High-energy QCD resummation effects at the LHC

Samuel Wallon

Université Pierre et Marie Curie

and

Laboratoire de Physique Théorique

CNRS / Université Paris Sud

Orsay

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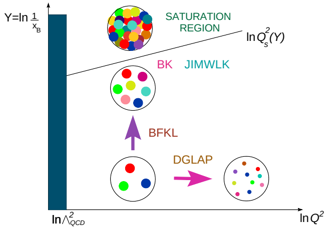
in collaboration with

R. Boussarie (INP, Kraków)
B. Ducloué (IPhT Saclay)
L. Szymanowski (NCBJ, Warsaw)

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)

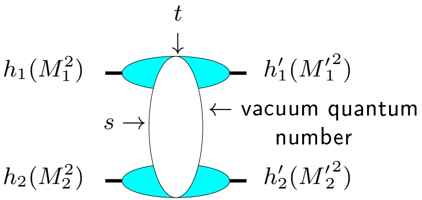
$$\underbrace{\sum_n (\alpha_s \ln Q^2)^n}_{\text{LLQ}} + \underbrace{\alpha_s \sum_n (\alpha_s \ln Q^2)^n}_{\text{NLLQ}} + \cdots$$

- 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)

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

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



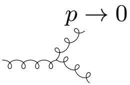
hard scales: $M_1^2,\, M_2^2 \gg \Lambda^2_{QCD}$ or $M'^2_1,\, M'^2_2 \gg \Lambda^2_{QCD}$ or $t \gg \Lambda^2_{QCD}$
where the $t-$channel exchanged state is the so-called hard Pomeron

How to test QCD in the perturbative Regge limit?

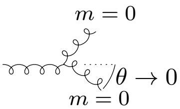
What kind of observable?

- 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?

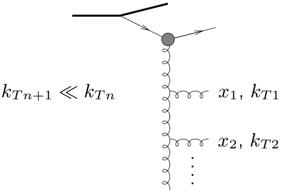
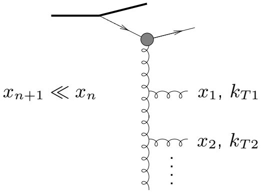
Some examples of processes

- 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
	
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

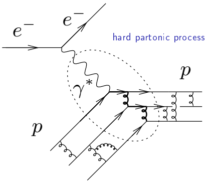
Perturbative QCD in a fixed order approach

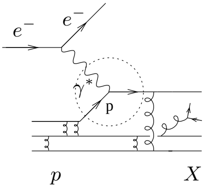
Hard processes in QCD and collinear factorization

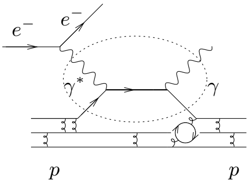
- This is justified if the process is governed by a hard scale:
  - Virtuality of the electromagnetic probe

    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

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





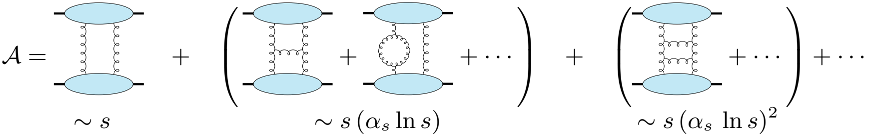


Semi-hard processes: resummed QCD at large s

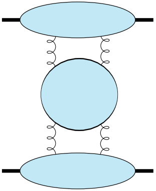
QCD in the perturbative Regge limit

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

The amplitude can be written as:



this can be put in the following form :



← Impact factor

← Green's function

← Impact factor

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

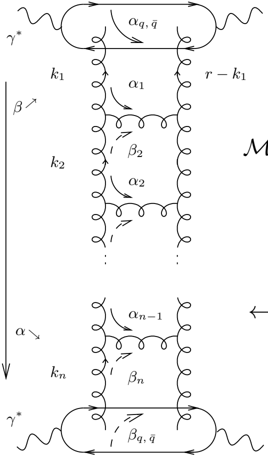
with $\alpha_{\mathbb{P}}(0) - 1 = C\,\alpha_s + C'\,\alpha_s^2 + \cdots$

$C > 0$: 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: $\epsilon^{up/down}_{NS} = \frac{2}{s}\, p_{2/1}$



$\Rightarrow$ 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

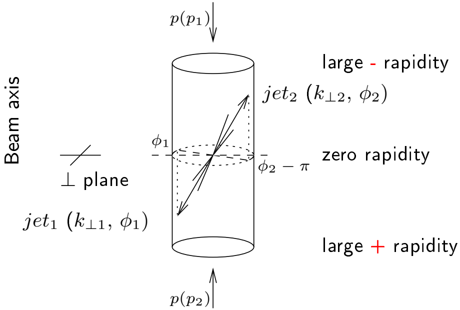
Only a few higher order corrections are known
and even fewer phenomenological implementations...

