The Remarkable Achievements of Lev Lipatov

The program of the Conference will address a broad range of topics covering the main areas of high-energy particle and nuclear physics. Our scientific program will include:

- Higgs Physics
- Hadron Spectroscopy
- Neutrino Physics
- Hadron Structure
- High-Energy QCD
- Non-perturbative QCD
- Heavy Ion collisions
- Particle Detectors and Instrumentation
- Beyond the SM Physics
- Dark Matter searches
- Phenomenology of AdS/CFT
- Astroparticles
- Future experiments, and other topics.

The aim of the Conference is to bring together young and senior scientists, theorists and experimentalists, to review the recent progress in high energy particle and nuclear physics. We strongly encourage presentations of physics results from experimental facilities (LHC, FermiLab, RHIC, JLab, DESY, etc), future experimental facilities (LHeC, FCC-ee, EIC, CTA, etc) and theoreticians to participate in the event.

Students and young postdocs are also encouraged to participate in the HEP School the week after the workshop on January 15-19.
Lev Nikolaevich Lipatov

Head of the Theoretical Physics Division at St. Petersburg's Nuclear Physics Institute of the Russian Academy of Sciences

Academician of the Russian Academy of Sciences

Pomeranchuk Prize (2001)

Gribov and Lipatov (DGLAP)

Balitsky Fadin Kuraev Lipatov (BFKL)

Renormalon Analysis

Tunneling Theory

Critical Phenomena

…..
The Pomeranchuk Prize is an international award for theoretical physics, awarded annually since 1998 by the Institute for Theoretical and Experimental Physics (ITEP) from Moscow. Isaak Yakovlevich Pomeranchuk, who together with Landau established the Institute.

Laureates

Source: Institute of Theoretical and Experimental Physics[1]

- 2016 Curtis J. Callan and Yuri A. Simonov[2]
- 2015 Stanley J. Brodsky and Victor Fadin[3]
- 2014 Leonid Keldysh and Alexander Zamolodchikov
- 2013 Mikhail Shifman and Andrey Slavnov
- 2012 Juan Martin Maldacena and Spartak Belyaev
- 2011 Heinrich Leutwyler and Semyon Gershtein
- 2010 André Martin and Valentine Zakharov
- 2009 Nicola Cabibbo and Boris Ioffe
- 2008 Leonard Susskind and Lev Okun
- 2007 Alexander Belavin and Yoichiro Nambu
- 2006 Vadim Kuzmin and Howard Georgi
- 2005 Iosif Khriplovich and Arkady Vainshtein
- 2004 Alexander F. Andreev and Alexander Polyakov
- 2003 Valery Rubakov and Freeman John Dyson
- 2002 Ludvig Faddeev and Bryce Seligman DeWitt
- 2001 Lev Lipatov and Tullio Regge
- 2000 Evgenii Feinberg and James Daniel Bjorken
- 1999 Karen Ter-Martirosian and Gabriele Veneziano
- 1998 Aleksander Ilyich Akhiezer and Sidney Drell
Lev’s Most Highly Cited Papers

BFKL pomeron in the next-to-leading approximation
DESY-98-033
DOI: 10.1016/S0370-2693(98)00473-0
e-Print: hep-ph/9802290 | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 983 records 500+

The Bare Pomeron in Quantum Chromodynamics
LENINGRAD-85-1137
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 870 records 500+

The Pomeranchuk Singularity in Quantum Chromodynamics
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 3304 records 1300+

Reggeization of the Vector Meson and the Vacuum Singularity in Nonabelian Gauge Theories
Published in Sov.J.Nucl.Phys. 23 (1976) 338-345, Yad.Fiz. 23 (1976) 642-656
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1188 records 1004+

On the Pomeranchuk Singularity in Asymptotically Free Theories
Published in Phys.Lett. 60B (1975) 50-52
DOI: 10.1016/0370-2693(75)90524-9
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1085 records 1004+

The parton model and perturbation theory
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1345 records 1004+

e+ e- pair annihilation and deep inelastic e p scattering in perturbation theory
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1212 records 1004+

Deep inelastic e p scattering in perturbation theory
IPTI-381-71
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1490 records 1004+

Multi - Reggeon Processes in the Yang-Mills Theory
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1490 records 1004+
Deep inelastic e p scattering in perturbation theory
Published in
IPTI-381-7
Cited by 3726 records


DGLAP Evolution Equations


Gluons and Quarks at Low-x

Distribution functions $xq(x, Q^2)$ and $xG(x, Q^2)$ rise steeply at low Bjorken $x$.

