HARD EXCLUSIVE SCATTERING

P. Kroll

Fachbereich Physik, Universität Wuppertal

Graz, April 2007

Outline:

- **Lecture 1: QCD, factorization, PDFs and all that**
- **Lecture 2: Generalized Parton Distributions (GPDs)**
- **Lecture 3: Applications: Deeply virtual and wide-angle exclusive scattering**

Lecture 1: QCD, factorization, PDFs and all that

Outline:

- **QCD, asymptotic freedom, factorization**
- **Evolution**
- **Deep inelastic scattering (DIS)**
- **Parton distribution functions (PDFs)**
- **Results, interpretration and use of PDFs**

Quarks

Multiplet structure of hadron spectrum lead to introduction of constituents

QUARKS u, d, s spin-$1/2$ Gell-Mann (64); Zweig (64)

today: three more quarks c, b, t (heavy)

light quarks form the fundamental triplets of the group SU(3)$_F$

light hadrons are members of the irreducible representations of the SU(3)$_F$

mesons: $q\overline{q}$ $3 \times \overline{3} = 1 + 8$

baryons: qqq $3 \times 3 \times 3 = 1 + 8 + 8 + 10$

Spectrum in agreement with this structure, SU(3)$_F$ broken by quark masses

Gell-Mann Nobel prize 1969

but - free quarks have not been observed

- baryon wf. symmetric unter quark interchange

  e.g. $\Delta^{++}(s_3 = 3/2) = f(r_1, r_2, r_3)\ |\uparrow\uparrow\uparrow\rangle\ |uuu\rangle$

  symmetric space $(L = 0)$ spin flavor wfs

by virtue of SU(3)$_F$ product wf of baryons symmetric - symmetric quark model

in conflict with Spin-Statistik theorem

Color

Greenberg (64), Han-Nambu(65) to cure this problem a new quantum number

color $\quad q_c \quad c = 1, 2, 3 \quad$ SU(3)$_C$ triplet

confinement hypothese: only color singlet states appear as free, asymp. states

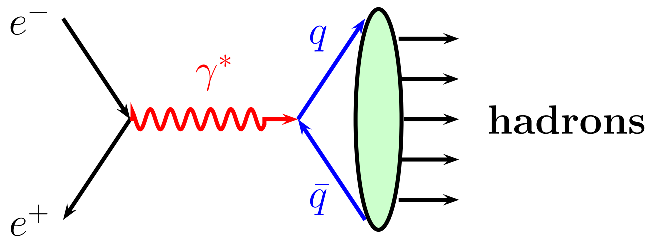
excludes existence of free quarks

color structure of baryons: $3 \times 3 \times 3 = 1 + 8 + 8 + 10$

singlet state is total antisymmetric $B = \sum_{i,j,k=1,2,3} \epsilon_{ijk}\, q_i\, q_j\, q_k$

$\Longrightarrow$ product of space, spin and flavor wfs must be symmetric

other evidence for color:

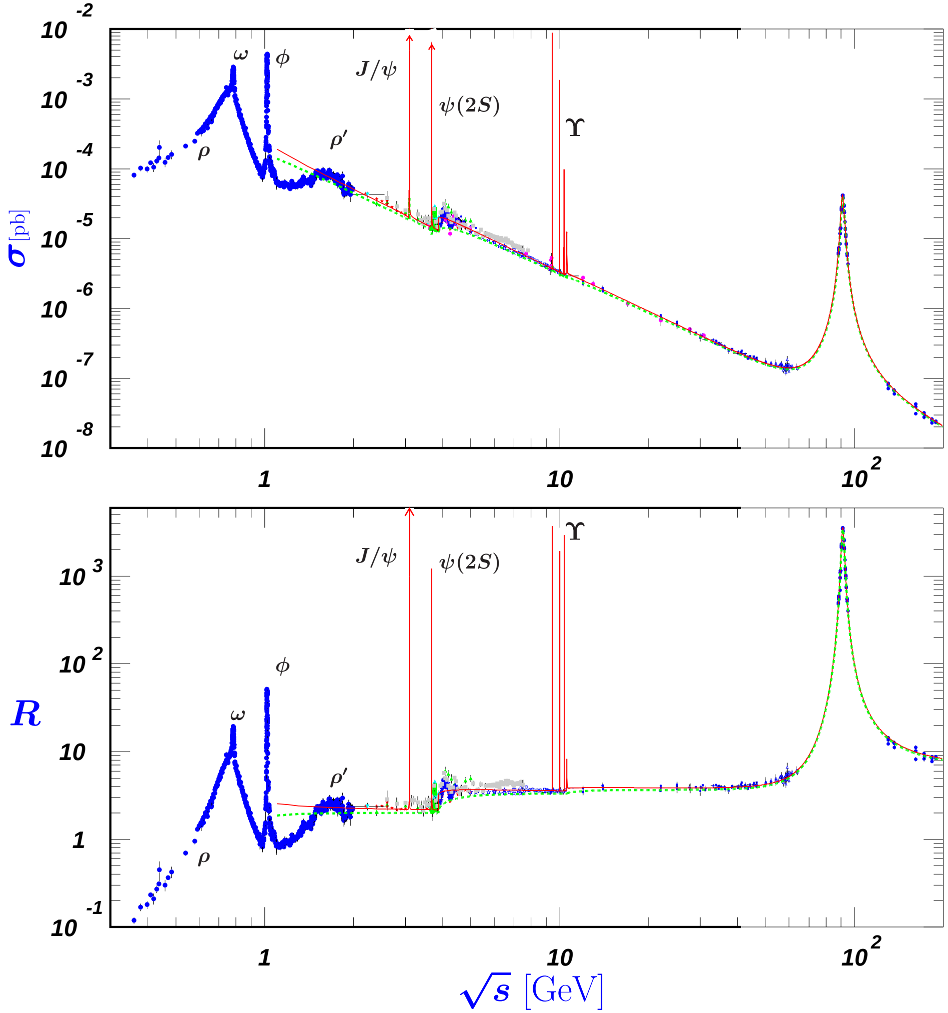


e^+e^- annihilation into hadrons

reaction mech.: $e^+e^- \to \gamma^* \to q\overline{q}$
and soft $q\overline{q} \to \mathrm{hadrons}$ transition
with probability 1 (confinement)
hence, up to charges, same cross
section as for $e^+e^- \to \mu^+\mu^-$

$$R = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 \sum_a e_a^2$$

$e^+e^- \rightarrow hadrons$



dashed: quark approach

steps: $2 \quad 10/3 \quad 11/3$

solid: 3-loop pQCD (NNNLO)

plot taken from PDG

QCD

Weyl (29), Yang-Mills (54): dynamical principle

require a locally phase invariant field with respect to a certain group

QED: U(1)

Fritzsch, Gell-Mann, Leutwyler (73): take SU(3)$_C$ (exact) for interaction among quarks

$\Psi(x) \to \Psi'(x) = \exp\left[ig_s \sum_{a=1}^{8} T_a \alpha_a(x)\right]\Psi(x)$

$T_a = \lambda_a/2$ generators of SU(3)$_C$, λ_a traceless, hermitic 3×3 matrices (8), $\alpha_a(x)$ arbitrary functions

free Lagrangian: $\mathcal{L}_0 = i\overline{\Psi}\,\partial\!\!\!/\Psi - m\overline{\Psi}\Psi$

replace ∂_μ by covariant derivative: $D_\mu = \partial_\mu + ig_s \sum T_a G_{a\mu}$

$$\mathcal{L}_{\mathrm{QCD}} = \overline{\Psi}(i\partial\!\!\!/ - m)\Psi - g_s \sum_a \overline{\Psi}\gamma^\mu T_a \Psi G_a^\mu - 1/4 \sum_a G_{\mu\nu}^a G_a^{\mu\nu}$$

field strength tensor of gauge field $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s \sum_{b,c} f_{abc} G_\mu^b G_\nu^c$

