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Low-x gluon density and rescattering effects

F. Hautmann

I. Parton distributions at $x \ll 1$

II. Parton picture, s-channel picture,
and a "dictionary" to connect them

III. Power corrections from rescattering

1. Motivation

Parton distributions at small momentum fraction $x \leftrightarrow$ very high energy scattering

Short-distance structure of protons and nuclei will be probed with the LHC in the new TeV energy range

- Are partonic degrees of freedom appropriate in the high energy limit?

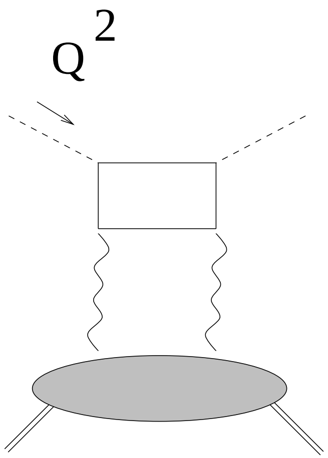
$\diamondsuit$ This talk's point of view: push parton framework into the very small x region

$\triangleright$ logarithmic resummations of perturbation theory

$\triangleright$ subleading-power corrections enhanced for $x \longrightarrow 0$

2. Determination of the gluon distribution at $x \ll 1$ from DIS

[MRST, CTEQ, Alekhin]



- $F_2 \sim \Sigma$ (flavor-singlet quark)
- $\dot{F}_2$ driven by gluon

$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Sigma \\ G\end{pmatrix} = \begin{pmatrix}P_{qq} & P_{qg} \\ P_{gq} & P_{gg}\end{pmatrix} \otimes \begin{pmatrix}\Sigma \\ G\end{pmatrix}$$

$$\Rightarrow \dot{F}_2 \sim \dot{\Sigma} \sim P_{qg} \otimes G \;\left[1 + \mathcal{O}(\Lambda^2/Q^2)\right] + \text{ quark term}$$

▷ very sensitive to higher-loop $\ln(1/x)$ corrections to P_{qg} Catani & H

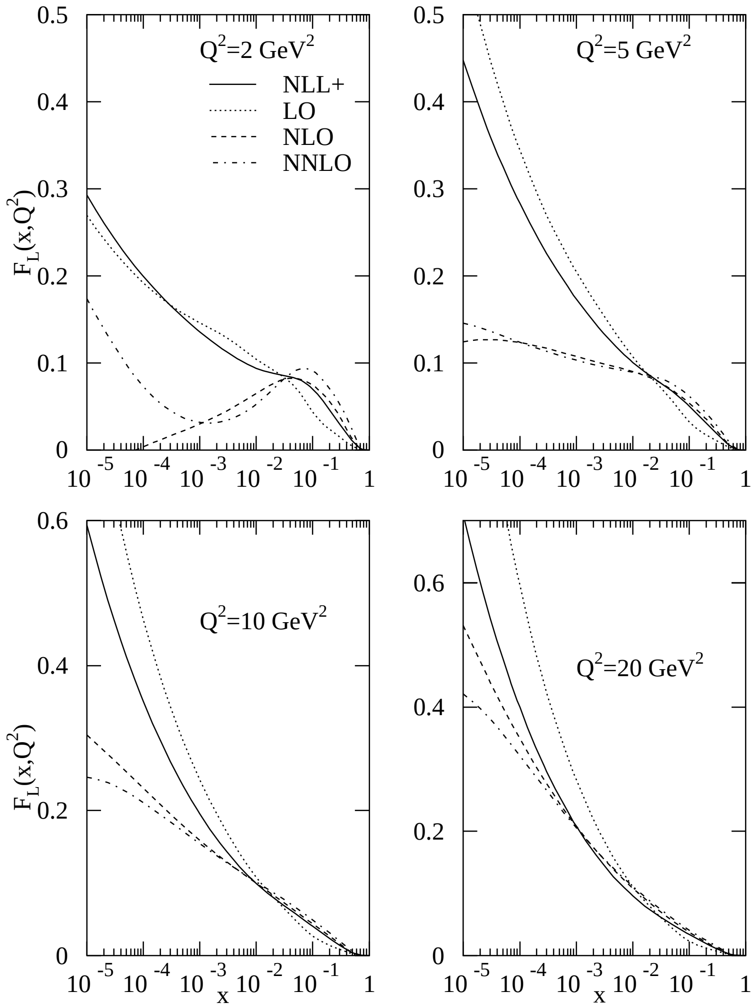
▷ further: $\ln(1/x)$ corrections through gluon evolution:

$$\dot{G} = P_{gg} \otimes G + \text{quark term}$$ Ciafaloni et al; Altarelli et al

