Bose-Einstein Correlations in $e^+e^- \to W^+W^-$ at a Linear Collider

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Abstract

We show that the most popular method to simulate Bose-Einstein (BE) interference effects predicts negligible correlations between identical pions originating from the hadronic decay of different W's produced in $e^+e^- \to W^+W^- \to 4$ jets at typical linear collider energies.

It is known that the Bose-Einstein (BE) effect can produce a systematic uncertainty on the W mass measurement in the process $e^+e^- \to W^+W^- \to 4$ jets. For the LEP2 experiments, this uncertainty can be serious [1] if it is as large as expected from the standard BE simulation included in the PYTHIA/JETSET Monte Carlo model [2]. Considering that the TESLA linear collider (LC) will make it possible to study e^+e^- annihilation with much larger statistics and at much higher centre-of-mass-energy, it is important to understand how strongly the W-mass measurement at a LC could be affected by the BE effect.

In this study we use the most popular and simplest BE simulation technique based on the LUBOEI algorithm, as included in PYTHIA/JETSET model. It is known that this algorithm has a strong effect on the W-mass reconstruction and the systematic uncertainties on the W mass can be as large as 50 MeV at LEP2 energies [3]. Other methods of BE simulation usually show much smaller uncertainties at LEP2 energies (see [4] for recent reviews).

In this paper we investigate the BE correlations at TESLA energies using the tools proposed in [5] and [6], without attempts to calculate shifts of the W mass for a particular reconstruction method. By comparing the behaviour of the correlations with those observed at LEP2 energies, quantitative information can be obtained on possible effects on W mass measurements.

To analyse the BE correlations, we use the following two methods:

1) Division method [5]. Here the correlations are measured using the ratio:

$$R^* = \frac{\rho^{\mathrm{WW}}(\pm,\pm) - 2\,\rho^{\mathrm{W}}(\pm,\pm)}{\rho^{\mathrm{WW}}(+,-) - 2\,\rho^{\mathrm{W}}(+,-)}, \tag{1}$$

where ρ^{WW} and ρ^{W} are the two-particle densities for 4 and 2-jet hadronic W decays, respectively, and $(\pm,\pm)$ and $(+,-)$ denote like-charge and unlike-charge particle combinations. With this definition, R^{*} is unity if there is no cross-talk between two W's. Thus R^{*} can be used as an indicator of BE interference between hadrons from different W bosons. We note that this quantity resembles the standard BE correlation function when unlike-charged particles are used as a reference, but has, in fact, little to do with it [6].

2) Subtraction method [6]:

$$\delta\rho = \rho^{\mathrm{WW}}(\pm,\pm) - 2\,\rho^{\mathrm{W}}(\pm,\pm) - \rho^{\mathrm{WW}}(+,-) + 2\,\rho^{\mathrm{W}}(+,-). \tag{2}$$

In the absence of cross-talk between W's, one has $\delta\rho = 0$. In the following we use $1+\delta\rho$, rather than (2) in analogy with R^{*}.

The two methods differ mainly in the fact that, for $\delta\rho$ the so-called mixing terms (terms determined by the product of single-particle densities) cancel, whereas such mixing terms are still present in the method 1, and largely determine the behaviour of R^{*} in the case of cross-talk between W bosons [6].

Results for both methods, using the LUBOEI algorithm, have been presented for LEP2 energies in [6]. About 20K WW events were generated at $\sqrt{s} = 190$ GeV. A clear enhancement of R^{*} and $\delta\rho$ was observed when the squared 4-momentum difference $Q_{12} \equiv \sqrt{-(p_1 - p_2)^2}$ between two like-sign particles decreases (see Fig. 8 and 9 of [6]).

Here we present results of a similar study at $\sqrt{s} = 180$ GeV and $\sqrt{s} = 500$ GeV, for a LC. The LC is expected to operate at $\sqrt{s} = 500$ GeV most of the time, collecting an integrated luminosity of 200 fb^{-1} per year. The TESLA proposal for the LC will include an option to run at smaller beam energies, down to $\sqrt{s} = 90$ GeV, but with reduced luminosity. If the physics motivation is sufficiently strong, TESLA can also run at energies slightly above the WW threshold, e.g. at $\sqrt{s} = 180$ or 200 GeV. Event samples which can reasonably expected to be collected at this energy, amount to 10-20 fb^{-1}, i.e. about 20 times larger than the data samples collected at LEP2.

The results for R^{*} and $1+\delta\rho$ are shown in Fig. 1 and Fig. 2. The solid lines in the figures correspond to the case of no BE correlations. At each energy 200K WW events were generated, corresponding to a luminosity of 15 fb^{-1} and 30 fb^{-1} at $\sqrt{s} = 180$ GeV and $\sqrt{s} = 500$ GeV, respectively.

