Forward jets at HERA and Mueller Navelet jets at Tevatron/LHC

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Sakura meeting, 24-26 August 2009, Tokyo, Japan

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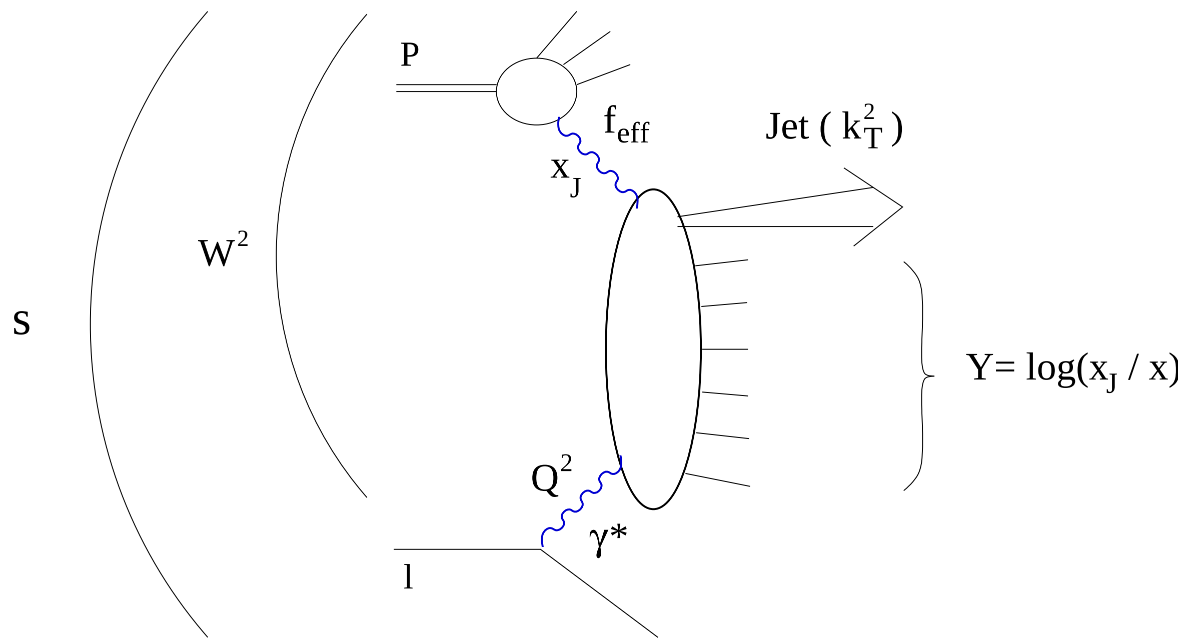
- BFKL-NLL formalism
- Fit to H1 $d\sigma/dx$ data
- Prediction for the H1 triple differential cross section
- Prediction for Mueller Navelet jets at the Tevatron/LHC
- Effect of energy conservation on BFKL equation

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

Phys. Lett. B 655 (2007) 236; Eur. Phys. J. C55 (2008) 259; Phys. Rev. D79 (2009) 034028

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
- LL BFKL forward jet cross section: 2 parameters α_S, normalisation
- NLL BFKL cross section: one single parameter: normalisation (α_S running via RGE)

BFKL NLL and resummation schemes

- NLL BFKL: Corrections were found to be large with respect to LL, and lead to unphysical results
- NLL BFKL kernels need resummation: to remove additional spurious singularities in γ and $(1-\gamma)$
- NLL BFKL kernel: (γ and ω associated to $\log Q^2$ and rapidity after Mellin transform)

$$\chi_{NLL}(\gamma,\omega) = \chi^{(0)}(\gamma,\omega) + \alpha(\chi_1(\gamma) - \chi_1^{(0)}(\gamma))$$

- $\chi_1(\gamma)$: calculated, NLL BFKL eigenvalues (Lipatov, Fadin, Camici, Ciafaloni)
- $\chi^{(0)}$ and $\chi_1(0)$: ambiguity of resummation at higher order than NLL, different ways to remove these singularities, not imposed by BFKL equation, Salam, Ciafaloni, Colferai
- BFKL NLL full calculation available (no saddle point approximation): resolution of implicit equation performed by numerical methods

BFKL NLL calculation

- Full BFKL NLL calculation used for the BFKL kernel, available in S3 and S4 resummation schemes to remove the spurious singularities (modulo the impact factors taken at LL)
- Equation:

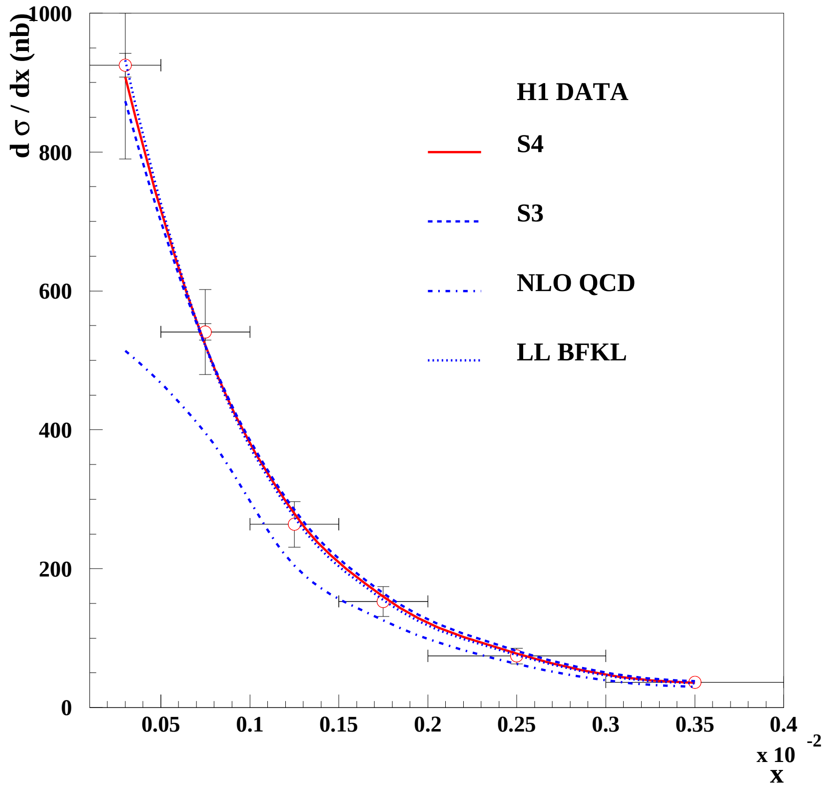
$$\frac{d\sigma_{T,L}^{\gamma^* p \to JX}}{dx_J dk_T^2} = \frac{\alpha_s(k_T^2)\alpha_s(Q^2)}{k_T^2 Q^2} \; f_{eff}(x_J, k_T^2)$$

$$\int \frac{d\gamma}{2i\pi} \left(\frac{Q^2}{k_T^2}\right)^{\gamma} \phi_{T,L}^{\gamma}(\gamma) \; e^{\bar{\alpha}(k_T Q)\chi_{eff}[\gamma, \bar{\alpha}(k_T Q)]Y}$$

- Implicit equation: $\chi_{eff}(\gamma, \alpha) = \chi_{NLL}(\gamma, \alpha, \chi_{eff}(\gamma, \alpha))$ solved numerically

