

A forward J/ψ and a backward jet at the LHC
A probe for the NRQCD color octet contribution?

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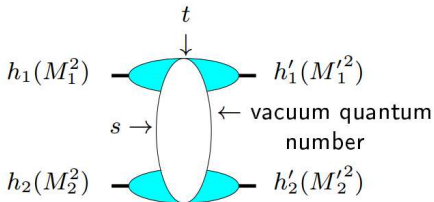
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The Regge limit

- 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 such 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**

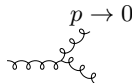
How to test QCD in the perturbative Regge limit?

What kind of observable?

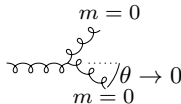
- perturbation theory should be applicable:

selecting external or internal probes with transverse sizes $\ll 1/\Lambda_{QCD}$ (*hard* γ^* , *heavy meson* (J/Ψ , Υ), *energetic forward jets*) or by choosing large t in order to provide the hard scale.

- governed by the *soft* perturbative dynamics of QCD



rather than its *collinear* dynamics



\implies 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**.

How to test QCD in the perturbative Regge limit?

Some examples of processes

- **inclusive**: DIS (HERA), diffractive DIS, total $\gamma^*\gamma^*$ cross-section (LEP, ILC)
- **semi-inclusive**: forward jet and π^0 production in DIS, Mueller-Navelet double jets, diffractive double jets, high p_T central jet, in hadron-hadron colliders (Tevatron, LHC)
- **exclusive**: exclusive meson production in DIS, double diffractive meson production at e^+e^- colliders (ILC), ultraperipheral events at LHC (Pomeron, Odderon)

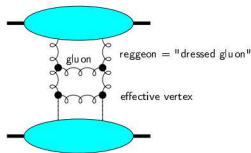
The specific case of QCD at large s

QCD in the perturbative Regge limit

- Small values of α_S (perturbation theory applies due to hard scales) can be compensated by large $\ln s$ enhancements. \Rightarrow resummation of $\sum_n (\alpha_S \ln s)^n$ series (Balitsky, Fadin, Kuraev, Lipatov)

$$\mathcal{A} = \underbrace{\text{Diagram 1}}_{\sim s} + \left(\text{Diagram 2} + \text{Diagram 3} + \dots \right)_{\sim s (\alpha_S \ln s)} + \left(\text{Diagram 4} + \dots \right)_{\sim s (\alpha_S \ln s)^2} + \dots$$

- this results in the effective BFKL ladder



$$\Rightarrow \sigma_{tot}^{h_1 h_2 \rightarrow anything} = \frac{1}{s} \text{Im} \mathcal{A} \sim s^{\alpha_P(0)-1}$$

with $\alpha_P(0) - 1 = C \alpha_S$ ($C > 0$) **Leading Log Pomeron**
 Balitsky, Fadin, Kuraev, Lipatov

Higher order corrections

- Higher order corrections to the 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
 - $\gamma^* \rightarrow \gamma^*$ at $t = 0$ (Bartels, Colferai, Gieseke, Kyrielleis, Qiao; Balitsky, 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)
 - $\gamma_L^* \rightarrow \rho_L$ in the forward limit (Ivanov, Kotsky, Papa)

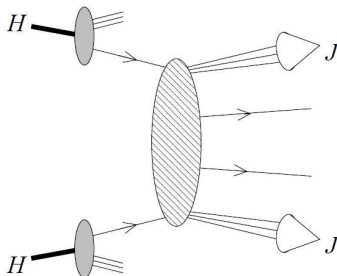
Example of a test of the BFKL dynamics

Mueller Navelet jet production

- Mueller, Navelet
- NLO impact factor : Bartels, Colferai, Vacca
 - In traditional QCD approach : Caporale, Ivanov, Murdaca, Papa, Perri
 - In the small R limit in cone algorithm : Ivanov, Papa
 - With Lipatov's effective action : Hentschinski, Sabio Vera
Chachamis, Hentschniski, Madrigal Martinez, Sabio Vera
- Phenomenological application :
 - Caporale, Ivanov, Murdaca, Papa
 - Caporale, Murdaca, Sabio Vera, Salas
 - Schwennsen, Szymanowski, Wallon
 - Ducloué , Szymanowski, Wallon
- NLO fixed-order : Aurenche, Basu, Fontannaz

