Production of a forward J/ψ and a backward jet at the LHC

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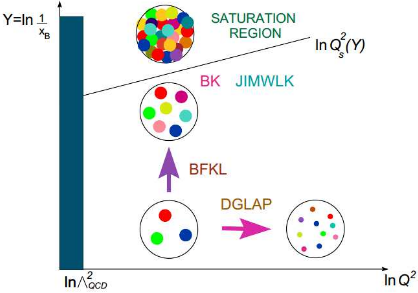
QCD in the Regge limit



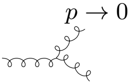
- DGLAP dynamics : $Q^2 \to \infty$, moderate x_B
  - Governed by collinear dynamics
  - Resummation of Q^2 logs : $(\alpha_s \ln Q^2)^n,\ \alpha_s(\alpha_s \ln Q^2)^n \ldots$
- BFKL dynamics (Regge limit) $s \gg Q^2 \gg \Lambda_{QCD}$ ($x_B \ll 1$)
  - Governed by soft dynamics
  - Resummation of $\frac{1}{x_B} \sim s$ logs : $(\alpha_s \ln s)^n,\ \alpha_s(\alpha_s \ln s)^n \ldots$

How to test QCD in the perturbative Regge limit?

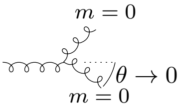
What kind of observable?

- perturbation theory should apply :
  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



$\Longrightarrow$ 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?

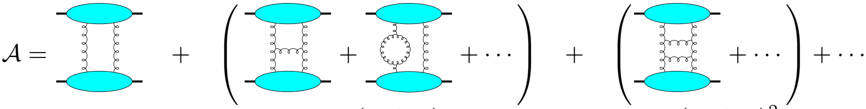
Some examples of processes

- 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

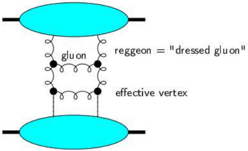
QCD in the perturbative Regge limit

- 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 (Balitsky, Fadin, Kuraev, Lipatov)



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

- 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 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
  - $\gamma^* \to \gamma^*$ at $t = 0$ (Bartels, Colferai, Gieseke, Kyrieleis, 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)
  - $\gamma_L^* \to \rho_L$ in the forward limit (Ivanov, Kotsky, Papa)

Mueller Navelet jets

Example of a test of the BFKL dynamics

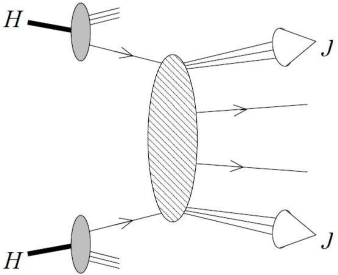
Mueller Navelet jet production

- 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
  - Schwennsen, Szymanowski, Wallon
  - Ducloué , Szymanowski, Wallon
- NLO fixed-order : Aurenche, Basu, Fontannaz

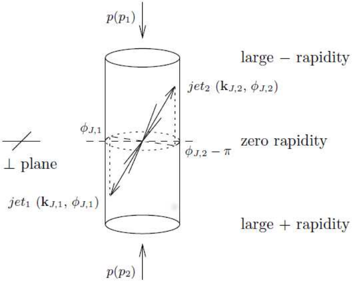
Mueller-Navelet jets

Production of two jets with a large rapidity difference.



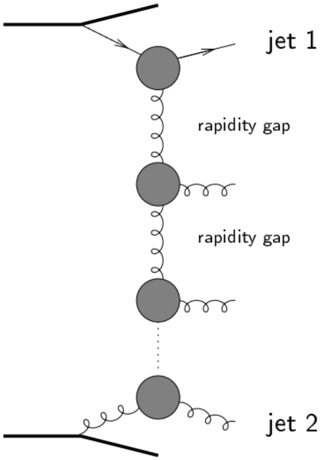
Bartels, Colferai, Vacca

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

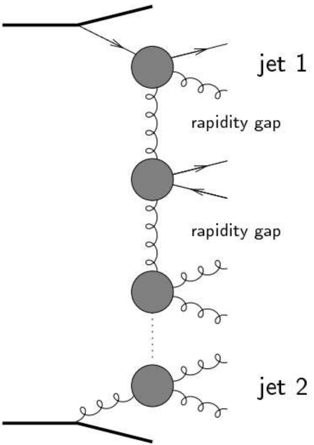


Mueller-Navelet jets: LL vs NLL

LL BFKL

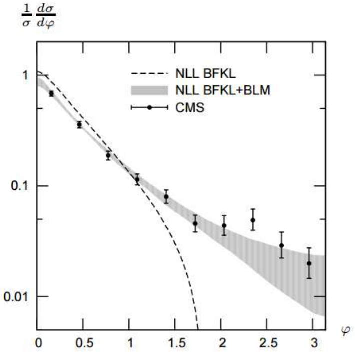


NLL BFKL

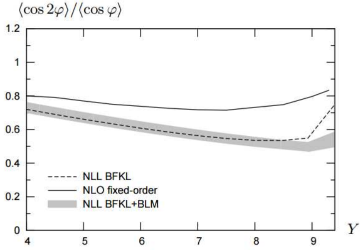


Comparison with the data

NLL BFKL vs NLO fixed-order
For 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.

