4-jet production with kt-factorization plus parton showers

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Work in collaboration with
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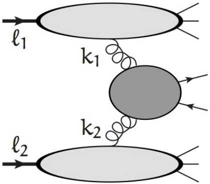
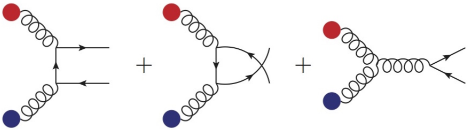
High-Energy-factorisation

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 $\Leftrightarrow$ 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 ⇒ 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 ⇒ Diehl, Kasemets and Gaunt's talks

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:

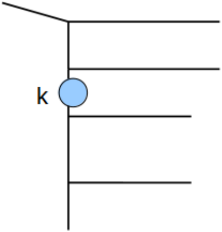
$$\Gamma_{ij}(x_1, x_2, b; t_1, t_2) = D_h^{ij}(x_1, x_2; t_1, t_2)\, F^{ij}(b) = D_h^{ij}(x_1, x_2; t_1, t_2)\, F(b)$$

- 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 $\sigma_{eff}^{-1} = \int d^2 b\, F(b)^2 \approx (15mb)^{-1}$ (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 :

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

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

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

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 MSTWnlo68cl 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**
Work by Rinaldi and collaborators ⇒ see Matteo's talk

Softer cuts: do we really see DPS in CMS data ?

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

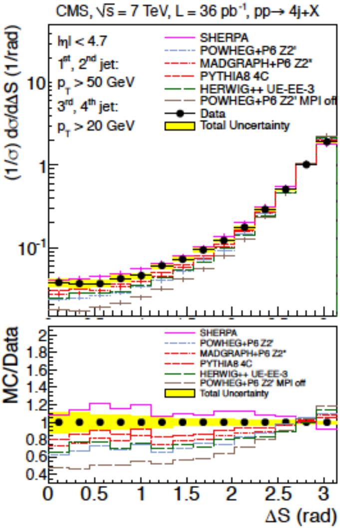
$$p_T(1,2) \geq 50\,\text{GeV}\,, \quad p_T(3,4) \geq 20\,\text{GeV}$$
$$|\eta| \leq 4.7\,, \quad R = 0.5$$

Potential smoking gun for DPS:

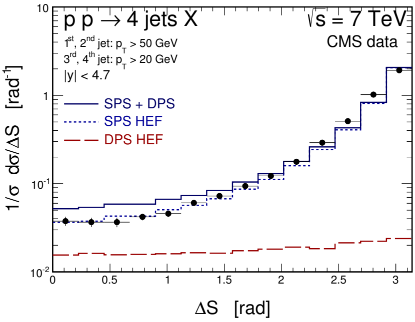
$$\Delta S = \arccos\left(\frac{\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|}\right)$$
$$\vec{p}_T(j_i, j_k) \equiv p_{T,i} + p_{T,j}$$

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

No collinear MonteCarlo manages to really describe al the data over the whole range. 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 $\Rightarrow$ 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

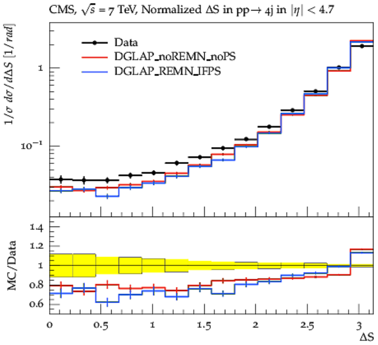
Difference with respect to the collinear generators (MadGraph, Pythia, etc.):

We do not need to perform boosts and rotations of the hard matrix element in order to accomodate for the transverse momentum. Exact kinematics from the very beginning.

