

Probing BFKL dynamics in Mueller-Navelet jet production at LHC

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Low-x Meeting 2016
6-11 June 2016, Károly Róbert College, Gyöngyös, Hungary

in collaboration with

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F. Schwennsen (DESY), S. Wallon (UPMC & LPT Orsay)

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

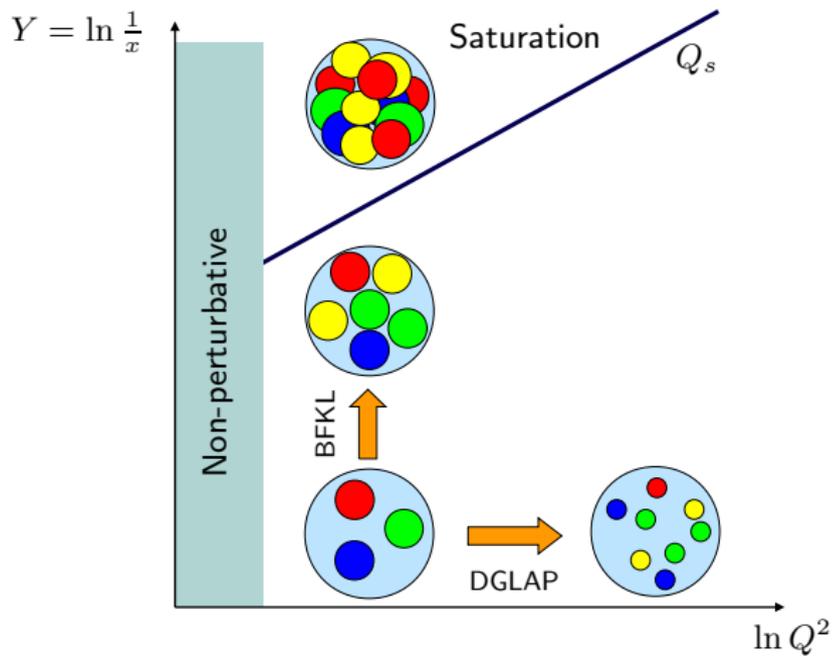
B. Ducloué, S. Wallon:

JHEP **1305** (2013) 096

PRL **112** (2014) 082003

Phys. Rev. D **92** (2015) 076002

The different regimes of QCD

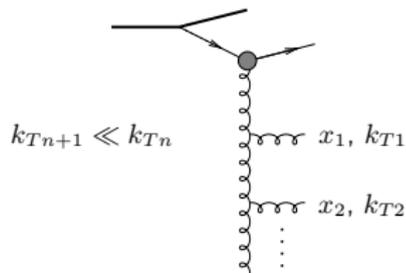


A hard scale exists \Rightarrow Small $\alpha_s \Rightarrow$ perturbation theory applies

small $\alpha_s * \text{large log} \approx \text{constant} \Rightarrow$ necessity of resummation

Collinear fact. of QCD
DGLAP

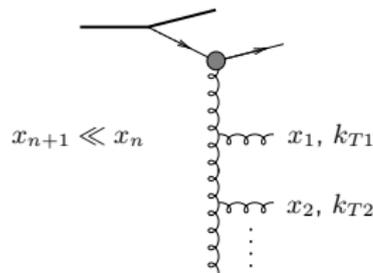
hard scale, e.g. Q^2



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

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

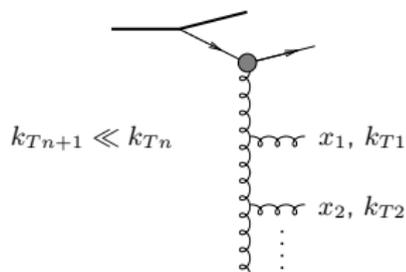
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Collinear fact. of QCD

