

# A Framework for High Energy Factorization matched to Parton Showers

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Work in collaboration with  
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High Energy Factorization and amplitudes

$4j$  and  $jj b \bar{b}$  in HEF plus Parton Showers

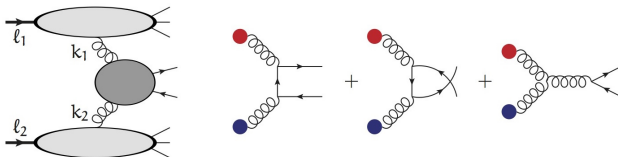
Conclusions

Backup Slides

## High Energy Factorization and amplitudes

# High Energy Factorization: more degrees of freedom

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



$$\sigma_{h_1, h_2 \rightarrow q\bar{q}} = \int d^2 k_{1\perp} d^2 k_{2\perp} \frac{dx_1}{x_1} \frac{dx_2}{x_2} f_g(x_1, k_{1\perp}) f_g(x_2, k_{2\perp}) \hat{\sigma}_{gg}(m, x_1, x_2, s, k_{1\perp}, k_{2\perp})$$

where the  $f_g$ 's are the gluon densities, obeying **BFKL**, **BK**, **CCFM** equations.

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

**Possibly suitable to the smaller- $x$  window opened up by the LHC, especially for intermediate energy events.**

**The initial state kinematic is exact.**

**Progress to connect TMD evolution and low- $x$  evolution (this approach)**

Applies if  $s \gg P_{\perp}^2 \gg \Lambda^2$

**Momentum parameterization:**

$$k_1^\mu = x_1 l_1^\mu + k_{1\perp}^\mu, \quad k_2^\mu = x_2 l_2^\mu + k_{2\perp}^\mu$$

$$l_i^2 = 0, \quad l_i \cdot k_i = 0, \quad k_i^2 = -k_{i\perp}^2, \quad i = 1, 2$$

# High Energy Factorization in Lipatov's approach

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

$$\sigma_{h_1, h_2 \rightarrow q \bar{q}} = \int d^2 k_{1\perp} d^2 k_{2\perp} \frac{dx_1}{x_1} \frac{dx_2}{x_2} f_g(x_1, k_{1\perp}) f_g(x_2, k_{2\perp}) \hat{\sigma}_{gg}(m, x_1, x_2, s, k_{1\perp}, k_{2\perp})$$

where the  $f_g$ 's are the gluon densities, obeying **BFKL**, **BK**, **CCFM** evolution equations.

Usual tool: Lipatov' *effective* (though not in the RG group sense) action

Lipatov, Nucl.Phys. B721 (1995) 111-135

Antonov, Cherednikov, Kuraev, Lipatov, Nucl.Phys. B452 (2005) 369-400

$$S_{eff} = S_{QCD} + \int d^4 x \left\{ \text{tr} \left[ (W_-[v] - A_-) \partial_\perp^2 A_+ + (W_+[v] - A_+) \partial_\perp^2 A_- \right] \right\}$$

$$W_\pm[v] = -\frac{1}{g} \partial_\pm U[v_\pm] = v_\pm - g v_\pm \frac{1}{\partial_\pm} v_\pm + g^2 v_\pm \frac{1}{\partial_\pm} v_\pm \frac{1}{\partial_\pm} v_\pm + \dots$$

$$v_\mu \equiv -i t^a A_\mu^a, \text{ gluon field} \quad A_\pm \equiv -i t^a A_\pm^a, \quad \text{reggeized gluon fields}$$

$$U[v_\pm] = \mathcal{P} \exp \left( -\frac{g}{2} \int_{-\infty}^{x_\pm^\pm} dz^\pm v_\pm(z^\pm, x_\perp) \right), \quad x_\perp = (x_\pm, \mathbf{x})$$

**Sudakov parameterisation of initial state for HEF:**

$$k_1^\mu = x_1 l_1^\mu + k_{1\perp}^\mu, \quad k_2^\mu = x_2 l_2^\mu + k_{2\perp}^\mu, \quad l_i^2 = 0, \quad l_i \cdot k_i = 0, \quad k_i^2 = -k_{i\perp}^2, \quad i = 1, 2$$

