

Experimentalphysik VI

Kern- und Teilchenphysik

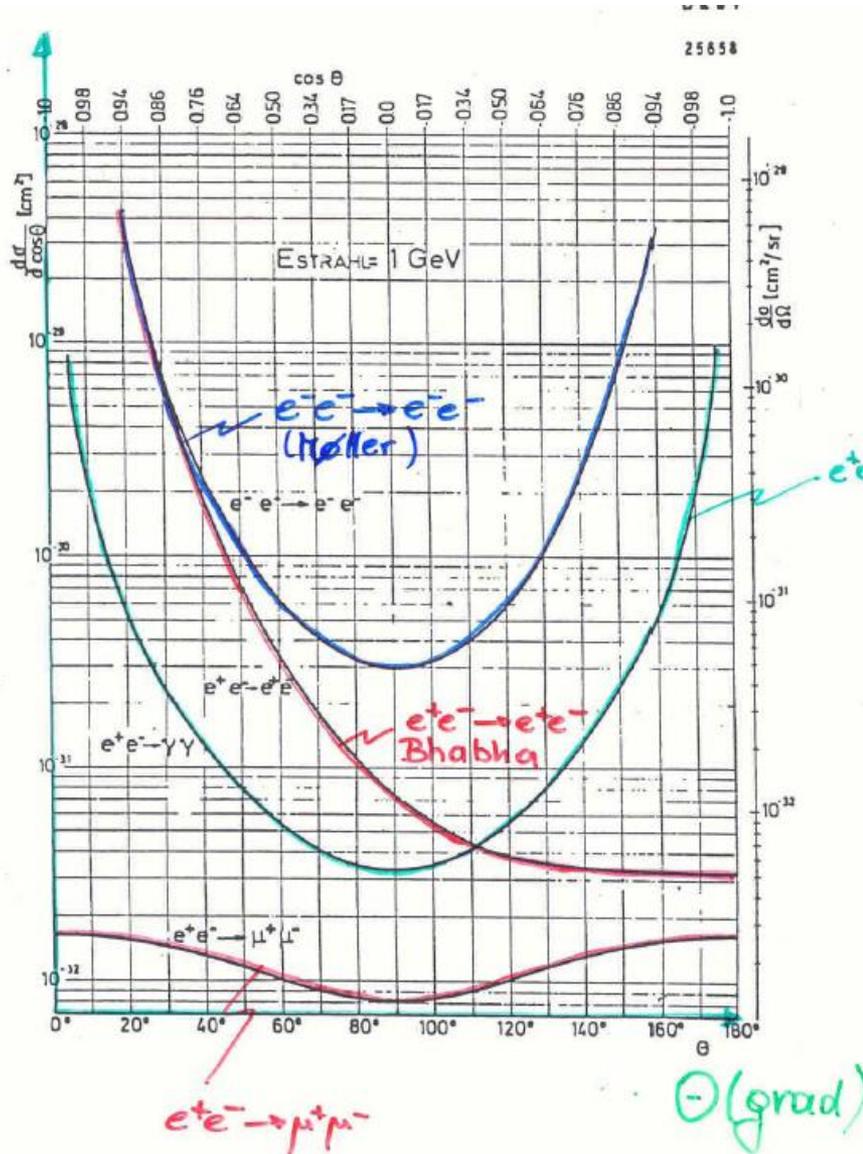
Prof. Markus Schumacher

ALU Freiburg, Sommersemester 2010

Kapitel 8: Quantenelektrodynamik

Übersicht: differentielle Wirkungsquerschnitte der QED

$$\frac{d\sigma}{d\cos\theta}$$



Moeller $e^-e^- \rightarrow e^-e^-$

Bhabha $e^+e^- \rightarrow e^+e^-$

$e^+e^- \rightarrow \gamma\gamma$

$e^+e^- \rightarrow \mu^+\mu^-$

Übersicht: differentielle Wirkungsquerschnitte der QED

TABLE 6.1

Leading Order Contributions to Representative QED Processes.

	Feynman Diagrams		$ \overline{\mathcal{M}} ^2/2e^4$
	Forward peak	Backward peak	Forward Interference Backward
<p><u>Møller scattering</u></p> <p>$e^- e^- \rightarrow e^- e^-$</p> <p>(Crossing $s \leftrightarrow u$)</p>			$\frac{s^2 + u^2}{t^2} + \frac{2s^2}{tu} + \frac{s^2 + t^2}{u^2}$ <p>($u \leftrightarrow t$ symmetric)</p>
<p><u>Bhabha scattering</u></p> <p>$e^- e^+ \rightarrow e^- e^+$</p>			$\frac{s^2 + u^2}{t^2} + \frac{2u^2}{ts} + \frac{u^2 + t^2}{s^2}$
<p>$e^- \mu^- \rightarrow e^- \mu^-$</p> <p>(Crossing $s \leftrightarrow t$)</p> <p>$e^- e^+ \rightarrow \mu^- \mu^+$</p>			$\frac{s^2 + u^2}{t^2}$ $\frac{u^2 + t^2}{s^2}$

PETRA: e+e- Kollider am DESY bei 14 bis 44 GeV

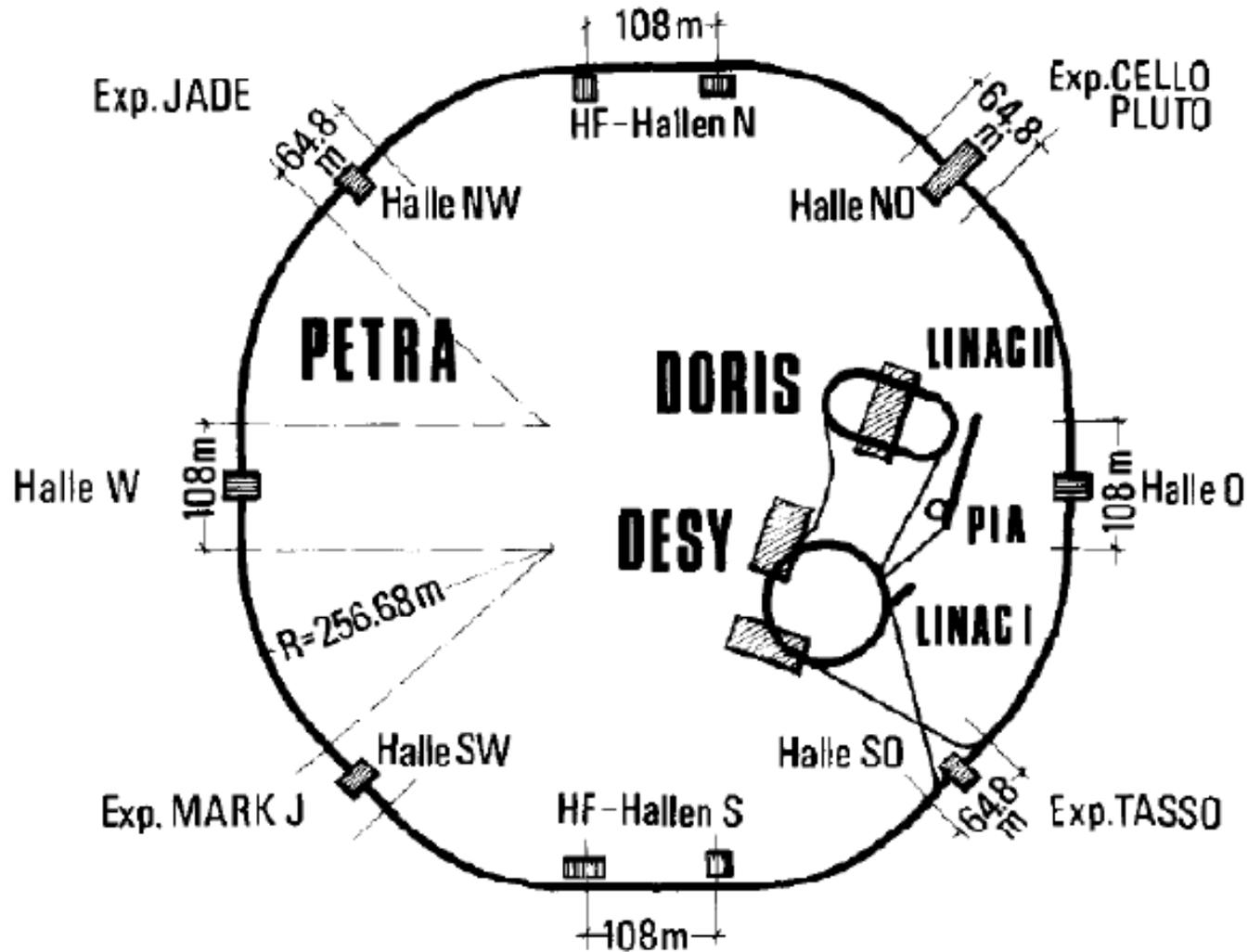


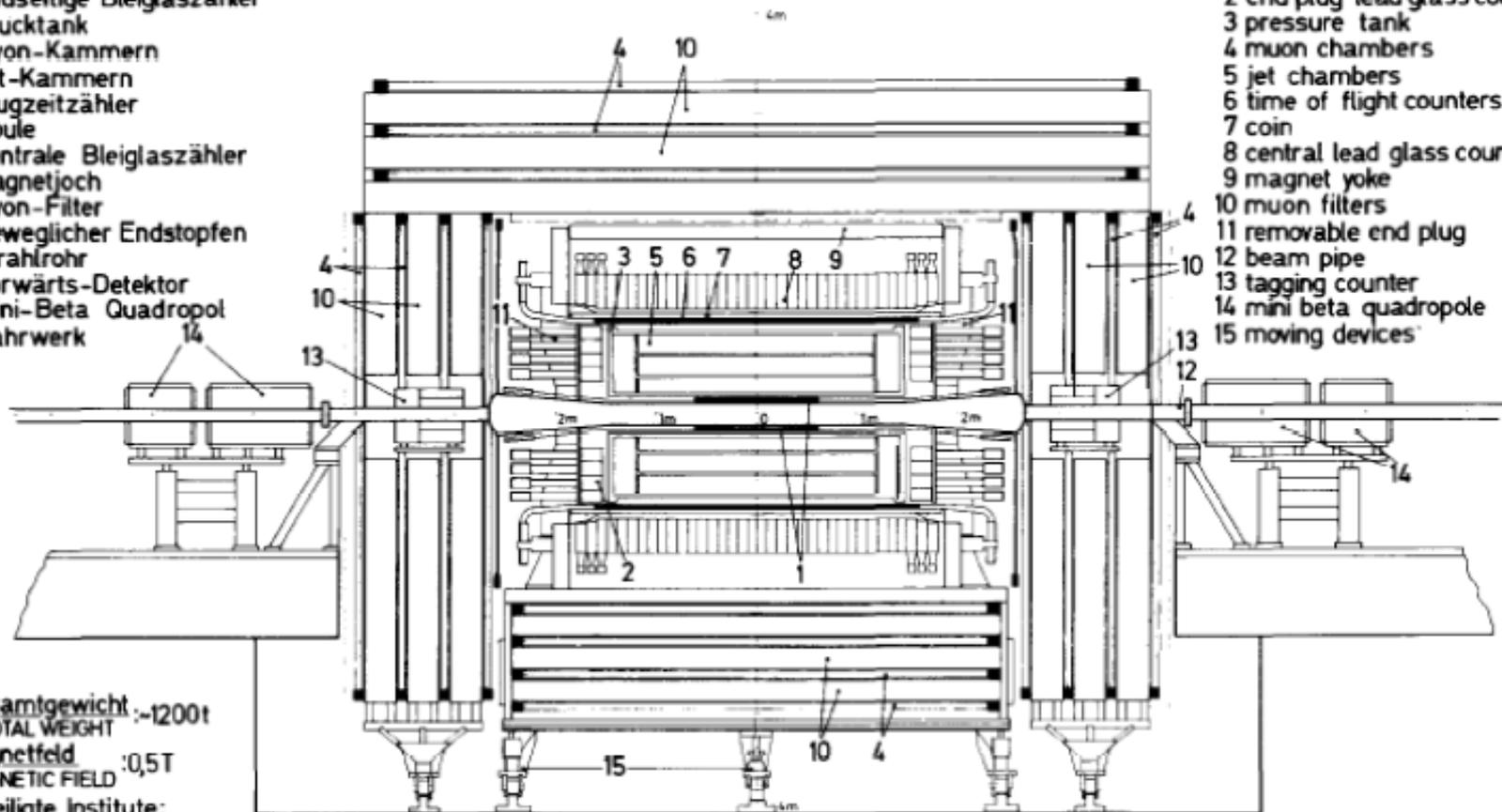
Fig. 1.1a. PETRA (Positron-Electron Tandem Ring Accelerator).

Der Jade-Detektor an PETRA

MAGNETDETEKTOR MAGNET DETECTOR **JADE**

- 1 Strahlrohrzähler
- 2 Endseitige Bleiglaszähler
- 3 Drucktank
- 4 Myon-Kammern
- 5 Jet-Kammern
- 6 Flugzeitzähler
- 7 Spule
- 8 Zentrale Bleiglaszähler
- 9 Magnetjoch
- 10 Myon-Filter
- 11 Beweglicher Endstopfen
- 12 Strahlrohr
- 13 Vorwärts-Detektor
- 14 Mini-Beta Quadropol
- 15 Fahrwerk

- 1 beampipe counters
- 2 end plug lead glass counters
- 3 pressure tank
- 4 muon chambers
- 5 jet chambers
- 6 time of flight counters
- 7 coil
- 8 central lead glass counters
- 9 magnet yoke
- 10 muon filters
- 11 removable end plug
- 12 beam pipe
- 13 tagging counter
- 14 mini beta quadropole
- 15 moving devices



Gesamtgewicht :~1200t
TOTAL WEIGHT

Magnetfeld :0,5T
MAGNETIC FIELD

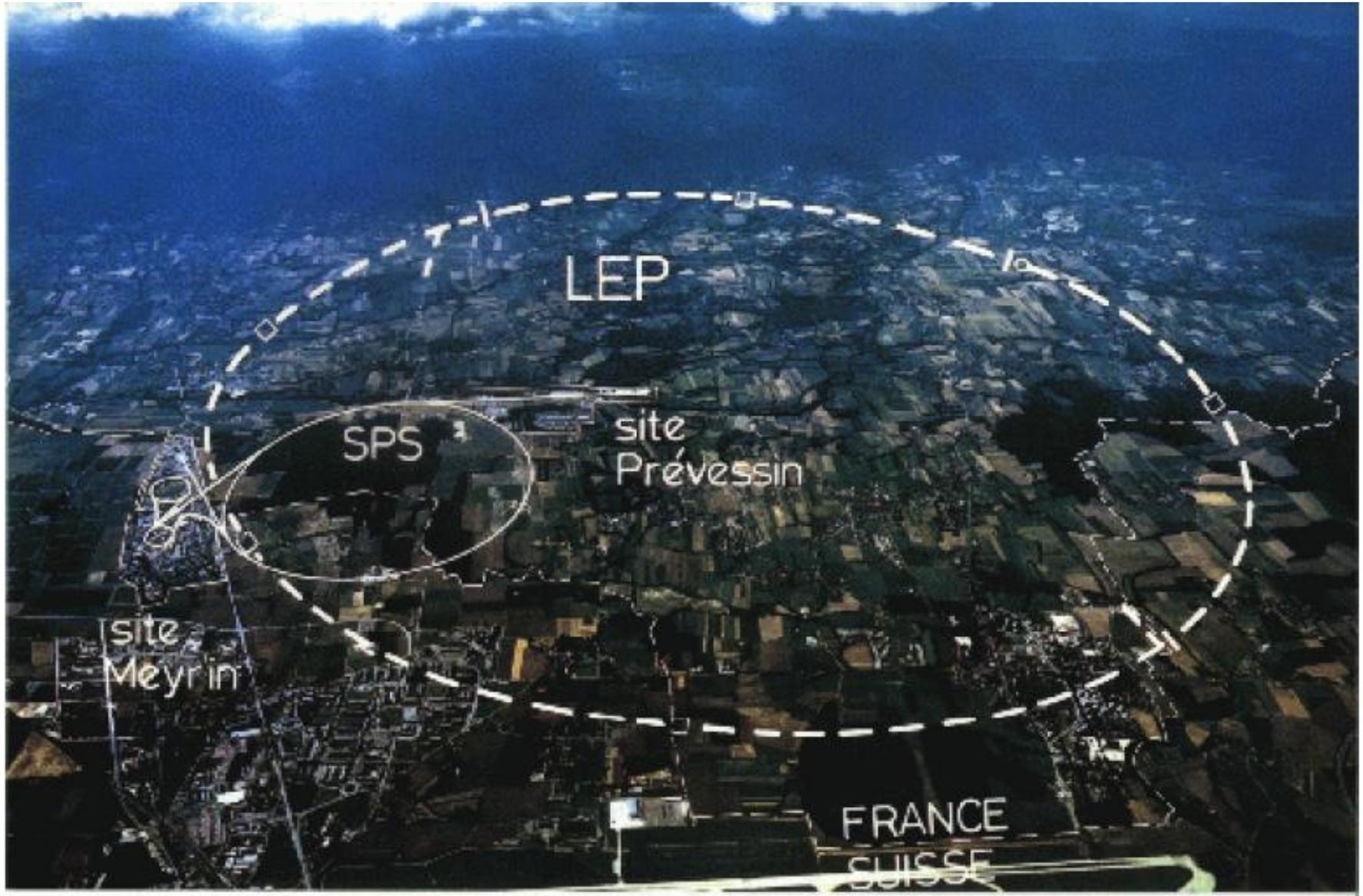
Beteiligte Institute:
PARTICIPANTS

DESY, Hamburg, Heidelberg,
Lancaster, Manchester,
Rutherford Lab, Tokio

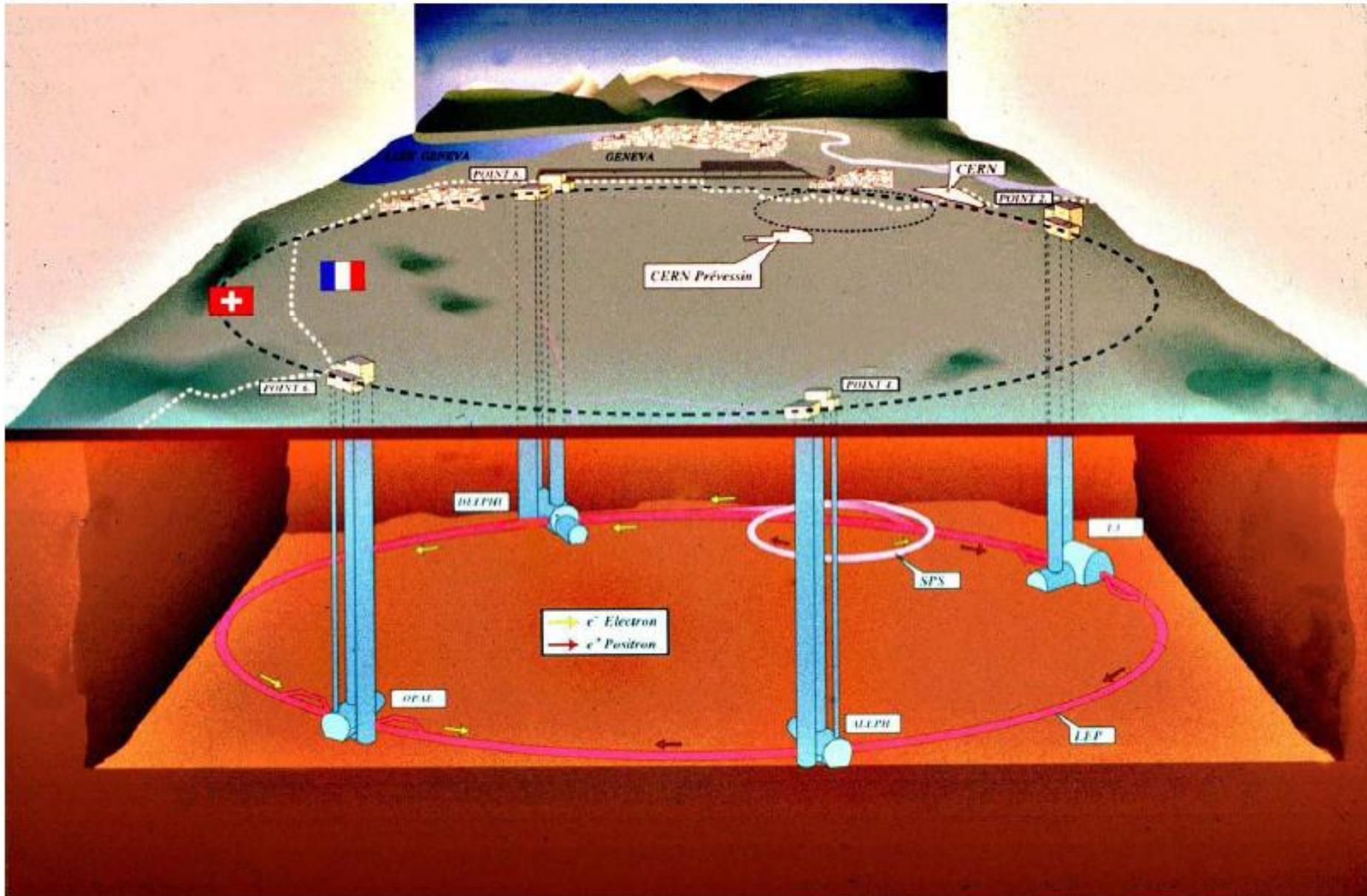
39152

Fig. 1.10. Cross section through the JADE detector.

