

Probing the BFKL dynamics at hadronic colliders

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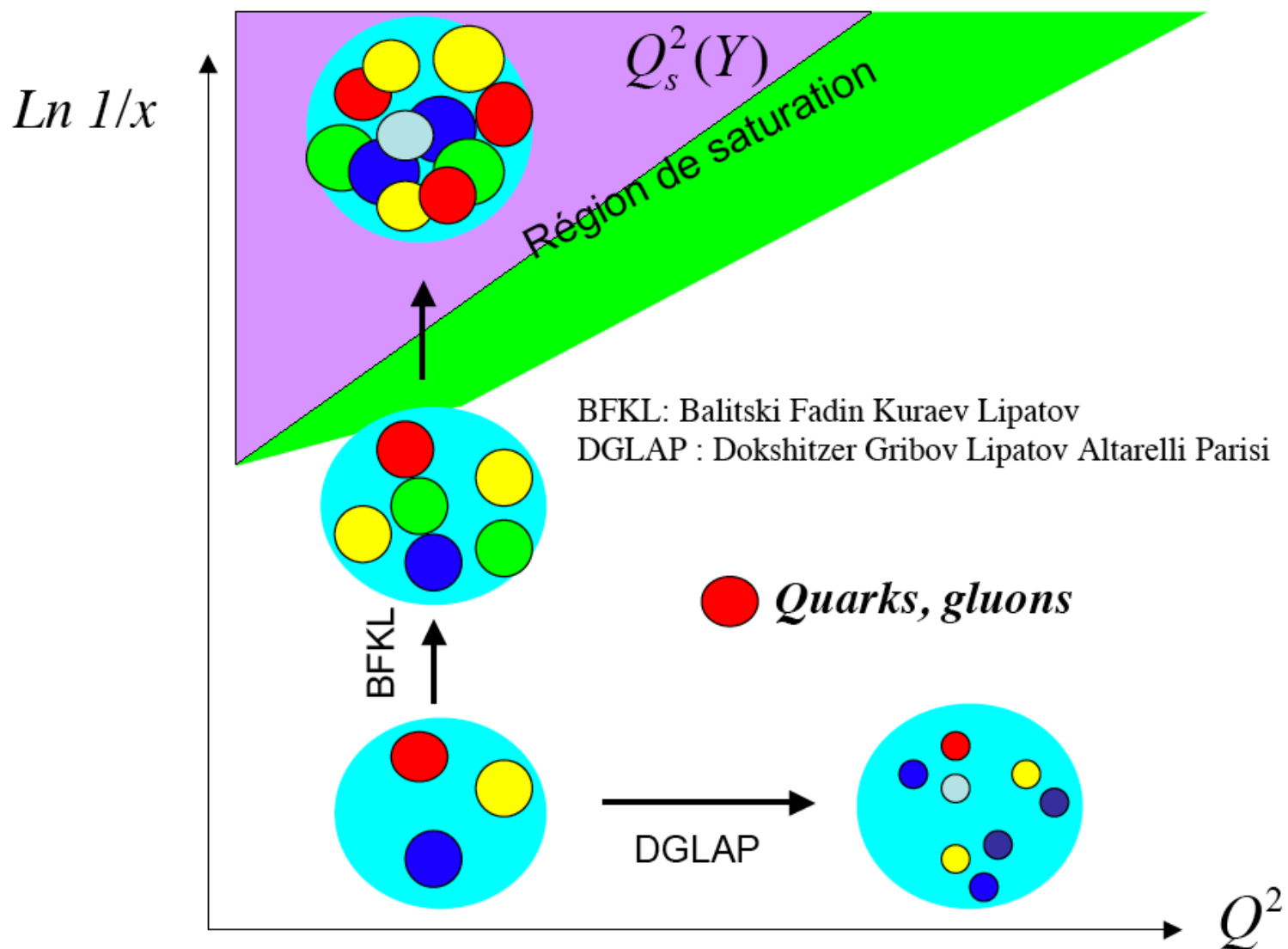
- Forward jets at HERA (short reminder)
- Mueller Navelet jet
- Jet veto (atlas measurement)
- Jet gap jet at Tevatron, LHC
- Jet gap jet in diffraction at the LHC

Work done in collaboration with D. Werder, O. Kepka, C. Marquet, R. Peschanski, M. Trzebinski, Y. Hatta, G. Soyez, T. Ueda, R. Zlebcik

