High-energy resummation effects in Mueller-Navelet jet production at the LHC

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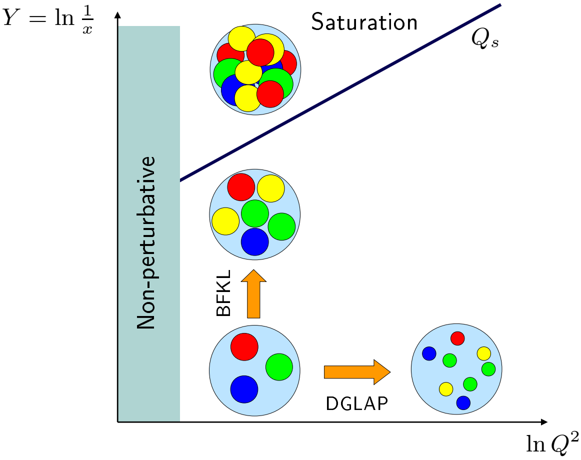
D. Colferai, F. Schwennsen, L. Szymanowski, S. W., JHEP 1012 (2010) 026 [arXiv:1002.1365 [hep-ph]]

B. Ducloué, L. Szymanowski, S. W., JHEP 1305 (2013) 096 [arXiv:1302.7012 [hep-ph]]

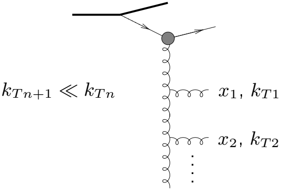
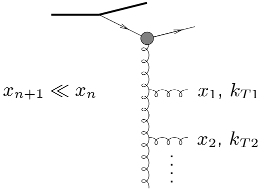
B. Ducloué, L. Szymanowski, S. W., PRL 112 (2014) 082003 [arXiv:1309.3229 [hep-ph]]

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.

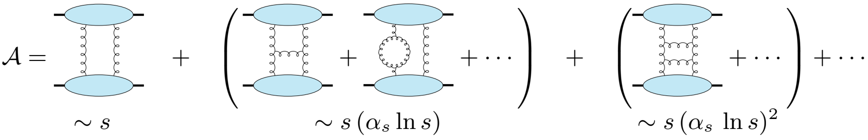
DGLAP	BFKL
	
strong ordering in k_T	strong ordering in x
$\sum(\alpha_s \ln Q^2)^n$	$\sum(\alpha_s \ln s)^n$

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

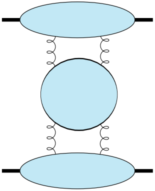
The specific case of QCD at large s

QCD in the perturbative Regge limit

The amplitude can be written as:



this can be put in the following form :



← Impact factor

← Green's function

← Impact factor

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

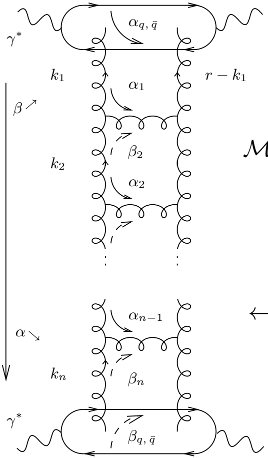
with $\alpha_{\mathbb{P}}(0) - 1 = C\,\alpha_s + +C'\,\alpha_s^2 + \cdots$

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

Balitsky, Fadin, Kuraev, Lipatov

Opening the boxes: Impact representation $\gamma^* \gamma^* \to \gamma^* \gamma^*$ as an example

- Sudakov decomposition: $k_i = \alpha_i \, p_1 + \beta_i \, p_2 + k_{\perp i} \quad (p_1^2 = p_2^2 = 0, \; 2p_1 \cdot p_2 = s)$
- write $\quad d^4 k_i = \frac{s}{2} \, d\alpha_i \, d\beta_i \, d^2 k_{\perp i} \quad$ ($\underline{k}$ = Eucl. $\leftrightarrow$ $k_\perp$ = Mink.)
- $t-$channel gluons have non-sense polarizations at large s: $\epsilon_{NS}^{up/down} = \frac{2}{s} \, p_{2/1}$



