

# **BFKL NLL phenomenology of forward jets at HERA and Mueller Navelet jets at the Tevatron and the LHC**

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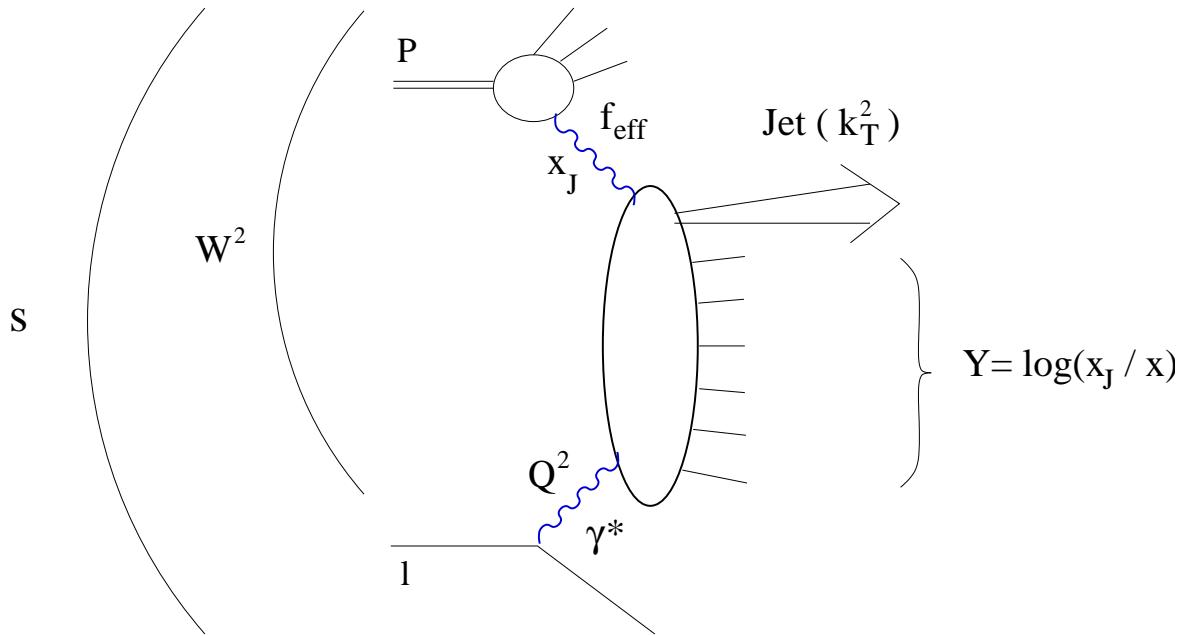
## Contents:

- BFKL-NLL formalism
- Fit to H1  $d\sigma/dx$  data (saddle point approximation)
- Prediction for the H1 triple differential cross section
- Prediction for Mueller Navelet jets at the Tevatron/LHC (exact calculation)

Work done in collaboration with O. Kepka, C. Marquet, R. Peschanski

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## Forward jet measurement at HERA



- Typical kinematical domain where BFKL effects are supposed to appear with respect to DGLAP:  $k_T^2 \sim Q^2$ , and  $Q^2$  not too large
- LO BFKL forward jet cross section: 2 parameters  $\alpha_S$ , normalisation
- NLL BFKL cross section: one single parameter: normalisation ( $\alpha_S$  running via RGE)

## BFKL LO formalism

- BFKL LO forward jet cross section, saddle point approximation:

$$\frac{d\sigma}{dx dk_T dQ^2 dx_{jet}} = N \sqrt{\frac{Q^2}{k_T^2}} \alpha_S(k_T^2) \alpha_S(Q^2) \sqrt{A} \\ \exp\left(4\alpha(\log 2) \frac{N_C}{\pi} \log\left(\frac{x_J}{x}\right)\right) \\ \exp\left(-A \log^2\left(\sqrt{\frac{Q}{k_T}}\right)\right)$$

where

$$\frac{1}{A} = \frac{7\zeta(3)}{\pi} \alpha \log \frac{x_J}{x}$$

- 2 parameters in fits to  $d\sigma/dx$ :  $N$ ,  $\alpha$

## How to go to BFKL-NLL formalism?

- Simple idea: Keep the saddle point approximation, and use the BFKL NLO kernel
- Formula at NLL:

$$\frac{d\sigma}{dx} = N \left( \frac{Q^2}{k_T^2} \right)^{\text{power}} \alpha_S(k_T^2) \alpha_S(Q^2) \sqrt{A} \\ \exp \left( \alpha_S(k_T Q) \frac{N_C}{\pi} \chi(\gamma_C) \log \left( \frac{x_J}{x} \right) \right) \\ \exp \left( -A \alpha_S(k_T Q) \log^2 \left( \sqrt{\frac{Q}{k_T}} \right) \right)$$

