

I. Potvrda kvarkova

U PROCESIMA RASPRŠENJA ELEKTRONA NA PROTONU

- REFERENTNI RUTHERFORDOV
i MOTTOV UDARNI PRESJEK
- ELASTIČNO RASPRŠENJE
(mjerenje dimenzija protona)
- DUBOKO NEELASTIČNO RASPRŠENJE
(nabijeni i neutralni partoni)

I.1 ELASTIČNO RASPRŠENJE (mjerjenje dimenzija protona)

Raspršenje e^- na p

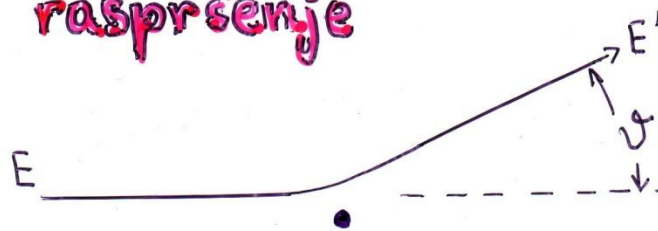
KVANTNA INAČICA

Keplerovog problema

§4.2

stanja raspršenja

Rutherfordovo
raspršenje



FEČ | str. 199

$$\frac{d\sigma}{d\Omega} = \frac{Z^2 \alpha^2}{4E^2} \frac{1}{\sin^4 \frac{\theta}{2}}$$



§3.1

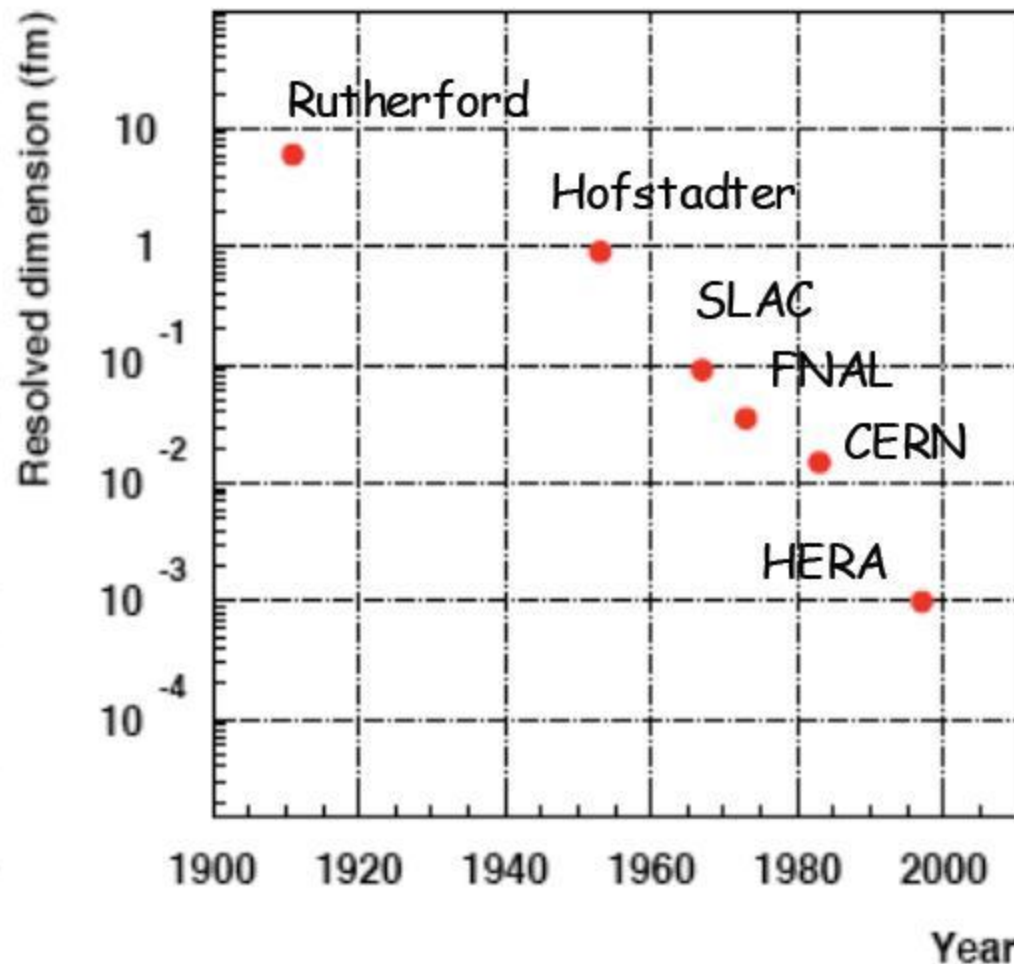
vezano stanje

H-atom

FEČ | str. 110

RASPRŠENJE ELEKTRONA NA PROTONU

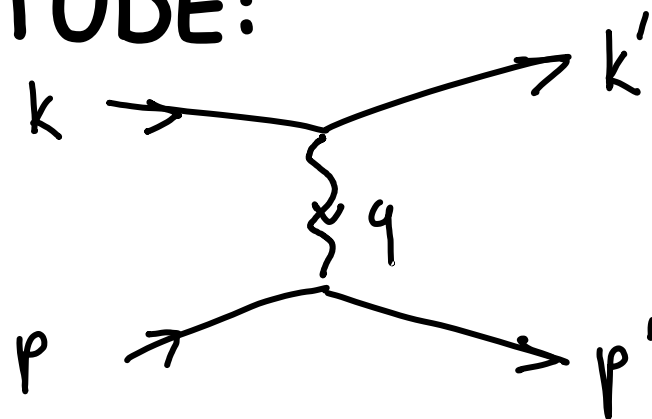
- Nobelove nagrade '61 & '90



$e^- \mu^- \rightarrow e^- \mu^-$ U LAB. SUSTAVU

- **FEČ I** USREDNJEN KVADRAT INVARIJANTNE AMPLITUDE:

$$\overline{|M|^2} = \frac{e^4}{q^4} L_e^{\mu\nu} L_{\mu\nu}^{\text{mion}}$$



$$L_e^{\mu\nu} = 2 \left[k'^{\mu} k^{\nu} + k'^{\nu} k^{\mu} - (k' \cdot k - m_e^2) g^{\mu\nu} \right]$$

$$L_{\mu\nu}^{\text{mion}} = 2 \left[p'^{\mu} p^{\nu} + p'^{\nu} p^{\mu} - (p' \cdot p - m_{\mu}^2) g_{\mu\nu} \right]$$

$$L_e^{\mu\nu} L_{\mu\nu}^{\text{mish}} = 8 \left[(k' \cdot p')(k \cdot p) + (k' \cdot p)(k \cdot p') - \cancel{m^2 p' \cdot p} - M^2 k' \cdot k + \cancel{2m^2 M^2} \right]$$

