Monte Carlo simulation of color singlet exchange between jets

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1. Introduction

Rapidity gaps between jets are an ideal configuration for searching for new-physics signatures [1]. They also provide a clean environment for testing the dynamics of perturbative QCD in Regge limit [2]. The large rapidity difference between the jets together with the transverse momentum of the two back-to-back pointing jets ensure that the center of mass energy of the hard process is much greater than its typical hard scale. In literature, alternative calculations have been proposed for such processes including the approximation of the n-gluon exchange by a BFKL pomeron [2,3] and soft color recombination (evaporation) [4,5]. Both models predict different dependences of the rapidity gap event fraction on the width of the rapidity gap and on the jet transverse momentum.

In this paper we shall calculate the experimentally observable cross section for color singlet exchange between jets using a detailed Monte Carlo simulation of both parton-parton interactions producing rapidity gaps and non-perturbative processes giving rise to the "underlying event". We use the model PHOJET [6,7] which treats perturbative QCD effects such as hard parton-parton scattering and parton showers as well as non-perturbative effects like soft hadronic interactions. This model is based on the Dual Parton Model [8] in its two-component version [9].

2. Implementation of color evaporation model

To describe events with color singlet exchange between jets within the PHOJET Monte Carlo, we implement a soft color reconnection (SCR) model [4,5,10]. The simplest hard q–q event, where SCR leads to a rapidity gap between two jets is an event with just one single hard valence–quark – valence–quark scattering. In normal events in the Dual Parton Model we get two color strings each being stretched between one scattered quark and the diquark of the other hadron. Large rapidity gaps are exponentially suppressed in such events. However, SCR can cause a color transfer due to the exchange of soft gluons resulting in a color configuration where the strings connect the hard scattered quark and the diquark of the same hadron. These are events with might lead to hadronic final states with a large rapidity gap between two jets. In PHOJET, we use the following probabilities of color singlet exchange $F_{qq} : F_{qg} : F_{gg} = 1/9 : 1/24 : 1/64$ [4].

In most of the hard scattering events we have a non-negligible contribution from the underlying event, mainly resulting from spectator interactions. Thus, even if a rapidity gap appears in one of the partonic collisions, the gap might be filled by hadrons produced in another parton-parton interaction. Furthermore, hard parton radiation (initial and final state radiation) can change the size of rapidity gaps considerably. Both effects are simulated in our Monte Carlo calculation which includes QCD parton showers and multiple soft and hard interactions as implemented in PHOJET. This means that the probability for the gap survival [1] is calculated in detail.

3. Comparison to data

Both the D0 and CDF collaborations have published data on dijet production with rapidity gaps [11–17]. In the following we will concentrate on the D0 data [14]. Further comparisons of our calculations with data can be found in [18–20].

D0 [14] uses at $\sqrt{s} = 1800$ GeV two different triggers. With the high $E_\perp$ trigger (we refer to this in short as D0–h) they find opposite side ($\eta^{\mathrm{jet1}} \times \eta^{\mathrm{jet2}} < 0$) dijets with $E_\perp^{\mathrm{jet-2}} > 30$ GeV and $|\eta^{\mathrm{jet}}| > 2$. The pseudorapidity gap is at $|\eta| < 1.3$. With this the fraction of JgJ events is found to be $R_{\mathrm{JgJ-D0-h}} = (\mathrm{JgJ})/(\mathrm{JJ}) = (0.94 \pm 0.04(stat) \pm 0.12(syst))$.

With the low $E_\perp$ trigger (we refer to this in short as D0–l) they find at $\sqrt{s} = 1800$ GeV opposite side ($\eta^{\mathrm{jet1}} \times \eta^{\mathrm{jet2}} < 0$) dijets with $E_\perp^{\mathrm{jet-2}} > 12$ GeV and $|\eta^{\mathrm{jet}}| > 2$. The pseudorapidity gap is at $|\eta| < 1.3$. With this the fraction of JgJ events is found to be $R_{\mathrm{JgJ-D0-l}} = (\mathrm{JgJ})/(\mathrm{JJ}) = (0.54 \pm 0.06(stat) \pm 0.16(syst))$. In PHOJET we find with the D0 triggers $R_{\mathrm{JgJ-PHOJET-D0-h}} = 1.06\%$, $R_{\mathrm{JgJ-PHOJET-D0-l}} = 0.45\%$. Here the background JgJ events with only an accidental gap were subtracted. These PHOJET results are fully consistent

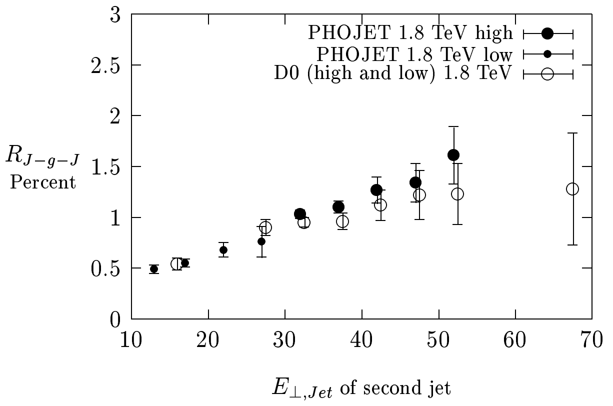

Figure 1. The change of $R_{\rm JgJ}$ with the $E_\perp^{\rm jet2}$ of he next to leading jet. Data from the D0 Collaboration are compared to the PHOJET results obtained with SCR.