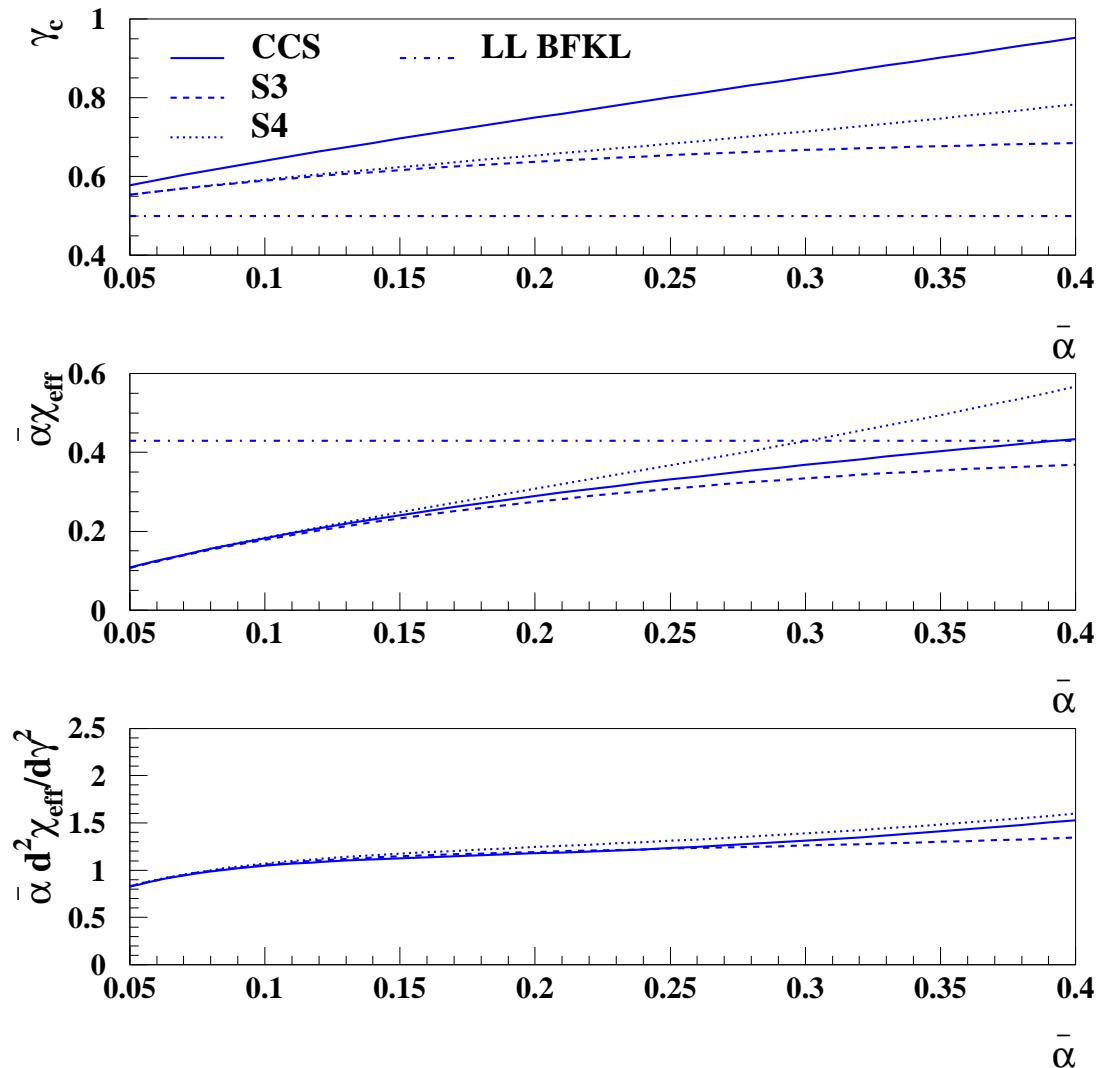
where

$$\frac{1}{A} = \frac{3\alpha_S(k_T Q)}{4\pi} \log \frac{x_J}{x} \chi''(\gamma_C) \\ \text{power} = \gamma_C + \frac{\alpha_S(k_T Q) \chi(\gamma_C)}{2}$$

- Only free parameter in the BFKL NLL fit: absolute normalisation
- Full calculation without saddle point approximation in progress

## $\gamma_C$ , $\chi(\gamma_C)$ , and $\chi''(\gamma_C)$ as a function of $\alpha$

Determination of  $\gamma_C$ ,  $\chi(\gamma_C)$ , and  $\chi''(\gamma_C)$  as a function of  $\alpha$



## **Cross section calculation, comparison with H1**

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- **Two difficulties:** We need to integrate over the bin in  $Q^2$ ,  $x_{jet}$ ,  $k_T$  to compare with the experimental measurement and we need to take into account the experimental cuts (as an example:  $E_e > 10$  GeV,  $k_T > 3.5$  GeV,  $7 \leq \theta_J \leq 20$  degrees....)
- **We perform the integration numerically:** we chose the variables for which the cross section is as flat as possible to avoid numerical difficulties in precision:  $k_T^2/Q^2$ ,  $1/Q^2$ ,  $\log 1/x_{jet}$
- **We take into account some of the cuts at the integration level ( $k_T$  for instance) and the other ones using a toy Monte Carlo**