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hard scale Q^2

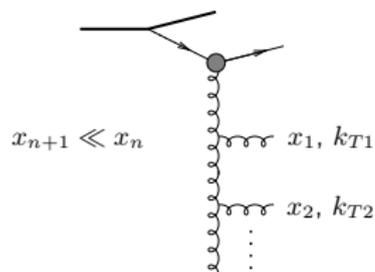


OPE, strong ordering in k_T
dynamics in longitudinal x 's

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

Regge k_T -factorization

BFKL



strong ordering in x , NO ORDERING in k_T
dynamics in transverse k_T 's

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

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

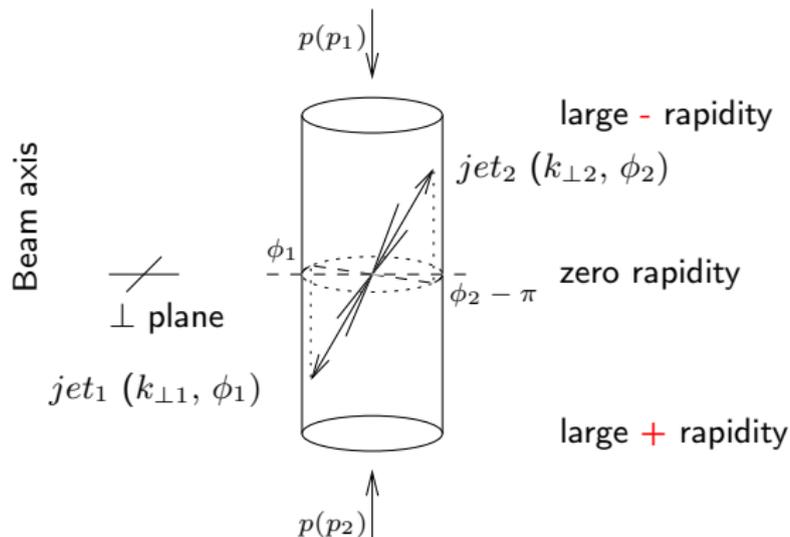
HERA exp's: conclusions unclear

DO EXPERIMENTS AT LHC CONFIRM SUCH EXPECTATION ?

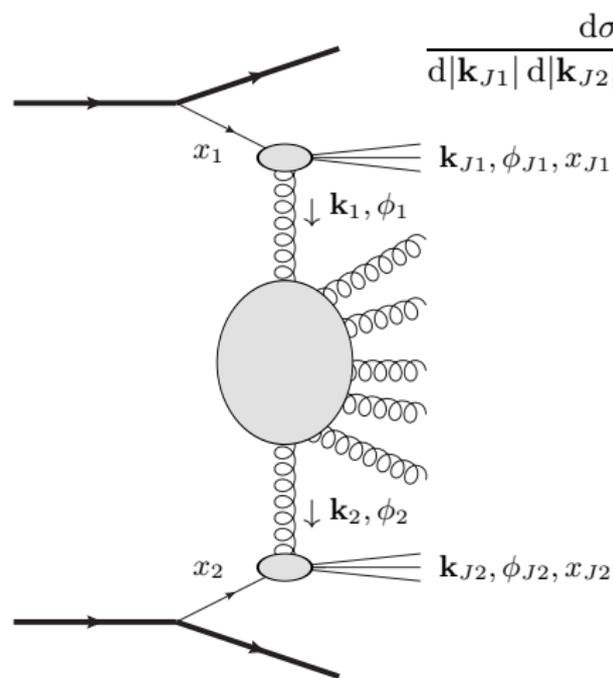
Mueller-Navelet jets

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



k_T -factorized differential cross section



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

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

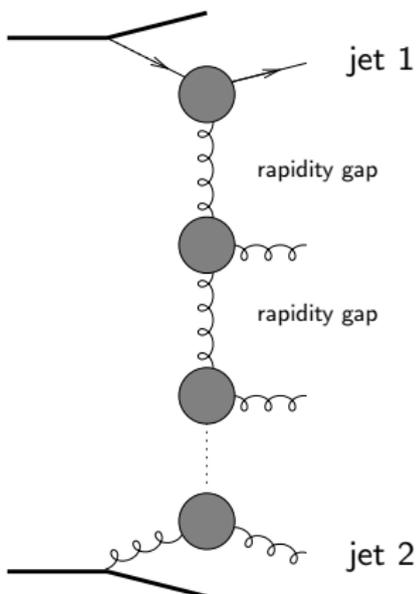
$$\times G(\mathbf{k}_1, \mathbf{k}_2, \hat{s})$$

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

with $\Phi(\mathbf{k}_{J2}, x_{J2}, \mathbf{k}_2) = \int dx_2 f(x_2) V(\mathbf{k}_2, x_2)$ $f \equiv \text{PDF}$ $x_J = \frac{|\mathbf{k}_{Jj}|}{\sqrt{s}} e^{y_J}$

