Emergence of jet dominance in $\gamma\gamma$ interactions at fixed-target energies

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In Fermilab experiment E683 we have used a large solid angle calorimeter to study the production of hadronic events with large transverse energy in $\gamma\gamma$ and $\pi\pi$ collisions at center-of-mass energies from 20 to 25 GeV. We observe a sudden shift in $\gamma\gamma$ event topology with increasing transverse energy, indicative of the emergence of jet dominance. This is the first observation of such a shift in event topology in fixed-target interactions. $\pi\pi$ interactions in the same kinematic region and under identical triggering conditions exhibit only a slight shift in event topology. [S0556-2821(97)50421-8]

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The production of particles with large momentum transverse to the beam direction in high energy hadronic interactions is well understood in terms of the hard scattering of the constituents of hadrons, quarks, and gluons, followed by the fragmentation of these constituents into “jets.” Ideally a jet is a well-collimated stream of particles whose kinematics reflect those of the parent parton.

The pioneering work of Hanson et al. [1] used event topology in $e^+e^-$ annihilation into hadrons to demonstrate the emergence of the jet signal as the center-of-mass energy ($E_{\text{c.m.}}$) increased from 3 to 7.4 GeV. Topological variables quantify the entire event shape, in contrast to analysis techniques which reconstruct the jets explicitly. An abrupt shift in event topology with increasing $E_{\text{c.m.}}$ was taken as evidence of jet production. At $E_{\text{c.m.}}$ of 20 GeV and higher, the reaction $e^+e^- \rightarrow \text{hadrons}$ is totally dominated by jet production and well described by the standard model [2].

Jets are also clearly seen in hadronic interactions at collider energies [3]. However, even at the highest center-of-mass energies available, the bulk of the hadronic cross section consists of “soft” interactions in the noncalculable regime of nonperturbative QCD. Even when jets are clearly present in hadron-hadron interactions, the event structure is complicated by the presence of the so-called “underlying event,” that is, the remnants of the beam and target partons which did not participate in the hard scattering process.

A simple phenomenological model by Åkesson and Bengtsson [4] discusses the emergence of the jet signal from the background of soft processes and the underlying event. As the hardness of the interaction increases, the jet-like structure emerges and rapidly dominates, leading to an abrupt shift in event topology. One measure of the hardness of a scatter is the total transverse energy $E_\perp$, defined as the scalar sum of $E_{\perp,i}=E_i \sin \theta_i$ for all the $i$ particles in the detector acceptance, where $\theta_i$ is the polar angle and $E_i$ is the energy. We therefore might expect a shift in event topology with increasing total $E_\perp$, indicating the emergence and dominance of the jet signal. The $E_\perp$ at which this change in event structure occurs depends on $E_{\text{c.m.}}$, the detector acceptance, the relative $E_\perp$ slopes of the hard and soft cross sections, and the amount of underlying event. For large solid angle detectors and low $E_{\text{c.m.}}$, the jet signal may not dominate for any $E_\perp$.

The first attempts to observe jets in hadron-hadron collisions were at fixed-target energies with $E_{\text{c.m.}}$ of 20–30 GeV. At these energies the jets are less well collimated than at higher energies, and the overlap with beam and target remnants is a serious problem. Early attempts using limited solid angle detectors [5], although suggestive, were generally considered inconclusive due to the lack of complete information. Subsequent experiments used large solid angle detectors in order to observe the event structure more completely [6–8]. These detectors were typically large solid angle, segmented calorimeters which had full azimuthal coverage over a pseudorapidity ($\eta$) range of about two units centered at or near $\eta=0$ in the c.m. A geometrically unbiased trigger, the so-
called "global" trigger was used. This trigger set a threshold on the transverse energy sum $E_T$, calculated using laboratory quantities. This trigger was intended to be sensitive to a hard-scattering process without imposing a particular structure on the event. In proton-proton collisions at $E_{c.m.}$ up to 40 GeV, the sudden shift in event topology indicative of the emergence of the jet signal was not observed, even with total event $E_T$'s that were more than 70% of the available $E_{c.m.}$. However, at the higher $E_{c.m.}$ of the CERN Intersecting Storage Rings (ISR) (45 GeV and more clearly at 60 GeV), the abrupt shift in event topology was observed and again interpreted as clear evidence for jet production [9]. The emergence of the jet signal with increasing event $E_T$ at collider energies has been studied in detail by UA2 [10].