# Gauge invariant amplitudes with off-shell gluons

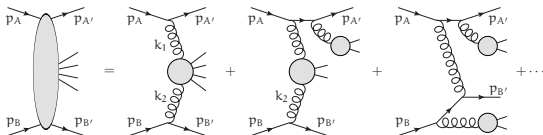
Kutak, Kotko, van Hameren, JHEP 1301 (2013) 078

Problem: general partonic processes must be described by gauge invariant amplitudes  
 $\Rightarrow$  ordinary Feynman rules are not enough !

## THE IDEA:

on-shell amplitudes are gauge invariant, so off-shell gauge-invariant amplitudes could be got by embedding them into on-shell processes...

**...first result...:** 1) For off-shell gluons: represent  $g^*$  as coming from a  $\bar{q}qg$  vertex, with the quarks taken to be on-shell



- embed the scattering of the off-shell gluons in the scattering of two quark pairs carrying momenta  $p_A^\mu = k_1^\mu$ ,  $p_B^\mu = k_2^\mu$ ,  $p_{A'}^\mu = 0$ ,  $p_{B'}^\mu = 0$
- Assign the spinors  $|p_1\rangle, |p_1]$  to the  $A$ -quark and the propagator  $\frac{i \not{p}_1}{p_1 \cdot k}$  instead of  $\frac{i \not{k}}{k^2}$  to the propagators of the  $A$ -quark carrying momentum  $k$ ; same thing for the  $B$ -quark line.
- ordinary Feynman elsewhere and factor  $x_1 \sqrt{-k_\perp^2/2}$  to match to the collinear limit
- **Big advantage: Spinor helicity formalism**

# BCFW: an analytic recursion for (almost) all massless QCD amplitudes

**Amazingly simple recursive relation, now fully generalised to the off-shell case :**

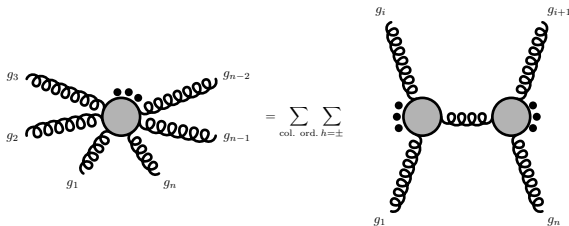
*any tree-level color-ordered amplitude is the sum of residues of the poles it develops when it is made dependent on a complex variable as above.*

*Such residues are simply products of color-ordered lower-point amplitudes evaluated at the pole times an intermediate propagator.*

*Shifted particles are always on opposite sides of the propagator.*

$$\mathcal{A}(g_1, \dots, g_n) = \sum_{i=2}^{n-2} \sum_{h=+,-} \mathcal{A}(g_1, \dots, g_i, \hat{p}^h) \frac{1}{(p_1 + \dots + p_i)^2} \mathcal{A}(-\hat{p}^{-h}, g_{i+1}, \dots, g_n)$$

$$z_i = \frac{(p_1 + \dots + p_i)^2}{[1|p_1 + \dots + p_i|n]} \quad \text{location of the pole corresponding for the "i-th" partition}$$

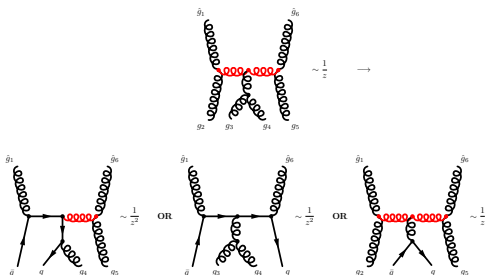


Natural to ask whether something like BCFW exists with off-shell particles.  
 For off shell gluons answer first given in [van Hameren, JHEP 1407 \(2014\) 138](#)

