

Fortgeschrittene Experimentalphysik für Lehramtsstudierende Teil II: Kern- und Teilchenphysik



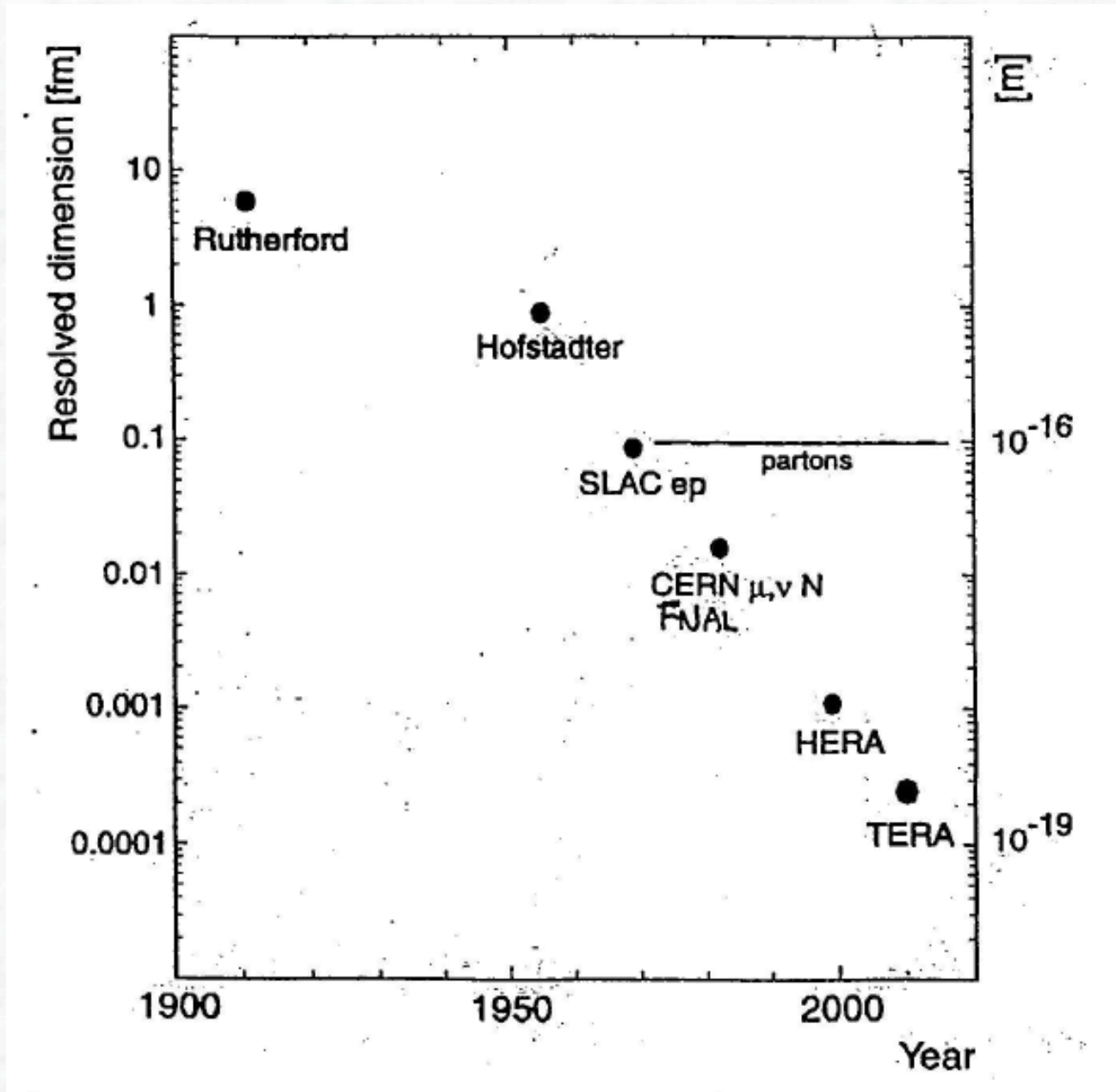
Prof. Markus Schumacher
Sommersemester 2013

Kapitel 2: Vom Atom zum Quark

Historische Meilensteine der Anfänge der Kernphysik

1896	Entdeckung der Radioaktivität durch Henri Becquerel (bei Luminoszenzuntersuchungen an Uransalzen, Schwärzung von lichtabgeschirmten Photoplaten (α , β -Strahlung))
1898	Entdeckung der Elemente Polonium und Radium (1902) durch Maria Sklodowska/Curie und Pierre Curie
1900	Entdeckung eines magnetisch nicht ablenkbaren Anteils radioaktiver Strahlung (γ -Strahlung) durch P.U. Villard
1902	Identifizierung der β -Strahlen als Elektronen durch H. Bequerel
1909	Identifizierung der α -Strahlen als ionisierte Helium-Atome durch E. Rutherford und Royds (Ablenkung im Magnetfeld \neq Elektronen, optische Spektren nach e^- -Einfang = He-Spektrum)
1911	Rutherford-Experiment: Untersuchung der Ablenkung von α -Strahlung an einer Goldfolie (Mitarbeiter: Geiger, Marsden) → Entdeckung des Atomkerns
1919	Erste künstliche Kernumwandlungen durch E. Rutherford: $\alpha + {}^{14}\text{N} \rightarrow {}^{17}\text{O} + \text{p}$ bei der Streuung von α -Teilchen an leichten Kernen (\neq elastische Streuung), Identifizierung des Protons (pos. geladenes Teilchen, rel. große Reichweite)
1932	Entdeckung des Neutrons durch J. Chadwick

Zeitliche Entwicklung des exp. Auflösungsvermögens



Zshg. Energie/Impuls und exp. Auflösungsvermögens

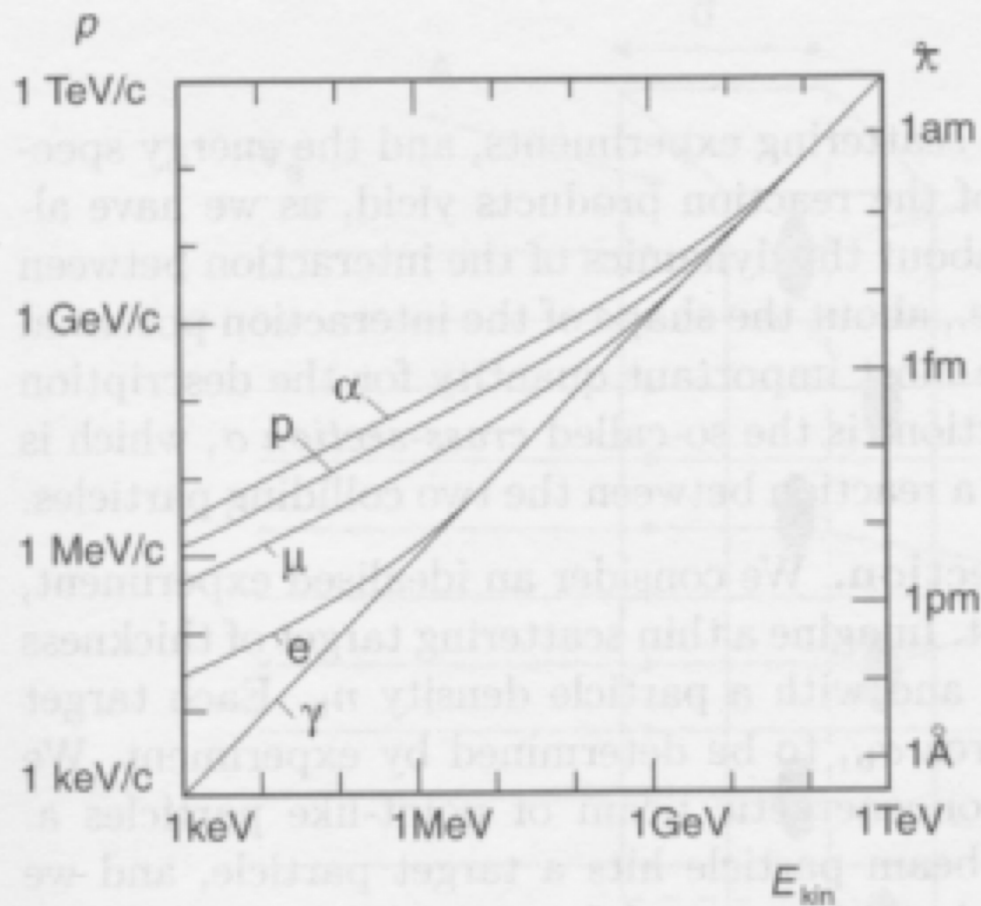
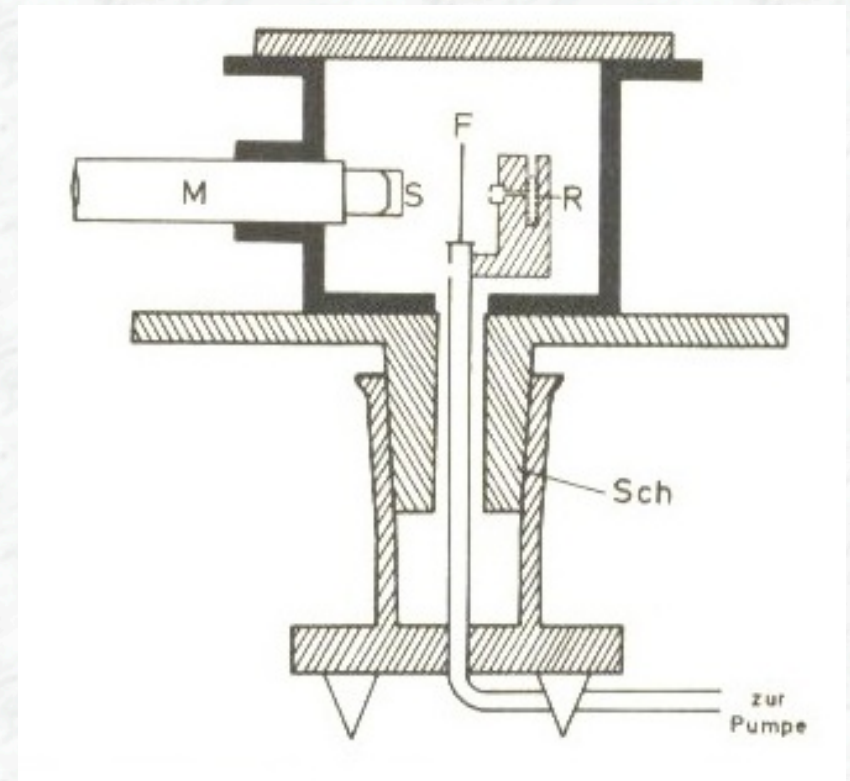
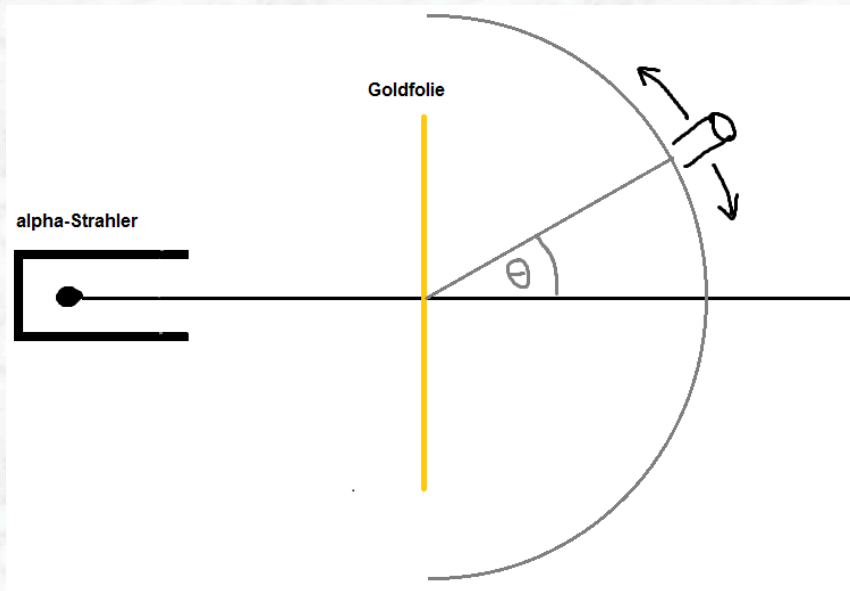


Fig. 4.2. The connection between kinetic energy, momentum and reduced wavelength of photons (γ), electrons (e), muons (μ), protons (p), and ^4He nuclei (α). Atomic diameters are typically a few Å (10^{-10} m), nuclear diameters a few fm (10^{-15} m).

Messprinzip und Apparatur von Rutherford et al.



Winkelabhängigkeit im Rutherfordexperiment

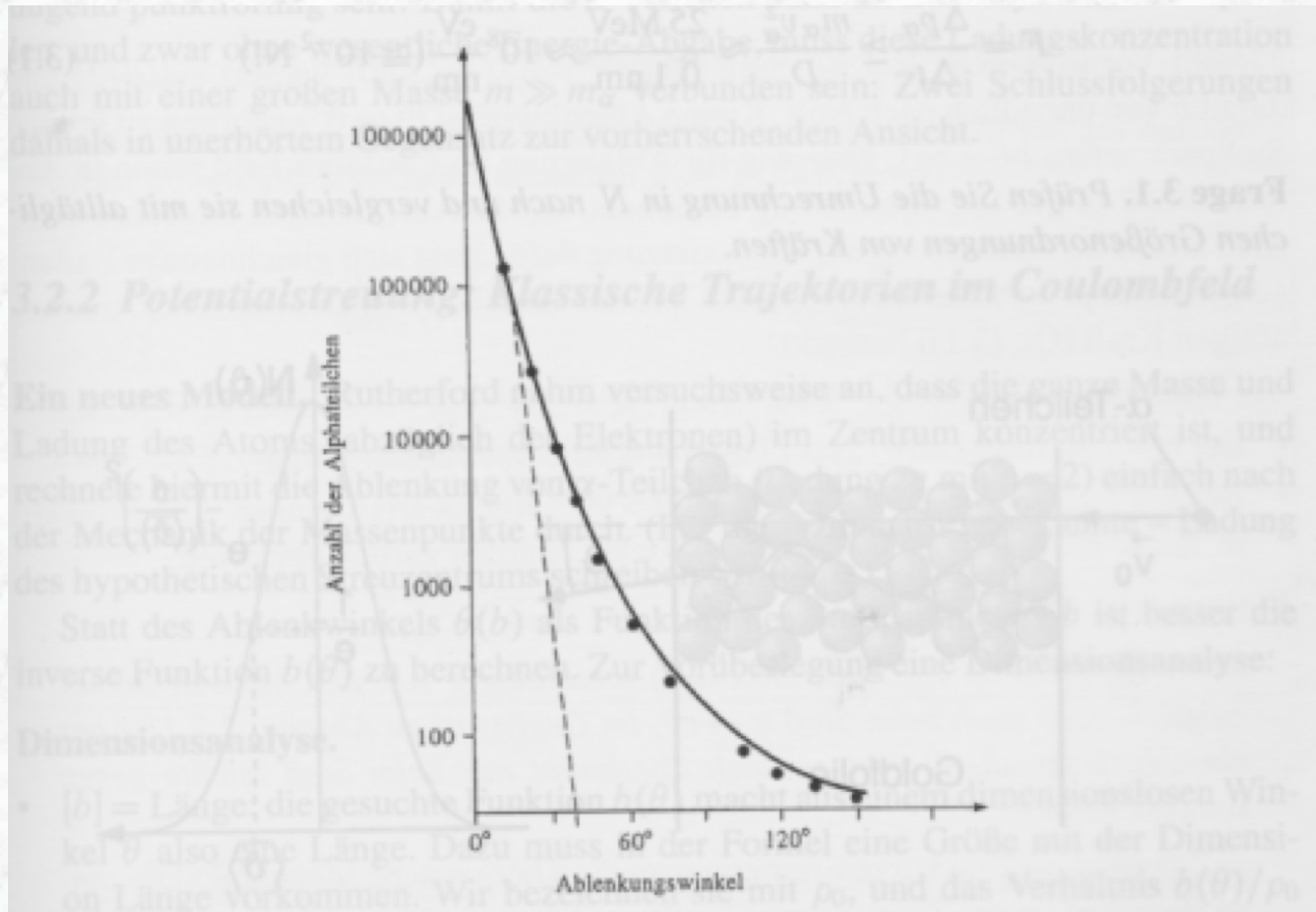
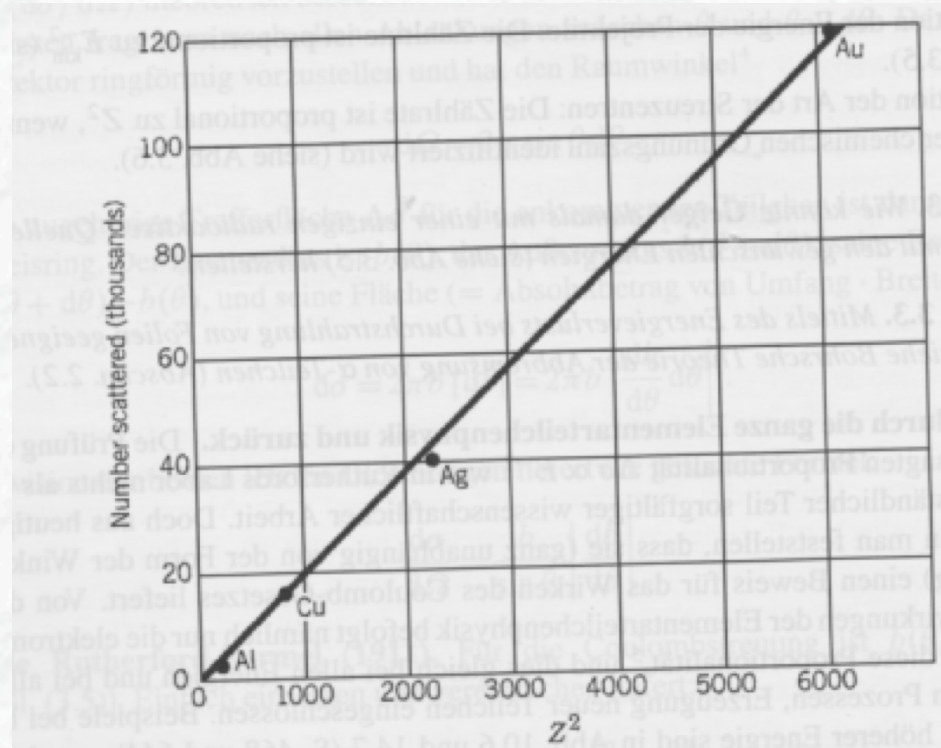
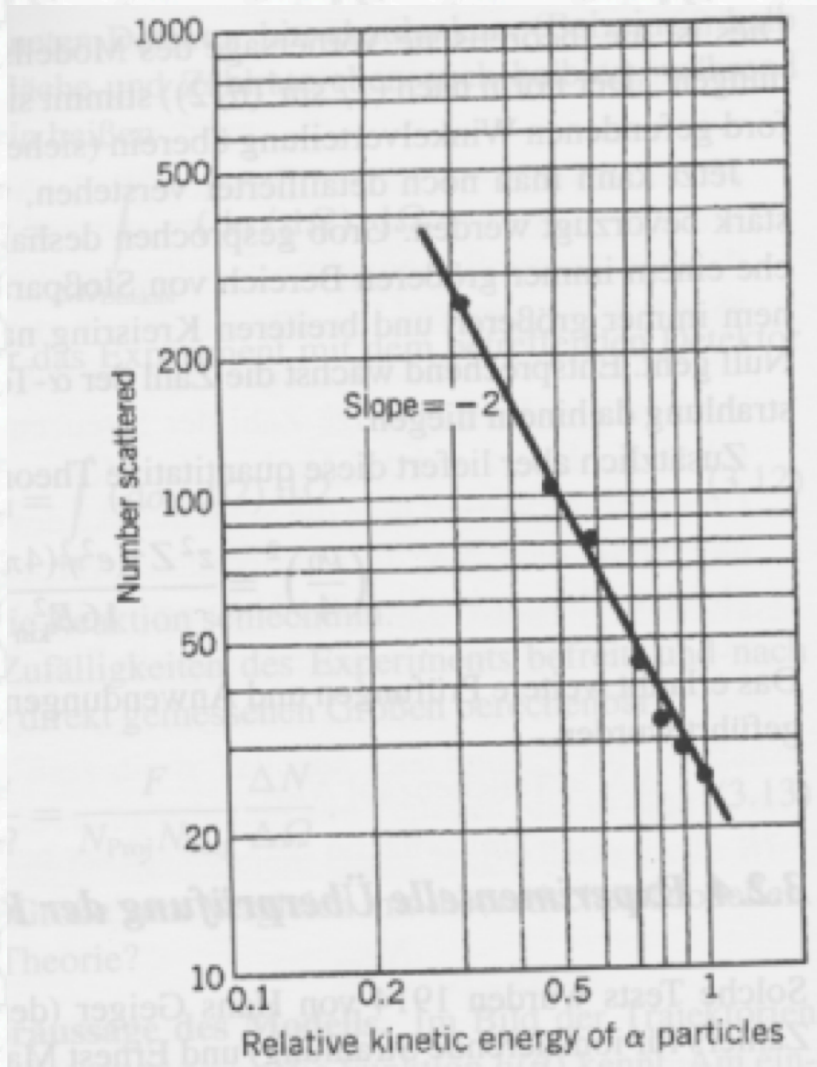
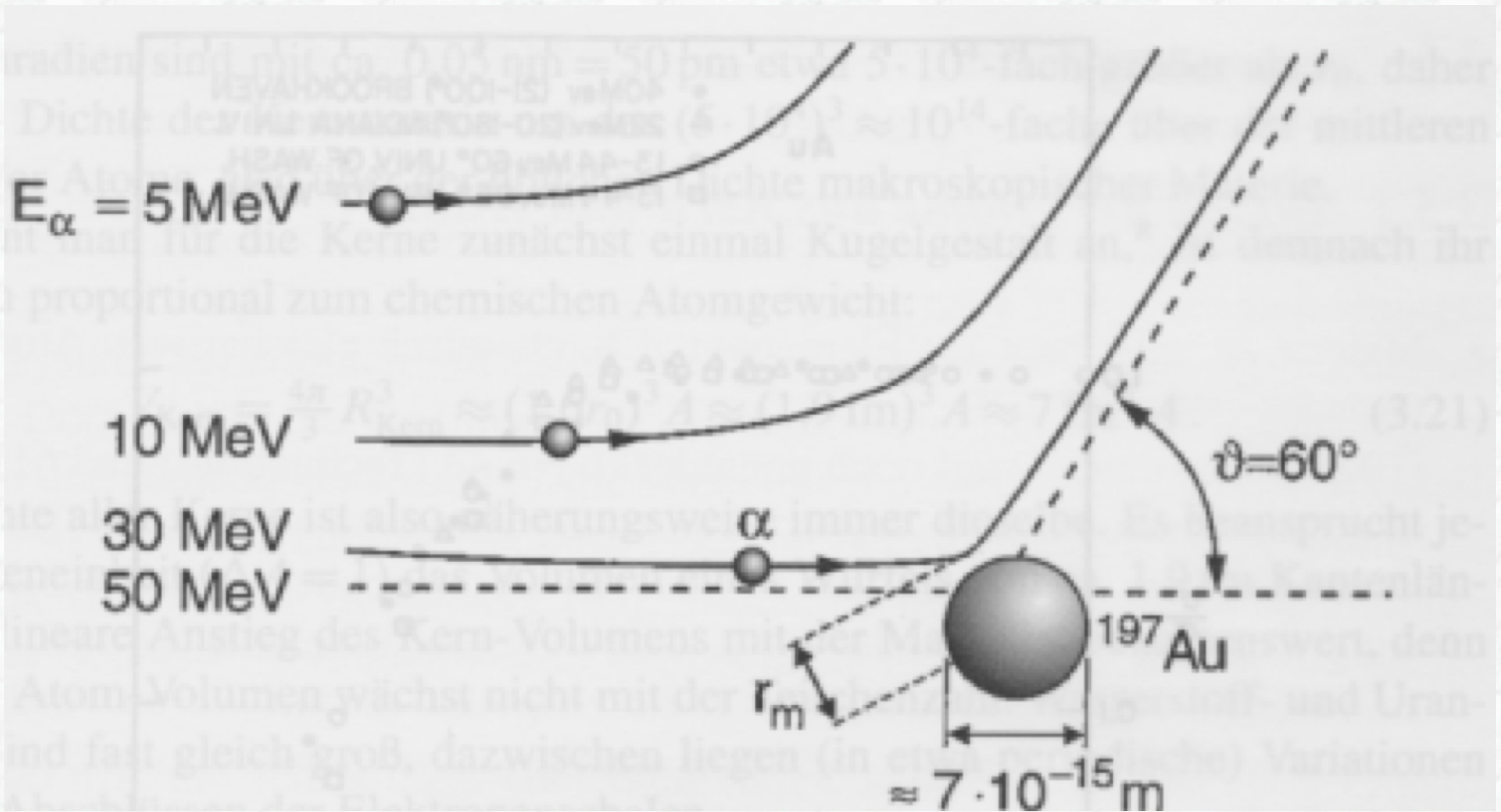