$$k^2 = k'^2 = 0, \quad q^2 = -2k \cdot k'$$

$$p' = q + p$$

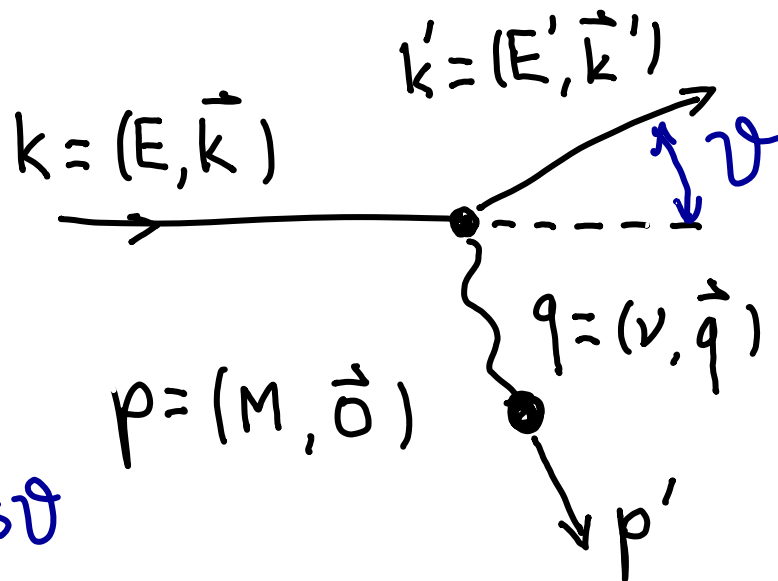
$$= 8 \left[-\frac{1}{2} q^2 (k \cdot p - k' \cdot p) + 2(k' \cdot p)(k \cdot p) \right]$$

Za proton sa strukturom: $+ \frac{1}{2} M^2 q^2$

$$L_e^{\mu\nu} \left(K_{\mu\nu}^{\text{protona}} \right) = -K_1 g_{\mu\nu} + \frac{K_2}{M_p^2} p_\mu p_\nu + \frac{K_4}{M_p^2} q_\mu q_\nu + \frac{K_5}{M_p^2} (p_\mu q_\nu + p_\nu q_\mu)$$

KINEMATIKA U LAB. SUSTAVU

Za sudar umjerene energije $E, E' \gg m_e c^2$



$$k = E(1, \hat{k})$$

$$k' = E'(1, \hat{k}'), \quad \hat{k} \cdot \hat{k}' = \cos\vartheta$$

$$q^2 = (k - k')^2 \approx -2k \cdot k' = -2EE'(1 - \cos\vartheta) = -4EE' \sin^2 \frac{\vartheta}{2}$$

$$|M|^2 = \frac{8e^4}{q^4} 2M^2 E' E \left\{ \cos^2 \frac{\vartheta}{2} - \frac{q^2}{2M^2} \sin^2 \frac{\vartheta}{2} \right\}$$

Mottovo raspršenje

$$\left. \frac{d\sigma}{d\Omega} \right|_{\text{lab}} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\vartheta}{2}} \frac{E'}{E} \left\{ \cos^2 \frac{\vartheta}{2} \right\}$$

učinak spina
elektrona (još uvijek
zabravljeno raspršenje
unutraž)

$$-\frac{q^2}{2M^2} \sin^2 \frac{\vartheta}{2}$$

uključeni spin protona, ali
točkasti proton

$$\left\{ K_2(q^2) \cos^2 \frac{\theta}{2} + 2 K_1(q^2) \sin^2 \frac{\theta}{2} \right\}$$



Elastic electron-proton scattering (DIS)

Summary Rosenbluth formula

$$\left(\frac{d\sigma}{d\Omega} \right) = \frac{\alpha^2}{4E^2 \sin^4(\theta/2)} \frac{E'}{E} \left\{ \cos^2 \left(\frac{\theta}{2} \right) \left(\frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \left(\frac{\theta}{2} \right) \right) \right\}$$

$\underbrace{\hspace{10em}}_{\text{Rutherford cross section}}$

Recoil term!

$\underbrace{\hspace{15em}}_{\text{Mott cross section}}$

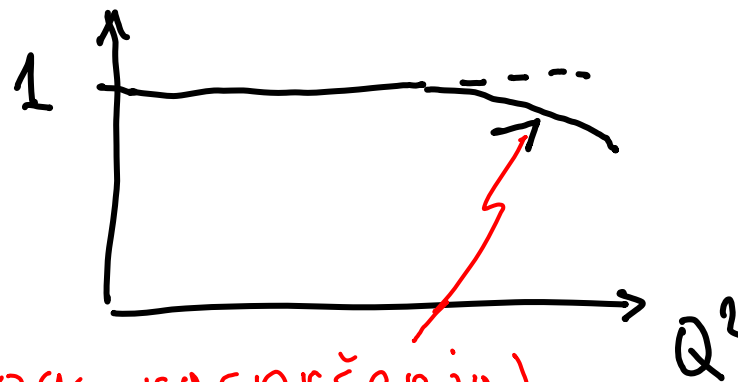
$$\left(\frac{d\sigma}{d\Omega} \right) = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \left(\frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \right)$$

REFERENTNI UDARNI PRESJEK

Uvođenjem $Q^2 = -q^2 = 4EE' \sin^2 \frac{\vartheta}{2}$

$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} = \frac{4\alpha^2 (E')^2}{Q^4} \frac{E'}{E} \cos^2 \frac{\vartheta}{2}$$

Omjer $\frac{\left(\frac{d\sigma}{d\Omega} \right)_{\text{opaženo}}}{\left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott/točk.}}}$



(devijacija od točkastog raspršenja)