G^a_μ potential of gauge field, 8 gauge fields

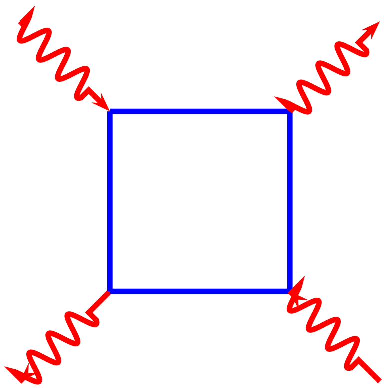
quant of gauge field - gluon $J^P = 1^-$, $a = 1..8$

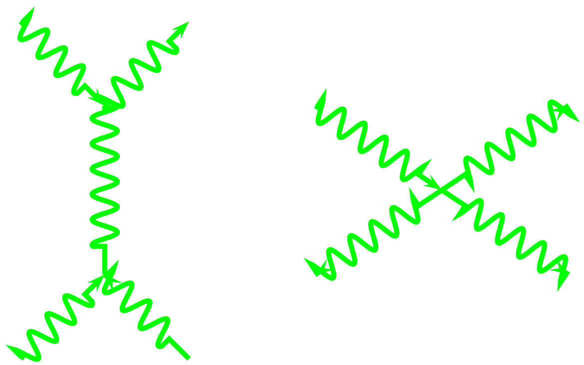
gauge transform $G_{a\mu} \to G'_{a\mu} = G_{a\mu} - \partial_\mu \alpha_a - g_s \sum_{bc} f_{abc} \alpha_b G_{c\mu}$

f_{abc} structure constants of SU(3)$_C$ $([\lambda_a, \lambda_b] = f_{abc} \lambda_c)$

similar to QED but gluon is colored: - self interaction, non-linear theory

$\gamma\gamma \to \gamma\gamma \quad \sigma \sim \mathcal{O}(e^8)$ $\qquad gg \to gg \quad \sigma \sim \mathcal{O}(g_s^4)$





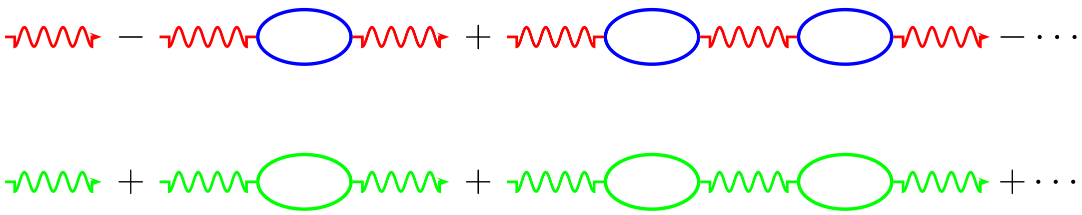
$e^+e^- \to \mu^+\mu^-$ of $\mathcal{O}(e^4)$ $\qquad u\overline{u} \to d\overline{d}$ of $\mathcal{O}(g_s^4)$

Gliding coupling

fundamental feature of relativistic QFT

- pair creation and annihilation
- i.e. strong fluctuations in particle number (in contrast to non-rel QM)
- complicated vacuum, can be polarized (screening/antiscreening)
- strength of coupling depends on scale/distance

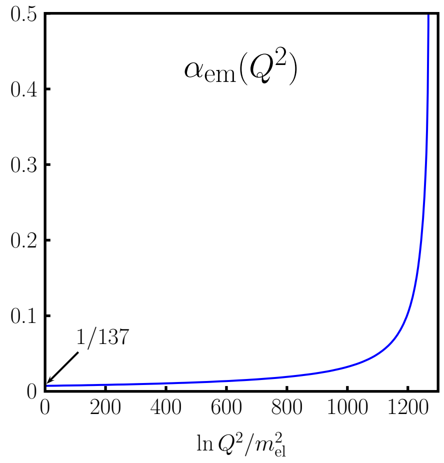
formally - pert. corrections to gauge boson propagator ($Q^2 = -q^2 > 0$)

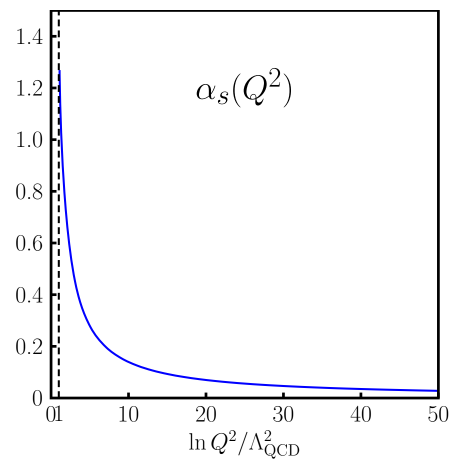


$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1-\beta_0\alpha(\mu^2)\ln(Q^2/\mu^2)}$ QED: $\beta_0 = 1/(3\pi)$

QCD: $\beta_0 = (2/3n_f - 11)/(4\pi) < 0$

breakdown of pert. theory if coupling $\alpha = g^2/4\pi \not\ll 1$





choose $\mu = m_e$ static limit

$\alpha_{\rm em}(0) = 1/137.03599976$

singular at $Q^2/m_e^2 \simeq 10^{556}$

$\alpha_{\rm em}(Q^2 = M_Z^2) \simeq 1/128$

distance $r = 1/Q$, $\hbar = c = 1$, natural units

(not anthropomorphic Planck)

with regard to position of singularity

$$\alpha_{\rm s}(Q^2) = \frac{4\pi}{(11 - 2/3 n_f) \ln Q^2/\Lambda^2_{\rm QCD}}$$

$\Lambda_{\rm QCD} \simeq 240\,{\rm MeV}$

asymptotic freedom - infrared slavery

Gross-Wilczek; Politzer (73); Nobel prize 04

singularity is severe problem - in any event

there are soft regions with large $\alpha_{\rm s}$

(where hadrons are formed)

is QCD of any use?

Factorization

IT IS: processes with a hard scale (Q^2) often factorize into

- hard partonic-level subprocesses
- and soft hadronic matrix elements

to all orders of $\alpha_{\rm s}$ and in all logs of $\mu_{\rm F}^2$, partons treated as on-shell part.
($\mu_{\rm F}$ factorization scale of $\mathcal{O}(Q^2)$, partons=quarks,gluons)

QFT: in higher orders

- ultraviolet singularities (renormalization of coupling and mass $\mu_{\rm R}$)
- infrared singularities (redefinition of observables)

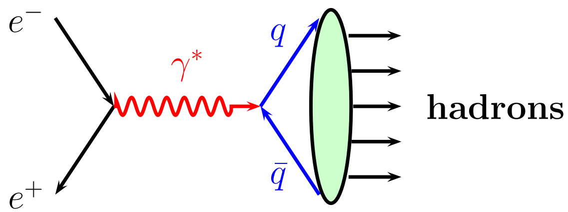
(e.g. from emission of (almost) collinear or soft gluons)

