4-jet production: DPS and SPS contributions

Krzysztof Kutak

Based on:
K. Kutak, R. Maciuła, M. Serino, A. Szczurek, A. van Hameren
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Motivation

Double parton scattering is a dominant mechanism of production of charm quarks and antiquarks

Cross section as a function of energy


Maciula, Luszczak, Szczurek '11

How universal is this mechanism? What about 4 jets?
Motivation

Double parton scattering is a dominant mechanism of production of charm quarks and antiquarks

Cross section as a function of rapidity distance between D0s


Maciula, van Hameren, Szczurek '14

How universal is this mechanism? What about 4 jets?
4 jets production: production mechanisms

**Single-parton scattering** (SPS 2 → 4)

Kutak, Maciula, Serino, Szczurek, Hameren, '16

High-Energy-Fact. (HEF) or $k_T$-factorization

first time: high multiplicity of final states with off-shell initial state partons

**Double-parton scattering**

So called factorized ansatz

$k_T$-factorization approach ($2 \rightarrow 2 \otimes 2 \rightarrow 2$)

offers more precise studies of kinematical characteristics and correlation observables
Single-parton scattering production of four jets

The collinear factorization approach

$\sigma^B_{4-jets} = \sum_i \int \frac{d x_1}{x_1} \frac{d x_2}{x_2} x_1 f_i(x_1, \mu_F) x_2 f_j(x_2, \mu_F)$

$x_1 P_1 + x_2 P_2 - \sum_{l=1}^4 k_i$

$\left| M(i, j \rightarrow 4 \text{ part.}) \right|^2$

Partonic center of mass energy squared

Takes into account kinematical cuts applied

Collinear pdfs of parton of $i$-th parton carrying $x_1, x_2$ momentum fraction probed at scale $\mu_F$

Hard matrix element characterizing parton-parton collision with production of 4 partons
Single-parton scattering production of four jets

The High Energy Factorization factorization approach

Formally emissions well separated from hard ME in rapidity

TMD pdf of parton of i-th parton carrying $x_1, x_2$ momentum fraction and transversal momentum $k_{T1}, k_{T2}$ probed at scale $u_F$

\[
\sigma_{4-jets} = \sum_{i,j} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} d^2 k_{T1} d^2 k_{T2} F_i(x_1, k_{T1}, \mu_F) F_j(x_2, k_{T2}, \mu_F)
\]

\[
\times \frac{1}{2^4} \prod_{l=i}^4 \frac{d^3 k_l}{(2\pi)^3 2E_l} \Theta_{4-jet} (2\pi)^4 \delta \left( P - \sum_{l=1}^4 k_i \right) \frac{|M(i^*, j^* \rightarrow 4 \text{ part.})|^2}{2}\]

offshell initial state partons
Off-shell matrix elements

One considers embedding off-shell amplitude in onshell and introduces eikonal lines or Wilson lines

\[ p_A \rightarrow p_{A'} = \left( \begin{array}{c} k_1 \\ k_2 \end{array} \right) + \left( \begin{array}{c} k' \end{array} \right) + \ldots \]

\[ j \quad \rightarrow \quad i = -i \delta_{i,j} u(p_1) \]

\[ j \quad \rightarrow \quad i = -i T_{i,j}^a p_1^\mu \quad \mu, \alpha \]

\[ j \quad \rightarrow \quad i = \delta_{i,j} \frac{i}{p_1 \cdot K} \]

\[ q_A \rightarrow q = q(k_1) + \ldots \]
Off-shell matrix elements

Kotko, Kutak, van Hameren 2013,
Kutak, Salwa, van Hameren 2013

Effective action based approach
Lipatov 95, Lipatov, Vyazovsky 2000

Gauge link based derivation
Kotko'14

Agrees with:

\[ i = \delta_{i,j} \frac{i}{p_1 \cdot K} \]
**Numerical tool for HEF**

**AVHLIB (A. van Hameren)**

https://bitbucket.org/hameren/avhlib

- complete Monte Carlo program for $k_T$ factorized calculations
- any process within the Standard Model
- any initial-state partons on-shell or off-shell
- employs numerical Dyson-Schwinger recursion to calculate helicity amplitudes
- automatic phase space optimization
Contributing partons in single parton scattering process