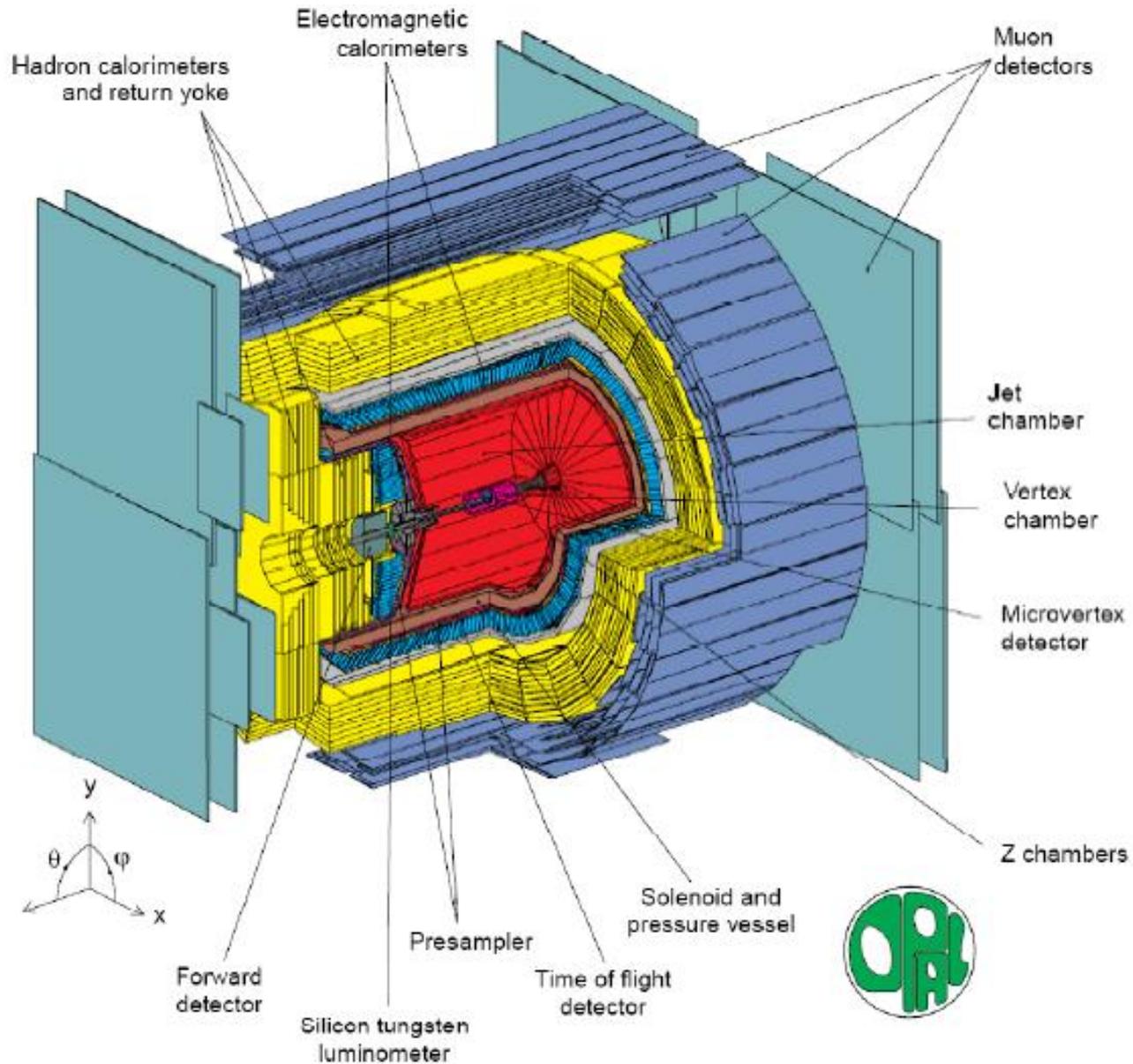
LEP: Large Electron Positron Collider bei CERN



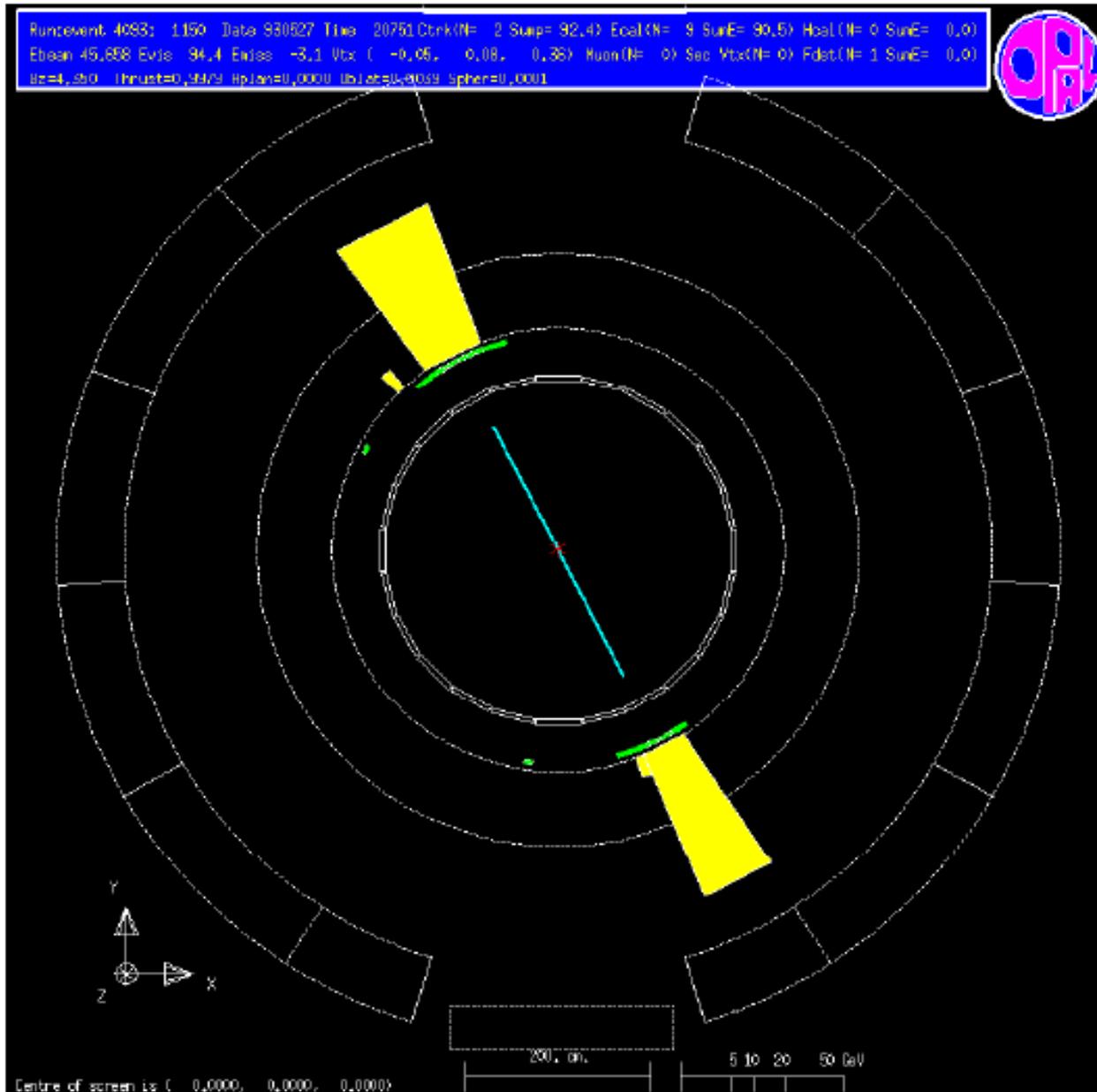
LEP: e+e- -Kollisionen von 90 bis 209 GeV



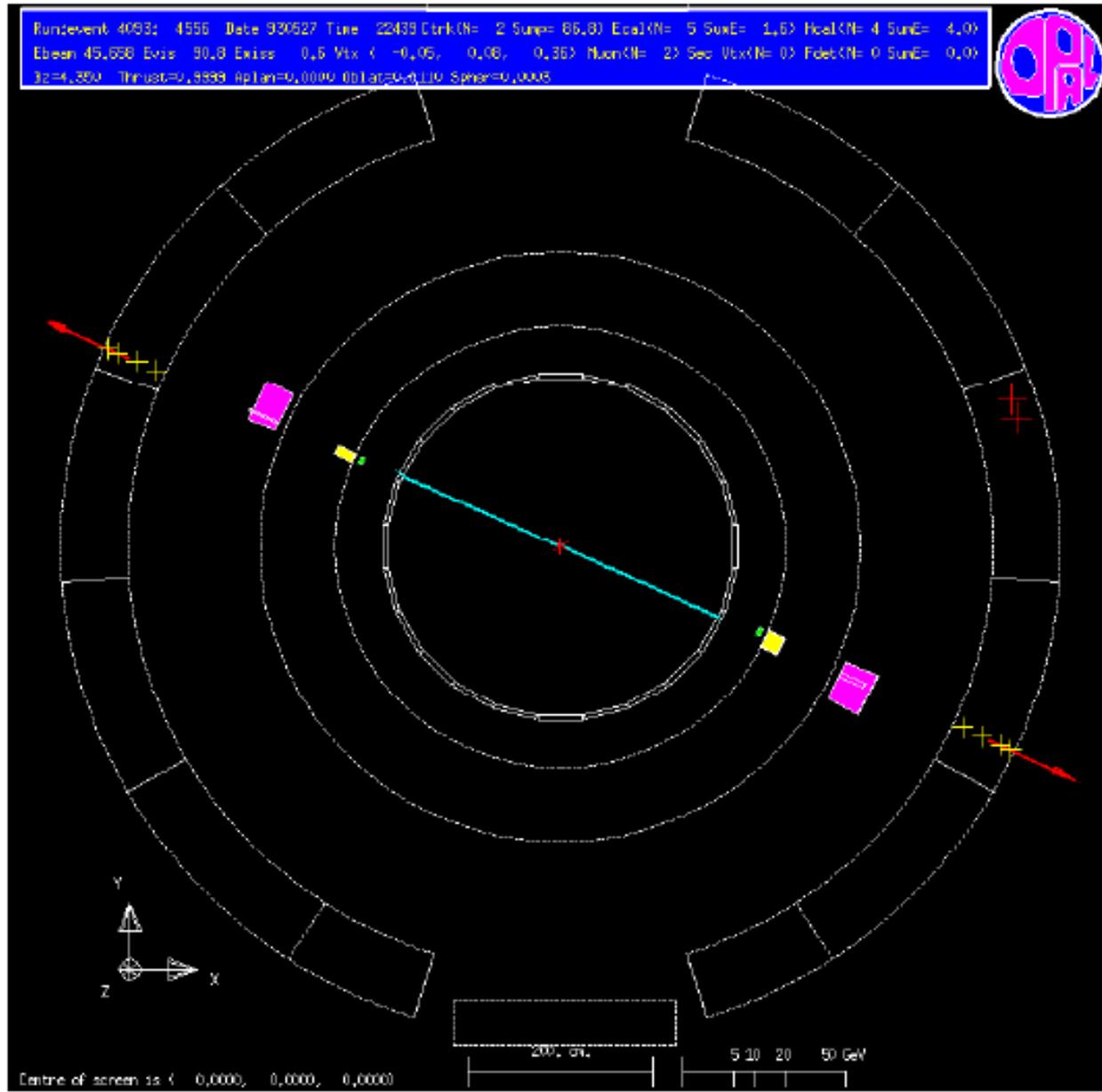
Der OPAL-Detektor an LEP



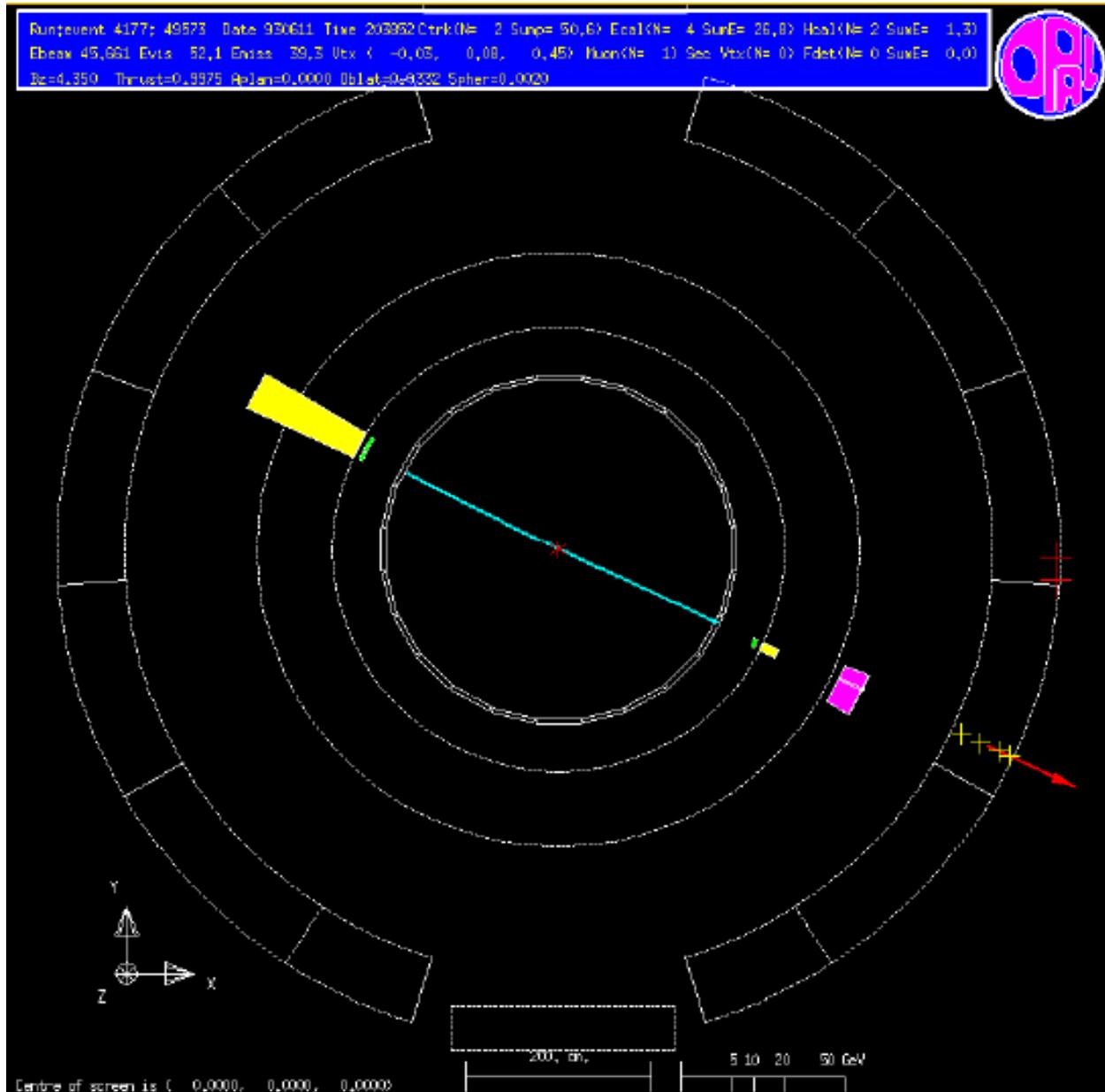
Ein Bhabha-Ereignis



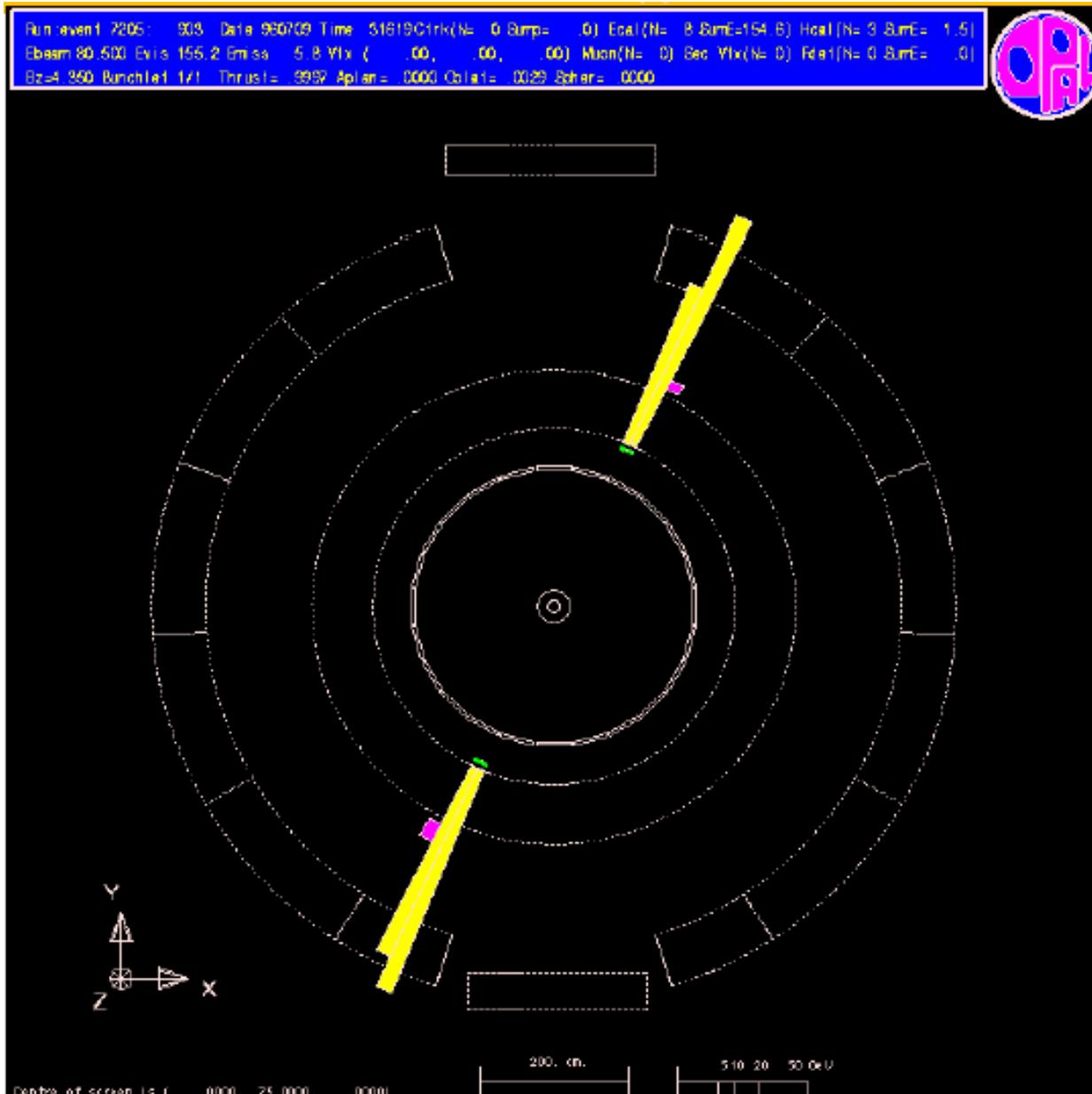
$$e^+e^- \rightarrow \mu^+\mu^-$$



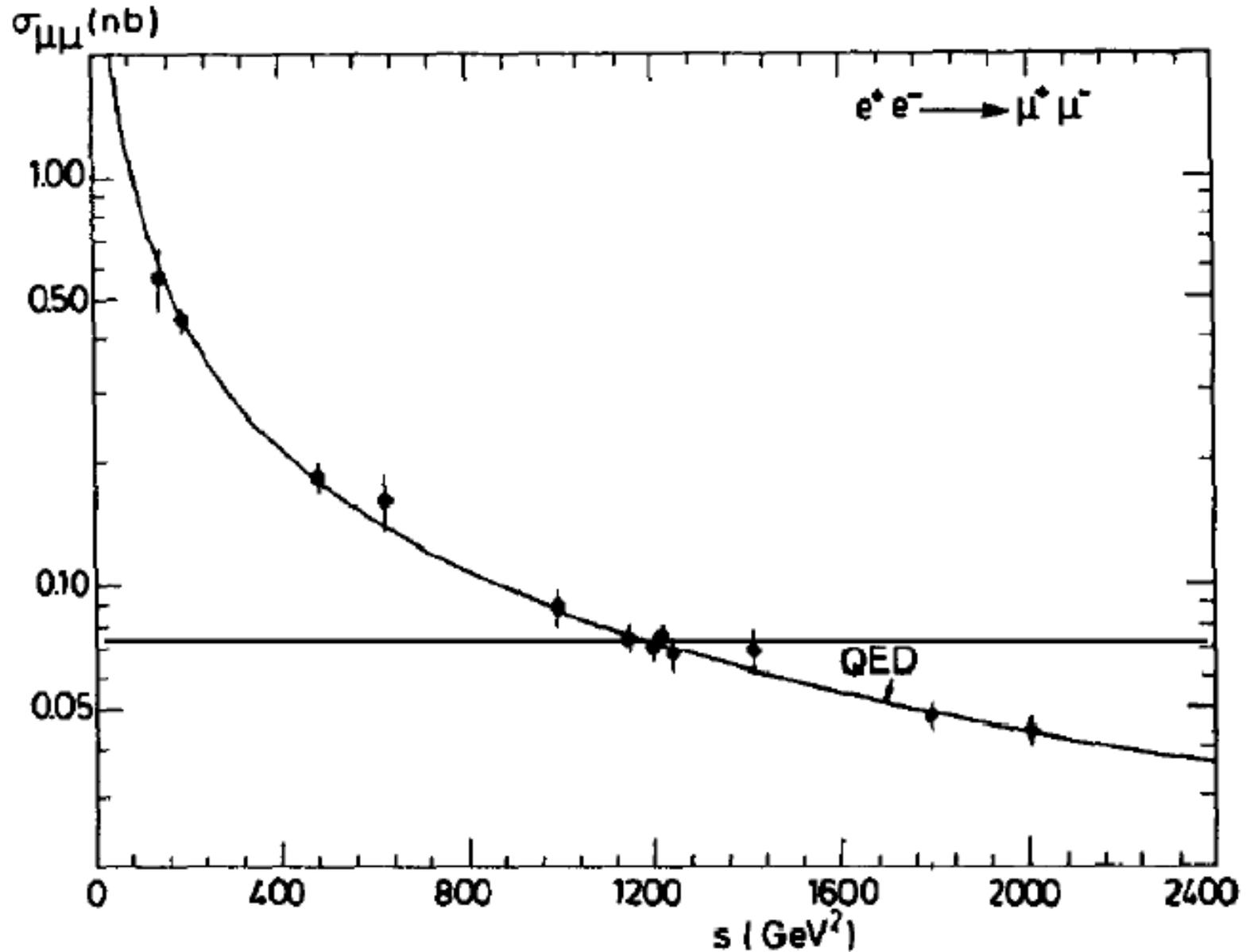
$$e^+e^- \rightarrow \tau^+\tau^-$$



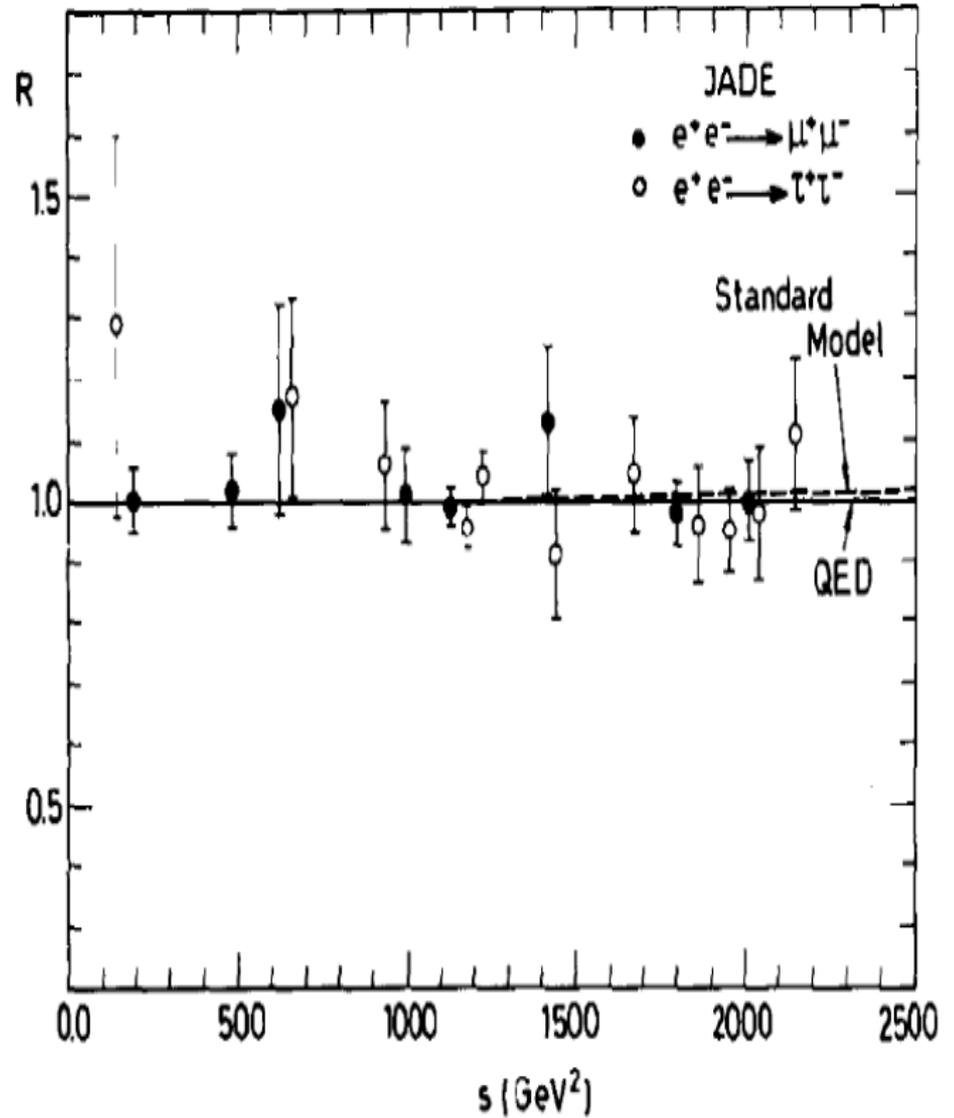
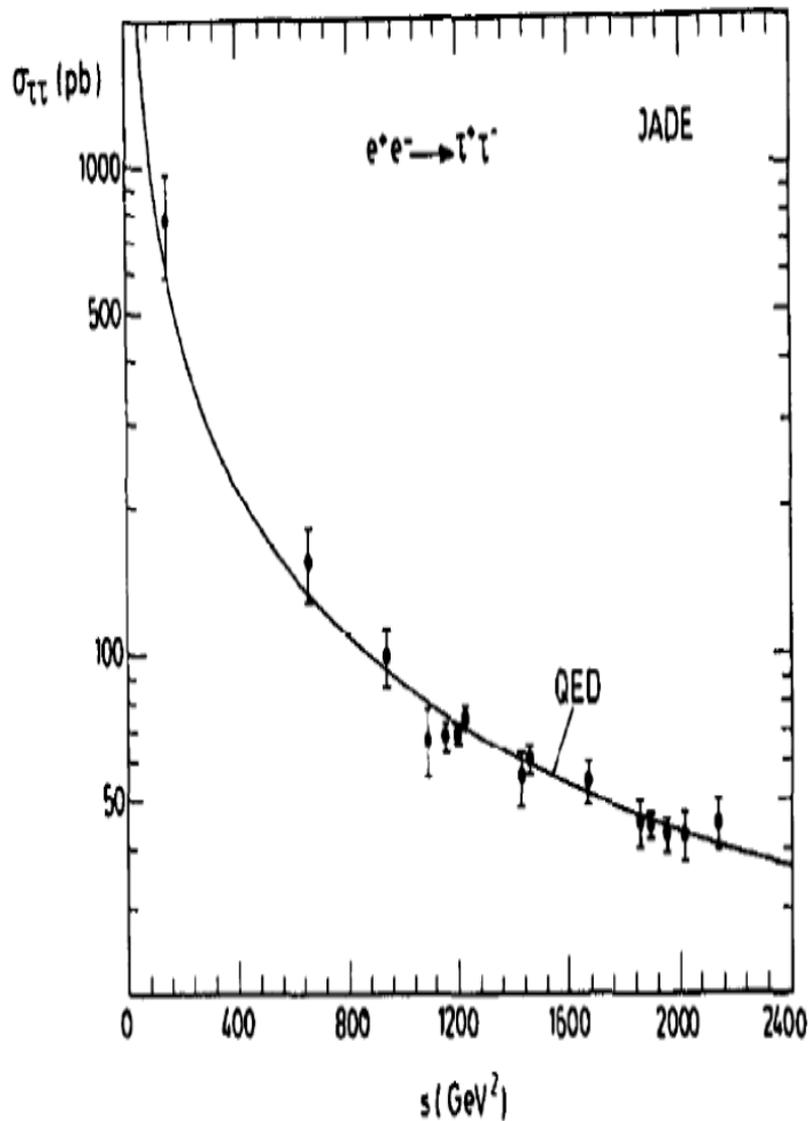
$$e^+e^- \rightarrow \gamma\gamma$$



