Transverse Momentum Distribution of the Z Produced at the Large Hadron Collider and Related Phenomena

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From the recent theoretical result on the production of the Higgs boson at the large Hadron Collider, it follows that other particles will also be produced with small transverse momentum, of the order of 1 GeV/c. The leptonic decay mode of the Z is especially suited for a first observation of this phenomenon. Other related effects, such as paired jets, are also discussed.

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1. Recently, it was found [1], in the production of an isolated Higgs particle [2] at the energy of the Large Hadron Collider, that the transverse momentum of this Higgs particle is small, of the order of 1 GeV/c. The details of this theoretical work may be found in Ref. [3]. A typical transverse momentum distribution is shown in Fig. 1. The effects of QCD radiative corrections have been discussed in [1, 3]. Such very narrow distributions have major implications in the hadronic interactions at high energies, much beyond Higgs production.

It is the purpose of this paper to study some of these implications.

2. Gluon fusion is the most important production process for the Higgs particle at the Large Hadron Collider. Indeed, this is the process studied in Refs. [1, 3], leading to this narrow distribution of the Higgs' transverse momentum. Since the two gluons in gluon fusion come from the two incoming protons, one gluon from each proton, such narrow distribution for the produced Higgs particle must *imply* that the transverse momentum distribution of the gluons in the proton is also narrow.

On physical grounds, this result is understandable through the following considerations. Take a proton at rest: since the proton mass is about 1 GeV/c^2, all its constituents — quarks, anti-quarks, and gluons — may be expected to have a typical momentum of the order of 1 GeV/c. By a Lorentz transformation, the proton is boosted to a high energy. Since the momentum transverse to the direction of motion of the proton is invariant under such a Lorentz transformation, the transverse momenta of the constituents must remain of the order of 1 GeV/c.

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3. It is therefore seen that the transverse momenta of the order of 1 GeV/c are consequences of the properties of the constituents of protons, and are in no way limited to the production of the Higgs particle. In other words, at high energies, there are production processes besides that of the Higgs particle, where the transverse momentum distributions have peaks at or near zero with widths of the order of 1 GeV/c.

The emphasis is on this width of the order of 1 GeV/c and its consequences. In contrast, even for the Higgs production by gluon fusion, the existing Monte Carlo predictions give a width of about 10 to 20 GeV/c.

4. Of course, particles are also produced with large transverse momenta. Here are, for example, two ways how this can happen.

(a) Particles may be produced in pairs. Gluon fusion can lead to the production of not only one Higgs particle, but also a pair of Higgs particles. In this case, the vector sum of the transverse momenta of the Higgs particles is small, but that of each of the two Higgs particles can be large.

(b) Even in the gluon fusion to produce a single Higgs particle, there is a significant tail in the distribution of the transverse momentum, as shown in Fig. 1. Such Higgs particles in the tail are of interest by themselves; furthermore, this part of the distribution is enhanced by QCD radiative corrections.

It will have to be determined by experiments at the Large Hadron Collider or the Tevatron Collider how large the fraction is for the various produced particles with transverse momenta of the order of 1 GeV/c. For each produced particle, the importance of the present considerations is determined by the size of this fraction.

