

High-energy QCD asymptotics of photon-photon collisions

S. J. Brodsky[∇], V. S. Fadin[†], V. T. Kim^{*□}, L. N. Lipatov[□], G. B. Pivovarov[△]

[∇]SLAC, Stanford, CA 94309, USA

[†]Budker Institute for Nuclear Physics, 630090 Novosibirsk, Russia

^{*}CERN, CH-1211, Switzerland

[□]St.Petersburg Nuclear Physics Institute, 188300 Gatchina, Russia

[△]Institute for Nuclear Research, 117312 Moscow, Russia

Submitted 25 July 2002

The high-energy behaviour of the total cross section for highly virtual photons, as predicted by the BFKL equation at next-to-leading order (NLO) in QCD, is discussed. The NLO BFKL predictions, improved by the BLM optimal scale setting, are in good agreement with recent OPAL and L3 data at CERN LEP2. NLO BFKL predictions for future linear colliders are presented.

PACS: 12.38.Cy

Photon-photon collisions, particularly $\gamma^*\gamma^*$ processes, play a special role in QCD [1], since their analysis is under much better control than the calculation of hadronic processes, which require the input of non-perturbative hadronic structure functions or wave functions. In addition, unitarization (screening) corrections due to multiple Pomeron exchange should be less important for the scattering of γ^* of high virtuality than for hadronic collisions.

The high-energy asymptotic behaviour of the $\gamma\gamma$ total cross section in QED can be calculated [2] by an all-orders resummation of the leading terms: $\sigma \sim \alpha^4 s^\omega$, $\omega = \frac{11}{32}\pi\alpha^2 \simeq 6 \cdot 10^{-5}$ (Fig.1). However, the slowly ris-

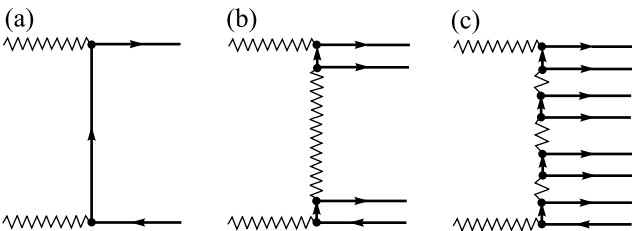


Fig.1. Photon-photon collisions in QED: (a) electron-box diagram: $\sigma \sim \alpha^2(\log s)/s$; (b) one-photon exchange diagram: $\sigma \sim \alpha^4 s^0$; (c) a typical higher-order diagram, its resummation leads to $\sigma \sim \alpha^4 s^\omega$, $\omega = \frac{11}{32}\pi\alpha^2$ [2]

ing asymptotic behaviour of the QED cross section is not apparent since large contributions come from other sources, such as the cut of the fermion-box contribution: $\sigma \sim \alpha^2(\log s)/s$ [1] (which although subleading in energy dependence, dominates the rising contributions by

powers of the QED coupling constant) and QCD-driven processes (Fig.2).

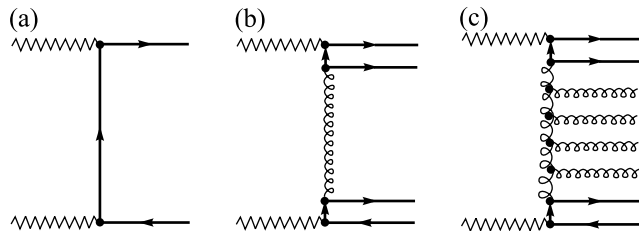


Fig.2. High-energy photon-photon collisions in QCD: (a) quark-box diagram: $\sigma \sim \alpha^2(\log s)/s$; (b) one-gluon exchange diagram: $\sigma \sim \alpha^2\alpha_s^2 s^0$; (c) a typical higher-order diagram; its resummation leads to $\sigma \sim \alpha^2\alpha_s^2 s^\omega$, $\omega_{LO} = 12 \ln 2 (\alpha_S/\pi) \simeq 0.55$ [3] and $\omega_{NLO} = 0.13-0.18$ [6]

