Signal of high-energy resummation effects in Mueller-Navelet jets at the LHC

Bertrand Ducloué
(Laboratoire de Physique Théorique, Orsay)

Workshop on Multi-Parton Interactions at the LHC

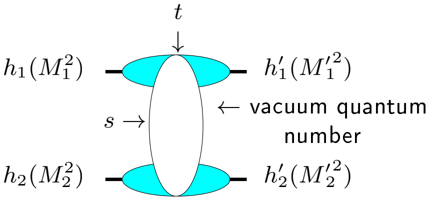
December 2, 2013

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

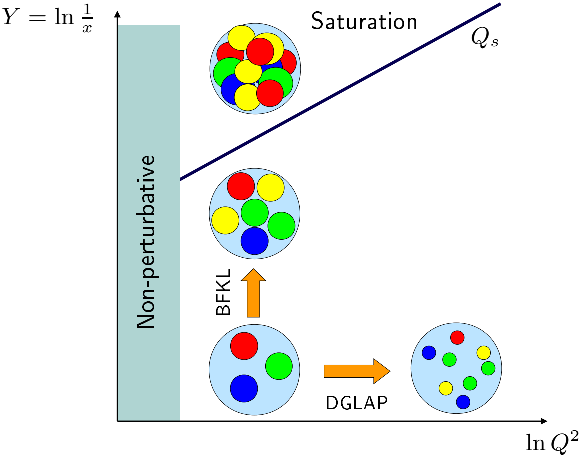
B. D, L. Szymanowski, S. Wallon, JHEP **1305** (2013) 096 [arXiv:1302.7012 [hep-ph]]
B. D, L. Szymanowski, S. Wallon, arXiv:1309.3229 [hep-ph]

Motivations

- 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

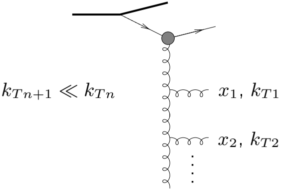
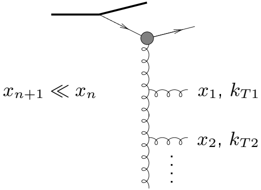


hard scales: $M_1^2,\, M_2^2 \gg \Lambda^2_{QCD}$ or $M_1'^2,\, M_2'^2 \gg \Lambda^2_{QCD}$ or $t \gg \Lambda^2_{QCD}$
where the $t-$channel exchanged state is the so-called hard Pomeron


$Y = \ln \frac{1}{x}$
Saturation
Q_s
Non-perturbative
BFKL
DGLAP
$\ln Q^2$

Small values of α_S (perturbation theory applies due to hard scales) can be compensated by large logarithmic enhancements.

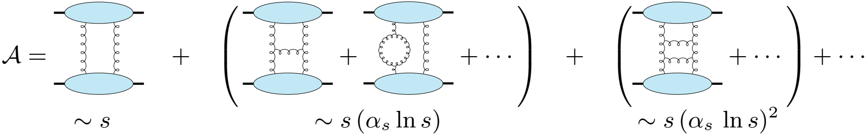
$\Rightarrow$ resummation of $\sum_n (\alpha_S \, \ln \mathrm{A})^n$ series

DGLAP	BFKL
	
strong ordering in k_T	strong ordering in x
$\sum(\alpha_S \, \ln \frac{Q^2}{\mu^2})^n$	$\sum(\alpha_S \, \ln \frac{s}{s_0})^n$

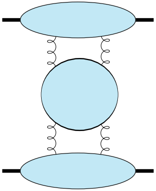
When $\sqrt{s}$ becomes very large, it is expected that a BFKL description is needed to get accurate predictions

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

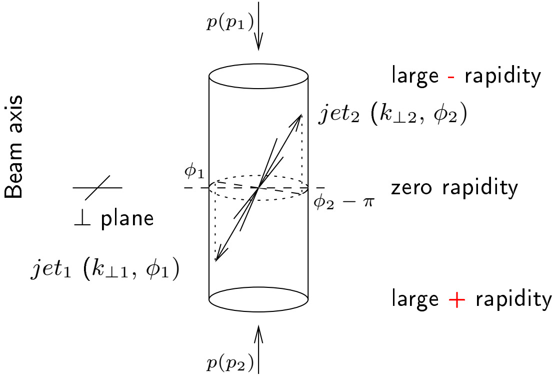
Higher order corrections

- 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)