LL BFKL

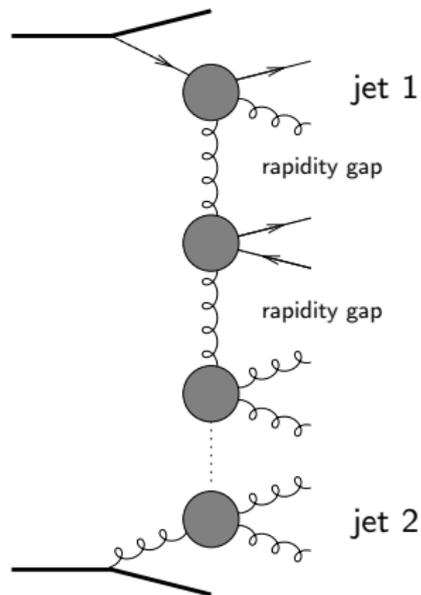
tree vertices, 1-loop Regge trajectory



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

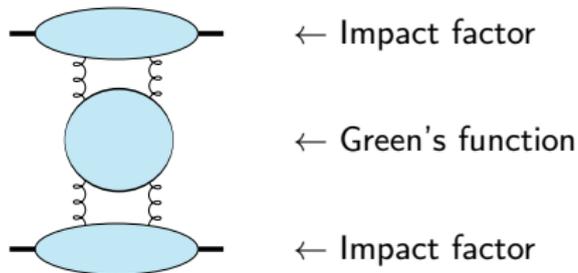
NLL BFKL

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



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

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

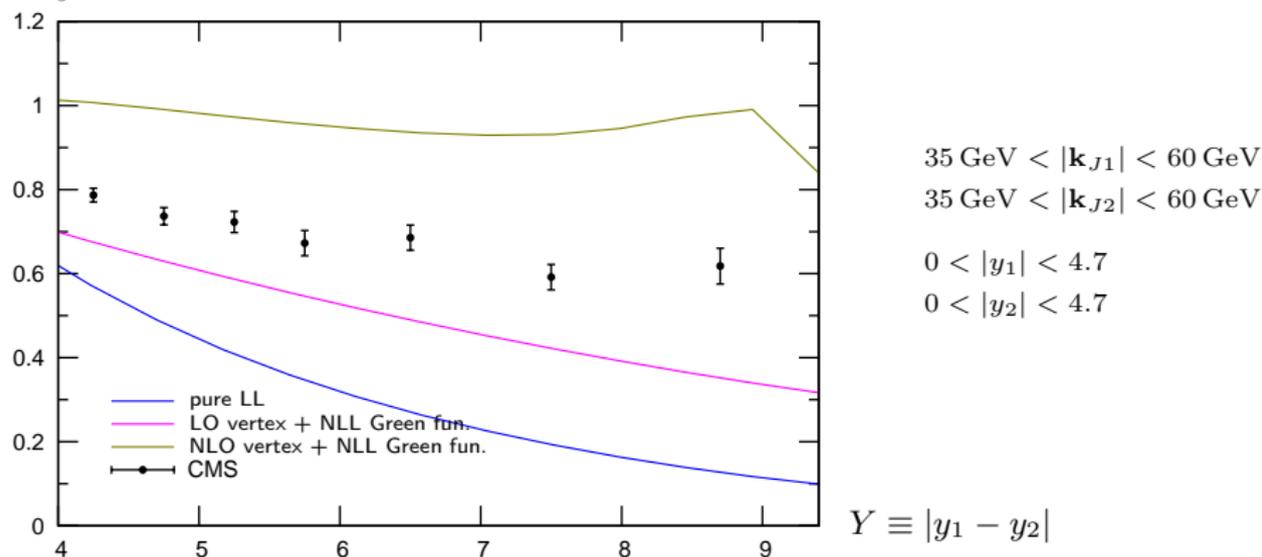
- $\sqrt{s} = 7 \text{ TeV}$
- $35 \text{ GeV} < |\mathbf{k}_{J1}|, |\mathbf{k}_{J2}| < 60 \text{ GeV}$
- $0 < |y_1|, |y_2| < 4.7$

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 & 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 $\langle \cos \varphi \rangle$

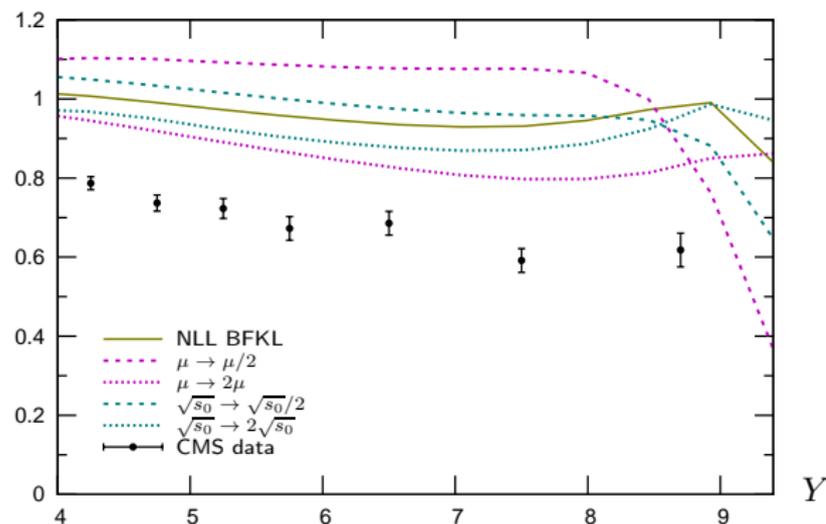
$$\frac{c_1}{c_0} = \langle \cos \varphi \rangle \equiv \langle \cos(\phi_{J_1} - \phi_{J_2} - \pi) \rangle$$