In Fermilab experiment E683, we have observed the production of events with large total $E_T$ in $\gamma p$ collisions using a large solid angle calorimeter with a global trigger at $E_{c.m.}$ from 20–25 GeV. Photoproduction of jets is interesting because the photon is expected to have an extremely hard parton distribution function [11], leading to both more energy in the hard-scattering system and less energy left in the spectator system. Both of these effects should produce a cleaner jet signal in $\gamma p$ interactions compared to $pp$ or $\pi p$ interactions. Consistent with that expectation, and unlike $pp$ collisions at this energy, we observe an abrupt change in event topology with increasing $E_T$ for $\gamma p$ interactions. For $\pi p$ collisions at the same $E_{c.m.}$ and under identical conditions, the shift in event topology is much less pronounced.

E683 was performed in Fermilab’s Wide Band Photon laboratory during the 1991 fixed-target run. The beam and detector have been described in greater detail elsewhere [12]. Bremsstrahlung photons interacted in a liquid hydrogen target. After triggering and acceptance, photon energies of 50–450 GeV are observed, with a mean energy of 250 GeV. Each photon’s energy was measured to within 4%, exclusive of multiple bremsstrahlung effects. In addition, it was possible to configure the same beamline to accept a $\pi^-$ beam. The energy of the $\pi^-$ beam was chosen to have generally the same mean and range as the triggered photon spectrum.

For purposes of this analysis the primary detector used was a highly-segmented calorimeter with a projective tower geometry. The calorimeter was segmented into four layers longitudinally and 132 towers transversely. Energy resolution was measured to be 35%/\sqrt{E} for electromagnetic showers and 80%/\sqrt{E} for hadronic showers. For our central beam energy of 250 GeV, this detector had full azimuthal coverage over the c.m. $\eta$ range of 1.75 to $-0.18$, with partial azimuthal coverage out to $\eta=-0.55$. For this study, only the section of the calorimeter with full azimuthal coverage was used. Since the solid angle that the calorimeter subtended in the c.m. frame varied with beam energy, a cut restricting beam energies to the range 225–325 GeV was imposed. Events were triggered by forming the scalar sum of individual tower $E_T$'s, forming a global trigger. Two separate hardware thresholds on total $E_T$ were applied, with the lower $E_T$ trigger being prescaled. Events passing these triggers were then stored to tape. Software cuts of 5 GeV and 9 GeV were imposed on $E_T$ to ensure that events were in a region of full efficiency. The two trigger thresholds were consistent and have been combined in the results presented below. Loose cuts were imposed to reject spurious events caused by muons or by electrical discharge in the photomultiplier tubes. In addition, a loose cut on energy conservation was made ($E_{\text{observed}} < E_{\text{beam}} + 75$ GeV). Target-empty corrections have been made to the data in Figs. 2 and 4. In order to increase the number of events in the regions of poor statistics, we have not made target-empty corrections to Figs 1 and 3. Target-empty corrections in the regions with good statistics removed 15–20% of the events and had no qualitative effect on these distributions. The results presented here represent the full $\gamma p$ and $\pi p$ data sets, with 22 591 $\gamma p$ and 16 157 $\pi p$ events passing all cuts.

Several variables have been used to quantify the jet-like nature of hadronic events. We use planarity, which we define as follows. In the plane transverse to the beam direction we define a $2 \times 2$ matrix:

$$\begin{pmatrix}
\Sigma p_x^2 & \Sigma p_x p_y \\
\Sigma p_y p_x & \Sigma p_y^2
\end{pmatrix},$$

where the sum is taken over all calorimeter towers, and $p_x, p_y$ are the components of transverse momentum. One may solve the resultant eigenvalue problem for $\lambda_1$ and $\lambda_2$ and the corresponding eigenvectors $\hat{\lambda}_1$ and $\hat{\lambda}_2$. For $\lambda_1 > \lambda_2$, the eigenvector $\hat{\lambda}_1$ defines the direction of the transverse plane such that $\lambda_1 = \Sigma p_x^2$, the sum of momenta parallel to that direction is maximized, and $\lambda_2 = \Sigma p_y^2$, the sum of momenta perpendicular to that direction is minimized. Planarity is then defined as $P = (\lambda_1 - \lambda_2)/(\lambda_1 + \lambda_2)$. For jet-like topologies, $\lambda_1 \gg \lambda_2$ and $P \rightarrow 1$. For isotropic topologies $\lambda_1 \sim \lambda_2$ and $P \rightarrow 0$. So if jet-like event topologies emerge naturally with increasing $E_T$, we should observe an increasing $\langle P \rangle$ with increasing $E_T$.

