Uncovering BFKL dynamics in production of Mueller-Navelet jets at the LHC

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in collaboration with
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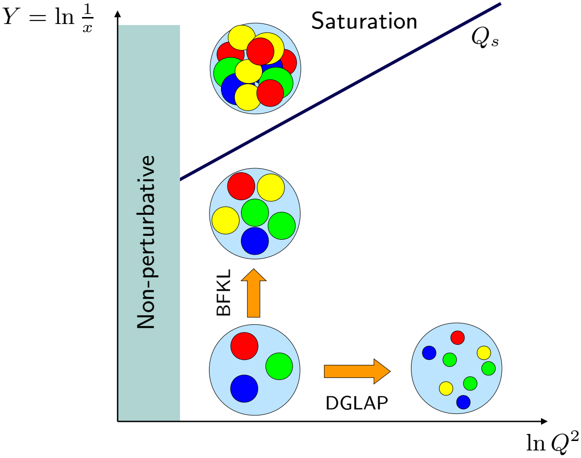
F. Schwennsen (DESY), S. Wallon (UPMC & LPT Orsay)
and recently with
A. H. Mueller (Columbia U.), Bo-Wen Xiao (Hua-Zhong Normal U. & Hua-Zhong Normal U., LQLP), Feng Yuan (LBNL, NSD),

D. Colferai, F. Schwennsen, LS, S. Wallon, JHEP **1012** (2010) 026

B. Ducloué, LS, S. Wallon:
JHEP **1305** (2013) 096 PRL **112** (2014) 082003 Phys. Rev. D **92** (2015) 076002

A. H. Mueller, LS, S. Wallon, B. W. Xiao, F. Yuan: JHEP **1603** (2016) 096


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

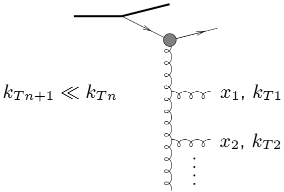
Resummation in QCD: DGLAP vs BFKL

A hard scale exists ⇒ Small α_s ⇒ perturbation theory applies

small α_s $*$ large log ≈ constant ⇒ necessity of resummation

Collinear fact. of QCD
DGLAP

hard scale, e.g. Q^2

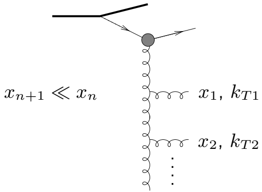


OPE, strong ordering in k_T

dynamics in longitudinal x's

$$\sum(\alpha_s \ln Q^2)^n$$

Regge k_T-factorization
BFKL



strong ordering in x, NO ORDERING in k_T

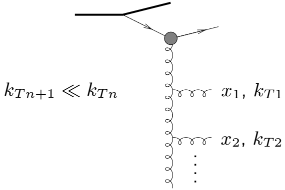
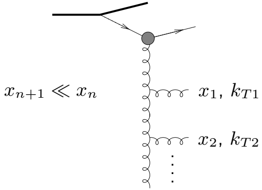
dynamics in transverse k_T's

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

Resummation in QCD: DGLAP vs BFKL

A hard scale exists $\Rightarrow$ Small α_s $\Rightarrow$ perturbation theory applies

small α_s $*$ large log $\approx$ constant $\Rightarrow$ necessity of resummation

Collinear fact. of QCD DGLAP hard scale Q^2	Regge k_T-factorization BFKL
	
OPE, strong ordering in k_T dynamics in longitudinal x's $\sum(\alpha_s \ln Q^2)^n$	strong ordering in x, NO ORDERING in k_T dynamics in transverse k_T's $\sum(\alpha_s \ln s)^n$

$\sqrt{s}$ becomes very large $\Rightarrow$ BFKL description is expected to be more adequate:

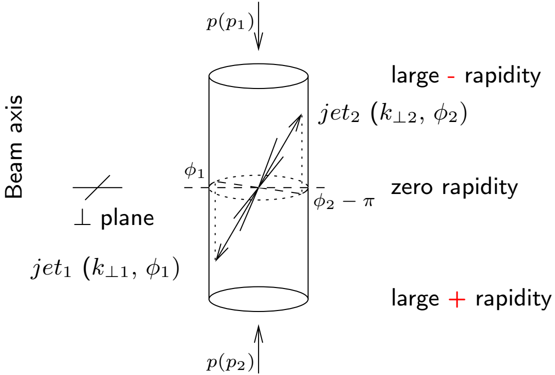
HERA exp's: conclusions unclear

DO EXPERIMENTS AT LHC CONFIRM SUCH EXPECTATION ?

