Azimuthal correlations of Mueller-Navelet jets at the LHC

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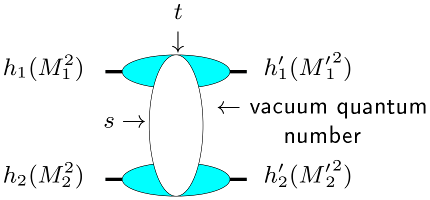
B. D, L. Szymanowski, S. Wallon, JHEP **1305** (2013) 096 [arXiv:1302.7012 [hep-ph]]

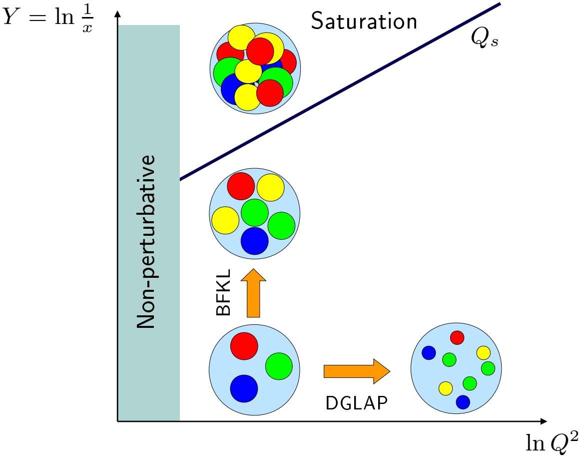
B. D, L. Szymanowski, S. Wallon, arXiv:1309.3229 [hep-ph]

- One of the important longstanding theoretical questions raised by QCD is its behaviour in the perturbative Regge limit $s \gg -t$
- Based on theoretical grounds, one should identify and test suitable observables in order to test this peculiar dynamics



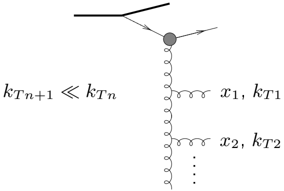
hard scales: $M_1^2,\, M_2^2 \gg \Lambda_{QCD}^2$ or $M_1'^2,\, M_2'^2 \gg \Lambda_{QCD}^2$ or $t \gg \Lambda_{QCD}^2$
where the $t-$channel exchanged state is the so-called hard Pomeron

The different regimes of QCD



Small values of α_S (perturbation theory applies due to hard scales) can be compensated by large logarithmic enhancements.
$\Rightarrow$ resummation of $\sum_n (\alpha_S \ln \mathrm{A})^n$ series

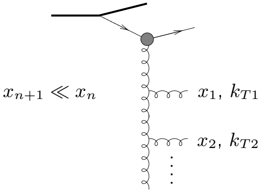
DGLAP



strong ordering in k_T

$$\sum(\alpha_S \ln \frac{Q^2}{\mu^2})^n$$

BFKL



strong ordering in x

$$\sum(\alpha_S \ln \frac{s}{s_0})^n$$

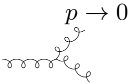
When $\sqrt{s}$ becomes very large, it is expected that a BFKL description is needed to get accurate predictions

How to test QCD in the perturbative Regge limit?

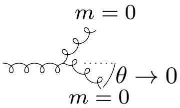
What kind of observables?

- perturbation theory should be applicable:
  selecting external or internal probes with transverse sizes $\ll 1/\Lambda_{QCD}$ or by choosing large t in order to provide the hard scale

- governed by the *soft* perturbative dynamics of QCD



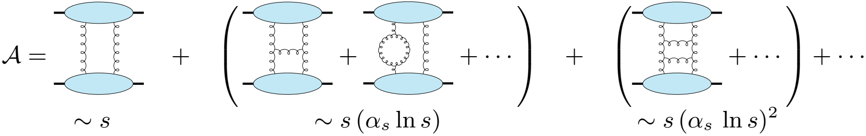
and *not* by its *collinear* dynamics



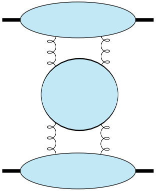
$\Rightarrow$ select semi-hard processes with $s \gg p_{T\,i}^2 \gg \Lambda_{QCD}^2$ where $p_{T\,i}^2$ are typical transverse scale, all of the same order

