The QCD pomeron at TESLA — doubly tagged e^+e^- events [1]

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Abstract

We analyze $\gamma^*\gamma^*$ processes in the high energy regime. For similar virtualities of photons such processes are governed by the QCD pomeron. We give the predictions for the cross-sections using the BFKL equation including dominant non-leading contributions. We also take into account the contribution of the soft pomeron. We give predictions for the total cross-section for the process $e^+e^- \to e^+e^- + hadrons$ with two tagged leptons for the e^+e^- energy which can become accessible at TESLA.

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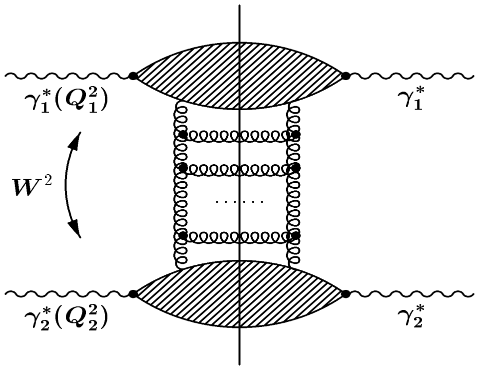
The doubly tagged $e^+e^- \to e^+e^-$ hadrons events at high energies give access to diffractive $\gamma^*\gamma^*$ physics. With the tagging angle greater than 30 mrad, the typical virtualities of the photons which will mediate the doubly tagged events at TESLA would be larger than 50 GeV^2. Furthermore, by imposing suitable cuts on the tagged electrons energies one may select events with the $\gamma^*\gamma^*$ energy W falling into the high energy regime. Such two photon processes are governed by perturbative QCD at high energies (see Fig. 1), and may therefore provide excellent tests of our understanding of the QCD pomeron [1, 2, 3]. The additional advantage comes from the fact that in these processes the virtualities of both (virtual) photons are of comparable size and the DGLAP effects are rather small. Thus the Balitzkij, Fadin, Kuraev, Lipatov (BFKL) [4, 5] evolution should play a crucial role here.

Existing estimates of the total cross-sections of the process $\gamma^*\gamma^* \to hadrons$ have been performed within the leading logarithmic approximation of the QCD pomeron. As explained in a previous report [6], it is necessary to include also the non-leading corrections to the BFKL equation [7]. As in the previous case [6] we shall present results of calculations [8] based on the BFKL equation with the consistency constraint which corresponds to the condition that the virtualities of the gluons propagating along the gluon ladder [9] are dominated by the transverse momenta squared.



The QCD pomeron exchange mechanism of the process $\gamma_1^*(Q_1^2)\gamma_2^*(Q_2^2) \to hadrons$.

The cross-section of the process $e^+e^- \to e^+e^- + hadrons$ (averaged over the angle ϕ between the lepton scattering planes in the frame in which the virtual photons are aligned along the z axis) is given by the following formula (see e.g Ref [1]):

$$\frac{Q_1^2 Q_2^2 d\sigma}{dy_1 dy_2 dQ_1^2 dQ_2^2} = \left(\frac{\alpha}{2\pi}\right)^2 [P^{(T)}_{\gamma/e^+}(y_1)P^{(T)}_{\gamma/e^-}(y_2)\sigma^{TT}_{\gamma^*\gamma^*}(Q_1^2, Q_2^2, W^2)+$$

$$P^{(T)}_{\gamma/e^+}(y_1)P^{(L)}_{\gamma/e^-}(y_2)\sigma^{TL}_{\gamma^*\gamma^*}(Q_1^2, Q_2^2, W^2) + P^{(L)}_{\gamma/e^+}(y_1)P^{(T)}_{\gamma/e^-}(y_2)\sigma^{LT}_{\gamma^*\gamma^*}(Q_1^2, Q_2^2, W^2)+$$

$$P^{(L)}_{\gamma/e^+}(y_1)P^{(L)}_{\gamma/e^-}(y_2)\sigma^{LL}_{\gamma^*\gamma^*}(Q_1^2,Q_2^2,W^2)] \tag{1}$$