$\mu_{\rm F}$ - defines separation of short-distance from long-distance effects
i.e. any propagator that is off-shell by a scale $> \mu_{\rm F}^2$ is considered as short-range effect, scales $\leq \mu_{\rm F}^2$ as long range

hard subprocess: calculable in pert. theory, infrared save,
independent of the hadrons, depends on $\mu_{\rm F}$

soft hadr. matrix elem.: infrared singular, is specific to the hadrons,
is universal, i.e. does not depend on particular hard process
depends on $\mu_{\rm F}$ (evolution)

example: $e^+e^- \to \gamma^* \to q\overline{q} \to \text{hadrons}$ at large s

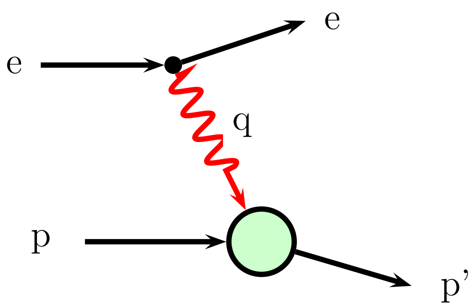


$e^+e^- \to q\overline{q}$ hard (QED)
$q\overline{q} \to \text{hadrons}$ soft

for a number of processes factorization has been rigorously shown to hold
$e^+e^- \to \text{hadrons}$, $ep \to e'X$, $AB \to e^+e^-X$, F_π, $F_{\pi\gamma}$, DVCS, ...
for others still a hypothesis (often in very good agreement with experiment)
e.g. $AB \to HX$, $AB \to \text{jets}$, F_p,....

Inelastic ep scattering

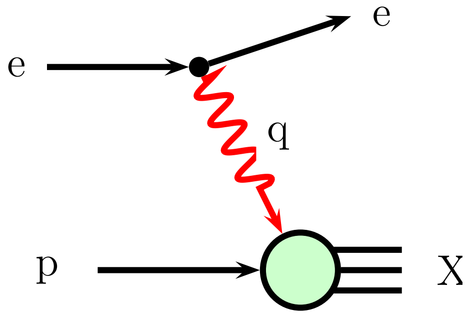
elastic - form factors $[\tau = -q^2/(4m^2)]$



$$\frac{d\sigma_L}{d\Omega} = \frac{d\sigma_{\rm Mott}}{d\Omega}\left\{\frac{G_E^2 + \tau G_M^2}{1+\tau} - 2\tau G_M^2 \tan^2\theta/2\right\}$$

Hoftadter et al (56), Nobel prize 1961

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \qquad F_2 = \frac{G_M - G_E}{1+\tau}$$



inelastic - structure functions

$q = k' - k; \quad Q^2 = -q^2 > 0$

$\nu = E_L - E'_L = p \cdot q/m$

$x_{\rm Bj} = Q^2/(2p\cdot q); \quad 0 \le x_{\rm Bj} \le 1$

$$\frac{d^2\sigma_L}{dQ^2 d\nu} = \frac{4\pi\alpha_{\rm em}^2 E'}{mEQ^4}\left[2\sin^2\theta/2\, W_1 + \cos^2\theta/2\, W_2\right]$$

Bjorken limit

Bjorken limit: $Q^2, \nu \to \infty \quad , x_{\rm Bj} fixed$

$$\lim_{\rm Bj} mW_1(\nu, Q^2) = F_1(x_{\rm Bj}) \qquad \lim_{\rm Bj} \nu W_2(\nu, Q^2) = F_2(x_{\rm Bj})$$

scaling with finite F_i

Friedman-Kendall-Taylor *et al* (72), Nobel prize 1990

scaling already at low Q^2 early scaling parton model

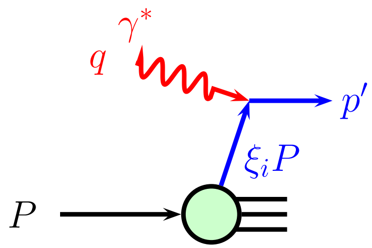
more precise measurements Chan et al (75)

scaling violations $F_i(x_{\rm Bj}, Q^2)$ QCD

Interpretation of scaling

scaling with finite limits is evidence for elastic electron scattering off point-like constituents (partons)

- nucleon at rest - partons possess isotrope momentum distribution (rotational symmetry) $\sum \mathbf{p}_i = 0$ $\Delta p = 1/\Delta x \simeq 200\mathrm{MeV}$
- boost to frame with large momentum P of proton (IMF)
  $\mathbf{p}_{\perp i}/P \ll 1$ neglect collinear appr.
  neglect binding energy too, treat partons as quasi free
- $p_i = \xi_i P$, $0 < \xi_i < 1$ momentum fraction (IMF: $\xi_i = p_i^+/P^+$)



mass-shell condition

$$\frac{d^3p'}{2E'}\delta(p' - q - \xi_i P) = \delta(Q^2 - \xi_i 2P \cdot q)$$
$$= \frac{x_{\mathrm{Bj}}}{Q^2}\delta(\xi_i - x_{\mathrm{Bj}})$$

---

light-cone coordinates $a = (a_0, a_1, a_2, a_3) \Rightarrow [(a_0 + a_3)/\sqrt{2}, (a_0 - a_3)/\sqrt{2}, a_\perp]$

different types of partons may exist

$q_i(\xi)(\geq 0)$ number of partons of type i (with charge $e_i e_0$) with momentum fractions between ξ and $\xi + d\xi$ Feynman (69)

Consequences

- contribution to structure functions

$$2mW_1 = \sum_i e_i^2 \int_0^1 d\xi q_i(\xi)\delta(\xi - x_{\rm Bj}) = \sum_i e_i^2 q_i(x_{\rm Bj}),\ \nu W_2 = \sum_i e_i^2 x_{\rm Bj} q_i(x_{\rm Bj})$$

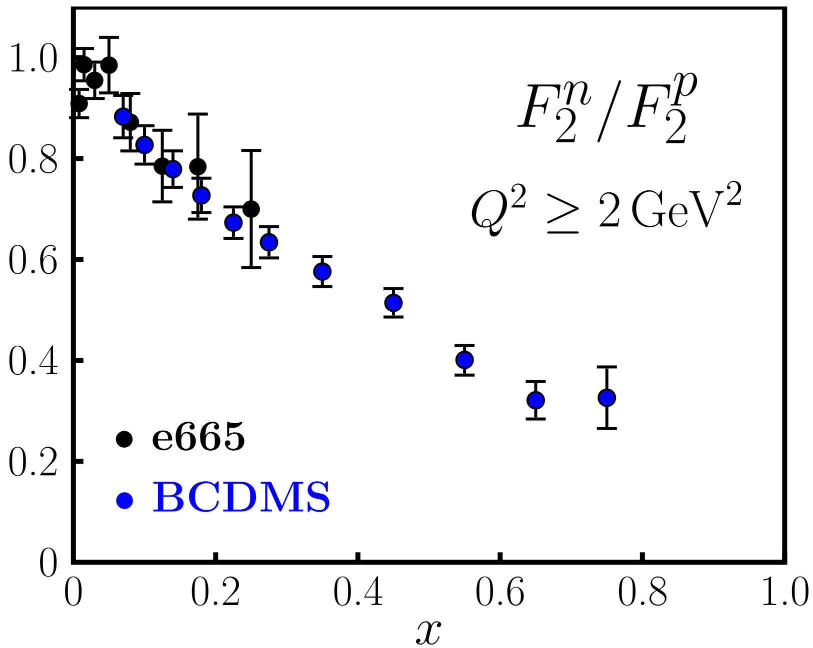
  only partons with $\xi = x_{\rm Bj}$ contribute at fixed Q^2, ν

