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Jet production in pp collisions: Dependence on jet algorithm

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Summary. — We report on a recent calculation of single-inclusive high-p_T jet production in unpolarized and longitudinally polarized pp collisions at RHIC, investigating the effect of the algorithm adopted to define the jets on the numerical results for cross sections and spin asymmetries.

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1. – Introduction

Jets are important tools in QCD for investigating the partonic substructure of hadrons and interactions among partons. There is no unique way to define a jet. It is thus important to compare and contrast the different available algorithms. The jet algorithms can be divided into two broad classes;

i) successive combination [1]: in this scheme, one defines a distance between a pair of objects and a beam distance for every object as follows:

$$d_{ij} = \min(k_{t,i}^{2p}, k_{t,j}^{2p}) \frac{R_{ij}^2}{R^2}, \quad d_{iB} = k_{t,i}^{2p}. \tag{1}$$

d_{ij} is called the distance between two particles i and j and d_{iB} is the distance between the beam and the particle; $k_{t,i}$ is the transverse momentum of the i-th particle with respect to the beam direction and

$$R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2. \tag{2}$$

At each step, the smallest of all distances is determined. If it is a beam distance, the object is called a jet and is removed from the event; otherwise the two objects j, k are combined into a single one. Examples of successive combination algorithms are the k_t algorithm [2], where $p = 1$, and the anti-k_t algorithm [3] for which $p = -1$.

ii) Cone algorithms: in these algorithms the jet is defined in terms of stable cones as circles of fixed radius in the η-ϕ plane, such that the sum of the 4-momenta of the particles in it points in the direction of the center of the cone. One defines the jet by all particles j that satisfy [4]

$$R_{jJ}^2 \equiv (\eta_J - \eta_j)^2 + (\phi_J - \phi_j)^2 \leq R^2, \tag{3}$$

where η_J and ϕ_J are the pseudo-rapidity and azimuthal angle of the jet, respectively. Higher order QCD corrections are important as the dependence on the factorization and renormalization scales is expected to be reduced when the corrections are included. In the case of jet production, higher order corrections are particularly important, as only at NLO the QCD structure of the jet starts to play a role in the theoretical description of the process. In fact, some of the popular cone algorithms are known to be collinear and infra-red unsafe at NNLO or when multiple jets are considered.

Single inclusive large p_T jets in longitudinally polarized pp collisions at RHIC are important tools to gain access to the polarized gluon distribution in the nucleon. The cross section for single inclusive jet production at RHIC has been calculated at NLO using a Monte-Carlo technique [5] in the cone algorithm. However a largely analytic technique was developed in [6] in the limit when the cone opening is relatively small (small cone approximation). This is advantageous because it leads to much faster and more efficient computer codes as the singularities in the intermediate steps cancel analytically and one does not have to treat them through delicate numerical techniques. The basis of such an analytic calculation is the observation that the inclusive jet production proceeds through the same partonic subprocesses as single inclusive hadron production and it is possible to convert an NLO cross section for single inclusive hadron production to the one for jet production. The main difference between the two cases is the fact that in single inclusive hadron production, one integrates over the full phase space of the unobserved partons. This leads to collinear singularities, which are absorbed in the parton to hadron fragmentation functions. In contrast, for a jet, final-state particles that move in roughly the same direction will jointly produce the jet. This makes the cross section more inclusive, and (for a proper jet definition) final state singularities must cancel. The cross section for single inclusive hadron production can however be transformed into that for single inclusive jet production [6]. In the limit of small cone size, this transformation can even be performed analytically.

We have recently extended the above analytic technique to the more widely used successive combination schemes (for example, k_t or anti-k_t), assuming again that the jet parameter R used to define the distance between two objects in this algorithm is not too large [7]. When systematically expanded around $R = 0$, the dependence of the partonic cross sections on R is of the form $\mathcal{A} \log R + \mathcal{B} + \mathcal{O}(R^2)$. The coefficients $\mathcal{A}$ and $\mathcal{B}$ are calculated analytically, and the remaining terms $\mathcal{O}(R^2)$ and beyond are neglected. We refer to this approximation as "Narrow Jet Approximation" (NJA). The NJA gives a very accurate description of the single inclusive jet cross sections at RHIC, Tevatron and even at the LHC [7]. It turned out that the cross sections for single inclusive jet production in the cone and the successive recombination algorithms differ by calculable finite terms. We have also given numerical estimates of the cross section both for unpolarized and longitudinally polarized collisions at RHIC, and examined the effect of the choice of jet algorithm on the double longitudinal spin asymmetry. Here we give a brief report of [7].

