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Physics of double parton interactions

Recent results from DØ experiment

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Abstract. A study of processes with double parton interactions (DPI) in $p\bar{p}$ collisions collected by DØ detector at the Tevatron collider at $\sqrt{s} = 1.96$ TeV is presented. The study includes measurements of DPI event fraction and the effective cross section, a process-independent parameter related to the effective interaction region inside a hadron. The measurements are done using processes with photon and hadronic jets in different parton-parton scatterings: photon+jet + dijet, photon+b/c + dijet and diphoton + dijet. The measured effective cross section is applied in order to estimate background from DPI processes to WH production at the Tevatron energy.

1 Introduction

High energy inelastic hadron-hadron collisions are generally described as a hard $2 \rightarrow 2$ partonic scattering with soft gluon radiation in initial and final states with account of fragmentation and hadronization effects. However, there is a possibility to find more than one hard parton-parton scattering within the same hadron-hadron collision. The cross section of a process with double parton interaction is proportional to cross sections of two partonic scatterings A and B: $\sigma_{\rm DPI} \equiv \sigma^{\rm A}\sigma^{\rm B}/\sigma_{\rm eff}$. The scaling parameter, $\sigma_{\rm eff}$, historically called the *effective cross section*, having a unit of cross section, characterizes the size of the effective interaction region within a hadron. The effective cross section is directly related to the spatial distribution of partons within a hadron and being a phenomenological parameter strongly needs experimental input. Moreover, some final states being produced by DPI mechanism can mimic rare processes produced by single parton-parton interaction (SPI). A study of DPI at high-$p_{\rm T}$ regime provides the important information about hadron structure and crucial for precise estimates of background for many rare processes.

2 Study of DPI kinematics in final states containing photons and jets

The DØ detector is a general purpose detector described in [1]. The events should pass triggers based on the identification of high-$p_{\rm T}$ cluster in the electromagnetic calorimeter with loose shower shape requirements for photons. Photon candidates are selected using calorimeter cells by creating clusters inside a cone with radii $\mathcal{R} \equiv [\Delta\eta^2 + \Delta\phi^2]^{1/2} = 0.2$ around a cell-initiator. A photon candidate in an event should be isolated in a ring $\mathcal{R} = 0.2$, the electromagnetic fraction of the total photon energy

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disposition should be > 96% and the probability to have a track associated to the calorimeter cluster to be < 0.1%.

Jets are reconstructed using the DØ Run II iterative midpoint cone algorithm with a cone size $\mathcal{R} = 0.5$. Measured jet energy does not necessarily match the energy of the parent parton caused by the parton-to-hadron fragmentation and interaction of hadrons with calorimeter material. Jet energy scale procedure is applied in order to correct measured jet energy to the true energy sum of all particles in a jet [2].

The technique used for $\sigma_{\rm eff}$ measurement is based on the difference of double parton-parton interaction and double $p\bar{p}$ collision event rates [3]. Assuming that scatterings in the two parton-parton hard processes are uncorrelated, DPI and double $p\bar{p}$ collision events should be kinematically identical. The effective cross section is extracted from the ratio of observed DPI and double $p\bar{p}$ collision event rates.

2.1 DPI in $p\bar{p} \to \gamma$+jet + dijet process

The associate production of photons and hadronic jets in leading order is based on Compton-like $qg \to q\gamma$ and annihilation $q\bar{q} \to g\gamma$ processes. Additional hadronic jets in an event are caused by gluon radiation in initial and final states that also leads to $p_{\rm T}$-imbalance between the photon and the leading jet. The main source of background to γ + jets production comes from processes with photons produced by hadron decays (π^0, η, etc.) and fragmentation photons, that mostly suppressed by the photon isolation requirement. The $qg \to q\gamma$ process dominates in broad kinematic region with the photon transverse momentum $p_{\rm T}^{\gamma} < 150$ GeV and its contribution to the total $\gamma +$ jets cross section becomes comparable to the annihilation process at $p_{\rm T}^{\gamma} \simeq 150$ GeV. The fraction of $qg \to q\gamma$ relative to the total $\gamma +$ jets event cross section is shown in figure 1(a).

