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

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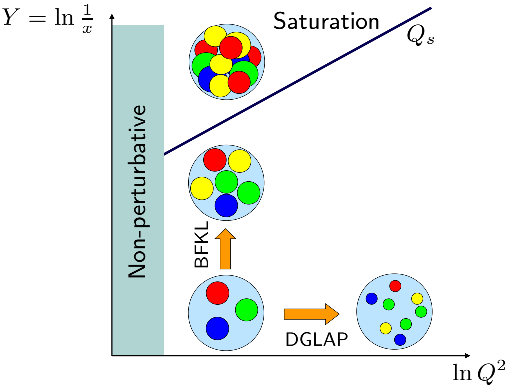
B. D, L. Szymanowski, S. Wallon, arXiv:1302.7012, 1309.3229, 1407.6593

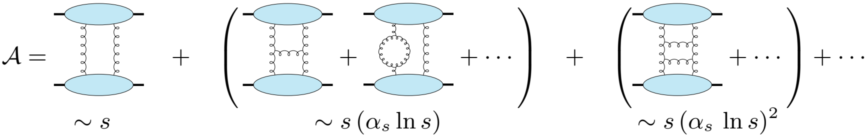
- One of the important longstanding theoretical questions raised by QCD is its behaviour in the perturbative Regge limit $s \gg -t$
- We want to identify and test suitable observables in order to test these peculiar dynamics



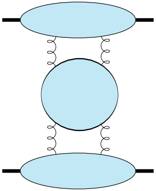
$\Rightarrow$ select semi-hard processes with $s \gg p_{T\,i}^2 \gg \Lambda_{QCD}^2$ where $p_{T\,i}^2$ are typical transverse scales, all of the same order

QCD in the perturbative Regge limit

At leading logarithmic (LL) accuracy (resumming terms $(\alpha_s \ln s)^n$), the scattering amplitude can be written as:



this can be put in the following form :



$\leftarrow$ Impact factor (process-dependent)

$\leftarrow$ Green's function
obeys the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation

$\leftarrow$ Impact factor

Often LL calculations don't describe experimental data very well
$\Rightarrow$ What about higher orders?

- The next-to-leading logarithmic (NLL) corrections to the BFKL kernel are known (Lipatov, Fadin; Camici, Ciafaloni)
  Corresponds to resumming also $\alpha_s(\alpha_s \ln s)^n$ terms

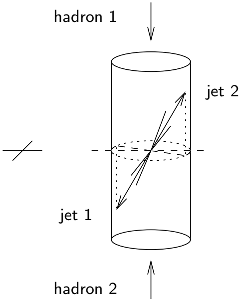
- Impact factors are known in some cases at NLL
  - $\gamma^* \to \gamma^*$ at $t = 0$ (Bartels, Colferai, Gieseke, Kyrieleis, Qiao; Balitski, Chirilli)
  - Forward jet production (Bartels, Colferai, Vacca; Caporale, Ivanov, Murdaca, Papa, Perri; Chachamis, Hentschinski, Madrigal, Sabio Vera)
  - Inclusive 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 were proposed as a possible test of BFKL dynamics at hadron colliders

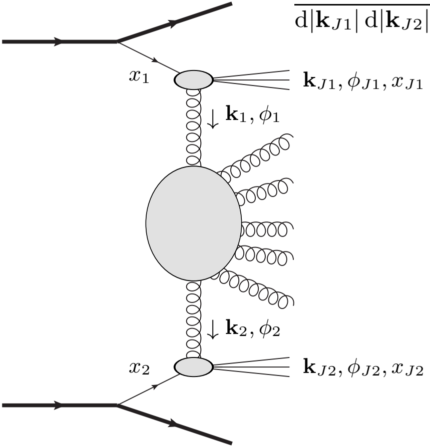
Consider two jets separated by a large interval rapidity, i.e. each of them almost fly in the direction of the hadron "close" to it, and with similar transverse momenta

In a pure LO collinear treatment, these two jets should be emitted exactly back to back: $\varphi = 0$ ($\varphi = \phi_{J,1} - \phi_{J,2} - \pi$)

A BFKL calculation predicts some decorrelation because of the emission of soft gluons in the rapidity interval



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 convenient to define the coefficients $\mathcal{C}_n$ as