$\Rightarrow$ set $\alpha_1 = 0$ and $\int d\beta_1 \;\; \Rightarrow \;\; \Phi^{\gamma^* \to \gamma^*}(\underline{k}_1, \underline{r} - \underline{k}_1)$
impact factor

$$\mathcal{M} = \frac{is}{(2\pi)^2} \int \frac{d^2\underline{k}}{\underline{k}^2} \, \Phi^{up}(\underline{k}, \, \underline{r} - \underline{k}) \int \frac{d^2\underline{k}'}{\underline{k}'^2} \, \Phi^{down}(-\underline{k}', \, -\underline{r} + \underline{k}')$$
$$\times \int_{\delta - i\infty}^{\delta + i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0} \right)^{\omega} G_\omega(\underline{k}, \underline{k}', \underline{r})$$

$\longleftarrow$ multi-Regge kinematics

$\Rightarrow$ set $\beta_n = 0$ and $\int d\alpha_n \;\; \Rightarrow \;\; \Phi^{\gamma^* \to \gamma^*}(-\underline{k}_n, -\underline{r} + \underline{k}_n)$

Higher order corrections

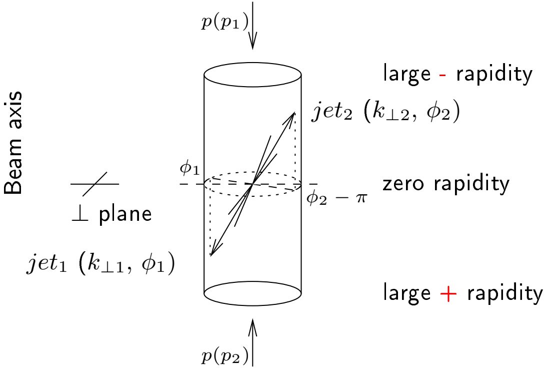
- Higher order corrections to BFKL kernel are known at NLL order (Lipatov Fadin; Camici, Ciafaloni), now for arbitrary impact parameter
  $\alpha_S \sum_n (\alpha_S \ln s)^n$ resummation

- 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

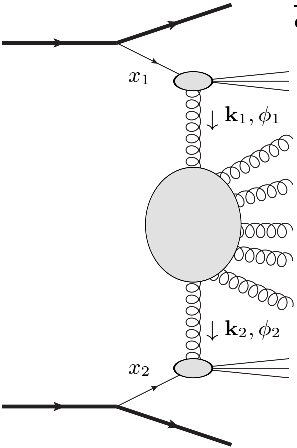
Mueller-Navelet jets

- 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

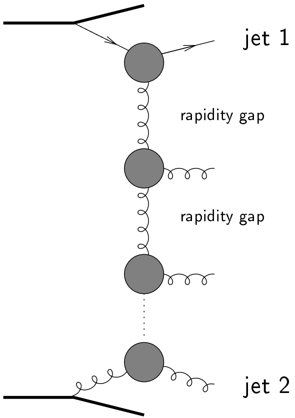


$$\frac{d\sigma}{d|\mathbf{k}_{J1}|\, d|\mathbf{k}_{J2}|\, dy_{J1}\, dy_{J2}} = \int d\phi_{J1}\, d\phi_{J2} \int d^2\mathbf{k}_1\, d^2\mathbf{k}_2 \times \Phi(\mathbf{k}_{J1}, x_{J1}, -\mathbf{k}_1) \times G(\mathbf{k}_1, \mathbf{k}_2, \hat{s}) \times \Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2)$$

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 $\quad x_J = \frac{|\mathbf{k}_J|}{\sqrt{s}} e^{y_J}$