The high-energy asymptotic behaviour of hard QCD processes is governed by the Balitsky–Fadin–Kuraev–Lipatov (BFKL) formalism [3, 4]. The highest eigenvalue, ω , of the BFKL equation [3] is related to the intercept of the QCD BFKL Pomeron, which in turn governs the high-energy asymptotics of the cross sections: $\sigma \sim s^{\alpha_{IP}-1} = s^\omega$. The BFKL Pomeron intercept in the leading order (LO) turns out to be rather large: $\alpha_{IP} - 1 = \omega_{LO} = 12 \ln 2 (\alpha_S/\pi) \simeq 0.55$ for $\alpha_S = 0.2$ [3]. The next-to-leading order (NLO) corrections to the BFKL intercept have recently been calculated [5], but the results in the \overline{MS} scheme have a strong renormalization scale dependence. In Ref. [6] we used the Brodsky–Lepage–Mackenzie (BLM) optimal scale setting procedure [7] to eliminate the renormalization scale ambiguo-

ity. (For other approaches to the NLO BFKL predictions, see Refs. [8, 6] and references therein.) The BLM optimal scale setting resums the conformal-violating β_0 -terms into the running coupling in all orders of perturbation theory, thus preserving the conformal properties of the theory. The NLO BFKL predictions, as improved by the BLM scale setting, yields $\alpha_{IP} - 1 = \omega_{NLO} = 0.13 - 0.18$ [6]. Strictly speaking the integral kernel of the BFKL equation at NLO is not conformally invariant and, hence, one should use a more accurate method for its solution (see Ref. [9]). But in the BLM approach the dependence of the eigenvalue of the kernel from the gluon virtuality is extremely weak [6] and, therefore, ω_{NLO} coincides basically with the eigenvalue.

The photon-photon cross sections with LO BFKL resummation was considered in Refs. [4, 10–12]. The total cross section of two unpolarized gammas with virtualities Q_A and Q_B in the LO BFKL [11, 4] reads as follows:

$$\sigma(s, Q_A^2, Q_B^2) = \sum_{i,k=T,L} \frac{1}{\pi \sqrt{Q_A^2 Q_B^2}} \times \int_0^\infty \frac{d\nu}{2\pi} \cos\left(\nu \ln\left(\frac{Q_A^2}{Q_B^2}\right)\right) F_i(\nu) F_k(-\nu) \left(\frac{s}{s_0}\right)^{\omega(Q^2, \nu)},$$

with the gamma impact factors in the LO for the transverse and longitudinal polarizations:

$$F_T(\nu) = F_T(-\nu) = \alpha \alpha_S \left(\sum_q e_q^2 \right) \frac{\pi}{2} \times \frac{\left[\frac{3}{2} - i\nu \right] \left[\frac{3}{2} + i\nu \right] \Gamma\left(\frac{1}{2} - i\nu\right)^2 \Gamma\left(\frac{1}{2} + i\nu\right)^2}{\Gamma(2 - i\nu) \Gamma(2 + i\nu)}$$

$$F_L(\nu) = F_L(-\nu) = \alpha \alpha_S \left(\sum_q e_q^2 \right) \pi \times \frac{\Gamma\left(\frac{3}{2} - i\nu\right) \Gamma\left(\frac{3}{2} + i\nu\right) \Gamma\left(\frac{1}{2} - i\nu\right) \Gamma\left(\frac{1}{2} + i\nu\right)}{\Gamma(2 - i\nu) \Gamma(2 + i\nu)},$$

where a Regge scale parameter s_0 is proportional to a hard scale $Q^2 \sim Q_A^2, Q_B^2$; Γ is the Euler Γ -function and e_q is the quark electric charge.

Although the NLO impact factor of the virtual photon is not known [13], one can use the LO impact factor of Refs. [2, 11], assuming that the main energy-dependent NLO corrections come from the NLO BFKL subprocess rather than from the photon impact factors [14, 15].