- 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)
  - diffractive dijet production (Boussarie, Grabovsky, Szymanowski, S.W.) (in the saturation "shockwave" approach)
  - 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)
    - in arbitrary kinematics (Boussarie, Grabovsky, Ivanov, Szymanowski, S.W.) (in the saturation "shockwave" approach)

Mueller-Navelet jets: Basics

Mueller-Navelet jets

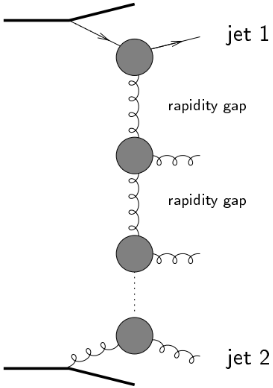
- Consider two jets (hadrons flying within a narrow cone) separated by a large rapidity, i.e. each of them almost fly in the direction of the hadron "close" to it, and with very similar transverse momenta
- Pure LO *collinear* treatment: these two jets should be emitted back to back at leading order:
    - $\varphi \equiv \Delta\phi - \pi = 0$ ($\Delta\phi = \phi_1 - \phi_2 =$ 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)



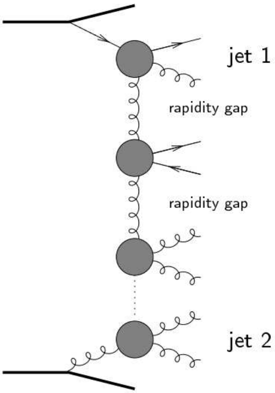
Multi-Regge kinematics (LL BFKL)

Mueller-Navelet jets: beyond LL

Mueller Navelet jets at NLL BFKL

- up to $\sim$ 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.

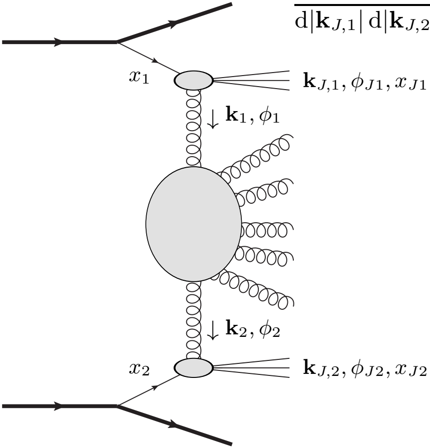
  for similar studies and results:
  Caporale, Celiberto,
  Chachamis, Hentschinski, Ivanov, Madrigal,
  Murdaca, Papa, Perri, Sabio Vera, Salas



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

Mueller-Navelet jets at NLL: Renormalization scale fixing

Renormalization scale uncertainty

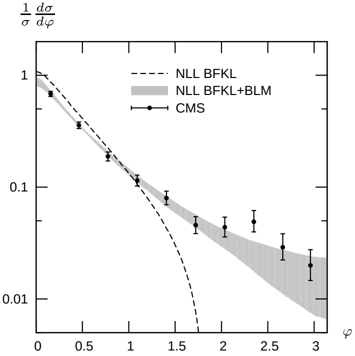
- We used the Brodsky-Lepage-Mackenzie (BLM) procedure to fix the renormalization scale
- The BLM procedure resums the self-energy corrections to the gluon propagator at one loop into the running coupling.
- First attempts to apply BLM scale fixing to BFKL processes lead to problematic results. Brodsky,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

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

- Multiparton description of Mueller-Navelet jets: **[Backup]**
  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: **[Backup]**
  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

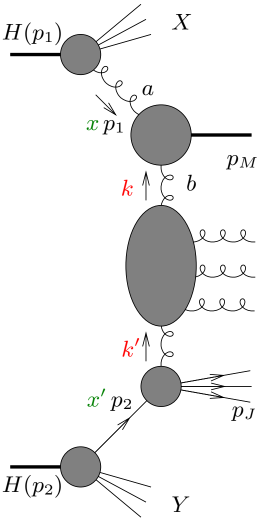
Why J/Ψ?

- 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

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



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

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

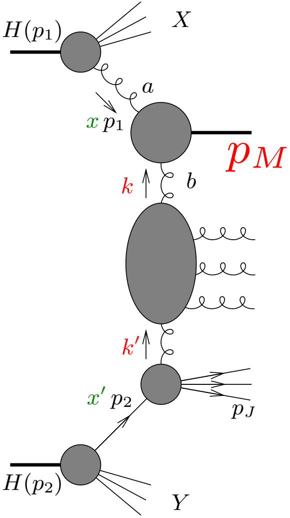
$$\times\, G(-k_\perp, -k'_\perp, \hat{s})$$

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

Master formula

k⊥-factorization description of the process

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



???

$$\frac{d\sigma}{dy_V\,d|p_{V\perp}|\,d\phi_V\,dy_J\,d|p_{J\perp}|\,d\phi_J} = \sum_{a,b}\int d^2k_\perp\,d^2k'_\perp \times \int_0^1 dx\,f_a(x)\,V_{V,a}(k_\perp,x) \times G(-k_\perp,-k'_\perp,\hat{s}) \times \int_0^1 dx'\,f_b(x')\,V_{J,b}(-k'_\perp,x'),$$

The NRQCD formalism

Quarkonium production in NRQCD

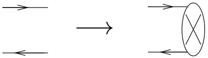
- We will first use the Non Relativistic QCD (NRQCD) formalism
  Bodwin, Braaten, Lepage; Cho, Leibovich ....
- Proof of NRQCD factorization: NLO Nayak Qiu Sterman 05; all orders Nayak 15.
- Expands the onium state wrt the velocity $v \sim \frac{1}{\log M}$ of its constituents:

$$|J/\psi\rangle = O(1)\left|Q\bar{Q}[^3S_1^{(1)}]\right\rangle + O(v)\left|Q\bar{Q}[^3P_J^{(8)}]g\right\rangle + O(v^2)\left|Q\bar{Q}[^1S_0^{(8)}]g\right\rangle +$$
$$+O(v^2)\left|Q\bar{Q}[^3S_1^{(1,8)}]gg\right\rangle + O(v^2)\left|Q\bar{Q}[^3D_J^{(1,8)}]gg\right\rangle + \ldots\ldots$$

