Studies on Double-Parton Scattering in Final States with one Photon and three Jets

Florian Bechtel (on behalf of the CMS collaboration)
Universität Hamburg - Department Physik,
Luruper Chaussee 149, 22761 Hamburg - Germany

Abstract
We discuss the search for two hard scatters (*double-parton scattering*) in final states with one photon and three jets ($\gamma + 3$ *jet events*) and its feasibility at LHC energies. Hadron-level studies are performed with the new event generators PYTHIA 8 and HERWIG++.

1 Signatures for Double High-p_T Scatters at Hadron Colliders

The production of four high-p_T jets is the most prominent process to directly study the impact of multiple interactions: Two independent scatters in the same pp or $p\bar{p}$ collision (*double-parton scattering, DPS*) each produce two jets. Such a signature has been searched for by the AFS experiment at the CERN ISR, by the UA2 experiment at the CERN S$\bar{p}p$S and most recently by the CDF experiment at the Fermilab Tevatron [1].

Searches for double-parton scattering in four-jet events at hadron colliders face significant backgrounds from other sources of jet production, in particular from QCD bremsstrahlung (Fig. 1-left). Typical thresholds employed in jet triggers bias the event sample towards hard scatterings. However, a high-p_T jet parton is more likely to radiate additional partons, thus producing further jets. Thus, the relative fraction of jets from final-state showers above a given threshold is enlarged in jet trigger streams which is an unwanted bias. On the other hand, looking for four jets in a minimum-bias stream will yield little statistics. In a novel approach to detect double-parton scattering, the CDF collaboration therefore studied final states with one photon and three jets looking for pairwise balanced photon-jet and dijet combinations [2]. The data sample was selected with the CDF experiment's inclusive photon trigger, thereby avoiding a bias on the jet energy. The superior energy resolution of photons

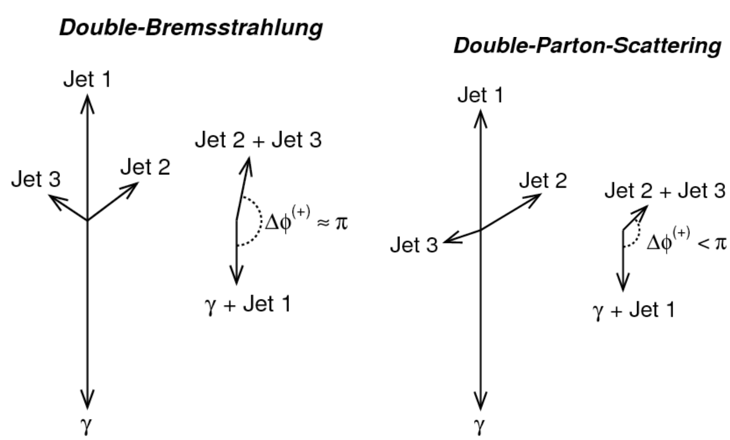

Fig. 1: CDF definition of azimuthal angle between pairs, together with typical configurations of double-bremsstrahlung (left) and double-parton scattering events (right).

compared to jets purifies the identification of E_T balanced pairs. CDF found an excess in pairs that are uncorrelated in azimuth with respect to the predictions from models without several hard parton scatters per proton-proton scatter. CDF interpreted this result as an observation of double-parton-scatters.

Analyses trying to identify two hard scatters in multi-jet events typically rely on methods to overcome combinatorics as there are three possible ways to group four objects into two pairs: Combinations are commonly selected pairwisely balanced in azimuth and energy. As an alternative, a final state without the need for p_T balancing is of great interest to searches for two hard scatters. One example of such a final state, that would not need p_T balancing, are events with two b jets together with two additional jets [3]. In this case, one pair would be composed of the two b jets, and one pair would be composed of the two additional jets.

