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Transverse Momentum Distributions in High-Energy Hadron Interactions

R. Gastmans[a1], Sau Lan Wu[b2], and Tai Tsun Wu[c]

[a] Instituut voor Theoretische Fysica, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

[b] Department of Physics, University of Wisconsin, Madison WI 53706, USA

[c] Gordon McKay Laboratory, Harvard University, Cambridge MA 02138, USA,

and

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Abstract

From the recent theoretical result on the production of the Higgs boson at the Large Hadron Collider, it follows that the transverse momenta of the gluons in the protons are of the order of 1 GeV/c. Thus, a fraction of the Z's is expected to be produced with a transverse momentum of this order of magnitude and this phenomenon should be observable in the near future through the leptonic decay of the Z. If this fraction is found experimentally to be sizeable, then one possibility is the appearance of paired jets, i.e., two jets with the property that the vector sum of their transverse momenta is of the order of 1 GeV/c, even if these jets do not come from the decay of the Z. Such narrow transverse momenta imply that the quark and the gluon distribution functions appropriate for proton-proton and proton-antiproton interactions are significantly different from those for electron-proton interactions.

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1 Introduction

On March 30, 2010, the Large Hadron Collider (LHC) at CERN began to produce data at the center-of-mass energy of 7 TeV. Since this opens up a new energy regime, it is now the opportune time to investigate some possible simple features of the data at such energies.

Recently, we have studied [1, 2], at the energy of the Large Hadron Collider, the production process

$$p + p \to A + H + B\,, \tag{1.1}$$

via gluon fusion, where H is the Higgs particle [3], while A (or B) is a group of particles going down one (or the other) beam pipe.

The theoretical calculations for Higgs production presented in Refs. [1, 2] are exceptionally difficult and lengthy. It is believed that, at least in the near future, no similar calculation will be carried out for any other particle. It is therefore desirable to extract as much physics information as possible from these calculations. This is the purpose of the present paper. In particular, we shall concentrate on the following important feature: the transverse momentum of the produced Higgs particle is quite small, of the order of 1 GeV/c. A typical distribution in transverse momentum is shown in Fig. 1.

This is the second time that the feature of small transverse momentum has appeared. Many years earlier, in connection with the elastic hadron scatterings pp, $\bar{p}p$, π^+p, π^-p, K^+p, and K^-p, the widths of the peaks in the forward direction are all of the order of 1 GeV/c. An example is shown in Fig. 2 [6].

In view of this feature of small transverse momenta in elastic hadron scattering, this similar feature in the production process (1.1) cannot be specific to the Higgs particle, but it must also be a feature of various other production processes.

2 Physical considerations

This small transverse momentum is obtained under the assumption of gluon fusion, which is the most important production process for the Higgs particle at the Large Hadron Collider. As indicated by the name, in this process the Higgs particle is produced through the combination of two gluons. Thus, one of the gluons comes from one incoming proton, with the other gluon from the other incoming proton. Since the two gluons come from different sources, the narrow transverse momentum distribution of the produced Higgs particle must imply that the transverse momenta of the gluons in the protons are also small.

The following consideration may be invoked for a better understanding of this statement on gluon transverse momentum distribution. Take a proton at rest: its mass is about 1 GeV/c^2, while its size is about 1 fm, corresponding to 0.2 GeV/c. For the present consideration, no distinction is made between 1 GeV and 0.2 GeV. For a gluon as constituent of the proton, its energy must be less than the proton mass, and hence its momentum must be less than 1 GeV/c. Even if the gluon is off its mass shell, its momentum must remain of the order of 1 GeV/c, because the proton mass provides the largest momentum scale.