**With off shell fermions** [van Hameren, MS, JHEP 1507 \(2015\) 010](#);  
[Kutak, van Hameren, MS JHEP 1702 \(2017\) 009](#)

$$\mathcal{A}(0) = \sum_{s=g,f} \left( \sum_p \sum_{h=+,-} A_{p,h}^s + \sum_i B_i^s + C^s + D^s \right),$$

- $A_{p,h}^{g/f}$  are the same poles as in the original BCFW recursion for on-shell amplitudes: intermediate virtual gluon or fermion.
- $B_i^{g/f}$  are due to the poles in auxiliary eikonal quark propagators.
- $C^{g/f}$  and  $D^{g/f}$  show up as the first/last shifted particle is off-shell and their external propagator develops a pole. **External propagators for off-shell particles necessary to ensure  $\lim_{z \rightarrow \infty} \mathcal{A}(z) = 0$**





# Novel results and Tools in High Energy Factorization QCD

- With growing number of legs, it is necessary to figure out practical ways to compute amplitudes efficiently. A promising possibility is the BCFW (Britto-Cachazo-Feng-Witten) recursion relation, originally discovered for on-shell QCD amplitudes and extended to off-shell gluon amplitudes in [A. van Hameren, JHEP 1407 \(2014\) 138](#)
- A general analysis extending the modified BCFW to amplitudes with fermion pairs has been developed in [A. van Hameren, MS JHEP 1507 \(2015\) 010](#) and [A. van Hameren, K. Kutak, MS, JHEP 1702 \(2017\) 009](#)
- Numerical implementation and cross-checks are done and always successful. A program exists implementing Berends-Giele recursion relation, [A. van Hameren, M. Bury, Comput.Phys.Commun. 196 \(2015\) 592-598](#)
- **The big player for phenomenology: KaTie**, a parton level event generator for  $k_T$ -dependent initial states [A. van Hameren, arXiv:1611.00680](#). Once interfaced with the **AvHlib** library by the same author and supplied with the desired TMDs, it can compute cross sections in HEF for any process in the Standard Model, providing automatised phase space optimisation (**KALEU**).
- **Loops in HEF: very challenging, for now;**  
**what is the next best thing ? Of course parton showers !**

## 4j and $jj b \bar{b}$ in HEF plus Parton Showers

# Adding Parton Showers to High Energy Factorization: When KaTie met CASCADE



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

- **KaTie** (A. van Hameren) : [arXiv:1611.00680](https://arxiv.org/abs/1611.00680)  
Monte Carlo program for tree-level calculations of *any process within the Standard Model*; initial-state partons either on-shell or off-shell.
- **u and d** initial state quarks, final states with all the  $N_f = 5$  lightest flavours, massless quark approximation.
- **Martin-Ryskin-Watt prescription** to generate the  $k_T$ -dependence from the collinear set CT10nlo
- **CASCADE-2.4.07:**  
[Comput.Phys.Commun. 143 \(2002\) 100-111](#) .  
All-flavour TMD evolution, no coherence assumption.
- **Scales:**  $\mu_R = \mu_F \equiv \mu = \frac{H_T}{2} \equiv \frac{1}{2} \sum_i p_T^i$ , (sum over final state particles)



# Integrated MRW PDFs and comparison to the collinear PDFs

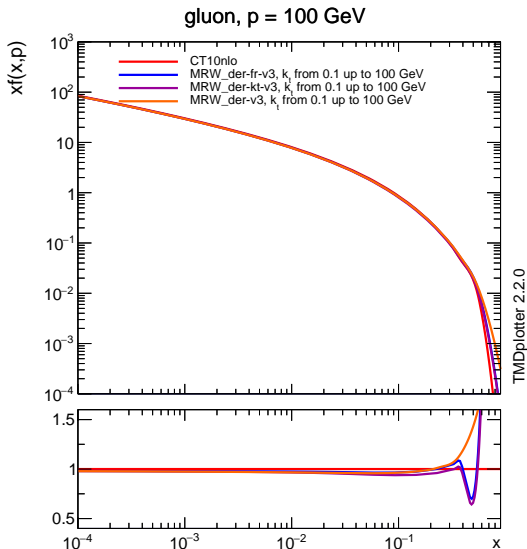
Martin, Ryskin and Watt on the prescription for obtaining unintegrated PDFs and its extension to NLO:

