Fizika čestica
na sudarivačima

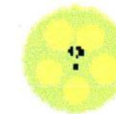
I. PRODUKCIJE I RASPADI ČESTICA DO ERE LEP-a

- ELEKTRON - POZITRON
- PROTON - AT. JEZGRE
- ELEKTRON - PROTON

KRATKA POVIJEST HADRONSKE FIZIKE

1932: Discovery of the neutron

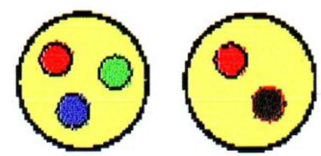
1933: $\vec{\mu}_p \equiv 2.5 \frac{e}{2\,m_p} \vec{\sigma} \Rightarrow$ Substructure of the proton



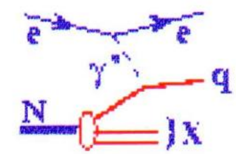
1947: Discovery of π-mesons and of long-lived V-particles (K^0, Λ) in cosmic rays

1953: V-particles produced at accelerators; new inner quantum number ('strangeness').

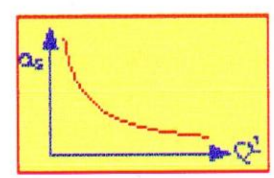
1964: Static Quark-Model; new inner quantum number: color.



1969: Dynamic Parton Model:

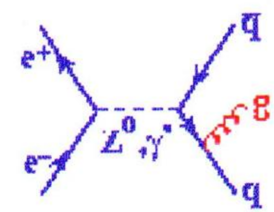


1973: Concept of Asymptotic Freedom; non-abelian gauge theory: QCD.



1975: 2-Jet structure in e^+e^--annihilation: confirmation of Quark-Parton-Model.

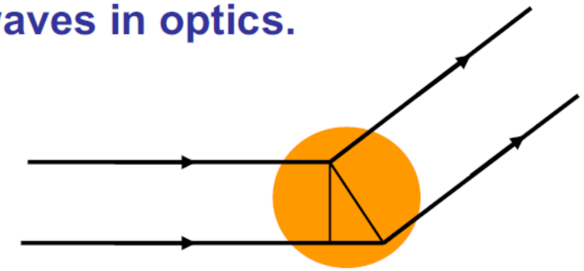
1979: Discovery of the gluon in 3-Jet-events of e^+e^--annihilation.



IZUČAVANJE (PARTONSKE) STRUKTURE HADRONA

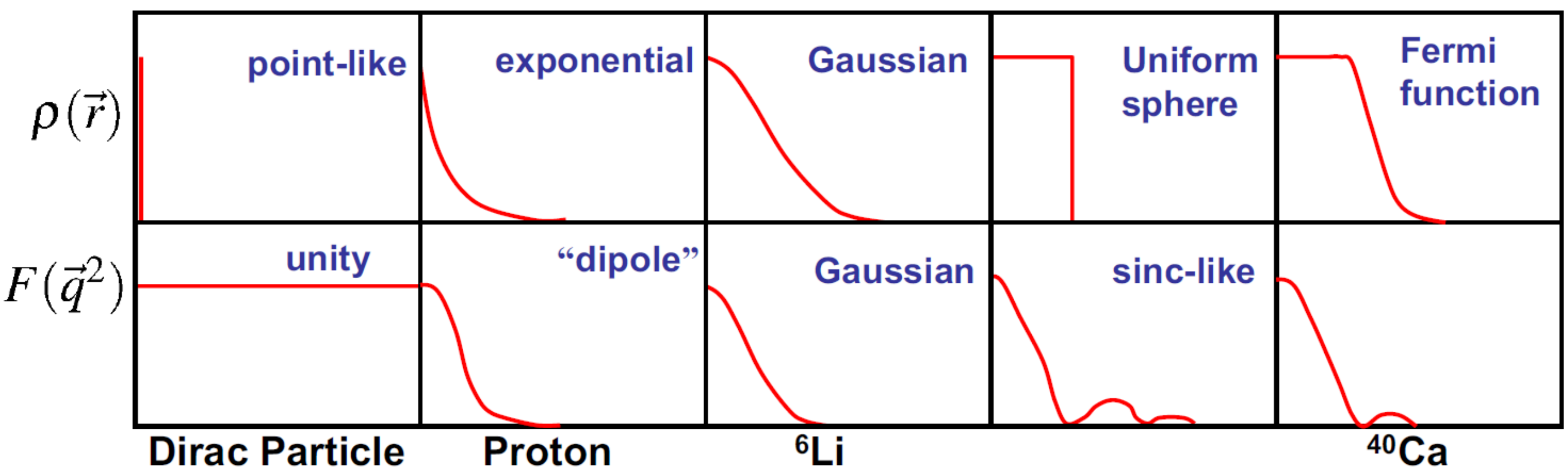
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \rightarrow \frac{\alpha^2}{4E^2 \sin^4 \theta/2} \cos^2 \frac{\theta}{2} |F(\vec{q}^2)|^2$$

- There is nothing mysterious about form factors – similar to diffraction of plane waves in optics.



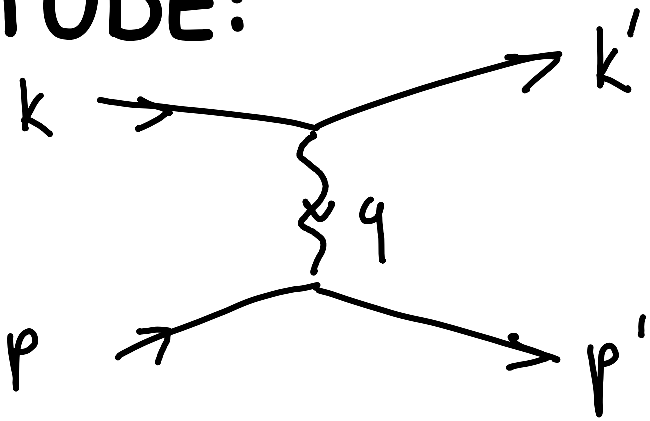
- The finite size of the scattering centre introduces a phase difference between plane waves "scattered from different points in space". If wavelength is long compared to size all waves in phase and $F(\vec{q}^2) = 1$

For example:



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

- FEČ I USREDNJEN KVADRAT INVARIJANTNE AMPLITUDE:



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

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

$m^2 \equiv m_e^2$

$$L^{mion}_{\mu\nu} = 2\left[p'_{\mu} p_{\nu} + p'_{\nu} p_{\mu} - (p' \cdot p - M^2) g_{\mu\nu}\right]$$

$M^2 \equiv m_\mu^2$

$$L_e^{\mu\nu} L^{mion}_{\mu\nu} = 8\left[(k'\cdot p')(k\cdot p) + (k'\cdot p)(k\cdot p') - \cancel{m^2\, p'\cdot p} - M^2\, k'\cdot k + \cancel{2m^2 M^2}\right]$$

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

$p' = q + p$

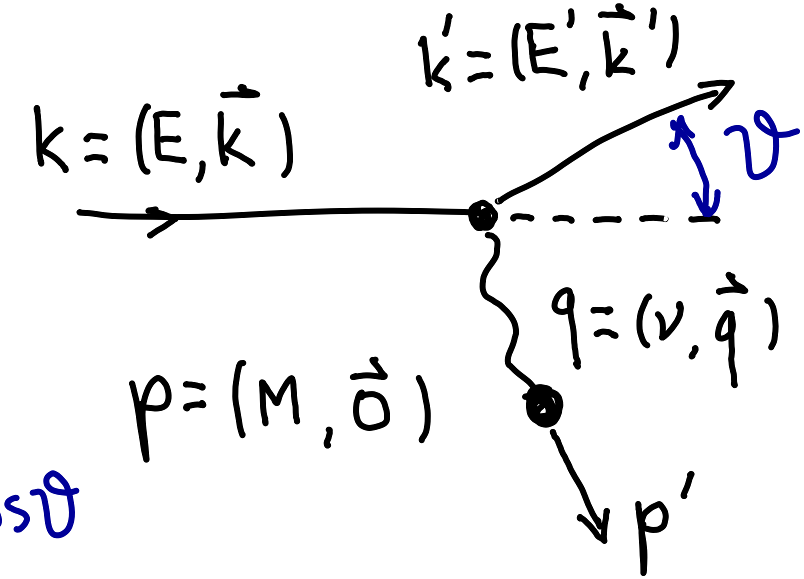
$$= 8\left[-\frac{1}{2} q^2 (k\cdot p - k'\cdot p) + 2(k'\cdot p)(k\cdot p) + \frac{1}{2} M^2 q^2\right]$$

Za proton sa strukturom:

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

KINEMATIKA U LAB. SUSTAVU

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



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

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

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

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

Mottovo raspršenje

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

učinak spina elektrona (još uvijek zabranjeno raspršenje unatrag)

uključen spin protona, ali točkasti proton

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

Elastic electron-proton scattering (DIS)

Summary Rosenbluth formula

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

Rutherford cross section

Recoil term!