5. The first step is to consider the production of Z:

$$p + p \to Z + X \,, \tag{1}$$

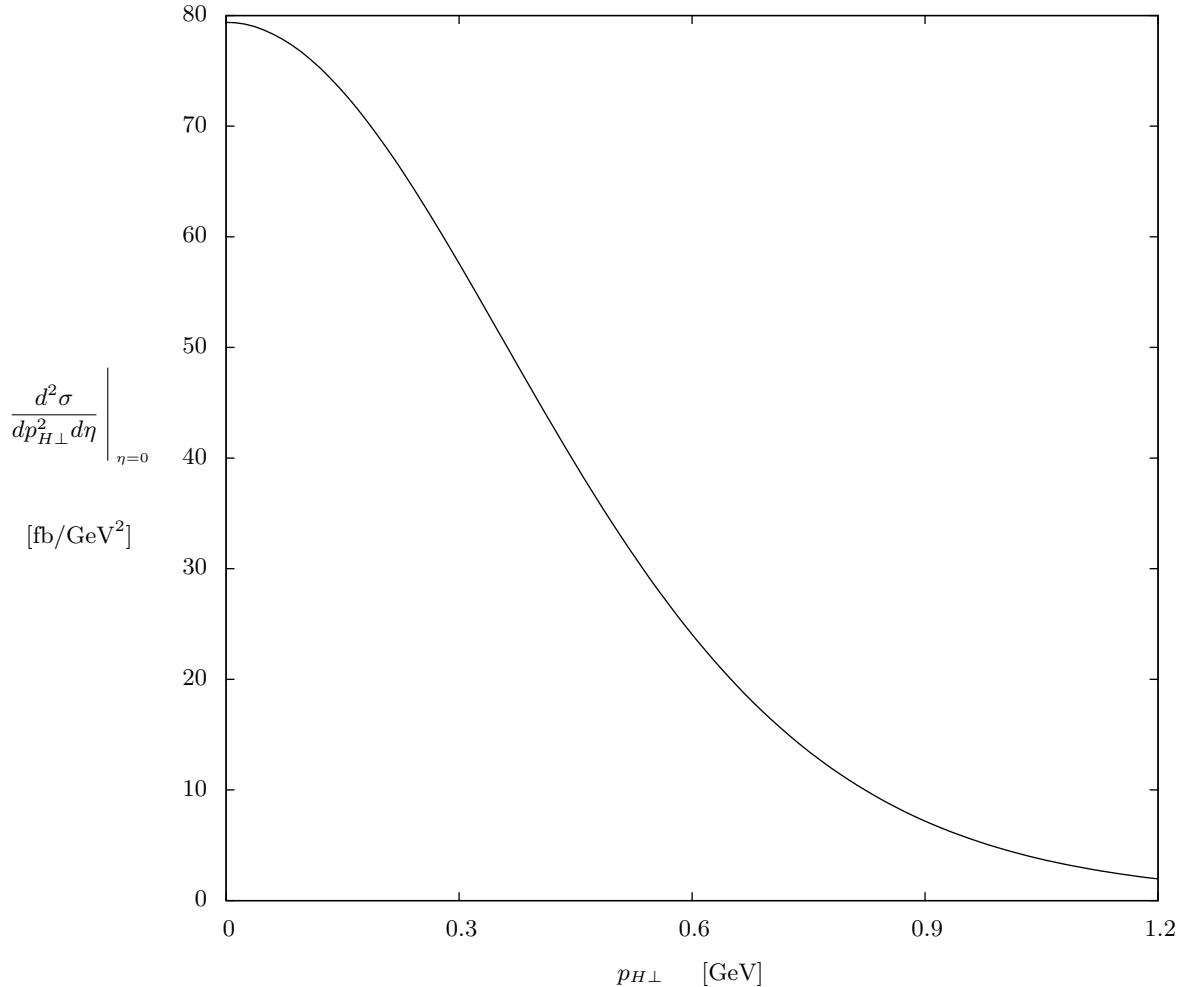where X is anything. The case of interest here is when this Z is produced with a small transverse momentum

FIG. 1: A typical distribution of the transverse momentum $p_{H\perp}$ of the produced Higgs particle with rapidity $\eta = 0$. This curve is for the Higgs mass of $M = 115\ \mathrm{GeV}/c^2$ [4, 5].

of the order of 1 GeV/c. It is assumed that the fraction of Z's with such a small transverse momentum is significant — see the preceding paragraph.

In general, let f denote this fraction. Let the experimental data on the transverse momentum distribution be fitted with a narrow peak of the order of 1 GeV/c over a broad background; the value of f is then the percentage of events under this narrow peak. Thus, $f = 0$ means the absence of this narrow peak, while $f = 1$ means that all the events are under this narrow peak. In particular, f_Z denotes this fraction for the production process (1). It is assumed here that the value of this f_Z is not too small.

