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Studies of multi-parton interactions in photon+jets events at D0

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We consider sample of inclusive $\gamma + 3$ jet events collected by the D0 experiment. The double parton fraction ($f_{\rm DP}$) and effective cross section $\sigma_{\rm eff}$, a process-independent scale parameter related to the parton density inside the nucleon, are measured in three intervals of the second (ordered in p_T) jet transverse momentum $p_T^{\rm jet2}$ within the $15 \leq p_T^{\rm jet2} \leq 30$ GeV range. Also we measured cross sections as a function of the angle in the plane transverse to the beam direction between the transverse momentum (p_T) of the γ+leading jet system and p_T of the other jet for $\gamma + 2$ jet, or p_T sum of the two other jets for $\gamma + 3$ jet events. The results are compared to different models of multiple parton interactions (MPI) in the PYTHIA and SHERPA Monte Carlo (MC) generators.

1. Introduction

Many features of high energy inelastic hadron collisions depend directly on the parton structure of hadrons. The inelastic scattering of nucleons occurs mainly through a single parton-parton interaction but the contribution from double (or multiple) parton collisions can be significant. Information about DP rates is needed for understanding of nature of MPI events and correct estimating background to many rare processes, especially with multi-jet final state.

2. Double parton interactions in γ+3 jet events

The cross section of DP events production directly proportional to cross sections of two processes A and B and should be normalized by some scaling parameter $\sigma_{\rm eff}$ in cross section's units.

$$\sigma_{DP} \equiv \frac{\sigma^A \sigma^B}{\sigma_{\rm eff}}. \tag{1}$$

In general sense, $\sigma_{\rm eff}$ is a factor which characterizes a size of the effective interaction region.

We have used a sample of $\gamma + 3$ jets events collected by the DO experiment with an integrated luminosity of about 1 fb^{-1}. The D0 detector is a general purpose detector described in [1]. The events should pass triggers based on the identification of high p_T cluster in the EM calorimeter with loose shower shape requirements for photons. Jets are reconstructed using the D0 Run II iterative midpoint cone algorithm [2] with a cone size 0.7. Each event must contain at least one γ in the rapidity region $|y| < 1.0$ or $1.5 < |y| < 2.5$ and at least three jets with $|y| < 3.0$. Events are selected with γ transverse momentum $60 < p_T^{\gamma} < 80$ GeV, leading (in p_T) jet $p_T > 25$ GeV, while the next-to-leading (second) and third jets must have $p_T > 15$ GeV. The DP fractions and $\sigma_{\rm eff}$ are determined in three $p_T^{\rm jet2}$ bins: 15–20, 20–25, and 25–30 GeV.

We use rates of double interactions (DI) from two separate $p\bar{p}$ collisions and DP from a single $p\bar{p}$ collision to extract $\sigma_{\rm eff}$ from their ratio [3]. The DI events differ from the DP events by the fact that the second parton scattering happens at a separate $p\bar{p}$ collision vertex. Data events with a single $p\bar{p}$ collision vertex, which compose the sample of DP candidates, are selected separately from events with two vertices which compose a sample of DI candidates. A distinctive feature of the DP events is a presence of two independent parton-parton scatterings within the same $p\bar{p}$ collision. We define the variable sensitive to the kinematics of the DP events:

$$\Delta S \equiv \Delta\phi \left(\vec{p}_T^{\,\gamma,jet1},\ \vec{p}_T^{\,jet2,jet3} \right), \tag{2}$$

where $\Delta\phi$ is an azimuthal angle between the p_T vectors of the total transverse momenta of the two two-body systems, $\vec{p}_T^{\,\gamma,jet1}$ and $\vec{p}_T^{\,jet2,jet3}$, in $\gamma + 3$ jet events. This angle is schematically shown in Fig. 1.