↑ BFKL, NL-BFKL ↑ P_{gq} (not yet NL)

▷ comparable logarithmic effects from Wilson coefficient functions

Example: longitudinal F_L including resummation



Thorne & White, presented at the

"HERA and the LHC" Workshop, March 2007

- includes NL $\ln(1/x)$ resummation (evolution [Fadin & Lipatov, Camici & Ciafaloni] and coefficient function [Catani & H])

- instability of fixed-order results improved by resummation

- Physical interpretation: gluons radiated over large rapidity intervals with no particular ordering in p_t

- Resummation signals onset of effects beyond perturbation theory through singularity

$$R_\omega(\alpha_s) \sim 1/\sqrt{1/2 - \gamma_\omega(\alpha_s)}, \ \gamma_\omega \rightarrow 1/2$$

- Data used to extract G for $x < 10^{-2}$ do not have very high Q^2

$\Rightarrow$ $1/Q^2$ terms with $x \rightarrow 0$ enhancement?

$$\dot{F}_2 \sim P_{qg} \otimes G \ \ [1 + \delta] \quad , \quad \delta \simeq \sum_{k \geq 1} a_k \ (\alpha_s \ \frac{1}{x^\nu} \ \frac{\Lambda^2}{Q^2})^k$$

♢ correction δ arises from multi-parton correlation terms in the OPE:

$$F = C \otimes f + \frac{1}{Q^2} C^{(4)} \otimes f^{(4)} + \ldots$$

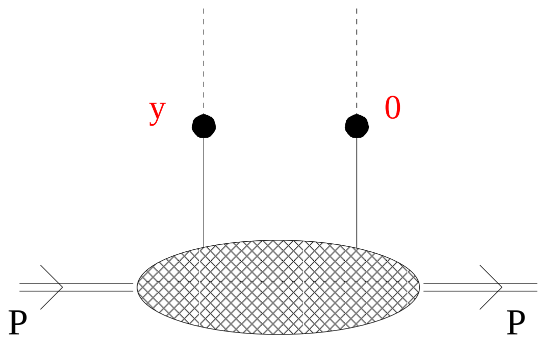
♢ can be produced from graphs with multiple gluon scatterings

$\Rightarrow$ use results from s-channel methods?

3. An approach to relate parton picture and s-channel picture

Soper & H, hep-ph/0702077

Parton distribution function for quarks:



$$z^{\pm} = \frac{z^0 \pm z^3}{\sqrt{2}}$$

$$P = (P^+, P^-, P_\perp) = \left(P^+, \frac{M_p^2}{2P^+}, \mathbf{0}\right)$$

$$f_q(x,\mu) = \frac{1}{4\pi}\left(\frac{1}{2}\sum_s\right)\int dy^- e^{ixP^+y^-}\langle P,s|\bar{\psi}(0)Q(0)\gamma^+Q^\dagger(y^-)\psi(0,y^-,\mathbf{0})|P,s\rangle_c$$

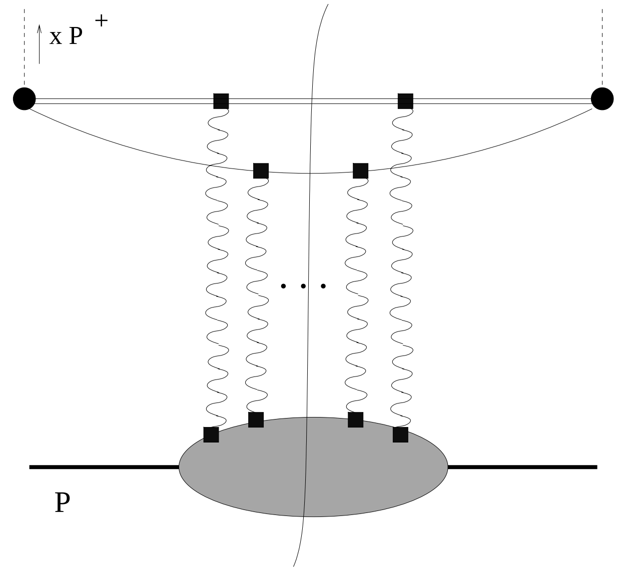
$$Q^\dagger(y^-) = \mathcal{P}\exp\left\{-ig\int_{y^-}^{+\infty} dz^- A_a^+(0,z^-,\mathbf{0})t_a\right\}$$