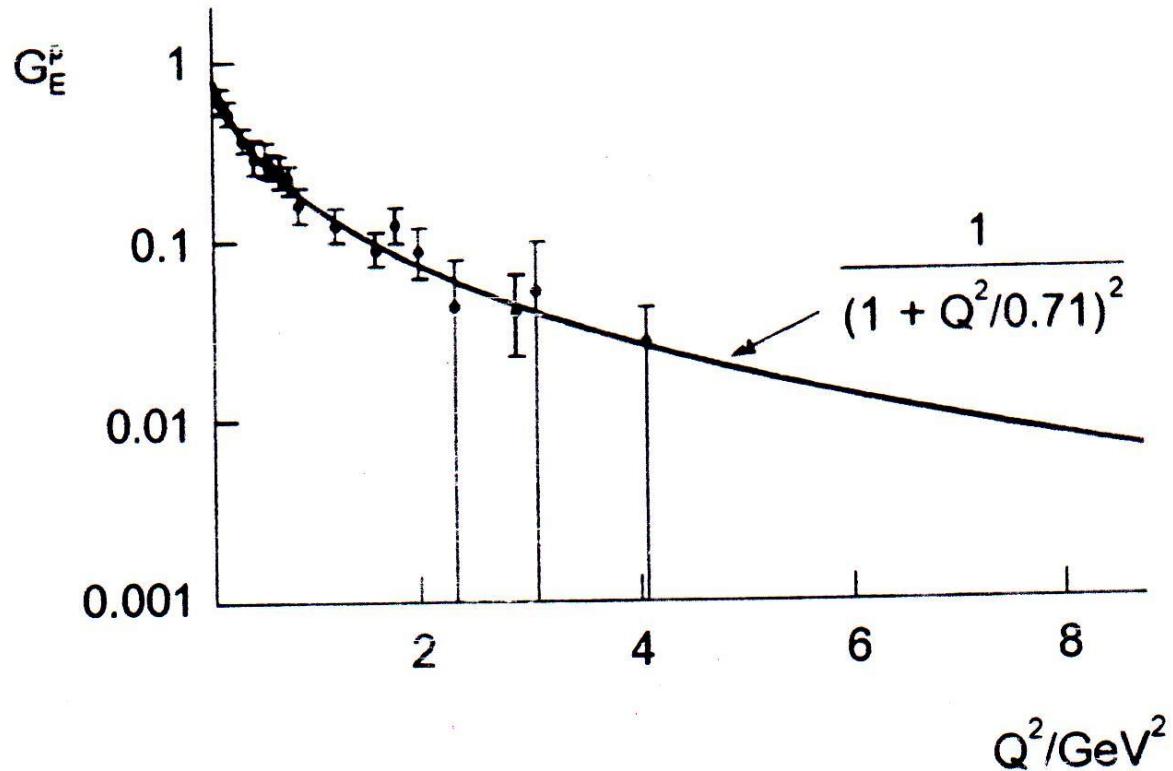
MJERENJE DIMENZIJA PROTONA U PODRUČJU

$$Q^2 \ll M^2$$

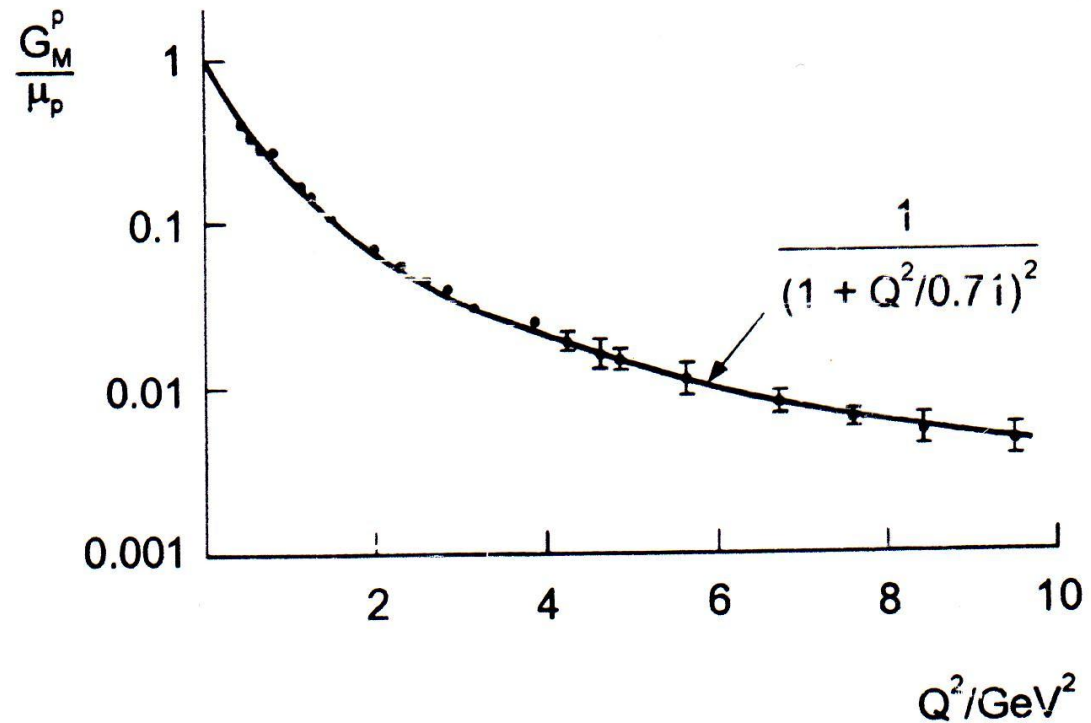
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} G_E^2(Q^2)$$

$$\langle r^2 \rangle_E = -6 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2=0} = [0.85(2) \text{ fm}]^2$$