- structure fcts. reveal scaling $F_1(x) = 1/2 \sum e_i^2 q_i(x)$
  $F_2(x) = 2xF_1(x)$ Callan-Gross relation characteristic of spin 1/2

- partons as quarks (isospin symmetry $u_p = d_n$, $d_p = u_n$, $s_p = s_n$)
  $1/xF_2^{ep}(x) = 4/9[u(x) + \overline{u}(x)] + 1/9[d(x) + \overline{d}(x)] + 1/9[s(x) + \overline{s}(x)] + \cdots$
  $1/xF_2^{en}(x) = 4/9[d(x) + \overline{d}(x)] + 1/9[u(x) + \overline{u}(x)] + 1/9[s(x) + \overline{s}(x)] + \cdots$

Nachtmann inequality $\frac{1}{4} \leq \frac{F_2^{en}(x)}{F_2^{ep}(x)} \leq 4$

dominance of $u + \overline{u}$ $d + \overline{d}$



exp: - dominance of u (d) in proton (neutron) at large x

- $x \to 0$ many types of partons contribute
- SU(3)$_F$ symmetric PDFs $F_2^{en}/F_2^{ep} = 1$

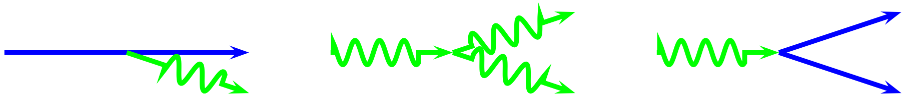
- how many quarks are in the proton?
  $\int_{x_0}^{1} F_2^{ep} dx/x = \sum e_i^2 \int q_i(x) dx = \sum e_i^2 n_i$
  integral seems to diverge HERA: $x_0 = 10^{-4} \Longrightarrow n = 12$

- does sea contribute equally to proton and neutron?
  Gottfried sum rule $u_v = u - \overline{u} \quad d_v = d - \overline{d}$ (definition)
  $1/x(F_2^{ep} - F_2^{en}) = 1/3[u - d + \overline{u} - \overline{d}] = 1/3[u_v - d_v] + 2/3[\overline{u} - \overline{d}]$
  $\int_0^1 dx/x(F_2^{ep} - F_2^{en}) = 1/3 + 2/3(n_{\overline{u}} - n_{\overline{d}})$
  integral seems to exist exp: $0.24 \pm 0.016 \Longrightarrow n_{\overline{u}} - n_{\overline{d}} \simeq -0.14$

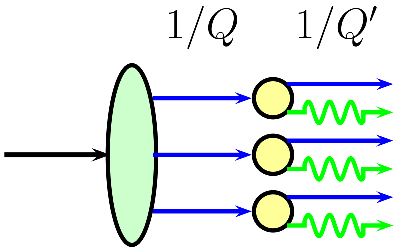
- momentum sum rule $xq_i(x)$ momentum distr. of type i partons
  $F = \int_0^1 dx x \left[u + \overline{u} + d + \overline{d} + s + \overline{s}\right]$ total momentum carried by charged partons (i.e. quarks) exp: $F \simeq 0.5$ at $10\,\mathrm{GeV}^2$
  $\Longrightarrow$ there are uncharged partons in the proton as well: gluons

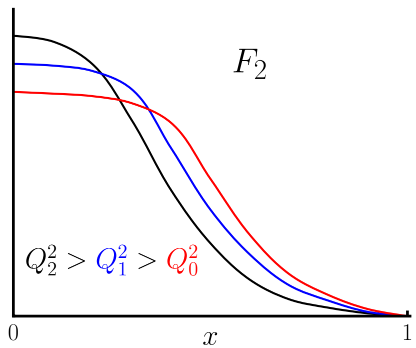
Evolution

QFT: due to splitting processes - a particle is always surrounded by a cloud of other particles (with strong fluctuations)



What one sees in an experiment depends on resolution
DIS: resolution set by wave length of virtual photon $1/Q$
with increasing Q one sees more (effective) constituents - with different PDFs
$F_2(x, Q^2) = x \sum_i e_i^2 q_i(x, Q^2)$ scaling violations





$Q < Q'$

evolution is calculable within pert. theory (in contrast to PDFs at Q_0)

DGLAP equation

- change of PDFs $\propto \alpha_\mathrm{s}$
- change of $q(x)$ only depends on $q(y)$ with $x \leq y$ (mom. distr. over larger number)
- change of q can only depend on ratios of momenta (quark masses neglected)

$$\frac{\partial q_i(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_\mathrm{s}}{2\pi}\int_x^1 \frac{dy}{y}\left[\, q_i(y,Q^2)\; P_{qq}(x/y) + g(y,Q^2) P_{qg}(x/y)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_\mathrm{s}}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j q_j(y,Q^2) P_{gq}(x/y) + g(y,Q^2) P_{gg}(x/y)\right]$$

DGLAP equation continued

splitting function P_{ij} represent leading $\ln Q^2$ of parton cross sections ($\mu_{\rm F} = Q$) (DIS: $\gamma^* q \to qg$, $\gamma^* g \to q\overline{q}$, $\gamma^* g \to q\overline{q}g$)

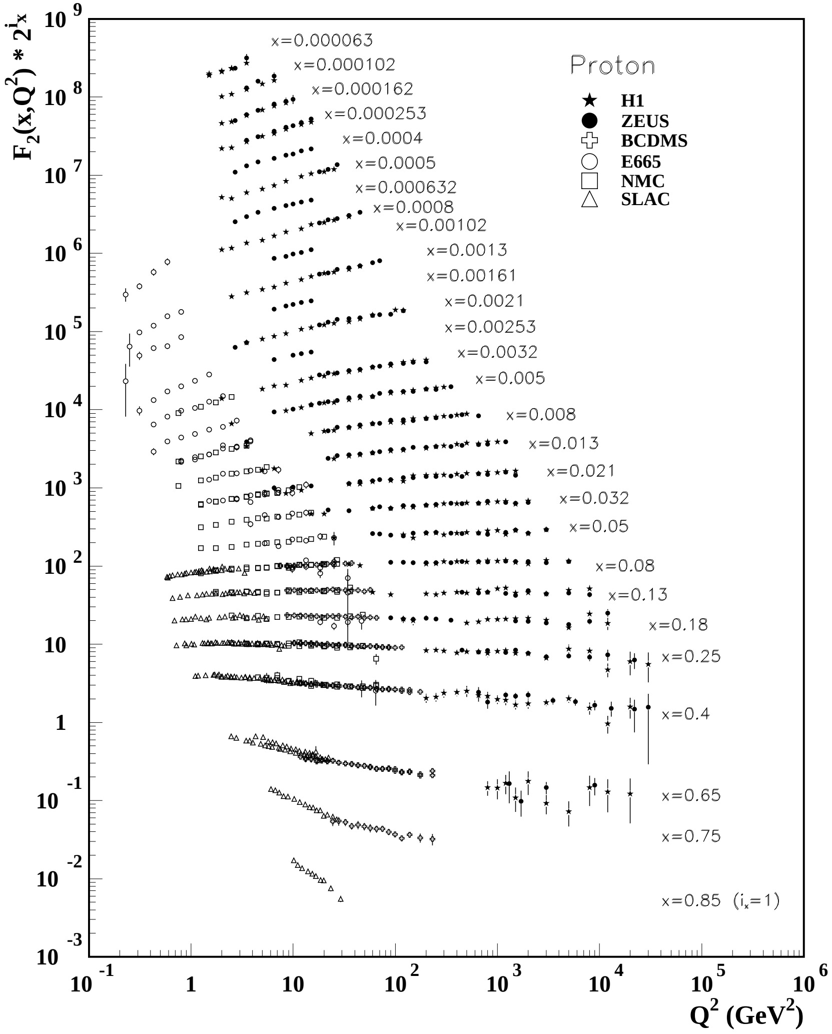
$$P_{qq}(x) = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x))\right] \qquad P_{gq}(x) = \frac{4}{3}\frac{1+(1-x)^2}{x}$$

$$P_{gg}(x) = 6\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) + (\frac{11}{12} - \frac{n_f}{18})\delta(1-x)\right]$$

$$P_{qg}(x) = \frac{1}{2}\left[x^2 + (1-x)^2\right] \qquad \int dx f(x)\frac{1}{(1-x)_+} = \int_0^1 dx\frac{f(x)-f(1)}{1-x}$$

