Production of a forward J/ψ and a backward jet at LHC as a test of BFKL dynamics

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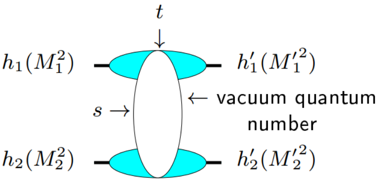
Motivations

- 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



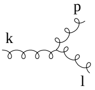
Hard scales: $M_1^2,\, M_2^2 \gg \Lambda_{QCD}^2$ or $M_1'^2,\, M_2'^2 \gg \Lambda_{QCD}^2$ or $t \gg \Lambda_{QCD}^2$
where the $t-$channel exchanged state is the so-called hard Pomeron

How to test QCD in the perturbative Regge limit?

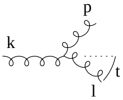
What kind of observable?

- 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



and *not* by its *collinear* dynamics



$\Longrightarrow$ select 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?

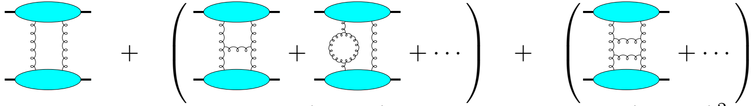
Some examples of processes

- 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 ($\mathbb{P}$omeron, $\mathbb{O}$dderon)

The specific case of QCD at large s

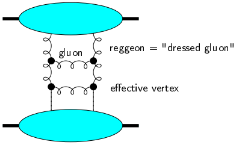
QCD in the perturbative Regge limit

- 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 (Balitski, Fadin, Kuraev, Lipatov)

$\mathcal{A} =$  $+ \cdots$

$\sim s \qquad \sim s\,(\alpha_s \ln s) \qquad \sim s\,(\alpha_s \ln s)^2$

- this results in the effective BFKL ladder



$$\Longrightarrow \sigma_{tot}^{h_1\, h_2 \to anything} = \frac{1}{s} Im\mathcal{A} \sim s^{\alpha_{\mathbb{P}}(0)-1}$$

with $\alpha_{\mathbb{P}}(0) - 1 = C\,\alpha_s \quad (C > 0)$ Leading Log Pomeron
Balitsky, Fadin, Kuraev, Lipatov

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

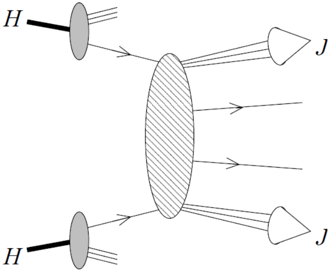
Example of a test of the BFKL dynamics

Mueller Navelet jet production

- Mueller, Navelet
- NLO impact factor : Bartels, Colferai, Vacca
  - In traditionnal 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
  - Colferai, Schwennsen, Szymanowski, Wallon
  - Ducloué , Szymanowski, Wallon
- NLO fixed-order : Aurenche, Basu, Fontannaz

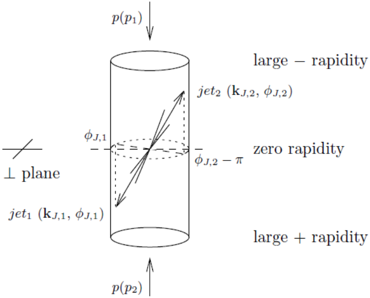
Mueller-Navelet jets

Production two jets with a large rapidity gap.



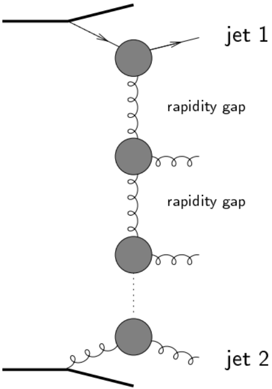
Bartels, Colferai, Vacca

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



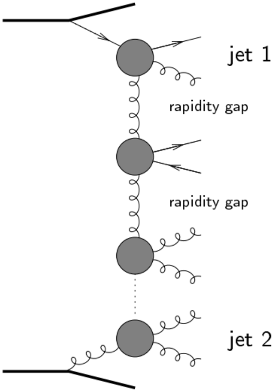
Mueller-Navelet jets: LL vs NLL

LL BFKL



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

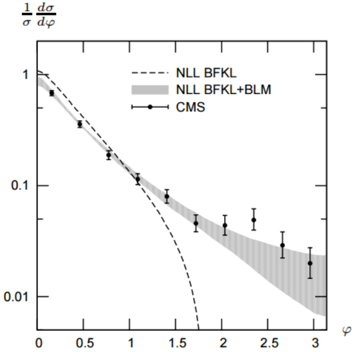
NLL BFKL



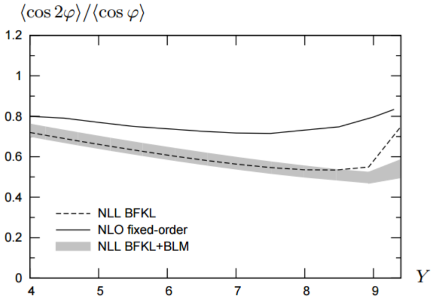
$$\sum(\alpha_s \ln s)^n + \alpha_s \sum(\alpha_s \ln s)^n$$

