Looking for BFKL effects at the LHC with Mueller-Navelet jets

Bertrand Ducloué
(Laboratoire de Physique Théorique, Orsay)

Small x mini workshop

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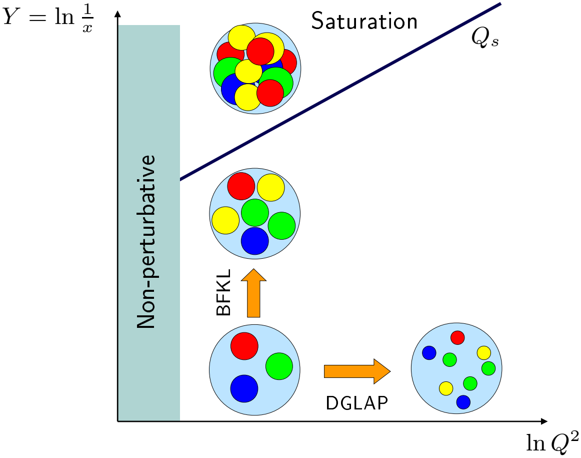
in collaboration with
L. Szymanowski (NCBJ Warsaw), S. Wallon (UPMC & LPT Orsay)

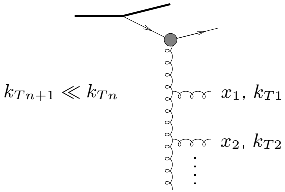
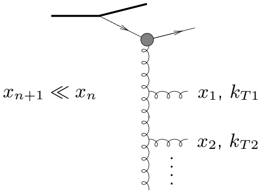
B. D, L. Szymanowski, S. Wallon, JHEP **1305** (2013) 096 [arXiv:1302.7012 [hep-ph]]
B. D, L. Szymanowski, S. Wallon, arXiv:1309.3229 [hep-ph] (to appear in PRL)

The different regimes of QCD



Resummation in QCD: DGLAP vs BFKL

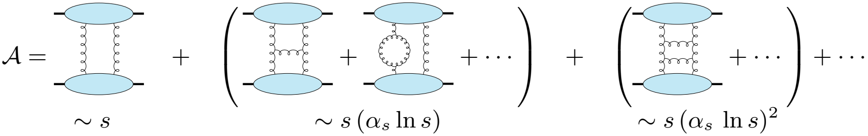
Small values of α_s (perturbation theory applies if there is a hard scale) can be compensated by large logarithmic enhancements.

DGLAP	BFKL
	
strong ordering in k_T	strong ordering in x
$\sum(\alpha_s \ln Q^2)^n$	$\sum(\alpha_s \ln s)^n$

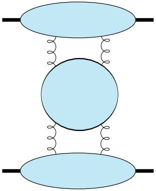
When $\sqrt{s}$ becomes very large, it is expected that a BFKL description is needed to get accurate predictions

QCD in the perturbative Regge limit

The amplitude can be written as:



this can be put in the following form :



$\leftarrow$ Impact factor

$\leftarrow$ Green's function

$\leftarrow$ Impact factor

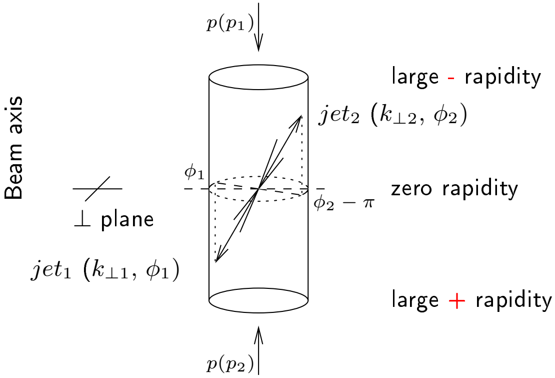
Higher order corrections

- 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

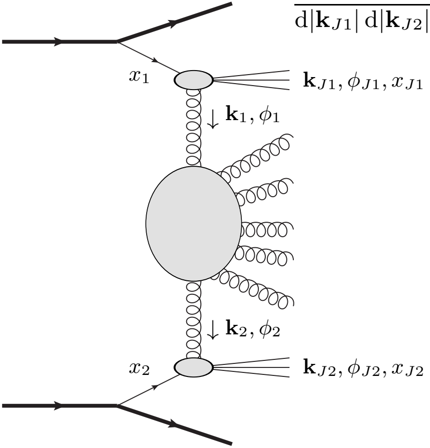
- impact factors are known in some cases at NLL
  - $\gamma^* \to \gamma^*$ at $t = 0$ (Bartels, Colferai, Gieseke, Kyrieleis, Qiao; Balitski, Chirilli)
  - forward jet production (Bartels, Colferai, Vacca; Caporale, Ivanov, Murdaca, Papa, Perri; Chachamis, Hentschinski, Madrigal, Sabio Vera)
  - inclusive 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