Mueller-Navelet jets

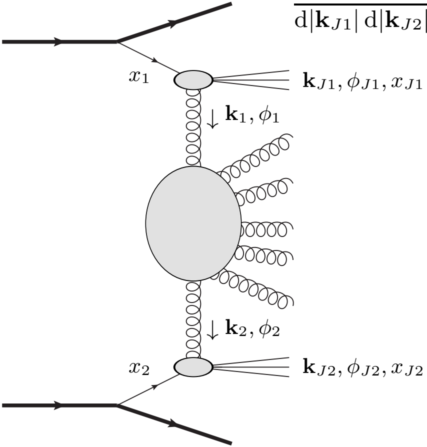
A.H. Mueller & H. Navelet, 1987

- 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



A.H. Mueller & H. Navelet, 1987

k_T-factorized differential cross section



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

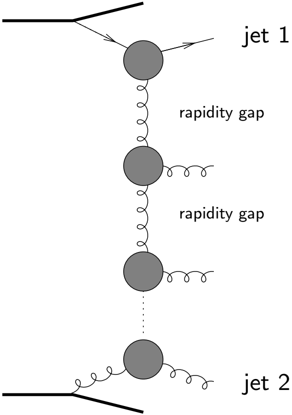
$$\times\, \Phi(\mathbf{k}_{J1}, x_{J1}, -\mathbf{k}_1)$$

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

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

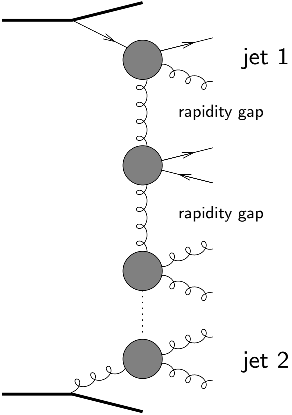
with $\Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2) = \int \mathrm{d}x_2\, f(x_2) V(\mathbf{k}_2, x_2)$ $\quad f \equiv$ PDF $\quad x_J = \frac{|\mathbf{k}_J|}{\sqrt{s}} e^{y_J}$

LL BFKL
tree vertices, 1-loop Regge trajectory



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

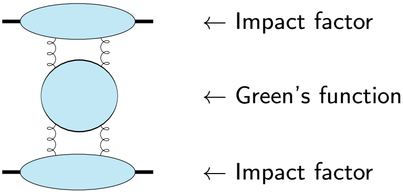
NLL BFKL
0+1-loop vertices, 1+2-loops Regge trajectories



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

The cross section:

can be put in the following form :



- 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

  - forward jet production (Bartels, Colferai, Vacca;
    Caporale, Ivanov, Murdaca, Papa, Perri;
    Chachamis, Hentschinski, Madrigal, Sabio Vera)

Results for a symmetric configuration

In the following we show results for

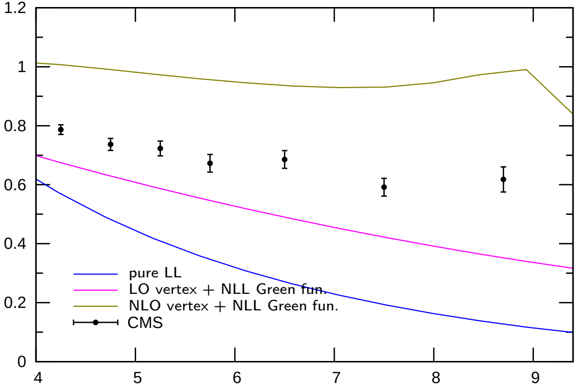
- $\sqrt{s} = 7$ TeV
- $35\,\mathrm{GeV} < |\mathbf{k}_{J1}|\,, |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$
- $0 < |y_1|\,, |y_2| < 4.7$