The DP γ+jet + dijet event sample is selected from DØ data with a single $p\bar{p}$ collision vertex [3]. The collected statistics of the sample corresponds to the integrated luminosity of 8.7 fb^{-1}. Each event must contain at least one photon in the pseudorapidity region $|\eta| < 1.0$ or $1.5 < |\eta| < 2.5$ and at least three jets with $|\eta| < 2.5$. Events are selected with the photon transverse momentum $p_{\rm T}^{\gamma} > 26$ GeV, leading (in $p_{\rm T}$) jet $p_{\rm T}^{jet\ 1} > 15$ GeV, while the next-to-leading (second) and third jets must have $15 < p_{\rm T}^{jet\ 2,3} < 30$ GeV. To avoid photon/jets overlapping the topology cuts requiring all object pairs (photon-jet or jet-jet) to be separated in $(\eta - \phi)$ space by distance $\Delta R(\gamma, \text{jet}) > 0.7$ and $\Delta R(\text{jet}, \text{jet}) > 1.0$ are applied.

Any event in γ+jet + dijet sample can be produced by two independent $2 \to 2$ parton-parton scatterings or by a single parton-parton $2 \to 4$ scattering with gluon radiation in an initial or final state as well. To identify the events with two independent parton-parton scatterings that produce γ+jet + dijet final state, an angular distribution sensitive to the kinematics of the DPI events is used. Among others, one can define a variable:

$$\Delta S \equiv \Delta\phi(\vec{q}_{\rm T}^{\,1}, \vec{q}_{\rm T}^{\,2}), \tag{1}$$

where $\Delta\phi$ is an azimuthal angle between the imbalance vectors of photon-leading jet ($\vec{q}_{\rm T}^{\,1}$) and dijet ($\vec{q}_{\rm T}^{\,2}$) pairs in γ+jet + dijet events. This angle is schematically shown in figure 2(a). The distribution of ΔS variable reflects angular properties of a mixture of γ+jet + dijet events containing both single and double parton-parton scatterings. The contribution from SPI events to the ΔS tends to shift distribution towards π because of the well-balanced in $p_{\rm T}$ photon and jets in a $2 \to 4$ process. The contribution from the DPI events should be flat since the ΔS angle between $\vec{q}_{\rm T}$ vectors of two independent $2 \to 2$ scatterings is arbitrary.

To study properties of DPI events and calculate their fractions in a single $p\bar{p}$ collision γ+jet + dijet data sample, one needs to construct a model that correctly reflects properties of DPI kinematics. The

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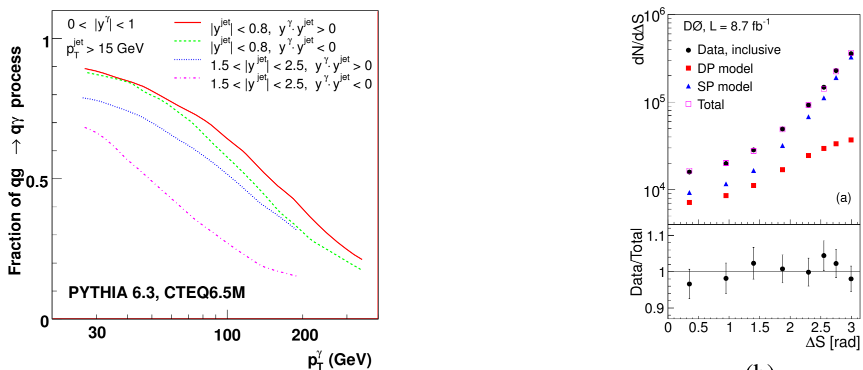

(a) (b)

Figure 1. (a) The fraction of events produced via the $qg \to q\gamma$ subprocess relative to the total associated photon and jet production for various photon and jet rapidity regions. (b) The ΔS distribution in the data, DPI, SPI models, and the sum of the DPI and SPI contributions weighted with their fractions ("Total") in γ+jet + dijet final state.

(a) (b)

Figure 2. A possible orientation of photon and jets transverse momenta vectors. Vectors $\vec{q}_T^{\,1}$ and $\vec{q}_T^{\,2}$ are the p_T-imbalance vectors of (a) γ+jet and dijet pairs in γ+jet + dijet events and (b) diphoton and dijet pairs in $\gamma\gamma$ + dijet events.