We consider the data-driven method to extract the DP fractions $f_{\rm DP}$. Specifically, we consider data in two adjacent p_T intervals of the second jet. The distribution for ΔS variable in data can be expressed as a sum of signal and background distributions. If we known properties of data and DP model, the only unknown parameter is the fraction of DP events in one $p_T^{\rm jet2}$ bin. It is obtained from a minimization. The found $f_{\rm DP}$ values with total uncertainties are 0.466 ± 0.041 for $15 < p_T^{\rm jet2} < 20$ GeV, 0.334 ± 0.023 for $20 < p_T^{\rm jet2} < 25$ GeV, and 0.235 ± 0.027 for $25 < p_T^{\rm jet2} < 30$ GeV. They are shown in Fig. 2 (three sets of the points correspond to

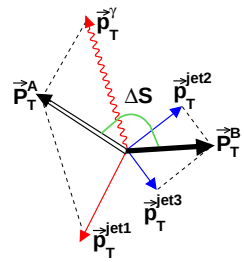

Figure 1: A possible orientation of photon and jets transverse momenta vectors in $\gamma + 3$ jet events. Vectors $\vec{P}_T^1$ and $\vec{P}_T^2$ are the p_T imbalance vectors of γ+jet and jet-jet pairs. The figure illustrates a general case for the production of γ+3 jets +X events.

three possible definitions for the ΔS variable [3]). The values of $\sigma_{\rm eff}$ are shown in Fig. 3. The main systematic uncertainty are caused by determinations of the DI and DP fractions giving a total systematic uncertainty of $(20.5 - 32.2)\%$. The obtained $\sigma_{\rm eff}$ values in different $p_T^{\rm jet2}$ bins agree with each other within their uncertainties and highly uncorrelated, and are used to calculate the average value:

$$\sigma_{\rm eff}^{\rm ave} = 16.4 \pm 0.3({\rm stat}) \pm 2.3({\rm syst})\ {\rm mb}. \tag{3}$$

This average value is in the range of those found in previous measurements [4–7] performed at different energy scales of parton interactions.

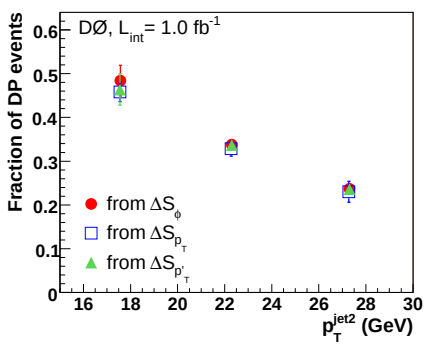

Figure 2: Fractions of $\gamma + 3$ jetevents with double parton interactions in the three $p_T^{\rm jet2}$ intervals.

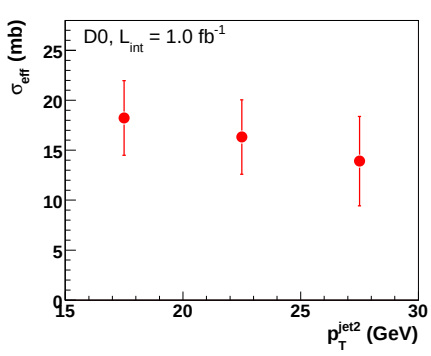

Figure 3: Effective cross section $\sigma_{\rm eff}$ (mb) measured in the three $p_T^{\rm jet2}$ intervals.

3. Azimuthal decorrelations and multiple parton interactions in $\gamma + 2$ jet and $\gamma + 3$ jet events in $p\bar{p}$ collisions

Samples of $\gamma + 2(3)$ jets events with the same cuts as [3] are considered. The next modifications are applied: each event must contain at least one γ in the pseudorapidity region $|y| < 1.0$ or $1.5 < |y| < 2.5$ and at least