- 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
- in a 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 $k_{\perp 1}{=}k_{\perp 2}$. There is no phase space for (untagged) emission between them



k_T-factorized differential cross section



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

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

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

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

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

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

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

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

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

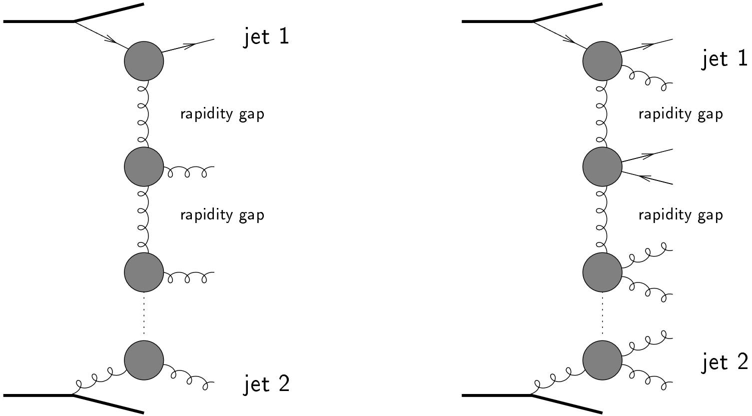
- $n > 0 \Longrightarrow$ azimuthal decorrelation

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

- sum over $n \Longrightarrow$ azimuthal distribution

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

LL BFKL | NLL BFKL



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

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

Results for a symmetric configuration

In the following we show results for

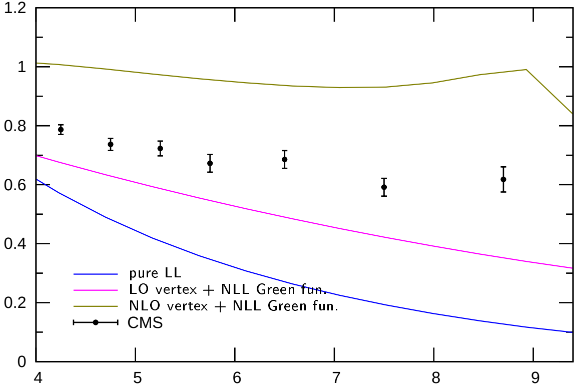
- $\sqrt{s} = 7$ TeV
- $35\,\mathrm{GeV} < |\mathbf{k}_{J1}|\,, |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
- $0 < y_1\,, y_2 < 4.7$

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 don't depend on this cut significantly.

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

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



$Y \equiv y_1 + y_2$

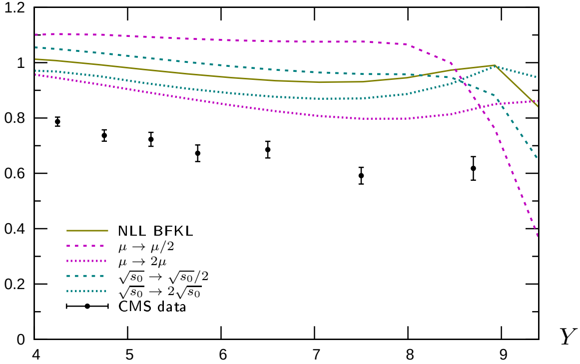
$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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

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

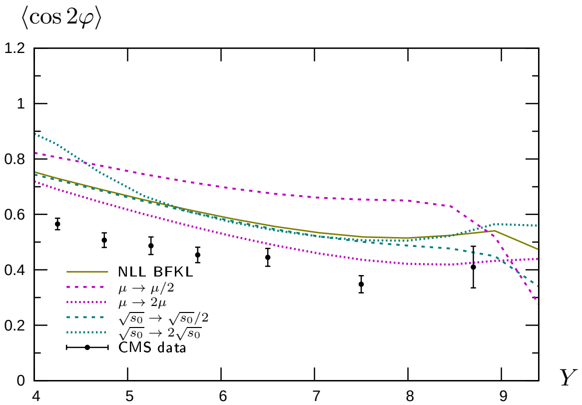


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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

