Double scattering contribution to small-x processes: Mueller-Navelet Jets at the LHC

Lech Szymanowski

National Centre for Nuclear Research, Warsaw

and

Laboratoire de Physique Théorique, CNRS / Université Paris Sud, Orsay

MPI 2015

ICTP, Trieste, 23-27 November 2015

in collaboration with

D. Colferai (Florence U. & INFN, Florence), B. Ducloué (Jyväskylä U.),
F. Schwennsen (DESY), S. Wallon (LPT, Orsay)

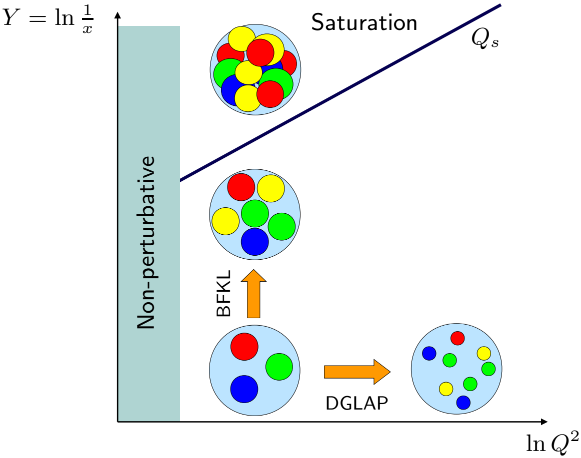
Based on:

D. Colferai, F. Schwennsen, L. Sz., S. Wallon: JHEP **1012** (2010) 026

B. Ducloué, L. Sz., S. Wallon: JHEP **1305** (2013) 096, Phys. Rev. Lett. **112** (2014) 082003
Phys. Lett. B738 (2014) 311, Phys. Rev. D **92** (2015) 7, 076002

The different regimes of QCD

k_T factorization

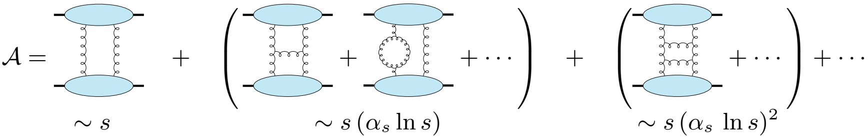


collinear factorization

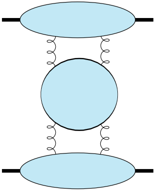
The specific case of QCD at large s

QCD in the perturbative Regge limit

The amplitude can be written as: k_T factorization



this can be put in the following form :



$\leftarrow$ Impact factor

$\leftarrow$ Green's function

$\leftarrow$ Impact factor

$$\sigma_{tot}^{h_1\,h_2\to anything} = \frac{1}{s} Im\mathcal{A} \sim s^{\alpha_{\mathbb{P}}(0)-1}$$

with $\alpha_{\mathbb{P}}(0) - 1 = C\,\alpha_s + C'\,\alpha_s^2 + \cdots$

$C > 0$: Leading Log $\mathbb{P}$omeron

Balitsky, Fadin, Kuraev, Lipatov

Higher order corrections

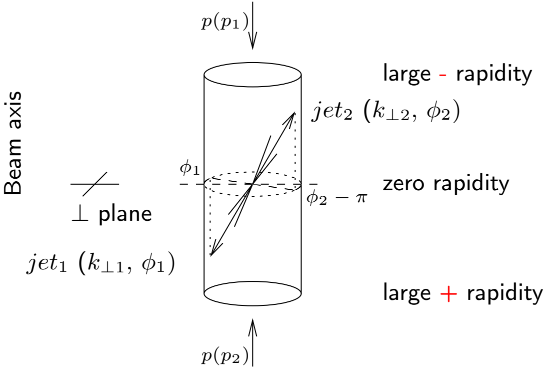
- Higher order corrections to BFKL kernel are known at NLL order (Lipatov Fadin; Camici, Ciafaloni), now for arbitrary impact parameter $\alpha_S \sum_n (\alpha_S \ln s)^n$ resummation

- impact factors are known in some cases at NLL
  - $\gamma^* \to \gamma^*$ at $t = 0$ (Bartels, Colferai, Gieseke, Kyrieleis, Qiao; Balitski, Chirilli)
  - forward jet production (Bartels, Colferai, Vacca; Caporale, Ivanov, Murdaca, Papa, Perri; Chachamis, Hentschinski, Madrigal, Sabio Vera)
  - inclusive production of a pair of hadrons separated by a large interval of rapidity (Ivanov, Papa)
  - $\gamma_L^* \to \rho_L$ in the forward limit (Ivanov, Kotsky, Papa)

Mueller-Navelet jets: Basics

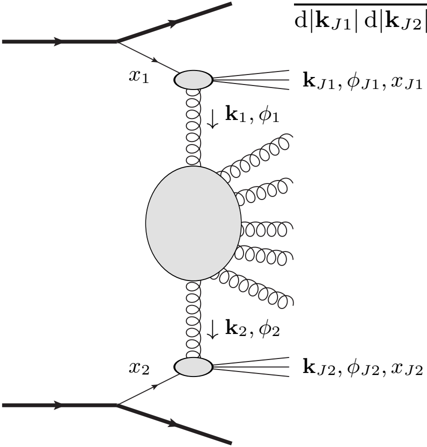
Mueller-Navelet jets

- Consider two jets (hadrons flying within a narrow cone) separated by a large rapidity, i.e. each of them almost fly in the direction of the hadron "close" to it, and with very similar transverse momenta
- Pure LO *collinear* treatment: these two jets should be emitted back to back at leading order: $\Delta\phi - \pi = 0$ ($\Delta\phi = \phi_1 - \phi_2 =$ relative azimuthal angle) and $k_{\perp 1} = k_{\perp 2}$. No phase space for (untagged) emission between them