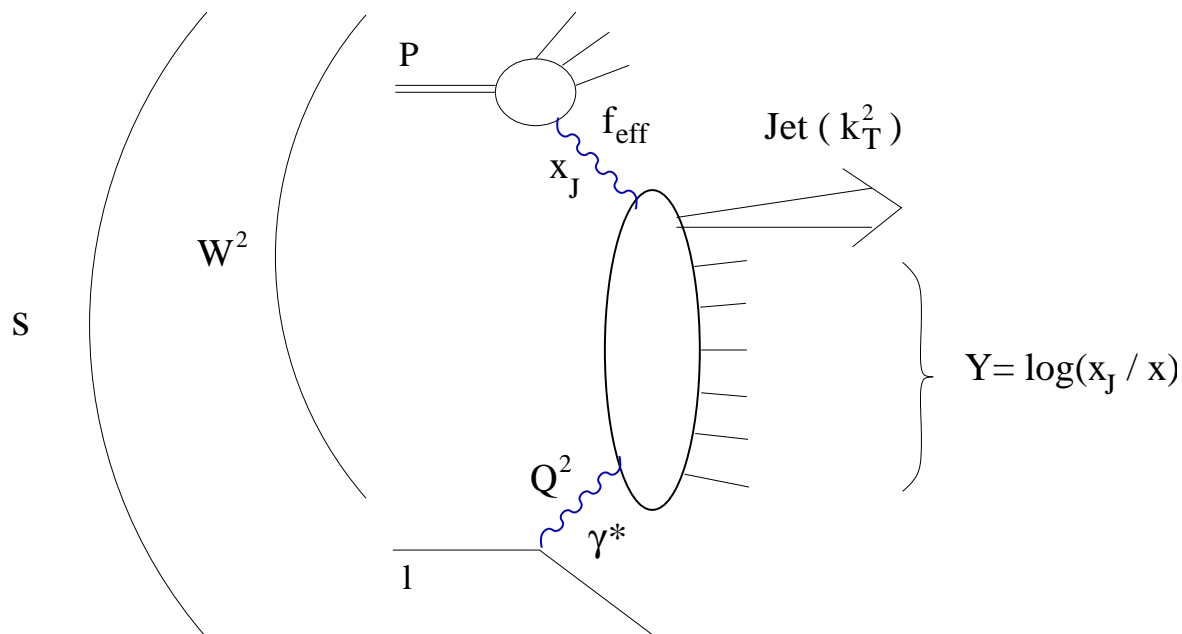
- Forward jets: Nucl. Phys. B 739 (2006) 131; Phys. Lett. B 655 (2007) 236; Eur. Phys. J. C55 (2008) 259;
- Mueller Navelet jets: Phys. Rev. D79 (2009) 034028;
- Jet Gap Jet: Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036; Phys. Rev. D 87 (2013) 034010
- Jet veto: Phys.Rev. D87 (2013) 054016

Looking for BFKL/saturation effects

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



Forward jet measurement at HERA



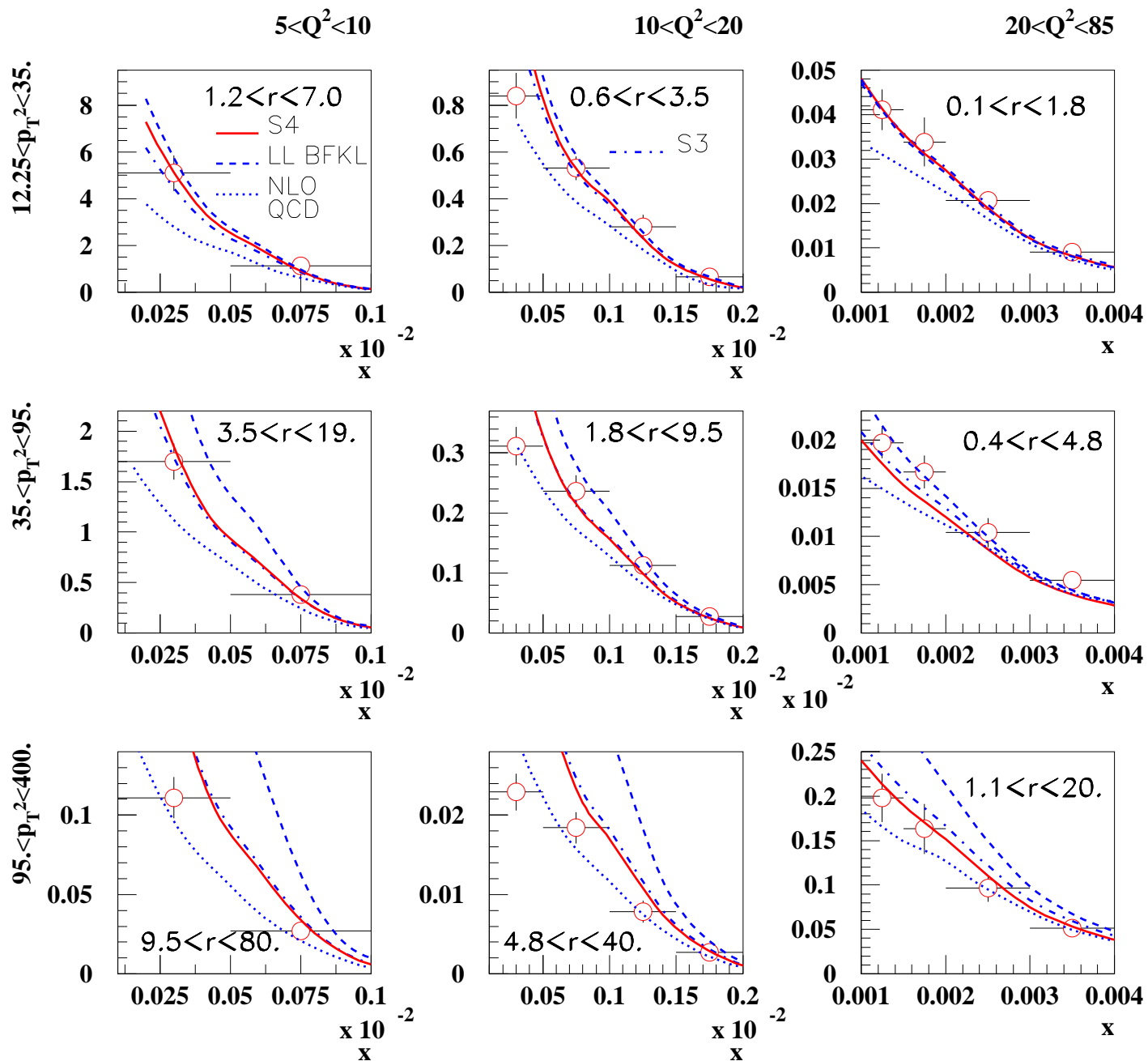
- Full BFKL NLL calculation used for the BFKL kernel, available in S3 and S4 resummation schemes to remove the spurious singularities (modulo the impact factors taken at LL)
- Equation:

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow JX}}{dx_J dk_T^2} = \frac{\alpha_s(k_T^2)\alpha_s(Q^2)}{k_T^2 Q^2} f_{eff}(x_J, k_T^2) \int \frac{d\gamma}{2i\pi} \left(\frac{Q^2}{k_T^2}\right)^\gamma \phi_{T,L}^\gamma(\gamma) e^{\bar{\alpha}(k_T Q)\chi_{eff}[\gamma, \bar{\alpha}(k_T Q)]Y}$$

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

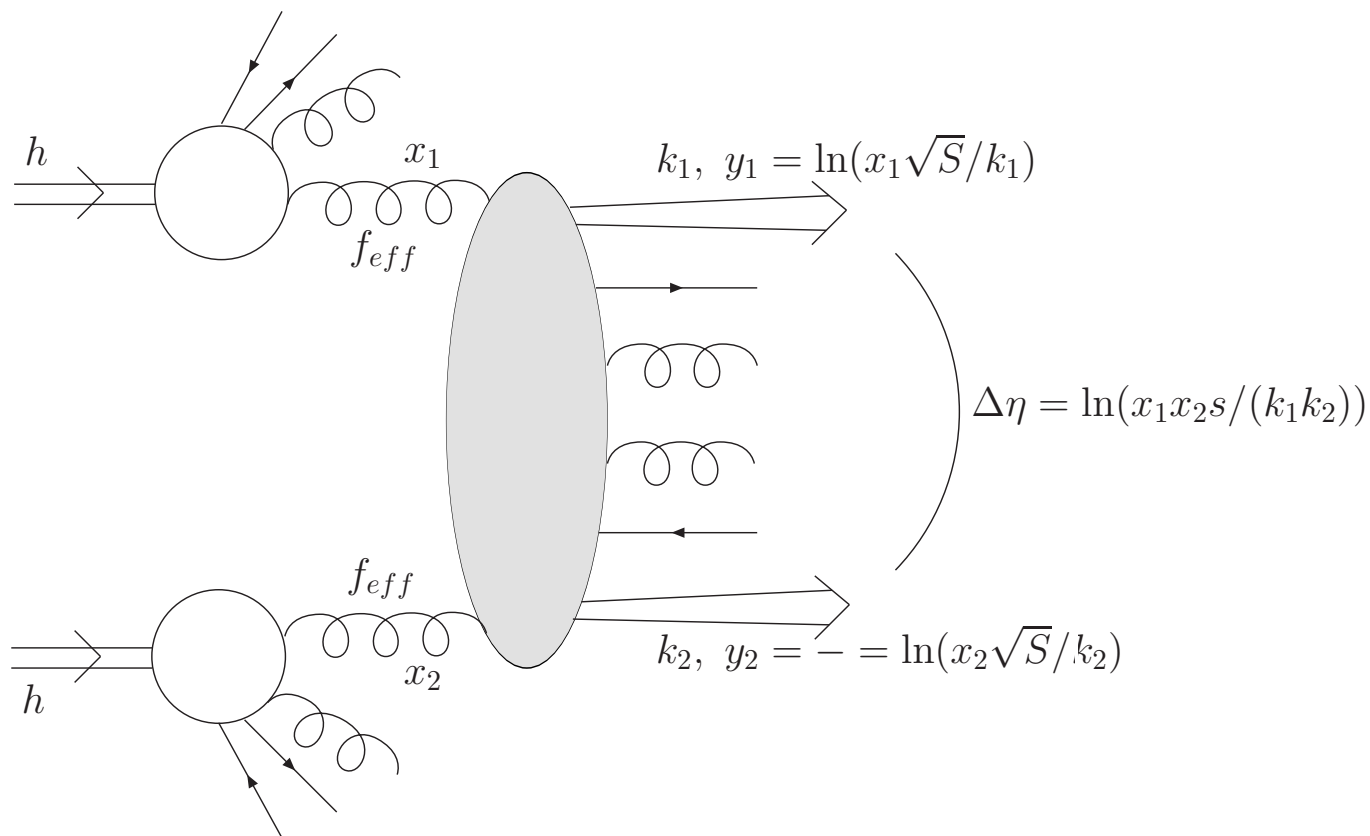
Comparison with H1 triple differential data

$d\sigma/dx dp_T^2 dQ^2$ - H1 DATA



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:
- See papers by Papa, Murdaca, Wallon, Szymanowski, Ducloue...