- ♢ $Q^\dagger(y^-)$ can be thought of as creating an eikonal line in minus direction, starting at position y^-
- ♢ Operator product is UV divergent. $\rightarrow$ $\overline{\mathrm{MS}}$ subtraction

s-channel picture: For $x \ll 1$ parton system created by operator is far outside the hadron

▷ The antiquark and the eikonal develop into a shower of partons with $k^- = (k_\perp^2 + k^2)/(2k^+) \sim m^2/(xP^+)$ very large ($m^2 \equiv (300 \text{ MeV})^2$)

▷ The "fast" partons travel a long distance in y^-, then scatter from the proton's color field. This consists of gluons with $k^+ \gg xP^+$, $k^- \ll m^2/(xP^+)$ ("slow" gluons)



▷ Treat this as an external field $\mathcal{A}^\mu(x)$. That is, gluons with $k^+ < x_c P^+$ are associated with "fast partons"; gluons with $k^+ > x_c P^+$ are included in $\mathcal{A}$.

s-channel representation for the quark distribution function

In this representation we obtain that the parton distribution function is given by convolution of a Wilson line correlator with a lightcone wavefunction:

$$x f_q(x,\mu) = \int d\boldsymbol{z} \int d\boldsymbol{b} \; u(\mu,\boldsymbol{z}) \; \Xi(\boldsymbol{z},\boldsymbol{b}),$$

where $\Xi(\boldsymbol{z},\boldsymbol{b}) = \int \frac{dP'^+}{(2\pi)2P'^+} \langle P' | \frac{1}{N_c} \, \mathrm{Tr}[1 - V^\dagger(\boldsymbol{b}+\boldsymbol{z}/2) V(\boldsymbol{b}-\boldsymbol{z}/2)] | P \rangle$

$$V(\boldsymbol{z}) = \mathcal{P} \exp \left\{ -ig \int_{-\infty}^{+\infty} dz^- \mathcal{A}_a^+(0,z^-,\boldsymbol{z}) t_a \right\}$$

and $u(\mu,\boldsymbol{z})$ is evaluated at one loop using $\overline{\mathrm{MS}}$ [Soper & H, hep-ph/0702077]

This representation allows one to

- relate s-channel calculations for structure functions to OPE factorization
- identify power correction from multiple scatterings (in high-energy approximation)

4. Power corrections from rescattering

$$\frac{dF_2}{d\ln Q^2} = \left(\frac{dF_2}{d\ln Q^2}\right)_{\rm LP} + \sum_{n=1}^{\infty} R_n \, \frac{\lambda^2(n)}{(Q^2)^n}$$

♢ R_n calculated to order α_s from lightcone wavefunctions

♢ λ^2 nonperturbative moments of matrix elements Ξ:

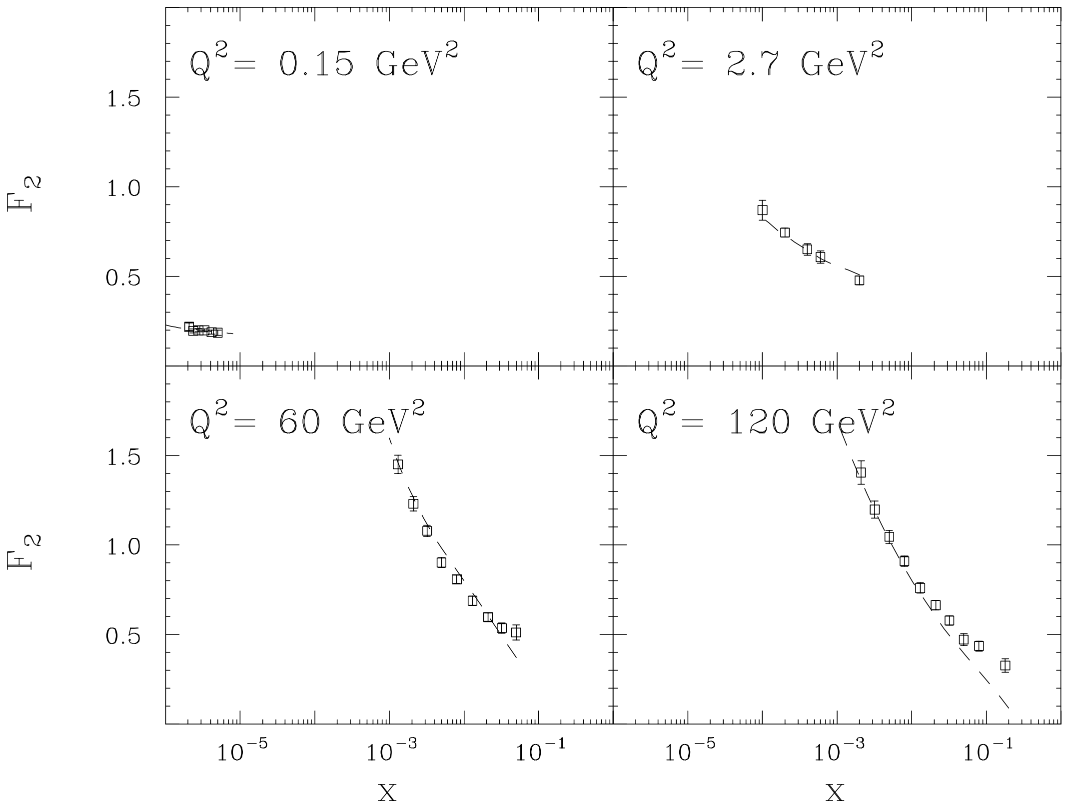
$$\lambda^2(-v) = \frac{1}{\Gamma(v)} \int \frac{d\boldsymbol{z}}{\pi \boldsymbol{z}^2} \, (\boldsymbol{z}^2)^{v-1} \int d\boldsymbol{b} \, \Xi(\boldsymbol{z}, \boldsymbol{b})$$

▷ Ξ related to gluon distribution by short-distance expansion $|\boldsymbol{z}| \to 0$

⇒ λ^2 parameterized in terms of factorization/renormalization scales ($\sim 1/|\boldsymbol{z}|$)
and fitted to data

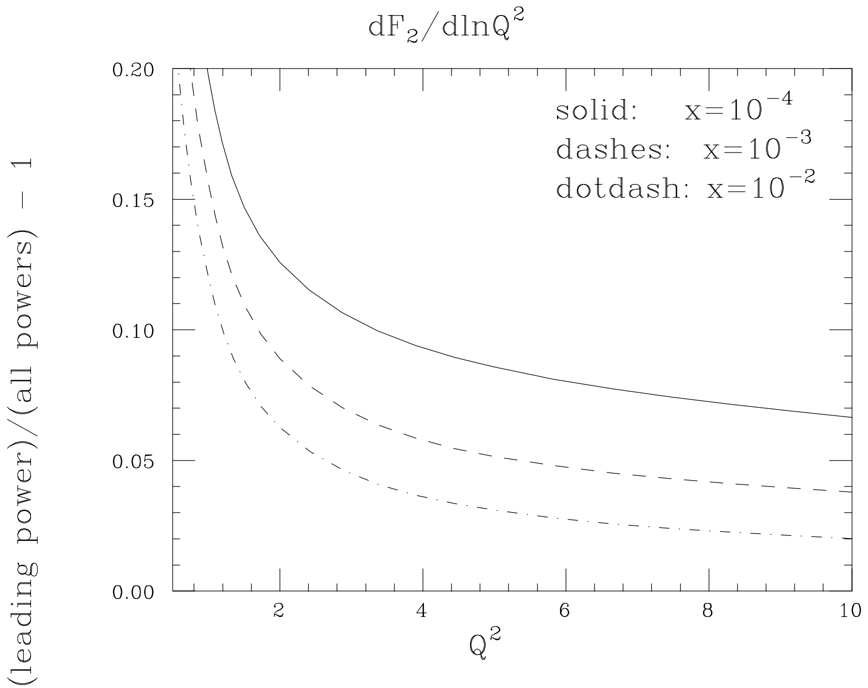
• any number of rescatterings contributes to fixed n
through eikonal operators in Ξ

Tune the factorization/renormalization scales, $\mu_f \sim c_1/|\boldsymbol{z}|$ and $\mu_r \sim c_2/|\boldsymbol{z}|$, to the F_2 data (ZEUS, EPJC2001):



