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

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Orsay

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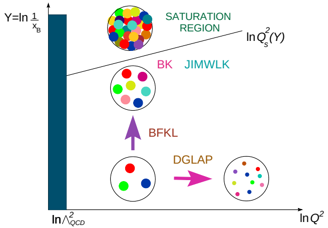
The partonic content of the proton

The various regimes governing the perturbative content of the proton



- "usual" regime: x_B moderate ($x_B \gtrsim .01$):
  Evolution in Q governed by the QCD renormalization group
  (Dokshitser, Gribov, Lipatov, Altarelli, Parisi equation)

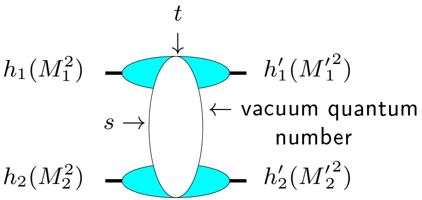
$$\underset{\text{LLQ}}{\sum_n (\alpha_s \ln Q^2)^n} + \underset{\text{NLLQ}}{\alpha_s \sum_n (\alpha_s \ln Q^2)^n} + \cdots$$

- perturbative Regge limit: $s_{\gamma^* p} \to \infty$ i.e. $x_B \sim Q^2/s_{\gamma^* p} \to 0$
  in the perturbative regime (hard scale Q^2)
  (Balitski Fadin Kuraev Lipatov equation)

$$\underset{\text{LLs}}{\sum_n (\alpha_s \ln s)^n} + \underset{\text{NLLs}}{\alpha_s \sum_n (\alpha_s \ln s)^n} + \cdots$$

QCD in the perturbative 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 this peculiar dynamics



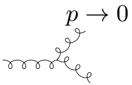
hard scales: $M_1^2,\, M_2^2 \gg \Lambda_{QCD}^2$ or $M_1'^2,\, M_2'^2 \gg \Lambda_{QCD}^2$ or $t \gg \Lambda_{QCD}^2$
where the $t-$channel exchanged state is the so-called hard Pomeron

How to test QCD in the perturbative Regge limit?

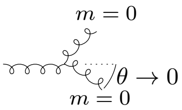
What kind of observable?

- 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?

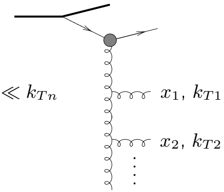
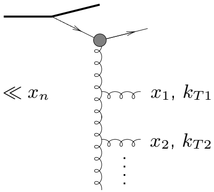
Some examples of processes

- 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)

Resummation in QCD: DGLAP vs BFKL

Dynamics of resummations

Small values of α_s (perturbation theory applies if there is a hard scale) can be compensated by large logarithmic enhancements.

DGLAP	BFKL
$k_{Tn+1} \ll k_{Tn}$ 	$x_{n+1} \ll x_n$ 
strong ordering in k_T	strong ordering in x
$\sum(\alpha_s \ln Q^2)^n$	$\sum(\alpha_s \ln s)^n$

When $\sqrt{s}$ becomes very large, it is expected that a BFKL description is needed to get accurate predictions

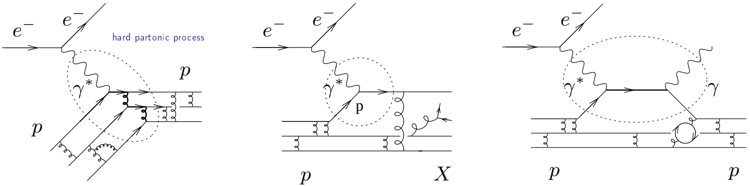
Perturbative QCD in a fixed order approach