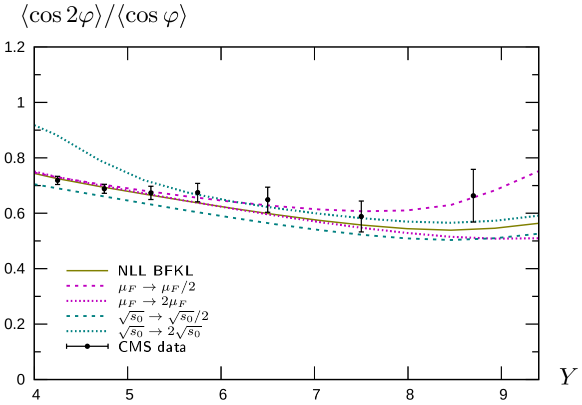


$35\,\mathrm{GeV} < |\mathbf{k}_{J1}| < 60\,\mathrm{GeV}$
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

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

- 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

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

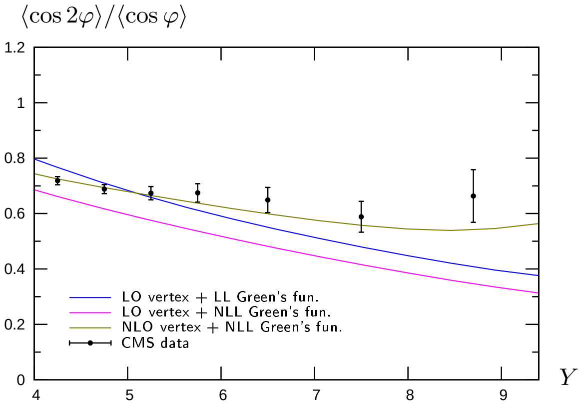


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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



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

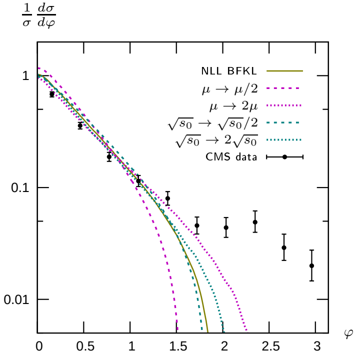
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

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

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



- 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

- 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

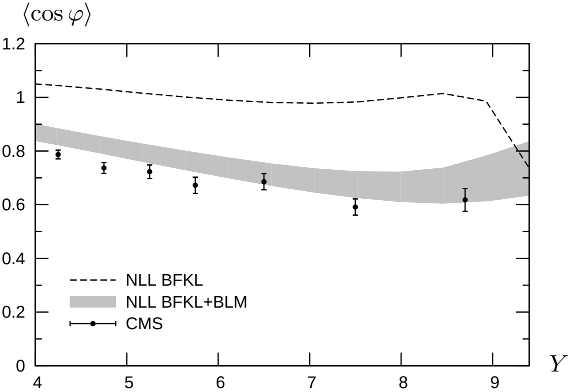
We decided to use the Brodsky-Lepage-Mackenzie (BLM) procedure to fix the renormalization scale

The Brodsky-Lepage-Mackenzie (BLM) procedure resums the self-energy corrections to the gluon propagator at one loop into the running coupling. These contributions are formally of higher-order but they are proportional to $\beta_0 = \frac{11N_c - 2N_f}{3} \simeq 7.67$

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 find a scale which is typically about 5 times larger than $\sqrt{|\mathbf{k}_{J1}| \cdot |\mathbf{k}_{J2}|}$

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

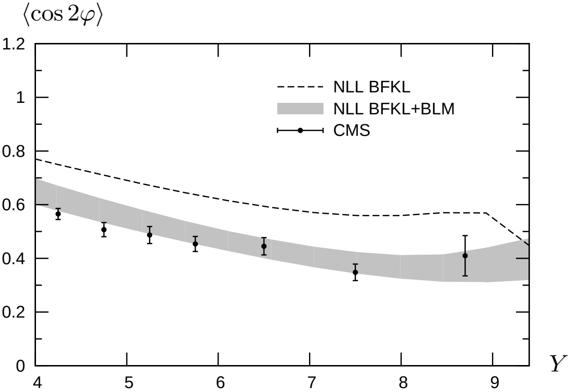


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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