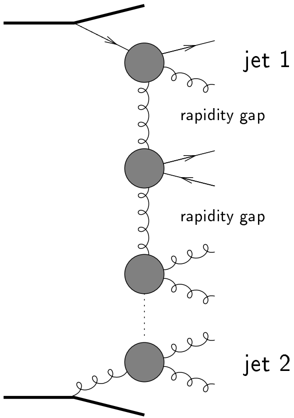
Mueller-Navelet jets: LL vs NLL

LL BFKL



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

NLL BFKL



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

Results

Results for a symmetric configuration

In the following we show results for

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

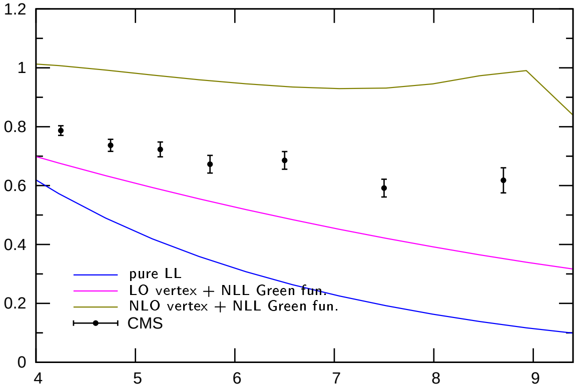
These cuts allow us to compare our predictions with the first experimental data on azimuthal correlations of Mueller-Navelet jets at the LHC presented by the CMS collaboration (CMS-PAS-FSQ-12-002)

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 $\langle \cos\varphi \rangle$

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



$Y \equiv |y_1 - y_2|$

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

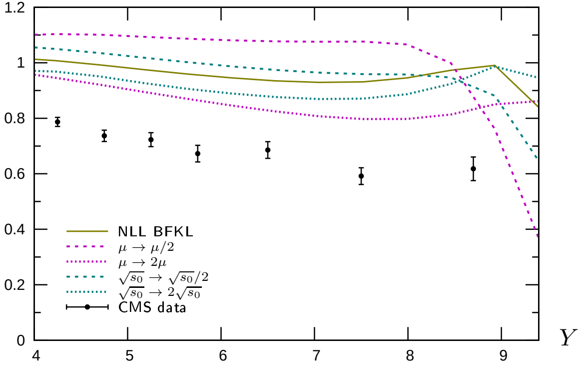
$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

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

Results: azimuthal correlations

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

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



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

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

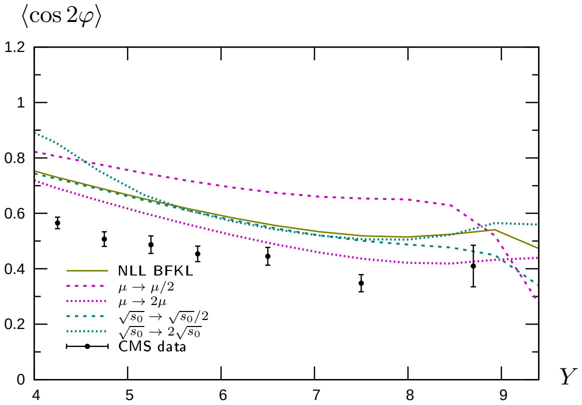
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

Results: azimuthal correlations

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



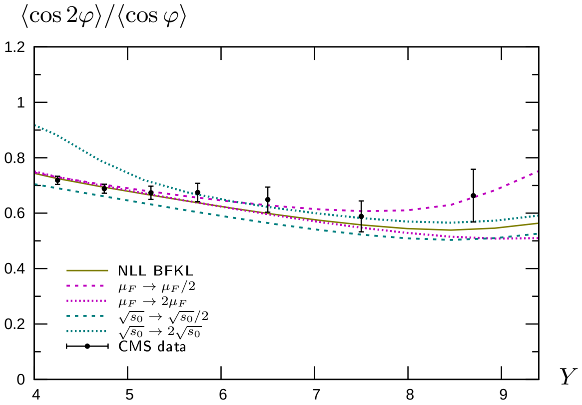
$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
$35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$

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

- 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 $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$