where $P^{(T)}_{\gamma/e}(y) = [1+(1-y)^2]/y$ and $P^{(L)}_{\gamma/e}(y) = 2(1-y)/y$. In Eq. (1) y_1 and y_2 are the longitudinal momentum fractions of the parent leptons carried by virtual photons, $Q_i^2 = -q_i^2$ $(i = 1,2)$ where $q_{1,2}$ denote the four momenta of the virtual photons and W^2 is the total CM energy squared of the two (virtual) photon system, i.e. $W^2 = (q_1+q_2)^2$. The cross-sections $\sigma^{ij}_{\gamma^*\gamma^*}(Q_1^2,Q_2^2,W^2)$ are the total cross-sections of the process $\gamma^*\gamma^* \to$ *hadrons* and the indices $i,j = T,L$ denote the polarization of the virtual photons. The functions $P^{(T)}_{\gamma/e}(y)$ and $P^{(L)}_{\gamma/e}(y)$ are the transverse and longitudinal photon flux factors.

The total $\gamma^*\gamma^*$ cross-section at very large photon virtualities is dominated by the perturbative contribution. However, it is necessary to check at which value of Q^2 the hard part starts to dominate over the soft effects. In our study we model the latter ones using a Regge motivated description of the soft pomeron. Thus we may write:

$$\sigma_{\gamma^*\gamma^*}(Q_1^2,Q_2^2,W^2) = \sigma_{hard}(Q_1^2,Q_2^2,W^2) + \sigma_{soft}(Q_1^2,Q_2^2,W^2). \tag{2}$$

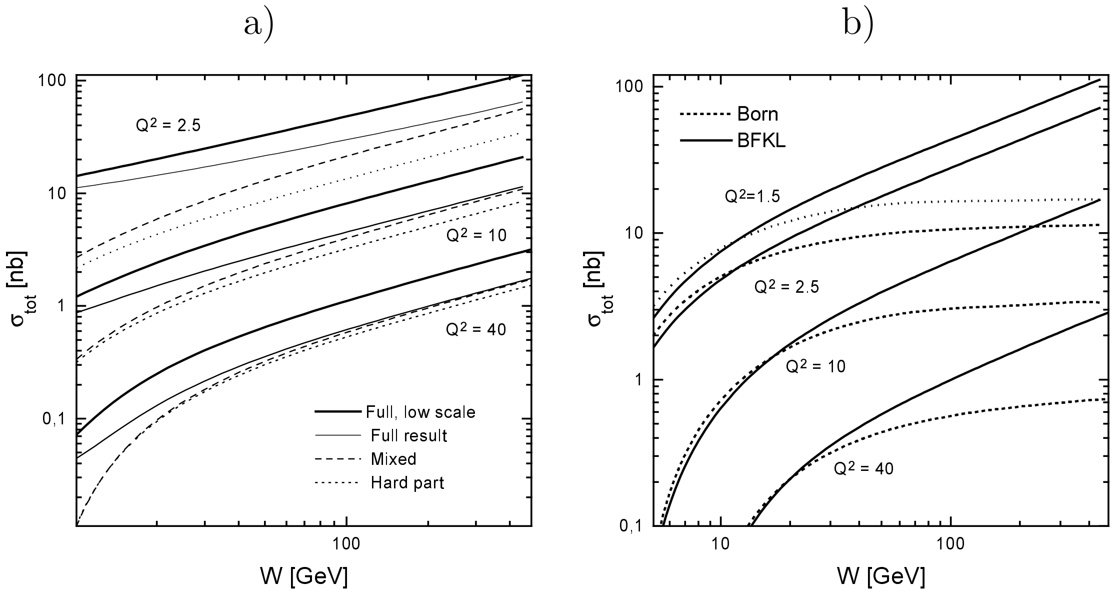
Since the perturbation theory is only reliable if the transverse gluons along the ladder are hard enough i.e the transverse momenta of these gluons $\boldsymbol{k}^2 > k_0^2$, we neglect contributions to the perturbative part from the configurations with $\boldsymbol{k}^2 < k_0^2$. The contribution from this infra-red region is entirely assigned to the soft pomeron. The precise choice of k_0 is rather arbitrary, but this parameter should be of the order of Λ_{QCD} so we make a rather conservative choice and set $k_0 = 1$ GeV.

