Signals for Double Parton Scattering at the Fermilab Tevatron

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Four double parton scattering processes are examined at the Fermilab Tevatron energy. With optimized kinematical cuts and realistic parton level simulation for both signals and backgrounds, we find large samples of four-jet and three-jet + one-photon events with signal to background ratio being 30%–50%, and much cleaner signals from two-jet + two-photon and two-jet + e^+e^- final states. The last channel may provide the first unambiguous observation of multiple parton interactions, even with the existing data sample accumulated by the Tevatron collider experiments. [S0031-9007(96)01613-4]

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There are good reasons to believe that multiple partonic interactions, where two or more *pairs* of partons scatter off each other, occur in many, or even most, $p\bar{p}$ collisions at the Tevatron ($\sqrt{s} = 1.8$ TeV). On the theoretical side, multiple partonic interactions are an integral part of the eikonalized minijet model [1], which attempts to describe the observed increase of the total $p\bar{p}$ cross section with energy in terms of the rapidly growing cross section for the production of (mini)jets with transverse momentum $p_T \geq p_{T,\min} \simeq 2$ GeV. Sjöstrand and van Zijl [2] also pointed out that including multiple interactions in the PYTHIA event generator greatly improves the description of the "underlying event" in $p\bar{p}$ collisions. A similar result was found recently by the H1 Collaboration [3] in a study of γp collisions.

However, hadronic event generators have many ingredients. This makes it difficult to draw unambiguous conclusions from such studies. It is therefore desirable to search for more direct evidence for multiple partonic interactions, using final states that are amenable to a perturbative treatment. Clearly, the cross section will be largest if only strong interactions are involved. The simplest signal of this kind is the production of four high-p_T jets in independent partonic scatters within the same $p\bar{p}$ collision [4] ($4 \rightarrow 4$ reactions). Since energy and momentum are assumed to be conserved independently in each partonic collision, the signal for a $4 \rightarrow 4$ reaction is two pairs of jets with the members of each pair having equal and opposite transverse momentum. Various hadron collider experiments have searched for this signature. The AFS Collaboration at the CERN ISR reported [5] a strong signal. However, the exact matrix elements for the quantum chromodynamics (QCD) background $2 \rightarrow 4$ processes were not used, and the size of the signal claimed was considerably larger than expected. The UA2 Collaboration at the CERN SppS collider saw a hint of a signal, but preferred to quote only an upper bound [6]. More recently, the CDF Collaboration at the Fermilab Tevatron found evidence at the 2.5σ level that $4 \rightarrow 4$ processes contribute about 5% to the production of four jets with $p_T \geq 25$ GeV [7].

While final states consisting only of jets offer large cross sections, they suffer from severe backgrounds. There are three possible ways to group four jets into two pairs. Further, the experimental error on the energy of jets with $p_T \simeq 20$ GeV is quite large. Hence even four-jet events that result from $2 \rightarrow 4$ background processes often contain two pairs of jets with transverse momenta that are equal and opposite within the experimental errors. The study of "cleaner" final states has therefore been advocated: The production of two pairs of leptons (double Drell-Yan production) has been studied in Ref. [8], the production of two J/ψ mesons in Ref. [9], and the production of a W boson and a pair of jets in Ref. [10]. However, in our opinion, none of these processes is ideally suited for studying multiple partonic interactions. Double Drell-Yan production offers a very clean final state, but the cross section at Tevatron energies is very small once simple acceptance cuts have been applied. The cross section for double J/ψ production is quite uncertain, since it depends on several poorly known hadronic matrix elements [11]. Finally, W + jets events can only be identified if the W boson decays leptonically, which makes it impossible to fully reconstruct the final state.