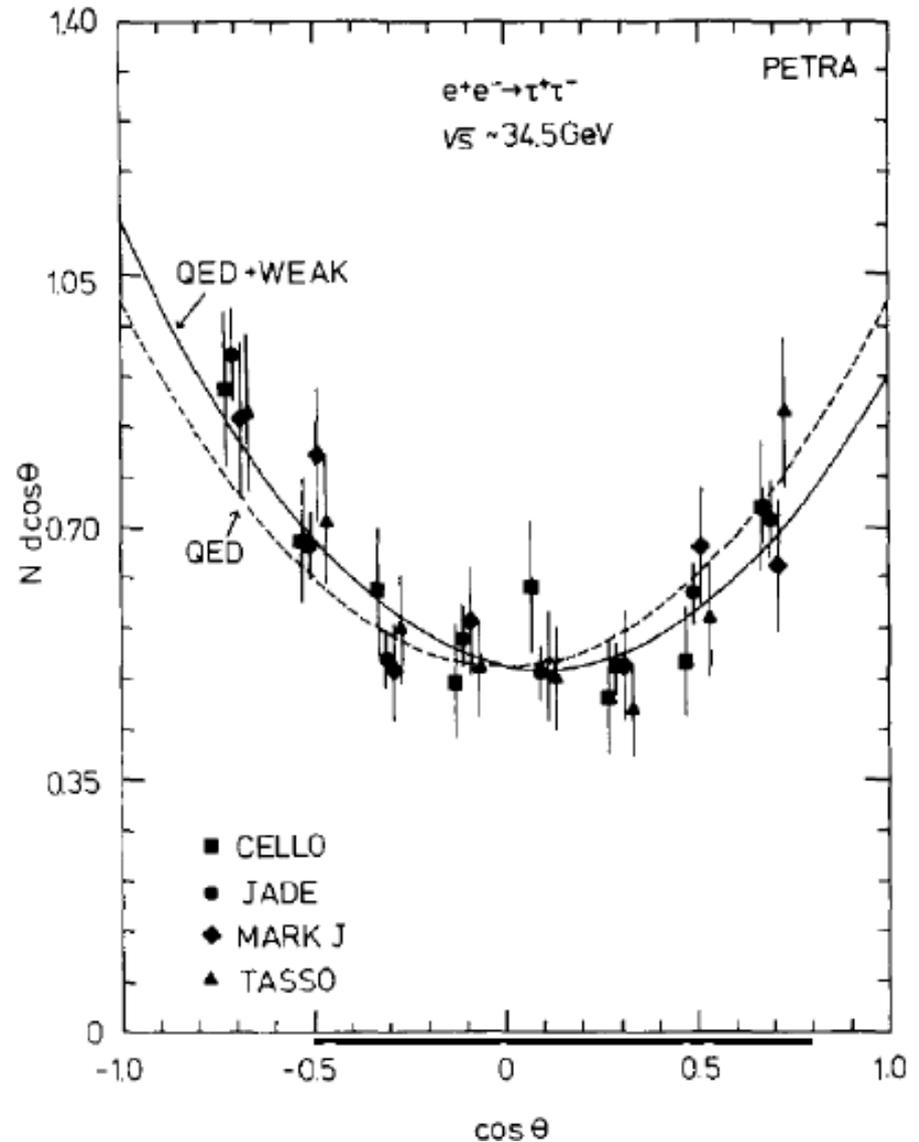
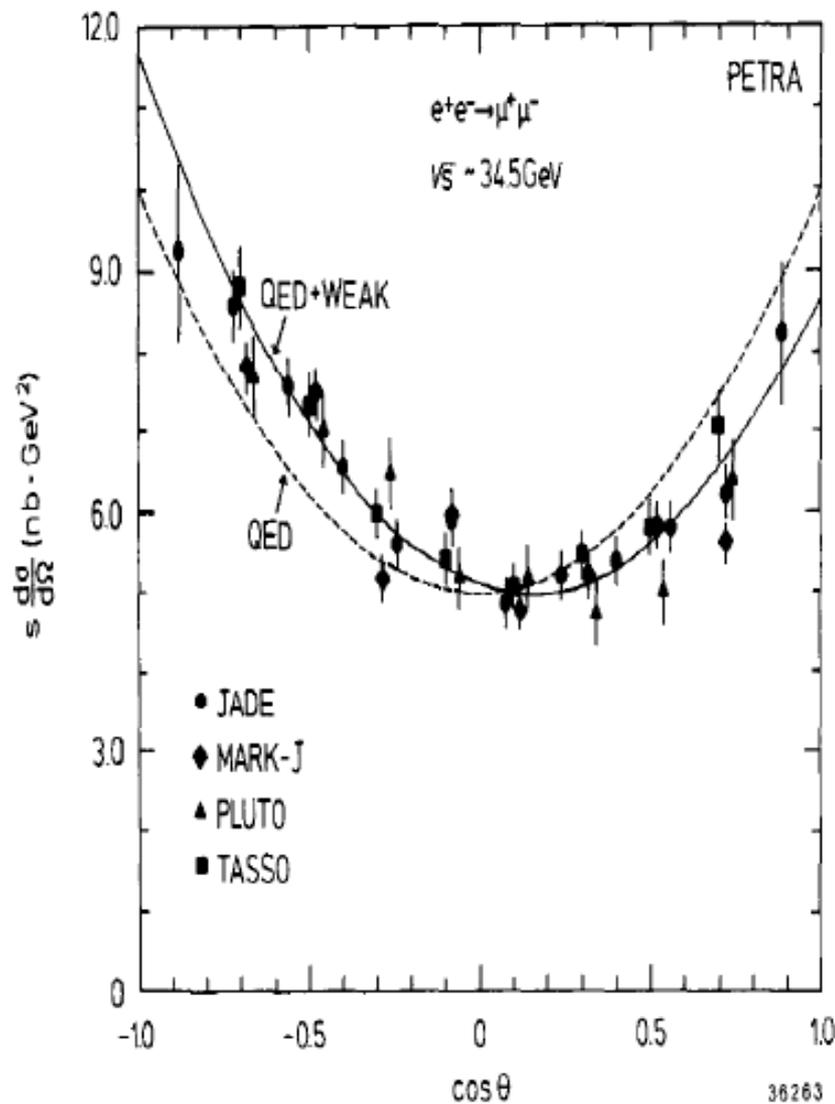
Totaler Wirkungsquerschnitt für $e^+e^- \rightarrow \mu^+\mu^-$



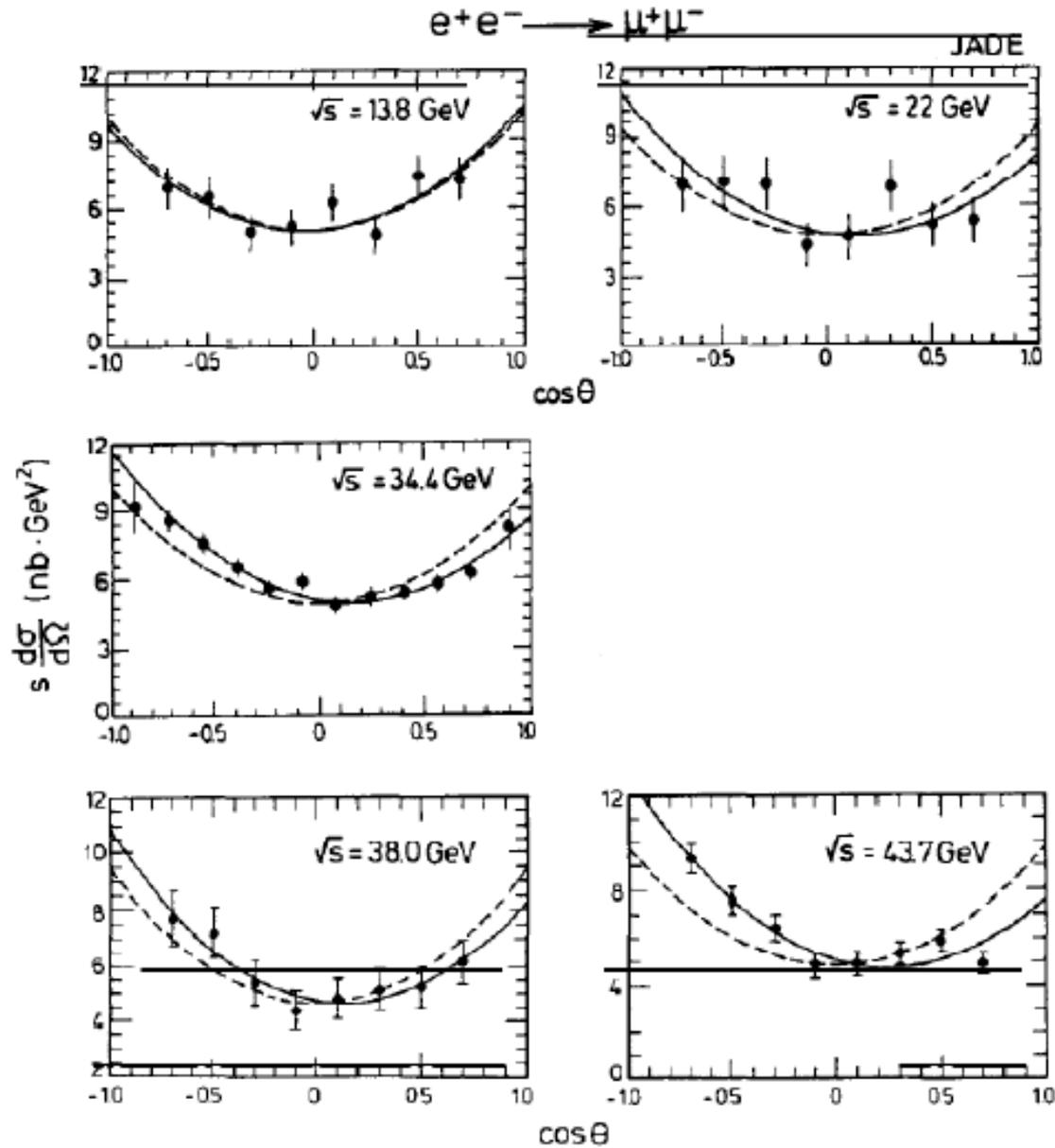
Test der Leptonuniversalität



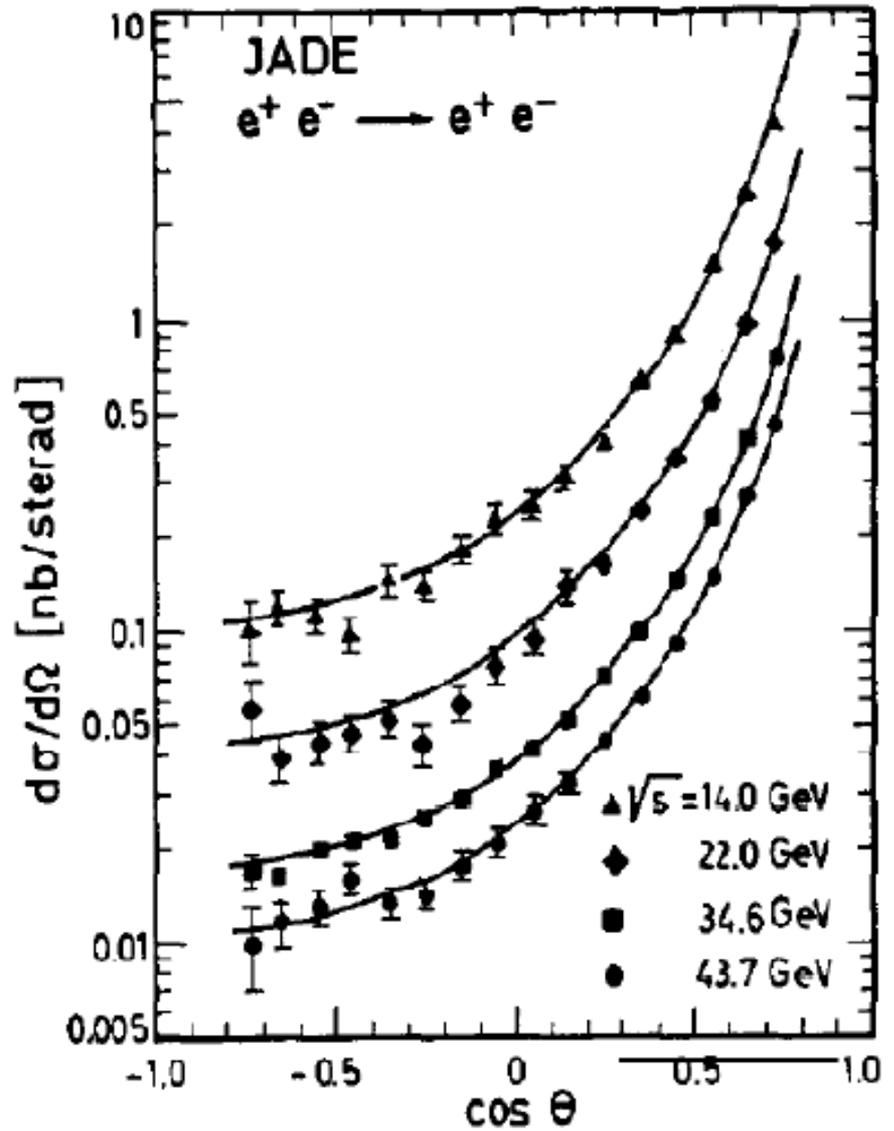
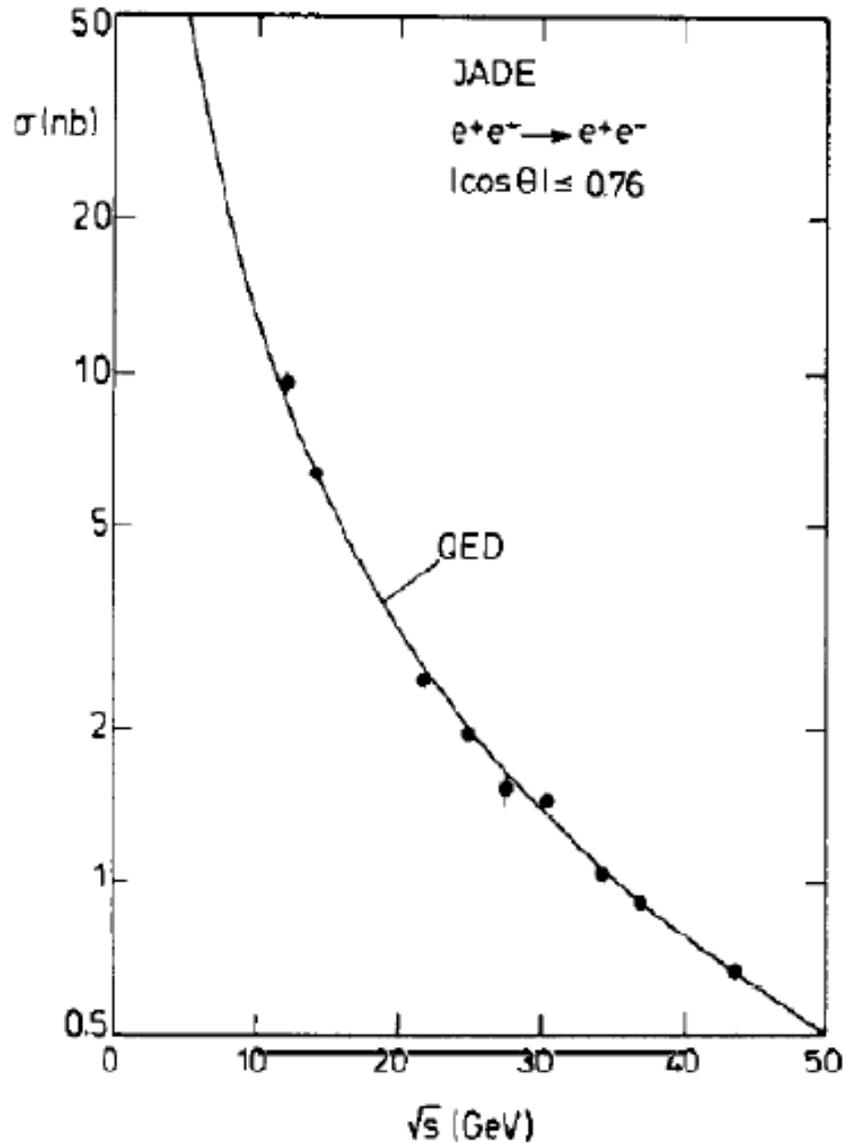
Differentieller Wirkungsquerschnitt für $e^+e^- \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$



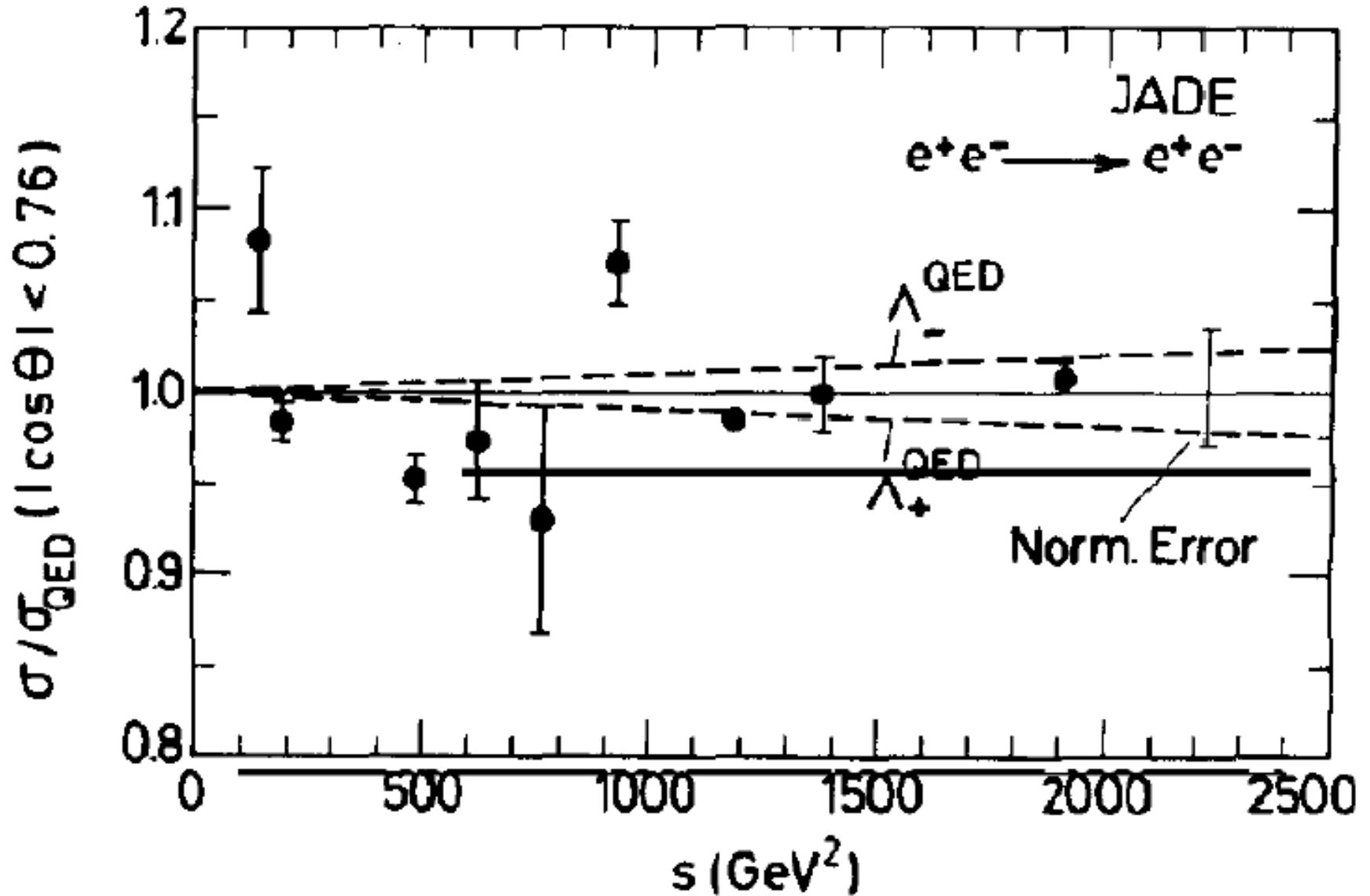
Differentieller Wirkungsquerschnitt für $e^+e^- \rightarrow \mu^+\mu^-$



