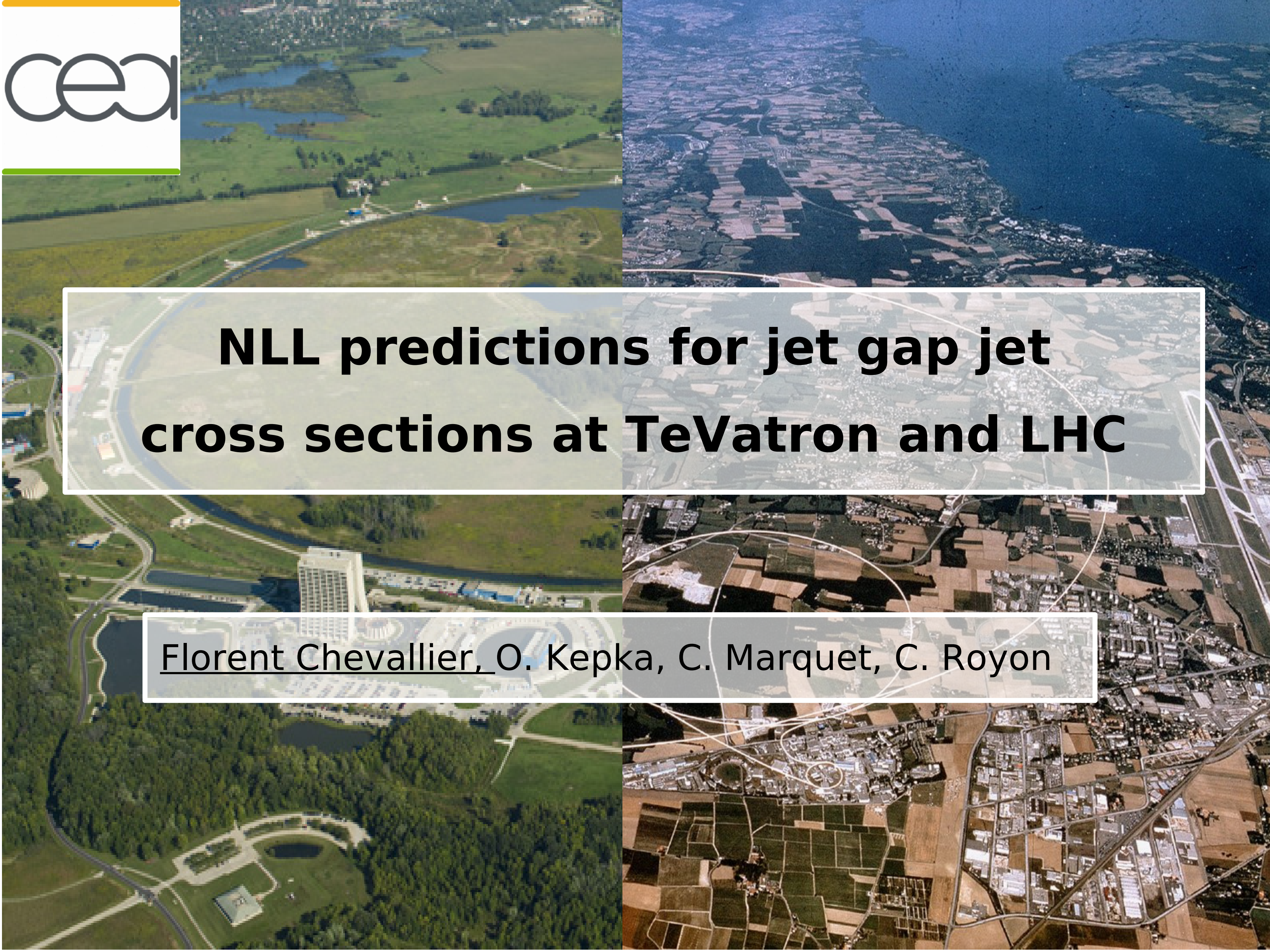

# NLL predictions for jet gap jet cross sections at TeVatron and LHC

Florent Chevallier, O. Kepka, C. Marquet, C. Royon

# Content

**Introduction**

- BFKL evolution
- Process of interest

**Phenomenology of jet-gap-jet events**

- Theoretical production cross-section
- Going to NLL-BFKL
- Implementation in Herwig Monte Carlo

**Jet-gap-jet cross-sections at hadron colliders**

- Corrections to LL-BFKL
- Comparison with DØ and CDF measurements
- Predictions for LHC

**Conclusion**

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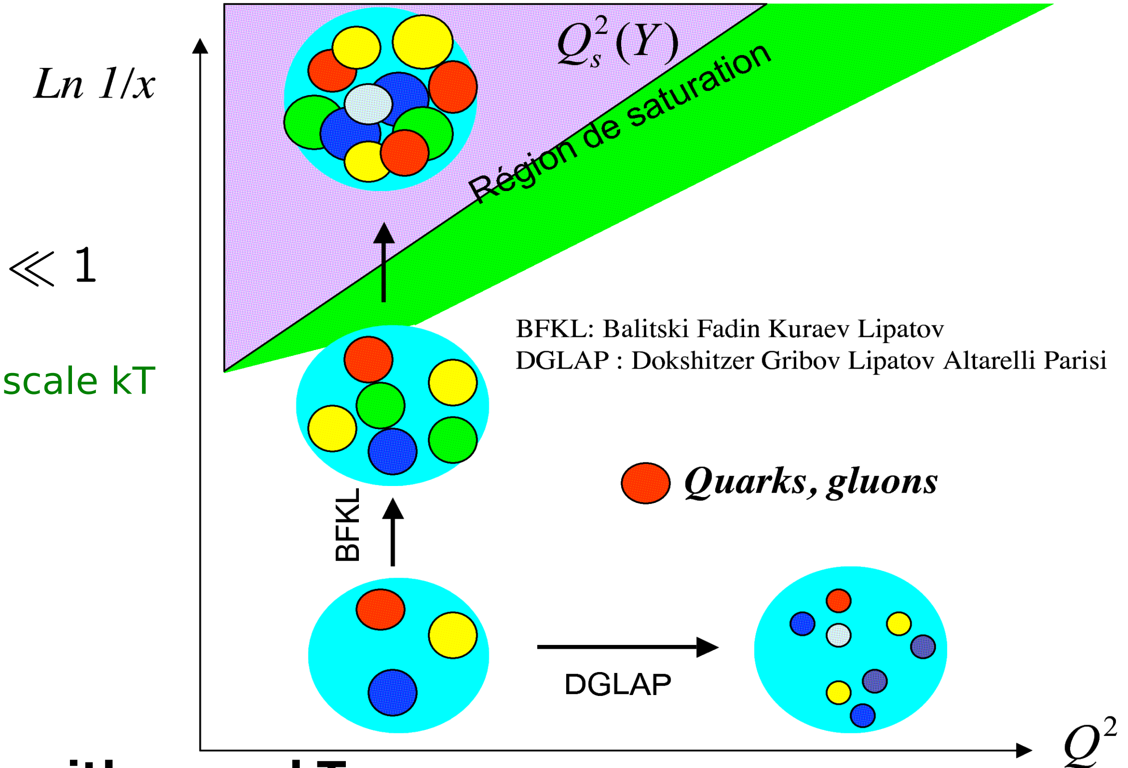
# Introduction : BFKL evolution