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

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

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



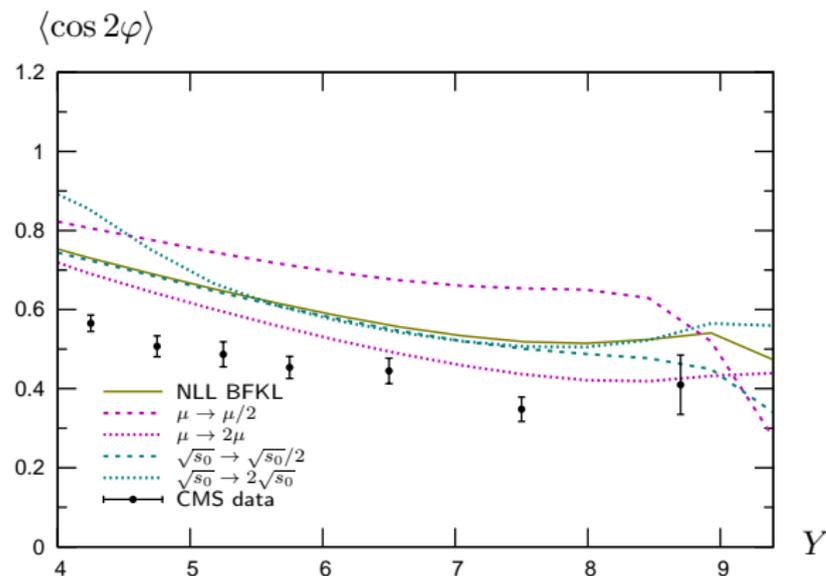
$$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$$

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

$$0 < |y_1| < 4.7$$

$$0 < |y_2| < 4.7$$

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

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

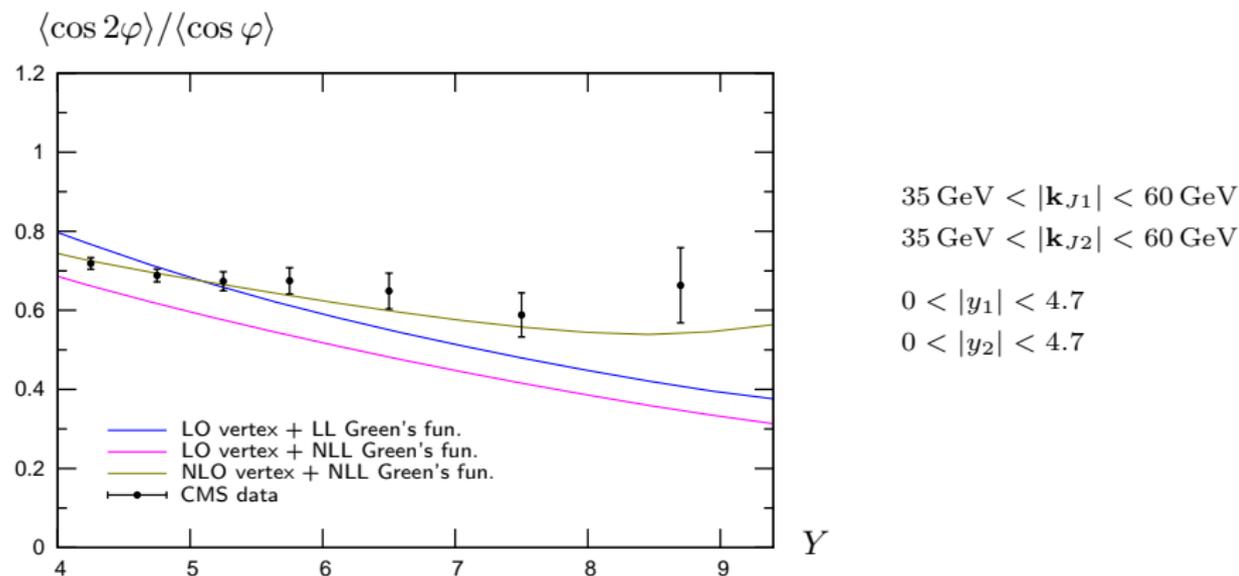
$$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$$