In order to discriminate double-parton scatters against double-bremsstrahlung events, we study prompt-photon events with additional jets coming from multiple interactions, from the parton shower, or from both. Observables $\Delta\phi^{(-)}$, employed by AFS, and $\Delta\phi^{(+)}$, employed by CDF, probe the azimuthal angle between photon-jet pair and dijet pair (Fig. 1):

$$\Delta\phi^{(-)} = \angle\left(\vec{p}_T^{\,\gamma} - \vec{p}_T^{\,1}, \vec{p}_T^{\,2} - \vec{p}_T^{\,3}\right) \ , \tag{1}$$

$$\Delta\phi^{(+)} = \angle\left(\vec{p}_T^{\,\gamma} + \vec{p}_T^{\,1}, \vec{p}_T^{\,2} + \vec{p}_T^{\,3}\right) \ , \tag{2}$$

where $\vec{p}_T^{\,1}$ stands for the transverse momentum of the jet combined with the photon, and the photon-jet pair is selected such that the term

$$\frac{|\vec{p}_T^{\,\gamma} + \vec{p}_T^{\,i}|^2}{|\vec{p}_T^{\,\gamma}| + |\vec{p}_T^{\,i}|} + \frac{|\vec{p}_T^{\,j} + \vec{p}_T^{\,k}|^2}{|\vec{p}_T^{\,j}| + |\vec{p}_T^{\,k}|} \tag{3}$$

is minimized. Thus, pairs are assigned based on pairwise p_T balance. Additional jets produced in double-bremsstrahlung typically point away from the photon and surround the jet balancing the photon. Expectations for the above described variables are therefore $\Delta\phi^{(-)} \approx \pi/2$ and $\Delta\phi^{(+)} \approx \pi$ if additional jets come from double-Bremsstrahlung. Otherwise, i. e. if additional jets come from multiple interactions, both variables should be distributed uniformly.

2 Simulation of Multiple Scatters

Hadron-level studies have been carried out employing the parton shower programs PYTHIA [4], version 8.108, and HERWIG++ [5], version 2.2.0, which both implement new models for multiple parton-parton scatters in non-diffractive events[1].

Main features of PYTHIA's multiple interaction framework are $p_\perp$-ordering and interleaving, small-$p_\perp$-dampening of perturbative QCD cross sections, variable impact parameters, and rescaling of parton density distributions [6]. The model is currently being expanded to include the simulation of parton rescattering [7]. HERWIG simulates multiple scatters that are not ordered and not interleaved with parton showering [8]. At small transverse momenta $p_\perp$, no dampening but a sharp cutoff on additional interactions is imposed. The matter distribution inside the proton follows the electromagnetic form factor, where the hadron radius is kept as a free parameter.

[1] In the remainder of this article, PYTHIA refers to PYTHIA 8.108 and HERWIG refers to HERWIG++ 2.2.0.

Table 1: CDF selection of photon-three-jet events together with a suggested extrapolation to LHC energies.

	CDF	LHC extrapolation
Photon	$\|\eta\| \leq 1.1$	$\|\eta\| \leq 2.5$
	$E_T \geq 16$ GeV	$E_T \geq 50$ GeV
	Cone $R = 0.7$	$k_\perp$ $D = 0.4$
	$\|\eta\| \leq 4.2$	$\|\eta\| \leq 5$
Jets	$E_T \geq 5$ GeV	$E_T \geq 20$ GeV
	$E_{T4} < 5$ GeV	$E_{T4} < 10$ GeV
	$E_{T2}, E_{T3} < 7$ GeV	$E_{T2}, E_{T3} < 30$ GeV

Parton densities are not modified except for the exclusion valence contributions. Violations of energy-momentum conservation are vetoed. Color-connections are included for all parton-parton scatters.

The analysis considers 1.8 million prompt-photon events with event scales ranging from 5 GeV to 100 GeV, normalized to the total prompt-photon-production cross section.