**Linear pQCD evolutions** $\alpha_s \ll 1$

- DGLAP evolution

  Towards larger momentum scale kT

- BFKL evolution

  Towards smaller x

**2 to 2 scattering processes with same kT**

- DGLAP evolution

  No additional radiation is possible since jets have same kT

- BFKL evolution with Regge limit

  Large rapidity interval between final-state particles

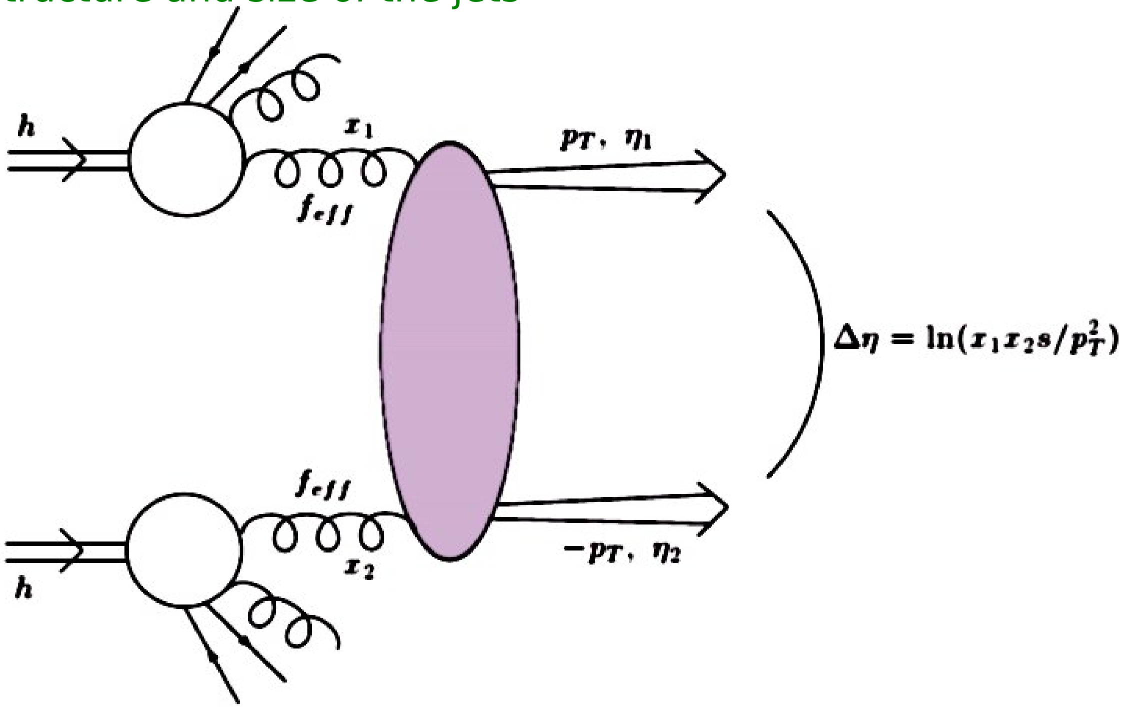
  Resummation of the large higher-order leading logs

**Signs of BFKL evolution in di-jets processes with same $p_T$ and large $\Delta\eta$ gap.**

**Gaps between jets**

- No energy deposits between jets
  Observed at TeVatron and HERA
  Measurement sensitive to the structure and size of the jets

- Test of the BFKL approach
  Production cross-sections

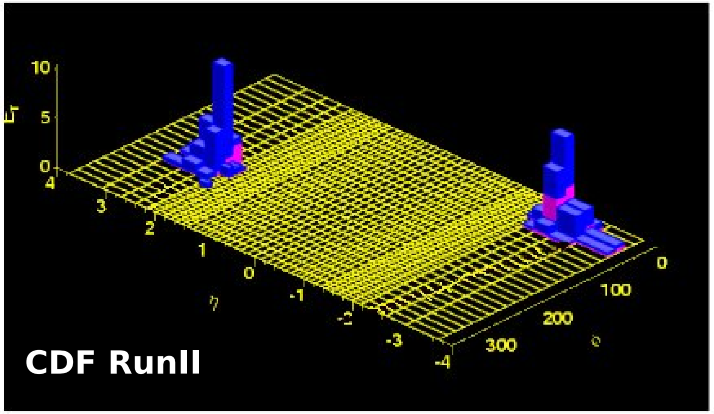


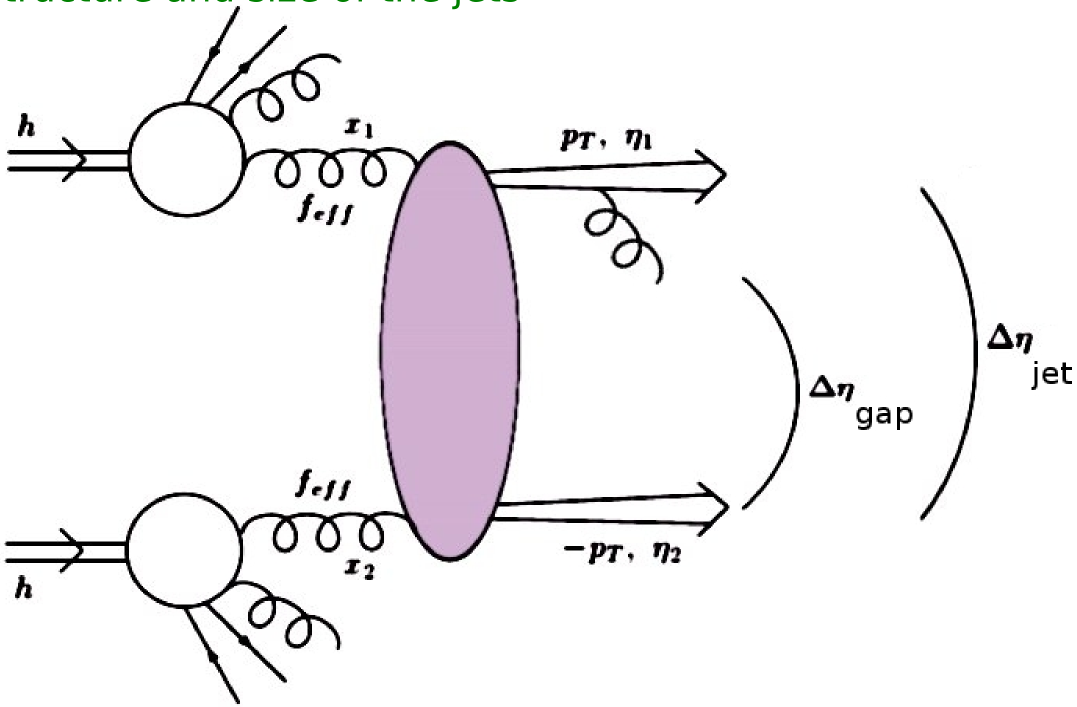

**1) Compute $d^2\sigma / dp_T\, d\Delta\eta$ for large $\Delta\eta$, same pT for both jets**

# Process of interest

**Gaps between jets**

- No energy deposits between jets
  - Observed at TeVatron and HERA
  - Measurement sensitive to the structure and size of the jets
- Test of the BFKL approach
  - Production cross-sections