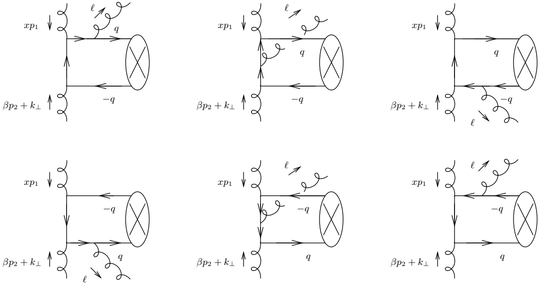
  - all the non-perturbative physics is encoded in Long Distance Matrix Elements (LDME) obtained from $|J/\psi\rangle$
  - hard part (series in α_s): obtained by the usual Feynman diagram methods
  - the cross-sec. = convolution of (the hard part)^2 * LDME
- In NRQCD, the two Q and $\bar{Q}$ share the quarkonium momentum: $p_V = 2q$
- The relative importance of color-singlet versus color-octet mechanisms is still subject of discussions.
- We consider the case where the $Q\bar{Q}$-pair has the same spin and orbital momentum as the J/Ψ : $\left|Q\bar{Q}[^3S_1^{(1)}]\right\rangle$ and $\left|Q\bar{Q}[^3S_1^{(8)}]gg\right\rangle$ Fock states
- We treat the vertex V_V at LO

The J/ψ impact factor: NRQCD color singlet contribution

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

NRQCD color-singlet transition vertex: 

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

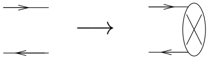


note the unobserved gluon due to C-parity conservation

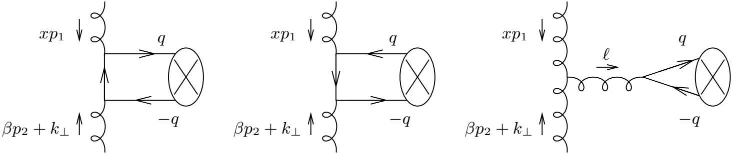
$\langle\mathcal{O}_1\rangle_{J/\psi}$ from leptonic J/Ψ decay rate $\qquad \langle\mathcal{O}_1\rangle_{J/\psi} \in [0.387, 0.444]\ \mathrm{GeV}^3$

The J/ψ impact factor: NRQCD color octet contribution

From open quark-antiquark production to J/ψ production

NRQCD color-octet transition vertex: 

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



- the $Q\bar{Q}$ color-octet pair subsequently emits two soft gluons and turns into a $Q\bar{Q}$ color-singlet pair
- the $Q\bar{Q}$ color-singlet pair then hadronizes into a J/ψ.

$$\langle \mathcal{O}_8\rangle_{J/\psi} \in [0.224 \times 10^{-2}, 1.1 \times 10^{-2}]\,\mathrm{GeV}^3$$

The Color Evaporation Model

Quarkonium production in the color evaporation model

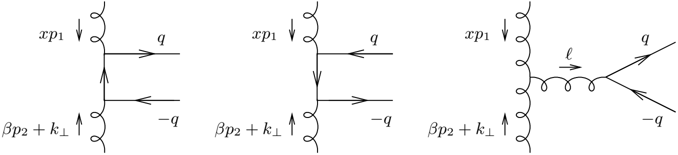
Relies on the local duality hypothesis
Fritzsch, Halzen ...

Very crude approximation!

- Consider a heavy quark pair $Q\bar{Q}$ with $m_{Q\bar{Q}} < 2\,m_{Q\bar{q}}$
  $Q\bar{q} =$ 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



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

$F_{J/\psi}$: varied in [0.02, 0.04], poorly known

Numerical results

Kinematics and parameters

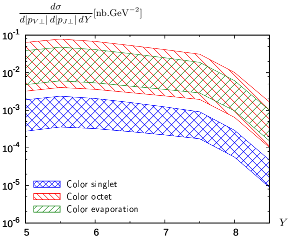
- Two center-of-mass energies: $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV
- Equal value of the transverse momenta of the J/ψ and the jet:

$$|p_{V\perp}| = |p_{J\perp}| = p_\perp$$

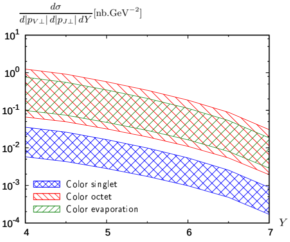
- Four different kinematic configurations:
  - CASTOR@CMS:
    - $0 < y_V < 2.5, \; -6.5 < y_J < -5, \; p_\perp = 10$ GeV
  - main detectors at ATLAS and CMS:
    - $0 < y_V < 2.5, \; -4.5 < y_J < 0, \; p_\perp = 10$ GeV
    - $0 < y_V < 2.5, \; -4.5 < y_J < 0, \; p_\perp = 20$ GeV
    - $0 < y_V < 2.5, \; -4.5 < y_J < 0, \; p_\perp = 30$ GeV
- Uncertainty bands:
  - variation of non-pert. constants
  - variation of scales μ_R, μ_F

Numerical results

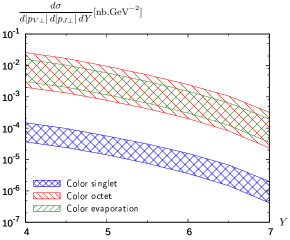
Differential cross sections $\sqrt{s} = 8$ TeV