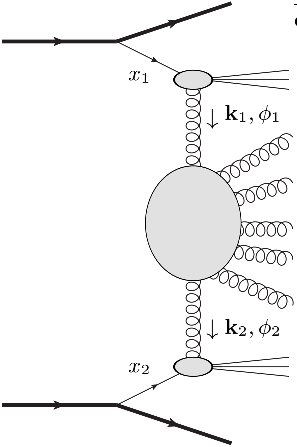
Mueller-Navelet jets

- 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



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

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

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

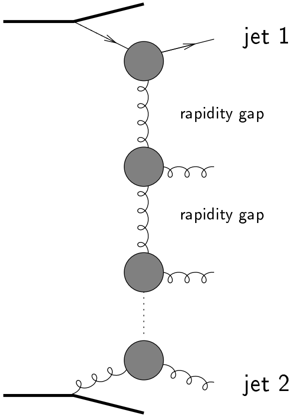
- $n > 0 \implies$ azimuthal decorrelation

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

- sum over $n \implies$ azimuthal distribution

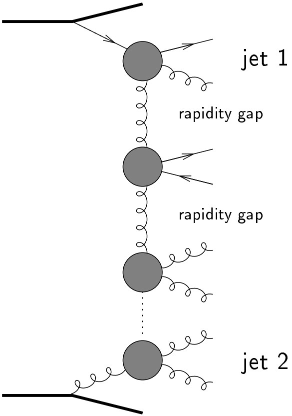
$$\frac{1}{\sigma}\frac{d\sigma}{d\varphi} = \frac{1}{2\pi}\left\{1+2\sum_{n=1}^{\infty}\cos(n\varphi)\,\langle\cos(n\varphi)\rangle\right\}$$

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

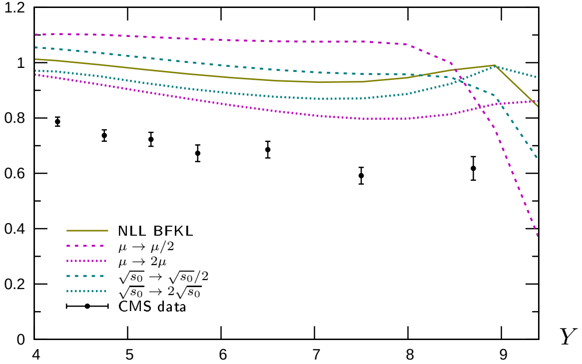
- $\sqrt{s} = 7$ TeV
- $35\,\mathrm{GeV} < |\mathbf{k}_{J1}|\,, |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
- $0 < y_1\,, y_2 < 4.7$

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

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



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

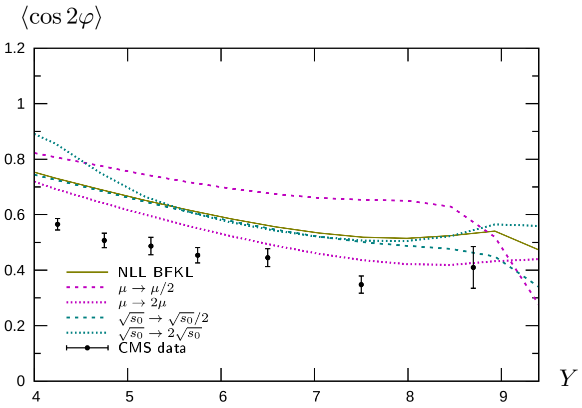
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