⇒ **1) Compute $d^2\sigma / dp_T \, d\Delta\eta$ for large Δη, same pT for both jets**

**2) Implementation of BFKL NLL formalism in event generator (HERWIG)**

# Content

# BFKL formalism for jet-gap-jet production

**Cross-section in the BFKL framework**

- Relevant variables

$$y = \frac{y_1 + y_2}{2} \quad ; \quad \Delta\eta = | y_1 - y_2 |$$

- Jet-gap-jet cross-section

Gap survival probability
S = 0.1 at Tevatron, 0.03 at LHC

$\propto | A(\Delta\eta, E_T^2) |^2$

$$\frac{d\sigma^{pp \to XJJY}}{dy.d\Delta\eta.dE_T^2} = S\, x_1 f_{eff}(x_1, E_T^2)\,.\, x_2 f_{eff}(x_2, E_T^2) \frac{d\sigma^{gg \to gg}}{dE_T^2}(y, \Delta\eta)$$

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

Sum over conformal spin

LL / NLL BFKL kernel

$\alpha_s$ = 0.17 at LL (constant), running using RGE at NLL

⇒ 1 free parameter : the normalization

# Going to NLL-BFKL

## Going to NLL-BFKL

- Large corrections w.r.t. LL and lead to unphysical results

  NLL BFKL kernels need resummation

  Truncation of the perturbative series → spurious singularities in BFKL-NLL kernel

- Use of Salam's regularisation schemes

  Singularities cancel when add some higher order corrections → meaningful NLL-BFKL results

  S3 and S4 schemes for forward jet production (modulo the impact factors taken at LL)

## Full NLL-BFKL kernel available

- Resolution of implicit equation performed by numerical methods

$$\chi_{NLL} \xrightarrow{\text{regularization}} \chi_{S4} \xrightarrow{\text{implicit equation}} \chi_{eff}$$

$$\chi_{\mathrm{eff}} = \chi^{\mathrm{NLL-S4}}(\gamma, \alpha, \chi_{\mathrm{eff}})$$

# Implementation in Herwig Monte Carlo

## Parametrization of the hard cross-section

- Fit to BFKL NLL cross section

  2200 points fitted between $10<E_T<120$ GeV, $0.1<\Delta\eta<10$

  Fit $\chi 2 \sim 0.1$ (better than 1% difference per point)

$$\frac{d\sigma^{gg \to gg}}{dE_T^2} = f(E_T, \Delta\eta) \;.\; \left(\hat{s}/E_T^2\right)^2 \;/\; (4\pi\alpha_s^4)$$

Example for BFKL NLL, with all p

$$f(E_T, \Delta\eta) = A + F*E_T + L*\sqrt{E_T}$$
$$+ \left(B + G*E_T + M*\sqrt{E_T}\right)\left(\frac{3\pi\alpha_s\Delta\eta}{2}\right)$$
$$+ \left(C + H*E_T \qquad\qquad\right)\left(\frac{3\pi\alpha_s\Delta\eta}{2}\right)^2$$
$$+ \left(I \qquad\qquad + N*\sqrt{E_T}\right)\left(\frac{3\pi\alpha_s\Delta\eta}{2}\right)^3$$
$$+ e^{D + \frac{3E\pi\alpha_s\Delta\eta}{2}}$$

## Integration over $\Delta\eta$, $E_T$ performed in Herwig event generation

⇒ **Meaningful predictions which takes into account jet structure and size**

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# Resummation over conformal spins at LL

**Contributions from non-zero conformal spins**

- Not perfomed before
- Study of the ratio

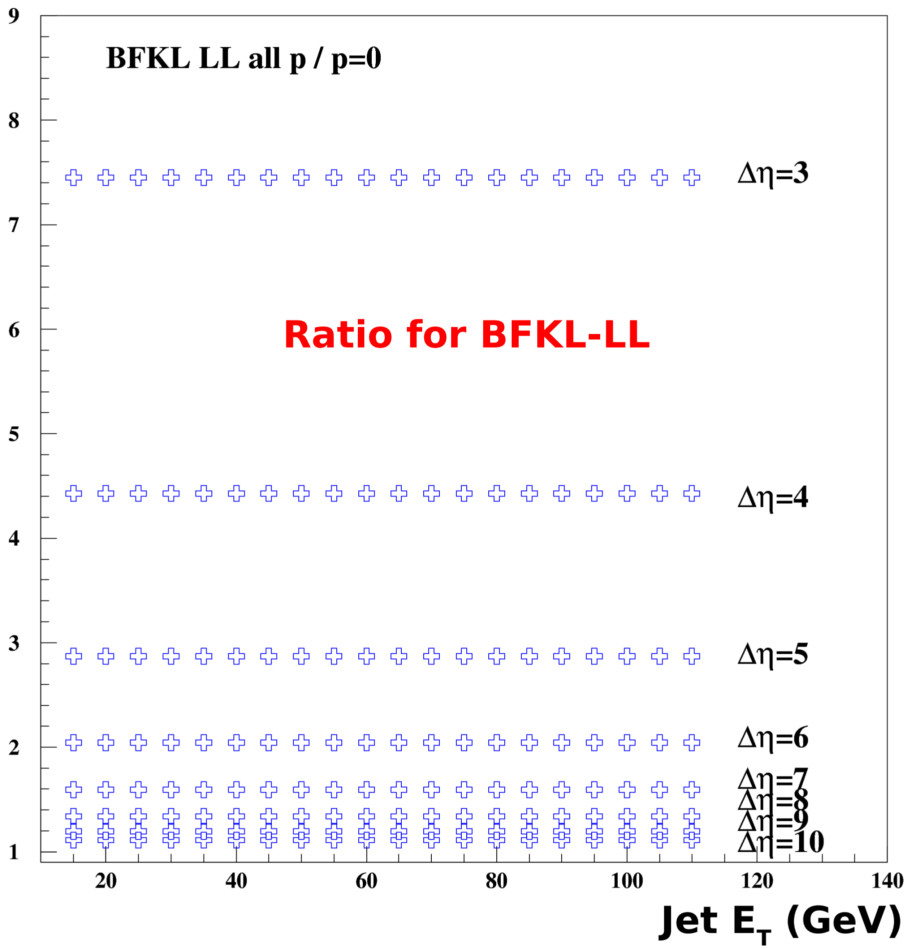
$$\frac{d\sigma/dE_T(\text{all}\,p)}{d\sigma/dE_T(p=0)}$$