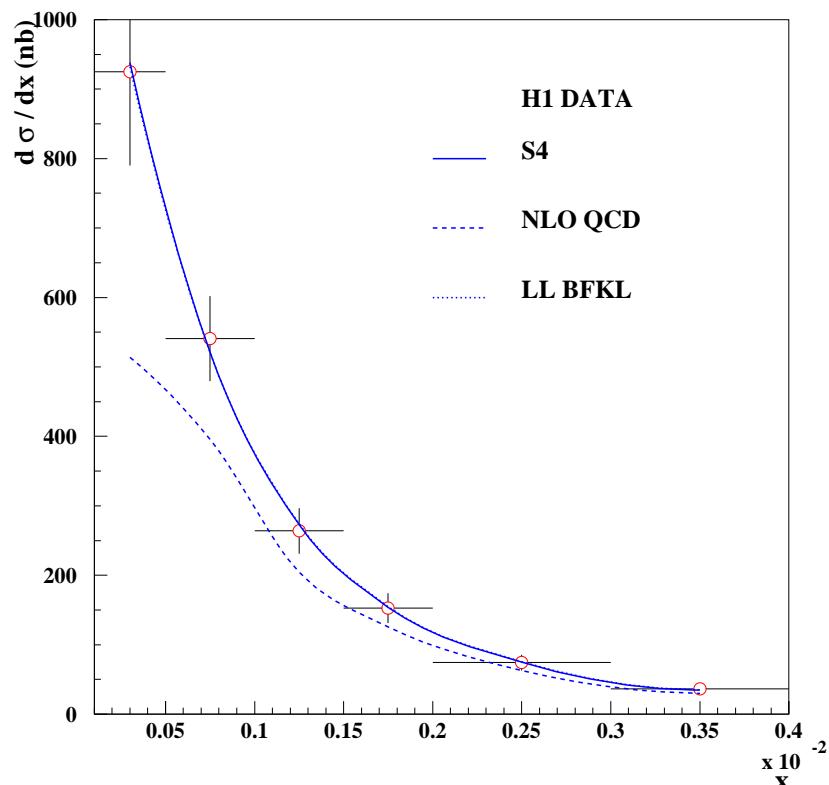
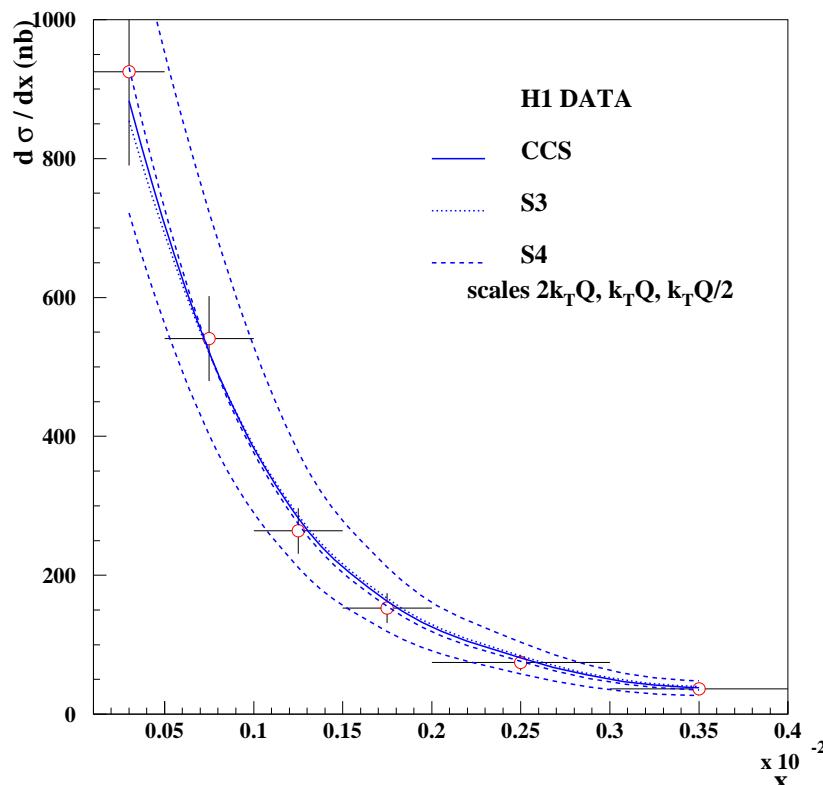
## Fit procedure

- Fit to H1  $d\sigma/dx$  data only
- Fit using the 6 data points
- Results at LO: Good fit ( $\chi^2 \sim 0.5/5$ ), but  $\alpha_S$  small ( $\alpha_S \sim 0.1$ )
- $\alpha_S(k_T Q)$  is imposed using the renormalisation group equation at NLL
- Full calculation without saddle point approximation in progress, leads to similar results

scheme	fit	$\chi^2/dof$	$N$
CCS	stat. + syst.	0.90/5	$0.1332 \pm 0.0074$
CCS	stat. only	22.2/5	$0.1367 \pm 0.0016 \pm 0.0170$
S3	stat. + syst.	1.74/5	$0.1514 \pm 0.0085$
S3	stat. only	46.5/5	$0.1576 \pm 0.0018 \pm 0.0196$
S4	stat. + syst.	0.29/5	$0.1094 \pm 0.0061$
S4	stat. only	5.4/5	$0.1096 \pm 0.0013 \pm 0.0137$
S4 full	stat. + syst.	0.80/5	$1.32 \pm 0.07$
S4 full	stat. only	20.3/5	$1.35 \pm 0.02 \pm 0.16$

## Fit results

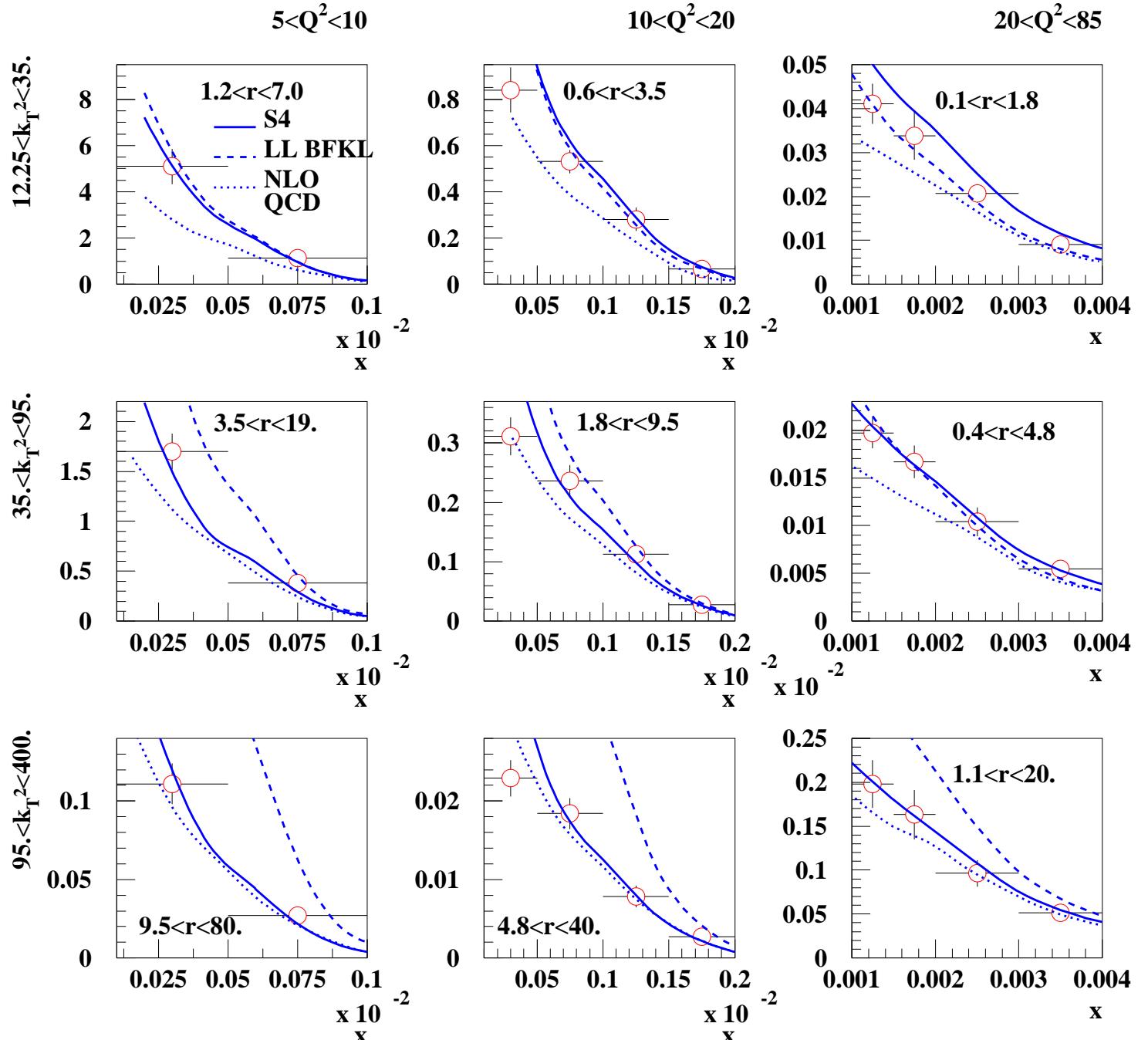
- $\chi^2$  for CCS: 22.2 (0.9), S3: 46.5 (1.7), S4: 5.4 (0.3)
- Good description of H1 data using BFKL LO and BFKL NLL formalism, DGLAP-NLO fails to describe the data
- BFKL higher corrections found to be small (We are in the BFKL-LO region, cut on  $0.5 < k_T^2/Q^2 < 5$ )