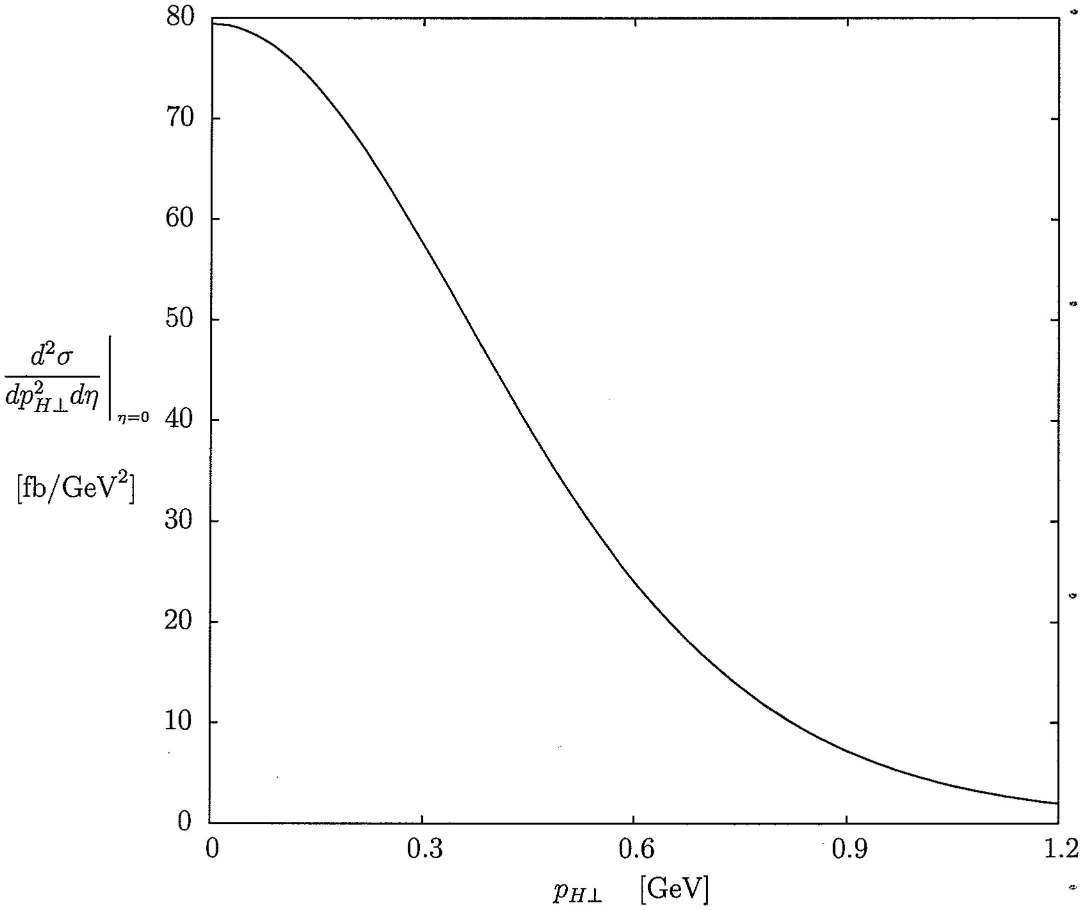

Figure 1: A typical distribution of the transverse momentum $p_{H\perp}$ of the produced Higgs particle with rapidity $\eta = 0$. This curve is for the Higgs mass of $M = 115$ GeV/c^2 [4, 5].

The proton can be boosted to a high energy through the application of a Lorentz transformation. However, under any Lorentz transformation, the transverse momentum is invariant. The conclusion is therefore reached that the transverse momentum of a gluon inside the proton must remain of the order of only 1 GeV/c or less. The same result must also apply to the other constituents of the proton, namely quarks and anti-quarks.

This situation can be clarified by referring to the calculations of Ref. [2]. As represented schematically in Fig. 3, the production process (1.1) can be viewed as the production of the Higgs particle by two Pomerons $\mathcal{P}$:

$$\mathcal{P} + \mathcal{P} \to H\,. \tag{2.1}$$

Strictly speaking, this production is not by two Pomerons, which are defined as whatever is responsible for elastic scattering; rather, the $\mathcal{P}$ here is an object that is very similar to

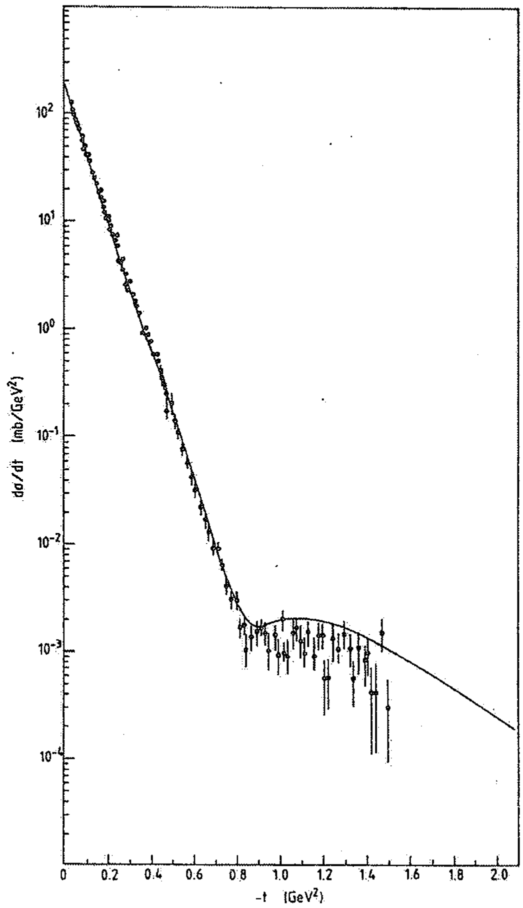

Figure 2: $p\bar{p}$ elastic scattering at the center-of-mass energy of 546 GeV. The data are from Ref. [7].

the Pomeron. Because of this process (2.1), the Large Hadron Collider can be considered a Pomeron Collider, in fact an excellent one [1].

The study of such two-Pomeron processes was pioneered by Schäfer, Nachtmann, and Schöpf [8] and by Müller and Schramm [9]. Ref. [10] lists a small sample of later papers on this topic.

The simplest approximation to a Pomeron is a pair of gluons. Thus, the process (2.1) involves not two but four gluons. Even in the simplest case where one gluon in each Pomeron does not interact with the Higgs particle, while the two other gluons fuse to produce the Higgs particle, the gluons are correlated in order to form the Pomerons, and thus the situation is different from gluon fusion with two uncorrelated gluons.