Hard processes in QCD and collinear factorization

- This is justified if the process is governed by a hard scale:
  - Virtuality of the electromagnetic probe

    in elastic scattering $e^\pm\, p \to e^\pm\, p$
    in Deep Inelastic Scattering (DIS) $e^\pm\, p \to e^\pm\, X$
    in Deep Virtual Compton Scattering (DVCS) $e^\pm\, p \to e^\pm\, p\, \gamma$
  - Total center of mass energy in $e^+e^- \to X$ annihilation
  - t-channel momentum exchange in meson photoproduction $\gamma\, p \to M\, p$
  - Mass of a heavy bound state e.g. $J/\Psi, \Upsilon$
- A precise treatment relies on collinear factorization theorems
- Scattering amplitude

$$= \quad \underset{\text{(computed at a given fixed order)}}{\text{partonic amplitude}} \quad \overset{\text{convolution}}{\otimes} \quad \text{non-perturbative hadronic content}$$

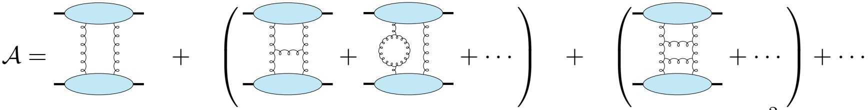


Semi-hard processes: resummed QCD at large s

QCD in the perturbative Regge limit

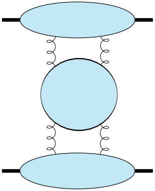
$$s \gg M^2_{\text{hard scale}} \gg \Lambda^2_{QCD}$$

The amplitude can be written as:



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

this can be put in the following form :



← Impact factor

← Green's function

← Impact factor

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

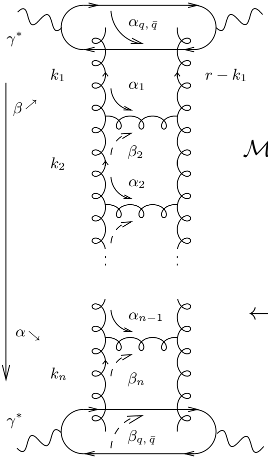
with $\alpha_{\mathbb{P}}(0) - 1 = C\,\alpha_s + C'\,\alpha_s^2 + \cdots$

$C > 0$: Leading Log $\mathbb{P}$omeron

Balitsky, Fadin, Kuraev, Lipatov

Opening the boxes: Impact representation $\gamma^*\gamma^* \to \gamma^*\gamma^*$ as an example

- Sudakov decomposition: $k_i = \alpha_i\, p_1 + \beta_i\, p_2 + k_{\perp i}$ $\quad (p_1^2 = p_2^2 = 0,\ 2p_1 \cdot p_2 = s)$
- write $\quad d^4k_i = \frac{s}{2}\, d\alpha_i\, d\beta_i\, d^2k_{\perp i}$ $\quad$ ($\underline{k}$ = Eucl. $\leftrightarrow$ $k_\perp$ = Mink.)
- $t-$channel gluons have non-sense polarizations at large s: $\epsilon_{NS}^{up/down} = \frac{2}{s}\, p_{2/1}$



$\Rightarrow$ set $\alpha_1 = 0$ and $\int d\beta_1 \ \Rightarrow\ \Phi^{\gamma^* \to \gamma^*}(\underline{k}_1, \underline{r} - \underline{k}_1)$
impact factor

$$\mathcal{M} = \frac{is}{(2\pi)^2} \int \frac{d^2\underline{k}}{\underline{k}^2}\, \Phi^{up}(\underline{k},\, \underline{r} - \underline{k}) \int \frac{d^2\underline{k}'}{\underline{k}'^2}\, \Phi^{down}(-\underline{k}',\, -\underline{r} + \underline{k}')$$
$$\times \int_{\delta - i\infty}^{\delta + i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^{\omega} G_\omega(\underline{k}, \underline{k}', \underline{r})$$

$\longleftarrow$ multi-Regge kinematics

$\Rightarrow$ set $\beta_n = 0$ and $\int d\alpha_n \ \Rightarrow\ \Phi^{\gamma^* \to \gamma^*}(-\underline{k}_n, -\underline{r} + \underline{k}_n)$