## Comparison with H1 triple differential data

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$d\sigma/dx dk_T^2 dQ^2 - \text{H1 DATA}$

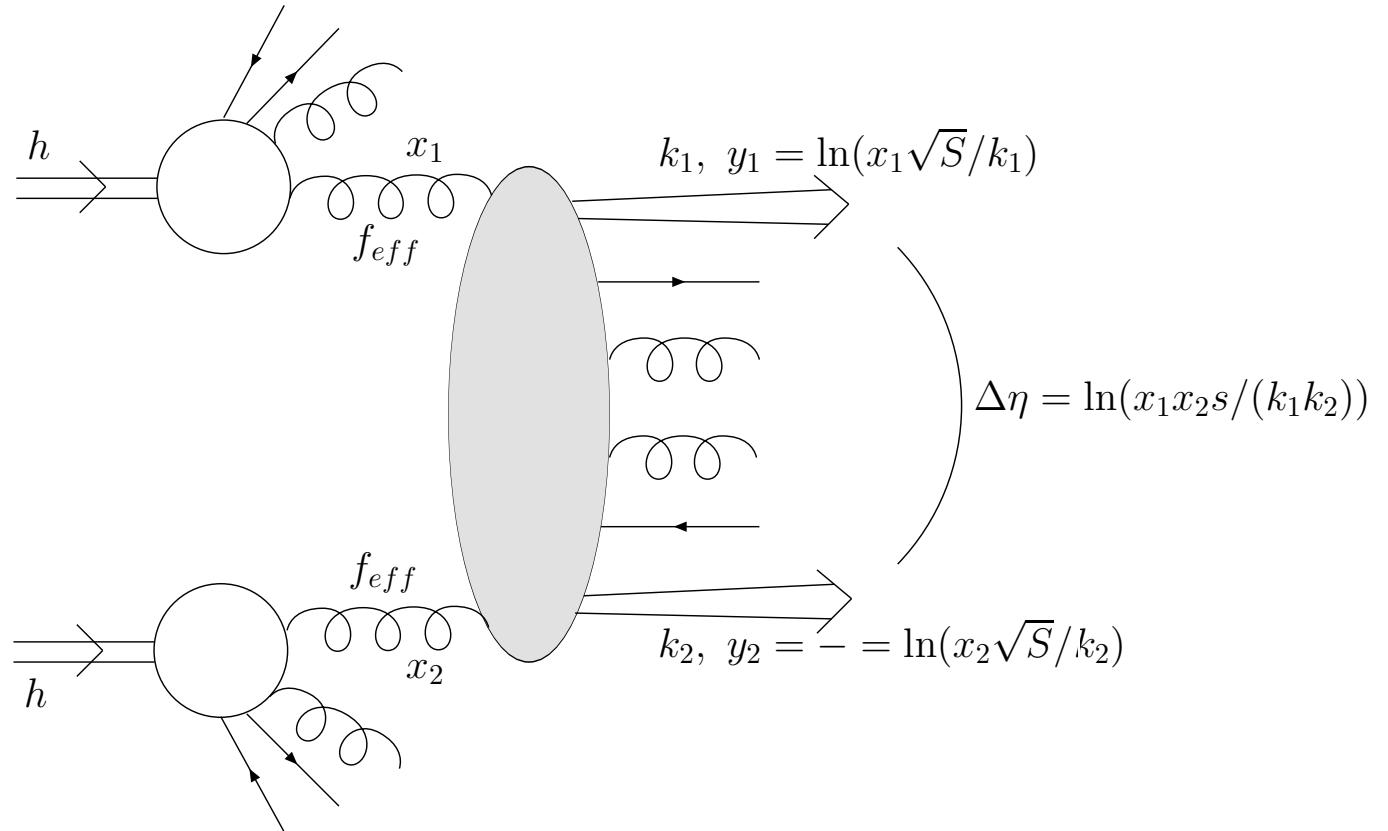


## Remarks about BFKL NLL calculations

- DGLAP NLO predictions cannot describe H1 data in the full range, and large difference between DGLAP NLO and DGLAP LO results (DGLAP NLO includes part of the small  $x$  resummation effects)
- BFKL LO describes the H1 data when  $r = k_T^2/Q^2$  is close to 1 and BFKL LO fails outside the region  $r \sim 1$  specially at high  $Q^2$
- BFKL higher order corrections found to be small (as expected) when  $r \sim 1$
- Higher order BFKL corrections larger when  $r$  further away from 1, where the BFKL NLL prediction is closer to the DGLAP one ( $Q^2$  resummation effects are starting to be large)
- Systematic additional studies: Check the effect of varying scale in  $\alpha_S$  ( $2Qk_T$ ,  $Qk_T/2$ ,  $Q^2$ ,  $k_T^2$ ), different assumptions for the unknown impact factors
- Small differences between CCS, S3 and S4 schemes: S4 slightly favoured
- Full calculation without saddle point approximation in progress to check how these results are influenced by the saddle point approximation