3 Event Selection and Background Discrimination

Stable particles (except neutrinos) are clustered into jets using a longitudinally invariant $k_\perp$ algorithm with parameter $D = 0.4$ [9]. Table 1 summarizes the kinematic selection on photon and jets as imposed by CDF [2] together with a suggested extrapolation of these cuts to LHC energies [10]. The suggested thresholds follow the CMS detector's acceptance [11], but should merely be seen as a first approximation to a final event selection. The threshold choices are motivated in the following. The polar acceptances of the CMS electromagnetic and hadronic calorimeters are reflected in pseudorapidity cuts of $|\eta(\gamma)| \leq 2.5$ and $|\eta(\text{jet})| \leq 5$. Photon transverse energies are required to be above $E_T(\text{photon}) > 50$ GeV, jet transverse energies have to be above $E_T(\text{jet}) > 20$ GeV, in order to ensure a sufficient purity in reconstruction [11]. Three PYTHIA settings are studied:

Default: PYTHIA is used "out-of-the-box". Parton showers and multiple interactions are included in the event selection.

MI: The simulation of parton showers is switched off. Additional jets are produced exclusively by the multiple interaction framework.

Shower: Multiple interactions are switched off. Additional jets come from initial- or final-state radiation.

In the following, all comparisons between PYTHIA and HERWIG are carried out using PYTHIA *Default* settings and HERWIG with its default underlying event tune. Specifically, the simulations of multiple interactions and parton showers are switched on.

Differential cross section shape predictions for the variable suggested by AFS, $\Delta\phi^{(-)}$, are shown in Fig. 2. HERWIG and PYTHIA predict similar cross section shapes for the default set-

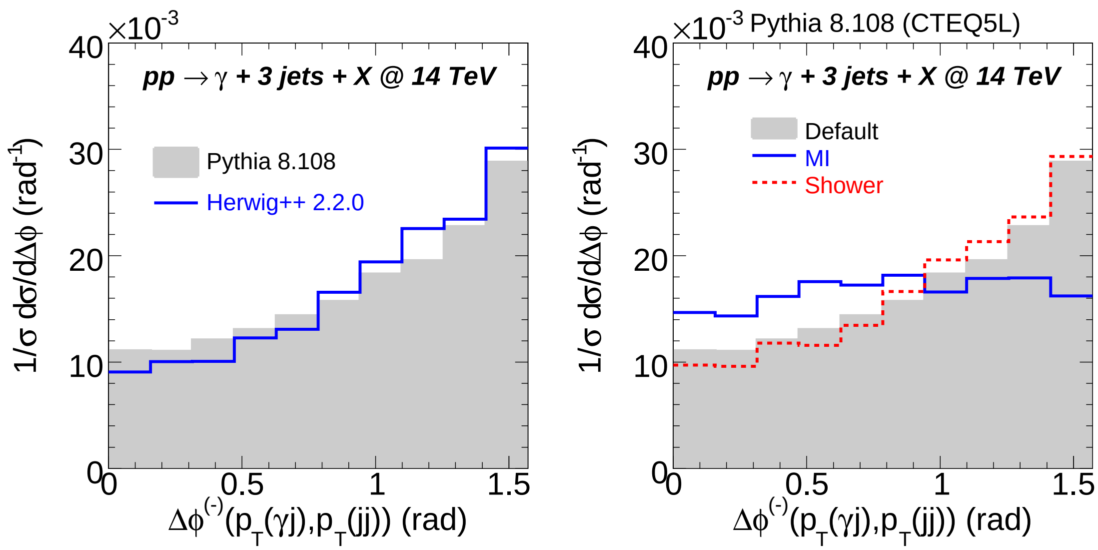

Fig. 2: Differential cross section shape as a function of $\Delta\phi^{(-)}$ (Eq. 1). Predictions from PYTHIA (*Default* scenario) and HERWIG (left panel) and from three different PYTHIA settings (right panel) shown.

tings which include multiple interactions and showering (Fig. 2-left). With multiple interactions switched off, $\Delta\phi^{(-)}$ is indeed most likely to be $\Delta\phi^{(-)} \approx \pi/2$. However, the correlation is weak with a factor of 3 between first bin and last bin, i. e. between events with both pairs being aligned in azimuth and events being orthogonal in azimuth. In fact, the difference between PYTHIA's *Default* and *Shower* scenarios is not significant within the available statistics (Fig. 2-right). Yet, both pairs are more or less uncorrelated if additional jets come from multiple interactions (*MI* scenario, Fig. 2-right).

