Chapter 4

Jet Substructure as a Tool to Study Double Parton Scatterings in V + Jets Processes at the LHC

Ramandeep Kumar, Monika Bansal, and Sunil Bansal

Abstract Double parton scatterings (DPS) provide vital information on the parton–parton correlations and parton distributions in a hadron. It also constitute as a background to new physics searches. Measurement of DPS in Vector Boson (V) + jets processes is important because of clean experimental signature and large production cross-section. The available DPS measurements, with V + jets, are dominated by large contamination from V (W or Z) + jets processes produced with single parton scatterings (SPS). In this document, the importance of jet sub-structure in controlling SPS backgrounds for Z + jets DPS processes is discussed.

4.1 Introduction

Two or more than two parton–parton interactions in a single proton–proton (pp) collision are termed as multiple parton interactions (MPI) [1]. The probability of MPI increases with increase in collision energy at the Large Hadron Collider (LHC). MPI may produce particles with small transverse momenta as well as particles with large transverse momenta. Double parton scattering (DPS), a subset of MPI, includes the production of particles with large transverse momenta from at-least two parton–parton interactions. The study of DPS is important to understand parton–parton correlations and parton distributions in a hadron [2]. DPS processes can also contribute as background in the new physics searches [3, 4] as well. The experimental measurements of the DPS processes are usually contaminated by the particles from single

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R. Kumar (✉)
Akal University Talwandi Sabo, Punjab 151302, India
e-mail: raman_phy@auts.ac.in; kumardeepraman@gmail.com

M. Bansal
DAV College, Sector 10, Chandigarh 160011, India
e-mail: 83.monu@gmail.com

S. Bansal
UIET, Panjab University, Chandigarh 160014, India
e-mail: sbansal@pu.ac.in

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parton scatterings (SPS). Usually, the correlation observables are used to disentangle the DPS processes from the SPS ones as in the existing measurements [5, 6]. The jet multiplicity distribution provides other opportunity to enhance the DPS signal contribution [7]. The presented studies [8] demonstrate that the fragmentation properties of a jet can be used to suppress the SPS backgrounds.

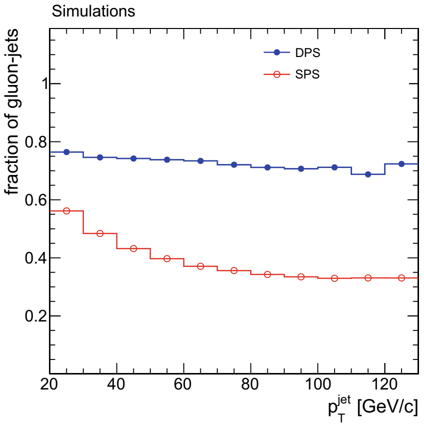
This study is performed using Z + jets events which are simulated using MADGRAPH [9] and POWHEG [10, 11]. PYTHIA8 [12] is used for the parton showering and hadronization of these events. To investigate effect of hadronization models, events are also simulated using hadronization and parton showering with HERWIG++. The DPS production of Z + 2-jets events is simulated using PYTHIA8, where one parton–parton scattering produces a Z-boson and the second one produces two jets. The following selection criteria, motivated from experimental constraints, is imposed on the simulated events:

- Two muons with transverse momenta larger than 20 GeV/c and absolute pseudo-rapidity less than 2.5.
- The dimuon invariant mass is required to be in range of 60−120 GeV/c^2.
- Two jets with minimum transverse momenta of 20 GeV/c and $|\eta| < 2.5$, which are clustered using anti-k_T algorithm with the radius parameter equal to 0.5.

The dijet production from DPS is dominated by the gluon-initiated jets and most of the jets produced via SPS are supposed to be initiated by quarks as depicted in Fig. 4.1. The jets are identified as initiated by quarks or gluons using jet-parton matching in $\eta \times \phi$ space. It can be seen that the contribution of gluon-initiated jets is $\approx$75% and $\approx$ 45% in DPS and SPS processes, respectively. Therefore, the contribution of DPS events can be increased by identifying the flavor of a jet and choosing the events with gluon-initiated jets only.

The fragmentation properties of the quark-initiated jets are different from the gluon-initiated jets [13–15]. The intrinsic properties of jets may be used to construct

Fig. 4.1 The fraction of gluon-initiated jets as a function of the jet p_{T} in the simulated DPS (blue solid circle markers) and SPS (red hollow circle markers) events



a number of different observables. A certain number of observables, as listed below, are used to construct the quark–gluon discriminator:

- major axis (σ_1^{jet})
- minor axis (σ_2^{jet})
- jet constituents multiplicity (N_p^{jet})
- jet fragmentation function ($p_{\text{T}}^{\text{jet}} D$)

The details of these observables can be found in [15]. Figure 4.2 shows the distributions of these observables for gluon- and quark-initiated jets using the events

