# Probing the BFKL dynamics at hadronic colliders: Jet gap jet events

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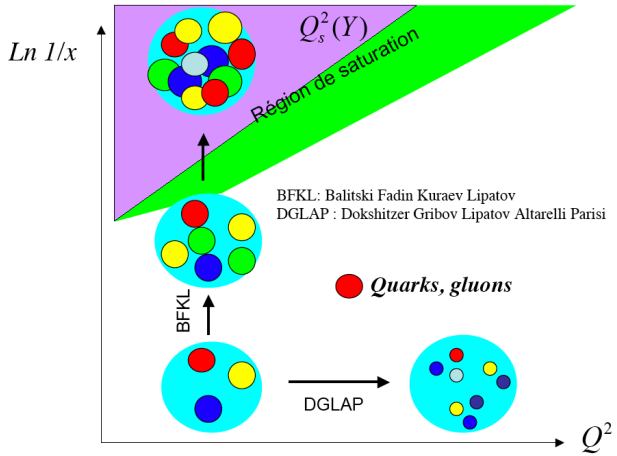
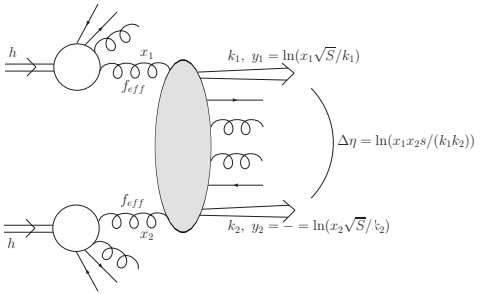
- Mueller Navelet jets
- Jet gap jet at Tevatron, LHC: BFKL NLL kernel
- Jet gap jet: full NLL calculation (kernel and impact factor)
- Jet gap jet in diffraction at the LHC

# Looking for BFKL/saturation effects

Looking for BFKL effects (x-resummation) at HERA/LHC in dedicated final states



# Looking for BFKL resummation effects at hadron colliders




- Mueller Navelet jets: Look for dijet events separated by a large interval in rapidity
- If jets have similar $p_T$, DGLAP cross section suppressed because of the $k_T$ ordering of the gluons emitted between the two jets
- BFKL cross section enhanced: gluon emissions possible because of large rapidity interval
- Study the $\Delta\Phi$ between jets dependence of the cross section as an example

# Mueller Navelet jets: $\Delta\Phi$ dependence

- Study the $\Delta\Phi$ dependence of the relative cross section using BFKL NLL formalism
- Relevant variables:

$$\begin{aligned} \Delta\eta &= y_1 - y_2 \qquad & y &= (y_1 + y_2)/2 \\ Q &= \sqrt{k_1 k_2} \qquad & R &= k_2/k_1 \end{aligned}$$

- Azimuthal correlation of dijets:

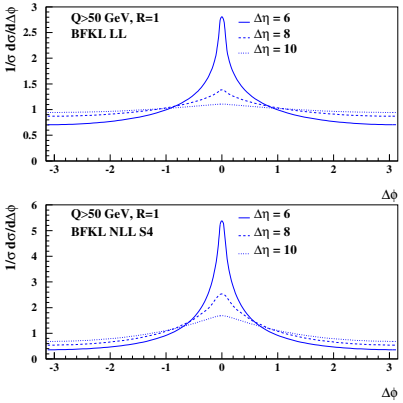
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Big/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

where

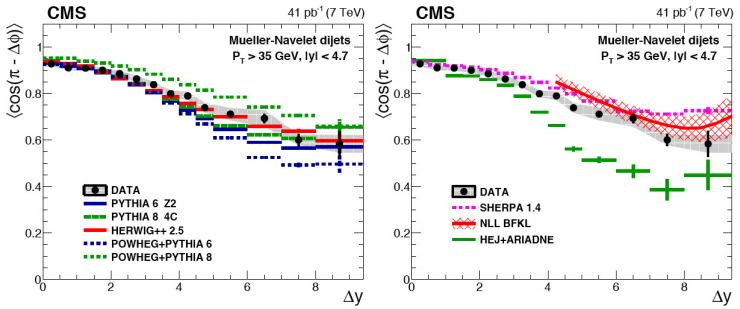
$$\sigma_p = \int_{E_T}^{\infty} \frac{dQ}{Q^3} \alpha_s(Q^2/R)\alpha_s(Q^2 R) \left( \int_{y_<}^{y_>} dy x_1 f_{eff}(x_1, Q^2/R) x_2 f_{eff}(x_2, Q^2 R) \right)$$
$$\int_{1/2-\infty}^{1/2+\infty} \frac{d\gamma}{2i\pi} R^{-2\gamma} \; e^{\bar{\alpha}(Q^2)\chi_{eff}(p)\Delta\eta}$$