Higher order corrections

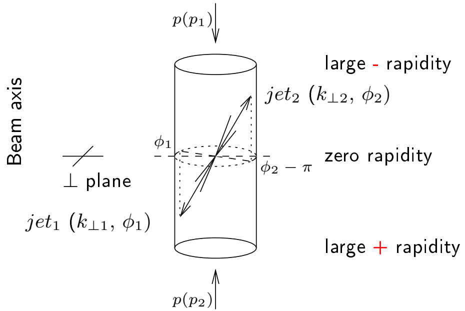
Only a few higher order corrections are known

- 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: Basics

Mueller-Navelet jets

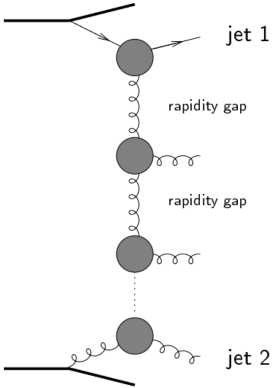
- Consider two jets (hadrons flying within a narrow cone) separated by a large rapidity, i.e. each of them almost fly in the direction of the hadron "close" to it, and with very similar transverse momenta
- Pure LO *collinear* treatment: these two jets should be emitted back to back at leading order:
  - $\varphi \equiv \Delta\phi - \pi = 0$ ($\Delta\phi = \phi_1 - \phi_2 =$ relative azimuthal angle)
  - $k_{\perp 1}{=}k_{\perp 2}$. No phase space for (untagged) multiple (DGLAP) emission between them



Mueller-Navelet jets: LL fails

Mueller Navelet jets at LL BFKL

- in LL BFKL ($\sim \sum(\alpha_s \ln s)^n$), emission between these jets $\longrightarrow$ strong decorrelation between the relative azimutal angle jets, incompatible with $p\bar{p}$ Tevatron collider data
- a collinear treatment at next-to-leading order (NLO) can describe the data
- important issue: non-conservation of energy-momentum along the BFKL ladder. A LL BFKL-based Monte Carlo combined with e-m conservation improves dramatically the situation (Orr and Stirling)



Multi-Regge kinematics (LL BFKL)

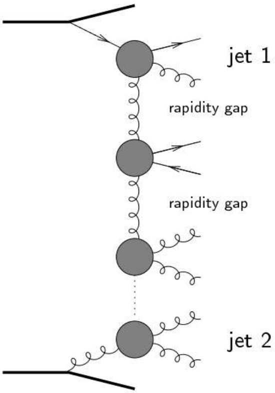
Mueller-Navelet jets: beyond LL

Mueller Navelet jets at NLL BFKL

- up to ∼ 2010, the subseries $\alpha_s \sum(\alpha_s \ln s)^n$ NLL was included only in the exchanged $\mathbb{P}$omeron state, and not inside the jet vertices
  Sabio Vera, Schwennsen
  Marquet, Royon

- our studies have shown was that these corrections are very important
  Colferai, Schwennsen, Szymanowski, S. W.
  Ducloué, Szymanowski, S. W.

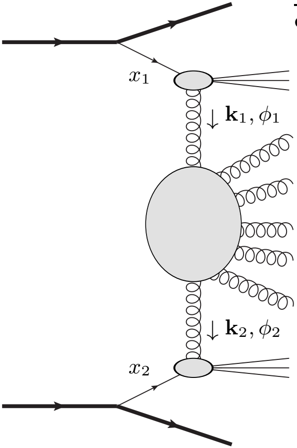
  for similar studies and results:
  Caporale, Ivanov, Murdaca, Papa
  Caporale, Murdaca, Sabio Vera, Salas



Quasi Multi-Regge kinematics
(here for NLL BFKL)

