

Particle Physics II

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<http://terascale.physik.uni-freiburg.de/lehre/>

Kapitel 6

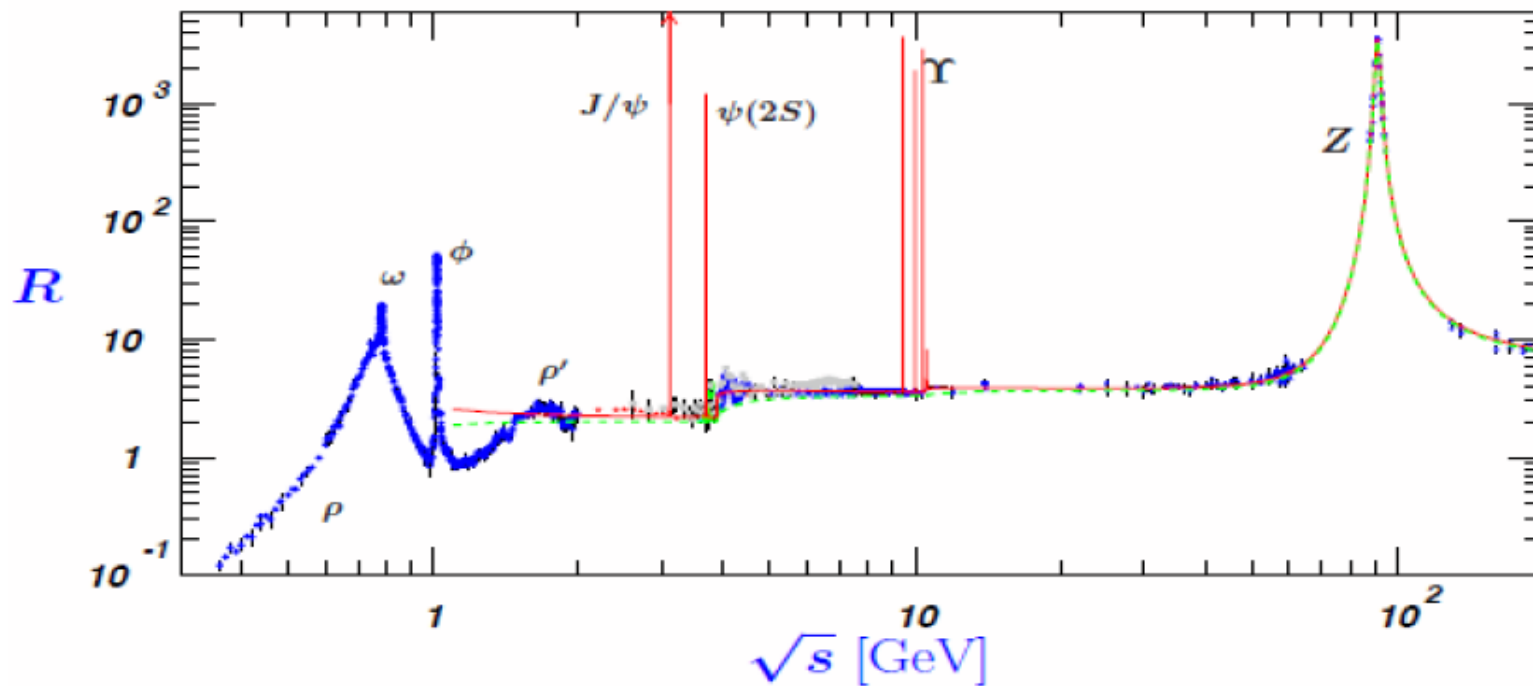
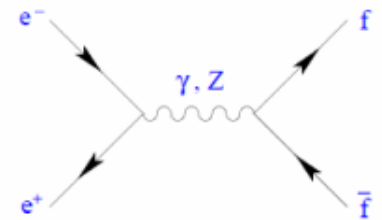
Die starke Wechselwirkung und die Struktur des Nukleons

Evidenz für drei Farben

a) R-Verhältnis in e^+e^- -Kollisionen

$$R_{e^+e^-} \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

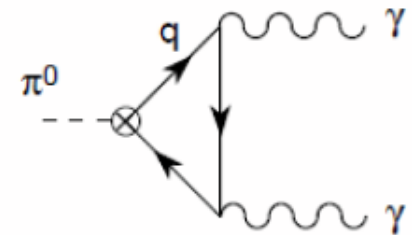
$$R_{e^+e^-} \approx N_C \sum_{f=1}^{N_f} Q_f^2 = \begin{cases} \frac{2}{3} N_C = 2, & (N_f = 3 : u, d, s) \\ \frac{10}{9} N_C = \frac{10}{3}, & (N_f = 4 : u, d, s, c) \\ \frac{11}{9} N_C = \frac{11}{3}, & (N_f = 5 : u, d, s, c, b) \end{cases}$$



Evidenz für 3 Farben

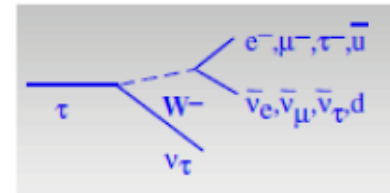
b) Zerfallsbreite $\pi^0 \rightarrow \gamma\gamma$ Exp: $\Gamma = 7.7 \pm 0.6 \text{ eV}$

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \left(\frac{N_C}{3}\right)^2 \frac{\alpha^2 m_\pi^3}{64\pi^3 f_\pi^2} = 7.73 \text{ eV},$$

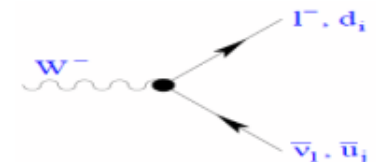


c) Verzweigungsverhältnisse

i) $\tau \rightarrow \mu \nu$: Exp: 18% Theorie: $1/(2+N_C)$
alle Zerfälle $\tau \rightarrow \mu \nu$, $\tau \rightarrow e \nu$, $\tau \rightarrow u d' \nu$



ii) $W \rightarrow \mu \nu$: Exp: 11% Theorie: $1/(3+2*N_C)$
alle Zerfälle $W \rightarrow e \nu$, $W \rightarrow \mu \nu$, $W \rightarrow \tau \nu$, $W \rightarrow u d'$, $W \rightarrow c s'$



Die Generatoren der SU(3)

Generatoren der SU(3) und ihre Lie-Algebra $[T^a, T^b] = i f^{abc} T^c$

mit Strukturkonstanten $f^{123} = 1, f^{147} = f^{246} = f^{257} = f^{345} = \frac{1}{2}, f^{156} = f^{367} = -\frac{1}{2}, f^{458} = f^{678} = \frac{\sqrt{3}}{2}$

Wahl in der Teilchenphysik: die Gell-Mann-Matrizen λ $T^a = \frac{1}{2} \lambda^a$

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$$\text{tr}(\lambda_i) = 0 \quad \text{tr}(\lambda_i \lambda_j) = 2\delta_{ij}$$

Die Lagrangedichte der QCD

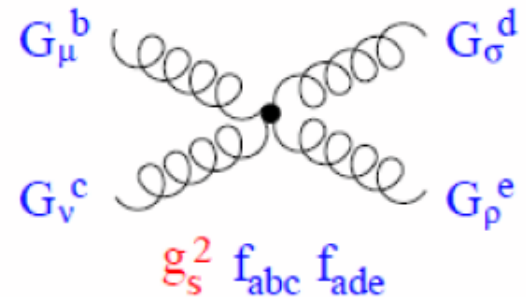
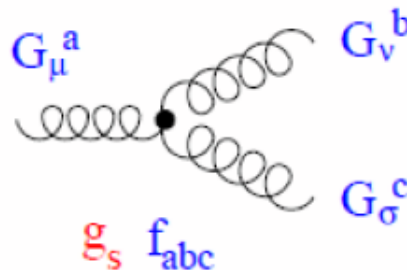
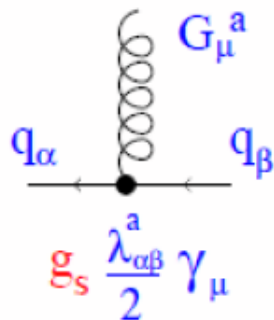
$$\begin{aligned} \mathcal{L}_{\text{QCD}} = & -\frac{1}{4} (\partial^\mu G_\nu^a - \partial^\nu G_\mu^a) (\partial_\mu G_\nu^a - \partial_\nu G_\mu^a) + \sum_f \bar{q}_f^\alpha (i\gamma^\mu \partial_\mu - m_f) q_f^\alpha \\ & - g_s G_\mu^a \sum_f \bar{q}_f^\alpha \gamma_\mu \left(\frac{\lambda^a}{2} \right)_{\alpha\beta} q_f^\beta \\ & + \frac{g_s}{2} f^{abc} (\partial^\mu G_\nu^a - \partial^\nu G_\mu^a) G_\mu^b G_\nu^c - \frac{g_s^2}{4} f^{abc} f_{ade} G_\mu^a G_\nu^b G_\mu^c G_\nu^d. \end{aligned}$$

Interpretation der Terme:

Erste Zeile: kinetische Energie/Propagation der Gluonen und Quarks

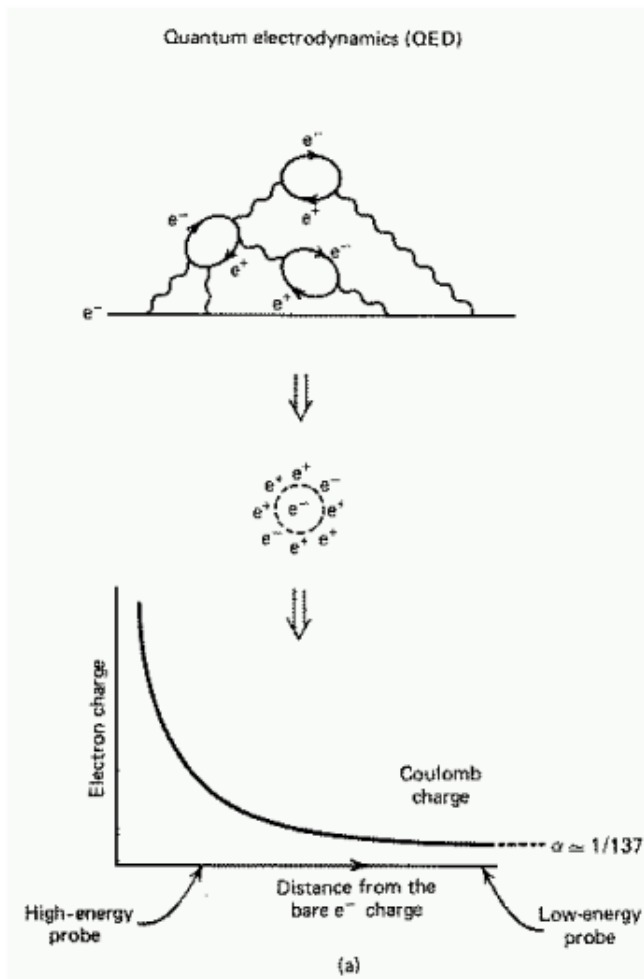
Zweite Zeile: Wechselwirkung zwischen Quarks durch Gluonaustausch

Dritte Zeile: Selbstwechselwirkung der Gluonen (3- und 4-Gluonvertex)
wegen Nicht-Abelscher Natur der Eichgruppe SU(3)



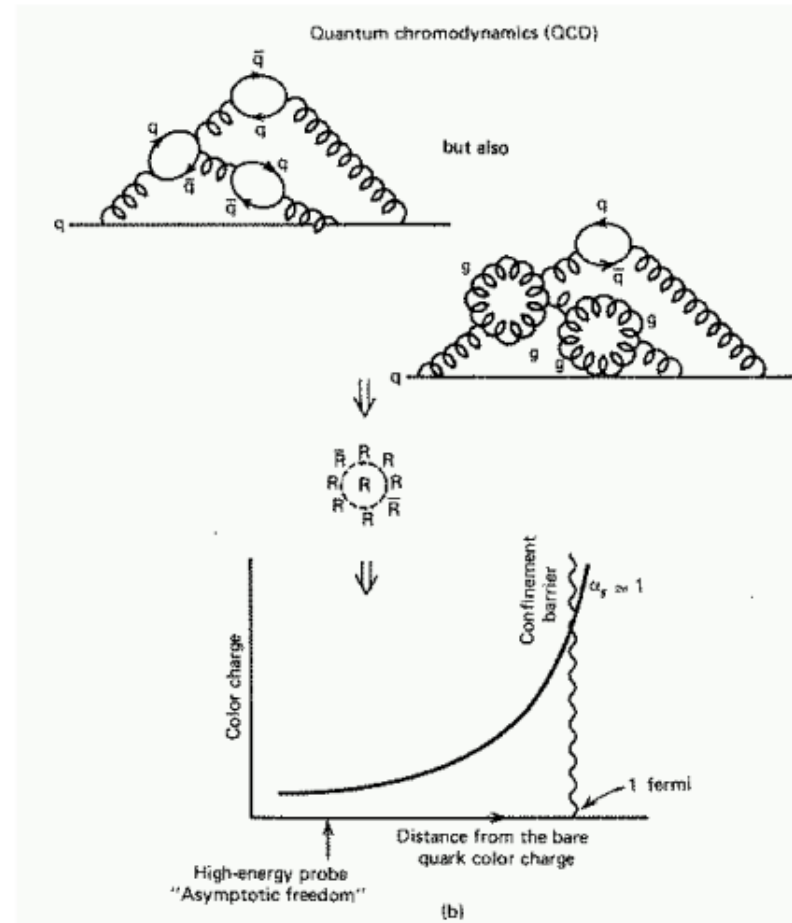
Beiträge zum Laufen der Kopplung

QED



Nur Abschirmung

QCD



Abschirmung durch Quarkschleifen
Antiabschirmung durch Gluonschleifen

Energieabhängigkeit der starken Kopplung

Unterschiedliches Verhalten auf Einschleifenniveau:

$$\left(\alpha_s(q^2)\right)_{q\bar{q}} = \alpha_s(\mu^2) \left(1 + N_f \cdot \frac{\alpha_s(\mu^2)}{6\pi} \cdot \ln\left(\frac{q^2}{\mu^2}\right)\right)$$

$$\left(\alpha_s(q^2)\right)_{gg} = \alpha_s(\mu^2) \left(1 - 11 \cdot \frac{\alpha_s(\mu^2)}{4\pi} \cdot \ln\left(\frac{q^2}{\mu^2}\right)\right)$$

N_f die Zahl der aktiven Quarkflavours mit $2m_f < \sqrt{q^2}$

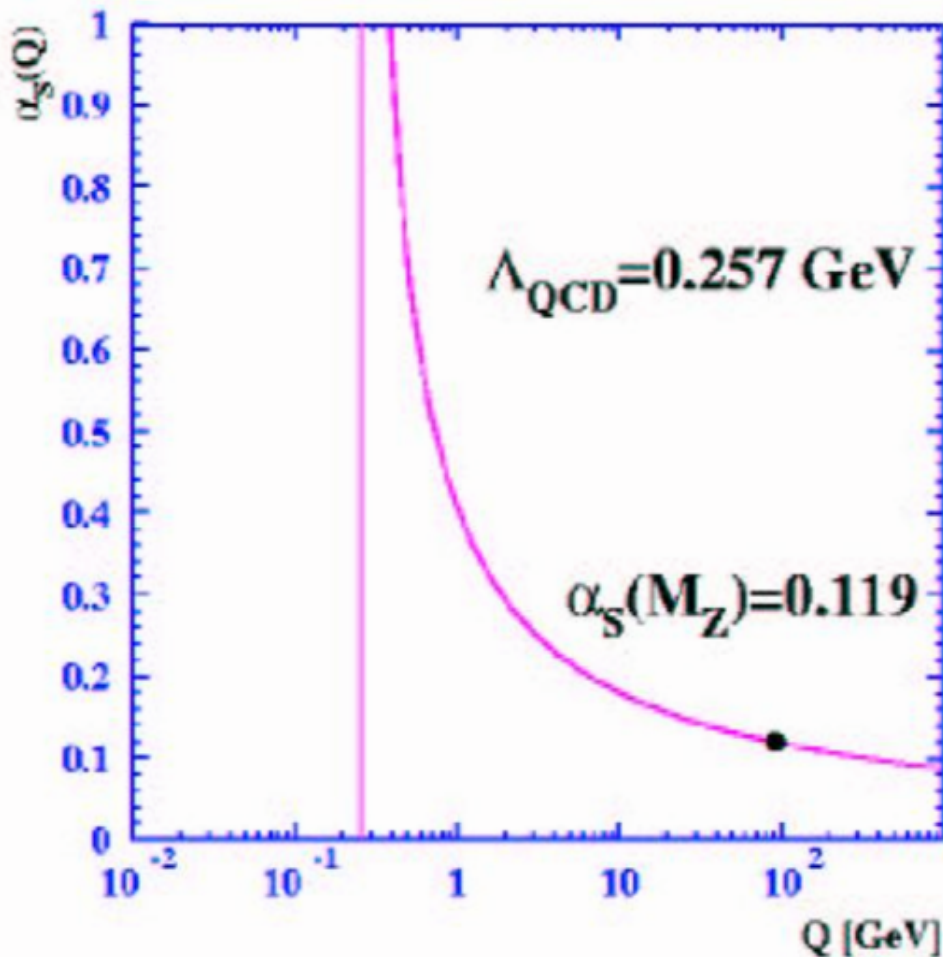
Alle Schleifen aufaddiert:

$$\alpha_s(q^2) = \frac{\alpha_s(\mu^2)}{1 + (33 - 2N_f) \frac{\alpha_s(\mu^2)}{12\pi} \ln\left(\frac{q^2}{\mu^2}\right)}$$

$\alpha_s \rightarrow 0$ für $q^2 \rightarrow \infty$, falls $33 - 2N_f > 0$, also $N_f < 16.5$

- Für $q^2 \rightarrow \infty$ folgt $\alpha_s(q^2) \rightarrow 0$:
asymptotische Freiheit
- Für $q^2 \rightarrow 0$ folgt $\alpha_s(q^2) \rightarrow \infty$:
Confinement: Störungstheorie versagt, Quarks und Gluonen existieren nicht als ungebundene, freie Objekte.