The advantage of studying the production of Z rather than that of the Higgs boson is that many Z's will be produced at the Large Hadron Collider. The Z has the leptonic decay mode

$$ Z \to \ell^+ + \ell^- \,, \tag{2} $$

where ℓ is either e or μ, and the hadronic decay mode

$$ Z \to q + \bar{q} \,. \tag{3} $$

The branching ratios for these decay modes are 6.7 % and 70 % respectively [6].

Consider first the leptonic decay mode (2). Since the decay product consists of only two charged leptons, the events are clean and thus provide a prime candidate for the first observation of the 1 GeV/c transverse momentum scale in high-energy hadron interactions. Several of the detectors at the Large Hadron Collider — including ALICE, ATLAS, and CMS — have sufficiently good azimuth-angle resolutions to study such narrow transverse momentum distributions in detail, especially the component perpendicular to the decay direction and the leptonic azimuth opening angle.

Once the transverse momentum distribution of the produced Z is found to have a component with a width of the order of 1 GeV/c through the leptonic decay mode (2),

then this width must also hold for the hadronic mode (3). In this decay (3), both the quark q and the anti-quark $\bar{q}$ are seen in the detector as jets, and the success of the jet analysis is conveniently defined as giving similar results from both the leptonic and the hadronic modes. It may be expected that the analysis is more difficult for the c and b jets than for u and d jets.

There is no reason for f_Z to be more significant than the f for some other produced particles. It is therefore important to determine the value of the fraction f not only for Z but also for other particles.

6. If the value of f is found experimentally to be sufficiently large for some produced particles, this will have far-reaching consequences.

In a nutshell, *at high energies there is an important new scale of* 1 GeV/c *for hadronic interactions, including proton-proton and proton-antiproton interactions.* [It is perhaps more proper to call this new scale the oldest scale of 1 GeV/c from the proton mass. What is new here is that this scale remains important at high energies.]

This new, or oldest, scale has a number of immediate implications, including the following one: the quark and gluon distribution functions for proton-proton and proton-antiproton interactions should be significantly different from the corresponding ones from electron-proton interactions [7]. The reason is that, for ep interactions, the off-shell nature of the virtual photon emitted by the electron masks this scale of 1 GeV/c from the proton.

The following contrast between the HERA and the LHC experiments is perhaps instructive.

(a) One of the original reasons for building HERA is to be able to reach larger values of Q^2, the squared four-momentum of the virtual photon emitted by the electron. The cross section, which decreases as Q^2 increases, is small at such larger values of Q^2.

(b) On the other hand, for the search for new physics at LHC, the primary interest is in regions of relatively large production cross sections. For example, as shown in Fig. 1, the cross section for the production of an isolated Higgs particle is largest at small transverse momenta of the Higgs.

Since large values of Q^2 are usually associated with large transverse momenta, the kinematic regions of interest are thus seen to be different for the experiments at HERA and LHC. The relevant momentum scales are quite different, relatively large for HERA because of Q^2 and quite small for LHC of the order of 1 GeV/c. In particular, it is difficult to get, from the HERA data, the needed information for the important LHC cross sections.

From this point of view, it may be interesting to compare the present results with those in the pioneering work by Schäfer, Nachtmann, and Schöpf [8], and by Müller and Schramm [9], and also with those in some later papers [10].

7. It is sometimes argued that, because of the "factorization theorem", the quark and the gluon distribution functions must be the same for proton-proton and electron-proton interactions. Here are the reasons why this argument should not be considered to be conclusive.

(a) The failure of the factorization theorem in terms of quark and gluon distributions has been thoroughly discussed by Collins, Rogers, and Staśto [11]. What they have found is that, in the factorization theorem, the quark and the gluon distribution functions must be replaced by quark and gluon correlations functions [12]. These correlation functions depend on one more variable than the unintegrated distribution functions; to our best knowledge, the correlation functions have not been widely used by experimentalists.