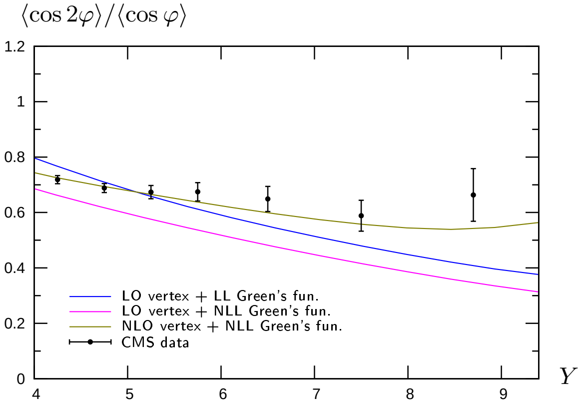
$35\ \text{GeV} < |\mathbf{k}_{J1}| < 60\ \text{GeV}$
$35\ \text{GeV} < |\mathbf{k}_{J2}| < 60\ \text{GeV}$

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

- 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 $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$



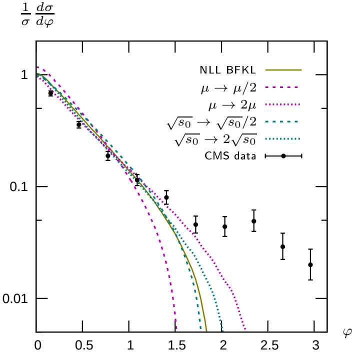
35 GeV $< |\mathbf{k}_{J1}| <$ 60 GeV
35 GeV $< |\mathbf{k}_{J2}| <$ 60 GeV

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

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

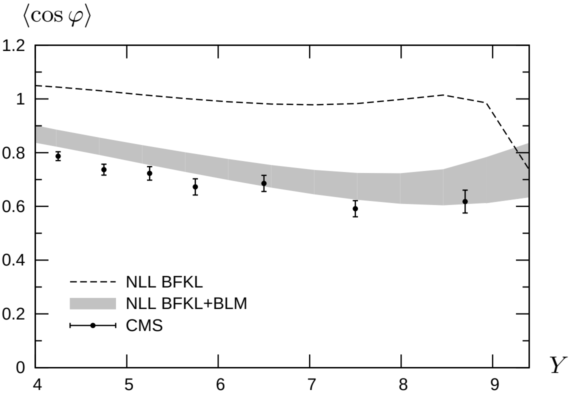
The Brodsky-Lepage-Mackenzie (BLM) procedure resums the self-energy corrections to the gluon propagator at one loop into the running coupling.

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.

Results with BLM

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



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

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

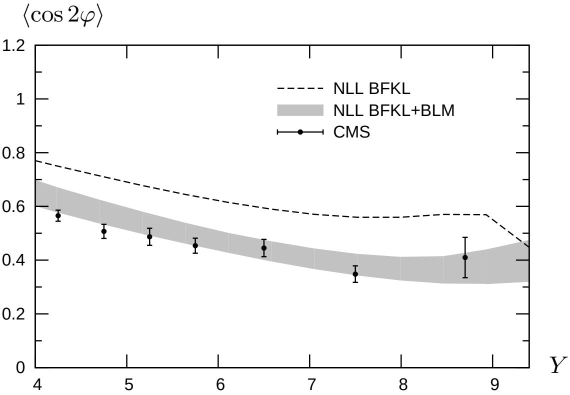
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

Results with BLM

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



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

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

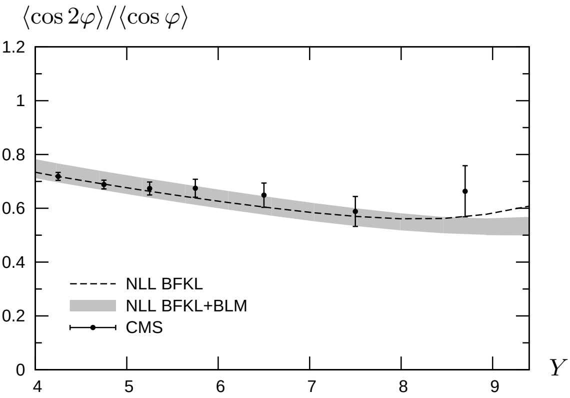
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