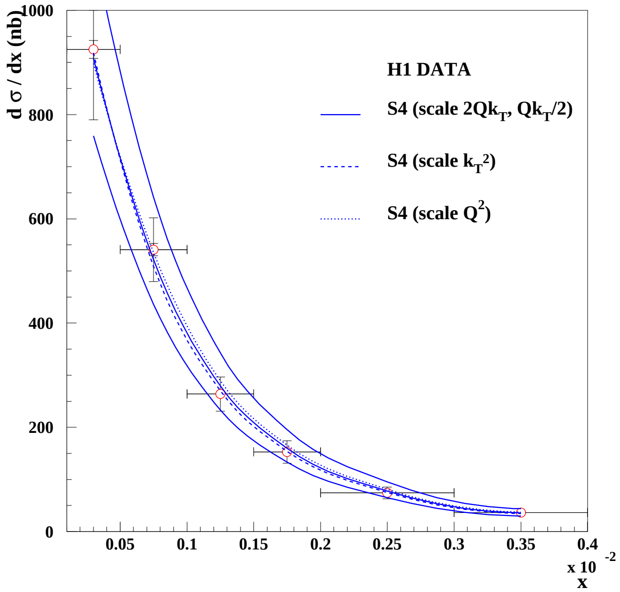
Fit results

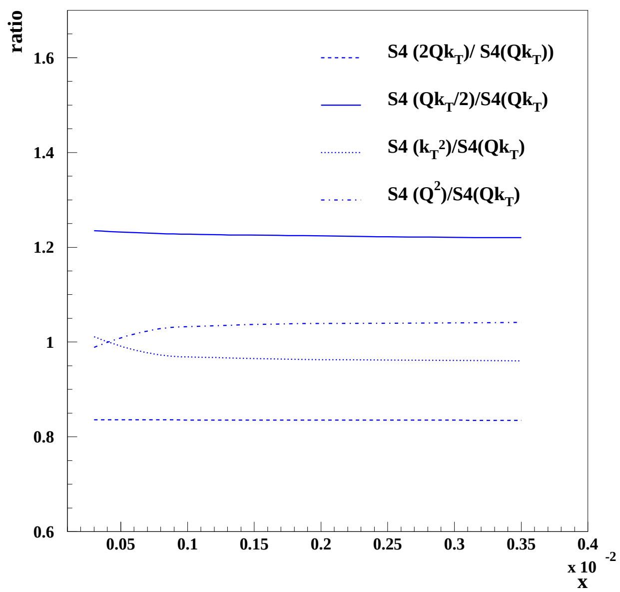
- Fit of NLL BFKL calculation to the H1 $d\sigma/dx$ data: one single parameter, normalisation of cross section
- χ^2 for S3: 29.5 (1.15), S4: 10.0 (0.48)
- Good description of H1 data using BFKL LL and BFKL NLL formalism, DGLAP-NLO fails to describe the data
- BFKL higher corrections found to be small (We are in the BFKL-LL region, cut on $0.5 < k_T^2/Q^2 < 5$)

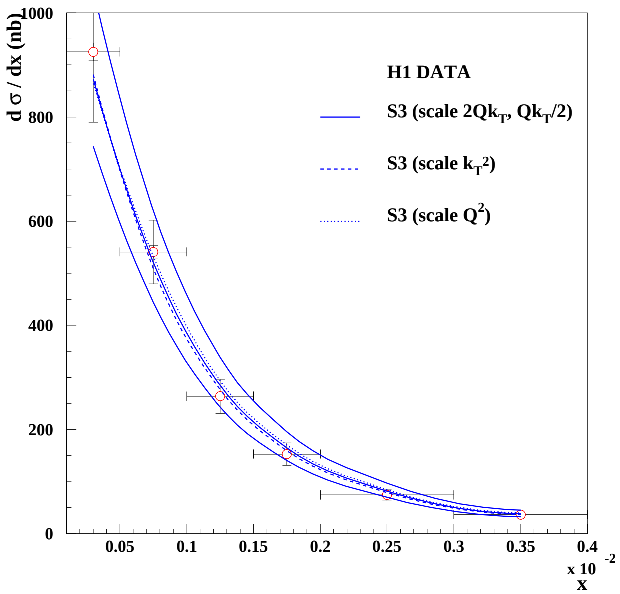


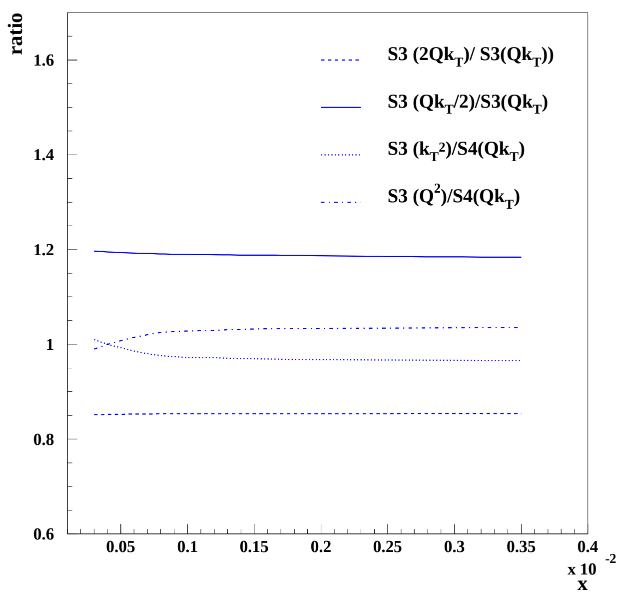
Scale variation - Resummation model variation

- Scale dependence: variation of the scale between $2Qk_T$, $Qk_T/2$, Q^2, k_T^2: $\sim 20\%$ difference
- Resummation scheme dependence: Use S3 and S4, S4 is slightly better