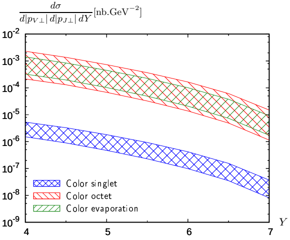
$0 < y_V < 2.5,\ -6.5 < y_J < -5,\ p_\perp = 10$ GeV



$0 < y_V < 2.5,\ -4.5 < y_J < 0,\ p_\perp = 10$ GeV



$0 < y_V < 2.5,\ -4.5 < y_J < 0,\ p_\perp = 20$ GeV

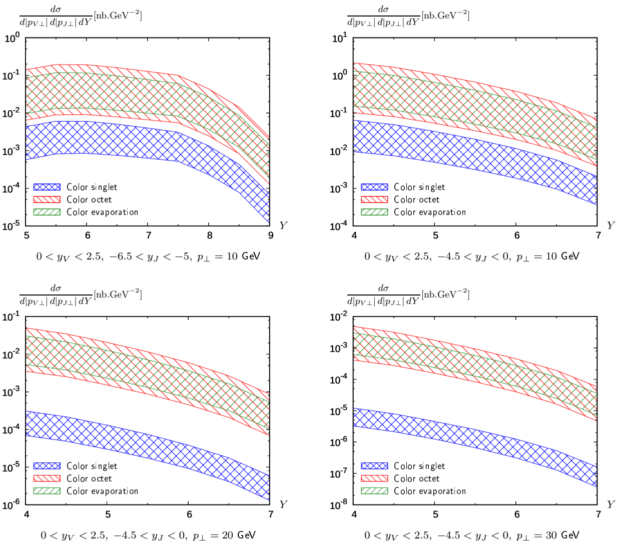


$0 < y_V < 2.5,\ -4.5 < y_J < 0,\ p_\perp = 30$ GeV

- color-octet dominates over color-singlet specially for large $p_\perp$
- color-octet and color-evaporation model give similar results

Numerical results

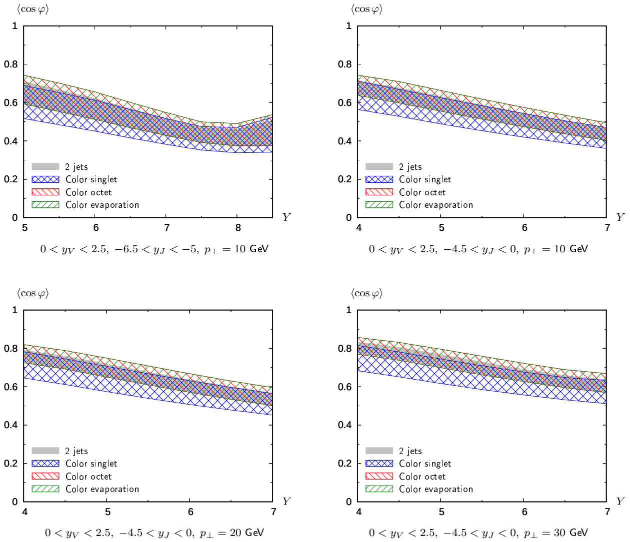
Differential cross sections $\sqrt{s} = 13$ TeV



- color-octet dominates over color-singlet specially for large $p_\perp$
- color-octet and color-evaporation model give similar results
- slight increase of cross-sections when $\sqrt{s} = 8$ TeV $\rightarrow$ $\sqrt{s} = 13$ TeV

Numerical results

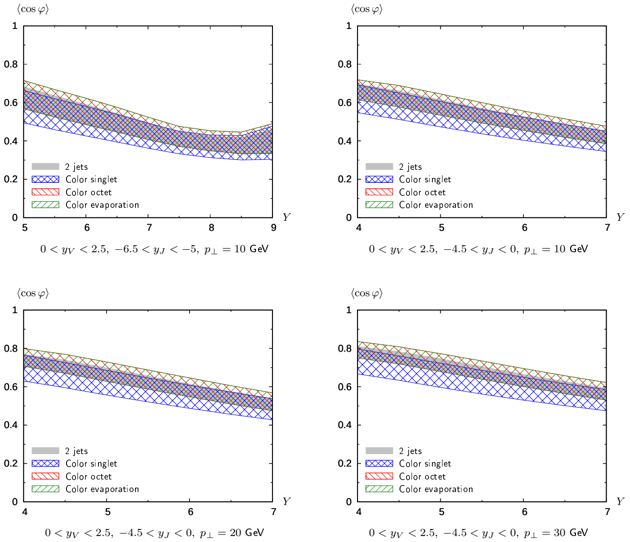
$\langle \cos\varphi \rangle$ $\sqrt{s} = 8$ TeV



- all 3 models lead to similar decorrelation effects
- they are compatible with the case where $V_{J/\psi} \longrightarrow LO\, V_{jet}$

Numerical results

$\langle \cos\varphi \rangle$ $\sqrt{s} = 13$ TeV



- all 3 models lead to similar decorrelation effects
- they are compatible with the case where $V_{J/\psi} \longrightarrow LO\, V_{jet}$
- slight increase of decorrelation effects when $\sqrt{s} = 8$ TeV $\rightarrow$ $\sqrt{s} = 13$ TeV

Summary

- The production of Mueller-Navelet was successfully described using the BFKL formalism:
  The very first signs of high-energy resummation effects at the LHC were obtained at CMS
- 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 importance of the color-singlet contribution versus the color-octet contribution in NRQCD
- 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

