# FOUR-JET PRODUCTION WITH HIGH-ENERGY FACTORIZATION PLUS PARTON SHOWERS*

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We report on the preliminary results of the ongoing update of our study of 4-jet production at the LHC in High-energy Factorization (HEF), which is being supplemented by parton showers. We focus on a specific angular variable introduced in two papers by the CMS Collaboration on 4-jet production with and without two $b$-tagged jets. The variable is, by construction, sensitive to contributions from Multi Parton Interactions (MPIs), specifically hard Double Parton Scattering (DPS). We preliminarily find that, adding parton showers to the single parton scattering channel, the evidence for the need for MPIs is compatible with the one reported by the CMS Collaboration after a comparison of the data with simulations based on collinear Monte Carlo event generators.

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## 1. Introduction

Using gauge-invariant scattering amplitudes with initial state off-shell particles, we elaborate on our previous studies of 4-jet production and Double Parton Scattering effects [1, 2], adding on top of them CCFM parton showers [3].

The problem of efficiently computing gauge invariant tree level scattering amplitudes in High-energy Factorization (HEF) [4] has been analytically and numerically completely solved in recent years [5–11].

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## 2. Outline of previous results in High-energy Factorization without parton showers

The HEF formula for 4-jet production is

$$\begin{aligned}\sigma^{B}_{4-\mathrm{jets}} &= \sum_{i,j} \int \frac{\mathrm{d}x_1}{x_1}\frac{\mathrm{d}x_2}{x_2}\,\mathrm{d}^2k_{\mathrm{T}1}\mathrm{d}^2k_{\mathrm{T}2}\,\mathcal{F}_i\left(x_1,k_{\mathrm{T}1},\mu_{\mathrm{F}}\right)\,\mathcal{F}_j\left(x_2,k_{\mathrm{T}2},\mu_{\mathrm{F}}\right)\\ &\quad\times\frac{1}{2\hat{s}}\prod_{l=1}^{4}\frac{\mathrm{d}^3k_l}{(2\pi)^3 2E_l}\Theta_{4-\mathrm{jet}}(2\pi)^4\delta\left(x_1P_1+x_2P_2+\vec{k}_{\mathrm{T}1}+\vec{k}_{\mathrm{T}2}-\sum_{l=1}^{4}k_l\right)\\ &\quad\times\overline{\left|\mathcal{M}\left(i^*,j^*\to 4\,\mathrm{part.}\right)\right|^2}\,. \end{aligned} \tag{1}$$

Here, $\mathcal{F}_i(x_k,k_{\mathrm{T}k},\mu_{\mathrm{F}})$ is a transverse-momentum-dependent (TMD) parton distribution function for a given type of parton; $x_k$ are the longitudinal momentum fractions and $\mu_{\mathrm{F}}$ is a factorization scale. The new degree of freedom introduced w.r.t. collinear factorization is the transverse momenutm $k_{\mathrm{T}k}$, which is perpendicular to the collision axis. The formula is valid when the $x$s are not too large and not too small (in the latter case, non-linear effects due to saturation and other high-multiplicity phenomena could come into play) and, in order to construct a full set of TMD parton densities, we apply the Kimber–Martin–Ryskin–Watt prescription [12, 13] to the CT10nlo collinear PDF set and employ the running $\alpha_{\mathrm{s}}$ coming with it; both the renormalization and factorization scales are set equal to half the transverse energy, *i.e.* the sum of the final state transverse momenta, $\mu_{\mathrm{F}}=\mu_{\mathrm{R}}=\frac{\hat{H}_{\mathrm{T}}}{2}=\frac{1}{2}\sum_{l=1}^{4}k^l_{\mathrm{T}}$, working in the $n_{\mathrm{F}}=5$ flavour scheme.

On the side of the hard process, $\mathcal{M}(i^*,j^*\to 4\,\mathrm{part.})$ is the gauge invariant matrix element for $2\to 4$ particle scattering with two initial off-shell legs. For the purpose of the present investigation, we rely on the numerical Dyson–Schwinger recursion in the KaTie library [14] for its computation.

The Single Parton Scattering (SPS) channel clearly dominates for final states with very high transverse momenta, because it is highly unlikely that two partons from one proton and two from the other one are energetic enough for two hard scatterings to take place, as the well-known behaviour of the PDFs for large momentum fractions suggests. For lower cuts on the final state transverse momenta, a window opens to observe a significant contribution from a higher-twist effect, double parton scattering; it consists of the simultaneous occurrence of two hard scatterings, each initiated by two partons coming from the first and the second colliding proton respectively. It was analysed in detail, in the context of HEF and for this final state, in our previous works [1, 2].

