4 jet production in High Energy Factorization

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Work in collaboration with
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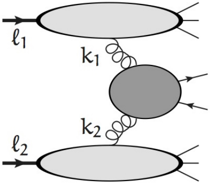
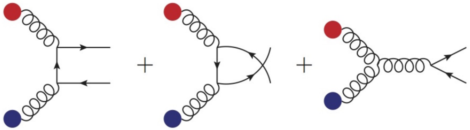
1. The framework: off-shell amplitudes and PDFs
2. Test of HE factorisation for hard central 4-jet production
3. Collinear-factorisation vs. HEF in DPS for central 4-jet production
4. Summary and perspectives
5. Backup

High-Energy-factorisation: original formulation

High-Energy-factorisation *(Catani,Ciafaloni,Hautmann, 1991 / Collins,Ellis, 1991)*





$$\sigma_{h_1,h_2\to q\bar{q}} = \int d^2k_{1\perp}\, d^2k_{2\perp}\, \frac{dx_1}{x_1}\, \frac{dx_2}{x_2}\, \mathcal{F}_g(x_1,k_{1\perp})\, \mathcal{F}_g(x_2,k_{2\perp})\, \hat{\sigma}_{gg}\left(\frac{m^2}{x_1x_2s}, \frac{k_{1\perp}}{m}, \frac{k_{2\perp}}{m}\right)$$

where the $\mathcal{F}_g$'s are the gluon densities, obeying BFKL, BK, CCFM evolution equations.

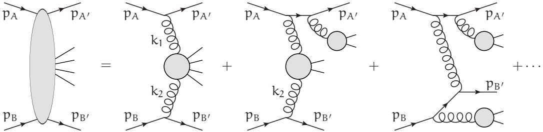
Non negligible transverse momentum is associated to small-x physics.

Momentum parameterisation:

$$k_1^\mu = x_1\, p_1^\mu + k_{1\perp}^\mu \quad , \quad k_2^\mu = x_2\, p_2^\mu + k_{2\perp}^\mu \quad \text{for} \quad p_i \cdot k_i = 0 \quad k_i^2 = -k_{i\perp}^2 \quad i = 1,2$$

Off-shell amplitudes

Problem: general partonic processes must be described by gauge invariant amplitudes
(⇒ See A. van Hameren's Talk)
Off-shell gauge-invariant amplitudes obtained by embedding them into on-shell processes. For off-shell gluons: represent g^* as coming from a $\bar{q}qg$ vertex, with the quarks taken to be on-shell

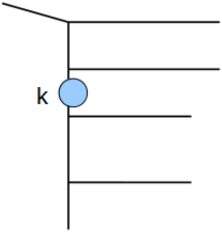


Prescriptions: *K. Kutak, P. Kotko, A. van Hameren, T. Salwa (2013)*

Any legs via recursion relations: *P. Kotko (2014), A. van Hameren (2014)*

Applications:
- production of forward dijets initiated with gluons : $gg^* \to gg$
- production of forward dijets initiated with quarks : $q\bar{q}^* \to gg$
- **Test of TMDs in multi-jet production** : $p\,p \to n$ (**= 4 in this talk**) jets

Our PDFs: the prescription



Survival probability without emissions

Kimber, Martin, Ryskin prescription, '01 :

μ

$$T_s(\mu^2, k^2) = exp\left(- \int_{\mu^2}^{k^2} \frac{dk'^2}{k'^2} \frac{\alpha_s(k'^2)}{2\pi} \times \sum_{a'} \int_0^{1-\Delta} dz' P_{aa'}(z') \right)$$

$$\Delta = \frac{\mu}{\mu + k}, \quad \mu = \text{hard scale}$$

$$\mathcal{F}(x, k^2, \mu^2) \sim \partial_{\lambda^2} \left(T_s(\lambda^2, \mu^2) \, x \, g(x, \lambda^2) \right) \Big|_{\lambda^2 = k^2}$$

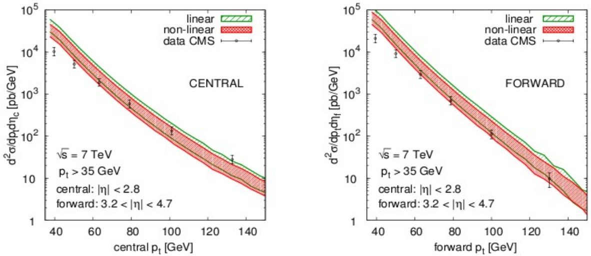
DLC 2016 (Double Log Coherence)
K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren,
JHEP 1604 (2016) 175 (arXiv:1602.06814)
Available on request to krzysztof.kutak@ifj.edu.pl