Master formulas

k_T-factorized differential cross section



$$\frac{d\sigma}{d|\mathbf{k}_{J1}|\, d|\mathbf{k}_{J2}|\, dy_{J1}\, dy_{J2}} = \int d\phi_{J1}\, d\phi_{J2} \int d^2\mathbf{k}_1\, d^2\mathbf{k}_2$$

$$\times\, \Phi(\mathbf{k}_{J1}, x_{J1}, -\mathbf{k}_1)$$

$$\times\, G(\mathbf{k}_1, \mathbf{k}_2, \hat{s})$$

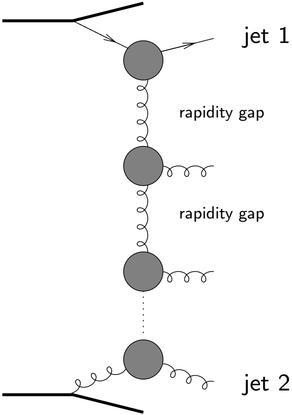
$$\times\, \Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2)$$

with $\Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2) = \int dx_2\, f(x_2) V(\mathbf{k}_2, x_2)$ $\quad f \equiv$ PDF $\quad x_J = \frac{|\mathbf{k}_J|}{\sqrt{s}} e^{y_J}$

Mueller-Navelet jets: LL vs NLL

LL BFKL

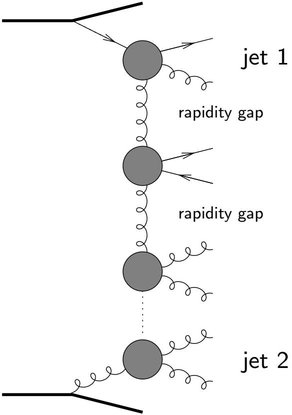
tree eff. vertex



$$\sum(\alpha_s \ln s)^n$$

NLL BFKL

eff. vertex with 1-loop



$$\sum(\alpha_s \ln s)^n + \alpha_s \sum(\alpha_s \ln s)^n$$

Results

Results for a symmetric configuration

In the following we show results for

- $\sqrt{s} = 7$ TeV
- $35\,\mathrm{GeV} < |\mathbf{k}_{J1}|\,, |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
- $0 < |y_1|\,, |y_2| < 4.7$

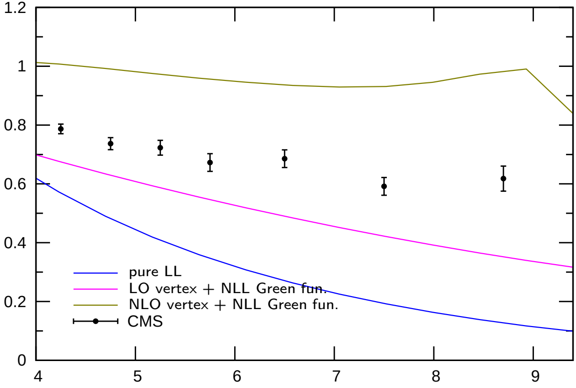
These cuts allow us to compare our predictions with the first experimental data on azimuthal correlations of Mueller-Navelet jets at the LHC presented by the CMS collaboration (CMS-PAS-FSQ-12-002)

note: unlike experiments we have to set an upper cut on $|\mathbf{k}_{J1}|$ and $|\mathbf{k}_{J2}|$. We have checked that our results do not depend on this cut significantly.

Results: azimuthal correlations

Azimuthal correlation $\langle \cos \varphi \rangle$

$$\frac{\mathcal{C}_1}{\mathcal{C}_0} = \langle \cos \varphi \rangle \equiv \langle \cos(\phi_{J1} - \phi_{J2} - \pi) \rangle$$



$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$

$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

$Y \equiv |y_1 - y_2|$

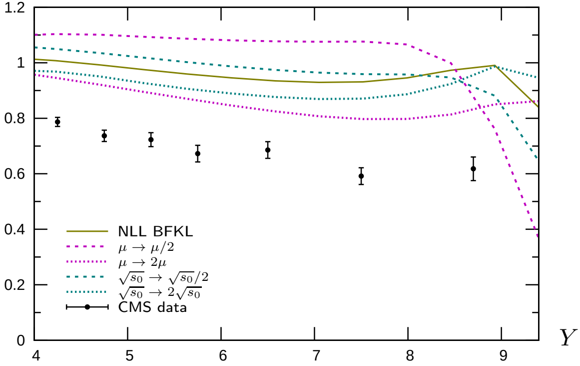
The NLO corrections to the jet vertex lead to a large increase of the correlation

Note: LO vertex + NLL Green done by F. Schwennsen, A. Sabio-Vera; C. Marquet, C. Royon

Results: azimuthal correlations

Azimuthal correlation $\langle \cos \varphi \rangle$

$$\langle \cos \varphi \rangle \equiv \langle \cos(\phi_{J1} - \phi_{J2} - \pi) \rangle$$



35 GeV $< |\mathbf{k}_{J1}| <$ 60 GeV

35 GeV $< |\mathbf{k}_{J2}| <$ 60 GeV

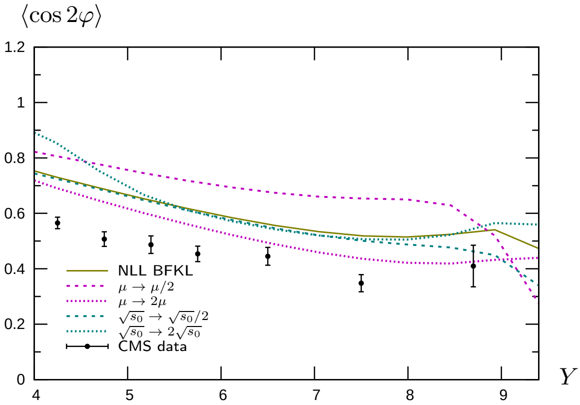
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

- NLL BFKL predicts a too small decorrelation
- The NLL BFKL calculation is still rather dependent on the scales, especially the renormalization / factorization scale

Results: azimuthal correlations

Azimuthal correlation $\langle \cos 2\varphi \rangle$



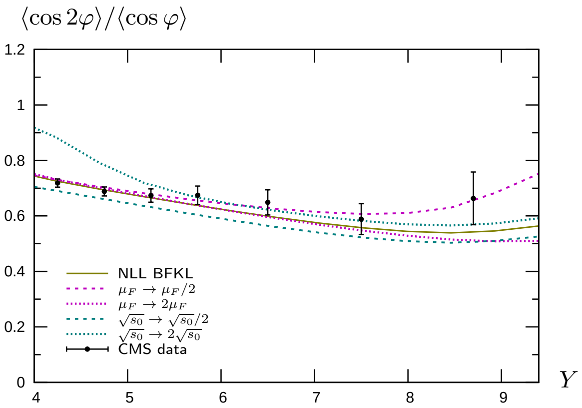
$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
$35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$