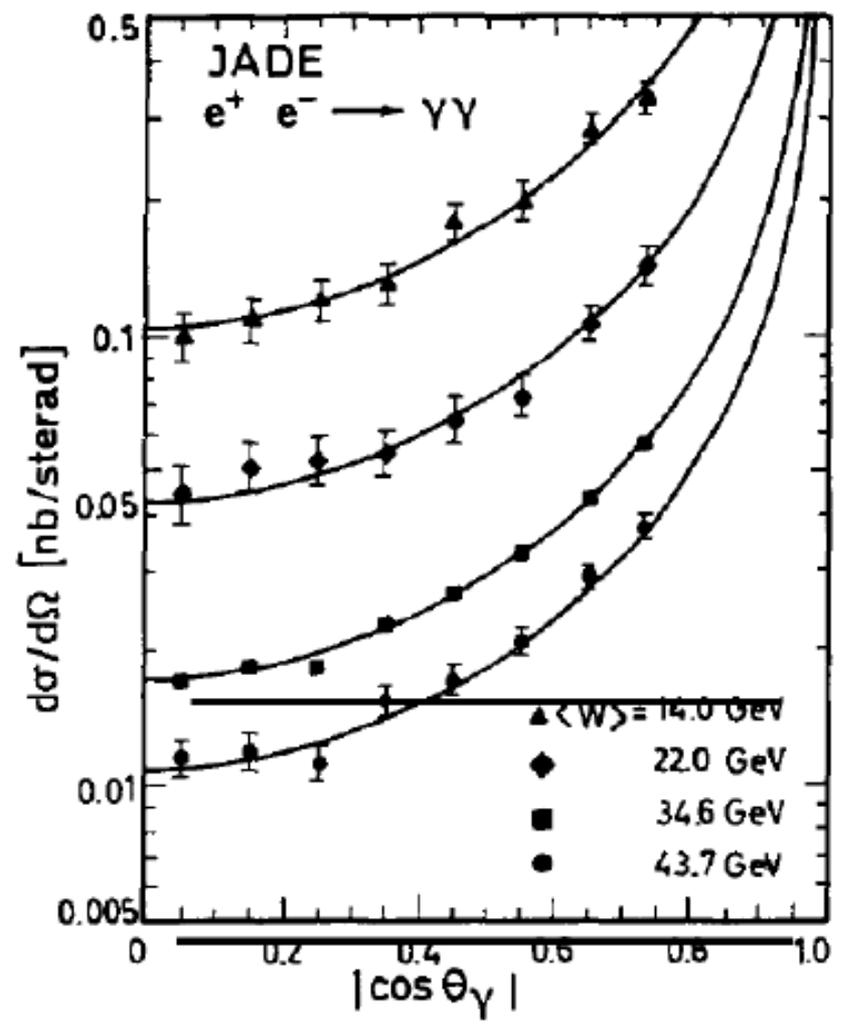
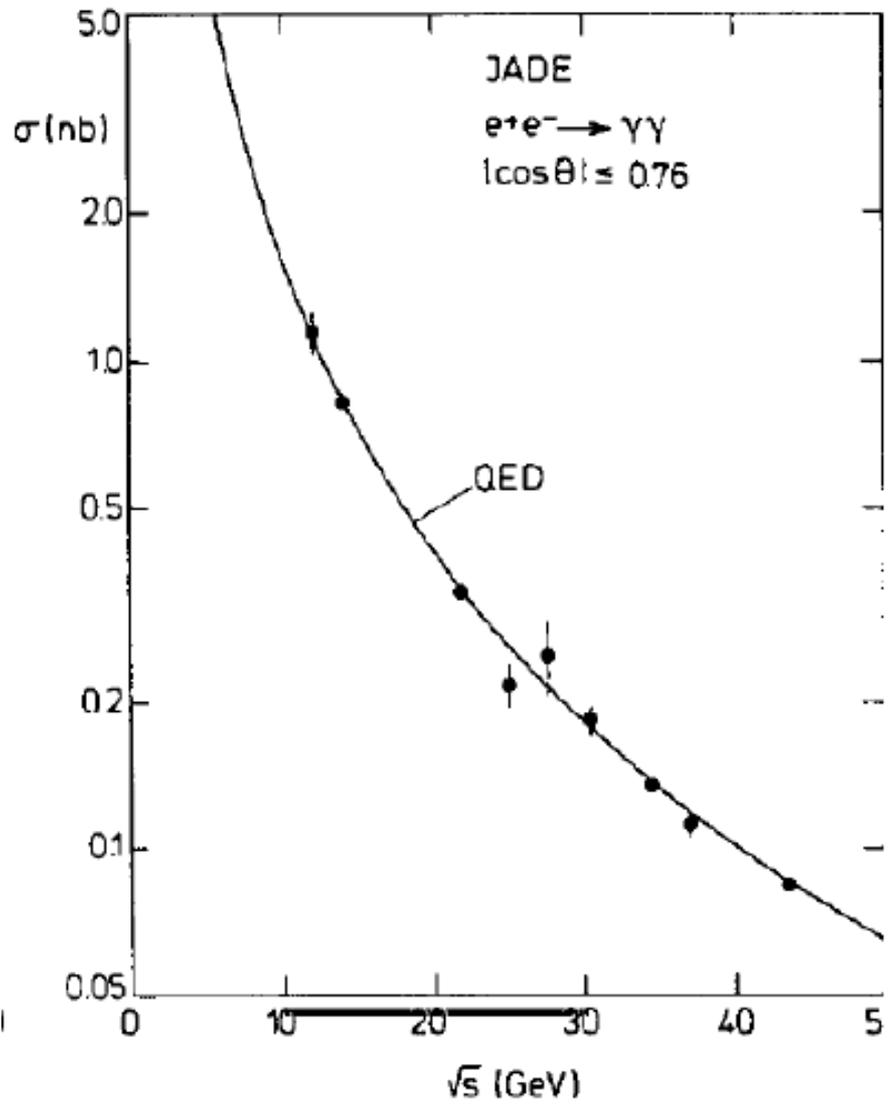
Tot. und. Differentieller Wirkungsquerschnitt für $e^+e^- \rightarrow e^+e^-$



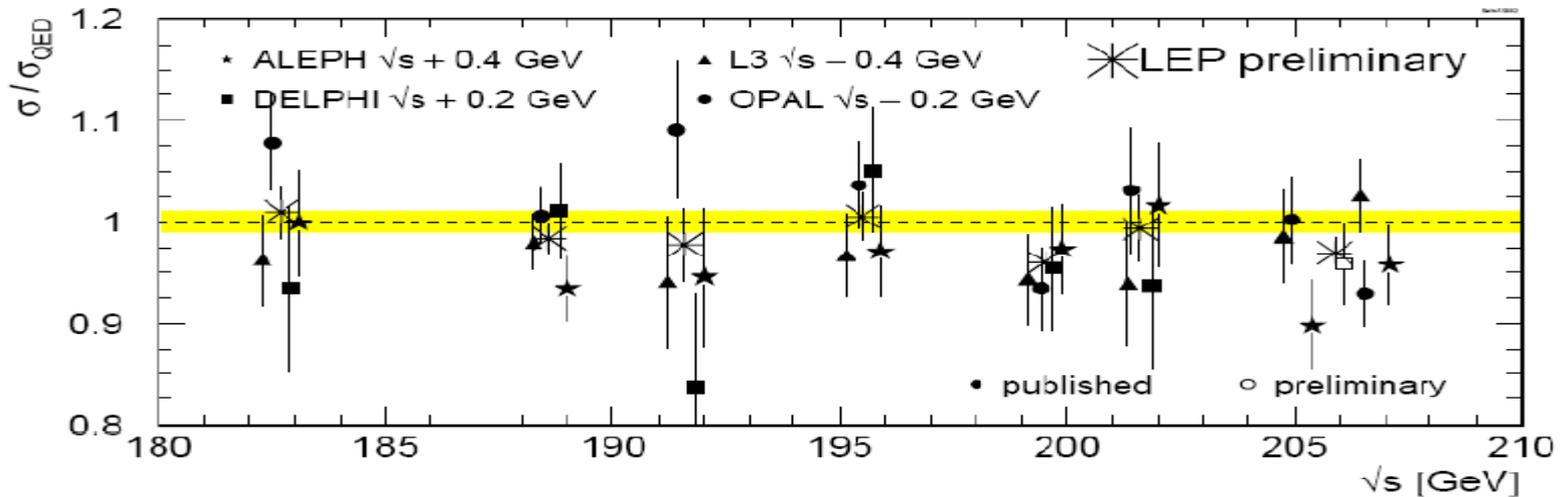
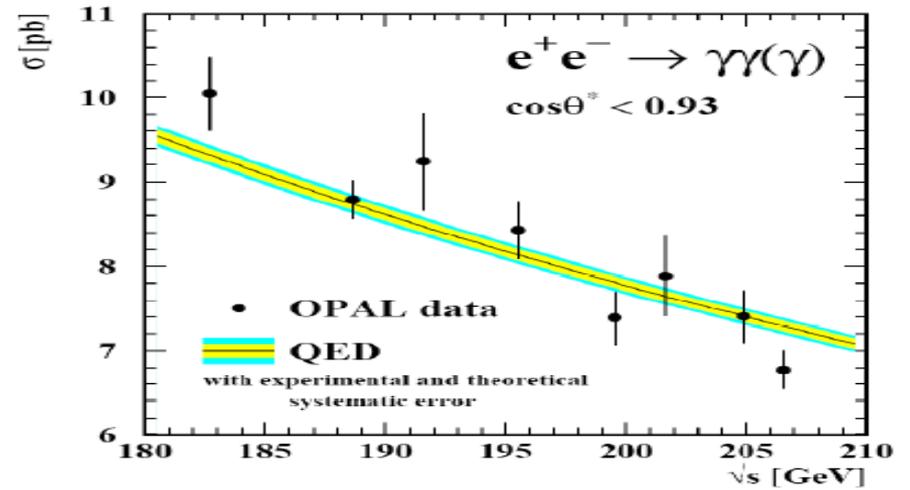
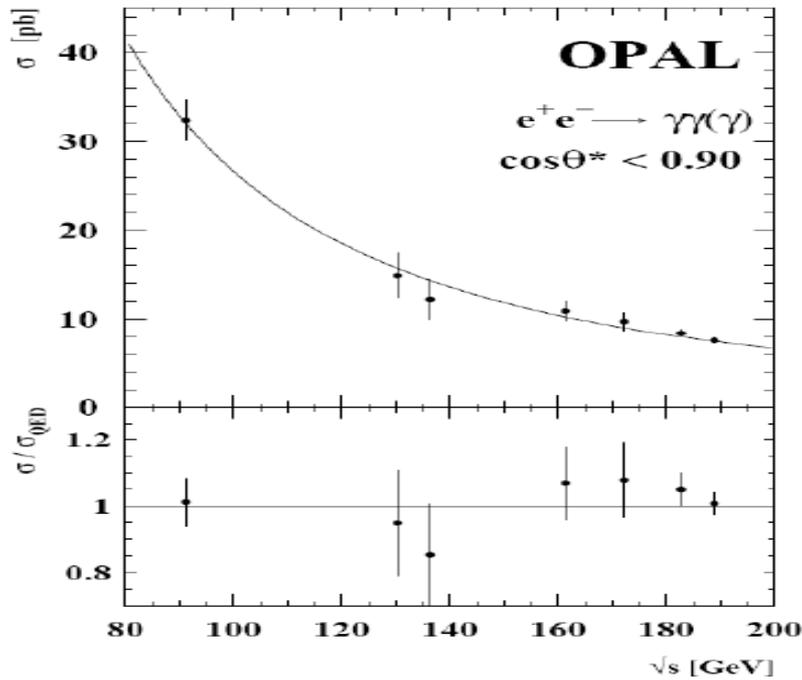
Test der QED



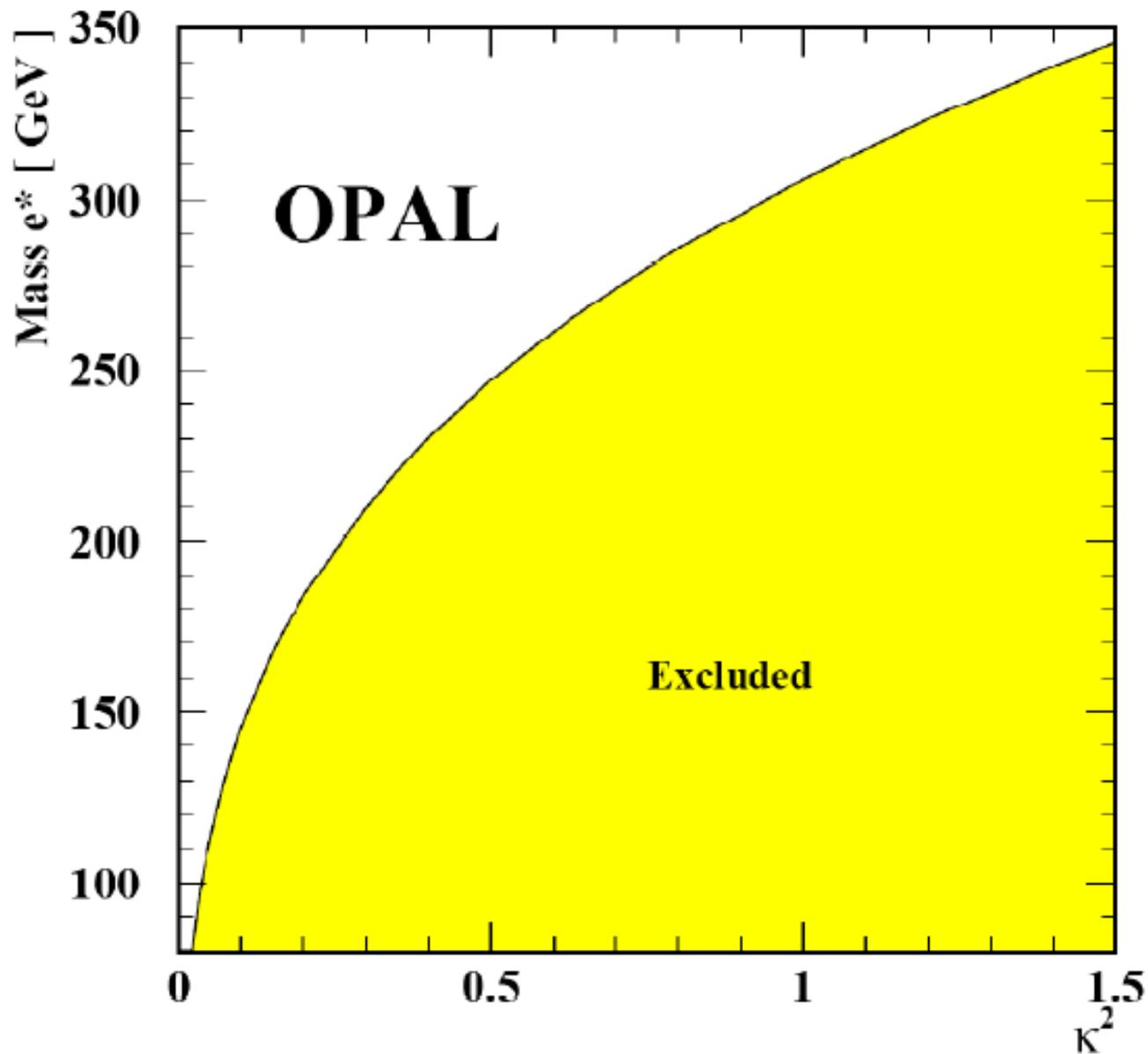
Tot. und differentieller Wirkungsquerschnitt für $e^+e^- \rightarrow \gamma\gamma$



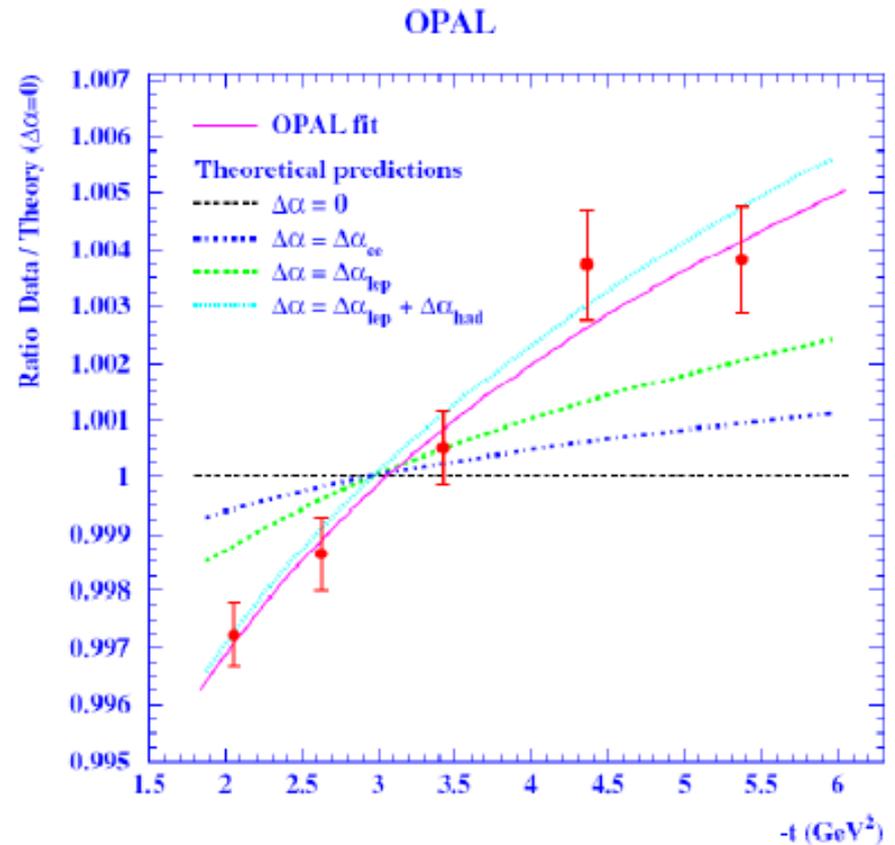
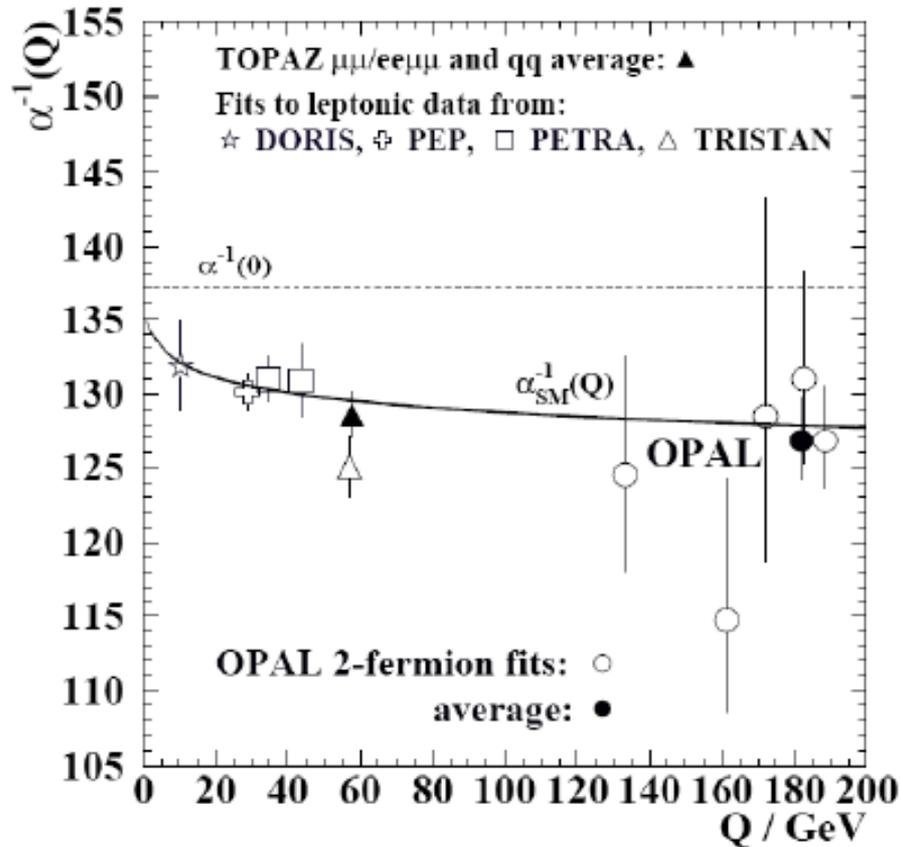
Tot. und differentieller Wirkungsquerschnitt für $e^+e^- \rightarrow \gamma\gamma$ bei LEP



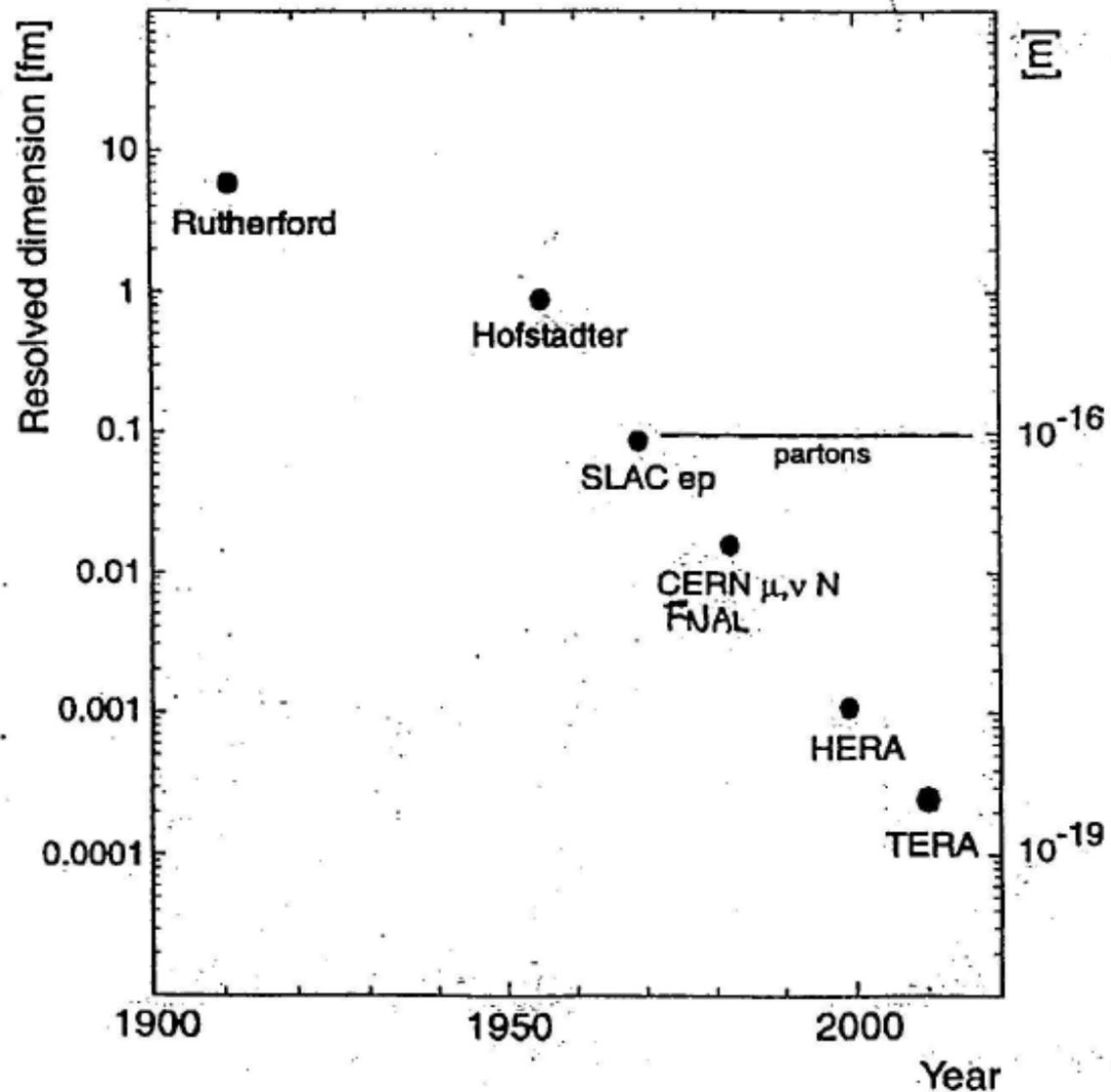
Grenze auf Masse eines schweren Elektrons



Laufende Kopplung der QED



Auflösungsvermögen in der Zeit



Von Rutherford zu 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 $\frac{1}{2}$!