# Mueller Navelet jets: $\Delta\Phi$ dependence

- $1/\sigma d\sigma/d\Delta\Phi$ spectrum for BFKL NLL as a function of $\Delta\Phi$ for different values of $\Delta\eta$, scale dependence: $\sim$20%
- Stronger decorrelation for BFKL prediction than for DGLAP
- C. Marquet, C.Royon, Phys. Rev. D79 (2009) 034028



# Mueller Navelet jets: $\Delta\Phi$ dependence: CMS measurements

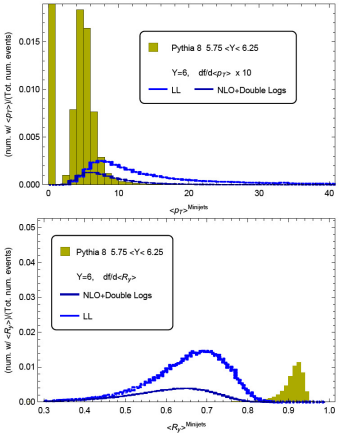



- CMS collaboration: Azimuthal decorrelation between jets at 7 TeV: J. High Energy Phys. 08 (2016) 139
- BFKL NLL leads to a good description of data but also PYTHIA/HERWIG after MPI tuning...
- More differential observables needed or completely new ones

# BFKL dynamics: looking for less inclusive variables

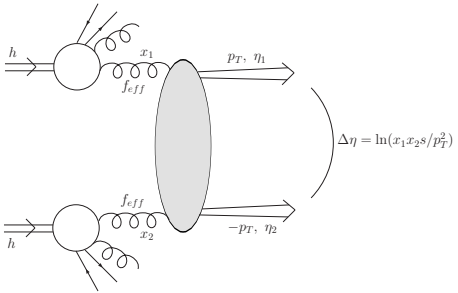
$$\langle p_T \rangle = \frac{1}{N} \sum_{i=1}^{N} |p_{Ti}|$$

$$\langle R_y \rangle = \frac{1}{N+1} \sum_{i=1}^{N+1} \frac{y_i}{y_{i-1}}$$



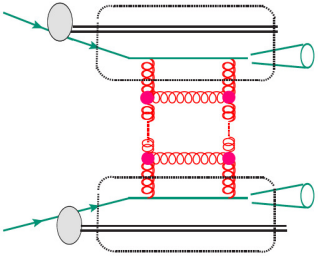

- Looking for multiple gluon emission along ladder characteristic of BFKL: number, $p_T$, rapidity distributions of "minijets"
- Comparison between BFKL-ex MC and pythia/herwig to find best variables: collaboration with A. Sabio Vera, D, Gordo, G. Chachamis, F. Deganutti, T. Raben

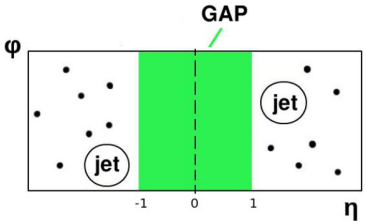
# Jet gap jet cross sections




- Test of BFKL evolution: gap between jets, colorless exchange between the two jets (BFKL pomeron)
- Probe BFKL evoluation by measuring the jet gap jet cross section
- Implementation of BFKL NLL formalism in HERWIG Monte Carlo (Measurement sensitive to jet structure and size; gap size smaller than $\Delta\eta$ between jets, gap size is between the edge of the jets than $\Delta\eta$ between jets)

# Jet gap jet cross sections: the experimental observable






- Measure two jets in the forward region of ATLAS/CMS
- Define a region (for instance $-1 < \eta < 1$) devoid of any energy (outside noise)
- Measure cross section as a function of $\Delta\eta$ between jets, jet $p_T$....