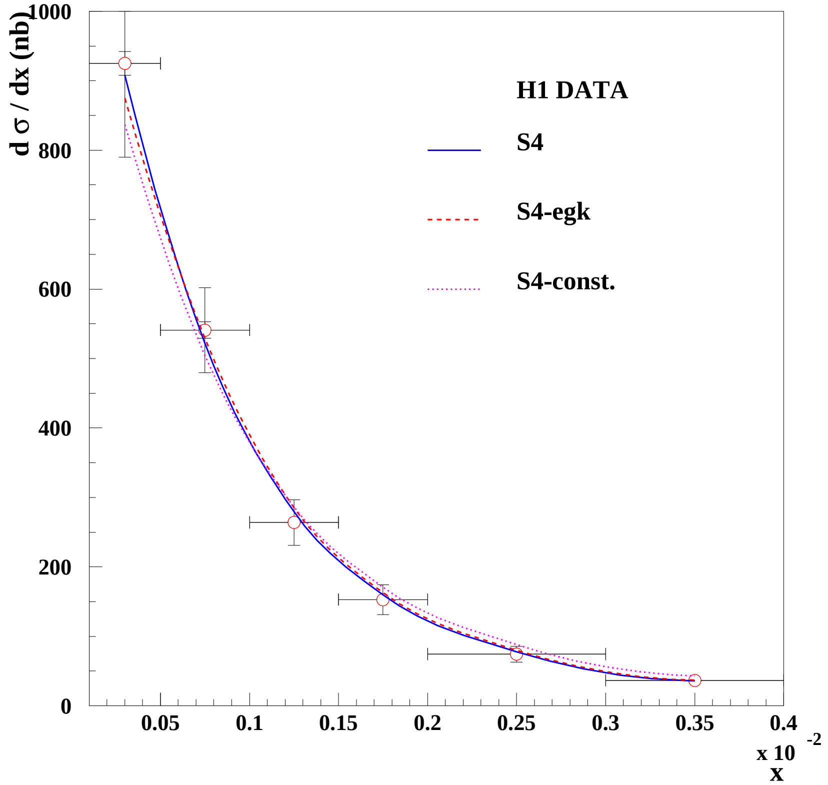


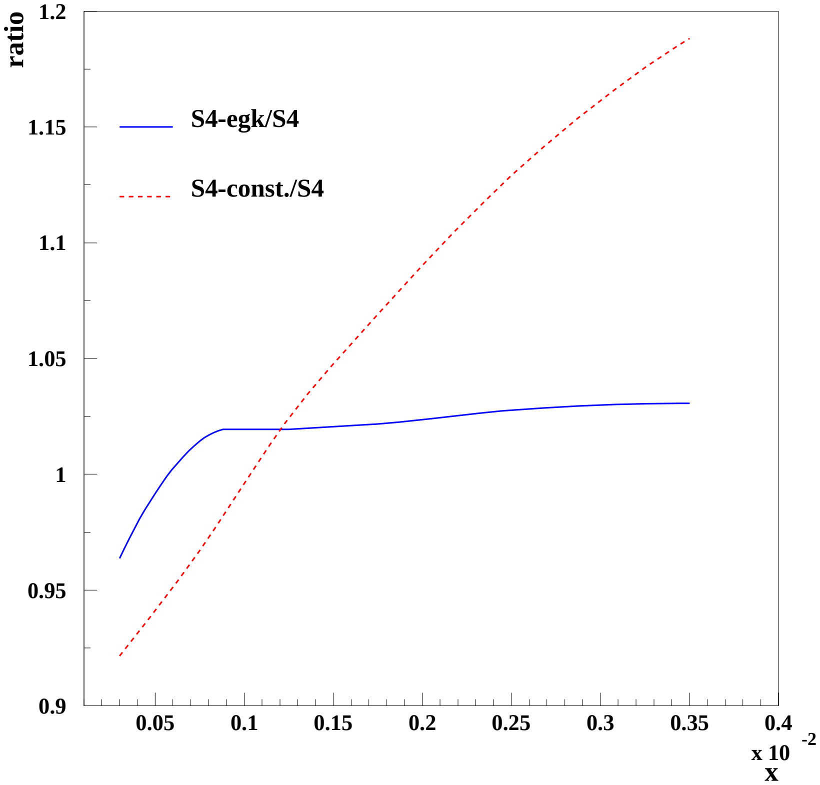




Dependence on impact factor

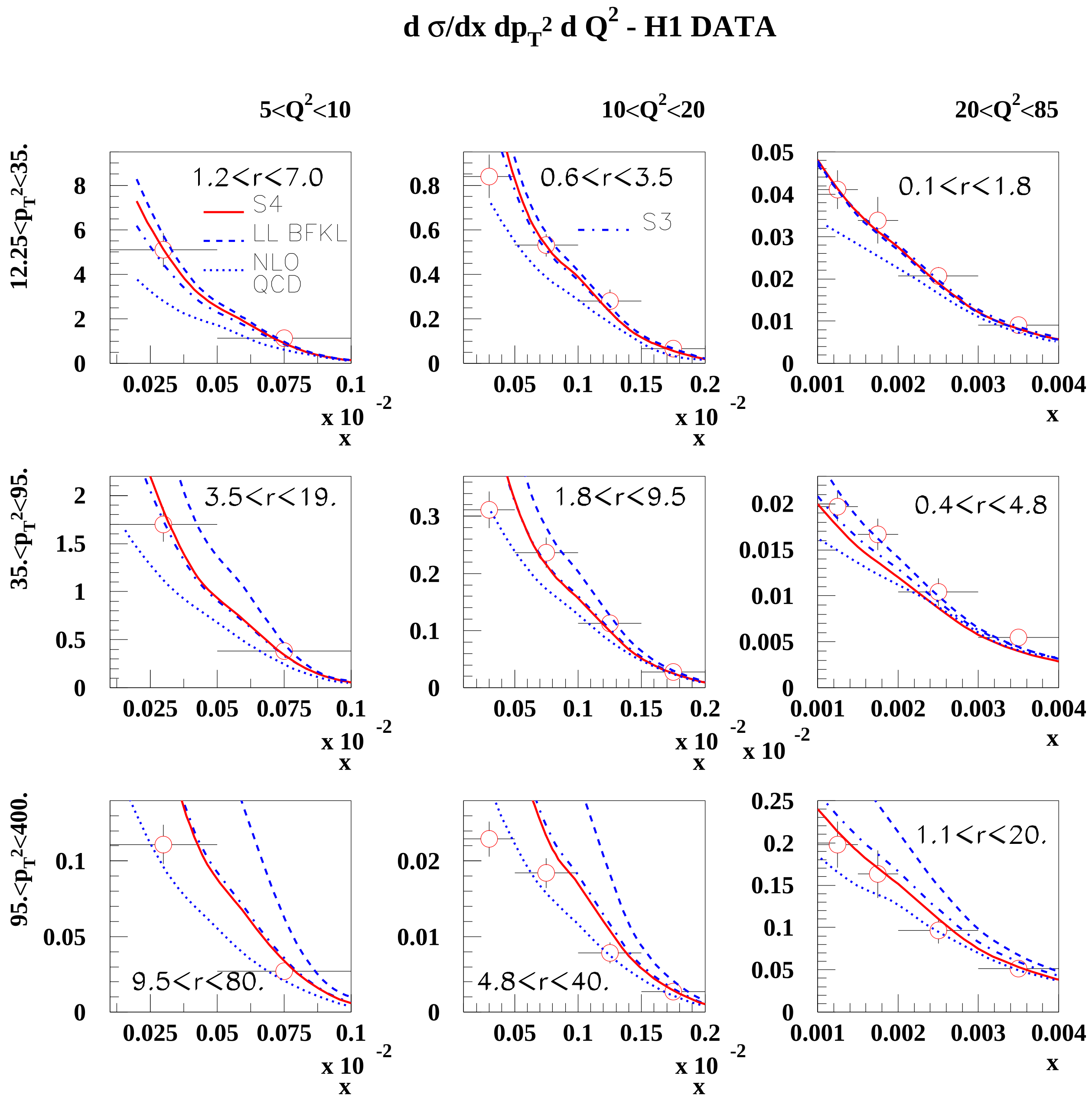
- Impact factor not yet fully known at NLL
- Variation of impact factor, 3 studies: $h_T,\ h_L(\gamma)$ at LO; $h_T,\ h_L(1/2)$ constant; implement the higher-order corrections in the impact factor due to exact gluon kinematics in the $\gamma^* \to q\bar{q}$ transition (see C.D. White, R. Peschanski, R.S. Thorne, Phys. Lett. B 639 (2006) 652)





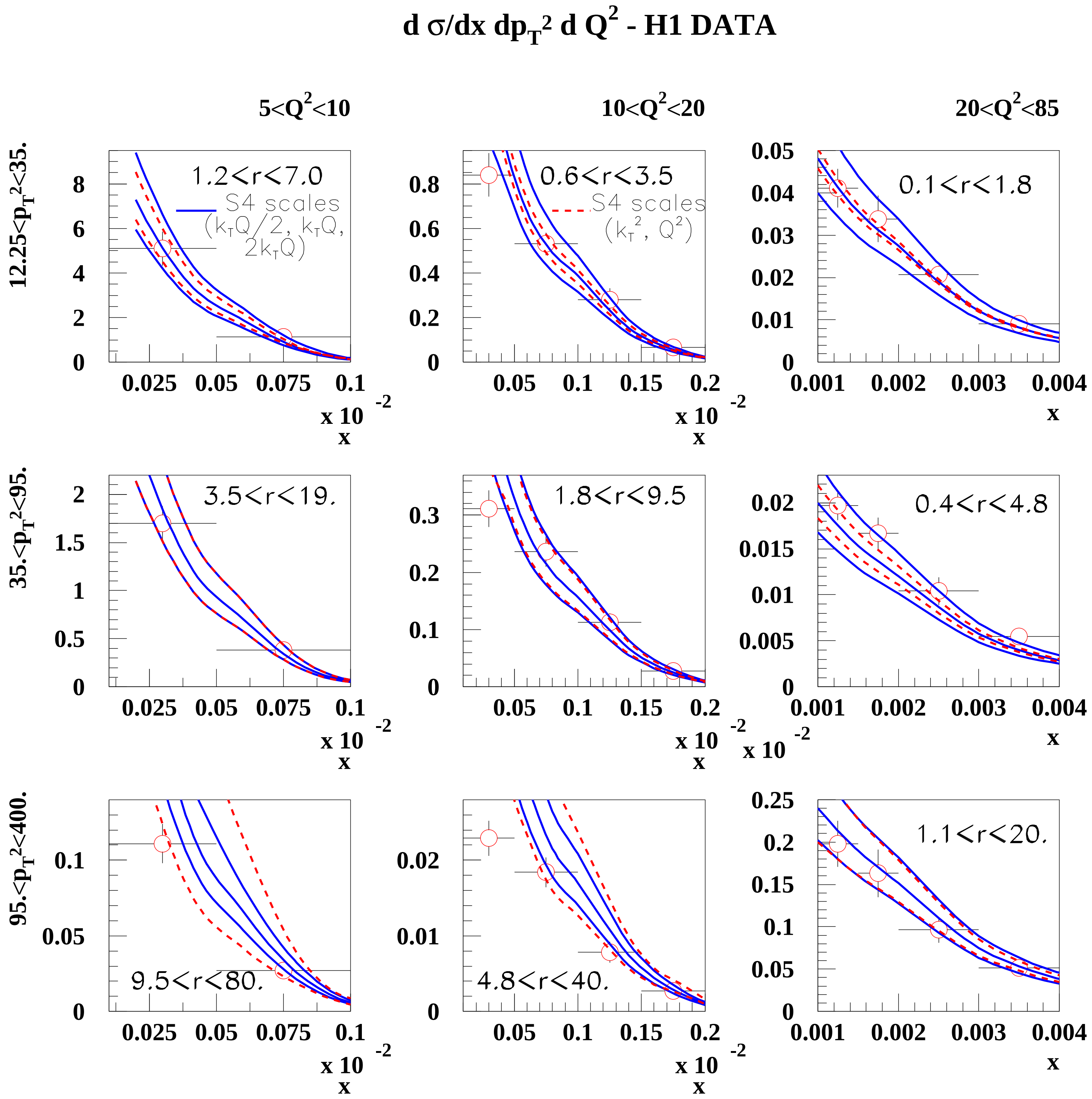
Comparison with H1 triple differential data

- Triple differential cross section: Keep the normalisation from the fit to $d\sigma/dx$ and predict the triple differential cross section
- Good description over the full range