Comparison with the data

NLL BFKL vs NLO fixed-order
For large rapidity gap and unequal transverse momenta



Azimuthal distribution
Ducloué, Szymanowski, Wallon



Azimuthal correlation $\frac{\langle cos2\phi\rangle}{\langle cos\phi\rangle}$
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.

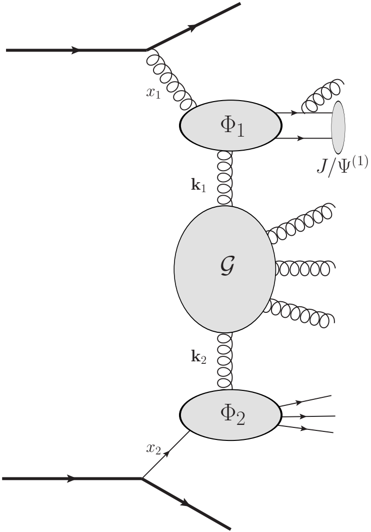
J/ψ and jet production

Production of a forward J/ψ and a backward jet

Why $J\psi$?

- Natural presence of a hard scale given by its mass
- Numerous J/ψ mesons are produced at LHC
- J/ψ is easy to reconstruct experimentaly through its decay to $\mu^+\mu^-$ pairs
- The mechanism for the production of $J\psi$ 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 $J\Psi$ theoretical predictions are done in the collinear factorization framework : would k_t factorization give something else?
- 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



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

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

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

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

The J/ψ production vertex

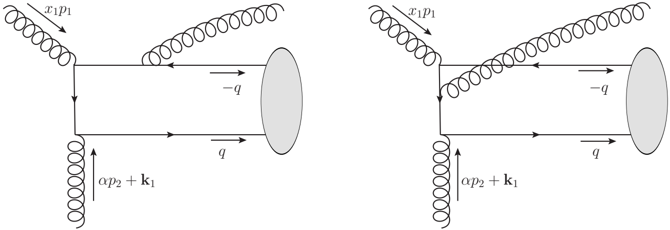
We will use well-known Non Relativistic QCD (NRQCD) results [Bodwin, Braaten, Lepage], [Cho, Leibovich] for heavy quarkonium

Onium wavefunctions expansion wrt the velocity of its constituents $v \sim \frac{1}{\log M}$:
$$|\Psi\rangle = O(1) \left|Q\bar{Q}[^3S_1^{(1)}]\right\rangle + O(v) \left|Q\bar{Q}[^3P_J^{(8)}]g\right\rangle + O(v^2)$$

Hence from a theoretical point of view a J/ψ meson can be produced not only from a color singlet quark-antiquark pair along with a gluon but also from a color octet quark-antiquark pair

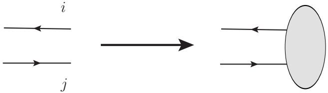
The relative importance of this additional color-octet contribution is still to be determined

The J/ψ impact factor for color singlet production



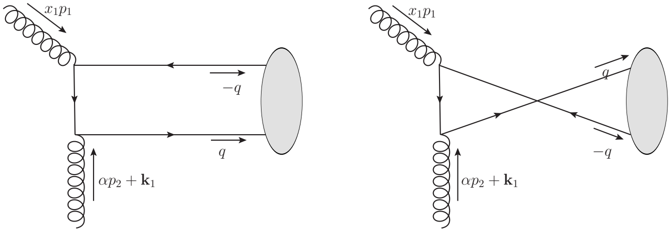
Two examples out of 6 diagrams

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



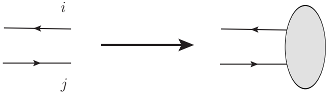
$$v_i(q_2)\bar{u}_j(q_1) \rightarrow \frac{\delta_{ij}}{4N_c} \left(\frac{\langle \mathcal{O}_1 \rangle_V}{m} \right)^{\frac{1}{2}} \hat{\epsilon}_V^* \left(\hat{k}_{J/\psi} + M \right)$$