Example: central-forward dijets production

Hybrid factorization, (Deak, Hautmann, Jung, Kutak, '09):

$$\sigma_{h_1,h_2\to q\bar{q}} = \int d^2k_{1\perp}\, dx_1\, dx_2\, \mathcal{F}(x_1, k_{1\perp}, \mu)\, f(x_2, \mu)\, \hat{\sigma}\ (x_1, x_2, k_{1\perp}, \mu)$$

Kutak, Sapeta, '12:



- Reasonable agreement with data
- No traditional parton showers: the Unintegrated PDF as a parton shower.
- Hybrid factorization formula for dijet production (fully differential) can be derived from Color-Glass-Condensate P. Kotko, K. Kutak, C. Marquet, E. Petreska, A. van Hameren, JHEP 1509 (2015) 106

Conjectured formula for 4 jets production:

Following content based on

K. Kutak, R. Maciula, M. S., A. Szczurek, A. van Hameren, JHEP 1604 (2016) 175
&
K. Kutak, R. Maciula, M. S., A. Szczurek, A. van Hameren, *in preparation*

$$\sigma_{4-jets} = \sum_{i,j} \int \frac{dx_1}{x_1}\frac{dx_2}{x_2} d^2k_{T1} d^2k_{T2}\, \mathcal{F}_i(x_1, k_{T1}, \mu_F)\, \mathcal{F}_j(x_2, k_{T2}, \mu_F)$$
$$\times \frac{1}{2\hat{s}} \prod_{l=i}^{4} \frac{d^3k_l}{(2\pi)^3 2E_l} \Theta_{4-jet}\, (2\pi)^4\, \delta\left(P - \sum_{l=1}^{4} k_i\right) \overline{|\mathcal{M}(i^*, j^* \to 4\,\text{part.})|^2}$$

- Ansatz motivated by $2 \to 2$ case
- PDFs and matrix elements well defined.
- No proof à la Collins-Soper-Sterman around (not yet...)
- Reasonable description of data justifies this formula *a posteriori*

Our framework

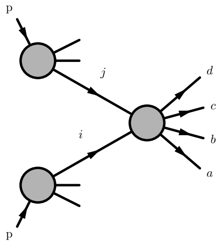
AVHLIB (A. van Hameren) : https://bitbucket.org/hameren/avhlib

- complete Monte Carlo program for tree-level 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

- **Flavour scheme**: $N_f = 5$
- **Running** α_s from the MSTW68cl PDF sets
- **Massless quarks approximation** $E_{cm} = 7/8\,TeV \Rightarrow m_{q/\bar{q}} = 0.$
- **Scale** $\mu_R = \mu_F \equiv \mu = \frac{H_T}{2} \equiv \frac{1}{2} \sum_i p_T^i$, (sum over final state particles)

We don't take into account correlations in DPS: $D(x_1, x_2, \mu) = f(x_1, \mu)\, f(x_2, \mu)$.
There are attempts to go beyond this approximation:
Golec-Biernat, Lewandowska, Snyder, M.S., Stasto, Phys.Lett. B750 (2015) 559-564
Rinaldi, Scopetta, Traini, Vento, JHEP 1412 (2014) 028

4-jet production: Single Parton Scattering (SPS)



We take into account all the (according to our conventions) 20 channels.

Here u and d stand for different quark flavours in the initial (final) state.

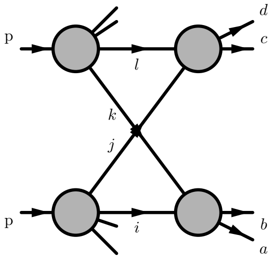
We do not introduce K factors, amplitudes@LO.

$\sim$ 95 % of the total cross section

There are 19 different channels contributing to the cross section at the parton-level:

$$gg \to 4g\,, gg \to q\bar{q}\,2g\,, qg \to q\,3g\,, q\bar{q} \to q\bar{q}\,2g\,, qq \to qq\,2g\,, qq' \to qq'\,2g\,,$$
$$gg \to q\bar{q}q\bar{q}\,, gg \to q\bar{q}q'\bar{q}'\,, qg \to qgq\bar{q}\,, qg \to qgq'\bar{q}'\,,$$
$$q\bar{q} \to 4g\,, q\bar{q} \to q'\bar{q}'\,2g\,, q\bar{q} \to q\bar{q}q\bar{q}\,, q\bar{q} \to q\bar{q}q'\bar{q}'\,, q\bar{q} \to q'\bar{q}'q'\bar{q}'\,,$$
$$q\bar{q} \to q'\bar{q}'q''\bar{q}''\,, qq \to qqq\bar{q}\,, qq \to qqq'\bar{q}'\,, qq' \to qq'q\bar{q}\,,$$

