Search for BFKL-evolution manifestations at high energies

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Outline:

- Motivation: high energy asymptotics
- NLA BFKL within the generalized BLM
- γ*γ*- collisions
- Dijets from QCD dynamics: GLAPD vs. BFKL
- Forward dijets at LHC: dijet “K-factor” vs |y|
- Forward dijets at LHC: azimuthal decorrelations vs |y|
- Summary
Vladimir N. Gribov: high energy asymptotics
1930-1997

QCD in Bjorken limit
- GLAPD: V. Gribov & L. Lipatov (71-72); L. Lipatov (74);
  G. Altarelli & G. Parisi (77); Yu. Dokshitzer (77)

QED in Gribov-Regge limit
- V. Gribov, V. Gorshkov, L. Lipatov & G. Frolov (67-70)
  H. Cheng & T. Wu (66-70)

QCD in Gribov-Regge limit
- BFKL: V. Fadin, E. Kuraev & L. Lipatov (75-78)
  I. Balitsky & L. Lipatov (78)
x-section asymptotics

Bjorken limit (GLAPD):
\[ s \sim Q^2 \gg m^2 \]
\[ Q^2/s = x \sim 1 \]
Large-angle (large-x) scattering

Gribov-Regge limit (BFKL):
\[ s \gg Q^2 \gg m^2 \]
\[ Q^2/s = x \rightarrow 0 \]
Small-angle (small-x) scattering
High-energy QCD asymptotics: GLAPD and BFKL

\[ s = \left( p_1 + p_2 \right)^2 \]
\[ t = \left( p_1 - p_3 \right)^2 \quad Q^2 = -t \]
Scattering in the Standard Model (QCD) at high energies:
Large logarithms: as \( \log(s) \), as \( \log(Q^2) \)

**Bjorken limit (large-angle scattering):**
\[ s \sim Q^2 \gg m^2 \]
\[ Q^2/s = x \sim 1 \]
Gribov-Lipatov-Altarelli-Parisi-Dokshitzer (GLAPD):
(\( \text{as } \log(Q^2) \))\(^n\) resummation
Inclusive cross section \( \sim 1/Q^4 \)

**Gribov-Regge limit (small-angle scattering):**
\[ s \gg Q^2 \gg m^2 \]
\[ Q^2/s = x \leftrightarrow 0 \]
Balitsky-Fadin-Kuraev-Lipatov (BFKL):
(as \( \log(s) \))\(^n\) resummation
Total cross section \( \sim s^{(a_p-1)} \)

\( a_p \) – Pomeron intercept  
soft scattering data: \( a_p = 1.1 \)
Leading Log (LL) BFKL: problems

LL BFKL: designed for infinite collision energies

Problems (at finite energies):
- fixed (non-running) coupling $a_s$
- energy-momentum conservation
- transverse momentum conservation

Cross section in LL BFKL:
$$\sigma_0 \left( \frac{S}{S_0} \right)^{a_P-1} \quad a_P = 1 + C a_s \approx 1.5 - 1.6$$
BFKL: next-to-leading log (NLL)

V.S. Fadin & L.N. Lipatov (89-98)
C.Camici & M. Ciafaloni (96-98)

next-to-leading log approximation (NLL) BFKL

MSbar-renormalization scheme: large corrections

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov (98-99) BFKLP

BFKLP: NLL BFKL + resummation of running coupling as

(Brodsky, Lepage & Mackenzie - 83) BLM approach
NLL BFKL: BLM?