Fourth International Summer School of QCD

QCD meets precision

18-22th of June 2018

Laboratoire de Physique Théorique, Orsay

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  Adam K. Leibovich (Pittsburg)
- Introduction to Monte Carlo event generators
  Emanuele Re (LAPTh)
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RBI-T-WINNING, Labex P2IO, GDR QCD, CNRS, Université Paris Sud

Energy-momentum conservation

- 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

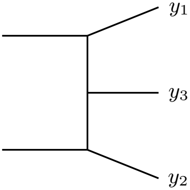
$$Y_{\text{eff}} \equiv Y \frac{\sigma^{2\to 3}}{\sigma^{\text{BFKL},\mathcal{O}(\alpha_{\text{s}}^3)}}$$

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

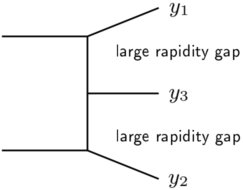
Energy-momentum conservation

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

exact $2 \to 3$



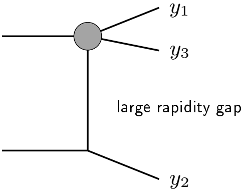
BFKL



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

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

+



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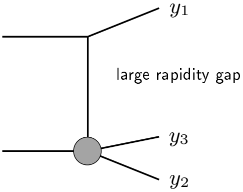
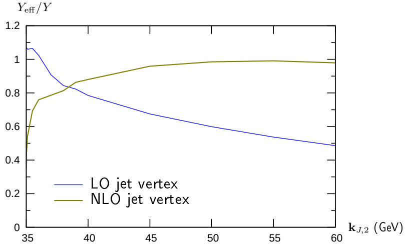


no emission from the Green's function + NLO jet vertex

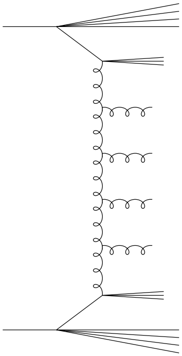
Energy-momentum conservation

Variation of $Y_{\rm eff}/Y$ as a function of $\mathbf{k}_{J,2}$ for fixed $\mathbf{k}_{J,1} = 35$ GeV (with $\sqrt{s} = 7$ TeV, $Y = 8$):



- With the LO jet vertex, $Y_{\rm eff}$ is much smaller than Y when $\mathbf{k}_{J,1}$ and $\mathbf{k}_{J,2}$ 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 $\mathbf{k}_{J,1} = 35$ GeV and $\mathbf{k}_{J,2} = 50$ GeV, typical of the values we used for comparison with fixed order, we get $\frac{Y_{\rm eff}}{Y} \simeq 0.98$ at NLO vs. ~ 0.6 at LO

Can Mueller-Navelet jets be a manifestation of multiparton interactions?



MN jets in the single partonic model

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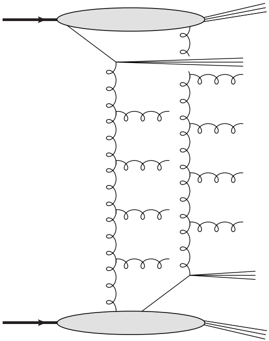
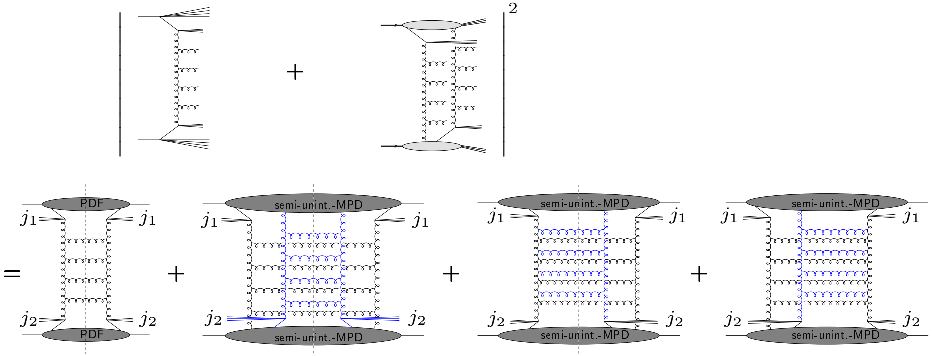


MN jets in MPI

here MPI = DPS (double parton scattering)

Can Mueller-Navelet jets be a manifestation of multiparton interactions?



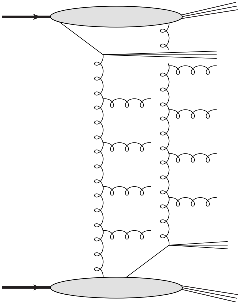
single $\mathbb{P}$ ladder | two $\mathbb{P}$ ladders | interferences

scaling: $s^{\alpha_{\mathbb{P}}}$ | (??) $s^{2\alpha_{\mathbb{P}}}$ | ??

- The twist counting is not easy for MPI kinds of contributions at small x
- $k_{\perp 1,2}$ are not integrated $\Rightarrow$ MPI may be competitive, and enhanced by small-x resummation
- Interference terms are not governed by BJKP (this is not a fully interacting 3-reggeons system) (for BJKP, $\alpha_{\mathbb{P}} < 1 \Rightarrow$ suppressed)

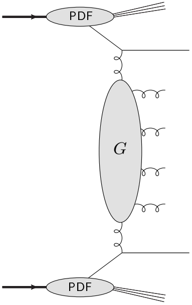
A phenomenological test: the problem

- Simplification: we neglect any interference contribution between the two mecchanisms
- How to evaluate the DPS contribution?

