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Measurement of Double Parton Scattering in $\bar{p}p$ Collisions at $\sqrt{s}$ = 1.8 Tev

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Distribution

Measurement of Double Parton Scattering in $\bar{p}p$ Collisions at $\sqrt{s}$=1.8 TeV

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Abstract

A strong signal for Double Parton scattering (DP) is observed in a 16pb^{-1} sample of $\bar{p}p \rightarrow \gamma +$ 3 jets + X data from the CDF experiment at the Fermilab Tevatron. The process-independent DP parameter, σ_{eff}, is obtained without reference to theoretical calculations by comparing observed DP events to events with hard scatterings at separate p̄p collisions. The result, $\sigma_{\text{eff}}=(14.5\pm1.7^{+1.7}_{-2.3})$ mb, represents a significant improvement over previous measurements. For the first time, the Feynman x dependence of the σ_{eff} parameter is investigated, and no dependence is seen.

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The Double Parton scattering (DP) process [1], in which two parton-parton hard scatterings take place within one p̄p collision, can provide information on both the distribution of partons within the proton and on possible parton-parton correlations, topics difficult to address within the framework of perturbative QCD. The cross section for DP comprised of scatterings A and B is written

$$\sigma_{\text{DP}} \equiv \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}, \tag{1}$$

with a process-independent parameter $\sigma_{\rm eff}$ [2, 3, 4, 5]. This expression assumes that the number of parton-parton interactions per collision is distributed according to Poisson statistics [6], and that the two scatterings are distinguishable [7].

Previous searches for DP have come from the AFS [3], UA2[4], and CDF[5] experiments. The best measurement of $\sigma_{\rm eff}$, $12.1^{+10.7}_{-5.4}$ mb, was obtained from the CDF analysis of four jet events. Based on a simple model of proton structure and the measured inelastic $\bar{\rm p}$p cross section at $\sqrt{\rm s}$=1.8 TeV, the expected value is $\sigma_{\rm eff}$=11 mb [5].

In this Letter we summarize a new measurement of DP from the Collider Detector at Fermilab (CDF). The analysis is documented fully in Ref. [8]. The final state studied is photon + 3 jets, where "photon" signifies either a single direct photon, or neutral mesons from jet fragmentation. The two dominant single parton-parton scattering (SP) backgrounds are photon + 1 jet and dijet (two final state jets) production, with bremsstrahlung radiation of two gluons. The DP process consists of photon + 1 (or 2) jet production overlaid with 2 (or 1) observed jets from dijet production. As a result of the trigger used in this analysis (below), jets are accepted down to low energies where the cross section for the dijet scattering in DP is large. Also, photon energy is better measured than jet energy at CDF, improving the ability to distinguish the two scatterings in DP photon + 3 jet events, compared to a four jet final state. In consequence, the present analysis benefits from a substantial DP event sample and an order of magnitude improvement in the ratio of DP to SP events compared to the earlier CDF study. These improvements have permitted an investigation of the kinematic dependence of $\sigma_{\rm eff}$ and a search for correlations between the two scatterings.

A new technique for extracting σ_{eff} has also been developed. In previous analyses σ_{eff} was derived using the measured DP cross section, and QCD calculations for the two cross sections in Eq. 1 which suffer from sizeable uncertainties [9, 10]. In the present analysis, σ_{eff} is extracted independently of theoretical calculations, through a comparison of observed DP events to events with hard-scatterings at two separate $\bar{\mathrm{p}}\mathrm{p}$ collisions within the same beam crossing (Double Interactions, or DI). Because this method does not rely on theoretical input, it represents a substantial advance over previous measurements. The number of observed $\bar{\mathrm{p}}\mathrm{p}$ collisions per crossing is used to segregate data into DP candidates (one collision) and DI candidates (two collisions).