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:

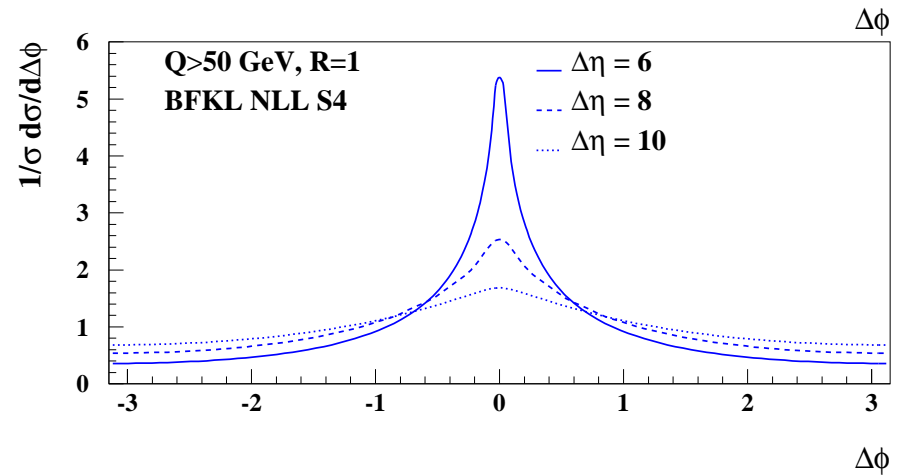
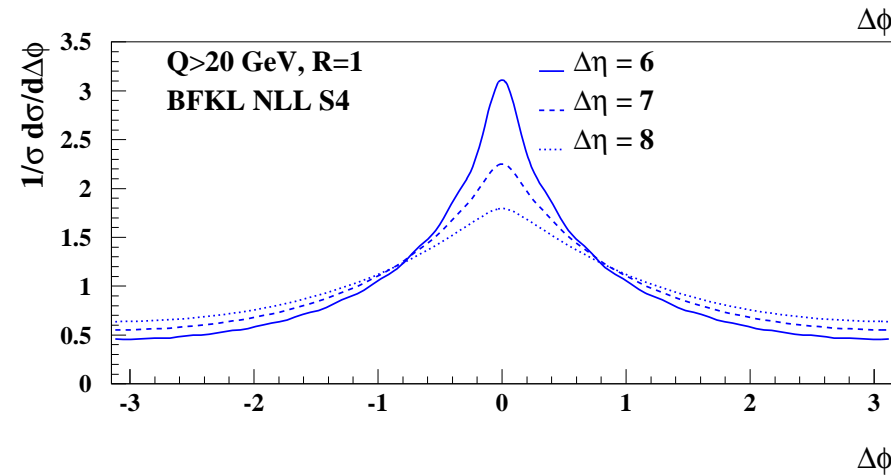
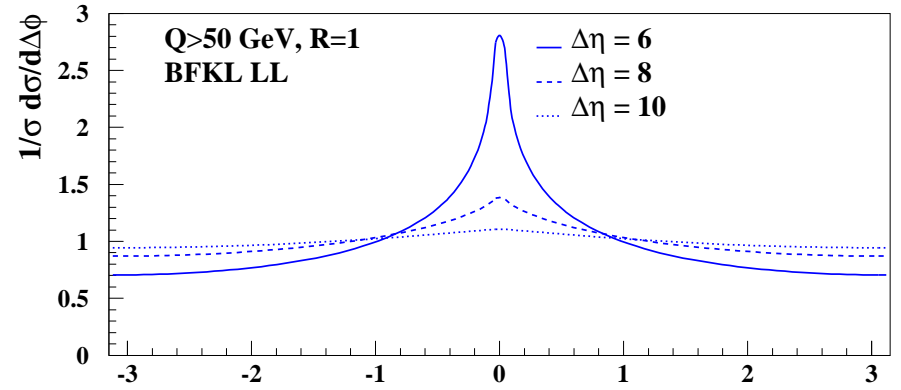
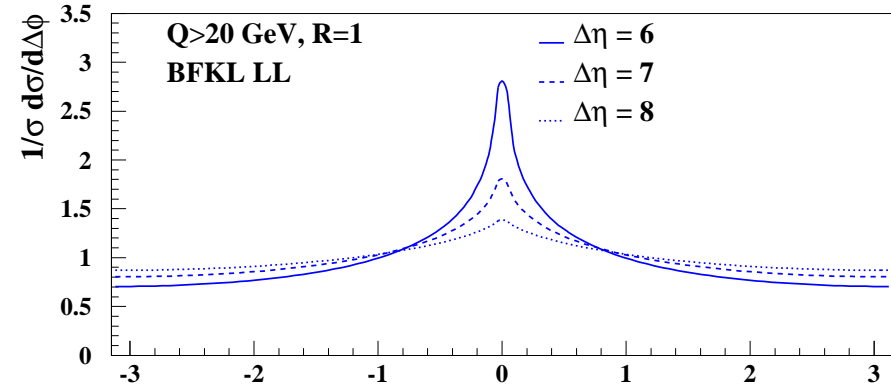
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \bigg/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

where

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

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 $\Delta\eta$, scale dependence: $\sim 20\%$