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

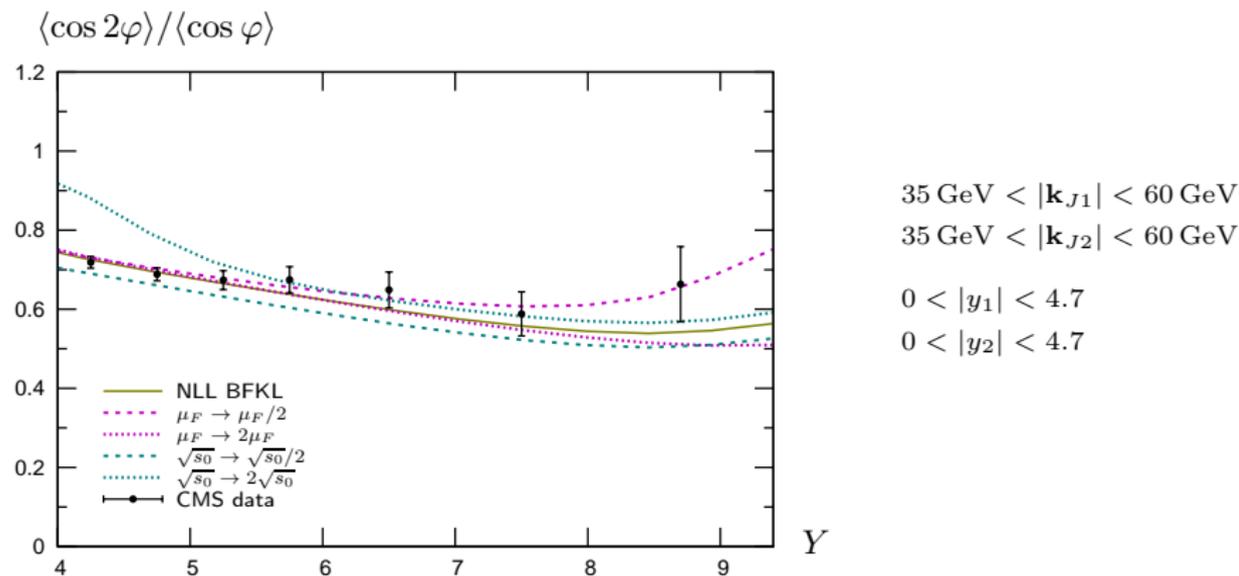
$$0 < |y_1| < 4.7$$

$$0 < |y_2| < 4.7$$

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

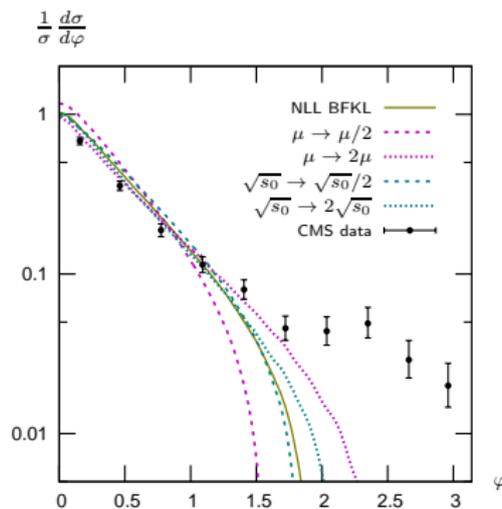
It is necessary to include the NLO corrections to the jet vertex to reproduce the behavior of the data at large Y

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

- 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

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

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



- Our calculation predicts a too large value of $\frac{1}{\sigma} \frac{d\sigma}{d\phi}$ for $\phi \lesssim \frac{\pi}{2}$ and a too small value for $\phi \gtrsim \frac{\pi}{2}$
- It is not possible to describe the data even when varying the scales by a factor of 2

- 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
⇒ 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

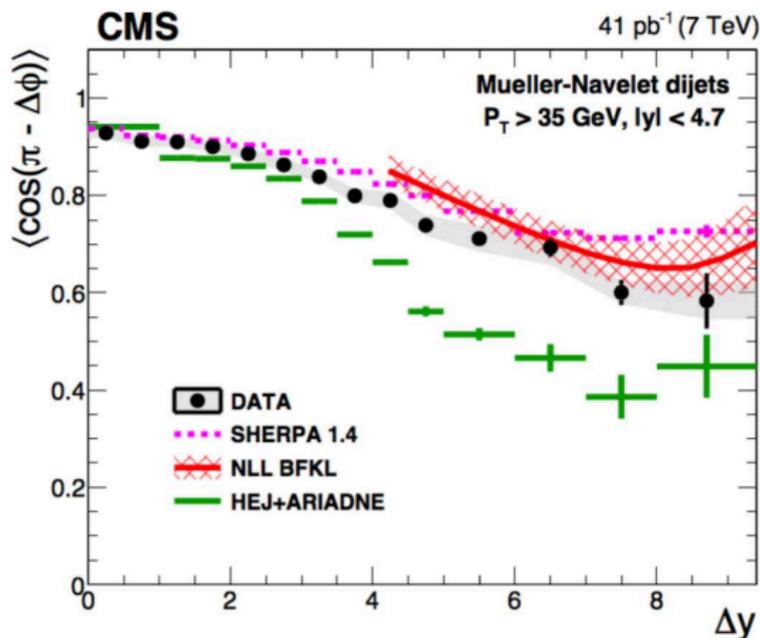
The **Brodsky-Lepage-Mackenzie** (BLM) procedure resums the self-energy corrections to the gluon propagator at one loop into the running coupling.

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.