Expressions were derived for the expected numbers of DP and DI events (N_{DP} and N_{DI}). Their ratio is independent of theoretical cross sections, and yields

$$\sigma_{\mathrm{eff}} \;=\; \left(\frac{\mathrm{N}_{\mathrm{DI}}}{\mathrm{N}_{\mathrm{DP}}}\right)\left(\frac{\mathrm{A}_{\mathrm{DP}}}{\mathrm{A}_{\mathrm{DI}}}\right)(\mathrm{R}_{\mathrm{c}})\,(\sigma_{\mathrm{NSD}})\,. \tag{2}$$

A_{DP} and A_{DI} are acceptances for DP and DI events to pass kinematic selection requirements. The factor R_{c} is the ratio of acceptances for requiring one (DP) and two (DI) collisions per event. Collisions are taken to be non-single-diffractive inelastic interactions (NSD) with cross section σ_{NSD}. The value of R_{c} is calculable in terms of the number of NSD collisions per beam crossing and collision identification efficiencies. These parameters will be evaluated below. The numbers of events, N_{DP} and N_{DI}, will be measured.

The CDF Detector is described in detail elsewhere [11]. Instantaneous luminosity measurements are made with a pair of up- and down-stream scintillator hodoscopes (BBC). Photons are detected in the

Central Calorimeter (pseudorapidity interval $|\eta| < 1.1$). The Plug and Forward Calorimeters extend coverage for jet identification to $|\eta| < 4.2$. Charged particles are reconstructed in the Central Tracking Chamber (CTC). The location of the collision vertex (or vertices) along the beam-line is established with a set of time projection chambers (VTX). The z axis is along the beam-line.

The 1992-3 Collider Run accumulated 16 pb^{-1} of data with an inclusive photon trigger [12] which demanded a predominantly electromagnetic transverse energy deposition ($E_T = E\sin(\theta)$) in the Central Calorimeter above 16 GeV. No jets were required in the trigger. Offline, jet reconstruction [13] was performed on these events using a cone of radius 0.7 in (η, ϕ) to define jet E_T. Events with three and only three jets with $E_T > 5$ GeV (uncorrected for detector effects) were accepted. A further requirement of $E_T < 7$ GeV was made on the two lowest E_T jets, which enhances DP over SP. Events with a single collision vertex found in the VTX ("1VTX") were taken as DP candidates, while two-vertex events ("2VTX") formed the DI candidate sample. A total of 16853 and 5983 events pass the two selections. A second trigger sample of interest is the minimum bias dataset, collected by requiring coincident signals in the BBC.

To identify DP, and to extract σ_{eff}, models for the DP and DI processes and their backgrounds were constructed. The DP model, MIXDP, assumes independent scatterings, and was obtained by mixing CDF inclusive photon events and minimum bias events, both required to have ≥ 1 jet with $E_T > 5$ GeV. The resulting mixed events were required to pass the photon + 3 jet event selection. The two "ingredient events" were each required to have a single VTX vertex, and only the reconstructed objects of the events (the jets, photons, and CTC tracks) were actually mixed. This technique ensures that photons and jets in MIXDP events incorporate an "underlying event" energy contribution (arising from soft interactions among spectator partons in the p and $\bar{\text{p}}$) that is appropriate for single $\bar{\text{p}}$p collision events. This should be correct for modelling DP events in the 1VTX sample. The DI model, MIXDI, was also obtained from this event mixing, but modified to add extra underlying event energy to the jets and photon. This modification simulates the presence of the two $\bar{\text{p}}$p collisions in DI events in the 2VTX sample. The non-DI background in the 2VTX sample consists of "pile-up" events (a photon + 3 jets scattering accompanied by a second soft $\bar{\text{p}}$p collision) and was modelled by mixing single vertex photon + 3 jet events and minimum bias events without jets. These data-derived models alone are used to determine the number of DP and DI events in data.

Six variables were identified which exploit the independence and pairwise momentum balance of the two scatterings in DP events. The most sensitive variable, ΔS [5], is the azimuthal angle between the transverse momentum (p_T) vectors of the two best-balancing pairs (photon + 1 jet, and dijet). In SP events, momentum conservation biases ΔS towards 180^o, while in DP events the ΔS distribution is flatter. The ΔS distribution for 1VTX data is shown in Fig. 1.

