Photon '95

Incorporating the Xth International Workshop on Gamma–Gamma Collisions and Related Processes

Editors

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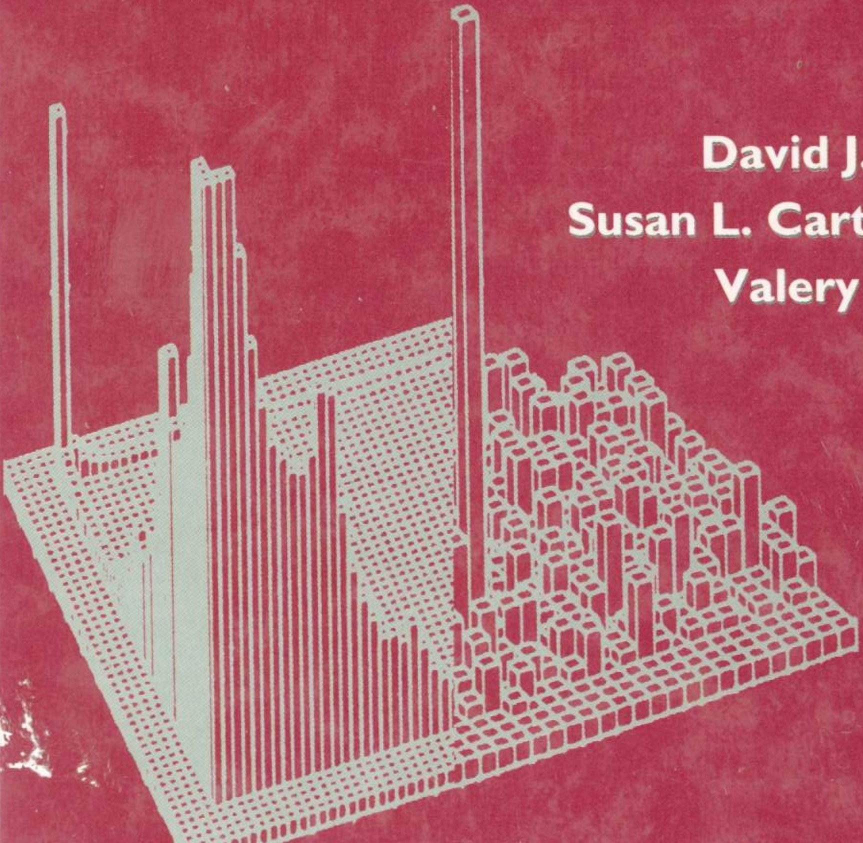

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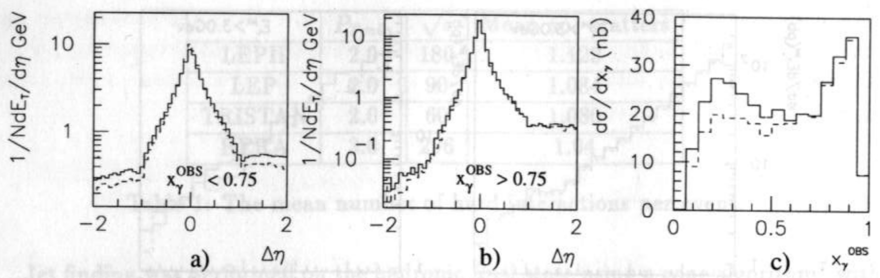

Figure 3: The E_T jet profile in η, for a) $x_\gamma^{obs} < 0.75$ and b) $x_\gamma^{obs} \geq 0.75$. c) x_γ^{obs} distribution for dijets, at HERA energies, with direct contribution. Including multiple scattering (solid line) and with multiple scattering turned off (broken line).

order that unitarity is not violated. Our model indicates that the effect of multiple scattering is significant at both HERA and LEPII energies. For reasonable experimental cuts, the inclusion of multiple scattering leads to significant changes in inclusive and dijet cross sections which should be understood before attempting to unfold to parton distribution functions.

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THE GLUON TRAJECTORY IN THE NEXT TO LEADING APPROXIMATION

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ABSTRACT

The trajectory of the Reggeized gluon in QCD is obtained in two-loop approximation. It is extracted from scattering amplitudes with gluon quantum numbers in t-channel, calculated in the two-loop approximation at large energy $\sqrt{s}$ and fixed momentum transfer $\sqrt{-t}$, for two processes: quark-quark scattering and gluon-gluon scattering. Both approaches give the same result, confirming the gluon Reggeization beyond the leading logarithmic approximation.

1. Introduction

It's often claimed, that the QCD perturbation theory can be used for calculation of parton distributions and cross sections with typical virtuality Q^2 large enough to ensure a smallness of the strong coupling constant $\alpha_s(Q^2)$. But at sufficiently high energy $\sqrt{s}$ of colliding particles logarithm of the ratio $\frac{1}{x} = \frac{s}{Q^2}$ happens to be so large that it becomes necessary to sum up terms of the type $\alpha_s^n(ln\frac{1}{x})^m$. In the leading logarithmic approximation (LLA) this problem was solved many years ago[1]. Now the results of the LLA are widely used. But these results have at least two serious disadvantages.

Firstly, the Froissart bound $\sigma_{tot} < c \ln^2 s$ is violated in LLA:

$$\sigma_{tot}^{LLA} \sim \frac{s^{\omega_0}}{\sqrt{\ln s}}, \tag{1}$$

where, for the gauge group SU(N) ($N = 3$ for QCD),

$$\omega_0 = \frac{g^2}{\pi^2} N \ln 2 \tag{2}$$

Here g is the coupling constant of the gauge theory ($\alpha_s = \frac{g^2}{4\pi}$).

In terms of structure functions it means a strong power increase in the small x region. The Froissart bound is violated in LLA because the s-channel unitarity constraints for scattering amplitudes are not completely taken into account in this approximation. The problem of *unitarization* of LLA results is extremely important from a theoretical point of view. It is concerned in a lot of papers (see, for example, Ref.[2]).

Another disadvantage seems to be even more important from a practical point of view. Since the results of LLA are applied to the small x phenomenology (see, for instance, Ref.[3]), there is an uncertainty of the argument of the running coupling constant which appears because the scale dependence of α_s is beyond of the accuracy of LLA. This uncertainty diminishes a predictive power of LLA, permitting to strongly vary numerical results by changing a scale.