DPI model is composed by overlaying in a single event one event of an inclusive sample of γ + 1 jet events and one event of a sample of inelastic non-diffractive events selected with the minimum bias trigger and a requirement of at least one jet. Both samples contain only single $p\bar{p}$ collision events. The resulting mixed events, with jets re-ordered in p_T, are required to pass the γ+jet + dijet event selections described above. This model of DP events, called MIXDP, assumes independent parton scatterings with γ + jets and dijet final states by construction.

The DPI event fraction, $f_{\rm DPI}$, is found using a maximum likelihood fit of the ΔS distribution of the data to signal DPI and background SPI templates that are taken to be shapes of the ΔS distribution in the MIXDP model and SPI model simulated by SHERPA, respectively. Signal and background samples used as templates satisfy all the selection criteria applied to the data sample. The result of the fit is shown in figure 1(b). The found fraction of DPI events with total uncertainty is $f_{\rm DPI}^{\gamma jjj} = 0.206 \pm 0.007(stat) \pm 0.004(syst)$. Heaving measured number of DPI events, corresponding selection efficiencies and geometrical acceptances one can calculate effective cross section, which is found to be $\sigma_{\rm DPI}^{\gamma jjj} = 12.7 \pm 0.2(stat) \pm 1.3(syst)$ mb.

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2.2 DPI in $p\bar{p} \rightarrow \gamma$+b/c + dijet process

The evolution of the study described in section 2.1 is a first measurement of the DPI rates and σ_{eff} involving heavy flavor leading jet using the γ+b/c + dijet final state and direct comparison to the results obtained with γ+jet + dijet events. The γ+b/c + dijet production is mainly caused by $b(c)g \rightarrow b(c)\gamma$ and $q\bar{q} \rightarrow g\gamma$ with $g \rightarrow Q\bar{Q}$, where $Q = b(c)$ [3]. Figure 3(a) shows the fractions of qg and bg subprocesses in events with γ+jet and $\gamma + b$-jet final states, calculated using default PYTHIA 6.4 settings and the CTEQ 6.1L parton distribution function. At $p_T^\gamma \simeq 30$ GeV the Compton-like scattering dominates over the annihilation process, contributing about $(85 - 88)\%$ of events. Since the initial quarks in the Compton-like scattering for inclusive γ+jet and $\gamma + b$-jet production are typically light and b/c quarks, respectively, the difference between effective cross sections measured in the two processes should be sensitive to the difference between light quark and heavy quark transverse spatial distributions in a hadron.

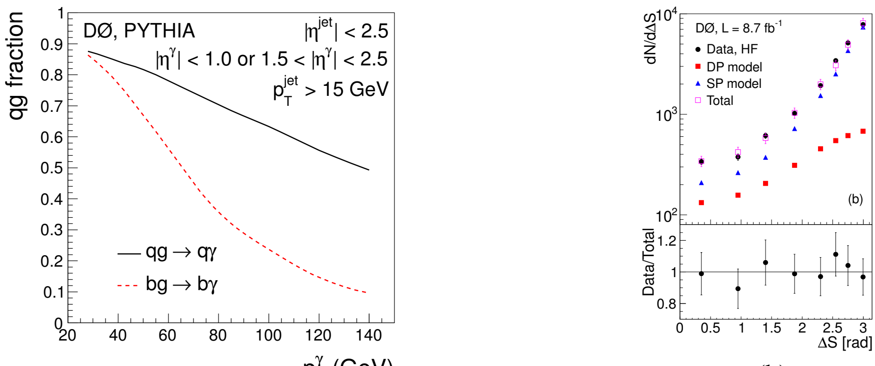


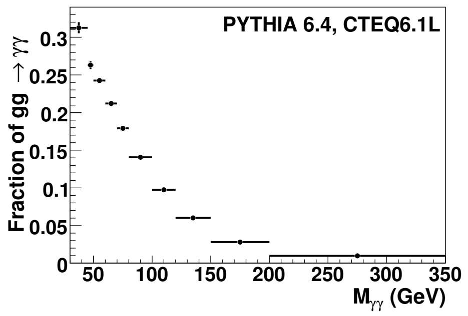
Figure 3. (a) The fractions of events produced via the $qg \rightarrow q\gamma$ and $bg \rightarrow b\gamma$ subprocesses. (b) The ΔS distribution in the data, DPI, SPI models, and the sum of the DPI and SPI contributions weighted with their fractions ("Total") in γ+b/c + dijet final state.