Growth of quark and gluon distributions with $Q^2$ at low $x$.
DGLAP Evolution in QCD

\[ \mu^2 \frac{\partial q_v(x, \mu^2)}{\partial \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int x^1 \frac{dy}{y} P_{qq} \left( \frac{x}{y} \right) q_v(y, \mu^2) \]
Use LF perturbation theory

\[ \ell p \rightarrow \ell' + (qq) + q + g + q\bar{q} \]

\[ T = H_I + H_I \frac{\mathcal{M}_{\text{intermediate}}^2}{\mathcal{M}_{\text{initial}}^2 - i\epsilon} + H_I + \cdots \]
$$t = \log \frac{Q^2}{Q_0^2}$$

$$\frac{d}{dt} q_i(x, t) = \frac{\alpha_s(Q)}{2\pi} [q_i \times P_{qq}] + \frac{\alpha_s(Q)}{2\pi} [g \times P_{qg}]$$

$$\frac{d}{dt} g(x, t) = \frac{\alpha_s(Q)}{2\pi} [\sum_i (q_i + \bar{q}_i) \times P_{qg}] + \frac{\alpha_s(Q)}{2\pi} [g \times P_{gg}]$$

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

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

$$P_{gg} = \frac{1}{2} [x^2 + (1-x)^2]$$

$$P_{gg} = 6 \left[ \frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x) \right] + \frac{33-2n_f}{6} \delta(1-x)$$
Prediction from AdS/QCD: Meson LFWF

\[ e^{\varphi(z)} = e^{+\kappa^2 z} \]

\[ \psi_M(x, k^2_\perp) \]

**Note coupling**

\[ k^2_\perp, x \]

\[ \psi_M(x, k_\perp) = \frac{4\pi}{\kappa \sqrt{x(1-x)}} e^{-\frac{k^2_\perp}{2\kappa^2 x(1-x)}} \]

\[ f_\pi = \sqrt{P_{q\bar{q}}} \frac{\sqrt{3}}{8} \kappa = 92.4 \text{ MeV} \]

\[ \phi_\pi(x) = \frac{4}{\sqrt{3\pi}} f_\pi \sqrt{x(1-x)} \]

Same as DSE! C. D. Roberts et al.

Provides Connection of Confinement to Hadron Structure
AdS/QCD Holographic Wave Function for the $\rho$ Meson and Diffractive $\rho$ Meson Electroproduction

$\gamma^* p \rightarrow \rho^0 p'$

$\psi_M(x, k_{\perp}) = \frac{4\pi}{\kappa \sqrt{x(1-x)}} e^{-\frac{k_{\perp}^2}{2\kappa^2 x(1-x)}}$
Start DGLAP evolution at transition scale $Q^2_0 = 0.75 \, \text{GeV}^2$.

No parameters
AdS/QCD dilaton captures the higher twist corrections to effective charges for $Q < 1$ GeV

$$e^\varphi = e^{+\kappa^2 z^2}$$

Deur, de Teramond, sjb
\[ m_\rho = \sqrt{2\kappa} \]
\[ m_p = 2\kappa \]

\[ \frac{\alpha_s(Q^2)}{\pi} \left( 1 - \frac{Q^2}{4\kappa^2} \right) \]

Transition scale \( Q_0 = 0.87 \pm 0.08 \text{ GeV} \)

\( \lambda \equiv \kappa^2 \)

Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:
\( \kappa = 0.513 \pm 0.007 \text{ GeV} \)

5-Loop \( \beta \) Prediction:
\( \Lambda_{\overline{MS}} = 0.339 \pm 0.019 \text{ GeV} \)

Experiment:
\( \Lambda_{\overline{MS}} = 0.332 \pm 0.017 \text{ GeV} \)

Reverse Dimensional Transmutation!
BFKL Dynamics


BFKL pomeron in the next-to-leading approximation
V. S. Fadin and L. N. Lipatov
An introduction to BFKL dynamics