Because a kinematic relationship exists between $E_{c.m.}$ and the maximum $E_T$ achievable, we define the normalized variable $x_T = E_T / E_{c.m.}$. Planarity and $x_T$ were calculated using the sum over calorimeter towers. Studies with the LUND Monte Carlo programs LUCIFER and TWISTER [13] showed that on average detector effects did not affect the measurement of either $x_T$ or planarity by more than 5%. We have not corrected the data for these small instrumental effects.

Figure 1 plots the planarity distribution for three bins of $x_T$ for $\gamma p$ (a) and $\pi p$ (b) data. All distributions are normalized to unit area. A striking feature of the $\gamma p$ data is the sudden shift to higher planarity with increasing $x_T$. The $\pi p$ data exhibit a much less pronounced shift. This point is further demonstrated in Fig. 2, where the average planarity $\langle P \rangle$ is plotted as a function of $x_T$ for both $\gamma p$ and $\pi p$ interactions. The photon data show a sharp increase in planarity with increasing $x_T$, while the pion data exhibit a most at a slight rise.

We can compare our data with standard QCD Monte Carlo programs, but we expect that such comparisons will only be qualitative in nature. The hard-scattering process is well described by perturbative QCD, but no reliable model exists for the evolution of the spectator system which produces the underlying event. In addition, all QCD Monte Carlo programs must impose a cutoff in $p_T$ of the hard scatter ($\hat{p}_T$), since the cross section becomes infinite as $\hat{p}_T \rightarrow 0$. This analysis specifically studies the emergence of the jet signal from the background of soft processes and the underlying...
event, and therefore we expect any Monte Carlo calculation for our conditions to be sensitive to both the $p_t^0$ cutoff and the details of the underlying event. Indeed, these data provide a sensitive test of the Monte Carlo treatment of the underlying event.

Figure 2 shows the expectations from two standard Monte Carlo models—HERWIG 5.6 [14] and the LUND programs mentioned previously. For the LUND programs, we have used the independent fragmentation option, with all other parameters at their default values. For HERWIG, the enhanced underlying event option was not used for $\gamma p$ interactions, but was used for $\pi p$ results. These choices were made to improve agreement between Monte Carlo and data.

We have used a minimum $p_t^0$ of 1.0 GeV, as the lowest reasonable value consistent with the perturbative nature of the calculations. In the intermediate $x_\perp$ region, there is some dependence on the $p_t^0$ cutoff for both models studied. For example, as the minimum $p_t^0$ increases from 1 to 2 GeV, $\langle P \rangle$ increases by about 0.1 for $x_\perp$ between 0.2 and 0.5. However, in the region of rising $\langle P \rangle$, the Monte Carlo results become insensitive to the minimum $p_t^0$, indicating that the rise in $\langle P \rangle$ corresponds to events with increasing $p_t^0$. Therefore the traditional interpretation that the shift in planarity signifies the emergence of the jet signal is confirmed by the Monte Carlo calculations.

The LUND Monte Carlo program reproduces the $\gamma p$ data reasonably well, consistent with our previous observation that this Monte Carlo reproduces the jet structure, including the underlying event, for $\gamma p$ interactions quite well. We have observed previously that the $\pi p$ data exhibit significantly greater underlying event than the $\gamma p$ data, an effect which is not well reproduced by the LUND Monte Carlo program [12,15]. Therefore it is not surprising that this model exhibits a much sharper rise in $\langle P \rangle$ at lower values of $x_\perp$ for $\pi p$ interactions than is seen in the data.

HERWIG $\gamma p$ reproduces the general shape of the $\gamma p$ data but is somewhat too planar. HERWIG $\pi p$ (with enhanced underlying event), however, exhibits a significantly less planar event structure than is seen in the data and does not exhibit a rise in $\langle P \rangle$ at any value of $x_\perp$. On the other hand, HERWIG $\pi p$, without the enhanced underlying event, is very similar to HERWIG $\gamma p$ and is much more planar than the $\pi p$ data. Clearly the behavior of $\langle P \rangle$ vs $x_\perp$ is quite sensitive to the details of the underlying event. The two options available in this version of HERWIG bracket the data, with the correct amount of underlying event apparently lying somewhere in between.

The striking difference between the HERWIG and LUND $\pi p$ results is likely also due to the very different treatments of the underlying event in these models. Neither Monte Carlo program reproduces both sets of data quantitatively, but the qualitative behavior, particularly for the $\gamma p$ data, is reproduced reasonably well.