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

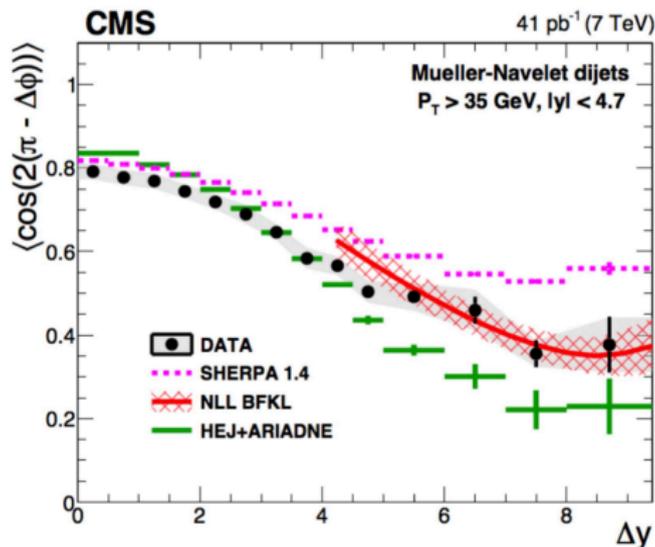
arXiv: CMS 1601.06713



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

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

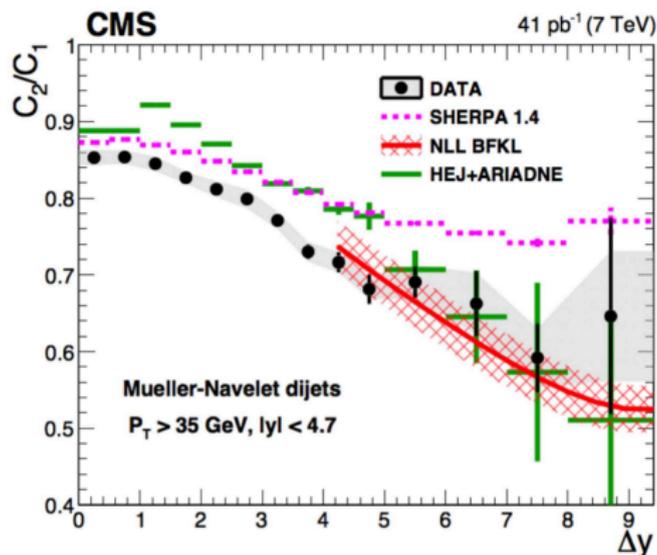
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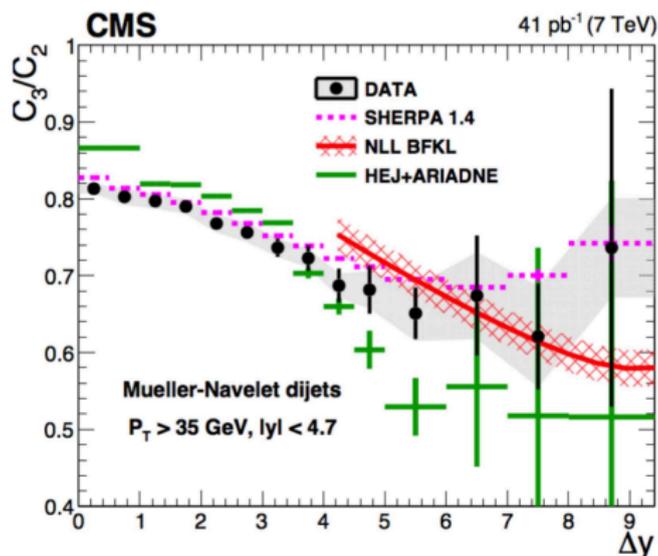
Using the BLM scale setting, the agreement with data becomes much better

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

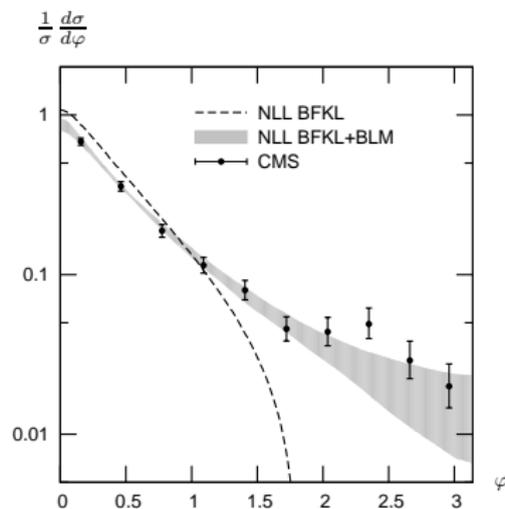
arXiv: CMS 1601.06713



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



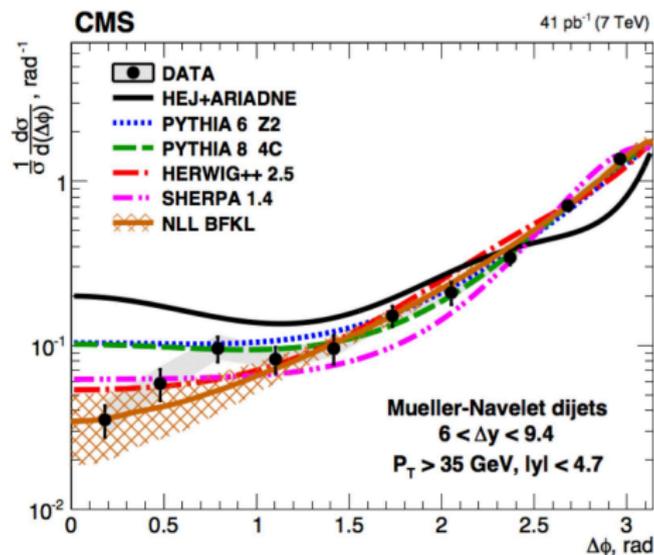
Because it is much less dependent on the scales, the observable $\langle \cos 3\varphi \rangle / \langle \cos 2\varphi \rangle$ is almost not affected by the BLM procedure and is still in good agreement with the data