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

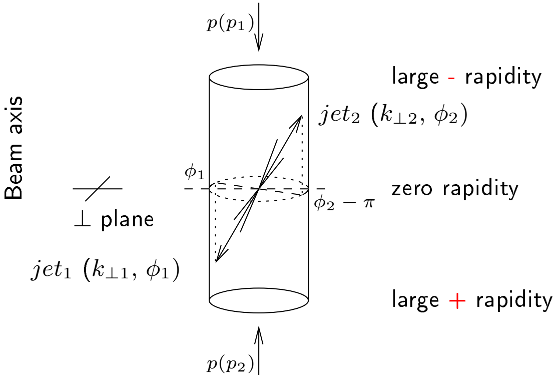
$\leftarrow$ Impact factor

- Higher order corrections 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)

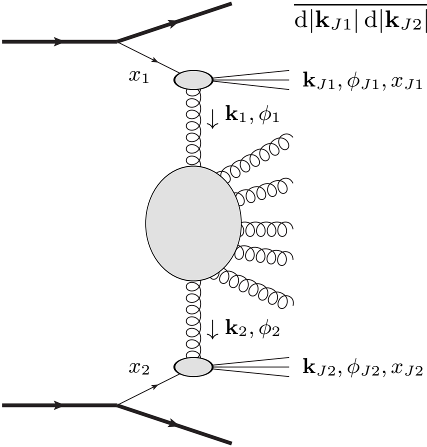
Mueller-Navelet jets

- 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



Master formulas

k_T-factorized differential cross section



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

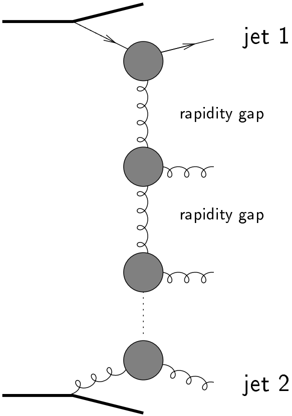
$$\times\, \Phi(\mathbf{k}_{J1}, x_{J1}, -\mathbf{k}_1)$$

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

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

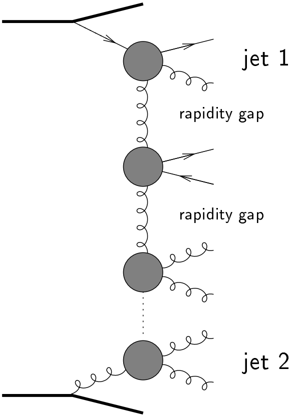
with $\Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2) = \int \mathrm{d}x_2\, f(x_2) V(\mathbf{k}_2, x_2)$ $\quad f \equiv$ PDF $\quad x_J = \frac{|\mathbf{k}_J|}{\sqrt{s}} e^{y_J}$

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 for a symmetric configuration

In the following we show results for

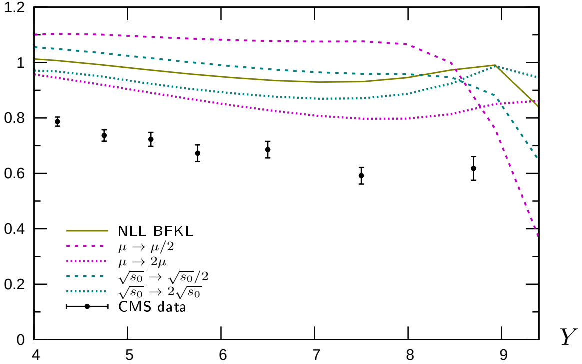
- $\sqrt{s} = 7$ TeV
- $35\,\mathrm{GeV} < |\mathbf{k}_{J1}|\,, |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
- $0 < y_1\,, y_2 < 4.7$

These cuts allow us to compare our predictions with the first experimental data on azimuthal correlations of Mueller-Navelet jets from 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 $\langle \cos\varphi \rangle$