Here we study mixed strong and electroweak final states: (i) three jets and an isolated photon ($jjj\gamma$), (ii) two jets and two isolated photons ($jj\gamma\gamma$), (iii) two jets and an e^+e^- pair ($jjee$). For comparison, we also include (iv) four-jet final states (denoted by 4-jet). We try to be as close to experiment as possible within a parton level calculation. To this end we not only apply acceptance cuts, but also allow for finite energy resolution, and try to model transverse momentum "kicks" due to initial and final state radiation. We find that the $jjj\gamma$ final state offers a slightly worse signal to background ratio than the 4-jet final state; note that the combinatorial background is the same in these two cases. This combinatorial background does not exist for the $jj\gamma\gamma$ and $jjee$ final states, which offer much better signal to noise ratios, at the price of small cross sections.

The calculation of our signal cross sections is based on the standard assumption [1,2,8–10] that the two partonic

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interactions occur *independently* of each other. The cross section for a $4 \to 4$ process is then simply proportional to the square of the $2 \to 2$ cross section:

$$\sigma(4 \to 4) = [\sigma(2 \to 2)]^2/\sigma_0 \,. \tag{1}$$

This assumption cannot be entirely correct, since energy-momentum conservation restricts the available range of Bjorken x values of the second interaction, depending on the x values of the first one. We include this (small) effect using the prescription of Ref. [2]. Generally speaking, σ_0 is related to the transverse distribution of partons in the proton. Unfortunately, total cross section data do not allow to determine this quantity very precisely. We find values between about 20 and 60 mb, depending on the choice of the numerous free parameters of the model. The recent CDF study [7] found $\sigma_0 = 24.2^{+21.4}_{-10.8}$ mb, within the range that can be accommodated in minijet models. We will take $\sigma_0 = 30$ mb in our numerical analysis; the results can be scaled trivially to other values of σ_0.

The relevant $2 \to 2$ cross section can be written as a sum of different terms

$$\sigma(2 \to 2) = \sigma(p\bar{p} \to jjX) + \sigma(p\bar{p} \to j\gamma X) + \sigma(p\bar{p} \to \gamma\gamma X) + \sigma(p\bar{p} \to e^+e^-X)\,, \tag{2}$$

where j stands for a high-p_T jet. Inserting Eq. (2) into Eq. (1) gives a $4 \to 4$ cross section that sums over many different states; it should be obvious which terms in the sum are of relevance to us. Note that this procedure gives an extra factor of 2 in the cross section for the production of final states made up from two *different* $2 \to 2$ reactions (e.g, $jjj\gamma$) compared to those produced from two identical reactions. Partly for this reason we only consider $jj\gamma\gamma$ configurations, where the two jets are produced in one partonic scatter and the two photons in another. The other possible configuration ($j\gamma j\gamma$), where each jet pairs up with one photon, also suffers from larger backgrounds, since there are two ways to form such pairs. We use leading order matrix elements in Eq. (2), but we include the contribution from $gg \to \gamma\gamma$, which enhances the total $p\bar{p} \to \gamma\gamma X$ cross section by about 50% at $\sqrt{s} = 1.8$ TeV. We take MRS(A) structure functions [12]; other modern parametrizations give very similar results. We use the leading order expression for α_s, with $\Lambda_{\rm QCD} = 0.2$ GeV, and take the (average) partonic p_T as the factorization and renormalization scale. We use exact leading order matrix elements to compute the backgrounds from $2 \to 4$ processes. These have been computed in Ref. [13] for the 4-jet final state, in Ref. [14] for the $jjj\gamma$ final state, in Ref. [15] for $jj\gamma\gamma$ production, and in Ref. [16] for $jjee$ production.

In order to approximately mimic the acceptance of the CDF and D0 detectors, we require all jets to have rapidity $|y_{\rm jet}| \leq 3.5$, while we require $|y_{e,\gamma}| \leq 2.5$ for electrons and photons. We also require the isolation cut $\Delta R_{ij} \equiv \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} \geq 0.7$ for all combinations ij of final state particles. We generally find that the $4 \to 4$ signal decreases more quickly than the $2 \to 4$ background when the (transverse) momentum of the outgoing particles is increased, partly because the signal cross section contains 4 factors of parton densities, while the background only has 2. We therefore try to keep the minimal acceptable p_T as small as possible, subject to the constraint that the event can still be triggered on [17]. Specifically, we chose