MJERENA FUNKCIJA ELEKTRIČNE STRUKTURE PROTONA

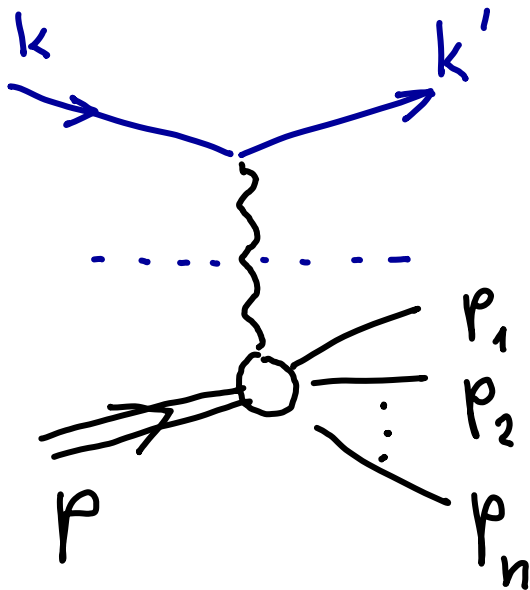


MJERENA FUNKCIJA MAGNETSKE STRUKTURE PROTONA



I.2 NEELASTIČNO RASPRŠENJE

POBUĐENJA PROTONA ZA UMJERENE
PRIJENOSE Q^2



$$e^- p \rightarrow e^- \Delta^+ \rightarrow e^- p \pi^0$$

} invarijantna
masa

$$W \text{ (GeV): } 1.236$$

$$1.525$$

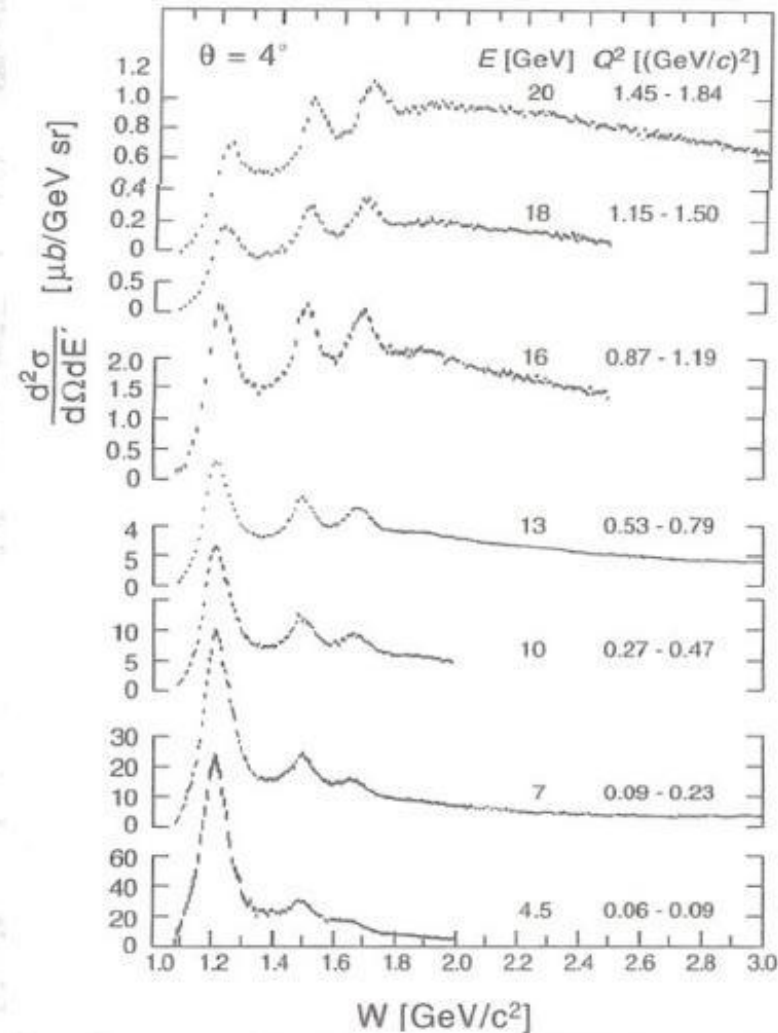
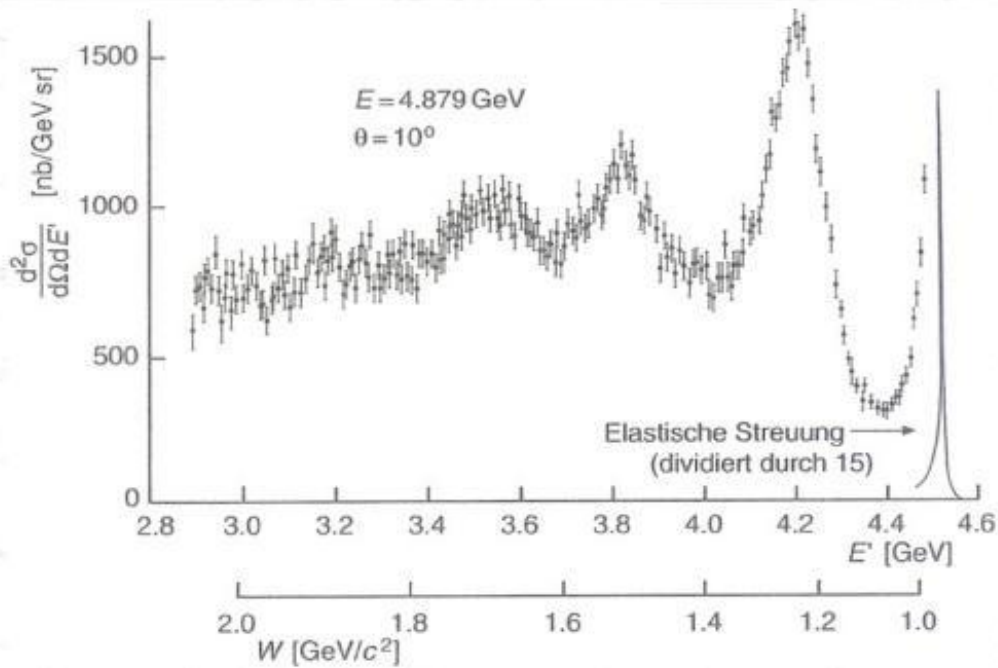
$$1.688$$

:

$$W^2 = M_{\Delta}^2$$

REZONANTNI VRHOVI

Inelastic ep scattering results



NEELASTIČNO RASPRŠENJE (i granica elastičnog)

$$\frac{d\sigma}{dE' d\Omega} = \frac{4\alpha^2 (E')^2}{Q^4} \frac{E'}{E} \left[W_2(\nu, Q^2) \cos^2 \frac{\vartheta}{2} + 2W_1(\nu, Q^2) \sin^2 \frac{\vartheta}{2} \right]$$

gdje

$$\nu = E - E'$$

$$Q^2 = 4EE' \sin^2 \frac{\vartheta}{2}$$

ili bezdim. $x = Q^2 / 2M\nu$ - Bjorkenova varijabla

$$W_1(q^2, x) \xrightarrow{\text{elast.}} - \frac{K_1(q^2)}{2Mq^2} \delta(x-1) \xrightarrow{\text{točk.}} \frac{1}{2M} \delta(x-1)$$

$$W_2(q^2, x) \xrightarrow{\text{elast.}} - \frac{K_2(q^2)}{2Mq^2} \delta(x-1) \xrightarrow{\text{točk.}} - \frac{2M}{q^2} \delta(x-1)$$

I.3 DUBOKO NEELASTIČNO RASPRŠENJE

DIS surprises

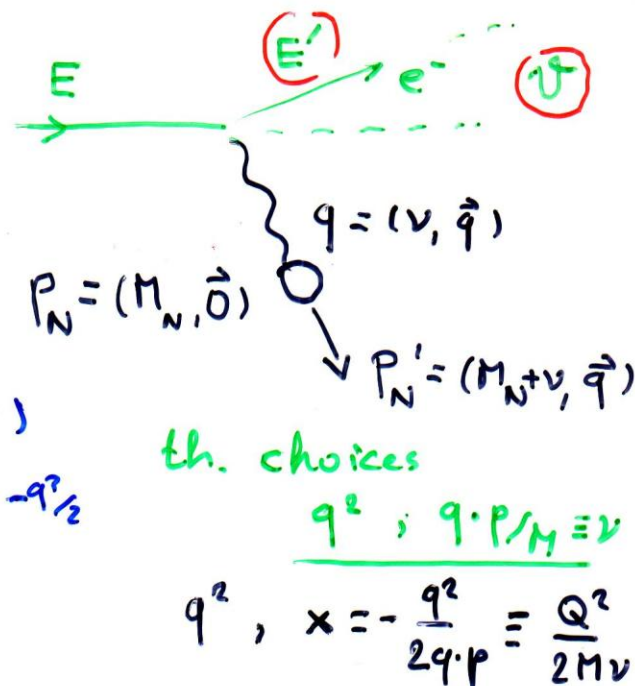
$$d\sigma \sim L_{\mu\nu}^{el} W_{\mu\nu}^{prot}$$

$$K_{1,2}^{(q^2)} \Big|_{\text{elast.}} \rightarrow W_{1,2}(q^2, q \cdot p) \quad \underbrace{\neq -q^2/2}$$