Laufende Kopplung: QCD-Skala

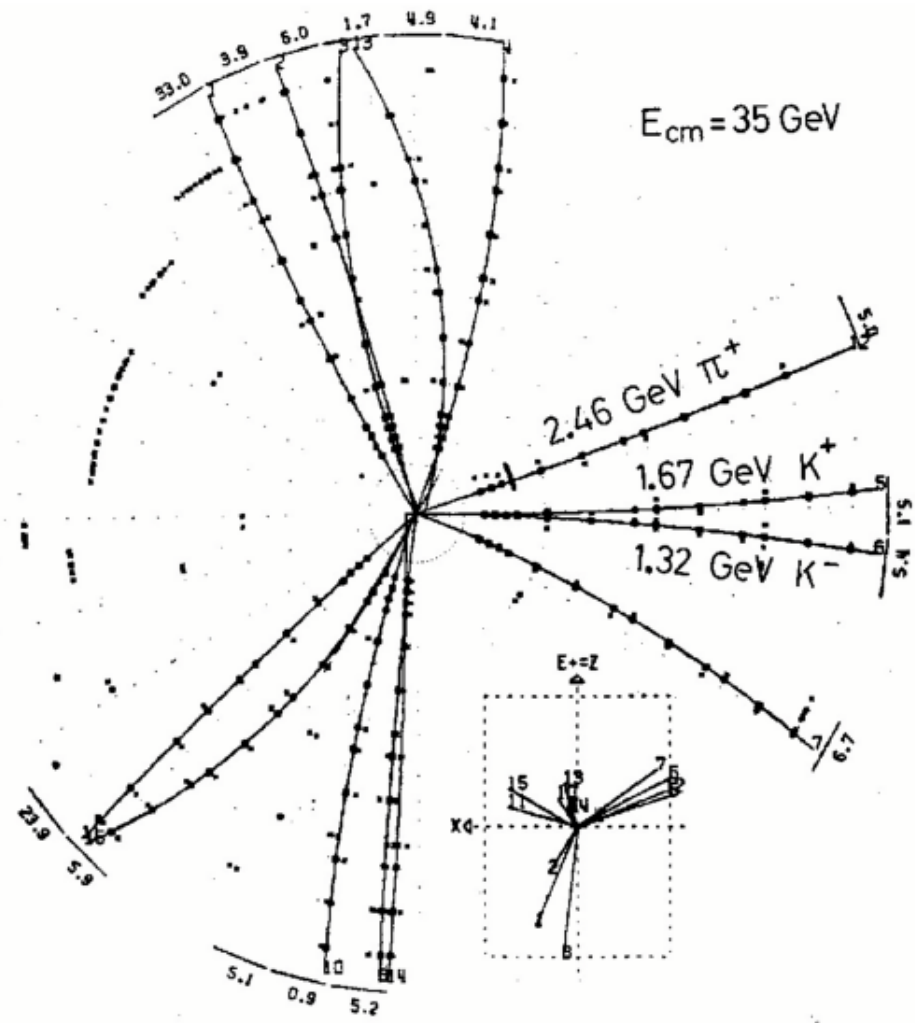
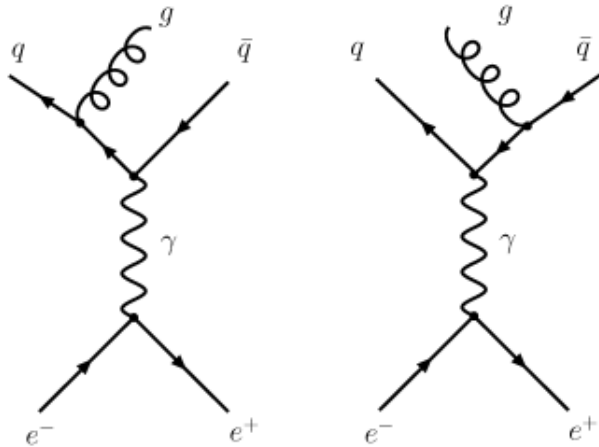
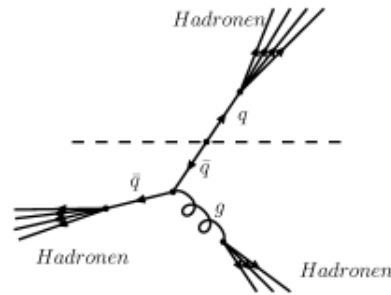


- Starke Kopplungs"konstante" läuft
- "Landaupol" ist Divergenz bei kleinen Q
- "Asymptotische Freiheit" meint, daß $\alpha_s(Q)$ für große Q verschwindet

Interpretation des Landaupoles:
Energieskala bei der Confinement/
Hadronisierung einsetzt

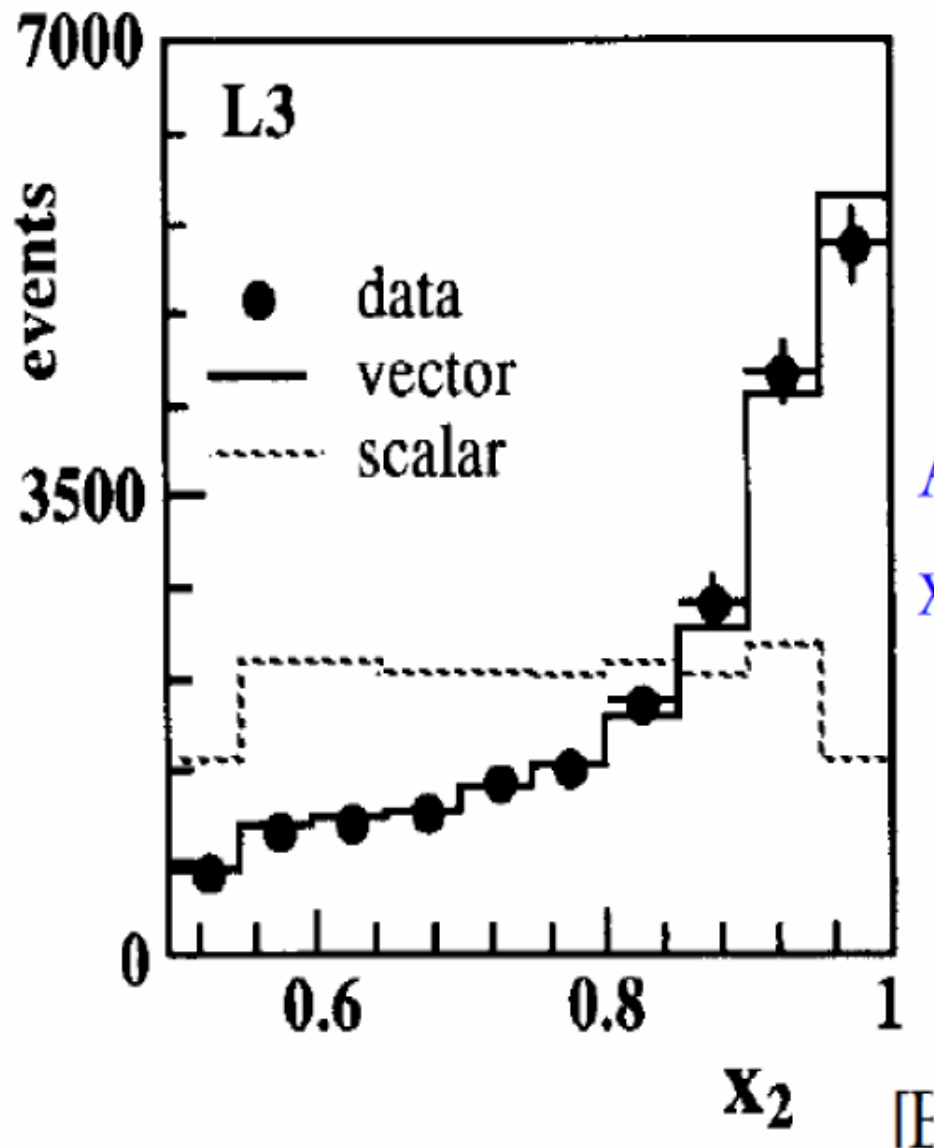
Entdeckung des Gluons 1979 bei PETRA

1979 PETRA bei $\sqrt{s} = 27$ GeV betrieben
 → Frühjahr 1979 erste 3-Jet-Ereignisse bei TASSO



22.9.80

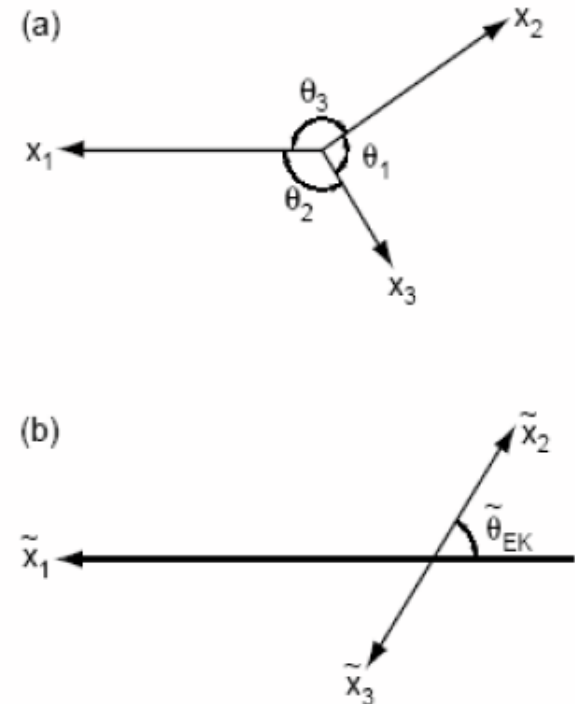
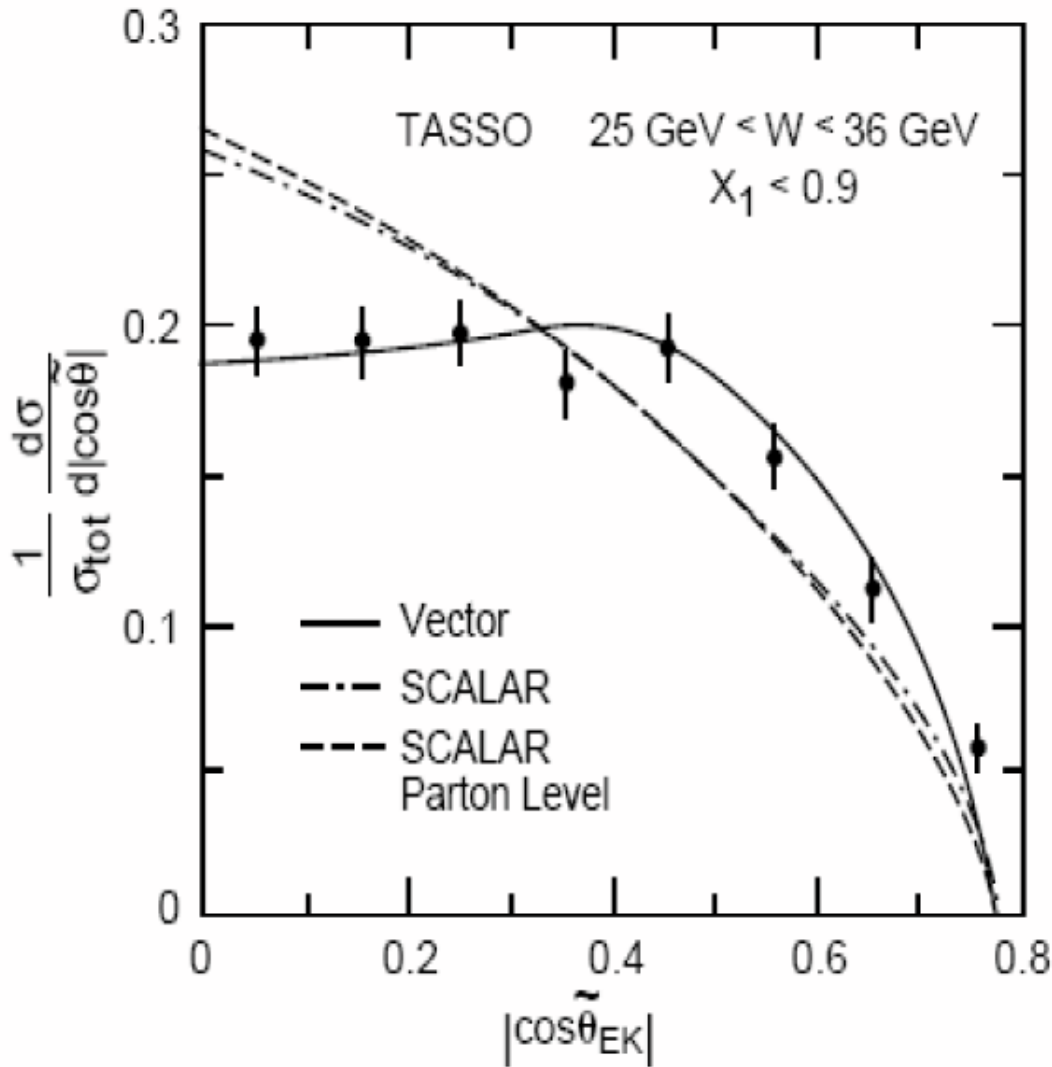
Evidenz für Spin = 1 Charakter des Gluons



Auswahl von 3-Jet Ereignissen

$$x_i = 2E_i/\sqrt{s}, x_1 > x_2 > x_3$$

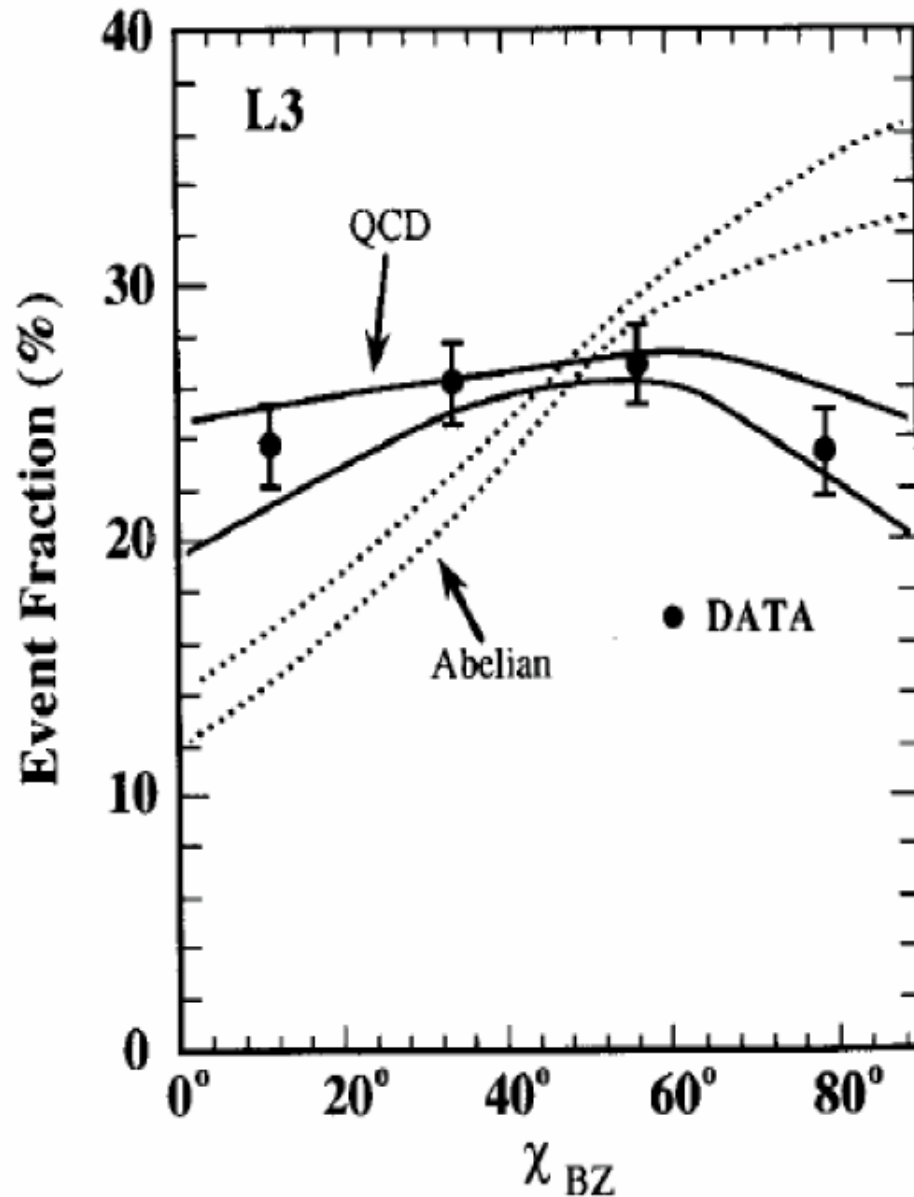
Evidenz für Spin = 1 Charakter des Gluons



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Evidenz für Gluonselfkopplung



Nachweis der Gluonselfkopplung:

Auswahl von 4-Jet Endzuständen

$x_i = 2E_i/\sqrt{s}$, $x_1 > x_2 > x_3 > x_4$ (Energieordnung)

χ_{BZ} ist Winkel zwischen Ebenen

von p_1 mit p_2 und p_3 mit p_4

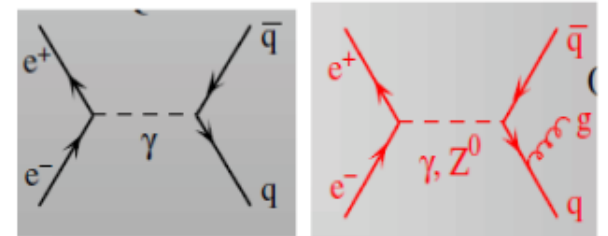
Bestimmung der starken Kopplungskonstanten

a) R-Verhältnis in e+e- -Kollisionen

$$R = \frac{\sigma(e^+e^- \rightarrow \text{Hadronen})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = R_{\alpha_s=0}^{theo.} \cdot (1 + a_1\alpha_s(Q^2) + a_2\alpha_s^2(Q^2) + \dots)$$

b) Verhältnisse von Jetraten in e+e-, ep-Streuungen

$$\frac{N((n+1) \text{ Jets})}{N(n \text{ Jets})} \propto \alpha_s(Q^2)$$



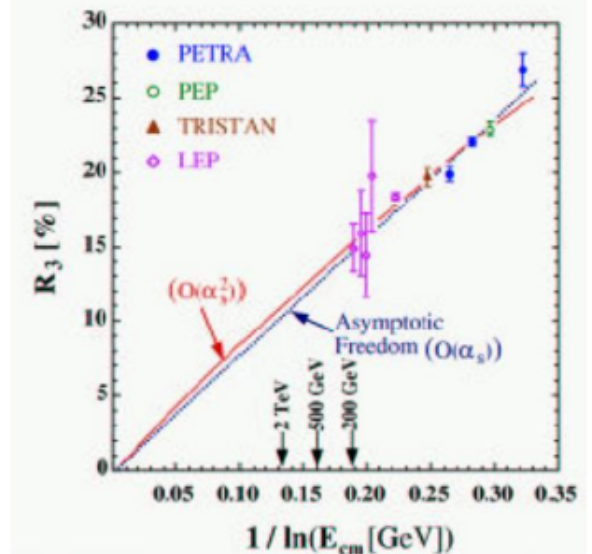
$$R_3 \equiv \frac{\sigma_{3\text{-jet}}}{\sigma_{\text{tot}}} \propto \alpha_s(E_{\text{cm}}) \propto \frac{1}{\ln E_{\text{cm}}}$$

c) R-Verhältnis in Tau-Leptonzerfällen

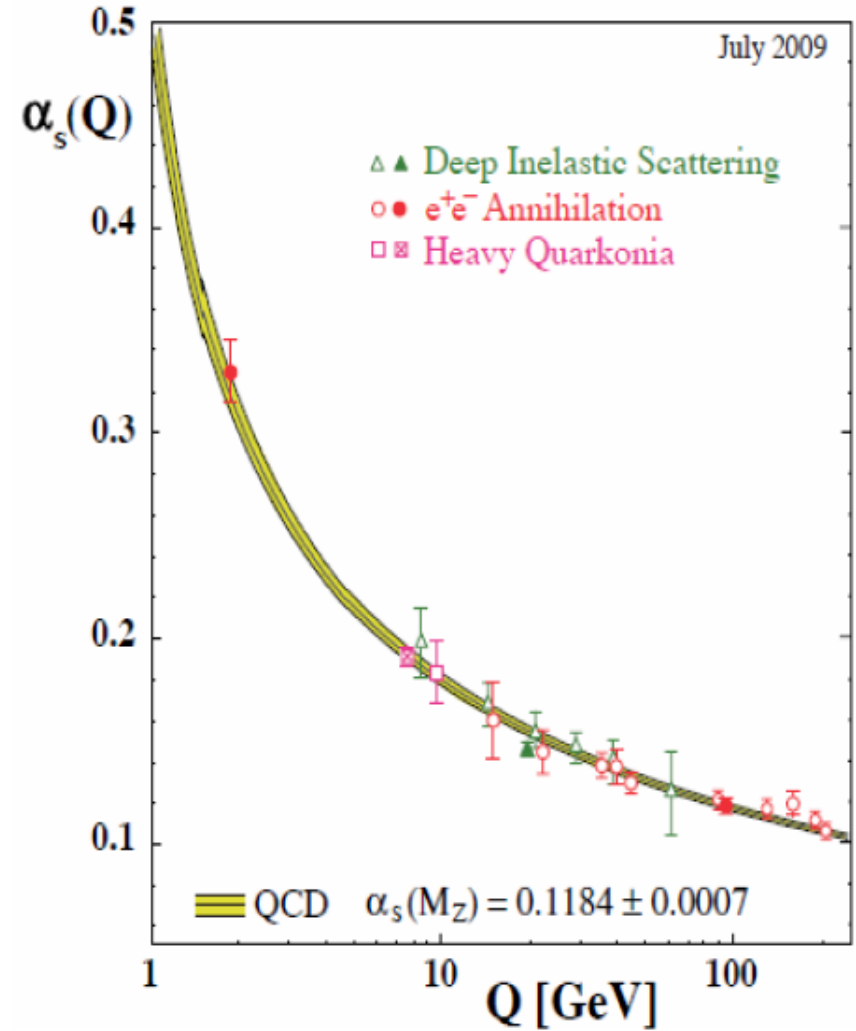
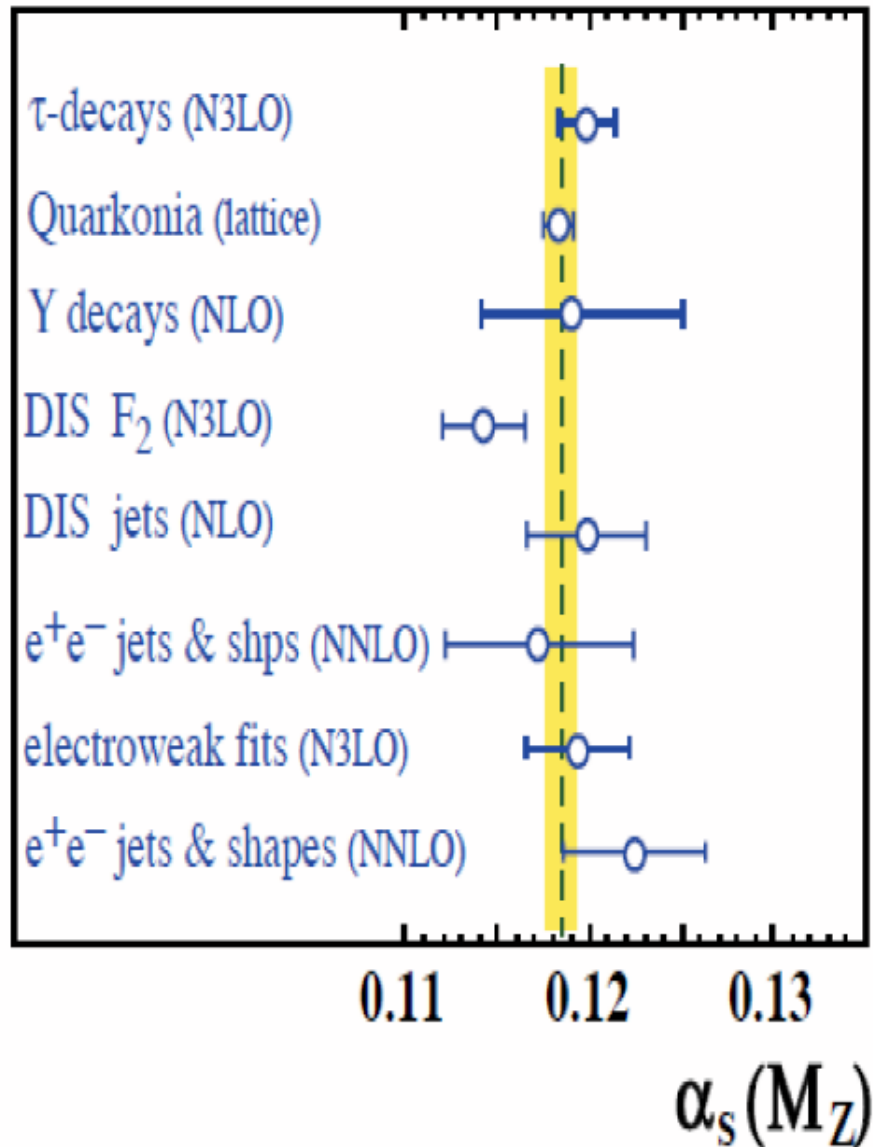
$$R_\tau = \frac{\Gamma(\tau^- \rightarrow \text{Hadronen})}{\Gamma(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)} \propto \alpha_s(m_\tau^2)$$