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}

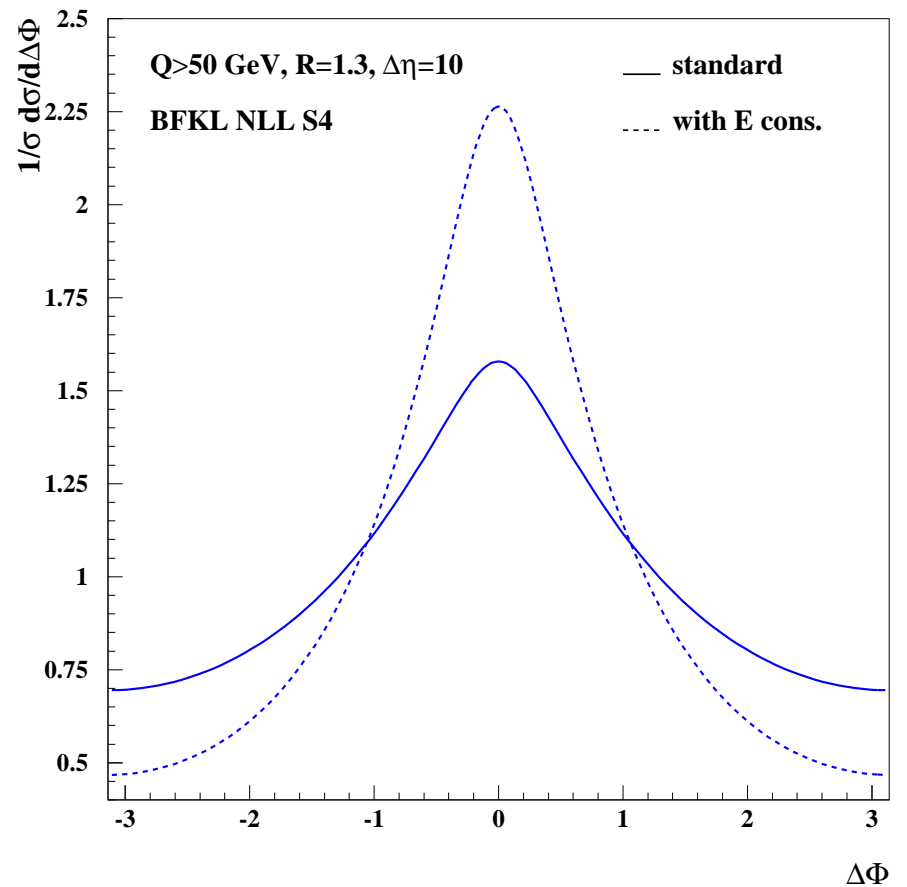
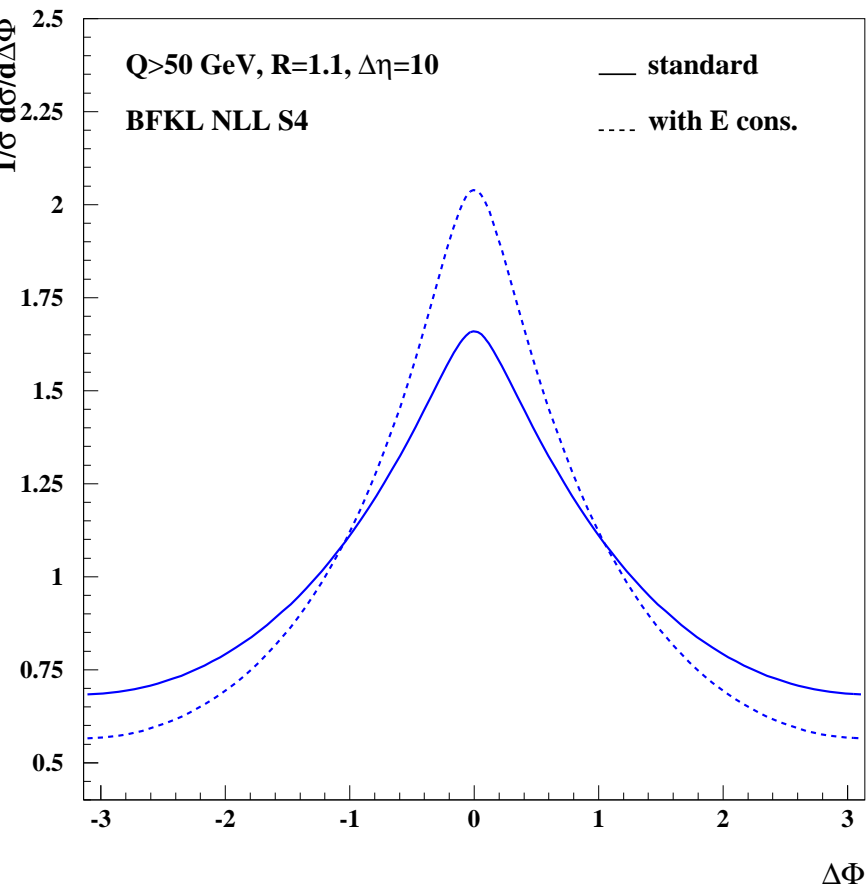
$$y_{eff} = \Delta\eta \left(\int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right) \left(\int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right)^{-1}$$