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 $6 < Y < 9.4$)

arXiv: CMS 1601.06713



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)

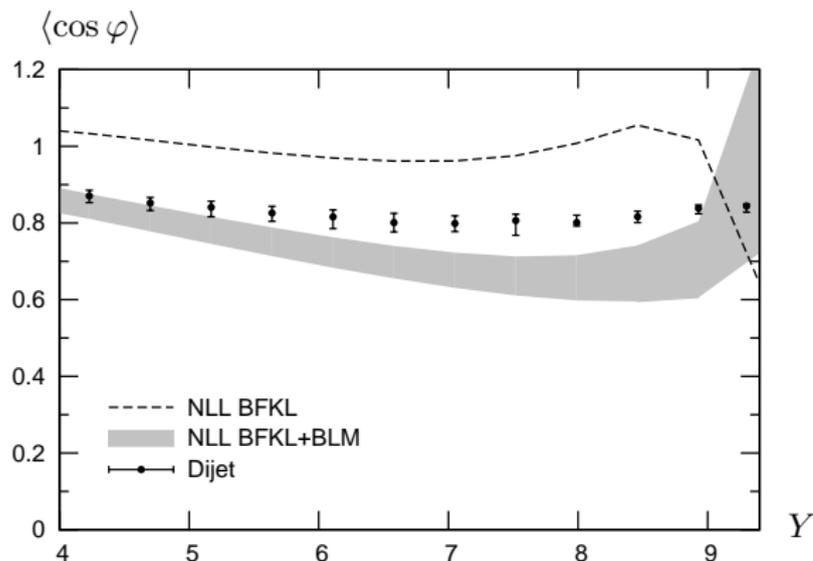
These calculations are unstable when $\mathbf{k}_{J_{\min 1}} = \mathbf{k}_{J_{\min 2}}$ because the cancellation of some divergencies is difficult to obtain numerically

Results for an asymmetric configuration

In this section we choose the cuts as

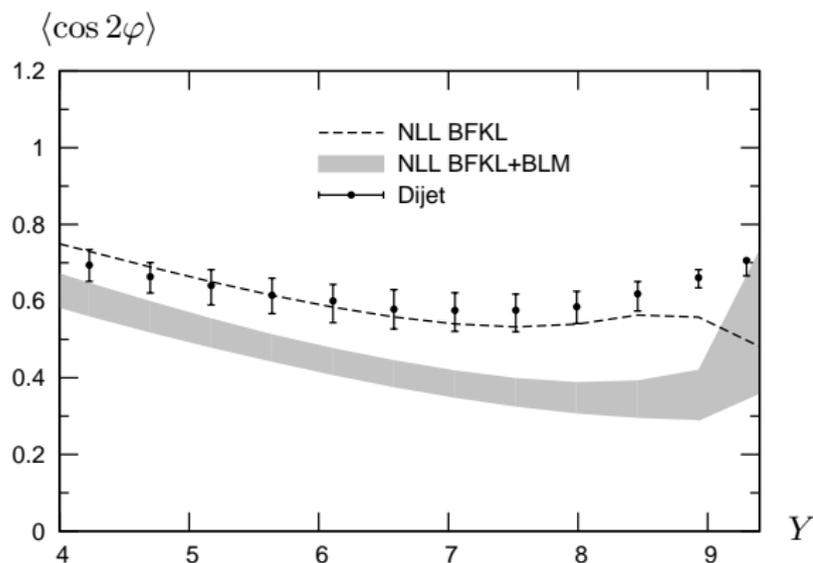
- $35 \text{ GeV} < |\mathbf{k}_{J1}|, |\mathbf{k}_{J2}| < 60 \text{ GeV}$
- $50 \text{ GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$
- $0 < |y_1|, |y_2| < 4.7$

And we compare our results with the NLO fixed-order code Dijet ([Aurenche](#), [Basu](#), [Fontannaz](#)) in the same configuration

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

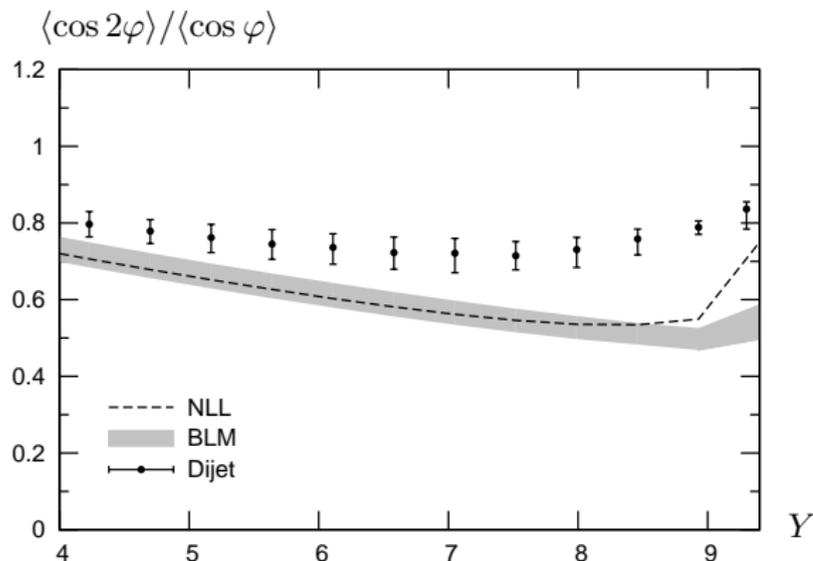
$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
 $35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$
 $50 \text{ GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$
 $0 < |y_1| < 4.7$
 $0 < |y_2| < 4.7$