Abb. 3.3 Die originalen Messergebnisse von Rutherford für die Streuung von α -Teilchen an Goldatomen (Punkte), und zwei theoretische Winkelverteilungen: Thomson (gestrichelt), Rutherford (durchgezogen). (Abb. aus [57])

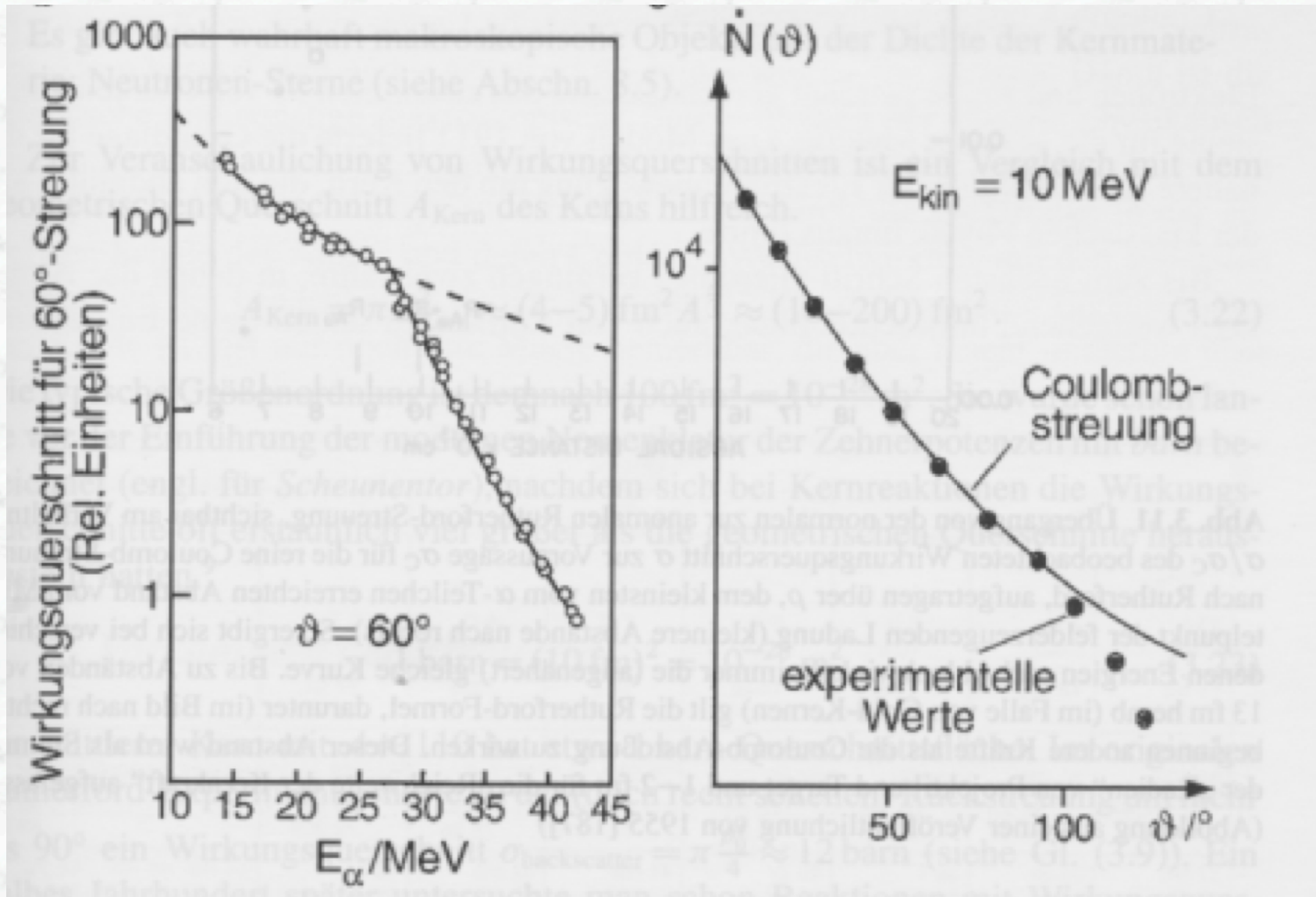
Test der E- und Z-Abhängigkeit



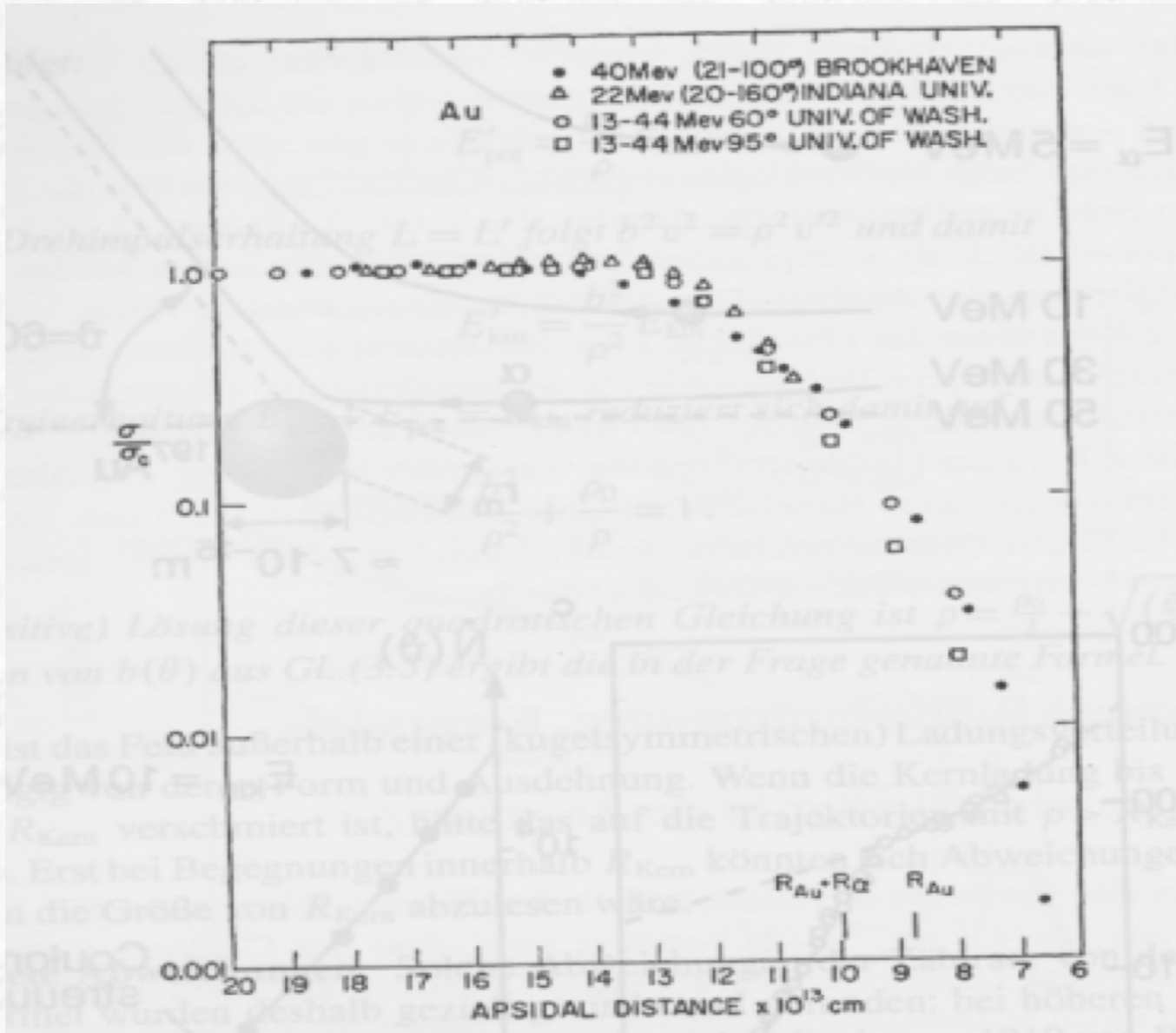
Zshg: Stoßparameter, Energie und Streuwinkel



Anomale Rutherfordstreuung



Erste Abschätzung des Kernradius



Von Rutherford zur Elektron-Proton-Streuung

$$\left(\frac{d\sigma}{d\Omega}\right) = \underbrace{\left(\frac{Z^2\alpha^2}{4E^2} \frac{1}{\sin^4\frac{\theta}{2}}\right)}_{\text{Coulomb potential}} \times \cos^2\frac{\theta}{2} \times \underbrace{\left(\frac{1}{1 + \frac{E}{M}(1 - \cos\theta)}\right)}_{\substack{=E/E' \\ \text{target recoil}}} \times \left[1 - \frac{q^2}{2M^2} \tan^2\frac{\theta}{2}\right]$$

Coulomb potential
 $M_p = \infty$, no spin at all involved
 \Rightarrow Rutherford formula
 \Rightarrow mostly in forward direction

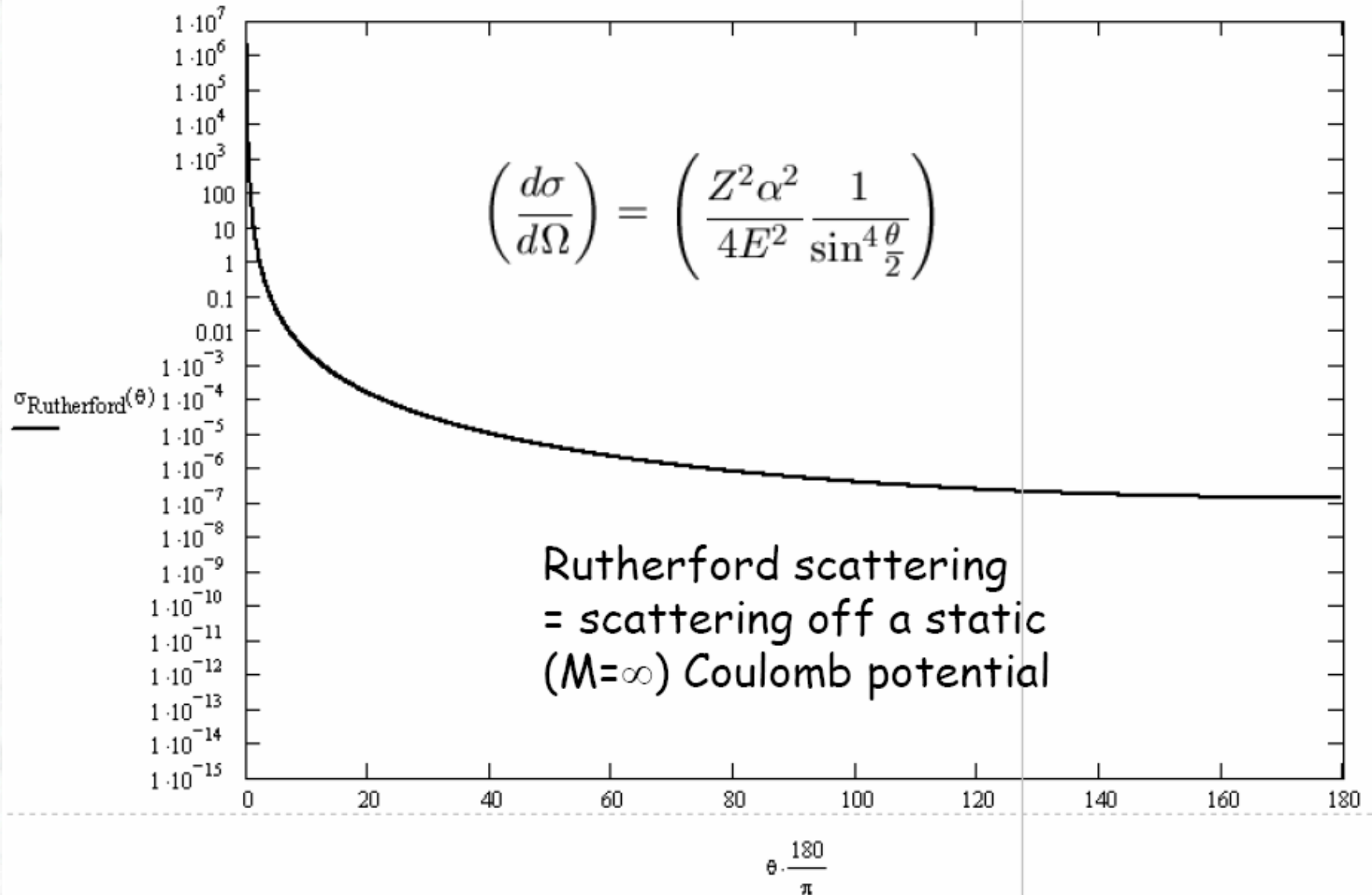
$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$ electron has spin $\frac{1}{2}$!

180° scattering is impossible

$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott-Recoil}}$ proton has a mass $M_p < \infty$!