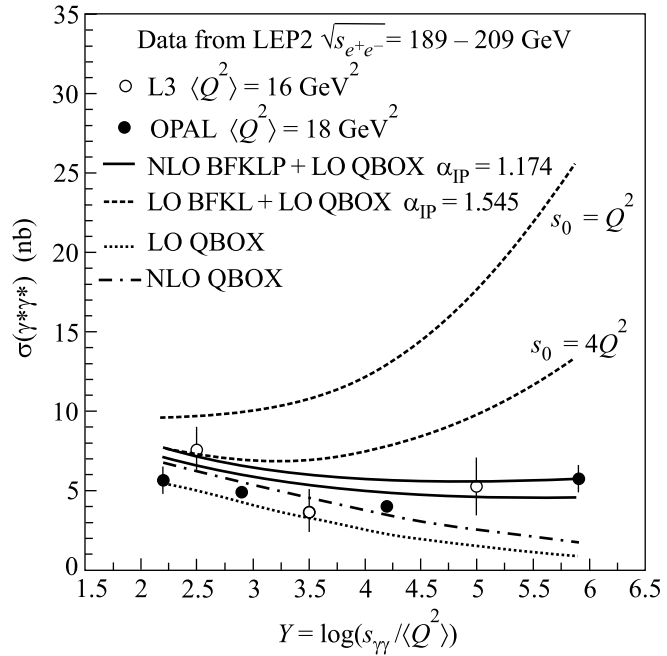


Fig.3. The energy dependence of the total cross section for highly virtual photon-photon collisions predicted by the BLM scale-fixed NLO BFKL [14, 15, 6] compared with OPAL [16] and L3 [17] data from LEP2 at CERN. The (solid) dashed curves correspond to the (N)LO BFKL predictions for two different choices of the Regge scale: $s_0 = Q^2$ for upper curves and $s_0 = 4Q^2$ for lower curves

Fig.3 compares the LO and BLM scale-fixed NLO BFKL predictions $\sigma \sim \alpha^2 \alpha_S^2 s^\omega$ [6, 14, 15] with recent CERN LEP2 data from OPAL [16] and L3 [17]. The spread in the curves reflects the uncertainty in the choice of the Regge scale parameter, which defines the beginning of the asymptotic regime: $s_0 = Q^2$ to $4Q^2$ for LO and NLO BFKL, where Q^2 is the mean virtuality of the colliding photons. One can see from Fig.3 that the agreement of the NLO BFKL predictions [14, 15, 6] with the data is quite good. The sensitivity of the NLO BFKL results to the Regge parameter s_0 is much smaller than in the case of the LO BFKL. The variation of the predictions in the value of s_0 reflects uncertainties from uncalculated subleading terms. The parametric variation of the LO BFKL predictions is so large that it can be, in fact, neither ruled out nor confirmed at the energy range of CERN LEP2.

The double-logarithmic DGLAP asymptotics related with $\log(Q_A^2/Q_B^2)$ -terms for the total photon-photon cross section was considered in Ref. [12] and found to be small for the CERN LEP2 kinematical region. The point is that most of the CERN LEP2 data [16–18] are collected at the approximately equal virtualities

ties of the colliding photons: $1/2 < Q_A^2/Q_B^2 < 2$. It should be stressed that the soft Pomeron contribution to the $\gamma^*\gamma^*$ total cross section, if estimated within the vector-dominance model, is proportional to $\sigma_{\gamma^*\gamma^*} \sim (m_V^2/Q^2)^4 \sigma_{\gamma\gamma}$ and therefore suppressed for such highly virtual photons as those under consideration.

We also note that the NLO BFKL predictions are consistent [15] with data recently presented by ALEPH [18]. In contrast, the NLO quark-box contribution [19] underestimates the L3 data point at $Y \equiv \log(s_{\gamma\gamma}/\langle Q^2 \rangle) = 6$ by 4 standard deviations. Indeed, the NLO quark-box contribution [19], calculated in massless approximation, can be scaled down from general considerations with the quark masses. For example, at leading order, the inclusion of masses to the quark-box diagram reduces its contribution by 10-15% [19]. Also, the one-gluon exchange added to the (N)LO quark-box contribution is not sufficient to describe the data at $Y = 6$ within (3) 4 standard deviations (see also Fig.4).

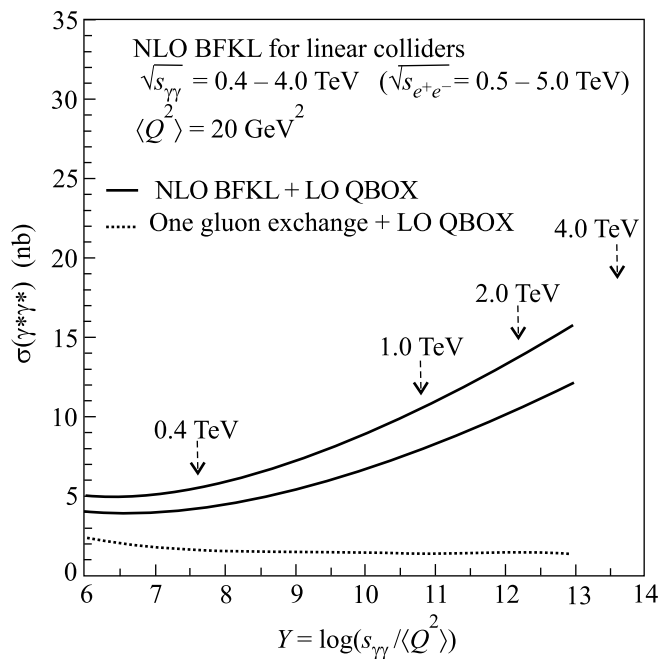


Fig.4. The energy dependence of the total cross section for virtual photon-photon collisions predicted by the NLO BFKL for future linear colliders. The solid curves correspond to the BLM scale-fixed NLO BFKL predictions with $s_0 = Q^2$ (upper curve) and $s_0 = 4Q^2$ (lower curve). The dotted curve shows the one-gluon exchange contribution