• Bjorken scaling =====

$$M W_1(q^2, x) \rightarrow F_1(x)$$

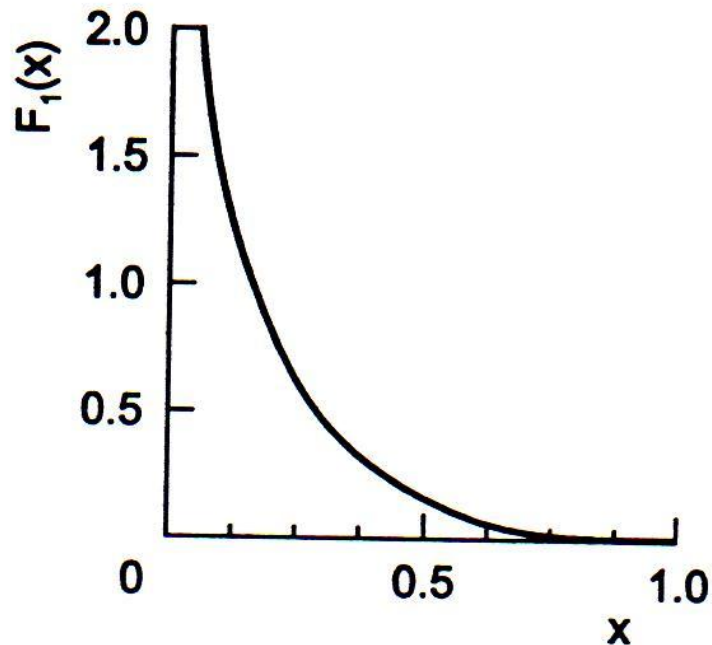
$$-\frac{q^2}{2Mx} W_2(q^2, x) \rightarrow F_2(x)$$



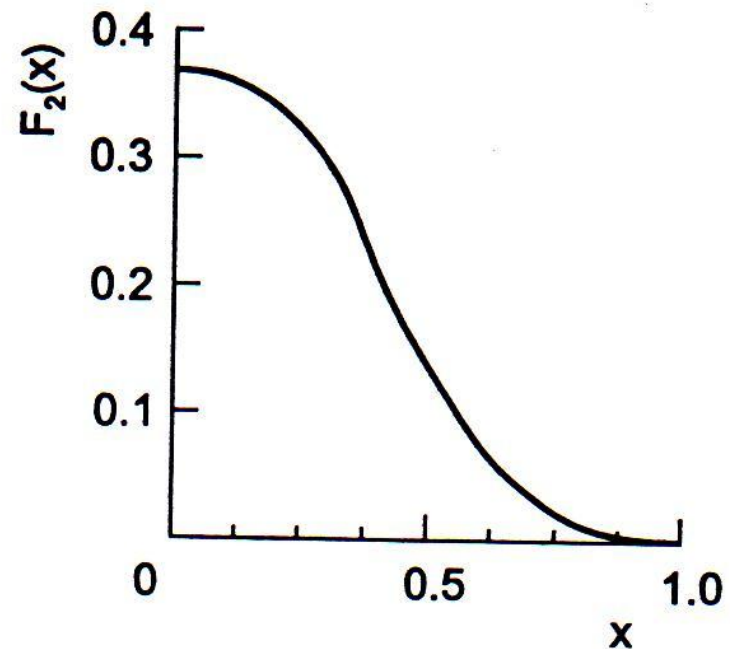
Callan & Gross (spin $1/2$)

$$2x F_1(x) = F_2(x)$$

MJERENE STRUKTURNIH F-ja DUBOKO NEELASTIČNOG RASPRŠENJA (FEČ §4.2.3)



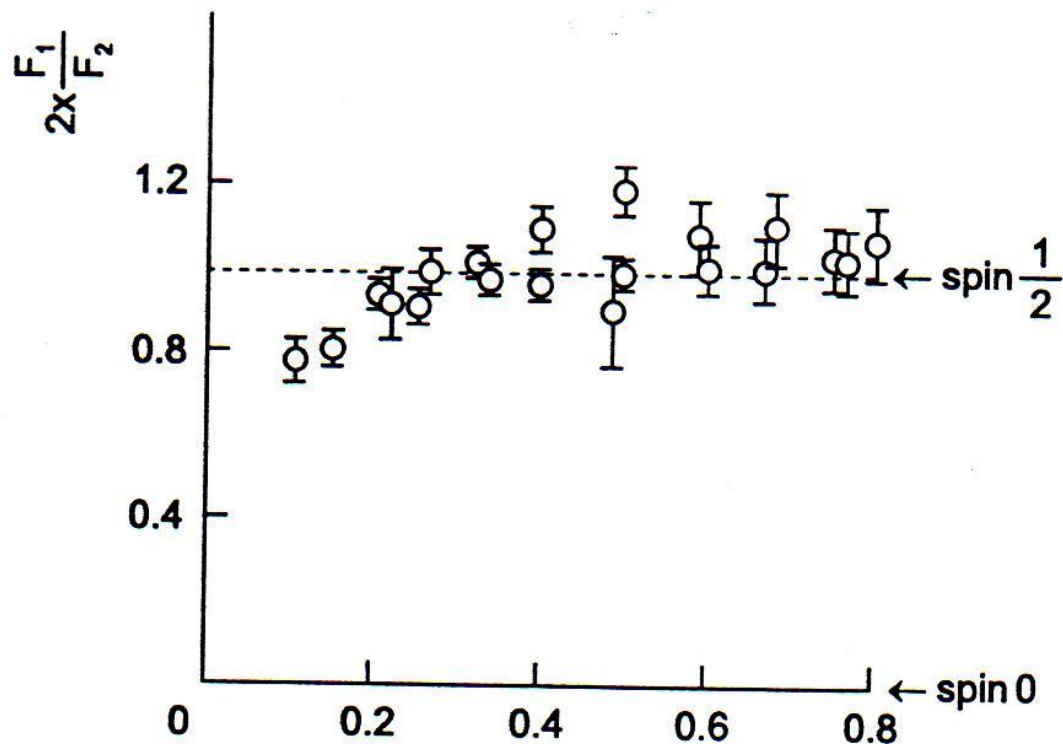
(a)



(b)

Slika 4.20: Strukturne funkcije $F_1(x)$ i $F_2(x)$

ODGOVARAJU PARTONIMA SPINA 1/2



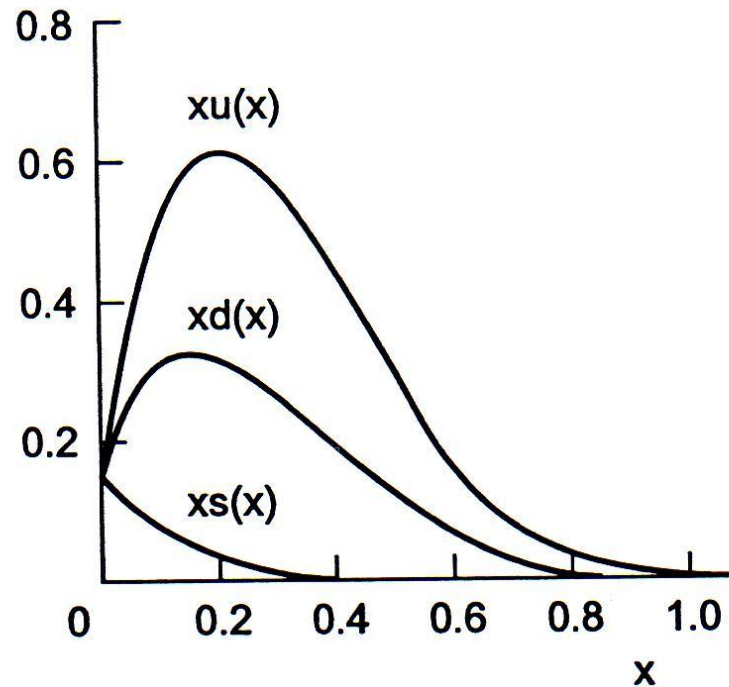
Slika 4.21: Eksperimentalno provjerene Callan–Gross-ove relacije (4.118)