Therefore, the problem of the calculation of radiative corrections to LLA becomes very important now, as it gives us the possibility to fix the scale dependence of the coupling constant, to reduce the uncertainty of the predictions of LLA and to determine a region of its applicability.

2. Method of calculation

A solution of this problem can be strongly simplified[4] by using the Reggeization property of the non-Abelian SU(N) gauge theories. It was proved[1,5] in LLA that gauge bosons are Reggeized in these theories with the trajectory

$$j(t) = 1 + \omega(t) \, , \tag{3}$$

where in the leading approximation,

$$\omega(t) = \omega^{(1)}(t) = \frac{g^2 t}{(2\pi)^{3+\epsilon}} \frac{N}{2} \int \frac{d^{2+\epsilon} k_\perp}{k_\perp^2 (q-k)_\perp^2} \, , \tag{4}$$

Here q is the momentum transfer and $t = q_\perp^2$. The integration is performed over the two-dimensional momentum orthogonal to the initial particle momentum plane, and dimensional regularization of Feynman integrals is used:

$$\frac{d^2 k}{(2\pi)^2} \to \frac{d^{2+\epsilon} k}{(2\pi)^{2+\epsilon}}, \qquad \varepsilon = D - 4 \, , \tag{5}$$

where D is the space-time dimension ($D = 4$ for the physical case).

The problem of calculation of the radiative corrections to the LLA is reduced [4] to calculation of corrections to the kernel of the Bethe-Salpeter type equation for the t-channel partial amplitude with the vacuum quantum numbers[1]. The equation is constructed in terms of the gluon trajectory and the Reggeon-Reggeon-Gluon (RRG) vertex. Corrections to the vertex are known now[6,7], so the problem of calculation of the contibution $\omega^{(2)}(t)$ to the trajectory in the next (two-loop) approximation became most urgent. This contribution can be obtained from s-channel discontinuity $\left[\left(\mathcal{A}_8^{(-)} \right)_{AB}^{A'B'} \right]_s$ of the elastic scattering amplitude $\left(\mathcal{A}_8^{(-)} \right)_{AB}^{A'B'}$ $(two - loop)$ with gluon quantum numbers and negative signature in the t-channel, calculated in the two-loop approximation with accuracy up to constant. Indeed, let us consider the amplitude of the scattering process $A + B \longrightarrow A' + B'$ with the gluon quantum numbers in the t-channel and negative signature. If high energy asymptotic of this amplitude at fixed momentum transfer is given by simple Regge pole, it has the following factorized form:

$$\left(\mathcal{A}_8^{(-)} \right)_{AB}^{A'B'} = \Gamma^c_{A'A} \frac{s}{t} [(\frac{s}{-t})^{\omega(t)} + (\frac{-s}{-t})^{\omega(t)}] \Gamma^c_{B'B} \, , \tag{6}$$

where $\Gamma^c_{A'A}$ are the particle-particle-reggeon (PPR) vertices. They can be presented as

$$\Gamma^i_{A'A} = g < A'|T^i|A > (\Gamma^{(0)}_{A'A} + \Gamma^{(1)}_{A'A}), \tag{7}$$

where $< A'|T^i|A >$ stands for a matrix element of a colour group generator in corresponding representation (i.e. adjoint for gluons and fundamental for quarks), $\Gamma^{(0)}_{A'A}$ and $\Gamma^{(1)}_{A'A}$ are the Born and one-loop contributions to the PPR vertices. Using this form one obtains for the two loop contribution to the discontinuity $\left[\left(\mathcal{A}_8^{(-)} \right)_{AB}^{A'B'} \right]_s$ from eq.(6):

$$\left[\left(\mathcal{A}_8^{(-)} \right)_{AB}^{A'B'} \right]_s (two - loop) = -2\pi i g^2 < A'|T^i|A >< B'|T^i|B > \frac{s}{t} \times$$
$$\times [\Gamma^{(0)}_{A'A} (\omega^{(1)}(t))^2 (\ln \frac{s}{-t}) \Gamma^{(0)}_{B'B} + (\Gamma^{(0)}_{A'A} \Gamma^{(1)}_{B'B} + \Gamma^{(1)}_{A'A} \Gamma^{(0)}_{B'B}) \omega^{(1)}(t)$$
$$+ \Gamma^{(0)}_{A'A} \omega^{(2)}(t) \Gamma^{(0)}_{B'B}]. \tag{8}$$

Since one-loop corrections $\Gamma^{(1)}_{A'A}$ to the PPR vertices became available[6,8,9], the only unknown quantity in the r.h.s. of the eq.(8) is the two loop contribution $\omega^{(2)}(t)$ to the gluon trajectory. Therefore one can find it having $\left[\mathcal{A}_8^{(-)} \right]_{AB}^{A'B'}$ $(two - loop)$ with accuracy up to constant.

3. The discontinuity of the quark-quark scattering amplitude

By definition the trajectory should not depend on scattered particles, so we may choose any process for its calculation. Here we will discuss the process of quark-quark scattering. Calculation of the s-channel discontinuity of the quark-quark scattering amplitude is briefly presented below. Details of the calculation will be given elsewhere[10]. For simplicity the case of massless quarks is considered here. In this case the helicity of each of the colliding particles is strictly conserved, therefore the PPR vertices $\Gamma^c_{A'A}$ have definite spin structure, as well as the colour structure[1,9]:

$$\Gamma^i_{Q'Q} = g < Q'|T^i|Q > \delta_{\lambda_{Q'} \lambda_Q} (1 + \Gamma^{(+)}_{QQ}). \tag{9}$$

where $\lambda_{Q'}$, λ_Q are quark helicities and $\Gamma^{(+)}_{QQ}$ is a one-loop correction to the vertex calculated in Ref.[9].