Brodsky, Lepage & Mackenzie (83) BLM approach

- QCD – asymptotically conformal
- non-conformal corrections (running coupling corrections) are resummed into optimal scale

Naïve BLM application does not work (!):
- NLL BFKL in Msbar scheme
- Upsilon ->ggg decay in NLO in Msbar scheme

MSbar-renormalization scheme: nonphysical RG scheme (!)
Brodsky, Rathmann et al (97)
BFKL: next-to-leading log (NLL)

Naïve BLM application does not work (!):
- NLL BFKL in Msbar scheme
- Upsilon ->ggg decay in NLO in MSbar scheme

MSbar-renormalization scheme: nonphysical RG scheme (!)
numerically close to V-scheme (heavy quark potential) – Abelian in LO

physical RG scheme: MOM scheme (guage dependent)

- NLL BFKL in non-Abelian in LO
- Upsilon ->ggg decay in non-Abelian in LO

one can use MOM-scheme based on ggg-vertex non-Abelian in LO

BLM generalized on nonAbelian case:
S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov (98-99) BFKLP
BFKLP: NLL BFKL + resummation of running coupling as
BFKL: next-to-leading log (NLL)

V.S. Fadin & L.N. Lipatov (89-98)
C. Camici & M. Ciafaloni (96-98)

next-to-leading log approximation (NLL) BFKL
MSbar-renormalization scheme: large corrections

S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov, G.B. Pivovarov(98-99) BFKLP
D. Colferai, M. Ciafaloni & G. Salam (99) ...

BFKLP: NLL BFKL + resummation of running coupling $a_s$
BFKLP: Conformal BFKL kernel in NLL -> SUSY N=4
Pomeron intercept: $a_P=1.2 - 1.3$
Cross section: $\sigma_0 \left( S/S_0 \right)^{(a_P-1)} \quad a_P = 1 + C a_s$

L.N. Lipatov, A.V. Kotikov et al. (2000-06)
SUSY N=4 BFKL-Pomeron
Anomalous dimensions: test of AdS/CFT-conjecture
Asymptotics of QED cross sections

\[ \sigma \sim (a_{\text{QED}})^2 \log(s)/s \quad \sigma \sim (a_{\text{QED}})^4 \text{const}(s) \]

All orders: V.N. Gribov, L.N. Lipatov, G.V. Frolov & V.G. Gorshkov (69-71)
H. Cheng & T.T. Wu (69-70)

Cross section at \( s \rightarrow \infty \):
\[ \sim (a_{\text{QED}})^4 \left( S/S_0 \right)^{(a_P-1)} \]
\[ a_P = 1 + C (a_{\text{QED}})^2 \approx 1.002 \]
Asymptotics of QCD cross sections: $\gamma \gamma$

\[ \sigma \sim (a_{\text{QED}})^2 \log(s)/s \quad \sigma \sim (a_{\text{QED}})^2 (a_S)^2 \text{const}(s) \]

All orders: LL BFKL

Cross section at $s \to \infty$: $\sim (a_{\text{QED}})^2 (a_S)^2 (S/S_0)^{(a_P-1)}$

\[ a_P = 1 + C (a_S) \approx 1.5 \quad \text{LL BFKL S. Brodsky & F. Hautmann (96)} \]
\[ a_P = 1 + C (a_S) \approx 1.2 \quad \text{NLL BFKL S. Brodsky, V Fadin, VK, L. Lipatov, G. Pivovarov (2001-02)} \]
Asymptotics of QED cross sections

V.N. Gribov, L.N. Lipatov, G.V. Frolov & V.G. Gorshkov (69-71)
Cheng & T.T. Wu (69-71)

Asymptotics of QCD cross sections

LL BFKL
J. Bartels et al (96), S.J. Brodsky & Hautmann (97)

NLL BFKL (with LO impact factors)
S.J. Brodsky, V.S. Fadin, VK, L.N. Lipatov & G.B. Pivovarov (2001-02)

NLO impact factors and full NLL BFKL:
I. Balitsky, J.Chirilli, J. Bartels et al.
Highly virtual photon scattering at LEP-2


BFKLP: NLL BFKL + generalized BLM

LL BFKL: ruled out
BFKL: dijet processes

Jet production
- GLAPD: ordering on $\kappa T$
- $y$ – no ordering

- BFKL: ordering on $y$
- $\kappa T$ – no ordering

A. Mueller & H. Navelet, Nucl. Phys. (87)
Most forward/backward (Mueller-Navelet) dijets: $x$-section $\sim \exp(|\Delta y|)$