two (or three) jets with $|y| < 3.5$. Events are selected with γ transverse momentum $50 < p_T^{\gamma} < 90$ GeV, leading jet $p_T > 30$ GeV, and the second jet $p_T > 15$ GeV. If there is a third jet with $p_T > 15$ GeV that passes the selection criteria, the event is also considered for the $\gamma + 3$ jet analysis. By measuring differential cross sections vs. the azimuthal angles in $\gamma + 2(3)$ jet events we can better tune MPI models in events with high p_T jets. We present the four measurements of normalized differential cross sections, ΔS in a single bin $15 < p_T^{\rm jet2} < 30$ for $\gamma + 3$ jet events (see Fig. 1), and $\Delta\phi$ in three $p_T^{\rm jet2}$ bins, 15-20, 20-25, and 25-30 GeV, for $\gamma + 2$ jet events. The $\Delta\phi$ is an angle between the p_T vector obtained by pairing the γ and the leading jet p_T vectors and the second jet p_T vector [8]). It is shown in Fig. 4. We consider a few MPI models and two models without MPI simulated by PYTHIA and SHERPA MC generators. Figure 5 shows the measured cross section for the two angular variables ΔS (left plot) and $\Delta\phi$ (right plot). The data have a good sensitivity to the various MPI models, which predictions vary significantly and differ from each other by up to a factor 2 at small ΔS and $\Delta\phi$, i.e. in the region where the relative DP contributi

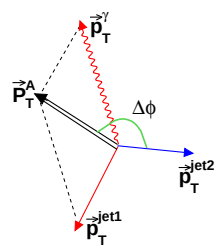

Figure 4: A possible orientation of photon and jets transverse momenta vectors in $\gamma + 2$ jet events.

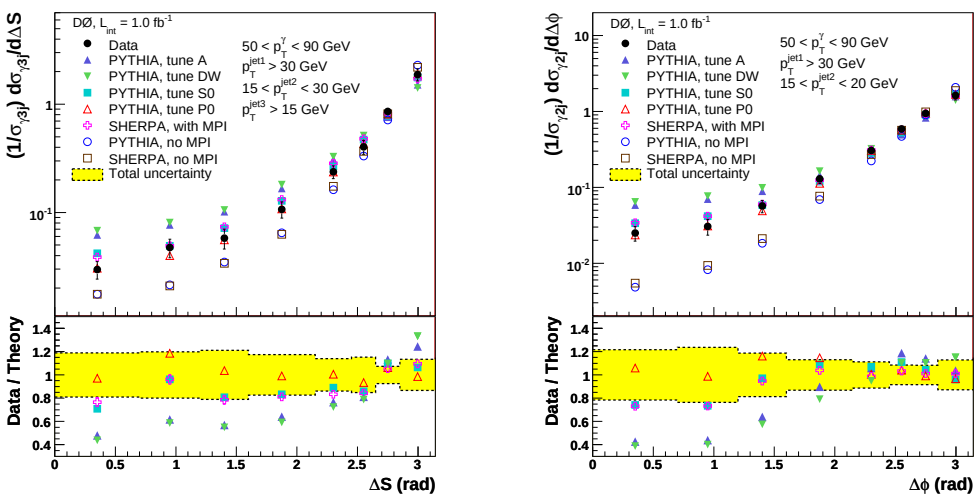

Figure 5: Left: Normalized differential cross section in the $\gamma + 3$-jet events, $(1/\sigma_{\gamma 3j})\sigma_{\gamma 3j}/d\Delta S$, in data compared to MC models and the ratio of data over theory, only for models including MPI, in the range $15 < p_T^{jet2} < 30$ GeV. Right: Normalized differential cross section in $\gamma + 2$-jet events, $(1/\sigma_{\gamma 2j})\sigma_{\gamma 2j}/d\Delta\phi$, in data compared to MC models and the ratio of data over theory, only for models including MPI, in the range $15 < p_T^{jet2} < 20$ GeV.

From these two plots we may conclude that: (a) a large difference between single parton-parton interaction (SP) models and data confirms a presence of DP events in the data sample; (b) the data favor the predictions of the MPI models with P0, S0 and Sherpa MPI tunes with p_T-ordered showers; (c) the predictions from tune A and DW MPI models are disfavored. It is important that our preferable choice of MPI models is stable for all our measurements.