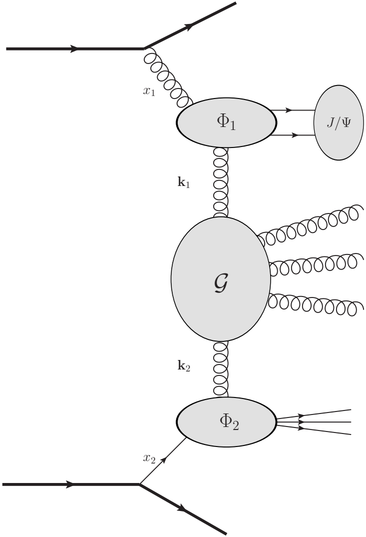
J/ψ and jet production

Production of a forward J/ψ and a backward jet

Why $J\psi$?

- 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/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



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

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

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

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

Non Relativistic QCD

The NRQCD formalism

J/ψ production in NRQCD

We will first use the Non Relativistic QCD (NRQCD) formalism [Bodwin, Braaten, Lepage], [Cho, Leibovich].

Basically, one expands the onium wavefunction wrt the velocity of its constituents $v \sim \frac{1}{\log M}$:

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

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

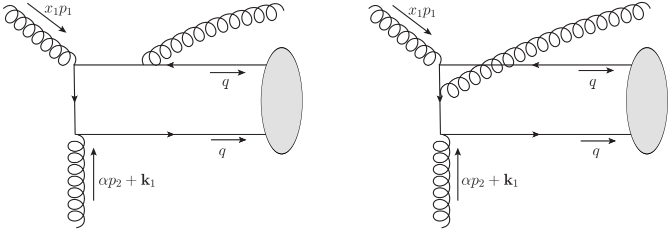
$\Rightarrow$ One computes the hard part using the usual Feynman diagram methods and convolute it with the wavefunction afterwards.

Charge parity conservation $\rightarrow$ 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.

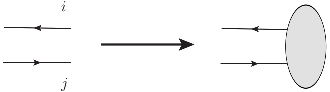
There is no proof of NRQCD factorization at all orders.

The J/ψ impact factor for color singlet production



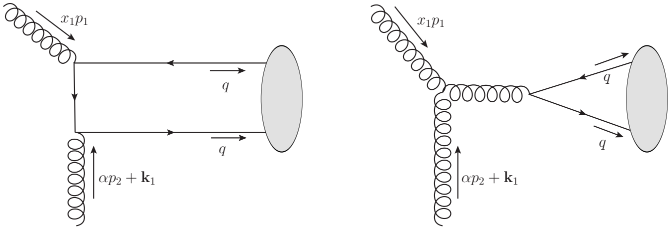
Two examples out of 6 diagrams

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



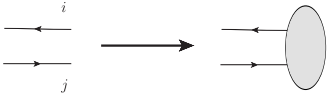
$$v^i_\alpha(q_2)\bar{u}^j_\beta(q_1) \to \frac{\delta^{ij}}{4N_c}\left(\frac{\langle \mathcal{O}_1 \rangle_{J/\psi}}{m}\right)^{\frac{1}{2}} \left[\hat{\varepsilon}^*_{J/\psi}\left(\hat{k}_{J/\psi} + M\right)\right]_{\alpha,\,\beta} \qquad (1)$$

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 :



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

Color Evaporation Model

The Color Evaporation Model

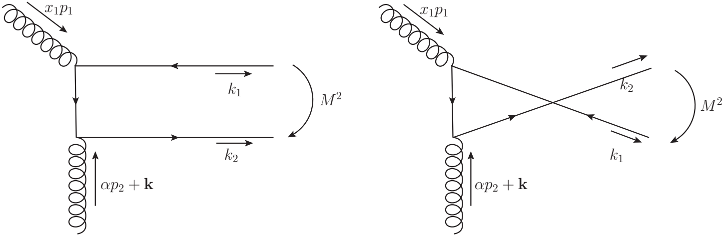
The Color Evaporation Model

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

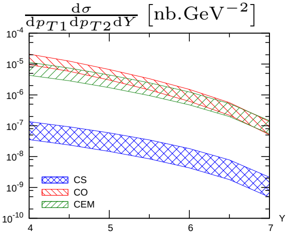
Then, neglecting the contributions from $Q\bar{Q}$ pairs with an invariant mass above the threshold, use :

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

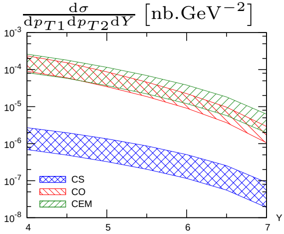


2 examples out of 3 diagrams to compute in the CEM

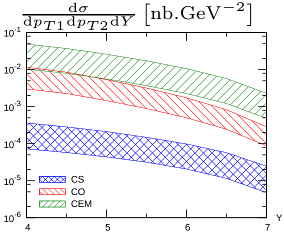
Numerical results [PRELIMINARY]



$p_{T1} = 30$ GeV, $p_{T2} = 30$ GeV



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



$p_{T1} = 10$ GeV, $p_{T2} = 10$ 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
- This new process could constitute a good probe of the color octet contribution in NRQCD