Events undergo the same selection criteria as described in Section 2.1 with additional leading jet requirements which ensure that there is sufficient information to identify the leading jet as a heavy flavor candidate and have typical efficiency of about 90%. The technique of the f_{DPI} and σ_{eff} extraction is similar to the previous measurements and the found fraction is $f_{\text{DPI}}^{\gamma bjj} = 0.173 \pm 0.020(stat) \pm 0.002(syst)$, that gives the effective cross section $\sigma_{\text{DPI}}^{\gamma bjj} = 14.6 \pm 0.6(stat) \pm 3.2(syst)$ mb. Figure 3(b) illustrates the results of the fitting procedure. Within uncertainties, the effective cross section in the γ+jet + dijet event sample is consistent with that in the event sample with identified heavy flavor jets, allowing to conclude that there is no evidence of σ_{eff} dependence on the initial parton flavor.

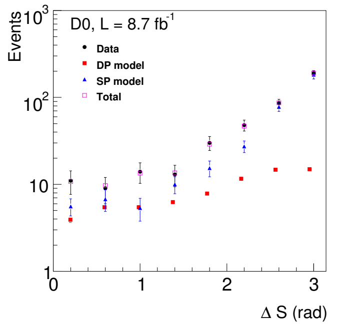
2.3 DPI in $p\bar{p} \rightarrow \gamma\gamma$ + dijet process

The goal of this study is to obtain the DPI rate and the effective cross section in the $\gamma\gamma$ + dijet final state [4]. The main contributions to diphoton production at the Tevatron are from the $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ via direct $2 \rightarrow 2$ partonic processes, as well as from bremsstrahlung processes with a single and double parton-to-photon fragmentations. Figure 4(a) shows the relative fraction of the $gg \rightarrow \gamma\gamma$

contribution to the total diphoton cross section. In this analysis which restricts the transverse momenta of each of the two leading jets to the range of (15 – 40) GeV and the transverse momenta of each of the two leading photons to be above 15 GeV, the $q\bar{q}$ scattering significantly dominates the gg process, with $q\bar{q}$ fraction of about (70 – 80)%.



(a)



(b)

Figure 4. (a) The fraction of events produced via the $gg \to \gamma\gamma$ subprocess relative to the total diphoton cross section. (b) The ΔS distribution in the data, DPI, SPI models, and the sum of the DPI and SPI contributions weighted with their fractions ("Total") in $\gamma\gamma$ + dijet final state.

The DPI event fraction is found by fitting signal (MIXDP model constructed similarly to those described in sections 2.1 and 2.2) and background (SHERPA SPI sample) event models to the data using ΔS variable which is shown in figure 2(b). The result of the fit is presented in figure 4(b) and the found fraction of DPI events is $f_{\rm DPI}^{\gamma\gamma jj} = 0.213 \pm 0.061(stat) \pm 0.028(syst)$. Along with the measured selection efficiencies and geometric acceptances it gives the effective cross section $\sigma_{\rm DPI}^{\gamma\gamma jj} = 19.3 \pm 1.4(stat) \pm 7.8(syst)$ mb, which is in agreement with the previous measurements within uncertainties.

3 DPI as a background to WH production at the Tevatron

As it was mentioned above a distinctive feature of DPI events is an interaction of two parton-parton pairs within the same $p\bar{p}$ collision. The measured effective cross section, which is directly related to the spatial distribution of partons within a hadron, is used to estimate the rate of DPI events at the Tevatron energy as a background to associate WH production with $H \to b\bar{b}$ decay mode.