$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Dirac - Proton}}$ proton also has spin $\frac{1}{2} \Rightarrow 180^\circ$ scattering is possible again
 i.e. has a mass M_p , but not yet a structure

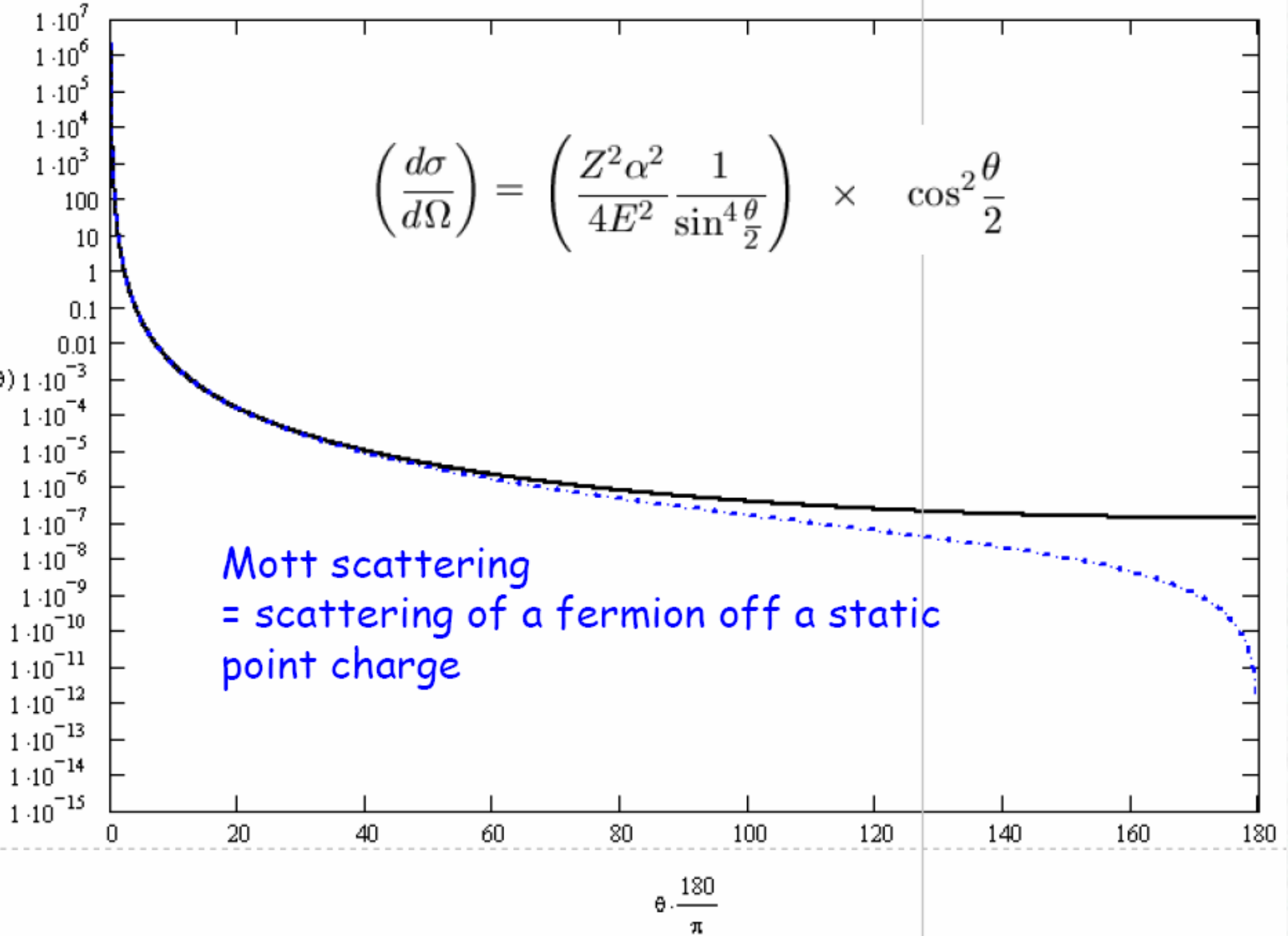
Rutherford-Streuung: Spin=0 an schwerem Spin=0



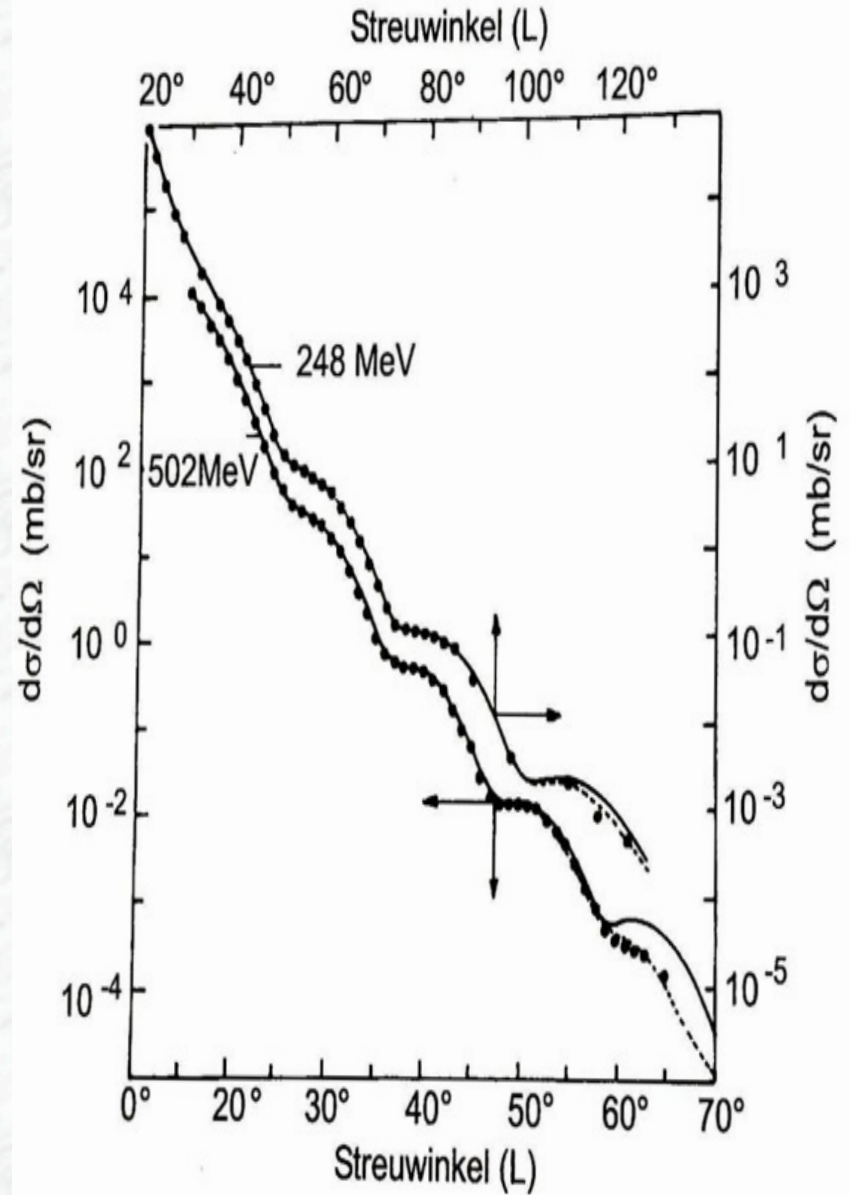
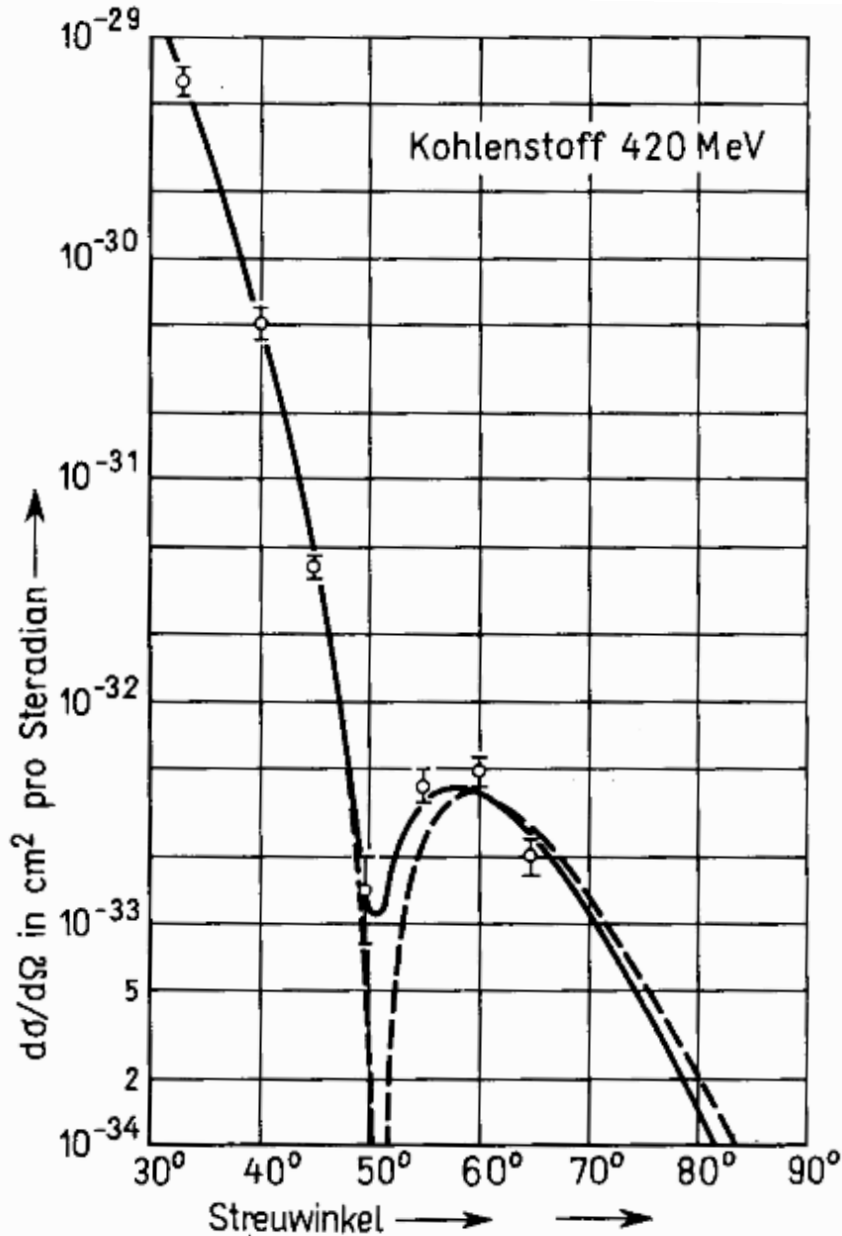
Mott-Streuung: Spin=1/2 an schwerem Spin=0

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{Z^2\alpha^2}{4E^2} \frac{1}{\sin^4\frac{\theta}{2}}\right) \times \cos^2\frac{\theta}{2}$$

$\sigma_{\text{Rutherford}}(\theta)$
—
 $\sigma_{\text{Mott}}(\theta)$
- - -



Elektron-Streuung an Kernen

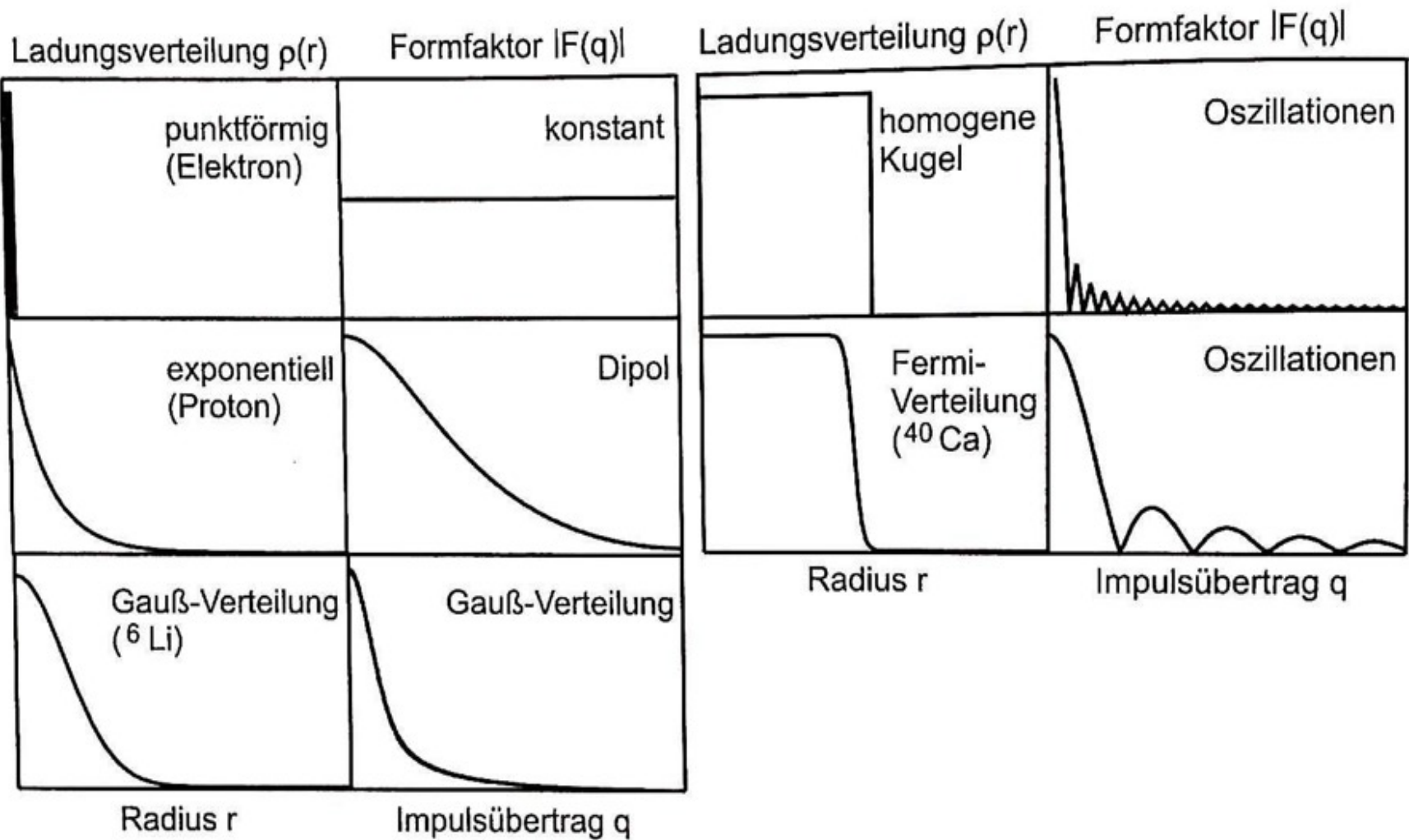


Formfaktoren und Ladungsverteilung

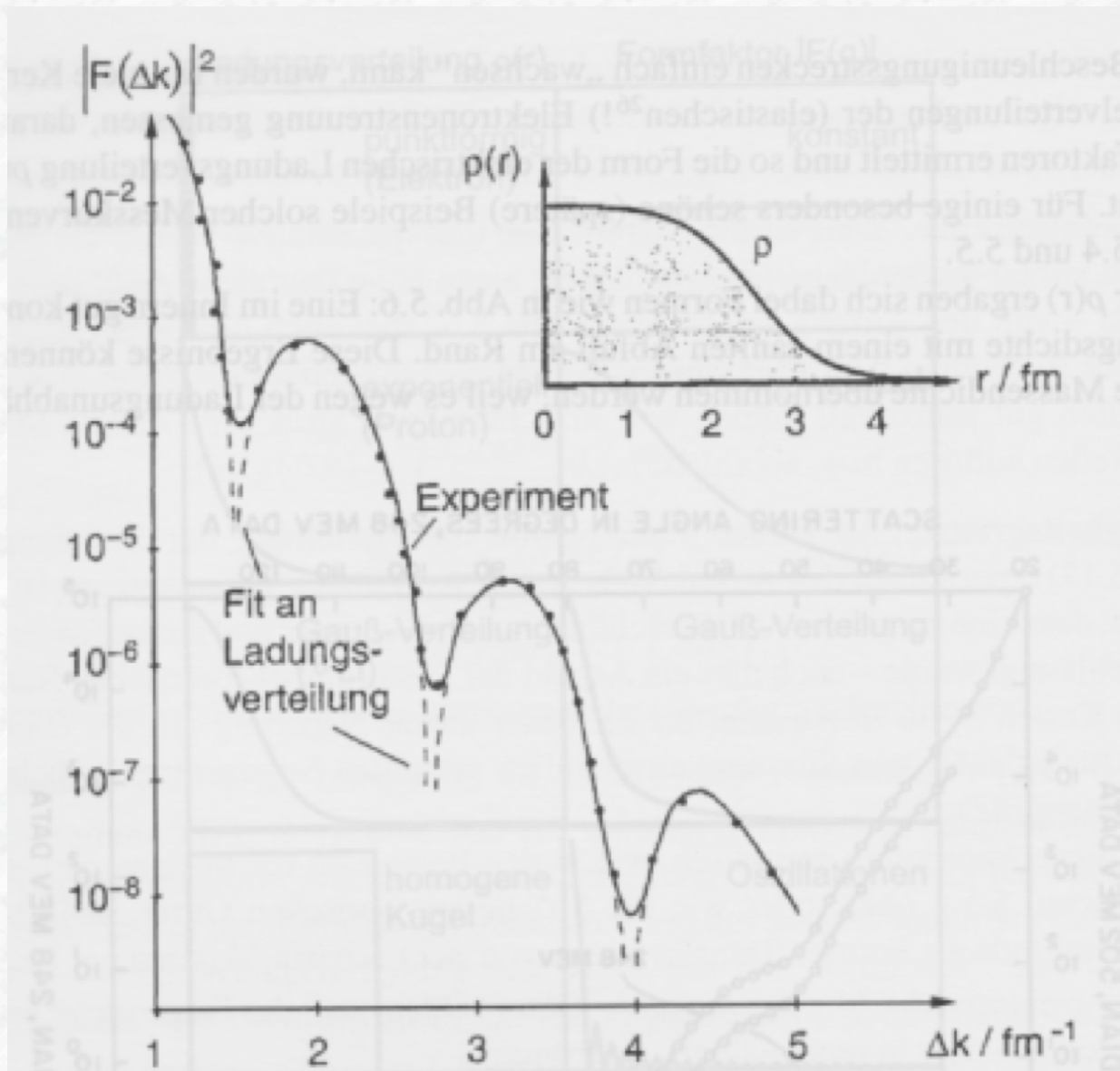
Tabelle 2.1. Zusammenhang zwischen Ladungsverteilung und Formfaktor für einige kugelsymmetrische Ladungsverteilungen