Results with BLM

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



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

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

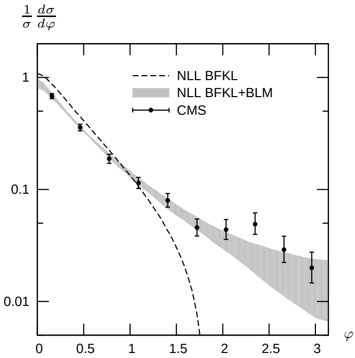
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

Comparison with fixed-order

Results for an asymmetric configuration

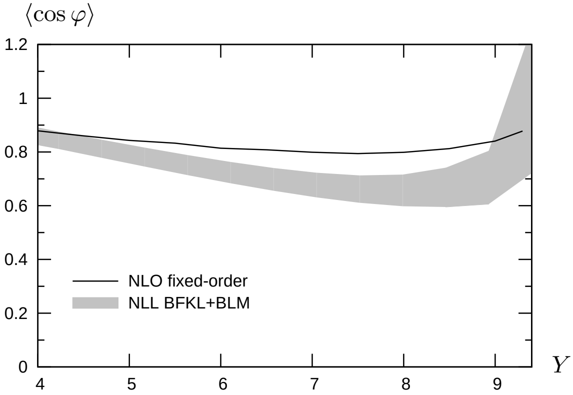
In this section we choose the cuts as

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

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 $\langle \cos \varphi \rangle$



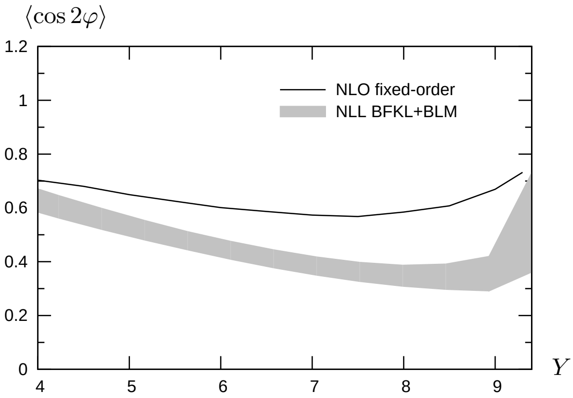
$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

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

Comparison with fixed-order

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



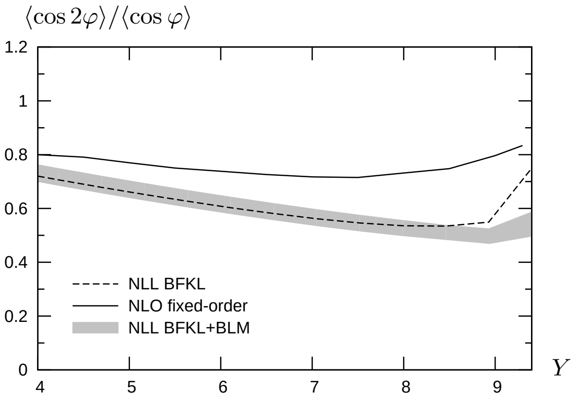
$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

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

Comparison with fixed-order

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



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

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

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

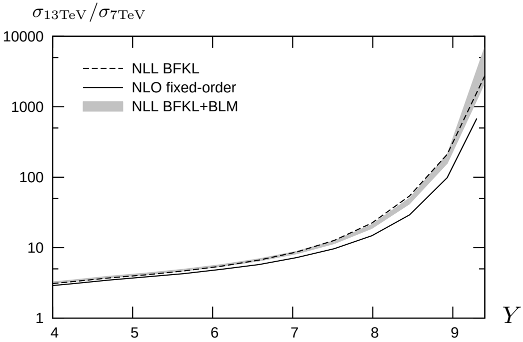
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

