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

F. Abe,[17] H. Akimoto,[36] A. Akopian,[31] M. G. Albrow,[7] S. R. Amendolia,[27] D. Amidei,[20] J. Antos,[33] S. Aota,[36] G. Apollinari,[31] T. Asakawa,[36] W. Ashmanskas,[18] M. Atac,[7] F. Azfar,[26] P. Azzi-Bacchetta,[25] N. Bacchetta,[25] W. Badgett,[20] S. Bagdasarov,[31] M. W. Bailey,[22] J. Bao,[39] P. de Barbaro,[30] A. Barbaro-Galtieri,[18] V. E. Barnes,[29] B. A. Barnett,[15] M. Barone,[9] E. Barzi,[9] G. Bauer,[19] T. Baumann,[11] F. Bedeschi,[27] S. Behrends,[3] S. Belforte,[27] G. Bellettini,[27] J. Bellinger,[38] D. Benjamin,[35] J. Benlloch,[19] J. Bensinger,[3] D. Benton,[26] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] B. Bevensee,[26] A. Bhatti,[31] K. Biery,[7] M. Binkley,[7] D. Bisello,[25] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[30] W. Bokhari,[19] V. Bolognesi,[2] G. Bolla,[29] D. Bortoletto,[29] J. Boudreau,[28] L. Breccia,[2] C. Bromberg,[21] N. Bruner,[22] E. Buckley-Geer,[7] H. S. Budd,[30] K. Burkett,[20] G. Busetto,[25] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[15] C. Campagnari,[7] M. Campbell,[20] A. Caner,[27] W. Carithers,[18] D. Carlsmith,[38] A. Castro,[25] D. Cauz,[27] Y. Cen,[30] F. Cervelli,[27] P. S. Chang,[33] P. T. Chang,[33] H. Y. Chao,[33] J. Chapman,[20] M.-T. Cheng,[33] G. Chiarelli,[27] T. Chikamatsu,[36] C. N. Chiou,[33] L. Christofek,[13] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[27] E. Cocca,[27] M. Contreras,[5] J. Conway,[32] J. Cooper,[7] M. Cordelli,[9] C. Couyoumtzelis,[10] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] T. Daniels,[19] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[27] M. Dell'Orso,[27] R. Demina,[7] L. Demortier,[31] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[32] J. R. Dittmann,[6] S. Donati,[27] J. Done,[34] T. Dorigo,[25] A. Dunn,[20] N. Eddy,[20] K. Einsweiler,[18] J. E. Elias,[7] R. Ely,[18] E. Engels, Jr.,[28] D. Errede,[13] S. Errede,[13] Q. Fan,[30] G. Feild,[39] C. Ferretti,[27] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. 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A. Tollestrup,[7] H. Toyoda,[24] W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[20] J. Tseng,[19] N. Turini,[27] T. Uchida,[36] N. Uemura,[36] F. Ukegawa,[26] G. Unal,[26] J. Valls,[7,*] S. C. van den Brink,[28] S. Vejcik III,[20] G. Velev,[27] R. Vidal,[7] R. Vilar,[7,*] M. Vondracek,[13] D. Vucinic,[19] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[27] A. M. Walsh,[32] C. Wang,[6] C. H. Wang,[33] J. Wang,[5] M. J. Wang,[33] Q. F. Wang,[31] A. Warburton,[14] T. Watts,[32] R. Webb,[34] C. Wei,[6] H. Wenzel,[16] W. C. Wester III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[26] H. H. Williams,[26] P. Wilson,[5] B. L. Winer,[23] D. Winn,[20] D. Wolinski,[20] J. Wolinski,[21] S. Worm,[22] X. Wu,[10] J. Wyss,[25] A. Yagil,[7] W. Yao,[18] K. Yasuoka,[36] Y. Ye,[14] G. P. Yeh,[7] P. Yeh,[33] M. Yin,[6] J. Yoh,[7] C. Yosef,[21] T. Yoshida,[24] D. Yovanovitch,[7] I. Yu,[7] L. Yu,[22] J. C. Yun,[7] A. Zanetti,[27] F. Zetti,[27] L. Zhang,[38] W. Zhang,[26] and S. Zucchelli[2]