Mott cross section

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

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 $\nu = E - E'$

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

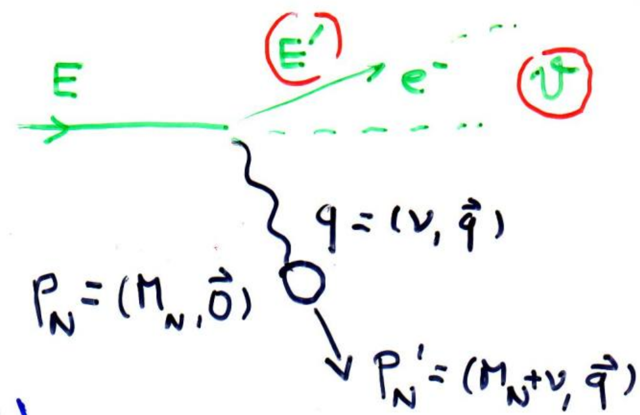
ili bezdim. $x = Q^2/2M\nu$ - Bjorkenova varijabla

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

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

I.3 DUBOKO NEELASTIČNO RASPRŠENJE

DIS surprises



$$d\sigma \sim L^{el}_{\mu\nu}\, W^{\mu\nu}_{proton}$$

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

th. choices

$$q^2\ ;\ q\cdot p/M \equiv \nu$$

$$q^2\ ,\quad x = -\frac{q^2}{2q\cdot p} = \frac{Q^2}{2M\nu}$$

- Bjorken scaling

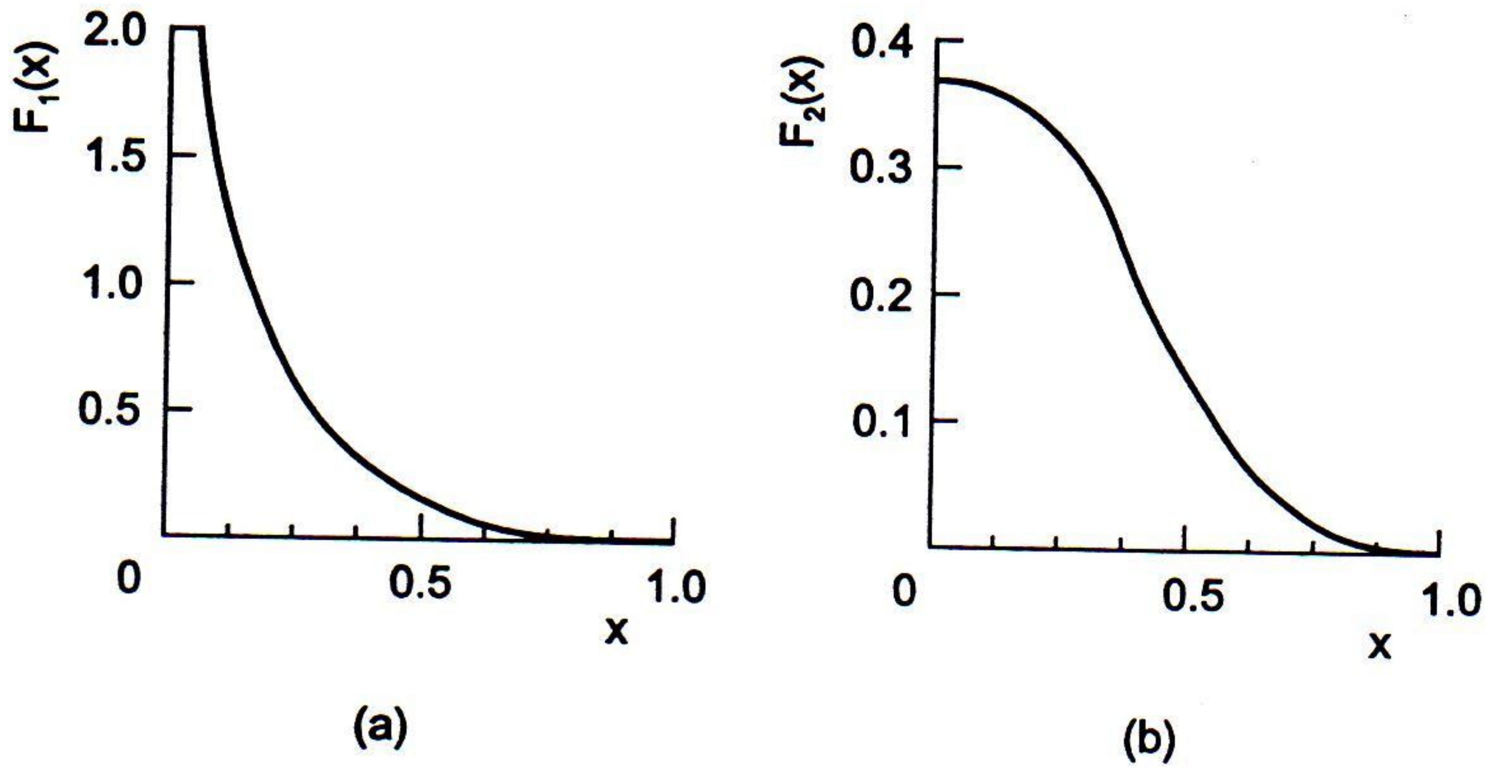
$$M\, W_1(q^2, x) \rightarrow F_1(x)$$

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

Callan Gross (spin 1/2)

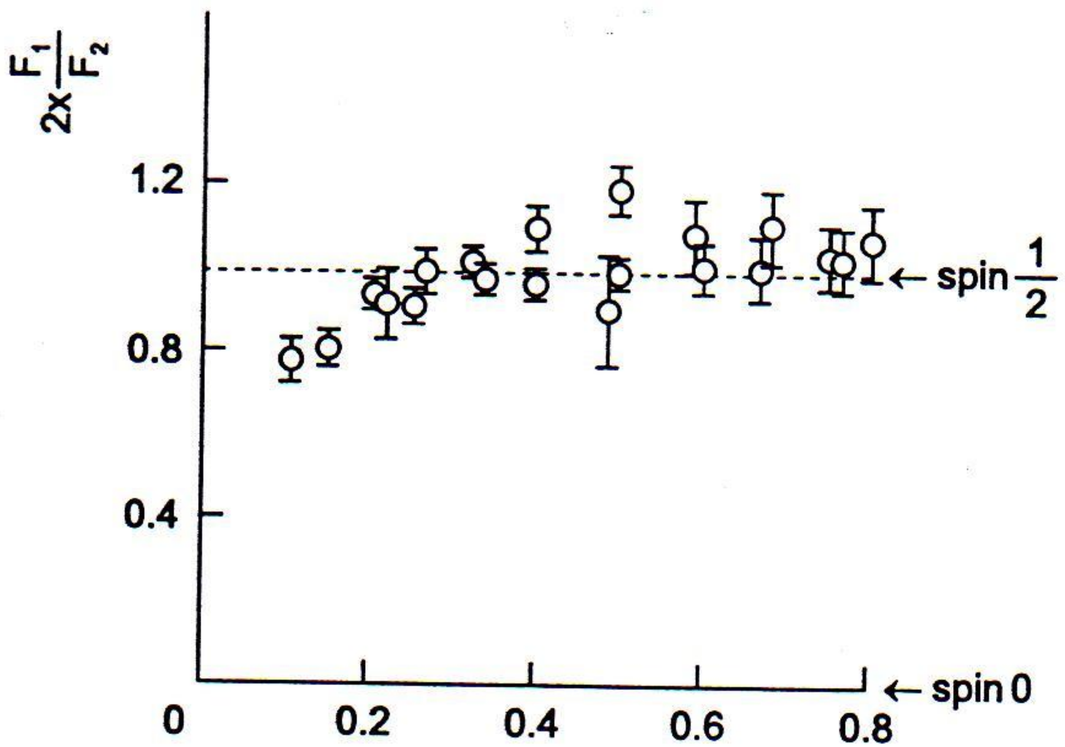
$$2x F_1(x) = F_2(x)$$

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



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

ODGOVARAJU PARTONIMA SPINA 1/2



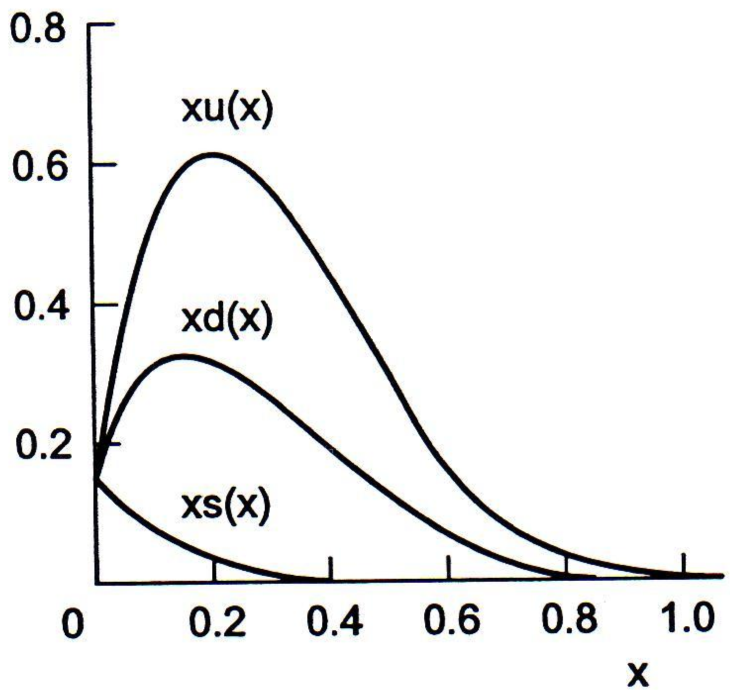
Slika 4.21: Eksperimentalno provjerene Callan–Gross-ove relacije (4.118)

SREDNJI impuls nošen u kvarkom

$$\int_0^1 p x u(x) dx$$

očekujemo da je dvostruk od onog nošenog d kvarkom:

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

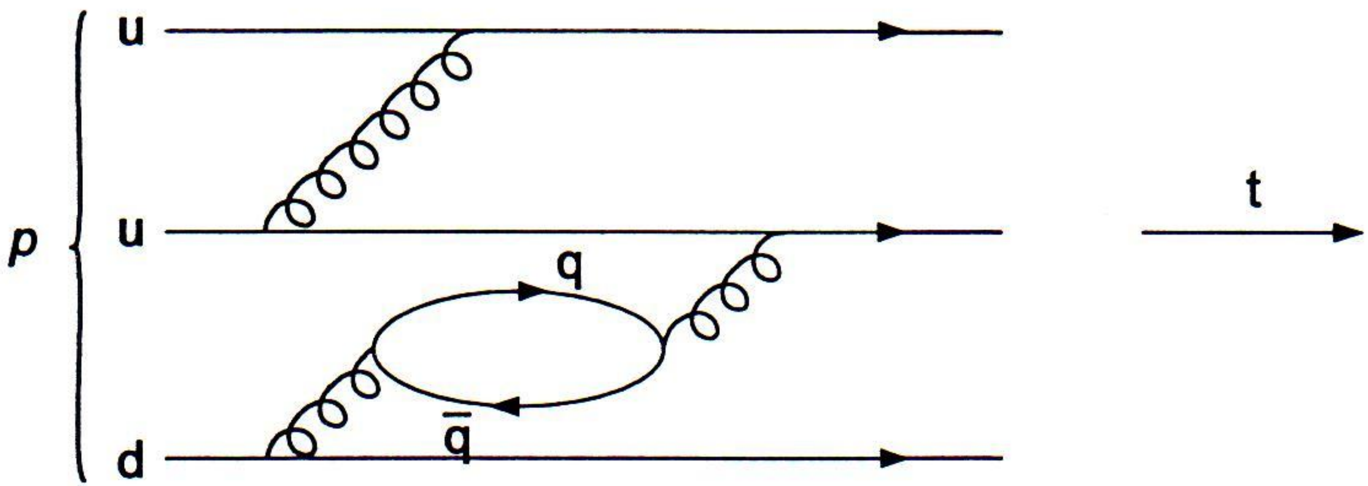


Slika 4.23: Mjerene funkcije raspodjele kvarkova

KRIZA IMPULSA PROTONA

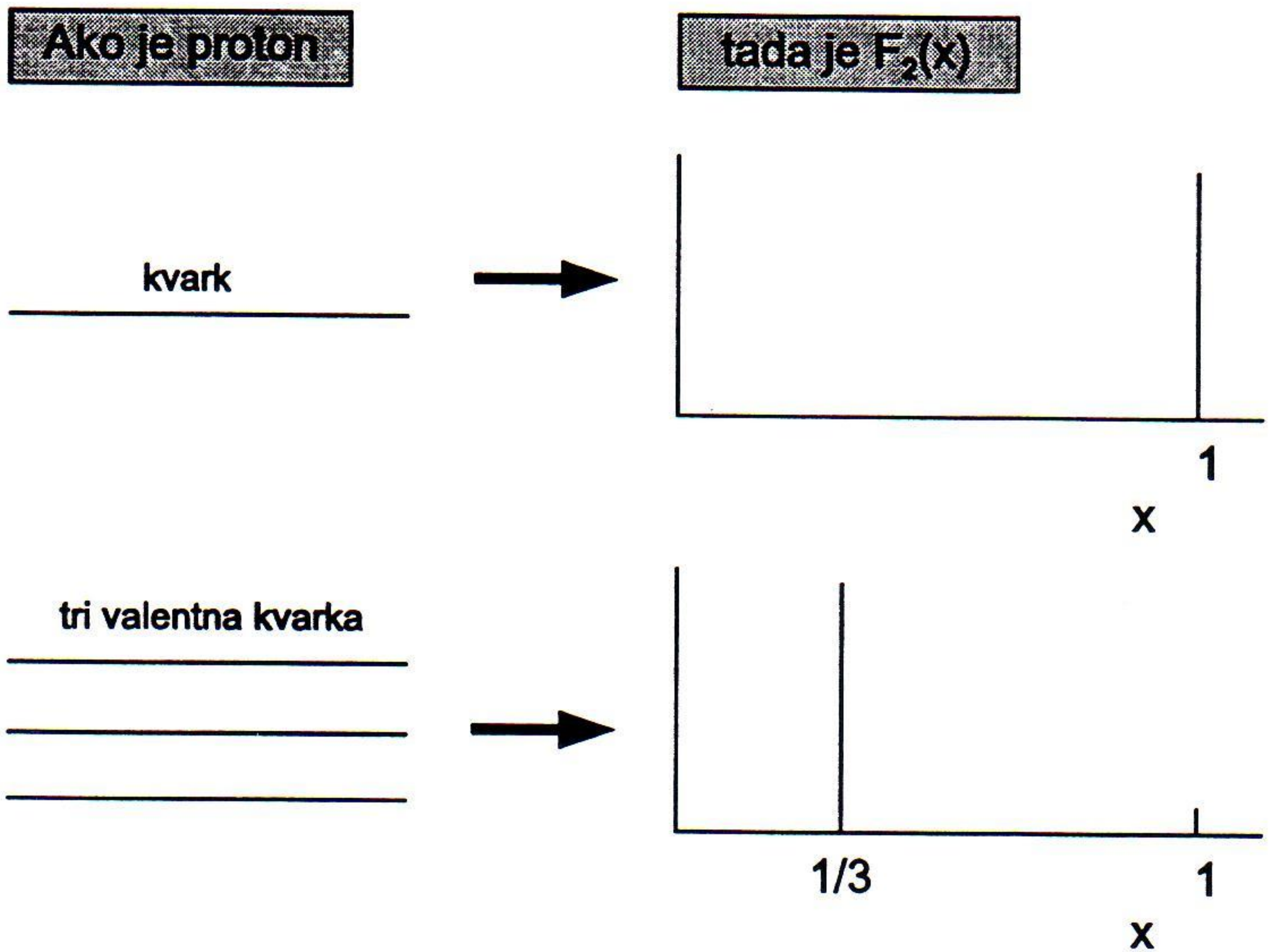
- MJERENJEM POVRŠINE ISPOD EKSPERIMENTALNE KRIVULJE:
- U srednjem, samo 54% impulsa protona sadržano je u kvarkovima
- Ostatak mora biti nošen nenabijenim partonima – gluonima, što odmah čini sliku složenijom:

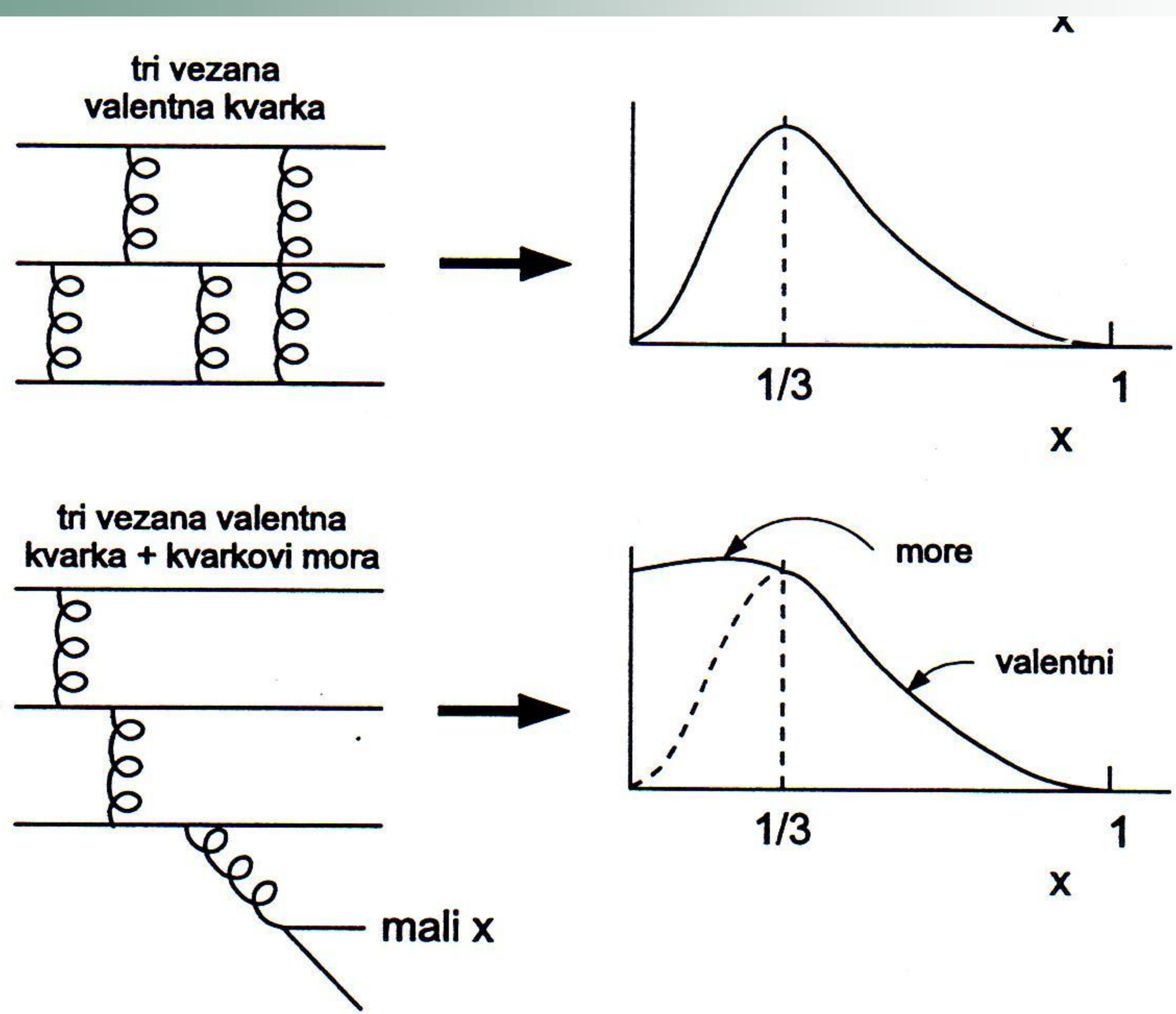
UVOĐENJE GLUONA I QCD
FEČ 4.3, STR.220



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

REPRODUCIRANJE EKSPERIMENTALNE KRIVULJE

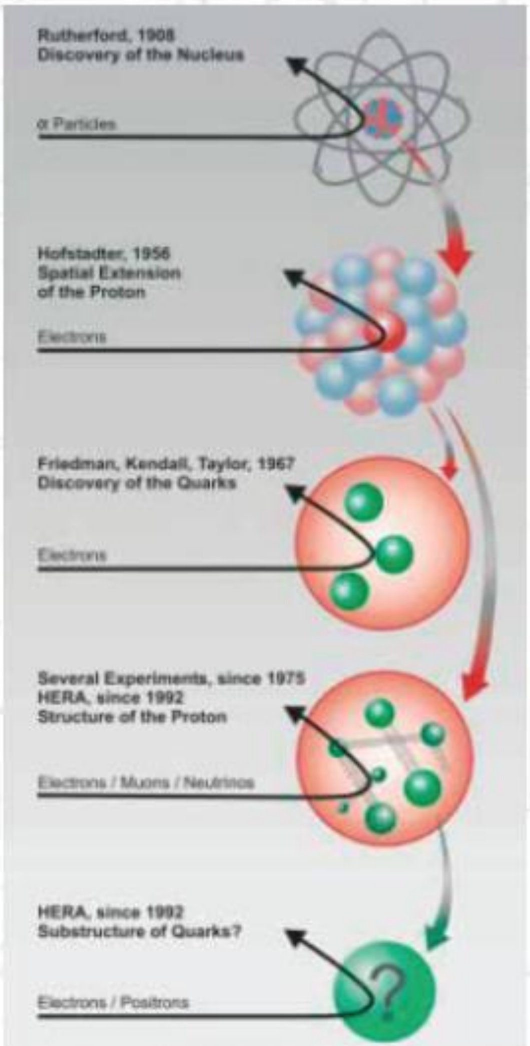




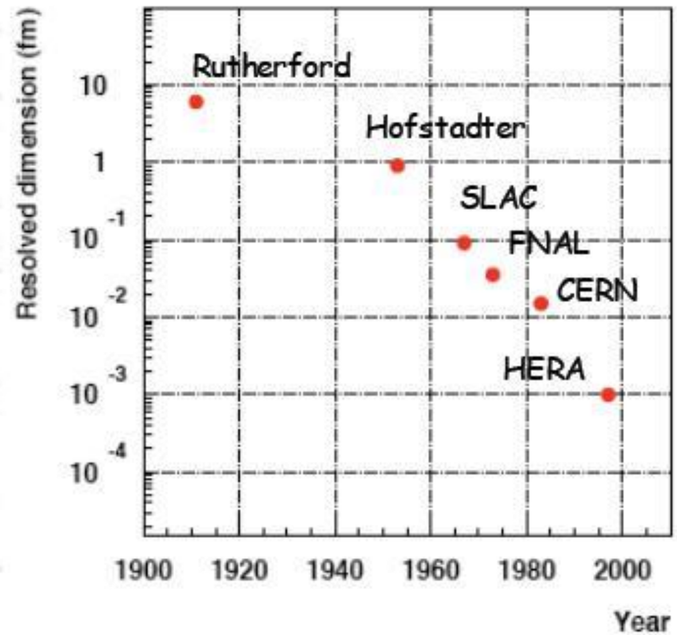
Slika 4.25: *Ovisnost strukturne funkcije o pretpostavljenoj strukturi protona*

PDFovi na energijama sudarivača

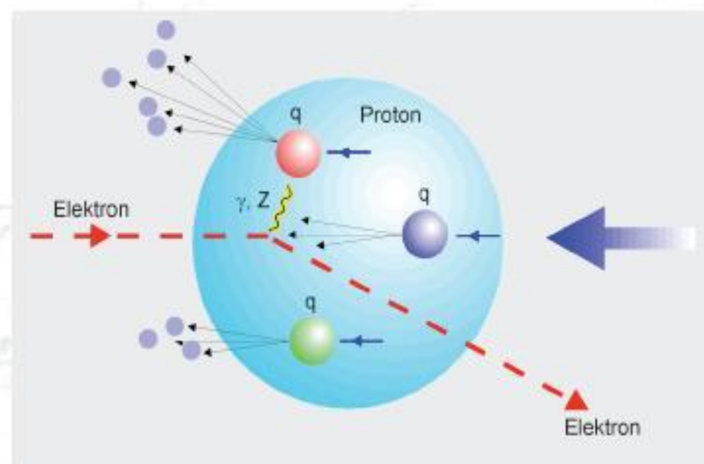
General considerations on scattering experiments



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

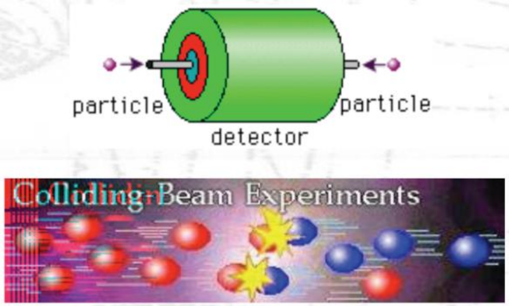


- Measurement of the final-state (scattered electron): ⇒ Structure of target!
- Scatter point-like probe onto object (target)

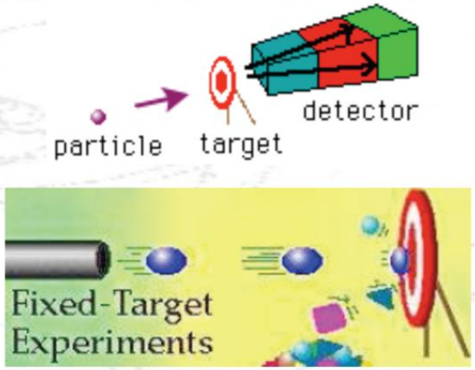


Hadron Electron Ring Accelerator

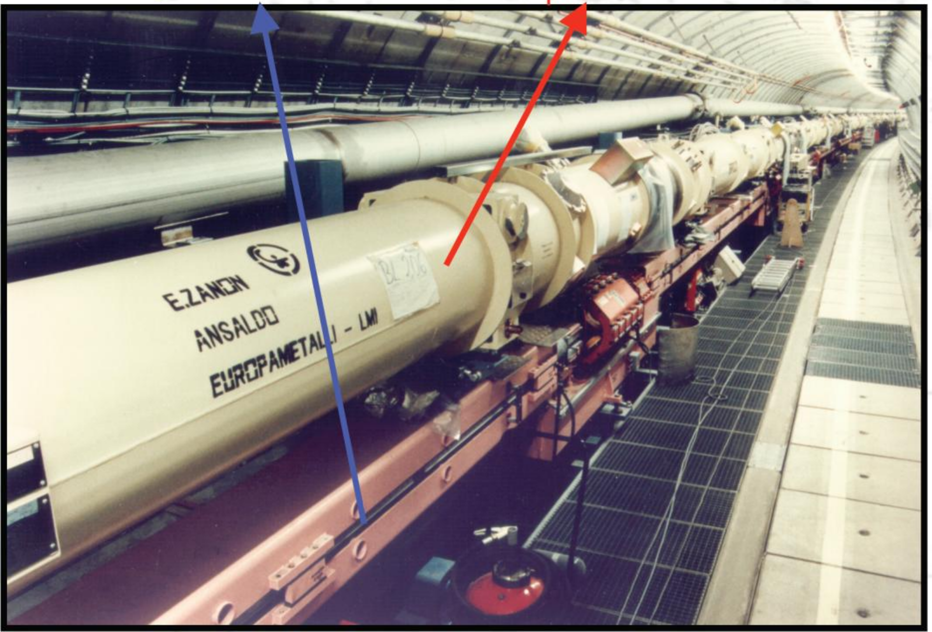
- Collider experiment: Electron-Proton collisions at HERA (DESY, Hamburg, Germany)

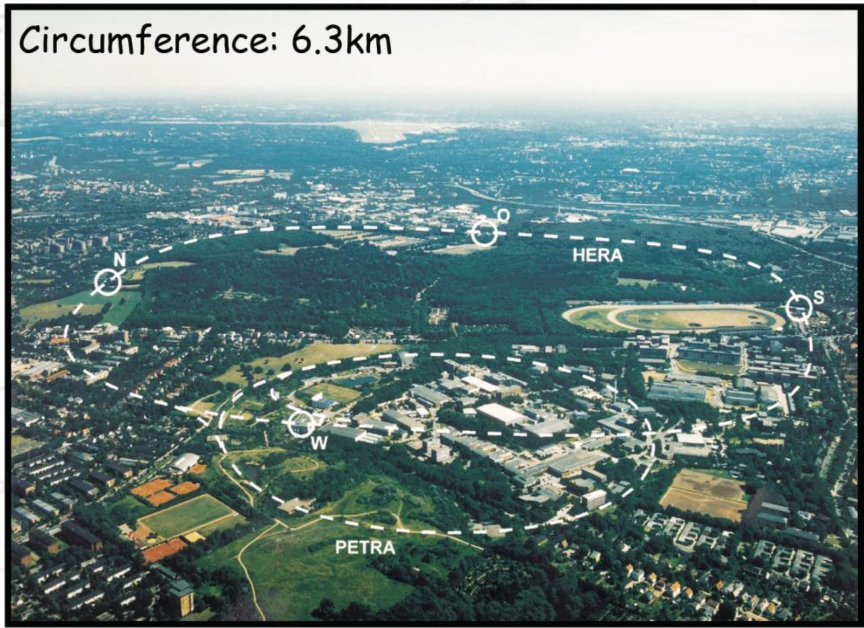


Equivalent to fixed target of
E_e = 50600 GeV:



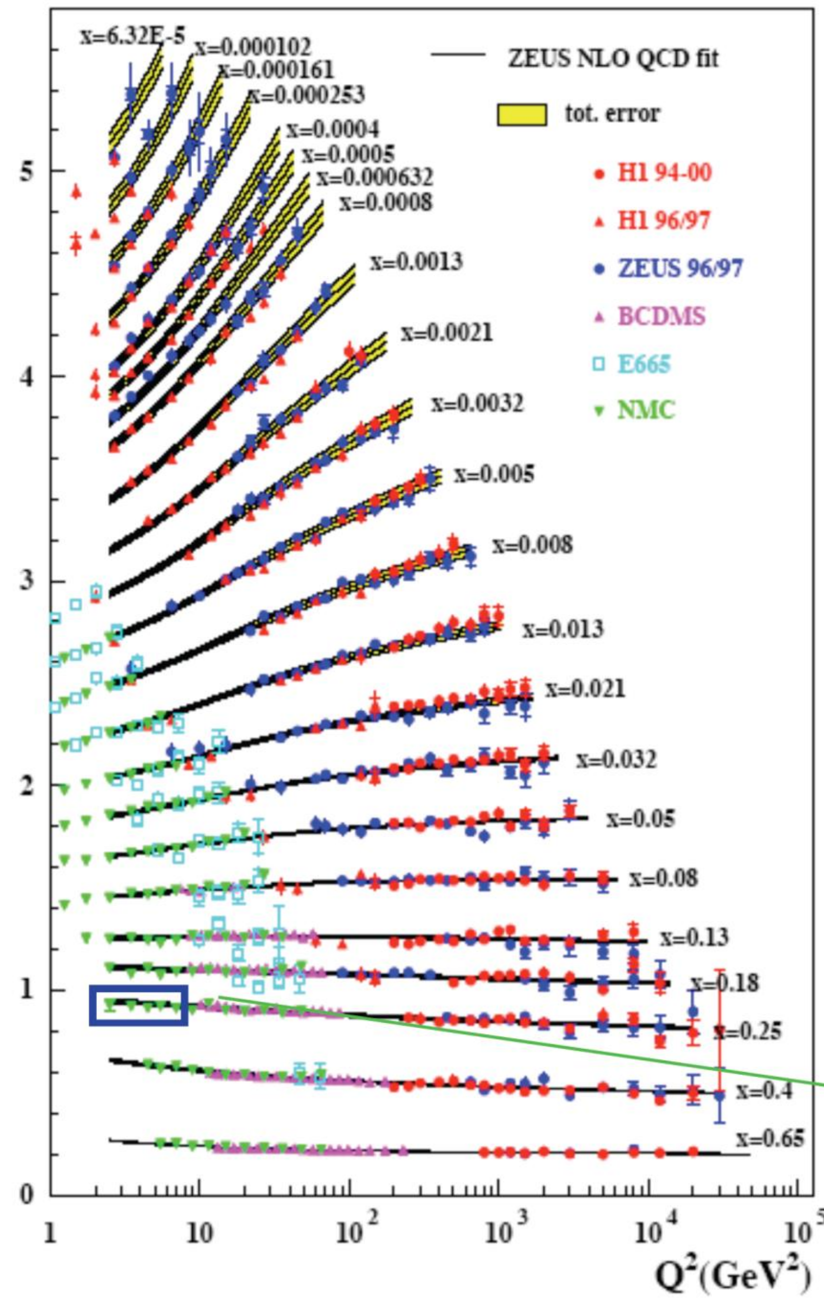
E_e = 27.5 GeV E_p = 920 GeV





OPAŽANJE NARUŠENJA SKALIRANJA -nakon preranog ("precocious")

ZEUS NLO DGLAP fits (pert. QCD): F_2

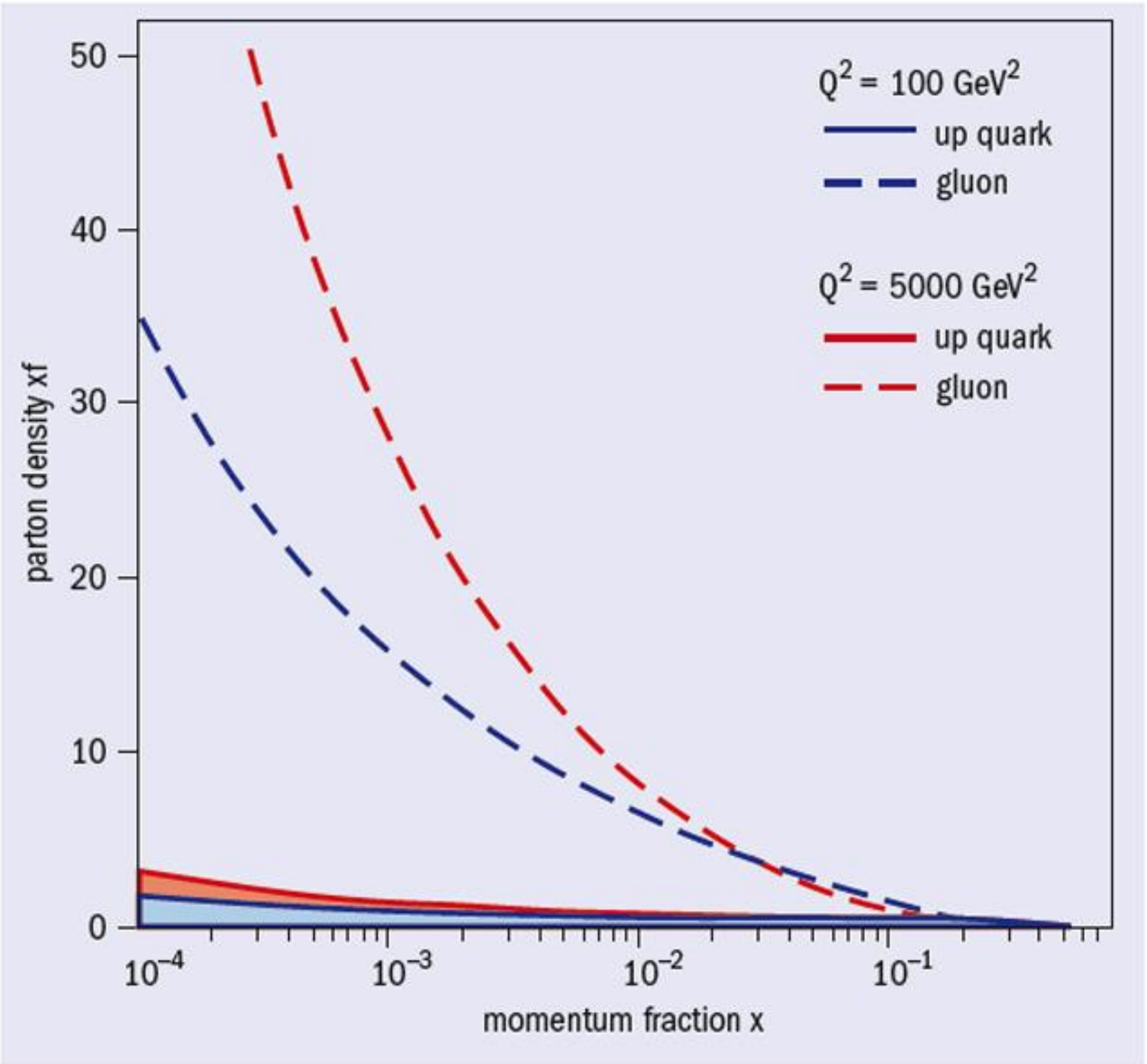


Strong violation of scaling at low x and high Q^2

In contrast to:

Low Q^2 high x!

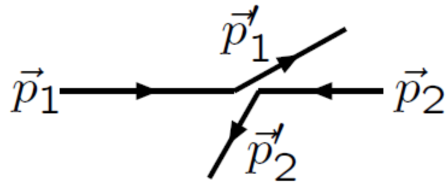
Raspodjele partonskih gustoća u-kvarka i gluona kao f-je x, za dvije vrijednosti Q^2. Očigledan je dramatičan porast gluonske gustoće s povećanom rezolucijom, Q^2



PARAMETRI SUDARIVAČA:

- ENERGIJA
- LUMINOZNOST

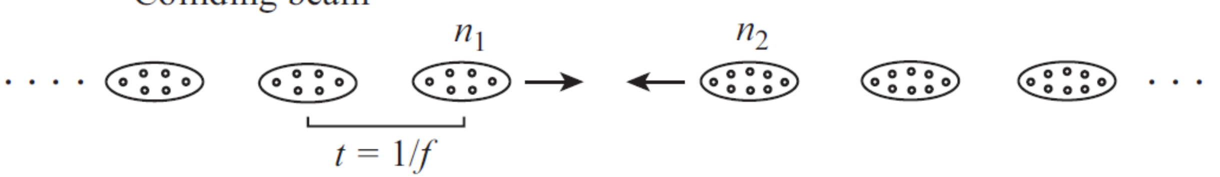
The energy:



$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2). & \end{cases}$$

$$E_{cm} \equiv \sqrt{s} \approx \begin{cases} 2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ \sqrt{2E_1 m_2} & \text{in the fixed target frame } \vec{p}_2 = 0. \end{cases}$$

The luminosity:



$$\mathcal{L} \propto f n_1 n_2 / a,$$

#particles/cm^2/s $\quad 10^{33}\ \text{cm}^{-2}\text{s}^{-1} = 1\ \text{nb}^{-1}\ \text{s}^{-1} \approx 10\ \text{fb}^{-1}/\text{year}$

O SUDARIVAČIMA - FEČ 1.2.2

Table 1. Recent and future energy-frontier particle colliders. (Parameters listed for the LHC and the ILC are design values.)

Name	Type	$\sqrt{s}$ (GeV)	L_{int} (pb^{-1})	Years of operation	Detectors	Location
LEP	e^+e^-	91.2 (LEP-1)	$\approx$ 200 (LEP-1)	1989-95 (LEP-1)	ALEPH, OPAL,	CERN
		130-209 (LEP-2)	$\approx$ 600 (LEP-2)	1996-2000 (LEP-2)	DELPHI, L3	
SLC	e^+e^-	91.2	20	1992-98	SLD	SLAC
HERA	$e^\pm p$	320	500	1992-2007	ZEUS, H1	DESY
Tevatron	$p\bar{p}$	1800 (Run-I)	160 (Run-I)	1987-96 (Run-I)	CDF, DØ	FNAL
		1960 (Run-II)	6 K (Run-II, 06/09)	2000-??? (Run-II)		
LHC	pp	14000	10 K/yr ("low-L")	2010? - 2013?	ATLAS, CMS	CERN
			100 K/yr ("high-L")	2013?? - 2016???		
ILC	e^+e^-	500-1000	1 M???	???	???	???

