4-jet production with kt-factorization plus parton showers

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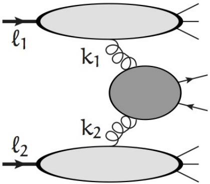
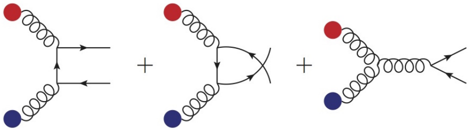
1. 4-jet production in kt-factorization: Single and Double Parton scattering without parton showers
2. 4-jet production in kt-factorization: Single Parton scattering plus parton showers
3. Improving the search for DPS: asymmetric cuts and new variables
4. Summary and perspectives
5. Backup Slides

High-Energy-factorisation

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, and $\hat{\sigma}$ the **gauge invariant** parton cross section (!!!)

Non negligible transverse momentum ⇔ small-x physics.

Momentum parameterisation:

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

Introduction

We had a couple of papers on Double Parton Scattering (DPS) in 4-jet production:
K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren
JHEP 1604 (2016) 175, Phys.Rev. D94 (2016) no.1, 014019

- Approach: pure k_T-factorization approach with fully gauge-invariant tree-level matrix elements: KaTie Monte Carlo by Andreas van Hameren
- Conclusions: the symmetric cuts of the only existing analysis of 4-jet production, Phys.Rev. D89 (2014) no.9, 092010, suppress DPS because of a phase-space effect to be discussed later $\Rightarrow$ recommending asymmetric cuts in a future analysis
- **Idea to move further**: interface KaTie with the CASCADE parton shower Monte Carlo by Hannes Jung and collaborators.

Introducing Double Parton Scattering

For a review of DPS: Diehl, Ostermeier, Schafer, JHEP 1203 (2012) 089
For more formal approach to DPS ⇒ Buffing's talk

DPS ≡ the simultaneous occurrence of two partonic hard scatterings in the same proton-proton collision

$$\sigma^D = \mathcal{S} \sum_{i,j,k,l} \int \Gamma_{ij}(x_1, x_2, b; t_1, t_2)\, \Gamma_{kl}(x_1', x_2', b; t_1, t_2)\, \hat{\sigma}(x_1, x_1')\, \hat{\sigma}(x_2, x_2')\, dx_1 dx_2 dx_1' dx_2' d^2 b$$

Usual assumption: separation of longitudinal and transverse DOFs:

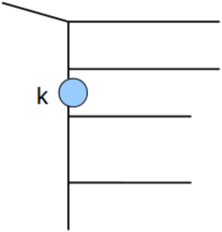
$$\Gamma_{ij}(x_1, x_2, b; t_1, t_2) = D_h^{ij}(x_1, x_2; t_1, t_2)\, F^{ij}(b) = D_h^{ij}(x_1, x_2; t_1, t_2)\, F(b)$$

- Longitudinal correlations, most often ignored or assumed to be negligible, especially at small x : $D_h^{ij}(x_1, x_2; t_1, t_2) = D^i(x_1; t_1)\, D^j(x_2; t_2)$
- Transverse correlation, assumed to be independent of the parton species, taken into account via $\sigma_{eff}^{-1} = \int d^2 b\, F(b)^2 \approx (15 mb)^{-1}$ (CDF and D0)

Usual final kind-of-crafty formula:

$$\sigma^D = \frac{\mathcal{S}}{\sigma_{eff}} \sum_{i_1, j_1, k_1, l_1; i_2, j_2, k_2, l_2} \sigma(i_1 j_1 \to k_1 l_1) \times \sigma(i_2 j_2 \to k_2 l_2)$$

Our PDFs: KMR prescription



Survival probability without emissions

Kimber, Martin, Ryskin prescription, '01 :

μ

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

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

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

DLC 2016 (Double Log Coherence)
K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren, JHEP 1604 (2016) 175

Technical framework

KaTie (A. van Hameren) : https://bitbucket.org/hameren/KaTie, arXiv:1611.00680

- complete Monte Carlo program for tree-level calculations of any process within the Standard Model; any initial-state partons on-shell or off-shell; numerical Dyson-Schwinger recursion to calculate helicity amplitudes
- CASCADE-2.4.07: DGLAP or CCFM initial and final state parton showers (Hannes Jung et al.)