d) Massenspektren von Charmonium und Botonium

e) Verletzung der Bjorkenschen Skaleninvarianz in Tiefinelastischer Streuung



Das "Laufen" der starken Kopplungskonstanten



Streung vom Elektronen am Dirac-Proton

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

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

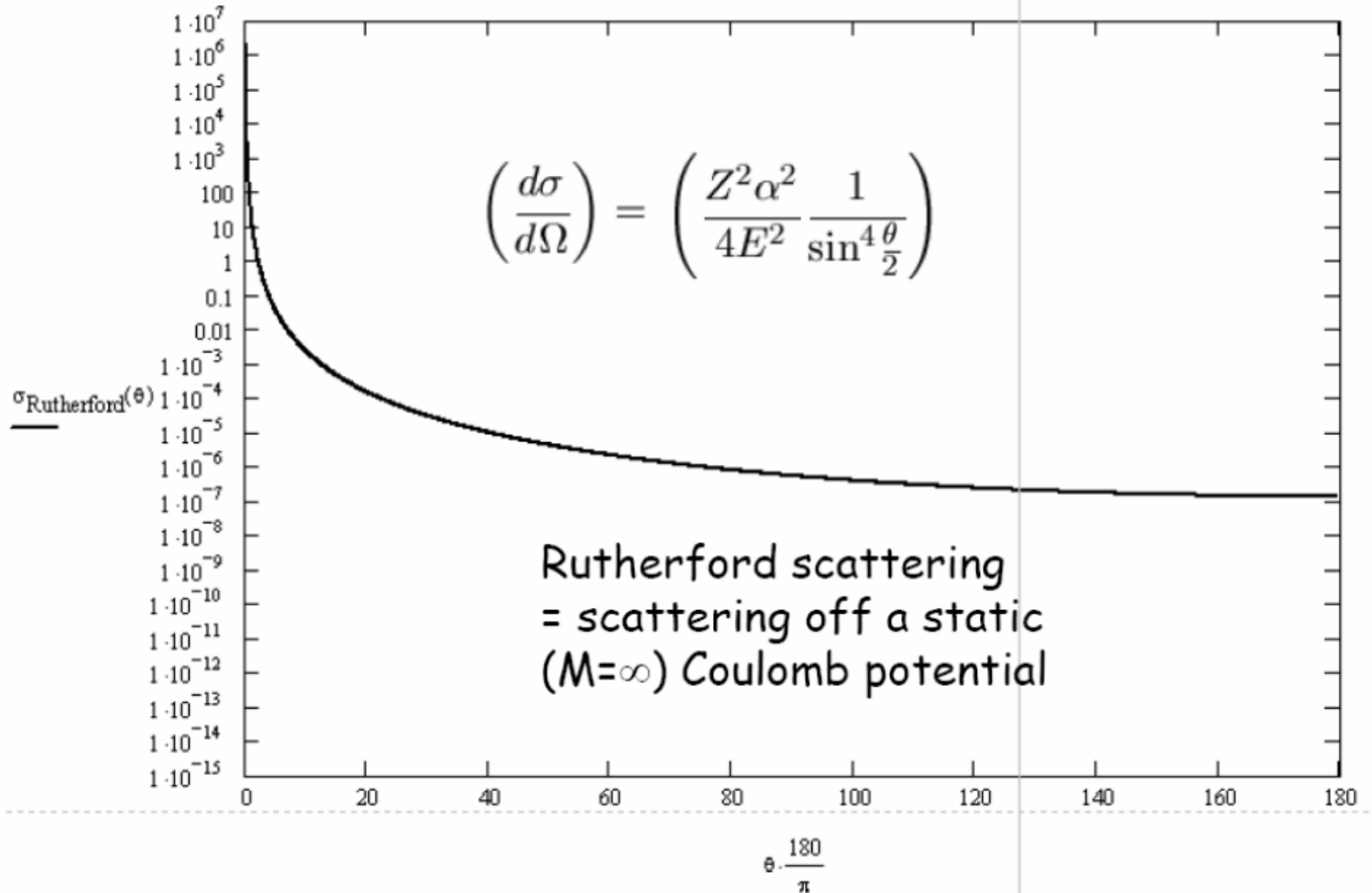
$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$ electron has spin $\frac{1}{2}$!

180° scattering is impossible

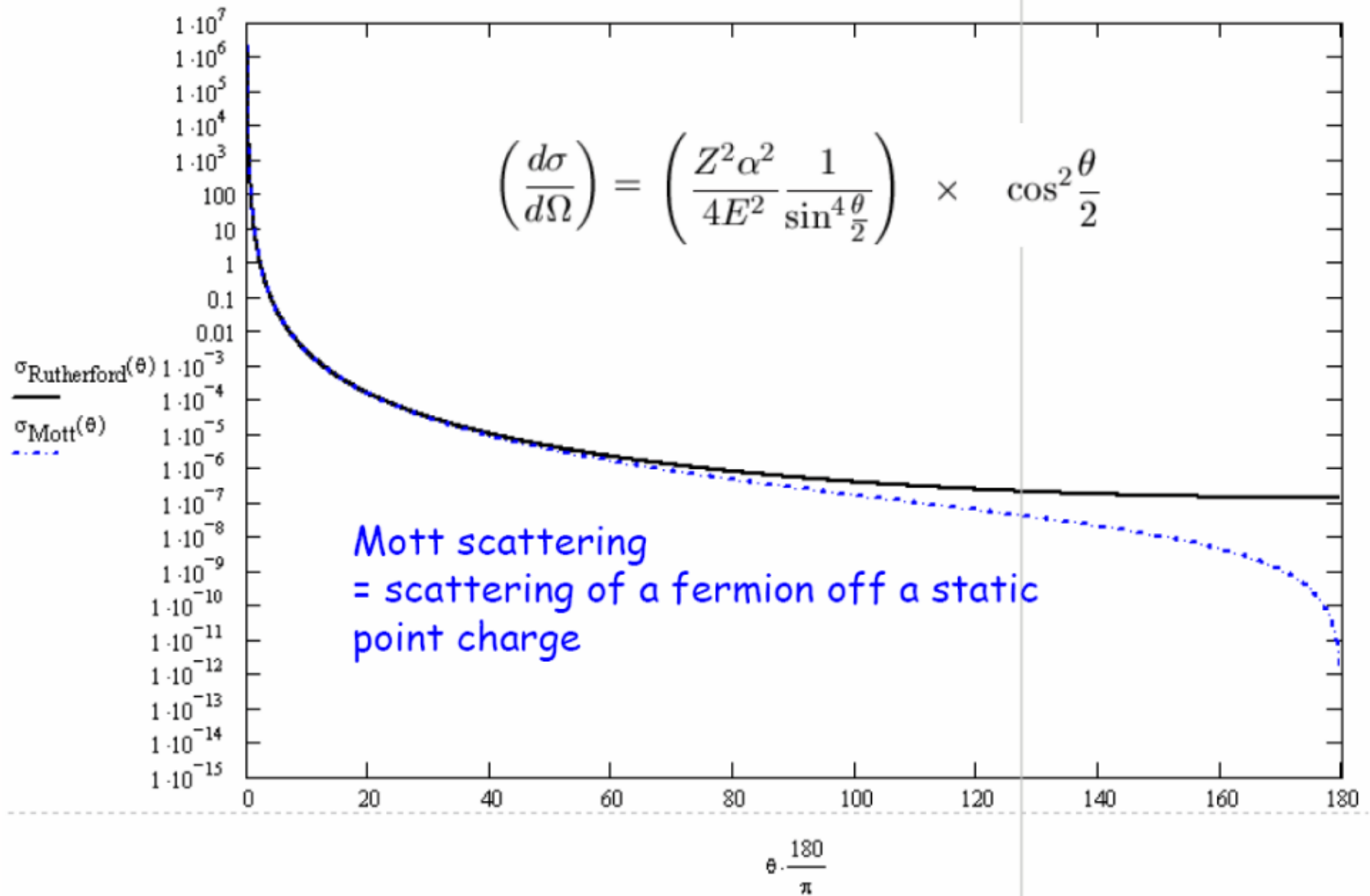
$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott-Recoil}}$ proton has a mass $M_p < \infty$!

$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Dirac-Proton}}$ 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

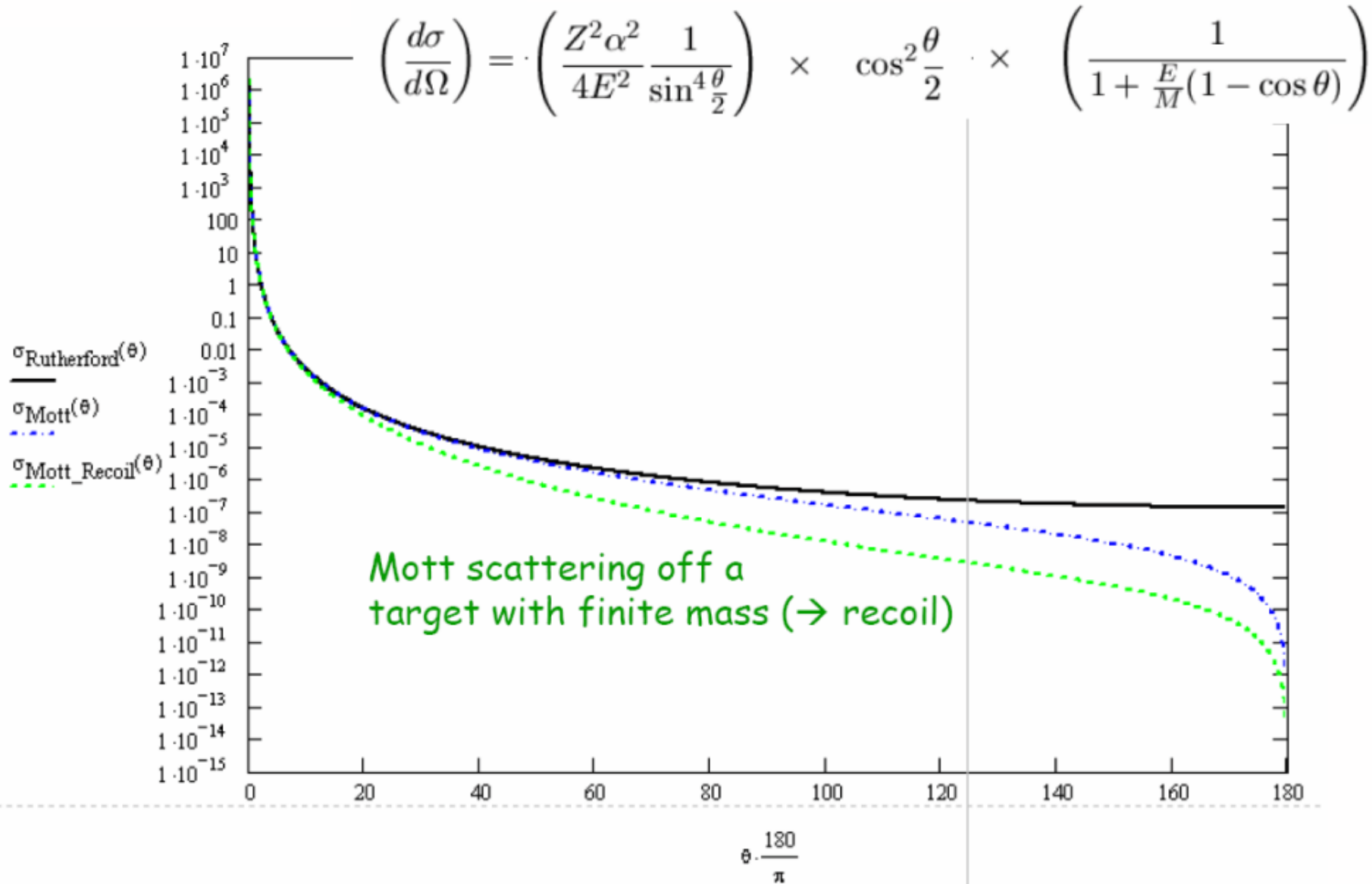
Rutherfordstreueung am unendlichschweren Kern



Mottstreuung am unendlichschweren Kern

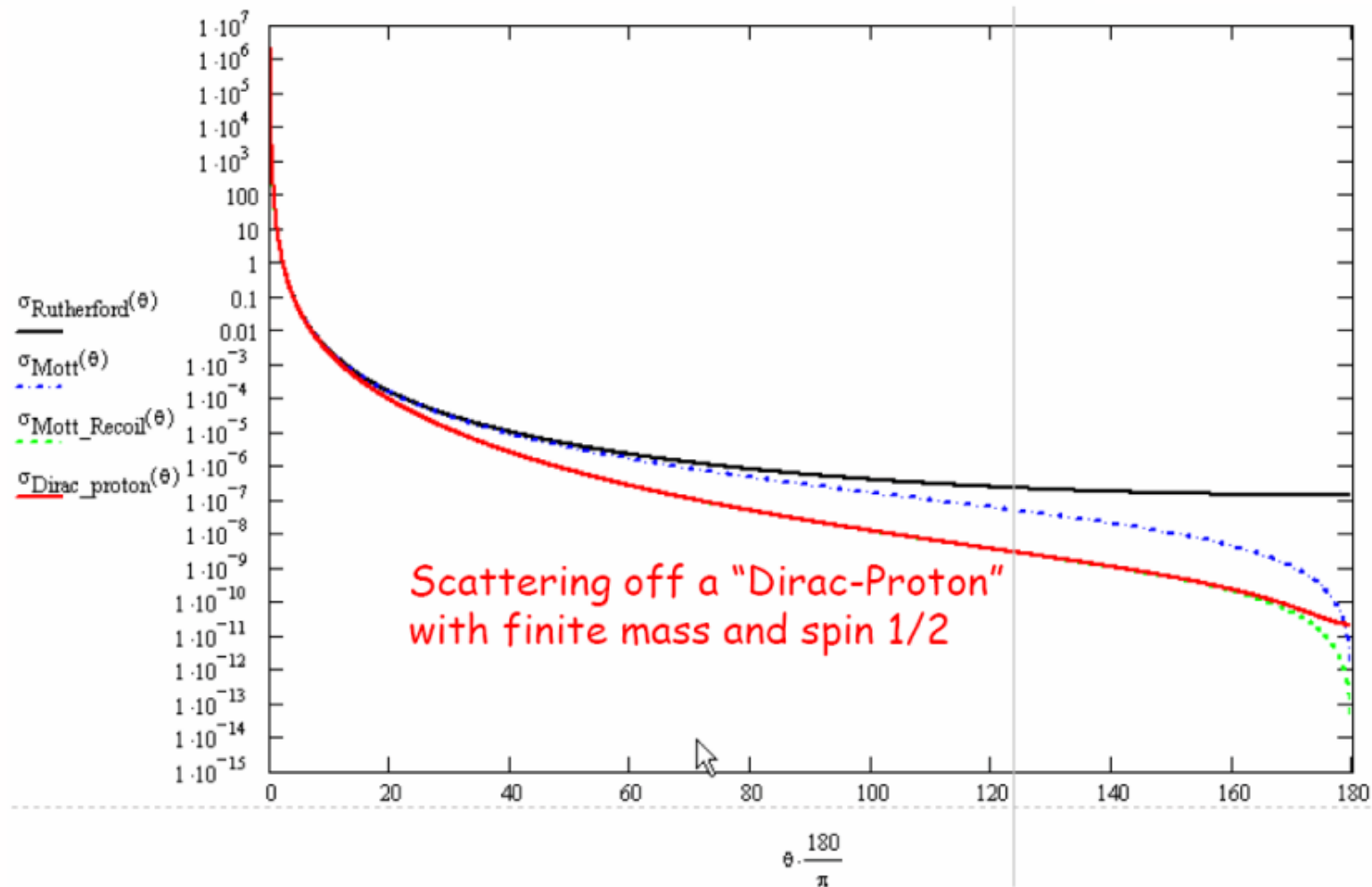


Mottstreuung an endlicher Masse (Spin=0)