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

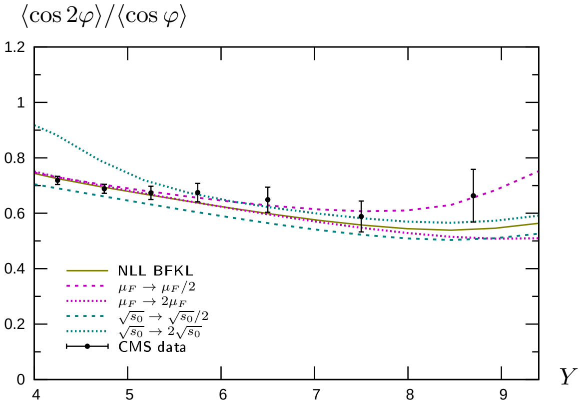


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

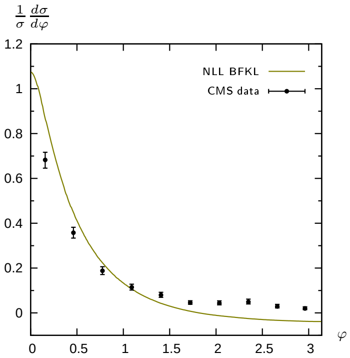


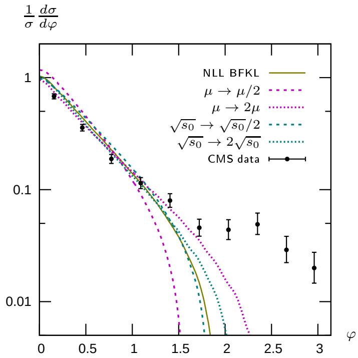
$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
$35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$

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

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





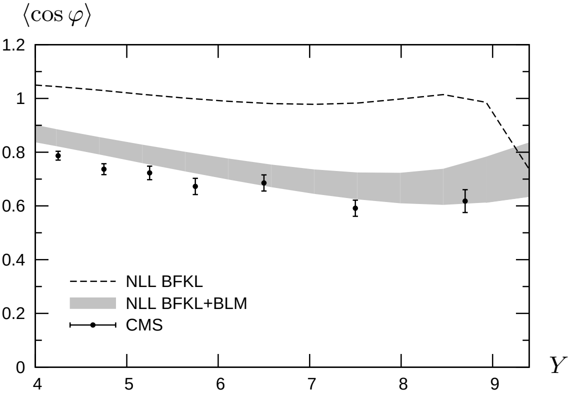
- Our calculation predicts a too large value of $\frac{1}{\sigma}\frac{d\sigma}{d\varphi}$ for $\varphi \lesssim \frac{\pi}{2}$ and a too small value for $\varphi \gtrsim \frac{\pi}{2}$
- For large values of φ, the distribution even becomes negative

- 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 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 $\beta_0 = \frac{11N_c - 2N_f}{3} \simeq 7.67$

The BLM procedure was applied to NLL BFKL by Brodsky, Fadin, Kim, Lipatov, Pivovarov. We follow the same idea, taking into account the NLL corrections to the jet vertex.

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

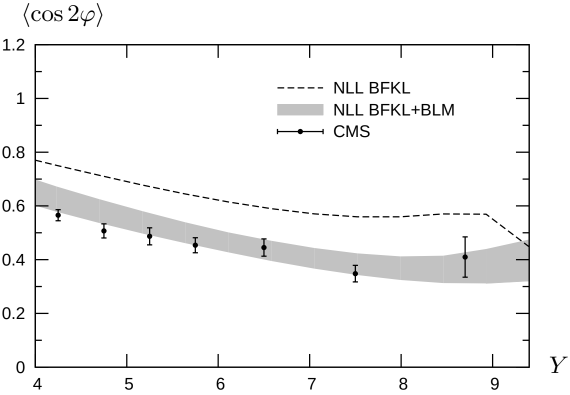


$35\,\mathrm{GeV} < |\mathbf{k}_{J1}| < 60\,\mathrm{GeV}$
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

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

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

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



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

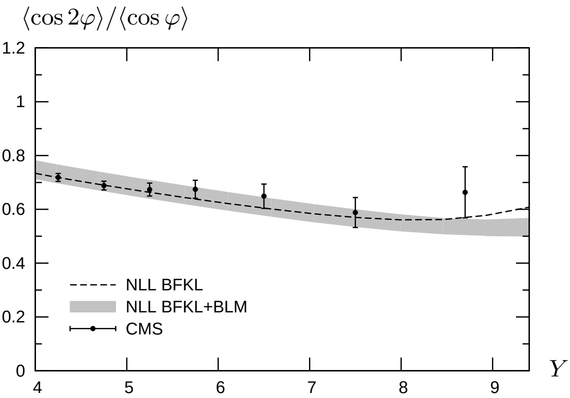
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