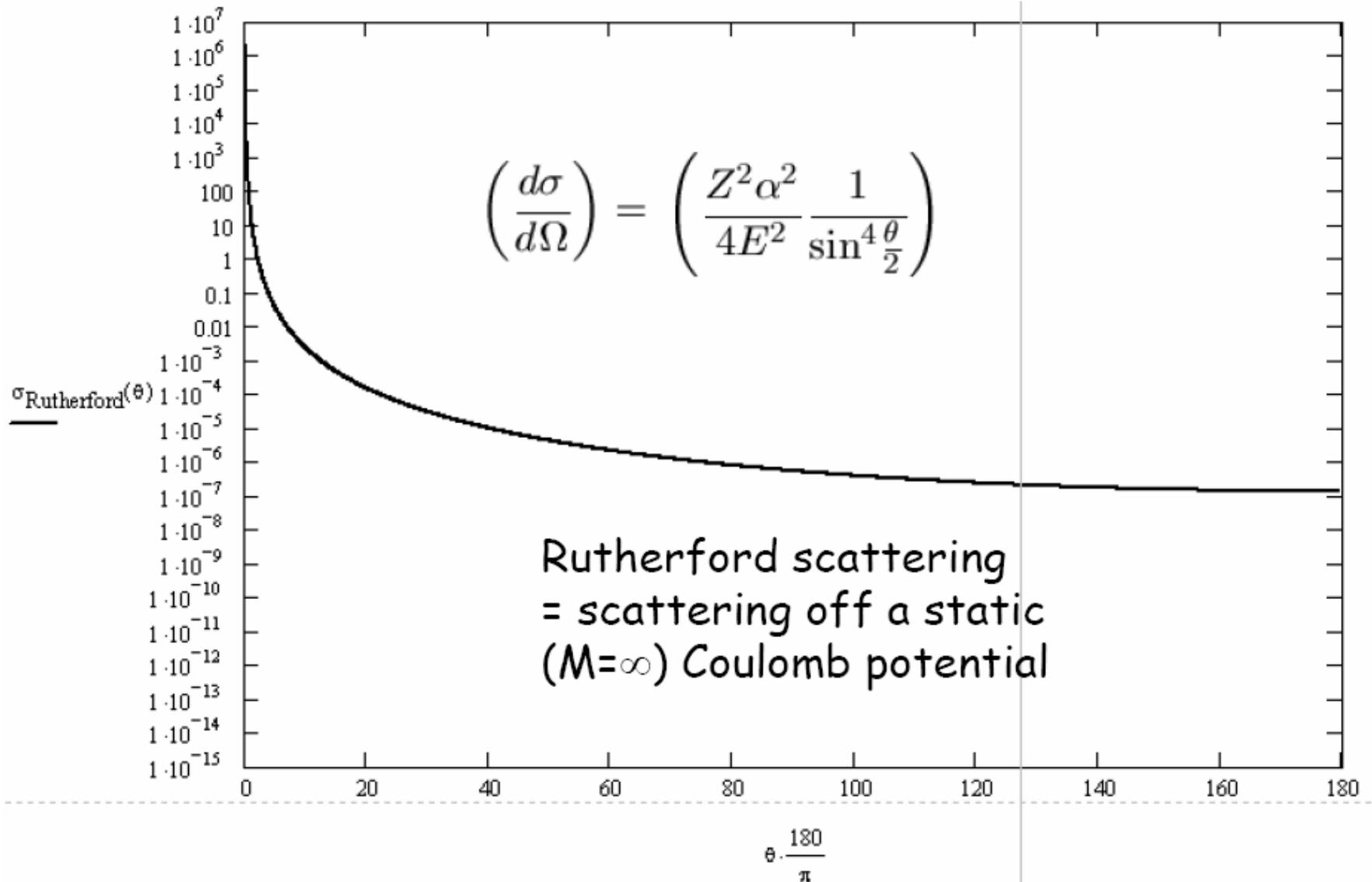
180° scattering is impossible

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

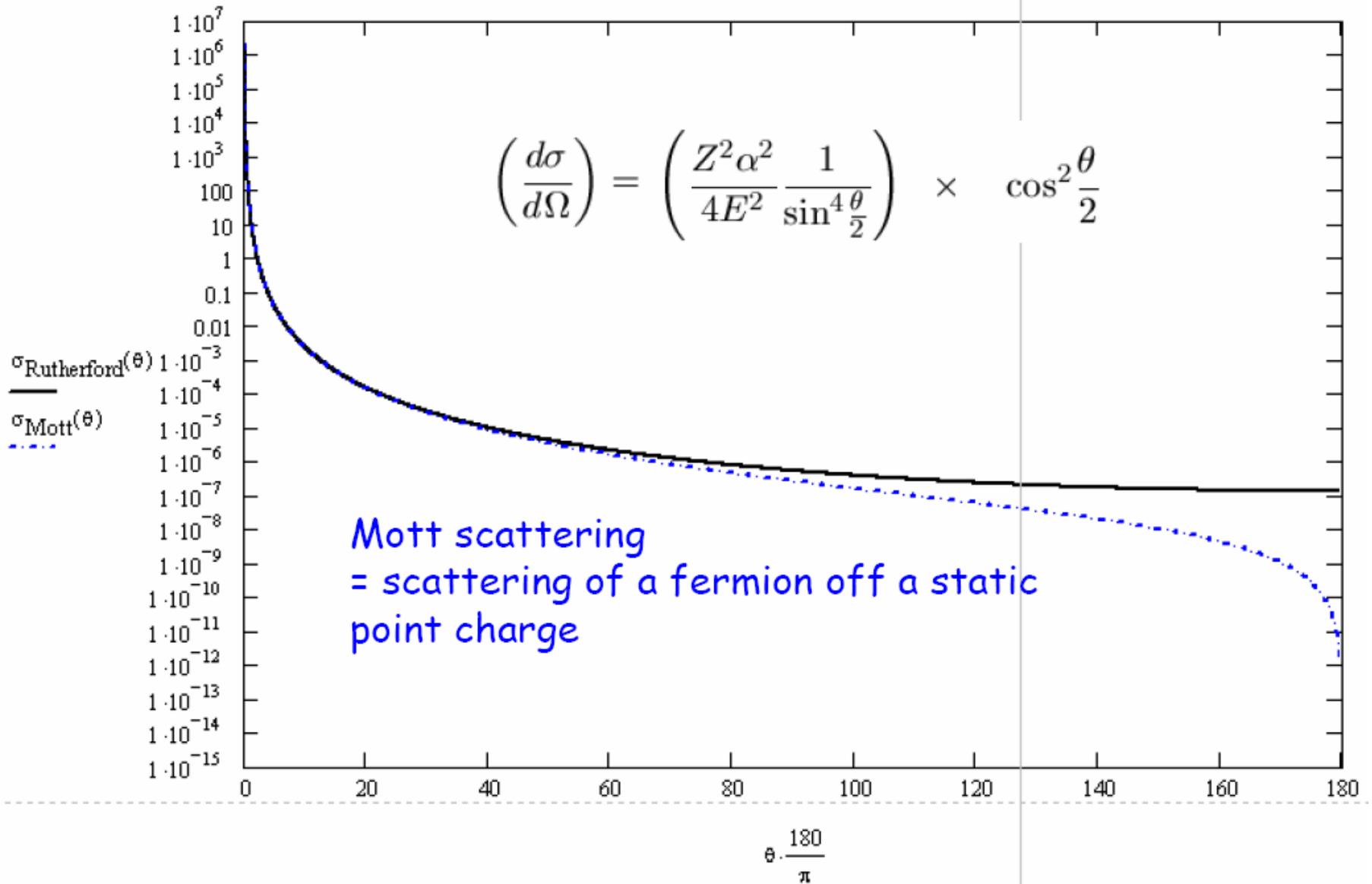
$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Dirac - Proton}}$ proton also has spin $\frac{1}{2} \Rightarrow 180^\circ$ scattering is possible again
 i.e. has a mass M_p , but not yet a structure



Rutherfordstreung (Spin 0 and schwerem Spin 0)

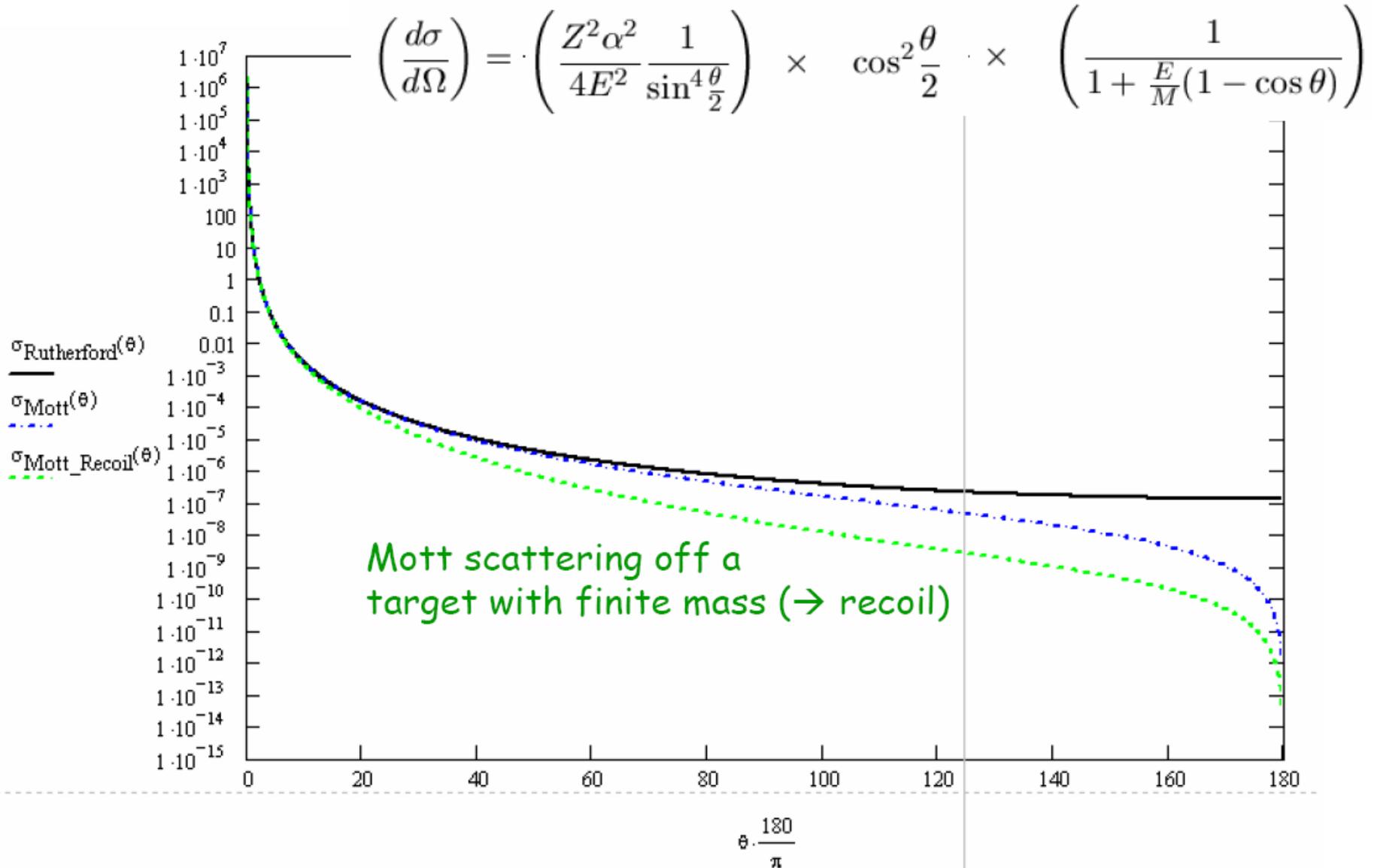


Mott-Streuung am unendlich schweren Kern



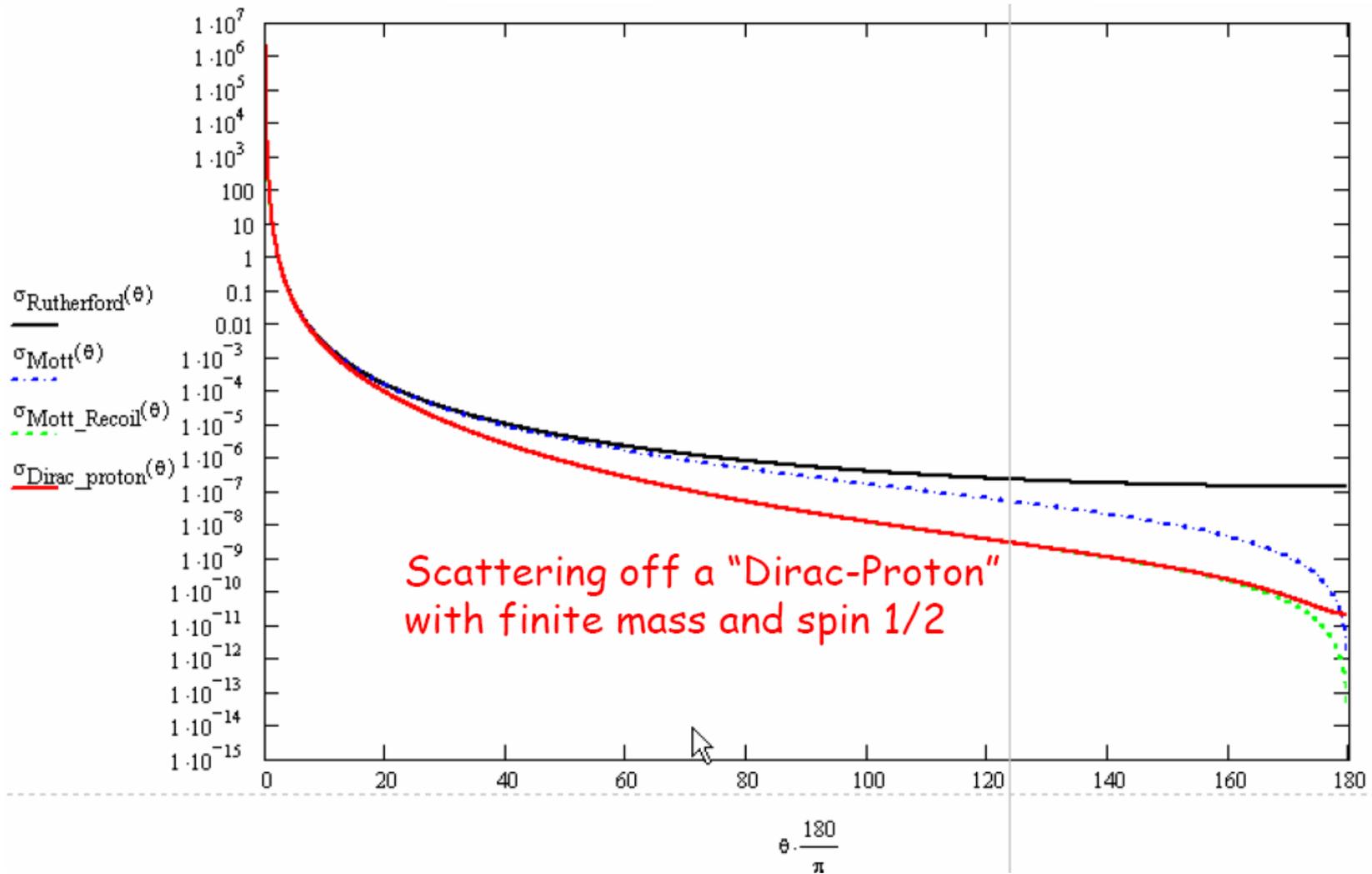
Mottstreuung am Teilchen mit endlicher Masse

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

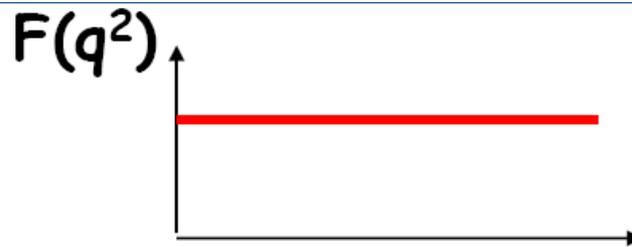


Streung am Diracproton

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

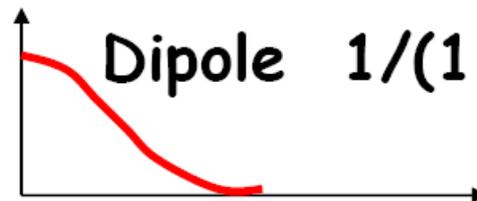
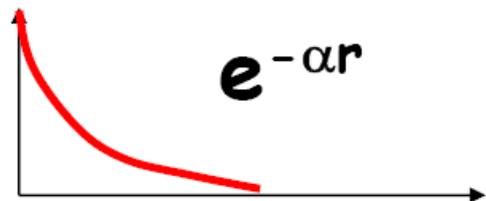


Ladungsverteilung und Formfaktor



Example

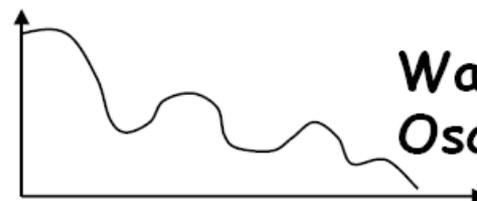
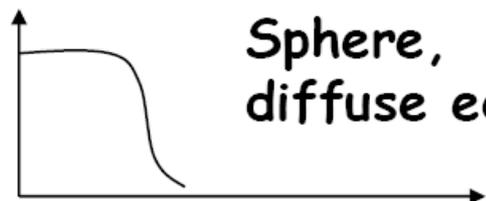
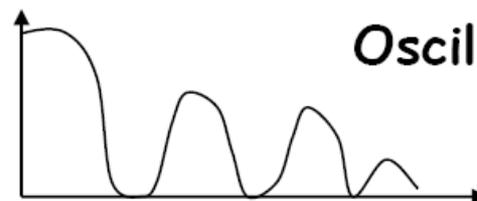
e^-



proton



${}^6\text{Li}$



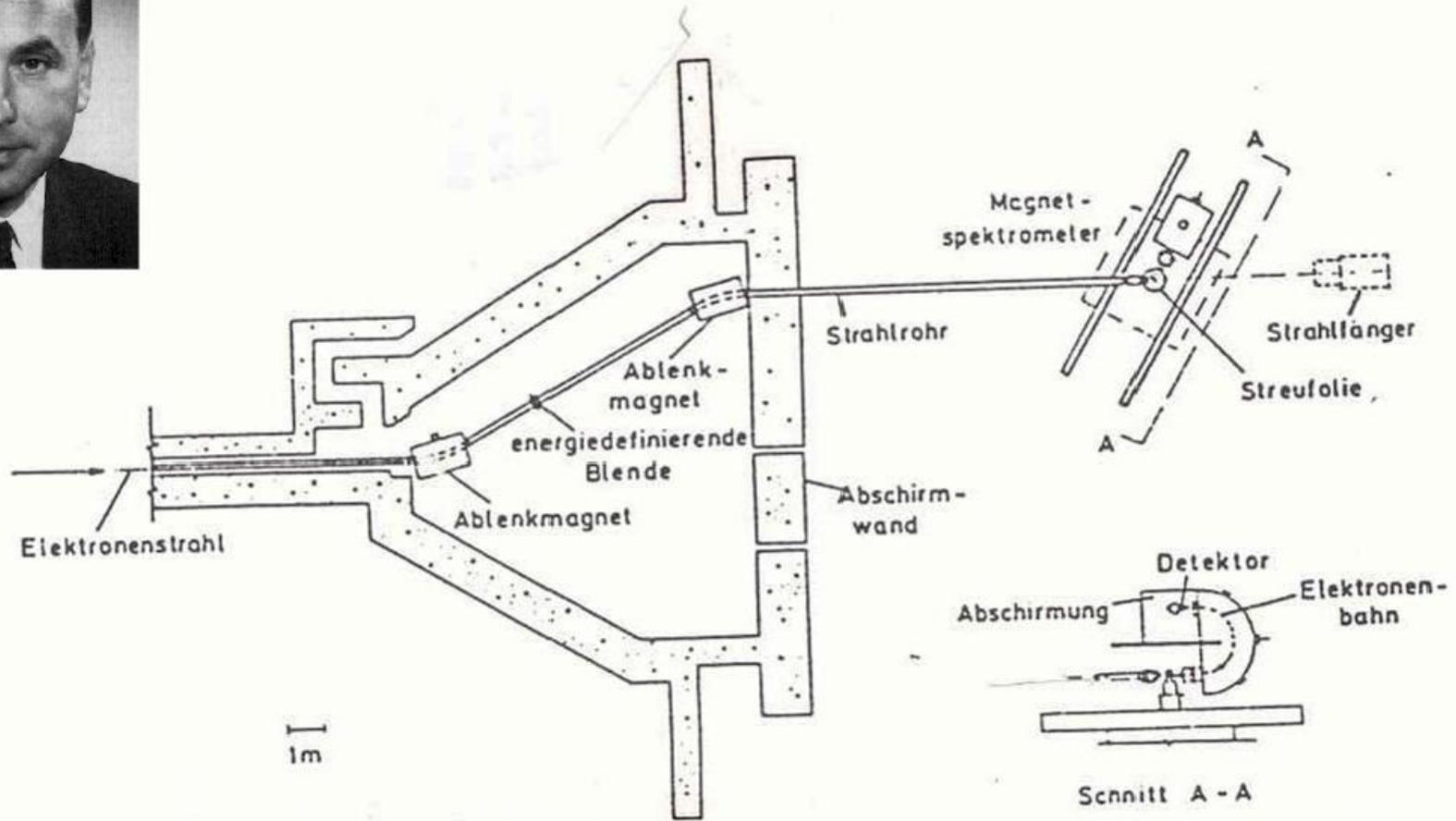
${}^{40}\text{Ca}$

Hofstadter Experiment Stanford 1955



Robert Hofstadter
Nobel Prize 1961

from
Linac



goal: detection and energy measurement of scattered electron

Hofstadter Experiment Stanford 1955

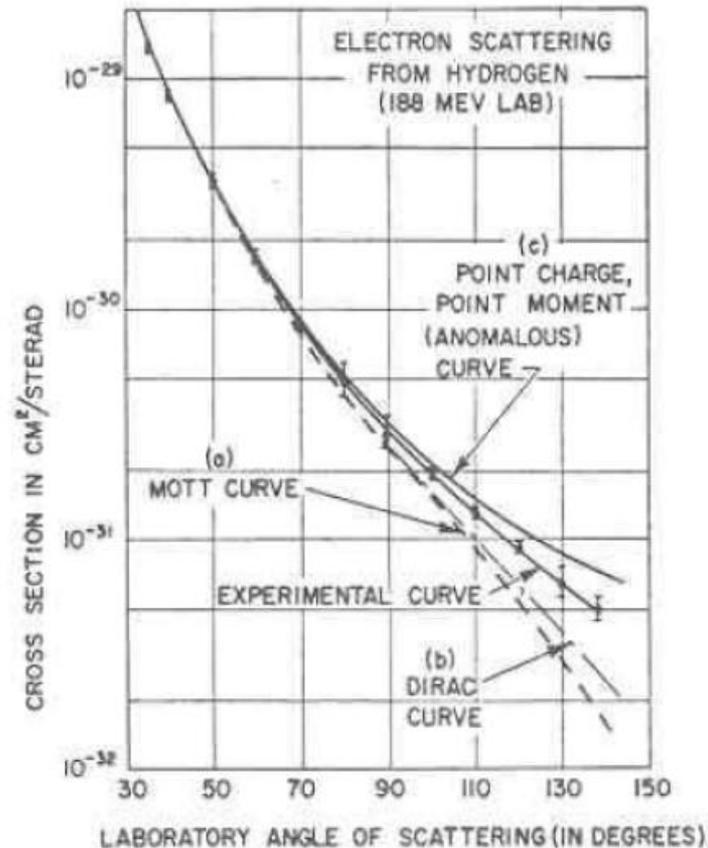
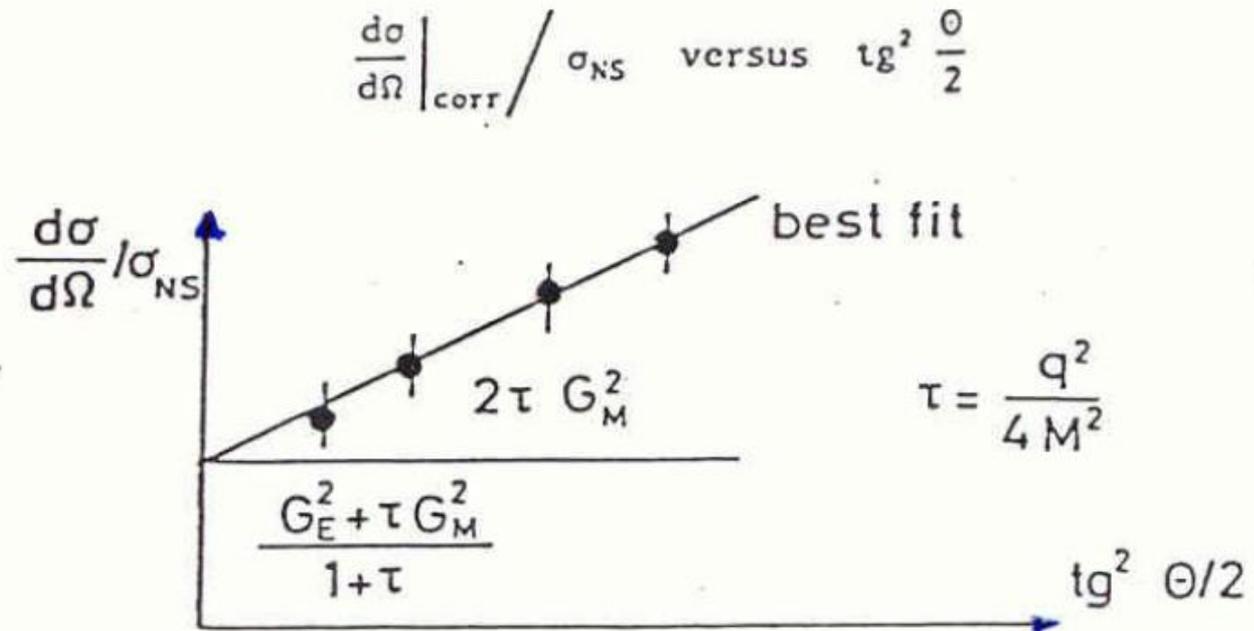


FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. 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 Formfaktoren



The form factors are then extracted from

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

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

Messung des Protonformfaktors

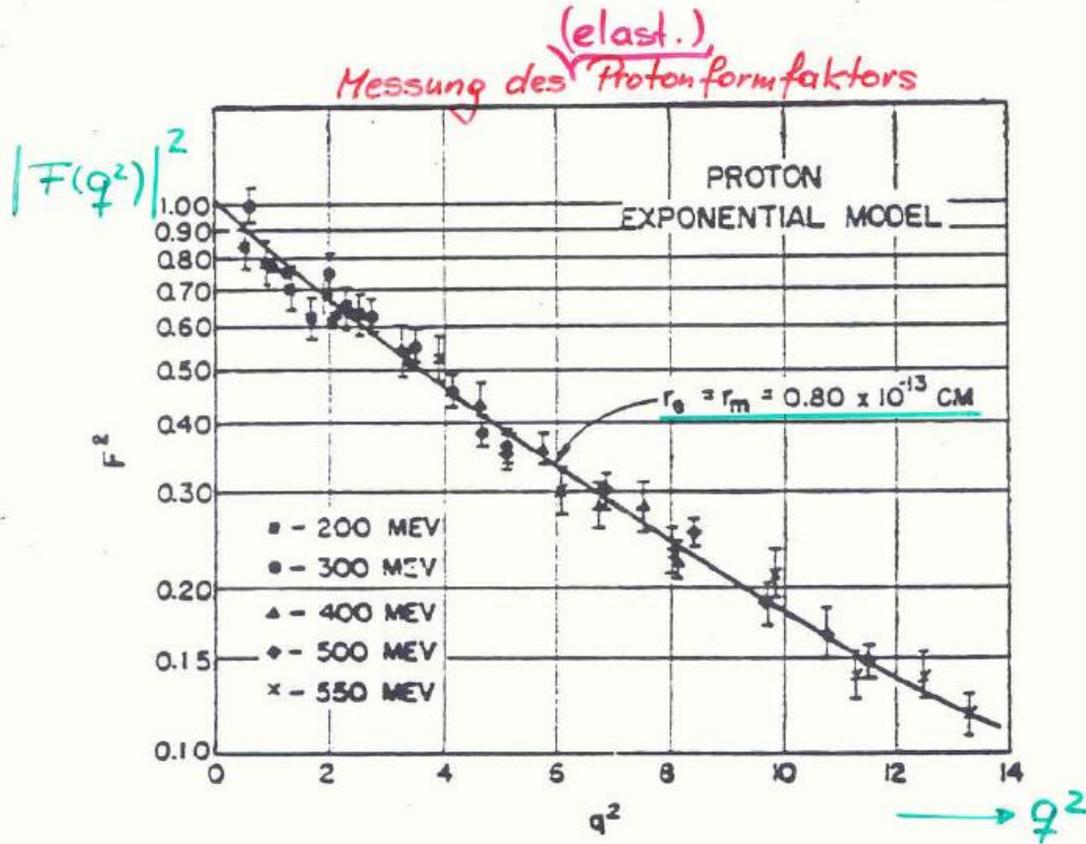
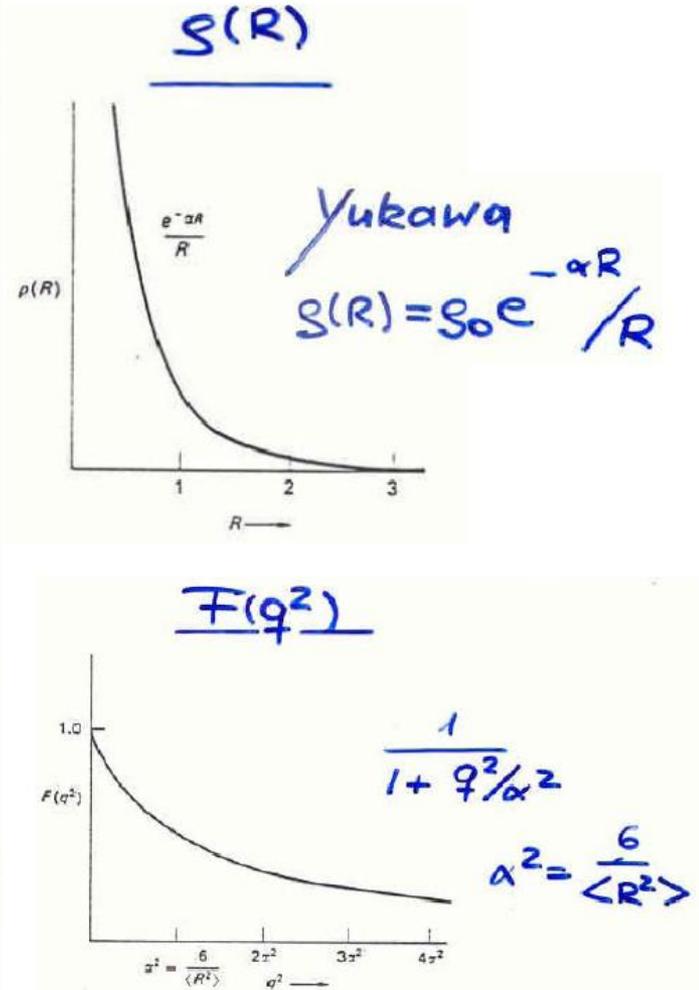
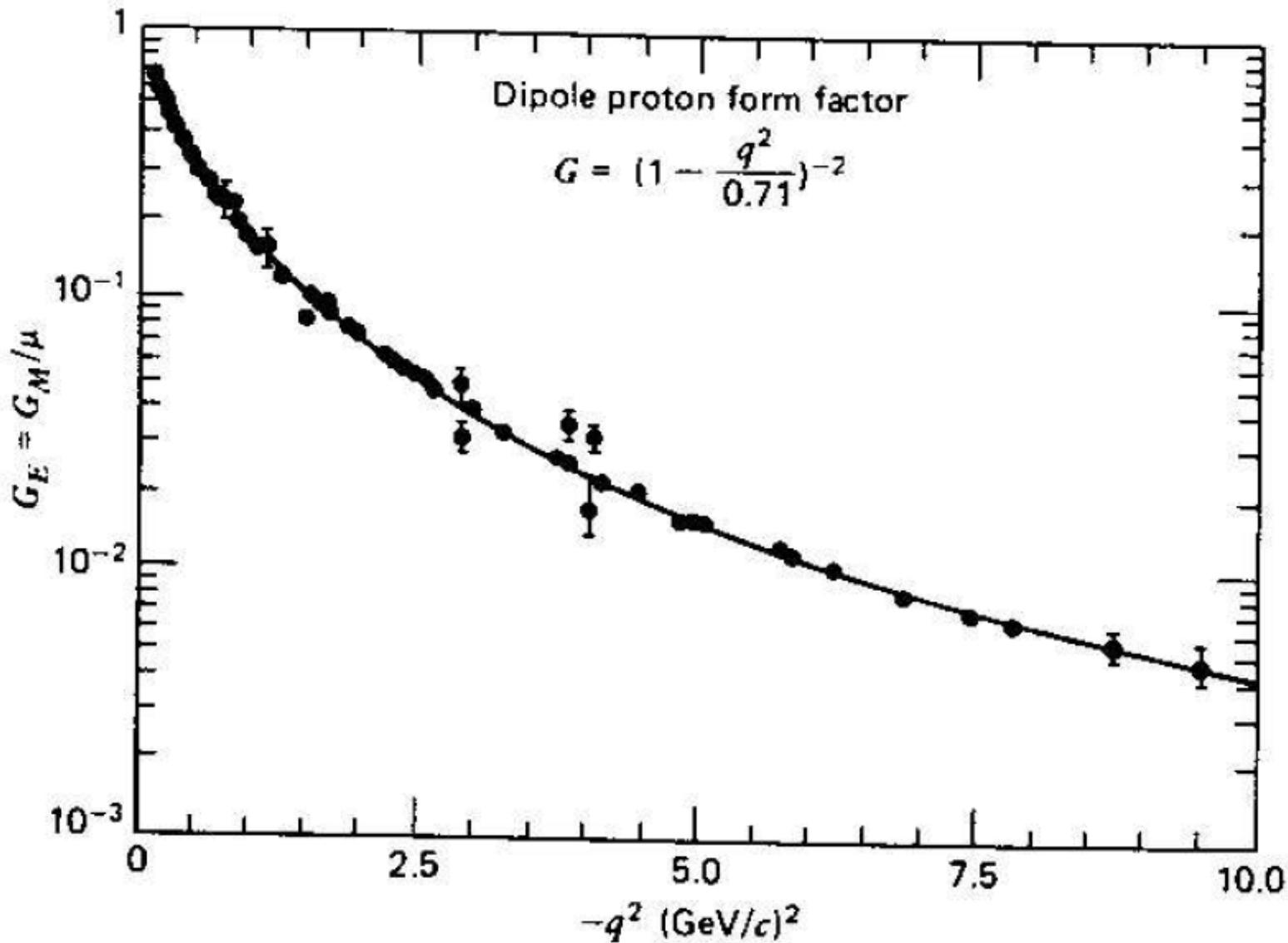


FIG. 27. The square of the form factor plotted against q^2 . q^2 is given in units of 10^{-26} cm^2 . The solid line is calculated for the exponential model with rms radii $= 0.80 \times 10^{-13} \text{ cm}$.

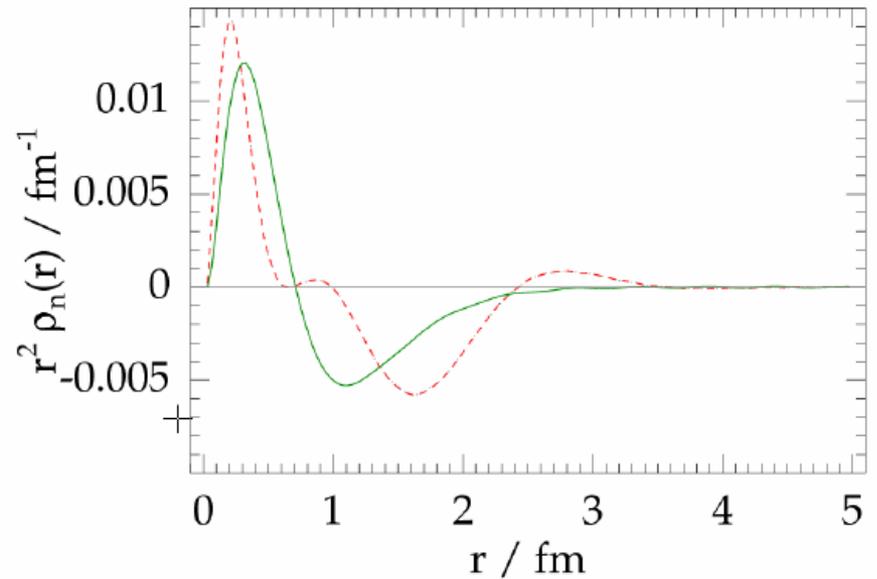
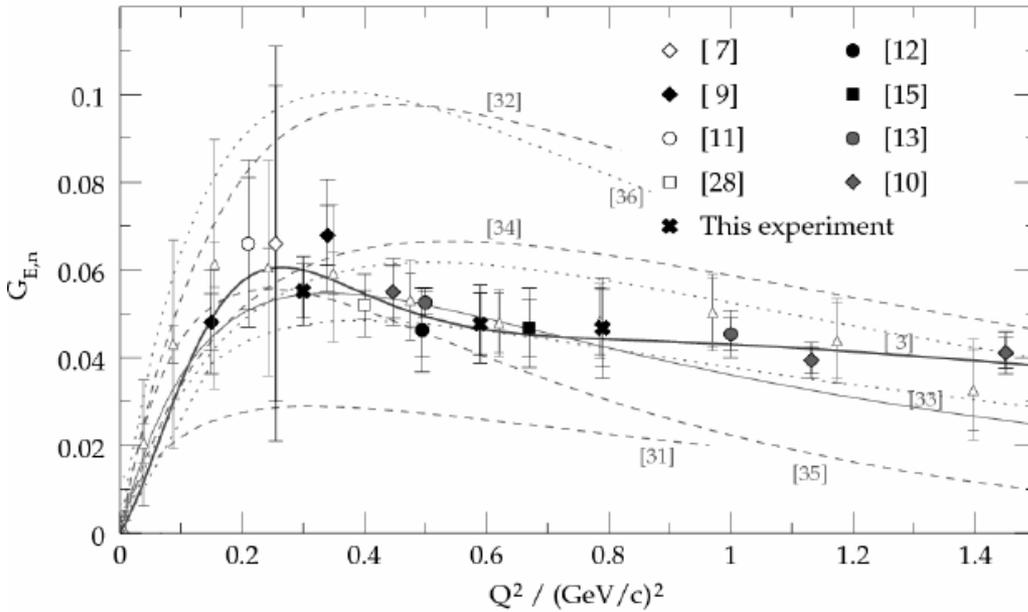
$\langle R_p \rangle = 0.8 \text{ fm} !$



Der Dipolformfaktor des Protons



E-Formfaktor des Neutrons und Ladungsverteilung



SLAC Endstation A

8 GeV Electron Spectrometer

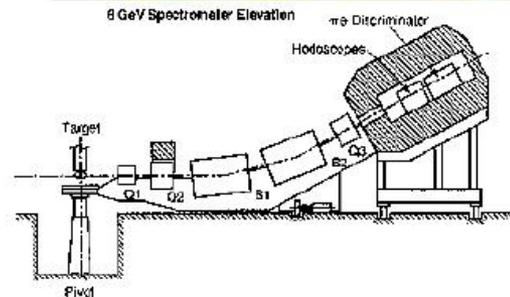


SLAC

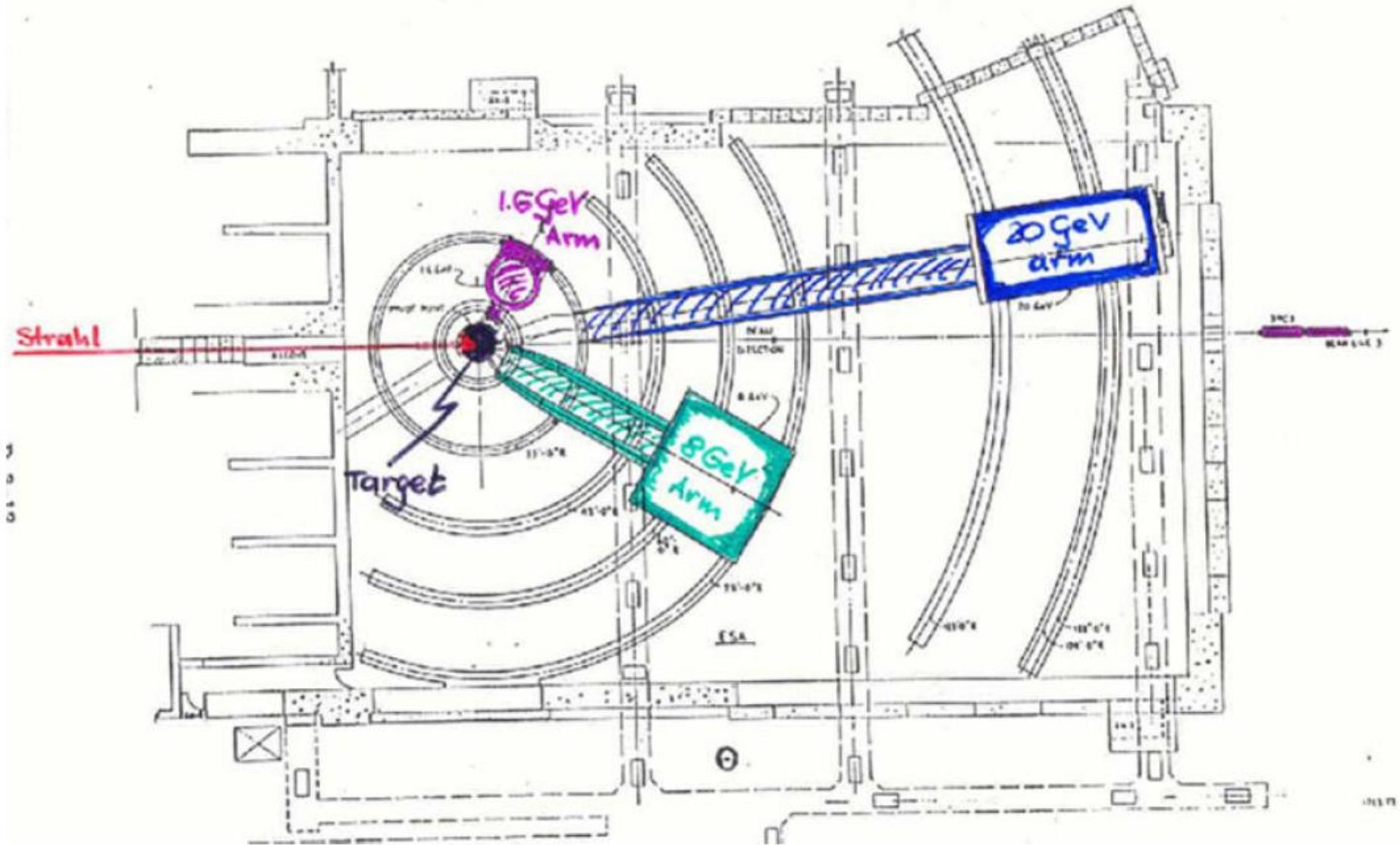
up to 20 GeV beam



endstation A



Typisches ep Streuexperiment



Inelastische ep Streuung

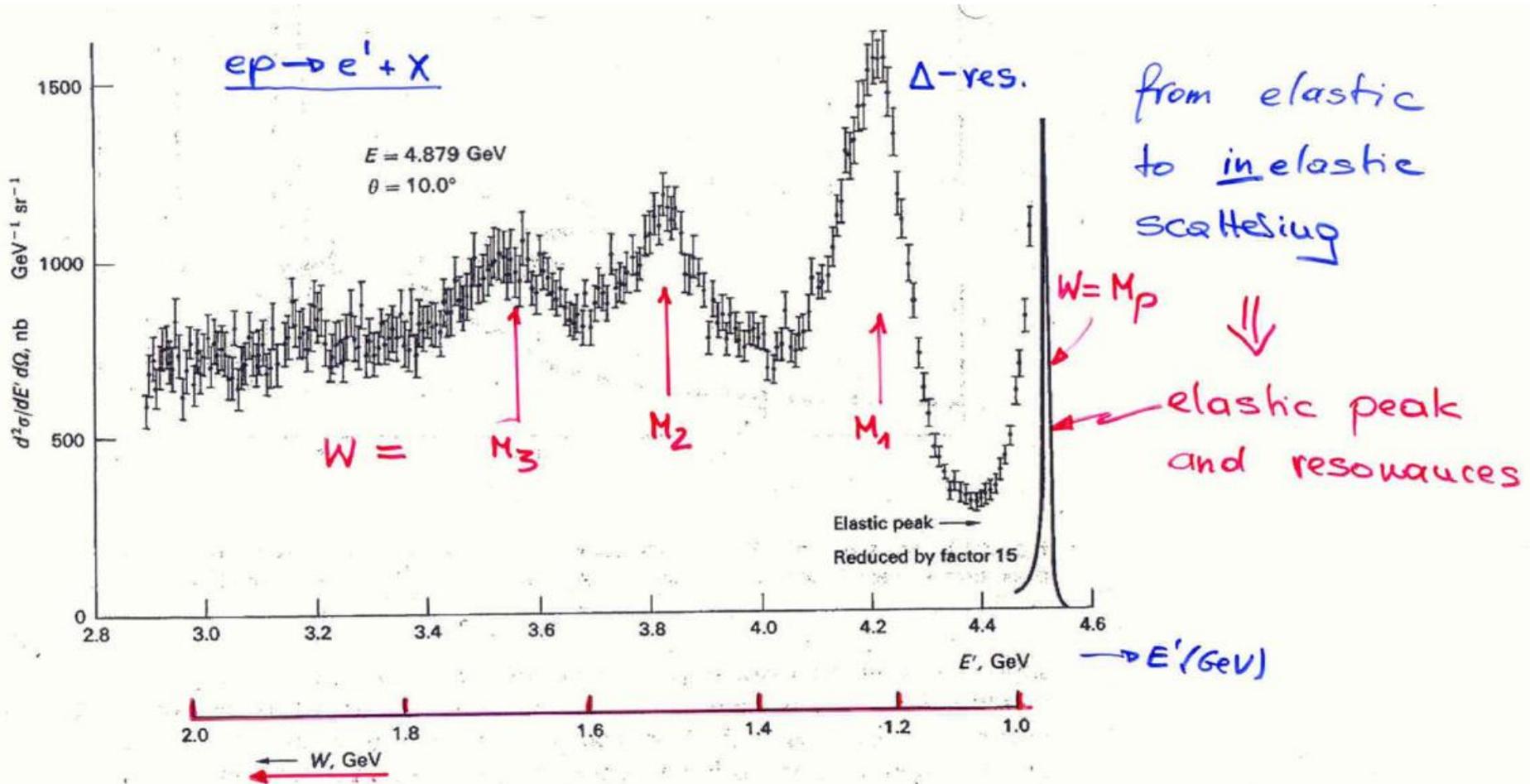


Fig. 7.15 Excitation curve of inelastic ep scattering, obtained at the DESY electron accelerator (Bartel *et al.* 1968). E and E' are the energies of the incident and the scattered electron, and W is the mass of the recoiling hadronic state. The peaks due to the pion-nucleon resonances of masses 1.24,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

