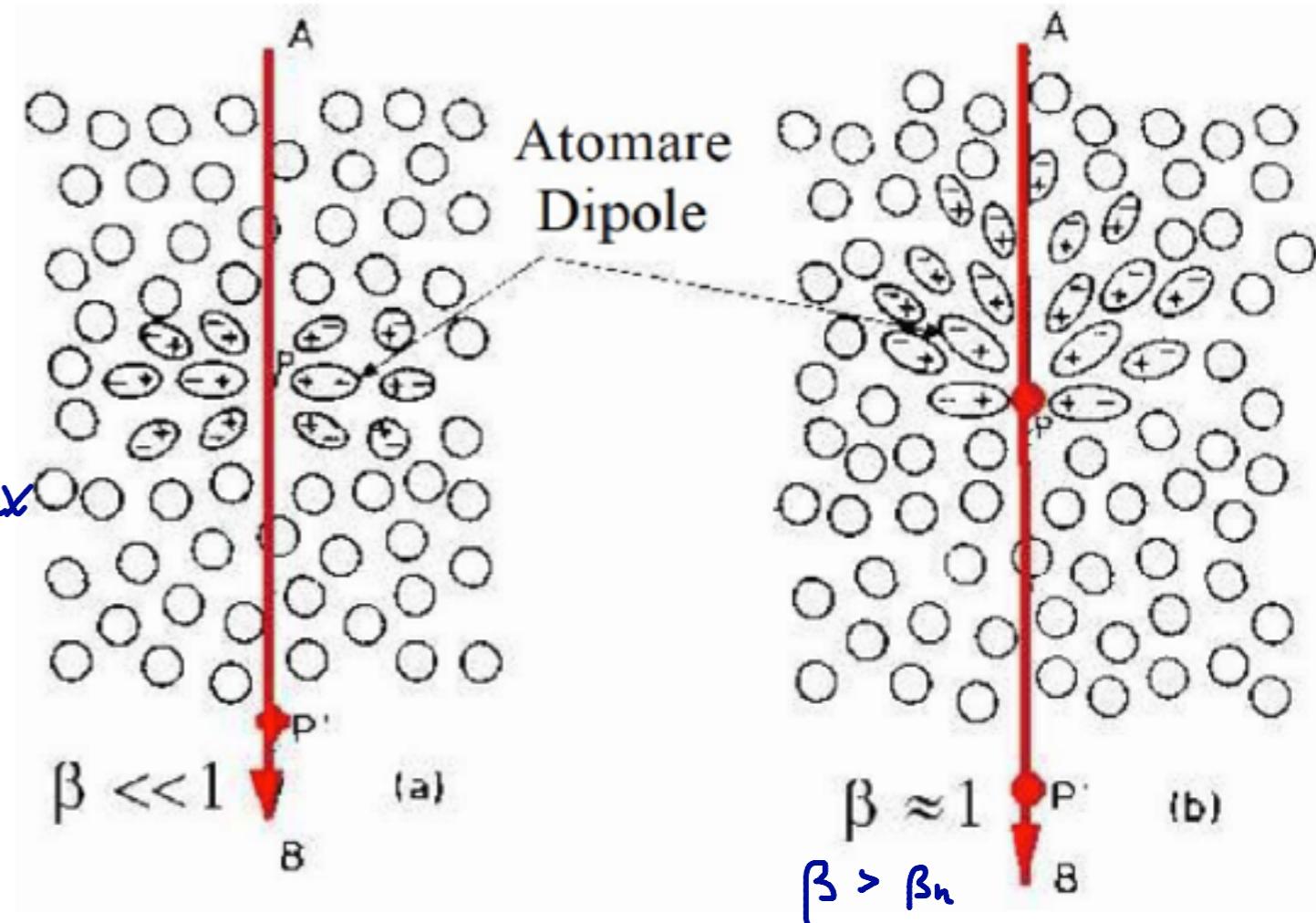
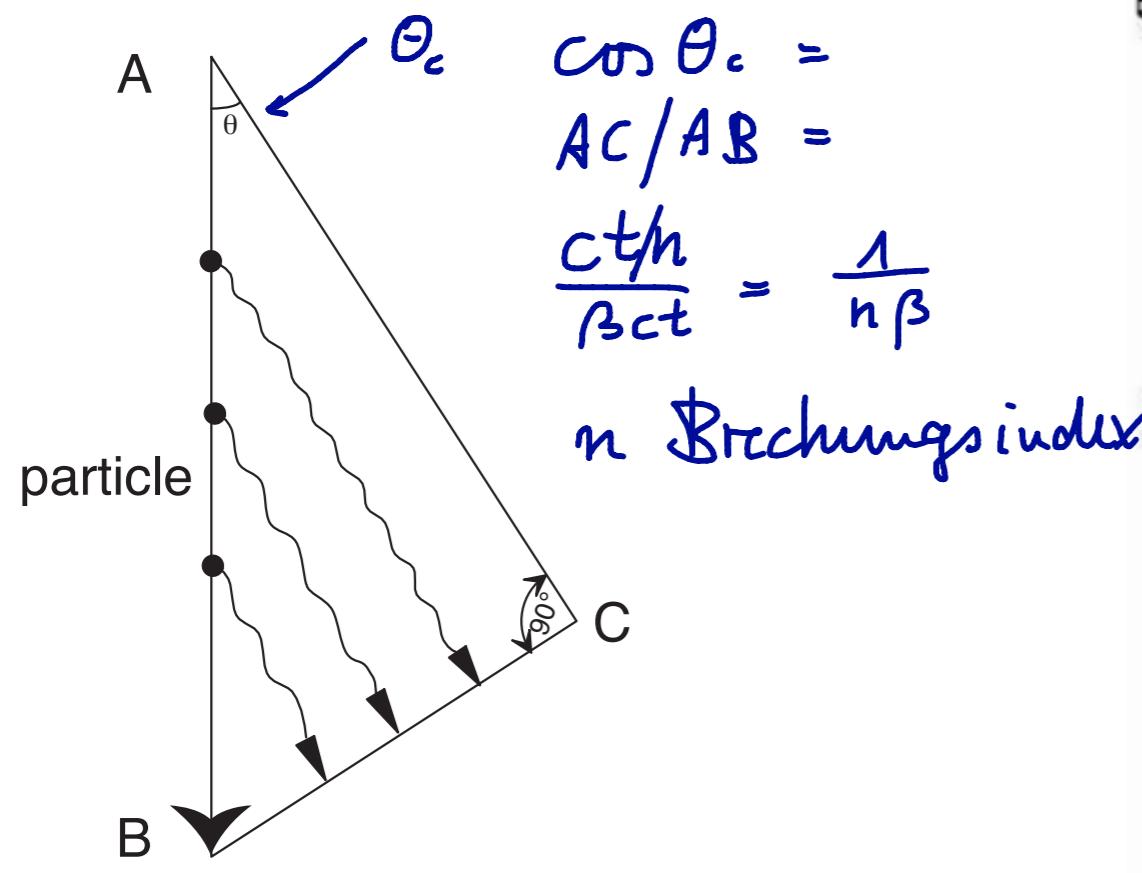


Figure 27.13: Electron critical energy for the chemical elements, using Rossi's definition [2]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases. (Computed with code supplied by A. Fassó.)

$E_{k,c}$ kritische Energie, oberhalb
 dieser $\frac{dE}{dx}|_{\text{rad}} > \frac{dE}{dx}|_{\text{ion}}$

Cherenkov-Effekt



Anzahl Cherenkov-γ's:

$$\frac{d^2N}{dx dE} = \frac{\alpha^2 z^2}{r_e \cdot m_e c^2} \times \sin^2 \Theta_c = 370 \times z^2 \sin^2 \Theta_c(E)/\text{eVcm}$$

$$\frac{d^2N}{dx d\lambda} = 2\pi \alpha z^2 \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \sin^2 \Theta_c$$

In 400 ... 700 nm →

$$\frac{dN}{dx} = 480 z^2 \sin^2 \Theta_c/\text{cm.} \rightarrow$$

220 für 1 m Wasser
30 für 1 m Luft

γ -Astronomie (später)