- Large contribution

  x 4.5 for Δη=4

  x 1.5 for Δη=8

  Larger contribution at low Δη



# Resummation over conformal spins at NLL

**Contributions from non-zero conformal spins**

- Not perfomed before
- Study of the ratio

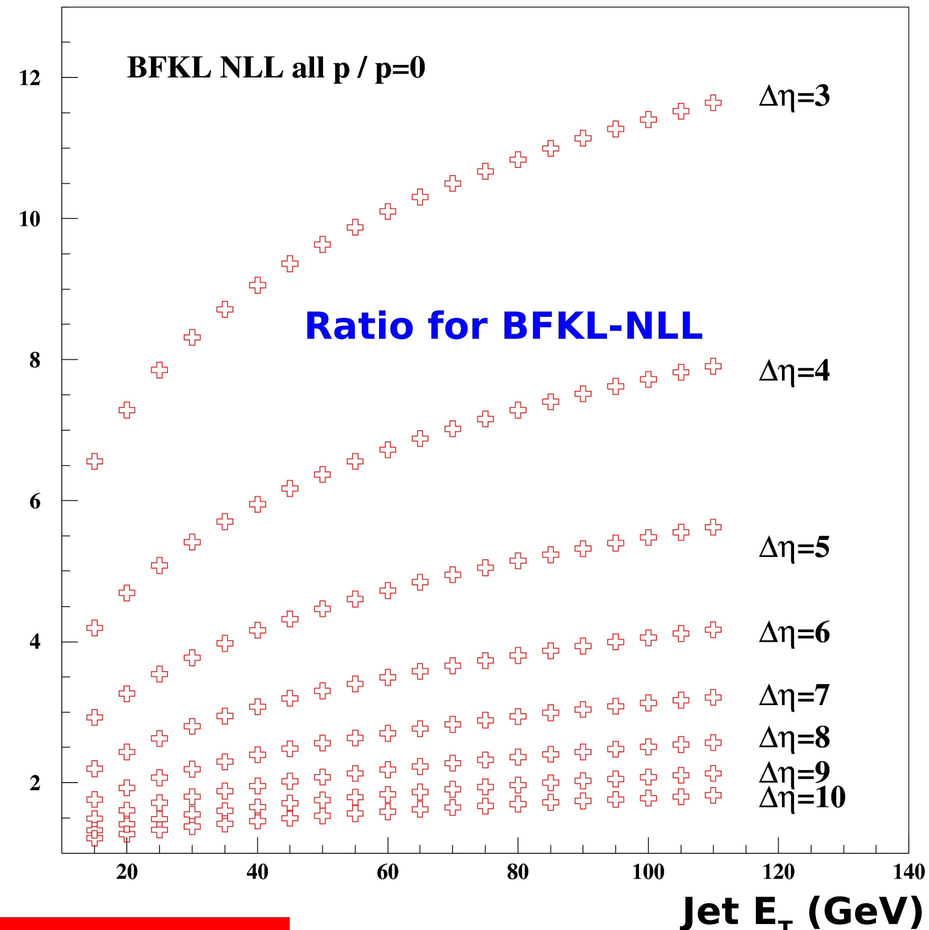
$$\frac{d\sigma/dE_T(\mathrm{all}\,p)}{d\sigma/dE_T(p=0)}$$

- Large contribution

  x 4 – 8 for $\Delta\eta=4$

  x 1.5 – 2 for $\Delta\eta=8$

  Larger contribution at high $E_T$ and low $\Delta\eta$



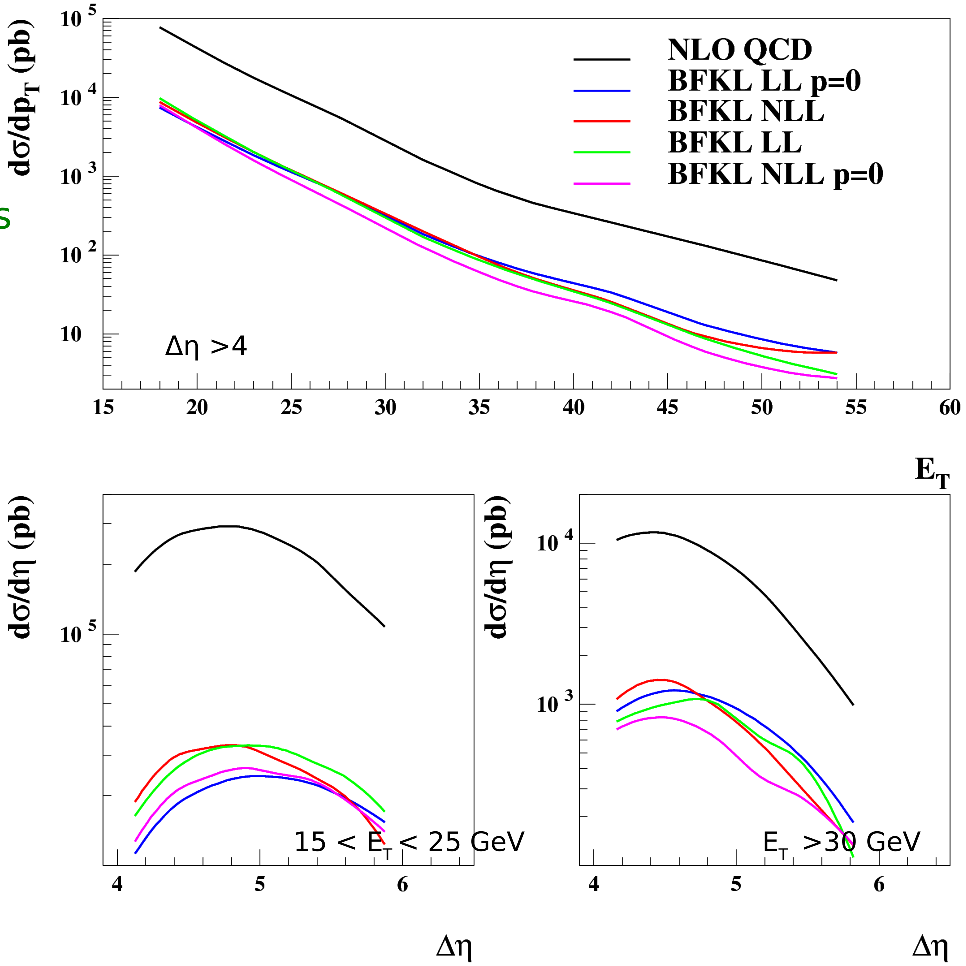

⇒ **p≠0 contributions are needed both at LL and NLL**

# Effect of higher-order BFKL corrections

**LL / NLL-BFKL comparison**

- Normalization is a free parameter
  Is adjusted to describe the data
  → Compare the shape of distributions

- Small differences in shape
  NLL effect more important at high $E_T$
  Dependence vs Δη