2. – Cross section for single inclusive jet production in pp collisions

We consider single-inclusive jet production in hadronic collisions, $pp \to \text{jet}\, X$, where the jet has a transverse momentum p_{T_J}, rapidity η_J, and azimuthal angle ϕ_J. Note that on top of the choice of jet algorithm one also has to define how objects are to be merged to form the jet. We choose to define the four-momentum of the jet as the sum of four-momenta of the partons that form the jet for both algorithms ("E recombination scheme" [4]).

In order to calculate the single-inclusive jet cross section at NLO, we start from the NLO single-parton inclusive cross sections $\mathrm{d}\hat{\sigma}_{ab\to cX}$, relevant for single-inclusive hadron production process $pp \to hX$ and analytically known. For a jet cross section, the observed final state should not be given by parton c only, but by partons c and d jointly, when the two are close to each other (as two partons together can form the jet). In order to calculate this one first considers a "jet cone" characterized by a jet parameter R around the observed parton c and notices that in the NLO single-parton inclusive cross section there is a configuration where an additional parton d is inside the cone (we use the term "cone" for simplicity, the considerations apply to any jet definition). One subtracts these contributions and replaces them by terms for which partons c and d are both inside the cone and form the observed jet together. For a given partonic process $ab \to cde$ we then have,

$$
\begin{aligned}
\mathrm{d}\hat{\sigma}_{ab\to \mathrm{jet}X} = {} & [\mathrm{d}\hat{\sigma}_c - \mathrm{d}\hat{\sigma}_{c(d)} - \mathrm{d}\hat{\sigma}_{c(e)}] \\
& + [\mathrm{d}\hat{\sigma}_d - \mathrm{d}\hat{\sigma}_{d(c)} - \mathrm{d}\hat{\sigma}_{d(e)}] \\
& + [\mathrm{d}\hat{\sigma}_e - \mathrm{d}\hat{\sigma}_{e(c)} - \mathrm{d}\hat{\sigma}_{e(d)}] \\
& + \mathrm{d}\hat{\sigma}_{cd} + \mathrm{d}\hat{\sigma}_{ce} + \mathrm{d}\hat{\sigma}_{de}.
\end{aligned} \tag{4}
$$

Here $\mathrm{d}\hat{\sigma}_j$ is the single-parton inclusive cross section where parton j is observed (which also includes the virtual corrections), $\mathrm{d}\hat{\sigma}_{j(k)}$ is the cross section where parton j is observed but parton k is also in the cone, and $\mathrm{d}\hat{\sigma}_{jk}$ is the cross section when both partons j and k are inside the cone and jointly form the jet. One has to note that the single-parton inclusive cross section contains a subtraction of final-state collinear singularities in the modified minimal subtraction ($\overline{\mathrm{MS}}$) scheme. One has to perform an $\overline{\mathrm{MS}}$ subtraction also of the singularities in the $\mathrm{d}\hat{\sigma}_{j(k)} + \mathrm{d}\hat{\sigma}_{k(j)} - \mathrm{d}\hat{\sigma}_{jk}$.

The difference between the cone and k_t type algorithms resides entirely in the $\mathrm{d}\hat{\sigma}_{jk}$, which can be calculated analytically in the NJA. The reason for this difference is as follows: for the k_t-type algorithms the two partons j, k are merged into one jet if their distance defined in (1) is smaller than their respective beam distances d_{iB} and d_{jB} defined in (1). For $\mathrm{d}\hat{\sigma}_{jk}$ this has to hold, and we arrive at the condition

$$R_{jk}^2 \le R^2 \quad \text{for } k_t\text{-type algorithms,} \tag{5}$$

with R_{jk} defined in eq. (2). This condition is true for *all* k_t-type algorithms. Whereas in cone algorithm, eq. (3) is valid:

$$R_{jJ}^2 \le R^2 \ \wedge \ R_{kJ}^2 \le R^2 \quad \text{for cone algorithm.} \tag{6}$$

We find that the difference in the cross sections calculated for the two algorithms is finite, as it must be.