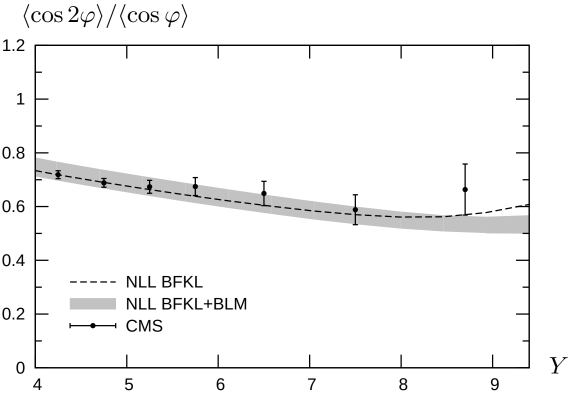


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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

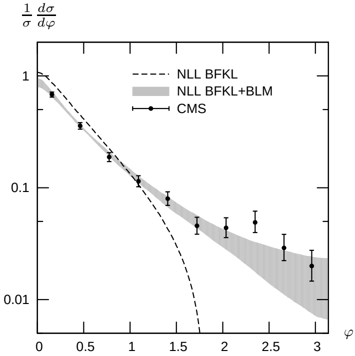


$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
$35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$

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

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

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.

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 $\mathbf{k}_{J\mathrm{min}1} = \mathbf{k}_{J\mathrm{min}2}$ 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 $\mathbf{k}_{J\mathrm{min}1} = \mathbf{k}_{J\mathrm{min}2}$ because the cancellation of some divergencies is difficult to obtain numerically

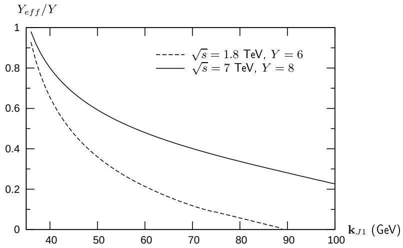
An asymmetric configuration is necessary for fixed order but can be problematic for BFKL: a BFKL calculation does not preserve energy-momentum conservation.

This was studied at LL by Del Duca and Schmidt. They introduced an effective rapidity Y_{eff} defined as

$$Y_{eff} \equiv Y \frac{\int d\phi \cos(n\phi) \frac{d\sigma^{\mathcal{O}(\alpha^3)}}{dy_1 dy_2 d\mathbf{k}_{J1} d\mathbf{k}_{J2}}}{\int d\phi \cos(n\phi) \frac{d\sigma^{\mathrm{BFKL}}}{dy_1 dy_2 d\mathbf{k}_{J1} d\mathbf{k}_{J2}}}$$

When one replaces Y by Y_{eff} in the expression of $\mathcal{C}_n$ and truncates to $\mathcal{O}(\alpha^3)$, the exact $2 \to 3$ result is obtained

Variation of Y_{eff}/Y as a function of $\mathbf{k}_{J2}$ for fixed $\mathbf{k}_{J1} = 35$ GeV:



- When $\mathbf{k}_{J1}$ and $\mathbf{k}_{J2}$ are close, Y_{eff} is close to 1 $\rightarrow$ this effect should not be very important when $\mathbf{k}_{J\min 1} = \mathbf{k}_{J\min 2}$
- Y_{eff} decreases quickly when the difference between $\mathbf{k}_{J1}$ and $\mathbf{k}_{J2}$ increases
- Y_{eff} is closer to Y when going to higher energies and/or rapidities
- One can hope that the effect is less severe at NLL (work in progress)