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

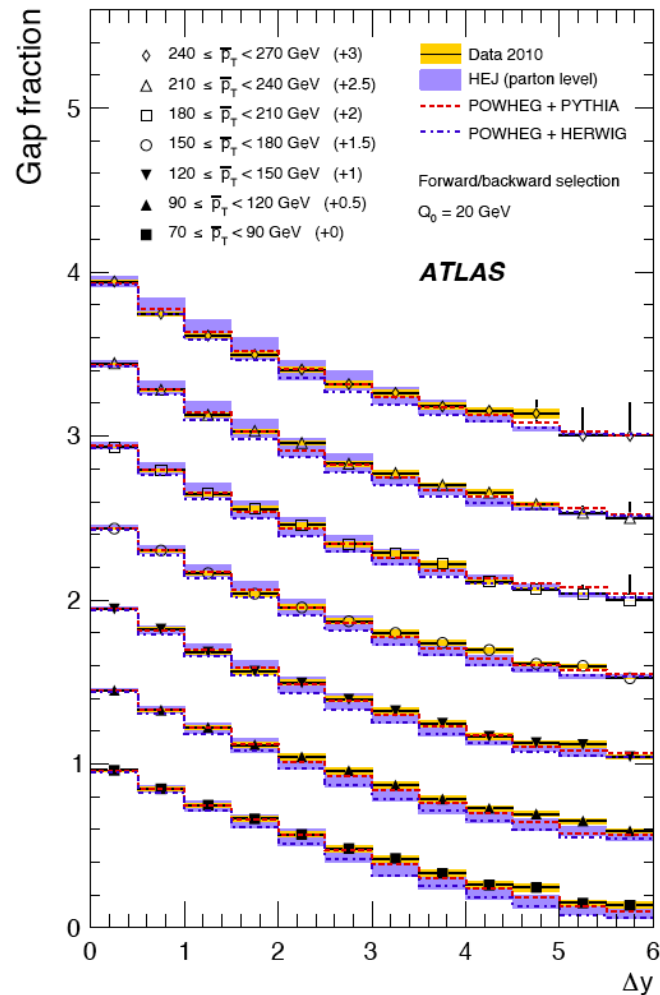
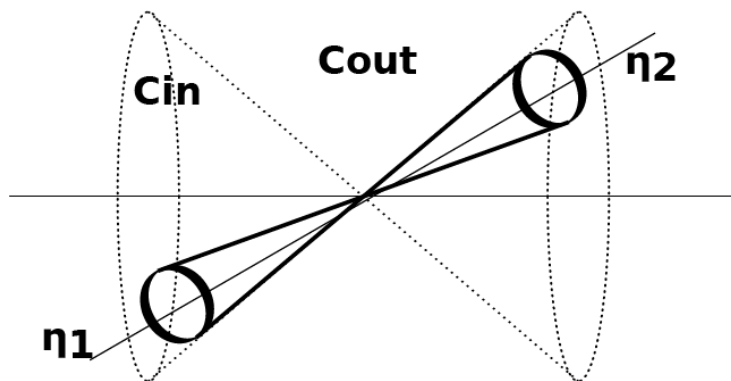
- To compute $d\sigma^{O(\alpha_s^3)}$, we use the standard jet cone size $R_{cut} = 0.5$ when integrating over the third particle's momentum

Mueller Navelet cross sections: energy conservation effect in BFKL

- Effect of energy conservation on BFKL dynamics
- Large effect if jet p_T ratios not close to 1: goes closer to DGLAP predictions, needs jet p_T ratio $< 1.1-1.15$

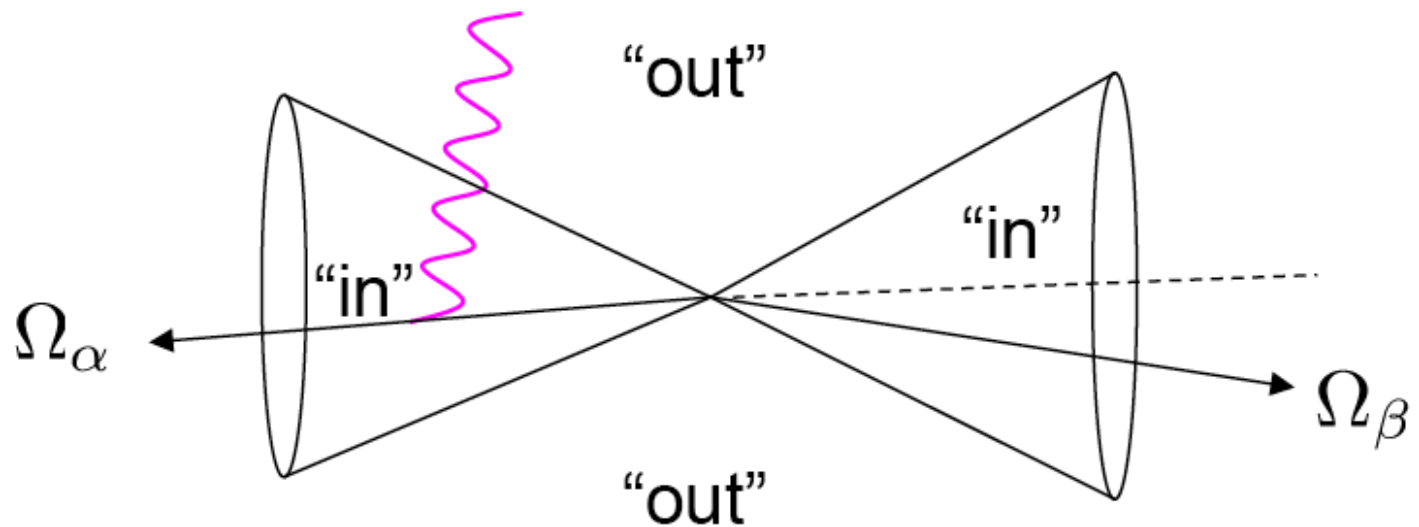


ATLAS “jet veto” measurement: sign of BFKL?