This is the reason why the result in Refs. [1] and [2] *cannot* be described in terms of

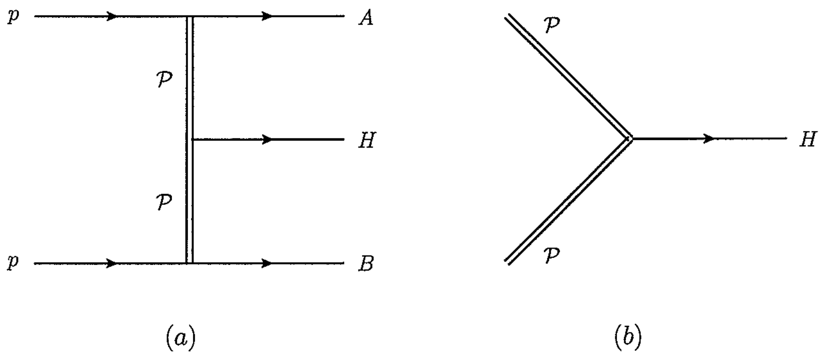

Figure 3: Schematic representations for the processes (1.1) and (2.1), showing the relations between them.

any gluon distribution function. More precisely, no gluon distribution function, no matter how complicated, can be used to describe the result of Refs. [1] and [2] on the momentum distribution of the produced Higgs particle, provided the two-gluon distribution function is assumed to be the product of the two one-gluon distribution functions.

3 Small vs. large transverse momenta

In the process (1.1), where the Higgs particle is produced via gluon fusion, the transverse momentum of this Higgs particle is small, of the order of 1 GeV/c or less. If, instead, for the same process (1.1), the Higgs is produced through vector boson fusion of W or Z, then the transverse momentum of the Higgs is large, i.e., of the order of 10 GeV/c or larger. Thus, in the same process, particles are produced with both small and large transverse momenta.

In this particular case of Higgs production, gluon fusion leads to a larger cross section than vector boson fusion, and hence the fraction of the produced particle with a small transverse momentum is large. In the other processes to be discussed in this paper, this fraction is in general not known, even when the particle is produced singly. It should also be noted that, in the case of gluon fusion to produce a single Higgs particle, there is a significant tail in the distribution shown in Fig. 1. Such Higgs particles in the tail with relatively large transverse momenta are of interest; furthermore, such Higgs particles are likely to be enhanced through QCD radiative corrections.

A particle is not always be produced singly; it may be produced in association with another particle. Even in the context of Higgs production, gluon fusion can lead to

$$p + p \to A + H + H + B \tag{3.1}$$

in addition to (1.1). Similar to (2.1), this process (3.1) can also be viewed as production by Pomerons:

$$\mathcal{P} + \mathcal{P} \to H + H\,. \tag{3.2}$$

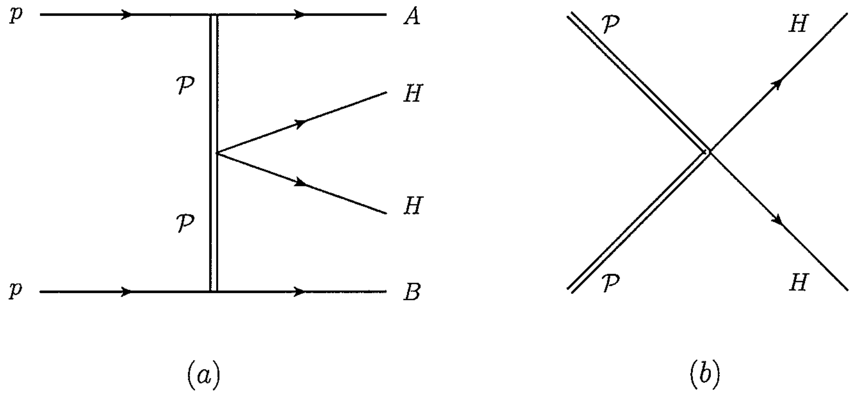

Figure 4: Schematic representations for the processes (3.1) and (3.2), showing the relations between them.

Fig. 4 shows the modification to Fig. 3 to give schematically these two processes. Note that these figures 4(a) and 4(b) do not include all possibilities for these processes.

In the production process (3.1), the vector sum of the transverse momenta of the two Higgs particles is small, but each of these two Higgs particles can have a large transverse momentum.

It is thus seen that, for any particle produced in high-energy hadron interactions, it can

(a) have a large transverse momentum of the order of 10 GeV/c or more; and

(b) have a small transverse momentum of the order of 1 GeV/c or less.

If this produced particle has a large mass, the possibility (a) is well known. In contrast, the possibility (b) is new, based on the recent result of Refs. [1] and [2]. What remains unknown is the fraction f of particles with this small transverse momentum.

We proceed to apply this result to well-established particles, beginning with the Z in the next section. The importance of these considerations depends on the size of f in each case; the larger f is, the more important the present considerations are. The value of f for each particle has to be determined by experiment at the Large Hadron Collider for pp interactions, or at the Tevatron Collider for $\bar{p}p$ interactions.

4 Production of Z

The first step is to consider the production of Z, which is an especially nice choice. Thus, the Higgs production process (1.1) is replaced by

$$p + p \to Z + X\,, \tag{4.1}$$

where X is anything, not necessarily going down the beam pipes. The case of interest here is when this Z is produced with a small transverse momentum of the order of 1 GeV/c.