Mottstreuung am Diracproton

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

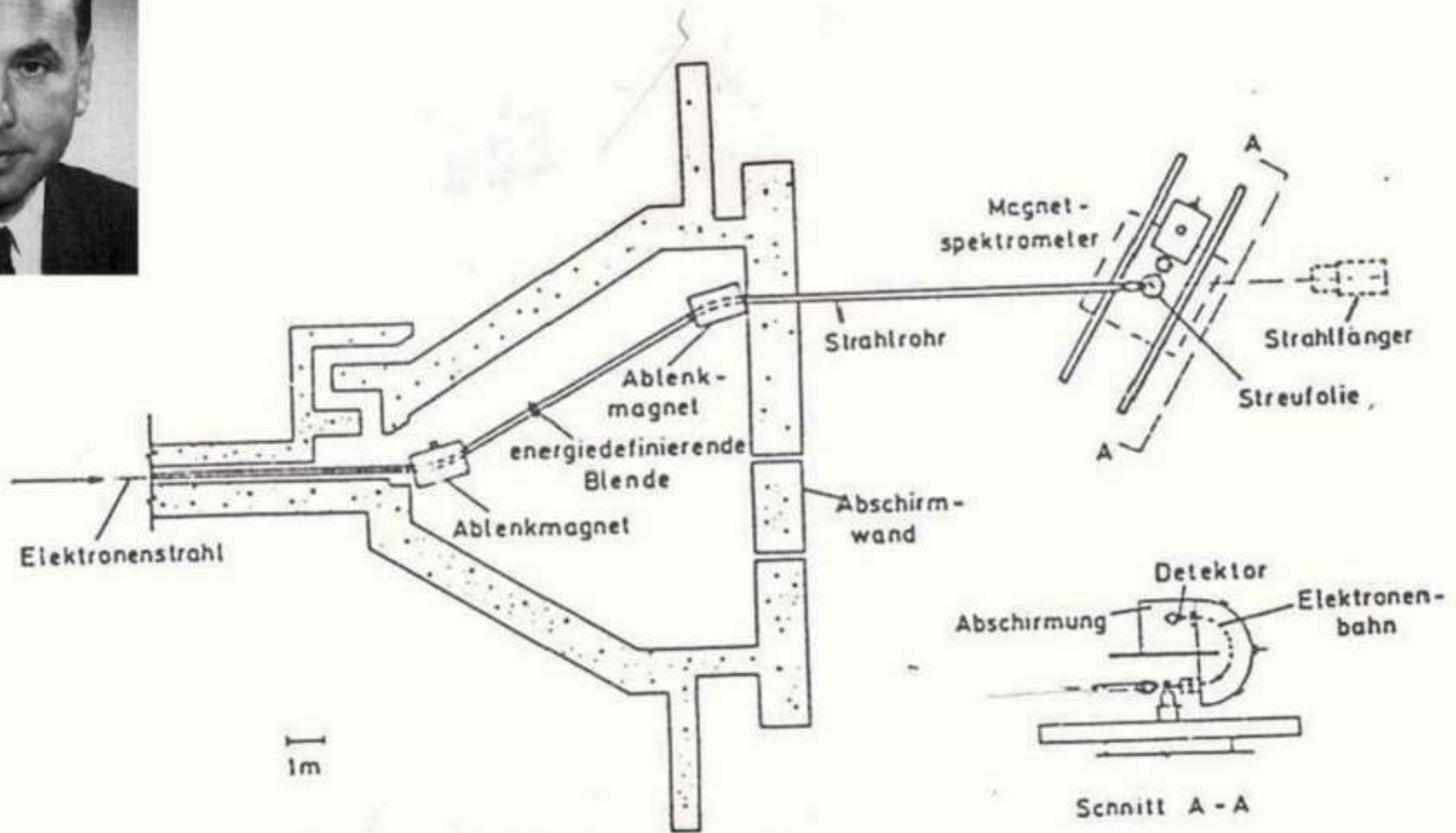


Elastische e-p-Streuung

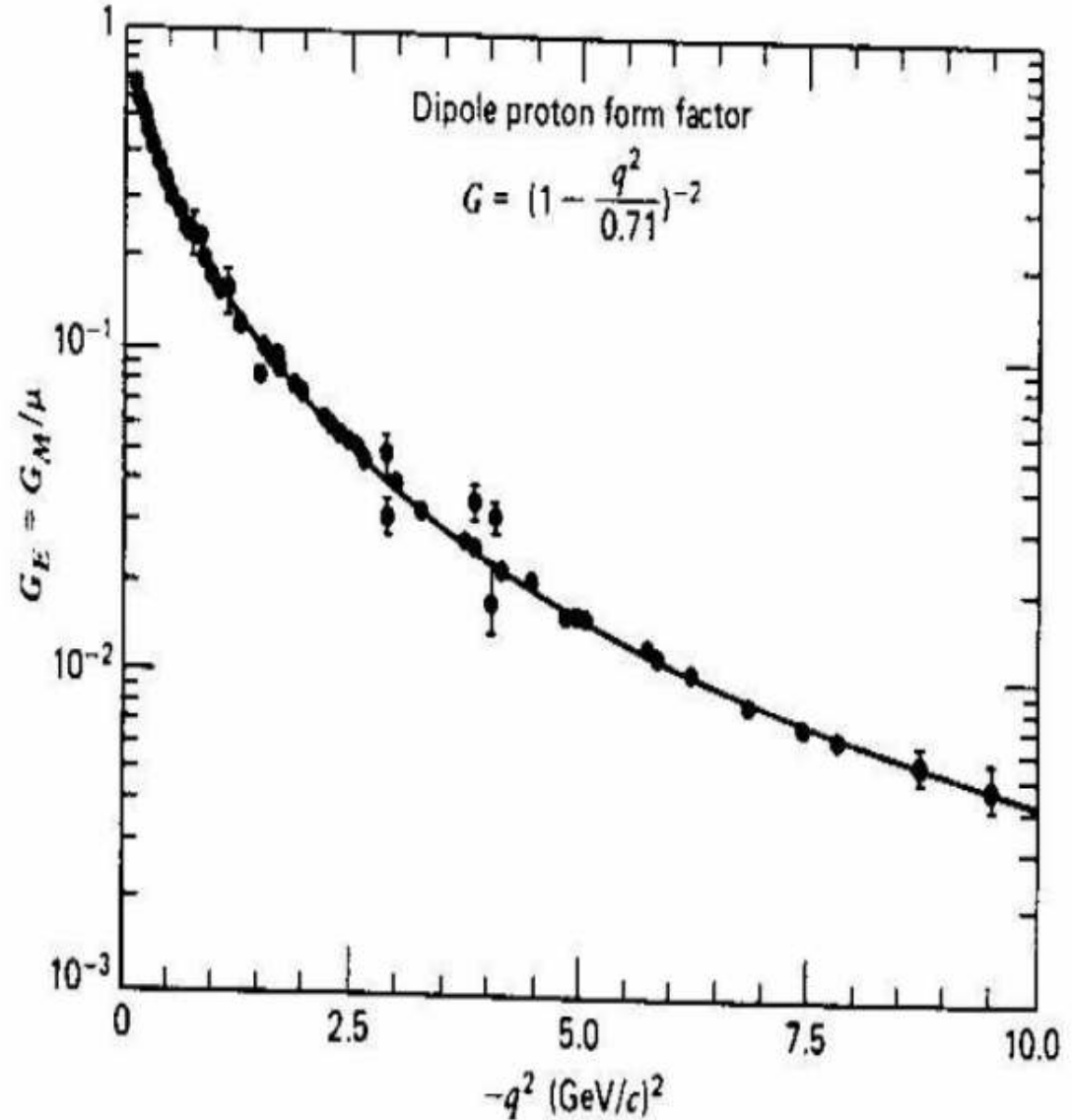
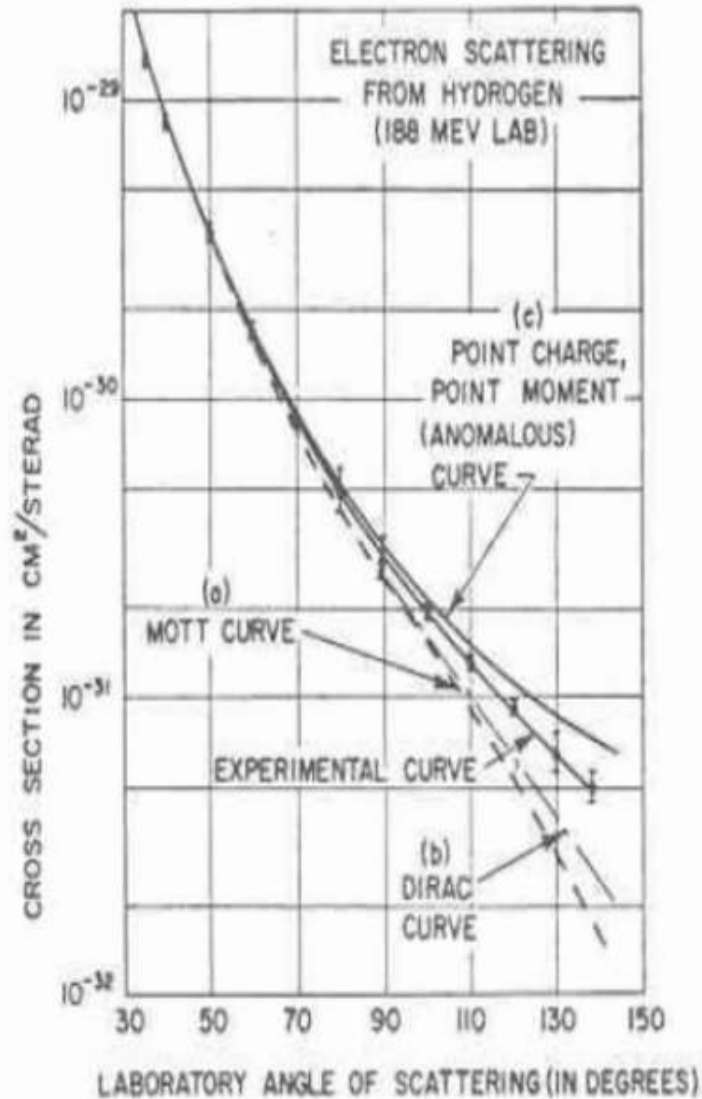


Robert Hofstadter
Nobel Prize 1961

from
Linac



Elastische e-p-Streuung



SLAC Endstation A



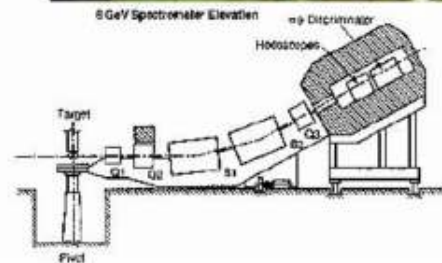
SLAC

up to 20 GeV beam

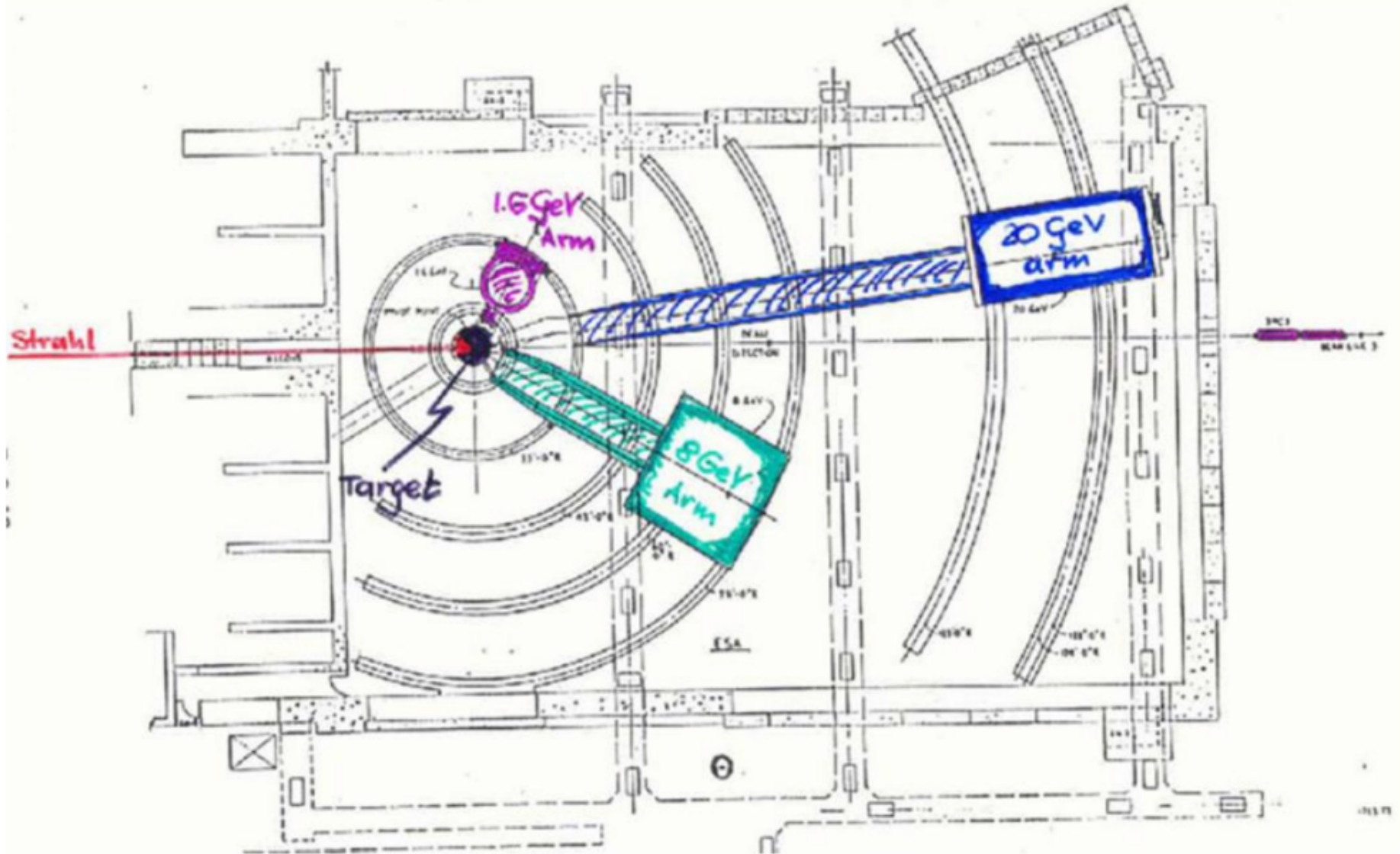


endstation A

8 GeV Electron Spectrometer



SLAC Endstation A



Inelastische e-p Streuung

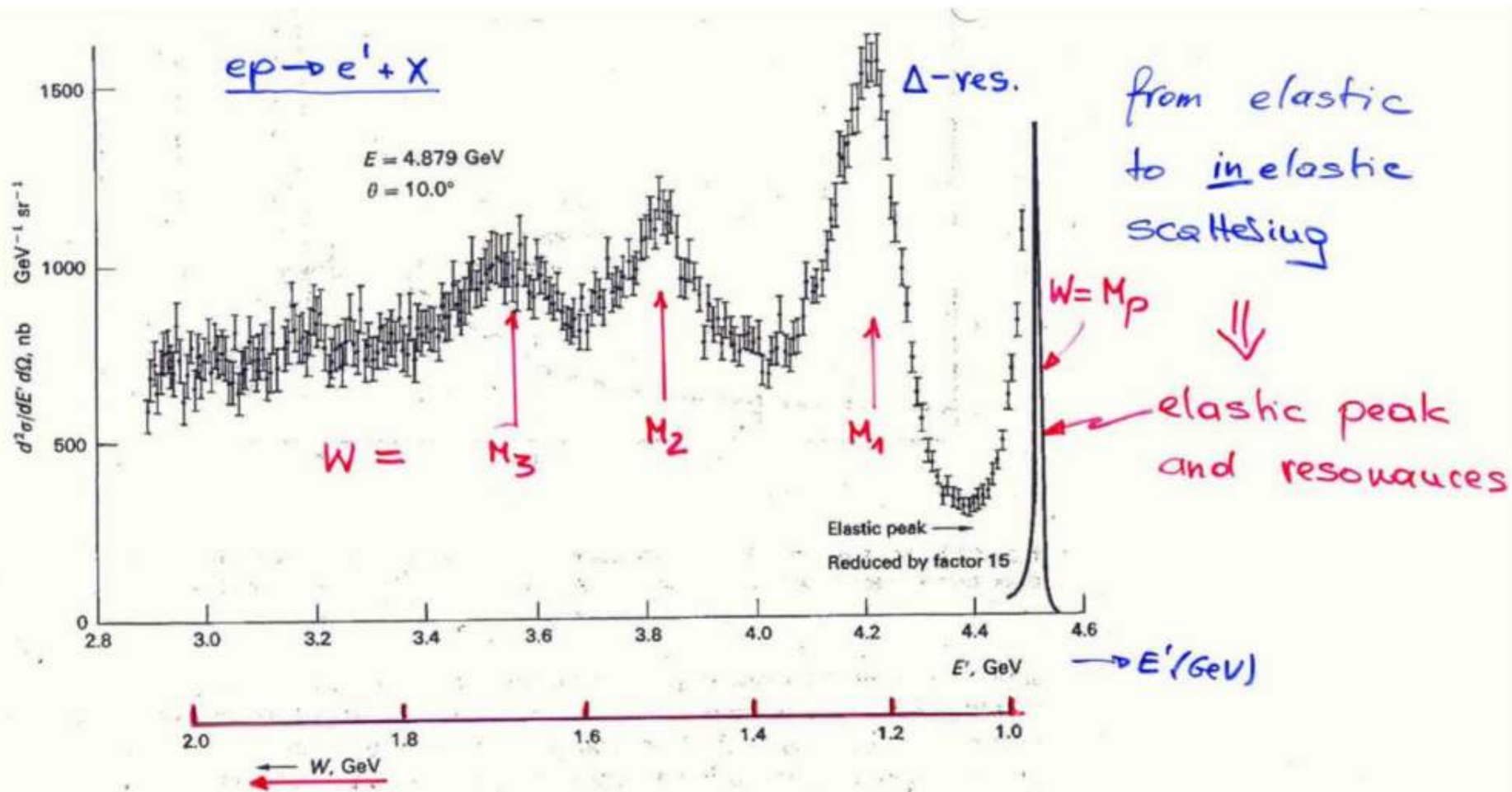


Fig. 7.15 Excitation curve of inelastic ep scattering, obtained at the DESY electron accelerator (Bartel *et al.* 1968). E and E' are the energies of the incident and the scattered electron, and W is the mass of the recoiling hadronic state. The peaks due to the pion-nucleon resonances of masses 1.24,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

Messungen bei SLAC

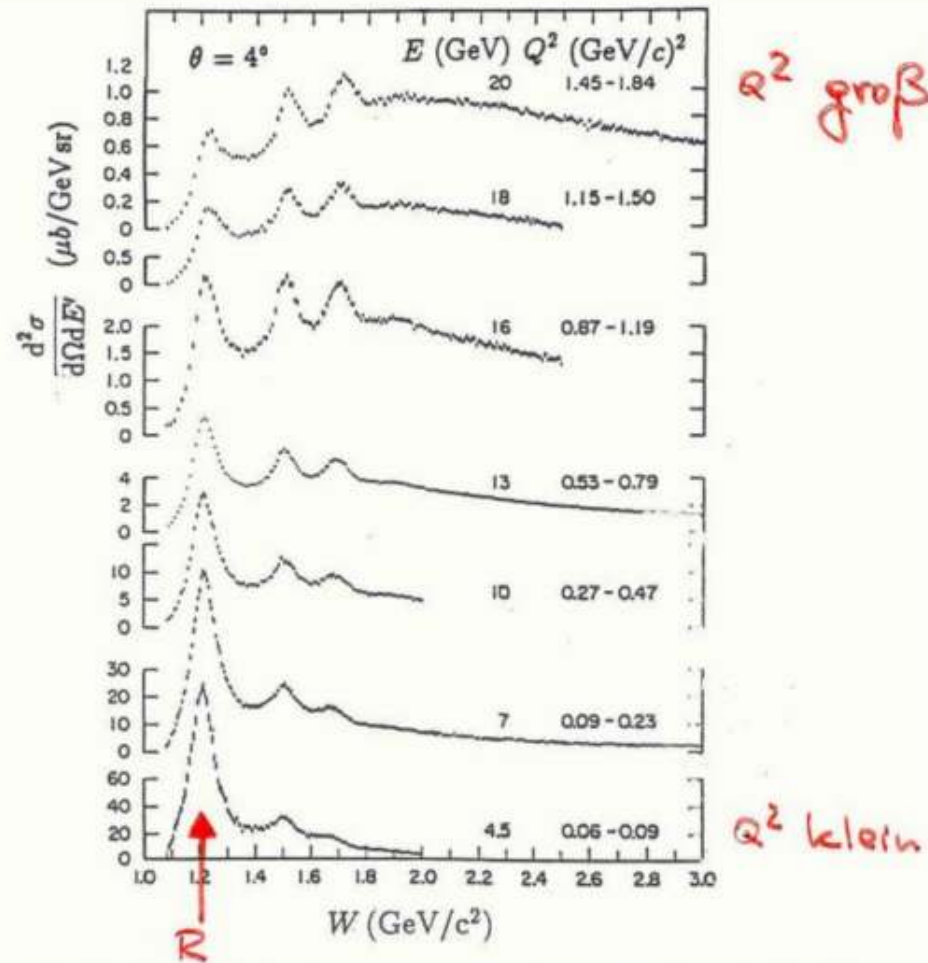
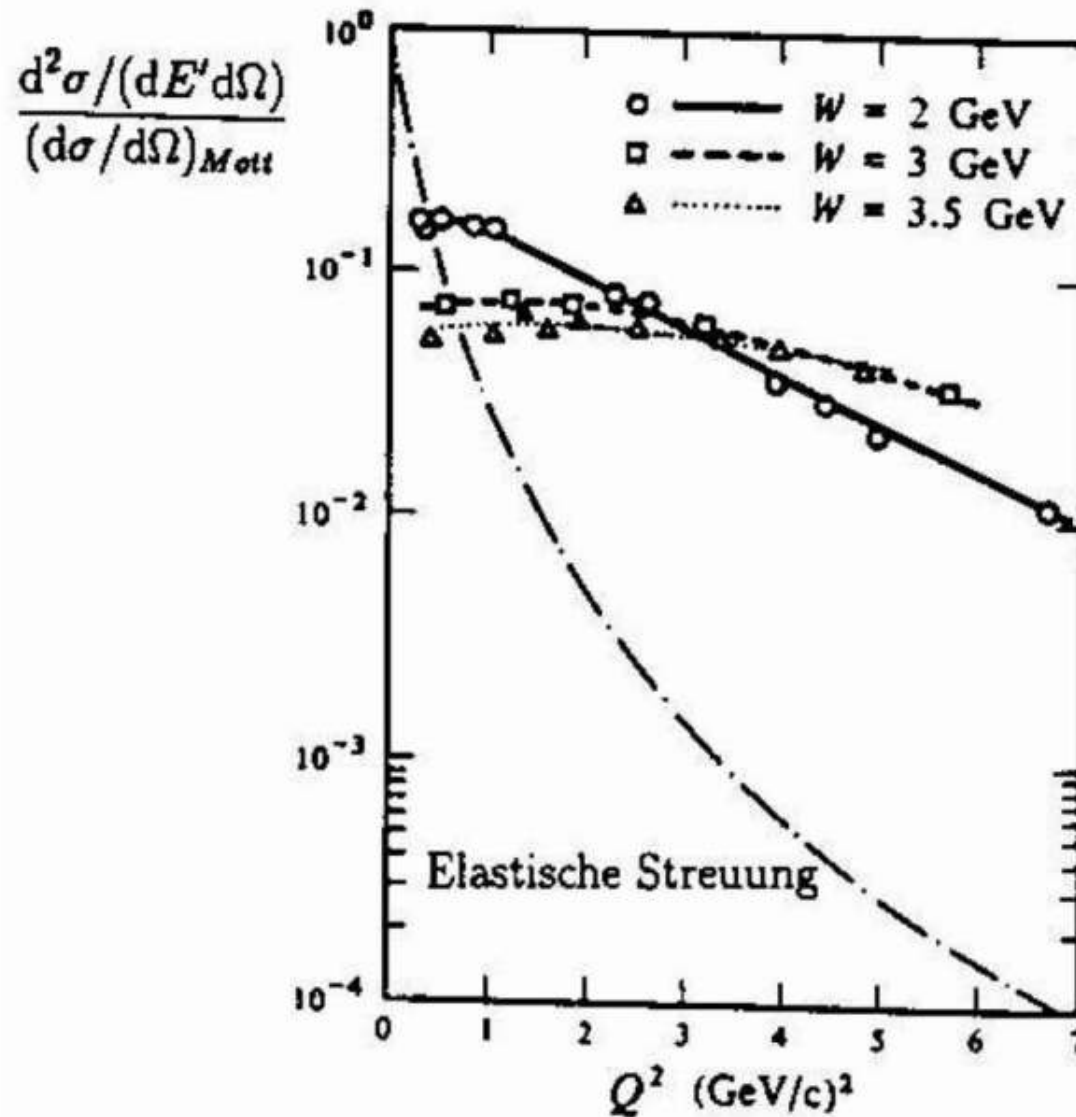