The conservation of helicities of each of colliding particles permits us to present the s-channel discontinuity of the part $\mathcal{A}_8^{(-)}$ of the amplitude with gluon quantum numbers in the t-channel and negative signature in the following form

$$\left[\left(\mathcal{A}_8^{(-)}\right)_{AB}^{A'B'}\right]_s = g^2 < A'|T^i|A >< B'|T^i|B > \delta_{\lambda_A\lambda_{A'}}\delta_{\lambda_B\lambda_{B'}}(\frac{-2\pi i s}{t})\Delta_s. \qquad (10)$$

In the two-loop approximation the discontinuity under consideration is given by sum of contributions coming from two particle intermediate state in the s-channel and from three particle one:

$$\Delta_s = \Delta_s^{(2)} + \Delta_s^{(3)}. \qquad (11)$$

For the first contribution we obtain (here and below all vectors are $(D-2)$-dimensional, transverse to the p_A, p_B-plane, $k = q_1 - q_2$, $t = q^2$)

$$\Delta_s^{(2)} = \frac{-2g^4N^2t}{(4\pi)^{\frac{D}{2}}}\frac{\Gamma(2-\frac{D}{2})\Gamma^2(\frac{D}{2}-1)}{\Gamma(D-3)}\int\frac{d^{(D-2)}q_1}{(2\pi)^{(D-1)}}\frac{1}{(q_1-q)^2(-q_1^2)^{3-\frac{D}{2}}}\times$$

$$\times\left[\ln(\frac{s}{-q_1^2}) + c_g + c_q\right] \qquad (12)$$

where c_g and c_q - coefficients connected with gluon and quark contributions correspondingly;

$$c_g = \psi(3-\frac{D}{2}) - 2\psi(\frac{D}{2}-2) + \psi(1) + \frac{1}{(D-3)}(\frac{1}{4(D-1)} - \frac{2}{D-4} - \frac{7}{4}),$$

$$c_q = \frac{1}{N(D-3)}\left[-\frac{n_f(D-2)}{2(D-1)} - \frac{1}{2N}(D-4+\frac{D}{D-4})\right]. \qquad (13)$$

Here $\psi(x)$ is the logarithmic derivative of the gamma-function:

$$\psi(x) = \frac{\Gamma'(x)}{\Gamma(x)}.$$

It is convenient to divide the contribution $\Delta_s^{(3)}$ into two pieces:

$$\Delta_s^{(3)} = \Delta_s^{(3a)} + \Delta_s^{(3na)} \qquad (14)$$

The first one has an abelian nature, and only this part survives in the abelian case; the second is essentially nonabelian. We obtain:

$$\Delta_s^{(3a)} = \frac{g^4t}{4}(\frac{2}{D-4} - \frac{2}{D-3} + \frac{1}{2})\int\frac{d^{(D-2)}q_1 d^{(D-2)}q_2}{(2\pi)^{(2D-2)}q_1^2q_2^2}\times$$

$$\times\left[\frac{-q^2}{(q_1-q)^2(q_2-q)^2} + \frac{2}{(q_1+q_2-q)^2}\right], \qquad (15)$$

and

$$\Delta_s^{(3na)} = \frac{g^4N^2t}{4}\int\frac{d^{(D-2)}q_1d^{(D-2)}q_2}{(2\pi)^{(2D-2)}q_2^2(q_2-q)^2}[2(\psi(D-3)-\psi(1) \qquad (16)$$

$$+\frac{3}{4(D-3)})\left(\frac{-q^2}{q_1^2(q_1-q)^2} + \frac{2q_2^2}{q_1^2(q_1-q_2)^2}\right) + \frac{q^2\ln(\frac{s}{-k^2})}{q_1^2(q_1-q)^2} - \frac{2q_2^2\ln(\frac{s}{-q_1^2})}{q_1^2(q_1-q_2)^2}\Bigg].$$

4. Two-loop correction to the gluon trajectory

Eq.(8), together with eqs.(9) and (10), gives us

$$\omega^{(2)}(t) = \Delta_s - \left(\omega^{(1)}(t)\right)^2\ln\left(\frac{s}{-t}\right) - 2\Gamma_{QQ}^{(+)}\omega^{(1)}(t). \qquad (17)$$

The one-loop correction to the helicity conserving part of the quark-quark-reggeon vertex[9] can be presented as

$$\Gamma_{QQ}^{(+)} = \frac{g^2N}{(4\pi)^{\frac{D}{2}}}(-t)^{\frac{D}{2}-2}\frac{\Gamma(2-\frac{D}{2})\Gamma^2(\frac{D}{2}-1)}{\Gamma(D-3)}(c_g+c_q), \qquad (18)$$

where c_g and c_q are given by eq.(13), whereas the one-loop conribution for the trajectory (4) can be written as

$$\omega^{(1)}(t) = \frac{g^2N}{(4\pi)^{\frac{D}{2}}}(-t)^{\frac{D}{2}-2}2\frac{\Gamma(2-\frac{D}{2})\Gamma^2(\frac{D}{2}-1)}{\Gamma(D-3)}. \qquad (19)$$

Using these relations together with eqs.(11)-(16) we obtain from eq.(17) the final result:

$$\omega^{(2)}(t) = \frac{g^4t}{4}\int\frac{d^{(D-2)}q_1d^{(D-2)}q_2}{(2\pi)^{(2D-2)}q_1^2q_2^2}\left[\frac{q^2N^2}{(q_1-q)^2(q_2-q)^2}\ln(\frac{q^2}{(q_1-q_2)^2}) + \right.$$

$$\frac{2N^2}{(q_1+q_2-q)^2}\ln(\frac{q_1^2}{(q_1-q)^2}) + \left(\frac{-q^2}{(q_1-q)^2(q_2-q)^2} + \frac{2}{(q_1+q_2-q)^2}\right)\times$$

$$\times\left(N^2(2\psi(D-3) + \psi(3-\frac{D}{2}) - 2\psi(\frac{D}{2}-2) - \psi(1) + \right.$$

$$\left.\left.\frac{1}{(D-3)}(\frac{1}{4(D-1)} - \frac{2}{D-4} - \frac{1}{4})) - \frac{n_fN(D-2)}{2(D-1)(D-3)}\right)\right]. \qquad (20)$$

5. Discussion

In the physical case $D = 4$ the correction (20) shows up divergences which are both ultraviolet and infrared. The former ones are not difficult to deal with. They are due to simple first order poles and can be removed by expressing the bare coupling constant g in terms of the renormalized one in the total expression for the trajectory. The infrared divergences, on the contrary, are much more severe. They could not be cancelled inside the trajectory $\omega(t)$ because the gluon is a colour object, whereas we may expect their cancellation only for the scattering of a colourless objects. So, we should check the cancellation of the infrared divergences when the trajectory were put into the Bethe-Salpeter type equation for the amplitude with vacuum quantum numbers in the t channel.