The major decay modes and branching ratios of the Z are [11]

$$Z \to e^+ + e^- \qquad (3.363 \pm 0.004)\%\,, \tag{4.2a}$$

$$Z \to \mu^+ + \mu^- \qquad (3.366 \pm 0.007)\%\,, \tag{4.2b}$$

$$Z \to \tau^+ + \tau^- \qquad (3.370 \pm 0.008)\%\,, \tag{4.2c}$$

$$Z \to \text{invisible} \qquad (20.00 \pm 0.06)\%\,, \tag{4.2d}$$

and

$$Z \to \text{hadrons} \qquad (69.91 \pm 0.06)\%\,. \tag{4.2e}$$

Of these five decay modes, (4.2d) cannot be detected, and (4.2c) is difficult to analyze. Leaving these two aside, there remains

$$Z \to \ell^+ + \ell^- \qquad (6.73 \pm 0.01)\%\,, \tag{4.3}$$

and

$$Z \to \text{hadrons} \qquad (69.91 \pm 0.06)\%\,, \tag{4.4}$$

where ℓ means e or μ. This (4.3) is referred to as the leptonic mode and (4.4) as the hadronic mode.

(A) Leptonic mode

For this case of Z production, it is predicted that the measured distribution, as a function of the square of the transverse momentum, has a peak at or near zero — see Fig. 1. What needs to be determined *experimentally* is the fraction f introduced in the preceding section; for the present case, it is

$$f_Z = \frac{\text{No. of observed } Z\text{'s under this peak near zero transverse momentum}}{\text{total No. of observed } Z\text{'s}}\,. \tag{4.5}$$

See the last paragraph of Sec. 3. It is of course desirable to take into account the detection efficiency.

(B) Hadronic mode

The hadronic decay (4.4) comes mostly from

$$Z \to q + \bar{q}\,. \tag{4.6}$$

Experimentally, both the quark q and the anti-quark $\bar{q}$ are seen in the detector as a jet. It is much more complicated to determine the properties of a jet than those of a lepton.

These two distributions obtained experimentally under (A) and (B) from the leptonic and hadronic decays of the Z must be the same in principle, but there are various detector effects that lead, in practice, to important differences between these two distributions. Because of the possible presence of a neutrino, the experimental determination of the jet momentum is even more difficult for c and b jets than for u and d jets.

If a good analysis is found for jets, even if limited to u and d jets, the payoff can be tremendous. The transverse momentum distribution of the produced Z can be determined through its leptonic mode; if f_Z in (4.5) is significant, then even a relatively poor knowledge of the jets is quite useful, since the hadronic branching ratio is ten times larger than the leptonic branching ratio.

5 Production of W

Next, consider briefly the very similar process

$$p + p \to W^{\pm} + X\,, \tag{5.1}$$

where again X can be anything. Corresponding to (4.2), the major decay modes and branching ratios of the W are [11]

$$W^+ \to e^+ + \nu_e \qquad (10.75 \pm 0.13)\%\,, \tag{5.2a}$$

$$W^+ \to \mu^+ + \nu_\mu \qquad (10.57 \pm 0.15)\%\,, \tag{5.2b}$$

$$W^+ \to \tau^+ + \nu_\tau \qquad (11.25 \pm 0.20)\%\,, \tag{5.2c}$$

and

$$W^+ \to \text{hadrons} \qquad (67.60 \pm 0.27)\%\,. \tag{5.2d}$$

Since the first three major modes are useless in determining the transverse momentum of the W to the required accuracy, (5.2d) is the only one left. In other words, for the purpose of the present paper, while both the leptonic decay and the hadronic decay are of importance for the Z, only the hadronic decay needs to be studied for the W.

This present case of the W can be treated in an identical manner as that for the Z in Sec. 4(B). The hadronic decay (5.2d) comes mostly from

$$W \to q + \bar{q}'\,, \tag{5.3}$$

where the right-hand side differs from that of (4.5) only in $q \neq q'$. This makes no essential difference because experimentally it is difficult to associate, case by case, a specific quark with an observed jet.

Because of the close relation between Z and W, a peak at or near zero transverse momentum is similarly expected for the W, and the definition of f_Z by (4.5) also applies to the W:

$$f_W = \frac{\text{No. of observed } W\text{'s under this peak near zero transverse momentum}}{\text{total No. of observed } W\text{'s}}\,. \tag{5.4}$$

However, it is not clear to what extent these two quantities f_Z and f_W are related to each other.

6 Concept of paired jets

So far as jets are concerned, the first stage of the present development, as discussed in the last two sections, can be described succinctly as follows. From the elastic hadronic scattering cross section and the recently calculated Higgs production cross section at the energy of the Large Hadron Collider, the transverse momenta are small, of the order of 1 GeV/c or less. Generalizing this small transverse momentum to the production of Z and W at high energies, momentum conservation implies that, for a fraction f of the events, the sum of the transverse momenta of the two jets from the decay of Z and W is small.

Beginning with the pairs of jets from the hadronic decays of Z and W, consider a histogram of the events versus the invariant mass of the jet pair. Clearly, there will be two peaks, one at the Z mass and another at the W mass; in addition, there must also be events away from these two peaks. For these off-peak events, there are two possibilities:

(a) The property that the vector sum of the transverse momenta of the two jets is small is valid only under the Z and W peaks, but not for the off-peak events, or

(b) This property is not limited to the Z and W peaks, but also holds for the off-peak events.