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

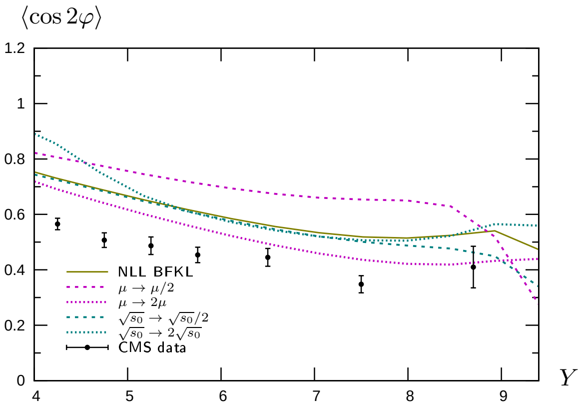


$35\,\mathrm{GeV} < |\mathbf{k}_{J1}| < 60\,\mathrm{GeV}$
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

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

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



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

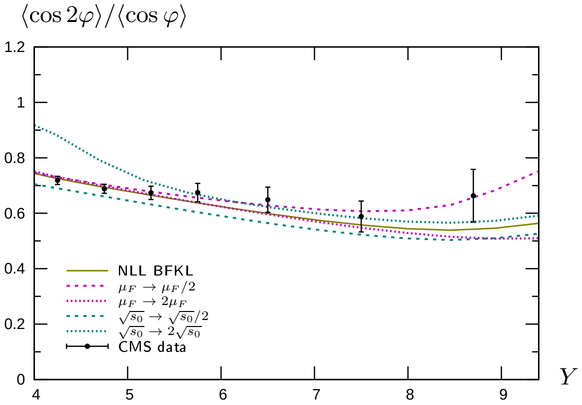
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

- 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

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



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

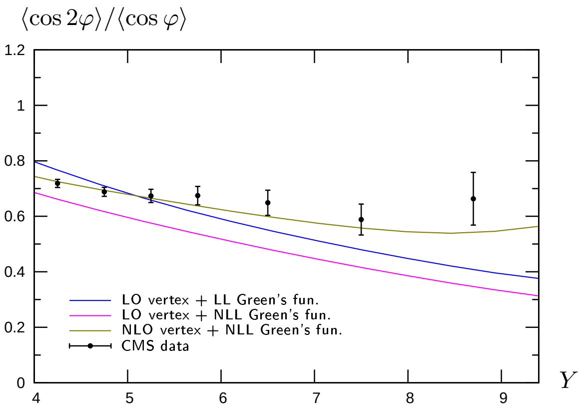
$35\ \text{GeV} < |\mathbf{k}_{J2}| < 60\ \text{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

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



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

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

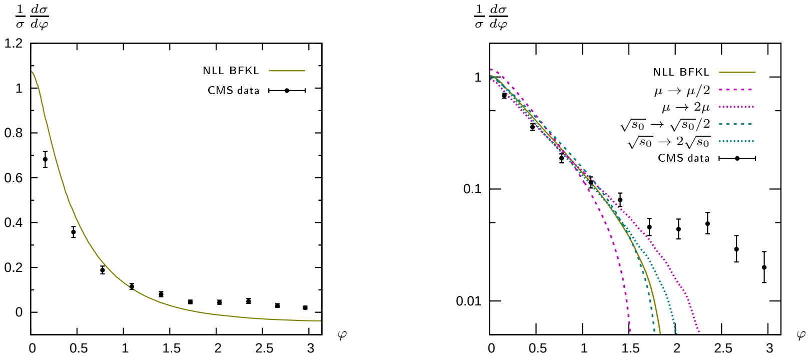
It is necessary to include the NLO corrections to the jet vertex to reproduce the behavior of the data at large Y

Azimuthal distribution

The azimuthal distribution $\frac{1}{\sigma}\frac{d\sigma}{d\varphi}$ has also been measured by the CMS collaboration. It can be written as

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

Azimuthal distribution: comparison to CMS data

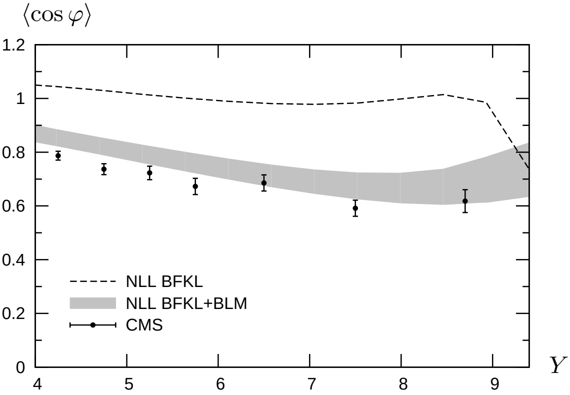


- Our calculation predicts a too large value of $\frac{1}{\sigma}\frac{d\sigma}{d\varphi}$ for $\varphi \lesssim \frac{\pi}{2}$ and a too small value for $\varphi \gtrsim \frac{\pi}{2}$
- For large values of φ, the distribution even becomes negative