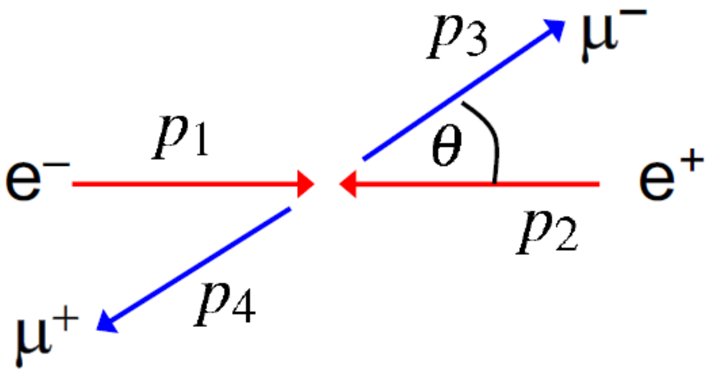
Table 1. Comparison of the LHC and Tevatron accelerator statistics.

	LHC (design)	Tevatron (achieved)
Center-of-mass energy	14 TeV	1.96 TeV
Number of bunches	2808	36
Bunch spacing	25ns	396ns
Energy stored in beam	360MJ	1MJ
Peak Luminosity	$10^{33} - 10^{34} cm^{-2}s^{-1}$	3.87×10^{32} (April 2010)
Integrated Luminosity / year	10-100 fb^{-1}	$> 2fb^{-1}$ (2008)

ANIHILACIJE ELEKTRONA I POZITRONA U MIONE – Račun FEČ 3.3.3

Consider the process: $e^+e^- \rightarrow \mu^+\mu^-$

- Work in C.o.M. frame (this is appropriate for most e^+e^- colliders).

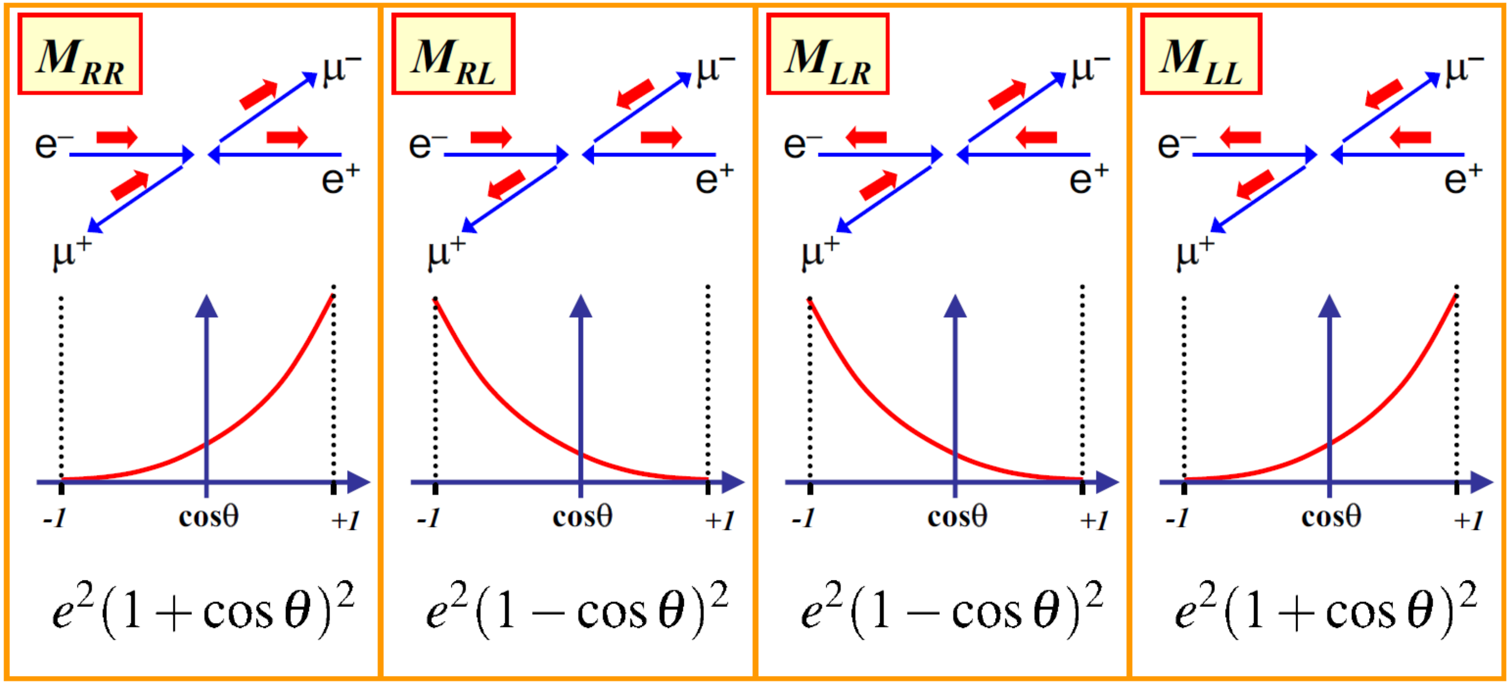


$$p_1 = (E, 0, 0, p) \qquad p_2 = (E, 0, 0, -p)$$

$$p_3 = (E, \vec{p}_f) \qquad p_4 = (E, -\vec{p}_f)$$

In the C.o.M. frame have

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \frac{|\vec{p}_f|}{|\vec{p}_i|} |M_{fi}|^2 \qquad \text{with} \qquad s = (p_1 + p_2)^2 = (E + E)^2 = 4E^2$$

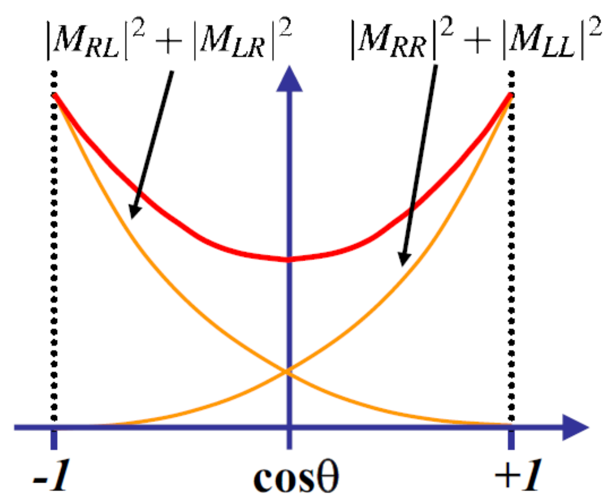


The cross section is obtained by averaging over the initial spin states and summing over the final spin states:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \times \frac{1}{64\pi^2 s}(|M_{RR}|^2 + |M_{RL}|^2 + |M_{LR}|^2 + |M_{LL}^2|)$$

$$= \frac{(4\pi\alpha)^2}{256\pi^2 s}(2(1+\cos\theta)^2 + 2(1-\cos\theta)^2)$$

$$\Rightarrow \boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)}$$

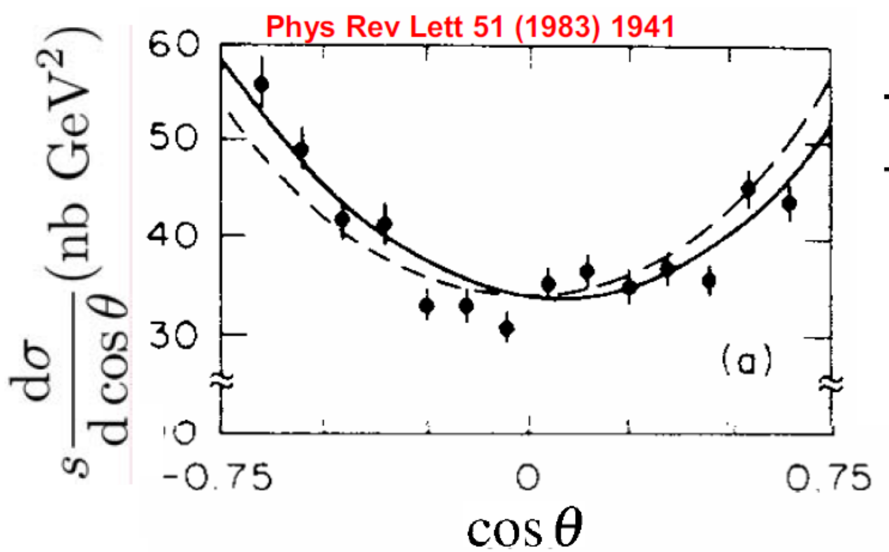


xample:

DOPRINOS Z-BOZONA ASIMETRIJI PRODUKCIJE

$e^+e^- \to \mu^+\mu^-$

$\sqrt{s} = 29$ GeV



pure QED, $O(\alpha^3)$

QED plus Z contribution

Angular distribution becomes slightly asymmetric in higher order QED or when Z contribution is included

ANIHILACIJE ELEKTRONA I POZITRONA U HADRONE

Colour is conserved and quarks are produced as $r\bar{r},\ g\bar{g},\ b\bar{b}$

For a single quark flavour and single colour

$$\sigma(e^+e^- \to q_i\bar{q}_i) = \frac{4\pi\alpha^2}{3s}Q_q^2$$

- Experimentally observe jets of hadrons:

$$\sigma(e^+e^- \to \text{hadrons}) = 3\sum_{u,d,s,..}\frac{4\pi\alpha^2}{3s}Q_q^2$$