## Mueller Navelet jets

Same kind of processes at the Tevatron and the LHC



- Same kind of processes at the Tevatron and the LHC:  
Mueller Navelet jets
- Study the  $\Delta\Phi$  between jets dependence of the cross section:

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

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- Study the  $\Delta\Phi$  dependence of the relative cross section
- Relevant variables:

$$\begin{aligned}
 \Delta\eta &= y_1 - y_2 \\
 y &= (y_1 + y_2)/2 \\
 Q &= \sqrt{k_1 k_2} \\
 R &= k_2/k_1
 \end{aligned}
 \tag{1}$$

- Azimuthal correlation of dijets:

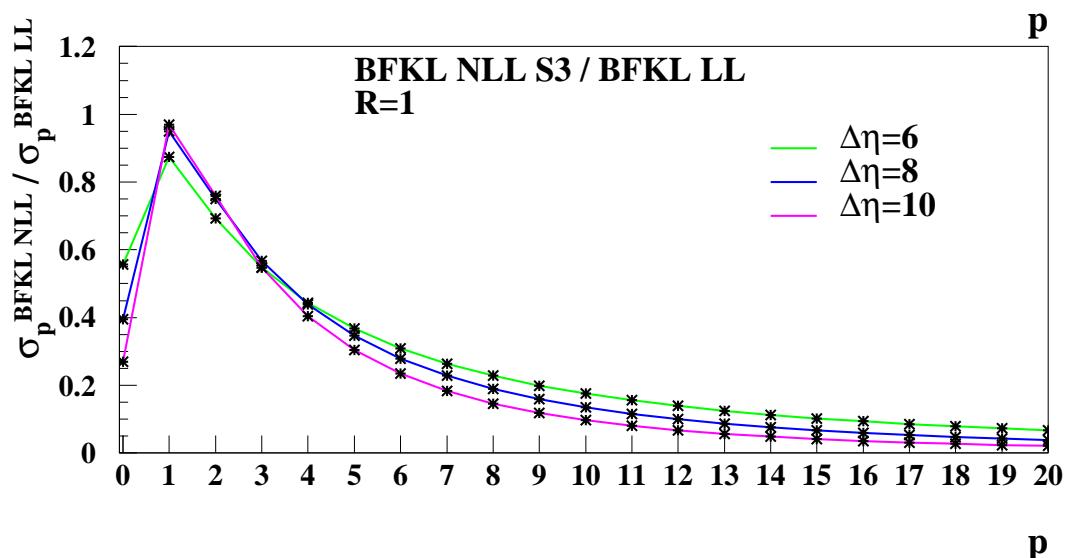
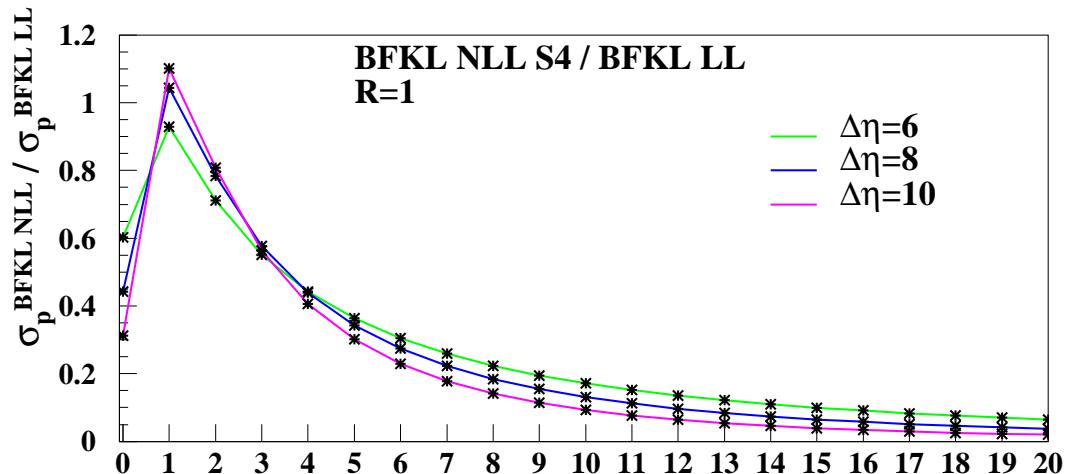
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Bigg/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