Which one of these two possibilities is true for the 7 TeV data at the Large Hadron Collider has to be determined experimentally.

These two possibilities can be conveniently restated in terms of the fraction f of events where the vector sum of the transverse momenta of the two jets is of the order of 1 GeV/c; see Sec. 3. In (a), this f, as a function of the invariant mass of the two jets, is small except near the Z and the W masses. On the other hand, in (b), this f is sizeable for a range of invariant masses.

From the point of view of theory, little is known about this fraction f. Therefore, there is no reliable way to choose theoretically between these two possibilities. Nevertheless, the authors prefer the possibility (b); this is because we do not see a close connection between this fraction f and the invariant mass.

While this argument may or may not be correct, the rest of the paper is going to be devoted entirely to the possibility (b). This (b) has the advantage of having a much richer physics content than the (a).

Under the assumption that (b) holds, then

- the property of importance is that there are pairs of jets such that the vector sum of their transverse momenta is small, but
- it is *not* important whether this pair of jets comes from the decay of a Z (Sec. 4) or a W (Sec. 5) or not.

In this way, liberation is achieved from the decay of a known particle; instead, the emphasis is shifted to the pairs of jets themselves. 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.

In principle, here 'small' should mean of the order of 1 GeV/c; however, because of measurement errors, this sum should be compared with their measurement error, which is likely to be more than 1 GeV/c for jets.

One of the first experimental issues is: how prevalent are the 'paired jets'? The more prevalent they are, the more important the present considerations become.

It should be noted that there can be ambiguities in pairing the jets. For example, it is possible that jet A and jet B form paired jets by satisfying the definition, and so do jet B and jet C. Since jet B cannot be counted twice, other considerations are needed to decide how these jets should be paired.

7 First mechanism for producing paired jets

Where do the paired jets come from? If a significant number of paired jets are observed at the Large Hadron Collider, there are at least two likely ways to produce them. Since these two ways are quite different, it will have to be determined experimentally which one is more important, and it is quite possible that they both are. These two mechanisms are to be described in this section and the next one, together with some of the implications.

The first one is easy to describe: as an example, a quark in one of the incident protons scatters from a quark from the other incident proton via Møller scattering:

$$q + q \to q + q \,. \tag{7.1}$$

As discussed in Sec. 2, the transverse momenta of the incoming quarks are each of the order of 1 GeV/c or less, and therefore, by momentum conservation, the vector sum of the transverse momenta of the produced quarks must also be of the order of 1 GeV/c. In other words, by the definition of Sec. 6, the two q's in the final state of the process (7.1) form paired jets.

With the quarks, anti-quarks, and gluons in the two incident protons, other similar two-body processes, not all elastic, are

$$\begin{aligned} & q + \bar{q} \to q + \bar{q} \,, \\ & \bar{q} + \bar{q} \to \bar{q} + \bar{q} \,, \\ & q + g \to q + g \,, \\ & \bar{q} + g \to \bar{q} + g \,, \\ & g + g \to g + g \,, \\ & q + \bar{q} \to g + g \,, \\ \text{and} \quad & g + g \to q + \bar{q} \,. \end{aligned} \tag{7.2}$$

If the quarks, anti-quarks, and gluons are treated approximately as free particles, then the cross sections and the angular distributions of these eight processes (7.1) and (7.2) are well known. Therefore, if the distributions for the quark, anti-quark, and gluon are known, then those for the paired jets are also known. Conversely, if the distribution functions for the paired jets have been determined by experiment at the Large Hadron Collider, then, at least in principle, those of the quark, anti-quark, and gluon can be determined.

It is interesting to make a detailed comparison between the present picture of quark, anti-quark, and gluon distributions for the Large Hadron Collider and the conventional one.

(a) For the Large Hadron Collider, these distribution functions depend on both the longitudinal and the transverse components of the momentum. As seen from the physics considerations of Sec. 2 and also from the present section, the quark, anti-quark, and gluon distribution functions in the proton have a characteristic transverse momentum of the order of 1 GeV/c or less. In fact, this is what led to the concept of 'paired jets' in Sec. 6. In other words, if this small width of the order of 1 GeV/c is neglected, then

these distributions functions depend only on the longitudinal momentum, conveniently parametrized by x, which is this longitudinal momentum divided by the momentum of the incident protons in the center-of-mass system. This is to be contrasted with the corresponding ep distribution functions, which are functions of x and a variable Q^2 for the virtual photon. [As already stated in Sec. 3, these distribution functions for the present approach do have significant tails for larger transverse momenta, and these tails are of importance themselves.]

(b) It is worth examining what the underlying reasons are for this difference between the distribution functions from the present approach and the conventional one. We believe that the following point is of fundamental importance.

One of the popular distribution functions used extensively by the experimentalists in studying the physics at the Large Hadron Collider is from the CTEQ Collaboration [12]; those from the other Collaborations are not very different. The input data used by this CTEQ Collaboration consist mostly of those from HERA of DESY. But, HERA is an electron-proton collider, not a proton-proton or a proton-antiproton collider.

There is no physics reason why the quark, anti-quark, and gluon distribution functions in the proton should be the same for ep and pp interactions.