SU(3)$_F$: $q_i^{NS} = q_i - \overline{q}_i$ no mixture with gluons $\qquad q^S = \sum_i(q_i + \overline{q}_i)$ mixes with gluons

Scaling violation in F_2



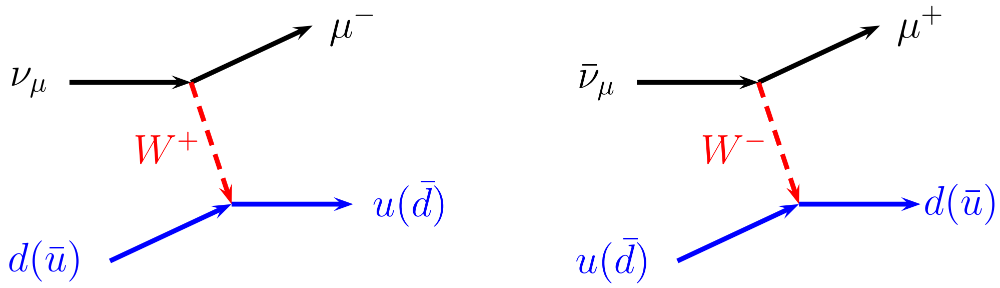
taken from PDG

DIS with neutrinos

weak interaction

$\nu_\mu N \to \mu^- X$ and $\bar{\nu}_\mu N \to \mu^+ X$ $\qquad$ $W_1^{\nu,\bar{\nu}}$, $W_2^{\nu,\bar{\nu}}$ and $\pm W_3^{\nu,\bar{\nu}}$

$$lim_{\rm Bj} \nu W_3(\nu, Q^2) = -F_3(x_{\rm Bj})$$



$+(s,c)$ and flavor mixing

below charm threshold

$1/xF_2^\nu(x) \sim 2d(x) + 2\overline{u}(x)$ $\qquad$ $1/xF_2^{\overline{\nu}}(x) \sim 2u(x) + 2\overline{d}(x)$

$1/xF_3^\nu(x) \sim 2d(x) - 2\overline{u}(x)$ $\qquad$ $1/xF_2^{\overline{\nu}}(x) \sim 2u(x) - 2\overline{d}(x)$

Parton Distributions

extraction of quark PDFs from DIS eN and νN scattering (and some other inclusive reactions in order to improve the flavor separation)

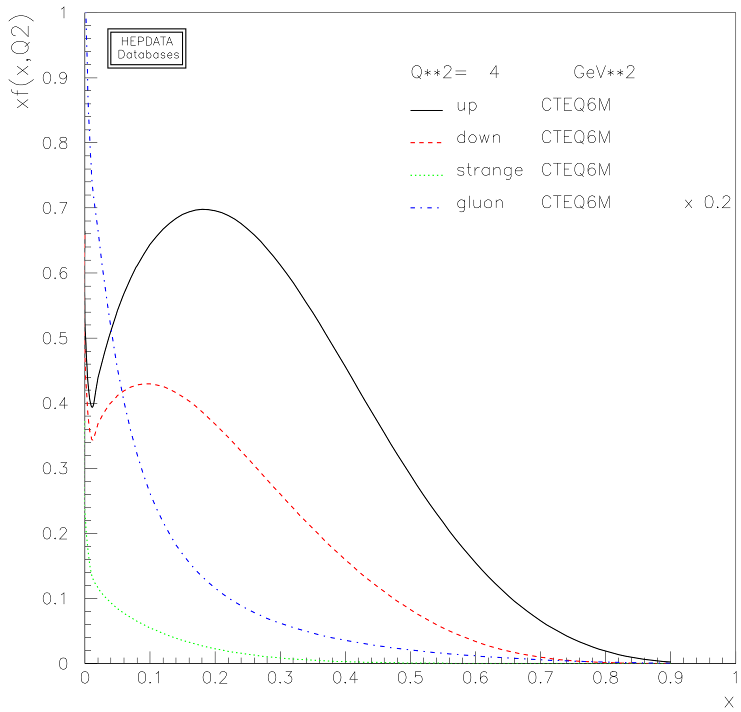
determination of $g(x)$ with the help of DGLAP (evolution with Q^2)

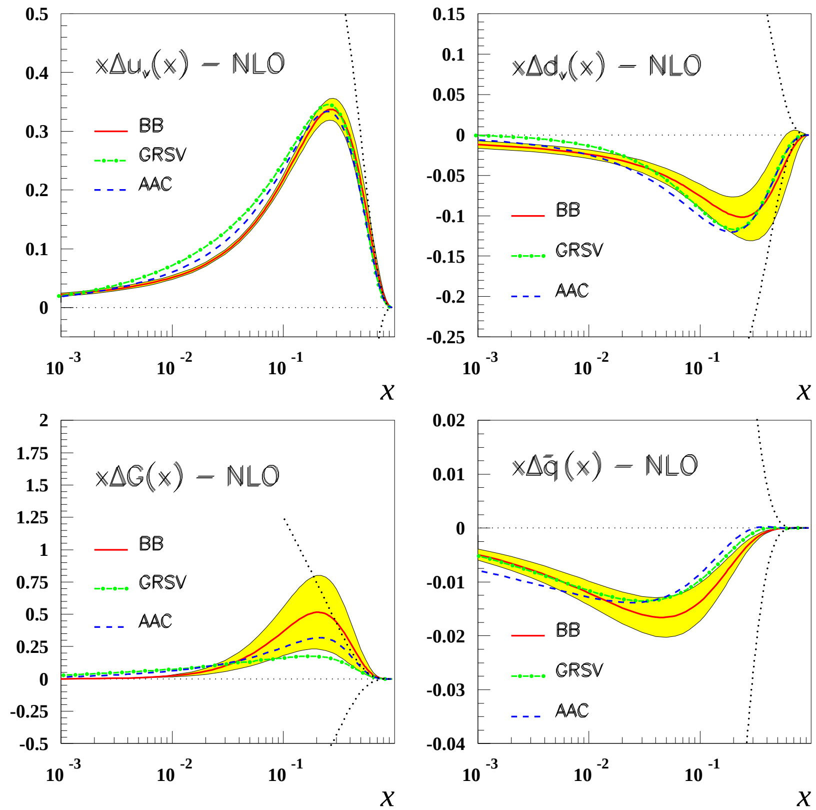
Polarized DIS: Δq, Δg $\qquad (q(\Delta q) = q(\rightarrow) \pm q(\leftarrow)\,, \quad |\Delta q| \leq q)$

PDFs describe longitudinal momentum distr. of partons within proton (IMF)