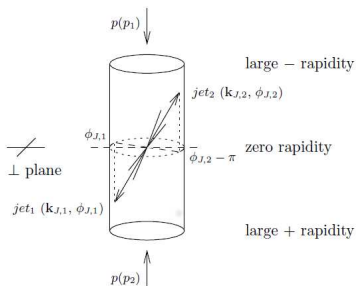
Mueller-Navelet jets

Production of two jets with a large rapidity gap.



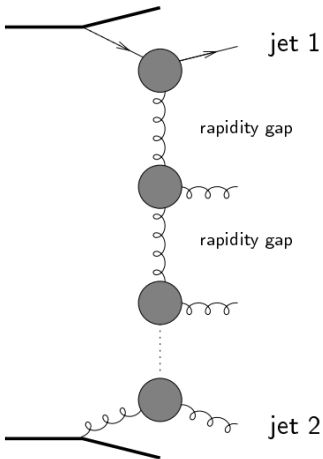
Bartels, Colferai, Vacca

At LO in **collinear factorization**, these jets are **back to back**.

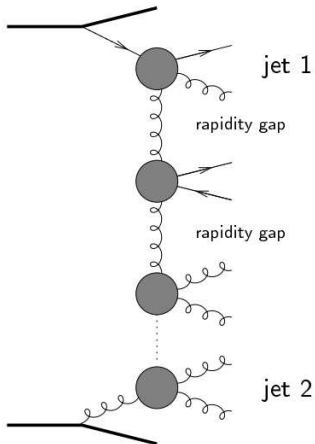


Mueller-Navelet jets: LL vs NLL

LL BFKL



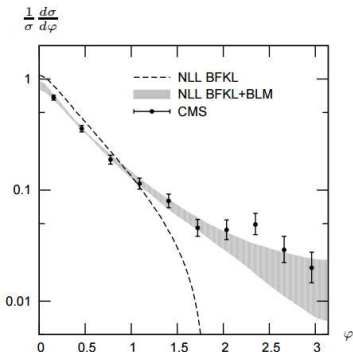
NLL BFKL



Comparison with the data

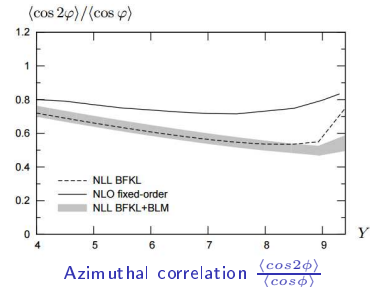
NLL BFKL vs NLO fixed-order

For a large rapidity gap and unequal transverse momenta



Azimuthal distribution

Ducloué, Szymanowski, Wallon

Azimuthal correlation $\frac{\langle \cos 2\phi \rangle}{\langle \cos \phi \rangle}$
Compared with Aurenche, Basu, Fontannaz

The theoretical prediction for the azimuthal distribution in MN jet production is in good agreement with the data.

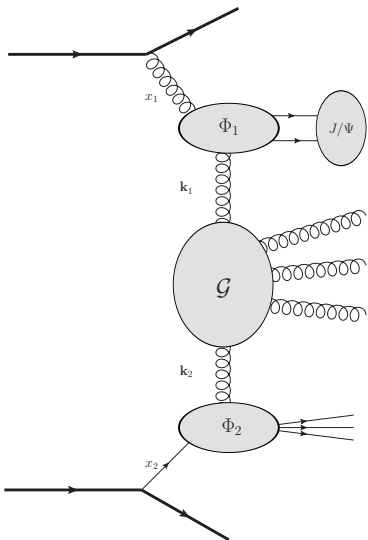
See also the many papers of Caporale, Celiberto, Ivanov, Murdaca, Papa, Perri, Sabio Vera, Salas on this subject.