(c) Are there physics reasons why these distribution functions should be different for ep and pp interactions? Yes, there are, if paired jets indeed play a significant role at the energy of the Large Hadron Collider — see Sec. 6. By the definition of 'paired jets' in that section, there is, for proton-proton and proton-antiproton interactions, an important transverse momentum scale of 1 GeV/c, while this scale does not appear in electron-proton interactions.

For electron-proton interactions as studied at HERA, the electron emits a highly virtual photon, which is then absorbed by the proton. The photon being virtual, it masks the scale of 1 GeV/c from the proton. It is thus difficult to see this scale of 1 GeV/c at HERA; through the observation of paired jets, this difficulty is absent at the Large Hadron Collider. In other words, *the basic difference between the quark, anti-quark, and gluon distribution functions can be traced to the fact that the virtual photon plays a central role in electron-proton interactions, but no significant role in proton-proton and proton-antiproton interactions.*

The authors realized, nearly a decade ago, this difference due to the virtual photon. Indeed, this is the original motivation for carrying out the exceptionally difficult and lengthy calculation underlying Refs. [1] and [2].

(d) What method can be used to determine the quark, anti-quark, and gluon distribution functions suitable for use at the Large Hadron Collider? Clearly, this determination has to be based on data from this Large Hadron Collider, and all information from electron-proton colliders such as HERA has to be avoided.

Several different strategies can be used to develop various methods to determine these distribution functions, and it is at present difficult to decide the relative merits of

these strategies. Here is one possible choice of data to be used. Among the two-body processes (7.2), there are

$$q+\bar{q}\rightarrow c+\bar{c}\,, \tag{7.3}$$

$$q+\bar{q}\rightarrow b+\bar{b}\,, \tag{7.4}$$

$$g+g\rightarrow c+\bar{c}\,, \tag{7.5}$$

and

$$g+g\rightarrow b+\bar{b}\,, \tag{7.6}$$

and the q on the left-hand side means u or d quarks. In this way, $c\bar{c}$ and $b\bar{b}$ can be produced as paired jets, and such paired jets can be identified by, for example, the presence of secondary vertices. It is probably not essential to separate the $c\bar{c}$ and $b\bar{b}$ pairs cleanly.

If there is a sufficient number of events, the two-body processes

$$q+\bar{q}\rightarrow t+\bar{t}\,, \tag{7.7}$$

and

$$g+g\rightarrow t+\bar{t}\,, \tag{7.8}$$

can also be useful.

It should be emphasized that, in order to apply this procedure or a similar one to determine the distribution functions, it is first necessary to remove the second mechanism to produce paired jets, discussed in the next section.

8 Second mechanism for producing paired jets

In Refs. [1] and [2], where the narrow transverse momentum distribution of Fig. 1 was first found for the produced Higgs particle, the process is that of (1.1). In this production process in proton-proton collisions, the Higgs may be replaced by one or more paired jets:

$$p+p\rightarrow A+\text{paired jet}+B\,, \tag{8.1}$$

$$p+p\rightarrow A+\text{two paired jets}+B\,, \tag{8.2}$$

$$p+p\rightarrow A+\text{three paired jets}+B\,, \tag{8.3}$$

and, more generally,

$$p+p\rightarrow A+n\text{ paired jets}+B\,. \tag{8.4}$$

In these processes, as before, A (or B) is a group of particles going down one (or the other) beam pipe.

Just as the process (1.1) is represented schematically by Fig. 3(a), these processes (8.1), (8.2), (8.3), and (8.4) can be represented similarly in Fig. 5. This second way of producing paired jets differs from the first one of the preceding section in at least the following ways.

(a) For the paired jets produced through the two-body scattering (7.1) and (7.2), the two jets may or may not form a particle-antiparticle pair. In contrast, the paired jets from the present mechanism are necessarily $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, $b\bar{b}$, or gg pairs. It may also be a $t\bar{t}$ pair, since the energy of the Large Hadron Collider is likely to be high enough.