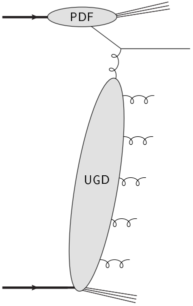


- This would require some kind of "hybrid" double parton distributions, with
  - one collinear parton
  - one off-shell parton (with some $k_\perp$)
- Almost nothing is known on such distributions

A phenomenological test: our ansatz



$\longrightarrow$



Mueller-Navelet jets production at LL accuracy

Inclusive forward jet production

Factorized ansatz for the DPS contribution:

$$\sigma_{\rm DPS} = \frac{\sigma_{\rm fwd}\ \sigma_{\rm bwd}}{\sigma_{\rm eff}}$$

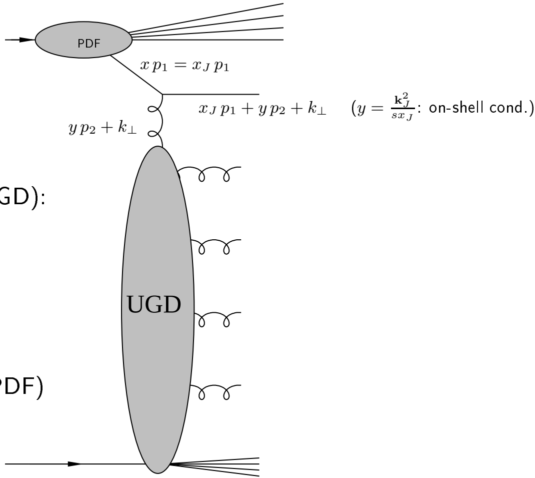
Tevatron, LHC: $\sigma_{\rm eff} \simeq 15$ mb

To account for some discrepancy between various measurements, we take

$$\sigma_{\rm eff} \simeq 10 - 20 \text{ mb}$$

A phenomenological test: our ansatz

At LO for the jet vertex:



unintegrated gluon distribution (UGD):

$$\mathcal{F}_g\left(\frac{\mathbf{k}_J^2}{s\,x_J}, |\mathbf{k}_J|\right)$$

normalized according to:

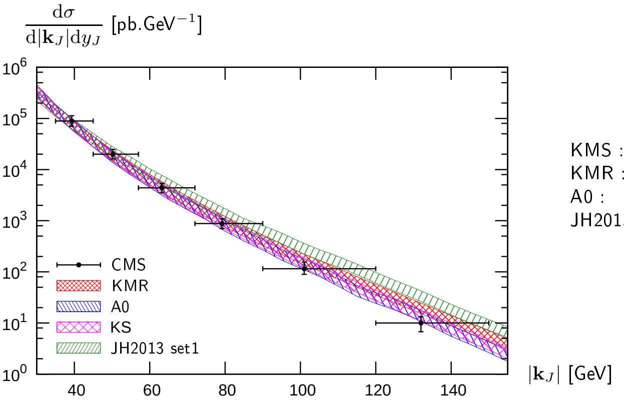
$\int \mathrm{d}\mathbf{k}^2 \mathcal{F}_g(x, |\mathbf{k}|) = x f_g(x)$ (usual PDF)

inclusive forward jet cross-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\mathbf{k}_J|\mathrm{d}y_J} = K\,\frac{\alpha_s}{|\mathbf{k}_J|}\,x_J\,(C_F\,f_q(x_J) + C_A\,f_g(x_J))\,\mathcal{F}_g\left(\frac{\mathbf{k}_J^2}{s\,x_J}, |\mathbf{k}_J|\right)$$

A phenomenological test

- We use CMS data at $\sqrt{s} = 7$ TeV, $3.2 < |y_J| < 4.7$
- We use various parametrization for the UGD
- For each parametrization we determine the range of K compatible with the CMS measurement in the lowest transverse momentum bin



	K_{min}	K_{max}
KMS :	1.20	1.94
KMR :	1.05	1.69
A0 :	4.27	6.89
JH2013 :	2.44	3.94

$$\frac{d\sigma}{d|\mathbf{k}_J| dy_J} = K \frac{\alpha_s}{|\mathbf{k}_J|} x_J \left(C_F f_q(x_J) + C_A f_g(x_J)\right) \mathcal{F}_g\left(\frac{\mathbf{k}_J^2}{s\, x_J}, |\mathbf{k}_J|\right)$$

SPS vs DPS: Results

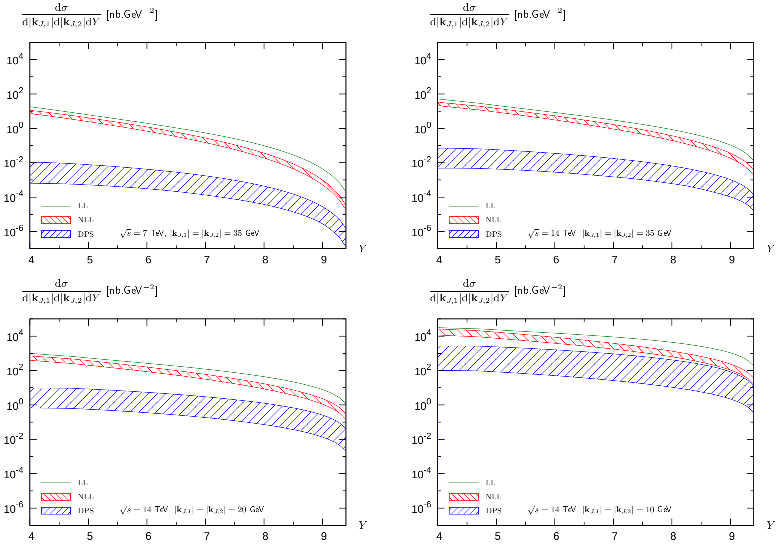
We will focus on four choices of kinematical cuts:

- $\sqrt{s} = 7$ TeV, $|\mathbf{k}_{J,1}| = |\mathbf{k}_{J,2}| = 35$ GeV,
  (like in the CMS analysis for azimuthal correlations of MN jets)
- $\sqrt{s} = 14$ TeV, $|\mathbf{k}_{J,1}| = |\mathbf{k}_{J,2}| = 35$ GeV,
- $\sqrt{s} = 14$ TeV, $|\mathbf{k}_{J,1}| = |\mathbf{k}_{J,2}| = 20$ GeV,
- $\sqrt{s} = 14$ TeV, $|\mathbf{k}_{J,1}| = |\mathbf{k}_{J,2}| = 10$ GeV $\leftarrow$ highest DPS effect expected

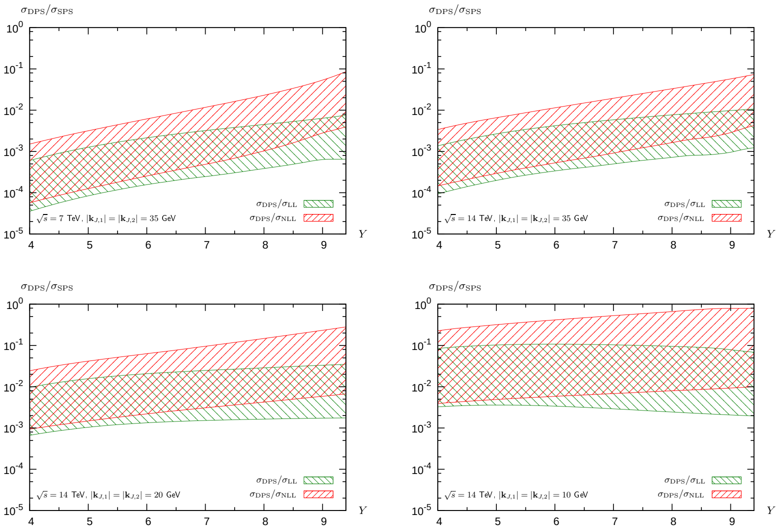
parameters:

- $0 < y_{J,1} < 4.7$ and $-4.7 < y_{J,2} < 0$
- MSTW 2008 parametrization for PDFs
- In the case of the NLL NFKL calculation, anti-k_t jet algorithm with $R = 0.5$.

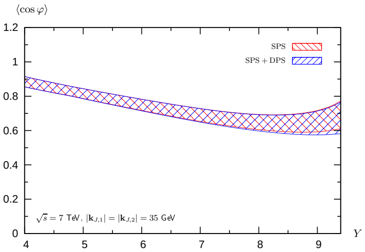
SPS vs DPS: cross-sections

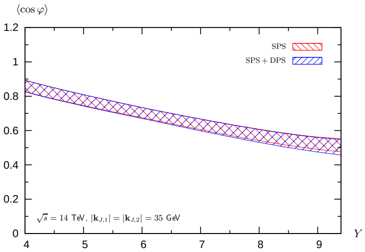


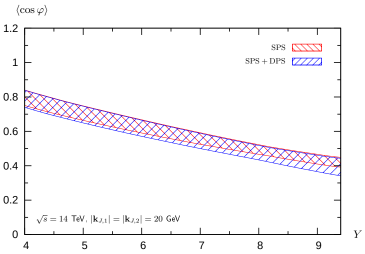
SPS vs DPS: cross-sections (ratios)

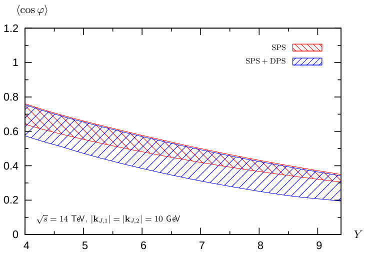


SPS vs DPS: Azimuthal correlations

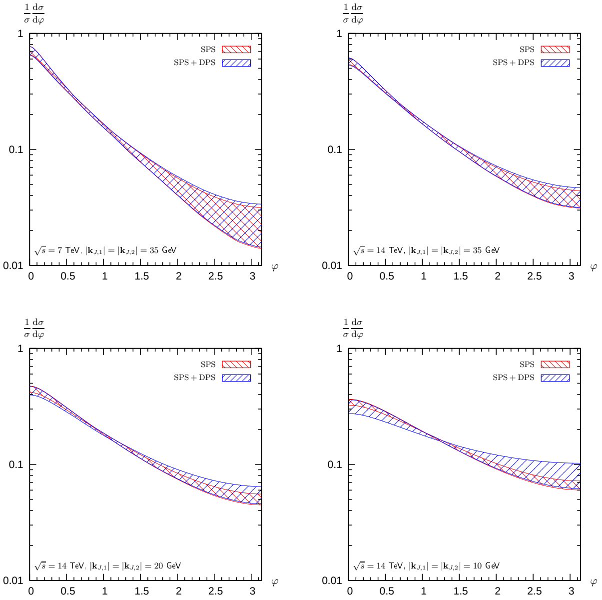








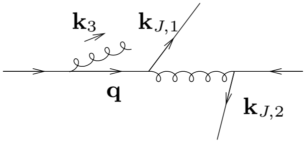
SPS vs DPS: Azimuthal distributions



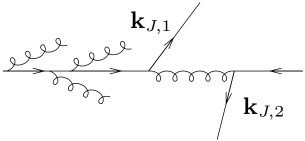
$8 < Y < 9.4$

Motivation for asymmetric configurations

- Initial state radiation (unseen) produces divergencies if one touches the collinear singularity $\mathbf{q}^2 \to 0$