In Fig.4 the BLM fixed-scale NLO BFKL predictions for a future linear collider with the photon-photon col-

lider option ($\sqrt{s_{\gamma\gamma}} \leq 0.8\sqrt{s_{e^+e^-}}$) under discussion [20] are shown.

The NLO BFKL phenomenology is consistent with the assumption of small unitarization corrections in the photon-photon scattering at large Q^2 . Thus one can accommodate the NLO BFKL Pomeron intercept value 1.13–1.18 [6] predicted by the BLM optimal scale setting. In the case of hadron scattering, the larger unitarization corrections [21] lead to a smaller effective Pomeron intercept value, about 1.10 [22].

In summary, highly virtual photon-photon collisions provide a very unique opportunity to test high-energy asymptotics of QCD. The NLO BFKL predictions for the $\gamma^*\gamma^*$ total cross section, with the renormalization scale fixed by the BLM procedure, show good agreement with the recent data from OPAL [16] and L3 [17] at CERN LEP2. The obtained results can be very important for future lepton and photon colliders.

The authors thank V. A. Andreev, A. Bohrer, A. De Roeck, J. R. Ellis, J. H. Field, I. M. Ginzburg, A. B. Kaidalov, V. A. Khoze, M. Kienzle-Focacci, M. Krawczyk, C.-N. Lin, V. A. Schegelsky, V. G. Serbo, M. Przybycień, A. A. Vorobyov and M. Wadhwa for helpful discussions. This work was supported in part by the Russian Foundation for Basic Research (RFBR), the INTAS Foundation, the U.S. National Science Foundation, and the U.S. Dept. of Energy under contract # DE-AC03-76SF00515.

1. V. M. Budnev, I. F. Ginzburg, G. V. Meledin, and V. G. Serbo, *Phys. Rep.* **C15**, 181 (1975).
2. V. N. Gribov, L. N. Lipatov, and G. V. Frolov, *Phys. Lett.* **B31**, 34 (1970); *Yad. Fiz.* **12**, 994 (1970) [*Sov. J. Nucl. Phys.* **12**, 543 (1971)]; H. Cheng and T. T. Wu, *Phys. Rev.* **D1**, 2775 (1970).
3. V. S. Fadin, L. N. Lipatov, and E. A. Kuraev, *Phys. Lett.* **B60**, 50 (1975); *Zh. Eksp. Teor. Fiz.* **71**, 840 (1976) [*Sov. Phys. – JETP* **44**, 443 (1976)]; *ibid.* **72**, 377 (1977) [**45**, 199 (1977)].
4. I. I. Balitsky and L. N. Lipatov, *Yad. Fiz.* **28**, 1597 (1978) [*Sov. J. Nucl. Phys.* **28**, 822 (1978)].
5. V. S. Fadin and L. N. Lipatov, *Phys. Lett.* **B429**, 127 (1998); G. Camici and M. Ciafaloni, *Phys. Lett.* **B430**, 349 (1998).
6. S. J. Brodsky, V. S. Fadin, V. T. Kim et al., *Pis'ma ZhETF* **70**, 161 (1999) [*JETP Lett.* **70**, 155 (1999)].
7. S. J. Brodsky, G. P. Lepage, and P. B. Mackenzie, *Phys. Rev.* **D28**, 228 (1983).
8. B. Andersson, G. Gustafson, and J. Samuelsson, *Nucl. Phys.* **B467**, 443 (1996); M. Ciafaloni, D. Colferai, and G. P. Salam, *Phys. Rev.* **D60**, 114036 (1999);