SREDNJI impuls nošen u kvarkom

očekujemo da je dvostruk od onog nošenog d kvarkom:

$$\int_0^1 x u(x) dx = 2 \int_0^1 x d(x) dx$$

$$\int_0^1 pxu(x)dx$$



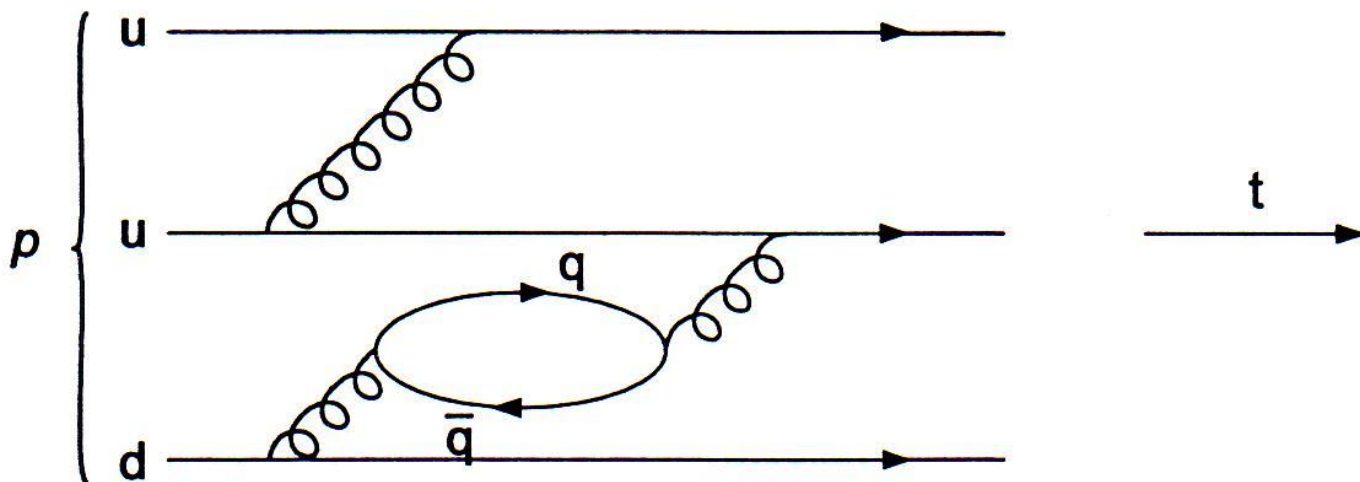
Slika 4.23: Mjerene funkcije raspodjele kvarkova

KRIZA IMPULSA PROTONA

- MJERENJEM POVRŠINE ISPOD EKSPERIMENTALNE KRIVULJE:
- U srednjem, samo 54% impulsa protona sadržano je u kvarkovima
- Ostatak mora biti nošen nenabijenim partonima - gluonima, što odmah čini sliku složenijom:

UVOĐENJE GLUONA I QCD

FEČ 4.3, STR.220



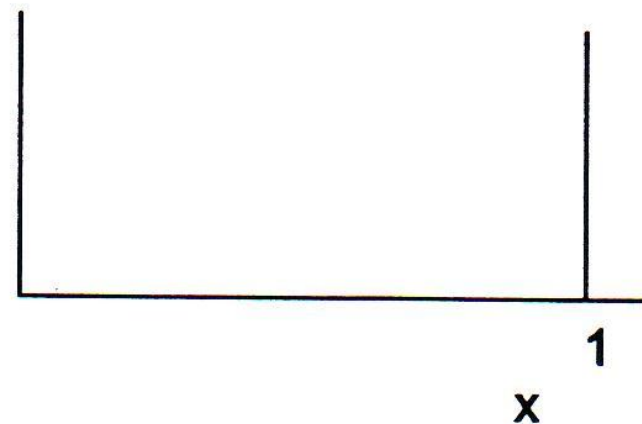
Slika 4.24: "Originalne kvarkove zvat ćemo valentnima, a dodatne (lake, $q = u, d, s$ kvarkove) kvarkovima mora