where

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

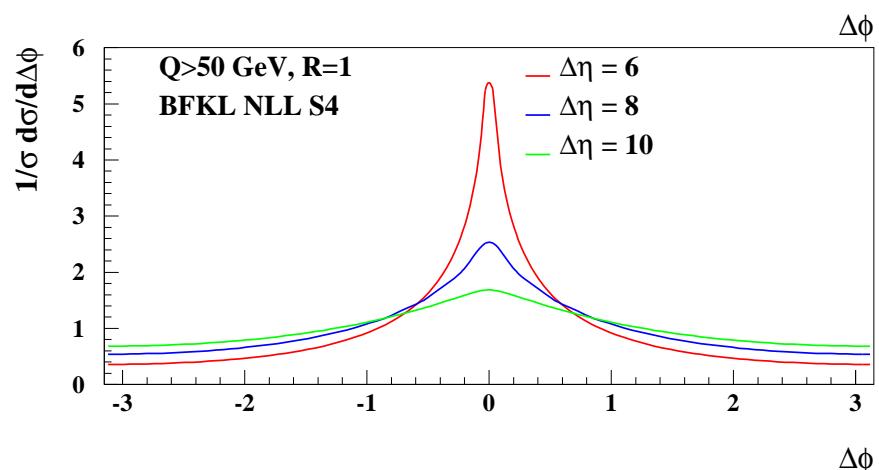
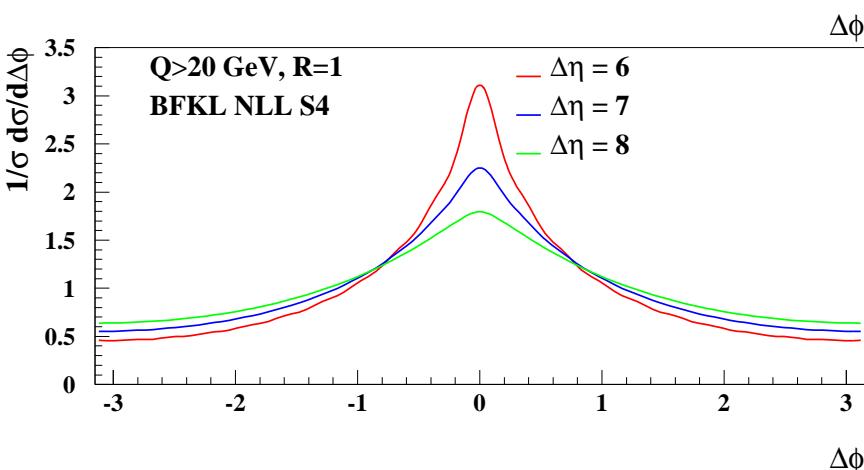
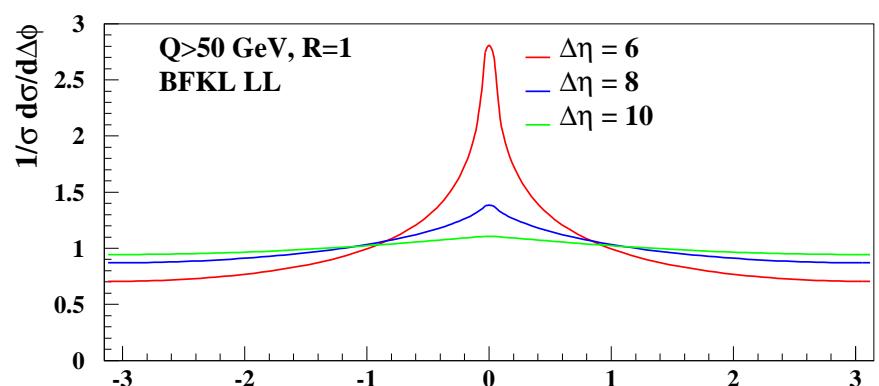
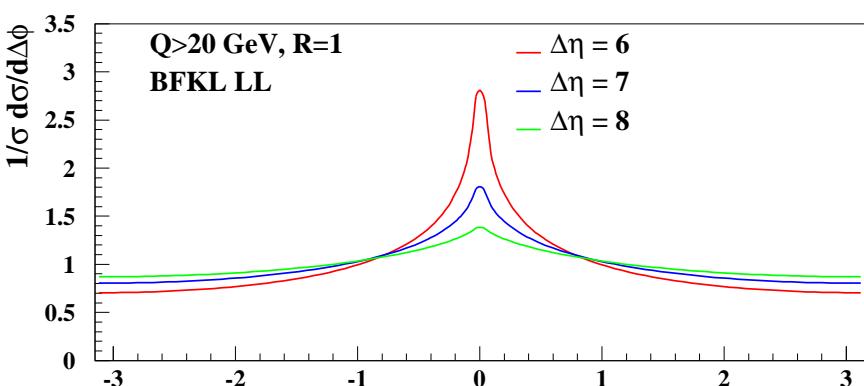
## Mueller Navelet jets: $\Delta\Phi$ dependence

Ratio of the values of  $\sigma_i$  entering into the  $\Delta\Phi$  spectrum between BFKL NLL and BFKL LL for different intervals in rapidity