- Only u and d initial state quarks, final states with all the $N_f = 5$ lightest flavours.
- **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
Golec-Biernat, Stasto: arXiv:1611.02033, **WITH k_T dependence**
Rinaldi, Scopetta, Traini, Vento, JHEP 1412 (2014) 028, JHEP 1610 (2016) 063, arXiv:1609.07242

Validation with hard jets: total cross sections

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: MSTW2008LO@68cl

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

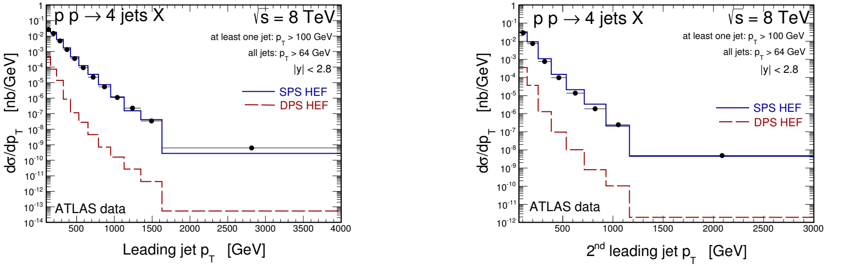
Cuts are too hard to pin down DPS and/or benefit from HEF: 4-jet case

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

Validation with hard jets: differential distribution

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

$$p_T \geq 100\,\text{GeV}\,, \quad \text{for leading jet}$$
$$p_T \geq 64\,\text{GeV}\,, \quad \text{for non leading jets}$$
$$|\eta| \leq 2.8\,, \quad R = 0.4$$



- 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.

Softer cuts: do we really see DPS ?

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

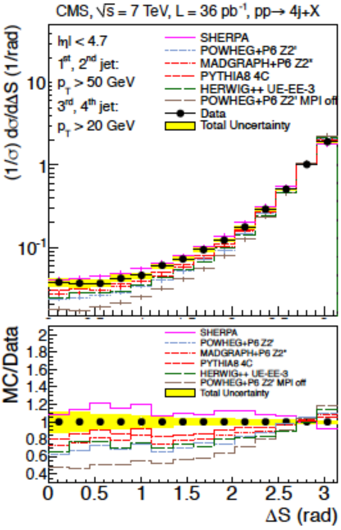
$$p_T(1,2) \geq 50\,\text{GeV}\,, \quad p_T(3,4) \geq 20\,\text{GeV}$$
$$|\eta| \leq 4.7\,, \quad R = 0.5$$

Potential smoking gun for DPS:

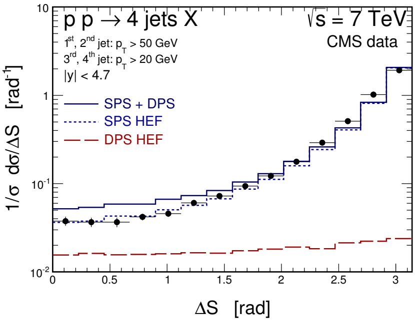
$$\Delta S = \arccos\left(\frac{\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|}\right)$$
$$\vec{p}_T(j_i, j_k) \equiv p_{T,i} + p_{T,j}$$

Angle between the soft and the hard jet pair: expected to be flat for DPS.

No collinear MonteCarlo manages to satisfactoriyl describe the data.
What can k_T factorization say about it ?



ΔS: the only-matrix-element prediction



- 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. K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren, JHEP 1604 (2016) 175
- We seem to overshoot the data when adding DPS
- Natural to ask what happens when we include initial and final state radiation ⇒ we need to match parton-level k_T-factorization with parton showers.