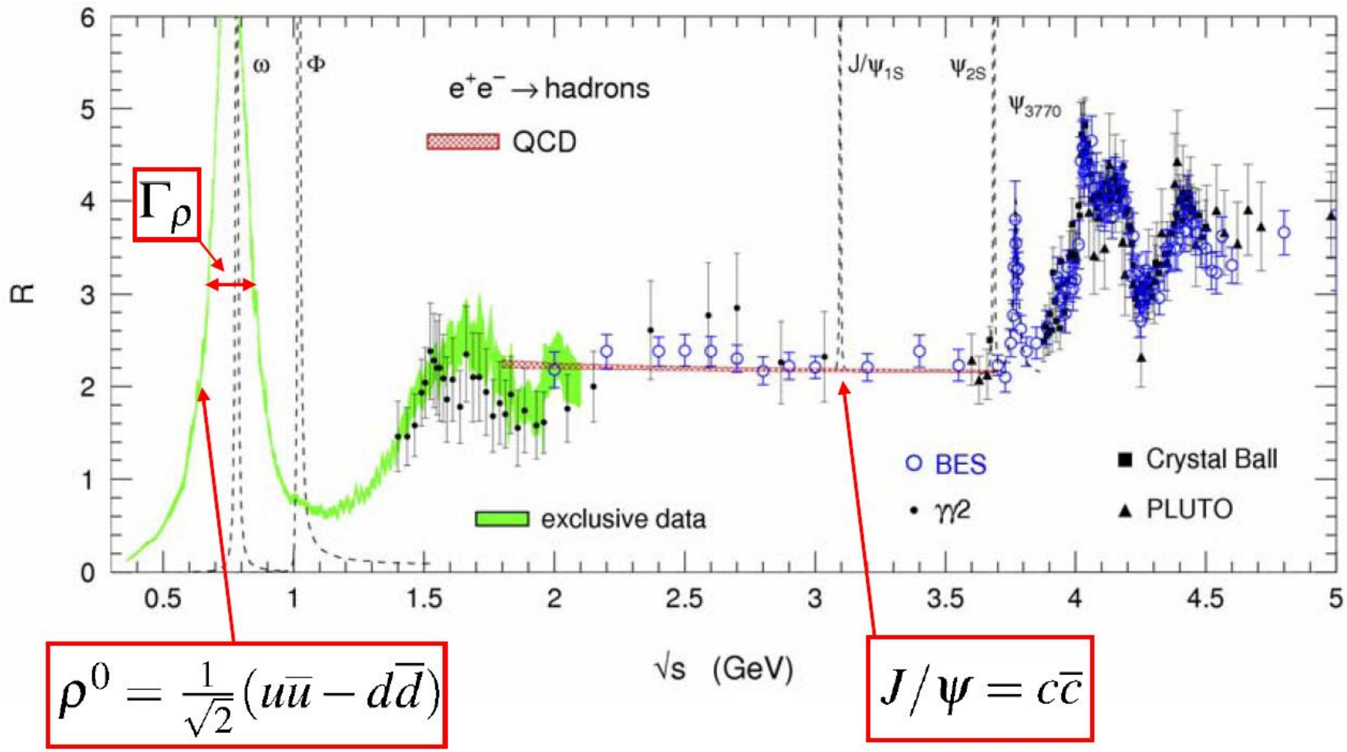
Factor 3 comes from colours

- Usual to express as ratio compared to $\sigma(e^+e^- \to \mu^+\mu^-)$

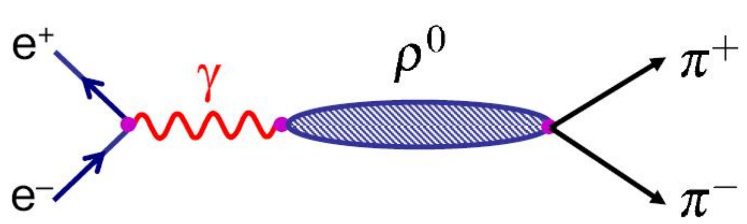
$$R_\mu = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_{u,d,s,..}Q_q^2$$

NISKOENERGIJSKE REZONANTNE PRODUKCIJE

- Low energy region complicated by resonant production of decaying meson states



e.g.



FWHM Width of resonance:

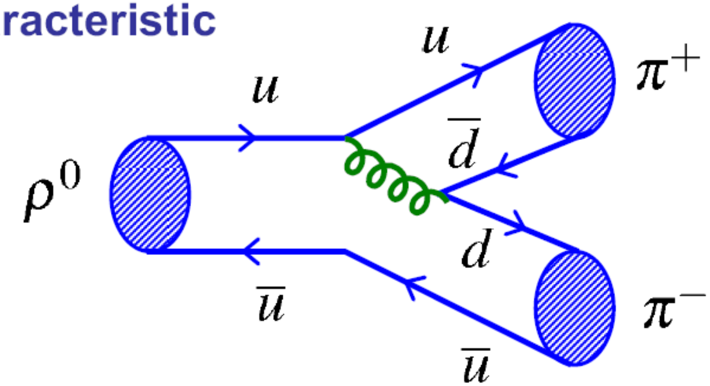
$$\Gamma_\rho = 146\,\text{MeV}$$

Wide resonance implies short lifetime
(see part II or later discussion of Z)

$$\tau = \frac{\hbar}{\Gamma}$$

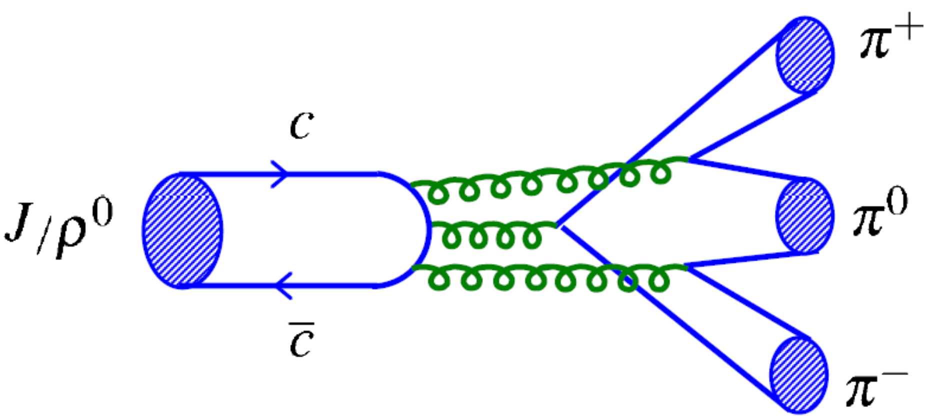
e.g. $\Gamma_\rho = 146\,\mathrm{MeV}$ ➡ $\tau_\rho = 4.5 \times 10^{-24} s$

Very short lifetimes are characteristic of strong decays



Narrower resonances characteristic of suppressed strong decays

e.g. $\Gamma_{J/\psi} = 94\,\mathrm{keV}$ ➡ $\tau_{J/\psi} = 7.0 \times 10^{-21} s$



ZWEIG Suppression

No decay to $D^+(c\bar{d})D^-(d\bar{c})$

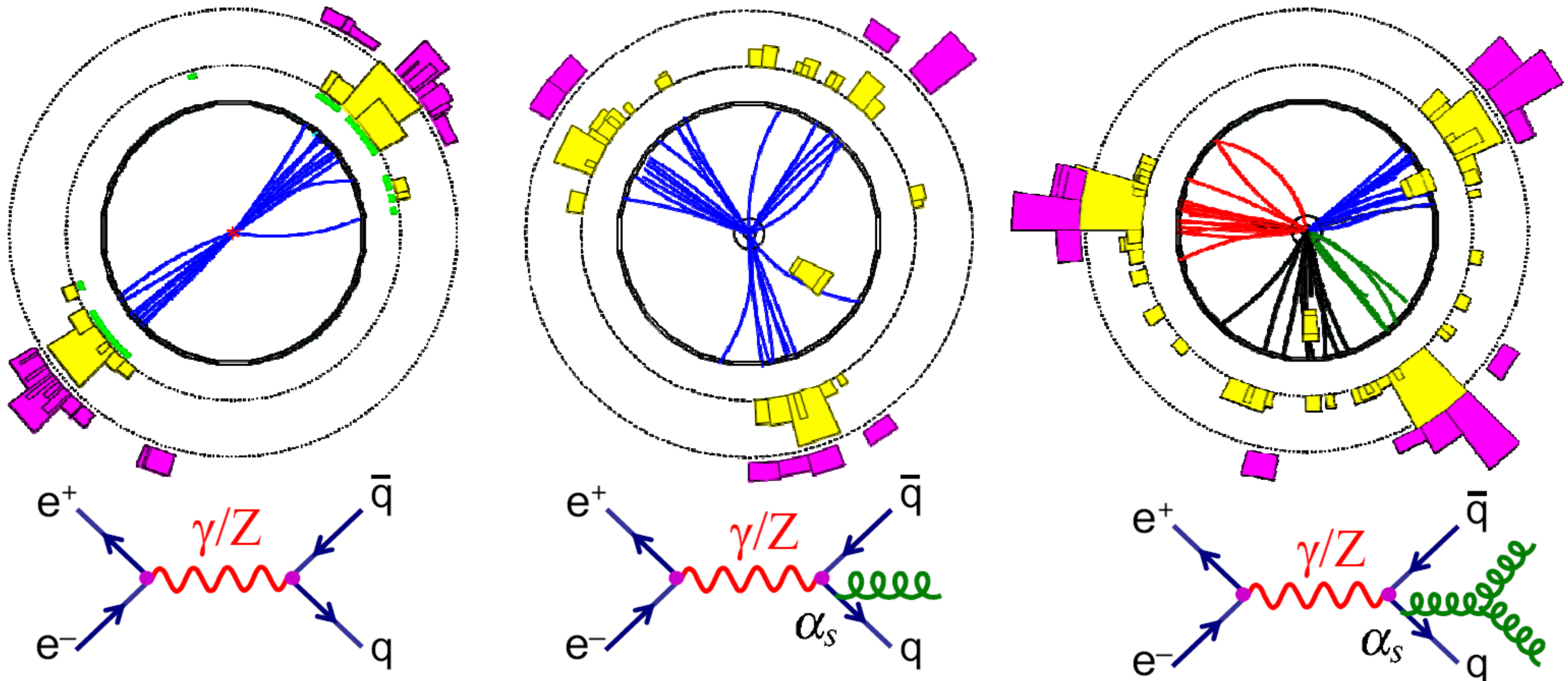
since $m_{J/\psi} < 2m_{D^\pm}$

PRODUKCIJE GLUONA

★ e^+e^- colliders are also a good place to study gluons

$e^+e^- \to q\bar{q} \to 2\text{jets}$ $\quad$ $e^+e^- \to q\bar{q}g \to 3\text{jets}$ $\quad$ $e^+e^- \to q\bar{q}gg \to 4\text{jets}$