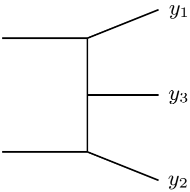
$$Y_{\rm eff} \equiv Y \frac{\sigma^{2\to 3}}{\sigma^{{\rm BFKL},\mathcal{O}(\alpha_s^3)}}$$

- 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

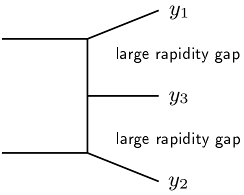
Energy-momentum conservation

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

exact $2 \to 3$



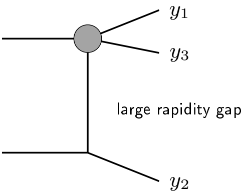
BFKL



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

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

+



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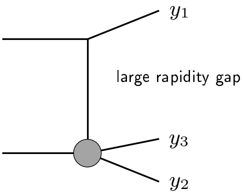
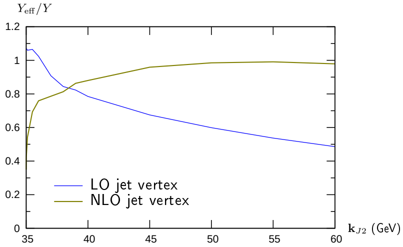


no emission from the Green's function + NLO jet vertex

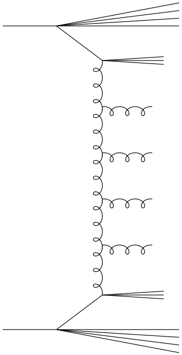
Energy-momentum conservation

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, $Y = 8$):

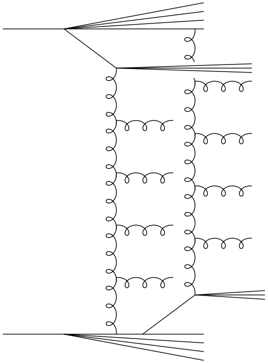


- With the LO jet vertex, $Y_{\rm eff}$ is much smaller than Y when $\mathbf{k}_{J1}$ and $\mathbf{k}_{J2}$ are significantly different
- This is the region important for comparison with fixed order calculations
- The improvement coming from the NLO jet vertex is very large in this region
- For $\mathbf{k}_{J1} = 35$ 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?



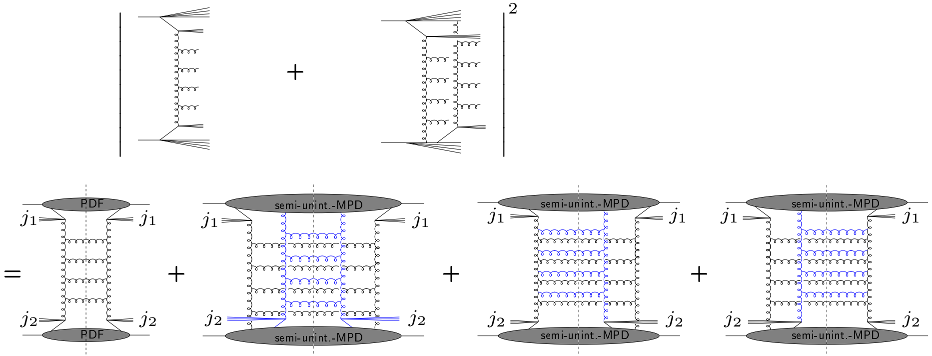
+



MN jets in the single partonic model

MN jets in MPI

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)

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 did the same analysis at 13 TeV:

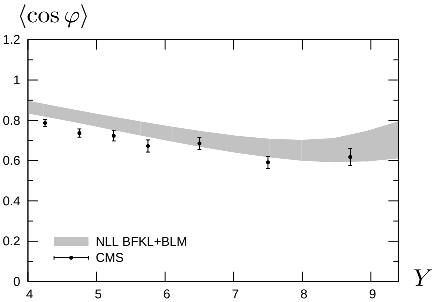
  - Azimuthal decorrelations don't show a very different behavior at 13 TeV compared to 7 TeV

  - NLL BFKL predicts a stronger rise of the cross section with increasing energy than a NLO fixed-order calculation