30 years of experimental (SLAC, CERN, HERA, FNAL, JLab)
and theoretical (Barger-Phillips (74), GRV, CTEQ, MRST, ...)
effort has lead to a fair knowledge of the PDFs
(although not perfect, e.g. $x \to 0, 1$, g, Δg)

quark PDFs





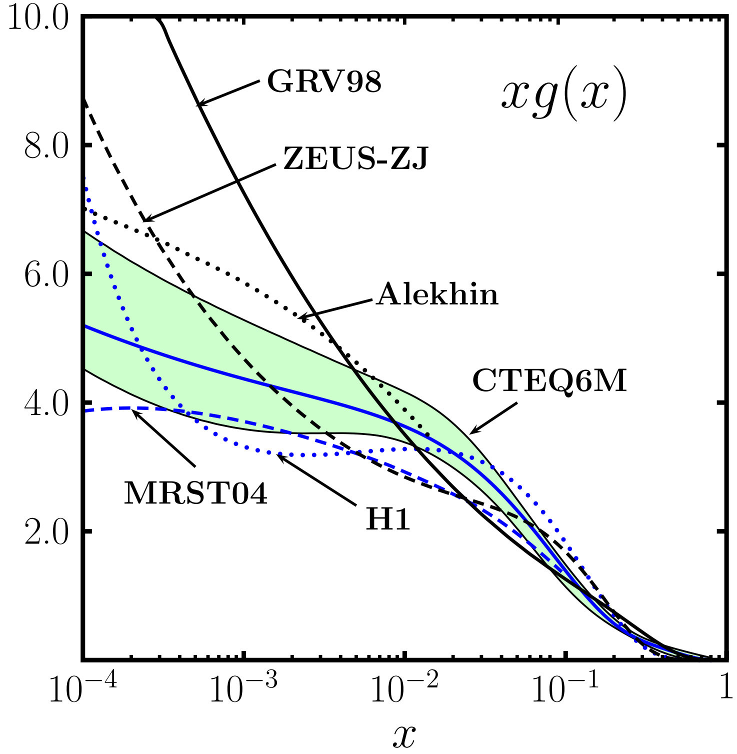
$Q^2 = 4\,\mathrm{GeV}^2$

from Bluemlein-Boettcher (02)

dotted line: bound $|\Delta q| \leq 2q$

SU(3)$_F$ symmetric sea assumed

What do we know about the gluon PDF?

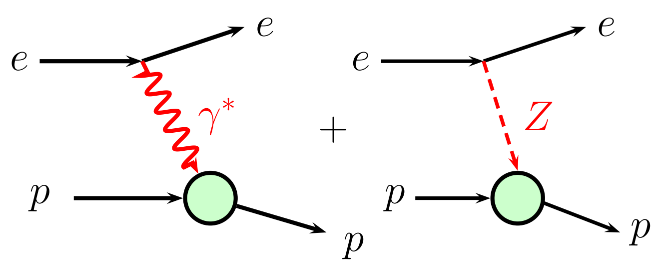


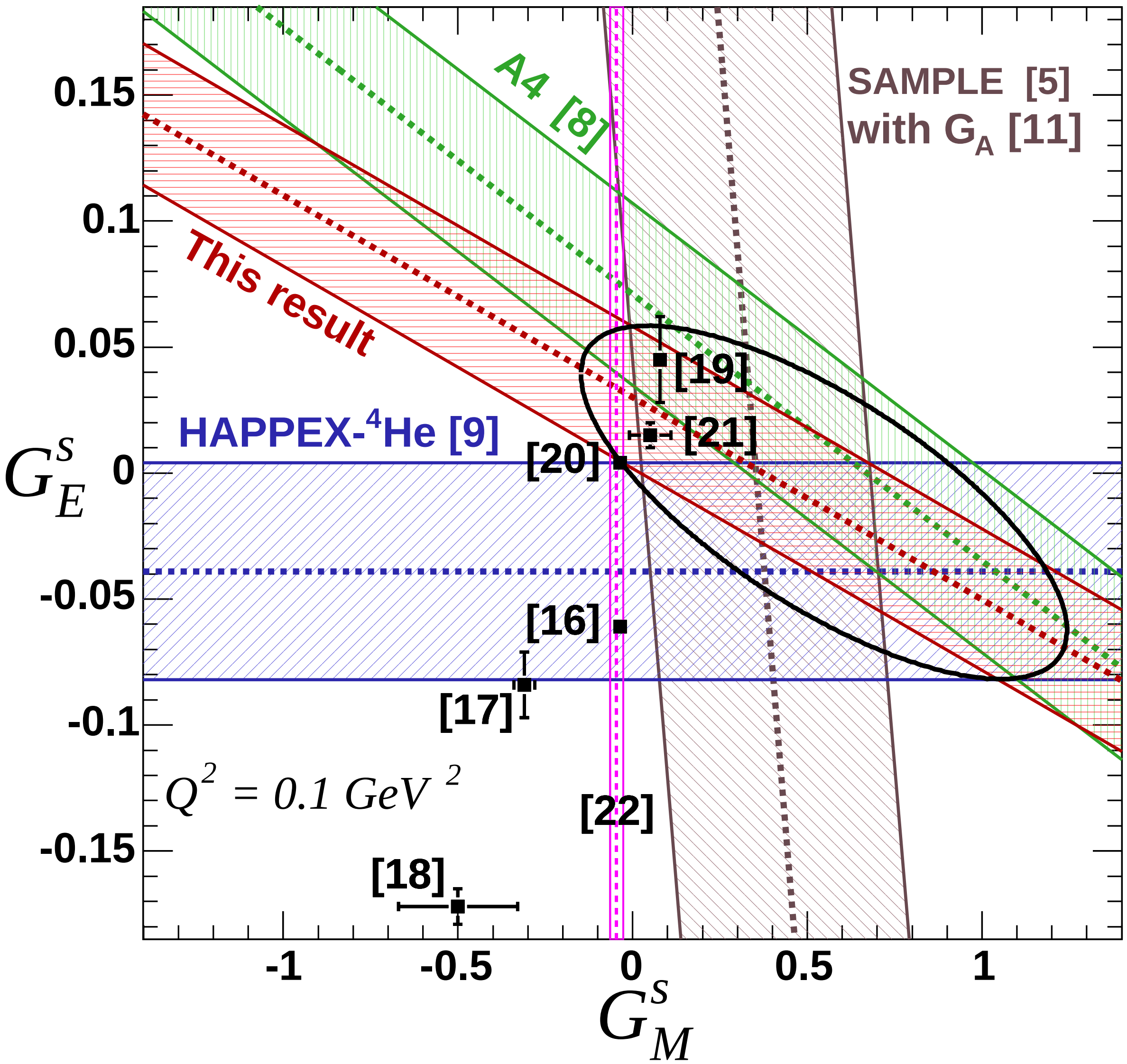
not too well constrained in region $\simeq 10^{-2}$ $\quad\quad Q^2 = 4\,\mathrm{GeV}^2$

$s(x) \neq \overline{s}(x)$?

there is no net strangeness in the proton $\Longrightarrow \int_0^1 dx[s(x) - \overline{s}(x)] = n_s - n_{\overline{s}} = 0$
CTEQ PDFs: weak indication for $s(x) \neq \overline{s}(x)$