Mueller-Navelet jets at NLL: master formulas

k_T-factorized differential cross section



$$\frac{d\sigma}{d|\mathbf{k}_{J,1}|\, d|\mathbf{k}_{J,2}|\, dy_{J,1}\, dy_{J,2}} = \int d\phi_{J,1}\, d\phi_{J,2} \int d^2\mathbf{k}_1\, d^2\mathbf{k}_2$$

$$\times\, \Phi(\mathbf{k}_{J,1}, x_{J1}, -\mathbf{k}_1)$$

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

$$\times\, \Phi(\mathbf{k}_{J,2}, x_{J2}, \mathbf{k}_2)$$

with $\Phi(\mathbf{k}_{J,2}, x_{J2}, \mathbf{k}_2) = \int dx_2\, f(x_2) V(\mathbf{k}_2, x_2)$ $\quad f \equiv$ PDF $\quad x_J = \frac{|\mathbf{k}_J|}{\sqrt{s}} e^{y_J}$

Mueller-Navelet jets at NLL: Renormalization scale fixing

Renormalization scale uncertainty

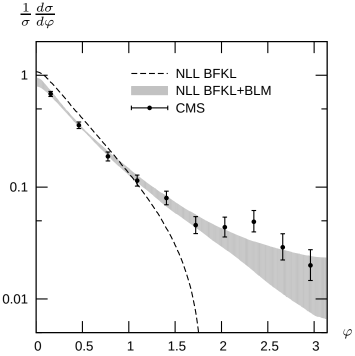
- We used the Brodsky-Lepage-Mackenzie (BLM) procedure to fix the renormalization scale
- The BLM procedure resums the self-energy corrections to the gluon propagator at one loop into the running coupling.
- First attempts to apply BLM scale fixing to BFKL processes lead to problematic results. Brodsky, 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.

Mueller-Navelet jets at NLL: comparison with the data

Comparison with the data

recall: $\varphi = 0 \Leftrightarrow$ back-to-back



Ducloué, Szymanowski, S. W.

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

$$6 < Y < 9.4$$

$$35 \text{ GeV}^2 < \mathbf{k}_{J,1}, \mathbf{k}_{J,2}$$

Mueller-Navelet jets at NLL

Other effects and references

- Full NLL description

D. Colferai, F. Schwennsen, L. Szymanowski, S. W., JHEP 1012 (2010) 026 [arXiv:1002.1365 [hep-ph]]

B. Ducloué, L. Szymanowski, S. W., JHEP 1305 (2013) 096 [arXiv:1302.7012 [hep-ph]]

- BLM renormalization scale fixing and comparison with data

B. Ducloué, L. Szymanowski, S. W., Phys. Rev. Lett. 112 (2014) 082003 [arXiv:1309.3229 [hep-ph]]

- Energy momentum violation: the situation is much improved when including full NLL corrections

B. Ducloué, L. Szymanowski, S. W., Phys. Lett. B738 (2014) 311-316 [arXiv:1407.6593 [hep-ph]]

- Multiparton description of Mueller-Navelet jets:
  two uncorrelated ladders suppressed at LHC kinematics

B. Ducloué, L. Szymanowski, S. W., Phys. Rev. D92 (2015) 7, 076002 [arXiv:1507.04735 [hep-ph]]

- Sudakov resummation effects:
  in the almost back-to-back region, and at LL, the resummation as been performed: no overlap with low-x resummation effects

A. H. Mueller, L. Szymanowski, S. W., B.-W. Xiao, F. Yuan, JHEP 1603 (2016) 096 [arXiv:1512.07127 [hep-ph]]

Inclusive forward J/Ψ and backward jet production at the LHC

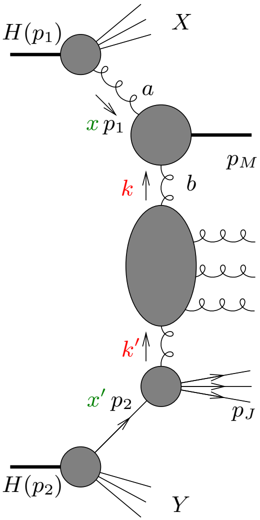
Why J/Ψ?