# BFKL formalism at NLL/LL

- BFKL jet gap jet cross section: integration over $\xi$, $p_T$ performed in Herwig event generation

$$\frac{d\sigma^{pp\to XJJY}}{dx_1 dx_2 dp_T^2} = \mathcal{S}\frac{f_{eff}(x_1,p_T^2)f_{eff}(x_2,p_T^2)}{16\pi}\left|A(\Delta\eta,p_T^2)\right|^2$$

$$A(\Delta\eta,p_T^2) = \frac{16N_c\pi\alpha_s^2}{C_F p_T^2}\sum_{p=-\infty}^{\infty}\int\frac{d\gamma}{2i\pi}\frac{[p^2-(\gamma-1/2)^2]}{[(\gamma-1/2)^2-(p-1/2)^2]}\frac{\exp\left\{\frac{\alpha_S N_C}{\pi}\chi_{eff}\Delta\eta\right\}}{[(\gamma-1/2)^2-(p+1/2)^2]}$$

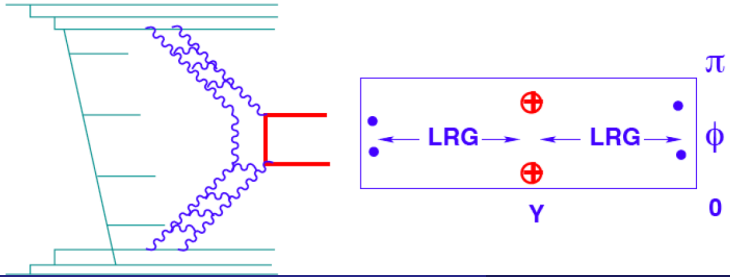
- $\alpha_S$: 0.17 at LL (constant), running using RGE at NLL

# BFKL formalism at NLL/LL

- Gluon evolution: BFKL effective kernel $\chi_{eff}$: determined numerically, solving the implicit equation: $\chi_{eff} = \chi_{NLL}(\gamma, \bar{\alpha}\ \chi_{eff})$
- Impact factors (coupling to protons): treated at LL
- S4 resummation (Salam et al.) scheme used to remove spurious singularities in BFKL NLL kernel
- Implementation in Herwig Monte Carlo: needed to take into account jet size and at parton level the gap size is equal to $\Delta\eta$ between jets
- Herwig MC: Parametrised distribution of $d\sigma/dp_T^2$ fitted to BFKL NLL cross section (2200 points fitted between $10 < p_T < 120$ GeV, $0.1 < \Delta\eta < 10$ with a $\chi^2 \sim 0.1$)

# One aside: survival probability

- Gaps can be suppressed by additional soft gluon emissions in initial/final states (MPI for instance)
- Survival probability: Probability that there is no soft additional interaction, that the diffractive event is kept
- We assume that the survival probability does not depend much on kinematics with respect to BFKL cross section (exponential $\Delta\eta$ dependence between jets dependence for instance): taken as a constant

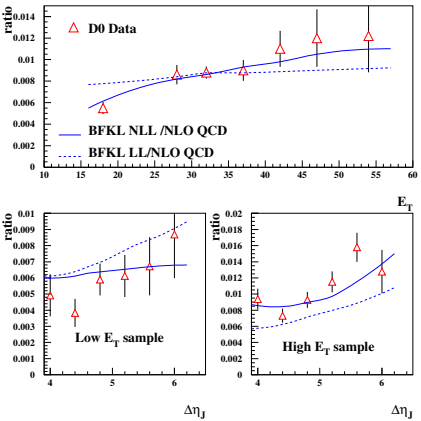


# Comparison with D0 data

- D0 measurement: Jet gap jet cross section ratios as a function of second highest $E_T$ jet, or $\Delta\eta$ for the low and high $E_T$ samples, the gap between jets being between -1 and 1 in rapidity
- Comparison with BFKL formalism:

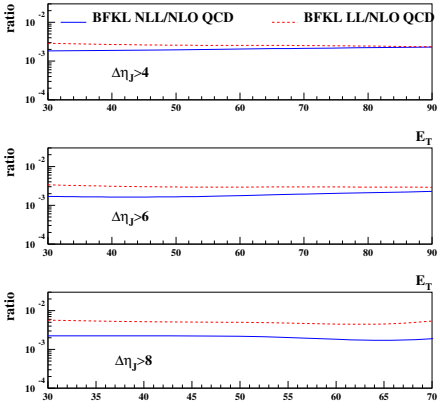
$$R = \frac{BFKL\ NLL\ Herwig}{Dijet\ Herwig} \times \frac{LO\ QCD\ NLOJet}{NLO\ QCD\ NLOJet}$$

- Reasonable description using BFKL NLL formalism



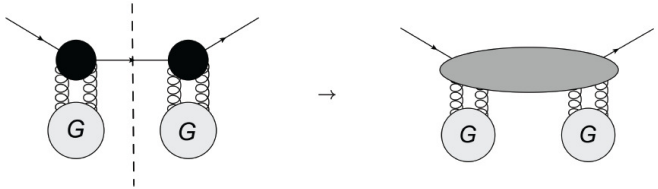
# Predictions for the LHC

- Weak $E_T$ and $\Delta\eta$ dependence
- Large differences in normalisation between BFKL LL and NLL predictions



# Full NLL calculation: Gluon evolution and Impact factors

- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)
- At NLO, impact factors are much more complicated!



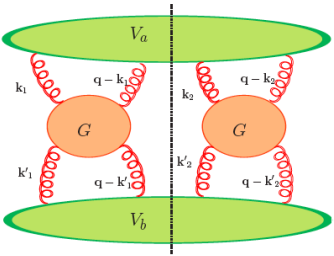

NLL impact factors

- Mix loop momenta (not factorized)
- Involve jet distributions with two final states
- Contain complicated non-analytic progress
- Work in progress by D. Colferai, F. Daganutti, T. Raben

- Will lead to an improved parametrisation to be implemented in HERWIG

# NLL BFKL jet gap jet cross section

$$\frac{d\hat{\sigma}}{dJ_1 dJ_2 d^2\mathbf{q}} = \int d^2k_1 d^2k_2 V^1(\mathbf{k}_1, \mathbf{k}_2, \mathbf{q}; J_1) \times \underbrace{\int d^2k'_1 G(\mathbf{k}_1, \mathbf{k}'_1, \mathbf{q}, Y)}_{\overline{G}(\mathbf{k}_1, \mathbf{q}, Y)} \underbrace{\int d^2k'_2 G(\mathbf{k}_2, \mathbf{k}'_2, \mathbf{q}, Y)}_{\overline{G}(\mathbf{k}_2, \mathbf{q}, Y)} V^0(J_2, \mathbf{q})$$



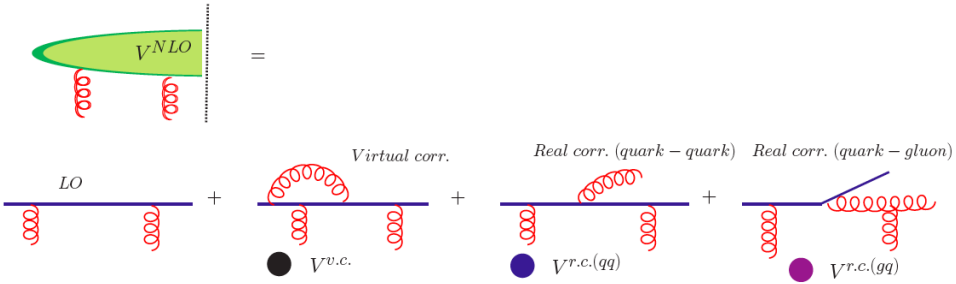

- Full NLL BFKL calculation: NLO impact factors have been computed
- Cross section given as a multiple convolution between the jet vertices (impact factors, green blobs) and the gluon Green functions in red

# NLL BFKL jet gap jet cross section: Gluon Green function

$$\bar{G}(x_1 x_2, q, \Delta\theta, k) = \propto \left[ k^{*\bar{h}-2} k'^{*h-2} \; {}_2F_1(1-h, 2-h; 2, -\frac{k}{k'}) \; {}_2F_1(1-\bar{h}, 2-\bar{h}; 2, -\frac{k'^*}{k_1^*}) + \{1 \to 2\} \right]$$

