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Characteristics and Estimates of Double Parton Scattering at the Large Hadron Collider

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I discuss signature kinematic variables and characteristic concentrations in phase space that allow the double-parton contribution to $pp \to b\ \bar{b}$ jet jet X at Large Hadron Collider energies to be distinguished from the usual single parton scattering contribution. A methodology is suggested to measure the size of the double-parton cross section.

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1. Introduction

Double parton scattering (DPS) means that two short-distance subprocesses occur in a given hadronic interaction, with two initial partons being active from each of the incident protons in a collision at the Large Hadron Collider (LHC). The concept is shown for illustrative purposes in Fig. 1, and it may be contrasted with conventional single parton scattering (SPS) in which one short-distance subprocess occurs, with one parton active from each initial hadron. Investigations of double parton scattering have a long history theoretically, with many references to prior work listed in [1], and there is some evidence in data [2]. A greater role for double-parton processes may be expected at the LHC where higher luminosities are anticipated along with the higher collision energies. A large contribution from double parton scattering could result in a larger than otherwise anticipated rate for multi-jet production and produce relevant backgrounds in searches for signals of new phenomena. The high energy of the LHC also provides an increased dynamic range of available phase space for detailed investigations of DPS.

Of substantial importance is to know empirically how large the double parton contribution may be and its dependence on relevant kinematic variables. Our aims in Ref. [1] are to address whether double parton scattering can be shown to exist as a discernible contribution in well defined and accessible final states, and to establish the characteristics features that allow its measurement. We show that double parton scattering produces an enhancement of events in regions of phase space in which the "background" from single parton scattering is relatively small. If such enhancements are observed experimentally, with the kinematic dependence we predict, then we will have a direct empirical means to measure the size of the double parton contribution. In addition to its role in general LHC phenomenology, this measurement will have an impact on the development of partonic models of hadrons, since the effective cross section for double parton scattering measures the size in impact parameter space of the incident hadron's partonic hard core.

From the perspective of sensible rates and experimental tagging, a good process to examine should be the 4 parton final state in which there are 2 hadronic jets plus a b quark and a $\bar{b}$ antiquark, *viz.* $b\ \bar{b}\ j_1\ j_2$. If the final state arises from double parton scattering, then it is plausible that one subprocess produces the $b\ \bar{b}$ system and another subprocess produces the two jets. There are, of course, many single parton scattering (2 to 4 parton) subprocesses that can result in the $b\ \bar{b}\ j_1\ j_2$ final state, and we identify kinematic distributions that show notable separations of the two contributions.

The state-of-the-art of calculations of single parton scattering is well developed whereas the phenomenology of double parton scattering is less advanced. For $pp \to b\bar{b} j_1 j_2 X$, assuming that the two subprocesses $A(i\ j \to b\ \bar{b})$ and $B(k\ l \to j_1\ j_2)$ in Fig. 1 are dynamically uncorrelated, and that kinematic and dynamic correlations between the two partons from each hadron may be safely neglected, we employ the common heuristic expression for the DPS differential cross section

$$d\sigma^{DPS}(pp \to b\bar{b} j_1 j_2 X) = \frac{d\sigma^{SPS}(pp \to b\bar{b}X)\, d\sigma^{SPS}(pp \to j_1 j_2 X)}{\sigma_{\rm eff}}. \tag{1.1}$$

The numerator is a product of single parton scattering cross sections. In the denominator, there is a factor $\sigma_{\rm eff}$ with the dimensions of a cross section. Given that one hard-scatter has taken place, $\sigma_{\rm eff}$ measures the size of the partonic core in which the flux of accompanying short-distance partons

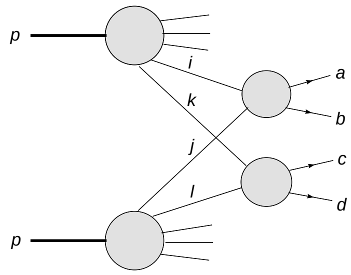

Figure 1: Sketch of a double-parton process in which the active partons are i and k from one proton and j and l from the second proton. The two hard scattering subprocess are $A(i\ j \to a\ b)$ and $B(k\ l \to c\ d)$.

is confined. Collider data [2] yield values in the range $\sigma_{\text{eff}} \sim 12$ mb. We use this value for the estimates we make, but we emphasize that the goal should be determine its value at LHC energies.

