SIMULATIONS OF THE INTERACTION POINT FOR TeV-SCALE e^+e^- COLLIDERS

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Abstract

The design of a detector and post-collisional line of a future linear collider calls for detailed knowledge of the beam-beam dynamics at the interaction point. We here describe the implementation and results of new simulation tools in the program `GUINEA-PIG++`. The subjects are direct trident production which is relevant in the deep quantum-regime, incoherent muon generation, synchrotron radiation from secondary particles and depolarization effects. We choose beam parameters in the range relevant for `CLIC` and comment on the implications for the design of such a machine.

COHERENT EFFECTS

The large field imposed on one beam electron from the collective field of the oncoming bunch in a TeV collider can reach a magnitude near the quantum mechanical critical field $\mathcal{E}_0 = m^2c^3/e\hbar = 1.32 \times 10^{16}$V/cm in the rest frame of the electron. This is the case when the mean of the Lorentz invariant Υ [14]

$$\langle\Upsilon\rangle = \frac{5}{6}\frac{Nr_e^2\gamma}{\alpha(\sigma_x+\sigma_y)\sigma_z} \tag{1}$$

becomes of order unity. N is the number of particles per bunch, σ are the Gaussian dimensions of the beam and α is the fine structure constant and r_e is the classical electron radius. This marks the onset of the quantum regime where coherent QED radiation effects will be observed. For `CLIC` $rangle\Upsilon\langle$ is around 4.

TRIDENT INTRODUCTION

Events where an electron produces a pair in the interaction with an electromagnetic field may proceed either through the sequential process where the electron emits a real photon that converts into a pair, or directly where the intermediate stage contains a virtual photon. In amorphous matter, both types of events $e^- + Z \rightarrow e^- + Z + e^- + e^+$ (where Z symbolizes the presence of the nucleus) were originally termed 'tridents' because of the observed three-prong track, but are also referred to as 'electroproduction'. The same phenomena arise when the electric field supplied by the nucleus is replaced by an electric field $\mathcal{E}$ of sufficient strength, $e^- + \mathcal{E} \rightarrow e^- + \mathcal{E} + e^- + e^+$, as e.g. provided by an oncoming bunch of particles in a collider or in a crystal [1]. A recent measurement of trident events from both amorphous and crystalline matter may be found in [2].

The sequential trident events, which are also known as coherent pairs, are important when considering the design of a TeV scale linear e^+e^- collider. They are the result of beamstrahlung photons converting in the strong field of the oncoming bunch and may contribute ~10% of the total charge after the bunch crossing. Likewise, the result of the conversion of virtual photons in the field of the oncoming bunch, trident events, may be significant.

Not many analytical expressions for the yield of direct tridents exist [3, 4, 7], and to the knowledge of the authors, a single cross section in closed form valid in the intermediate range $\Upsilon \approx 1$ does not exist. According to [5, 4] the total number of created tridents is

$$n_{tr} = \frac{4\sqrt{3}}{25\pi}\left(\frac{\alpha\sigma_z\Upsilon}{\gamma\lambda\!\!\!^{-}_c}\right)\Omega(\Upsilon), \tag{2}$$

and

$$\Omega(\Upsilon) = 2.6\alpha\ln(\Upsilon) \quad \Upsilon \gg 1 \tag{3}$$

This expression, however fails at small energies. In order to mitigate, we here use a QED Weizsäcker-Williams calculation [6]. To perform such a calculation, the maximum squared four-momentum of the photon (the virtuality) must be chosen. Estimating the upper limit on the momontum supplied by the field sets the virtuality cut to $(mc)^2$. Since this relevant virtuality is very small, the virtual photon has got near on-shell properties. Therefore it can for simplicity be assumed to convert in the external field with the probability and spectrum of an unpolarized photon on the mass shell, $q^2 = 0$. The total probability and differential spectrum are well known [3, 9] which allows for accurate sampling of energies.

This calculation has been added to the beam-beam simulation program `GUINEA-PIG++` and calculations using the current baseline parameters of `CLIC` have been used to produce the results presented here.