- Select events with two high p_T jets, well separated in rapidity by Δy
- Veto on additional jet activity (with $k_T > Q_0$, with $Q_0 \gg \Lambda_{QCD}$) between the two jets
- Measure the “gap” fraction: dijet events with veto/total dijet events
- Y.Hatta, C. Marquet, C. Royon, G. Soyez, T. Ueda, D. Werder: Phys.Rev. D87 (2013) 054016

Banfi Marchesini Sme equation



- Compute the probability P_T that the total energy emitted outside the jet cone is less than E_{out}

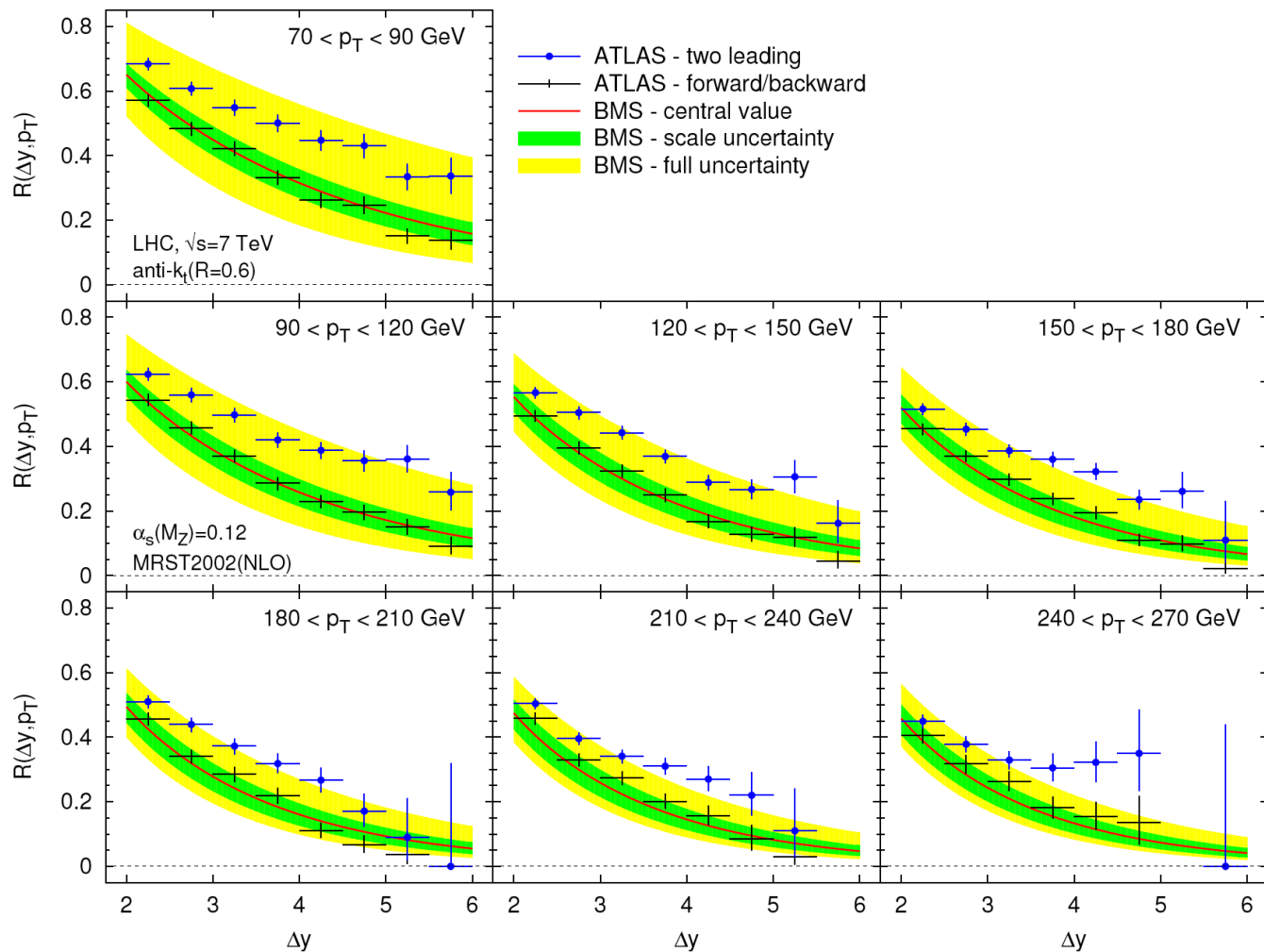
$$\partial_\tau P_T(\Omega_\alpha, \Omega_\beta) = - \int_{\mathcal{C}_{out}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1 - \cos\theta_{\alpha\beta}}{(1 - \cos\theta_{\alpha\gamma})(1 - \cos\theta_{\gamma\beta})} P_T(\Omega_\alpha, \Omega_\beta) \quad \leftarrow \text{Sudakov logs}$$