Lev Lipatov
Petersburg Nuclear Physics Institute

1. Gluon reggeization
2. BFKL equation and its solution
3. Möbius invariance
4. Holomorphic separability
5. Integrability at large $N_c$
6. Odderon problem in QCD
7. Baxter-Sklyanin representation
8. Solution of the Baxter equation
9. Pomeron in the thermostat
10. Next-to-leading corrections in $N = 4$ SUSY
Results

1. Reggeization of gluons and quarks in QCD
2. Pomeron as a composite state of two reggeons
3. Odderon as a composite state of three reggeons
4. Möbius invariance of the BFKL equation
5. Holomorphic separability of BFKL Hamiltonian
6. Duality symmetry of BKP equations at $N_c \to \infty$
7. Integrability of the BFKL dynamics at $N_c \to \infty$
8. Effective action for reggeized gluon interactions
9. $s$- and $t$- chanel unitarity
10. Next-to-leading corrections to the BFKL equation
11. Remarkable properties of high energy dynamics in $N=4$ SUSY
BFKL Dynamics


BFKL pomeron in the next-to-leading approximation
V. S. Fadin and L. N. Lipatov

Connection to ‘H’-diagrams
Gluonic Flux Tube
Confining Potential
Static Heavy Quark Potential is IR Divergent in QCD

\[ V(Q^2) = -\frac{(4\pi)^2 C_F}{Q^2} a(Q^2) \left[ 1 + (c_{2,0} + c_{2,1} N_f) a(Q^2) + (c_{3,0} + c_{3,1} N_f + c_{3,2} N_f^2) a(Q^2)^2 
+ (c_{4,0} + c_{4,1} N_f + c_{4,2} N_f^2 + c_{4,3} N_f^3) a(Q^2)^3 + 8\pi^2 C_A \ln \frac{\mu_{IR}^2}{Q^2} a(Q^2)^3 \right] \]

Smirnov, Smirnov, Steinhauser, 2010

Summation of H graphs: confining potential?

Confinement eliminates IR divergences
Self-consistent mass scale \( \kappa \)
BFKL pomeron with massive gluons and running coupling

Eugene Levin\textsuperscript{a,b}, Lev Lipatov\textsuperscript{c,d} and Marat Siddikov\textsuperscript{a}
\textsuperscript{a}Departamento de Física, Universidad Técnica Federico Santa María, y Centro Científico - Tecnológico de Valparaíso, Casilla 110-V, Valparaíso, Chile
\textsuperscript{b}Department of Particle Physics, School of Physics and Astronomy, Tel Aviv University, Tel Aviv, 69978, Israel
\textsuperscript{c}Theoretical Physics Department, Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, 188300, St. Petersburg, Russia and
\textsuperscript{d}Physics Department, St.Petersburg State University, Ulyanovskaya 3, St.Petersburg 198504, Russia

In this paper we proceed with the study of the Pomeron spectrum, by solving numerically the BFKL equation with massive gluons and running coupling. The spectrum of Regge singularities is discrete and the leading Pomeron has a considerable dependence on nonperturbative effects, for which we use Higgs mechanism as a model. We cross-checked this result with variational method and confirmed the infrared sensitivity of leading Pomeron. This fact is related to the infrared instability of the BFKL equation in QCD, with a running coupling. The subleading poles have a mild sensitivity to the soft physics, and are well described by known semiclassical methods. We also discuss the dependence on various prescriptions of the running coupling arguments.

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The QCD pomeron with optimal renormalization
Published in JETP Lett. 70 (1999) 155-160
SLAC-PUB-8037, IITAP-98-010

High-energy QCD asymptotics of photon-photon collisions
SLAC-PUB-9318, CERN-TH-2002-143, PNPI-2484
The QCD Pomeron with Optimal Renormalization

Stanley J. Brodsky*, Victor S. Fadin†, Victor T. Kim‡&, Lev N. Lipatov‡
and
Grigorii B. Pivovarov§&

\[ s^{\alpha_P - 1} = s^\omega_P \]

Lowest order BFKL

\[ \omega_P = 12 \ln 2 \times \alpha_s / \pi \]