Abb. 7.2. Elektron-Proton-Streuung: gemessene Anregungsspektren in der tiefinelastischen Elektron-Nukleon-Streuung als Funktion der invarianten Masse W [St75]. Die Messungen wurden bei einem festen Streuwinkel von $\theta = 4^\circ$ durchgeführt. Mit zunehmender Einfallenergie E wächst der mittlere Q^2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

WQ im Vergleich zu elastischer Erwartung

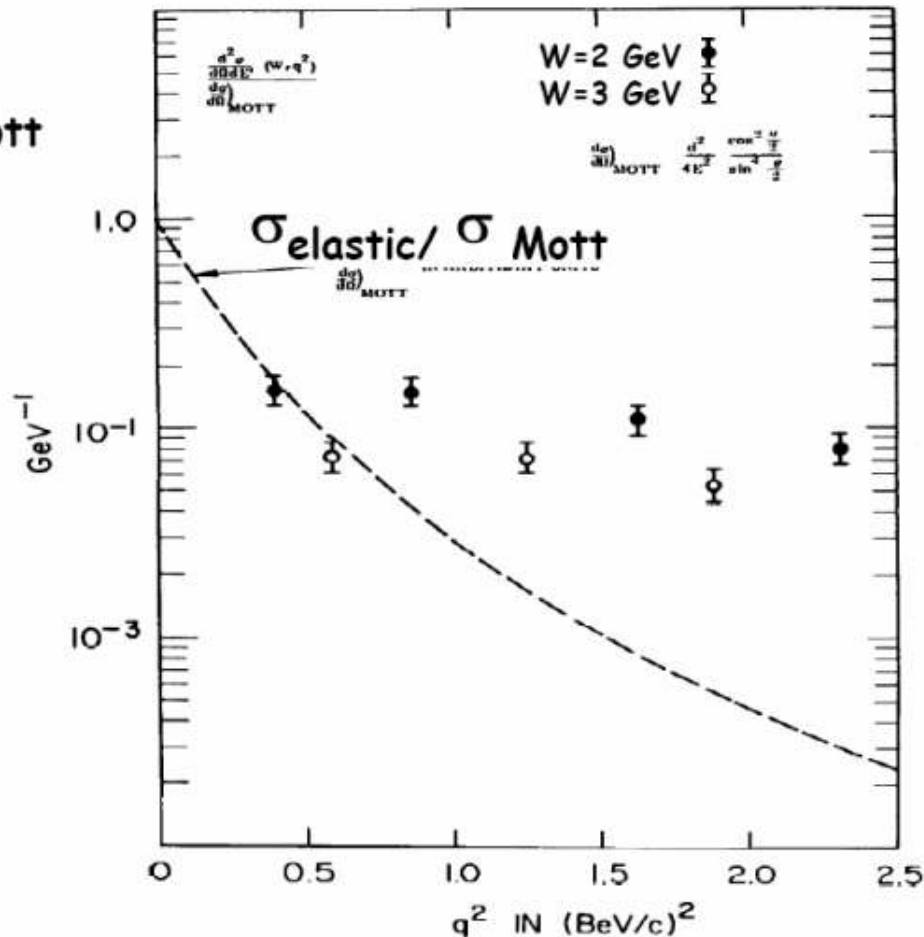


Evidenz für harte Streuung an Partonen

H. W. Kendall

697

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



SLAC ~1967

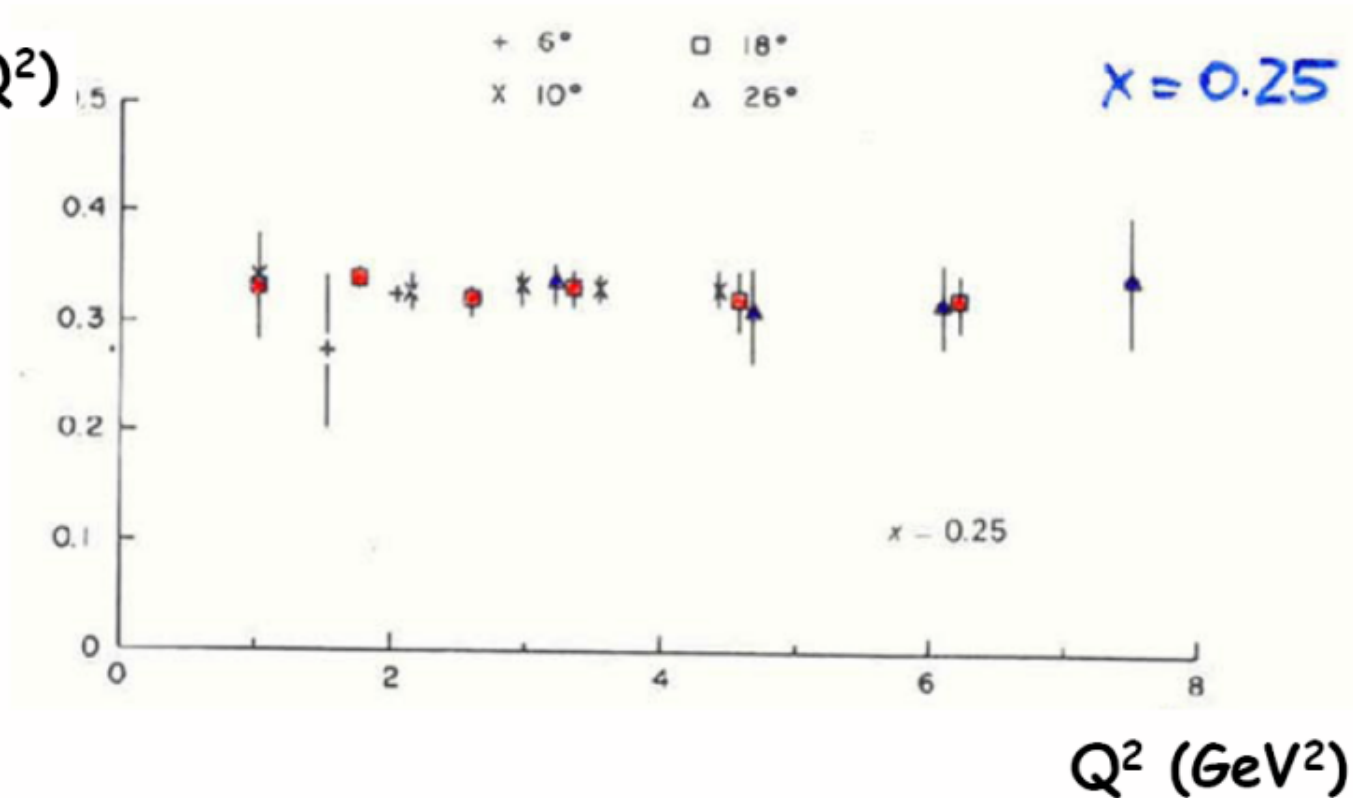


Jerome Friedman
Henry Kendall
Richard (Dick) Taylor
NP 1990

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”

$F_2(x, Q^2)$



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

“Callan-Gross”-Beziehung

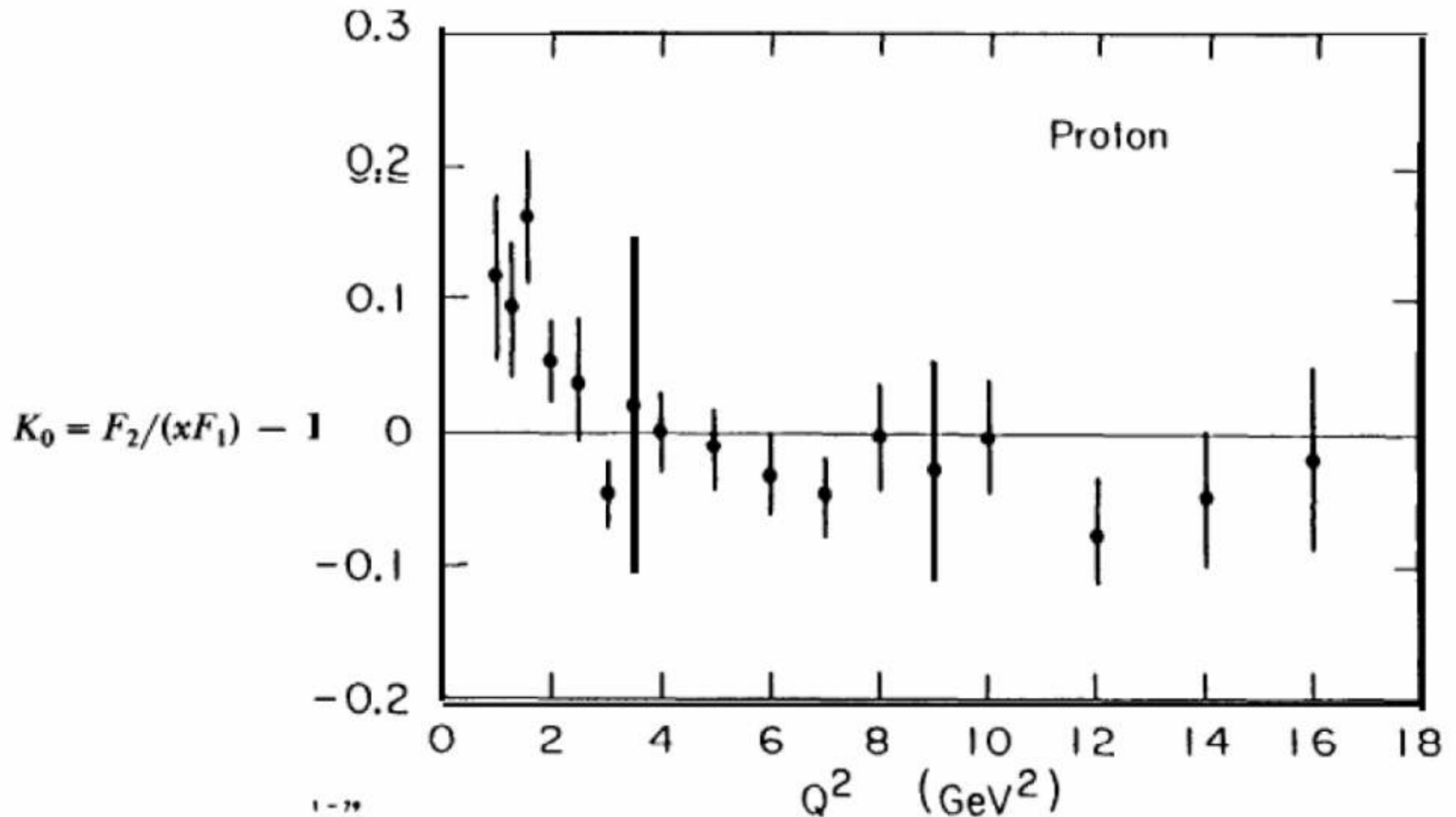
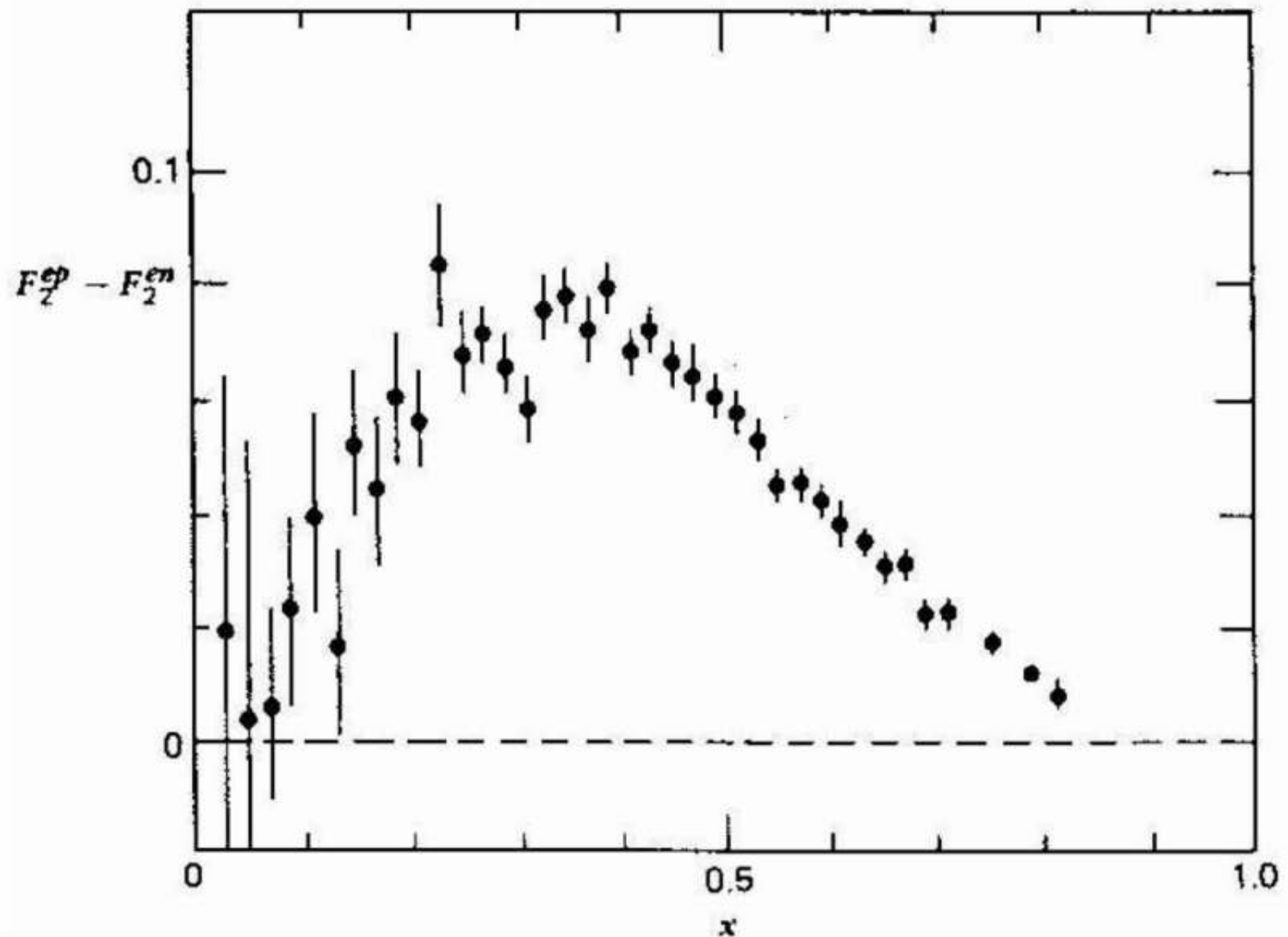


Fig. 18. The Callan-Gross relation: K_0 vs q^2 , where K_0 is defined in the text. These results established the spin of the partons as $1/2$.

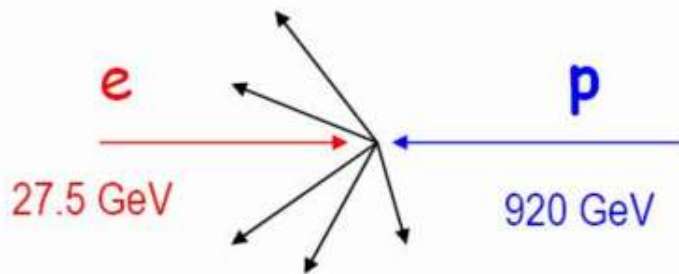
Partonverteilungsfunktionen der Valenzquarks