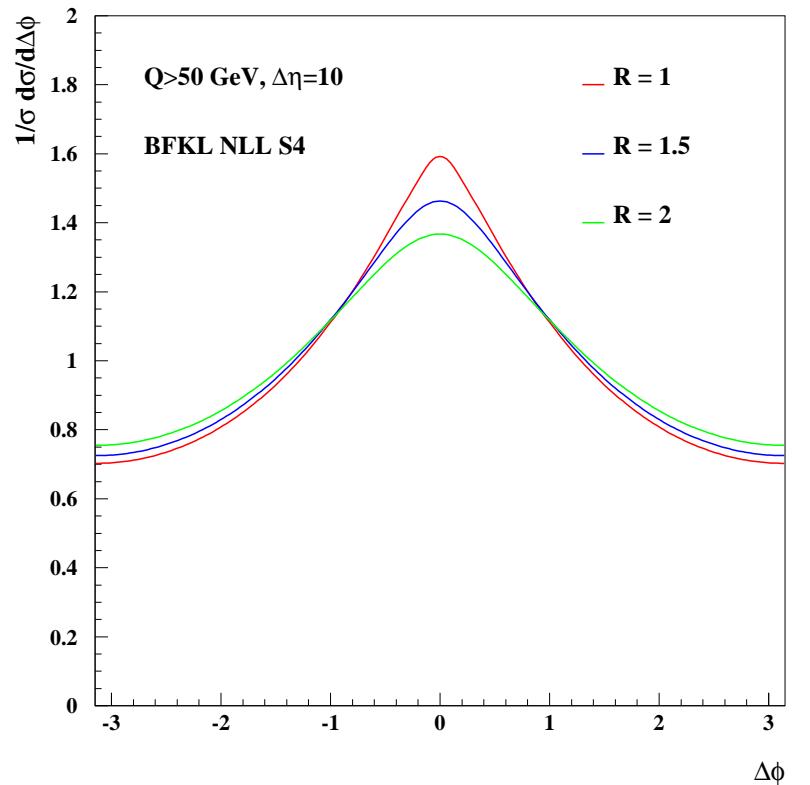
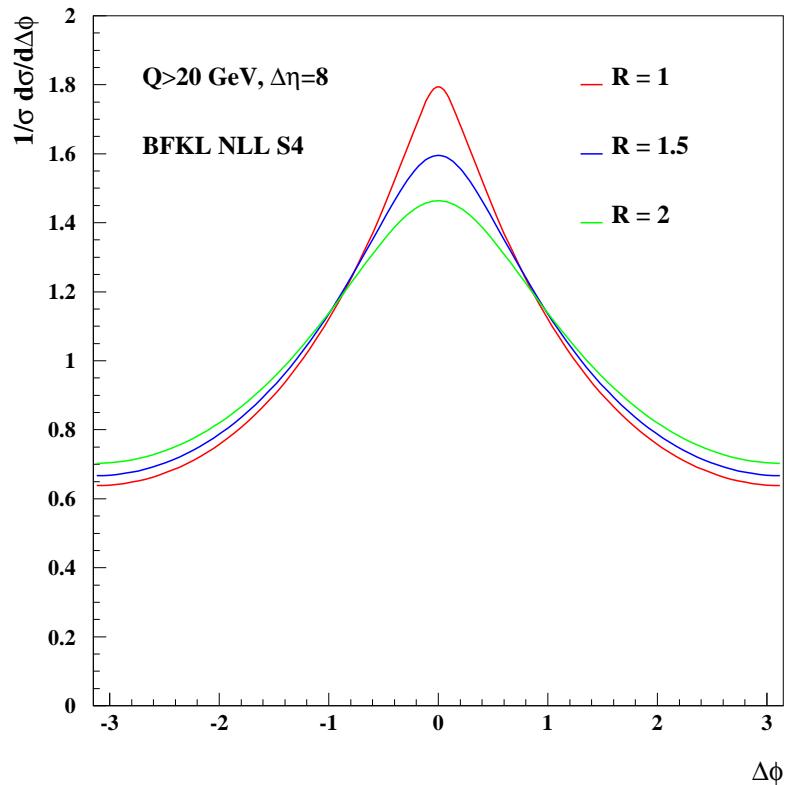
## Mueller Navelet jets: $\Delta\Phi$ dependence

- $1/\sigma d\sigma/d\Delta\Phi$  spectrum for BFKL LL and BFKL NLL as a function of  $\Delta\Phi$  for different values of  $\Delta\eta$
- Measurement to be performed at the Tevatron/LHC