Ladungsverteilung $f(r)$	Formfaktor $F(\mathbf{q})$	
Punkt	$\frac{1}{4\pi} \delta(r)$	1 konstant
exponentiell	$\left(\frac{a^3}{8\pi}\right) e^{-ar}$	$\left(\frac{1+\mathbf{q}^2}{a^2\hbar^2}\right)^{-2}$ Dipol
Gauß	$\left(\frac{a^2}{2\pi}\right)^{3/2} e^{-a^2 r^2/2}$	$\exp\left(-\frac{\mathbf{q}^2}{2a^2\hbar^2}\right)$ Gauß
homogene Kugel	$\begin{cases} C \text{ für } r \leq R \\ 0 \text{ für } r > R \end{cases}$	$3\alpha^{-3}(\sin \alpha - \alpha \cos \alpha)$ mit $\alpha = \mathbf{q} R/\hbar$ oszillierend

Formfaktoren und Ladungsverteilung

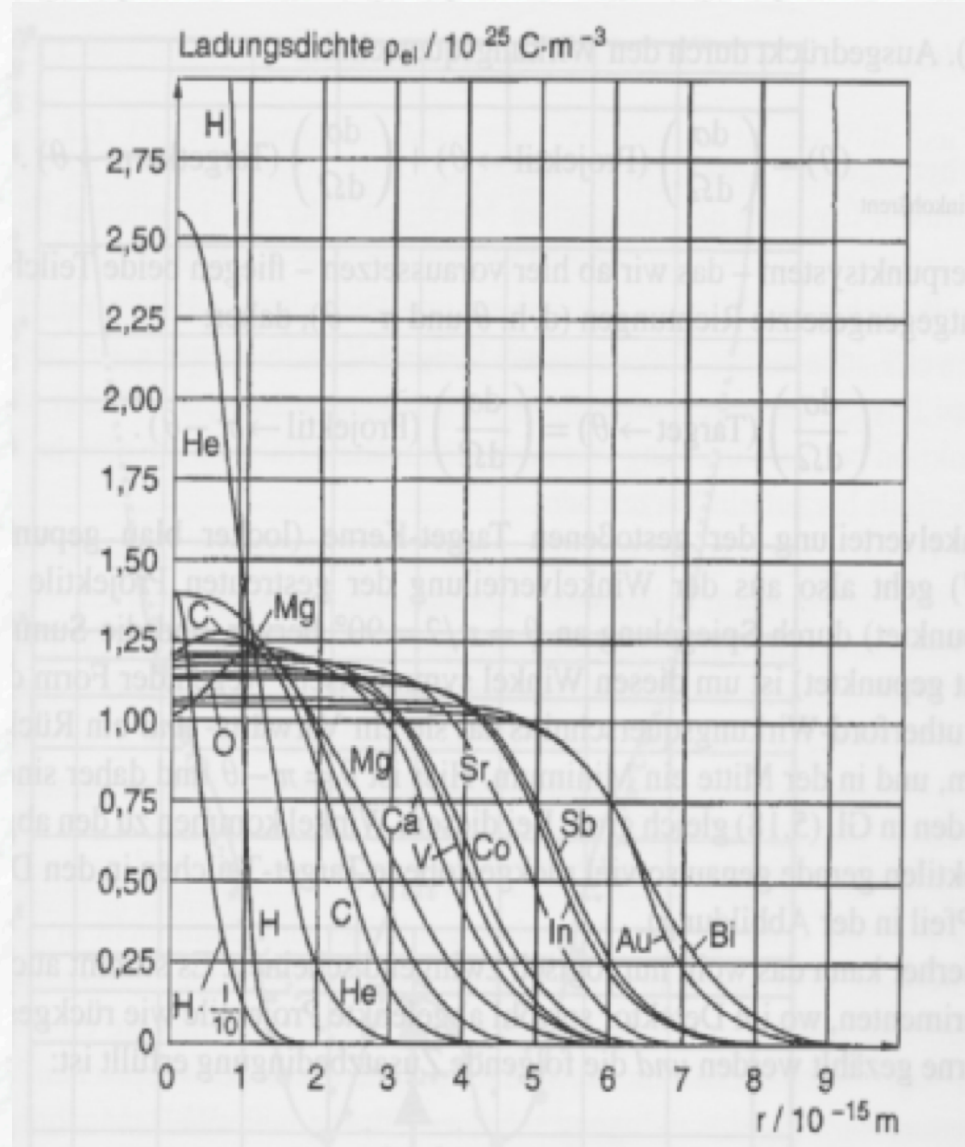
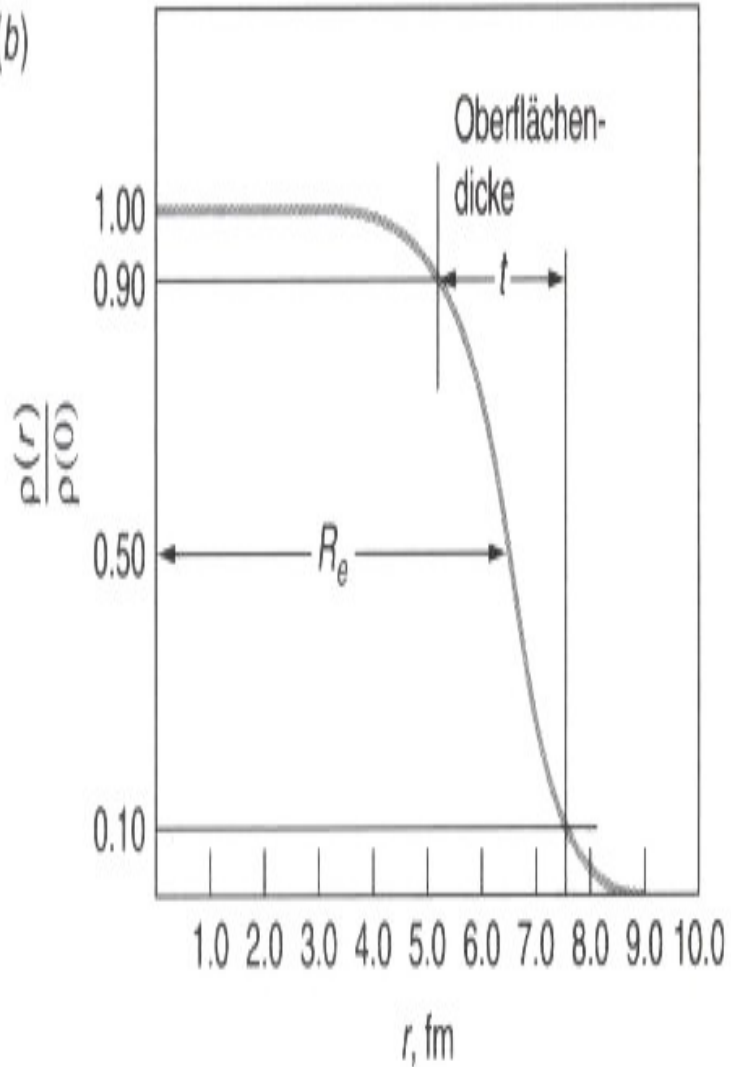


Formfaktoren und Ladungsverteilung



Ladungsverteilung in Kernen

(b)



Von Rutherford zur Elektron-Proton-Streuung

$$\left(\frac{d\sigma}{d\Omega}\right) = \underbrace{\left(\frac{Z^2\alpha^2}{4E^2} \frac{1}{\sin^4\frac{\theta}{2}}\right)}_{\text{Coulomb potential}} \times \cos^2\frac{\theta}{2} \times \underbrace{\left(\frac{1}{1 + \frac{E}{M}(1 - \cos\theta)}\right)}_{\substack{=E/E' \\ \text{target recoil}}} \times \left[1 - \frac{q^2}{2M^2} \tan^2\frac{\theta}{2}\right]$$

Coulomb potential
 $M_p = \infty$, no spin at all involved
 \Rightarrow Rutherford formula
 \Rightarrow mostly in forward direction

$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$ electron has spin $\frac{1}{2}$!

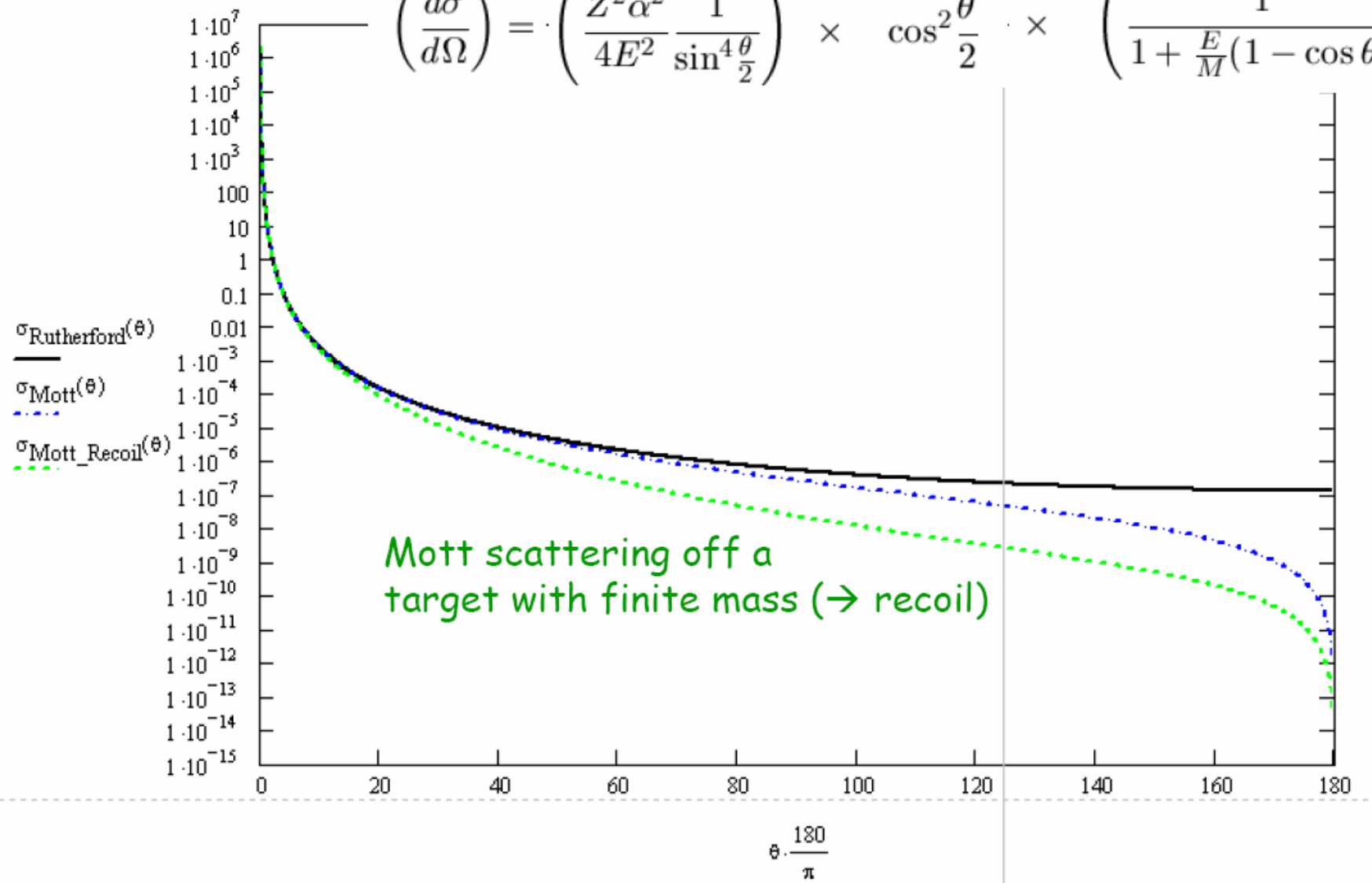
180° scattering is impossible

$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott-Recoil}}$ proton has a mass $M_p < \infty$!

$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Dirac - Proton}}$ proton also has spin $\frac{1}{2} \Rightarrow 180^\circ$ scattering is possible again
 i.e. has a mass M_p , but not yet a structure

Mott-Streuung: Spin=1/2 an Spin=0 mit endlicher Masse

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{Z^2\alpha^2}{4E^2} \frac{1}{\sin^4\frac{\theta}{2}}\right) \times \cos^2\frac{\theta}{2} \times \left(\frac{1}{1 + \frac{E}{M}(1 - \cos\theta)}\right)$$



Zshg. Streuwinkel u. Energie für elastische e-N-Streuung

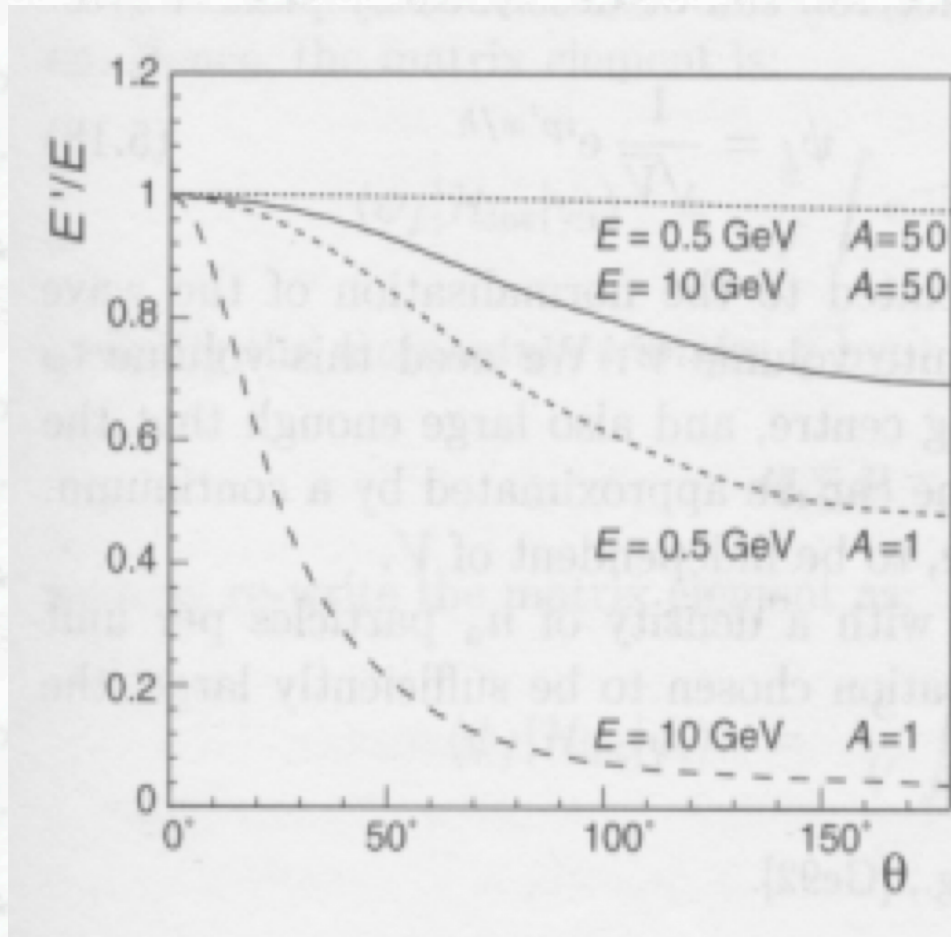
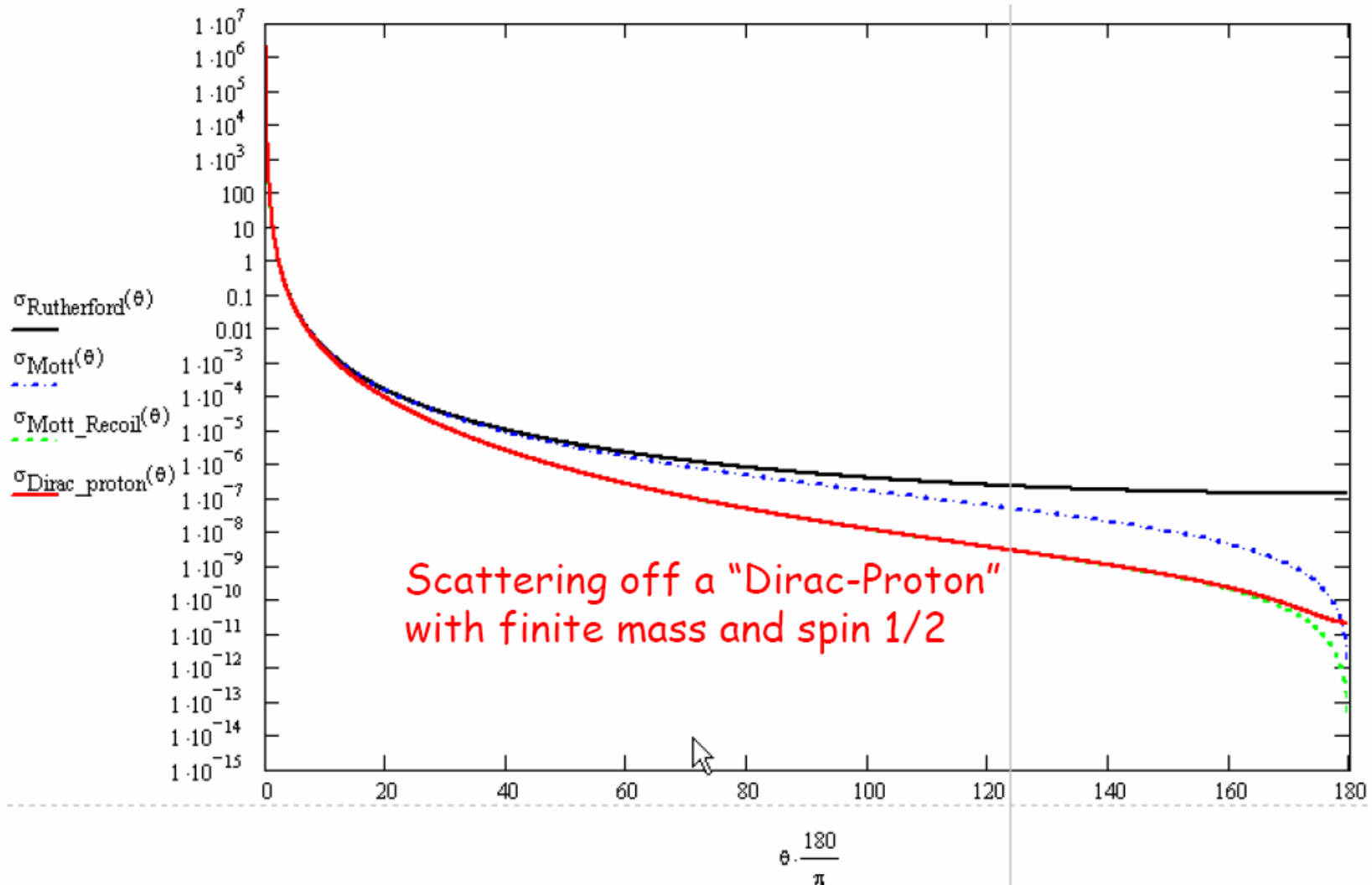


Fig. 5.2. Angular dependence of the scattering energy of electrons normalised to beam energy, E'/E , in elastic electron-nucleus scattering. The curves show this dependence for two different beam energies (0.5 GeV and 10 GeV) and for two nuclei with different masses ($A = 1$ and $A = 50$).