In Ref. [1], we present the details of our calculation of the double parton and the single parton contributions to $p\ p \to b\ \bar{b}\ j_1\ j_2\ X$. We perform full event simulations at the parton level and apply a series of cuts to emulate experimental analyses. We also treat the double parton and the single parton contributions to 4 jet production, again finding that good separation is possible despite the combinatorial uncertainty in the pairing of jets.

2. Distinguishing variables

Correlations in the final state are predicted to be quite different between the double parton and the single parton contributions. For example, we examine the distribution of events as function of the angle Φ between the planes defined by the $b\bar{b}$ system and by the jj system. If the two scattering processes $ij \to b\bar{b}$ and $kl \to jj$ which produce the DPS final state are truly independent, one would expect to see a flat distribution in the angle Φ. By contrast, many diagrams, including some with non-trivial spin correlations, contribute to the 2 parton to 4 parton final state in SPS, and one would expect some correlation between the two planes such as we observe.

Another interesting difference between DPS and SPS is the behavior of event rates as a function of the transverse momentum of the leading jet. SPS produces a relatively hard spectrum, and for the value of σ_{eff} and the cuts that we use, SPS tends to dominate over the full range of transverse momentum considered. On the other hand, DPS produces a much softer spectrum which (up to issues of normalization in the form of σ_{eff}) can dominate at small values of transverse momentum. The cross-over between the two contributions to the total event rate is ~ 30 GeV for the acceptance cuts we employ. A smaller (larger) value of σ_{eff} would move the cross-over to a larger (smaller) value of the transverse momentum of the leading jet.

Since the topology of the DPS events includes two $2 \to 2$ hard scattering events, the two pairs of jet objects are roughly back-to-back. We expect the azimuthal angle between the pairs of jets corresponding to each hard scattering event to be strongly peaked near $\Delta\phi_{jj} \sim \Delta\phi_{bb} \sim \pi$. The separation of DPS events from SPS events is more pronounced if information is used from both the $b\bar{b}$ and jj systems. We consider the distribution built from a combination of the azimuthal angle separations of both jj and $b\bar{b}$ pairs, using a variable adopted from Ref. [2]:

$$S_\phi = \frac{1}{\sqrt{2}}\sqrt{\Delta\phi(b_1,b_2)^2 + \Delta\phi(j_1,j_2)^2}. \tag{2.1}$$

We find that the SPS events are broadly distributed across the allowed range of S_ϕ. The DPS events produce a sharp and substantial peak near $S_\phi \simeq \pi$ which is well-separated from the total sample.

Another possibility for discerning DPS is the use of the total transverse momentum of both the $b\bar{b}$ and jj systems. At lowest order for a $2 \to 2$ process, the vector sum of the transverse momenta of the final state pair vanishes. To encapsulate this expectation for both light jet pairs and b-tagged pairs, we use the variable [2]:

$$S'_{p_T} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{|p_T(b_1,b_2)|}{|p_T(b_1)|+|p_T(b_2)|}\right)^2 + \left(\frac{|p_T(j_1,j_2)|}{|p_T(j_1)|+|p_T(j_2)|}\right)^2}. \tag{2.2}$$

Here $p_T(b_1,b_2)$ is the vector sum of the transverse momenta of the two final state b jets, and $p_T(j_1,j_2)$ is the vector sum of the transverse momenta of the two (non b) jets. The DPS events are peaked near $S'_{p_T} \sim 0$ and are well-separated from the total sample. The SPS events, on the other hand, tend to be far from a back-to-back configuration and, in fact, are peaked near $S'_{p_T} \sim 1$. This behavior of the SPS events is presumably related to the fact that a large number of the $b\bar{b}$ or jj pairs arise from gluon splitting which yields a large p_T imbalance and, thus, larger values of S'_{p_T}.

Our simulations suggest that the variable S'_{p_T} may be a more effective discriminator than S_ϕ. However, given the leading order nature of our calculations and the absence of smearing associated with initial state soft radiation, this picture may change and a variable such as S_ϕ (or some other variable) may become a clearer signal of DPS at the LHC. Realistically, it would be valuable to study both distributions once LHC data are available in order to determine which is more instructive.