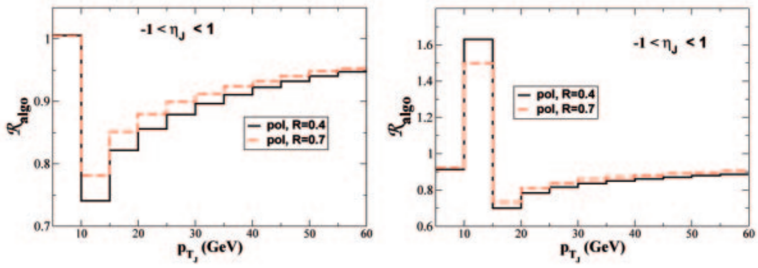

Fig. 1. – The ratio $\mathcal{R}_{\rm algo}$ at RHIC for $\sqrt{S} = 200\,{\rm GeV}$ (left) and $\sqrt{S} = 500\,{\rm GeV}$ (right), for the spin-dependent case. Results are shown for two different values of the jet parameter R. We have chosen the factorization and renormalization scales as $\mu_F = \mu_R = p_{T_J}$.

3. – Numerical results

Next, we present some numerical results for single-inclusive jet production cross sections and spin asymmetries in pp collisions at RHIC. We use the CTEQ6.6M parton distributions [8] for the unpolarized cross section and the "DSSV" helicity parton distributions of ref. [9] for the polarized case. We define the ratio

$$\mathcal{R}_{\rm algo} \equiv \frac{\left[{\rm d}^2(\Delta)\sigma/{\rm d}p_{T_J}{\rm d}\eta_J\right]_{k_t\text{-type}}}{\left[{\rm d}^2(\Delta)\sigma/{\rm d}p_{T_J}{\rm d}\eta_J\right]_{\rm cone}}\,, \tag{7}$$

where the jet parameter R is the same for both cross sections.

Figure 1 shows the ratio $\mathcal{R}_{\rm algo}$ for polarized collisions at RHIC, calculated for the factorization and renormalization scales as $\mu_F = \mu_R = p_{T_J}$, as a function of p_{T_J} in bins of p_{T_J}, for $R = 0.4$ and 0.7. We present results for two values of c.m.s. energies at RHIC, $\sqrt{S} = 200\,{\rm GeV}$ (left) and $\sqrt{S} = 500\,{\rm GeV}$ (right). $\mathcal{R}_{\rm algo}$ is around 90% at high p_{T_J}, but deviates largely from one in the bin around $p_{T_J} = 12.5\,{\rm GeV}$. The reason for this is that for the DSSV set of parton distributions the polarized jet cross section changes sign around $p_{T_J} = 10\,{\rm GeV}$. Depending on the jet algorithm, the zero is at a slightly different value of p_T. This shows that in regions where the polarized cross section is very small it is very sensitive to the choice of jet algorithm.

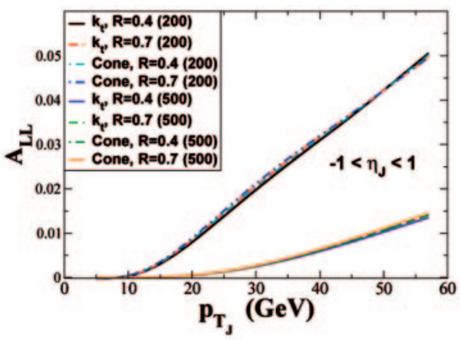

Fig. 2. – Double-longitudinal spin asymmetries A_{LL} at RHIC, for $\sqrt{S} = 200\,{\rm GeV}$ and $\sqrt{S} = 500\,{\rm GeV}$ and various jet definitions. We have averaged over $|\eta_J| \le 1$. The factorization and renormalization scales have been chosen to be $\mu_F = \mu_R = p_{T_J}$.

The double longitudinal spin asymmetries A_{LL} at RHIC are defined by

$$A_{LL} \equiv \frac{\mathrm{d}^2\Delta\sigma/\mathrm{d}p_{T_J}\mathrm{d}\eta_J}{\mathrm{d}^2\sigma/\mathrm{d}p_{T_J}\mathrm{d}\eta_J}\,. \tag{8}$$

For the denominator we use the spin-averaged cross sections and for the numerator the polarized ones. The results are shown in fig. 2. As one can see, the asymmetries are quite insensitive to the jet algorithm chosen, and also to the value of the jet parameter R for all values of p_{T_J} where the asymmetry is sizable. Our results are useful for the analysis of the data on the double longitudinal spin asymmetry in single inclusive jet production by the STAR Collaboration at RHIC [10].

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