The figures show no increase of R^{*} and $1+\delta\rho$ for small Q_{12} at $\sqrt{s} = 500$ GeV, whereas BE correlations are clearly seen at 180 GeV. At an intermediate energy, $\sqrt{s} =$ 300 GeV, both correlation quantities have also been studied (not shown). The BE effect was found to be much smaller than that at $\sqrt{s} = 180$ GeV. Therefore, in order to detect this effect at $\sqrt{s} = 300$ GeV much higher statistics than at LEP is needed.

The statistics used for the present paper are ten times larger than that used for LEP2 studies [6]. The figures illustrate that, with the much higher statistics expected at LC more details in the behaviour of BE correlations can be observed, especially for $1+\delta\rho$. This correlation function is slightly below unity for $Q_{12} \sim 0.3 - 1.2$ GeV and has a rather complex structure. This is much less evident for R^{*}, where the details of the genuine correlations are hidden due to the presence of large mixing terms in the definition (1).

Our results demonstrate that BE correlations between hadrons from different W's can be studied at energies close to the WW threshold. At much higher energies the effect is negligible. This is related to the large phase space available for secondary particles from hadronic W decays at high energy, and the small probability for two identical secondary particles from different W's to be emitted close in Q_{12} -phase space[1].

In conclusion, studies at $\sqrt{s} = 500$ GeV do not indicate the presence of Bose-Einstein correlations between identical hadrons from decays of different W bosons for realistic statistics attainable at a LC. The systematic uncertainty on a measurement of the W mass caused by these correlations is therefore expected to be negligible. This result is based on the most popular method to simulate BE correlations (LUBOEI in PYTHIA/JETSET) and two different experimental techniques. The LUBOEI algorithm is known to produce the largest effect on the W mass reconstruction at LEP2 energies. It is therefore reasonable to expect that the use of other available models, known to lead to smaller uncertainties on the reconstruction of W mass, can only strengthen the above conclusion. However when the LC will be operated at an energy close to but above the WW threshold, collecting event samples of the order of 10-20 fb^{-1}, BE effects between different W's can be studied with uncanny precision.

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[1] A similar observation was made in [7]

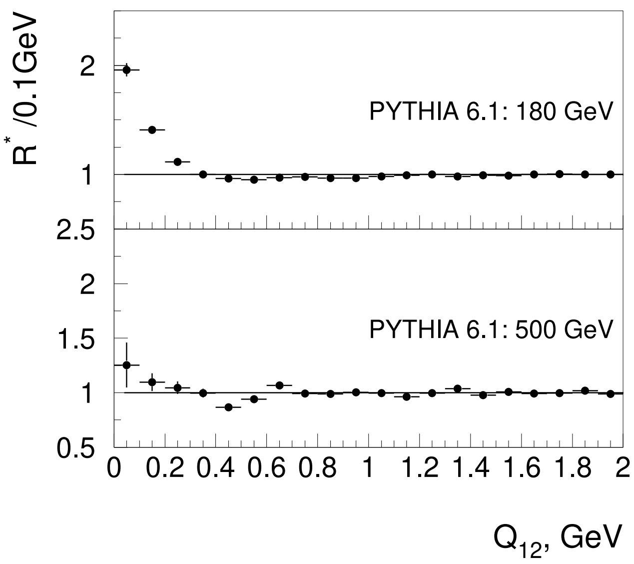

Figure 1: R^* for PYTHIA Monte Carlo model without and with BE correlations at $\sqrt{s} = 180, 500$ GeV. The solid line corresponds to the model without BE effect.

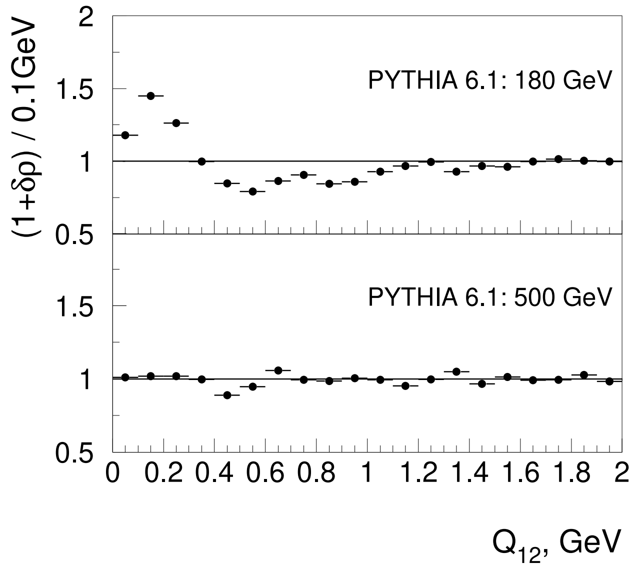

Figure 2: $1 + \delta\rho$ for PYTHIA Monte Carlo model without and with BE correlations at $\sqrt{s} = 180, 500$ GeV. The solid line corresponds to the model without BE effect.