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

- $n=0 \implies$ 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

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

- sum over $n \implies$ azimuthal distribution

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

Comparison with data

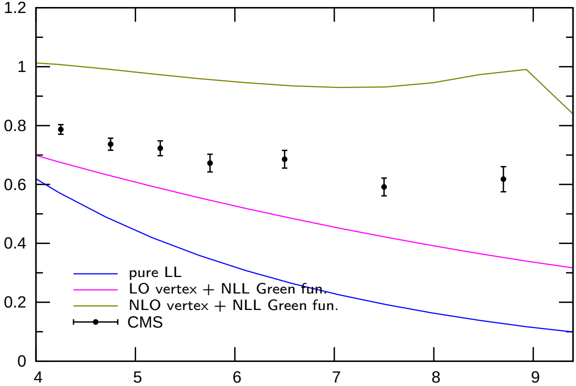
The following results are for

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

And we compare these with experimental data on the azimuthal correlations of Mueller-Navelet jets at the LHC from CMS (CMS-PAS-FSQ-12-002)

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

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



$Y \equiv |y_1 - y_2|$

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

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

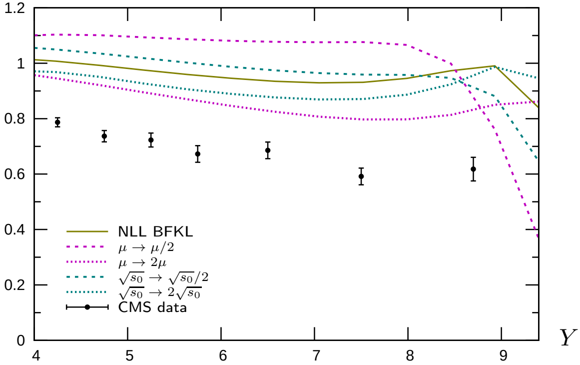
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

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

- A LL calculation cannot describe the experimental data
- A NLL calculation does not really provide a better agreement
- The NLL calculation still depends strongly on 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?

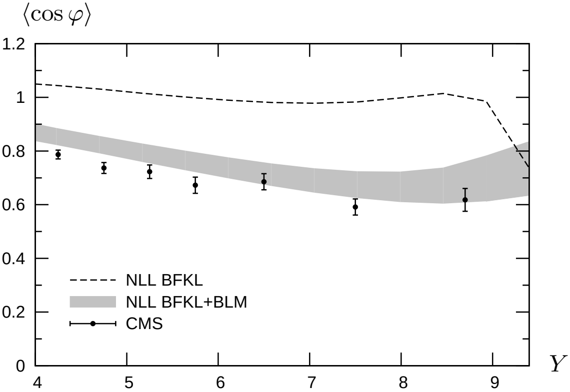
We decided to use the Brodsky-Lepage-Mackenzie (BLM) procedure to fix the renormalization scale

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

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.

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

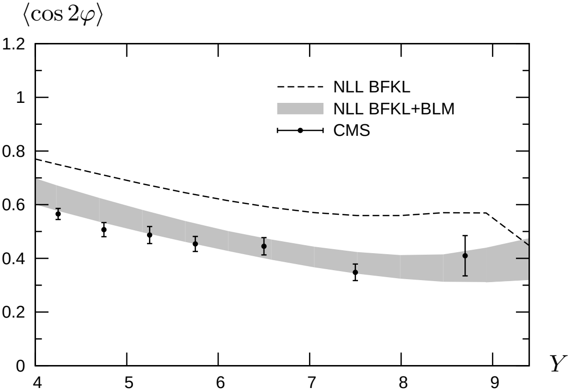


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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

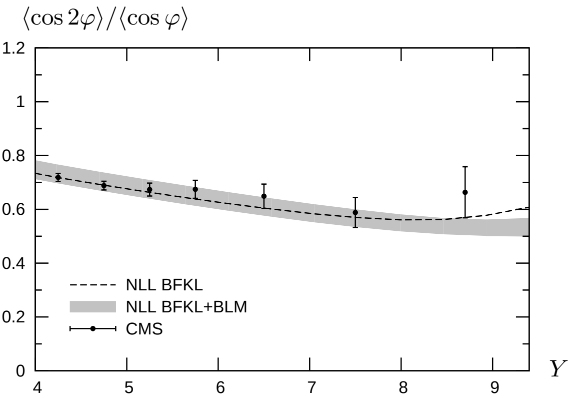


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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

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

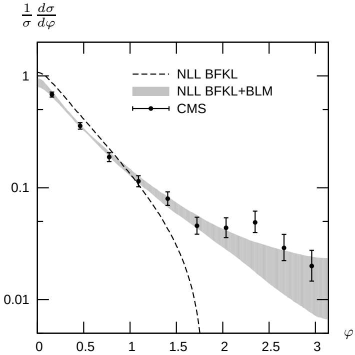


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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 of $\langle \cos n\varphi \rangle$ 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