- R. S. Thorne, Phys. Rev. **D60**, 054031 (1999); G. Altarelli, R. D. Ball, and S. Forte, Nucl. Phys. **B599**, 383 (2001).
9. L. N. Lipatov, Zh. Eksp. Teor. Fiz. **90**, 1536 (1986) [Sov. Phys. – JETP **63**, 904 (1986)]; Phys. Rep. **C286**, 131 (1997); L. V. Gribov, E. M. Levin, and M. G. Ryskin, Phys. Rep. **C100**, 1 (1983).
10. J. Bartels, A. De Roeck, and H. Lotter, Phys. Lett. **B389**, 742 (1996); A. Białas, W. Czyż, and W. Florkowski, Eur. Phys. J. **C2**, 683 (1998); J. Kwieciński and L. Motyka, Acta Phys. Pol. **B30**, 1817 (1999); Eur. Phys. J. **C18**, 343 (2000); J. Bartels, C. Ewerz, and R. Staritzbichler, Phys. Lett. **B492**, 56 (2000); N. N. Nikolaev, J. Speth, and V. R. Zoller, Zh. Eksp. Teor. Fiz. **93**, 1104 (2001) [JETP **93**, 957 (2001)].
11. S. J. Brodsky, F. Hautmann, and D. E. Soper, Phys. Rev. **D56**, 6957 (1997); Phys. Rev. Lett. **78**, 803 (1997), **E79**, 3544 (1997).
12. M. Boonekamp, A. De Roeck, C. Royon, and S. Wallon, Nucl. Phys. **B555**, 540 (1999).
13. V. S. Fadin, D. Yu. Ivanov, and M. I. Kotsky, BUDKER-INP-2001-33, DFCAL-TH-01-2 (2001), hep-ph/0106099; J. Bartels, S. Gieseke, and C. F. Qiao, Phys. Rev. **D63**, 056014 (2001), (E) **D65**, 079902 (2002); J. Bartels, S. Gieseke, and A. Kyrieleis, Phys. Rev. **D65**, 014006 (2002).
14. V. T. Kim, L. N. Lipatov, and G. B. Pivovarov, Proc. 29th Int. Symposium on Multiparticle Dynamics (ISMD99), Providence, USA, 1999, hep-ph/9911242; Proc. 8th Blois Workshop (EDS99), Protvino, Russia, 1999, hep-ph/9911228; V. S. Fadin, V. T. Kim, L. N. Lipatov, and G. B. Pivovarov, Proc. XXXV PNPI Winter School, Repino, Russia, 2001, hep-ph/0207296.
15. S. J. Brodsky, V. S. Fadin, V. T. Kim et al., presented at PHOTON2001, Ascona, Switzerland, 2001, SLAC-PUB-9069, CERN-TH/2001-341, hep-ph/0111390, to appear in the Proc.
16. OPAL, G. Abbiendi et al., Eur. Phys. J. **C24**, 17 (2002).
17. L3, P. Achard et al., Phys. Lett. **B531**, 39 (2002).
18. ALEPH, presented by G. Prange at PHOTON2001, Ascona, Switzerland, 2001, to appear in the Proc.
19. M. Cacciari, V. Del Duca, S. Frixione, and Z. Trocsanyi, JHEP **0102**, 029 (2001).
20. M. M. Velasco et al., APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, USA, 2001, hep-ex/0111055; ECFA/DESY Photon Collider Working Group, B. Badelek et al. DESY-TESLA-2001-23, DESY-TESLA-FEL-2001-05 (2001), hep-ex/0108012; CLIC Study Group, J.-P. Delahaye et al., CERN-PS/98-009-LP (1999), Acta Phys. Pol. **B30**, 2029 (1999); ACFA Linear Collider Working Group, K. Abe et al., KEK-REPORT-2001-11 (2001), hep-ph/0109166.
21. A. B. Kaidalov, L. A. Ponomarev, and K. A. Ter-Martirosyan, Yad. Fiz. **44**, 722 (1986) [Sov. J. Nucl. Phys. **44**, 468 (1986)]; M. S. Dubovikov, B. Z. Kopeliovich, L. I. Lapidus, and K. A. Ter-Martirosyan, Nucl. Phys. **B123**, 147 (1977); B. Z. Kopeliovich and L. I. Lapidus, Zh. Eksp. Teor. Fiz. **71**, 61 (1976) [Sov. Phys. – JETP **44**, 31 (1976)].
22. J. R. Cudell, V. Ezhela, K. Kang et al., Phys. Rev. **D61**, 034019 (2000), (E) **D63**, 059901 (2001); J. R. Cudell, A. Donnachie, and P. V. Landshoff, Phys. Lett. **B448**, 281 (1999); M. M. Block, E. M. Gregores, F. Halzen, and G. Pancheri, Phys. Rev. **D58**, 017503 (1998); P. Gauron and B. Nicolescu, Phys. Lett. **B486**, 71 (2000).