The evidence in one-dimensional distributions for distinct regions of DPS dominance prompts the search for greater discrimination in a plane represented by a two dimensional distribution of one variable against another. One scatter plot with interesting features is displayed in Fig. 2. The DPS events are seen to be clustered near $S'_{p_T} = 0$ and are uniformly distributed in Φ. The SPS events peak toward $S'_{p_T} = 1$ and show a roughly $\sin\Phi$ character. While already evident in one-dimensional distributions, these two features are more apparent in the scatter plot Fig. 2. Moreover, the scatter plot shows a valley of relatively low density between $S'_{p_T} \sim 0.1$ and ~ 0.4. In an experimental one-dimensional Φ distribution, one would see the sum of the DPS and SPS contributions. If structure is seen in data similar to that shown in the scatter plot Fig. 2, one could make a cut at $S'_{p_T} < 0.1$ or 0.2 and verify whether the experimental distribution in Φ is flat as expected for DPS events.

3. Strategy and Further Work

The clear separation of DPS from SPS events in Fig. 2 suggests a methodology for the study of DPS. One can begin with a clean process such as $pp \to b\bar{b}j_1j_2X$ and examine the distribution of events in the plane defined by S'_{p_T} and Φ. We expect to see a concentration of events near $S'_{p_T} = 0$ that are uniformly distributed in Φ. These are the DPS events. Assuming that a valley of low density is observed between $S'_{p_T} \sim 0.1$ and ~ 0.4, one can make a cut there that produces an

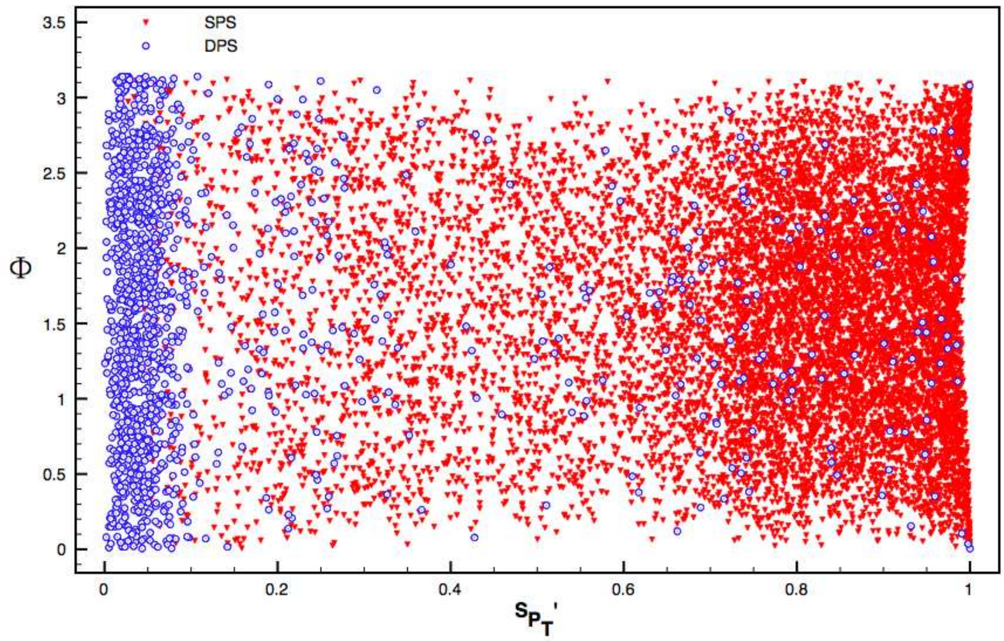

Figure 2: Two-dimensional distribution of events in the inter-plane angle Φ and the scaled transverse momentum variable S'_{p_T} for the DPS and SPS samples.

enhanced DPS sample. Relative to the overall sample, this enhanced sample should show a more rapid decrease of the cross section as a function of the transverse momentum of the leading jet, and the enhanced sample can be used to measure σ_{eff}. A similar examination of other final states, such as 4 jet production, will answer whether the extracted values of σ_{eff} are roughly the same. Theoretical and experimental studies of other processes can follow, such as $b\bar{b}t\bar{t}$, Wjj, and Hjj.

On the phenomenological front, next-to-leading order (NLO) expressions should be included for both the SPS and DPS contributions. The NLO effects are expected to change normalizations and, more importantly, the distributions in phase space. Finally, it would be good to examine the theoretical underpinnings of Eq. (1.1) and, in the process, gain better insight into the significance of σ_{eff}.

References

[1] E. L. Berger, C. B. Jackson and G. Shaughnessy, Phys. Rev. D **81**, 014014 (2010) [arXiv:0911.5348 [hep-ph]] and references therein.

[2] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **81**, 052012 (2010) [arXiv:0912.5104 [hep-ex]] and earlier experimental references cited therein.