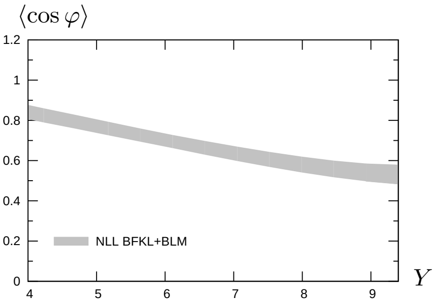
  A measurement of the cross section at $\sqrt{s} = 7$ or 8 TeV would be needed to test this

Backup

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



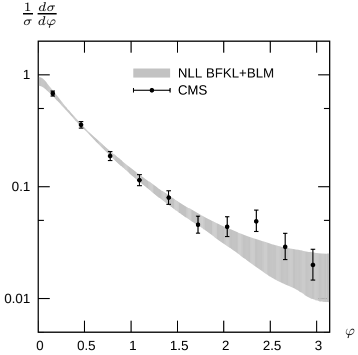
$\sqrt{s} = 7$ TeV



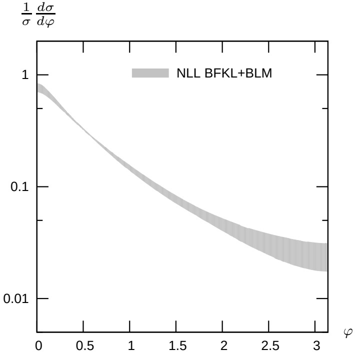
$\sqrt{s} = 13$ TeV

The behavior is similar at 13 TeV and at 7 TeV

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



$\sqrt{s} = 7$ TeV



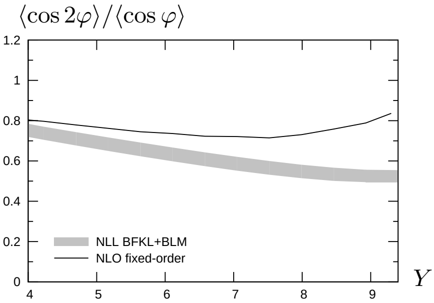
$\sqrt{s} = 13$ TeV

The behavior is similar at 13 TeV and at 7 TeV

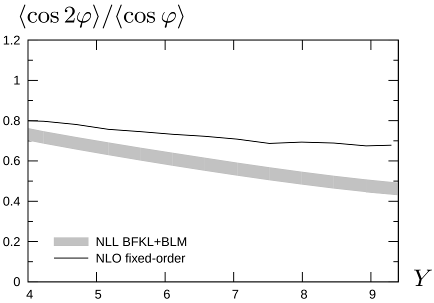
Comparison: 13 TeV vs. 7 TeV

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

(asymmetric configuration)



$\sqrt{s} = 7$ TeV

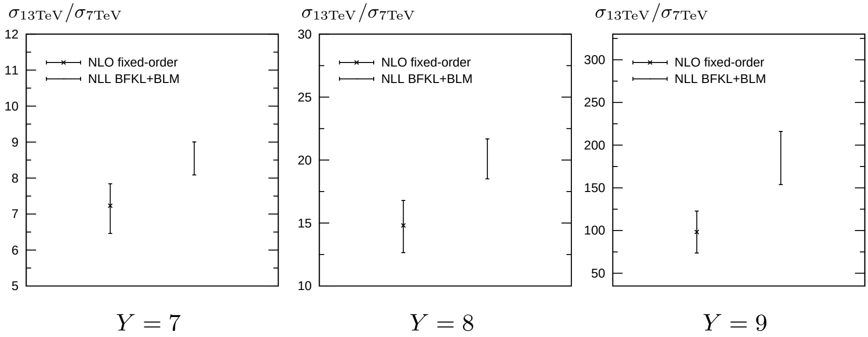


$\sqrt{s} = 13$ TeV

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

Comparison: 13 TeV vs. 7 TeV

Cross section



Master formulas

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

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

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

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

- $n > 0 \implies$ 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

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