(CDF Collaboration)

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40126 Bologna, Italy*
[3]*Brandeis University, Waltham, Massachusetts 02264*
[4]*University of California at Los Angeles, Los Angeles, California 90024*
[5]*University of Chicago, Chicago, Illinois 60638*
[6]*Duke University, Durham, North Carolina 28708*
[7]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8]*University of Florida, Gainesville, Florida 33611*
[9]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[10]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[11]*Harvard University, Cambridge, Massachusetts 02138*
[12]*Hiroshima University, Higashi-Hiroshima 724, Japan*
[13]*University of Illinois, Urbana, Illinois 61801*
[14]*Institute of Particle Physics, McGill University, Montreal H3A 2T8 and University of Toronto, Toronto M5S 1A7, Canada*
[15]*The Johns Hopkins University, Baltimore, Maryland 21218*
[16]*Universotaet Karlsruhe, 76128 Karlsruhe, Germany*
[17]*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 315, Japan*
[18]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[19]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[20]*University of Michigan, Ann Arbor, Michigan 48109*
[21]*Michigan State University, East Lansing, Michigan 48824*
[22]*University of New Mexico, Albuquerque, New Mexico 87132*
[23]*The Ohio State University, Columbus, Ohio 43320*
[24]*Osaka City University, Osaka 588, Japan*
[25]*Istituto Nazionale di Fisica Nucleare, Universita di Padova, Sezione di Padova, I-36132 Padova, Italy*
[26]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[27]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[28]*University of Pittsburgh, Pittsburgh, Pennsylvania 15270*
[29]*Purdue University, West Lafayette, Indiana 47907*
[30]*University of Rochester, Rochester, New York 14628*
[31]*Rockefeller University, New York, New York 10021*
[32]*Rutgers University, Piscataway, New Jersey 08854*
[33]*Academia Sinica, Taipei, Taiwan 11530, Republic of China*
[34]*Texas A&M University, College Station, Texas 77843*
[35]*Texas Tech University, Lubbock, Texas 79409*
[36]*University of Tsukuba, Tsukuba, Ibaraki 315, Japan*
[37]*Tufts University, Medford, Massachusetts 02155*
[38]*University of Wisconsin, Madison, Wisconsin 53806*
[39]*Yale University, New Haven, Connecticut 06511*

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A strong signal for double parton scattering (DP) is observed in a 16 pb^{-1} sample of $\overline{p}p \to \gamma + 3$ 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 $\overline{p}p$ collisions. The result, $\sigma_{\mathrm{eff}} = (14.5 \pm 1.7^{+1.7}_{-2.3})$ 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. [S0031-9007(97)03616-8]

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The double parton scattering (DP) process [1], in which two parton-parton hard scatterings take place within one $\bar{p}p$ 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

$$\sigma_{\rm DP} \equiv \frac{\sigma_A \sigma_B}{\sigma_{\rm eff}}, \qquad (1)$$

with a process-independent parameter $\sigma_{\rm eff}$ [2–5]. 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 DP measurements have come from the AFS [3], UA2 [4], and CDF [5] experiments. The best value for $\sigma_{\rm eff}$, $12.1^{+10.7}_{-5.4}$ mb, was obtained from the CDF analysis of four jet events. Based on a simple model of proton structure and the measured inelastic $\bar{p}p$ cross section at $\sqrt{s} = 1.8$ TeV, the expected value is $\sigma_{\rm eff} \approx 11$ mb [5].

This Letter reports a new measurement of DP from the Collider Detector at Fermilab (CDF). This extensive analysis is summarized here and 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. In this final state, the DP process is comprised of a photon-jet scattering and a dijet scattering. This leads to two observable configurations yielding a photon + 3 jets: a photon + 1 jet system overlaid with both jets from the dijet, or a photon + 2 jets system (one jet from gluon bremsstrahlung) plus one observed jet from the dijet. The single parton-parton scattering (SP) background is photon-jet production with bremsstrahlung radiation of two gluons. Compared to the previous CDF analysis, the photon + 3 jet data set has two advantages: (1) the jets are accepted down to low energies where the cross section for the dijet scattering in DP is large; and (2) the better energy measurement of photons at CDF (relative to jets) aids in distinguishing DP from SP. 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 over 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.