(i) for 4-jet:

$$p_T(j_1, j_2) \geq 20 \text{ GeV}, \qquad p_T(j_3, j_4) \geq 10 \text{ GeV}\,;$$

(ii) for $jjj\gamma$:

$$p_T(\gamma, j_1) \geq 15 \text{ GeV}, \qquad p_T(j_2, j_3) \geq 10 \text{ GeV}\,;$$

(iii) for $jj\gamma\gamma$: $p_T(\gamma_1, \gamma_2, j_1, j_2) \geq 10$ GeV;

(iv) for $jjee$:

$$p_T(e_1, e_2) \geq 15 \text{ GeV}, \qquad p_T(j_1, j_2) \geq 10 \text{ GeV}\,.$$

The signal and background cross sections with only these basic acceptance cuts included are listed in column 2 of Table I for the 4-jet and $jjj\gamma$ final states, and Table II for the $jj\gamma\gamma$ and $jjee$ final states. Increasing the p_T cut on the soft jets from 10 to 12 GeV reduces the signal by about a factor of 2, and the background by 30%–40%. We see that without further cuts, $4 \to 4$ processes only contribute between 9% ($jj\gamma\gamma$) and 18% ($jjee$), so additional cuts are clearly needed to extract the signal.

TABLE I. Signal and background cross sections, as well as their ratios (S/B), for 4-jet production (in nb) and $jjj\gamma$ production (in pb) at the Tevatron. In the first column only the basic acceptance cuts on the transverse momenta, rapidities, and on ΔR_{ij} have been applied. In the second column we, in addition, apply the cuts (6) and (7), with $c = 5$. In the last three columns we sharpen the ΔR cut to $\Delta R_{ij} \geq 1.2$, and gradually reduce c, as indicated. Note that the "basic" cross sections have been computed ignoring finite energy resolution and transverse kicks; these effects have been included in the other columns, as described in the text.

	Basic	$c = 5$, $\Delta R_{ij} \geq 0.7$	$c = 5$, $\Delta R_{ij} \geq 1.2$	$c = 2$, $\Delta R_{ij} \geq 1.2$	$c = 1$, $\Delta R_{ij} \geq 1.2$
$\sigma(4j)(S)$	518	257	183	175	115
$\sigma(4j)(B)$	3,990	878	485	442	246
S/B	0.13	0.29	0.38	0.40	0.47
$\sigma(jjj\gamma)(S)$	515	265	169	158	97
$\sigma(jjj\gamma)(B)$	5,370	1,310	611	571	311
S/B	0.096	0.20	0.28	0.28	0.31

TABLE II. Signal and background cross sections in pb, as well as their ratios, for $jj\gamma\gamma$ production and jje^+e^- production at the Tevatron. The notation is as in Table I, except that we use the basic isolation cut $\Delta R_{ij} \geq 0.7$ everywhere, and allow different values for $c_1 \equiv c_{jj}$ and $c_2 \equiv c_{ee}$ or $c_{\gamma\gamma}$.

	Basic	$c_1 = c_2 = 5$	$c_1 = c_2 = 2$	$c_1 = 1, c_2 = 2$	$c_1 = c_2 = 1$
$\sigma(jj\gamma\gamma)(S)$	1.86	0.96	0.71	0.59	0.37
$\sigma(jj\gamma\gamma)(B)$	20.8	2.34	1.16	0.94	0.52
S/B	0.089	0.41	0.61	0.63	0.71
$\sigma(jjee)(S)$	3.45	2.01	1.42	1.07	0.62
$\sigma(jjee)(B)$	19.0	1.94	1.00	0.70	0.37
S/B	0.18	1.04	1.42	1.53	1.68

As mentioned earlier, in $4 \rightarrow 4$ processes two pairs of particles are produced with equal and opposite transverse momenta, $\vec{p}_T(1) = -\vec{p}_T(2)$ and $\vec{p}_T(3) = -\vec{p}_T(4)$. However, additional radiation can change the kinematics significantly, and the finite resolution of real detectors means that we can require momenta to be equal only within the experimental uncertainty.