HERA-Beschleuniger bei DESY-Hamburg

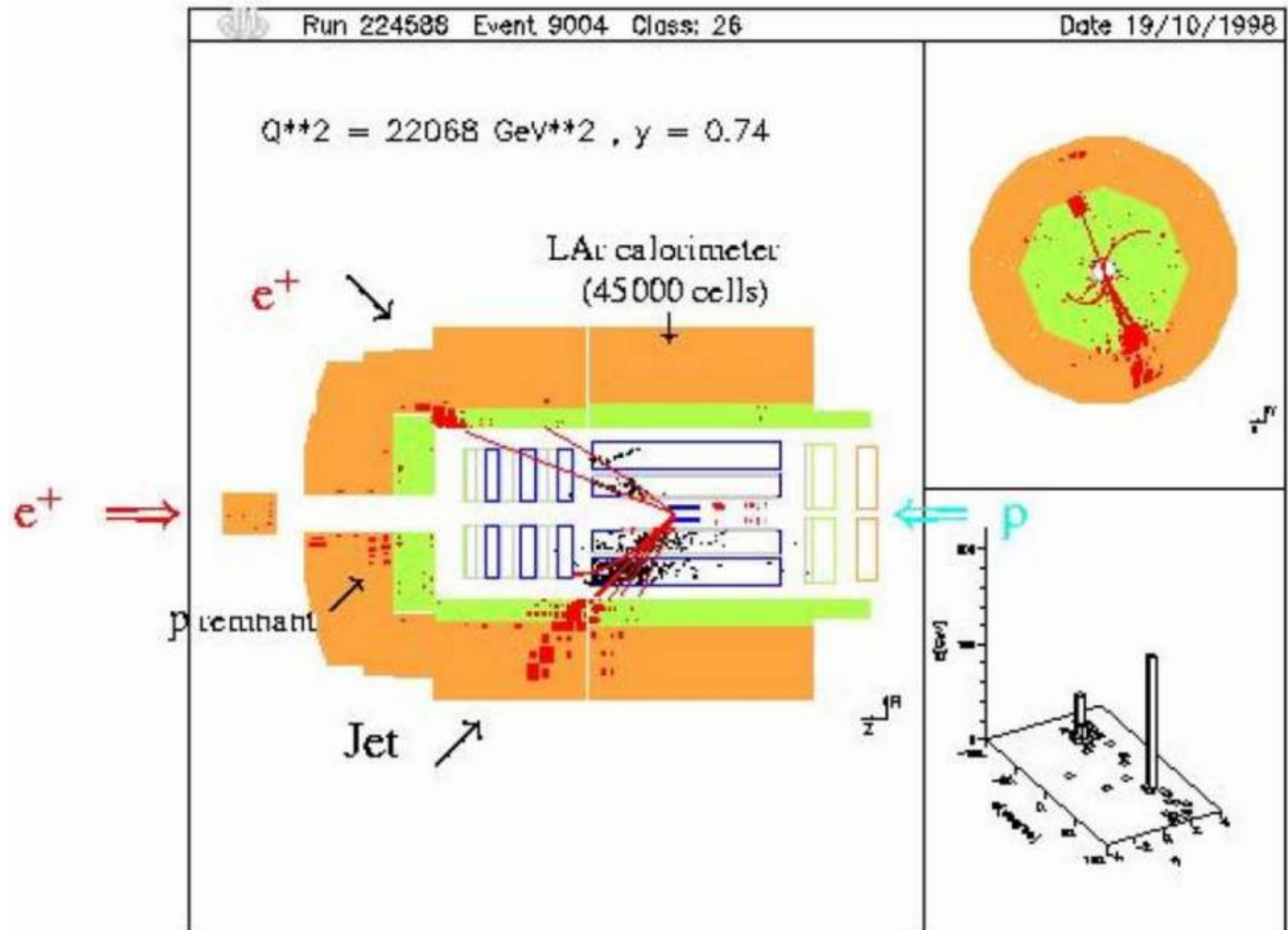


only ep collider world-wide

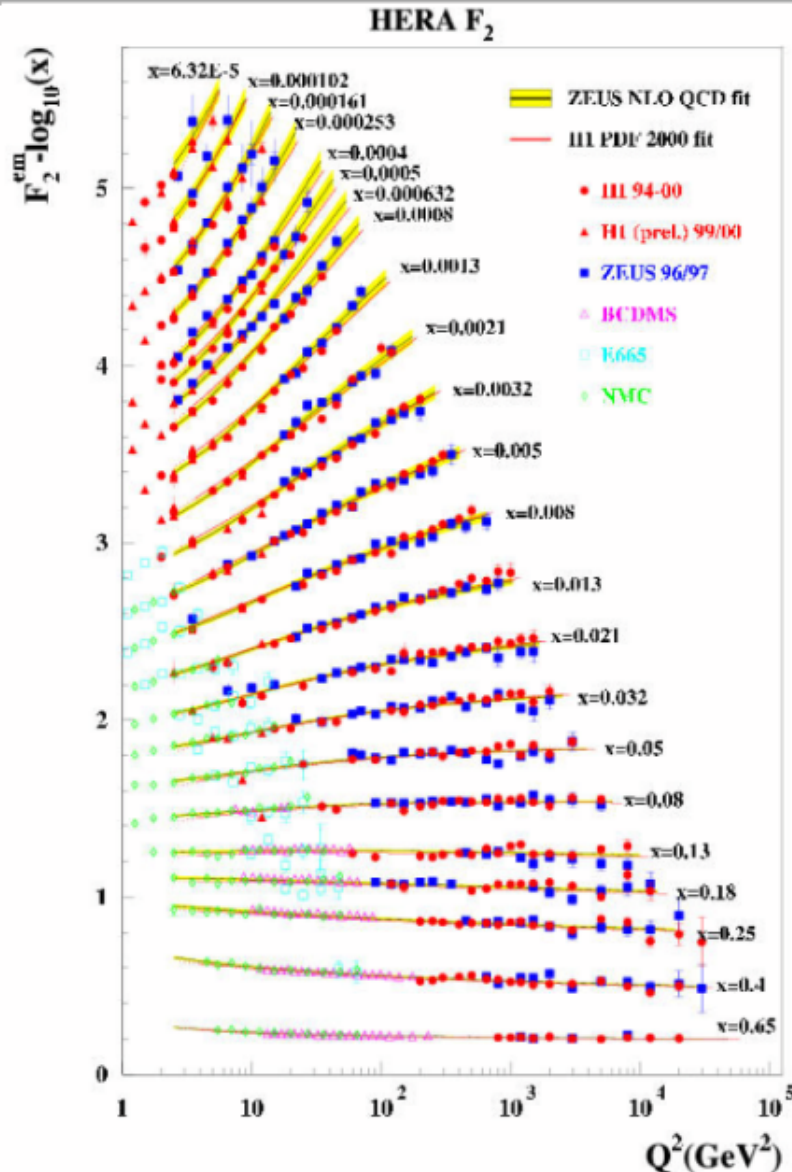


$$s = (318 \text{ GeV})^2$$
$$Q^2 \text{ up to } 10^5 \text{ GeV}^2$$

Ein DIS-Streuereignis in H1



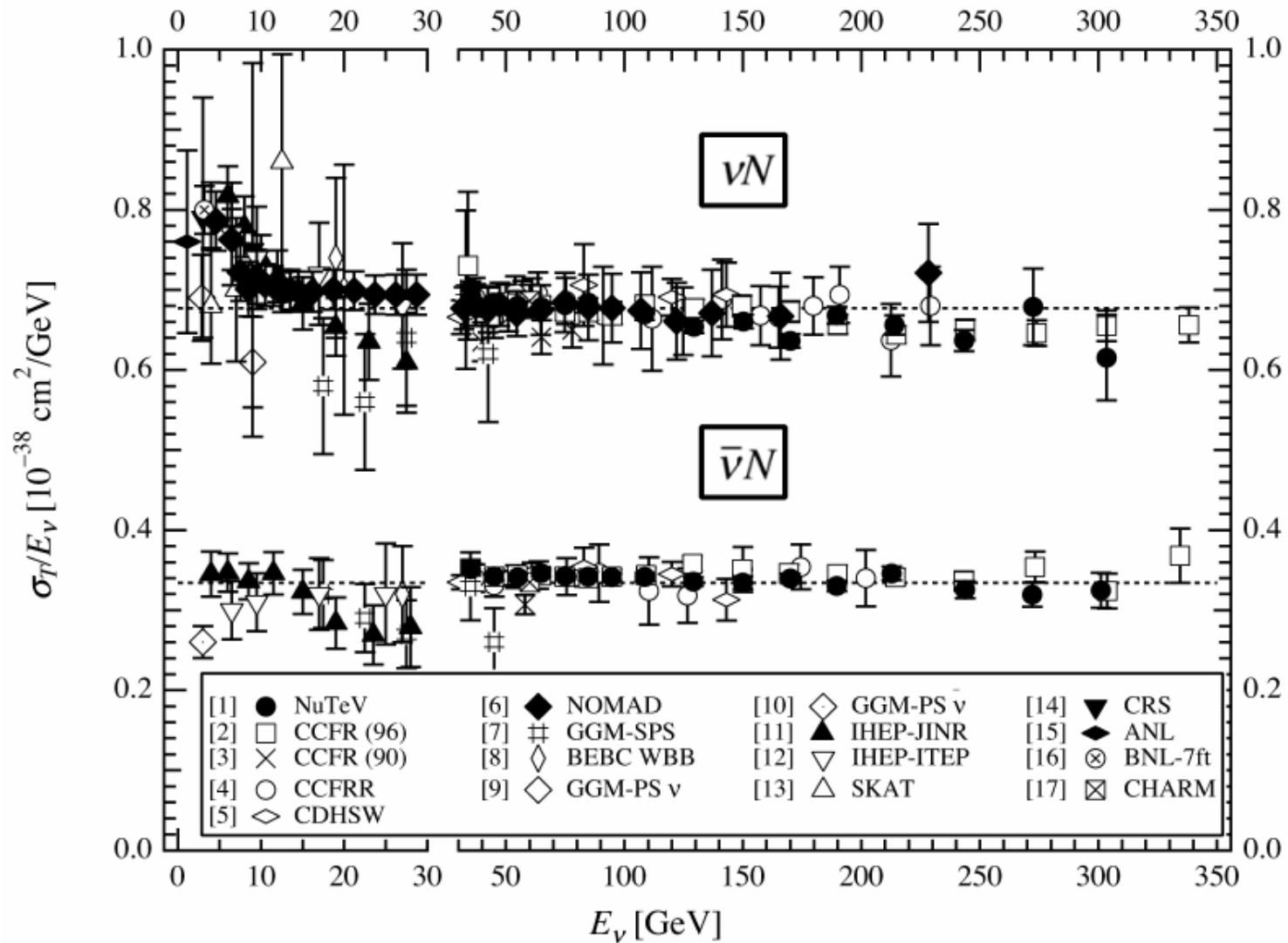
“Scaling violations”



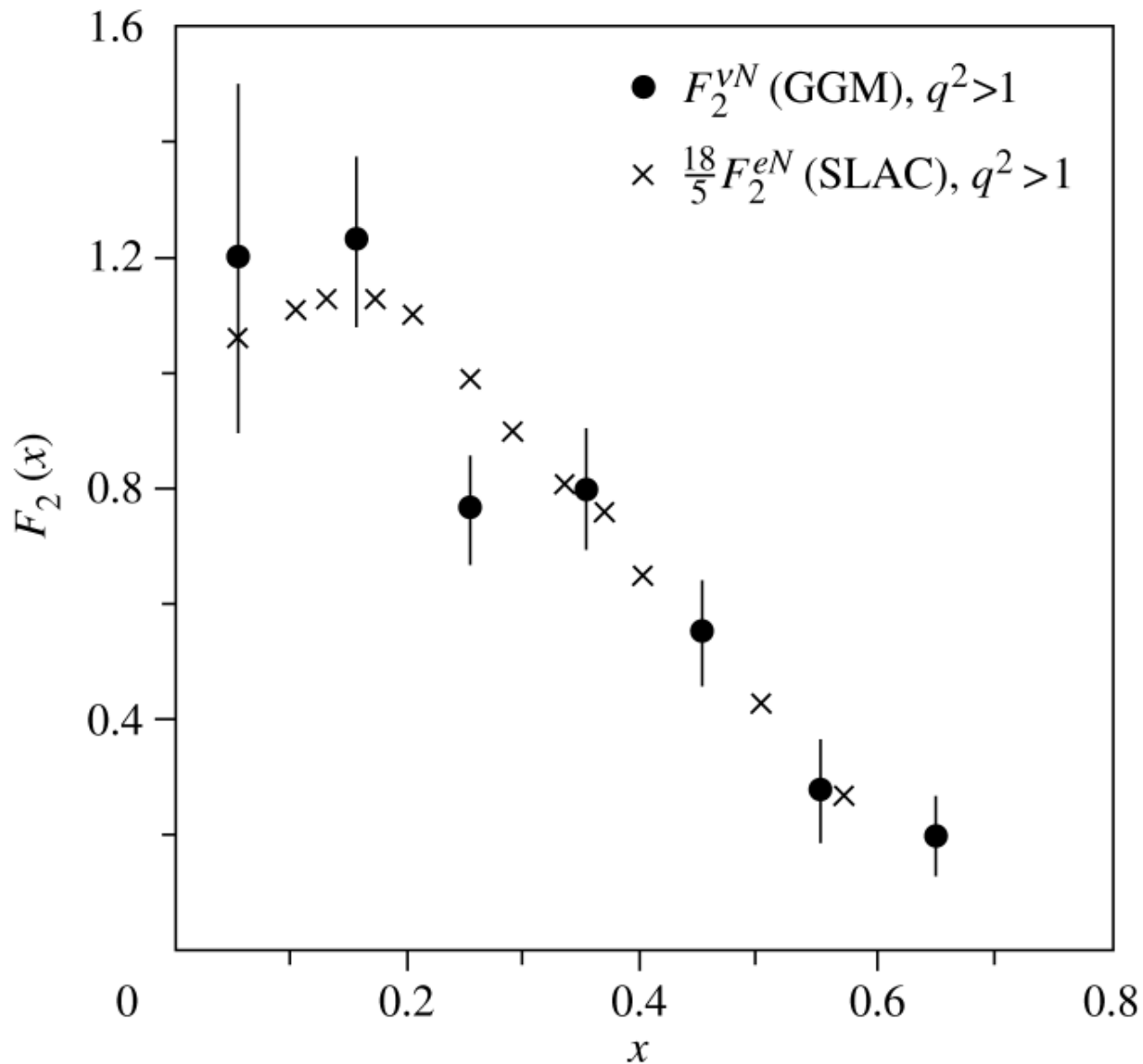
at higher Q^2
 $\Rightarrow F_2(x)$ does also depend
on Q^2 , not on x only

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

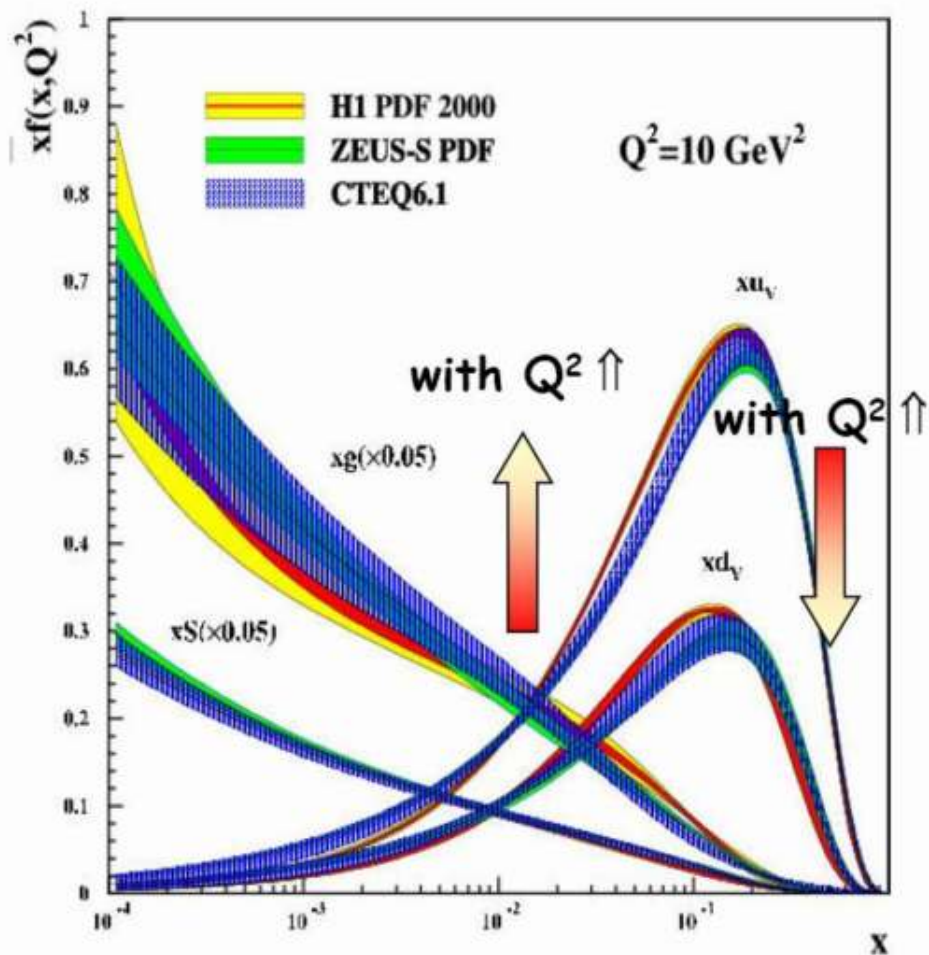
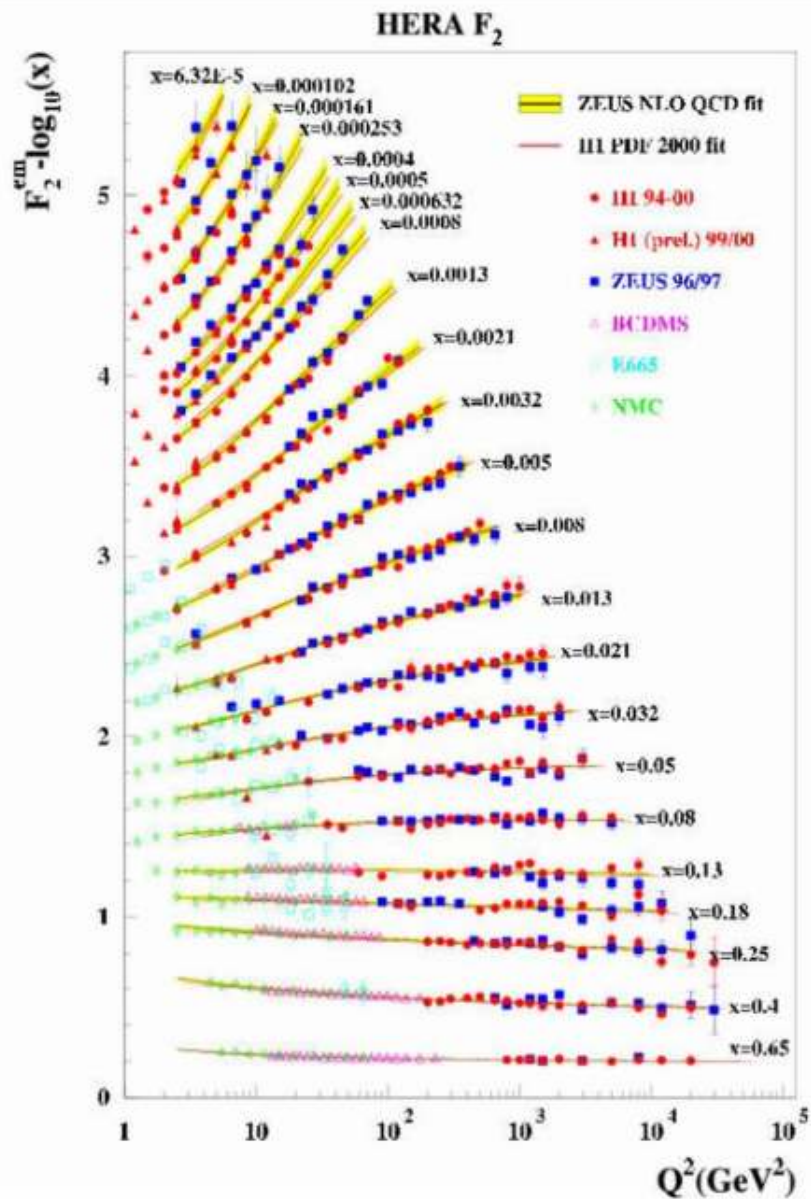
Neutrino und Antineutrino-Nukleon-Streuung



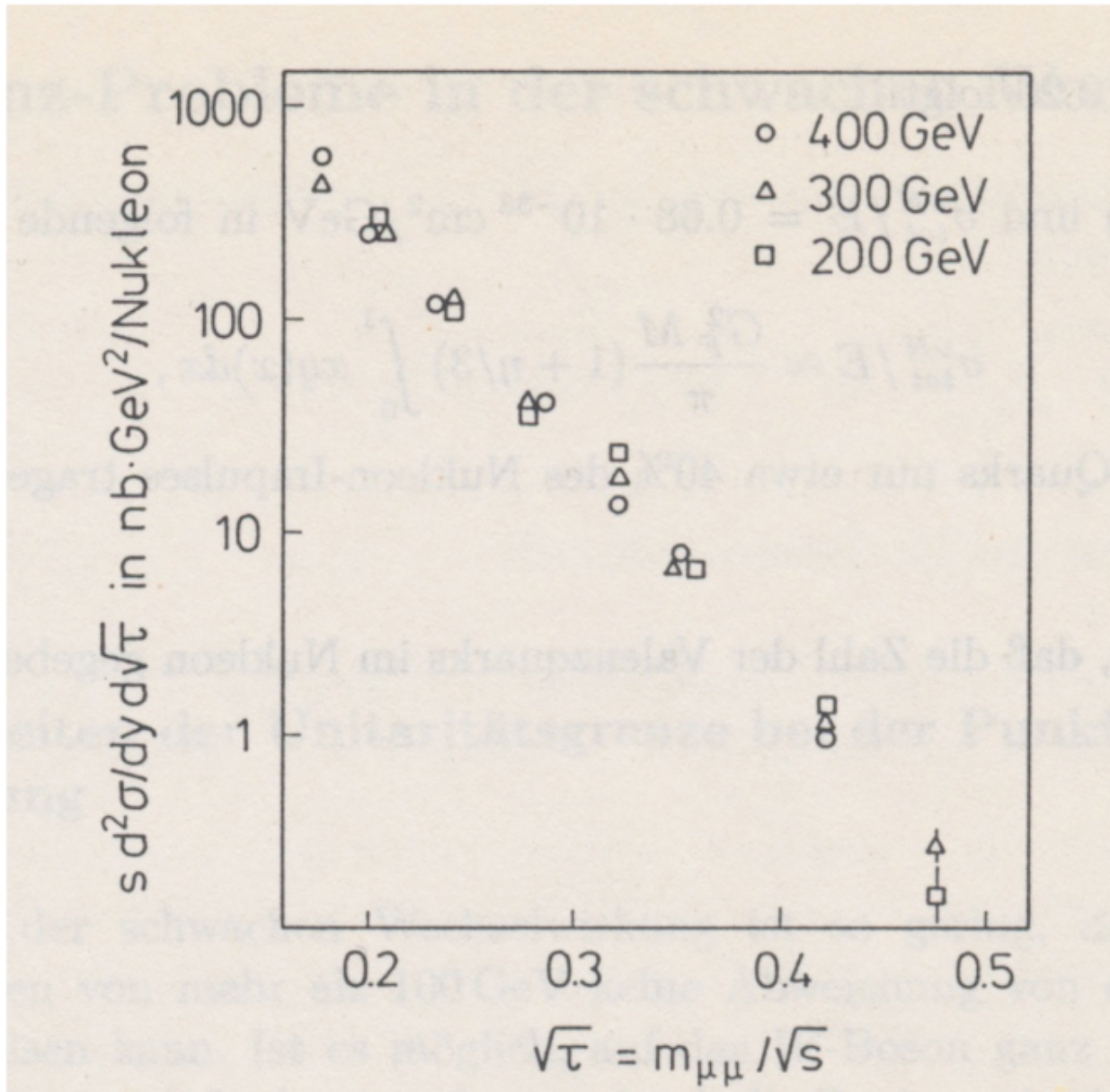
Vergleich von F_2 in e- und n-Nukleonstreuung



“Scaling Violations”



“Scaling” in Dress-Yan-Produktion



Messergebnisse die in PDF-Fir eingehen

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	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \rightarrow \text{jet}+X$	$gg, qq, q\bar{q} \rightarrow 2j$	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	$x \gtrsim 0.05$

Randbedingungen für PDF-Fit

- **Valence Sum Rules**

$$\int_0^1 [u(x, Q^2) - \bar{u}(x, Q^2)] dx = 2, \quad \int_0^1 [d(x, Q^2) - \bar{d}(x, Q^2)] dx = 1$$

$$\int_0^1 [s(x, Q^2) - \bar{s}(x, Q^2)] dx = 0$$

A proton has net quantum numbers of 2 up and 1 down quarks.