The standard *pocket formula* used for the computation of DPS cross sections for a four-parton final state is simply

$$\frac{\mathrm{d}\sigma^B_{4-\mathrm{jet,DPS}}}{\mathrm{d}\xi_1 \mathrm{d}\xi_2} = \frac{m}{\sigma_{\mathrm{eff}}} \sum_{i_1,j_1,k_1,l_1;i_2,j_2,k_2,l_2} \frac{\mathrm{d}\sigma^B(i_1 j_1 \to k_1 l_1)}{\mathrm{d}\xi_1} \frac{\mathrm{d}\sigma^B(i_2 j_2 \to k_2 l_2)}{\mathrm{d}\xi_2}\,, \tag{2}$$

where the $\sigma(ab \to cd)$ are standard $2 \to 2$ cross sections, $m$ is a symmetry factor to avoid double counting identical processes, whereas $\xi_1$ and $\xi_2$ are generic kinematical variables. The effective cross section $\sigma_{\mathrm{eff}}$ is a loose parameterization of the correlations in transverse space between two partons in the same proton. We use the widely popular value $\sigma_{\mathrm{eff}} = 15\,\mathrm{mb}$, on which the large majority of the experimental analyses at the Tevatron and at the LHC agree, within experimental errors. On the other hand, correlations in the longitudinal direction are assumed to be negligible, *i.e.*

$$D_{1,2}(x_1, x_2, \mu) = f_1(x_1, \mu)\, f_2(x_2, \mu)\, \theta(1 - x_1 - x_2)\,, \tag{3}$$

where $D_{1,2}(x_1, x_2, \mu)$ is the Double Parton Distribution Function and $f_i(x_i, \mu)$ are the ordinary PDFs and the subscripts 1 and 2 distinguish the two generic partons in the same proton.

The findings of [1, 2] can be summarised as follows:

— We performed the first full-fledged computation of 4-jet production in HEF, finding that the total cross sections are a bit suppressed w.r.t. the collinear framework [1]. We showed that some variables usually pointed at as potential smoking guns for the search for DPS are actually well-described by an SPS-only computation, at least as long as one sticks to the tree level HEF prediction. We elaborate on this below.

— The symmetric cuts imposed in the experimental analysis of [15] are not well-suited to maximize the DPS signal expected from the theory, because dijet production beyond pure LO collinear factorisation is perturbatively unstable for symmetric cuts, due to real radiation effects. The latter are present also in LO HEF. As dijet production enters the calculation of the DPS cross section, one possible solution is to perform searches with asymmetric cuts. We proposed one such set in [1].

— We proposed a set of new variables which could perform well for the search of DPS in the 4-jet channel [2].

## 3. High-energy Factorization plus parton showers in the Single Parton Scattering channel

There are, at present, two CMS analyses of 4-jet production [15, 16]. Ordering the jets in transverse momentum, the cuts used by the first are $p_{\mathrm{T}} > 50$ GeV for the first and second jets, $p_{\mathrm{T}} > 20$ GeV for the third and fourth jets, $|\eta| < 4.7$ for the rapidity and $\Delta R > 0.5$ for the jet cone radius parameter. For the second, the cuts are $p_{\mathrm{T}} > 20$ GeV uniformly for all the 4 jets, $|\eta| < 2.1$ for the $b$-tagged and $|\eta| < 4.7$ for the non-$b$-tagged jets, with $\Delta R > 0.3$.

We will set aside the problem of using an analysis with asymmetric cuts in order to maximize the chances to see the DPS contribution predicted by the theory, discussed at length in [1, 2], and we will rather focus on the description of a variable which is supposed to be a smoking gun for DPS and which, among the three variables first proposed in [15] to this purpose, is the least satisfactorily described by any collinear Monte Carlo. Its geometrical meaning is illustrated in Fig. 1, for clarity: in grey/red are the two hardest jets, in black/blue the two softest ones; the sum of the momenta of the first and second pair is taken and then $\Delta S$ is defined as the angle (light grey/green) between the two

$$\Delta S \equiv \arccos\left(\frac{\vec{p}_{\mathrm{T}}\left(j_1^{\mathrm{hard}}, j_2^{\mathrm{hard}}\right)\cdot\vec{p}_{\mathrm{T}}\left(j_1^{\mathrm{soft}}, j_2^{\mathrm{soft}}\right)}{\left|\vec{p}_{\mathrm{T}}\left(j_1^{\mathrm{hard}}, j_2^{\mathrm{hard}}\right)\right|\cdot\left|\vec{p}_{\mathrm{T}}\left(j_1^{\mathrm{soft}}, j_2^{\mathrm{soft}}\right)\right|}\right). \tag{4}$$

One of the key plots in [1] was Fig. 2. Notice that the data seem to be reasonably well-described by the SPS contribution only, without DPS.