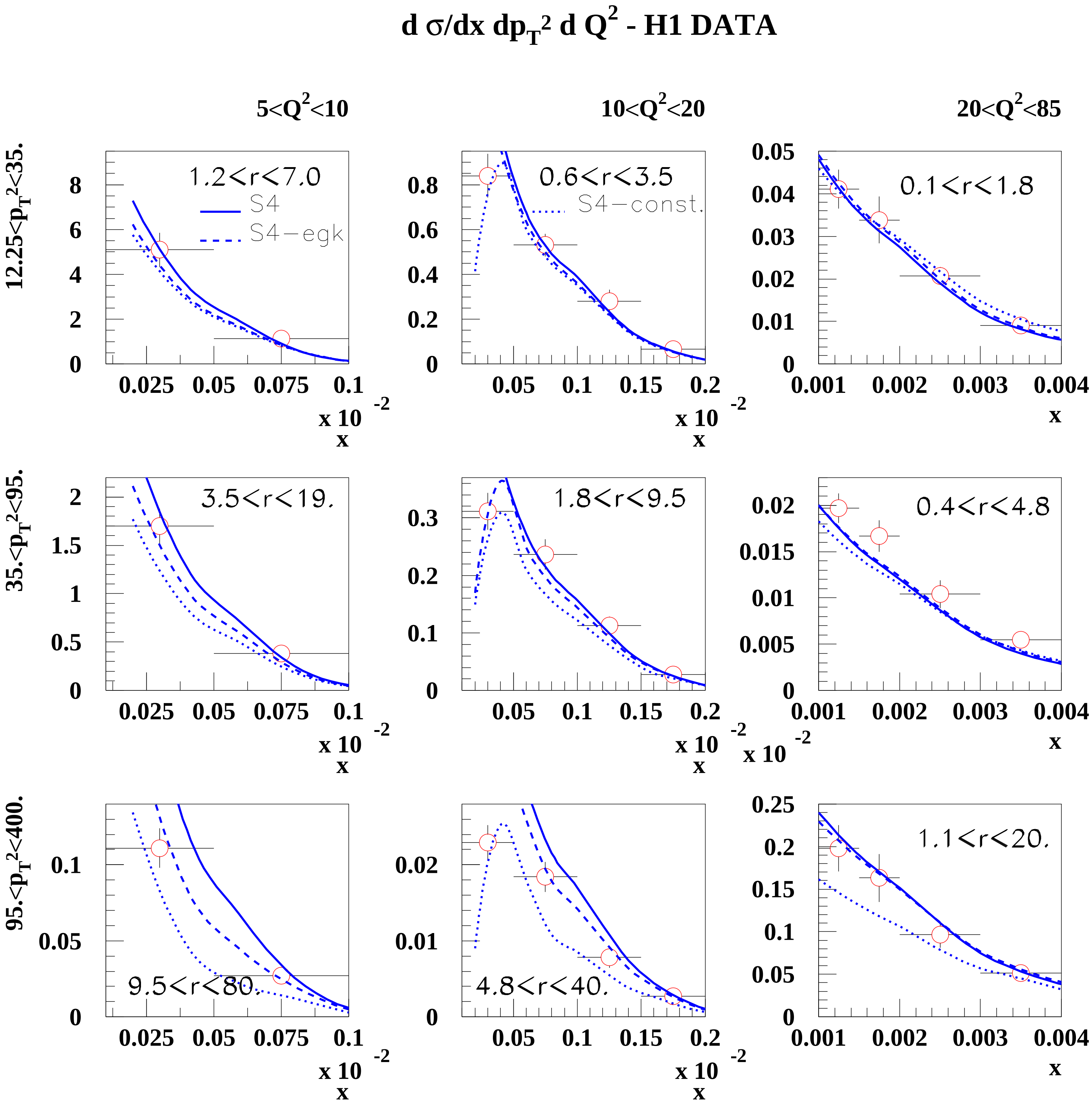
Comparison with H1 triple differential data

Study of scale variation: 20% at low p_T^2, $> 70\%$ at higher p_T^2 as for DGLAP



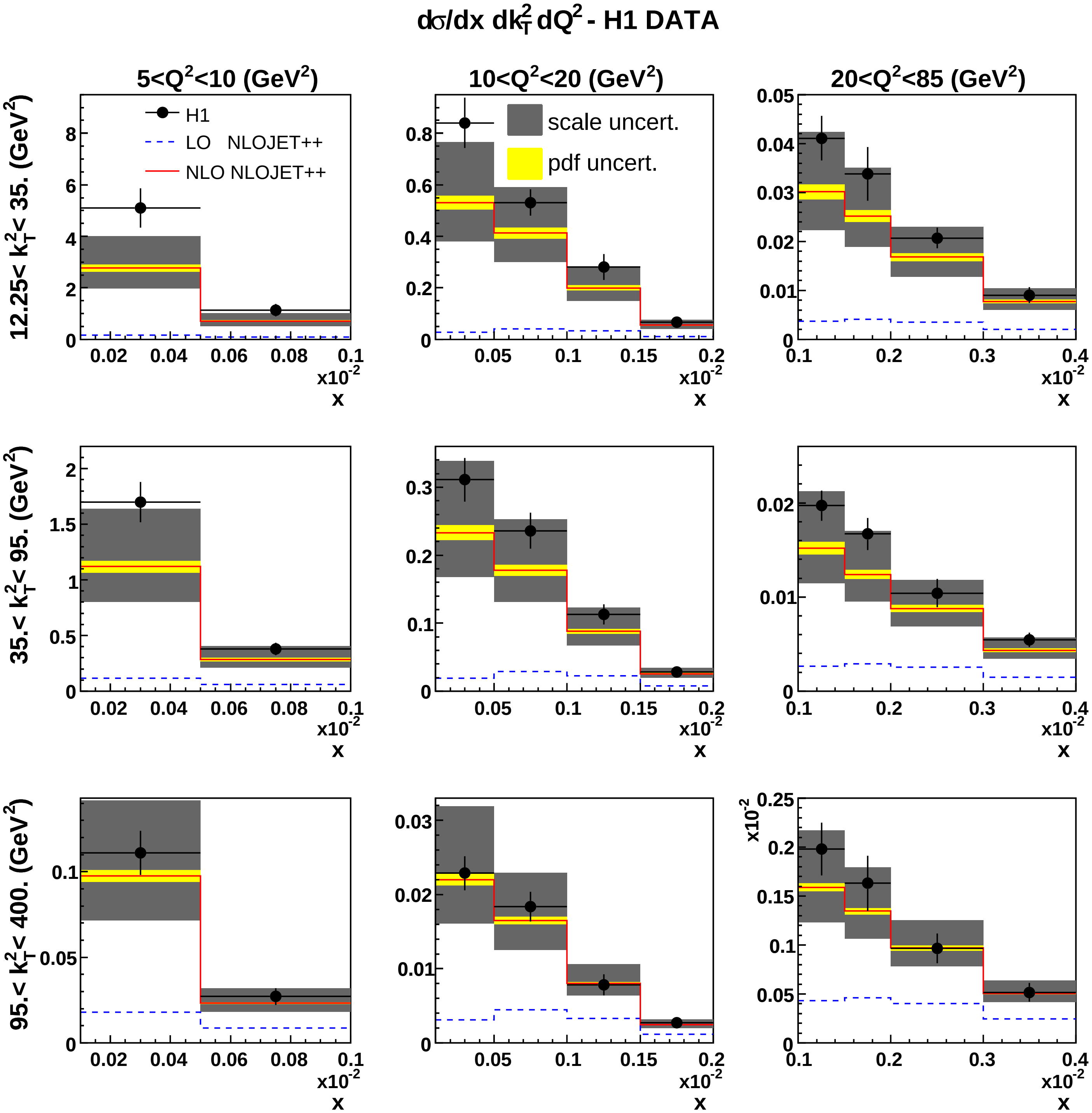
Comparison with H1 triple differential data