- The agreement of our calculation with the data for $\langle \cos 2\varphi\rangle / \langle \cos \varphi\rangle$ is good and very 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

The Brodsky-Lepage-Mackenzie (BLM) procedure resumes 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 $\beta_0 = \frac{11N_c - 2N_f}{3} \simeq 7.67$

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



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

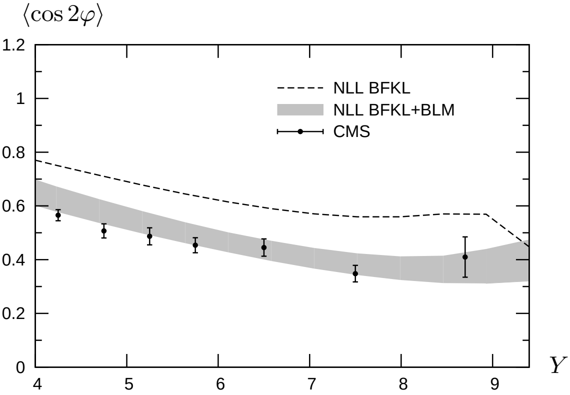
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

Using the BLM scale setting, the scale uncertainty is reduced and the agreement with data becomes much better

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



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

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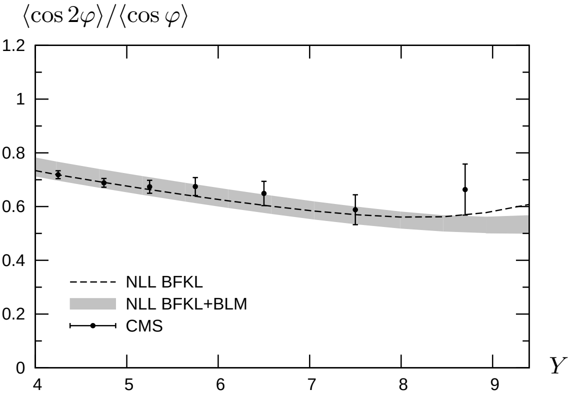
Using the BLM scale setting, the scale uncertainty is reduced and the agreement with data becomes much better

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



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

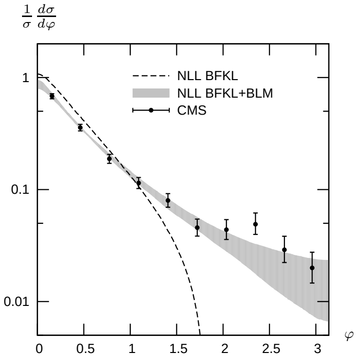
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

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 very good agreement with the data

Azimuthal distribution: comparison to CMS data



With the BLM scale setting the azimuthal distribution no longer reaches negative values and is in good agreement with the data across the full φ range.

Using the BLM scale setting:

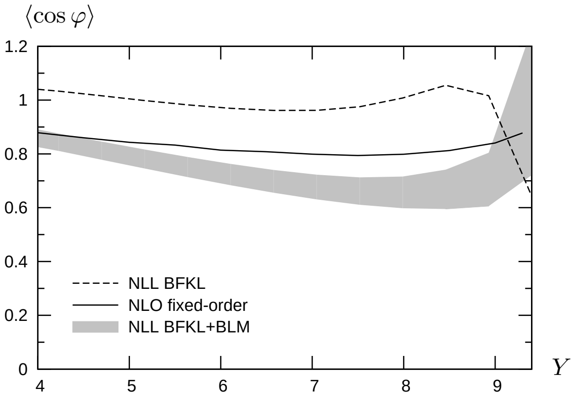
- The agreement $\langle \cos n\varphi \rangle$ with the data becomes much better
- The agreement for $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$ is still very good and unchanged as this observable is weakly dependent on μ_R
- The azimuthal distribution no longer reaches negative values and 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 to compare with a fixed-order treatment (i.e. without resummation)
We compare our results with the NLO fixed-order code Dijet (Aurenche, Basu, Fontannaz) in an asymmetric configuration