Adopting BLM scale setting, the NLO BFKL eigenvalue in the MOM-scheme is

\[ \omega_{BLM}^{MOM}(Q^2, \nu) = N_C \chi_L(\nu) \frac{\alpha_{MOM}(Q_{BLM}^{MOM})^2}{\pi} \left[ 1 + r_{BLM}^{MOM}(\nu) \frac{\alpha_{MOM}(Q_{BLM}^{MOM})^2}{\pi} \right], \]

\[ r_{BLM}^{MOM}(\nu) = r_{MOM}^{\text{conf}}(\nu). \]

BLM/PMC: Scale chosen to eliminate \( \beta \) terms
BLM: $\omega(\text{BFKL nlo})$ independent of $Q^2$

$$\omega(Q^2) = \alpha_P - 1$$
The QCD pomeron with optimal renormalization
Published in JETP Lett. 70 (1999) 155-160
SLAC-PUB-8037, IITAP-98-010

High-energy QCD asymptotics of photon-photon collisions
SLAC-PUB-9318, CERN-TH-2002-143, PNPI-2484
High-Energy Asymptotics of Photon-Photon Collisions in QCD

S. J. Brodsky, V. S. Fadin, V. T. Kim, L.N. Lipatov, G. B. Pivovarov

\[ \sigma_{\gamma^*\gamma^* \rightarrow X} \sim \left[ \frac{s}{s_0} \right] \alpha_P - 1 \]

\[ \alpha_P - 1 = 12 \log 2 \times \frac{\alpha_s}{\pi} \simeq 0.55 \]

\[ \alpha_P - 1 \simeq 0.13 - 0.18 \]
$\gamma^*\gamma^*$ Cross Section at NLO and Properties of the BFKL Evolution at Higher Orders

Giovanni A. Chirilli,* Yuri V. Kovchegov†

**BFKL Analysis**
Dihadron Production at LHC: BFKL Predictions for Cross Sections and Azimuthal Correlations

Francesco G. Celiberto, Dmitry Yu. Ivanov, Beatrice Murdaca, and Alessandro Papa

**BFKL Reggeon Exchange**

The process under investigation is the hadroproduction of a pair of identified hadrons in proton-proton collisions (PDFs) for the initial proton, but also the parton fragmentation functions (FFs) describing the detected hadron in the final state. The azimuthal correlation momenta is small, since the FFs uncertainties are largely canceled out when we take the ratios of the Mueller–Navelet jet cross sections and the jet azimuthal angle distributions. Similar features are expected also at natural scales.

Energy of the partonic cross section, the convolution of the latter with proton PDFs leads to a decrease with the respective ones of the Mueller–Navelet jet process. Although the BFKL resummation predicts a growth with the di-mass energy $Z_{\text{max}}$, the final state rapidity interval $Y_{\text{max}}$, always smaller than the BLM one. Plots of Figure 2 show that LLA results at BLM scales lie closer to the NLA BLM ones than LLA results at natural scales.

We present our first results neglecting the NLA parts of hadron vertices FFs: AKK [37] and HKNS [38]. Pursuing the goal to stress the potential relevance of the process we are proposing, we use the PDF set MSTW 2008 NLO [36] with two different NLO parameterizations for hadron vertices, we consider the cuts used by the CMS collaboration, we take as Sudakov vectors. The di-mass energy $Z_{\text{max}}$, of the two hadrons' azimuthal angles, while the di-mass energy $Y_{\text{max}}$, gives the total cross section and the -averaged cross section of the process can be presented as the differential cross section of the process can be presented as

$$\frac{d \sigma}{dy_1 dy_2} = \frac{C N}{2 \pi s} \left(1 + \frac{2}{\pi} \ln \left(\frac{s}{m^2}ight)\right) \frac{1}{y_1 y_2} \left(\frac{1}{y_1} + \frac{1}{y_2} - 1\right) \left(\frac{1}{y_1} - 1\right)\left(\frac{1}{y_2} - 1\right)$$

for $s > m^2$.