$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

- The agreement with data is a little better for $\langle \cos 2\varphi \rangle$ but still not very good
- This observable is also very sensitive to the scales

Results: azimuthal correlations

Azimuthal correlation $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$



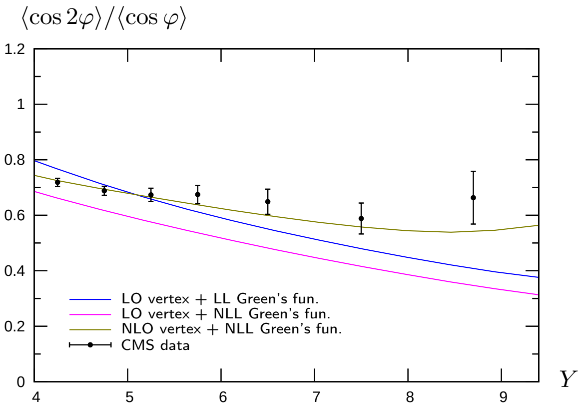
$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

- This observable is more stable with respect to the scales than the previous ones
- The agreement with data is good across the whole Y range

Results: azimuthal correlations

Azimuthal correlation $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$



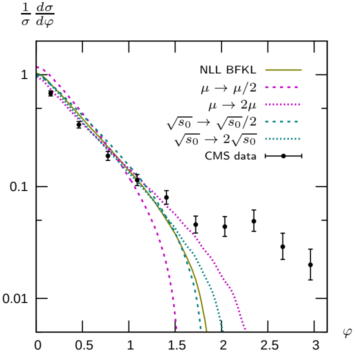
$35\,\mathrm{GeV} < |\mathbf{k}_{J1}| < 60\,\mathrm{GeV}$
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

It is necessary to include the NLO corrections to the jet vertex to reproduce the behavior of the data at large Y

Results: azimuthal distribution

Azimuthal distribution (integrated over $6 < Y < 9.4$)



$$\frac{1}{\sigma}\frac{d\sigma}{d\varphi} = \frac{1}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty}\cos(n\varphi)\langle\cos(n\varphi)\rangle\right\}.$$

- Our calculation predicts a too large value of $\frac{1}{\sigma}\frac{d\sigma}{d\varphi}$ for $\varphi \lesssim \frac{\pi}{2}$ and a too small value for $\varphi \gtrsim \frac{\pi}{2}$
- It is not possible to describe the data even when varying the scales by a factor of 2

Results: limitations

- The agreement of our calculation with the data for $\langle\cos 2\varphi\rangle/\langle\cos\varphi\rangle$ is good and quite stable with respect to the scales
- The agreement for $\langle\cos n\varphi\rangle$ and $\frac{1}{\sigma}\frac{d\sigma}{d\varphi}$ is not very good and very sensitive to the choice of the renormalization scale μ_R
- An all-order calculation would be independent of the choice of μ_R. This feature is lost if we truncate the perturbative series
  $\Rightarrow$ How to choose the renormalization scale?
  'Natural scale': sometimes the typical momenta in a loop diagram are different from the natural scale of the process

We decided to use the Brodsky-Lepage-Mackenzie (BLM) procedure to fix the renormalization scale

The BLM renormalization scale fixing procedure

The Brodsky-Lepage-Mackenzie (BLM) procedure resums the self-energy corrections to the gluon propagator at one loop into the running coupling.

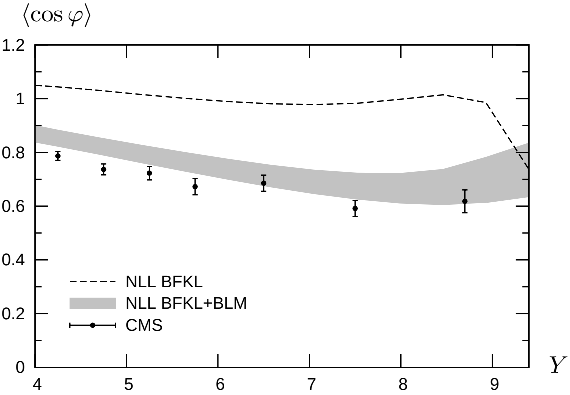
First attempts to apply BLM scale fixing to BFKL processes lead to problematic results. Brodsky, Fadin, Kim, Lipatov and Pivovarov suggested that one should first go to a physical renormalization scheme like MOM and then apply the 'traditional' BLM procedure, i.e. identify the β_0 dependent part and choose μ_R such that it vanishes.

We followed this prescription for the full amplitude at NLL.

BLM procedure globally increases μ of $\alpha_s(\mu)$

Results with BLM

Azimuthal correlation $\langle \cos\varphi \rangle$



$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$

$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

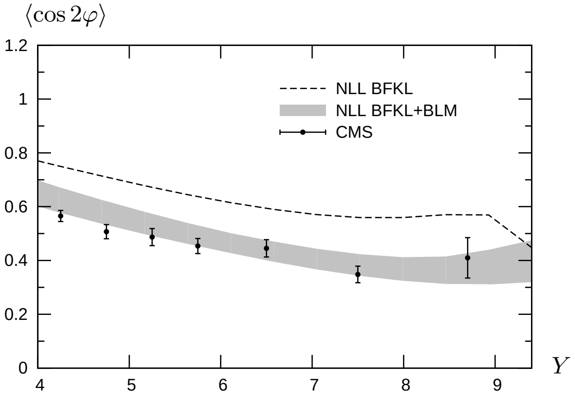
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

Using the BLM scale setting, the agreement with data becomes much better

Results with BLM

Azimuthal correlation $\langle \cos 2\varphi \rangle$



$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$

$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

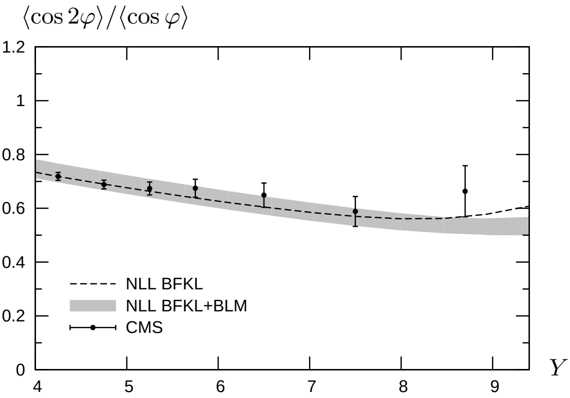
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

Using the BLM scale setting, the agreement with data becomes much better.

