Double parton scattering effects in kt-factorisation for 4 jet production

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Work in collaboration with Krzysztof Kutak and Andreas van Hameren

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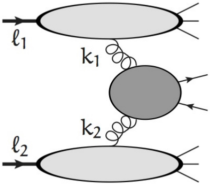
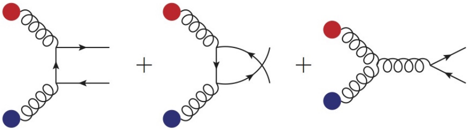
High-Energy-factorisation: original formulation

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





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

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

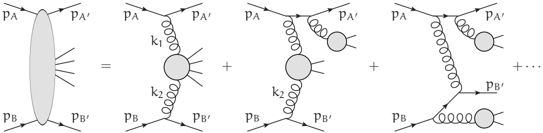
Non negligible transverse momentum is associated to small-x physics.

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
⇒ ordinary Feynman rules are not enough ! (**see 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

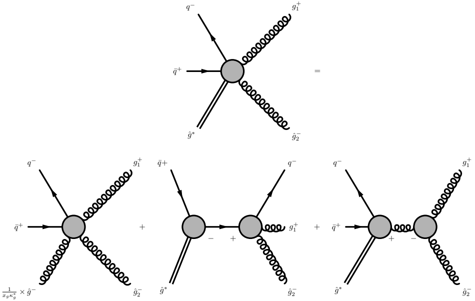


Prescriptions: *K. Kutak, P. Kotko, A. van Hameren, T. Salwa (2013)*

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

$$\text{Applications:}\begin{cases}\text{production of forward dijets initiated with gluons : } gg^* \to gg \\ \text{production of forward dijets initiated with quarks : } q\bar{q}^* \to gg \\ \textbf{Test of TMDs in multi-jet production} : p\,p \to n\,(= \textbf{4 in this talk})\text{ jets}\end{cases} \quad (1)$$

BCFW recursion for any off-shell parton

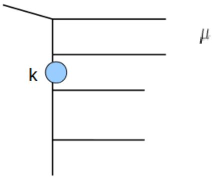


Numerical recursion up to 6-point amplitudes: M. Bury, A. van Hameren (2015),

Algorithm for recursion for any number of legs : A. van Hameren, M.S. (2015)

$$
\begin{aligned}
\mathcal{A}(g^*,\bar{q}^+,q^-,g_1^+,g_2^-) \quad &= \quad \frac{1}{\kappa_g^*}\,\frac{[\bar{q}1]^3\langle 2g\rangle^4}{[\bar{q}q]\langle g|\not{p}_2+\not{k}_g|1]\langle 2|\not{k}_g\;(\not{k}_g+\not{p}_2)\,|g]\langle 2|\not{k}_g|\bar{q}]} \\
&+ \frac{1}{\kappa_g}\,\frac{1}{(k_g+p_{\bar{q}})^2}\,\frac{[g\bar{q}]^2\langle 2q\rangle^3\langle 2|\not{k}_g+\not{p}_{\bar{q}}|g]}{\langle 1q\rangle\langle 12\rangle\,\{(k_g+p_{\bar{q}})^2[\bar{q}g]\langle 2q\rangle-\langle 2|\not{k}_g+\not{p}_{\bar{q}}|g]\langle q|\not{k}_g|\bar{q}]\}} \\
&+ \frac{\langle gq\rangle^3[g1]^4}{\langle\bar{q}q\rangle[12][g2]\langle q|\not{p}_1+\not{p}_2|g]\langle g|\not{p}_1+\not{p}_2|g]\langle g|\not{k}_g+\not{p}_2|1]}
\end{aligned}
$$

Our PDFs: the prescription



Survival probability without emissions

Kimber, Martin, Ryskin prescription, '01 :

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

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

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

K. Kutak, Phys.Rev. D91 (2015) 3, 034021 :

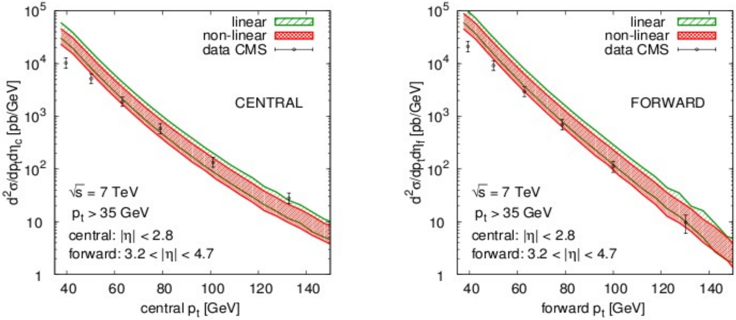
$$\mathcal{F}(x, k^2, \mu^2) = \theta(\mu^2 - k^2)\, T_s(\mu^2, k^2)\, \frac{x\, g(x, \mu^2)}{x\, g_{hs}(x, \mu^2)}\, \mathcal{F}(x, k^2) + \theta(k^2 - \mu^2)\, \mathcal{F}(x, k^2)$$