Adding parton showers to k_T factorization

Matching the hard off-shell matrix elements with parton showers:

- Generate the hard matrix element in full High Energy Factorization: KaTie
- Add final state CCFM or DGLAP parton showers: CASCADE
- Perform backward evolution in order to have the transverse momentum in the hard matrix element unfolded to initial state radiation: CASCADE
- Reconstruct jets with anti-k_T algorithm: FastJet

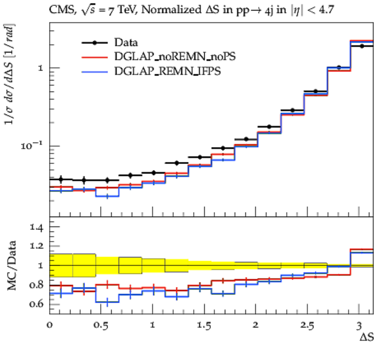
Difference with respect to the collinear generators (MadGraph, Pythia, etc.):

We do not need to perform boosts and rotations of the hard matrix element in order to accomodate for the transverse momentum (⇒see Plätzer's talk). Exact kinematics from the very beginning.

This is because this comes directly from the matrix element in a fully gauge invariant way (⇒ see Andreas van Hameren's talk). So, with respect to the fully collinear case, we include the additional hard dynamics coming form transverse momentum.

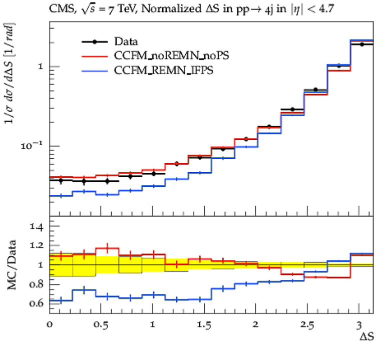
ΔS: k_T factorization plus DGLAP parton showers

- We generate matrix elements with the restriction $k_{T,i}^2 < \mu^2$, in order to stick to the transverse momentum ordering
- We undershoot the data both with and without parton showers and remnant treatment
- This could be expected, since the restriction imposed brings the dynamics closer to the collinear case



ΔS: k_T factorization plus CCFM parton showers

- We generate matrix elements without the restriction $k^2_{T,i} < \mu^2$.
- Jets equally hard or harder than those from the hard matrix element can come from the showering.
- The predictions without parton showers roughly agrees with the data
- Once we include showers and full remnant treatment, we see that we recover a similar result as in the collinear case.
- We conclude that, in this ME+PS scenario, High energy Factorization suggests the need for MPIs.



DPS effects in collinear and HEF: the problem of asymmetric cuts

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

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

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

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

Higher order corrections to 2-jet production

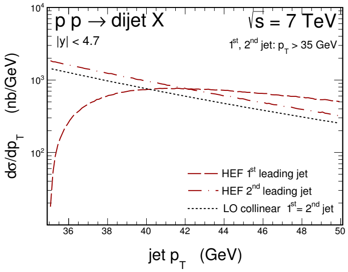


Figure: The transverse momentum distribution of the leading (long dashed line) and subleading (long dashed-dotted line) jet for the dijet production in HEF.

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	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$5.54(0.12)^{+0.08}_{-2.44}$

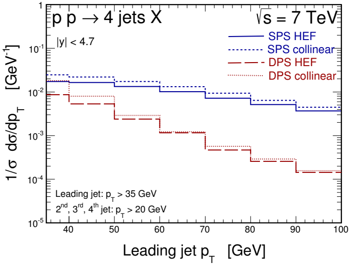
Reconciling HE and collinear factorisation: asymmetric p_T cuts

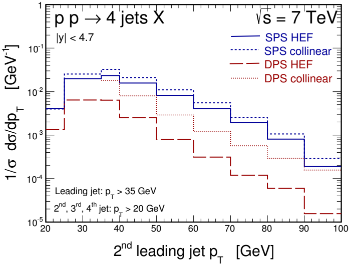
In order to open up wider region of soft final states and thereof expected that the DPS contribution increases