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 & article 1601.06713)

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 $\langle \cos\varphi \rangle$

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



$Y \equiv |y_1 - y_2|$

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

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

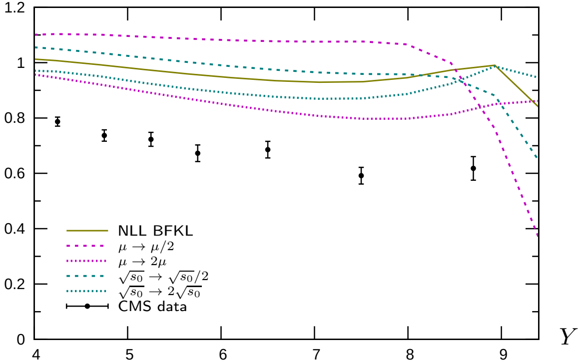
$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

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

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

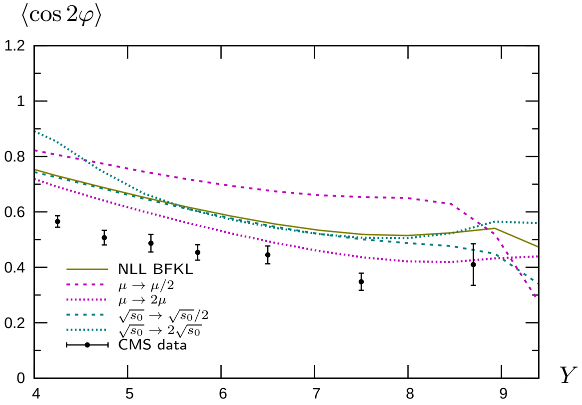


$35\,\mathrm{GeV} < |\mathbf{k}_{J1}| < 60\,\mathrm{GeV}$
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

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

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

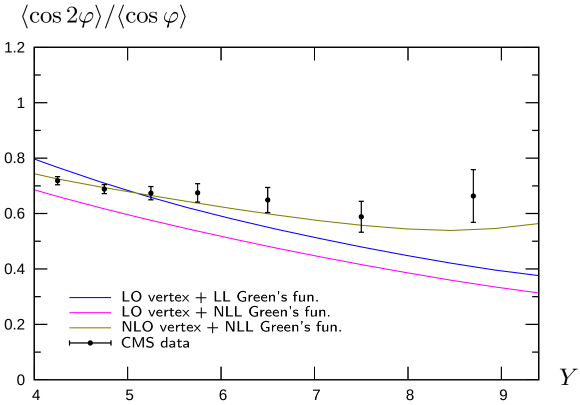


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$

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

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



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

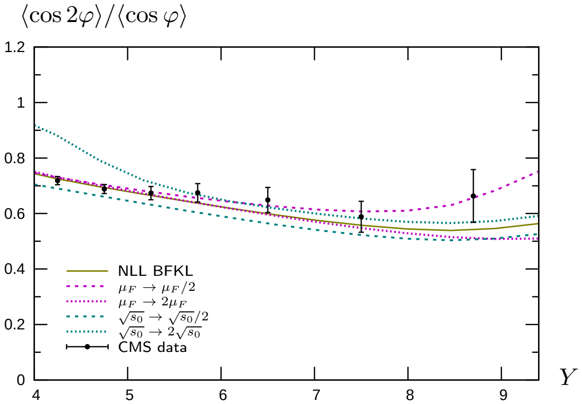
$35\,\mathrm{GeV} < |\mathbf{k}_{J2}| < 60\,\mathrm{GeV}$

$0 < |y_1| < 4.7$

$0 < |y_2| < 4.7$

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

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



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

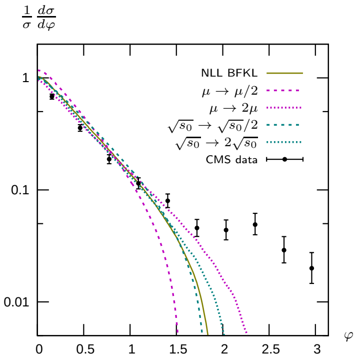
$0 < |y_1| < 4.7$
$0 < |y_2| < 4.7$

- 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

Results: azimuthal distribution

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

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

Results

- 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.