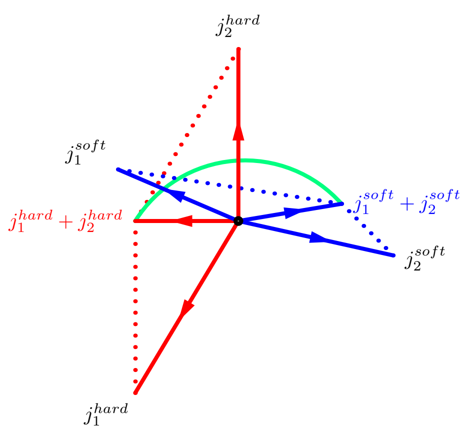


Fig. 1. (Colour on-line) Geometric visualisation of $\Delta S$ for a 4-jet final state.

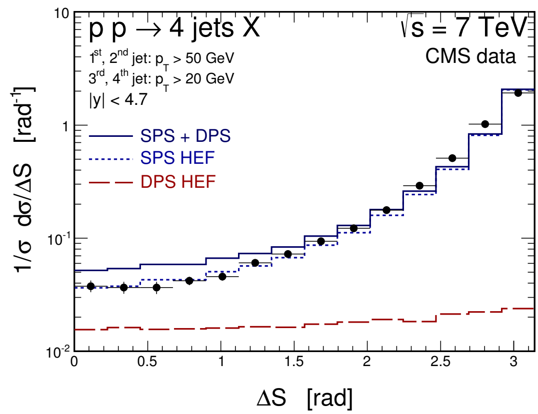


Fig. 2. The prediction for $\Delta S$ with a pure tree level HEF calculation: SPS alone seems to describe data better than after adding DPS.

It is natural to ask what is the best improvement which can be brought into our framework to push it beyond the pure tree level prediction. A natural answer is to add parton showers on top of the matrix-element calculation. In order to suit our $k_{\mathrm{T}}$-dependent framework, it is desirable that such parton showers are designed for a more general evolution than the purely DGLAP [17] one. Without saturation effects and for low values of $x$, anyway too low to be met in our case, the BFKL equation would be suitable [18]. An evolution which is built specifically to interpolate between these two frameworks is the CCFM equation [19], which is available, at the

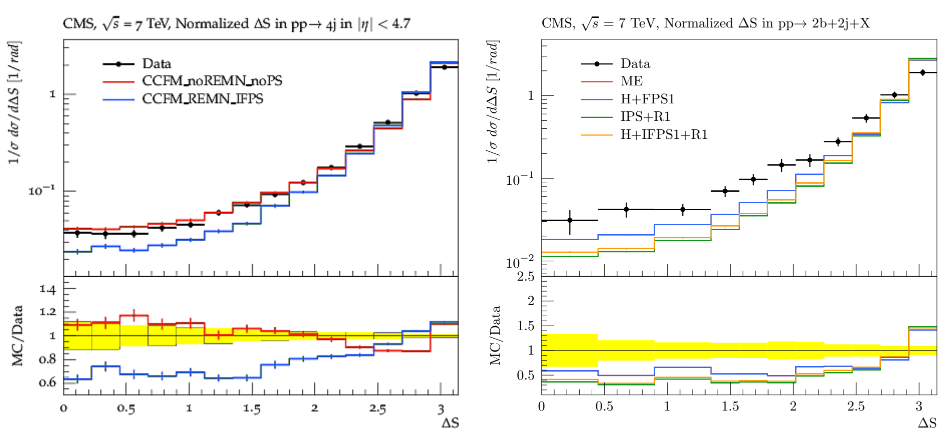


Fig. 3. After applying a CCFM parton shower with full remnant treatment, the pure SPS predictions undershoot considerably the data in the low $\Delta S$ region. The mismatch without DPS seen already for 4 jets is even more apparent when two of them are $b$ tagged.

moment, for the gluon channel, although efforts to extend the framework are in progress [20, 21]. The CCFM evolution is implemented in the CASCADE Monte Carlo program [3], which we match with our parton-level generator in order to preliminary assess the effect of such an evolution. Also, we choose to focus for the moment on the sole SPS contribution, as adding parton showers on top of DPS events is more laborious, due to the potential interplay of the showering from the two scatterings. Our preliminary findings are shown in Fig. 3. We observe that, after the showering and including a full remnant treatment, the SPS prediction is below the experimental data and even more in the case with two $b$-tagged jets. The predictions shown here have been tested for dependence on the underlying collinear PDF sets, employing three more sets and such a dependence was found to be safely negligible. Further study is in progress.

## 4. Conclusions

We provided the first-ever description of 4-jet production in a consistent HEF framework matched to CCFM parton showers. This seems to point to the need of Double Parton Scattering to explain the CMS data on 4-jet production with and without a pair of $b$-tagged jets. This need is apparently more strongly suggested by the comparison to experimental data in the first case.

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