Die Messungen bei SLAC

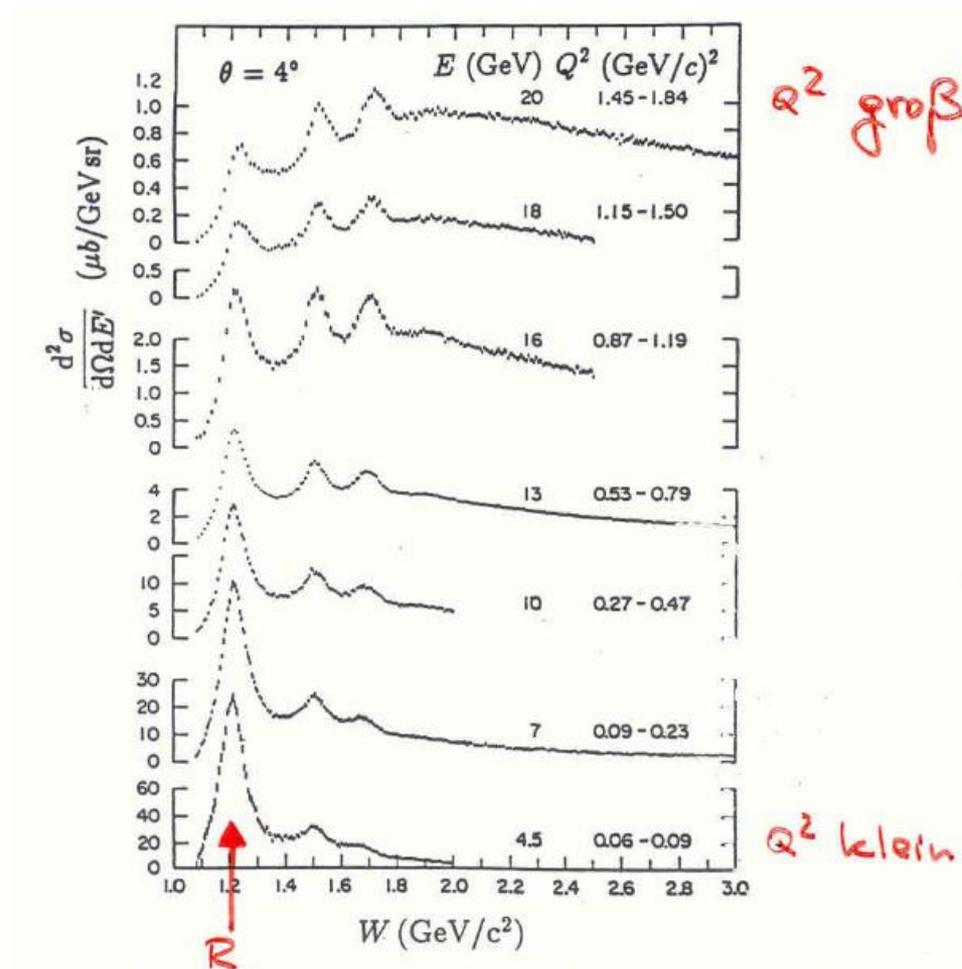
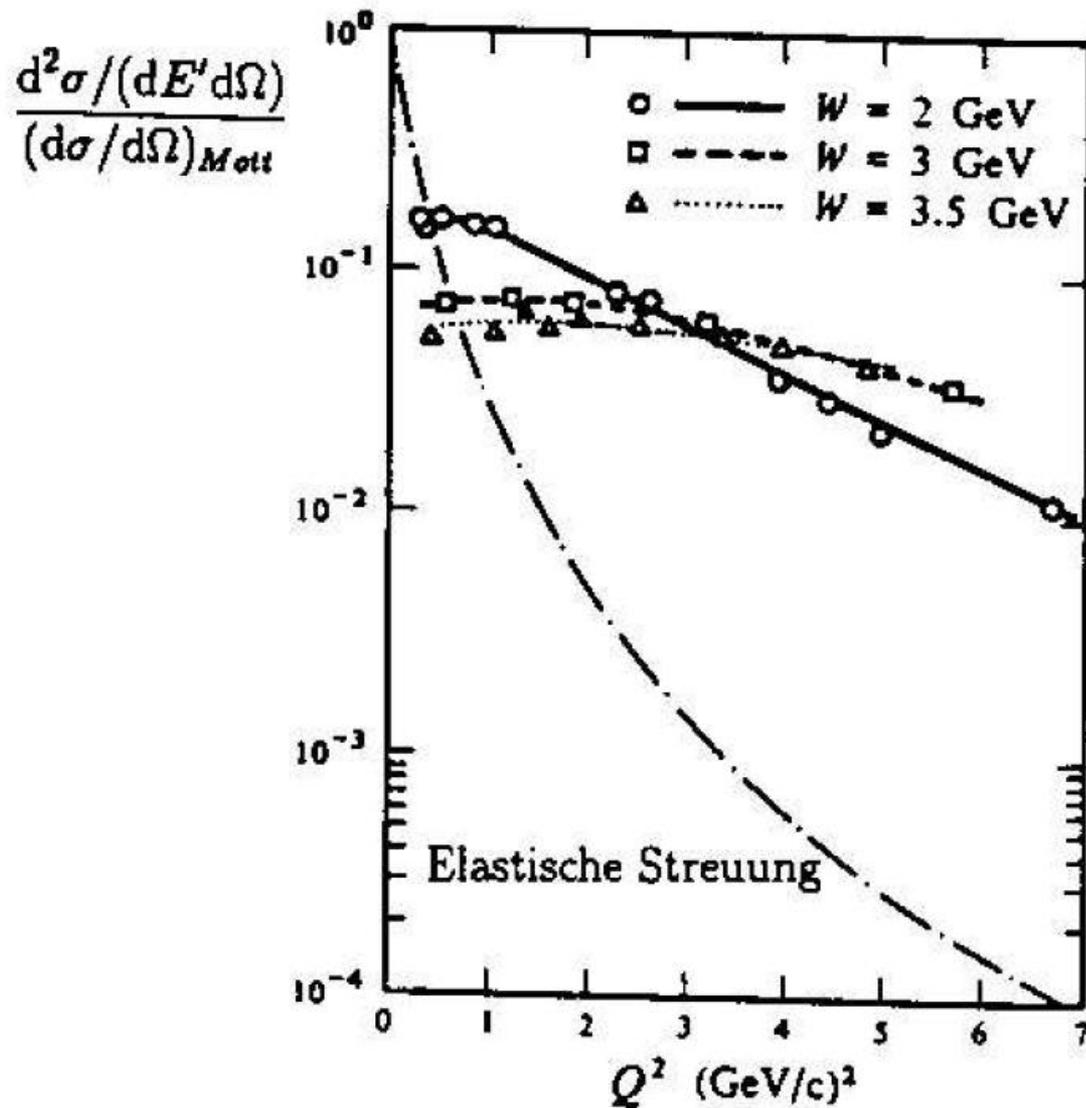


Abb. 7.2. Elektron-Proton-Streuung: gemessene Anregungsspektren in der tiefinelastischen Elektron-Nukleon-Streuung als Funktion der invarianten Masse W [St75]. Die Messungen wurden bei einem festen Streuwinkel von $\theta = 4^\circ$ durchgeführt. Mit zunehmender Einfallenergie E wächst der mittlere Q^2 -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.

Wirkungsquerschnitt im Vgl. zu elastischer Erwartung

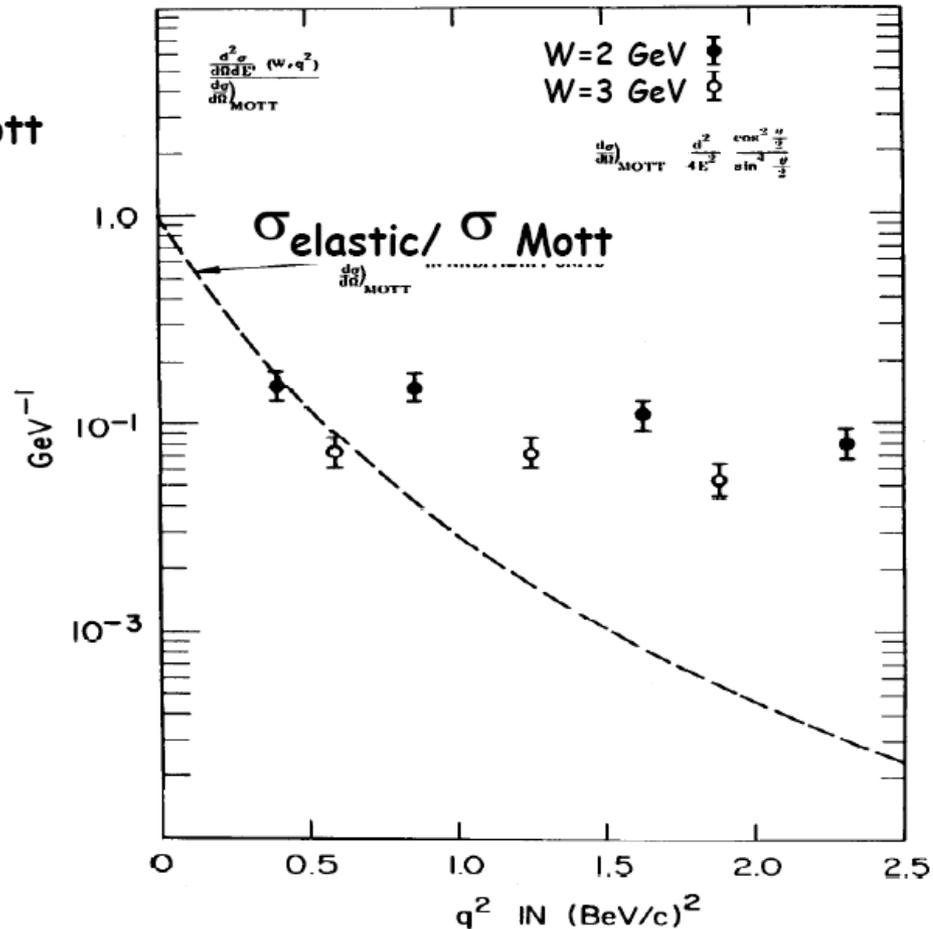


Evidenz für harte Streuung an „Partonen“

H. W. Kendall

697

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



SLAC ~1967

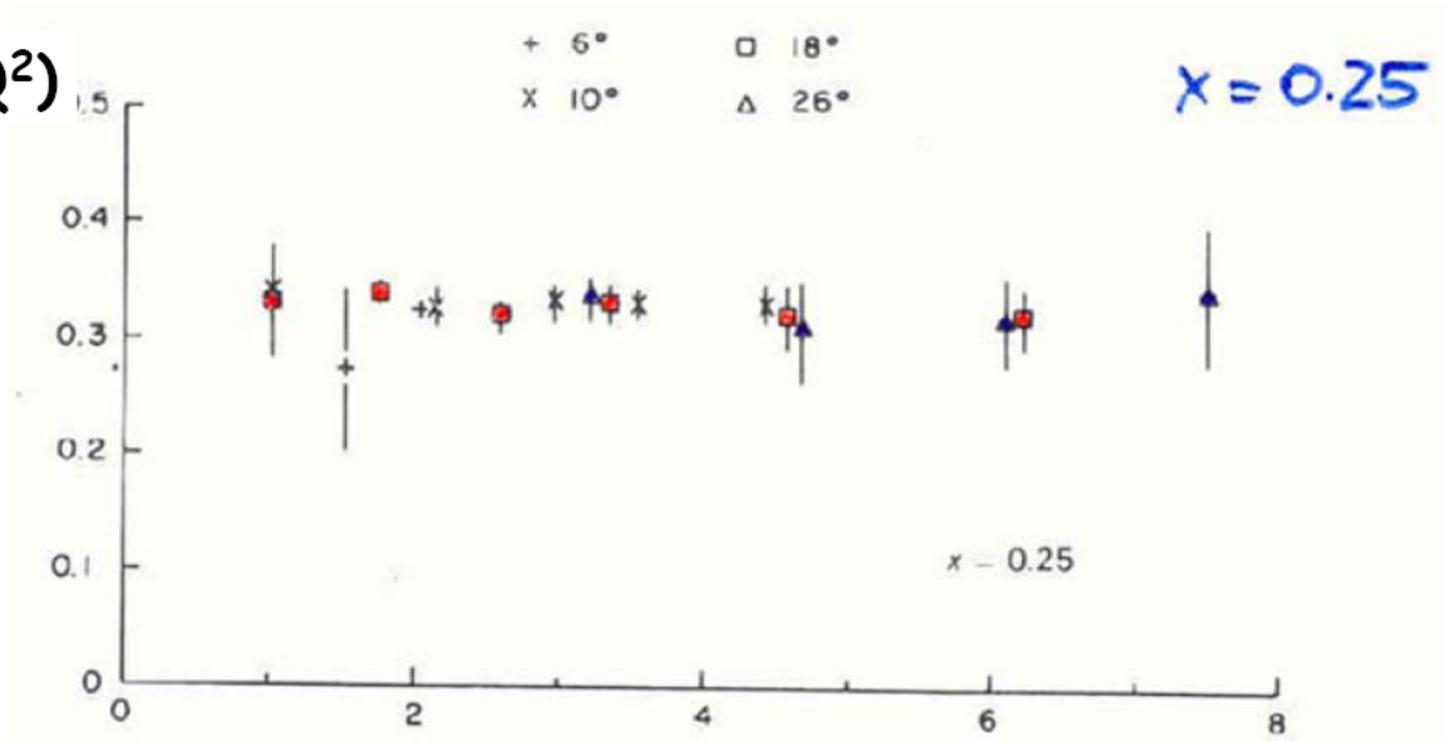


Jerome Friedman
Henry Kendall
Richard (Dick) Taylor
NP 1990

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

„Scaling“

$F_2(x, Q^2)$



Q^2 (GeV²)

“scaling”: F_2 depends on x only, not on Q^2

Callan-Gross-Relation

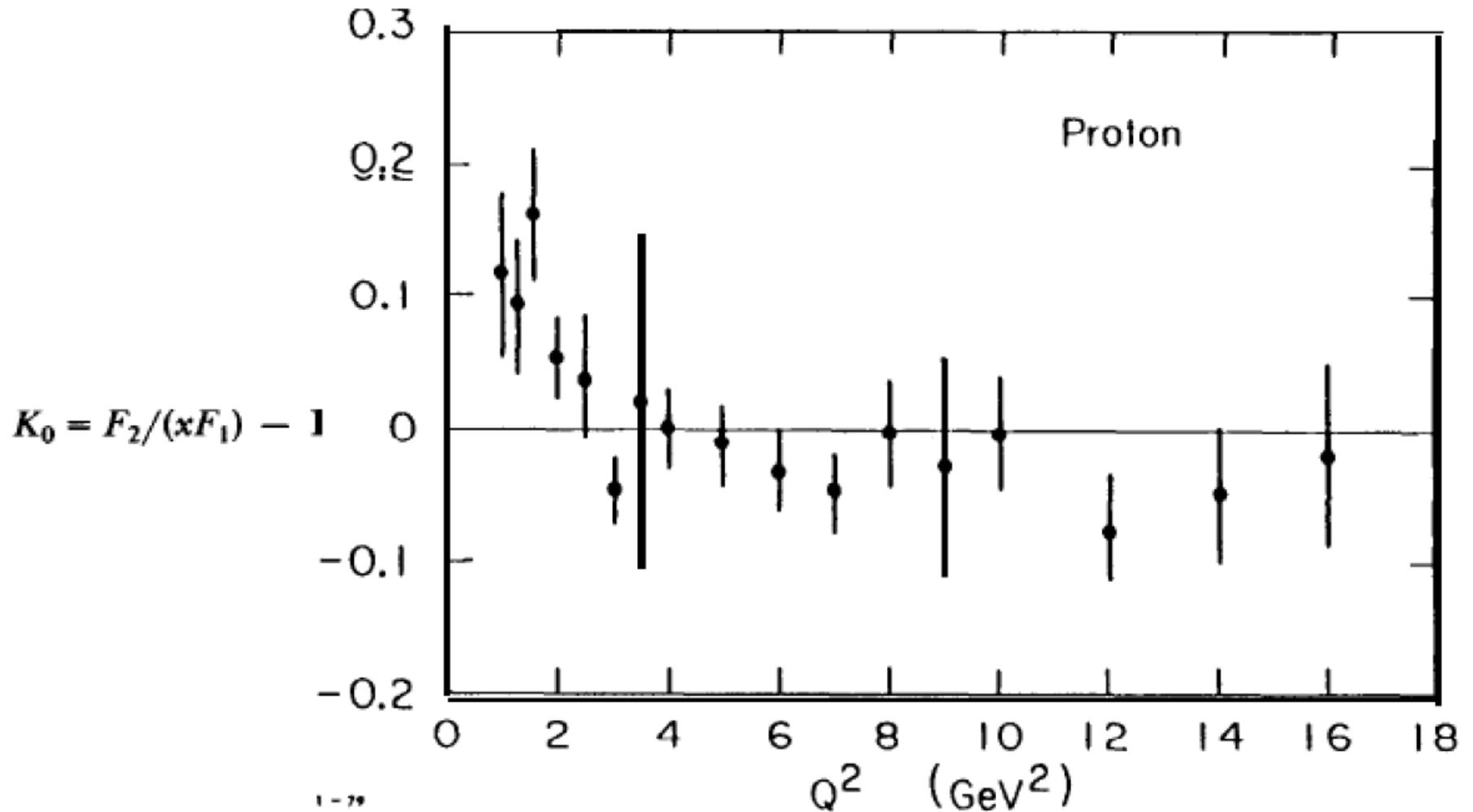
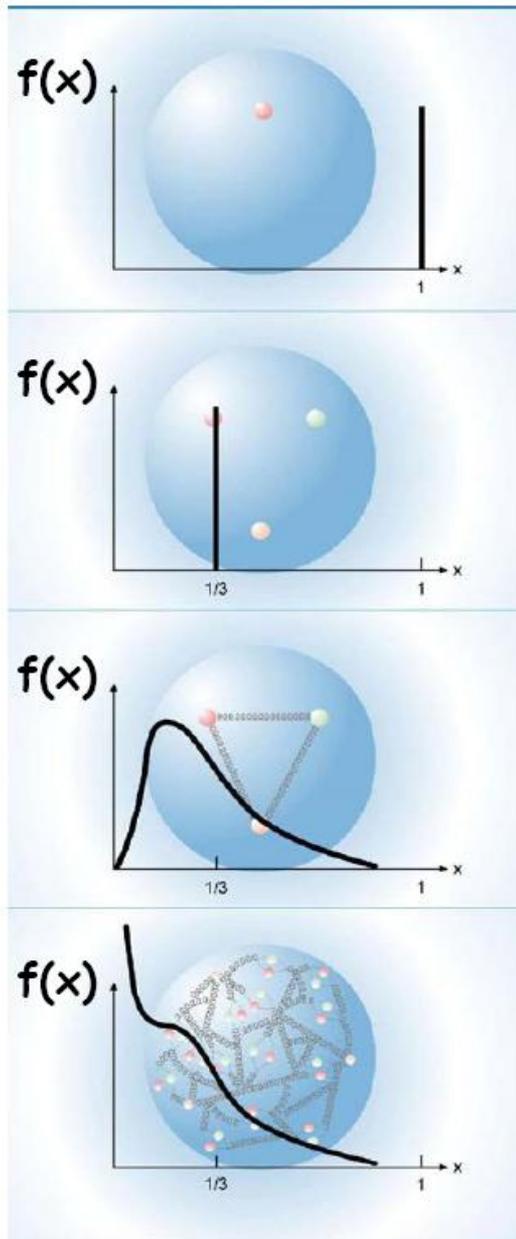


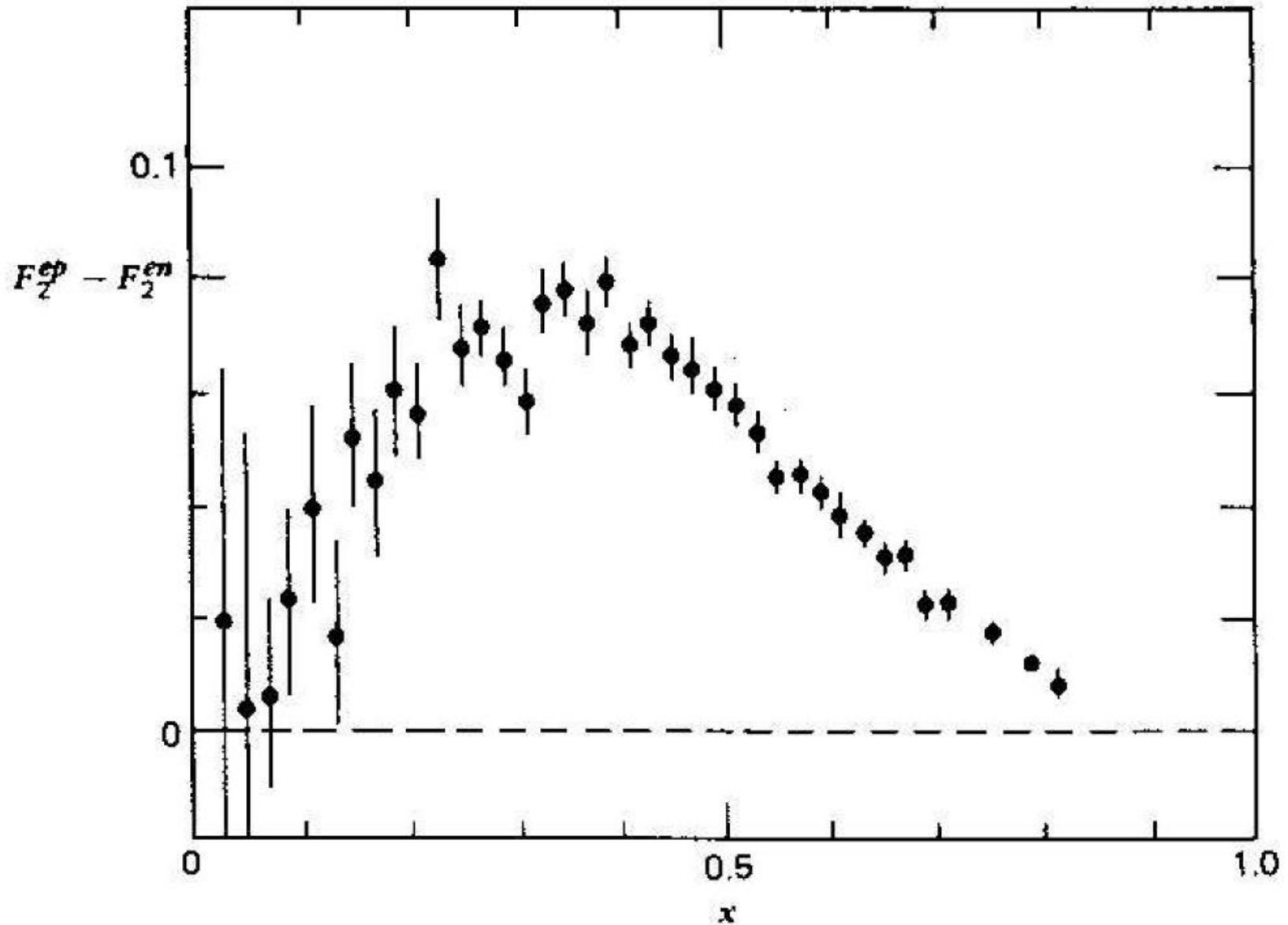
Fig. 18. The Callan-Gross relation: K_0 vs q^2 , where K_0 is defined in the text. These results established the spin of the partons as $1/2$.