Results of Trident Simulation

A comparison between a version of the trident generator with constant Υ and expressions from [4, 8] is seen in figure 1. Clearly, the approximate expressions are not adequate for determining the yield at the threshold for quantum effects around $\Upsilon = 1$. In Erber's classic paper [8] a semi-classical Weizsäcker-Williams approximation is used for the virtual photon spectrum. This spectrum weighs more

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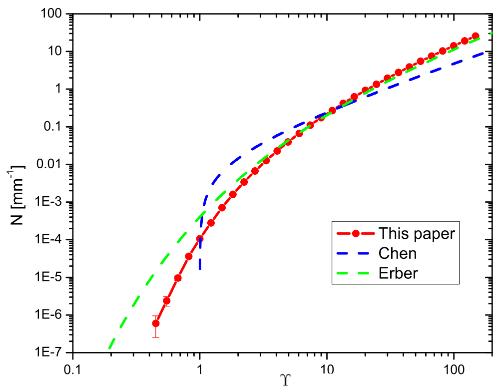

Figure 1: Total yield of direct tridents at a primary energy of 250GeV. Red: Monte-Carlo simulation with fixed Υ, this paper. Blue dashed: Approximate expression by Chen [4]. Green dotted: Erber [8]

Table 1: The used CLIC 3 TeV parameters. Numbers are only guidelines since realistic non-Gaussian bunches were used for simulations.

Centre of mass energy	3TeV
Particles/bunch	3.72 10^9
Horizontal beam size before pinch effect, σ_x	45nm
Vertical beam size before pinch effect, σ_y	1nm
Longitudinal beam size, σ_z	44μm

on high energies than the expression for the virtual photon spectrum implemented in the calculations, which explains the difference at $\Upsilon < 1$ and the similarity at $\Upsilon \gg 1$. The spectra coincide completely at low energies as can be verified analytically. The Weizsäcker-Williams approximation used here is much better in the intermediate range besides being valid in the quantum-regime.

When the trident generation is applied to a full crossing simulation using GUINEA-PIG++ with the parameters from table 1 where the particles are tracked in the beam beam field, the amount of direct tridents is $3.6 \cdot 10^6$ per beam per bunch crossing or approximately one per mil of the total initial bunch charge. By comparison, the sequential tridents contribute with two orders of magnitude more charge. Since the direct trident process is linearly dependent on the bunch length and the indirect has quadratic dependence, reducing the bunch length will favour increasing the number of direct tridents, making the bunch length a potentially dangerous quantity to decrease. The smallness of the yield of direct tridents means that this parameter region is quite far from any realistic CLIC parameter set.

Due to the difference in dependence of the distance travelled in the field an investigation of the bunch length dependence of the yield is interesting. This study using Gaussian beams in the CLIC nominal parameter range, is seen figure 2. Within a relatively small change of the bunch length,

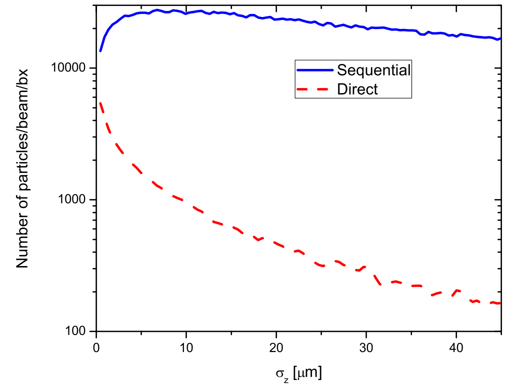

Figure 2: Bunch length dependence of the yield of the coherent pair production mechanisms.

a significant portion of the pairs produced coherently are trident pairs.

DEPOLARIZATION

Apart from generating backgrounds, the beam-beam field will depolarize any polarized incoming beams. One relevant mechanism for this effect is the spin flip radiation which is a γ-quantum radiated from an electron by interation of the electron spin with the field [12]. Another is the BMT [13] precession mechanism. In the latter mechanism, the quantity that defines the magnitude of the depolarization relative to the angular deflection of the particle is the anomalous magnetic moment of the electron, $a = g/2 - 1$. In the strong field regime above $\Upsilon \approx 1$ there is a large QED correction to this quantity. This reduces the magnitude of depolarization greatly for a machine with high-$\langle\Upsilon\rangle$. For a machine as CLIC, the total and luminosity weighted depolarization is 6% and 3%, respectively. Since these numbers are not critically large, it will therefore be just as relevant to investigate the effect of the beam delivery system om the depolarization when designing a polarized e^+e^- collider.