Phys.Rev. D70 (2004) 014012,  
Erratum: Phys.Rev. D70 (2004) 079902  
Eur.Phys.J. C66 (2010) 163-172

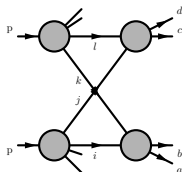
Idea: hard  $k_T$  emissions can come from the showering.  
Not the same ordering as in the DGLAP framework:  
angular ordering instead

$$\int d^2\mathbf{k}_T \mathcal{F}(\mathbf{x}, \mathbf{k}_\perp, \mu) = f(\mathbf{x}, \mu) \Rightarrow$$

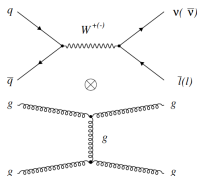
Mismatch limited to a region which contributes very little to the cross section for 4 jets.



# Introducing Double Parton Scattering



Two hard scatterings  
in the same  
hadron-hadron collision  
# scatterings > 2 also  
possible



$$\sigma^D = \sum_{i,j,k,l} S_{kl}^{ij} \int \Gamma_{ij}(x_1, x_2, b; t_1, t_2) \Gamma_{kl}(x'_1, x'_2, b; t_1, t_2) \hat{\sigma}(x_1, x'_1) \hat{\sigma}(x_2, x'_2) dx_1 dx_2 dx'_1 dx'_2 d^2b$$

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

- 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  $\sigma_{eff}^{-1} = \int d^2b F(b)^2 \approx (15mb)^{-1}$  (CDF, D0, LHCb ...)

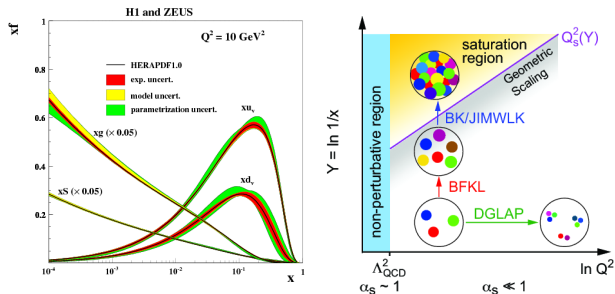
The so-called *pocket formula*: 
$$\sigma^D = \frac{1}{\sigma_{eff}} \sum_{A,B} \frac{\sigma^A \sigma^B}{1 + \delta_{AB}}$$

Paver, Treleani, Nuovo Cim. A70 (1982) 215, Mekhfi, Phys. Rev. D32 (1985) 2371.

Diehl, Ostermeier, Schäfer, Gaunt, Plöchl, Schönwald

JHEP 1203 (2012) 089, JHEP 1601 (2016) 076, arXiv:1702.06486

# Hunting for Double Parton Scattering: an acrobatics game



1. We do not know how to fully treat double parton correlations.
2. Too high  $x$ 's miss DPS, too small  $x$ 's hit the UE region. We cannot cleanly study DPS in the highly perturbative regime.
3. DPS is still power-suppressed w.r.t usual Single Parton Scattering:  $\frac{\sigma_{\text{DPS}}}{\sigma_{\text{SPS}}} \sim \frac{\Lambda^2}{Q^2}$

How these issues are addressed:

1. NP correlations are a second order effect at the pheno state of the art level. Community is working on them to (also) better constrain  $\sigma_{\text{eff}}$  from theory.
2. The kinematic window opened by the LHC allows to go for relatively small- $x$  at intermediate energies  $\Rightarrow$  High Energy Factorization
3. Not absolute rates, but rather the shape of carefully selected observables.