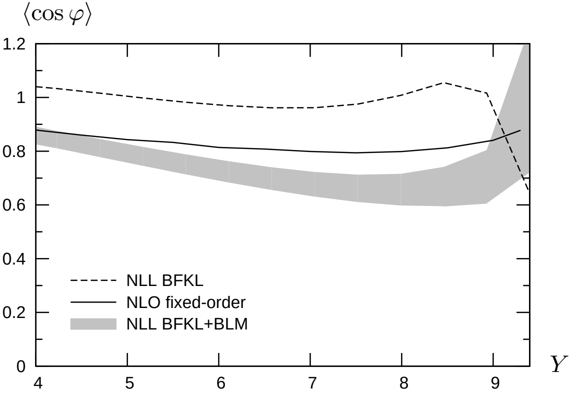
Results for an asymmetric configuration

In this section we choose the cuts as

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

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

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



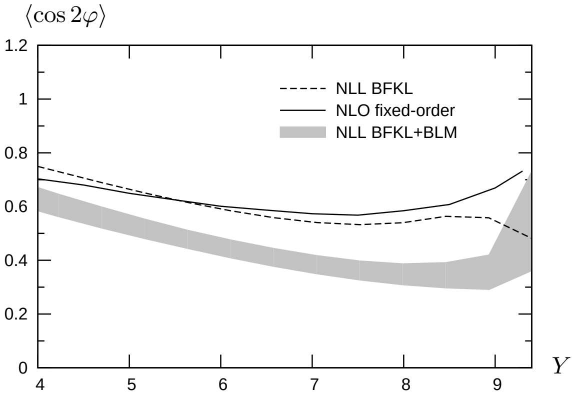
$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

- As in the symmetric case, the BLM procedure strongly modifies the result of our BFKL calculation
- The NLO fixed-order and NLL BFKL+BLM calculations are very close

Comparison with fixed-order

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



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

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

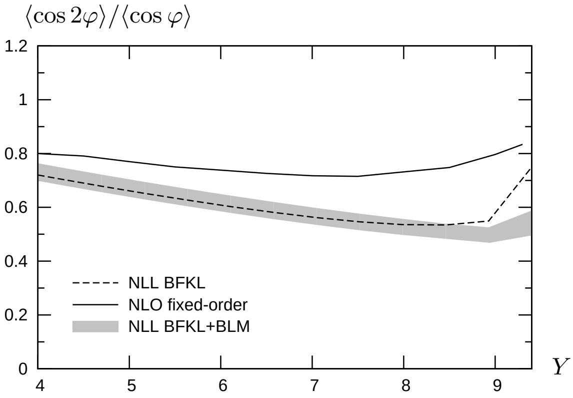
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

- As in the symmetric case, the BLM procedure strongly modifies the result of our BFKL calculation
- The BLM procedure leads to a larger difference between NLO fixed-order and NLL BFKL+BLM

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



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

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

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

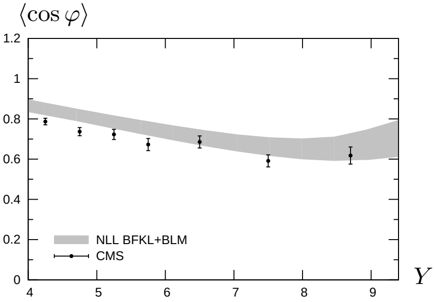
$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

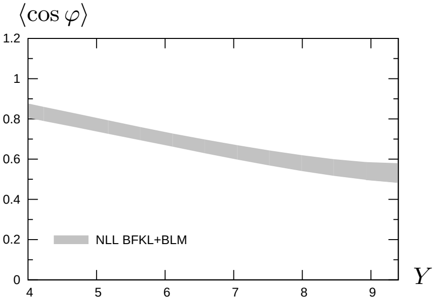
Using BLM or not, there is a sizable difference between BFKL and fixed-order

- With upcoming LHC data at higher energies, we could look for BFKL effects comparing with results at 7 TeV
- We reproduced our analysis with $\sqrt{s} = 13$ TeV with the same cuts:
  - $35\,\mathrm{GeV} < |\mathbf{k}_{J1}|\,,|\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
  - $50\,\mathrm{GeV} < \mathrm{Max}(|\mathbf{k}_{J1}|,|\mathbf{k}_{J2}|)$ (for asymmetric configuration)
  - $0 < y_1\,,y_2 < 4.7$
- Energy-momentum conservation should be less problematic because of the larger energy