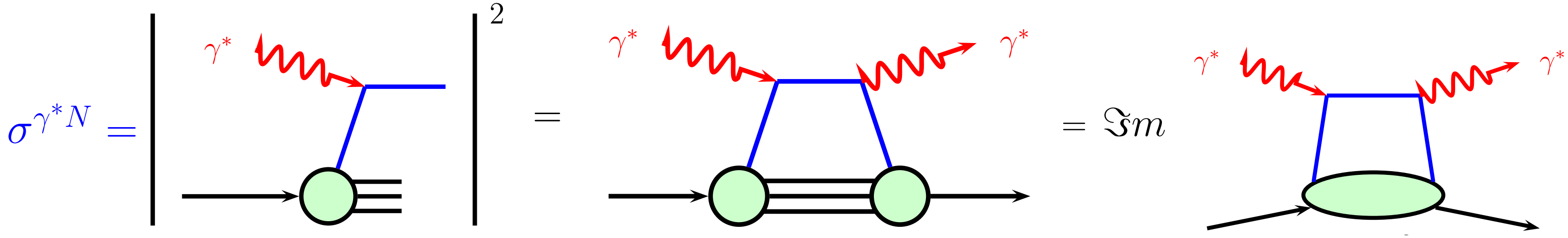
strangeness form factor (g0, HAPPEX, A4, SAMPLE)
$G^a_{E,M} \propto q^a - \overline{q}^a$ (see lecture 2)
ep scattering with long. pol. electrons $A^{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$ parity violation
measures interference between elm. FF and strange ones
data not yet conclusive but probably $s - \overline{s}$ small





taken from HAPPEX 05

Total cross section for absorption of virtual photons by unpolarized protons



optical theorem

$$\sum_n | \langle 1 \ldots n | T | \gamma^* \rangle |^2 = 2 \Im m \langle \gamma^* p | T(\theta = 0) | \gamma^* p \rangle = \sigma^{\gamma * N}$$

cross section for fixed helicity of photon

$\sigma_T = 1/2(\sigma_+ + \sigma_-) = 2mW_1\sigma_0 \qquad \sigma_L = 2m[-W_1 + W_2(1 + Q^2/(4m^2 x_{\mathrm{Bj}}^2))]\sigma_0$

$r = \sigma_L/\sigma_T = W_2/W_1(1 + Q^2/(4m^2 x_{\mathrm{Bj}}^2)) - 1$

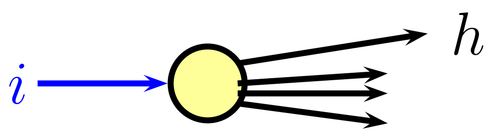
parton approach $r = 4m^2 x_{\mathrm{Bj}}^2/Q^2 \to 0$ for $Q^2 \to \infty$

in agreement with experiment

Fragmentation functions

in hard inclusice processes: sharply collimated jets of particles in final state

single particle spectra described by



fragmentation fct $\quad z = p_h^+/k^+$

$D_i^h(z)$ probability that a hadron h with mom. fraction between z and $z + dz$ is emitted by parton i

satisfy same evolution eq. as the PDFs $\quad \Longrightarrow D_i^h(z, Q^2)$

momentum conservation: $\quad \sum_h \int_0^1 dz z D_i^h(z) = 1$

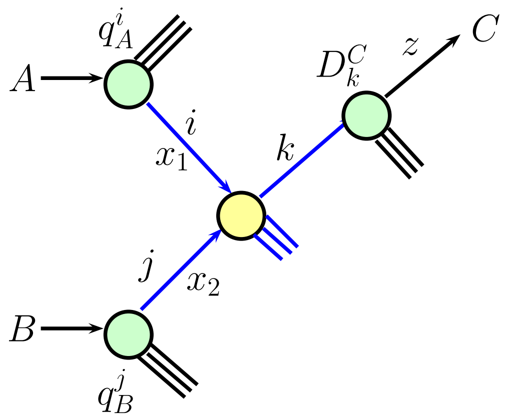
e.g. in $e^+e^- \to q\bar{q}$: $\quad \sum_h \int_0^1 dz [D_i^h(z) + D_{\bar{i}}^h(z)] = 1$

Applications

PDFs (and frag. fcts) are input to calculations of other hard inclusive processes

QCD gets predictive power

master formula (to leading-twist order or collinear appr.)



$\sigma(AB \to CX)$ and $\hat{\sigma}(q_i q_j \to q_k X)$

$$E_C \frac{d\sigma}{d^3 p_c} = \sum_{i,j,k} \int dx_1 dx_2 \frac{dz}{z^2} q_A^i(x_1) q_B^j(x_2) E_k \frac{d\hat{\sigma}}{d^3 k} D_k^C(z)$$

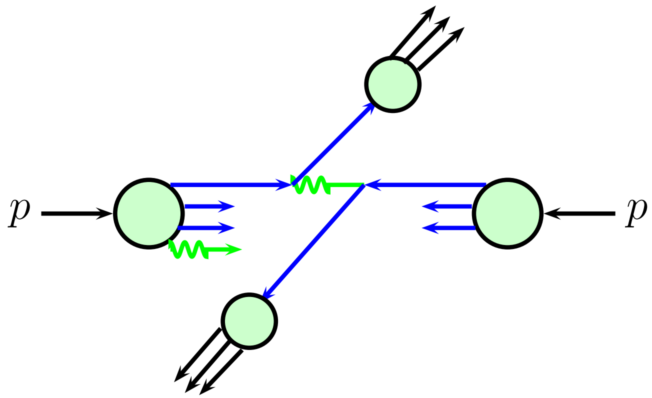
holds also if A, B or C is elementary

e.g. $\quad q_A^i = \delta_{iA}\, \delta(1 - x_1)$

if proton PDFs known ($\overline{p}$: $q \leftrightarrow \overline{q}$)

- $pp(\overline{p}) \to \pi X$
- $pp(\overline{p}) \to \gamma X$ — prompt photon prod.
- $pp(\overline{p}) \to e^+ e^- X$ — Drell-Yan process
- $pp(\overline{p}) \to \text{jets}$ — "QCD background" understanding important for discovery of new physics at LHC

Jet cross section at the TEVATRON



reconstruction of jet, i.e. the parton subprocesses to lowest order

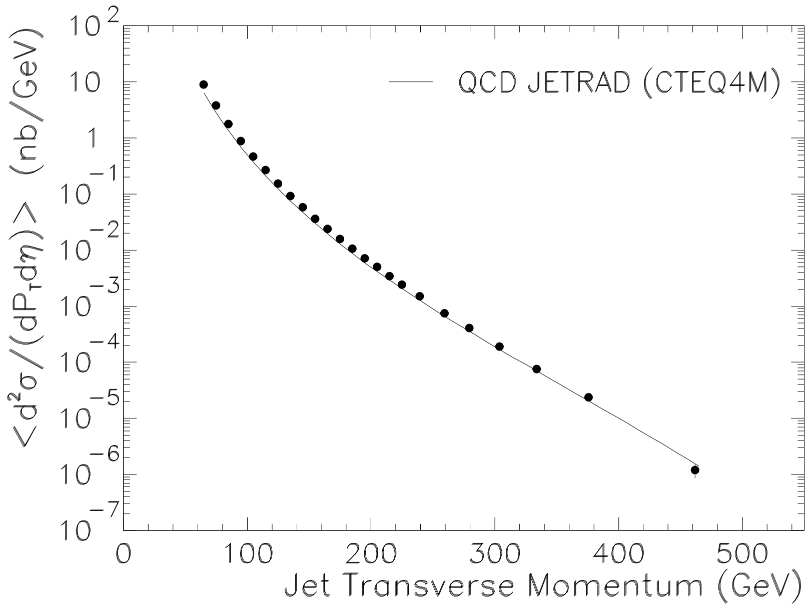
$qq \longrightarrow qq, \quad qg \longrightarrow qg, \quad gg \longrightarrow gg,$

$q\overline{q} \rightarrow gg, \ldots$

4-jet structure

today: NLO (5 jets)