As it was mentioned above, the trajectory can not depend on scattered particles. In the derivation presented we have used the quark-quark-scattering amplitude. Calculation of the s-channel discontinuity of the gluon-gluon scattering amplitude[11] gives us the same result.

6. Acknowledgement

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Modification of the equivalent photon approximation (EPA) for 'resolved' photon processes. *

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ABSTRACT

We propose a modification of the equivalent photon approximation (EPA) for processes which involve the parton content of the photon, to take into account the suppression of the photonic parton fluxes due to the virtuality of the photon. We present simple, physically motivated ansätze to model this suppression and show that even though the parton content of the electron no longer factorizes into an electron flux function and photon structure function, it is still possible to express it as a single integral. We also show that for the TRISTAN experiments its effect can be numerically of the same size as that of the NLO corrections. Further, we discuss a possible measurement at HERA, which can provide an experimental handle on the effect we model through our ansätze.

Studies of jet production in $\gamma\gamma$ (e^+e^-) collisions at TRISTAN and LEP[2] and in γp (ep) collisions at HERA[3] have yielded clear evidence for hard scattering from partons in the photon or the so called 'resolved' processes[4]. Having confirmed the existence of these contributions to jet production, the next step is to use them to get further information[5] about the parton content of the photon, especially $g^\gamma(x, Q^2)$, about which very little direct information is available so far. To that end one needs to address the question of uncertainties in the theoretical predictions of these cross-sections. This implies that the approximations made in the calculations need to be improved. In this short note we study the issue of improvement of one of these approximations.

Theoretical calculations for the e^+e^- and ep processes are usually done in the framework of the Weizsäcker–Williams (WW) approximation also alternatively called the equivalent photon approximation (EPA)[6,7]. In this approximation the cross–section for a process $e + X \to e + X'$ where a γ is exchanged in the t/u channel, is given in terms of the cross–section for the process $\gamma + X \to X'$ (for an *on-shell* γ) and the flux factor $f_{\gamma|e}(z)$ for a photon to carry energy fraction z of the e. For example,

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Current status of Photon Colliders

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Abstract

Future linear colliders offer unique opportunities to study $\gamma\gamma$, γe interactions. Using the laser backscattering method one can obtain $\gamma\gamma$,γe colliding beams with the energy and luminosity comparable to the luminosity in electron-positron collisions or even higher. Recent Workshops devoted to Photon Colliders have not revealed any show-stoppers and it was a common opinion that linear colliders should from the start have the capabilities of e^+e^-, ee, $\gamma\gamma$, γe collisions. In this talk a present status of Photon colliders is disscussed.

1 Introduction

Since 1970 two-photon physics has been actively studied at e^+e^- storage rings in collisions of virtual photons. These studies have essentially contributed to modern particle physics. Much of data were collected on C–even resonances, total cross sections, jets, photon structure functions etc. It was found that two-photon widths of some particles are much smaller than for $q\bar{q}$ states. This manifests their unusual structure.

However, we should agree that although the results obtained in these collisions are very important and supplemented essentially to those obtained in other collisions, frontiers of particle physics were not here. This is because the number of equivalent photons accompanying each electron is small: $dn \sim 0.035 d\omega/\omega$, and so the effective two-photon luminosity is much lower than that in e^+e^- collisions, has wide spread and decreases rapidly with the energy. For example, for $W_{\gamma\gamma}/2E_0 > 0.4$ the luminosity $L_{\gamma\gamma} \sim 10^{-3}\ L_{e^+e^-}$ (and even less after imposing cuts necessary for selection of two-photon events).

Future linear colliders which are being developed now offer unique, much richer than before, opportunities to study $\gamma\gamma$ and γe interactions with energies and luminosities comparable to those in e^+e^- collisions [1–2]. Photons with a high energy $\omega \sim E_0$ can be obtained by scattering of laser photons (of eV energy) on high energy electrons[3]. This is possible because, unlike the situation in storage rings, in linear colliders each bunch is used only once. It turns out that using a laser with 1-3 J flash energy one can "convert" most electrons to high energy photons. After scattering, the high energy photons follow the direction of initial electrons with a small additional angular spread about $1/\gamma$ to the

IP (interaction point) located at a distance b $\sim$ 1 cm away from the coversion point. The photon spot size at IP may be almost equal to that of electrons at IP and therefore the luminosity of $\gamma\gamma$ (or γe) collisions will be of the same order as the "geometric" luminosity of basic ee beams (positrons are not necessary for a photon collider). Due to the absence of some collision effects the luminosity of $\gamma\gamma$ collisions larger than in e^+e^- collisions may also be possible. The colliding photon beams will be nonmonochromatic but with the pronounced maximum of the energy spectrum near its high energy bound; moreover, one can prepare $\gamma\gamma$(or γe) collisions in such a way that the essential part of the luminosity will be concentrated within about 10% interval at highest invariant masses; the photons in this part of spectrum may have a high degree of circular polarization which is very advantageous for experiments.

The expected physics in $\gamma\gamma$ and γe collisions at high energies and luminosities is very rich and complements that in e^+e^- collisions[4-6]. Photons couple directly (at tree graph level) to all charged particles — leptons, quarks, W's, supersymmetric particles, etc.; they couple also to gluons, Z^0's or one or more Higgs bosons through quark and W box diagrams. Some examples are: a photon collider is a W-factory with 10^6–10^7 W's/year in different reactons, that is the best laboratory for a gauge boson studies and searches for their anomalous interactions; production and studies of charged particles (pairs, SUSY, leptoquarks, excited...) with the cross sections higher than in e^+e^- collisions; search for and measurement of the two photon width of the Higgs boson; study of tt-quark system in p-wave; study of structure functions, diffraction, total cross section.