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

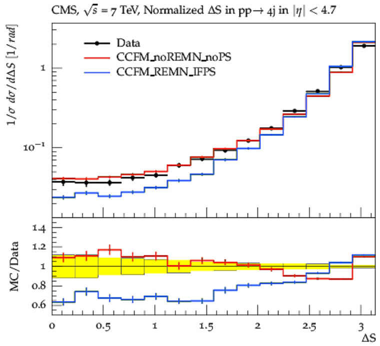
ΔS: k_T factorization plus DGLAP parton showers

- 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



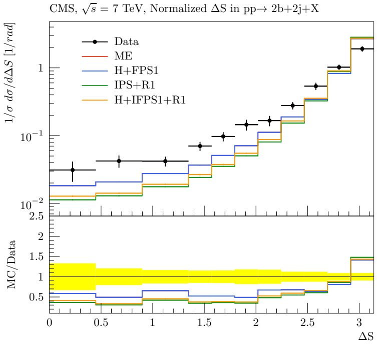
ΔS: k_T factorization plus CCFM parton showers

- We generate matrix elements without the restriction $k_{T,i}^2 < \mu^2$.
- 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 (!?)** .



ΔS: k_T factorization plus CCFM parton showers with two b-tagged jets

- We generate matrix elements without the restriction $k_{T,i}^2 < \mu^2$.
- Jets equally hard or harder than those from the hard matrix element can come from the showering.
- The predictions without parton showers now do not agree with the data
- Once we include showers and full remnant treatment, we are even more off.
- We conclude that, in this ME+PS scenario, High energy Factorization suggests the need for **MPIs (!?)** $\Rightarrow$ Paolo Gunnellini's talk



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

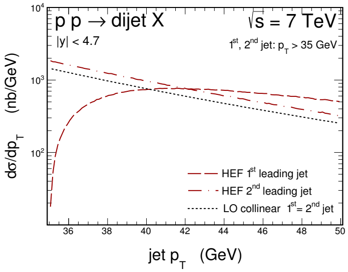


Figure: The transverse momentum distribution of the leading (long dashed line) and subleading (long dashed-dotted line) jet for the dijet production in HEF.

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

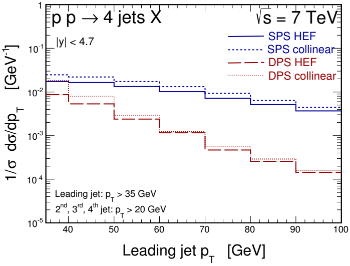
Reconciling HE and collinear factorisation: asymmetric p_T cuts

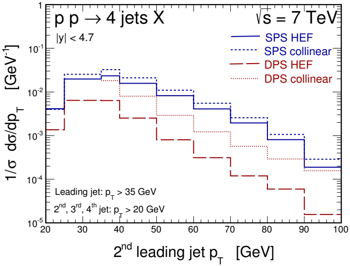
In order to open up wider region of soft final states and thereof expected that the DPS contribution increases

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

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

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

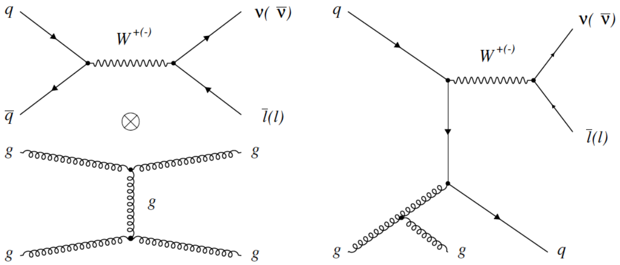




DPS dominance pushed to even lower p_T but restored in HE factorization as well

Next natural step: fully asymmetric cuts !

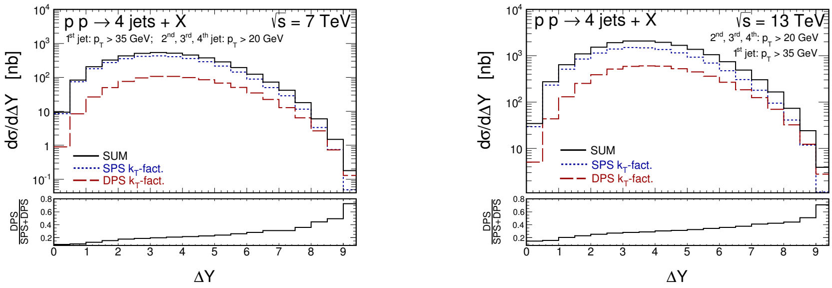
Why do we want it so bad ?