The number of 1VTX DP events was extracted using a background subtraction technique [8]. SP background was statistically removed from 1VTX data through the use of a second photon + 3 jets dataset, chosen to be poor in DP, and consisting of events which pass a modified 1VTX selection criteria requiring $7\leq E_T \leq 9$ GeV for the two lowest E_T jets. This "two dataset" method does not invoke any prediction or model for the SP component of the data. We find that the fraction of DP events in the 1VTX sample, f_{DP}, is $(52.6\pm2.5)\%$ (statistical uncertainty). The robustness of this method was tested by applying it to mock data constructed from MIXDP events and SP background events from the PYTHIA shower Monte Carlo [14]. The resulting measured MIXDP fractions agreed well with the input fractions, which ranged from 35% to 65%. Assigning a systematic uncertainty based on this test, we obtain f_{DP}=(52.6±2.5±0.9)%. As a check of this large DP fraction, the admixture 52.6% MIXDP + 47.4% PYTHIA is compared to the 1VTX sample in Fig. 1. The data are well described by this admixture [16].

A correction to the observed DP signal was applied for the possible presence of Triple Parton scattering events, necessary because we rely on Eq. 1, which we take to be the cross section for two and only two pairs of parton scatterings. MIXDP events were used to determine the correction, based on the possible presence of Double Parton scattering in the ingredient event samples. The correction is estimated to be $0.83^{+0.08}_{-0.04}$. Taking together the number of 1VTX events, f_{DP}, and the Triple Parton correction, we obtain $N_{DP}=7360\pm360^{+720}_{-380}$.

The number of DI events in the 2VTX sample was determined by identifying events with jets originating from both $\bar{p}p$ collisions. CTC tracks were used to specify jet origins. To increase the size of the data sample, the upper limit on jet E_T was removed for this analysis. Performance on DI and pile-up models indicates that misidentification (DI as pile-up and *vice versa*) occurs at the level of 20%. The numbers of data events found with common origin and with separated origins were compared to an admixture of MIXDI and pile-up. The data are best described with a (16.8±1.9)% DI component (statistical uncertainty). The systematic uncertainty was obtained by varying selection criteria and the jet origin algorithm. We find f_{DI}=(16.8±1.9±1.8)%. Based on this value and the number of 2VTX events, and after a correction (5%) for the special selection criteria of the jet origin analysis, we find N_{DI}=(1060±110±110). Results of the jet origin analysis are verified in Fig. 2, which compares ΔS distributions for common origin and separated origin events. The flatter shape seen in separate origin events is indicative of DI. The shaded histograms are predictions from 16.8% MIXDI + 83.2% pile-up. Good agreement is observed.

The ratio of kinematic acceptances in Eq. 2 was obtained by taking the ratio of accepted events from MIXDP and MIXDI event mixing, operating on the same ingredient events. The different levels of underlying event in single and double $\bar{\rm p}$p collision events result in slightly different acceptances. We find $\rm A_{DP}/A_{DI}$ =0.958 with negligible uncertainty. The NSD cross section, $\sigma_{\rm NSD}$=(50.9$\pm$1.5) mb, was obtained from the CDF measurements of Ref. [17]. The factor $\rm R_c$ in Eq. 2 was derived from measured vertex identification efficiencies and a prediction for the distribution of the number of NSD collisions per beam crossing. We calculate $\rm R_c$=2.06$\pm$0.02 (statistical uncertainty). The systematic uncertainty on $\rm R_c$ was obtained by evaluating a similar calculation, the ratio of the number of single vertex events to double vertex events in inclusive photon data, and comparing the result to the value actually seen in data. The ratio of measurement to prediction is $1.000^{+0.005}_{-0.064}$, where the uncertainty is systematic and arises from a subtraction of beam-gas background in data. Thus we obtain $\rm R_c$=$2.06\pm0.02^{+0.01}_{-0.13}$. Inserting these values into Eq. 2, we find $\sigma_{\rm eff}$=$(14.5\pm1.7^{+1.7}_{-2.3})$ mb.