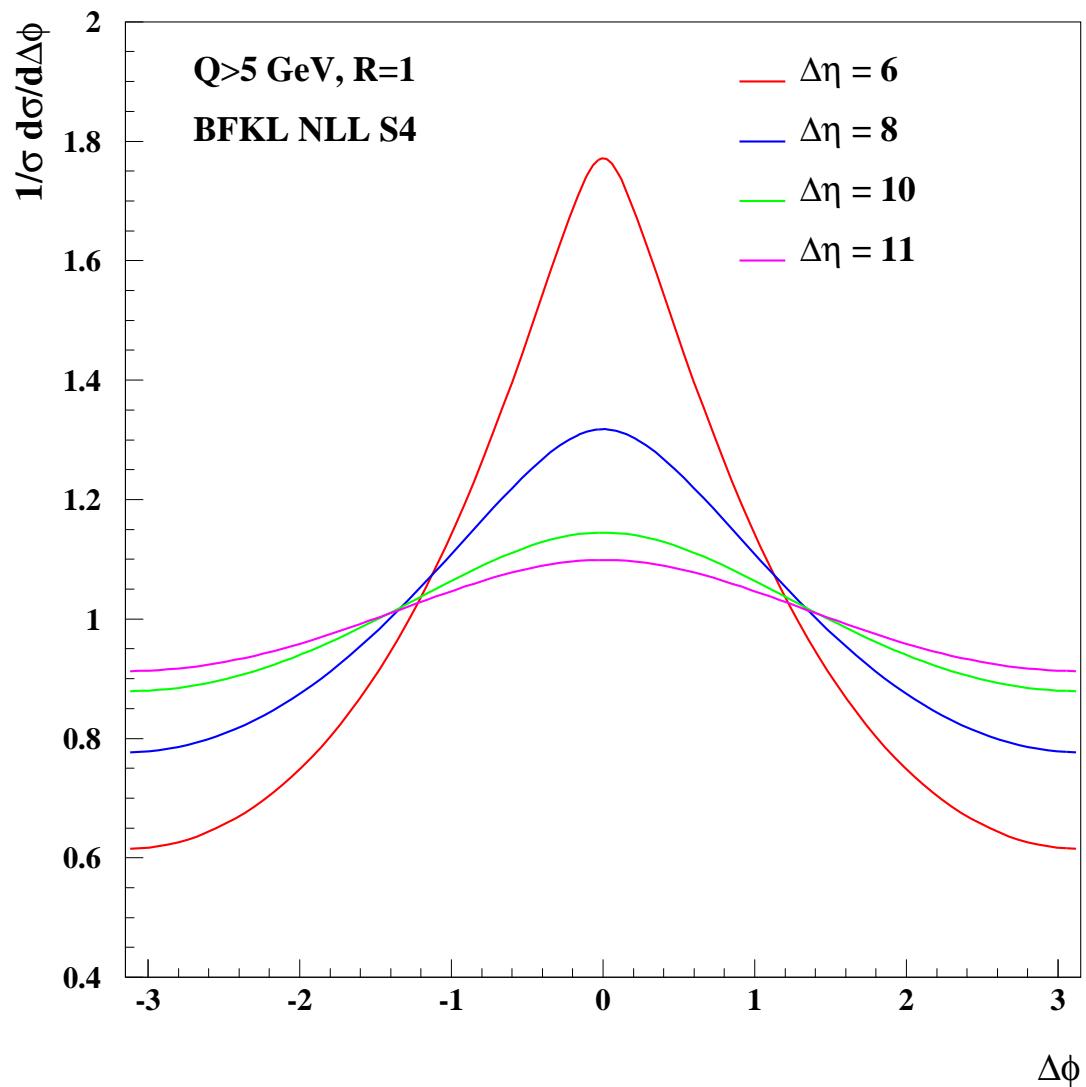
## Mueller Navelet jets: $R$ dependence

Weak  $R$  dependence, BFKL/DGLAP enhanced if  $R$  close to 1



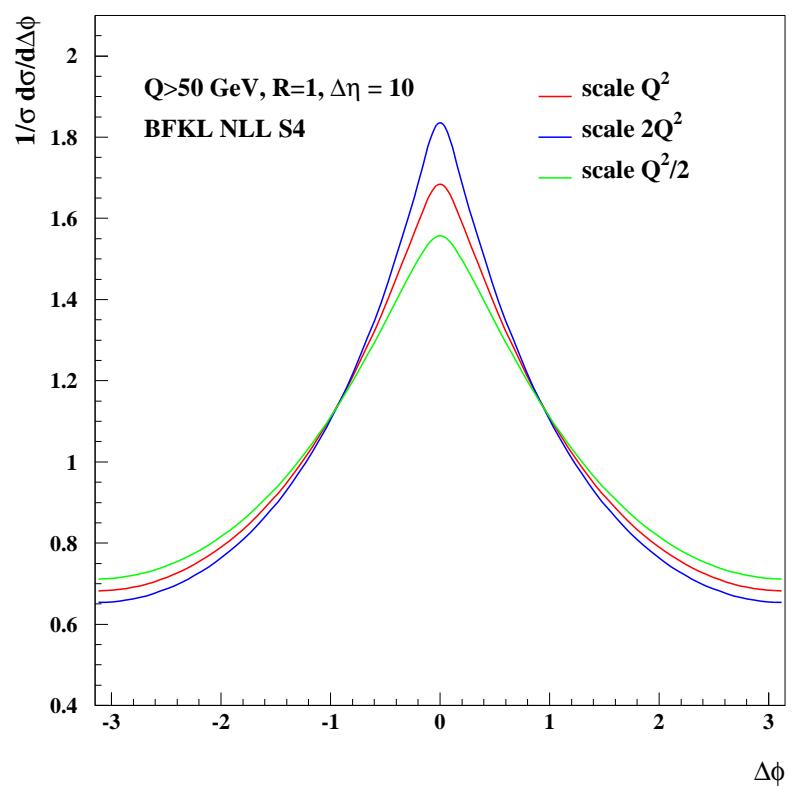
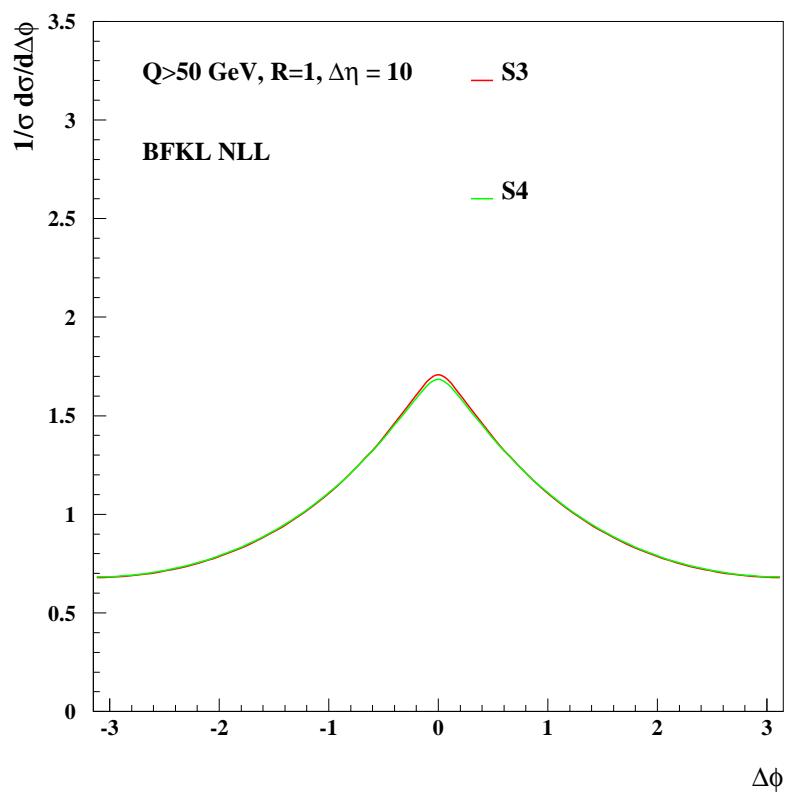
## Mueller Navelet jets in CDF

Possibility to measure  $\Delta\Phi$  distribution in CDF for large  $\Delta\eta$  and low jet  $p_T$  ( $p_T > 5$  GeV) using the CDF miniPLUG calorimeter



## Mueller Navelet jets: S3 and S4, scale dependence

- No difference between S3 and S4 schemes (as an example for LHC)
- Weak scale dependence (given as an example for the LHC):  $Q^2/2$ ,  $Q^2$ ,  $2Q^2$



## Conclusion

- DGLAP NLO fails to describe forward jet data
- First BFKL NLL description of H1 and ZEUS forward jet data: very good description
- Saddle point approximation used to perform calculation of forward jet cross section and full calculation in progress
- Mueller Navelet jets: Full calculation available using S3 and S4 schemes (without saddle point approximation)
- Mueller Navelet jets  $\Delta\Phi$  dependence: weak dependence even after NLL corrections, little sensitivity to chosen scale
- Mueller Navelet jets: Very nice measurement to be performed at the Tevatron/LHC, special use of CDF forward miniPLUG calorimeter which gives a good acceptance at large  $\eta$  and small  $p_T$  for jets