- sensible description of data below $x \sim 10^{-2}$ for low and high Q^2
- physically natural choice of parameters in nonperturbative matrix elements

Using the values for the model parameters determined from data, compute the power correction to $dF_2/d\ln Q^2$:



- corrections negative and below 20 % for $x \gtrsim 10^{-4}$ and $Q^2 \gtrsim 1$ GeV^2

  $\Rightarrow$ power expansion not breaking down

- but: slow fall-off for medium Q^2 (e.g., $1/Q^\lambda$, $\lambda = 1.2$, in $1 \div 10$ GeV^2 for $x \simeq 10^{-3}$)

  $\Rightarrow$ correction ~ 10 % up to $Q^2 \simeq$ a few GeV^2 for $x \leq 10^{-3}$

$\diamondsuit$ differs from parameterizations of higher twist commonly used in global analyses

5. Discussion and conclusions

Approximate quark distribution function by

$$x f_q(x,\mu) = \frac{N_c}{3\pi^4} \int d\boldsymbol{b} \int d\boldsymbol{z}\ \theta(\boldsymbol{z}^2\mu^2 > a^2)\ \frac{\Xi(\boldsymbol{b},\boldsymbol{z})}{\boldsymbol{z}^4}$$

When is this reliable?

♢ renormalization cut $\boldsymbol{z} > a/\mu$; suppose μ such that $a/\mu \ll R_p$

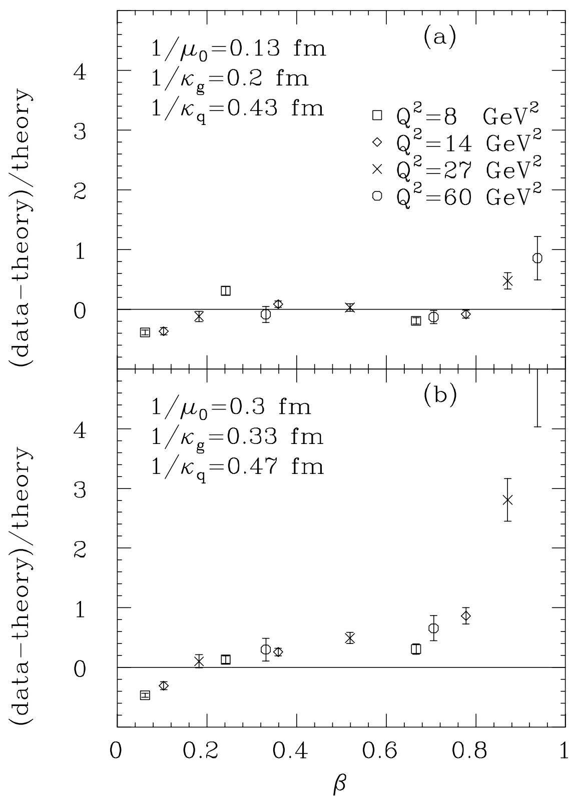
♢ integration extends to arbitrarily large $\boldsymbol{z}$, but once $\boldsymbol{z} > 1/Q_s(\boldsymbol{b})$ we have $\Xi(\boldsymbol{b},\boldsymbol{z}) \approx 1 \Rightarrow$ fast fall-off

- Q_s likely to be sizeable in the gluon sector
- lies at lower momenta for quarks

$\hookrightarrow$ e.g.: hard-diffractive data

▷ ZEUS data for diffractive $F_2^{(D)}$

▷ predictions based on diffractive parton distribution functions [Soper & H]



- top graph corresponds to $Q_s(\mathbf{0}, \text{fund.}) \simeq 0.65$ GeV ($Q_s \gtrsim 1$ GeV for adjoint)
- bottom graph (lower Q_s): shape disfavored by data

Prospects

• Methods to connect parton picture and s-channel picture
allow one to identify (certain classes of) power-suppressed contributions

• Possible impact of slow fall-off for medium Q^2 and $x \lesssim 10^{-3}$?
$\Rightarrow$ need firmer understanding of high-energy approximation

• Smaller corrections for F_T than for F_2? (measure F_L separately)

• Smaller corrections for NNLO partons?

• Effective Q_s larger for observables directly coupled to gluons:
e.g. $\rightarrow$ access rescattering effects in jet final states ?