Study of dependence on impact factor



Comparison with H1 triple differential data

DGLAP study: large scale dependence

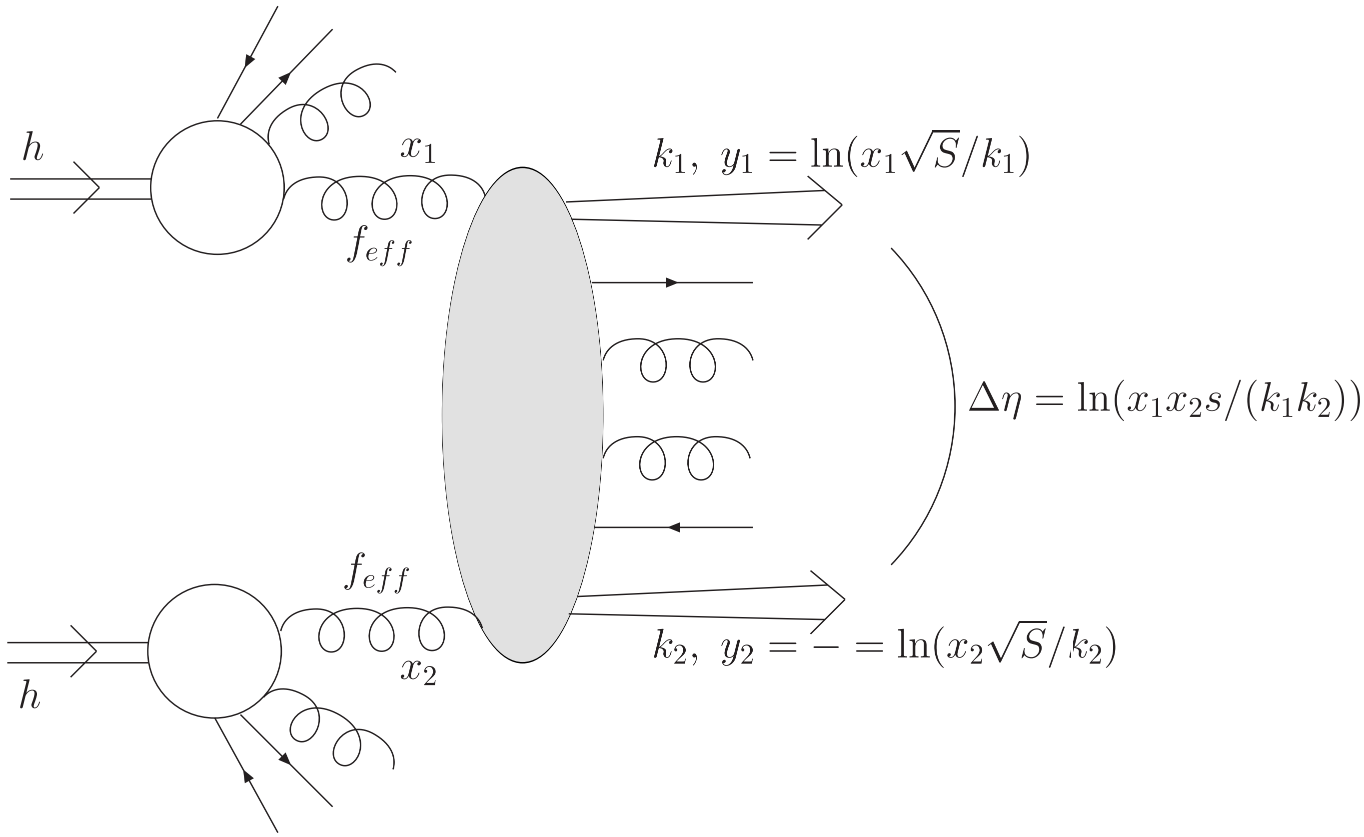


Remarks about BFKL NLL calculations

- 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 LL describes the H1 data when $r = k_T^2/Q^2$ is close to 1 and BFKL LL fails outside the region $r \sim 1$ specially at high Q^2
- Nice description of data on the full range using BFKL-NLL formalism (S4 slightly favoured)
- 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 α_S ($2Qk_T$, $Qk_T/2$, Q^2, k_T^2)
- Side remark: Comparison with saddle point approximation: not a bad approximation, leads to a worse description though

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

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

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

- Azimuthal correlation of dijets:

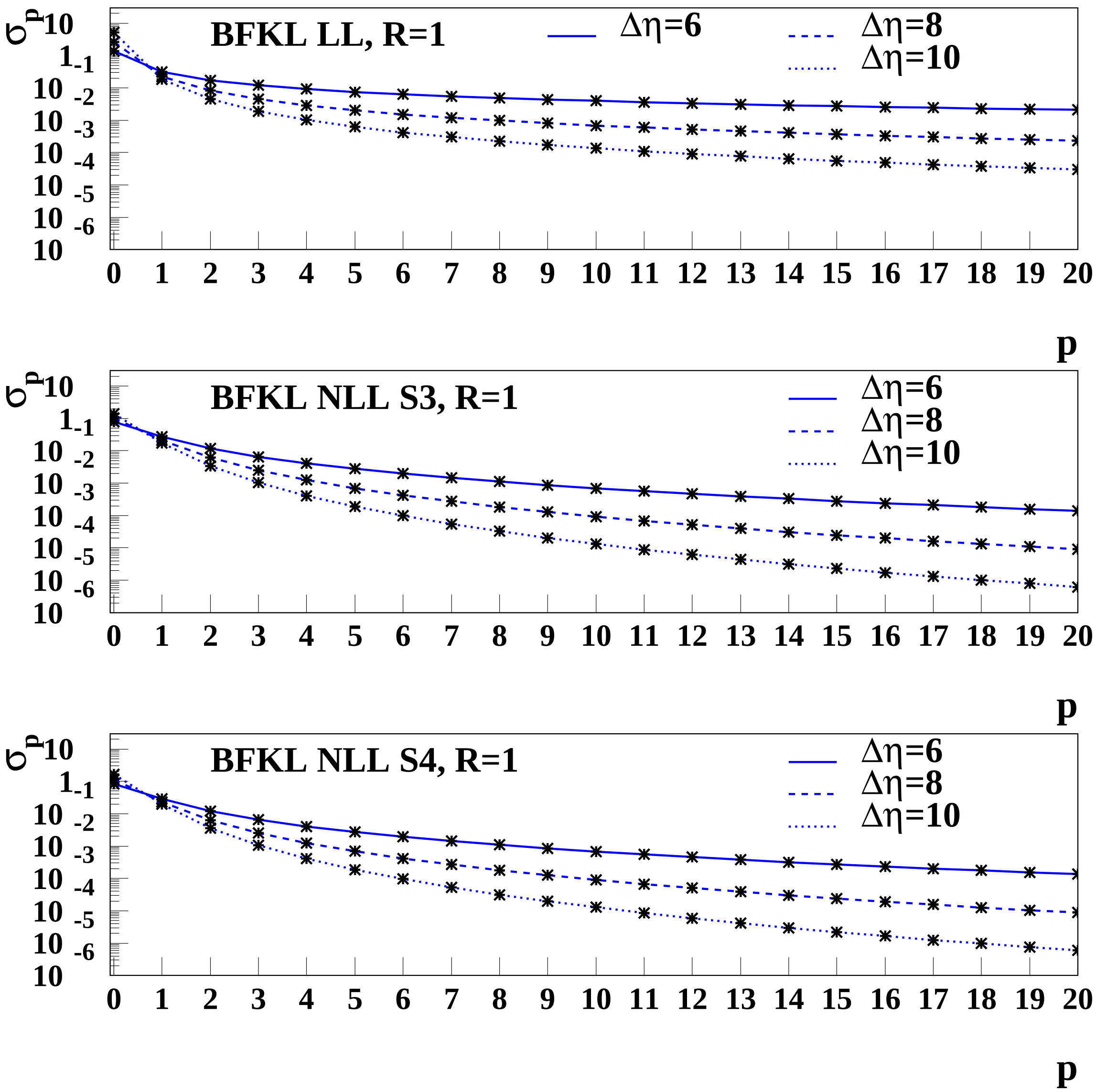
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Big/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