The photon colliders discussed will have no disadvantages enumerated for collisions of virtual photons because their energies and luminosities are roughly the same as those proposed for e^+e^- LC and near those for pp collider LHC. Therefore one can expect the conceptually new discoveries here — just as at other new high energy colliders.

Basic features of photon colliders (photon spectra and monochromatization of collisions, polarization effects, collision effects restricting the luminosities, schemes of the interaction region, requirements for accelerators, attainable luminosities etc.) are understood now rather well [2, 7, 8, 10]. A comprehensive review on various theoretical and experimental issues for $\gamma\gamma$ colliders can be found in the Proceedings of a recent workshop [11]. The common opinion of this workshop was expressed in the "Memorandum to HEPAP Sub-panel on the Future of High Energy Physics", below are some extracts:

...As a result of the $\gamma\gamma$ Workshop, we have come to the following conclusions:

1) ...we believe that some day a high energy linear collider is likely to be built...

2) ...the overwhelming consensus of the Workshop is that when a linear collider is built, it should from the start have the capability of $e^+e^-,\gamma e,\gamma\gamma$ collisions. Why? Because the physics capabilities and systematics of the different modes are often different and unique.

3) ...physics goals for a gamma-gamma collider are significant...

4) ...the technology (lasers etc.) is sufficiently advanced that it is now possible to seriously considers a $\gamma\gamma$ collider...

5) ...there are no show-stoppers to $\gamma\gamma,\gamma e$ colliders

6) ... required for $\gamma\gamma,\gamma e$ colliders is no more difficult or technologically risky than for e^+e^- colliders

7) ...design of a linear collider should include interaction region dedicated to γe, $\gamma\gamma$ collisions

8) ...incremental cost of adding gamma collisions is relatively small

9) R&D on photon colliders should be integrated immediatelly to the program for e^+e^- colliders

In the next sections we will discuss some important technical issues for the development of photon colliders, their expected performance, some new findings in understanding of collision effects and then plans for further R&D works.

2 Linear Colliders

It is well known that, due to the synchrotron radiation problem in e^+e^-storage rings, the energy region beyond LEP II can be explored only by linear colliders.

With an achieved accelerating gradient of about 100 MeV/m and a reasonable length of 10-20 km the next linear colliders can cover the energy region up to 1-2 TeV which is comparable with the constituent energy potentially available at LHC. Due to the complexity of the task, the linear collider community is now considering as a first step a linear collider with a c.m. energy up to 500 GeV with a yearly integrated luminosity of about 20 fb^{-1}. Table 1 gives some parameters essential for our task of linear colliders

Table 1: Some parameters of 0.5 TeV linear colliders

	VLEPP	NLC	JLC(X)	CLIC	SBLC	TESLA
	(Russia)	(SLAC)	(KEK)	(CERN)	(DESY)	(DESY)
$L, 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	15	7	5.3	2.5	3.75	6.1
L geometric	12	5.3	3.7	1.9	2.2	2.6
rep.rate,Hz	300	180	150	1700	50	10
# bunch/train	1	90	85	4	125	800
part./bunch(10^{10})	20	0.65	0.65	0.8	2.9	5.1
$\sigma_x(nm)$	2000	320	260	250	670	1000
$\sigma_y(nm)$	6	3.2	3	7.4	30	65
$\sigma_z(mm)$	0.75	0.1	0.08	0.2	0.5	1
Δt bunch(ns)		1.4	1.4	0.66	16	1000

now under consideration[12]. Beam parameters in table 1 have been optimized for e^+e^-

collisions but may be used as a reference point for Photon Colliders. The e^+e^- luminosity planned for 500 c.m. energy colliders is about $5 \cdot 10^{33}$ $cm^{-2}s^{-1}$ and 10^{34} $cm^{-2}s^{-1}$ for 1 TeV colliders.

At present there are no approved projects of linear colliders but all groups working on linear colliders have wide programs of experiments on test facilities for next couple years. Besides, the linear collider community have written the joint Linear Collider Technical Review which in fact is an attempt of critical comparison of different approaches which is a necessary step to a real Project.

3 Lasers

The maximum energy of photons after Compton scattering is given by

$$\omega_m = \frac{x}{x+1} E_0,$$

where

$$x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\mathrm{TeV}}\right]\left[\frac{\omega_0}{\mathrm{eV}}\right];$$

Here ω_0 is the energy of laser photons and E_0 is the initial energy of electrons. To avoid e^+e^- pair creation in collisions of high energy photons with laser photons (that restricts the conversion efficiency at the level ~ 20-30 %). the parameter x should be less than 4.8 [8]. To obtain the conversion probability $k = 65\%$ (one conversion length) at $x = 4.8$ a laser pulse with the following parameters is required[10]:

Flash energy	$A_0 \sim \max(15 l_e[\mathrm{cm}], 4E_0[\mathrm{TeV}])$, J
Duration	$c\tau \sim \max(l_e, 0.17E[\mathrm{TeV}])$, cm
Repetition rate	The same as the electron beam pulse rate
Wave length	$\lambda = 4.2E_0[\mathrm{TeV}]$ μm or $\omega_0 = 0.3/E_0[\mathrm{TeV}]$ eV
Transverse emittance	Near limited by diffraction
Polarization	Fully polarized with adjustable helicity

In the above, the first numbers for flash energy and duration are determined by diffraction and the second by nonlinear QED effect in the conversion region. So, for a 500 GeV c.m. energy collider we need a laser with the wave length about 1 μm, the flash energy about 1-3 J and pulse duration 1 – 5 ps. The peak power is therefore in the Terawatt range. The sequence of the optical pulses must have the same time structure as the electron beam pulses. The time averaged power of the optical beam would therefore be of the order of 10 kW.

Lasers with Terawatt peak power and picosecond pulse length have been built with the chirped pulse amplification and compression technique[13-15]. "Chirped" means time-frequency correlation in the pulse. After amplification a long chirped pulse is compressed to picosecon duration using a grating pair. This method allows to avoid nonlinear effects in medium and extract more energy due to broad band width. However, at present the

maximum average power of these lasers is only about 10 W. On the other hand, solid state lasers pumped by diode arrays (instead of flash lamps) producing 500 W have also been built. It will be necessary to combine these two technologies, for example , by pumping a Nd glass laser with diodes, which could in turn pump a broadband Ti-saphire laser whose pulse can then be compressed. The main challenge would be the power handling capability, which can be solved by techniques such as moving slab (or disk) geometry of amplifier, phase conjugate mirrors (or adaptive optics), dielectric gratings, etc. All these techniques are developed now in the fussion ignition program.