Production of a **forward J/ψ** and a **backward jet**

Why J/ψ ?

- Numerous J/ψ mesons are produced at the LHC
- J/ψ is easy to reconstruct experimentally through its decay to $\mu^+\mu^-$ pairs
- The mechanism for the production of J/ψ mesons is still to be completely understood (see discussion later), although it was observed more than 40 years ago [E598 collab 1974], [SLAC-SP collab 1974]
- The vast majority of J/ψ theoretical predictions are done in the collinear factorization framework : would k_t factorization give something different?
- We will perform an MN-like analysis, considering a process with a rapidity gap which is large enough to use BFKL dynamics but small enough to be able to detect J/ψ mesons.

An MN-like analysis



$$\frac{d\sigma}{d|\mathbf{k}_{J/\psi}| d|\mathbf{k}_{jet}| dy_{J/\psi} dy_{jet}} = \int d\phi_{J/\psi} d\phi_{jet} \int d^2\mathbf{k}_1 d^2\mathbf{k}_2$$

$$\times \int dk_{gluon} \Phi_1(\mathbf{k}_{J/\psi}, x_{J/\psi}, -\mathbf{k}_1, k_{gluon})$$

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

$$\times \Phi_2(\mathbf{k}_{jet}, x_{jet}, \mathbf{k}_2)$$

First computation : NRQCD formalism

The NRQCD formalism

J/ψ production in NRQCD

We will first use the Non Relativistic QCD (NRQCD) formalism

Basically, one expands the onium wavefunction wrt the velocity of its constituents v :

$$|\Psi\rangle = O(1) |Q\bar{Q}[{}^3S_1^{(1)}]\rangle + O(v) |Q\bar{Q}[{}^3S_1^{(8)}]g\rangle + O(v^2)$$

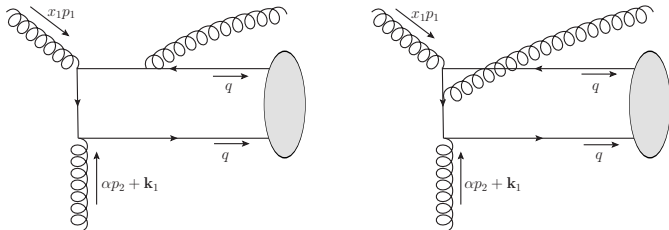
One assumes that all the non-perturbative physics is encoded in this wavefunction.

⇒ One computes the hard part using the usual Feynman diagram methods and convolute it with the wavefunction afterwards.

Charge parity conservation → Hard part : $c\bar{c}$ in a color singlet state + g , $c\bar{c}$ in a color octet state.

The relative importance of this additional color-octet contribution is **still to be determined**.

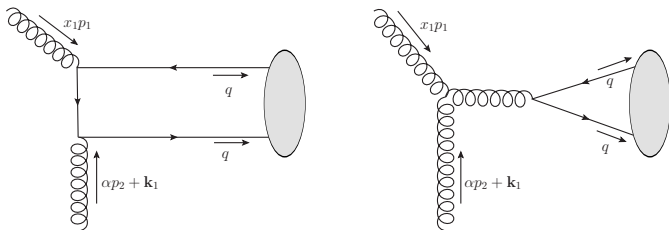
There is no proof of NRQCD factorization at all orders.