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

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

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

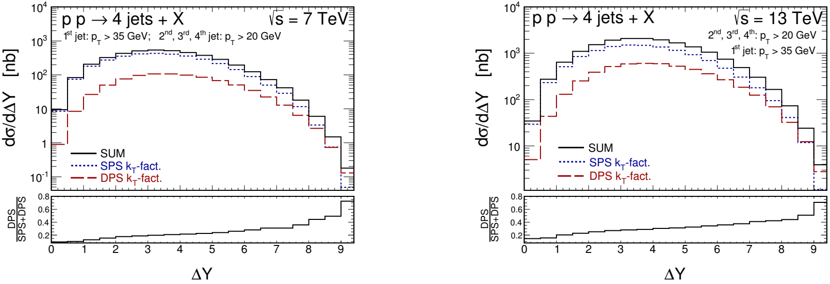




DPS dominance pushed to even lower p_T but restored in HE factorization as well
Next natural step: fully asymmetric cuts !

Pinning down double parton scattering: large rapidity separation

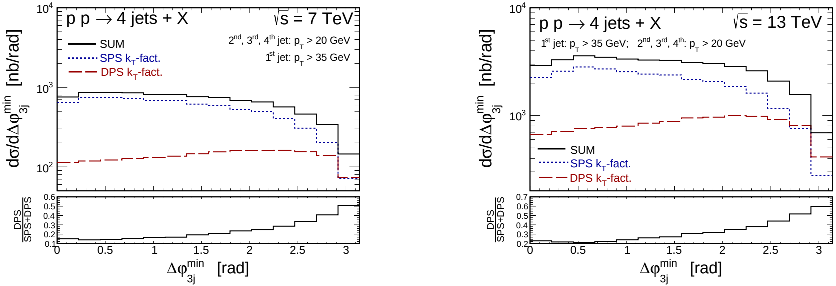
K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren
Phys.Rev. D94 (2016) no.1, 014019



- 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: $\Delta\phi_3^{min}$ - azimuthal separation

K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren
Phys.Rev. D94 (2016) no.1, 014019



- 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 perspectives

- We have a complete framework for the evaluation of cross sections from amplitudes with off-shell quarks and TMDs: KMR for this talk. The results form the KaTie are matched to the Monte Carlo CASCADE parton shower event generators
- **Previous results**: 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.
- ΔS variables, potential DPS smoking gun, does not exceptionally well without DPS with final state PS. With parton showers + remnant treatment, we get predictions under the pure matrix element result $\Rightarrow$ hardest k_T not always coming from the hard matrix element
- We will scan various PDFs, in order to gauge the dependence of these results on them.
- It will be interesting to have an experimental analysis with cuts which are *completely asymmetric and soft*, in order to enhance DPS. We are going to produce predictions with parton showers also for this configuration, because CMS plans to release such an analysis.
- Further planned studies: $2b$-jets and Z+jet

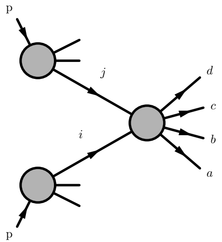
Conjectured formulas for 2 and 4 jets production:

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

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

- PDFs and matrix elements well defined.
- No rigorous factorization proof around (proving gauge invariance at loop order could help with factorization proofs in the TMD case : see Tuesday's morning session discussion)
- Reasonable description of data justifies this formula *a posteriori*

4-jet production: Single Parton Scattering (SPS)



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

Here q and q' stand for different quark flavours in the initial (final) state.

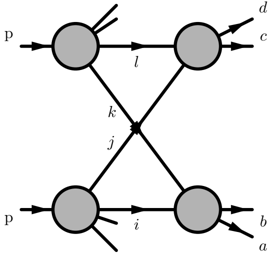
We do not introduce K factors, amplitudes@LO.

$\sim$ 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)



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

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

$$\sigma_{eff} = 15\, mb\,, \text{(CDF, D0 and LHCb collaborations)}\,,$$

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 :

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