In the presence of initial or final state radiation, the transverse momenta within a pair no longer balance exactly even if the resolution was perfect. We include this effect only for the signal, since, in the background, the final state particles in any case only pair up "accidentally"; we therefore do not expect large effects on the backgrounds. We randomly generate transverse kicks for each of the $2 \rightarrow 2$ processes in the signal. We assume that the direction of the kick is not correlated with the plane of the hard scattering. The absolute values q_T of these additional transverse momenta are generated according to the distribution

$$f(q_T) \propto \exp[-(q_0/q_T)^{0.7}]/q_T^2\,, \tag{3}$$

with $0 < q_T \leq q_{T,\max}$. This function describes the transverse momentum distribution [18] of W bosons produced at $\sqrt{s} = 1.8$ TeV quite well, with $q_0 = 9$ GeV. We adopt this choice of q_0 for the $jjee$ final state, which is dominated by the production of real Z bosons, but use the smaller value $q_0 = 4.5$ GeV for the other final states, which are characterized by a smaller momentum scale. Finally, we take $q_{T,\max} = 8$ GeV as our default value; this assumes that one can reliably veto against jets with transverse momentum exceeding this value.

We simulate finite energy resolutions by fluctuating the energies of all outgoing particles (keeping the 4-vectors lightlike), using Gaussian smearing functions. The width of the Gaussian is given by

$$\delta(E_i) = a_i \cdot \sqrt{E_i} \oplus b_i \cdot E_i \quad \text{with } i = \text{jet} \quad \text{or} \quad e, \gamma\,, \tag{4}$$

where $\oplus$ stands for an addition in quadrature and E is in GeV. We take

$$\begin{aligned} a_{\text{jet}} &= 0.80\,, & b_{\text{jet}} &= 0.05\,, \\ a_{e,\gamma} &= 0.20\,, & b_{e,\gamma} &= 0.01\,, \end{aligned} \tag{5}$$

which roughly corresponds to the performance of the CDF detector. We do not fluctuate the directions of the outgoing particles in this step. These are, however, affected by the transverse kicks mentioned earlier. For this reason, and in order to allow for an error in the determination of jet axes, we apply a relatively mild cut on the azimuthal opening angle of each pair:

$$\cos(\phi_i - \phi_j) \leq -0.9\,. \tag{6}$$

This allows an opening angle as small as 154°. As emphasized earlier, in $4 \rightarrow 4$ processes, the members of a pair should also have equal absolute values of p_T. As our final cut, we therefore require

$$||\vec{p}_T(i)| - |\vec{p}_T(j)|| \leq c_{ij}\sqrt{\delta^2[|\vec{p}_T(i)|] + \delta^2[|\vec{p}_T(j)|]}\,, \tag{7}$$

with $\delta(|\vec{p}_T|) = a\sqrt{|\vec{p}_T|} \oplus b|\vec{p}_T|$ as in Eqs. (4) and (5).

Our results for signal and background with these additional cuts included are summarized in the tables. For the 4-jet and $jjj\gamma$ final states (Table I), we always take $c_{12} = c_{34} \equiv c$, but we occasionally allow $c_{ee,\gamma\gamma} > c_{jj}$ in the $jjee$ and $jj\gamma\gamma$ final states. The reason is that the cut (7) is much more severe for e^+e^- and $\gamma\gamma$ pairs than for jet pairs, due to the better resolution of electromagnetic calorimeters, see Eq. (5). Inclusion of the transverse "kick" therefore leads to a significant loss of signal if we take $c_{ee,\gamma\gamma} = 1$. Although the stronger cut still gives a slightly better signal to noise ratio, given the limited available event sample employing a looser cut might give a statistically more significant signal. Finally, in the last three columns of Table I, we increase the cut on ΔR_{ij} from 0.7 to 1.2. This enhances the signal to background ratio by about 20% to 25%.