Elektron-Streuung am Dirac-Proton

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{Z^2\alpha^2}{4E^2} \frac{1}{\sin^4\frac{\theta}{2}}\right) \times \cos^2\frac{\theta}{2} \times \left(\frac{1}{1 + \frac{E}{M}(1 - \cos\theta)}\right) \times \left[1 - \frac{q^2}{2M^2} \tan^2\frac{\theta}{2}\right]$$

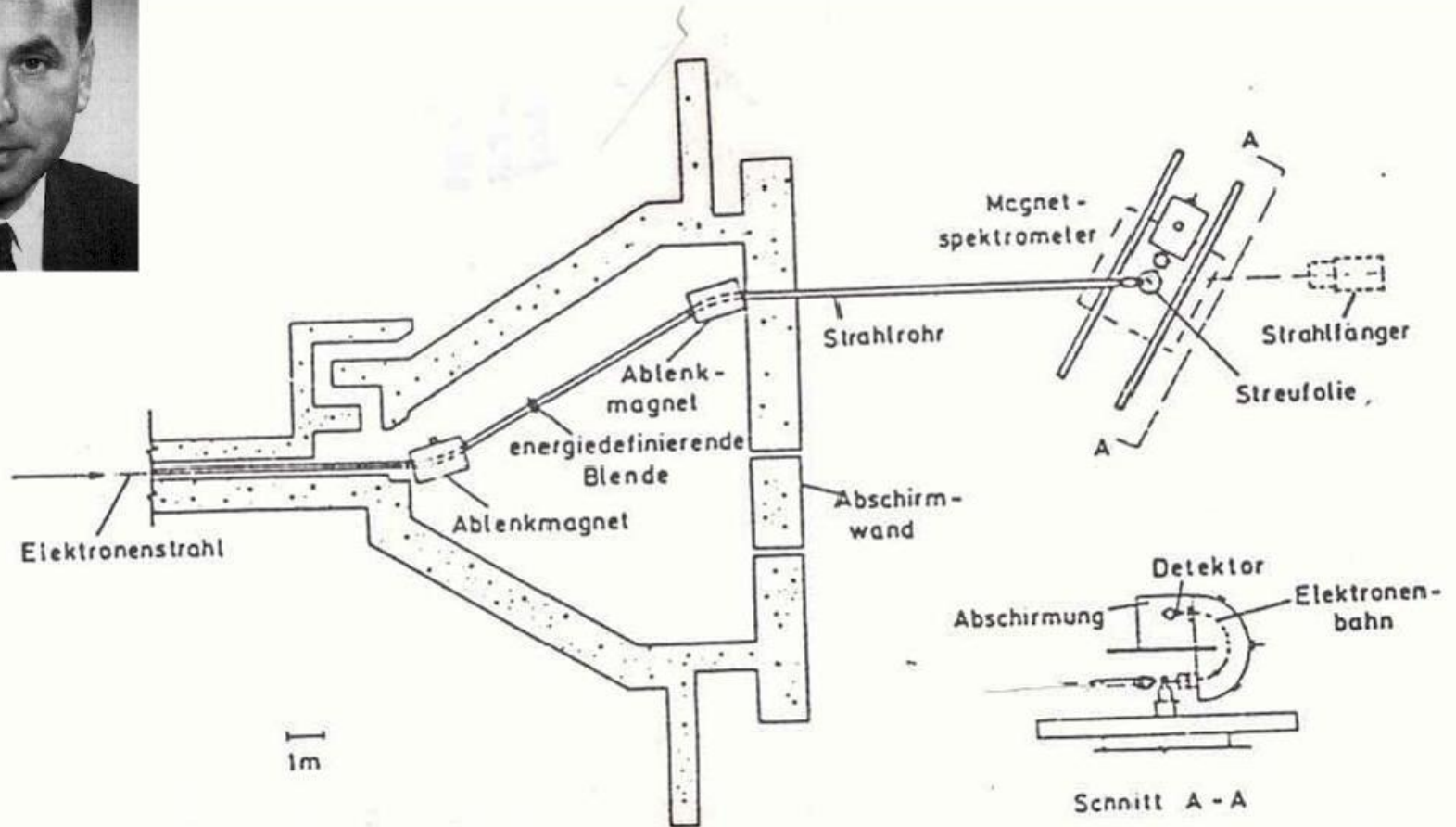


Hofstadter-Experiment in Stanford (1955)



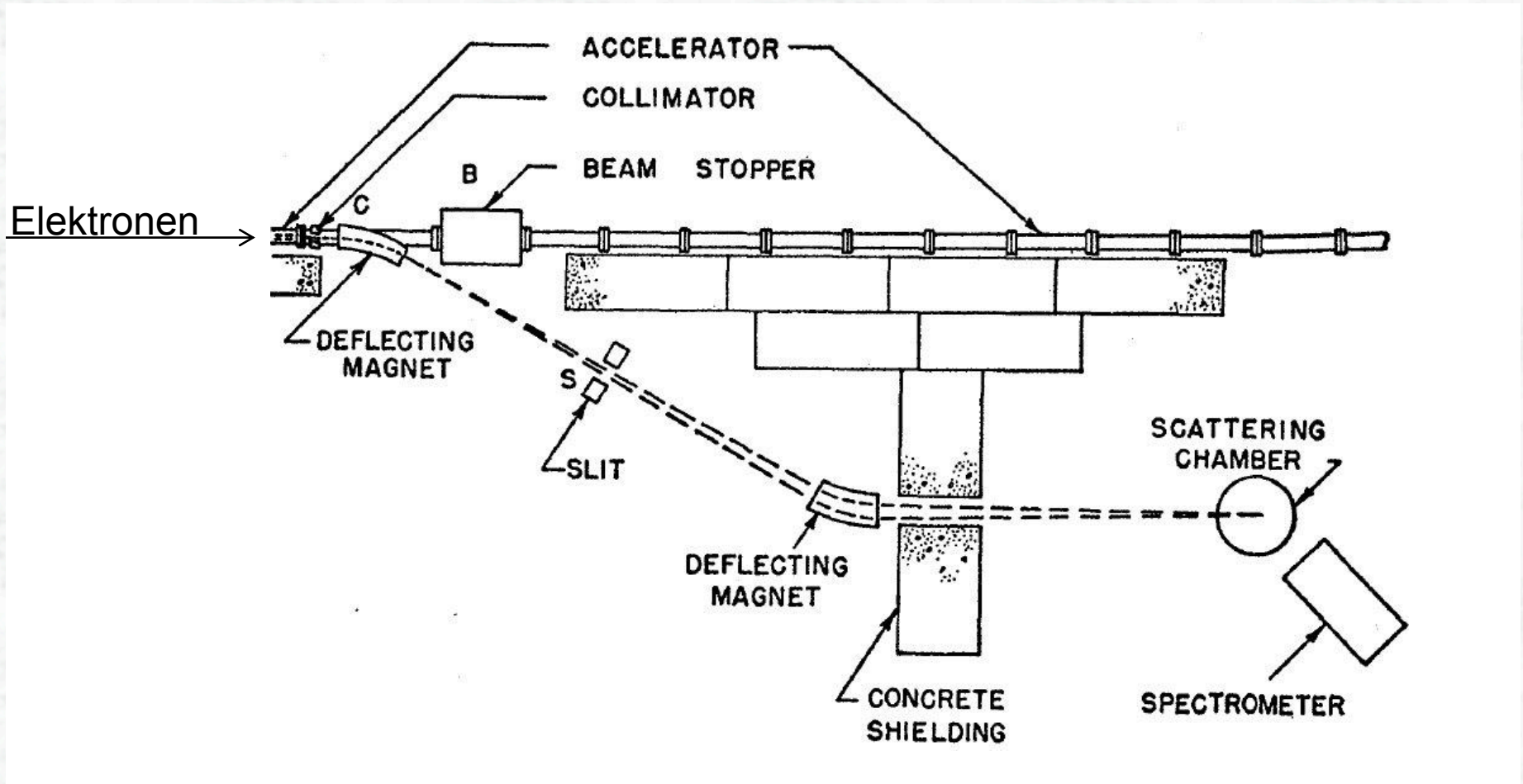
Robert Hofstadter
Nobel Prize 1961

from
Linac



Nachweis und Energiemessung des gestreuten Elektrons

Hofstadter-Experiment in Stanford (1955)



Nachweis und Energiemessung des gestreuten Elektrons

Hofstadter-Experiment in Stanford (1955)

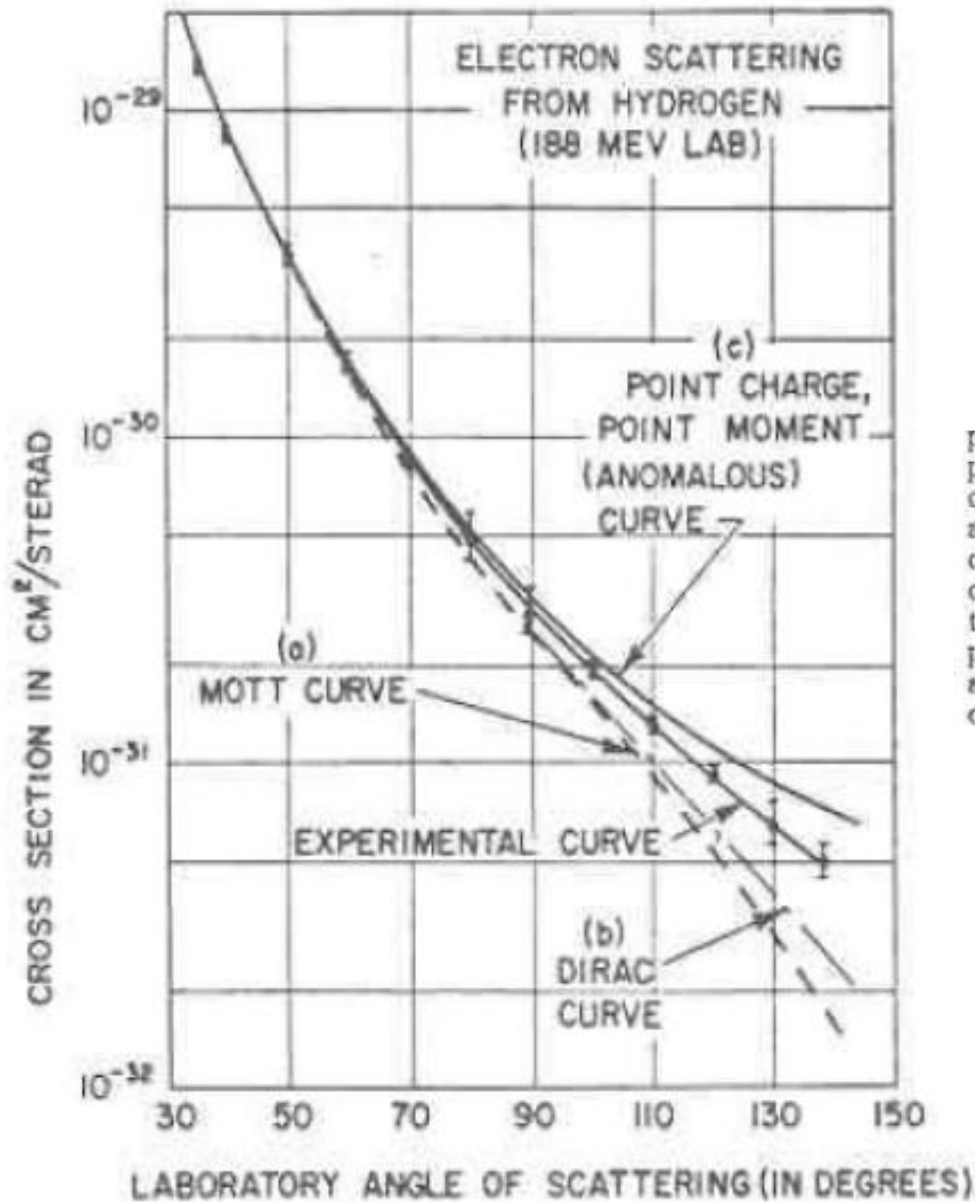


FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. The theoretical curves (b) and (c) are due to Rosenbluth.⁵ The experimental curve falls between curves (b) and (c). This deviation from the theoretical curves represents the effect of a form factor for the proton and indicates structure within the proton, or alternatively, a breakdown of the Coulomb law. The best fit indicates a size of 0.70×10^{-13} cm.

Bestimmung der Proton-Formfaktoren

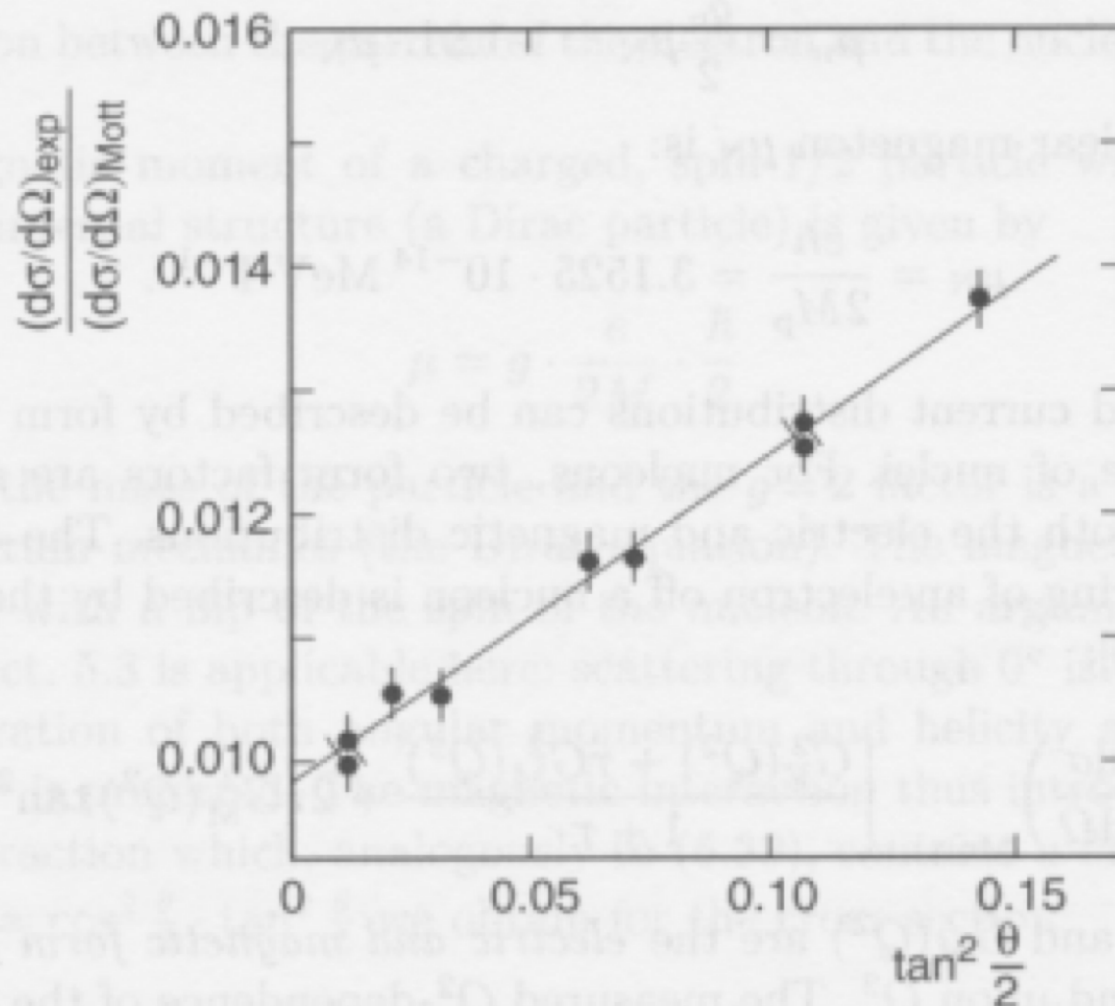
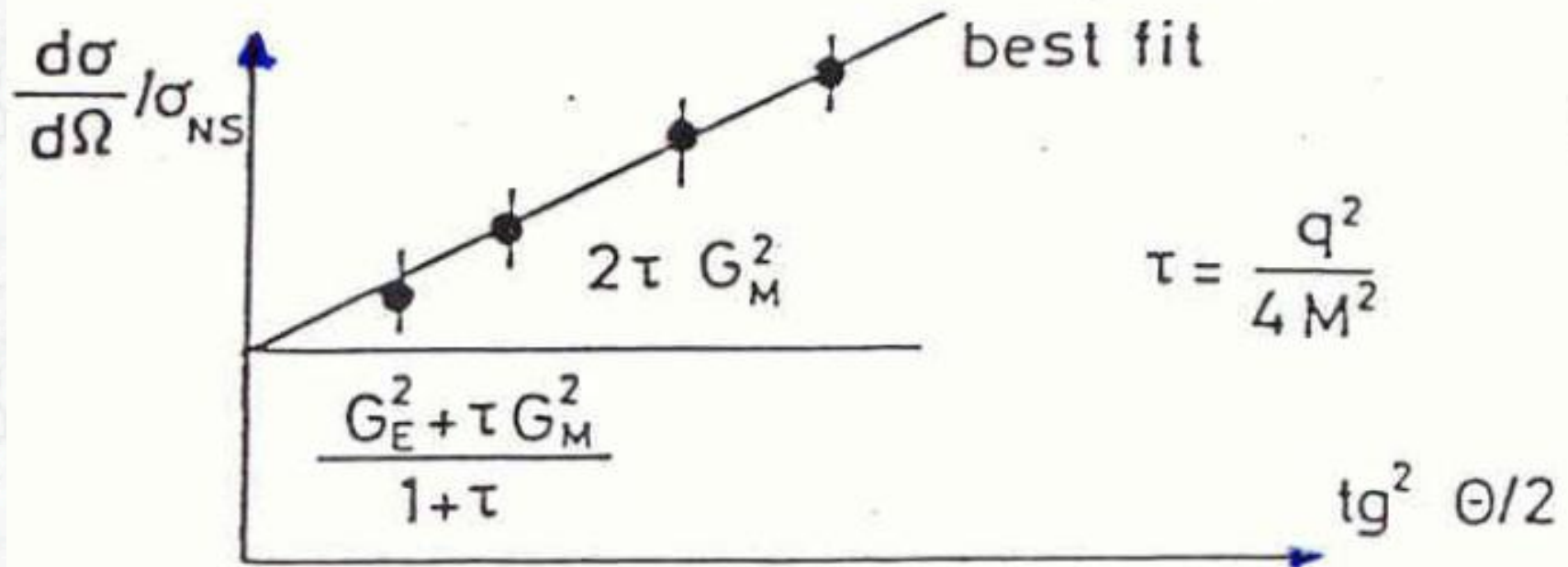


Fig. 6.1. Ratio of the measured cross-section and the Mott cross-section $\sigma_{\text{exp}}/\sigma_{\text{Mott}}$ as a function of $\tan^2 \theta/2$ at a four-momentum transfer of $Q^2 = 2.5 \text{ GeV}^2/c^2$ [Ta67].