Free-electron lasers (FEL) are another option for photon colliders[16]. Several schemes have been proposed based on different combinations of FEL oscillators and amplifiers and optical switching technique[17-19].

A scheme based on the chirped pulse amplification and compression, similar to the technique used in solid state lasers but replacing the amplifier with an FEL driven by an induction linac, is another attractive option[20].

The requirements on average power could be reduced significantly if an optical beam can be reused several times, for example, by employing a trapping cavity[21].

4 Interaction Region

Designing a high power optical transport system with a tight focus near IP, satisfying various constraints imposed by particle detectors, electron transport hardware, the coil arrangement for the sweeping magnet (discussed in the following paragraph), etc., will be a major task for a photon collider. Some of these constraints need to be thoroughly investigated in the future.

The energy of electrons after multiple Compton scatterings may be as low as 2% of the initial electron energy[8]. The low energy electrons will be deflected up by an angle of about 10 mrad due to collisions with the opposing electron beam. Crab crossing scheme of collisions is therefore essential for a $\gamma\gamma$ collider. To obtain good monochromaticity of $\gamma\gamma$ collisions and clean $\gamma\gamma$ or γe events, it is desirable to sweep the electrons after scattering by an external magnetic field. The magnetic field should extend about 0.5–3 cm with a strength 0.5–2 T. The sweeping magnet could be either superconducting[8, 22] or pulsed magnet[23]. A pulsed magnet with 1 mm thick Al coils can be designed. It is important that the magnet present a minimum obstraction to the detector. In $\gamma\gamma$ collisions at certain beam parameters the beams repulse due to mutual forces, and therefore the sweeping magnets are not necessary at all[24]. A plasma lens to overfocus the spent electron beam has also been proposed[25-26]. This method is especially useful for γe collisions. However, there are many questions to this method, first of all influence of the spread plasma on the electron beam before conversion region and backgrounds.

5 Expected $\gamma\gamma,\gamma e$ Luminosities

Luminosities in $\gamma\gamma,\gamma e$ collisions are determined by many factors:

- collision effects (coherent pair creation, beamstrahlung, beam displacement);
- luminosity induced backgrounds (hadron production in photon collisions etc.);
- beam collision induced backgrounds (large disruption angles of soft particles);
- technical problem of obtaining electron beams with large geometrical luminosity.

First three items were analyzed in refs.[8-10] and it was shown that collision effects restrict the $\gamma\gamma$ luminosity at the level much higher than the luminosity in e^+e^- collisions, therefore let us first consider the last item.

5.1 Expected $\gamma\gamma$, γe luminosities for the current e^+e^- linear collider projects

The optimization of the electron beam parameters for $\gamma\gamma$ collisions is different from that for the e^+e^- collisions. For e^+e^- collisions, the beam spot at IP is designed to be flat to minimize the beamstrahlung effect. In $\gamma\gamma$ collisions, on the other hand, electron beams with much smaller horizontal spot size and larger number of particles per pulse are allowed. For not too small electron beam sizes the $\gamma\gamma$ luminosity is approximately proportional to the geometric ee luminosity. Therefore, if other parameters are held fixed, a straightforward way to increase the $\gamma\gamma$ luminosity is to modify the final focus system for smaller beam sizes.

The spectral luminosity distribution depends on the distance between a conversion region and the IP. If this distance is small, the distribution is wide and the total $\gamma\gamma$ luminosity is about 40% of the geometric ee luminosity (we assume the conversion coefficient to be about 65% and ignore the multiple Compton scattering because they are not essential for high invariant masses). On the other hand, the most valuable part in the spectral luminosity distribution is the peak at the high energy end. Not only the photon energy is high, this region is also characterized by a high degree of polarization. The region account for about 25% of the total $\gamma\gamma$ luminosity, or about 10% of geometrical ee luminosity. The examples of $\gamma\gamma,\gamma e$ luminosity spectra and many other figures can be found elsewhere[10]. If one increases the distance between conversion region and IP then low energy part of luminosity spectrum is suppressed due to larger spot size for low energy photons (for flat beams the suppression is not as good as for round beams) and the high energy peak of spectra remains with a width of about 10% (in practical cases, with account of the multiple Compton scattering, the total residual luminosity below the high energy peak is comparable with that in the peak or even higher by a factor of 2). In the following, therefore, the monochromatized $\gamma\gamma$ luminosity (at $z = W_{\gamma\gamma}/2E_0 > 0.65$) will be taken to be one tenth of the geometic ee luminosity. It should be noted that for

Table 2: Monochromatized ($z > 0.65$) $\gamma\gamma$ luminosities attainable with current e^+e^- designs for $E_{cm} = 500$ GeV with optimized FFS, conversion coefficient $k = 0.63 (A = A_0)$.

Projects	$L_{\gamma\gamma}$ 10^{33}	ϵ_x/ϵ_y(cm rad) x10^{-6}	σ_x/σ_y (nm)	β_x/β_y (mm)	b cm	B kG
TESLA	0.92	2000/100	400/45	4/1	4.5	1.5
SBLC	0.4	1000/48	350/29	6/0.86	2.8	2.5
JLC	0.95	330/4.4	45/10	0.3/1.1	1.	7.
NLC	1.1	500/5	70/7	0.48/0.48	0.7	10.
CLIC	0.43	300/15	100/8	1.6/0.21	0.8	9.
VLEPP	2.0	2000/6.1	500/9.7	6.3/0.75	0.95	8.

some processes the monochromaticity and good polarization of collisions are not required and one can use the whole spectrum. In that case the total $\gamma\gamma$ luminosity will be larger by a factor of 3.