In addition to these improvements, a new technique for extracting $\sigma_{\rm eff}$ has been developed. Previously, $\sigma_{\rm eff}$ has been derived from measured DP cross sections, using QCD calculations of the two cross sections in Eq. (1) which suffer from sizable uncertainties [9,10]. In the present analysis, $\sigma_{\rm eff}$ is extracted independently of theoretical calculations, through a comparison of the number of observed DP events ($N_{\rm DP}$) to the number of events with hard scatterings at two separate $\bar{p}p$ collisions within the same beam crossing, referred to as double interactions or DI ($N_{\rm DI}$). Because this method does not rely on theoretical calculations, it represents a substantial advance over previous analyses. With these measurements we can write

$$\sigma_{\rm eff} = \left(\frac{N_{\rm DI}}{N_{\rm DP}}\right)\left(\frac{A_{\rm DP}}{A_{\rm DI}}\right)(R_c)\,(\sigma_{\rm NSD}), \qquad (2)$$

where $A_{\rm DP}$ and $A_{\rm DI}$ are acceptances for DP and DI events to pass kinematic selection requirements, and $\sigma_{\rm NSD}$ is the cross section for non-single-diffractive (NSD) inelastic $\bar{p}p$ interactions. Experimentally, DP and DI events will be taken from data sets with one or two observed $\bar{p}p$ collisions per event, respectively. The factor R_c is the ratio of acceptances for requiring one or two collisions per event, and is calculable in terms of the number of NSD collisions per beam crossing and collision identification efficiencies. We describe below the measurements of DP and DI production in the photon + 3 jet data, and the evaluation of the other parameters of Eq. (2).

The CDF detector is described in detail elsewhere [11]. Instantaneous luminosity measurements are made with a pair of up- and downstream 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.

In the 1992–1993 Collider Run, CDF accumulated 16 $\rm pb^{-1}$ 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. Off-line, 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 16 853 and 5983 events pass the two selections. A second trigger sample of interest is the minimum bias data set, collected by requiring coincident signals in the BBC.

Models for the two processes that we must identify, DP and DI, were obtained by combining pairs of CDF events. CDF inclusive photon events were mixed with minimum bias events, with both sets of events required to have ≥1 jet. The resulting mixed events were required to pass the photon + 3 jet event selection. The two models, MIXDP and MIXDI, differ only in the size of the "underlying event" energy contribution to the jets and photon, which arises from soft interactions among spectator partons in the p and $\overline{p}$. Studies of the DP candidate sample indicate that a typical single collision underlying event is present in these events, whereas for DI events with two $\overline{p}p$ collisions approximately twice that level is seen. This difference has an impact primarily on the acceptance ratio in Eq. (2). We note that, by construction, the DP model assumes independent scatterings.

Six variables were identified which exploit the independence and pairwise momentum balance of the two scatterings in DP events. In this Letter we concentrate on the most sensitive variable, ΔS [5,8], which is the azimuthal angle between the transverse momentum (p_T) vectors of the two best-balancing pairs (the event is divided into photon + 1 jet and dijet systems). In SP events, momentum conservation biases ΔS towards 180°, while in DP events the ΔS distribution is flatter. The ΔS distribution for 1VTX data is shown in Fig. 1.