V.T. Kim & G.B. Pivovarov, Phys. Rev. (96)
Inclusive dijets

J.C. Collins, R.K. Ellis (91), S. Catani et al (91)
E.M. Levin, M.G. Ryskin, Yu.M. Shabelsky, A.G. Shuvaev (91)
kT-factorization
Dijet K-factor

\[ K\text{-factor} = \frac{x\text{-section}}{\text{Born x-section}} \]

GLAPD: \[ x\text{-section} \rightarrow C_1 \alpha_s^2 + C_2 \alpha_s^3 + ... \]
\[ \text{Born x-section} \rightarrow C_1 \alpha_s^2 \]

\[ K\text{-factor} = (1 + \frac{C_2}{C_1} \alpha_s + \frac{C_3}{C_1} \alpha_s^2 + ...) \]

Mueller-Navelet (87):

\[ \text{BFKL} \rightarrow \text{enhanced } (\alpha_s \Delta y)-\text{terms} \]
\[ x\text{-section} \rightarrow B_1 \alpha_s^2 \Delta y + B_2 \alpha_s^3 \Delta y^2 + ... \]
\[ \text{Born x-section} \rightarrow B_1 \alpha_s^2 \Delta y \]

\[ K\text{-factor}_{\text{MN}} \rightarrow \exp(\alpha_s \Delta y) \]

\[ \Delta y = |y_1 - y_2| \]
Dijet K-factor: not measurable

K-factor = x-section / Born x-section
Born x-section: no real and no virtual corrections

only a theoretical quantity - > not measurable (!)
Experiment: one cannot forbid virtual corrections by kinematical conditions

Exclusive dijet x-section: always contains virtual corrections

VK & G. Pivovarov:
Using dijets with extra jet veto instead of Born dijets
Dijet observables:

“K-factor” = inclusive dijet /”exclusive” dijet
“K-factor” = MN dijet /”exclusive” dijet
as a function of rapidity separation between jets

Inclusive dijet: \( N_{\text{jets}} \geq 2 \)
\( p_T \geq p_{T\text{min}} \)
all jet pairs

Mueller-Navelet dijet: \( N_{\text{jets}} \geq 2 \)
\( p_T \geq p_{T\text{min}} \)
most forward & most backward jets

“exclusive” dijet (2-jet events) with extra jet veto:
\( N_{\text{jets}} = 2, \ p_T \geq p_{T\text{min}} \)
veto for extra jets \( p_T \geq p_{T\text{veto}} \)
\( p_{T\text{veto}} \leq p_{T\text{min}} \)
Forward dijets at Tevatron and LHC

Tevatron: D0 -> $|\Delta y| < 6 \quad p_{T_{\text{min}}} = 20 \text{ GeV}$
- azimuthal decorr. (1997)
- $1800/630 \text{ GeV x-section ratio}$ (2001)

LHC: ATLAS -> $|\Delta y| < 6 \quad 70 \text{ GeV} < p_T < 90 \text{ GeV}$
- (inverse) “K-factor” (2011)

LHC: CMS -> $|\Delta y| < 9.4 \quad p_{T_{\text{min}}} = 35 \text{ GeV}$
- “K-factor” (2012)
- azimuthal angle decorr. (prel. 2013)
Dijet “K-factor” at 7 TeV

1/ (MN dijet K-factor) = “exclusive” dijet/ MN dijet

ATLAS, JHEP (2011)

arXiv: 1107.1641

7 TeV

70 < pT < 90 GeV

|Δy| < 6

HS’15, High Tatras, July 2, 2015

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CMS: dijet “K-factor”

Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton–proton collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