If the current design parameters of various e^+e^- linear collider projects are held fixed, but the spotsizes are minimized by modifying the final focusing system, the attainable monochromatic $\gamma\gamma$ luminosities are given in table 2 [28]. In minimizing the spot sizes, the Oide effect has been taken into account as well as the constraint that the minimum β values are larger than the bunch length. It is seen that the monochromatized $\gamma\gamma$ luminosity is about 10^{33} cm^{-2}s^{-1} or about 20% of the luminosity in e^+e^- collisions for most projects. This is already sufficient for a study of many interesting processes. As was mentioned above, the total $\gamma\gamma$ luminosity is larger by a factor of 3.

We see that with "present" beam emittances the $\gamma\gamma$ luminosities are about 10^{33} for all projects. This is about 20% of e^+e^-luminosity and is much below restrictions due to collision effect. Since the $\gamma\gamma$ luminosity is not limited by collision effect, it is worthwhile to optimize the damping ring designs for a smaller horizontal emittance. Increasing the number of particles per bunch at a reduced pulse repetition rate will further increase the $\gamma\gamma$ luminosity. In fact, there were no serious attempts yet to optimize the linear colliders for a $\gamma\gamma$ mode. One can also increase a laser flash energy, at $A = 1.5A_0$ the $\gamma\gamma$ luminosity at $z > 0.65$ is large than at $A = A_0$ by a factor 1.7 (1.51 for most hard collisions).

In the last two columns of table 2 the distance b between IP and the conversion region and the horizontal magnatic field in this region are given. They are the following: $b = 2\gamma\sigma_y$ and $B = 2e/\gamma r_e \sigma_y \sim 70/\sigma_y$[nm], kG. At this external magnetic field "used" electrons of energy $E = E_0$ are deflected in vertical direction on the distance $4\sigma_y$. One can decrease this deflection somewhat but this leads to increase of low energy $\gamma\gamma$ luminosity due to collisions of Compton photons with beamstrahlung photons and also γe luminosity increases and become harder. Note, such criterion for selection of the value of the magnetic field is not a general rule. At certain beam parameters the deflection of electron beams during collision is much larger than deflection by the external magnetic field (this is so for the VLEPP parameters from table 2) and the final selection should be done using MC simulation. The magnetic deflection in this case help to reduce background collisions arising during collisions of beam heads. In ref.[24] it was suggested for this purpose to prepare electron beams with displaced heads and not to use the external magnetic field at all. An optimal solution depends strongly on beam parameters.

Some words about γe luminosity. It is not exactly proportional to geometrical ee luminosity. After conversion the "used" electron beam is deflected by the external magnetic field (~ 20 kG) in horizontal direction by a distance when collision effects (beamstrahlung, beam displacement) are not essential. The required distance between IP and the conversion region is about 1.5–3.5 cm for different projects and the vertical photon size at IP ($\sim b/2\gamma$) for some projects is larger than the vertical size of the electron beam. The MC simulation shows the γe luminosity at $z = W_{\gamma e}/2E_0 > 0.8$ is about 10–25% of geometrical luminosity that is about $(1--2.5)10^{33}$ cm^{-2}s^{-1}, somewhat larger than $\gamma\gamma$ luminosity. The spectra are very narrow, about 3% at half of maximum. Note that due to collision effects the ultimate γe luminosity is lower than in $\gamma\gamma$ collisions.

6 Some remarks on collision effects and ultimate luminosities

The expected luminosities presented in the previous section are quite moderate and hopefully the solution how to increase the geometrical luminosity will be found. What is a principle limit of the luminosity of Photon Colliders?

In $\gamma\gamma$ collisions, there is only one collision effect restricting luminosity, it is the coherent pair production by the photon in the field of opposite electron beam. If the corresponding parameter $\Upsilon = \gamma B/B_0 > 1$[27], most high energy photons may convert to e^+e^- pairs during beam collision. There are two methods to avoid this effect[10]:

a) to deflect electron beam after conversion on a sufficiently large distance x_0 from IP; electron beams even may have here infinitely small sizes, but the photon spot size is about b/γ, where the distance b between IP and the conversion region should be sufficient to provide the required deflection by a reasonable external magnetic field (about 10–30 kG).

b) to use flat electron beams with $\Upsilon < 1$ in the beams and make only a small vertical deflection to avoid background ee, γe and low energy $\gamma\gamma$ (where one or both photons are due to beamstrahlung) collisions.

Pair creation is not essential ($\Upsilon < 1$) when[10]

$$x_0 \;\; or \;\; \sigma_x \leq \frac{N r_e^2 \gamma}{\alpha \sigma_z} = 20 \left(\frac{N}{10^{10}}\right) \frac{E_0[\text{TeV}]}{\sigma_z[\text{mm}]} \text{ nm}$$

In both methods the ultimate $\gamma\gamma$ luminosity (when emittances of electron beams are not limited) due to collision effects is substantially higher than in e^+e^- collisions ($\sim (0.1--5)10^{35}$ for different projects[8–10]).

At some beam parameters in the case b) the external magnetic deflection is not necessary because during a collision the beams get a displacement due to repulsion much larger than the vertical beam size. For example, if beams are flat and $\Upsilon = 1$ (the field $|B| + |E| = B_0/\gamma = e\alpha/r_e^2\gamma$) then the vertical displacement during beam collisions

$$\Delta y \sim \frac{\alpha \sigma_z^2}{4\gamma^2 r_e} = 160 \frac{\sigma_z^2[\text{mm}]}{E_0^2[\text{TeV}]} \text{ nm}$$

As one can see for E = 250 GeV, the beam displacement is 25 nm even for short bunches with $\sigma_z = 0.1$ mm, that is larger than planned σ_y. For "long" bunches or low energies this should work perfectly. One such example of the photon collider on the energy 2x100 GeV without deflecting magnet was considered in ref.[24].