where

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

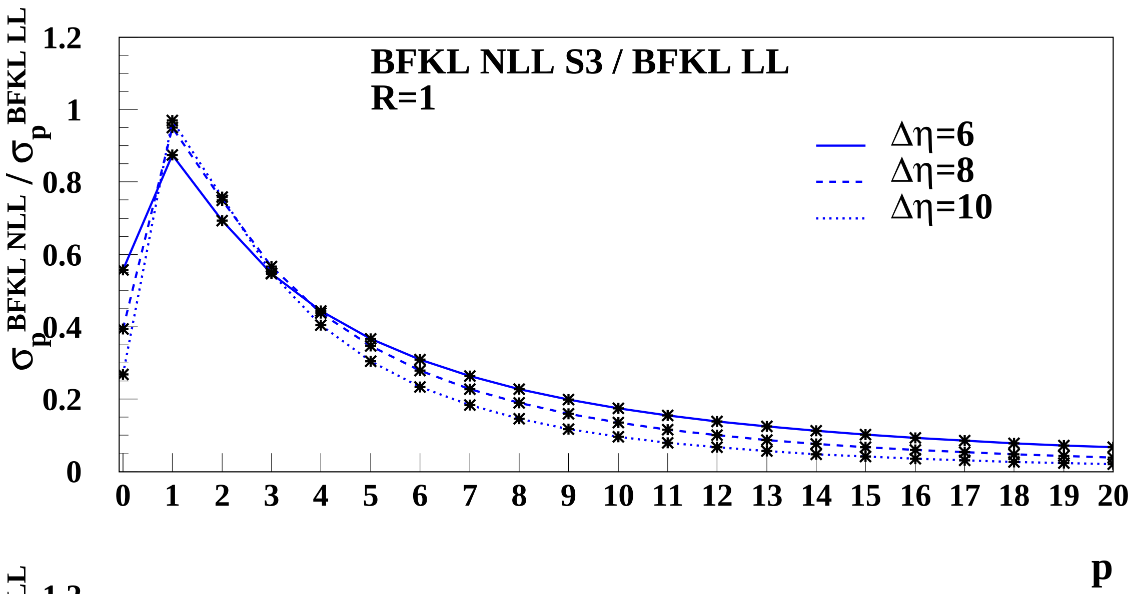
Different conformal spin components

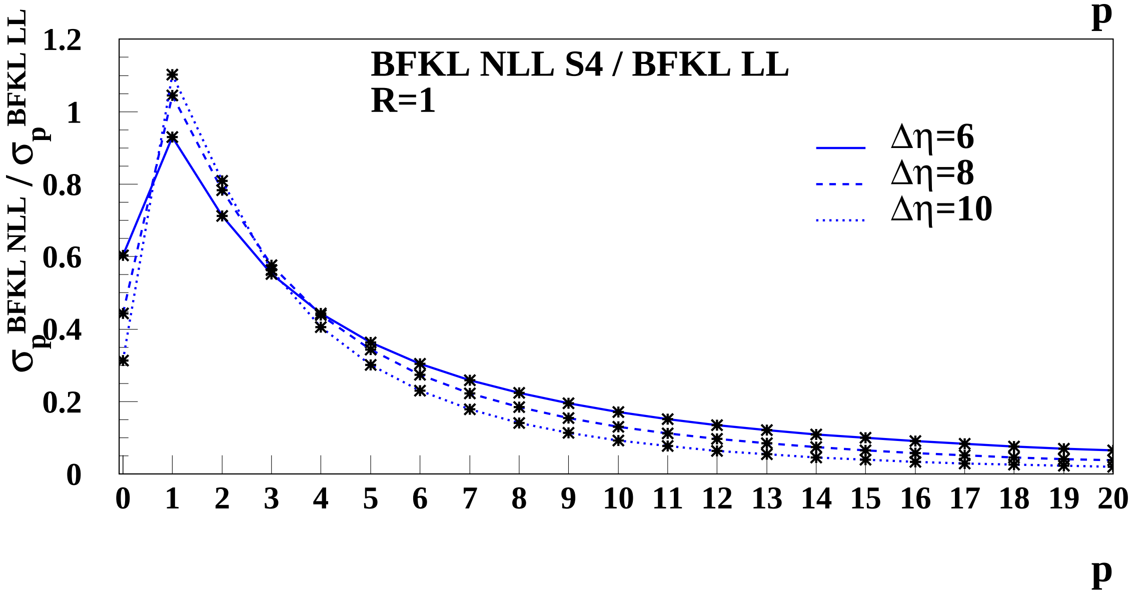
Values of σ_i entering into the $\Delta\Phi$ spectrum for BFKL NLL for different intervals in rapidity $\longrightarrow$ Resummation needed



Different conformal spin components

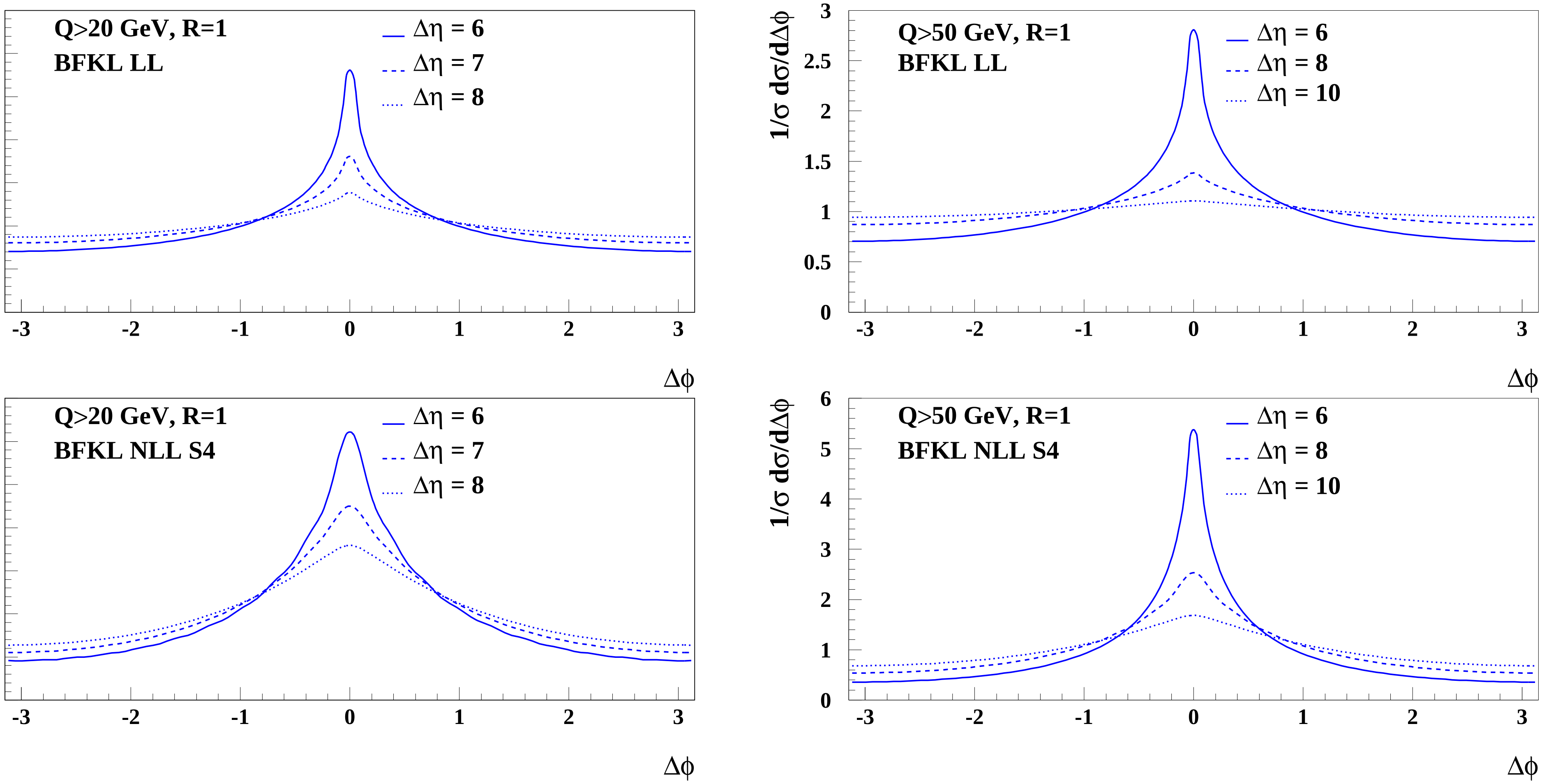
- Ratio of values of σ_i entering into the $\Delta\Phi$ spectrum between BFKL NLL and BFKL LL for different intervals in rapidity
- BFKL NLL order effect decrease the cross section except for the $p = 1$ component at large $\Delta\eta$