D0 results

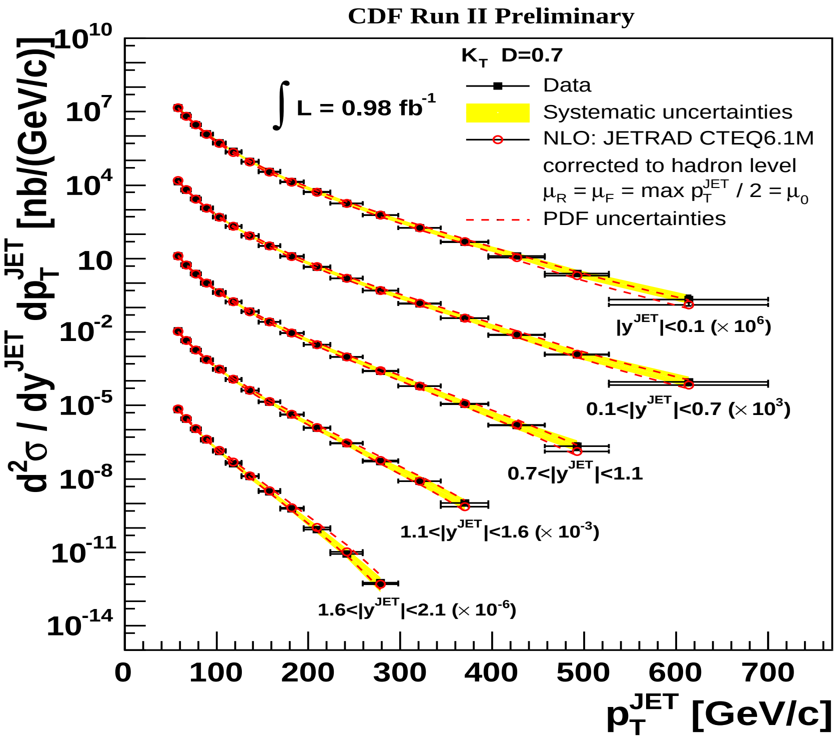


Tevatron $\sqrt{s} = 1.8\,\mathrm{TeV}$

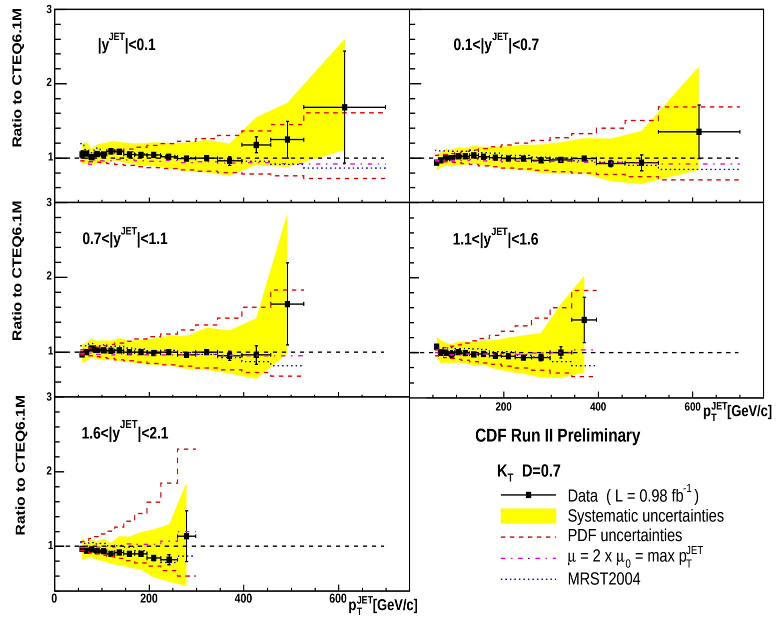
pseudorapidity $|\eta| = |\ln[\tan\theta/2]| < 0.5$

NLO QCD prediction using CTEQ4M

CDF results

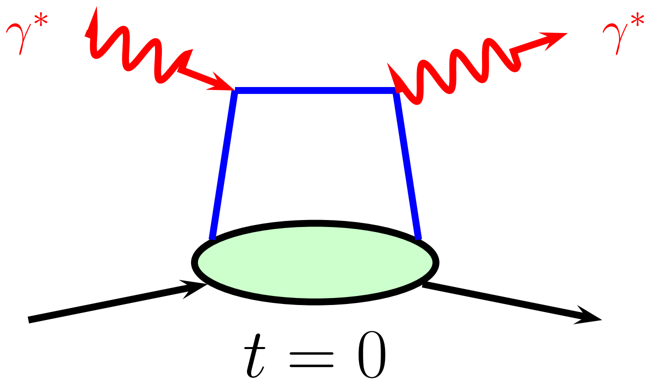


CDF Run II Preliminary
K_T D=0.7
$\int L = 0.98\ fb^{-1}$
Data
Systematic uncertainties
NLO: JETRAD CTEQ6.1M
corrected to hadron level
$\mu_R = \mu_F = \max p_T^{JET} / 2 = \mu_0$
PDF uncertainties
$|y^{JET}|<0.1$ ($\times 10^6$)
$0.1<|y^{JET}|<0.7$ ($\times 10^3$)
$0.7<|y^{JET}|<1.1$
$1.1<|y^{JET}|<1.6$ ($\times 10^{-3}$)
$1.6<|y^{JET}|<2.1$ ($\times 10^{-6}$)
$d^2\sigma / dy^{JET} dp_T^{JET}$ [nb/(GeV/c)]
p_T^{JET} [GeV/c]



Ratio to CTEQ6.1M
$|y^{JET}|<0.1$
$0.1<|y^{JET}|<0.7$
$0.7<|y^{JET}|<1.1$
$1.1<|y^{JET}|<1.6$
$1.6<|y^{JET}|<2.1$
p_T^{JET}[GeV/c]
CDF Run II Preliminary
K_T D=0.7
Data (L = 0.98 fb^{-1})
Systematic uncertainties
PDF uncertainties
$\mu = 2 \times \mu_0 = \max p_T^{JET}$
MRST2004

Generalization

$\Im m$ 

Only forward imaginary part of graph realized in nature?

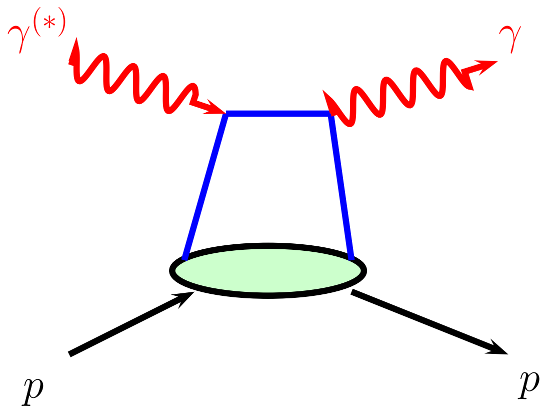
would be a bad feature of the theory

what about

- real part at $t = 0$?
- non-forward directions ($t \neq 0$)?
- unequal virtualities of the photons?

$\Longrightarrow$ hard exclusive reactions and generalized parton distributions (GPDs)

Handbag factorization in excl. reactions



only one active parton

(others are spectators)

hard process: $\gamma^{(*)}q \to \gamma q$

soft physics: GPDs

two classes of hard exclusive reactions:

DEEP VIRTUAL $\quad Q^2$ large $\quad -t/Q^2 \ll 1$

WIDE-ANGLE $\quad -t(-u)$ large $\quad Q^2/(-t) \leq 1$