INCOHERENT MUONS

The prodction of muons via binary collisions between beam particles may provide an inconvenient background in a detector. The production takes place through three primary channels

- Collisions between two (beamstrahlung) photons: The Breit-Wheeler process.
- Collisions between a photon and an electron (positron): The Bethe-Heitler process.
- Collisions between two electrons: The Landau-Lifschitz process.

Processes that involve the collision with a lepton can conveniently be described in a Weizsäcker-Williams calculation for determining the virtual photon flux [12].

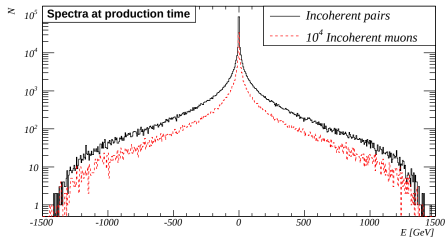

Figure 3: The spectrum of incoherent muons and electron-positron pairs. Note that the muon production cross section has been scaled up by a factor 10^4 to bring the prosesses to the same scale. These are the spectra of leptons before any tracking in the beam-beam field.

Since the Breit-Wheeler cross section is a relatively compact expression, one can sample $\beta\cos(\theta)$ where β is the velocity and θ is the production angle in the centre of mass frame. This means that it is straightforward to determine the energies and angles of the produced particles in the laboratory.

In order to do the Weizsäcker-Williams calculations of the corresponding virtual photon processes, the cut in the virtuality of the involved photons is $q^2_{max} = s$, where s is the usual Mandelstam-variable. The muon generator was confirmed to be functional by cross-checking with the yield of incoherently produced e^+e^- pairs in `GUINEA-PIG++` simulations. This is possible since the cross sections of these processes must be equal at transversal momenta larger than the muon mass.

A quick estimate of the yield of s-channel production of muon pairs via $Z_0 + \gamma$ revealed that the cross section is far too small to have an impact on muon yield in a TeV collider since there is not suffficient luminosity near the Z_0 mass to utilize the resonance or the s^{-1} dependence of the photon cross section.

Simulation Results

Using the current `CLIC` baseline parameters in table 1 the number of produced muons per beam crossing in simulations is 12.50 extending to large angles. This is certainly of interest when designing a muon trigger system for the collider.

TERTIARY PHOTONS

The large angles of the incoherent pairs makes synchrotron radiation from these particles a relevant effect for a brief study relevant for a detector. These pairs are produced via the same mechanism as the incoherent muons. In simulation, they radiate using the standard Sokolov-Ternov formula for radiation [12] which is valid in the classical regime of fields as well as the quantum one. These produced photons have until recently been discarded, only having the effect of lowering the energy of the emitting particle. In theory they could provide a luminosity signal, or provide a disruptive signal.

In reality these photons do not contribute greatly to any background, but the inability to deflect them with magnetic fields means that they should be kept under consideration.

CONCLUSION

We have presented a Weizsäcker-Williams calculation of the direct trident process that is valid in the quantum mechanical as well as in the intermediate $\Upsilon \approx 1$ regime. This simulation has been applied to beam-beam simulations relevant for the next generation linear colliders. The impact on any proposed 3TeV CLIC design is small when compared to other processes of e^+e^- pair creation, but may become significant in the limit of short bunches. The kinematic characteristics of the produced particles are not unlike those of sequential tridents. Since the relative contribution of the direct tridents to the post-collisional bunch charge is small, this will mean that they are most likely hard to distinguish from the coherent pairs in a detector without varying the bunch length.

Furthermore, the production of incoherent muons produced in collisions has been included and the number of produced muons per bunch crossing in `CLIC` has been determined to be 12.5. In addition depolarization and production of synchrotron radiation by incoherent pairs in `GUINEA-PIG++` is functional.

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