Switching on energy smearing and transverse momentum kicks, and imposing the cuts (6) and (7) with $c = 5$, reduces the signal by typically a factor of 2. This reduction is almost entirely due to the energy smearing. Ignoring the transverse kicks for the moment, in the signal both members of a pair have equal $|p_T|$. If it falls below the cutoff value, *both* energies have to fluctuate upward for the event to be accepted. In contrast, the downward fluctuation of *one* energy can be sufficient to remove an event from the sample. The reduction is smaller for $jjee$ production since most electrons have typically $p_T \simeq M_Z/2$, well above the lower limit. Fortunately the background is reduced even more in this step, by a factor of 4 for 4-jet and $jjj\gamma$ and by a factor of 9 for $jjee$ and $jj\gamma\gamma$

final states, mainly due to the cut (6). Making the cut (7) stricter, i.e., decreasing c, only slightly enhances the signal to background ratio in Table I. This is partly due to the transverse kicks. Without them, the $jjj\gamma$ signal for $c = 1.0$ would be about 50% larger. This indicates that restricting additional jet activity as much as possible is quite important.

Although in Table I the optimized S/B ratios are only about 0.47 for 4-jet and 0.31 for $jjj\gamma$, the signals are statistically quite significant; recall that the CDF and D0 experiments together have accumulated about 200 pb^{-1} of data. Given the normalization uncertainties of leading order QCD predictions, one will have to study the shapes of various distributions, such as the opening angle $\cos\phi_{ij}$, ΔR_{ij} and p_T balancing, etc., in order to convince oneself that a signal is indeed present. Clearly, the S/B ratio is much more favorable for the $jjee$ and $jj\gamma\gamma$ final states (Table II). For these final states, reducing c from its starting point $c = 5$ does increase this ratio significantly. Recall that for a fixed value of c the cut (7) is much more restrictive for e^+e^- and $\gamma\gamma$ pairs than for jj pairs; this reduces the background more than the signal. On the other hand, this also has the effect that, after imposing the cut (7) with $c_{jj} = c_{\gamma\gamma} = 1$, the size of the $jj\gamma\gamma$ signal depends quite sensitively on the treatment of the transverse kick. Had we used $q_0 = 9$ GeV in Eq. (3), as appropriate for W production, the signal would have been reduced by a factor of about 0.7, while, without any transverse kick, it would have been larger by a factor 1.6. Clearly, this uncertainty can be reduced by using the actual measured p_T distribution of $\gamma\gamma$ pairs produced at the Tevatron. Fortunately the $jjee$ signal is less sensitive to the kick, since the electrons are usually so hard that adding or subtracting a few GeV does not matter very much. This final state therefore offers our most promising and robust signal.

In summary, we have studied four different final states with a view of establishing an unambiguous signal for multiple partonic interactions in $p\bar{p}$ collisions at the Tevatron. The 4-jet and $jjj\gamma$ final states offer very large event samples, but with a S/B ratio about 0.3–0.5. One must study the shapes of various kinematical distributions for confirmation of the existence of the signal, as was indeed done by the CDF Collaboration in their study of the 4-jet final state [7]. The situation is much more favorable for the $jj\gamma\gamma$ and, especially, $jjee$ final states; in the latter case, one can increase the event sample (keeping S/B fixed) by including muon pairs as well. Although even in these channels the signal to noise ratio is less favorable than what we found for 4-jet production in $\gamma\gamma$ collisions [19], a clear signal should be visible already in the present data sample.

Once a signal is found, it would be important to establish if the normalization σ_0 in Eq. (1) is indeed the same for different processes, and independent of the Bjorken x range probed, as assumed in minijet models. Further, it would be very interesting to reduce the p_T cut for at least some of the jets as much as possible, so that one can get closer to the actual minijet region. This could greatly enhance our understanding of "minimum bias" physics, and give us some confidence that we can trust extrapolations to LHC energies, where the understanding of overlapping minimum bias events becomes a crucial issue in the assessment of the viability of various "new physics" signals. Finally, such studies might shed new light on the thirty-year-old problem of the rising total hadronic cross sections.

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