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



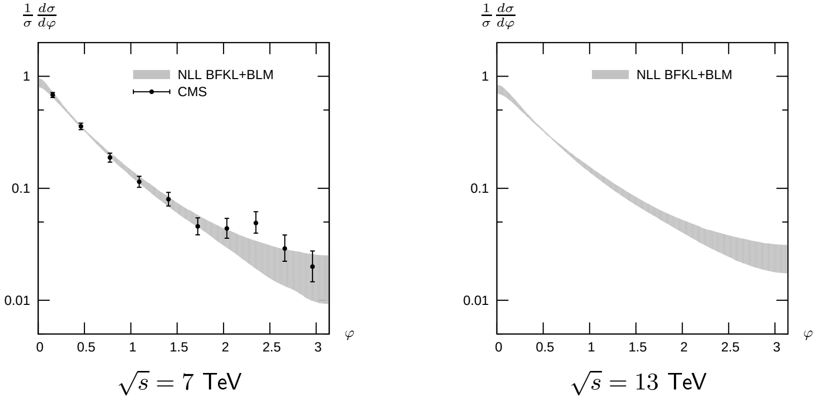
$\sqrt{s} = 7$ TeV



$\sqrt{s} = 13$ TeV

The behavior is similar at 13 TeV and at 7 TeV

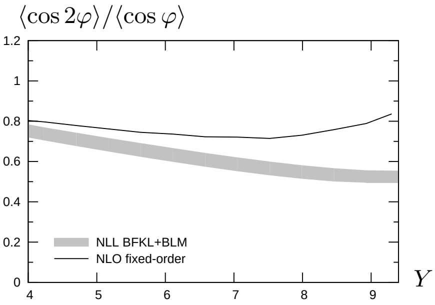
Azimuthal distribution (integrated over $6 < Y < 9.4$)



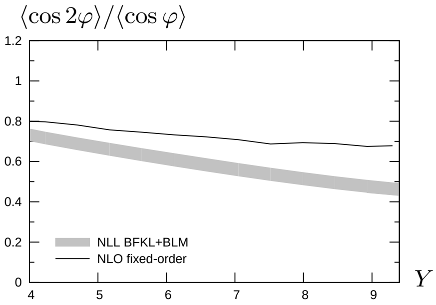
The behavior is similar at 13 TeV and at 7 TeV

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

(asymmetric configuration)



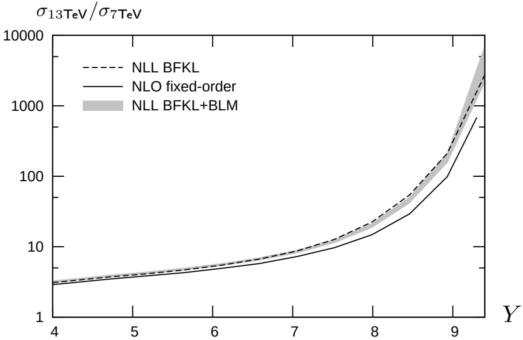
$\sqrt{s} = 7$ TeV



$\sqrt{s} = 13$ TeV

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

Cross section



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

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

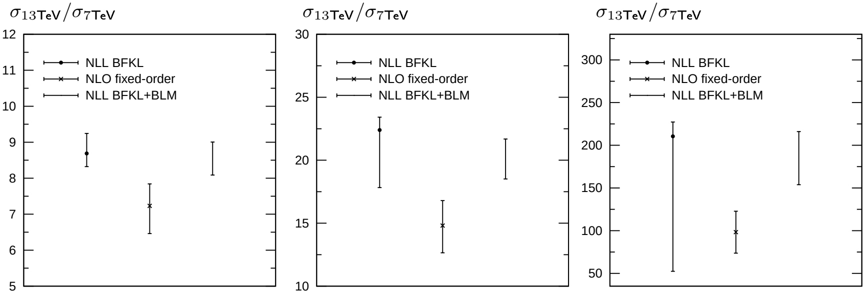
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

- 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

Cross section



$Y = 7$ $\quad$ $Y = 8$ $\quad$ $Y = 9$

Taking into account the scales and PDFs uncertainties, the difference between BFKL and fixed order is quite small

- We studied Mueller-Navelet jets at full (vertex + Green's function) NLL 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 but one should be careful because of energy-momentum conservation issues
- We did the same analysis at 13 TeV:
  - Azimuthal decorrelations don't show a very different behavior at 13 TeV compared to 7 TeV
  - NLL BFKL predicts a stronger rise of the cross section with increasing energy than a NLO fixed-order calculation