The J/ψ impact factor for color octet production



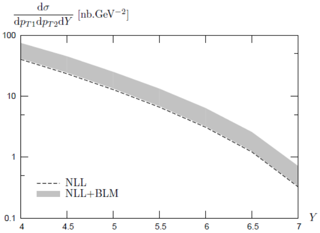
Diagrams for octet production

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

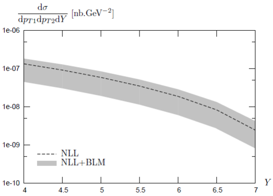


$$v_i(q_2)\bar{u}_j(q_1) \rightarrow \frac{cste}{4N_c}\left(\frac{\langle \mathcal{O}_8 \rangle_V}{m}\right)^{\frac{1}{2}} \hat{\epsilon}_V^* \left(\hat{k}_{J/\psi} + M\right)$$

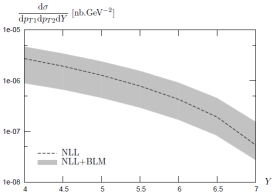
Differential cross section for color singlet production



Differential cross section for MN jets, $\mathbf{k}_{jet1} = 25GeV$, $\mathbf{k}_{jet2} = 25GeV$



$\mathbf{k}_{jet} = 25GeV$, $\mathbf{k}_{J/\psi} = 25GeV$

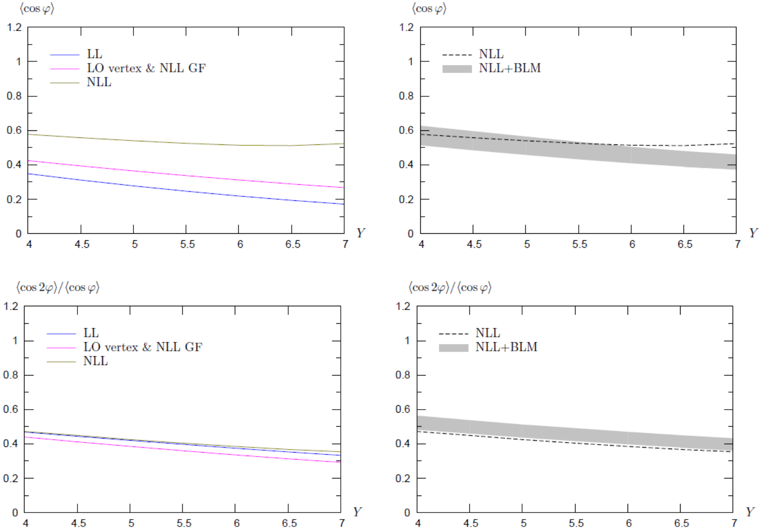


$\mathbf{k}_{jet} = 25GeV$, $\mathbf{k}_{J/\psi} = 10GeV$

Differential cross sections for J/ψ + jet

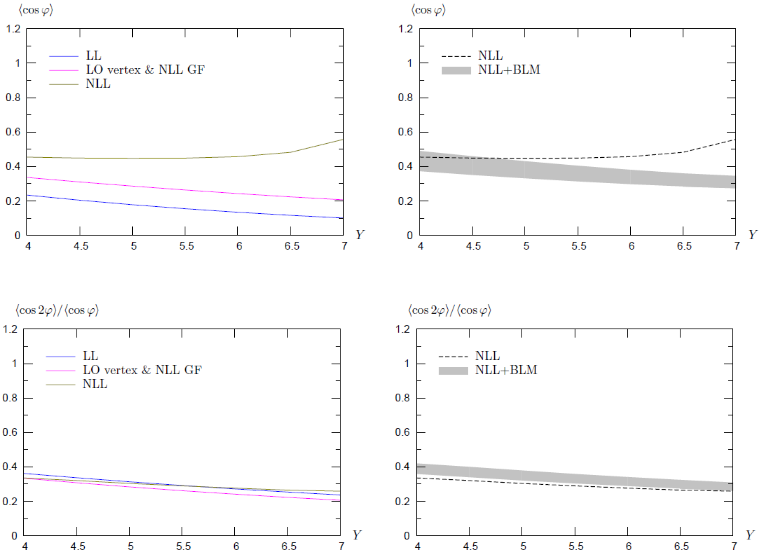
Azimuthal correlation

$$\mathbf{k}_{jet} = 25GeV,\ \mathbf{k}_{J/\psi} = 25GeV$$



Azimuthal correlation

$$\mathbf{k}_{jet} = 25GeV,\ \mathbf{k}_{J/\psi} = 10GeV$$



Numerical predictions for color octet production

- Our numerical predictions are not fully available yet
- First estimations show that the color octet process seems to dominates the color singlet process.

Conclusion

- This was a preliminary study : both mechanisms for J/ψ production should be taken into account
- This study differs from most of the current J/ψ production studies since it relies on the k_t-factorization formalism since we will use NLO BFKL
- The improvement of the impact factor from LO to NLO is to be done