Example: central-forward dijets production

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

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

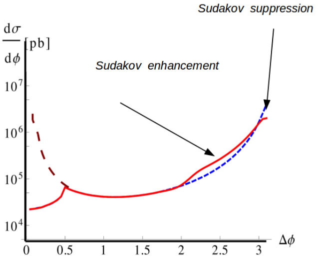
Kutak, Sapeta, '12:



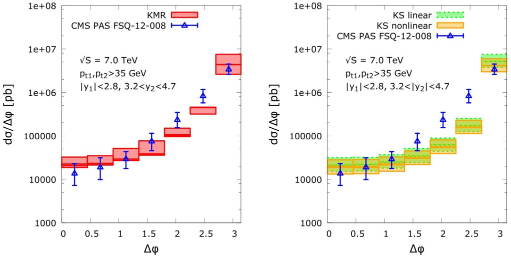
- Reasonable agreement with data
- No traditional parton showers: the Unintegrated PDF as a parton shower.

Azimuthal angle dependence in 2-jet production

Kutak, '15



van Hameren, Kotko, Kutak, Sapeta, '14



- Reasonable agreement with data
- The Sudakov form factor helps reconciling the discrepancy

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: $N_f = 5$ for the collinear case; $N_f = 4$ for HEF
Running α_s from the MSTW68cl PDF sets
kt-dependent PDFs are always @NLO

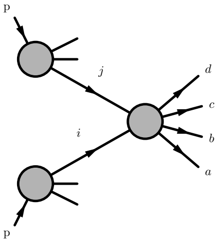
Massless quarks approximation $E_{cm} = 7\,TeV \Rightarrow m_{q/\bar{q}} = 0.$

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: $D(x_1, x_2, \mu) = f(x_1, \mu)\, f(x_2, \mu)$.

Correlations are important to describe data ($\rightarrow$ see Gunnellini's talk)
There are attempts to go beyond ($\rightarrow$ see Golec-Biernat's and Rinaldi's talk)

4-jet production: Single Parton Scattering (SPS)



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

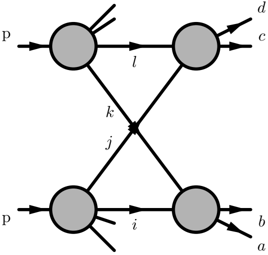
Here u and d stand for different quark flavours in the initial (final) state.

We do not introduce K factors, amplitudes@LO.

$\sim$ 95 % of the total cross section

$$gg \to gggg\,,\ gg \to u\bar{u}gg\,,\ gg \to u\bar{u}u\bar{u}\,,\ gg \to u\bar{u}d\bar{d}\,,\ ug \to uggg\,,$$
$$ug \to ugd\bar{d}\,,\ ug \to u\bar{u}ug\,,\ gu \to uggg\,,\ gu \to ugd\bar{d}\,,\ gu \to u\bar{u}ug\,,$$
$$u\bar{u} \to gggg\,,\ u\bar{u} \to u\bar{u}gg\,,\ u\bar{u} \to ggd\bar{d}\,,\ u\bar{u} \to u\bar{u}u\bar{u}\,,\ u\bar{u} \to u\bar{u}d\bar{d}\,,$$
$$uu \to uugg\,,\ uu \to uuu\bar{u}\,,\ uu \to uud\bar{d}\,,\ ud \to udgg\,,\ ud \to udu\bar{u}$$

4-jet production: Double parton scattering (DPS)



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

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

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

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,

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

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

$$\#1 \otimes \#1, \#1 \otimes \#2, \#1 \otimes \#3, \#1 \otimes \#4, \#1 \otimes \#8, \#1 \otimes \#9, \#3 \otimes \#3$$
$$\#3 \otimes \#4, \#3 \otimes \#8, \#3 \otimes \#9, \#4 \otimes \#4, \#4 \otimes \#8, \#4 \otimes \#9, \#9 \otimes \#9$$