The LUND package has a minimum-bias option which allows us to study possible minimum-bias contributions to our data. In this model, the photon is treated as a vector meson which interacts softly via the standard LUND low-$p_t$ model. We have checked that this model produces distributions in multiplicity, rapidity, and single-particle $p_t$ consistent with minimum-bias data. Since we do not expect any significant difference in the low-$p_t$ behavior of a vector meson and a pion, this model should be valid for both $\gamma p$ and $\pi p$ data. The model yields events with $\langle P \rangle$ of about 0.5, but produces no events in the interesting region beyond $x_\perp$ of 0.4. We therefore do not expect minimum-bias processes to contribute to our data beyond $x_\perp$ = 0.4.

We can observe the emergence of the jet signal in another way using the following definition of $E_\perp$ flow. The direction of the eigenvector $\hat{\lambda}_1$ (the planarity axis) defines $\Delta \phi=0$.\[\text{\textcircled{a}}\] FIG. 1. Normalized planarity distributions in bins of $x_\perp$ for (a) $\gamma p$ interactions and (b) $\pi p$ interactions. Typical error bars are shown in the highest $x_\perp$ bin, which contains 315 (154) events for $\gamma p$ ($\pi p$) interactions. The other bins contain more than a factor of 20 greater statistics.

FIG. 2. Average planarity vs $x_\perp$ for both $\gamma p$ and $\pi p$ interactions. Systematic errors due to the target-empty subtraction are shown as bands in the lower portion of the figure. Horizontal error bars indicate the bin sizes in $x_\perp$. The solid curve is the expectation from the LUND Monte Carlo program for $\gamma p$; dash curve is HERWIG $\gamma p$; dot-dash curve is LUND $\pi p$; dotted curve is HERWIG $\pi p$.\[\text{\textcircled{b}}\]
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Each calorimeter tower is then plotted at the appropriate $\Delta \phi$, weighted by the tower $E_\perp$. A dijet event would be characterized by strong peaks at $\Delta \phi=0$ and $\pi$, with much less energy in the region around $\Delta \phi=\pi/2$, the nonjet or underlying event region. $E_\perp$ flow has been used by other authors [16] to study jet structure, but earlier work used the direction of a reconstructed jet to define $\phi=0$. Our approach is much less biased in that we are not imposing a jet-like structure on the event by requiring a jet-finding algorithm to find one or more jets.

Figure 3(a) shows $\gamma p$ $E_\perp$ flow plots for the same bins of $x_\perp$ as shown in Fig 1. Figure 3(b) shows the same plots for $\pi p$ interactions. Once again the more jet-like nature of $\gamma p$ interactions compared to $\pi p$ interactions is apparent. In particular, it is interesting to note that, for the $\gamma p$ data, in going from the second to the third bin in $x_\perp$, all of the additional $E_\perp$ appears in the jet region ($\Delta \phi=0^\circ$ and $180^\circ$), while the same is not true for the $\pi p$ data.

In order to quantify the shapes of the $E_\perp$ flow plots, the region of $\Delta \phi$ from $54^\circ$ to $126^\circ$ was taken as representative of the non-jet fraction of the $E_\perp$. The contents of these bins, scaled up to the full $\Delta \phi$ range, was taken as the “nonjet” area and subtracted from the total area. The remaining area was defined as the “jet” area. Figure 4 plots the ratio of jet area to total area as a function of $x_\perp$ for both $\gamma p$ and $\pi p$ interactions. Once again we see a sudden shift in event topology for $\gamma p$ interactions which is much less apparent in the $\pi p$ case. Figure 4 also shows the expectations from the Monte Carlo calculations, which are similar to those of Fig. 2.

In conclusion we have used a geometrically unbiased, large solid angle trigger to study large $E_\perp$ events in $\gamma p$ and $\pi p$ collisions. For $\gamma p$ interactions we see an abrupt change in event topology as characterized by a sudden shift in planarity or $E_\perp$ flow, consistent with the dominance of jet production. A much weaker shift is observed in $\pi p$ interactions under identical conditions. It should be emphasized that this study employed a geometrically unbiased trigger and did not employ a jet-finding algorithm of any kind. We interpret the sudden shift in event topology as the emergence and dominance of jet production in $\gamma p$ interactions at $E_{c.m.}$ from 20 to 25 GeV. This is the first such observation of an abrupt change in event topology in fixed-target interactions.

The cleaner jet signal seen in $\gamma p$ compared to $\pi p$ interactions is expected due to the harder parton distribution function for photons compared to pions. Standard QCD-based Monte Carlo programs reproduce many of the qualitative features of the data, but do not reproduce these results quantitatively. The failure of the Monte Carlo calculations to reproduce the data quantitatively seems to be related to the details of the underlying event.

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