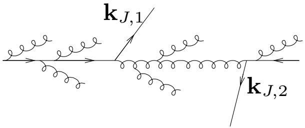


- they are compensated by virtual corrections
- this compensation is in practice difficult to implement, or *even incomplete*, when for some reason this additional emission is in a "corner" of the phase space (dip in the differential cross-section)
- this is the case when $\mathbf{k}_{J,1} + \mathbf{k}_{J,2} \to 0$
- this calls for a resummation of large remaing logs $\Rightarrow$ Sudakov resummation



Motivation for asymmetric configurations

- since these resummation have never been investigated in this context, one should better avoid that region
- note that for BFKL, due to additional emission between the two jets, one may expect a less severe problem (at least a smearing in the dip region $|\mathbf{k}_{J,1}| \sim |\mathbf{k}_{J,2}|$)



- this may however not mean that the region $|\mathbf{k}_{J,1}| \sim |\mathbf{k}_{J,2}|$ is perfectly trustable even in a BFKL type of treatment:
  in the limit $q_\perp^2 \equiv (\mathbf{k}_{J,1} + \mathbf{k}_{J,2})^2 \ll \tilde{P}_\perp^2 \equiv |\mathbf{k}_{J,1}||\mathbf{k}_{J,2}|$, at one-loop,

$$S_{qq\to qq} = -\frac{\alpha_s C_F}{2\pi} \ln^2 \frac{\tilde{P}_\perp^2 R_\perp^2}{c_0^2}$$

  where $R_\perp$ is the impact parameter, Fourier conjugated to $q_\perp$ $(c_0 = 2e^{-\gamma_E})$
  $R_\perp \sim 1/q_\perp \Rightarrow$ suppression of this back-to-back configuration (on top of BFKL large Y effects) A. H. Mueller, L. Szymanowski, S. W., B.-W. Xiao, F. Yuan
- we thus think that a measurement in a region where both NLO fixed order and NLL BFKL are under control would be safer!

CMS measurement

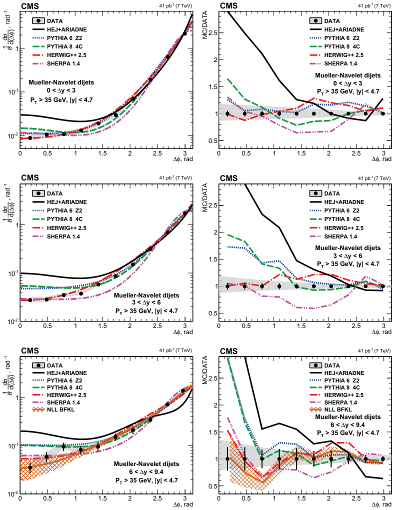


Figure 1: Left: Distributions of the azimuthal-angle difference, $\Delta\phi$, between MN jets in the rapidity intervals $\Delta y < 3.0$ (top row), $3.0 < \Delta y < 6.0$ (centre row), and $6.0 < \Delta y < 9.4$ (bottom row). Right: Ratios of predictions to the data in the corresponding rapidity intervals. The data (points) are plotted with experimental statistical (systematic) uncertainties indicated by the error bars (the shaded band), and compared to predictions from the LL DGLAP-based MC generators PYTHIA 6, PYTHIA 8, HERWIG++, and SHERPA, and to the LL BFKL-motivated MC generator HEJ with hadronisation performed with ARIADNE (solid line).

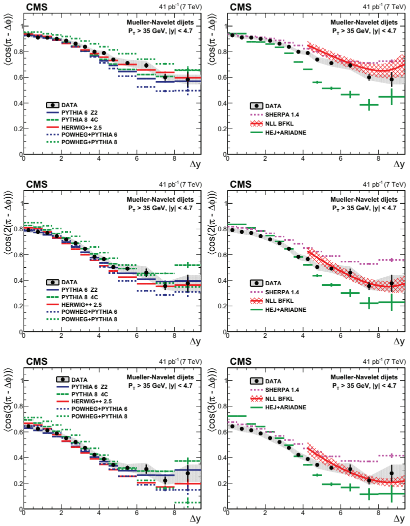


Figure 2: Left: Average $\langle\cos(n(\pi - \Delta\phi))\rangle (n = 1, 2, 3)$ as a function of Δy compared to LL DGLAP MC generators. In addition, the predictions of the NLO generator POWHEG interfaced with the LL DGLAP generators PYTHIA 6 and PYTHIA 8 are shown. Right: Comparison of the data to the MC generator SHERPA with parton matrix elements matched to a LL DGLAP parton shower, to the LL BFKL inspired generator HEJ with hadronisation by ARIADNE, and to analytical NLL BFKL calculations at the parton level ($4.0 < \Delta y < 9.4$).