The possible Feynman x ($\equiv p_{\rm parton}/p_{\rm beam}$) dependence of $\sigma_{\rm eff}$, such as would arise from a dynamic parton spatial density, was studied by searching for deviations from the MIXDP model, which by construction has the x dependence of the two scatterings only. We begin by establishing an enriched sample of DP candidate events, consisting of 1VTX data events that pass the cut ΔS $<$ 1.2 (2575 events). Based on the MIXDP+PYTHIA curve shown in Fig. 1, the data passing this cut should be 90% DP. Each event was subdivided into the two best-balancing pairs. Four x values were evaluated, since two partons contribute to each of the two pairs. Distributions of x are plotted in Fig. 3, along with the admixture

90% MIXDP + 10% PYTHIA. No systematic deviation of the DP rate vs. x, and thus no x-dependence to $\sigma_{\rm eff}$, is apparent over the x range accessible to this analysis (0.01-0.40 for the photon + jet scatter, 0.002-0.20 for the dijet scatter). Tests for x correlations between the scatterings, and for correlations in invariant mass, p_T, and longitudinal momentum were also studied [8]. In all cases, the DP-enriched data are well described by the uncorrelated prediction.

In summary, a strong signal for DP in CDF photon + 3 jet data has been established, using a technique that does not rely on models for SP background. The process-independent parameter $\sigma_{\rm eff}$ is measured to be $(14.5\pm1.7^{+1.7}_{-2.3})$ mb, and was determined without reliance on theoretical QCD calculations. High statistics and a large DP fraction have permitted, for the first time, a search for Feynman x dependence of $\sigma_{\rm eff}$. We see no evidence for x-dependence to $\sigma_{\rm eff}$ within the x-range of this analysis.

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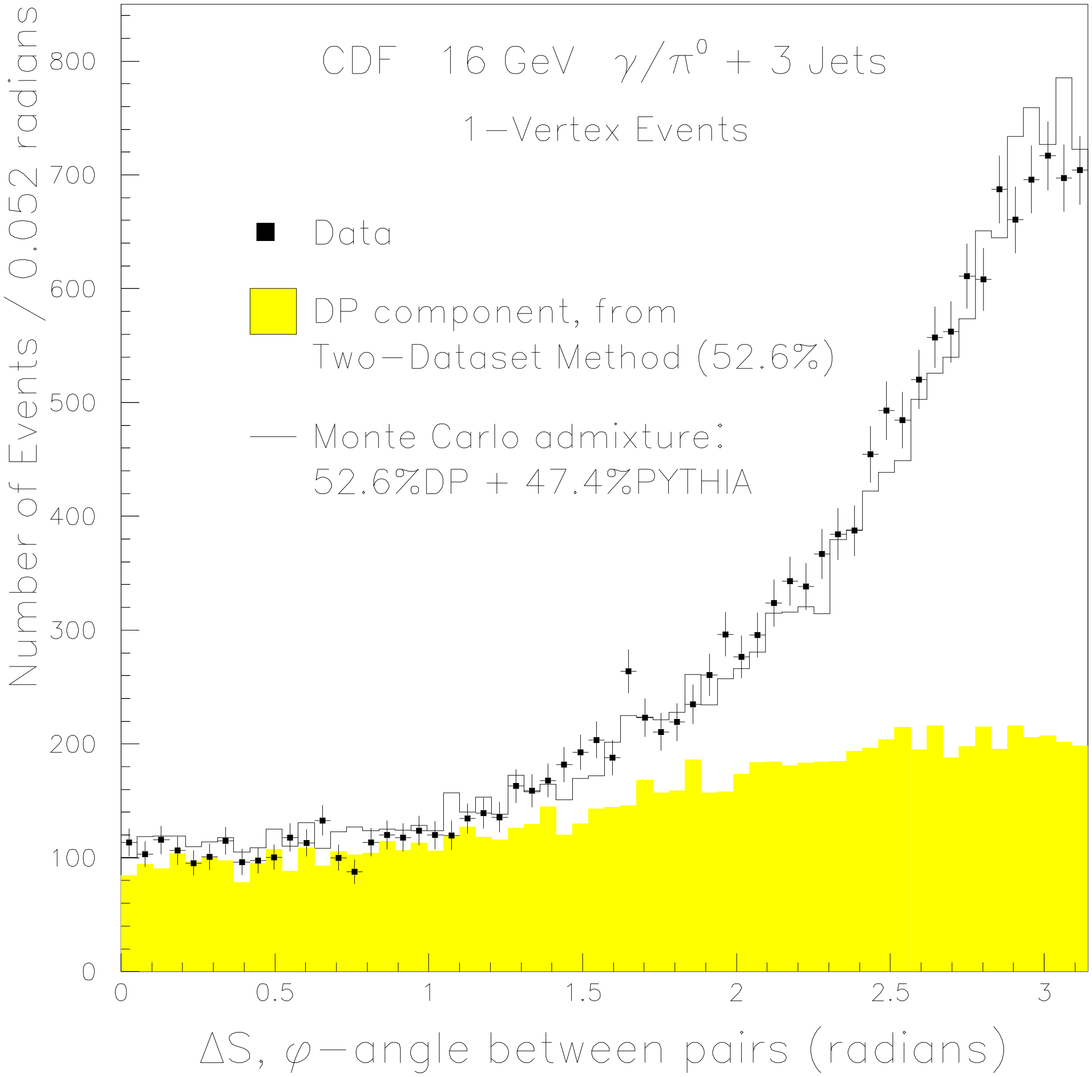