Bestimmung der Proton-Formfaktoren

$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{corr}} / \sigma_{\text{NS}} \quad \text{versus} \quad \text{tg}^2 \frac{\theta}{2}$$



$$\text{slope} = 2\tau G_M^2$$

$$\text{intersect} = \frac{G_E^2 + \tau G_M^2}{1 + \tau}$$

Dipol-Formfaktor des Nukleons

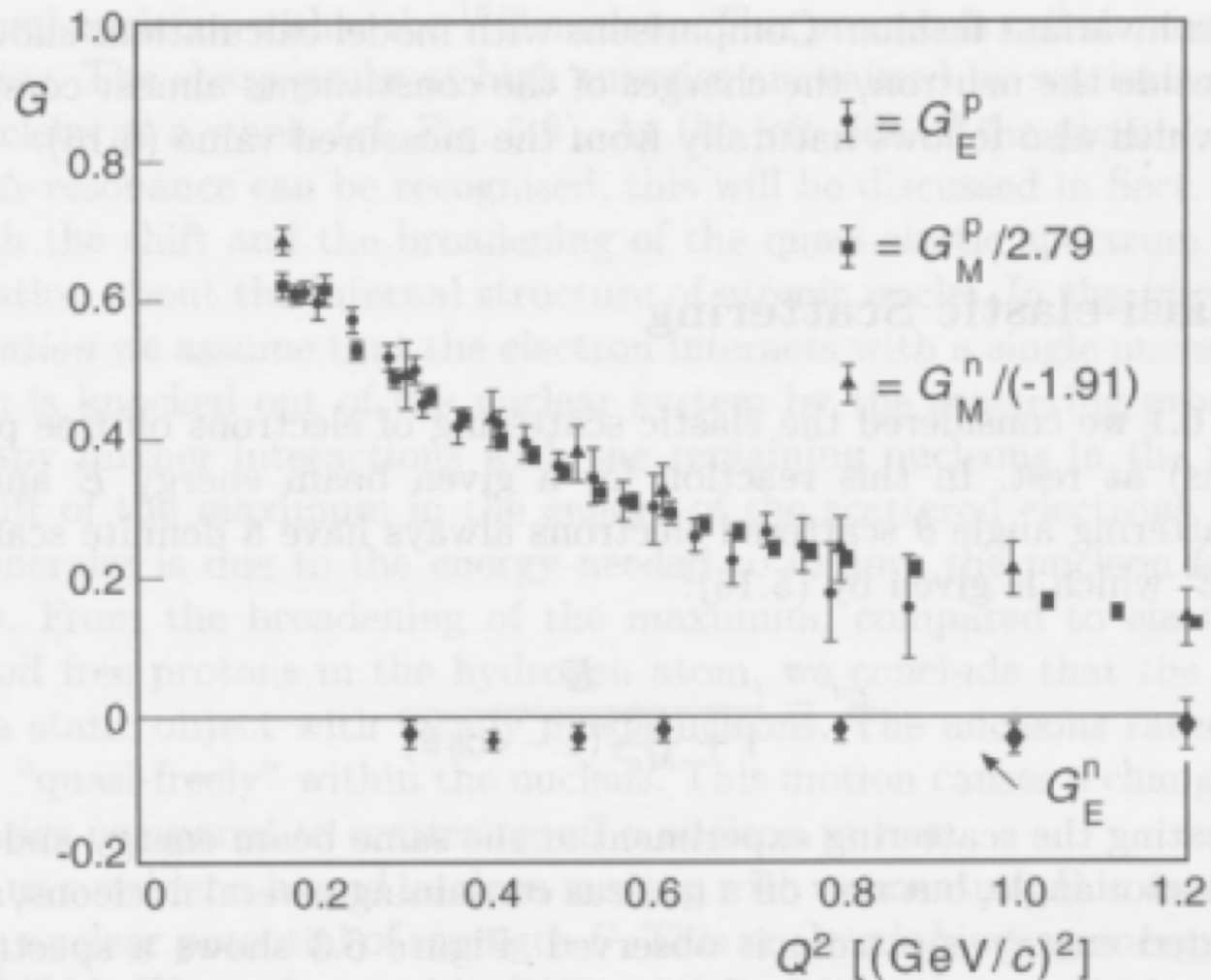


Fig. 6.2. Proton and neutron electric and magnetic form factors as functions of Q^2 . The data points are scaled by the factors noted in the diagram so that they coincide and thus more clearly display the global dipole-like behaviour [Hu65].

Tiefinelastische e-P-Streuung am SLAC



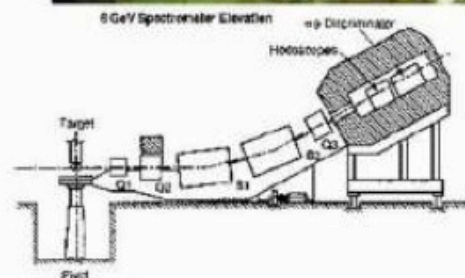
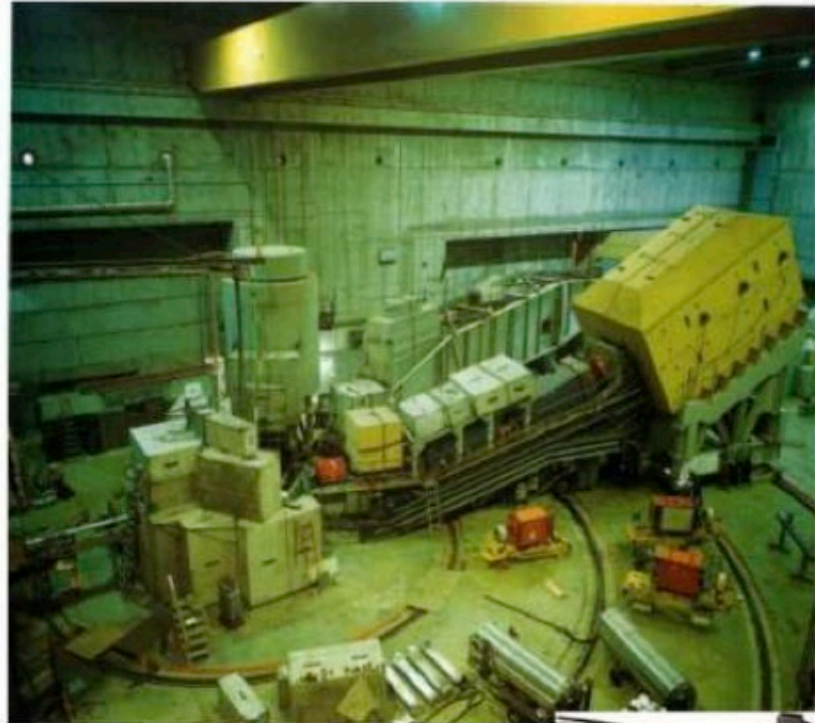
SLAC

up to 20 GeV beam



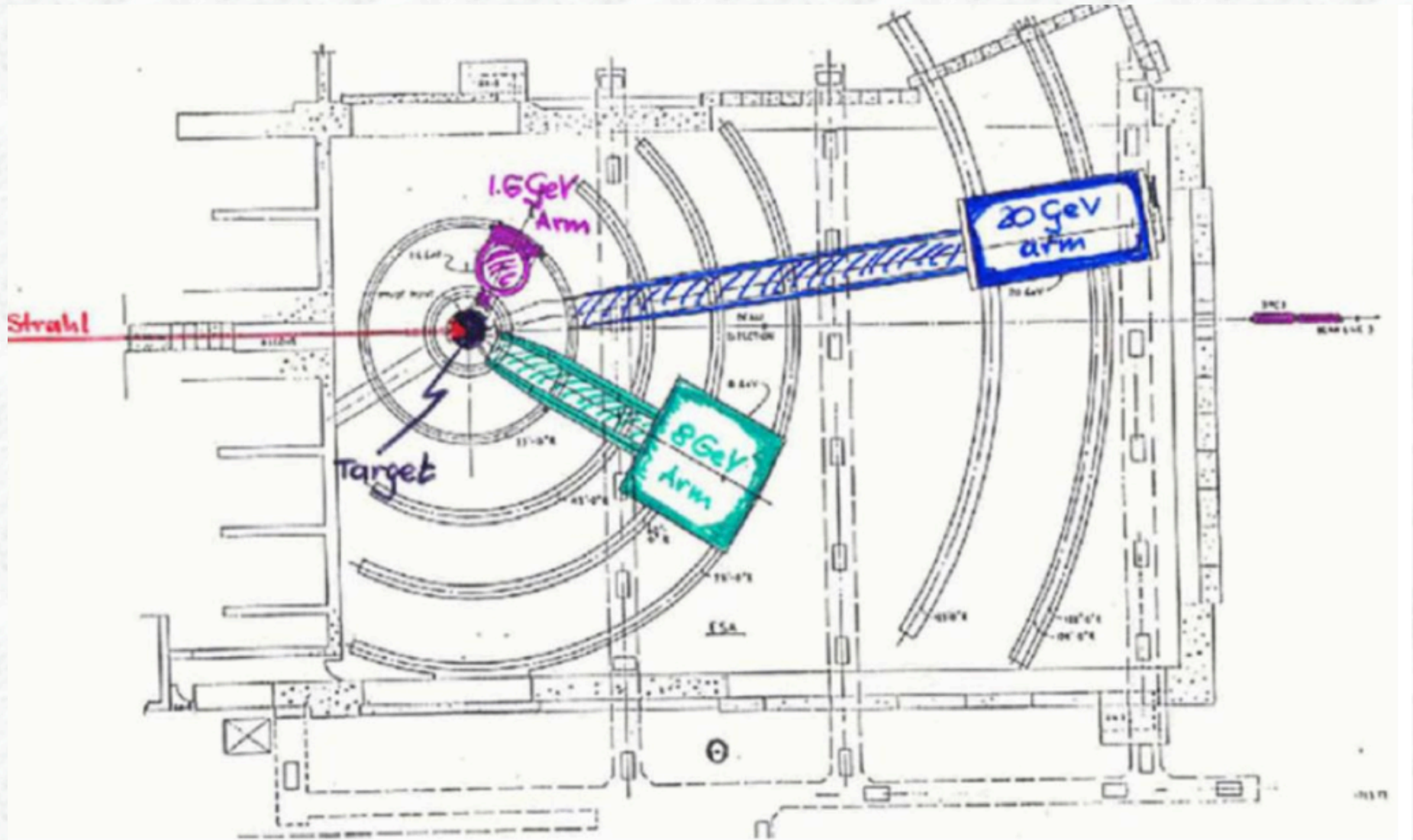
endstation A

8 GeV Electron Spectrometer



Dick Taylor

Tiefinelastische e-P-Streuung am SLAC



Energiespektrum der Elektronen in e-p-Streuung

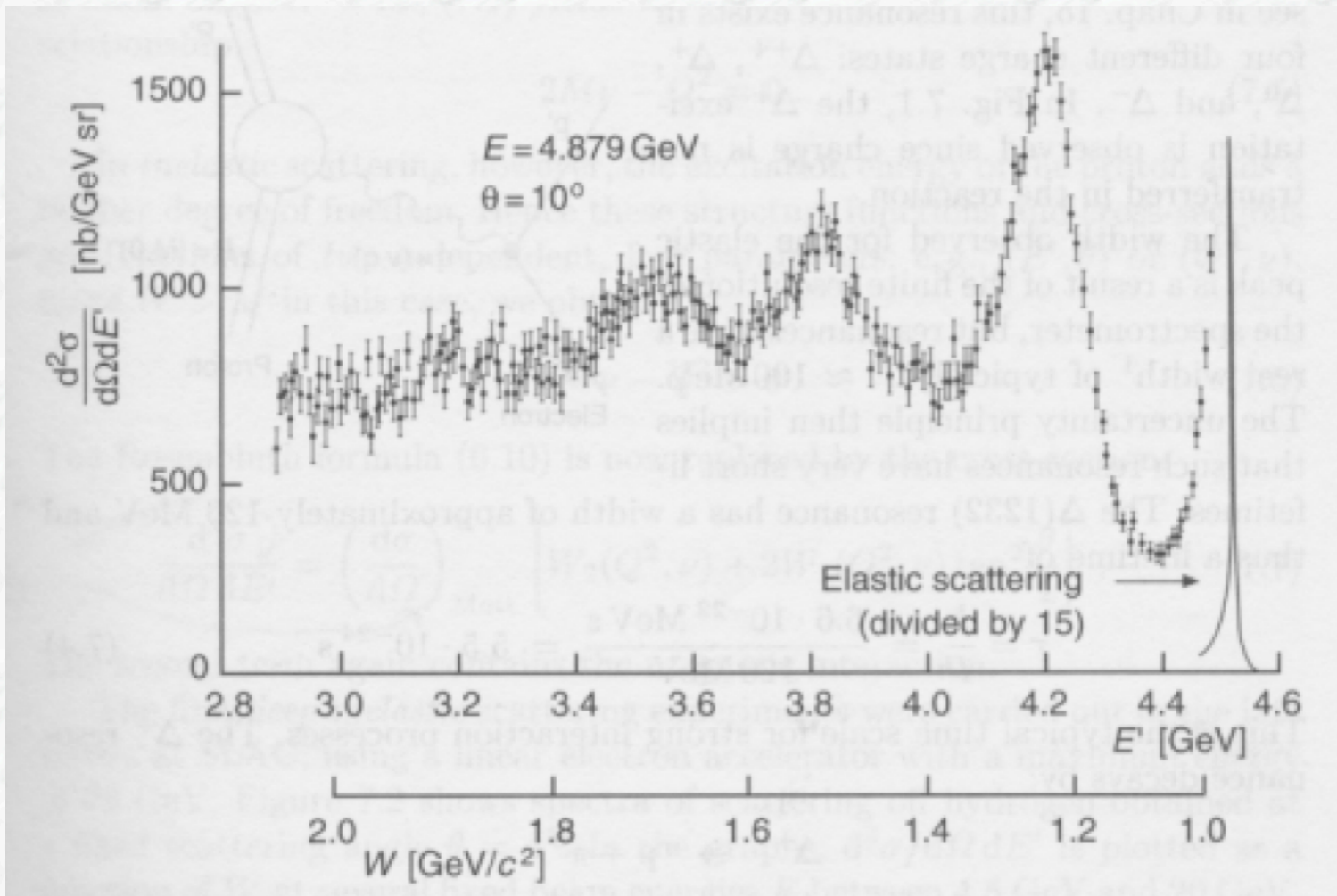


Fig. 7.1. Spectrum of scattered electrons from electron-proton scattering at an electron energy of $E = 4.9$ GeV and a scattering angle of $\theta = 10^\circ$ (from [Ba68]).

Energiespektrum der Elektronen in e-p-Streuung

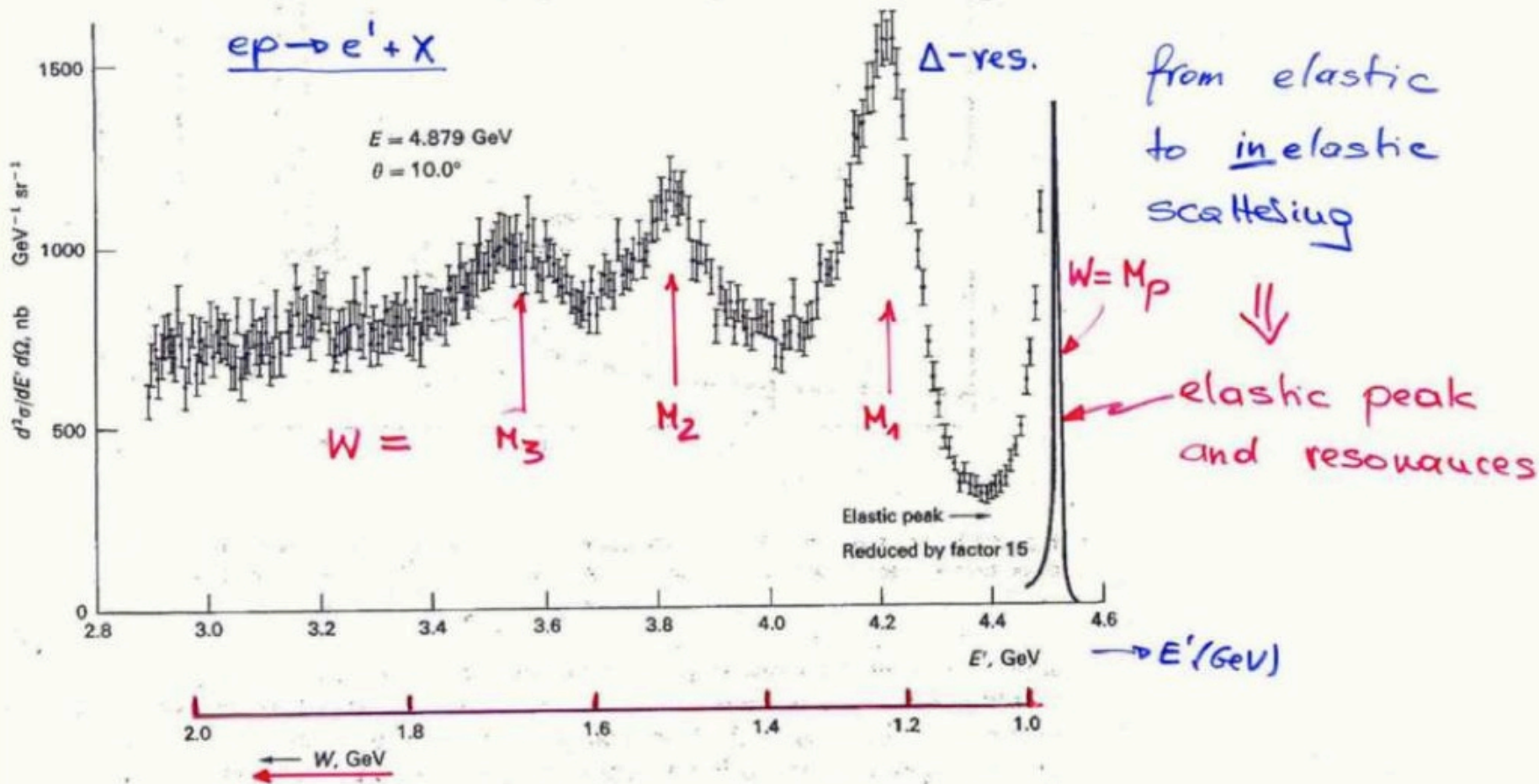


Fig. 7.15 Excitation curve of inelastic ep scattering, obtained at the DESY electron accelerator (Bartel *et al.* 1968). E and E' are the energies of the incident and the scattered electron, and W is the mass of the recoiling hadronic state. The peaks due to the pion-nucleon resonances of masses 1.24, 1.51, and 1.69 GeV are clearly visible.