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

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

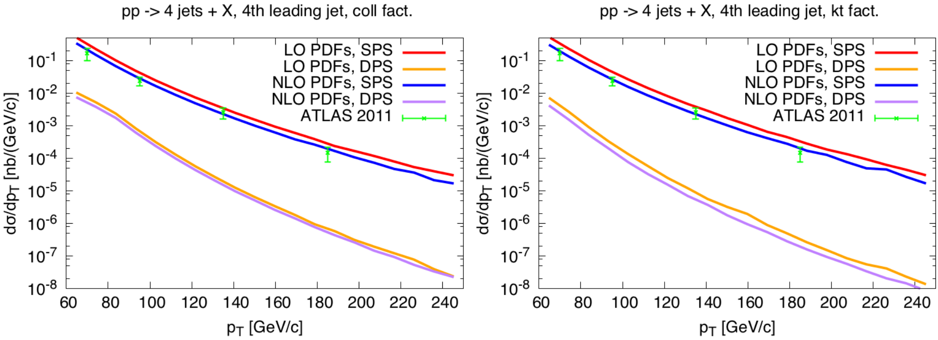
PDFs set: MSTW2008@68cl

$$\sigma^{SPS}_{coll.} = \begin{cases} 9.9^{+7.4}_{-3.9}\text{nb (} \alpha_s\text{@LO)} \\ 6.6^{+4.4}_{-2.4}\text{nb (} \alpha_s\text{@NLO)} \end{cases} \qquad \sigma^{SPS}_{kt} = \begin{cases} 10.0^{+6.9}_{-5.3}\text{nb (} \alpha_s\text{@LO)} \\ 5.8^{+3.7}_{-2.1}\text{nb (} \alpha_s\text{@NLO)} \end{cases}$$

$$\sigma^{DPS}_{coll.} = \begin{cases} 9.4^{+6.0}_{-3.6}\,10^{-2}\text{nb (} \alpha_s\text{@LO)} \\ 6.7^{+3.8}_{-2.3}\,10^{-2}\text{nb (} \alpha_s\text{@NLO)} \end{cases} \qquad \sigma^{DPS}_{kt} = \begin{cases} 5.5^{+5.4}_{-2.9}\,10^{-2}\text{nb (} \alpha_s\text{@LO)} \\ 3.1^{+2.9}_{-1.6}\,10^{-2}\text{nb (} \alpha_s\text{@NLO)} \end{cases}$$

ATLAS, Eur.Phys.J. C71 (2011) 1763 : $\sigma = 4.3^{+1.4}_{-0.79} \pm 0.04 \pm 0.24$

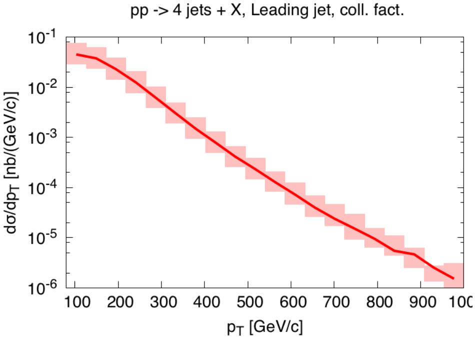
Differential cross section

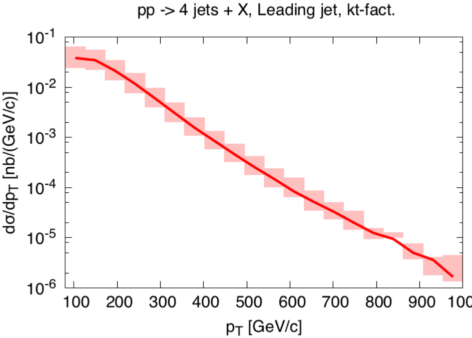


- All 20 channels included
- Good agreement with data
- DPS effects are manifestly too small for these central hard cuts: this could be expected.

Prediction for leading jet spectrum

α_s@NLO; with α_s@LO same shapes obtained





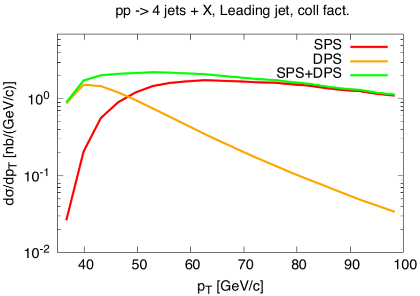
Collinear and kt-factorisation work consistently
DPS negligible for hard cuts, as expected

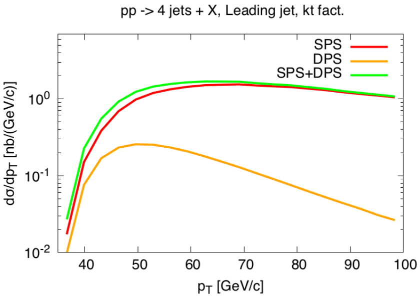
DPS effects in collinear and kt-factorisation

Inspired by Maciula, Szczurek, Phys.Lett. B749 (2015) 57-62
ALPGEN + MSTW2008NLO68cl
We reproduce all of their results modulo Montecarlo integration uncertainty