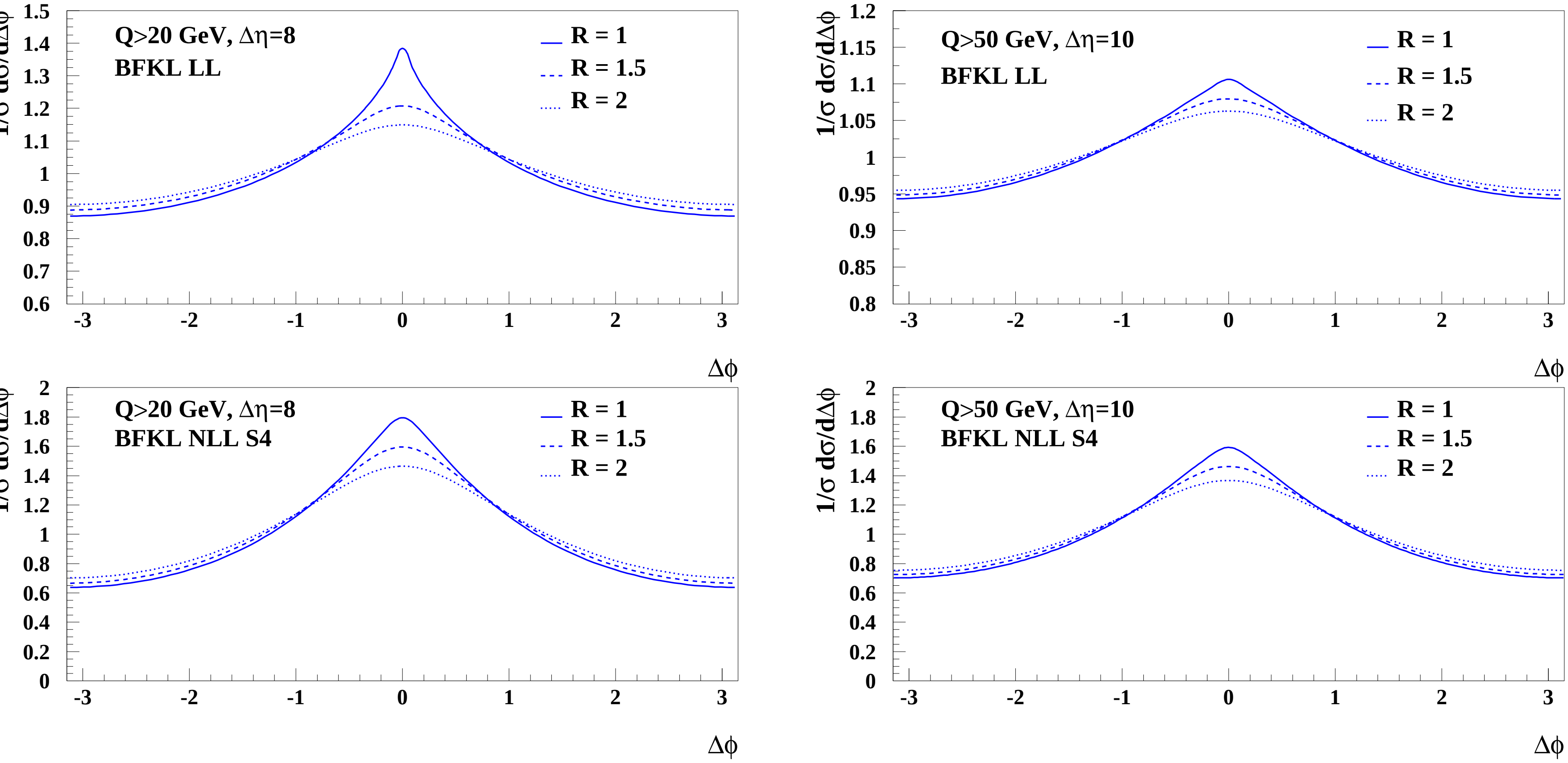
Mueller Navelet jets: $\Delta\Phi$ dependence

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



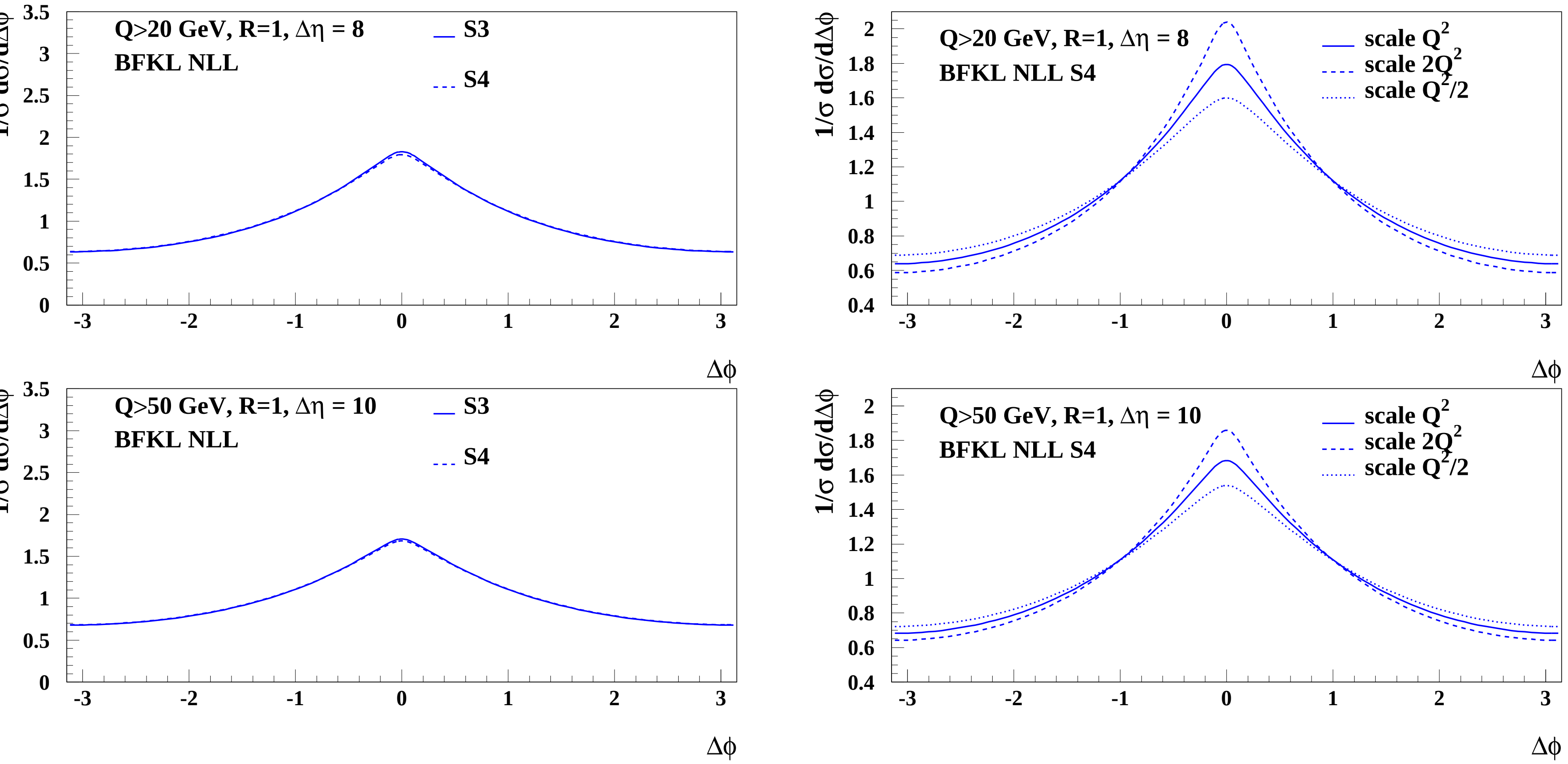
Mueller Navelet jets: R dependence

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



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, $2Q^2$



Effect of energy conservation on BFKL equation

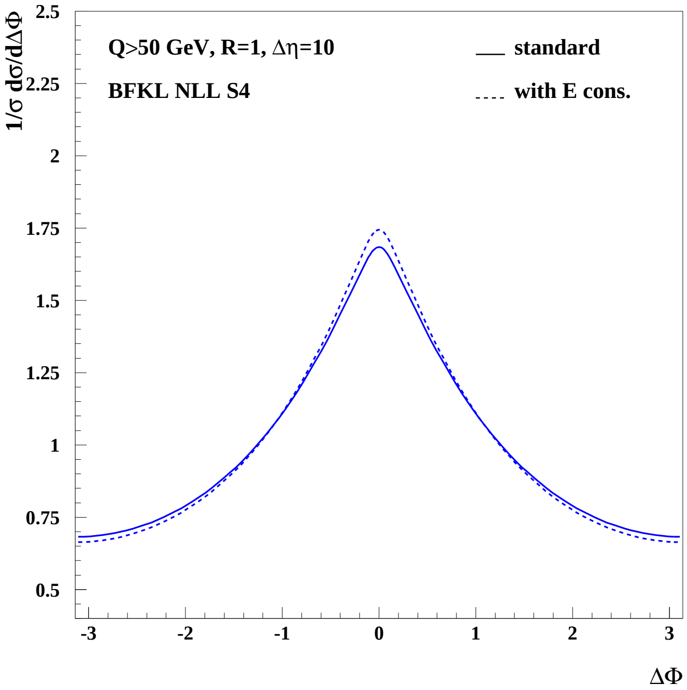
- BFKL cross section lacks energy-momentum conservation since these effects are higher order corrections
- Following Del Duca-Schmidt, we substitute $\Delta\eta$ by an effective rapidity interval y_{eff}