Results with BLM

Azimuthal correlation $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$



$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$

$35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$

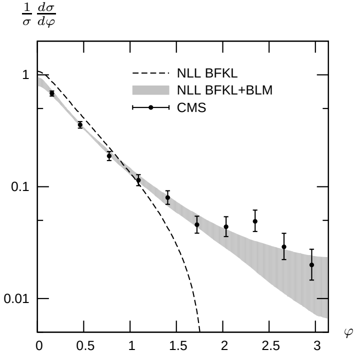
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

Because it is much less dependent on the scales, the observable $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$ is almost not affected by the BLM procedure and is still in good agreement with the data.

Results with BLM

Azimuthal distribution (integrated over $6 < Y < 9.4$)



With the BLM scale setting the azimuthal distribution is in good agreement with the data across the full φ range.

Comparison with fixed-order

Using the BLM scale setting:

- The agreement $\langle \cos n\varphi \rangle$ with the data becomes much better
- The agreement for $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$ is still good and unchanged as this observable is weakly dependent on μ_R
- The azimuthal distribution is in much better agreement with the data

But the configuration chosen by CMS with $\mathbf{k}_{J\min 1} = \mathbf{k}_{J\min 2}$ does not allow us to compare with a fixed-order $\mathcal{O}(\alpha_s^3)$ treatment (i.e. without resummation)

- These calculations are unstable when $\mathbf{k}_{J\min 1} = \mathbf{k}_{J\min 2}$ because the cancellation of some divergencies is difficult to obtain numerically
- Presumably, resummation effects à la Sudakov could be important in the limit $\mathbf{k}_{J1} \simeq \mathbf{k}_{J2}$ and require a special treatment
  Work in progress in collaboration with A. H .Mueller, B-W. Xiao, F. Yuan

Comparison with fixed-order

Results for an asymmetric configuration

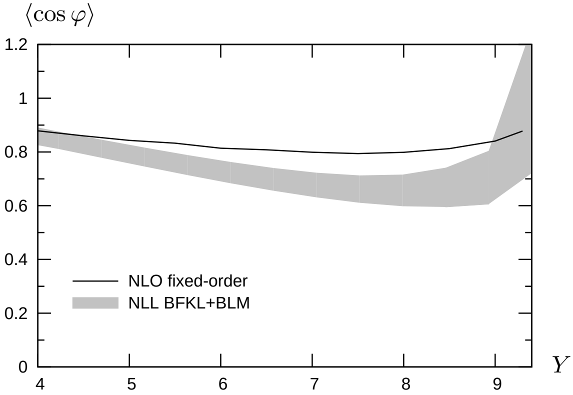
In this section we choose the cuts as

- $35\,\text{GeV} < |\mathbf{k}_{J1}|\,, |\mathbf{k}_{J2}| < 60\,\text{GeV}$
- $50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$
- $0 < |y_1|\,, |y_2| < 4.7$

and we compare our results with the NLO fixed-order code Dijet (Aurenche, Basu, Fontannaz) in the same configuration

Comparison with fixed-order

Azimuthal correlation $\langle \cos \varphi \rangle$



$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$

$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

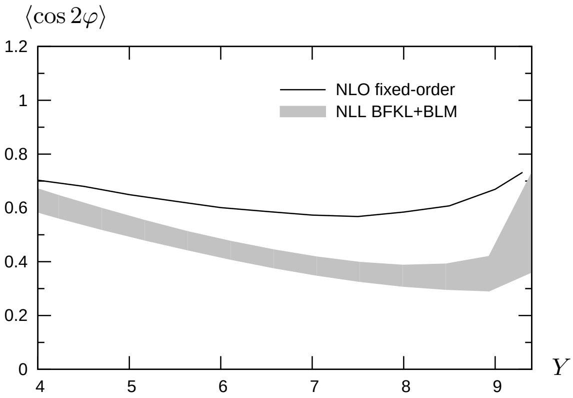
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

The NLO fixed-order and NLL BFKL+BLM calculations are very close

Comparison with fixed-order

Azimuthal correlation $\langle \cos 2\varphi \rangle$



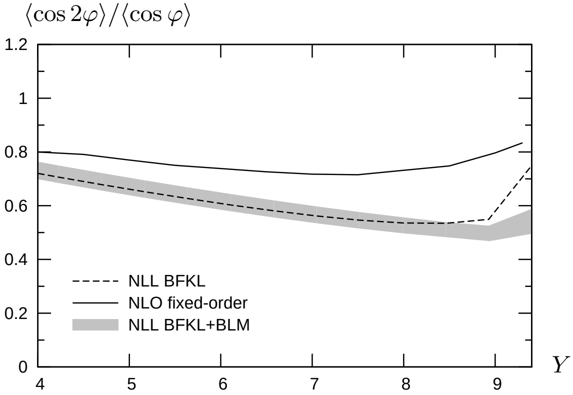
$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

The BLM procedure leads to a sizable difference between NLO fixed-order and NLL BFKL+BLM.

Comparison with fixed-order

Azimuthal correlation $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$

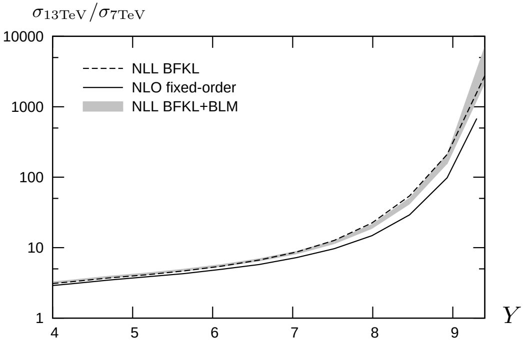


$$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$$
$$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$$
$$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$$
$$0 < |y_1| < 4.7$$
$$0 < |y_2| < 4.7$$

Using BLM or not, there is a sizable difference between BFKL and fixed-order.