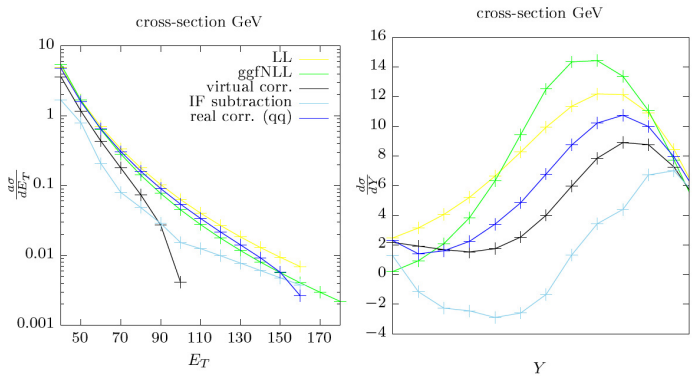
- We keep only NLO terms in the calculation
- Complex integrals to be computed and sum over many conformal spins
- Hypergeometric functions appear in the calculation and are hard to compute (recent mathematical developments in 2015, newer methods valid at high conformal spins were developed)

# NLL BFKL jet gap jet cross section: sum of 4 terms for impact factors




- Term 0: LO
- Term 1 (black): Virtual corrections
- Term 2: (Blue) Real corrections, quark-quark term
- Term 3 (Purple): Real correction, quark-gluon term

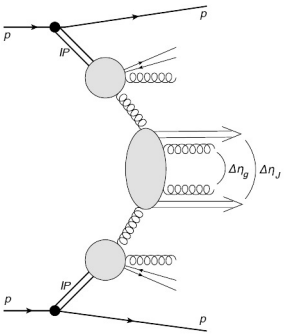
# NLL BFKL jet gap jet cross section: Results

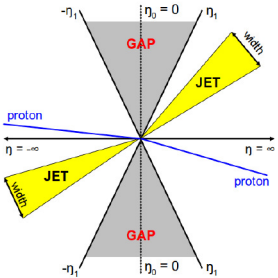



- Previous NLL calculations (in green) not too far from new NLL results including NLO impact factors
- One last term still to be computed (pure gluonic) before comparing with data

# Jet gap jet events in diffraction

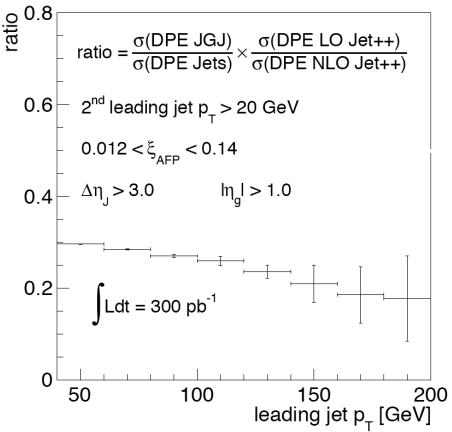
- Study BFKL dynamics using jet gap jet events
- Jet gap jet events in DPE processes: clean process, allows to go to larger $\Delta\eta$ between jets
- Reference: Gaps between jets in double-Pomeron-exchange processes at the LHC, C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D87 (2013) 3, 034010



# Jet gap jet events in diffraction

- Measure the ratio of the jet gap jet to the dijet cross sections: sensitivity to BFKL dynamics
- As an example, study as a function of leading jet $p_T$
- Advantage: ratio close to 10% (no survival probability), very clean events since jets not "polluted" by remnants)



# Conclusion

- Mueller Navelet jets: Larger decorrelation expected for BFKL formalism
- Mueller Navelet jets: not enough discrimination to observe clearly BFKL resummation effects $\rightarrow$ Looking for less inclusive variables more sensitive to BFKL dynamics
- Jet gap jets:
  - NLL BFKL cross section implemented in HERWIG (Kernel), LO impact factors
  - Fair description of D0 (and CDF) data
  - Full NLL calculation including impact factors in progress
  - Small changes due to NLO impact factors
- Jet gap jet events in diffraction: clean tests of BFKL, modulo the survival probability (and its dependence on kinematics)