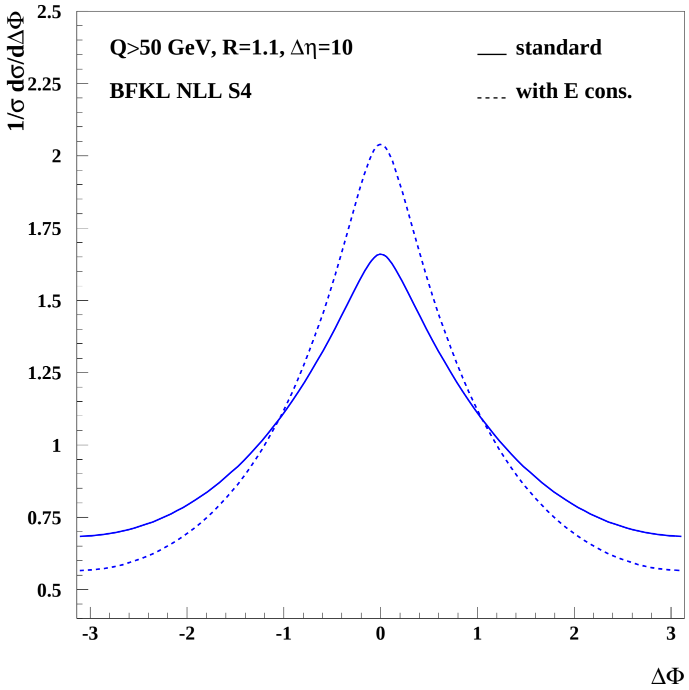
$$y_{eff} = \Delta\eta \left(\int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right)^{-1} \int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta\eta dy dQ dR d\Delta\Phi}$$

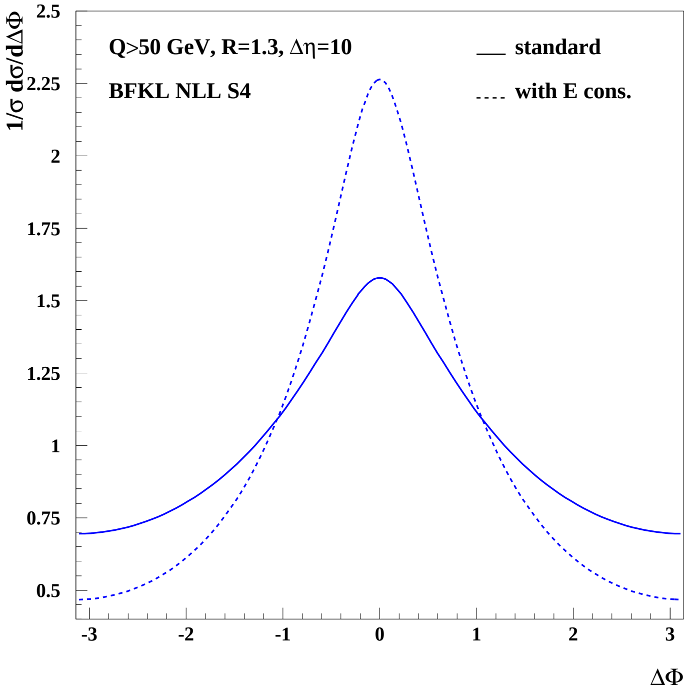
  where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \rightarrow 3$ contribution to the $hh \rightarrow JXJ$ cross-section at order α_s^3, and $d\sigma^{LL-BFKL}$ is the LL-BFKL result

- To compute $d\sigma^{O(\alpha_s^3)}$, we use the standard jet cone size $R_{cut} = 0.5$ when integrating over the third particle's momentum

Effect of energy conservation on BFKL equation

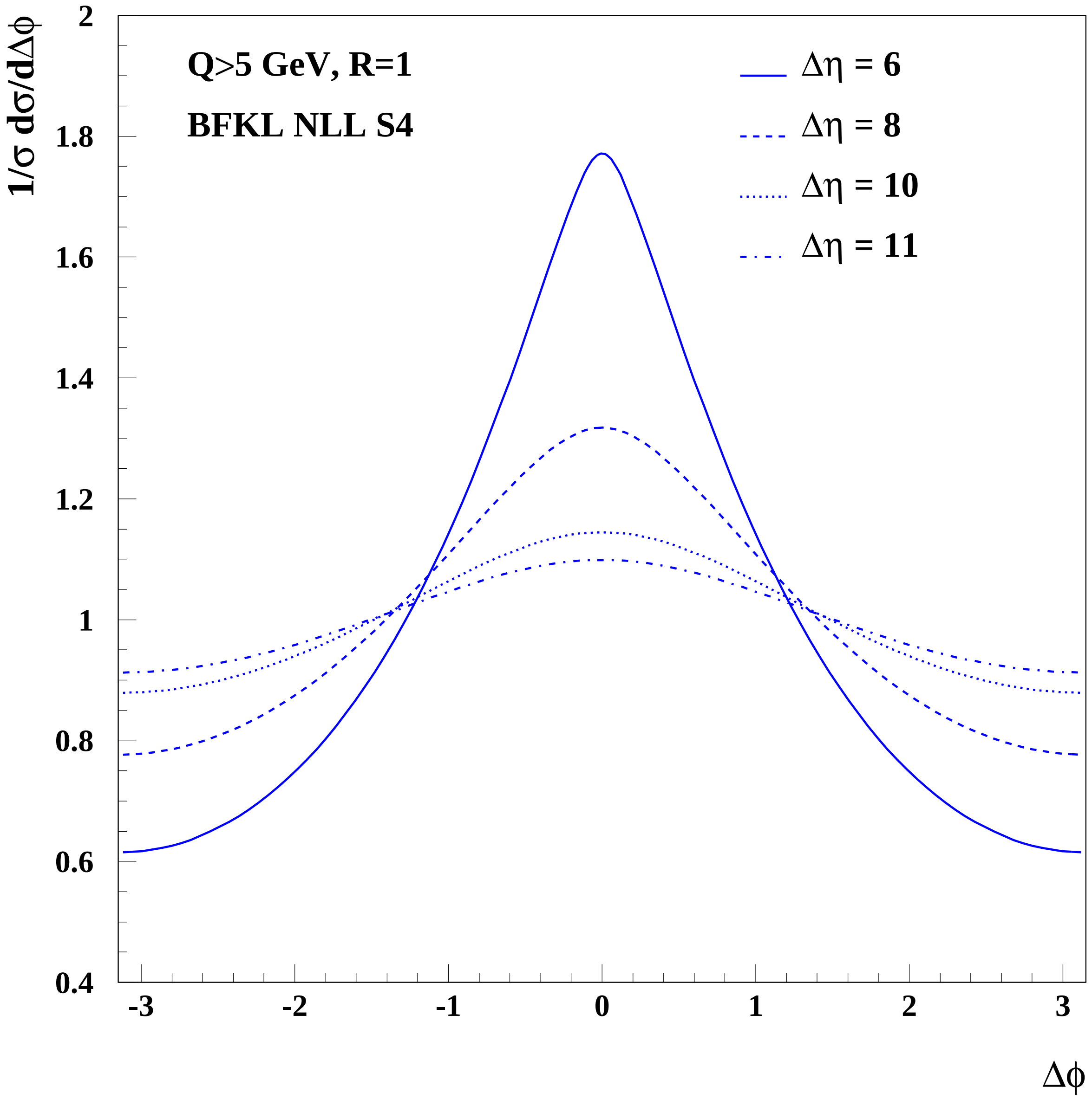






Mueller Navelet jets in CDF

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



Conclusion

- DGLAP NLO fails to describe forward jet data
- BFKL NLL description of H1 and ZEUS forward jet data: very good description using full BFKL-NLL kernel and LO impact factors
- Study scale dependence and also dependence on assumption of impact factor: typically $\sim 20\%$ uncertainty, larger at high p_T
- Mueller Navelet jets: Full calculation available using S3 and S4 schemes
- Mueller Navelet jets $\Delta\Phi$ dependence: weak dependence even after NLL corrections, little sensitivity to chosen scale
- Effet of energy conservation in BFKL equation: negligible if R close to 1, large effect if R further away from 1
- 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 η and small p_T for jets