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

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

$35 \text{ GeV} < |\mathbf{k}_{J1}| < 60 \text{ GeV}$
 $35 \text{ GeV} < |\mathbf{k}_{J2}| < 60 \text{ GeV}$
 $50 \text{ GeV} < \text{Max}(|\mathbf{k}_{J1}|, |\mathbf{k}_{J2}|)$
 $0 < |y_1| < 4.7$
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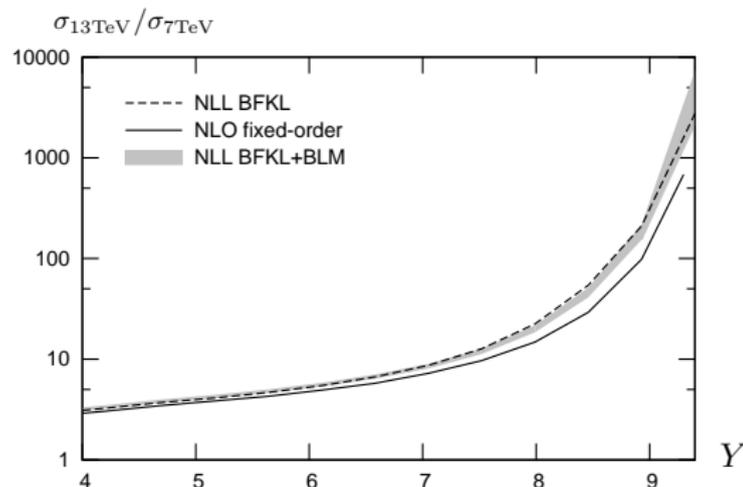
The BLM procedure leads to a sizable difference between NLO fixed-order and NLL BFKL+BLM

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

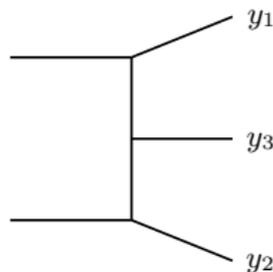
This was studied at LO by [Del Duca and Schmidt](#). They introduced an effective rapidity Y_{eff} defined as

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

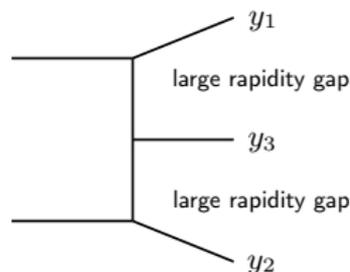
When one replaces Y by Y_{eff} in the expression of σ^{BFKL} and truncates to $\mathcal{O}(\alpha_s^3)$, the exact $2 \rightarrow 3$ result is obtained

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

exact $2 \rightarrow 3$

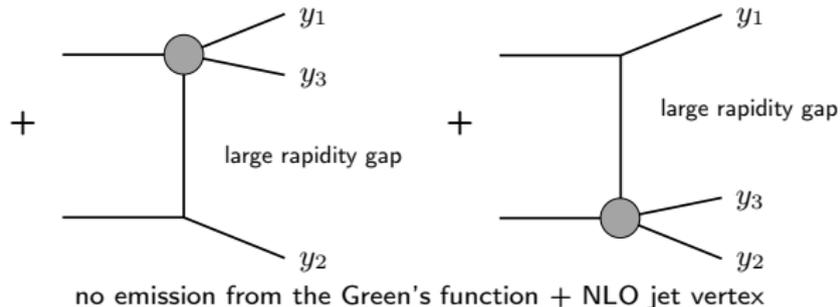


BFKL

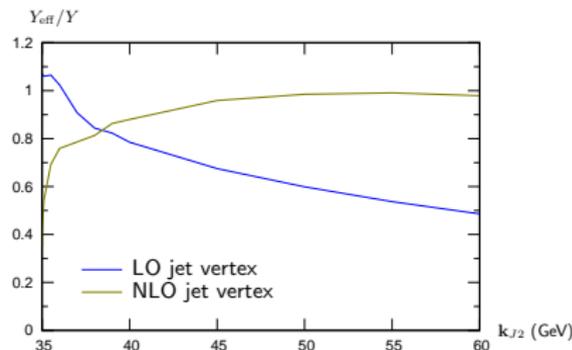


1 emission from the Green's function + LO jet vertex

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



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



- With the **LO** jet vertex, Y_{eff} is much smaller than Y when k_{J1} and 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 $k_{J1} = 35$ GeV and $k_{J2} = 50$ 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

- 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**

THANK YOU FOR YOUR ATTENTION!