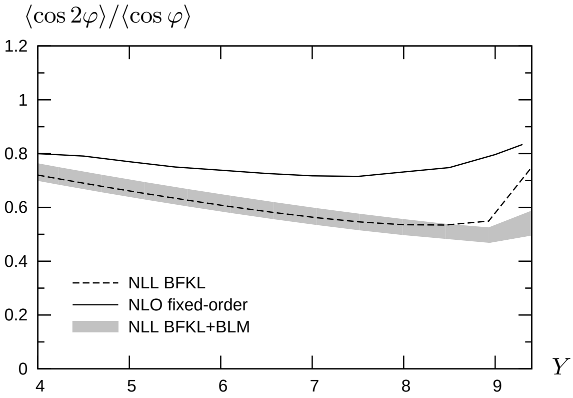
Results for an asymmetric configuration

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



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

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

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

$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

This observable is very stable in a BFKL calculation and shows a sizable difference between with a fixed-order treatment

Energy-momentum conservation

It is necessary to have $\mathbf{k}_{J\text{min}1} \neq \mathbf{k}_{J\text{min}2}$ 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

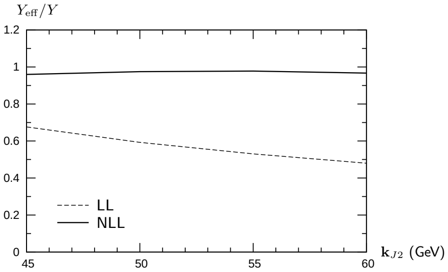
This was studied at LL by Del Duca and Schmidt. They introduced an effective rapidity Y_{eff} defined as

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

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

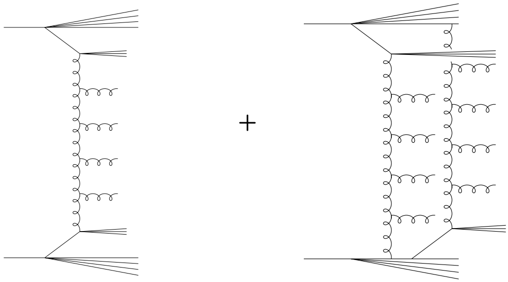
We follow the idea of Del Duca and Schmidt, but we also take into account the NLL corrections

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



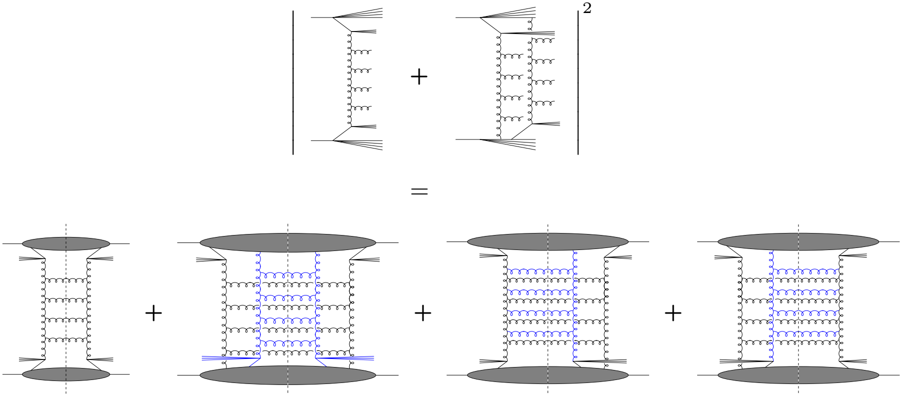
- At LL accuracy, $Y_{\rm eff}$ is much smaller than Y when $\mathbf{k}_{J1}$ and $\mathbf{k}_{J2}$ are not very similar (i.e. the BFKL calculation overestimates the cross section)
- Including the NLL corrections improves the situation a lot: $Y_{\rm eff}$ is now very close to Y

MPI contributions should be enhanced when going to higher energies / lower transverse momenta



single partonic contribution MPI-type contribution

When do these contributions start to be of the same order of magnitude as single parton scattering?



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

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

interferences ???

Problems to solve:

- Coupling to initial protons
- Interference terms
- ...

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 agreement with CMS data at 7 TeV is greatly improved by using the BLM scale fixing procedure
- A measurement with asymmetric p_T cuts would be useful to compare with a fixed-order treatment
- Energy-momentum conservation seems to be less severely violated at NLL accuracy
- Probably an interesting process to study MPI at small x but still several issues to solve