- **Momentum Sum Rule**

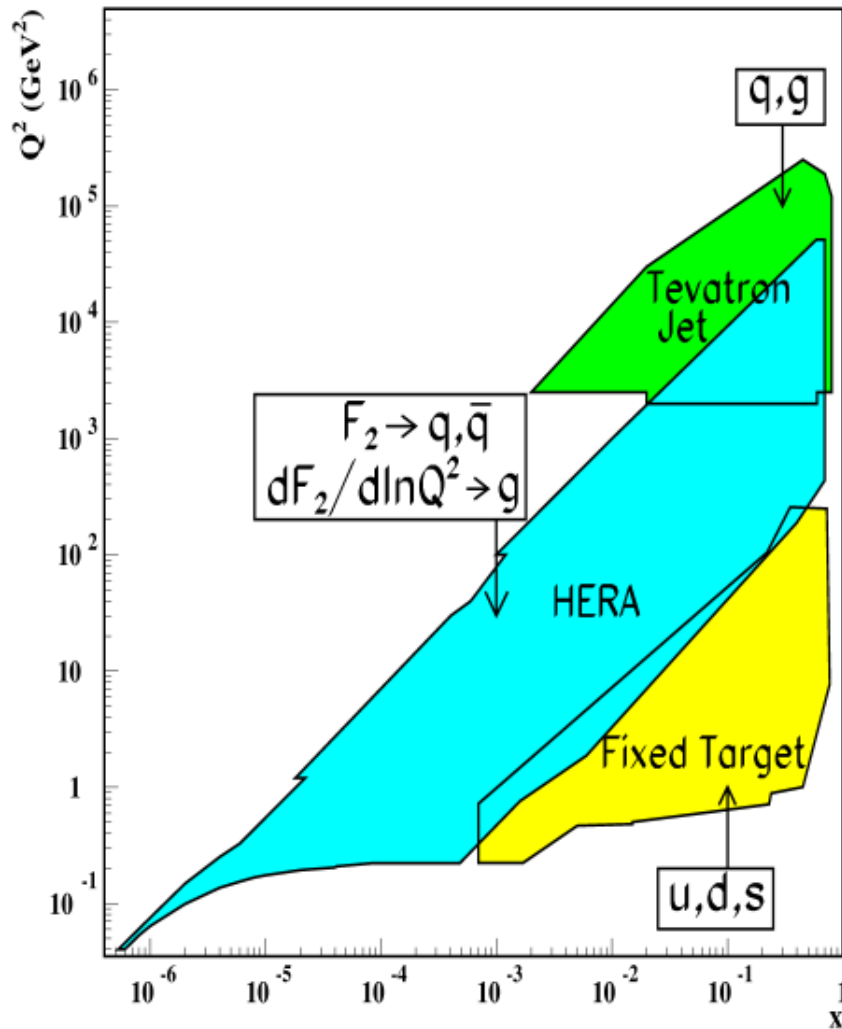
$$\sum_{a=q, \bar{q}, g} \int_0^1 x f_a(x, Q^2) = 1$$

Momenta of all partons must add up to the proton momentum.

- Introduce a simple functional form with enough free parameters

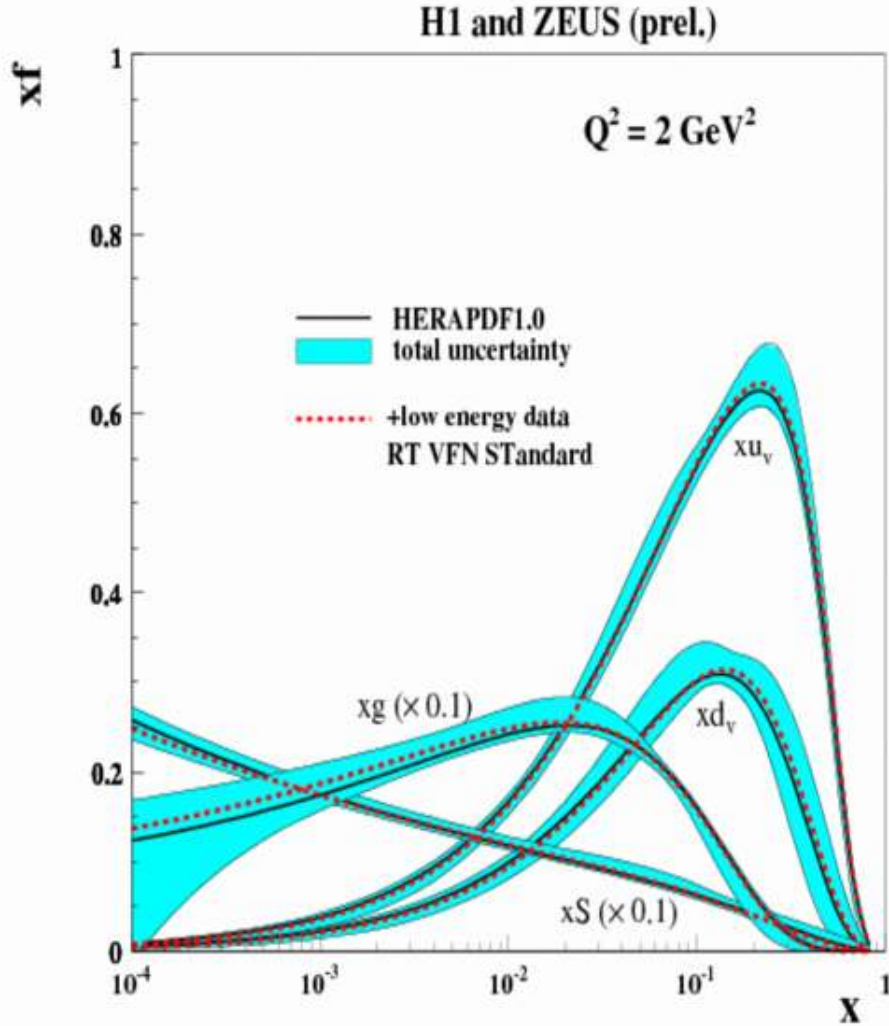
$$q(x, Q^2) = x^\alpha (1-x)^\beta P(x; \lambda_1, \dots, \lambda_n).$$

Messergebnisse und kinematische Region



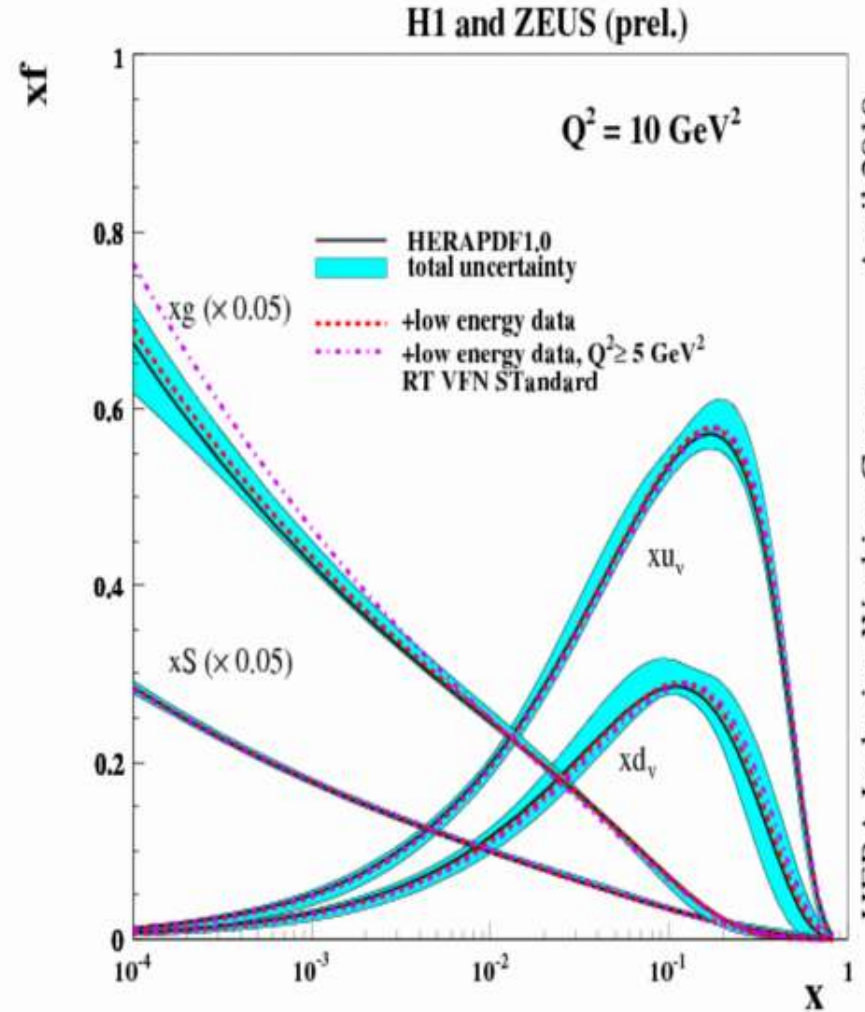
Process	Subprocess	Partons	x range
$\ell^\pm \{p, n\} \rightarrow \ell^\pm X$	$\gamma^* q \rightarrow q$	q, \bar{q}, g	$x \gtrsim 0.01$
$\ell^\pm n/p \rightarrow \ell^\pm X$	$\gamma^* d/u \rightarrow d/u$	d/u	$x \gtrsim 0.01$
$pp \rightarrow \mu^+ \mu^- X$	$u\bar{u}, d\bar{d} \rightarrow \gamma^*$	\bar{q}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

x mal f(x)



April 2010

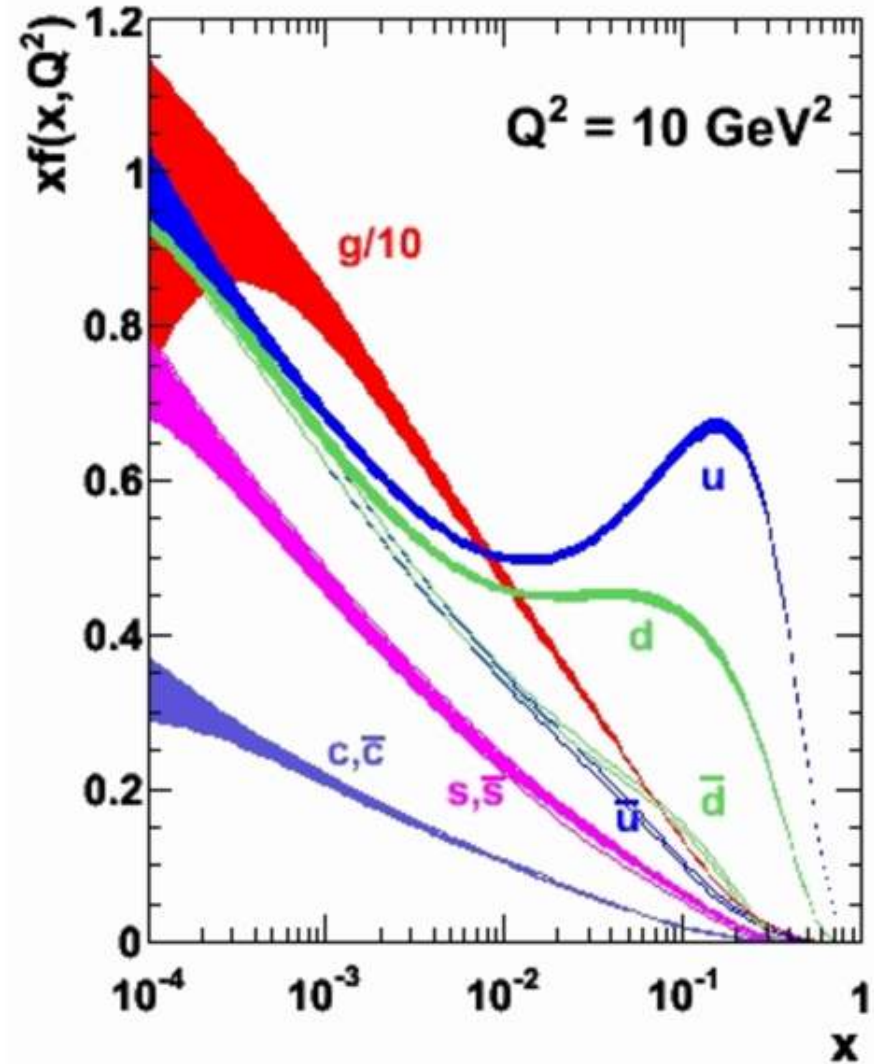
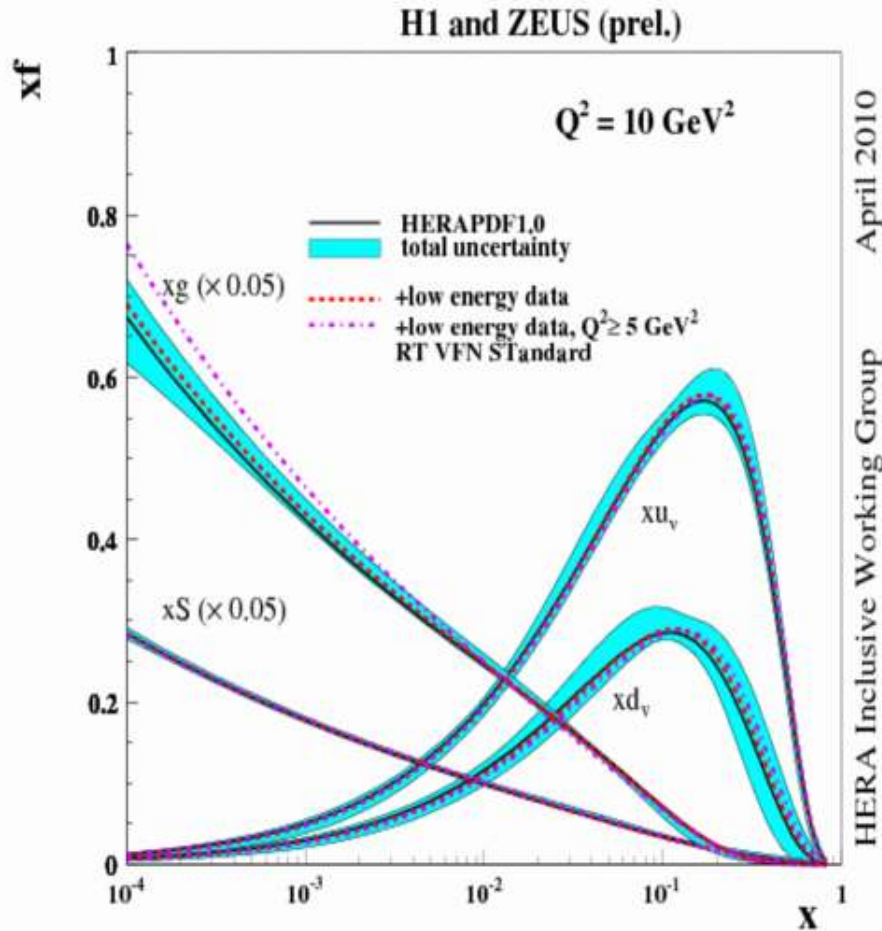
HERA Inclusive Working Group



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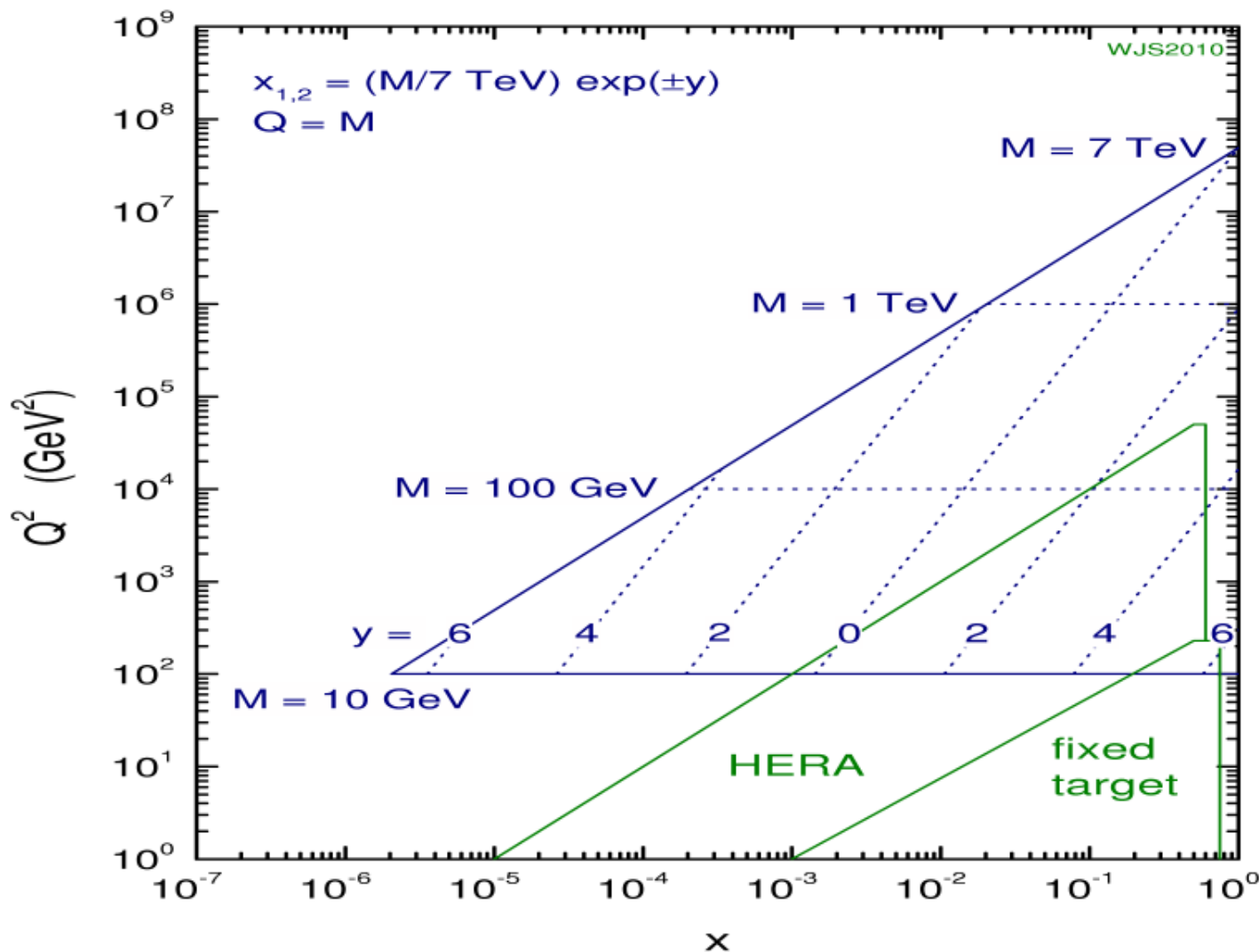
HERA Inclusive Working Group

$x \text{ mal } f(x)$

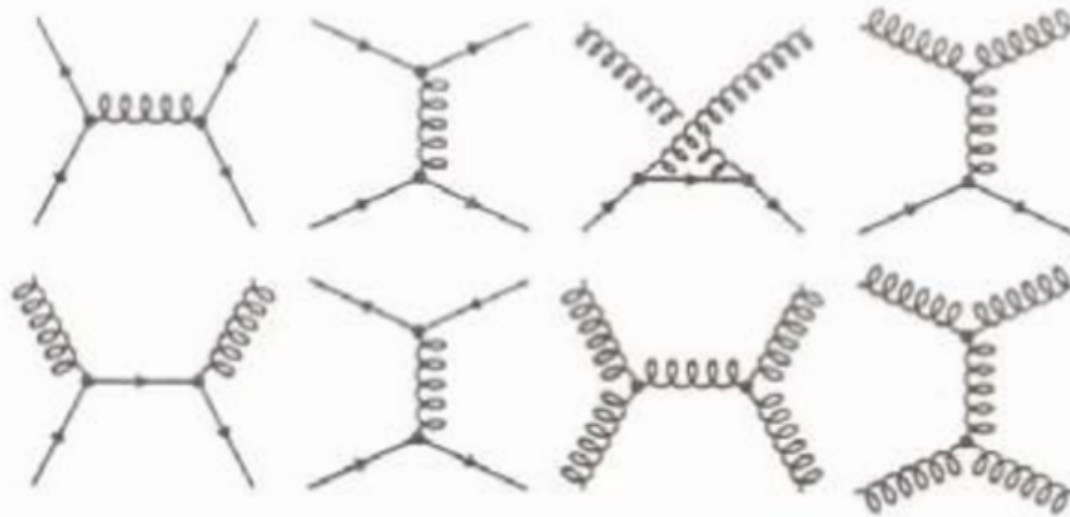


Wofür braucht man Kenntnis der PDF am LHC?