CERN, Geneva, Switzerland

Abstract A study of dijet production in proton–proton collisions was performed at $\sqrt{s} = 7$ TeV for jets with $p_T > 35$ GeV and $|y| < 4.7$ using data collected with the CMS detector at the LHC in 2010. Events with at least one pair of jets are denoted as “inclusive”. Events with exactly one pair of jets are called “exclusive”. The ratio of the cross sections for inclusive to exclusive dijet production of at medium and large rapidity intervals. A detailed comparison to the measurements of both the production cross sections as a function of the rapidity difference between the two jets, is a sensitive probe of effects beyond collinear factorization. The average number of produced jets grows rapidly, along with the phase space available in rapidity.
Forward dijets at LHC:
Color coherence and AO effects

GLAPD: strong kT-ordering & no rapidity ordering
BFKL: strong rapidity ordering & no kT-ordering

Color coherence effects $\Rightarrow$ rapidity ordering

Polar angle ordering (AO):
jet cone veto for larger cone angles $\Rightarrow$ rapidity ordering

Pythia 6 and 8: GLAPD + AO (AO cannot be fully switched off!)
Herwig++: GLAPD + color coherence (CC cannot be switched off)

No pure GLAPD MC generators (!) available
at present: Pythia and Herwig generators contain $|\Delta y|$-effects

small CC and AO $|\Delta y|$-effects in GLAPD-regime
can be large in BFKL-regime at large $|\Delta y|$
Forward dijets at LHC

GLAPD generators Pythia 6 and 8 (with AO) are consistent with CMS dijet “K-factor” data rather well:

1) no sizeable BFKL effects?
2) or BFKL effects cancels out in dijet ratio

in the latter case the “K-factor” with extra jet veto can be more sensitive BFKL effects

2-jet “exclusive” events: impose an extra jet veto $p_{T\text{veto}} < p_{T\text{min}}$
Forward dijets:

azimuthal angle decorrelations

Cosines
V. Del Duca & C. Schmidt (94)
J. Stirling (94)

Cosine ratios → more sensitive to BFKL (!)
A. Sabio Vera et al (2011)
Forward dijets: azimuthal decorrelations

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{T\text{min}}) = \frac{1}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} C_n(\Delta y, p_{T\text{min}}) \cdot \cos(n(\pi - \Delta\phi)) \right].
\]

\[
C_n(\Delta y, p_{T\text{min}}) = \langle \cos(n(\pi - \Delta\phi)) \rangle, \text{ where } \Delta\phi = \phi_1 - \phi_2
\]

V. del Duca & C. Schmidt (94-95) Striling (94)
V. Kim & G. Pivovarov (96-98)
A. Sabio Vera et al (2007-11)
Dijets: $\langle \cos \rangle$ vs NLL BFKL+BFKLP

CMS PAS-FSQ-12-002
7 TeV, $p_T_{\text{min}} = 35$ GeV
$\Delta y = |y| < 9.4$

NLL BFKL + BFKLP (2014)
B. Ducloue, L. Szymanowski & S. Wallon
Dijets: \langle \cos 2/\rangle/\langle \cos \rangle) vs NLL BFKL + BFKLP

CMS PAS-FSQ-12-002
7 TeV, pT_min = 35 GeV
\Delta y < 9.4

NLL BFKL + BFKLP (2014)
B. Ducloue, L. Szymanowski & S. Wallon

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Summary – 1

γ*γ*- collisions at LEP2

NLL BFKL improved by BFKLP (generalized BLM) (2001-02):

Indication on BFKL evolution

Outlooks: Future linear colliders
Summary - 2:

- **Forward dijet “K-factor” by CMS at 7 TeV:** moderate rise with increasing $|\Delta y|$.
  - Pythia describes the rise, Herwig overshoots the rise.
  - However: pure GLAPD -> const?

- **Azimuthal angle decorrelations (AAD) of CMS dijets:**
  - Agreement with NLL BFKL improved by BFKLP (generalized BLM).
  - GLAPD generators (Pythia, Herwig) describe AAD differently because different color coherence (CC) implementations.

  -> the first indication on BFKL at LHC?

  No pure LL GLAPD predictions (now only LL GLAPD with color coherence, angle ordering, ...)

Other observables:

- **K-factor with extra jet veto, number of extra jets, ... ?**

LHC Run 2 at 13 TeV ?!