Comparison with fixed-order

Cross section: 13 TeV vs. 7 TeV



$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

- In a BFKL treatment, a strong rise of the cross section with increasing energy is expected.
- This rise is faster than in a fixed-order treatment

Energy-momentum conservation

- It is necessary to have $\mathbf{k}_{J\min 1} \neq \mathbf{k}_{J\min 2}$ for comparison with fixed order calculations but this can be problematic for BFKL because of energy-momentum conservation
- There is no strict energy-momentum conservation in BFKL
- This was studied at LO by Del Duca and Schmidt. They introduced an effective rapidity $Y_{\rm eff}$ defined as

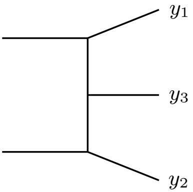
$$Y_{\rm eff} \equiv Y \frac{\sigma^{2\to 3}}{\sigma^{\rm BFKL, \mathcal{O}(\alpha_s^3)}}$$

- When one replaces Y by $Y_{\rm eff}$ in the expression of $\sigma^{\rm BFKL}$ and truncates to $\mathcal{O}(\alpha_s^3)$, the exact $2 \to 3$ result is obtained

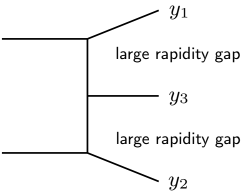
Energy-momentum conservation

We follow the idea of Del Duca and Schmidt, adding the NLO jet vertex contribution:

exact $2 \to 3$



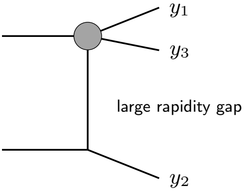
BFKL



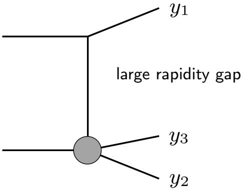
one emission from the Green's function + LO jet vertex

we have to take into account these additional $\mathcal{O}(\alpha_s^3)$ contributions:

+



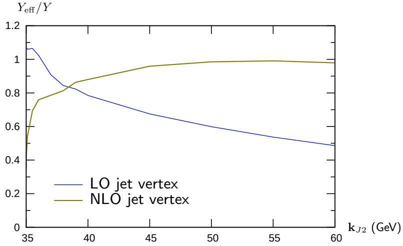
+



no emission from the Green's function + NLO jet vertex

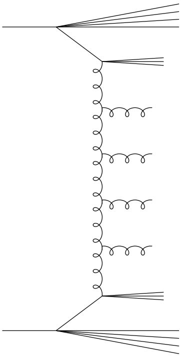
Energy-momentum conservation

Variation of $Y_{\rm eff}/Y$ as a function of $\mathbf{k}_{J2}$ for fixed $\mathbf{k}_{J1} = 35$ GeV (with $\sqrt{s} = 7$ TeV, $Y = 8$):

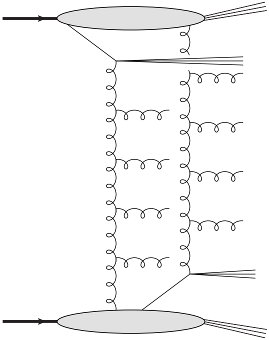


- With the LO jet vertex, $Y_{\rm eff}$ is much smaller than Y when $\mathbf{k}_{J1}$ and $\mathbf{k}_{J2}$ are significantly different
- This is the region important for comparison with fixed order calculations
- The improvement coming from the NLO jet vertex is very large in this region
- For $\mathbf{k}_{J1} = 35$ GeV and $\mathbf{k}_{J2} = 50$ GeV, typical of the values we used for comparison with fixed order, we get $\frac{Y_{\rm eff}}{Y} \simeq 0.98$ at NLO vs. ~ 0.6 at LO

Can Mueller-Navelet jets be a manifestation of multiparton interactions?



+



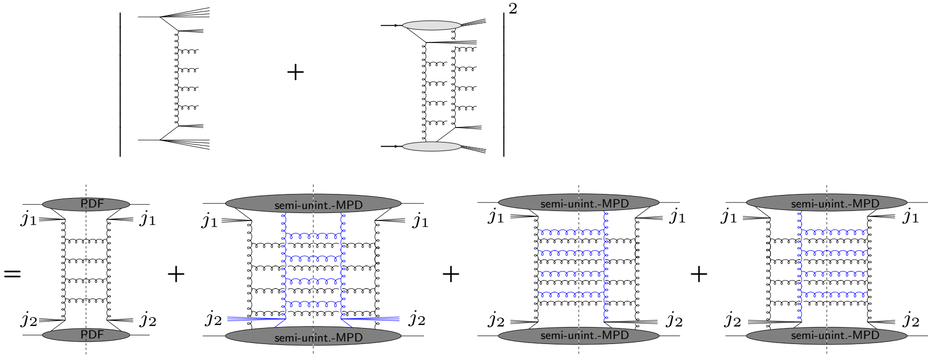
MN jets in the single partonic model

MN jets in MPI

here MPI = DPS (double parton scattering)

see also Maciula and Szczurek Phys. Rev. D90

Can Mueller-Navelet jets be a manifestation of multiparton interactions?



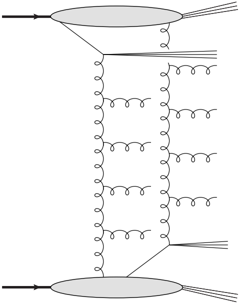
single $\mathbb{P}$ ladder — two $\mathbb{P}$ ladders — interferences

scaling: $s^{\alpha_{\mathbb{P}}}$ — $(??)\ s^{2\alpha_{\mathbb{P}}}$ — ??