# Double Parton Scattering for 4-jets: the case of the CMS data

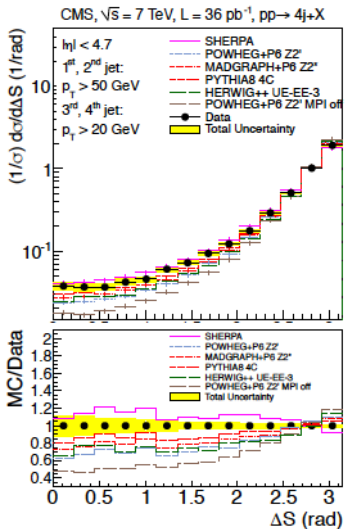
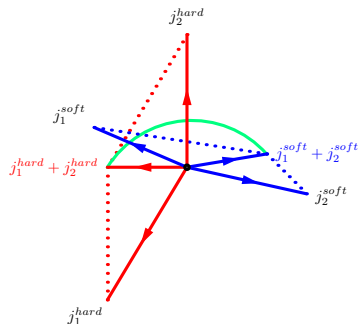
$$p_T(1,2) \geq 50 \text{ GeV}, p_T(3,4) \geq 20 \text{ GeV}, |\eta| \leq 4.7, l$$

$$\Delta S = \arccos \left( \frac{\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|} \right)$$

$$\vec{p}_T(j_i, j_k) \equiv p_{T,i} + p_{T,j}$$

Expected to be flat for DPS

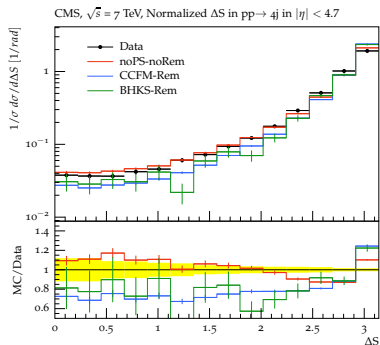
Not well described by available tools



# $\Delta S$ : HEF with MRW plus full DGLAP showers

$$\Delta S = \arccos \left( \frac{\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{hard}}, j_2^{\text{hard}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|} \right),$$

- Pure tree level: [K. Kutak, R. Maciula, MS, A. Szczurek, A. van Hameren, JHEP 1604 \(2016\) 175](#)
- 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 seems to suggest the need for MPI's .



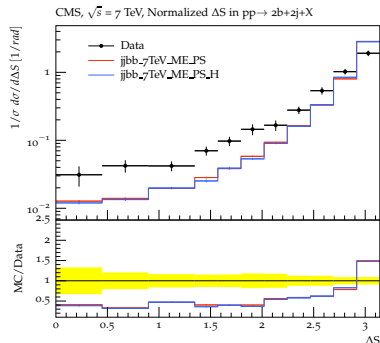


# $\Delta S$ : HEF factorization with MRW PDFs and full DGLAP showers with two b-tagged jets

CMS collaboration, Phys.Rev. D94 (2016) no.11, 112005  
 $p_T > 20\text{GeV}$ ,  $|\eta| < 2.4$  (tagged), 4.7 (untagged),  $R = 0.3$

$$\Delta S = \arccos \left( \frac{\vec{p}_T(j_1^{\text{bottom}}, j_2^{\text{bottom}}) \cdot \vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})}{|\vec{p}_T(j_1^{\text{bottom}}, j_2^{\text{bottom}})| \cdot |\vec{p}_T(j_1^{\text{soft}}, j_2^{\text{soft}})|} \right),$$

- Jets equally hard or harder than those from the hard matrix element can come from the showering.
- We present results directly with showers and with Martin-Ryskin-Watt uPDFS  $\mathcal{F}(x, k_T)$ ,  $\int \mathcal{F}(x, k_T, \mu) d^2 k_T = f(x, \mu)$
- We see that the predictions, including only Single Parton Scattering, are significantly off
- We conclude that, in this ME+PS scenario, High energy Factorization suggests the need for MPI's.