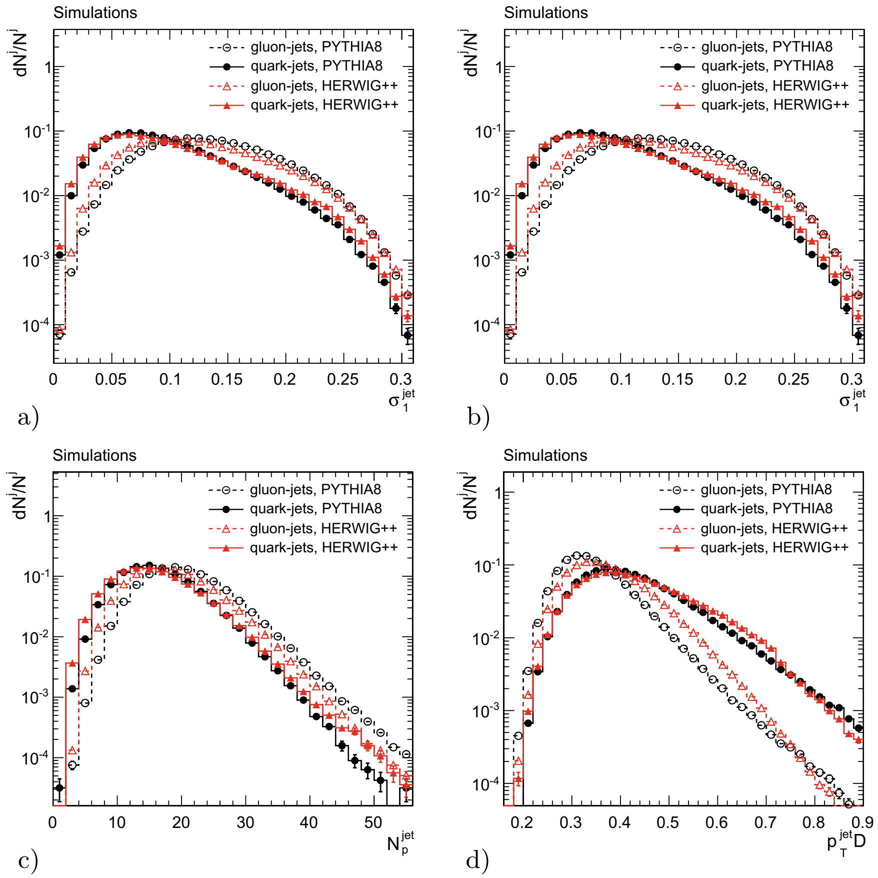


Fig. 4.2 The distributions of discriminating variables: **a** major axis size of jet cone (σ_1^{jet}), **b** minor axis size of jet cone (σ_2^{jet}), **c** jet constituents multiplicity (N_p^{jet}), and (d) jet fragmentation function ($p_{\text{T}}^{\text{jet}} D$) are compared for gluon-initiated jets (hollow markers) and quark-initiated jets (solid markers) events hadronized and parton showered with PYTHIA8 (black colored markers) and HERWIG++ (with red colored markers)

simulated by PYTHIA8 and HERWIG++. As evident from the distributions, jets are broader when initiated by gluons and constitute more number of particles. In addition, jets initiated by quarks constitute harder particles. Therefore, these observables may be used for a clear distinction between two types of jets. A multivariate analysis approach is followed for effective use of these observables along with the optimized cut-based analysis approach.

4.2 Results

It has been observed that in the selected Z + 2-jets events, the contribution from DPS processes is about 0.075. A simple cut-based analysis, implementing cuts summarized in Table 4.1 for observables based on the jet fragmentation properties, results in a gain of 41% in the DPS fraction.

The alternate approach for optimized use of the discriminating observables is based on the multivariate analysis, which is based on boosted decision trees (BDT) implemented in the TMVA framework [16]. A clear distinction is observed between two types of jets as depicted by the distribution of BDT discriminant shown in Fig. 4.3. A jet is considered to be initiated by gluon if the value of BDT is more than -0.105, otherwise it is considered to be initiated by quark. By selecting the Z + 2-jets events with two jets initiated by gluons, it has been observed that DPS fraction increases to 0.113, which is 51% larger if no jet fragmentation properties are used. A significant gain is observed with use of multivariate analysis approach as compared to cut-based analysis approach.

The effect of different hadronization model is also studied by considering the events hadronized with HERWIG++. The use of HERWIG++ also provides a gain of 43% with DPS fraction equal to 0.107. In addition, the effectiveness of the method is also tested by using event simulated by POWHEG. The gain in the DPS fraction, by using POWHEG, reduces to 36%, which arises due to different treatment at leading order and next-to-leading order for two models. It can be concluded from these studies that fragmentation properties of jets can be used to suppress the SPS background and hence DPS fraction may be enhanced.

Table 4.1 Conditions on observables for selection of gluon-initiated jets in cut-based analysis

Observable	condition
σ_1^{jet}	>0.04
σ_2^{jet}	>0.02
N_p^{jet}	>12.0
$p_{\text{T}}^{\text{jet}} D$	<0.49

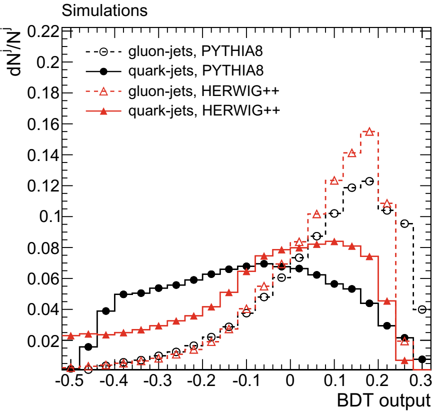


Fig. 4.3 BDT output for gluon-initiated (hollow markers) jets and quark-initiated jets (solid markers) in case of dijet events produced with PYTHIA8 (black colored markers) and HERWIG++ (red colored markers)

4.3 Summary

This report presents the possibility to explore the jet fragmentation properties for suppression of SPS events using Z + jets events. MADGRAPH and POWHEG Monte Carlo event generators are used to simulate Z + jets events, which are hadronized and parton showered using PYTHIA8. Four different observables are used to discriminate the jets initiated by gluons from those initiated by quarks. By considering the events with jets initiated by gluons, a gain of 40–50% in the DPS fraction is achieved. The presented study may play an important role for DPS studies under actual environmental conditions.

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