REPRODUCIRANJE EKSPERIMENTALNE KRIVULJE

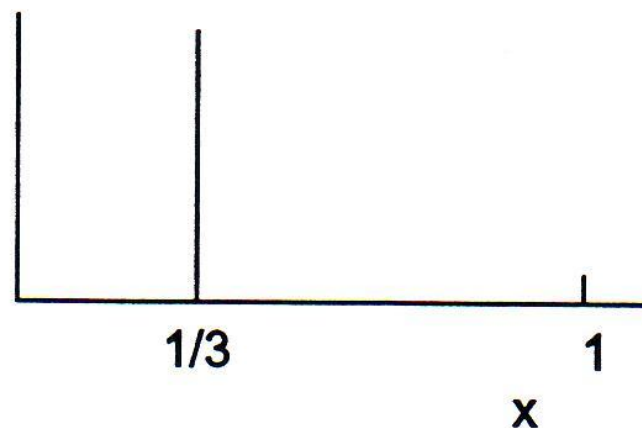
Ako je proton

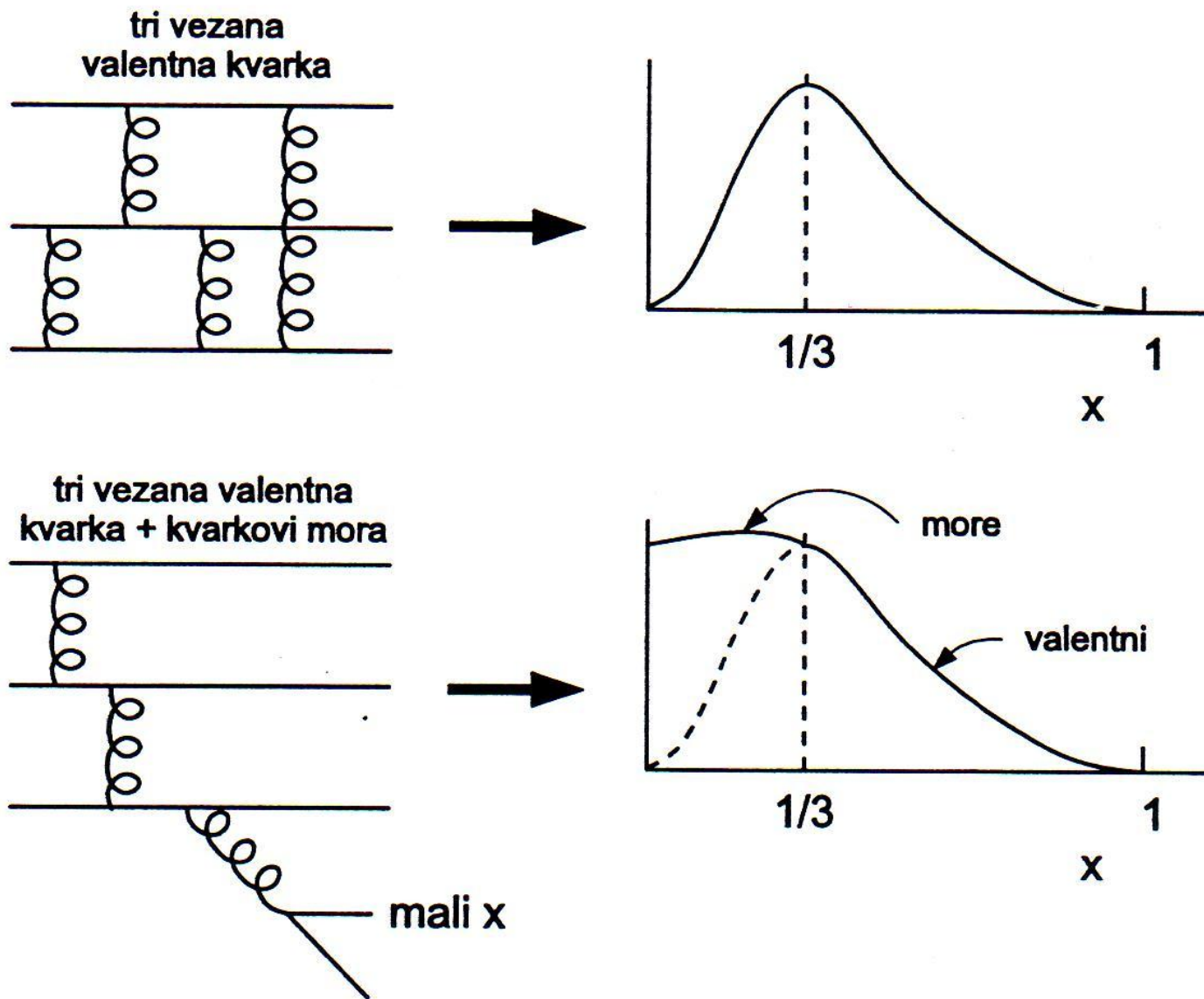
tada je $F_2(x)$

kvark



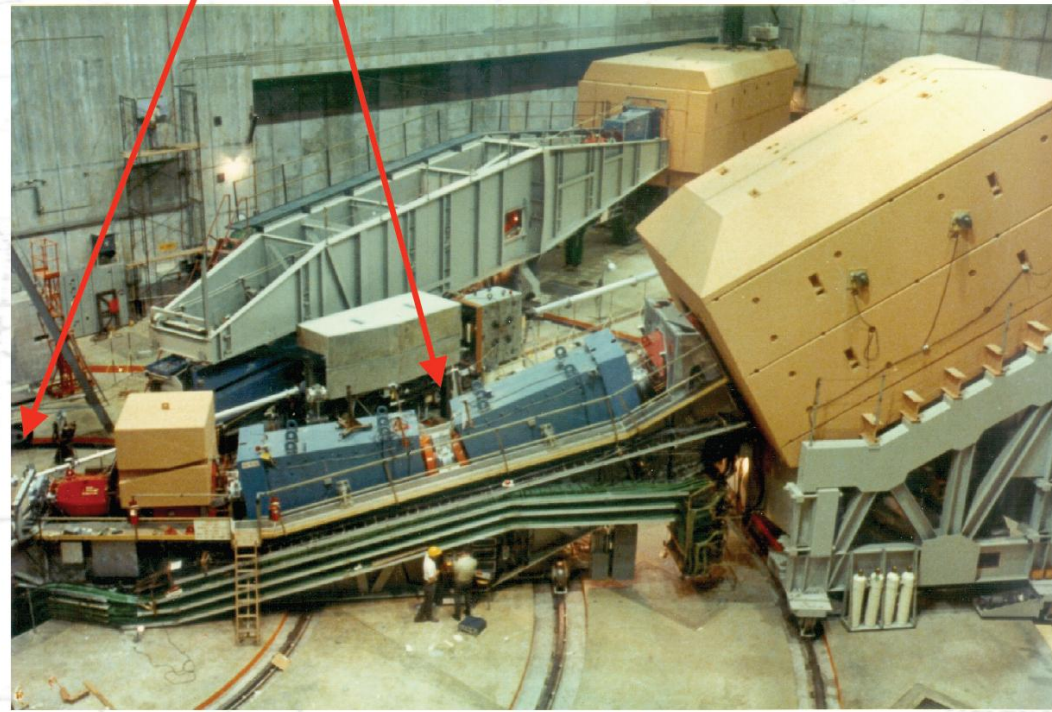
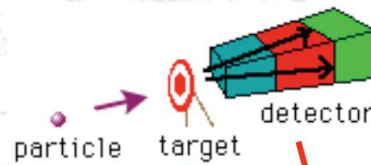
tri valentna kvarka





Slika 4.25: Ovisnost strukturne funkcije o pretpostavljenoj strukturi protona

Stanford Linear Accelerator Center (pokusi '67&'73, 20-50 GeV, prva evidencija kvarkova)



FIZIKA NA MALOM x

FEČ 4.3, STR.220

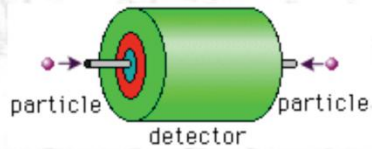
- IZAZOV za HERA-u kao QCD-stroj:
- PROBLEM SPINA PROTONA
- DIFRAKTIVNI PROCESI

- ZA VJEŽBE: rezonantna reakcija iz koje se određuje GZK GRANICA

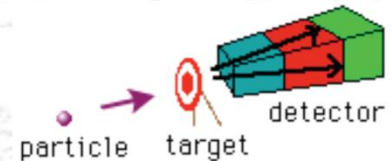


Hadron Electron Ring Accelerator

- Collider experiment: Electron-Proton collisions at HERA (DESY, Hamburg, Germany)