- Clean channel to see DPS (well, so far...) : $p\,p \Rightarrow W\,j\,j$ (exclusive)
- Exclusiveness makes the channel clean: just reject all events with $\#j > 2$: accepted jets from DPS around back-to-back configuration ! Extracted fraction of DPS $\quad f_{DPS} = 0.055 \pm 0.002(\text{stat.}) \pm 0.014(\text{syst.})$
- No chance that we can do anything exclusive on the two jets in four-jet production. See Paolo Gunnellini's take-home statement: **CMS sees MPIs** ; good, but **we want specifically DPS !** $\Rightarrow$ where does the theory tell us that the needed enhancement must be DPS itself ? At the pure ME level and $\sigma_{eff} = 15mb$ with asymmetric cuts we get $f_{DPS} \simeq 0.19$!!!

Pinning down double parton scattering: large rapidity separation

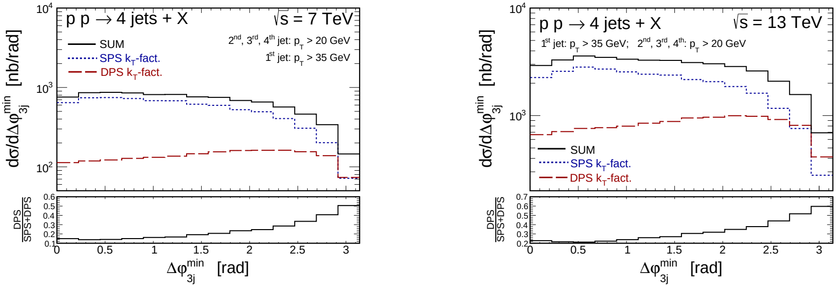
K. Kutak, R. Maciula, M.S., A. Szczurek, A. van Hameren
Phys.Rev. D94 (2016) no.1, 014019



- 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

- **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 really well without DPS with final state PS. With parton showers + remnant treatment: 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 and we will consistently perform an initial state evolution with KMR PDFs, improving the preliminary results showcased in this talk.
- 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 **now CMS plans to release such an analysis**.
- Personal interest: improving the pocket-formula framework integrating the more formal developments $\Rightarrow$ Diehl, Gaunt, Kasemets' talks. First step: include the effect of DPDFs.

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

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

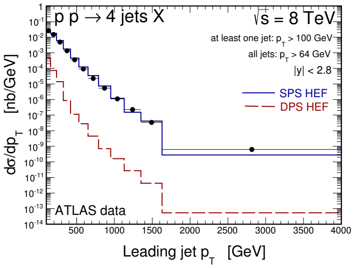
Cuts are too hard to pin down DPS and/or benefit from HEF: 4-jet case

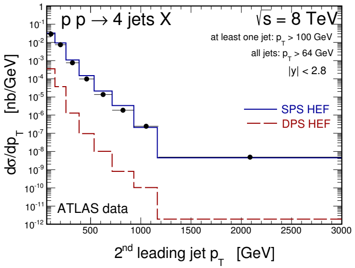
$$\text{Collinear case} \quad \begin{cases} 9.98^{+7.40}_{-3.95} & SPS \\ 0.094^{+0.06}_{-0.036} & DPS \end{cases} \qquad \text{HEF case} \quad \begin{cases} 10.0^{+6.9}_{-5.3} & SPS \\ 0.05^{+0.054}_{-0.029} & DPS \end{cases}$$

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.

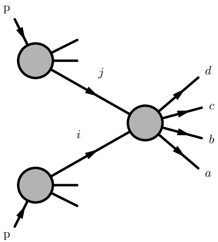
Conjectured formulas for 2 and 4 jets production:

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

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

- 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.

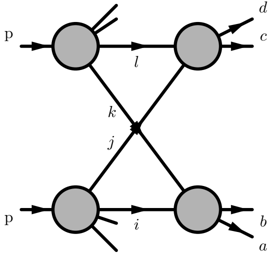
We do not introduce K factors, amplitudes@LO.

$\sim$ 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,

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

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

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