DPS effects are expected to become significant for lower p_T cuts:

$$35\,\text{GeV} \leq p_T \leq 100\,\text{GeV}\,, \quad |\eta| \leq 4.7\,, \quad R = 0.5$$

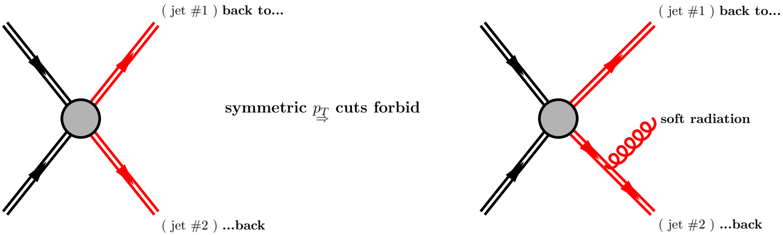




In kt-factorisation DPS is suppressed and does not dominate at low p_T

NLO instability for 2-jet production

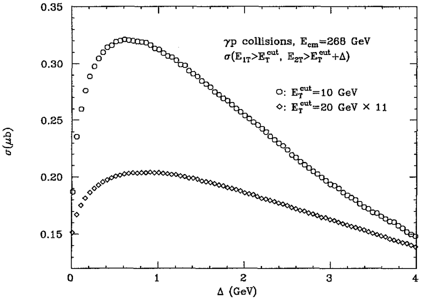
NLO corrections to 2-jet production suffer from instability problem when using symmetric cuts: Frixione, Ridolfi, Nucl.Phys. B507 (1997) 315-333



$2 \to 2$ scattering processes produce final states in back-to-back configuration
$\Rightarrow$ in collinear factorisation there is no room at all for additional gluon emissions.

#Fact.	SPS	DPS
collinear	90.2(0.2)	31.2(0.2)
kt	78.0(0.1)	7.94(0.06)

Total cross sections (nb) for SPS and DPS in collinear vs. kt-factorisation for $35\,GeV < p_T < 100\,GeV, |\eta| < 4.7, R = 0.5$



Symmetric cuts rule out from integration final states in which the momentum imbalance due to the initial state non vanishing transverse momenta gives to 1 of the jets a lower than the threshold (i.e. 35 GeV)

Figure: Inclusive total cross section for 2-jet production at HERA for cuts $E_T^1 > E_T^{cut}, E_T^2 > E_T^{cut} + \Delta$ as a function of Δ

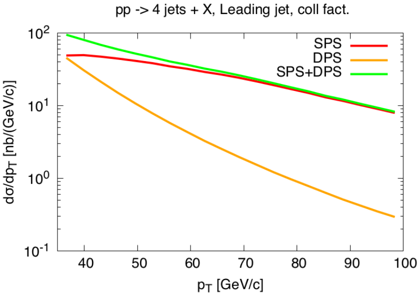
$\#jets$	$ATLAS$	LO	$LO + PS$	NLO
2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$
3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$
4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$3.97(0.08)$	$5.54(0.12)^{+0.08}_{-2.44}$

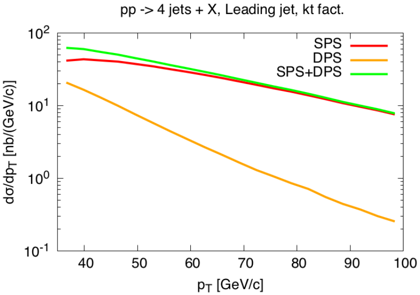
Table: ATLAS data vs. theory (nb) @ LHC7 for 2,3,4 jets. Cuts are defined in Eur.Phys.J. C71 (2011) 1763; theoretical predictions from Phys.Rev.Lett. 109 (2012) 042001

Reconciling kt- and collinear factorisation: asymmetric p_T cuts

$$35\,\text{GeV} \leq p_T \leq 100\,\text{GeV}\,, \quad \text{for leading jet}$$
$$20\,\text{GeV} \leq p_T \leq 100\,\text{GeV} \quad \text{for non leading jets}$$
$$|\eta| \leq 4.7\,, \quad R = 0.5$$

Opens a wider region of soft final states with respect to the previous choice, so it should be expected that the DPS contribution increases





Shapes agree qualitatively; DPS dominance tamed, pushed to lower p_T

Summary and conclusions

- We have a complete framework for the evaluation of cross sections from amplitudes with off-shell quarks and TMD PDFs via KMR procedure obtained from NLO collinear PDFs
- kt-factorisation reproduces well ATLAS data @ 7 TeV for hard central 4-jet inclusive production. Essential agreement with collinear predictions.
- kt-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.
- Further insight into kt-factorisation prediction will come with progress in NLO results. Work on this is already in progress...
- All the details to be published soon !

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Thank you for your attention !