Phenomenology with unintegrated parton showers

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Introduction

- Transversal momentum in DGLAP based Monte Carlo generators
  - Probabilistic interpretation of the splitting function
  - Sudakov form-factor - probability of no-emission
- Using relation between the scale and $z$ and $q_T$
- Using the on-shell condition for the emitted parton and generating azimuthal angle → full information about the momentum of the emitted parton
- Additional boosts and reshuffling to match the momentum
- Approach goes beyond the validity of approximation of the splitting functions
BFKL

- High energy factorisation
  - Multi-regge kinematics

\[ s_i \ll s_j \]

QCD virtual corrections

Reggeized gluon

\[ -i \frac{g^{\mu\nu}}{k^2} e^{\frac{N_c \alpha_s}{4\pi^2} \ln (k^2/s) \Delta y} \]
BFKL

- BFKL equation (for 0 momentum exchange) for gluon Green function

\[(\omega - 2\epsilon_R(-k_1^2))f(\omega, k_1, k_2, 0) = \delta^2(k_1 - k_2) + \frac{N_C\alpha_s}{\pi^2} \int d^2k' \frac{f(\omega, k', k_2, 0)}{(k' - k_1)^2}\]

V. S. Fadin, E. A. Kuraev, and L. N. Lipatov, Phys. Lett. B60, 50 (1975);
E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, Sov. Phys. JETP 44, 443 (1976);
E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, Sov. Phys. JETP 45, 199 (1977);
CCFM

- The CCFM equation
  - Accounts for low x physics
  - Coherence effects
  - Angular ordering
- The equation

\[
\mathcal{F}(x, k, q^2) = \mathcal{F}(x, k, q_0^2) + \int \frac{d^2 q'\, N_C \alpha_s}{q'^2} \frac{q_0^2}{\pi} + \int \mathcal{F}(x/z, k', q'^2)
\]

\[
1 - \frac{q_0}{q'} \int \frac{d z}{z} \mathcal{F}(x/z, k', q'^2) \left( \frac{\Delta_{NS}(k'^2, (z q')^2)}{z} + \frac{1}{1 - z} \right) \Delta_S(q'^2_0, (z q')^2)
\]

M. Ciafaloni, Nucl. Phys. B296, 49 (1988);
S. Catani, F. Fiorani, and G. Marchesini, Nucl. Phys. B336, 18 (1990);
Monte Carlo implementation

- Monte Carlo means random numbers
- Probabilistic interpretation of the kernel of the CCFM equation

\[
\mathcal{F}(x, k, q'^2) = \mathcal{F}(x, k, q'^2_0) + \int_{q'^2_0}^{q'^2} \frac{d^2q'}{q'^2} \frac{N_C \alpha_S}{\pi} \\
1 - \frac{q'^2_0}{q'^2} \int_x^{\frac{1}{z}} \mathcal{F}(x/z, k', q'^2) \left( \frac{\Delta_{NS}(k'^2, (zq')^2)}{z} + \frac{1}{1-z} \right) \Delta_s(q'^2_0, (zq')^2)
\]

Gluon splitting function - gives the probability of a gluon emission in a small scale interval

Sudakov form factor - gives the probability of gluon not being emitted
Monte Carlo implementation

- Generate splitting after splitting according to the probability distributions obtained from the kernel of the equation (BFKL or CCFM)
  - first find the new value of the scale using Sudakov form factor satisfying the ordering
  - then find the values of $z$ and $k_T$
- starting from some uPDF - **forward evolution** (implemented in Smallx)
- Inefficient

- **Backward evolution** more efficient
**CASCADE**

  - Backward evolution algorithm for initial state parton showers for
    - Exact kinematics in each step of the parton shower
    - No difference between parton shower evolved uPDF and CCFM evolved uPDF
    - Gluon chains
    - Valence quarks/Non-singlet uPDFs from one-loop CCFM equation
  - Final state parton showers by Pythia algorithm
  - Hadronisation of partons by the Lund String Model
  - Gluon uPDFs obtained from fits to HERA data
CASCADE

- The largest angle = the angle of the hard subprocess final state system

\[
\frac{|q_i|}{1 - z_i} > \frac{z_{i-1}|q_{i-1}|}{1 - z_{i-1}}
\]

1. \hspace{2cm} 2. \hspace{2cm} \ldots
Fitting uPDFs $F_2$

$$x A_0(x, k_T, q_0) = N \cdot x^{-B} \cdot (1 - x)^C \cdot (1 - Dx) \cdot \exp\left(-\frac{(k_T - \mu)^2}{2\sigma^2}\right)$$

Used in the CASCADE MC generator:

Evolve PDF according to the CCFM equation.

• First goal determine the $x$-dependence.

• Use the proton structure function (sigma reduced for positrons).

Latest combined measurement from H1 and ZEUS. (JHEP 1001:109 (2010))

Should be fairly insensitive to the $k_t$-dependent part of the gluon. Inclusive measurement with minimum restrictions on the hadronic final state.

Fitting program

Profit

“Dont care” about the rest
Fitting uPDFs $F_2$

$\chi^2/nd=2.2$

A. Bacchetta, H. Jung,
B. A. Knutsson, K. Kutak,
and F. von Samson-Himmelstjerna,
arxiv: 1001.4675

- possibility to use more exclusive observables more sensitive on $k_T$
Predictions for LHC physics

Forward jets - motivation

• Probes small-x parton densities

• Important signal for BFKL dynamics

• Extensive coverage of large rapidity regions at the LHC experiments (3<|η|<5 and -5.2>η>-6.6)
  – Possibility to study two jet correlations

Pt and rapidity spectra of forward jets

Forward jet
-3 < \eta < -5

- Different slopes of cross sections
- $k_T$ of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in $k_T$
- MPI only shift the jet rapidity cross section by a factor
Pt and rapidity spectra of central jets

Central jet

-2 < \eta < 2

Different slopes of cross sections

$k_T$ of incoming gluon allows for harder spectrum - CCFM parton showers not ordered in $k_T$

MPI only shift the jet rapidity cross section by a factor

Rapidity cross sections agree for central rapidity region
Z+QQbar - motivation

• Motivation
  – Well known properties of electroweak gauge bosons and quarks in the Standard Model - easy test of QCD
  – Background for Higgs production and beyond the Standard Model processes like SUSY particles production

• Gluon channel
  – $gg \rightarrow Z+Q+Q\bar{q}$
    • Fixed number of flavours scheme for heavy quarks
    • For light quarks we can rely on gluon dominance

• Formula for the cross section

$$d\sigma (pp \rightarrow q (W/Z) \bar{q} X) = \int \frac{d\alpha}{\alpha} \int \frac{d\phi_1}{2\pi} A(\alpha, \bar{q}_1^2, \mu^2) \times \int \frac{d\beta}{\beta} \int \frac{d\phi_2}{2\pi} A(\beta, \bar{q}_2^2, \mu^2) d\hat{\sigma} (g^* g^* \rightarrow q (W/Z) \bar{q})$$

Z+Q+Q\bar{Q} - cross sections

- Results obtained from convolution with uPDFs using \textit{CASCADE} - transversal momentum of the Z boson $p_{ZT}$

- Collinear denotes Monte Carlo generator \textit{Mcfm} (J. Campbell, K. Ellis. \url{http://mcfm.fnal.gov/})

Summary

• Unintegrated parton density functions based on solution of the CCFM equation implemented in Monte Carlo programs

• Successful fits to HERA $F_2$ and less inclusive data

• Applied to LHC physics