4-jet production: Double parton scattering (DPS)



$$\sigma = \sum_{i,j,a,b;k,l,c,d} \frac{\mathcal{S}}{\sigma_{eff}} \sigma(i,j \to a,b)\, \sigma(k,l \to c,d)$$

$$\mathcal{S} = \begin{cases} 1/2 & \text{if} \quad i\,j = k\,l \quad \text{and} \quad a\,b = c\,d \\ 1 & \text{if} \quad i\,j \neq k\,l \quad \text{or} \quad a\,b \neq c\,d \end{cases}$$

$$\sigma_{eff} = 15\, mb\,,$$

Experimental data may hint at different values of σ_{eff}; main conclusions not affected

In our conventions, 9 channels from $2 \to 2$ SPS events,

$$\begin{aligned} \#1 &= gg \to gg\,, \quad \#6 = u\bar{u} \to d\bar{d} \\ \#2 &= gg \to u\bar{u}\,, \quad \#7 = u\bar{u} \to gg \\ \#3 &= ug \to ug\,, \quad \#8 = uu \to uu \\ \#4 &= gu \to ug\,, \quad \#9 = ud \to ud \\ \#5 &= u\bar{u} \to u\bar{u} \end{aligned}$$

$\Rightarrow$ 45 channels for the DPS; only 14 contribute to $\geq 95\%$ of the cross section :

$$(1,1), (1,2), (1,3), (1,4), (1,8), (1,9), (3,3)$$
$$(3,4), (3,8), (3,9), (4,4), (4,8), (4,9), (9,9)$$

Hard jets

We reproduce all the LO results (only SPS) for $p\,p \to n\,jets\,, \quad n = 2, 3, 4$ published in
BlackHat collaboration, Phys.Rev.Lett. 109 (2012) 042001
S. Badger et al., Phys.Lett. B718 (2013) 965-978

Asymmetric cuts for hard central jets

$$
\begin{aligned}
&p_T \geq 80\,\text{GeV}\,, \quad \text{for leading jet}\\
&p_T \geq 60\,\text{GeV}\,, \quad \text{for non leading jets}\\
&|\eta| \leq 2.8\,, \quad R = 0.4
\end{aligned}
$$

PDFs set: MSTW2008LO@68cl

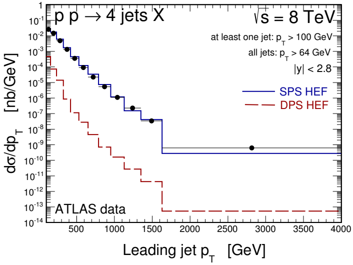
$$
\sigma(\geq 2\,\text{jets}) = 958^{+316}_{-221} \quad \sigma(\geq 3\,\text{jets}) = 93.4^{+50.4}_{-30.3} \quad \sigma(\geq 4\,\text{jets}) = 9.98^{+7.40}_{-3.95}
$$

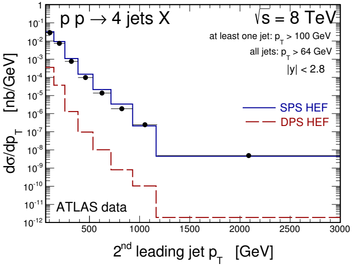
Cuts are too hard to pin down DPS and/or benefit from HEF: 4-jet case

$$
\text{Collinear case} \quad \begin{cases} 9.98^{+7.40}_{-3.95} & SPS \\ 0.094^{+0.06}_{-0.036} & DPS \end{cases} \qquad \text{HEF case} \quad \begin{cases} 10.0^{+6.9}_{-5.3} & SPS \\ 0.05^{+0.054}_{-0.029} & DPS \end{cases}
$$

Differential cross section

Most recent ATLAS paper on 4-jet production in proton-proton collision:
ATLAS, JHEP 1512 (2015) 105





- All channels included and running α_s @ NLO
- Good agreement with data
- DPS effects are manifestly too small for such hard cuts: this could be expected.