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 $\langle \cos \varphi \rangle$

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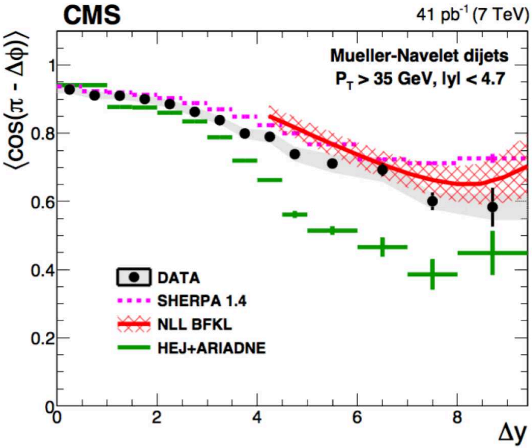

Using the BLM scale setting, the agreement with data becomes much better

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

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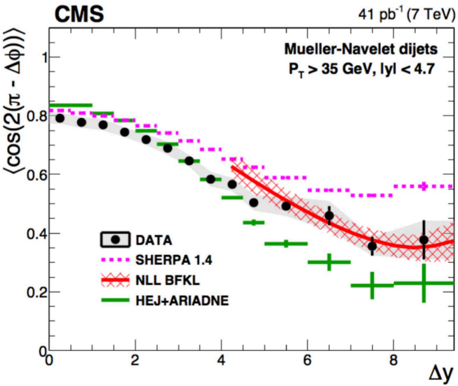

Using the BLM scale setting, the agreement with data becomes much better

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

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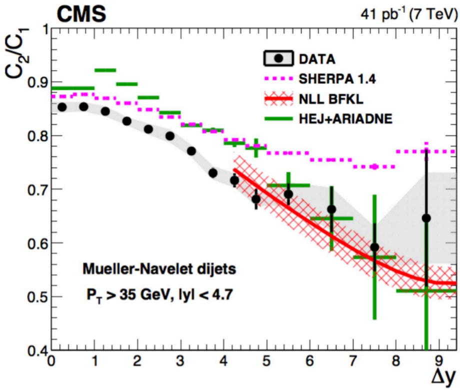

Because it is much less dependent on the scales, the observable $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$ is almost not affected by the BLM procedure and is still in good agreement with the data

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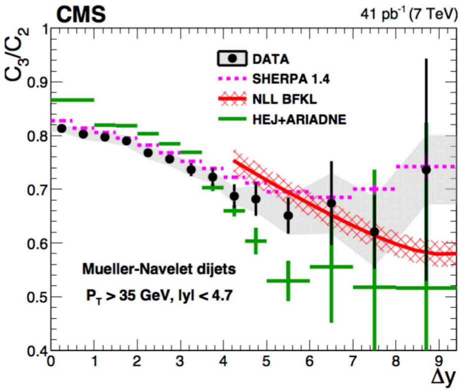
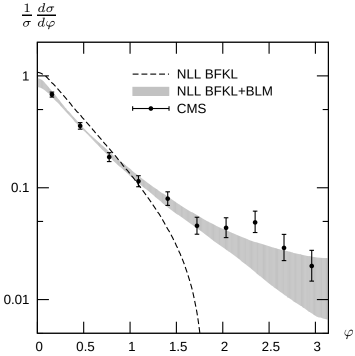


Because it is much less dependent on the scales, the observable $\langle \cos 3\varphi \rangle / \langle \cos 2\varphi \rangle$ is almost not affected by the BLM procedure and is still in good agreement with the data

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.

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

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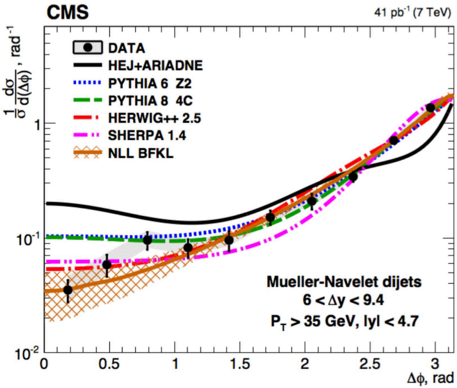


With the BLM scale setting the azimuthal distribution is in good agreement with the data across the full φ range.