$0 < y_1 < 4.7$

$0 < y_2 < 4.7$

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

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

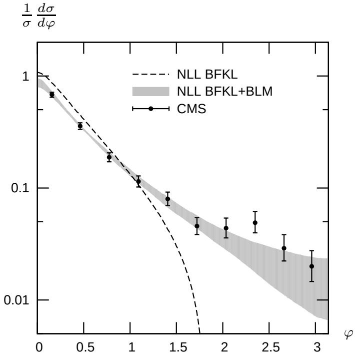


$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
$35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$

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

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 (integrated over $6 < Y < 9.4$)



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.

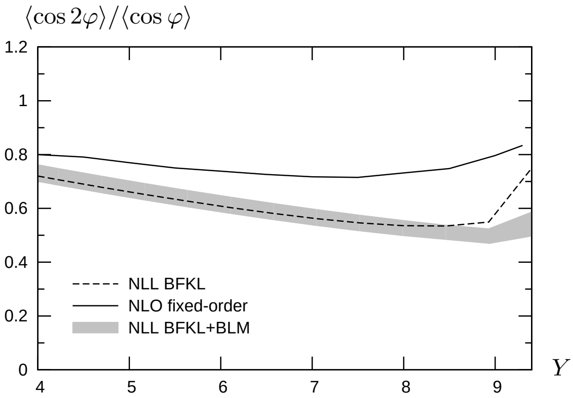
Using the BLM scale setting:

- The agreement for $\langle \cos n\varphi \rangle$ 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 $\mathbf{k}_{J\text{min}1} = \mathbf{k}_{J\text{min}2}$ 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

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

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

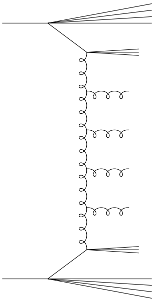


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

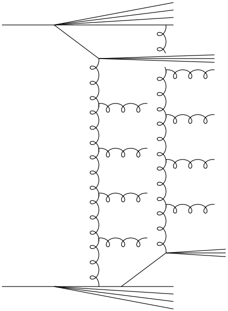
$0 < y_1 < 4.7$
$0 < y_2 < 4.7$

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

How could we evaluate the importance of MPI effects?



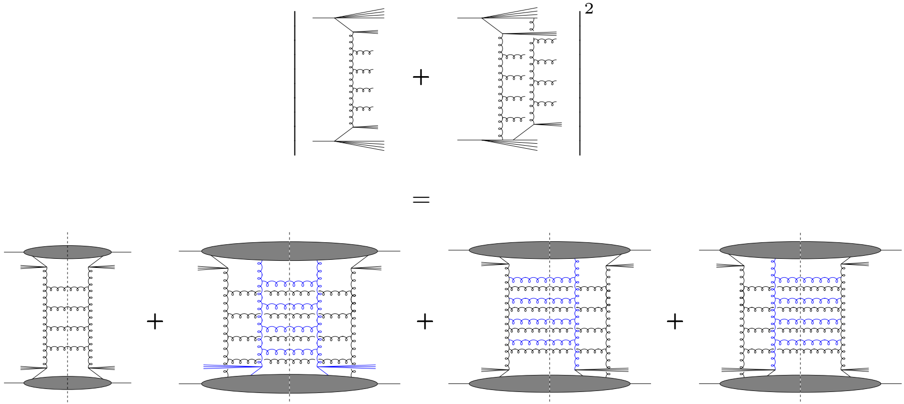
+



single partonic contribution

MPI-type contribution

Mueller-Navelet jets and MPI



single $\mathbb{P}$ ladder $\sim s^{\alpha_{\mathbb{P}}}$

two $\mathbb{P}$ ladders $\sim (??)\, s^{2\alpha_{\mathbb{P}}}$

interferences ???

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
- MPI processes could play an important role for angular correlations