In $\gamma + 2$ jet events in which the second jet is produced in the additional independent parton interaction, the $\Delta\phi$ distribution should be flat. Using this fact and also SP prediction for $\Delta\phi$ we can get the DP fractions from a fit to data. The distributions in data, SP, and DP models, as well as a sum of the SP and DP distributions, weighted with their respective fractions for $15 < p_T^{\rm jet2} < 20$ GeV, are shown in the left plot of Figure 6. The DP fractions in the $\gamma + 2$ jet samples decrease in the bins of $p_T^{\rm jet2}$ as $(11.6 \pm 1.0)\%$ for $15 - 20$ GeV, $(5.0 \pm 1.2)\%$ for $20 - 25$ GeV, and $(2.2 \pm 0.8)\%$ for $25 - 30$ GeV. To determine the fractions as a function of $\Delta\phi$, we perform a fit in the different $\Delta\phi$ regions by excluding the bins at high $\Delta\phi$. We find that they grow significantly towards

the smaller angles and are higher for smaller $p_T^{\rm jet2}$ (right plot of Figure 6).

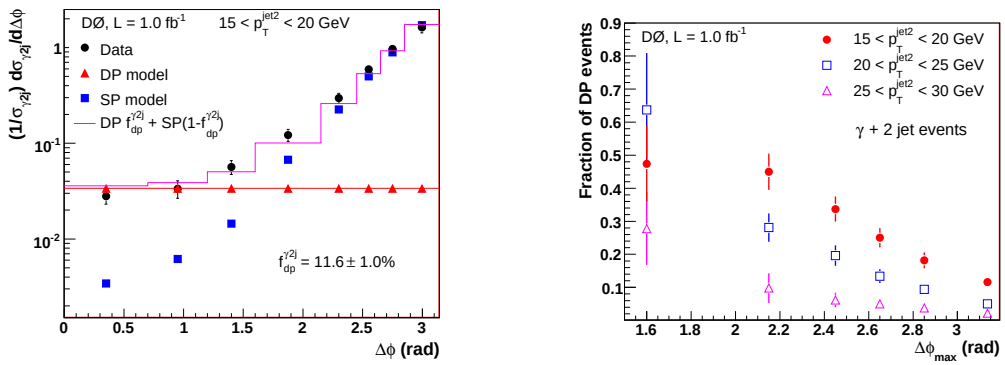

Figure 6: Left: the $\Delta\phi$ distribution in data, SP, and DP models, and the sum of the SP and DP contributions weighted with their fractions for $15 < p_T^{\rm jet2} < 20$ GeV. Right: the fractions of DP events with total uncertainties in $\gamma + 2$ jetfinal state as a function of the upper limit on $\Delta\phi$ for the three $p_T^{\rm jet2}$ intervals.

We also estimate the fraction of $\gamma + 3$ jet events from triple parton interactions (TP) in data as a function of $p_T^{\rm jet2}$. In $\gamma + 3$ jet TP events, the three jets come from three different parton interactions, one $\gamma+$ jet and two dijet final states. In each of the two dijet events, one of the jets is either not reconstructed or below the 15 GeV p_T selection threshold. The fractions of TP events in the $\gamma + 3$ jet data have been estimated and are shown in Fig. 7. As we see, they vary in the $p_T^{\rm jet2}$ bins as $(5.5 \pm 1.1)\%$ for $15 - 20$ GeV, $(2.1 \pm 0.6)\%$ for $20 - 25$ GeV, and $(0.9 \pm 0.3)\%$ for $25 - 30$ GeV.

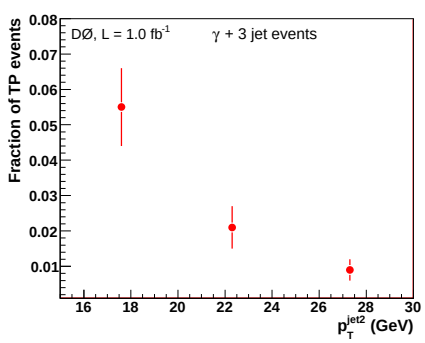

Figure 7: Fractions of $\gamma + 3$ jetevents with triple parton interactions in the three $p_T^{\rm jet2}$ intervals.

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