DPS effects in collinear and HEF

Inspired by Maciula, Szczurek, Phys.Lett. B749 (2015) 57-62

DPS effects are expected to become significant for lower p_T cuts, like the ones of the CMS collaboration, Phys.Rev. D89 (2014) no.9, 092010

$$p_T(1,2) \geq 50\,\mathrm{GeV}\,, \quad p_T(3,4) \geq 20\,\mathrm{GeV}\,, \quad |\eta| \leq 4.7\,, \quad R = 0.5$$

CMS collaboration : $\sigma_{tot} = 330 \pm 5\,(\mathrm{stat.}) \pm 45\,(\mathrm{syst.})\, nb$

LO collinear factorization : $\sigma_{SPS} = 697\, nb\,, \quad \sigma_{DPS} = \mathbf{125\,nb}\,, \quad \sigma_{tot} = 822\, nb$

LO HEF k_T-factorization : $\sigma_{SPS} = 548\, nb\,, \quad \sigma_{DPS} = \mathbf{33\,nb}\,, \quad \sigma_{tot} = 581\, nb$

In HE factorization DPS gets suppressed and does not dominate at low p_T

Counterintuitive result from well-tested perturbative framework $\Rightarrow$ phase space effect ?

An old problem: higher order corrections to 2-jet production

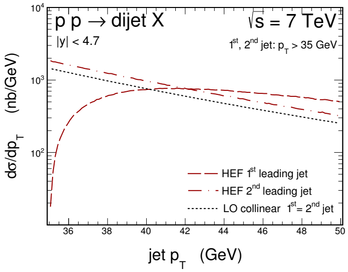


Figure: The transverse momentum distribution of the leading (long dashed line) and subleading (long dashed-dotted line) jet for the dijet production in HEF.

NLO corrections to 2-jet production suffer from instability problem when using symmetric cuts: Frixione, Ridolfi, Nucl.Phys. B507 (1997) 315-333

Symmetric cuts rule out from integration final states in which the momentum imbalance due to the initial state non vanishing transverse momenta gives to one of the jets a lower transverse momentum than the threshold.

ATLAS data vs. theory (nb) @ LHC7 for 2,3,4 jets. Cuts are defined in Eur.Phys.J. C71 (2011) 1763; theoretical predictions from Phys.Rev.Lett. 109 (2012) 042001

#jets	ATLAS	LO	NLO
2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$1193(3)^{+130}_{-135}$
3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$54.5(0.5)^{+2.2}_{-19.9}$
4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$5.54(0.12)^{+0.08}_{-2.44}$

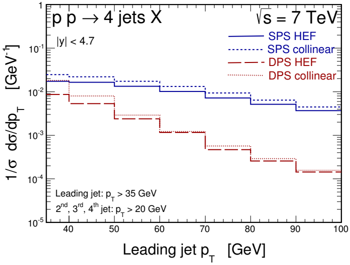
Reconciling HE and collinear factorisation: asymmetric p_T cuts

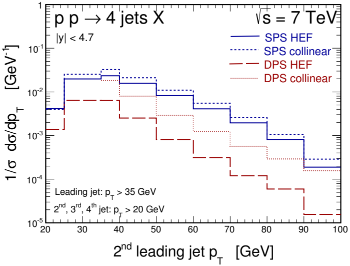
In order to open up wider region of soft final states and thereof expected that the DPS contribution increases

$$p_T(1) \geq 35\text{GeV}\,, \quad p_T(2,3,4) \geq 20\text{ GeV}\,, |\eta| < 4.7\,, \quad \Delta R > 0.5$$

$$\text{LO collinear factorization}: \sigma_{SPS} = 1969\,nb\,, \quad \sigma_{DPS} = 514\,nb\,, \quad \sigma_{tot} = 2309\,nb$$

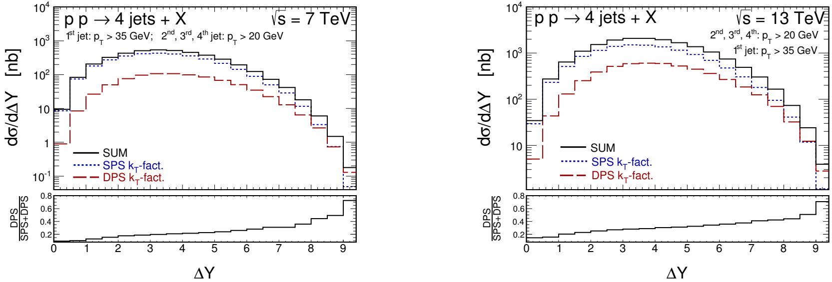
$$\text{LO HEF } k_T\text{-factorization}: \sigma_{SPS} = 1506\,nb\,, \quad \sigma_{DPS} = 297\,nb\,, \quad \sigma_{tot} = 1803\,nb$$