For the integrations over rapidities and transverse momenta we use the limits, $0 < y_1 < 1$ and $0 < y_2 < 1$.
Dihadron Production at LHC: BFKL Predictions for Cross Sections and Azimuthal Correlations

Francesco G. Celiberto Dmitry Yu. Ivanov, Beatrice Murdaca and Alessandro Papa

CONCLUSIONS AND OUTLOOK

In this paper we investigated the dihadron production process at the LHC at the center-of-mass energy of 13 TeV, giving the first theoretical predictions for cross sections and azimuthal angle correlations in the LLA and partial NLA BFKL approach. We implemented the exact version of the BLM optimization procedure in order to make completely vanish the $C_0$-dependence in our observables and minimize the size of the NLA corrections. We found that our NLA BLM predictions are close to the LLA BLM ones, while the LLA calculations at natural scales overestimate the total cross section $C_0$ and predict a stronger decorrelation for the azimuthal ratios $R_n$. The good agreement between LLA and NLA at BLM scales is a direct consequence of the small size of the higher-order corrections, representing so a clear signal of the reliability of the BLM method. However, more accurate analyses are still needed: full NLA calculations including next-to-leading order hadron vertices, together with the study of larger rapidity intervals in the final state and considering the effect of a different choice for the factorization scale $\mu_F$ with respect to the renormalization scale $\mu_R$, are underway [40]. In view of all these considerations, we encourage experimental collaborations to include the study of the dihadron production in the program of future analyses at the LHC, making use of a new suitable channel to improve our knowledge about the dynamics of strong interactions in the Regge limit.


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NLA: Leading Log Resummed + Next-to Leading Order

LLA: Leading Log Resummed

$NLO$ BFKL (BLM)

$LL + NLO$ (BLM)

Leading Log Resummed
CONCLUSIONS AND OUTLOOK

In this paper we investigated the dihadron production process at the LHC at the center-of-mass energy of 13 TeV, giving the first theoretical predictions for cross sections and azimuthal angle correlations in the LLA and partial NLA BFKL approach. We implemented the exact version of the BLM optimization procedure in order to make completely vanish the $\beta_0$-dependence in our observables and minimize the size of the NLA corrections. We found that our NLA BLM predictions are close to the LLA BLM ones, while the LLA calculations at natural scales overestimate the total cross section $C_0$ and predict a stronger de-correlation for the azimuthal ratios $R_{n0}$. The good agreement between LLA and NLA at BLM scales is a direct consequence of the small size of the higher-order corrections, representing so a clear signal of the reliability of the BLM method. However, more accurate analyses are still needed: full NLA calculations including next-to-leading order hadron vertices, together with the study of larger rapidity intervals in the final state and considering the effect of a different choice for the factorization scale $\mu_F$ with respect to the renormalization scale $\mu_R$, are underway. In view of all these considerations, we encourage experimental collaborations to include the study of the dihadron production in the program of future analyses at the LHC, making use of a new suitable channel to improve our knowledge about the dynamics of strong interactions in the Regge limit.
Probing BFKL dynamics in the Vector Meson Photoproduction at large – t in pPb collisions at the CERN LHC

V. P. Goncalves and W. K. Sauter

\[ \gamma^* p \rightarrow V^0 X \]
Probing the BFKL dynamics in the Vector Meson Photoproduction at large – t in pPb collisions at the CERN LHC

V. P. Gonçalves and W. K. Sauter

\[ \gamma^* p \rightarrow V^0 X \]
The Odderon intercept in perturbative QCD

P. Gauron, L.N. Lipatov, B. Nicolescu (Orsay, IPN & Paris U., VI-VII)

Jun 1993 - 7 pages

Z.Phys. C63 (1994) 253-256
DOI: 10.1007/BF01411017

Odderon-Pomeron interference

Stanley J. Brodsky, Johan Rathsman (SLAC) , Carlos Merino (Santiago de Compostela U.)

Apr 1999 - 10 pages

DOI: 10.1016/S0370-2693(99)00807-2
SLAC-PUB-8095
e-Print: hep-ph/9904280 | PDF

\[ A(t, M_X^2, z_c) \sim 2 \frac{\kappa_{pp}' \kappa_{cc}^\gamma}{\kappa_{pp}' \kappa_{c}^\gamma} \sin \left[ \frac{\pi (\alpha_{\gamma} - \alpha_{P})}{2} \right] \left( \frac{s_{\gamma P}}{M_X^2} \right)^{\alpha_{\gamma} - \alpha_{P}} \frac{\sin \frac{\pi \alpha_{P}}{2}}{\cos \frac{\pi \alpha_{\gamma}}{2} \frac{2 z_c - 1}{z_c^2 + (1 - z_c)^2}}. \]
\[ \gamma^* \rightarrow P/O \rightarrow C=+/− \]