In previous analyses, DP was identified by fitting distributions of kinematic variables (like ΔS) to admixtures of DP and SP Monte Carlo models. In this analysis, dependence on theoretical Monte Carlo calculations is avoided through the use of the data-driven MIXDP model for DP, and a background subtraction technique [8] that does not invoke any prediction or model for the SP component of the data. SP background was statistically removed from the 1VTX data using a second photon + 3 jets data set, selected to be poor in DP by requiring higher E_T jets ($7 \leq E_T \leq 9$ GeV for the two lowest E_T jets). We find that the fraction of DP events in 1VTX data, $f_{\rm DP}$, is 52.6% ± 2.5% (statistical uncertainty). The robustness of the background subtraction method was tested by applying it to mock data constructed from MIXDP events and SP background events from the PYTHIA shower Monte Carlo (with multiple interactions within the $\overline{p}p$ collision disabled) [14]. The resulting measured MIXDP fractions agreed well with the input fractions. Assigning a systematic uncertainty based on this test, we obtain $f_{\rm DP} = 52.6\% \pm 2.5\% \pm 0.9\%$. As a check of this large DP fraction, Fig. 1 compares ΔS distributions for the 1VTX data and the admixture 52.6% MIXDP + 47.4% PYTHIA. The data are well described by this admixture [16], as are the distributions for the other five variables examined. Taking together the number of 1VTX events, $f_{\rm DP}$, and a ~15% correction for higher order multiple parton scatterings [8], we obtain $N_{\rm DP} = 7360 \pm 360^{+720}_{-380}$.

The second measurement needed for the determination of $\sigma_{\rm eff}, N_{\rm DI}$, was obtained by identifying 2VTX events which have jets originating from both $\overline{p}p$ collisions. CTC tracks were used to specify jet origins. The 2VTX data are best described with a 16.8% ± 1.9% ± 1.8% DI component. This result is verified in Fig. 2, which compares ΔS distributions for events found with common and separated jet origins. The flatter shape seen in separate origin events is indicative of DI. The shaded histograms are predictions from 16.8% MIXDI + 83.2% multiple collision background (photon + 3 jets from one $\overline{p}p$ collision accompanied by a second soft collision; modeled by event mixing). Good agreement is observed. Based on the DI percentage and the number of 2VTX events, and after a 5%

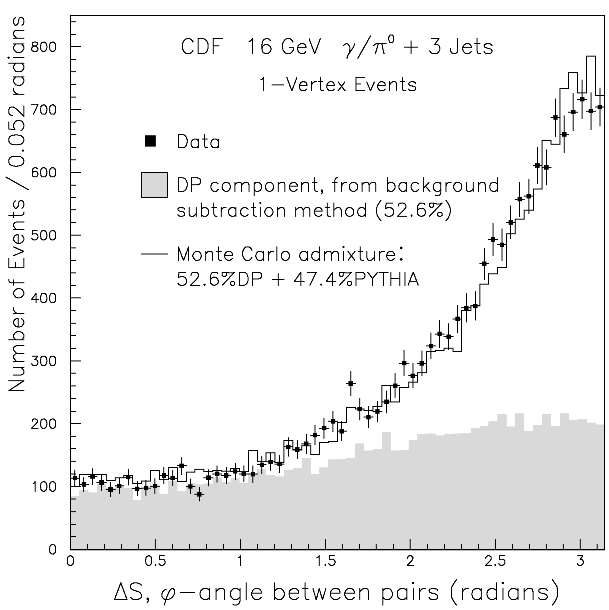

FIG. 1. ΔS distribution for 1VTX data (points). The DP component to the data, determined by the background subtraction method to be 52.6% of the sample, is shown as the shaded region (the shape is taken from MIXDP). Also shown is the admixture 52.6% MIXDP + 47.4% PYTHIA, normalized to the data (line).

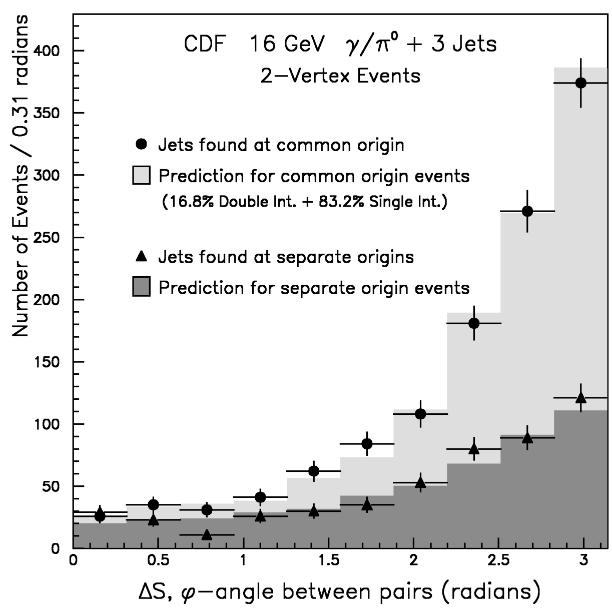

FIG. 2. ΔS distributions for two vertex events. Shown separately are events with jets originating from a common origin along the beam line (circles), and events with jets from separated origins (triangles). The shaded plots are predictions from the admixture 16.8% MIXDI + 83.2% multiple collision background.