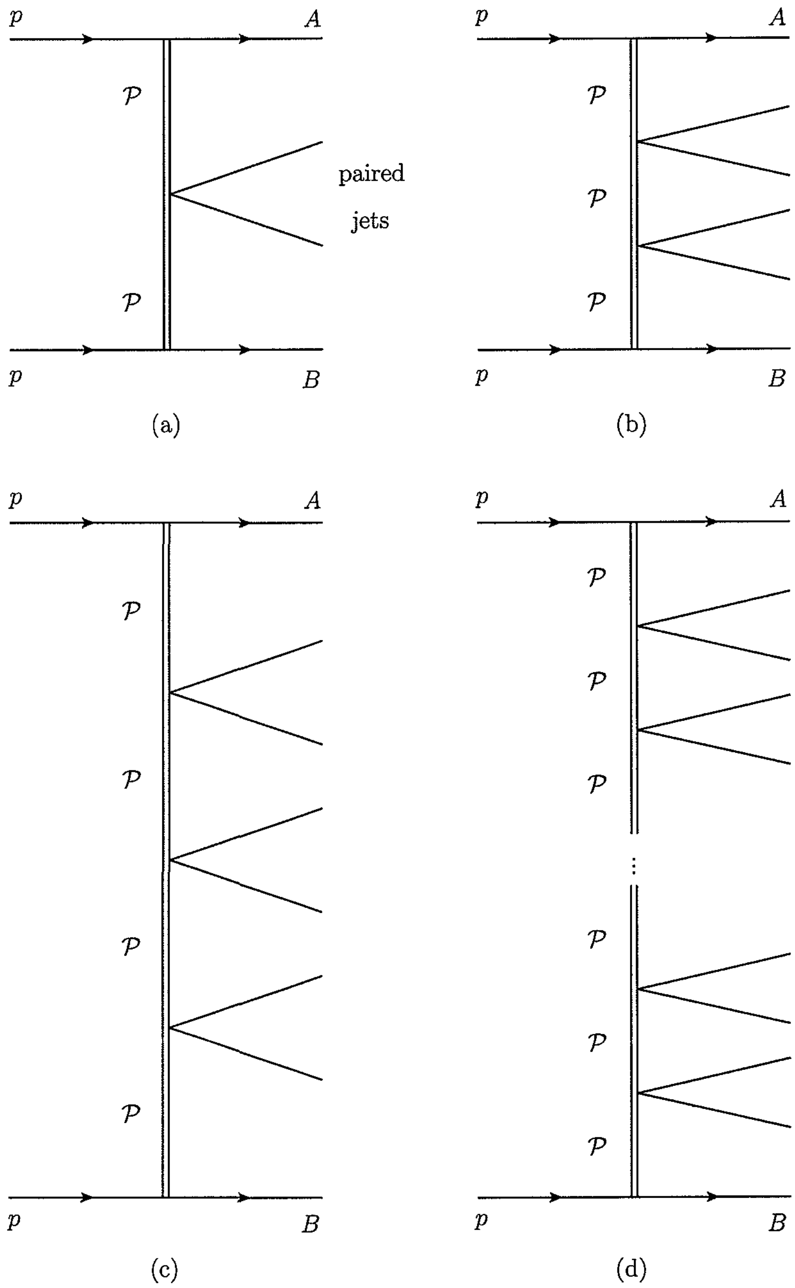

Figure 5: Schematic representation for the processes (8.1) (a), (8.2) (b), (8.3) (c), and (8.4) (d).

(b) The number of paired jets produced by the mechanism of the preceding section depends on the quark, anti-quark, and gluon distributions, and may be used to find the properties of such distribution functions [see (d) of Sec. 7]. In contrast, the number of paired jets produced through (8.1), (8.2), (8.3), or more generally (8.4) is not related to such distribution functions.

(c) As an immediate consequence of (b), the number of paired jets from this second mechanism is the same for proton-proton and proton-antiproton interactions at the same energy. This is not true for the process in the preceding section, because, for example, the cross section for the Møller scattering (7.1) is different from that of Bhabha scattering

$$q + \bar{q} \rightarrow q + \bar{q} \tag{8.5}$$

at the same energy.

There is the following interesting point and question about the present way of producing paired jets. Since the increasing total cross section was first found forty years ago [13], the question has been raised repeatedly what processes are responsible for this increase. It was known from the beginning that the integrated elastic and diffractive cross sections are responsible for perhaps 20% of the increase, but it is still not clear even now what processes are responsible for the rest of the increase. It is quite possible that this production (8.1)-(8.4) of paired jets may be responsible for some of the rest 80% of the increase, but it is doubtful that they give the entire 80%.

The plan for the energy of the Large Hadron Collider is presently as follows. For the years 2010 and 2011, it will run at the center-of-mass energy of 7 TeV. There will be a shutdown of a year in 2012 or perhaps slightly longer to upgrade the machine, and then the Large Hadron Collider will run starting from 2013 at or near its design center-of-mass energy of 14 TeV. From the present point of view, this is fortunate: if a significant number of paired jets are indeed present, then running the Large Hadron Collider at these two energies makes it possible to determine the contribution to the increase in the total cross section from the production processes (8.1)-(8.4).

Two mechanisms have been described in this section and the preceding one. Both mechanisms can often be operative in the same event. It should also be kept in mind that there may be additional possibilities of producing the paired jets besides these two.

9 Further applications of paired jets

The paired jets, together with their properties and utilizations, have been discussed in the previous three sections. It is the purpose of the present section to discuss some further possible applications of the paired jets, under the stronger assumption that a significant percentage of jets form paired jets.

It should be mentioned that, in addition to paired jets, there are *paired photon-jets*. Similar to the definition of the 'paired jet' in Sec. 6, a photon and a jet are called 'paired

photon-jet' if the vector sum of their measured transverse momenta is small. One of several examples for the utilization of such paired photon-jets is the calibration of the energy of jets.

(A) Event cleaning

Under this stronger assumption, besides the leptons, photons, and paired photon-jets, an event consists of

a) a number of paired jets, and

b) the remaining jets.

It is not clear what the relation is between a) and b); the simplest possibility is that they have little to do with each other. This simplest possibility is to be studied for the remainder of this Sec. 9.

In this case, it is perhaps not unreasonable to take the point of view that interesting physics resides mostly, if not entirely, in b). With this view, all the paired jets, together with the paired photon-jets, should be deleted from the events. In the present context, this deletion may be referred to as event cleaning. It is assumed that the events contain a significantly smaller number of jets after cleaning and that they are therefore simpler to analyze.