The J/ψ impact factor for color singlet production

Two examples out of 6 diagrams

Quark-antiquark to J/ψ transition vertex from NRQCD expansion :

$$v_{\alpha}^i(q_2) \bar{u}_{\beta}^j(q_1) \rightarrow \frac{\delta^{ij}}{4N_c} \left(\frac{\langle \mathcal{O}_1 \rangle_{J/\psi}}{m} \right)^{\frac{1}{2}} \left[\hat{\mathcal{E}}_{J/\psi}^* \left(\hat{k}_{J/\psi} + M \right) \right]_{\alpha, \beta} \quad (1)$$

The *J/ψ* impact factor for color octet production

2 examples out of 3 diagrams

Quark-antiquark to *J/ψ* transition vertex from NRQCD expansion :

$$\left[v_{\alpha}^i(q_2) \bar{u}_{\alpha}^j(q_1) \right]^a \rightarrow \frac{t_{ij}^a}{4N_c} \left(\frac{\langle \mathcal{O}_8 \rangle_V}{m} \right)^{\frac{1}{2}} \left[\hat{\epsilon}_V^* \left(\hat{k}_{J/\psi} + M \right) \right]_{\alpha, \beta}$$

Second computation : the Color Evaporation Model

The Color Evaporation Model

The Color Evaporation Model

Relies on the **local duality hypothesis** :

A heavy quark pair $Q\bar{Q}$ with an invariant mass below the threshold for the production of a pair of the lightest meson which contains Q will eventually produce a bound $Q\bar{Q}$ pair after a series of randomized soft interactions between its production and its confinement in $\frac{1}{9}$ cases, **independently of its color and spin**.

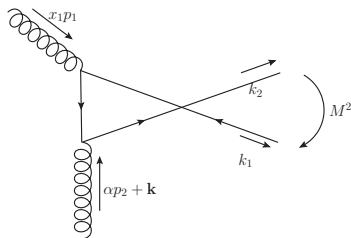
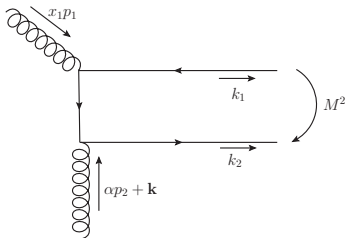
It is assumed that the repartition between all the possible charmonium states is universal.

Thus the procedure is the following :

- Compute all the Feynman diagrams for **open $Q\bar{Q}$** production
- Sum over **all spins and colors**
- Integrate over the $Q\bar{Q}$ invariant mass

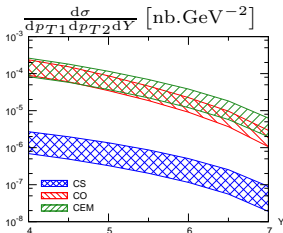
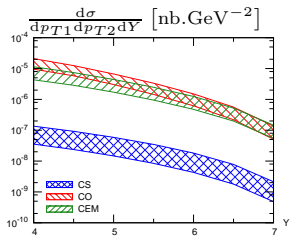
Then, neglecting the contributions from $Q\bar{Q}$ pairs with an invariant mass above the threshold, use :

$$\sigma_{J/\psi} = F_{J/\psi} \int_{4m_c^2}^{4m_D^2} dM^2 \frac{d\sigma_{c\bar{c}}}{dM^2}$$

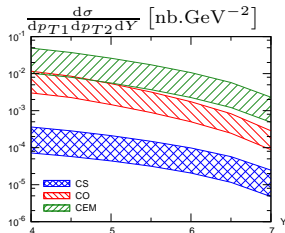


2 examples out of 3 diagrams to compute in the CEM

Numerical results



$p_{T1} = 20 \text{ GeV}, p_{T2} = 20 \text{ GeV}$



$p_{T1} = 10 \text{ GeV}, p_{T2} = 10 \text{ GeV}$

Differential cross sections from both models

Summary

- The production of **Mueller-Navelet jets** was successfully described using the **BFKL formalism**
- We applied the same formalism for the production of a **forward J/ψ meson** and a **backward jet**, using both the **NRQCD formalism** and the **Color Evaporation Model**
- In the NRQCD formalism, the **Color octet** contribution dominates