Interpretation: wenn das Proton bestünde aus

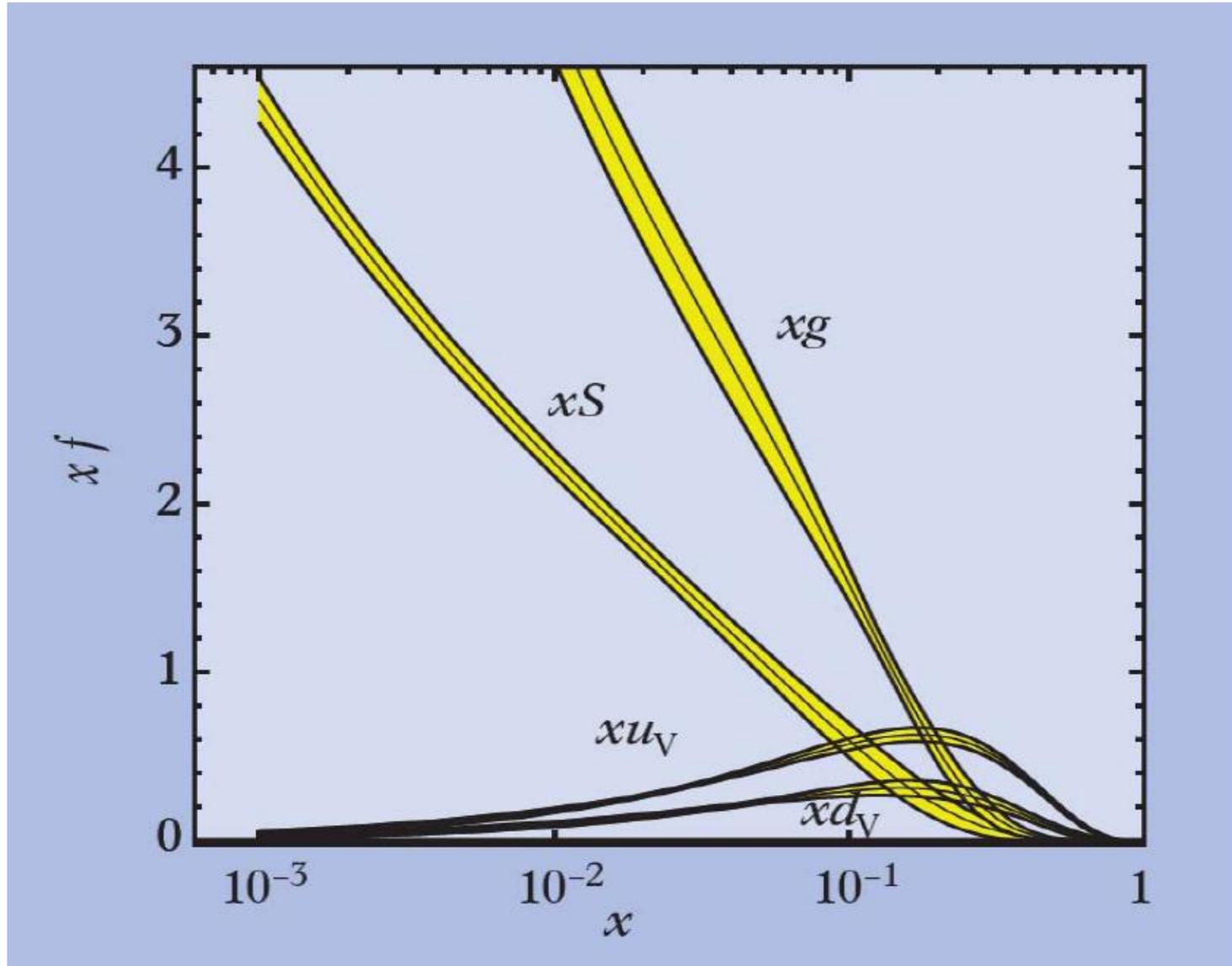


- a single point-like particle
- just 3 static valence quarks
- a bound system of 3 valence quarks in motion
- a structure of quarks and gluons

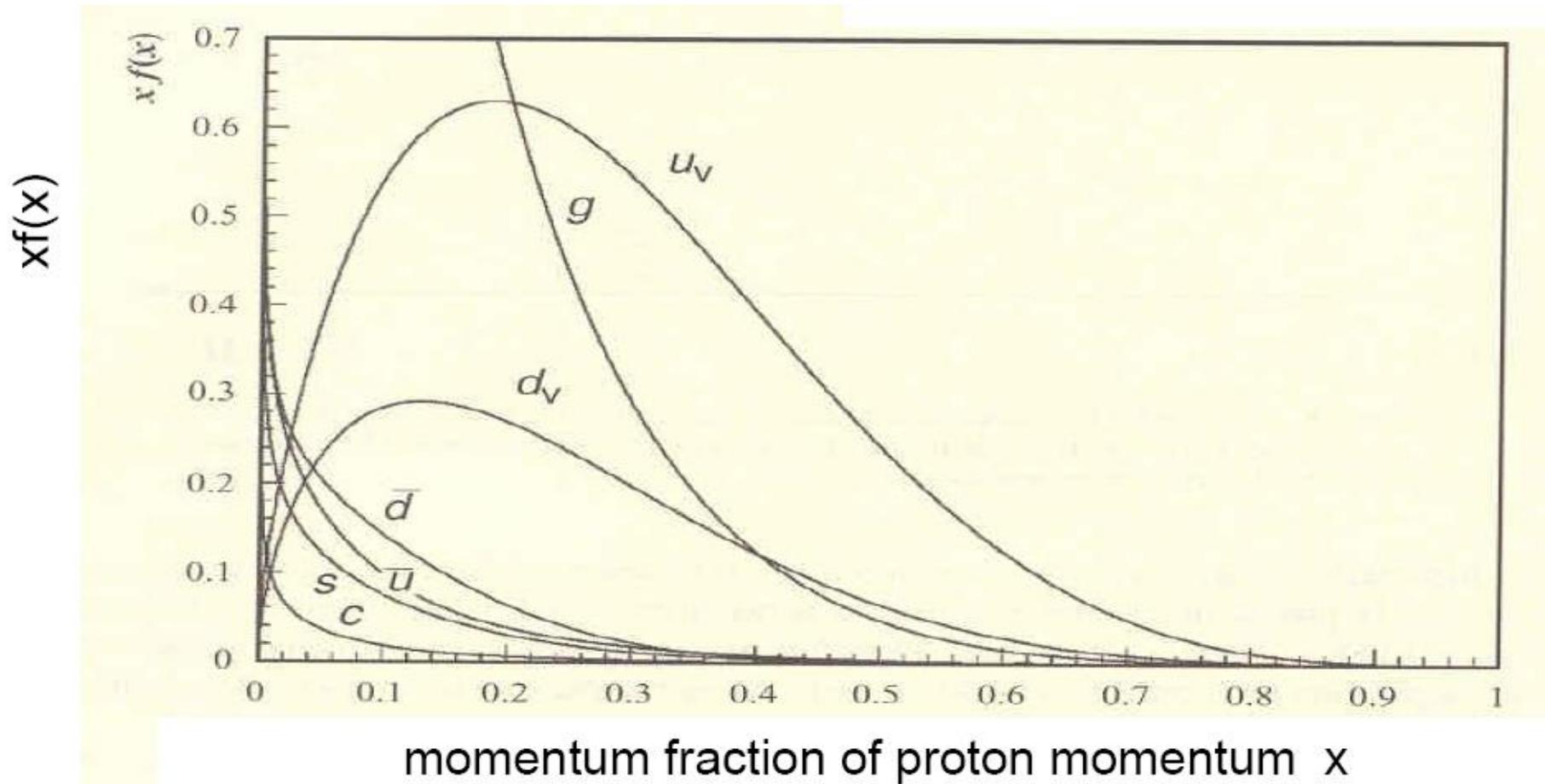
Verteilung der Valenzquarks



Quark- und Gluonverteilungen logarithmisch



Quark- und Gluonverteilungen linear

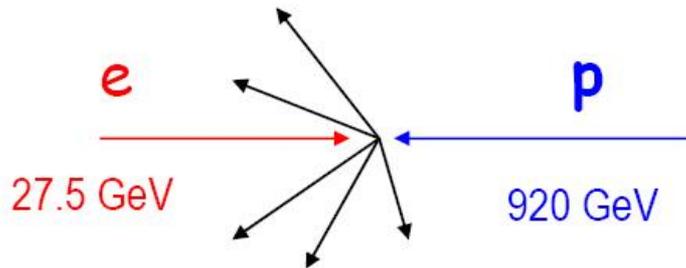


Der HERA-Beschleuniger bei DESY (Hamburg)

p ←
e →

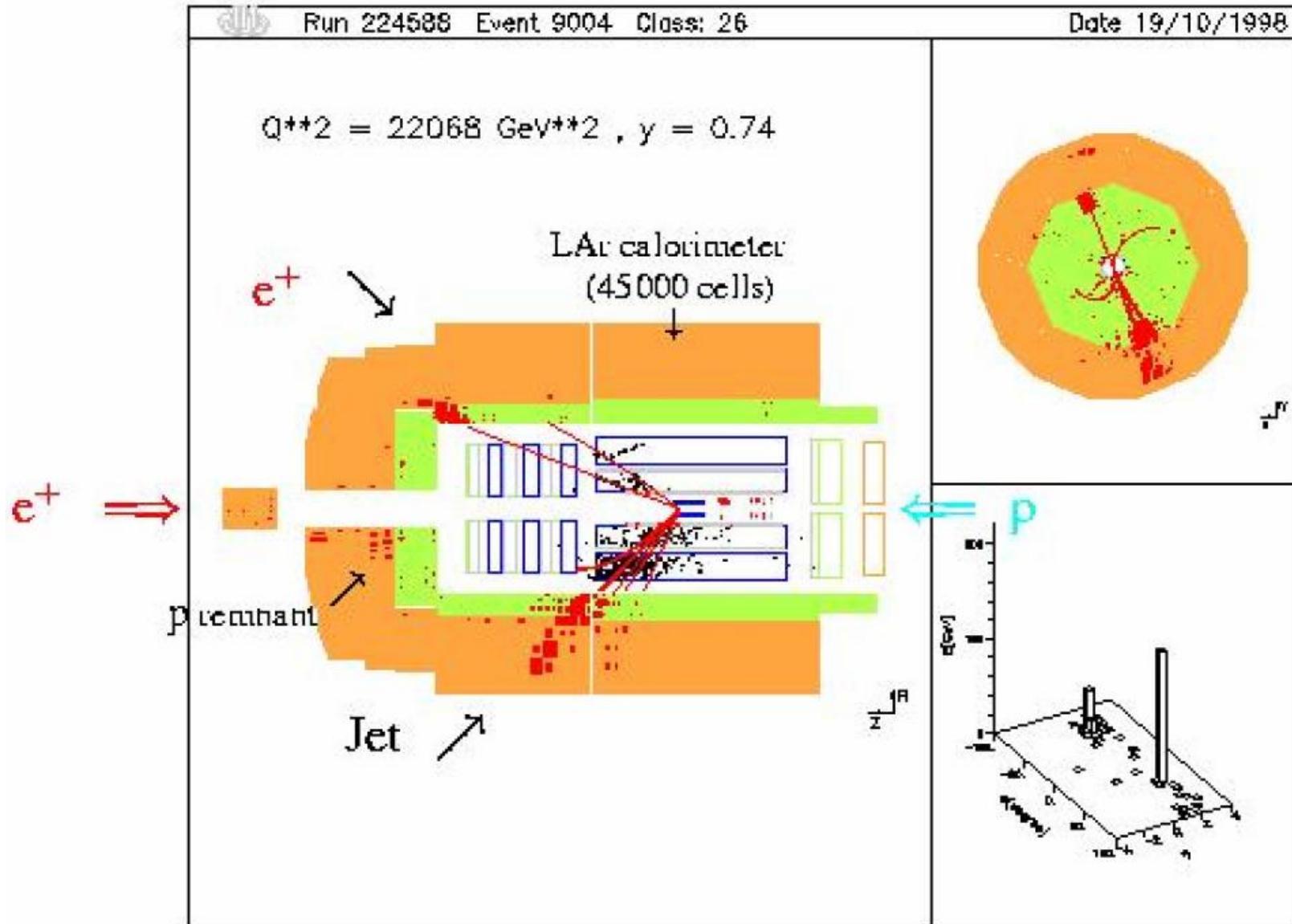


only ep collider world-wide

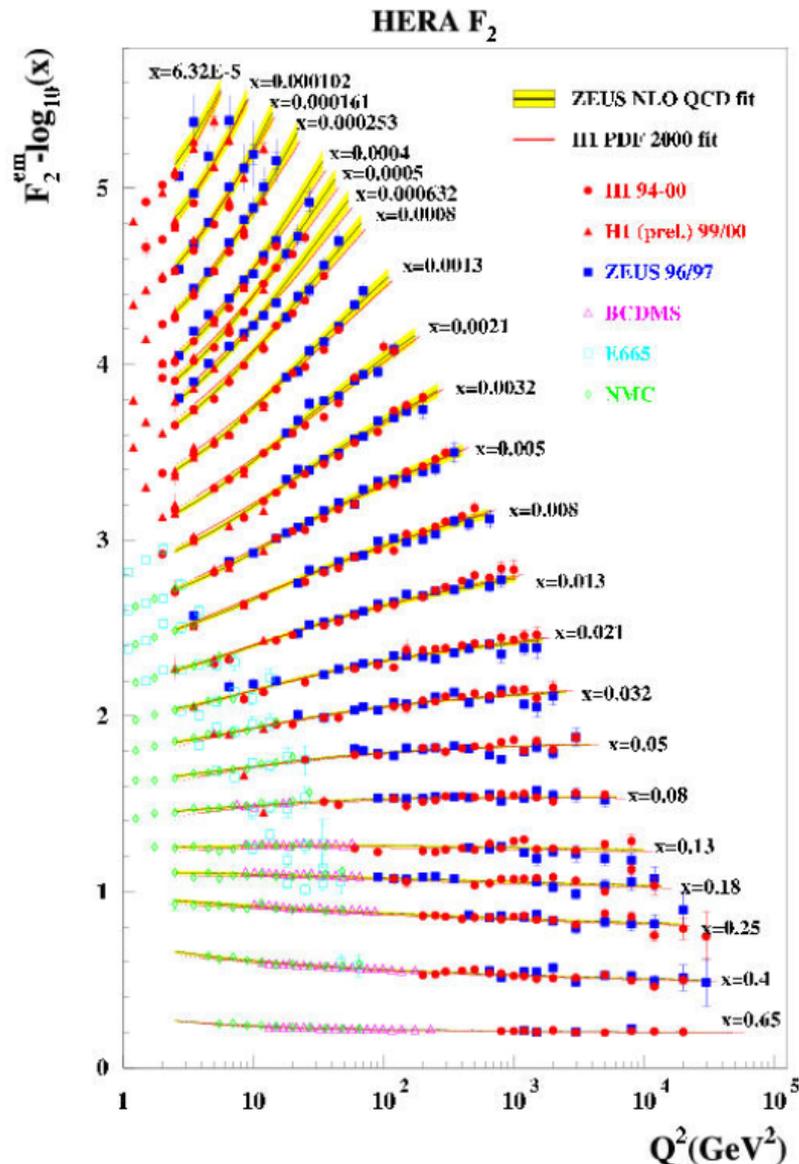


$$s = (318 \text{ GeV})^2$$
$$Q^2 \text{ up to } 10^5 \text{ GeV}^2$$

Ein HERA Streuereignis



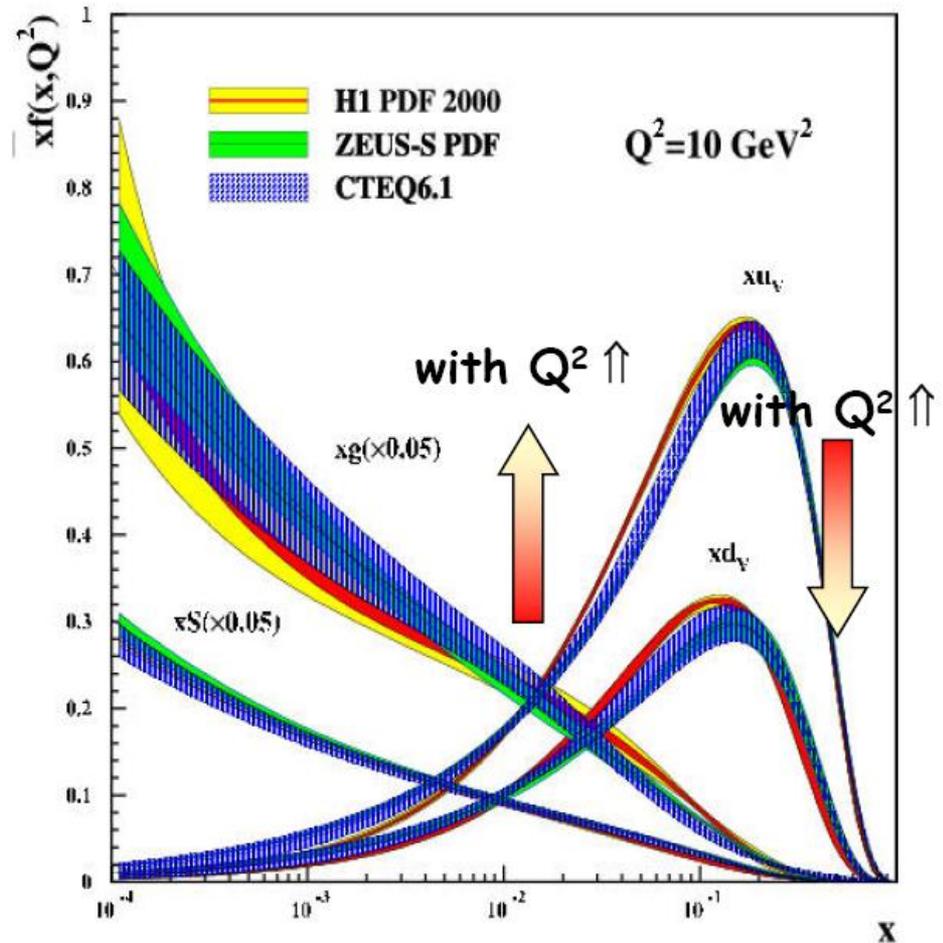
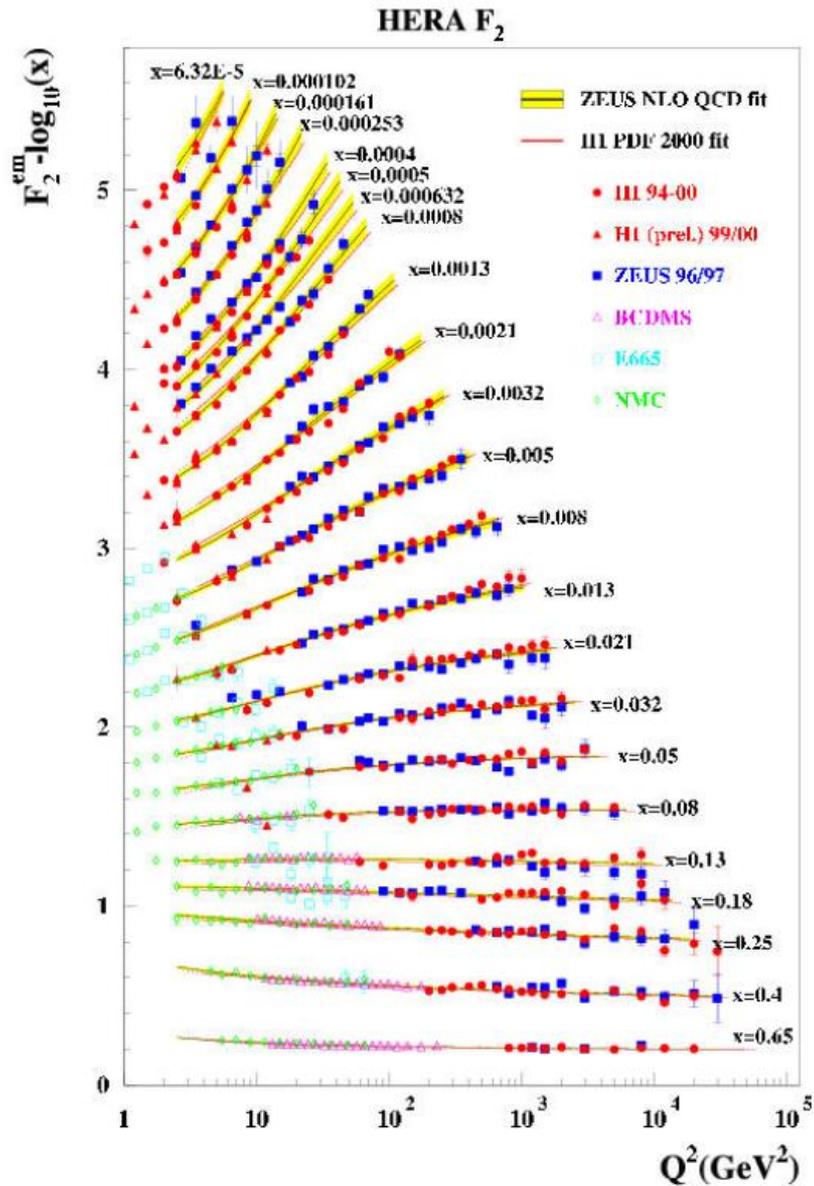
Verletzung des „Scaling“



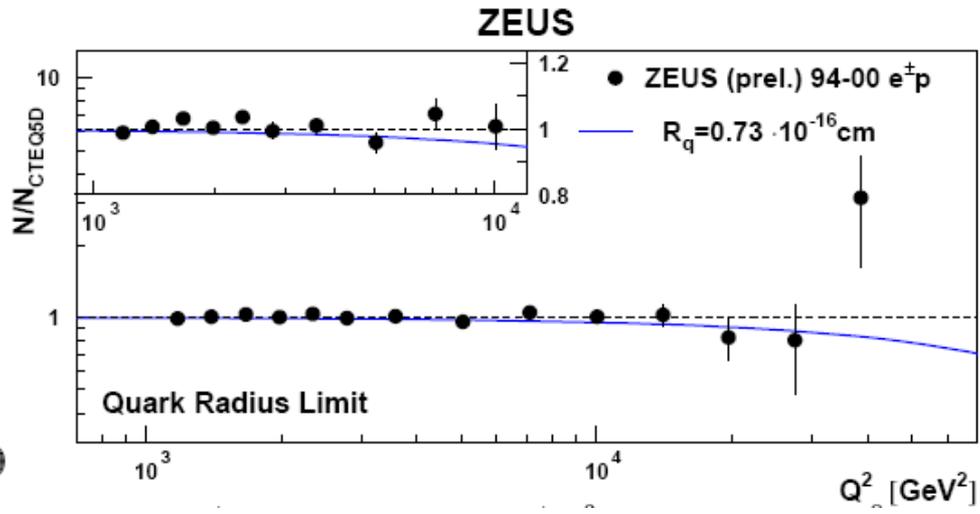
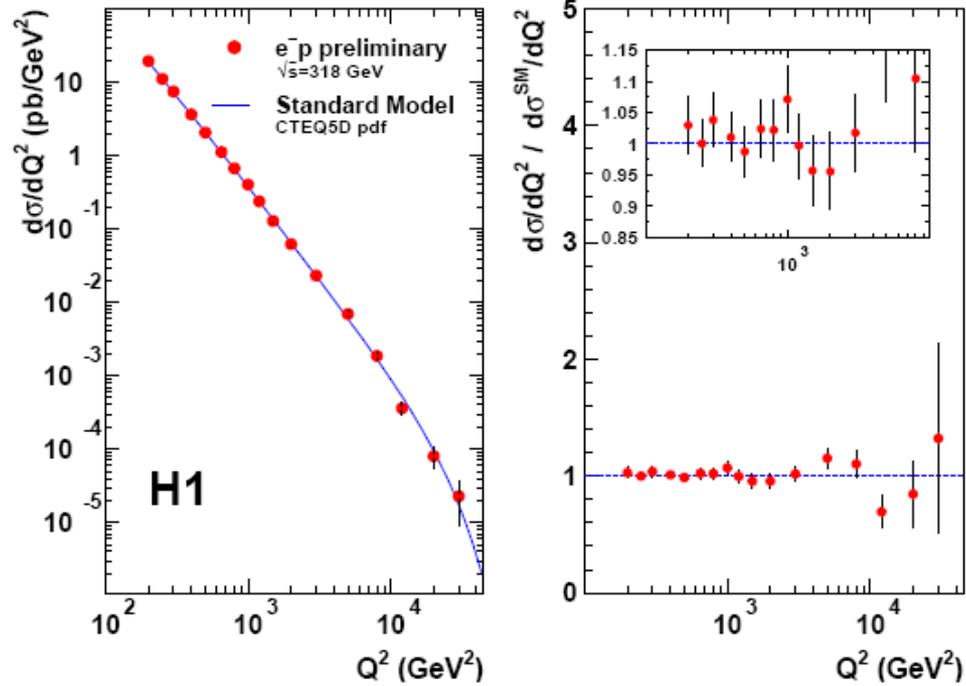
at higher Q^2
 $\Rightarrow F_2(x)$ does also depend
on Q^2 , not on x only

small $x \Rightarrow$ partons inside
the proton with small
momentum fractions

Strukturfunktionen: $f(x$ und $Q^2)$



Suche nach Substruktur der Quarks



b)