Doppelt differentieller WQ in inelastischer e-p-Streuung

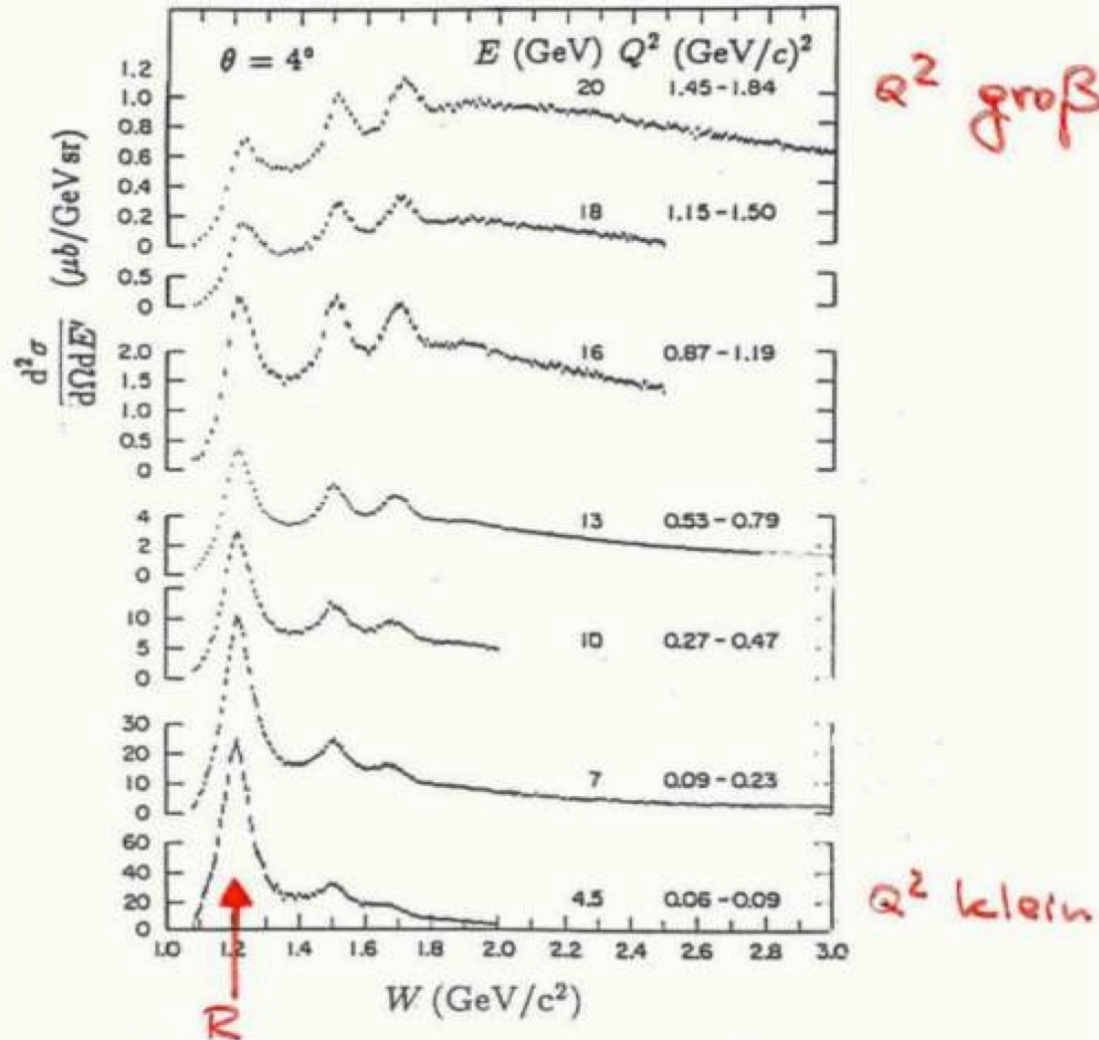
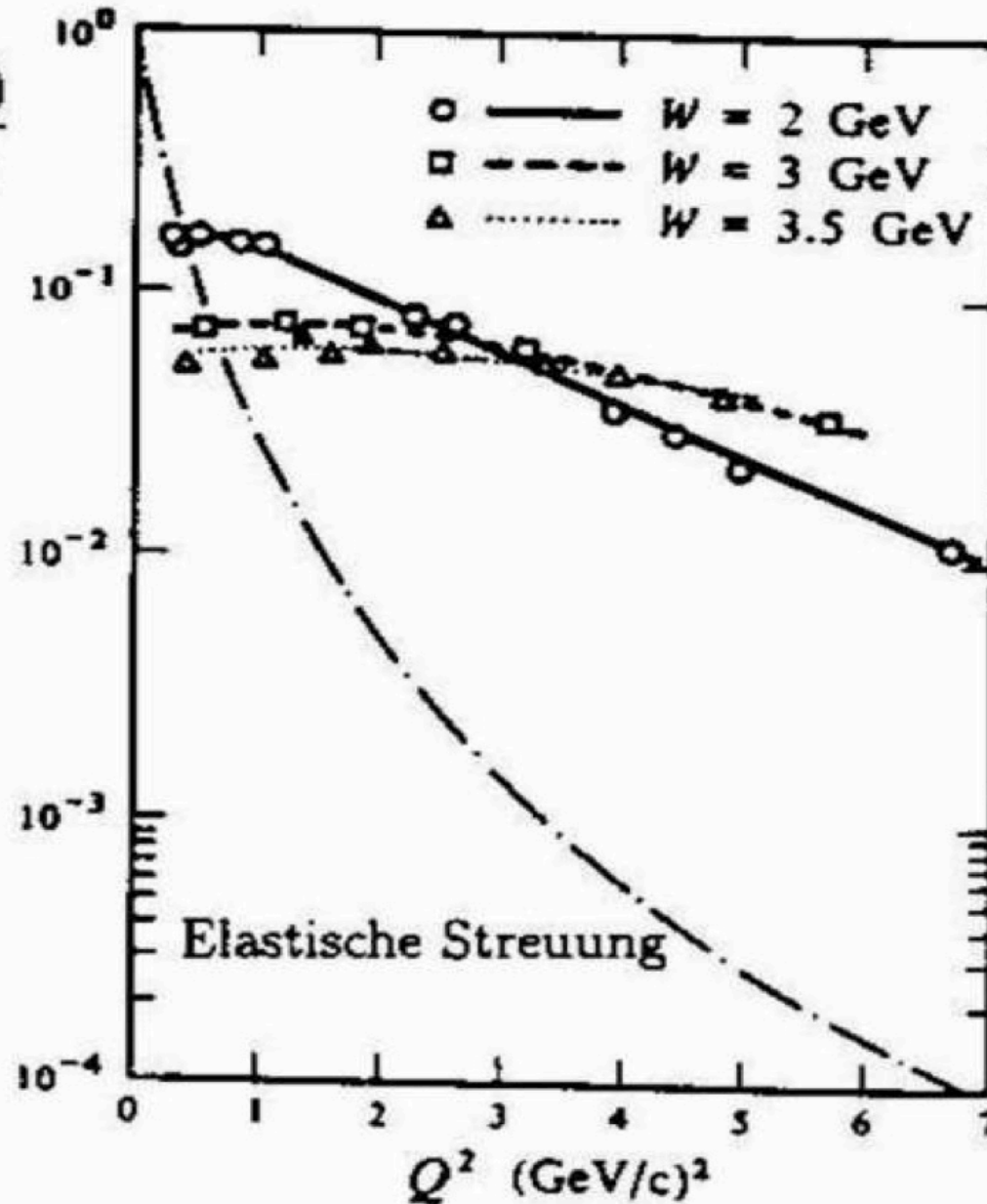


Abb. 7.2. Elektron-Proton-Streuung: gemessene Anregungsspektren in der tiefinelastischen Elektron-Nukleon-Streuung als Funktion der invarianten Masse W [St75]. Die Messungen wurden bei einem festen Streuwinkel von $\theta = 4^\circ$ durchgeführt. Mit zunehmender Einfallenergie E wächst der mittlere Q^2 -Bereich der Daten. Während insbesondere die erste Resonanz ($W=1,232 \text{ GeV}/c^2$) immer weniger ausgeprägt wird, nimmt das Kontinuum ($W \gtrsim 2,5 \text{ GeV}/c^2$) nur geringfügig ab.

Doppelt differentieller WQ in e-p-Streuung

$$\frac{d^2\sigma / (dE' d\Omega)}{(d\sigma / d\Omega)_{Mott}}$$

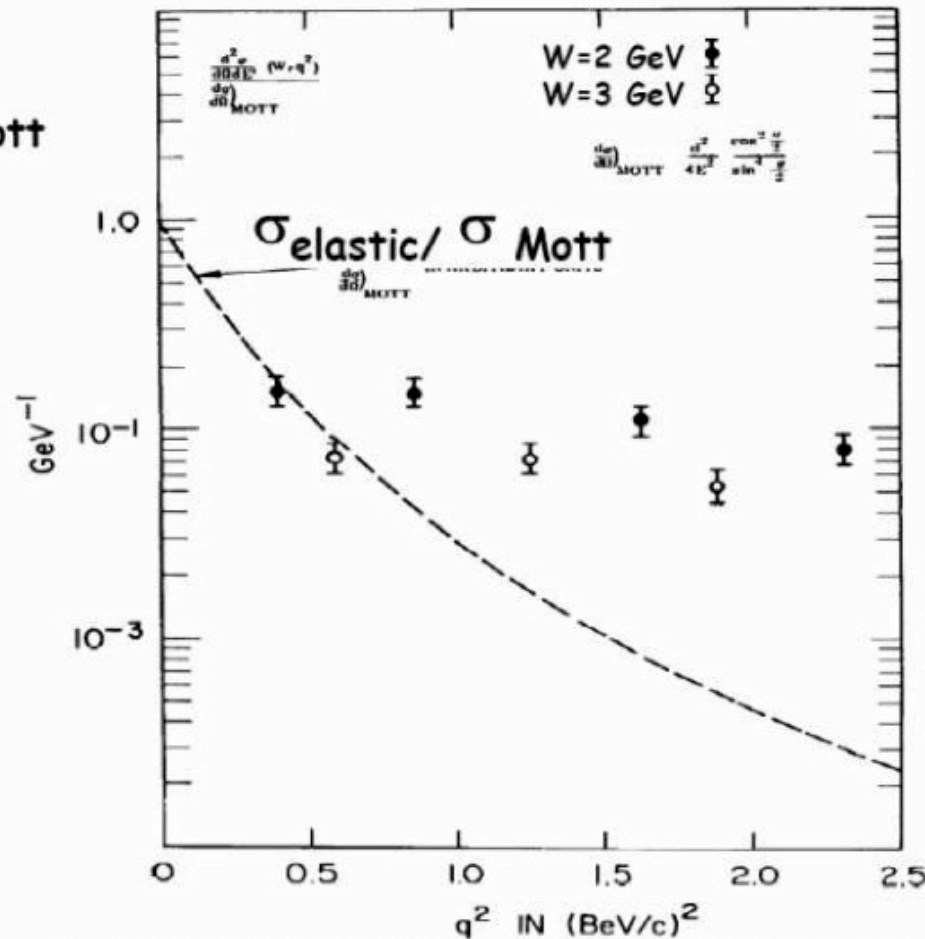


Evidenz für Streuung an punktförmigen Objekten

H. W. Kendall

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$\sigma_{\text{inelastic}} / \sigma_{\text{Mott}}$



SLAC ~1967



Jerome Friedman
Henry Kendall
Richard (Dick) Taylor
NP 1990

Fig. 11. Inelastic data for $W = 2$ and 3 GeV as a function of q^2 . This was one of the earliest examples of the relatively large cross sections and weak q^2 dependence that were later found to characterize the deep inelastic scattering and which suggested point-like nucleon constituents. The q^2 dependence of elastic scattering is shown also; these cross sections have been divided by σ_{M}

Bjorken-Scaling

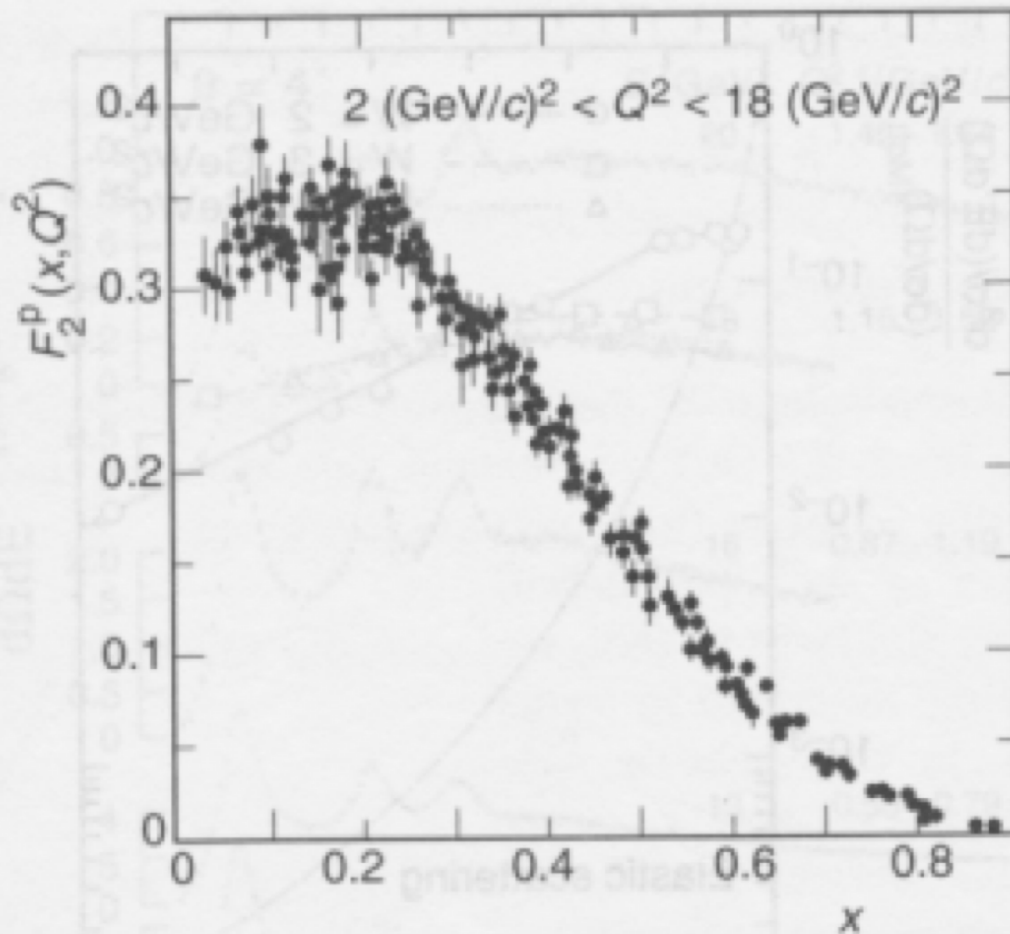
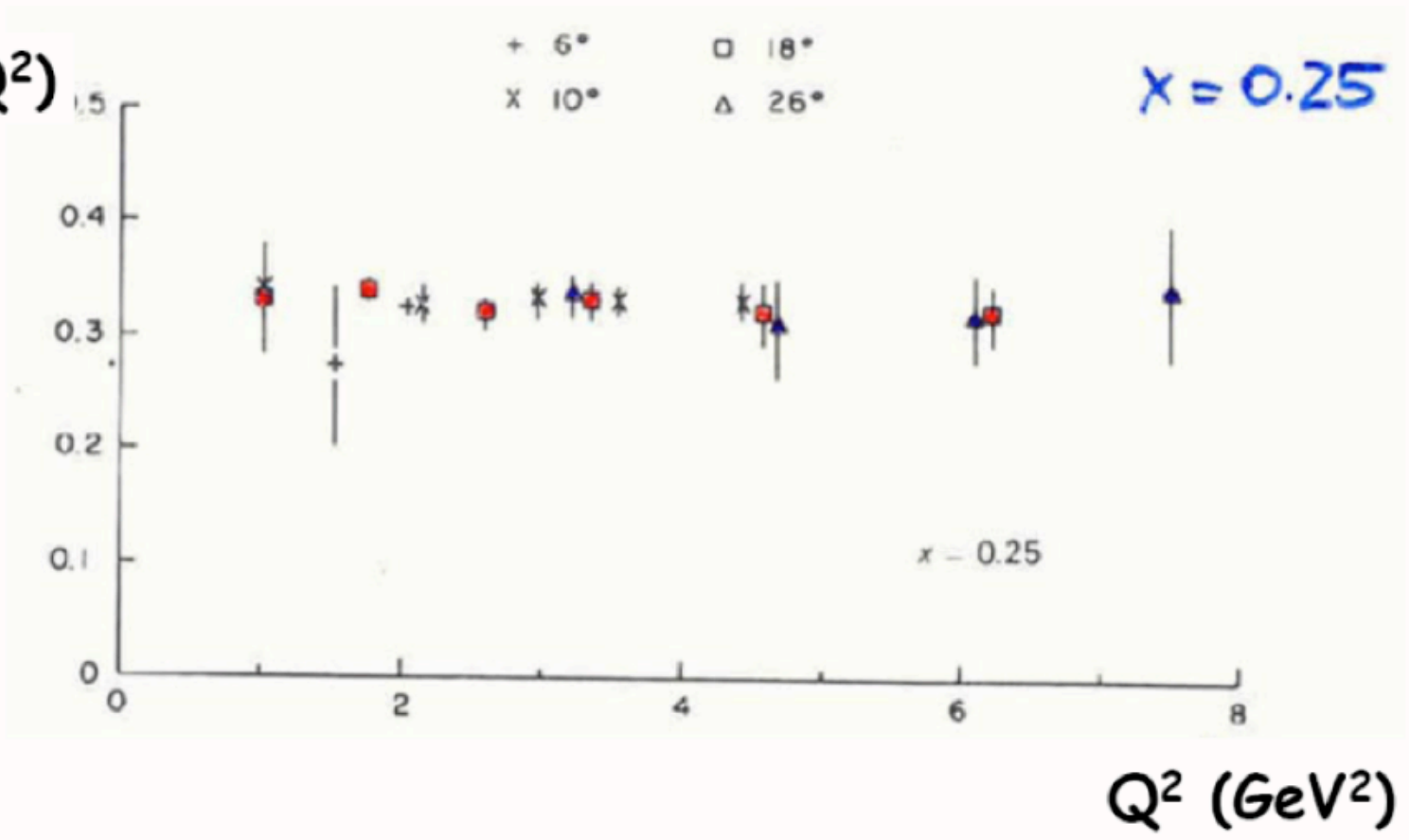


Fig. 7.4. The structure function F_2 of the proton as a function of x , for Q^2 between 2 (GeV/c)^2 and 18 (GeV/c)^2 [At82].