correction for selection criteria applied to facilitate CTC tracking, we find $N_{\rm DI} = 1060 \pm 110 \pm 110$.

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 sample of input events. The different levels of underlying event in single and double $\overline{p}p$ collision events result in different jet-finding efficiencies and jet multiplicities, and thus slightly different acceptances. We find $A_{\rm DP}/A_{\rm DI} = 0.958$ 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 R_c in Eq. (2) was derived from vertex identification efficiencies and a prediction for the distribution of the number of NSD collisions per beam crossing. We calculate $R_c = 2.06 \pm 0.02^{+0.01}_{-0.13}$. Inserting these values into Eq. (2), we find $\sigma_{\rm eff} = (14.5 \pm 1.7^{+1.7}_{-2.3})$ 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 first established an enriched sample of DP candidate events, consisting of 1VTX data events that pass the cut $\Delta S < 1.2$ (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 has been observed in CDF photon + 3 jet data. The signal was established, and the process-independent parameter $\sigma_{\rm eff}$ determined, without reliance on theoretical calculations. We find $\sigma_{\rm eff} = (14.5 \pm 1.7^{+1.7}_{-2.3})$ mb. High statistics and a large DP fraction have also 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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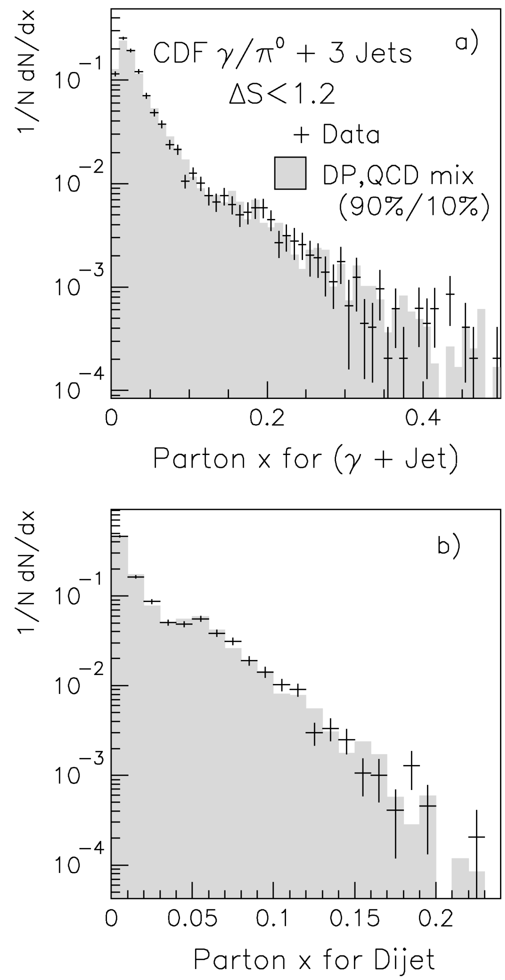

FIG. 3. Results of the Feynman x analysis on DP-enriched 1VTX data. Distributions, two entries per event, of (a) γ + 1 jet x values $[x^{\gamma J}_{p,\overline{p}} = (p^{\gamma}_T/p_{\rm beam})(e^{\pm\eta_\gamma} + e^{\pm\eta_J})]$ and (b) dijet x values $(x^{JJ}_{p,\overline{p}} = \{[E_T(i) + E_T(j)]/2p_{\rm beam}\}(e^{\pm\eta_{Ji}} + e^{\pm\eta_{Jj}})$, 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.

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