- 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
- Any improvement of the understanding of these mechanisms is important in view of QGP studies since J/Ψ suppression (melting) is one of the best probe. Cold nuclear effects are numerous and known to make life more complicate
- 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 difference which is large enough to use BFKL dynamics but small enough to be able to detect J/ψ mesons at LHC (ATLAS, CMS).

Master formula

$k_\perp$-factorization description of the process

$\hat{s} = x\, x'\, s$



$$\frac{d\sigma}{dy_V\, d|p_{V\perp}|\, d\phi_V\, dy_J\, d|p_{J\perp}|\, d\phi_J}$$

$$= \sum_{a,b} \int d^2k_\perp\, d^2k'_\perp$$

$$\times \int_0^1 dx\, f_a(x)\, V_{V,a}(k_\perp, x)$$

$$\times\, G(-k_\perp, -k'_\perp, \hat{s})$$

$$\times \int_0^1 dx'\, f_b(x')\, V_{J,b}(-k'_\perp, x'),$$

Master formula

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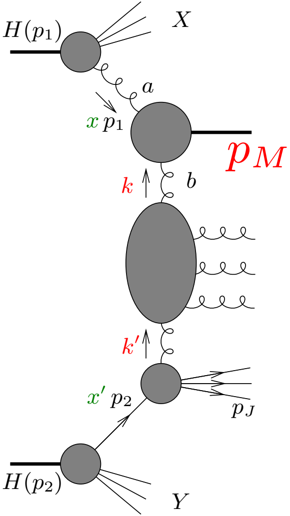
$\hat{s} = x\, x'\, s$



???

$$\frac{d\sigma}{dy_V\, d|p_{V\perp}|\, d\phi_V\, dy_J\, d|p_{J\perp}|\, d\phi_J} = \sum_{a,b} \int d^2k_\perp\, d^2k'_\perp$$

$$\times \int_0^1 dx\, f_a(x)\, V_{V,a}(k_\perp, x)$$

$$\times\, G(-k_\perp, -k'_\perp, \hat{s})$$

$$\times \int_0^1 dx'\, f_b(x')\, V_{J,b}(-k'_\perp, x'),$$

The NRQCD formalism

Quarkonium 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 $v \sim \frac{1}{\log M}$:

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

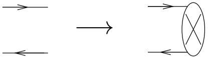
  Assumption: all the non-perturbative physics is encoded in $|V\rangle$

  $\Rightarrow$ One computes the hard part using the usual Feynman diagram methods and convolute it with the wavefunction afterwards.
- Charge parity conservation $\rightarrow$ Hard part M:

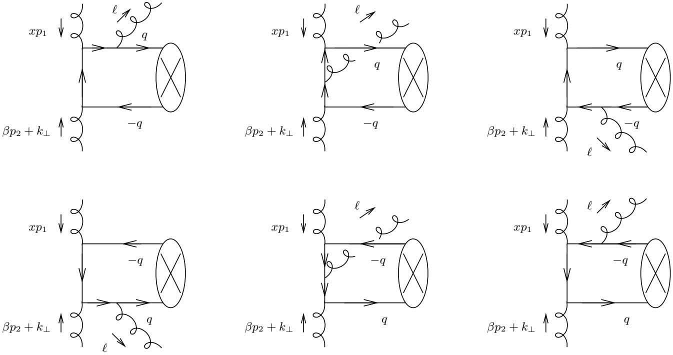
  $Q\bar{Q}$ in a color singlet state + g, $Q\bar{Q}$ in a color octet state.
- In NRQCD, the two Q and $\bar{Q}$ share the quarkonium momentum: $p_V = 2q$
  this would not be the case for a light meson
- The relative importance of this additional color-octet contribution is still to be determined.
- There is no proof of NRQCD factorization at all orders.