# Comparisons with DØ data

## DØ measurements

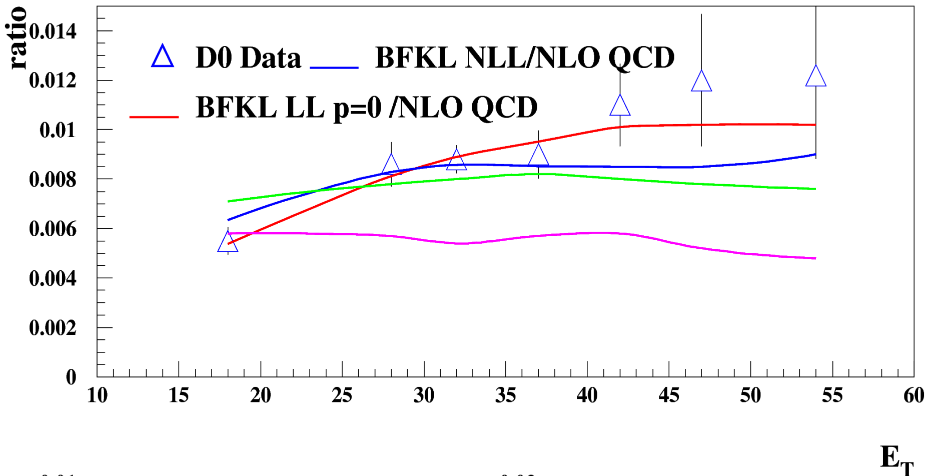
- Fraction of di-jets events with gap

  Ratio of jet gap jet / Inclusive di-jet cross sections

- Data selection

  Central gap between jets Δη>2 with no significant energy

  2 high ET jets in opposite forward regions




## Predictions

$$\text{Ratio} = \left|\frac{\sigma^{\text{NLL}}(\text{jet-gap-jet})}{\sigma^{\text{L0}}(\text{di-jet})}\right|_{\text{Herwig}}$$

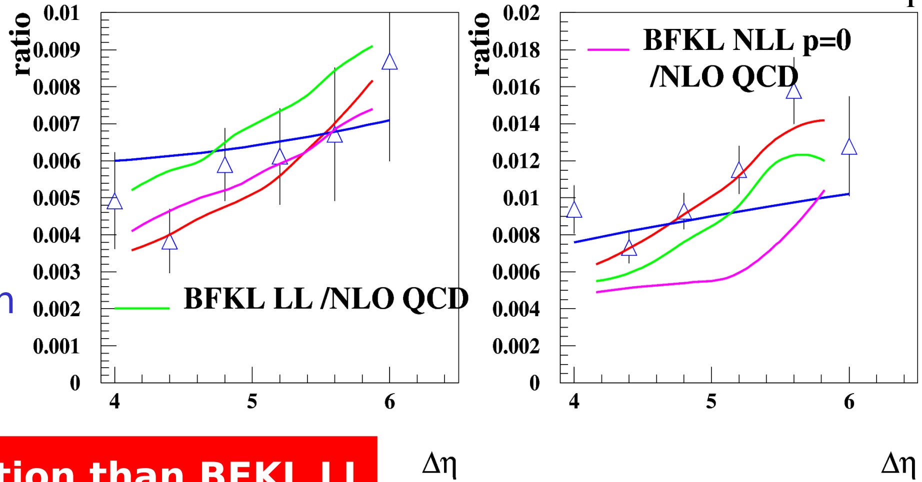
$$* \left|\frac{\sigma^{\text{NL0}}(\text{di-jet})}{\sigma^{\text{L0}}(\text{di-jet})}\right|_{\text{NLOJet++}}$$