Differential cross section shape predictions for the variable suggested by CDF, $\Delta\phi^{(+)}$, are shown in Fig. 3. Differences between HERWIG and PYTHIA are especially pronounced for small $\Delta\phi^{(+)}$, corresponding to the photon-jet pair and the dijet pair both pointing in the same direction in azimuth (Fig. 3-left). PYTHIA predicts a larger fraction of uncorrelated pairs than HERWIG does. Strong differences can also be seen when comparing PYTHIA's different simulation scenarios with each other (Fig. 3-right). As noted before, jets from initial- or final-state showers dominantly point away from the photon and combinations with small $\Delta\phi^{(+)}$ are largely suppressed. However, if additional jets come from multiple interactions (*MI* scenario), the dijet pair can have any orientation with respect to the photon-jet pair, thus the predicted distribution is approximately flat. This large difference between the several simulation scenarios makes $\Delta\phi^{(+)}$ a promising observable to search for double-parton-scattering.

4 Conclusions

We have studied a possible approach to identifying double-parton scatters in proton-proton interactions. Studies are performed on a final state composed of one photon and three jets, along the lines of a previous study by the CDF collaboration [2]. Different predictions from HERWIG and

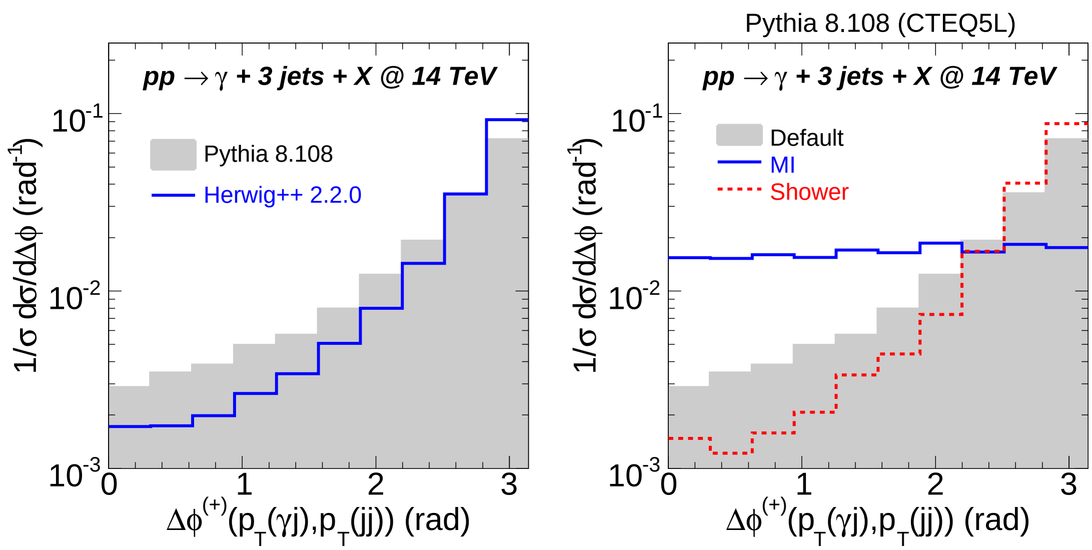

Fig. 3: Differential cross section shape as a function of $\Delta\phi^{(+)}$ (Eq. 2). Predictions from PYTHIA (*Default* scenario) and HERWIG (left panel) and from three different PYTHIA settings (right panel) shown. Note the logarithmic scale.

PYTHIA can in part be attributed to different default choices of parton densities in both programs. However, in some observables, both models yield clearly different differential predictions, most notably with respect to the $\Delta\phi^{(+)}$ variable put forward by CDF. It should be noted, however, that the imposed selection cuts were only a first approximation to an extrapolation to the LHC. More studies will be needed to find the optimal selection cuts and to assess their experimental feasibility. The one-dimensional variables under study try to describe correlations in four-object final states. This is likely to be a too simplistic approach and higher-dimensional observables might perform better to extract a double-parton-scattering signal at the LHC.

In addition, this analysis is one of the first to use the new event generators HERWIG++ and PYTHIA 8 that will become standard in the near future. Further tests are foreseen, in particular of the underlying event predictions of both models.

Acknowledgments

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