OPAL at LEP (1989-2000)

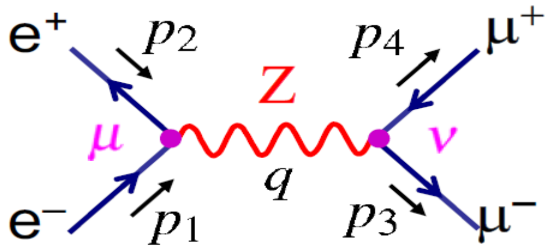


Experimentally:

- Three jet rate ➡ measurement of α_s
- Angular distributions ➡ gluons are spin-1
- Four-jet rate and distributions ➡ QCD has an underlying SU(3) symmetry

KRATKOŽIVUĆA REZONANCA

- Feynman rules for the diagram below give:



e⁺e⁻ vertex: $\overline{v}(p_2)\cdot -ig_Z\gamma^\mu \frac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)$

Z propagator: $\dfrac{-ig_{\mu\nu}}{q^2 - m_Z^2}$

μ⁺μ⁻ vertex: $\overline{u}(p_3)\cdot -ig_Z\gamma^\nu \frac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)$

$$\Rightarrow\quad -iM_{fi} = [\overline{v}(p_2)\cdot -ig_Z\gamma^\mu \tfrac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)].\frac{-ig_{\mu\nu}}{q^2-m_Z^2}.[\overline{u}(p_3)\cdot -ig_Z\gamma^\nu \tfrac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)]$$

$$\boxed{M_{fi} = -\frac{g_Z^2}{q^2-m_Z^2} g_{\mu\nu}[\overline{v}(p_2)\gamma^\mu \tfrac{1}{2}(c_V^e - c_A^e\gamma^5)\cdot u(p_1)].[\overline{u}(p_3)\gamma^\nu \tfrac{1}{2}(c_V^\mu - c_A^\mu\gamma^5)\cdot v(p_4)]}$$

★ In the Z boson propagator make the substitution:

$$m_Z \rightarrow m_Z - i\Gamma_Z/2$$

★ Which gives:

$$(s-m_Z^2) \longrightarrow [s-(m_Z - i\Gamma_Z/2)] = s - m_Z^2 + im_Z\Gamma_Z + \tfrac{1}{4}\Gamma_Z^2 \approx s - m_Z^2 + im_Z\Gamma_Z$$

where it has been assumed that $\Gamma_Z \ll m_Z$

★ Which gives

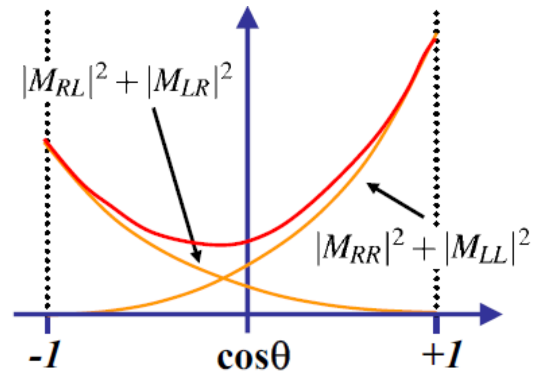
$$\left|\frac{1}{s-m_Z^2}\right|^2 \rightarrow \left|\frac{1}{s-m_Z^2+im_Z\Gamma_Z}\right|^2 = \frac{1}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

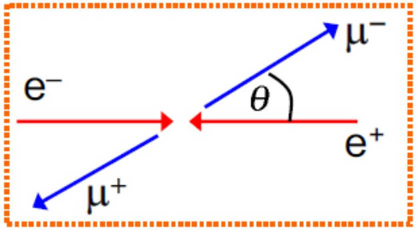
$$\frac{\mathrm{d}\sigma_{RR}}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_R^e)^2(c_R^\mu)^2(1+\cos\theta)^2$$

$$\frac{\mathrm{d}\sigma_{LL}}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_L^\mu)^2(1+\cos\theta)^2$$

$$\frac{\mathrm{d}\sigma_{LR}}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$

$$\frac{\mathrm{d}\sigma_{RL}}{\mathrm{d}\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$





★ **Because $|M_{LL}|^2+|M_{RR}|^2 \neq |M_{LR}|^2+|M_{RL}|^2$, the differential cross section is asymmetric, i.e. parity violation (although not maximal as was the case for the W boson).**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{1}{64\pi^2 s}\langle|M_{fi}|^2\rangle$$

$$= \frac{1}{64\pi^2}\cdot\frac{1}{4}\cdot\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\times$$

$$\left\{\tfrac{1}{4}[(c_V^e)^2+(c_A^e)^2][(c_V^\mu)^2+(c_A^\mu)^2](1+\cos^2\theta)+2c_V^e c_A^e c_V^\mu c_A^\mu\cos\theta\right\}$$

★ **Integrating over solid angle** $\mathrm{d}\Omega = \mathrm{d}\phi\,\mathrm{d}(\cos\theta) = 2\pi\mathrm{d}(\cos\theta)$

$\int_{-1}^{+1}(1+\cos^2\theta)\mathrm{d}(\cos\theta) = \int_{-1}^{+1}(1+x^2)dx = \frac{8}{3}$ **and** $\int_{-1}^{+1}\cos\theta\,\mathrm{d}(\cos\theta) = 0$

$$\sigma_{e^+e^-\to Z\to\mu^+\mu^-} = \frac{1}{192\pi}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\left[(c_V^e)^2+(c_A^e)^2\right]\left[(c_V^\mu)^2+(c_A^\mu)^2\right]$$

$$\Gamma(Z \to e^+e^-) = \frac{g_Z^2 m_Z}{48\pi}[(c_V^e)^2 + (c_A^e)^2] \quad \text{and} \quad \Gamma(Z \to \mu^+\mu^-) = \frac{g_Z^2 m_Z}{48\pi}[(c_V^\mu)^2 + (c_A^\mu)^2]$$

$$\Rightarrow \quad \sigma = \frac{12\pi}{m_Z^2} \frac{s}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma(Z \to e^+e^-)\Gamma(Z \to \mu^+\mu^-)$$

★ Writing the partial widths as $\Gamma_{ee} = \Gamma(Z \to e^+e^-)$ etc., the total cross section can be written

$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2} \frac{s}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma_e\Gamma_f \qquad (2)$$

where f is the final state fermion flavour:

Starting from

$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2} \frac{s}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma_e\Gamma_f \qquad (3)$$

maximum cross section occurs at $\sqrt{s} = m_Z$ with peak cross section equal to

$$\sigma_{f\bar{f}}^0 = \frac{12\pi}{m_Z^2} \frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}$$

Cross section falls to half peak value at $\sqrt{s} \approx m_z \pm \frac{\Gamma_Z}{2}$ which can be seen immediately from eqn. (3)

Hence $\Gamma_Z = \frac{\hbar}{\tau_Z} = \text{FWHM of resonance}$

BROJANJE NEUTRINA

★ Total decay width is the sum of the partial widths:

$$\Gamma_Z = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{\text{hadrons}} + \Gamma_{\nu_1} + \Gamma_{\nu_2} + \Gamma_{\nu_3} + ?$$

★ Although don't observe neutrinos, $Z \rightarrow \nu\overline{\nu}$ decays affect the Z resonance shape for all final states

★ For all other final states can determine partial decay widths from peak cross sections:

$$\sigma^0_{f\overline{f}} = \frac{12\pi}{m_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}$$

★ Assuming lepton universality:

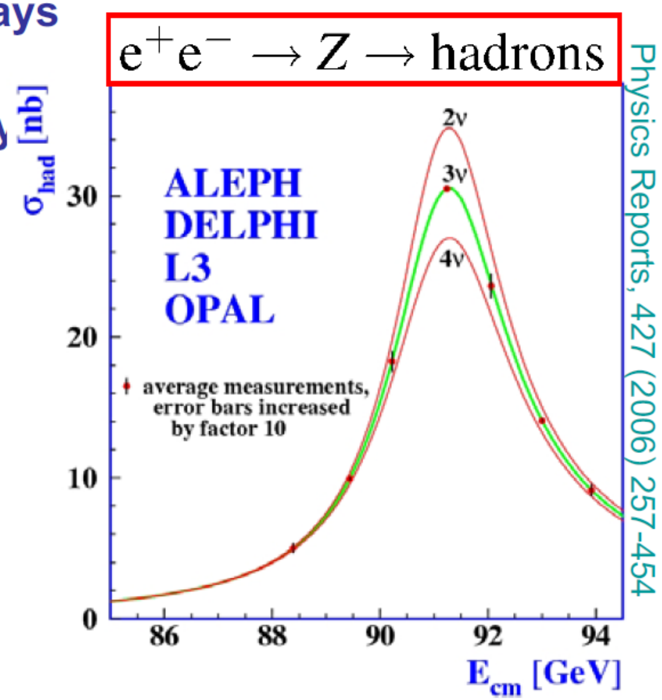
$$\Gamma_Z = 3\Gamma_\ell + \Gamma_{\text{hadrons}} + N_\nu\Gamma_\nu$$

measured from Z lineshape

measured from peak cross sections

calculated, e.g. question 26

$$N_\nu = 2.9840 \pm 0.0082$$



★ ONLY 3 GENERATIONS (unless a new 4th generation neutrino has very large mass)

Usporedba mjerenja i analize SM s globalnom EW-prilagodbom

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3