## Comparisons with BFKL formalism

- Good agreement with LL p=0 BFKL

  but p≠0 contributions are important

- Better description with BFKL NLL formalism




**BFKL NLL leads to a better description than BFKL LL**

# Comparisons with CDF data

## CDF measurements

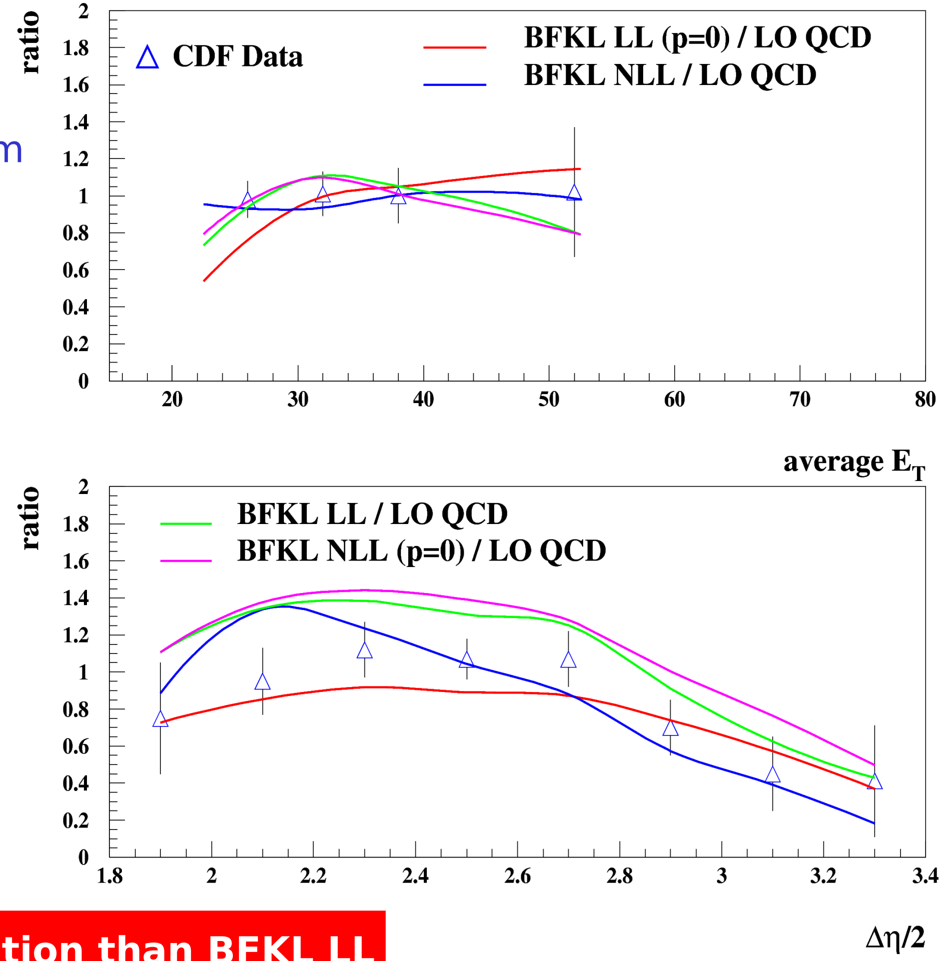
- Same as for DØ analysis

## Predictions

- Same as for DØ analysis

## Comparisons with BFKL formalism

- Better description with BFKL NLL formalism




**BFKL NLL leads to a better description than BFKL LL**

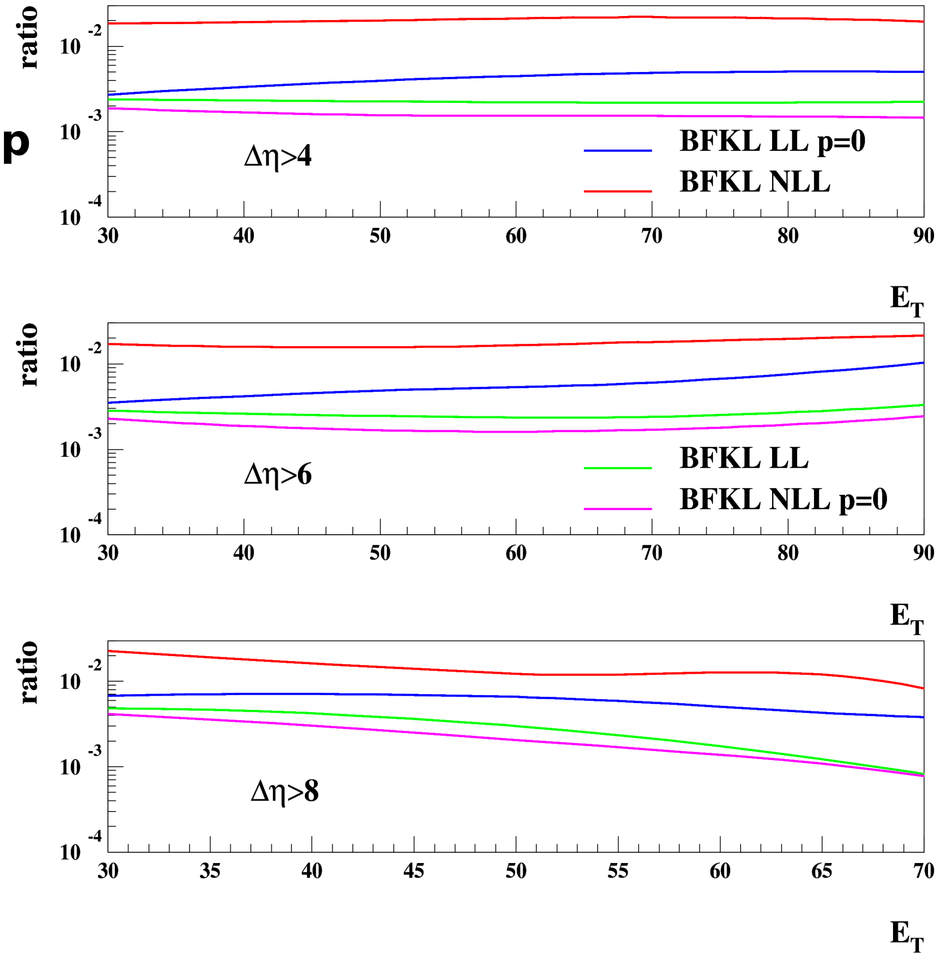
# Predictions for LHC

**Predictions**

- Use the same BFKL NLL formalism in Herwig at LHC energies
- Gap survival probability for LHC
- Rapidity gap -1 <Δη< 1

**Fraction of di-jets events with gap**

- Versus jet $E_T$
- Versus jet Δη




**Weak $E_T$ dependence**

**Large differences in normalisation between BFKL LL and NLL predictions**

# Predictions for LHC

## Predictions

- Use the same BFKL NLL formalism in Herwig at LHC energies
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## Fraction of di-jets events with gap

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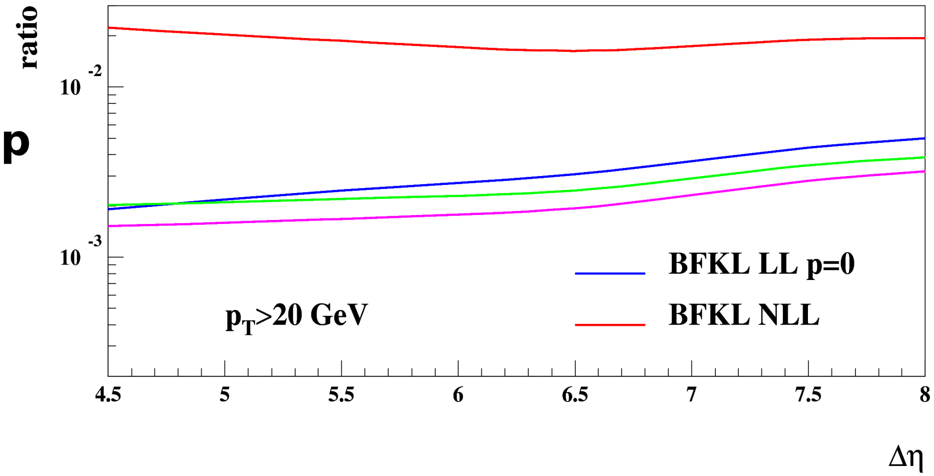
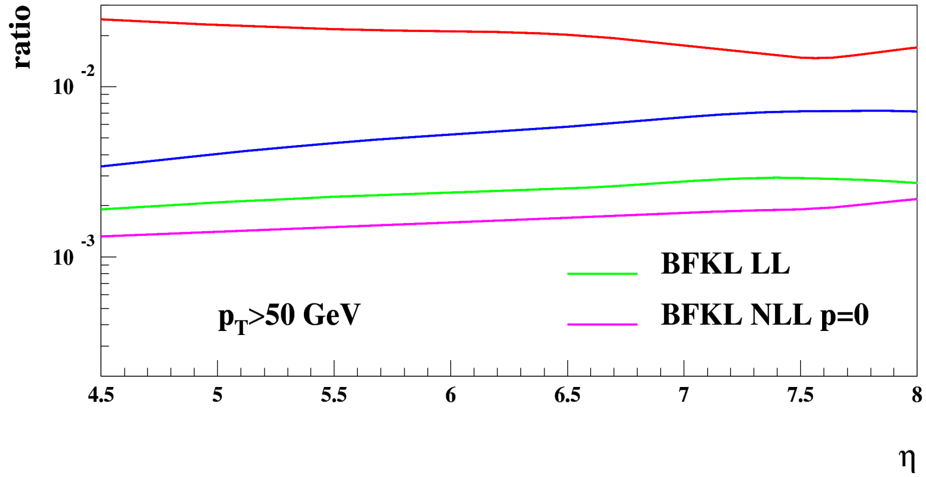



**Weak Δη dependence**
**Large differences in normalisation between BFKL LL and NLL predictions**

# Conclusion

**First study of processes with the BFKL kernel at next-leading accuracy**

Predictions obtained with the full analytic expression of the NLL-BFKL kernel

Non-zero conformal spins have large contributions

**BFKL NLL kernel fully implemented in HERWIG**

Fundamental to compare with data (takes into account jet structure and jet size)