(b) Even if the factorization theorem does hold for large values of Q^2, it does not help much in the present context. As seen from Fig. 1 and 6. above, the kinematic region of interest here is for the transverse momentum of the order of 1 GeV/c, corresponding to a Q^2 which is also quite small. In this kinematic region, the contributions from higher twist effects are sizable.

8. There are numerous possible physics applications to this scale of 1 GeV/c. Only one aspect is going to be discussed here: *the concept of paired jets.*

In the above, it has been pointed out that the recent theoretical result [1] on Higgs production at the Large Hadron Collider implies that such narrow transverse momentum distribution must hold for the constituents of the proton, and hence also for various produced particles besides the Higgs. So far as hadronic decays into two jets are concerned, the cases of Z and W are similar. In each case, there is a fraction of events where the vector sum of the transverse momenta of the two jets is small.

This leads to the concept of *paired jets.*

Two jets are called *paired jets* if the vector sum of their measured transverse momenta is small.

Here, 'small' means of the order of 1 GeV/c, provided that the transverse momentum resolution of the detector is better than 1 GeV/c.

Consider these events from the point of view of the paired jets, and plot the invariant mass of the these paired jets. If both f_Z and the corresponding f_W are significant, then this invariant-mass plot has two peaks at the masses of the Z and W.

How does this paired jets invariant mass looks like away from the Z and W peaks? There are two possibilities: either there is a significant number of off-peak events or there is not. From the existing knowledge, at present neither of these possibilities can be ruled out.

An alternative way in stating that there is a significant number of off-peak events is: the fraction f is significant not only on the Z and W peaks but also away from these peaks. In this case, the concept of 'paired jets' is most

useful, and some of their applications are going to be discussed below.

This concept of paired jets is readily generalized to triplets of jets, etc. Another important extension is to the idea of paired photon-jets.

9. Paired jets, especially if abundant, i.e., if the fraction f for paired jets is close to 1, have many practical applications. For example, some of the recorded events can be 'cleaned up' by removing the paired jets, thus reducing the background. Such a reduction of the number of background jets is expected to be useful, among others, in the search for supersymmetric particles. After the paired jets are removed, a larger fraction of the remaining particles seen in the detector is due to the decay of the produced supersymmetric particle or particles.

It may be of interest to return briefly to Higgs production and to consider the decay

$$H \to Z + Z \,. \tag{4}$$

If both Z's decay leptonically through (2), then the final state consists of 4ℓ ($\ell = e, \mu$). This channel is often referred to as 'golden', because the signal is exceptionally clean for the decay products. Unfortunately, the branching ratio is quite small, being $(6.7 \, \%)^2 \sim 0.45 \, \%$.

If the process of 'cleaning up', i.e., the removal of paired jets as described above, is successful, then the

hadronic decay of one or both Z's can also be important. This is so when use is made of the small transverse momentum of the produced Higgs particle. The major advantage of the hadronic mode is due to its much larger branching ratio. Thus, the case of one Z from (4) decaying hadronically and the other one leptonically gives a branching ratio 20 times larger than the leptonic case of the preceding paragraph, while that of both Z's decaying hadronically is 100 times larger. Such increases in event rates are of course very important.

It may be recalled that, at LEP, the first possible experimental evidence for the Higgs particle was mainly from the hadronic decay of the Higgs, due to its large branching ratio [4, 5].

10. In summary, it is the purpose of this paper to study the consequences of the recent theoretical work [1] on the transverse momentum distribution of the proposed Higgs particle. This result comes from a very long and difficult calculation [3]. The narrow transverse momentum distribution of the Higgs particle necessarily implies that the width of the transverse momenta of the constituents of the proton is of the order of 1 GeV/c, which in turn implies such narrow widths for various other produced particles at high energies, including Z and $W^{\pm}$, and more generally 'paired jets'.

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