The HW production channel is simulated with Higgs boson masses of $m_{\rm H} = 115$ GeV and $m_{\rm H} = 150$ GeV. The DPI scattering is simulated by PYTHIA 8 as inclusive $q\bar{q} \to W + X$ production in the first parton process and inclusive QCD dijet production in the second process. The cross sections of the simulated events are normalized to either experimentally measured cross sections or to theoretical NNLO predictions. The differential cross sections $d\sigma/dM_{\rm jj}$ are calculated for the HW and DPI (W + dijet) events. To match the detector resolution, the jet transverse momenta are smeared in order to approximately reproduce the jet $p_{\rm T}$ resolution of the DØ detector. It is shown that the DPI cross section dominates the HW signal by more than two orders of magnitude, and the DPI cross section is caused mainly by the W+2 light jets (stemming from $u/d/s$-quarks or gluons) production [5].

In the signal HW events there are two b-jets in the final state. Since the leading DPI background is caused by the W + 2 light jet events, one should expect a significant reduction after requiring the jet b-tagging. To check this numerically a specific b-tagging requirement to the HW and DPI events is applied. Figure 5(a) shows the ratios of the HW event yield to the inclusive DPI W + dijet one in the

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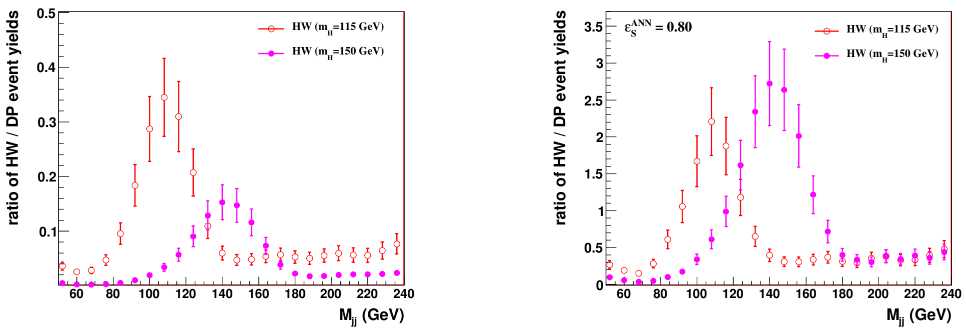
dijet mass M_{jj} bins for the events selected by b-tagging. The uncertainty in each bin is caused by the normalization factors and the effective cross section. One can see that the Higgs boson events with M_H = 115 GeV are expected to be suppressed by about a factor 3 ($S/B \simeq 0.35$) in the peak position, while the signal events with M_H = 150 GeV are suppressed by about a factor 7. A set of variables sensitive to DPI kinematics is used as an input to a dedicated artificial neural network (ANN) to separate the HW from the DPI events. The new signal-to-background ratios are shown in figure 5(b). This ratio reaches about 2.2 at $M_{jj} \simeq 115$ GeV and about 2.7 at $M_{jj} \simeq 150$ GeV.



(a) (b)

Figure 5. The ratio of HW signal to DPI background event yields (a) with the b-tagging and (b) with account of the ANN selection efficiency taken for the HW events to be 80%.

4 Conclusion

Kinematic features of processes with double parton-parton scatterings have been studied by DØ experiment at the Tevatron. The effective cross section, a process independent parameter directly related to the size of the interaction region within a hadron, has been measured in processes with various final states containing isolated photons and hadronic jets and found to be $\sigma_{\rm DPI}^{\gamma jjj} = 12.7 \pm 0.2(stat) \pm 1.3(syst)$ mb, $\sigma_{\rm DPI}^{\gamma bjj} = 14.6 \pm 0.6(stat) \pm 3.2(syst)$ mb and $\sigma_{\rm DPI}^{\gamma\gamma jj} = 19.3 \pm 1.4(stat) \pm 7.8(syst)$ mb. All measured values are in agreement within uncertainties with each other as well as with most of the $\sigma_{\rm eff}$ measurements performed at the Tevatron and LHC. It is also shown that DPI production can be a significant background to many rare processes, especially with multi-jet final state. A set of variables allowing to reduce the DPI background is suggested.

References

[1] V. M. Abazov et al. [D0 Collaboration], Nucl. Instrum. Meth. A **565**, 463 (2006)
[2] V. M. Abazov et al. [D0 Collaboration], Nucl. Instrum. Meth. A **763**, 442 (2014)
[3] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D **89(7)**, 072006 (2014)
[4] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. D **93(5)**, 052008 (2016)
[5] D. Bandurin, G. Golovanov and N. Skachkov, JHEP **1104**, 054 (2011)