The J/ψ impact factor: NRQCD color singlet contribution

From open quark-antiquark gluon production to J/ψ production

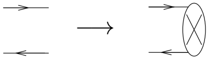
NRQCD color-singlet transition vertex: 

$$[v(q)\bar{u}(q)]^{ij}_{\alpha\beta} \to \frac{\delta^{ij}}{4N}\left(\frac{\langle\mathcal{O}_1\rangle_V}{m}\right)^{1/2}\left[\hat{\epsilon}^*_V\,(2\hat{q}+2m)\right]_{\alpha\beta}$$

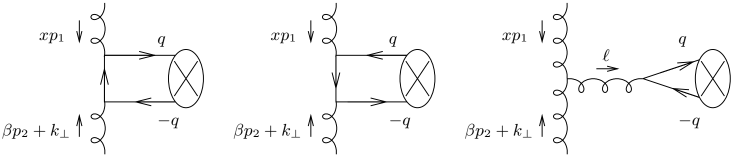


The J/ψ impact factor: NRQCD color octet contribution

From open quark-antiquark production to J/ψ production

NRQCD color-octet transition vertex: 

$$[v(q)\bar{u}(q)]^{ij\to d}_{\alpha\beta} \to t^d_{ij} d_8 \left(\frac{\langle \mathcal{O}_8 \rangle_V}{m}\right)^{1/2} [\hat{\epsilon}^*_V \, (2\hat{q} + 2m)]_{\alpha\beta}$$



The Color Evaporation Model

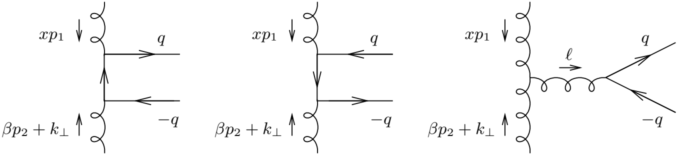
Quarkonium production in the color evaporation model

Relies on the local duality hypothesis
Fritzsch, Halzen ...

- Consider a heavy quark pair $Q\bar{Q}$ with $m_{Q\bar{Q}} < 2m_{Q\bar{q}}$
  $Q\bar{q}$ = lightest meson which contains Q
  e.g $D-$meson for $Q = c$
- it 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

The J/ψ impact factor: relying on the color evaporation model

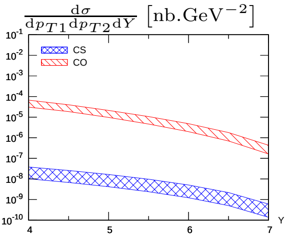
From open quark-antiquark gluon production to J/ψ production



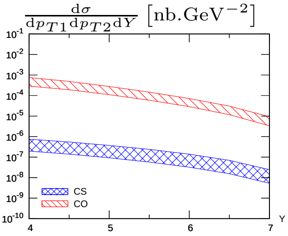
$$\sigma_{J/\psi} = F_{J/\psi} \int_{4m_c^2}^{4m_D^2} dM^2 \frac{d\sigma_{c\bar{c}}}{dM^2}$$

Numerical results [PRELIMINARY]

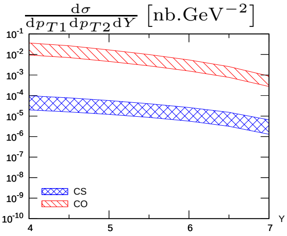
Differential cross sections from both models



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



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



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

Summary

- The production of Mueller-Navelet 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
- More to come about azimuthal correlations
- A comparison with a fixed order treatment is planned
- A complete NLL study is very challenging: requires to compute the NLO vertex for J/Ψ production
- Preliminary experimental studies (ATLAS) are very promising