with the experimental data. The same is found comparing to the 630 GeV data and to the CDF data. The change of $R_{\rm JgJ}$ with the $E_\perp^{\rm jet2}$ of the second leading jet was studied by the D0 Collaboration [14]. A modest rise of the color singlet fraction with $E_\perp^{\rm jet2}$ was found. In Fig. 1 we compare the PHOJET results on $R_{\rm JgJ}$ with these data. The PHOJET predictions exhibit a $E_\perp^{\rm jet2}$ dependence being compatible with the data. The D0 Collaboration [14] also studied for the D0–h and D0–l triggers the dependence of $R_{\rm JgJ}$ on $\Delta\eta = |\eta^{\rm jet1} - \eta^{\rm jet2}|$. For both triggers a slight rise of $R_{\rm JgJ}$ with $\Delta\eta$ was found which is well described by the PHOJET simulations (not shown here). It is important to notice that our calculation does not only describe the rise of $R_{\rm JgJ}$ with $E_\perp^{\rm jet2}$ and $\Delta\eta$, but also reproduces the absolute sizes of $R_{\rm JgJ}$ without free parameters.

We also compared the pseudorapidity distributions of charged hadrons of events passing the D0–h and D0–l triggers with and without gap. The remarkable feature of this comparison is, that the opposite side jet trigger without the gap requirement selects events with much higher rapidity distribution (particle multiplicity) than typically found in minimum bias events. We interpret this in the following way. With the jet trigger events are selected with an exceptional large number of soft and hard multiple interactions and parton emissions.

4. Rapidity gap survival probability

The rapidity gap survival probability $\langle|S|^2\rangle$ was originally defined by Bjorken [1]. In a series of recent papers, Gotsman, Levin and Maor [21–23] use a eikonal model to calculate the energy dependence of $\langle|S|^2\rangle$. For example, they obtain in $p\bar{p}$ collisions at 630 (1800) GeV values of 16.3% (5.6 %) [22]. The eikonal model used in PHOJET is a two-channel model which differs certainly from the one used by Gotsman et al., but the gap survival probability as contained in the PHOJET Monte Carlo events is calculated in a rather analogous way. We can use the JgJ events and JJ events obtained from PHOJET for given trigger conditions to give the gap survival probability according to PHOJET.

In the PHOJET Monte Carlo we can subdivide the hard scattering events into g–g, g–q and q–q scatterings. We calculate (not shown here) for the D0–h and D0–l triggers the fractions or weights W^i_{JJ} for i = g–g, g–q and q–q events for JJ events (without gap trigger), W^i_{JgJ} for JgJ events obtained with SCR and W^i_{JgJbg} for background JgJ events (obtained without SCR). We find, that q–q scattering dominates the JgJ events, but g–q and g–g scattering contributes also.

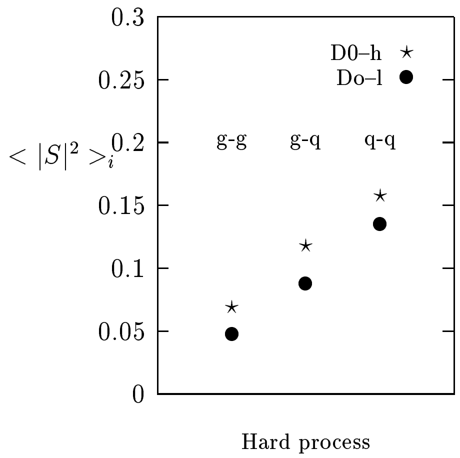

Figure 2. The gap survival probabilities $\langle|S|^2\rangle_i$ according to PHOJET given separately for i = g–g, g–q and q–q events and for the D0–h and D0–l triggers.

Starting from the JJ and JgJ weights W^i_{JJ} and W^i_{JgJ} (i = g–g, g–q and q–q) and the SCR probabilities F_i we work out the gap survival probabilities according to PHOJET. We obtain the gap survival probabilities as follows

$$\langle|S|^2\rangle_i = \frac{W^i_{JgJ}}{W^i_{JJ}F_i}. \qquad (1)$$

$W^i_{JJ}F_i$ is the probability to have two jets corresponding to the given trigger without gaps and furthermore a gap between the two jets due to SCR. Most of the gaps are filled by soft or hard multiple interactions and or parton showering, therefore W^i_{JgJ} is considerably smaller than $W^i_{JJ}F_i$. In Fig. 2 we plot for the D0–h and D0–l triggers at $\sqrt{s} = 1800$ GeV the $\langle|S|^2\rangle_i$ obtained. We find values larger than but roughly consistent to the calculation by Gotsman et al. [22]. However, in contrast to the assumptions used in [1,22], we find a slight dependence of the gap survival probability on the trigger conditions resulting in a smaller $\langle|S|^2\rangle_i$ for the D0–l trigger. Furthermore, we find $\langle|S|^2\rangle_i$ to depend on the hard scattering process with $\langle|S|^2\rangle_{q-q}$ larger than $\langle|S|^2\rangle_{g-g}$ and $\langle|S|^2\rangle_{g-q}$.

5. Concluding remarks

The processes implemented in PHOJET allow us to study hard and soft diffraction in many channels. Here we have been able to demonstrate, that the PHOJET model supplemented with the soft color recombination mechanism describes remarkably well the data from the TEVATRON on color singlet exchange between jets. Besides of finding a good agreement with the D0 and CDF data we are able in addition to study many features of the model, which would be useful to verify in the experiments.

We hope that the PHOJET tool and more TEVATRON data in Run II on color singlet exchange and on hard and soft single diffraction and central diffraction could help to answer important questions: (i) Is soft color recombination the correct mechanism to describe color singlet exchange processes between jets? Could this mechanism be responsible for other features of diffractive processes as well? (ii) Can hard diffraction consistently be described by pomeron structure functions? What is the best pomeron structure function?

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