Bjorken-Scaling

$F_2(x, Q^2)$



Callan-Cross-Beziehung

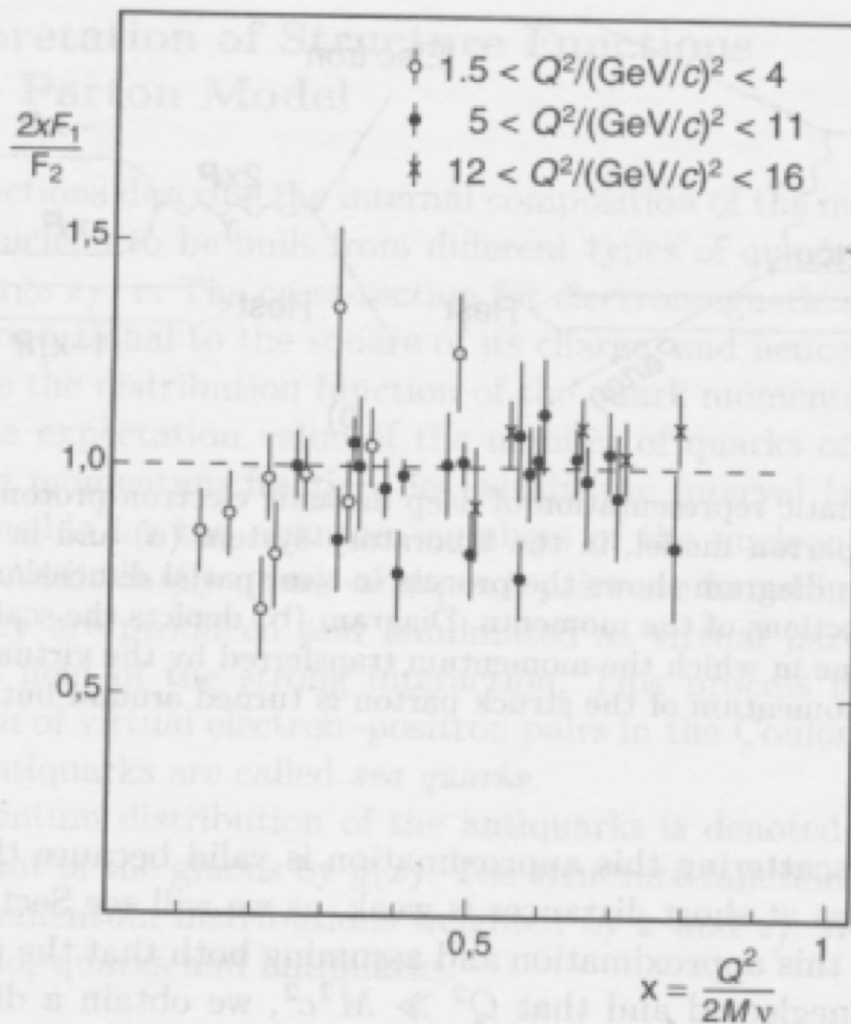
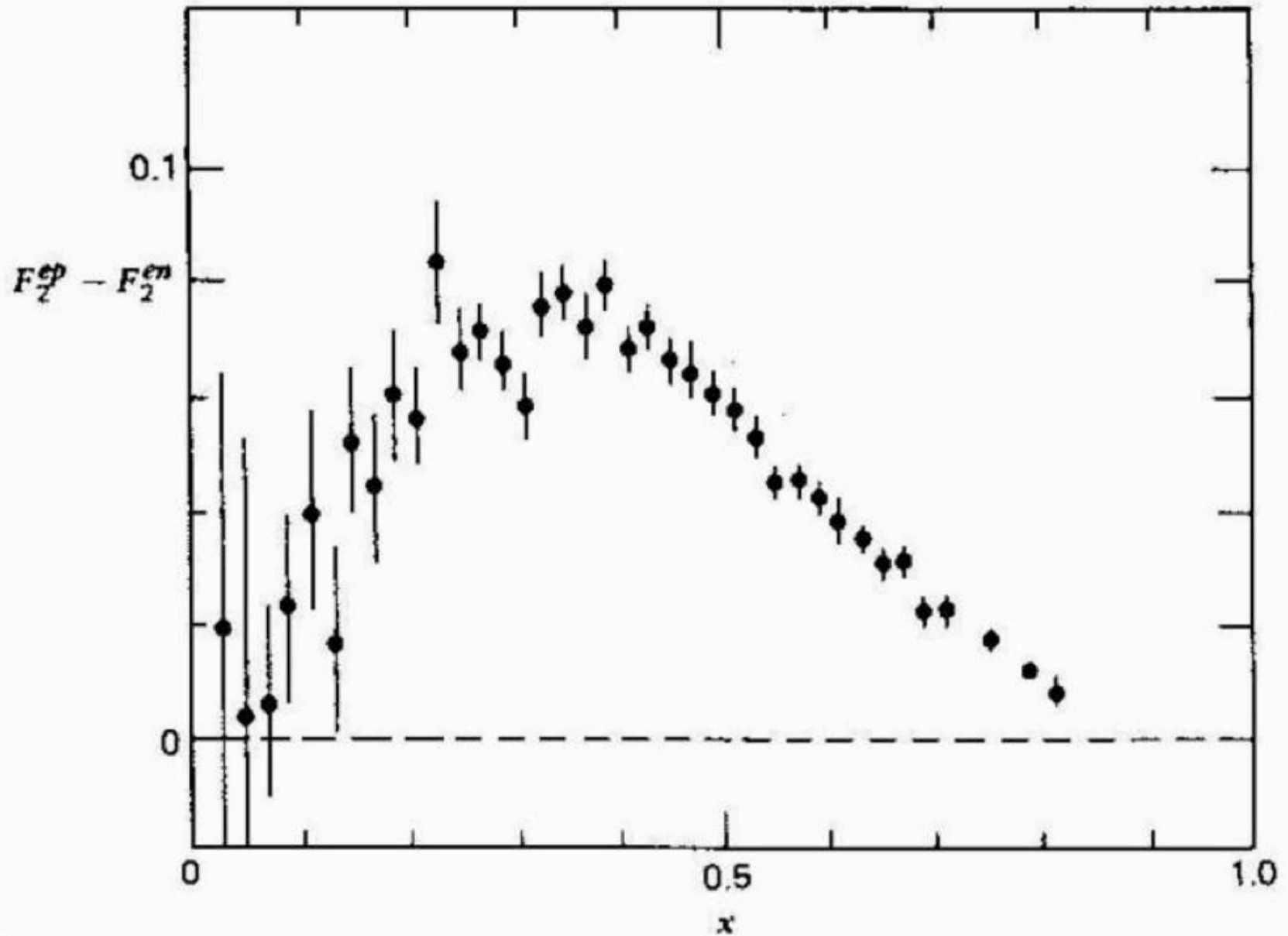


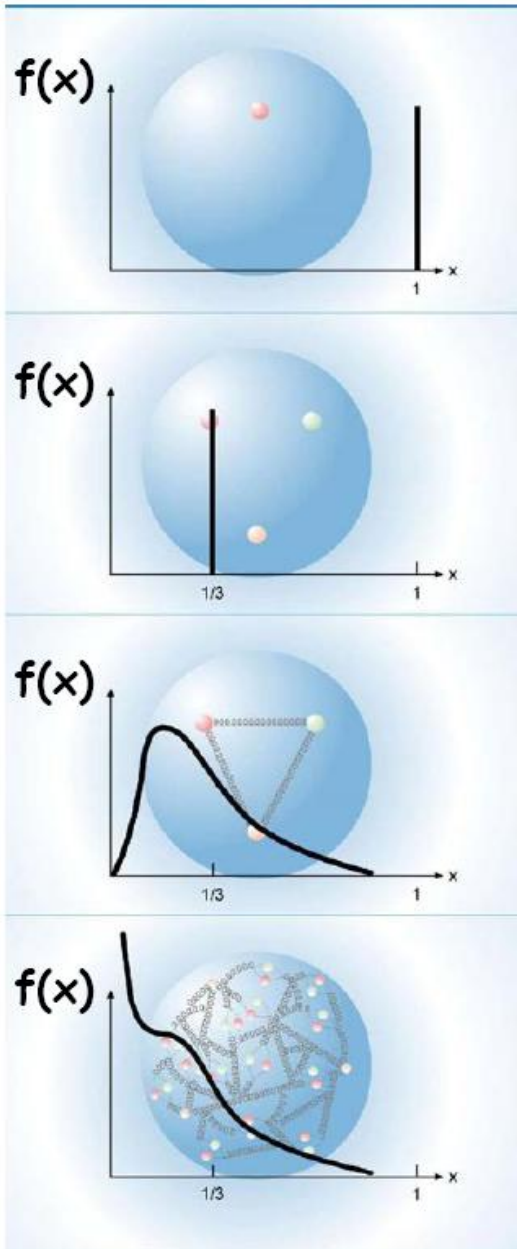
Fig. 7.5. Ratio of the structure functions $2xF_1(x)$ and $F_2(x)$. The data are from experiments at SLAC (from [Pe87]). It can be seen that the ratio is approximately constant (≈ 1).

Partonverteilungsfunktion der Valenzquarks



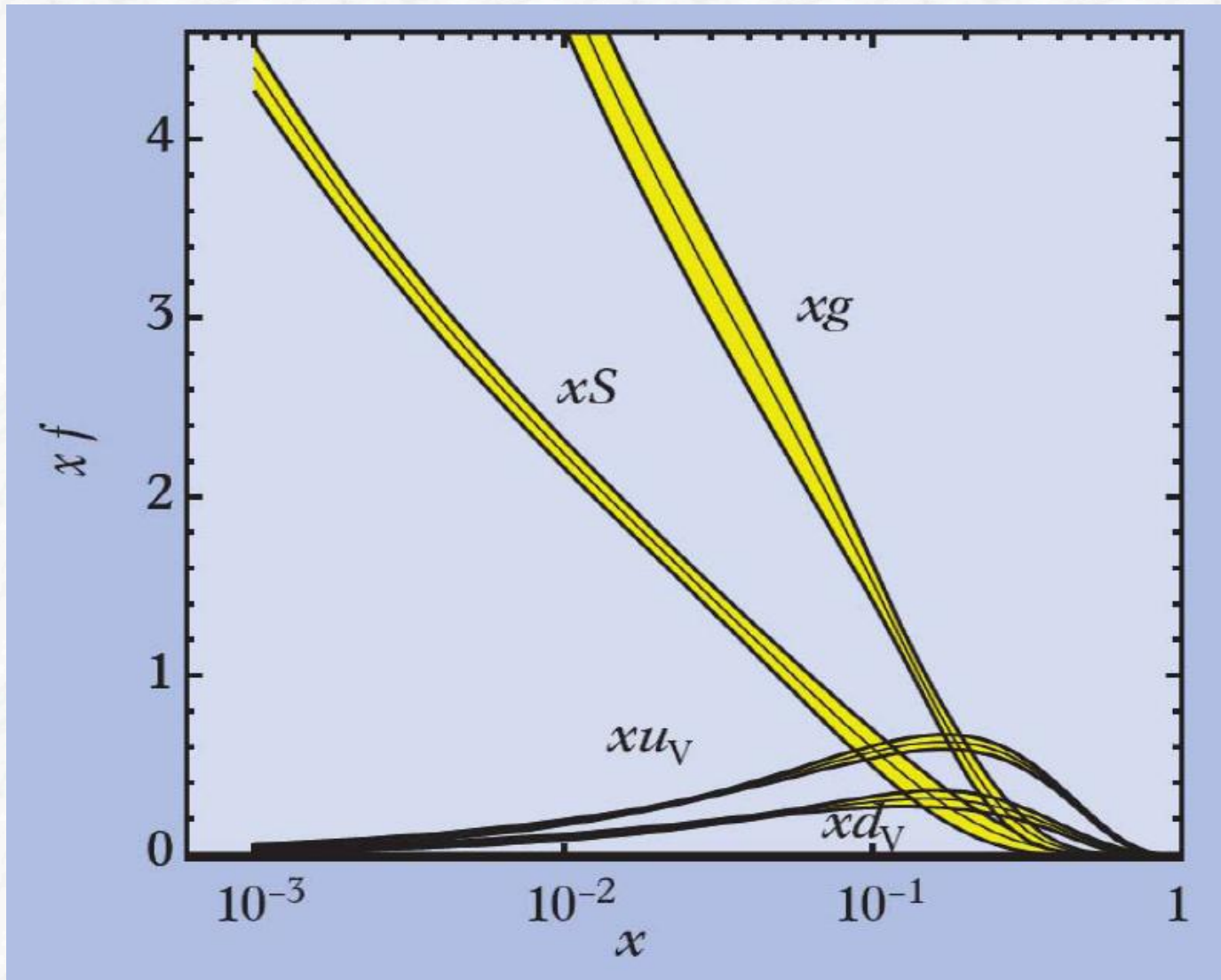
Partonverteilungsfunktion, wenn das Proton bestünde aus

Proton wäre



- a single point-like particle
- just 3 static valence quarks
- a bound system of 3 valence quarks in motion
- a structure of quarks and gluons

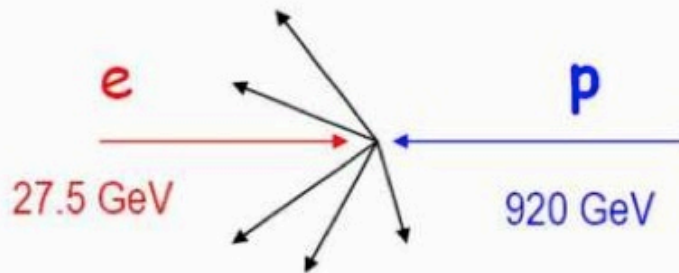
Partonverteilungsfunktionen des Protons



HERA-Beschleuniger in Hamburg

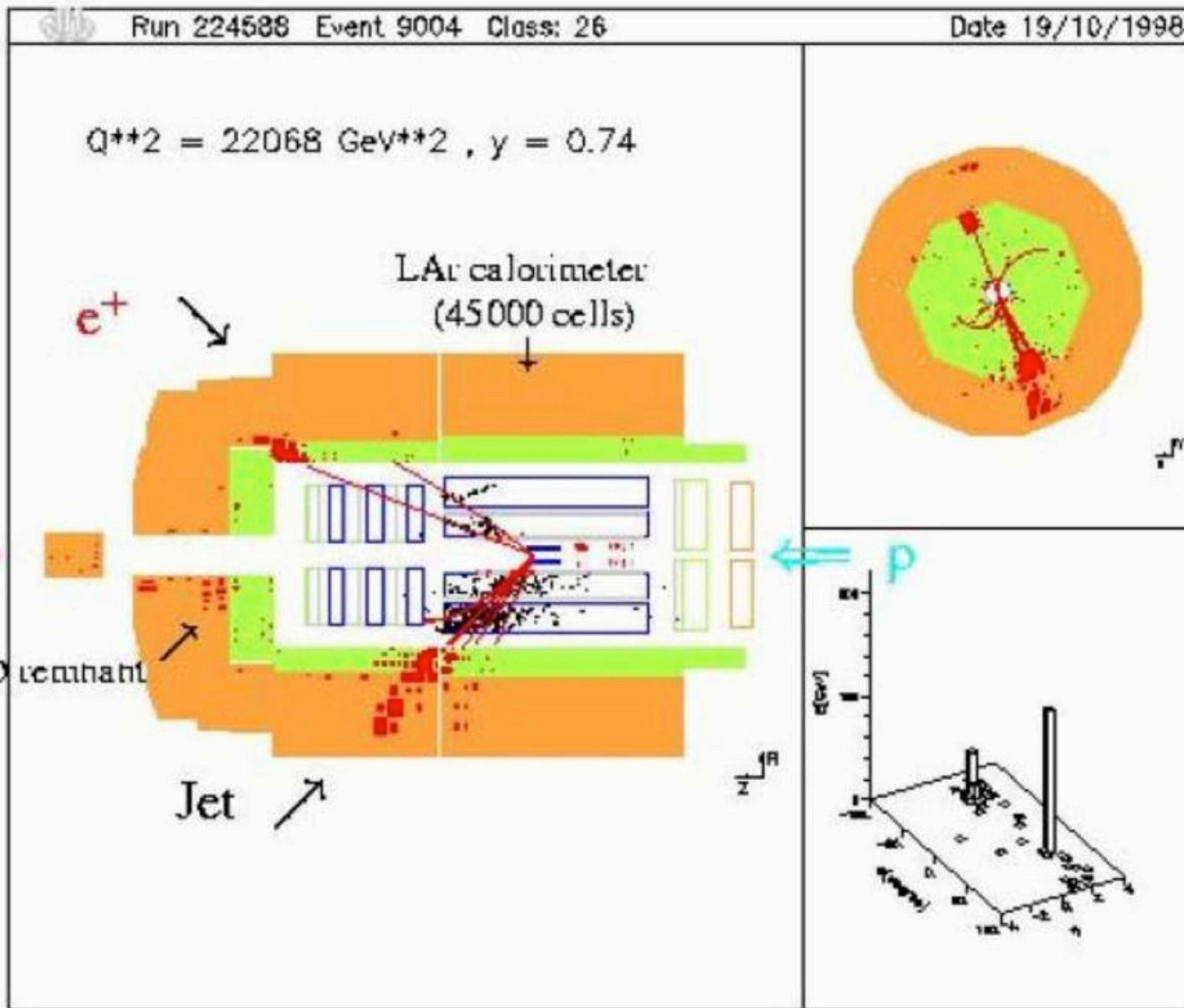


only ep collider world-wide



$$s = (318 \text{ GeV})^2$$
$$Q^2 \text{ up to } 10^5 \text{ GeV}^2$$

Ein Ereignis in tiefinelastischer Streuung



Übersicht über Input für Bestimmung der PDFs

Process	Subprocess	Partons	x range
$\ell^\pm \{p, n\} \rightarrow \ell^\pm X$	$\gamma^* q \rightarrow q$	q, \bar{q}, g	$x \gtrsim 0.01$
$\ell^\pm n/p \rightarrow \ell^\pm X$	$\gamma^* d/u \rightarrow d/u$	d/u	$x \gtrsim 0.01$
$pp \rightarrow \mu^+ \mu^- X$	$u\bar{u}, d\bar{d} \rightarrow \gamma^*$	\bar{q}	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \rightarrow \mu^+ \mu^- X$	$(u\bar{d})/(u\bar{u}) \rightarrow \gamma^*$	\bar{d}/\bar{u}	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu}) N \rightarrow \mu^-(\mu^+) X$	$W^* q \rightarrow q'$	q, \bar{q}	$0.01 \lesssim x \lesssim 0.5$
$\nu N \rightarrow \mu^- \mu^+ X$	$W^* s \rightarrow c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \rightarrow \mu^+ \mu^- X$	$W^* \bar{s} \rightarrow \bar{c}$	\bar{s}	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \rightarrow e^\pm X$	$\gamma^* q \rightarrow q$	g, q, \bar{q}	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \rightarrow \bar{\nu} X$	$W^+ \{d, s\} \rightarrow \{u, c\}$	d, s	$x \gtrsim 0.01$
$e^\pm p \rightarrow e^\pm c\bar{c} X$	$\gamma^* c \rightarrow c, \gamma^* g \rightarrow c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \rightarrow \text{jet}+X$	$\gamma^* g \rightarrow q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \rightarrow \text{jet}+X$	$gg, qg, qq \rightarrow 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \rightarrow (W^\pm \rightarrow \ell^\pm \nu) X$	$ud \rightarrow W, \bar{u}\bar{d} \rightarrow W$	u, d, \bar{u}, \bar{d}	$x \gtrsim 0.05$
$p\bar{p} \rightarrow (Z \rightarrow \ell^+ \ell^-) X$	$uu, dd \rightarrow Z$	d	$x \gtrsim 0.05$

Staus der PDFs heute