- The twist counting is not easy for MPI kinds of contributions at small x
- $k_{\perp 1,2}$ are not integrated $\Rightarrow$ MPI may be competitive, and enhanced by small-x resummation
- Interference terms are not governed by BJKP (this is not a fully interacting 3-reggeons system) (for BJKP, $\alpha_{\mathbb{P}} < 1 \Rightarrow$ suppressed)

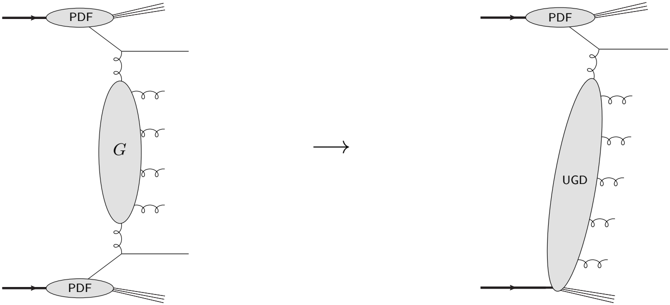
A phenomenological test: the problem

- Simplification: we neglect any interference contribution between the two mechanisms
- How to evaluate the DPS contribution?



- This would require some kind of "hybrid" double parton distributions, with
  - one collinear parton
  - one off-shell parton (with some $k_\perp$)
- Almost nothing is known on such distributions

A phenomenological test: our ansatz



Mueller-Navelet jets production at LL accuracy   Inclusive forward jet production

Factorized ansatz for the DPS contribution:

$$\sigma_{\mathrm{DPS}} = \frac{\sigma_{\mathrm{fwd}}\ \sigma_{\mathrm{bwd}}}{\sigma_{\mathrm{eff}}}$$

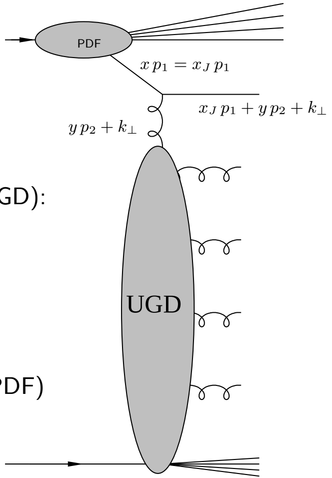
Tevatron, LHC: $\sigma_{\mathrm{eff}} \simeq 15$ mb

To account for some discrepancy between various measurements, we take

$$\sigma_{\mathrm{eff}} \simeq 10 - 20 \text{ mb}$$

A phenomenological test: our ansatz

At LO for the jet vertex:



($y = \frac{\mathbf{k}_J^2}{s x_J}$: on-shell cond.)

unintegrated gluon distribution (UGD):

$\mathcal{F}_g\left(\frac{\mathbf{k}_J^2}{s\,x_J}, |\mathbf{k}_J|\right)$

normalized according to:

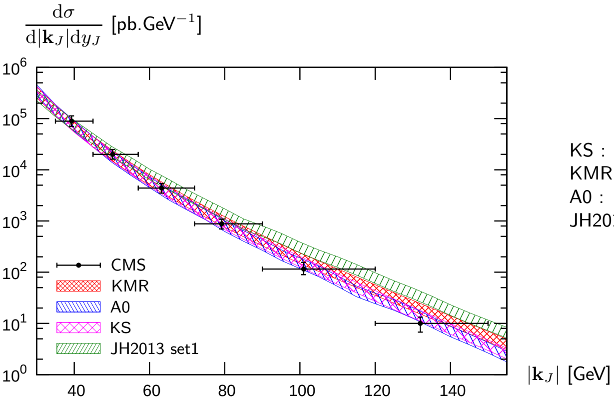
$\int \mathrm{d}\mathbf{k}^2 \mathcal{F}_g(x, |\mathbf{k}|) = x f_g(x)$ (usual PDF)

inclusive forward jet cross-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\mathbf{k}_J|\mathrm{d}y_J} = K\,\frac{\alpha_s}{|\mathbf{k}_J|}\,x_J\,(C_F\,f_q(x_J) + C_A\,f_g(x_J))\,\mathcal{F}_g\left(\frac{\mathbf{k}_J^2}{s\,x_J}, |\mathbf{k}_J|\right)$$

A phenomenological test

- We use CMS data at $\sqrt{s} = 7$ TeV, $3.2 < |y_J| < 4.7$
- We use various parametrization for the UGD
- For each parametrization we determine the range of K compatible with the CMS measurement in the lowest transverse momentum bin



	K_{min}	K_{max}
KS :	1.20	1.94
KMR :	1.05	1.69
A0 :	4.27	6.89
JH2013 :	2.44	3.94

$$\frac{d\sigma}{d|\mathbf{k}_J|dy_J} = K \frac{\alpha_s}{|\mathbf{k}_J|} x_J \left(C_F f_q(x_J) + C_A f_g(x_J)\right) \mathcal{F}_g\left(\frac{\mathbf{k}_J^2}{s\, x_J}, |\mathbf{k}_J|\right)$$

SPS vs DPS: Results — symmetric configuration

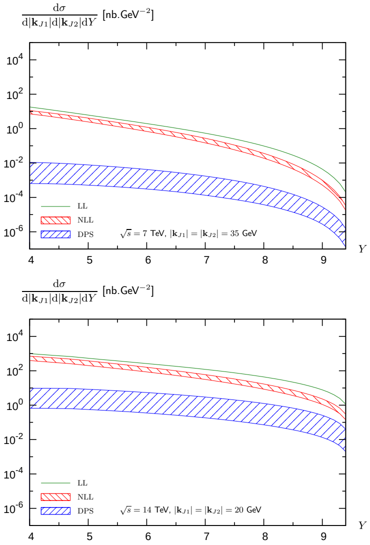
We will focus on four choices of kinematical cuts:

- $\sqrt{s} = 7$ TeV, $|\mathbf{k}_{J1}| = |\mathbf{k}_{J2}| = 35$ GeV,
  (like in the CMS analysis for azimuthal correlations of MN jets)
- $\sqrt{s} = 14$ TeV, $|\mathbf{k}_{J1}| = |\mathbf{k}_{J2}| = 35$ GeV,
- $\sqrt{s} = 14$ TeV, $|\mathbf{k}_{J1}| = |\mathbf{k}_{J2}| = 20$ GeV,
- $\sqrt{s} = 14$ TeV, $|\mathbf{k}_{J1}| = |\mathbf{k}_{J2}| = 10$ GeV $\leftarrow$ highest DPS effect expected