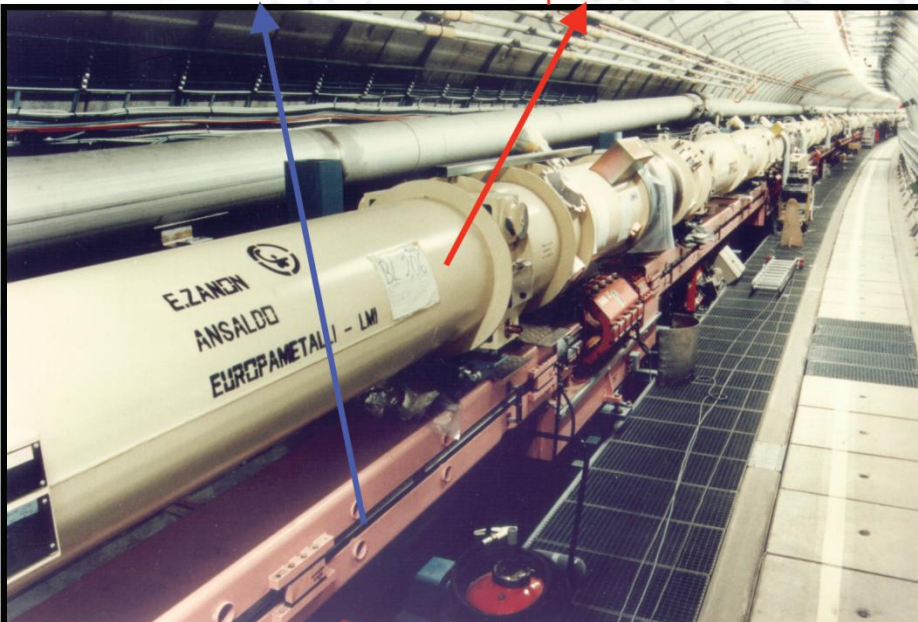


Equivalent to fixed target of
 $E_e = 50600 \text{ GeV}$:

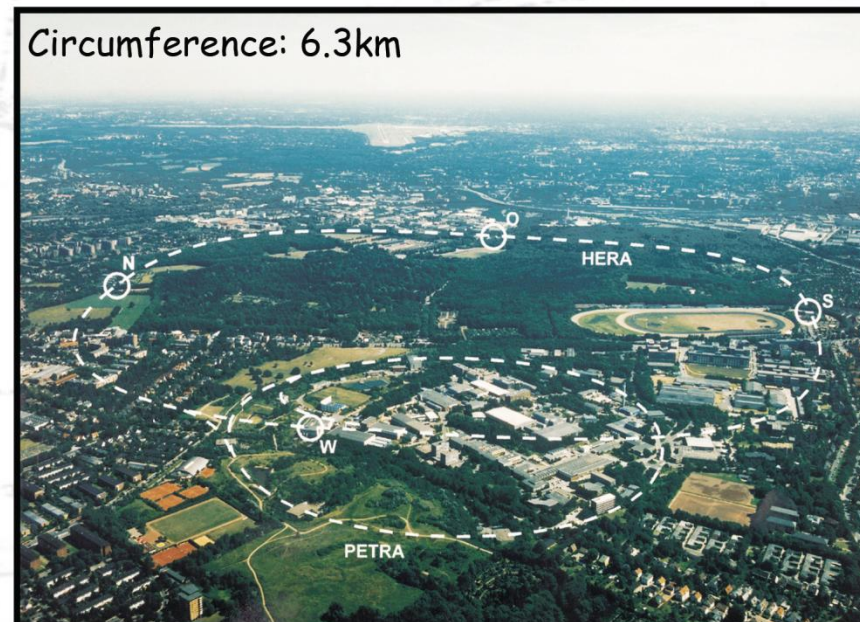


$E_e = 27.5 \text{ GeV}$

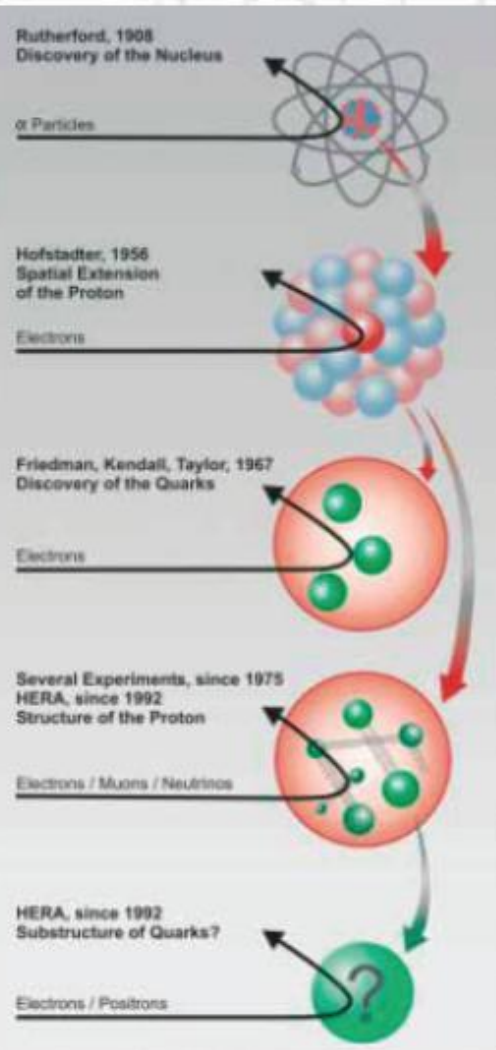
$E_p = 920 \text{ GeV}$



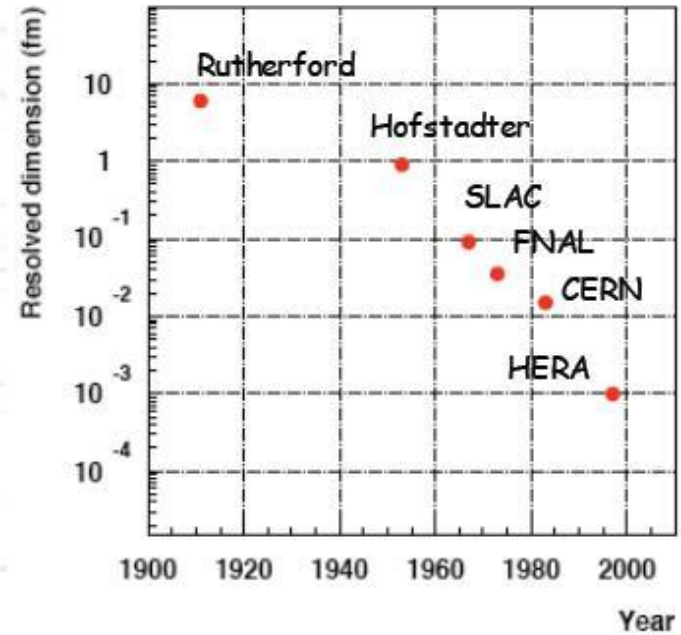
Circumference: 6.3km



General considerations on scattering experiments



Probing smaller distances requires larger momentum transfer q (small wavelength λ)



- Measurement of the final-state (**scattered electron**):
⇒ Structure of **target**!
- Scatter point-like **probe** onto object (**target**)