→ Provides meaningful predictions

**Comparison with TeVatron data and prediction for LHC**

Good agreement data/predictions

better agreement with NLL calculation than with full LL

For LHC : large differences in normalisation/shape between LL and NLL

→ Effects of higher order terms in the di-jet cross-section have to be checked

# Conclusions

- the correlation in azimuthal angle between two jets gets weaker as their separation in rapidity increases
- we obtained parameter free predictions in the BFKL framework at next-leading accuracy, valid for large enough rapidity intervals
- there is some data from the D0 collaboration at the Tevatron, but for rapidity intervals $\Delta\eta$ smaller than 5
- our predictions underestimate the correlation while pQCD@NLO predictions overestimate it prospects for future measurements:
- at the Tevatron : the CDF miniplugs cannot measure pT well but are suited for azimuthal angle measurements
- at the LHC : feasibility study in collaboration with Christophe Royon (D0/Atlas) and Ramiro Debbe (Star/Atlas)

Therefore a measurement of the cross-section $d\sigma$ hh→JXJ /$d\Delta\eta dR d\Delta\Phi$ at the Tevatron (Run 2) or the LHC would allow for a detailed study of the QCD dynamics of Mueller-Navelet jets. In particular, measurements with values of $\Delta\eta$ reaching 8 or 10 will be of great interest, as these could allow to distinguish between BFKL and DGLAP resummation effects and would provide important tests for the relevance of the BFKL formalism.

# Effect of non-zero conformal spin

## Different models proposed

- QCD di-jets production

  No gap because of soft QCD radiations
- Color-singlet exchange

  Gap between jets

  One color-singlet candidate is the BFKL pomeron

## Cross-section in the BFKL framework

- Relevant variables

$$y = \frac{y_1 + y_2}{2} \; ; \; \Delta\eta = | y_1 - y_2 |$$

- Jet-gap-jet cross-section

Gap survival probability

$$\frac{d\sigma^{pp \to XJJY}}{dy.d\Delta\eta.dE_T^2} = S \, x_1 f_{eff}(x_1, E_T^2) \, . \, x_2 f_{eff}(x_2, E_T^2) \, \frac{d\sigma^{gg \to gg}}{dE_T^2}(y, \Delta\eta)$$

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

Sum over conformal spin

LL / NLL BFKL kernel

$\Rightarrow$ 1 free parameter : the normalization

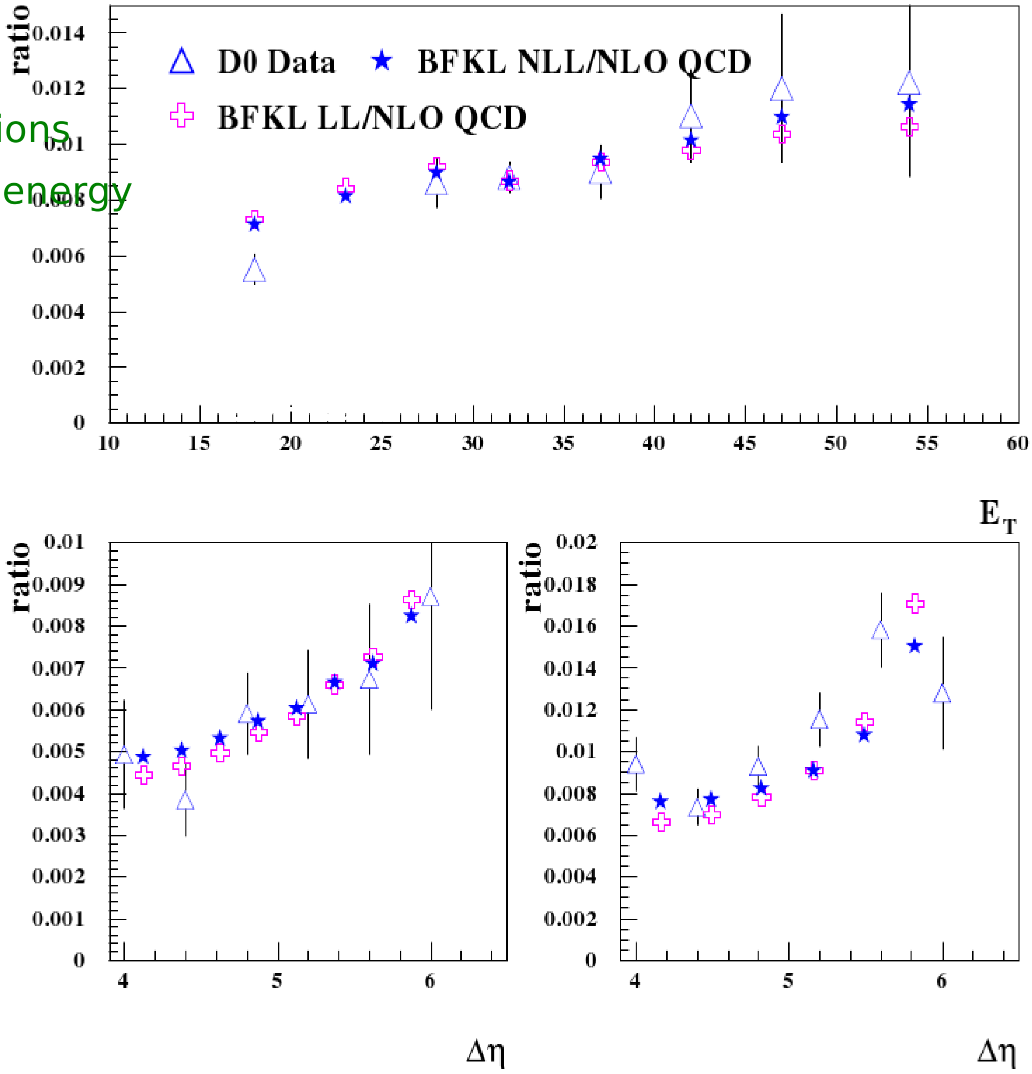
# Comparisons with DØ data

**DØ data selection**

- Inclusive di-jet sample
  - 2 high $E_T$ jets in opposite forward regions
  - Central gap $\Delta\eta>2$ with no significant energy
- Fraction of di-jets events with gap

**Prediction**

- BFKL jet-gap-jet cross-section
  - LL or NLL kernel
  - Gap survival probability S=0.1
  - Hadronization not taken into account
- Inclusive di-jet cross-section
  - QCD predictions with NLOJet++
  - Hadronization not taken into account




**Comparisons**

- Overall normalization fit to data
  - k=0.84 with LL-BFKL prescription
  - k=1.00 with NLL-BFKL prescription
- Shape
  - $E_T$ , $\Delta\eta$ dep

⇒ **Correct agreement between NLL-BFKL prediction and DØ data**
**Need checks with NNLO QCD**