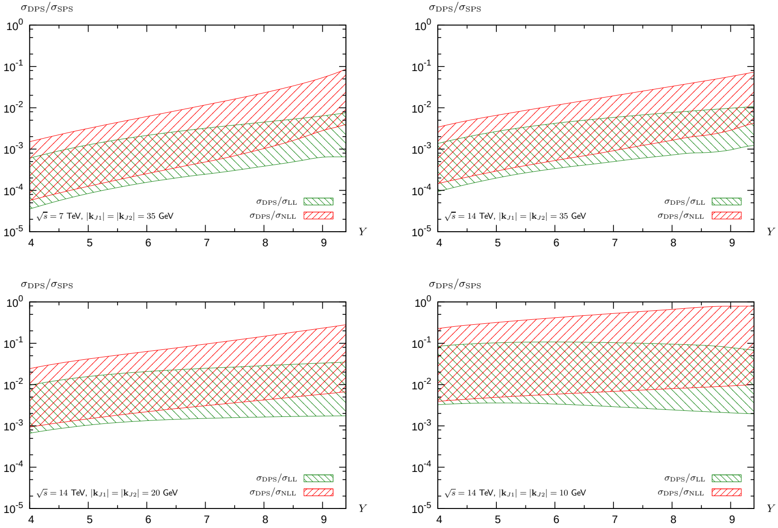
parameters:

- $0 < y_{J,1} < 4.7$ and $-4.7 < y_{J,2} < 0$
- MSTW 2008 parametrization for PDFs
- In the case of the NLL BFKL calculation, anti-k_t jet algorithm with $R = 0.5$.

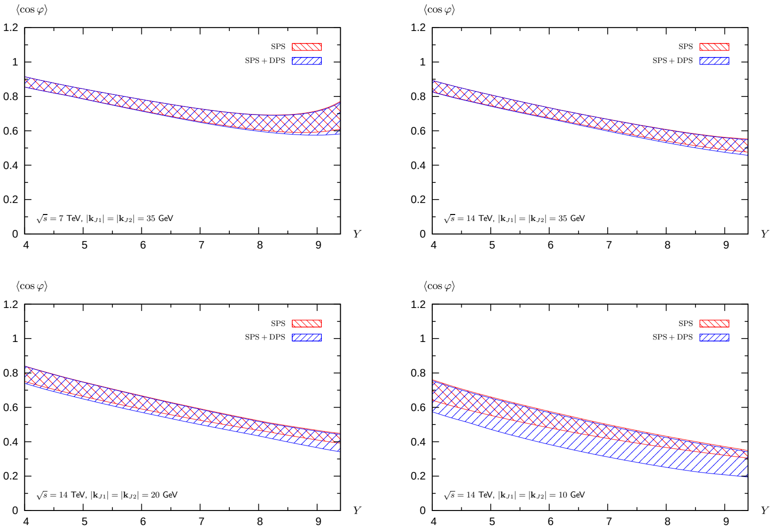
SPS vs DPS: cross-sections



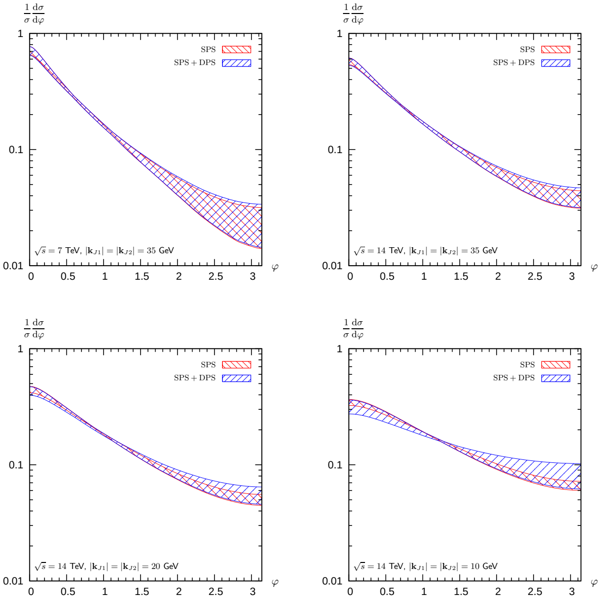
SPS vs DPS: cross-sections (ratios)



SPS vs DPS: Azimuthal correlations

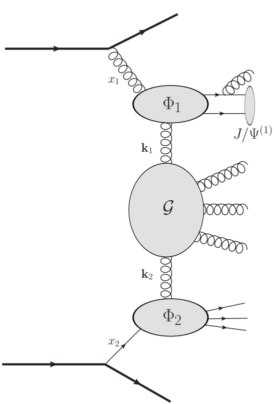


SPS vs DPS: Azimuthal distributions

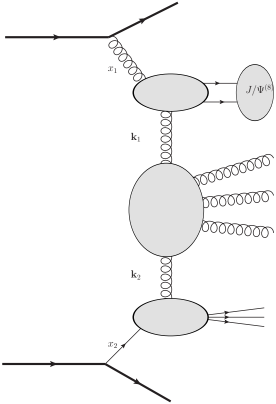


$$8 < Y < 9.4$$

Inclusive production of a forward J/ψ + a backward jet



Color singlet mechanism



Color octet mechanism

- Hard scales: $\mathbf{k}_J$ and $M_{J/\psi}$
- Very promising at ATLAS (and CMS?)
- To be studied: cross-section study and azimuthal correlation

Work in progress with LO vertex + NLO BFKL Green function
R. Boussarie, B. Ducloué, L. Sz., S. Wallon.

Conclusions

- We studied Mueller-Navelet jets at full (vertex + Green's function) NLL BFKL accuracy and compared our results with the first data from the LHC
- The agreement with CMS data at 7 TeV is greatly improved by using the BLM scale fixing procedure
- $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$ is almost not affected by BLM and shows a clear difference between NLO fixed-order and NLL BFKL in an asymmetric configuration
- Energy-momentum conservation seems to be less severely violated with the NLO jet vertex
- We studied the effect of DPS contributions which could mimic the MN jet
    - For cross-sections: The uncertainty on DPS is very large. Still, $\sigma_{DPS} < \sigma_{SPS}$ in the LHC kinematics
    - For angular correlations: including DPS does not significantly modify our NLL BFKL prediction
    - For low $\mathbf{k}_J$ and large Y, the effect of DPS can become larger than the uncertainty on the NLL BFKL calculation. One should focus on this region experimentally.