Figure 1: ΔS distribution for 1VTX data (points). The DP component to the data, determined by the two-dataset method to be 52.6% of the sample, is shown as the shaded region (the shape is taken from MIXDP). Also shown is the admixture 52.6% MIXDP + 47.4% PYTHIA, normalized to the data (line).

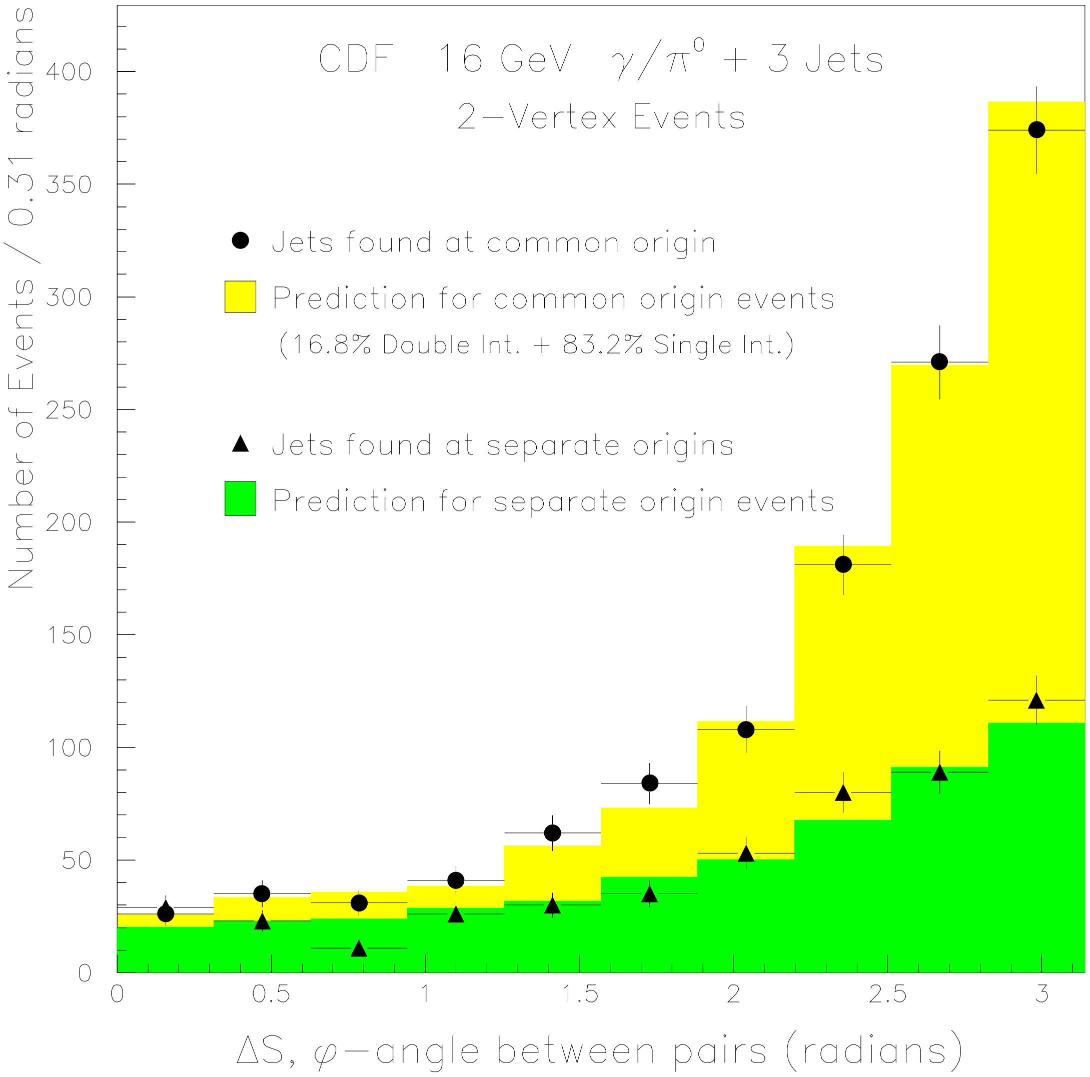

Figure 2: ΔS distributions for two vertex events. Shown separately are events with jets originating from a common origin along the beamline (circles), and events with jets from separated origins (triangles). The shaded plots are predictions from the admixture 16.8% MIXDI + 83.2% pile-up.

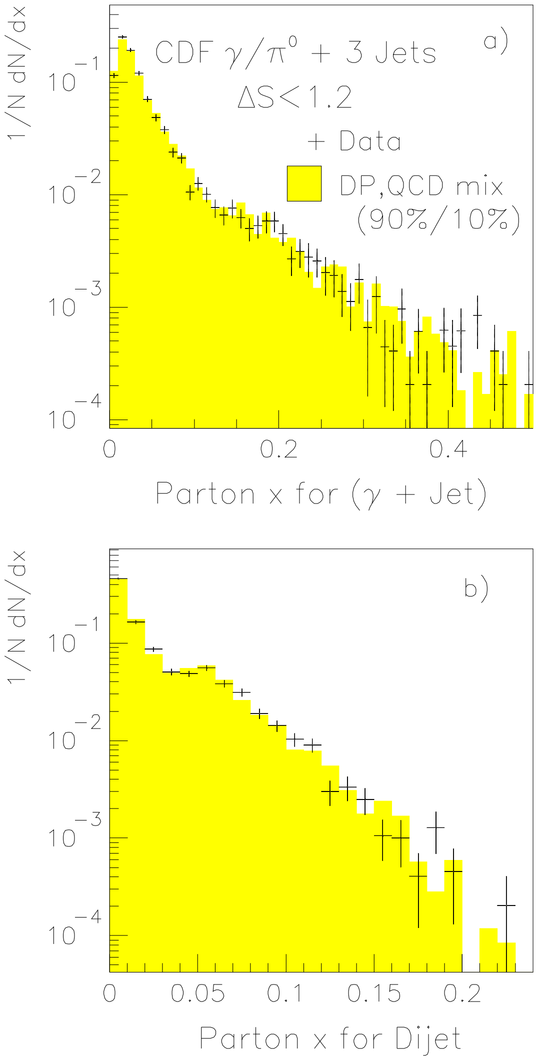

Figure 3: Results of the Feynman x analysis on DP-enriched 1VTX data. Distributions, two entries per event, of (a) $\gamma+$ 1 jet x values ($x^{\gamma \mathrm{J}}_{\mathrm{p},\bar{\mathrm{p}}} = [p_T^{\gamma}/p_{\mathrm{beam}}][\mathrm{e}^{\pm\eta_\gamma} + \mathrm{e}^{\pm\eta_\mathrm{J}}]$), and (b) dijet x values ($x^{\mathrm{JJ}}_{\mathrm{p},\bar{\mathrm{p}}} = [(E_T(i) + E_T(j))/(2p_{\mathrm{beam}})][\mathrm{e}^{\pm\eta_{\mathrm{J}i}} + \mathrm{e}^{\pm\eta_{\mathrm{J}j}}]$, where i, j signify the two jets of the dijet). The prediction, 90% MIXDP+10% PYTHIA, is shown as the shaded area. The distributions are presented without acceptance corrections.