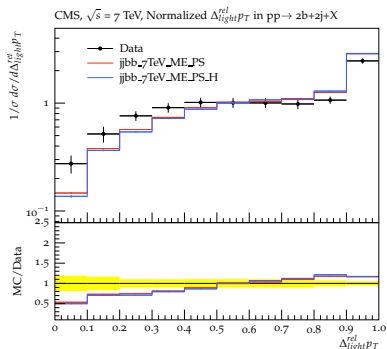


# $\Delta_{light}^{rel} p_T$ : HEF factorization with MRW PDFs and full DGLAP showers with two b-tagged jets

CMS collaboration, Phys.Rev. D94 (2016) no.11, 112005  
 $p_T > 20\text{GeV}$ ,  $|\eta| < 2.4$  (tagged), 4.7 (untagged),  $R = 0.3$

$$\Delta_{soft}^{rel} p_T = \frac{|\vec{p}_T^{\text{soft}1} + \vec{p}_T^{\text{soft}2}|}{|\vec{p}_T^{\text{soft}1}| + |\vec{p}_T^{\text{soft}2}|}$$

- Jets equally hard or harder than those from the hard matrix element can come from the showering.
- We present results directly with showers and with Martin-Ryskin-Watt uPDFS  $\mathcal{F}(x, k_T)$ ,  $\int \mathcal{F}(x, k_T, \mu) d^2 k_T = f(x, \mu)$
- We see that the predictions, including only Single Parton Scattering, are significantly off
- We conclude that, in this ME+PS scenario, High energy Factorization suggests the need for MPI's.



## Conclusions

## Summary and perspectives

- We have a complete framework for the evaluation of cross sections from amplitudes with off-shell quarks and TMDs. The results from KaTie are matched to the Monte Carlo CASCADE parton showers. **Task one: present a consistent framework whose tools the general user can profit from**
- Preliminary:  $\Delta S$  and other variables, potential smoking guns for MPIs, do not really seem to do well without them. With parton showers: hardest  $k_T$  not always coming from the hard matrix element. **Task two: more observables are under examination and also dijet production is being studied.**
- **Task three: another experimental analysis with asymmetric cuts is desirable, to pin down Double Parton Scattering more effectively.** We are working with the Antwerp CMS group to finalise it. CMS potentially better for 4-jets than ATLAS thanks to particle flow reconstruction.
- **Task four: apply the proposed framework to more and more processes.**

## Backup Slides

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

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 :  $\sigma_{tot} = 330 \pm 5 \text{ (stat.)} \pm 45 \text{ (syst.) nb}$

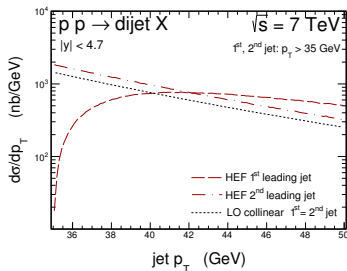
LO collinear factorization :  $\sigma_{SPS} = 697 \text{ nb}, \quad \sigma_{DPS} = \mathbf{125 \text{ nb}}, \quad \sigma_{tot} = 822 \text{ nb}$

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

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

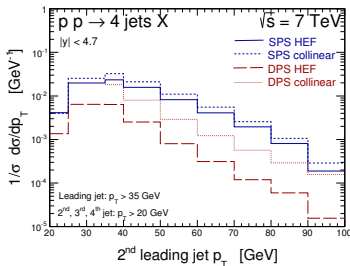
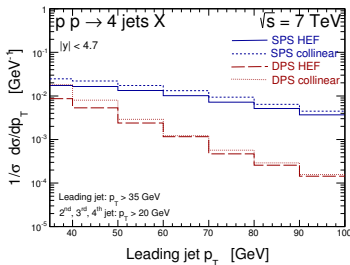
# Reconciling High Energy and Collinear Factorization : asymmetric $p_T$ cuts

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

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

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

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



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

Next natural step: fully asymmetric cuts !