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 $\mathbf{k}_{J\min 1} = \mathbf{k}_{J\min 2}$ 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

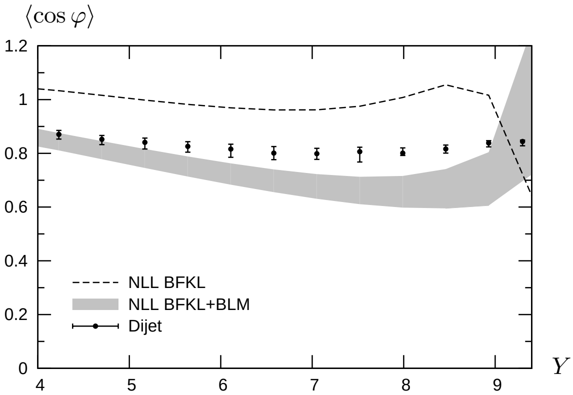
Results for an asymmetric configuration

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

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

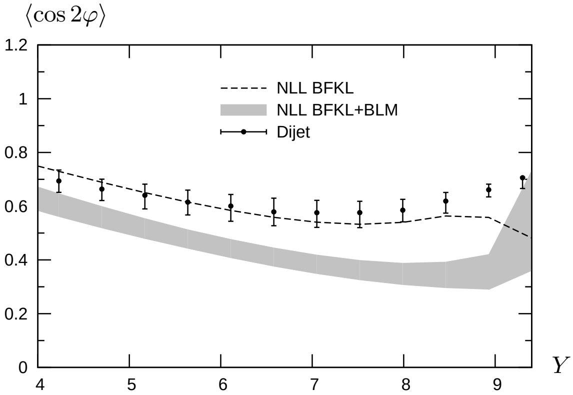


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

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

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

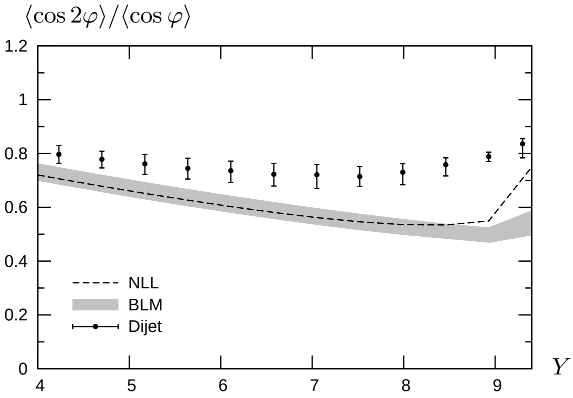


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

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

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

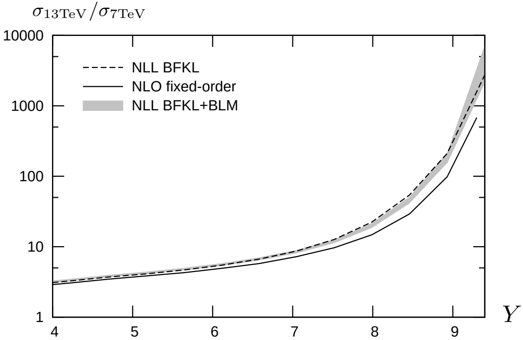


$35\,\text{GeV} < |\mathbf{k}_{J1}| < 60\,\text{GeV}$
$35\,\text{GeV} < |\mathbf{k}_{J2}| < 60\,\text{GeV}$
$50\,\text{GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$

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

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

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

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_{eff} defined as

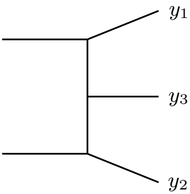
$$Y_{\text{eff}} \equiv Y \frac{\sigma^{2\to 3}}{\sigma^{\text{BFKL},\mathcal{O}(\alpha_{\text{s}}^3)}}$$