The soft pomeron contribution to $\gamma^*\gamma^*$ scattering may be obtained from the Gribov factorisation formula:

$$\sigma_{soft}(Q_1^2,Q_2^2,W^2) = \frac{\sigma^{SP}_{\gamma^*(Q_1^2)p}(Q_1^2,W^2)\sigma^{SP}_{\gamma^*(Q_2^2)p}(Q_2^2,W^2)}{\sigma_{pp}(W^2)} \tag{3}$$

We assume that this term is only contributing to the transverse part. In equation (3) the cross-sections $\sigma^{SP}_{\gamma^*(Q_i^2)p}(Q_i^2,W^2)$ and $\sigma^{SP}_{pp}(W^2)$ are the soft pomeron contributions to the γ^*p and pp total cross sections and their parametrisation is taken from Refs. [11, 12].

The perturbative parts of $\gamma^*\gamma^*$ cross-sections are obtained as follows. The impact factors Φ_0 illustrated by the shaded blobs in Fig. 1 are calculated in the lowest order of perturbative QCD. They correspond to the sum of all elementary diagrams in which a pair of gluons couples to a quark loop. We take into account the contributions from the light flavours and from the c-quark. The phase space for the quark-antiquark pairs in the final state is taken into account exactly i.e. we go beyond the asymptotic expression for very large energies which will result in the showing up of some threshold effects for moderate energies. Then the BFKL ladders are built on the impact factor Φ_0 corresponding to the lower γ^* virtuality. The resummation of the ladder diagrams is described by the BFKL equation for which the inhomogeneous term is given by the sum of the perturbative impact factor Φ_0 and some additional source of gluons from the soft pomeron.



Energy dependence of the cross-section $\sigma^{TT}_{\gamma^*\gamma^*}(Q_1^2, Q_2^2, W^2)$ for the process $\gamma^*(Q_1^2)\gamma^*(Q_2^2) \to$ hadrons for various choices of photon virtualities $Q^2 = Q_1^2 = Q_2^2$: a) Complete i.e. including soft and QCD pomeron contributions results. For each choice of the virtuality Q^2 four curves are shown taking into account hard effects only ("hard part"), hard amplitude with soft pomeron contributions added in the source term of the BFKL equation ("mixed"), the full cross-section including both soft and hard pomeron contributions ("full result"). We also show the "full result" with the low scale of α_s in the impact factors: $\mu^2 = (k^2 + m_q^2)/4$. b) Comparison of the complete contribution of the perturbative QCD pomeron to the cross-section $\sigma^{TT}_{\gamma^*\gamma^*}(Q^2, Q^2, W^2)$ (continuous line) with its Born term component corresponding to the two gluon exchange mechanism (dotted line).

In Fig. 2a we show our results for $\sigma^{TT}_{\gamma^*\gamma^*}(Q_1^2, Q_2^2, W^2)$ plotted as function of the CM energy W for three different values of Q^2 where $Q_1^2 = Q_2^2 = Q^2$. After confronting our predictions [8] with the results from LEP and LEP2 [13] we found that better description of data is obtained when we choose the value of $\mu^2 = (m_q^2 + k^2)/4$ (instead of the standard one: $\mu^2 = (m_q^2 + k^2)$) for the scale of the α_s which appears in the impact factors. Thus we shall rely on this choice also when studying the TESLA physics. Let us mention, that the uncertainty of the cross-section due to the ambiguous value of α_s is smaller at TESLA than at LEP.

We see from this figure that the effects of the soft pomeron contribution are non-negligible at low and moderately large values of $Q^2 < 10$ GeV^2 and for moderately large values of $W < 100$ GeV. The QCD pomeron however dominates already at $Q^2 = 40$ GeV^2. This means, that in contrast to the LEP case, at TESLA one can trust the perturbative result. We also see from this figure that for low energies $W < 40$ GeV the phase-space limitations are very important. For $W > 40$ GeV or so one observes that the cross-section exhibits the effective power-law behaviour $\sigma^{TT}_{\gamma^*\gamma^*}(Q^2, Q^2, W^2) \sim (W^2)^\lambda$. The (effective) exponent increases weakly with increasing Q^2 and varies from $\lambda = 0.28$ for $Q^2 = 2.5$ GeV^2 to $\lambda = 0.33$ for $Q^2 = 40$ GeV^2. This (weak) dependence of the effective exponent λ on Q^2 is the result of the interplay between soft and hard pomeron contributions, where the former becomes less important at large Q^2. The shape of the remaining cross sections $\sigma^{TL}_{\gamma^*\gamma^*}$, $\sigma^{LT}_{\gamma^*\gamma^*}$ and $\sigma^{LL}_{\gamma^*\gamma^*}$ as functions of W is the same as that of $\sigma^{TT}_{\gamma^*\gamma^*}$. They do however differ in their relative normalisation.