\[ P/O \rightarrow Y \rightarrow M^2_X \]

\[ Y^* \rightarrow P/\Phi \rightarrow M^2_Y \]

\[ \gamma^* \rightarrow \Phi/\gamma^* \rightarrow M^2_X \]

\[ P/\Phi \rightarrow M^2_Y \]
The asymmetry in fractional energy $z_c$ of charm versus anticharm jets predicted using the Donnachie-Landshoff Pomeron for $\alpha_P = 1.2$, $\alpha_O = 0.95$ and $s_{\gamma p}/M_X^2 = 100$.

**Also: Odderon Exchange in pion photoproduction**
Electron-Electron Scattering in QED

\[ \mathcal{M}_{ee\rightarrow ee}(++; ++) = \frac{8\pi s}{t} \alpha(t) + \frac{8\pi s}{u} \alpha(u) \]

\[ \alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)} \]

Gell-Mann--Low Effective Charge

- Dressed Photon Propagator sums all \( \beta \) (vacuum polarization) contributions, proper and improper

\[ \alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)} \]

\[ \Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)} \]

- Initial Scale Choice \( t_0 \) is Arbitrary!

- Any renormalization scheme can be used \( \alpha(t) \rightarrow \alpha_{\overline{MS}}(e^{-\frac{5}{3} t}) \)
BLM Scale Setting

\[ \beta_0 = 11 - \frac{2}{3} n_f \]

\[
\rho = C_0 \alpha_{\overline{\text{MS}}}(Q) \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}(Q)}{\pi} \left( -\frac{3}{2} \beta_0 A_{\text{VP}} + \frac{33}{2} A_{\text{VP}} + B \right) + \cdots \right] \]

by

\[
\rho = C_0 \alpha_{\overline{\text{MS}}}(Q^*) \left[ 1 + \frac{\alpha_{\overline{\text{MS}}}(Q^*)}{\pi} C_1^* + \cdots \right],
\]

where

Conformal coefficient - independent of \( \beta \)

\[ Q^* = Q \exp(3A_{\text{VP}}) \],

\[ C_1^* = \frac{33}{2} A_{\text{VP}} + B \].

The term \( 33A_{\text{VP}} / 2 \) in \( C_1^* \) serves to remove that part of the constant \( B \) which renormalizes the leading-order coupling. The ratio of these gluonic corrections to the light-quark corrections is fixed by \( \beta_0 = 11 - \frac{2}{3} n_f \).

Use skeleton expansion:
Gardi, Grunberg, Rathsman, sjb
BLM/PMC: Set Scales

\[ a(Q) \equiv \frac{\alpha_s(Q)}{\pi} \]

such to absorb all ‘renormalon-terms’, i.e. non-conformal terms

\[
\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + (\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \beta_2 a(Q)^4 + \cdots) r_{2,1} \\
+ (\beta_0^2 a(Q)^3 + \frac{5}{2} \beta_1 \beta_0 a(Q)^4 + \cdots) r_{3,2} + (\beta_0^3 + \cdots) r_{4,3} \\
+ r_{2,0} a(Q)^2 + 2a(Q)(\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \cdots) r_{3,1} \\
+ \cdots
\]

How do we identify the β terms?

BLM: Use \( n_f \) dependence of \( \beta_0 \) and \( \beta_1 \)
Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

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Stanley J. Brodsky†
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Xing-Gang Wu‡
Department of Physics, Chongqing University, Chongqing 401331, People’s Republic of China
(Received 13 January 2013; published 10 May 2013)

We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal \( \{\beta_i\} \) terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an unnecessary source of systematic error.
Principle of Maximum Conformality (PMC)

- Subtract extra constant $\delta$ in dimensional regularization. Defines new scheme $R_\delta$

$$\log 4\pi - \gamma_E - \delta \quad \overline{MS} : \delta = 0$$

(\(\delta\): Arbitrary constant!)

- Coefficients of $\delta$ identify $\beta$ terms!