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

Comparison with fixed-order

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



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

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

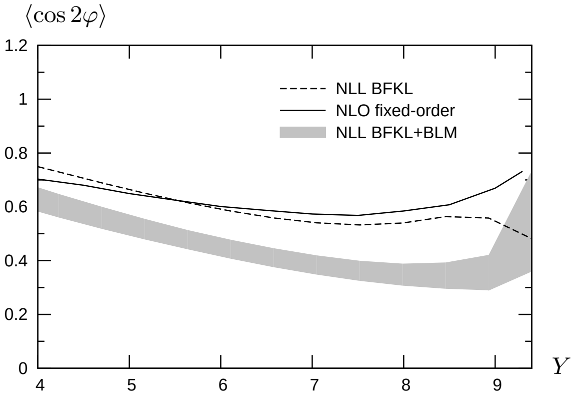
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

- 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

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

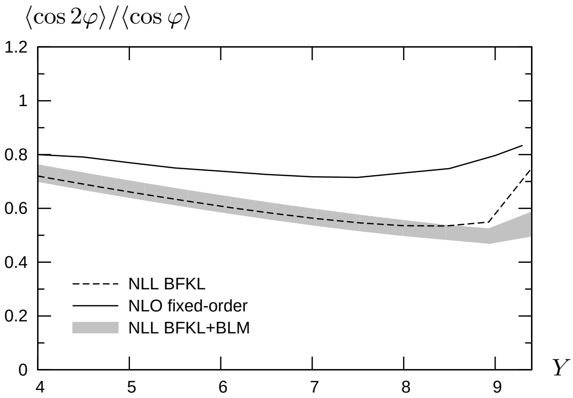


$35\,\mathrm{GeV} < |\mathbf{k}_{J1}| < 60\,\mathrm{GeV}$
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
$50\,\mathrm{GeV} < \mathrm{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

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



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

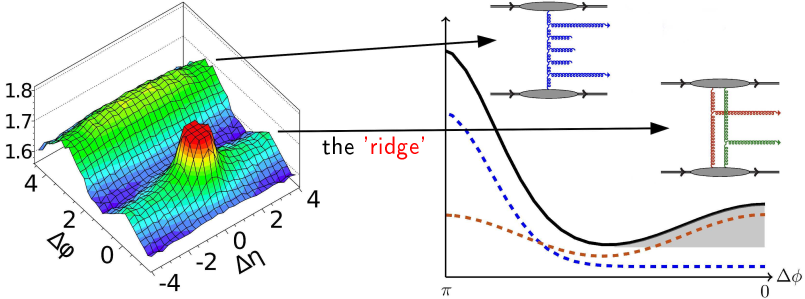
$0 < y_1 < 4.7$
$0 < y_2 < 4.7$

Using BLM or not, we see a sizable difference between BFKL and fixed-order
$\Rightarrow$ An experimental analysis with enough statistics should provide clear discrimination between these two treatments

The spectra of two-particle correlations in high multiplicity proton-proton, proton-nucleus and nucleus-nucleus collisions at RHIC and the LHC show two structures:

- one corresponding to almost back-to-back jets
- one corresponding to jets emitted in the same direction (the 'ridge').

The first one can be understood as a manifestation of BFKL dynamics and the second one can be explained by 'Glasma graphs' (Dusling, Venugopalan).



CMS p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
$\mathrm{N} \geq 110$, $1 < \mathrm{p_T} < 3$ GeV

Dusling, Venugopalan

Conclusions

- 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 observables $\langle \cos n\varphi \rangle$ and $\frac{1}{\sigma}\frac{d\sigma}{d\varphi}$ are very dependent on the choice of the scales and don't agree very well with data
- The agreement with CMS data is greatly improved by using the BLM scale fixing procedure
- For the observable $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$:
  - NLL BFKL predictions are much more stable with respect to the scales
  - the data is well described by BFKL in a symmetric configuration
  - there is a clear difference between NLO fixed-order and our NLL BFKL calculation in an asymmetric configuration
  $\Rightarrow$ In our opinion this is a strong motivation for an experimental analysis in an asymmetric configuration