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

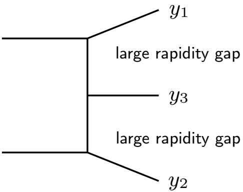
Energy-momentum conservation

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

exact $2 \to 3$



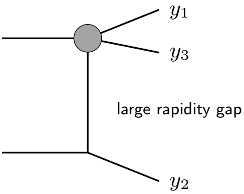
BFKL



1 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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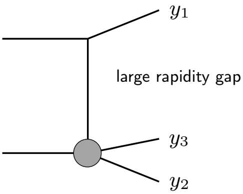
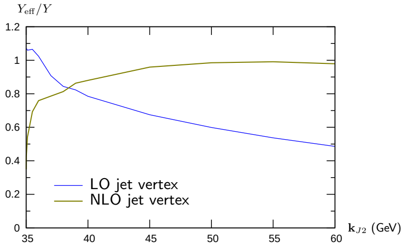


no emission from the Green's function + NLO jet vertex

Energy-momentum conservation

Variation of Y_{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_{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 $\frac{Y_{\text{eff}}}{Y} \simeq 0.98$ at NLO vs. ~ 0.6 at LO

Progress in studies of Sudakov resummation in small-x formalism:

A.H. Mueller, B.W. Xiao, F. Yuan, Phys. Rev. Lett. 110 (2013), Phys. Rev. **D 88**

Main idea:

• if two different scales are present in a small-x process

e.g. in M-N jets production:
$\mathbf{P}_\perp \sim |\mathbf{k_{J1}}| \sim |\mathbf{k_{J2}}|$
$\mathbf{q}_\perp = \mathbf{k_{J1}} + \mathbf{k_{J2}}$ dijet momentum imbalance

and if $\mathbf{P}_\perp^2 >> \mathbf{q_\perp^2}$

then Sudakov type logs $\alpha_s \log^2 \frac{\mathbf{P}_\perp^2}{\mathbf{q_\perp^2}}$ can appear and they can be resummed

• Actual precision of calculation:
leading order vertices and Green function & one-loop calculation of Sudakov double logs

Result:

A.H. Mueller, LS, S. Wallon, B.W. Xiao, F. Yuan, JHEP 03 (2016) 096

- cross section

$$\frac{d\sigma}{dy_1 dy_2 d^2k_{\perp 1} d^2k_{\perp 2}} = \int d^2q_{\perp 1} d^2q_{\perp 2} \mathcal{F}_a(x_1, q_{\perp 1}; \mu_F = k_{\perp 1}) \mathcal{F}_b(x_2, q_{\perp 2}; \mu_F = k_{\perp 2})$$

$$\times \, \hat{\sigma}_{ab}(k_{\perp 1}, k_{\perp 2}; \mu_F) \, G(k_{\perp 1} - q_{\perp 1}, k_{\perp 2} - q_{\perp 2}; Y = y_1 - y_2)$$

- parton a distributions with Sudakov resummation effects:

$$\mathcal{F}_a(x, q_\perp; \mu_F = k_\perp) = x \int \frac{d^2 R_\perp}{(2\pi)^2} \, e^{i q_\perp R_\perp} \, e^{-S^a_{Sud}(\mu_F = k_\perp, R_\perp)} \, f_a(x, \frac{c_0}{R_\perp})$$

- Sudakov form factor:

$$S^a_{Sud}(\mu_F = k_\perp, R_\perp) = \int_{c_0^2/R_\perp^2}^{k_\perp^2} \frac{d\mu^2}{\mu^2} \left(A_a \ln \frac{k_\perp^2}{\mu^2} + B_a + D_a \ln \frac{1}{R} \right)$$

where e.g. for a=quark: $A_q = D_q = \frac{\alpha_s}{2\pi} C_F$, $B_q = -\frac{\alpha_s}{2\pi} \frac{3}{2} C_F$, R- jet radius

- phenomenological consequences: work in progress

Conclusions

- We studied Mueller-Navelet jets at full (vertex + Green's function) NLL accuracy and compared our results with the first CMS data
- 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 have predictions for 13 TeV:

  - Azimuthal decorrelations at 13 TeV similar to those at 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 IS NEEDED to test them

MERCI POUR VOTRE ATTENTION!