There are 19 channels contributing to the cross section at the parton level
Combinations of partons in single parton scattering process

There are 19 channels contributing to the cross section at the parton level.

\[

gg \rightarrow 4g, \quad gg \rightarrow q\bar{q} 2g, \quad qg \rightarrow q 3g, \quad q\bar{q} \rightarrow q\bar{q} 2g, \quad qq \rightarrow qq 2g, \quad qq' \rightarrow qq' 2g, \\
gg \rightarrow q\bar{q}q\bar{q}, \quad gg \rightarrow q\bar{q}q'\bar{q}', \quad gg \rightarrow gqq\bar{q}, \quad gg \rightarrow ggq'\bar{q}', \\
q\bar{q} \rightarrow 4g, \quad q\bar{q} \rightarrow q'\bar{q}' 2g, \quad q\bar{q} \rightarrow q\bar{q}q\bar{q}, \quad q\bar{q} \rightarrow q\bar{q}q'\bar{q}', \quad q\bar{q} \rightarrow q'q'q'q', \quad q\bar{q} \rightarrow q'q'q''q'', \\
qq \rightarrow qqq\bar{q}, \quad qq \rightarrow qqq'\bar{q}', \quad qq' \rightarrow qq'q\bar{q}.
\]

The processes in the first line are the dominant channels, contributing together to \(\sim 93\%\) of the total cross section. This stays true in the \(kT\) framework as well.
Factorized ansatz and Double Parton Distributions

\[
\sigma^D_{(A,B)} = \frac{1}{1 + \delta_{AB}} \sum_i \int \Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) \hat{\sigma}^A_{ik}(x_1, x_1') \hat{\sigma}^B_{jl}(x_2, x_2') \times \Gamma_{kl}(x_1', x_2', b; Q_1^2, Q_2^2) dx_1 dx_2 dx_1' dx_2' d^2b
\]

\[
\Gamma_{ij}(b, x_1, x_2; \mu_1^2, \mu_2^2) = f_i(x_1, \mu_1^2) f_j(x_2, \mu_2^2) F(b; x_1, x_2, \mu_1^2, \mu_2^2)
\]

assumption: no x and scale dependence in F

\[
F_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = f_i(x_1, \mu_1^2) f_j(x_2, \mu_2^2) F(b)
\]

Used also in PYTHIA

\[
\sigma^D_{(A,B)} = \frac{1}{1 + \delta_{AB}} \frac{\sigma_A^S \sigma_B^S}{\sigma_{\text{eff}}} \quad \text{Factorization also supported by:}
\]

Golec-Biernat, Lewandowska Serino, Stasto, Snyder' 15

\[
\sigma_{\text{eff}} = \left[ \int d^2(F(b))^2 \right]^{-1}
\]

nonperturbative quantity
measure of correlation
Factorized ansatz and Double Parton Distributions

\[ \sigma_{(A,B)}^D = \frac{1}{1 + \delta_{AB}} \sum_i \int \Gamma_{ij}(x_1, x_2, b; Q_1^2, Q_2^2) \hat{\sigma}_{ik}^A(x_1, x_1') \hat{\sigma}_{jl}^B(x_2, x_2') \times \Gamma_{kl}(x_1', x_2', b; Q_1^2, Q_2^2) dx_1 dx_2 dx_1' dx_2' d^2b \]

\[ \Gamma_{ij}(b, x_1, x_2; \mu_1^2, \mu_2^2) = f_i(x_1, \mu_1^2) f_j(x_2, \mu_2^2) F(b; x_1, x_2, \mu_1^2, \mu_2^2) \]

assumption: no x and scale dependence in F

\[ F_{ij}(b; x_1, x_2, \mu_1^2, \mu_2^2) = f_i(x_1, \mu_1^2) f_j(x_2, \mu_2^2) F(b) \]

Used also in PYTHIA

\[ \sigma_{(A,B)} = \frac{1}{(1 + \delta_{AB})} \frac{\sigma_A^S \sigma_B^S}{\sigma_{\text{eff}}} \]

Factorization also supported by:

Golec-Biernat, Lewandowska Serino, Stasto, Snyder' 15

\[ \sigma_{\text{eff}} = 15 \text{mb} \]

nonperturbative quantity

measure of correlation
Double-parton scattering production of four jets

So finally we have:

$$\sigma^{DPS}(pp \rightarrow 4\text{jets}X) = \frac{C}{\sigma_{\text{eff}}} \cdot \sigma^{SPS}(pp \rightarrow \text{dijet}X_1) \cdot \sigma^{SPS}(pp \rightarrow \text{dijet}X_2)$$

two subprocesses are not correlated and do not interfere

$$i, j, k, l = g, u, d, s, c, \bar{u}, \bar{d}, \bar{s}, \bar{c}.$$  

C combinatorial factor
Combinations of partons in DPS scattering process

We have to include all the possible 45 channels which can be obtained by coupling in all possible distinct ways the 8 channels for the $2 \rightarrow 2$ SPS process, i.e.
Combinations of partons in DPS scattering process

We have to include all the possible 45 channels which can be obtained by coupling in all possible distinct ways the 8 channels for the $2 \to 2$ SPS process, i.e.

<table>
<thead>
<tr>
<th>#</th>
<th>Process</th>
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<tbody>
<tr>
<td>1</td>
<td>$gg \to gg$</td>
</tr>
<tr>
<td>2</td>
<td>$gg \to q\bar{q}$</td>
</tr>
<tr>
<td>3</td>
<td>$qg \to qg$</td>
</tr>
<tr>
<td>4</td>
<td>$q\bar{q} \to q\bar{q}$</td>
</tr>
<tr>
<td>5</td>
<td>$q\bar{q} \to q'\bar{q}'$</td>
</tr>
<tr>
<td>6</td>
<td>$q\bar{q} \to gg$</td>
</tr>
<tr>
<td>7</td>
<td>$qq \to qq$</td>
</tr>
<tr>
<td>8</td>
<td>$qq' \to qq'$</td>
</tr>
</tbody>
</table>

We find that the pairs $(1, 1), (1, 2), (1, 3), (1, 7), (1, 8), (3, 3), (3, 7), (3, 8)$ account for more than 95% of the total cross section for all the sets of cuts considered in this paper.
HEF prediction of the differential cross sections for the transverse momenta of the first two leading jets compared to the ATLAS data. In addition we show the ratio of the SPS HEF result to the ATLAS data.
HEF prediction of the differential cross sections for the transverse momenta of the first two leading jets compared to the ATLAS data. In addition we show the ratio of the SPS HEF result to the ATLAS data.
CMS four-jets: SPS + DPS in the $k_T$-factorization

At 13 TeV and $\Delta Y > 6$ four-jet sample dominated by DPS
DPS effects in four-jet sample: special angular correlation

\[ \Delta \varphi_{3j}^{\text{min}} \equiv \min_{i,j,k \in \{1,2,3,4\}} \left( |\varphi_i - \varphi_j| + |\varphi_j - \varphi_k| \right) \]

A minimum, is obtained in the first case for the three \( i, j, k \) jets in the same half hemisphere, whereas it is not possible for the second configuration. The first one is allowed only by SPS in a collinear framework, whereas the second is enhanced by DPS. In \( k_t \)-factorization approach this situation is smeared out by the presence of transverse momenta of the initial state partons.

Monte Carlo Generators used in ATLAS paper describe data well when the cuts are high enough.

Three out of four azimuthal angles enter. Configurations with one jet recoiling against the other three are characterized by lower values of the variable with respect to the two-against-two configurations.

variable proposed by ATLAS analysis: JHEP 12, 105 (2015)
DPS effects in four-jet sample: special angular correlation

distinguishes events with two-against-two jets (large $\Delta \phi_{3j}$ min) from the recoil of three jets against one jet (small $\Delta \phi_{3j}$ min)

At 13 TeV cross section dominated by DPS

$\Delta \phi_{3j}^{\text{min}} > \frac{\pi}{2}$
Conclusions and outlook

Smaller DPS effects than in D0 production

It is possible to enhance DPS e.g. larger energy larger rapidity separation or study of suitable defined variables

4 jets in p + A → probably more room for DPS

Try A+A → one needs to combine HEF with some framework for modeling medium

NLO, FSR

Update the pdfs