- Shift $\beta$ terms to argument of running coupling $\alpha_s(Q_n^2)$ at each order $n$ (analogous to all-orders vacuum polarization summation in QED)

- Resulting PQCD series matches $\beta = 0$ conformal series

- Scheme-independent predictions at each computed order

- Almost independent of initial scale $\mu_0$

M. Mojaza, L. di Giustino, Xing-Gang Wu, sjb
Choose renormalization scheme; e.g. $\alpha_s^R(\mu_{\text{init}}^R)$

Choose $\mu_{\text{init}}^R$; arbitrary initial renormalization scale

Identify $\beta_i$ via $\delta$-dependence

Shift scale of $\alpha_s$ to $\mu_{\text{PMC}}^R$ to eliminate $\{\beta_i^R\}$ terms

Conformal Series

Result is independent of $\mu_{\text{init}}^R$ and scheme at fixed order

PMC/BLM
No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at $N_C=0$

Eliminates unnecessary systematic uncertainty

Scale fixed at each order

$\delta$-Scheme automatically identifies $\beta$-terms!

Principle of Maximum Conformality

Supersymmetric Features of QCD from LF Holography

Xing-Gang Wu, Matin Mojaza Leonardo di Giustino, SJB Stan Brodsky

HEP2018
7th International Conference on High Energy Physics in the LHC Era Universidad Técnica Federico Santa María, Valparaíso, Chile 1-11-2018
Example of Multiple BLM/PMC Scales

QCD coupling at small scales at low relative velocity $v$

Angular distributions of massive quarks close to threshold.

$F_1 + F_2 = \left[ 1 - 2 \frac{\alpha_s (se^{3/4}/4)}{\pi} \right] \times \left[ 1 + \frac{\pi \alpha_s (sv^2)}{4v} \right]$
Implications for the $\bar{p}p \rightarrow t\bar{t}X$ asymmetry at the Tevatron
Implications for the $\bar{p}p \to t\bar{t}X$ asymmetry at the Tevatron

Small value of renormalization scale increases asymmetry, just as in QED!!

Xing-Gang Wu, sjb
NNLO QCD predictions for fully-differential top-quark pair production at the Tevatron

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Abstract:
We present a comprehensive study of differential distributions for Tevatron top-quark pair production at the level of stable top quarks. All calculations are performed in NNLO QCD perturbation theory. We present predictions for all kinematic distributions for which data exists. Particular attention is paid on the top-quark forward-backward asymmetry which we study in detail. We compare the NNLO results with existing approximate NNLO predictions derived in this work), NLO prediction of Ref. \[2\], and it should be easy to distinguish between the two with data, as well as di
cut

\[A_{FB}(p\bar{p} \rightarrow t\bar{t}X, m_{t\bar{t}} > m_{t\bar{t}}^{cut})\]

\(m_{t\bar{t}}^{cut}\) [GeV]

Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

Predictions for the cumulative front-back asymmetry.
The Renormalization Scale Ambiguity for Top-Pair Production Eliminated Using the ‘Principle of Maximum Conformality’ (PMC)

Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting
Features of BLM/PMC

- Predictions are scheme-independent at every order
- Matches conformal series
- Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)
- No $n!$ Renormalon growth (Lipatov)
- New scale appears at each order; $n_F$ determined at each order - matches virtuality of quark loops
- Multiple Physical Scales Incorporated (Hoang, Kuhn, Tuebner, sjb)
- Rigorous: Satisfies all Renormalization Group Principles
- Realistic Estimate of Higher-Order Terms
- Same as Gell-Mann Low for QED $N_C \to 0$
- Eliminates unnecessary theory error
- Maximal sensitivity to new physics
- Example: BFKL intercept (Fadin, Kim, Lipatov, Pivovarov, sjb)
The Remarkable Achievements of Lev Lipatov

DGLAP Evolution

- QCD Fits
  - (H1+BCDMS) total uncertainty
  - (H1+BCDMS) exp. + $\alpha_s$ uncert.
  - (H1+BCDMS) exp. uncertainty
  - (H1)

- $Q^2 = 5$ GeV$^2$
- $Q^2 = 20$ GeV$^2$
- $Q^2 = 200$ GeV$^2$

H1 Collaboration

Universidad Técnica Federico
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Stan Brodsky