# Predictions for LHC

## Selection cuts

- Inclusive di-jet sample

  2 high $E_T$ jets in opposite forward regions + trigger condition

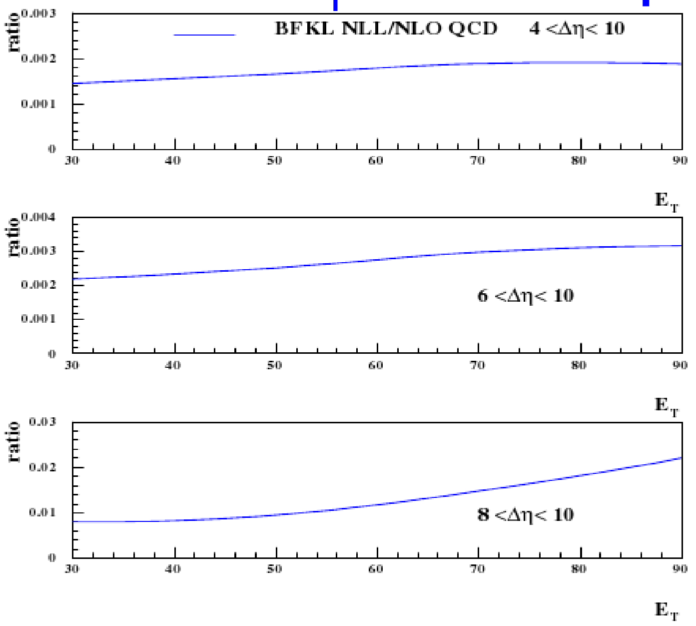
  Central gap with no significant energy

  → Need low-luminosity runs

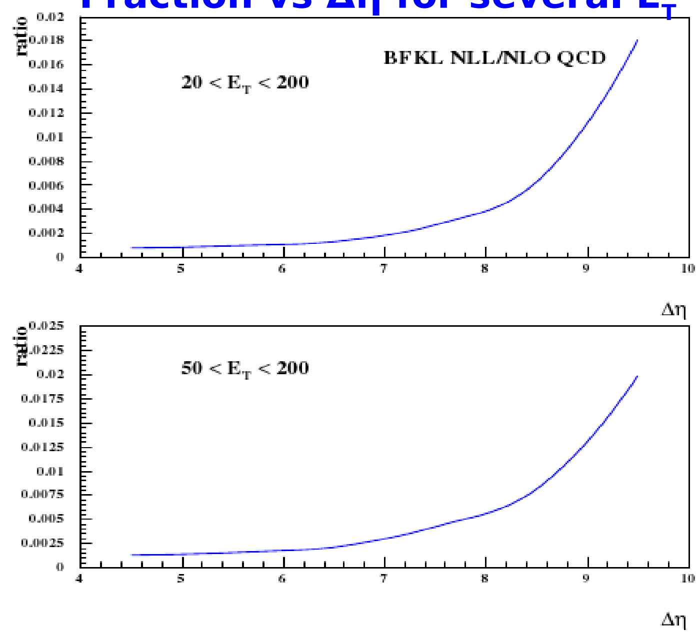
## Fraction of gap events

- σ(jet-gap-jet) / σ(inclusive di-jets)

**Fraction vs $E_T$ for several Δη**




**Fraction vs Δη for several $E_T$**




Contribut

Percentag

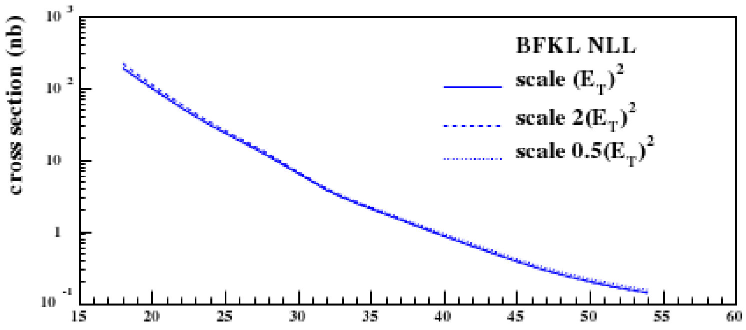
**High jet-gap-jet cross-section at LHC → need *O*(100 $pb^{-1}$)**

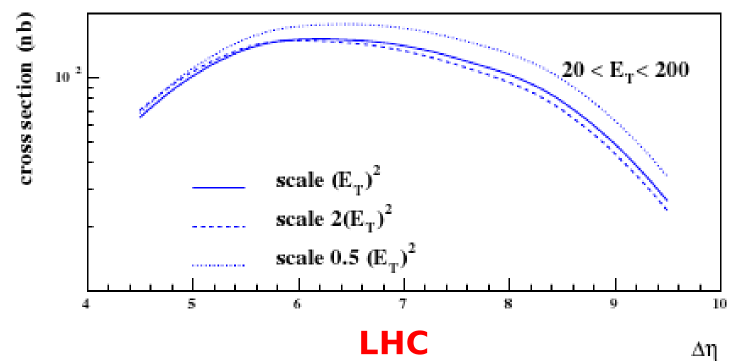
**Challenging because it needs a good calibration of forward jets**

# Systematic uncertainties

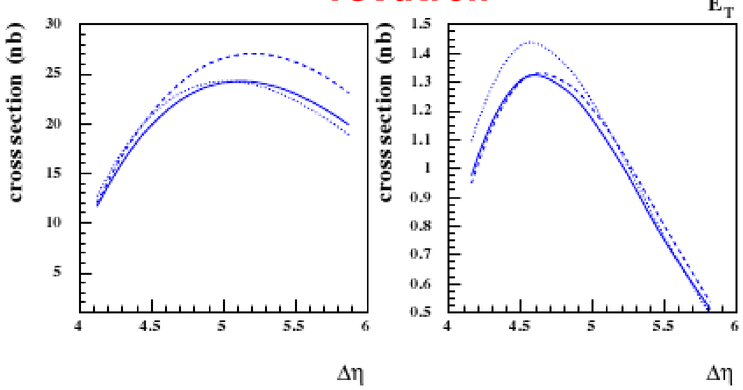
## Renormalization scale dependence

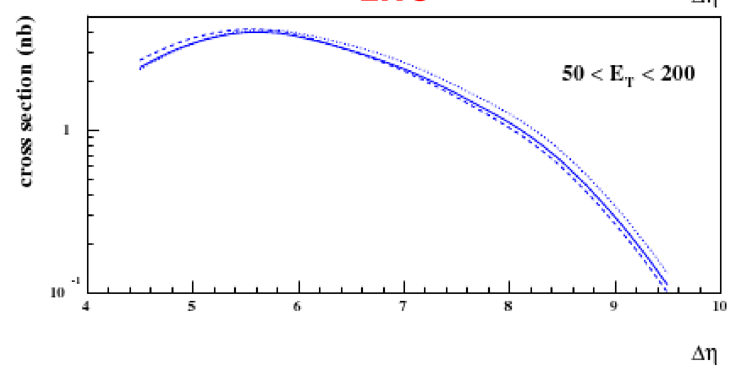
- Method
  - Variation ½ $Q^2 \rightarrow 2\ Q^2$
  - Appropriate substitution in $\bar{\alpha}(Q^2)$
  - Modify the effective BFKL kernel
  - Modify energy scale
- Results




**TeVatron** **LHC**




**Jet-gap-jet cross-section is a robust test of the BFKL regime**