Other possible approach: resummation (not covered in this talk)



# Preliminary assessments of the potential of various asymmetric cuts

Below, HEF predictions with **DLC2016** without PS for 4 jets (no b-tagging).  
Experimentally ideal: using track-jets, in order to optimally deal with high pile-up

$$\Rightarrow R = 0.4, |\eta| < 2.1.$$

(P. Van Mechelen, H. Van Haevermaet, M. Pieters, private communication )

## Competing effects at work :

1. The lower the highest cut, the more DPS we can see (see PDFs)
2. As the spread in transverse momentum between jets widens up, the phase space is reduced
3. One has to be careful to impose an asymmetry in  $p_t \geq 5$  GeV, in order to tame extra logarithms *Alioli, Andersen, Oleari, Re, Smillie, Phys.Rev. D85 (2012) 114034*

- $p_T(1) \geq 40$  GeV ,  $p_T(2) \geq 30$  GeV ,  $p_T(3) \geq 20$  GeV ,  $p_T(4) \geq 10$  GeV  
 $\sigma_{SPS} = 2132nb$  ,  $\sigma_{DPS} = 240nb \Rightarrow f_{DPS} \simeq 0.11$
- $p_T(1) \geq 40$  GeV ,  $p_T(2) \geq 25$  GeV ,  $p_T(3) \geq 25$  GeV ,  $p_T(4) \geq 10$  GeV  
 $\sigma_{SPS} = 1571nb$  ,  $\sigma_{DPS} = 151nb \Rightarrow f_{DPS} \simeq 0.10$
- $p_T(1) \geq 35$  GeV ,  $p_T(2) \geq 20$  GeV ,  $p_T(3) \geq 15$  GeV ,  $p_T(4) \geq 10$  GeV  
 $\sigma_{SPS} = 4654nb$  ,  $\sigma_{DPS} = 922nb \Rightarrow f_{DPS} \simeq 0.19$

Not very different for equal cuts on the second and third jet:

**lower highest cut is the dominant effect !**

Better to stick to 3 instead of 4 different cuts because of point 3.

# Pinning down double parton scattering: $\Delta\phi_3^{min}$ - azimuthal separation

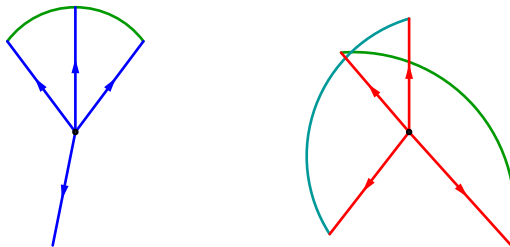


Figure: Left: typical 4-particle final state topology associated with SPS. Right: typical 4-particle final state topology generated by DPS. No way, in the latter case, to get a  $\Delta\phi_3^{min}$  below

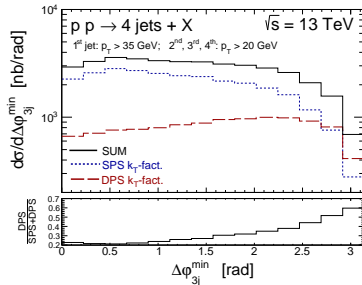
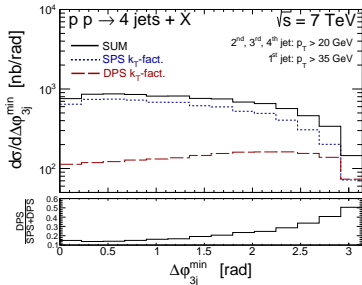
**Minimum total distance in azimuthal angle between triplets of jets:**

$$\Delta\phi_3^{min} = \min_{i,j,k[1,4]} (|\phi_i - \phi_j| + |\phi_j - \phi_k|) , \quad i \neq j \neq k$$

**Almost back-to-back topologies clearly favour high values of this variable !**  
 $\Rightarrow$  DPS is expected to push the cross section in the high- $\Delta\phi_3^{min}$  region

# Pinning down double parton scattering: $\Delta\phi_3^{min}$ - azimuthal separation

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- Definition:  $\Delta\phi_3^{min} = \min_{i,j,k[1,4]} (|\phi_i - \phi_j| + |\phi_j - \phi_k|)$ ,  $i \neq j \neq k$
- Proposed by ATLAS in [JHEP 12 105 \(2015\)](#) for high  $p_T$  analysis
- High values favour DPS, because there is no way to construct a low value from a (nearly) back-to-back configuration.
- For  $\Delta\phi_3^{min} \geq 2\pi/3$  the total cross section is heavily affected by DPS at 13 TeV.