(B) $H \to Z + Z$

As a first example, consider a Higgs particle of relatively high mass that decays into ZZ, where the Z's are on or near mass shell. Such a Higgs particle must have a mass larger than $2M_Z$, and is therefore not the Higgs of 115 GeV/c^2, the value of the preliminary experimental evidence from LEP [4, 5]. The existence of more than one physical Higgs particle is easily incorporated into the standard model [14], and is indeed a most interesting and exciting possibility that may be discovered at the Large Hadron Collider.

For a Higgs particle that decays

$$H \to Z + Z\,, \tag{9.1}$$

there is a 'golden channel' where

$$Z \to \ell^+ + \ell^- \tag{9.2}$$

holds for both Z's. This channel, with the final state of 4ℓ ($\ell = e\,,\mu$), is often referred to as golden because the signal is exceptionally clean for the decay products.

From (4.3) and (4.4), the decay sequence

$$H \to Z + Z\,, \qquad \text{with both} \qquad Z \to \text{hadrons} \tag{9.3}$$

has a branching ratio that is two orders of magnitude higher than the golden channel. This (9.3) is, however, usually not considered to be useful because there are often many other hadron jets in the event with the consequence that the data analysis is very difficult.

Suppose a large percentage of jets belongs to paired jets, as assumed for this section. In this case, a significant number of jets can be removed from consideration in studying the process (9.3). This is a concrete example of cleaning up an event. If this cleaning up is sufficiently successful, then (9.3), because of its much larger branching ratio, may be able to compete with, or perhaps do even better than, the golden channel.

There is also the mixed decay mode

$$H \to Z + Z, \qquad \text{with} \quad Z \to \ell^+ + \ell^- \quad \text{and} \quad Z \to \text{hadrons}, \tag{9.4}$$

i.e., one of the Z's decays leptonically and the other Z hadronically. This is intermediate between (9.3) and the golden channel, the event rate being about 20 times that of the golden channel. If the event cleaning is successful, the importance of this (9.4) may well be seen before the hadronic mode (9.3).

(C) Search for supersymmetry

This process of cleaning up events may be even more useful for the search for supersymmetry.

Suppose, after removing the paired jets, the paired photon-jets, and possibly the triplets of jets (where the sum of the three jet transverse momenta is small), there are many jets and leptons that can no longer be separated into any subset with small total transverse momentum. There are of course various possibilities of getting jets with such properties, and these possibilities need to be considered.

What is the simplest possibility of getting many jets and leptons with the property that

$$\sum_k \vec{p}_{\perp k} \tag{9.5}$$

is not small for any subset? One such possibility, perhaps the simplest possibility, is that these quarks and leptons come from the decay of one or more new particles whose decay gives many jets and/or leptons. No such particles are known, and therefore they must be new.

Supersymmetry gives such new particles.

This is the appropriate point to add the following comment. Even in MSSM, the minimal supersymmetric standard model, there are more than one hundred independent parameters for soft supersymmetry breaking. The present possibility of first cleaning up the events may provide a way of looking in a larger portion of this multi-dimensional supersymmetry parameter space.

This method supplements the one recently proposed using the 'magic triangle' for Higgs decay [2, 15]; these two methods are rather different in nature.

10 Conclusion and discussions

The main theme of this paper is the presence of a scale of 1 GeV/c in proton-proton and proton-antiproton interactions at high energies.

It is actually elementary to see the presence and importance of this scale, as discussed in Sec. 2. The recent theoretical result on the transverse momentum distribution of the Higgs particle produced through gluon fusion implies that the typical transverse momentum of a gluon in the proton must be of the order of 1 GeV/c [1, 2]. This point can be readily understood through the following two facts:

a) the proton mass is about 1 GeV/c^2, and the proton size of about 1 fm corresponds to a momentum of 0.2 GeV/c; and

b) under a Lorentz transformation, no matter how large, the transverse components of the momentum do not change.

It follows from a) that the momentum of a gluon inside a proton at rest is of the order of 1 GeV/c. Here, the distinction between 1 GeV/c and 0.2 GeV/c is ignored. The application of b) then shows that, in a high-energy proton-proton or proton-antiproton collisions, the transverse momentum of this gluon remains of the order of 1 GeV/c.

This order of magnitude for the transverse momentum cannot be restricted to the gluon, and must be equally valid for the quark and the anti-quark.

This new scale of 1 GeV/c — or perhaps more properly called this oldest scale of 1 GeV/c from the proton mass — is then applied successively to the leptonic decay of the Z, the hadronic decay of the Z, the hadronic decay of the W, and paired jets. If there is a sufficiently large number of paired jets, then they can be used for event cleaning. Such event cleaning may be useful for various physics analyses, two examples being the decay process $H \to ZZ$ and the search for supersymmetry.

We conclude with two remarks.

(A) The present considerations apply equally well to the proton-proton interactions at the Large Hadron Collider and to the proton-antiproton interactions at the Tevatron Collider. However, the important fraction f is most likely different for these two proton-proton and proton-antiproton cases.

(B) Since this scale of 1 GeV/c is quite small for high-energy experiments, efforts are required to observe the manifestations of this scale experimentally. An especially favorable channel to look for such effects is the leptonic decay of the Z.

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