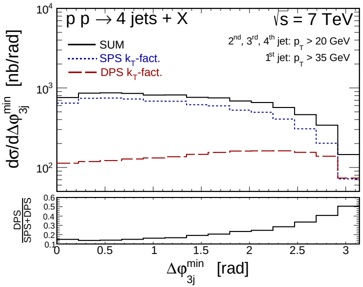
DPS dominance pushed to even lower p_T but restored in HE factorization as well

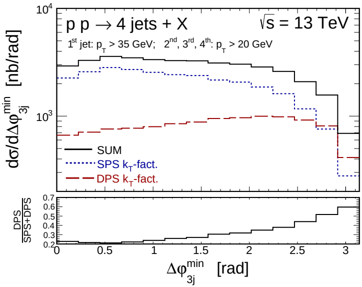
Pinning down double parton scattering: large rapidity separation



- It is interesting to look for kinematic variables which could make DPS apparent.
- The maximum rapidity separation in the four jet sample is one such variable, especially at 13 GeV.
- for $\Delta Y > 6$ the total cross section is dominated by DPS.

Pinning down double parton scattering: "min3" azimuthal separation





- Definition: $\Delta\phi_3^{min} = min_{i,j,k[1,4]}\left(\left|\phi_i - \phi_j\right| + \left|\phi_j - \phi_k\right|\right)\ , \quad i \neq j \neq k$
- Proposed by ATLAS in *JHEP 12 105 (2015)* for high p_T analysis
- High values favour configurations closer to back-to-back, i.e. DPS
- For $\Delta\phi_3^{min} \geq \pi/2$ the total cross section is dominated by DPS

Summary and conclusions

- We have a complete framework for the evaluation of cross sections from amplitudes with off-shell quarks and TMDs via KMR procedure obtained from NLO collinear PDFs
- HE factorisation reproduces well ATLAS data @ 7 and 8 TeV for hard central inclusive 4-jet production. Essential agreement with collinear predictions.
- HE factorisation smears out the DPS contribution to the cross section for less central jet, pushing the DPS-dominance region to lower p_T, but asymmetric cuts are in order: initial state transverse momentum generates asymmetries in the p_T of final state jet pairs.
- It would be interesting to have an experimental analysis with cuts which are *asymmetric* **and** *soft* ($\Rightarrow$ Szymanowski's talk).
- Further insight into HE factorisation prediction will come with progress in NLO results and with the addition of final state paton showers. Work in progress...

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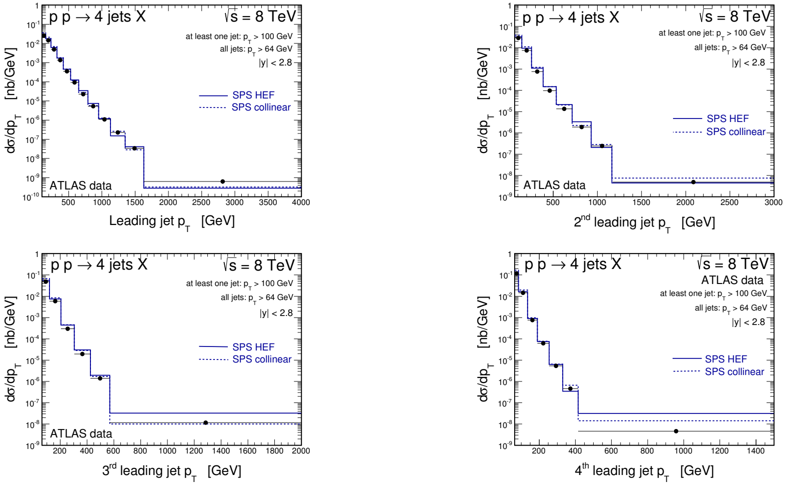
Thank you for your attention !

Comparing collinear factorization and HEF



Collinear factorization performs slightly better for intermediate values and HEF does a better job for the last bins, except for the 4th jet.

One more interesting variable

$$\Delta S = \arccos\left(\frac{\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|}\right), \quad \vec{p}_T(j_i, j_k) = p_{T,i} + p_{T,j}$$

We roughly describe the data via pQCD effects within our HEF approach which are (equally partially) described by parton-showers and soft MPIs by CMS.

For more variables to pin down DPS ⇒ see Maciula's talk

CMS collaboration Phys.Rev. D89 (2014) no.9, 092010