The collision effects are very many-sided and below I will tell about a new aspect which was not realized before. It turns out that in the case of sufficiently long bunches and not too high beam energy one can collide infinitely narrow electron beams without any deflection by external magnetic field (of course, there is no sense to have transverse beam sizes much less than b/γ) and even in this case there will be no coherent pair production (the only effect restricting $\gamma\gamma$ luminosity). This is because beams are repulsing during collision and their displacement is so large that the electromagnatic field is insufficient for coherent pair production. This is valid for the following conditions (roughly)

$$\frac{8 N r_e^3 \gamma^3}{\alpha^2 \sigma_z^3} = 0.25 \left(\frac{N}{10^{10}}\right) \frac{E^3[\text{TeV}]}{\sigma_z^3[\text{mm}]} < 1$$

Taking N and σ_z from the table 1 we obtain the following "critical" energy(in GeV) for different project: TESLA – 900, SBLC – 550, VLEPP – 450, CLIC – 350, NLC – 200, JLC – 150. Below this energy the ultimate luminosity (at $z > 0.65$) of these colliders can be found using the simple formula

$$L_{\gamma\gamma} \sim 0.35 \frac{k^2 N^2 f}{4\pi (b/\gamma)^2} \sim 0.7 \cdot 10^{36} \left(\frac{N}{10^{10}}\right)^2 \frac{E^2[\text{TeV}] f[kHz]}{b^2[\text{mm}]}$$

Here we assumed $k^2 = 0.6 (A = 1.5 A_0)$; a factor of 0.35 follows from the simulation with $\sigma_x, \sigma_y = b/2\gamma$. The distance b should be larger than a few bunch length to avoid deflection of electrons before conversion in the field of the opposite beam (of its head) and it should be also larger than the length of conversion region(which in the case of short bunches is determined by nonlinear effects, see section "Lasers"), for estimation we can take $b = \max(3\sigma_z, 3E[\text{TeV}]\text{mm})$.

For TESLA at $b = 3\sigma_z = 3$ mm at $E > 250$ GeV the $\gamma\gamma$ luminosity is about 10^{36} cm^{-2}s^{-1} ! For energy E = 1 TeV, close to "critical" energy, the direct simulation gives $L_{\gamma\gamma} \sim 3 \cdot 10^{36}$ cm^{-2}s^{-1}. Here some photons are already lost due to pair creation.

For NLC, where bunches are short, b is proportional to the energy and for energies below the critical one $L_{\gamma\gamma} \sim 5 \cdot 10^{35}$ cm^{-2}s^{-1}. This is by a factor 20–30 larger than follows from a consideration where the parameter Υ is kept below one "by hands" as described in the beginning of this section.

So, the analysis of collision effects done in previous publications as well as the new effect discussed above show principal possibility of obtaining very high $\gamma\gamma$ luminosity at Photon Colliders. The main problem here is preparation of electron beams with small emittances in both directions. This problem waits its decision. It should be considered together with possible increase of particle population in bunches and its length (as in VLEPP project).

Speaking about high luminosity, we should remember about hadronic background. The cross section $\sigma(\gamma\gamma \rightarrow hadrons) \sim 500$ nb and at the luminosity per beam collision $10^{36}/10^4 = 10^{32}$ cm^{-2}s^{-1} it will be about 50 hadronic events or even more due to a small time interval between bunches. Each event gives about 10 particles at large angles with momenta about half a GeV . This is not fatal for studies of many interesting processes with large transverse momenta. By the way, at LHC about 40 bias events with similar topology are expected and it is considered as tolerable.

7 R&D Program

It seems that the period of agitation for photon colliders comes to an end. Now all teams working on linear colliders consider this option. This work is in the very beginning. The R&D program for development of a photon collider has both immediate and long term aspects, and includes the following topics:

a) optimization of collision scheme, b) detectors and masking, c) high power lasers including FELs, d) special final focus components, e) bright source of polarized electrons, g) high power, low-loss optical components.

The SLAC can provide a realistic test bed for a higher energy $\gamma\gamma$ collider. The E–144 experiment to study nonlinear QED in collisions of laser photons with 50 GeV electrons can be considered as a prototype for the lasers required for $\gamma\gamma$ colliders. It is worth to consider the possibility of the SLC upgrading to allow for $\gamma\gamma$ and γe collisions which would provide interesting new particle physics.

8 Conclusions

With a small incremental cost and relatively straightforward modification , a future e^+e^- collider can enhance its capability significantly by providing $\gamma\gamma$ and γe collisions. A higher luminosity is feasible through re-optimizing the collider system designs. At present, lasers and the associated optics for Terawatts of peak power and kilowatts of average power, suitable for $\gamma\gamma$ colliders, are actively pursued for various applications. Many relevant and challenging issues in $\gamma\gamma$ collider design can be investigated by upgrade of SLC. Therefore, with a strong support from the HEP community, a $\gamma\gamma$ collider with the possibility of some fundamental physics not accessible to, and with highly desirable redundancy of the data from the e^+e^- collisions, appears to be a realistic possibility.

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Symmetry breaking and electroweak physics at Photon Linear Colliders

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ABSTRACT

The physics potential of a high-energy photon collider is reviewed. The emphasis is put on aspects related to the symmetry breaking sector, including Higgs searches and production of longitudinal vector bosons.

1. Introduction

The option of building a photon-photon interaction region at an e^+e^- linear collider is now taken seriously under consideration. Based on the idea of using laser-induced backscattered photons for inducing high-energy photon collisions, a $\gamma\gamma$ collider (PLC) gives rise to new physics opportunity.[1] The issues concerning electroweak physics will be summarized in this talk.[2]

Since the symmetry-breaking mechanism remains the last open question in the standard model, an important part of the planning at any future collider must be devoted to that. This obviously includes searches for the Higgs particle and the determination of its properties. One unique opportunity for $\gamma\gamma$ colliders in that respect is the direct measurement of the $H\gamma\gamma$ coupling. Should the Higgs searches remain fruitless, the study of the longitudinal W sector would give a handle on the symmetry breaking mechanism. Photon colliders, being essentially a W pair factory, could make a useful contribution in that respect.

Before going into the heart of the subject and to give a first idea of the possibilities of $\gamma\gamma$ colliders, I will present the main characteristics of high-energy $\gamma\gamma$ collisions:

- Any elementary charged particle, phase-space allowing, can be produced in $\gamma\gamma$ collisions with a model-independent predictable cross-section.
- $\gamma\gamma$ gives access to the $J_Z = 0$ channel, which is chirality suppressed in e^+e^-. To test the electroweak symmetry breaking (ESB) mechanism, this means producing the Higgs as a resonance.
- $\gamma\gamma$ collisions feature very large cross-sections, which are always larger than in e^+e^- for the same energy and luminosity.

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