THANK YOU FOR YOUR ATTENTION

Backup

for $\mathbf{k}_{J1} = \mathbf{k}_{J2} = 35$GeV

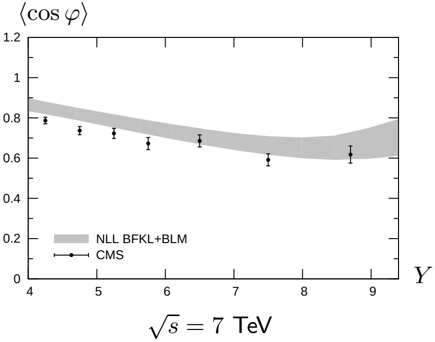
$Y \sim 4$ $\qquad \frac{G}{Q} \approx 5 - 10$

$Y \sim 7$ $\qquad \frac{G}{Q} \approx 1$

$Y \sim 9$ $\qquad \frac{Q}{G} \approx 5 - 10$

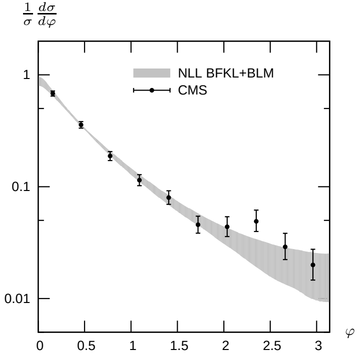
large Y large x

Azimuthal correlation $\langle \cos\varphi \rangle$

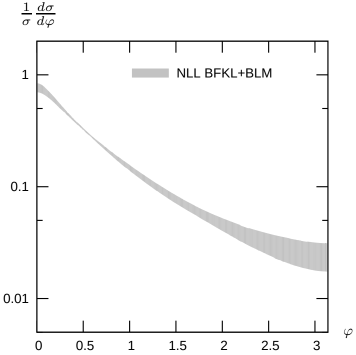


The behavior is similar at 13 TeV and at 7 TeV

Azimuthal distribution (integrated over $6 < Y < 9.4$)



$\sqrt{s} = 7$ TeV

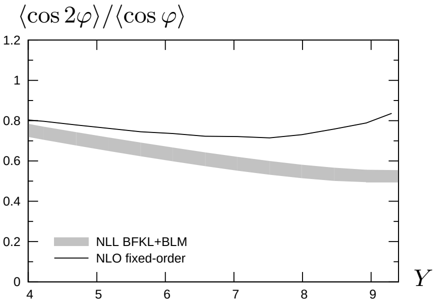


$\sqrt{s} = 13$ TeV

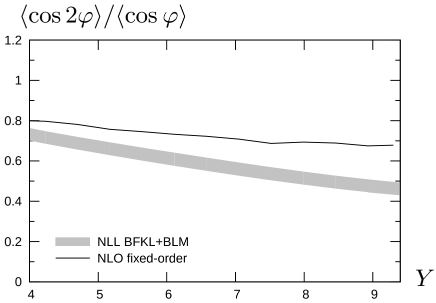
The behavior is similar at 13 TeV and at 7 TeV

Azimuthal correlation $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$

(asymmetric configuration)



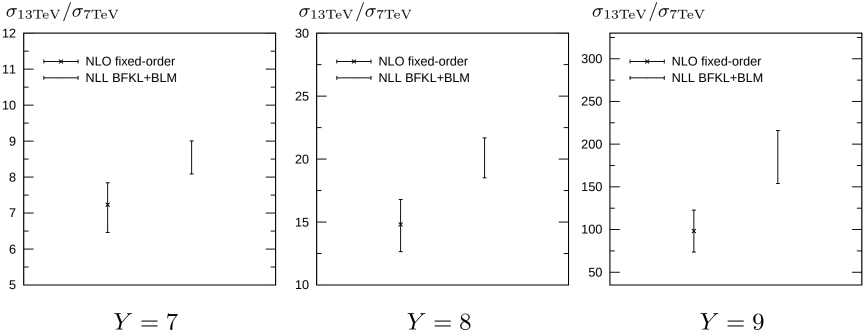
$\sqrt{s} = 7$ TeV



$\sqrt{s} = 13$ TeV

The difference between BFKL and fixed-order is smaller at 13 TeV than at 7 TeV

Cross section



Master formulas

It is useful to define the coefficients $\mathcal{C}_n$ as

$$\mathcal{C}_n \equiv \int \mathrm{d}\phi_{J1}\, \mathrm{d}\phi_{J2}\, \cos\left(n(\phi_{J1} - \phi_{J2} - \pi)\right)$$
$$\times \int \mathrm{d}^2\mathbf{k}_1\, \mathrm{d}^2\mathbf{k}_2\, \Phi(\mathbf{k}_{J1}, x_{J1}, -\mathbf{k}_1)\, G(\mathbf{k}_1, \mathbf{k}_2, \hat{s})\, \Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2)$$

- $n = 0 \implies$ differential cross-section

$$\mathcal{C}_0 = \frac{\mathrm{d}\sigma}{\mathrm{d}|\mathbf{k}_{J1}|\, \mathrm{d}|\mathbf{k}_{J2}|\, \mathrm{d}y_{J1}\, \mathrm{d}y_{J2}}$$

- $n > 0 \implies$ azimuthal decorrelation

$$\frac{\mathcal{C}_n}{\mathcal{C}_0} = \langle \cos\left(n(\phi_{J,1} - \phi_{J,2} - \pi)\right)\rangle \equiv \langle \cos(n\varphi)\rangle$$

- sum over $n \implies$ azimuthal distribution

$$\frac{1}{\sigma}\frac{d\sigma}{d\varphi} = \frac{1}{2\pi}\left\{1 + 2\sum_{n=1}^{\infty} \cos(n\varphi)\, \langle \cos(n\varphi)\rangle\right\}$$