In Fig. 2b we compare the QCD pomeron contribution to the cross-section $\sigma^{TT}_{\gamma^*\gamma^*}$ with the Born term, which corresponds to the two-gluon exchange mechanism. For large values of the CM energy W the two-gluon exchange mechanism gives energy independent contribution to the cross-section $\sigma^{TT}_{\gamma^*\gamma^*}$. In the low energy region its energy dependence (i.e. the onset of the constant asymptotic behaviour) is controlled by phase space effects. We can also see from this figure that the dominance of the BFKL pomeron over its Born term is delayed to higher energies. In the low energy region the cross-section corresponding to the solution of the modified BFKL equation is even smaller than that which is given by the Born term.

We have calculated the total cross-section of the process $e^+e^- \to e^+e^- + hadrons$ for LEP1 and LEP2 energies and confronted results of our calculation with the recent experimental data obtained by the L3 collaboration at LEP [13]. Comparison of our results with experimental data was summarised in [8]. We arrived at a rather unexpected conclusion, that the available LEP data for $\gamma^*\gamma^*$ cross-section probe mainly the region of energies and virtualities for which the soft pomeron contribution is non-negligible. Besides that, at LEP the BFKL enhancement of the two-gluon exchange amplitude should not occur. However, let us mention that our predictions tend to underestimate the LEP2 data, even with the choice of the lower scale for α_s, although the error bars are still too large to be conclusive about it. The two possible reasons for explaining this discrepancy could be either our choice of a too high value of the infrared cut-off k_0 or the lack of higher order QCD corrections to the impact factors in our calculations. Thus, our the predictions for TESLA may be also too low by a factor of about 1.5.

θ_{min} — θ_{max}	$\sigma(e^+e^- \to e^+e^- + hadrons)$ [fb]			Events / year
	Born	Hard	Full (LS)	Full (LS)
10–20	134	365	450	9000
20–30	16	41	46	920
30–40	3.5	8	9	180
40–50	1.1	2.3	2.5	50
50–70	0.6	1.1	1.3	26
30–70	5.2	11	13	260

Predictions for TESLA at e^+e^- energy equal to 500 GeV.
Cross-sections for the pomeron mediated $e^+e^- \to e^+e^- + hadrons$ process with tagged electrons $E_{tag} > 30$ GeV, $y_i > 0.1$, 2.5 GeV$^2 < Q_i^2 < 300$ GeV^2, $2 < \log[W^2/(Q_1Q_2)] < 10$, $\theta_{min} < \theta_{tag} < \theta_{max}$. Results of the calculation with the low scale of α_s in impact factors: two-gluon exchange, hard and full (hard+soft) contributions and the expected number of events per year, assuming the integrated luminosity per year to be $\mathcal{L} = 20$ fb^{-1}.

In Tab. 1 we show results of our estimate for the cross-section for the process $e^+e^- \to e^+e^- + hadrons$ with tagged e^+e^- in the final state for the total CM energy of the e^+e^- system equal to 500 GeV. We can see that in this very high energy region the QCD pomeron dominates over the soft pomeron contribution even for very low tagging angles. These cross-sections are also bigger by about a factor equal to 2–3 than the two-gluon exchange "background". Thus the BFKL enhancement should be well seen, especially when tagging at low angles could be realized. If the integrated luminosity at TESLA reached the planned value the collected statistics of doubly tagged $e^+e^- \to e^+e^- hadrons$ would be high enough to perform detailed studies of the energy dependence of the $\gamma^*\gamma^*$ cross-section. The optimal tagging angle for BFKL studies should lay between 20 and 30 mrad, to assure the virtualities of photons to be large and not to suppress the event rate too much. If such the conditions will be realized then TESLA may provide us with excellent data probing the nature of the QCD pomeron.

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