7 TeV LHC parton kinematics

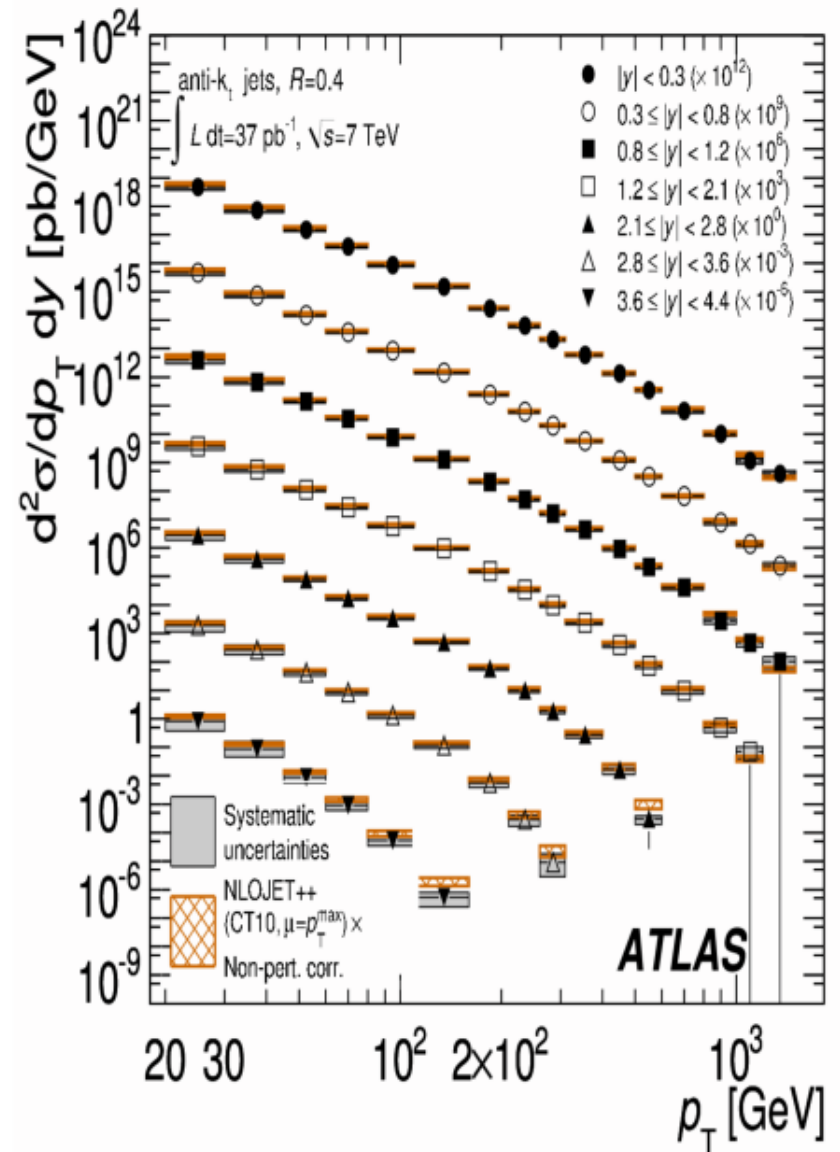
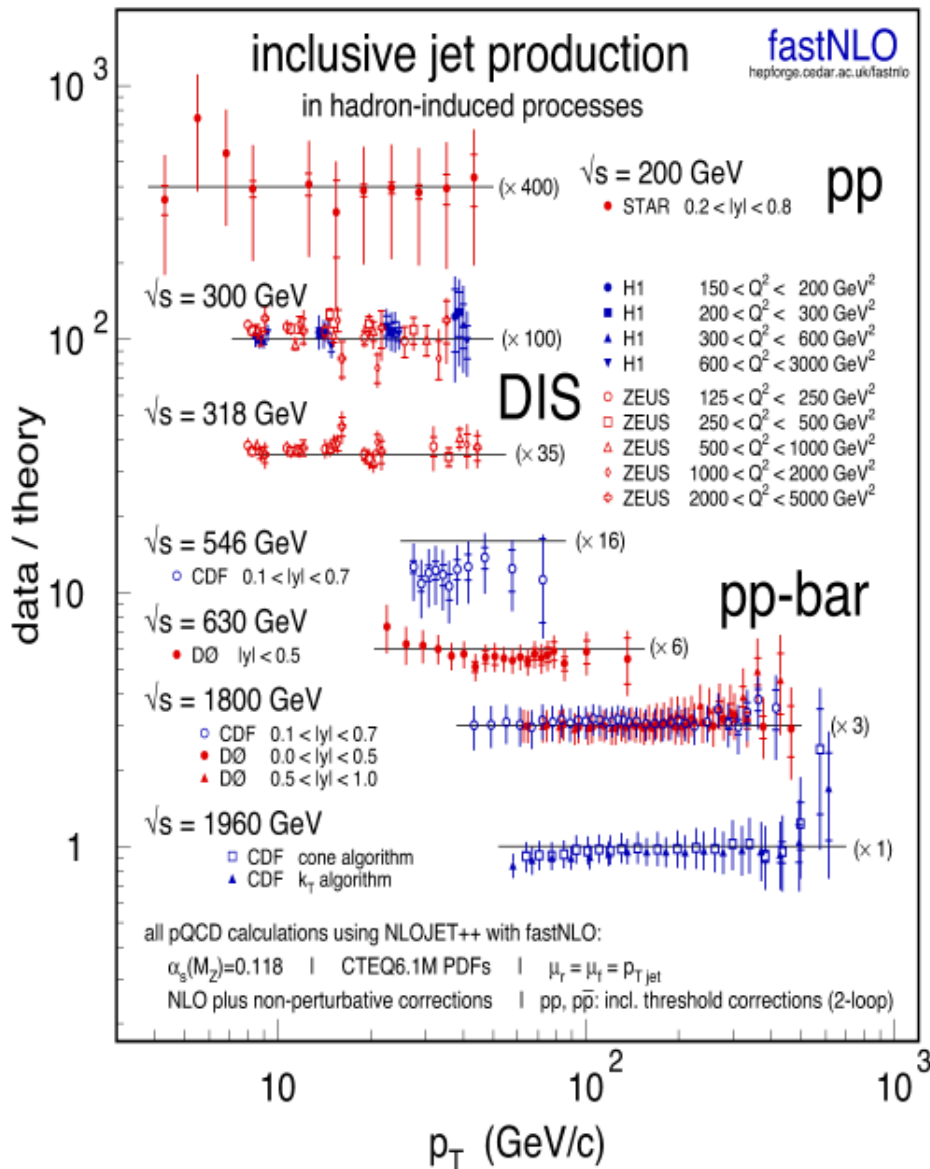


Streuprozess: 2 Partonen \rightarrow 2 Partonen

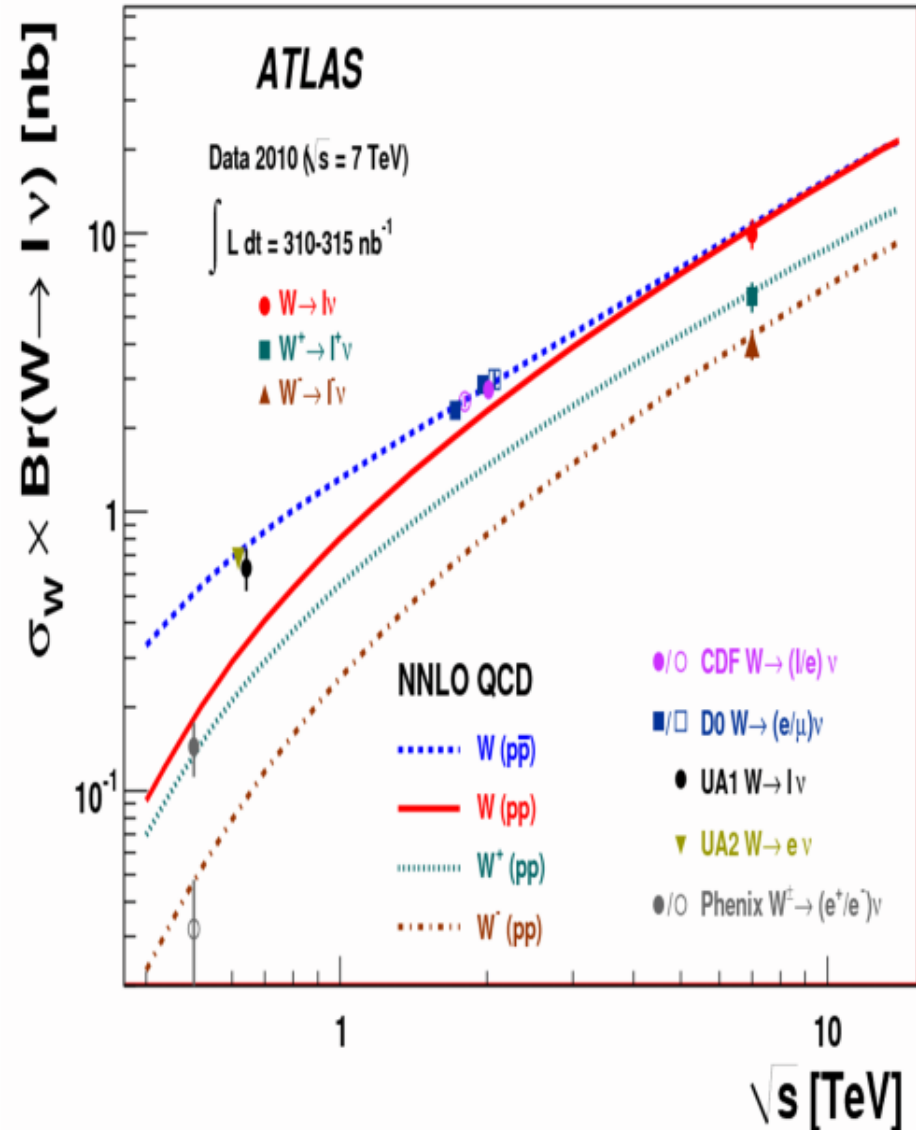
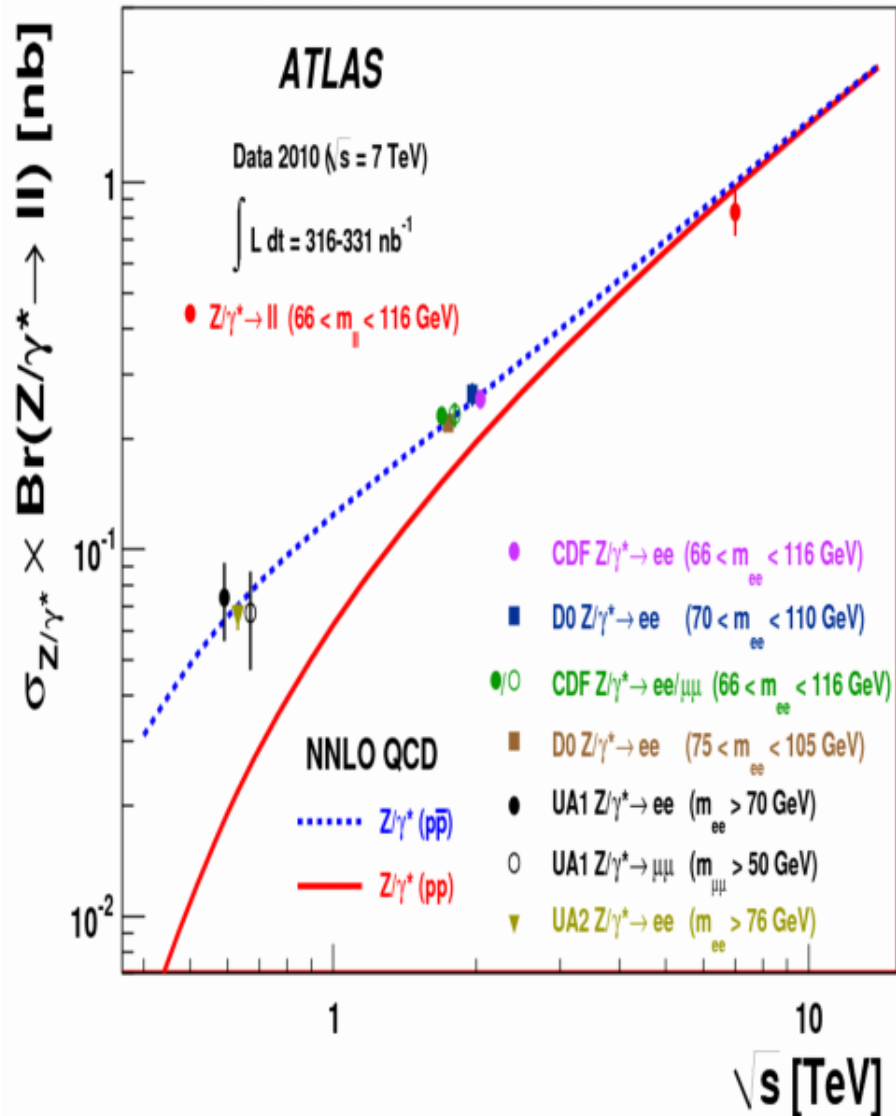


subprocess	$ M ^2$
$q\bar{q}' \rightarrow q\bar{q}'$	$\frac{4}{9} \frac{s^2 + u^2}{t^2}$
$q\bar{q} \rightarrow q\bar{q}$	$\frac{4}{9} \left(\frac{s^2 + u^2}{t^2} + \frac{s^2 + t^2}{u^2} \right) - \frac{8}{27} \frac{s^2}{t^2}$
$q\bar{q}' \rightarrow q'\bar{q}$	$\frac{4}{9} \frac{s^2 + t^2}{u^2}$
$q\bar{q} \rightarrow q\bar{q}$	$\frac{4}{9} \left(\frac{s^2 + u^2}{t^2} + \frac{t^2 + u^2}{s^2} \right) - \frac{8}{27} \frac{t^2}{s^2}$
$q\bar{q} \rightarrow gg$	$\frac{16}{9} \frac{s^2 + t^2}{u^2} - \frac{8}{9} \frac{t^2 + s^2}{u^2}$
$g\bar{g} \rightarrow q\bar{q}$	$\frac{4}{9} \frac{s^2 + t^2}{u^2} - \frac{8}{9} \frac{s^2 + t^2}{u^2}$
$q\bar{g} \rightarrow q\bar{g}$	$-\frac{4}{9} \frac{u^2 + s^2}{u^2} + \frac{u^2 + s^2}{t^2}$
$g\bar{g} \rightarrow g\bar{g}$	$\frac{16}{9} \left(3 - \frac{u^2}{s^2} - \frac{t^2}{s^2} - \frac{s^2}{u^2} \right)$

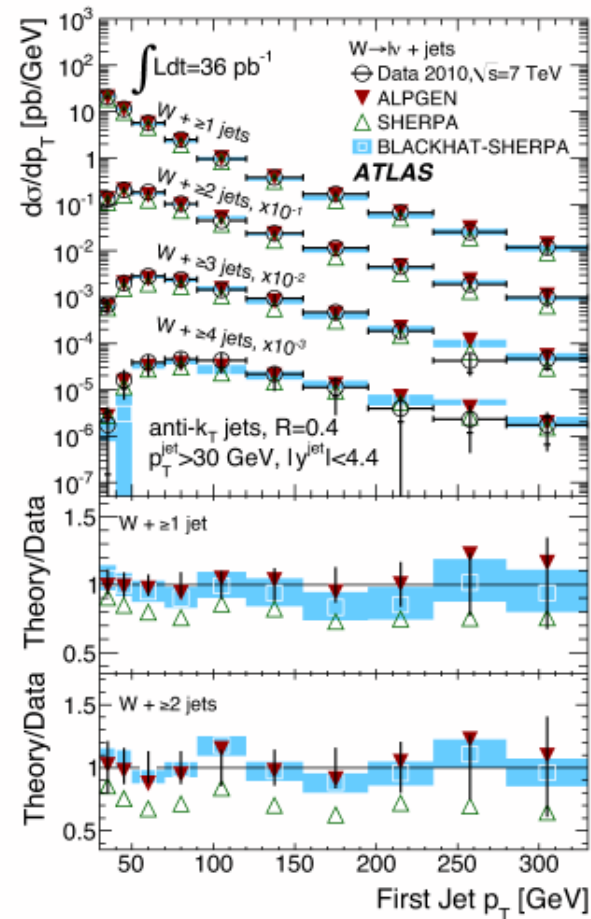
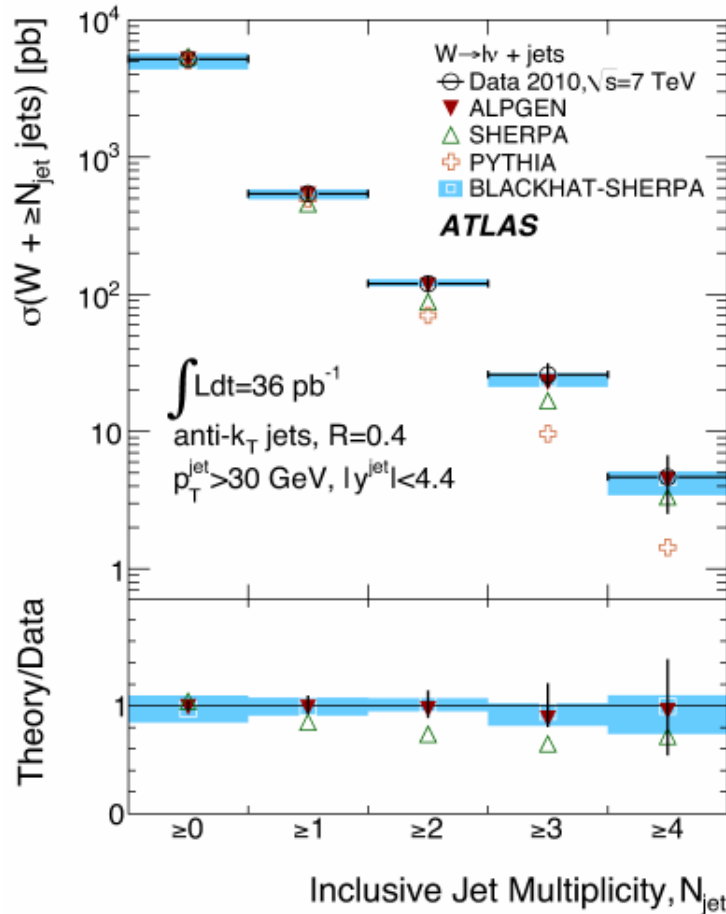
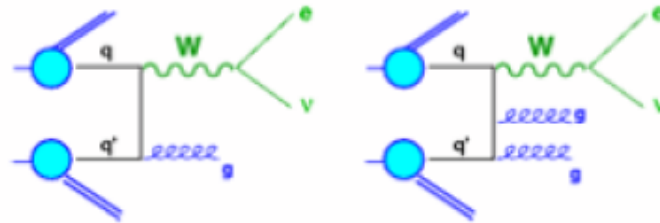
Test der QCD: Jetproduktion



Test der QCD: inklusive W und Z-Produktion



Test der QCD: W+Jets



Test der QCD: $Z \rightarrow 2 \text{ Myonen} + \text{Jets}$