$$+ \int_{\mathcal{C}_{in}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1 - \cos\theta_{\alpha\beta}}{(1 - \cos\theta_{\alpha\gamma})(1 - \cos\theta_{\gamma\beta})} \left(P_T(\Omega_\alpha, \Omega_\gamma) P_T(\Omega_\gamma, \Omega_\beta) - P_T(\Omega_\alpha, \Omega_\beta) \right)$$

non-global logs differential probability for the soft gluon emission

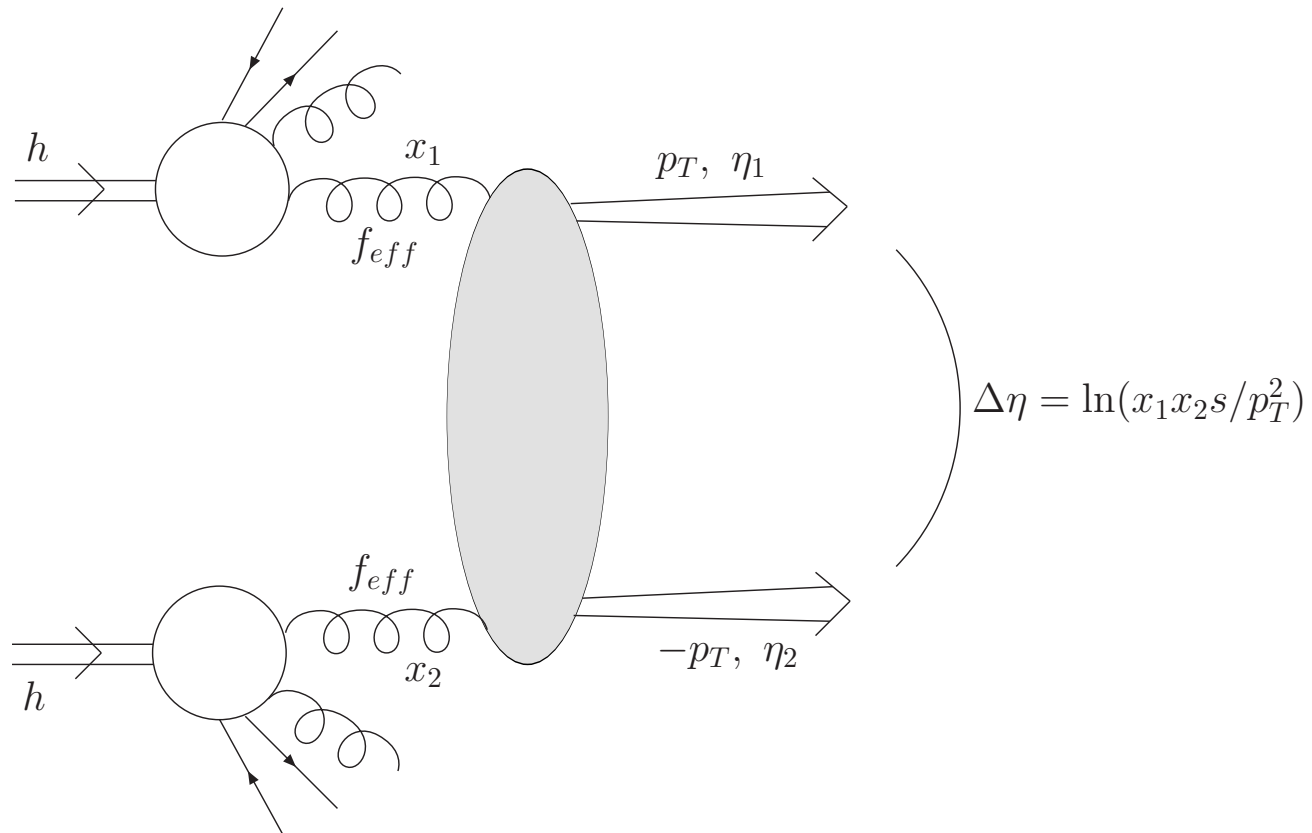
- Numerical solutions are available (Hatta and Ueda, 2009)

Comparison with ATLAS data



- Good agreement between prediction and ATLAS data (black points when the most forward and backward jets are selected and $E_{out}=20$ GeV)
- Plot as a function of Δy between jets in different jet p_T bins
- Green band: renormalisation and factorisation scale uncertainties (between $2p_T$ and $p_T/2$); yellow band: uncertainties related to sub-leading logs

Jet gap jet cross sections



- **Test of BFKL evolution:** jet gap jet events, large $\Delta\eta$, same p_T for both jets in BFKL calculation
- **Principle:** Implementation of BFKL NLL formalism in HERWIG Monte Carlo (Measurement sensitive to jet structure and size, gap size smaller than $\Delta\eta$ between jets)

BFKL formalism

- **BFKL jet gap jet cross section:** integration over ξ , p_T performed in Herwig event generation

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

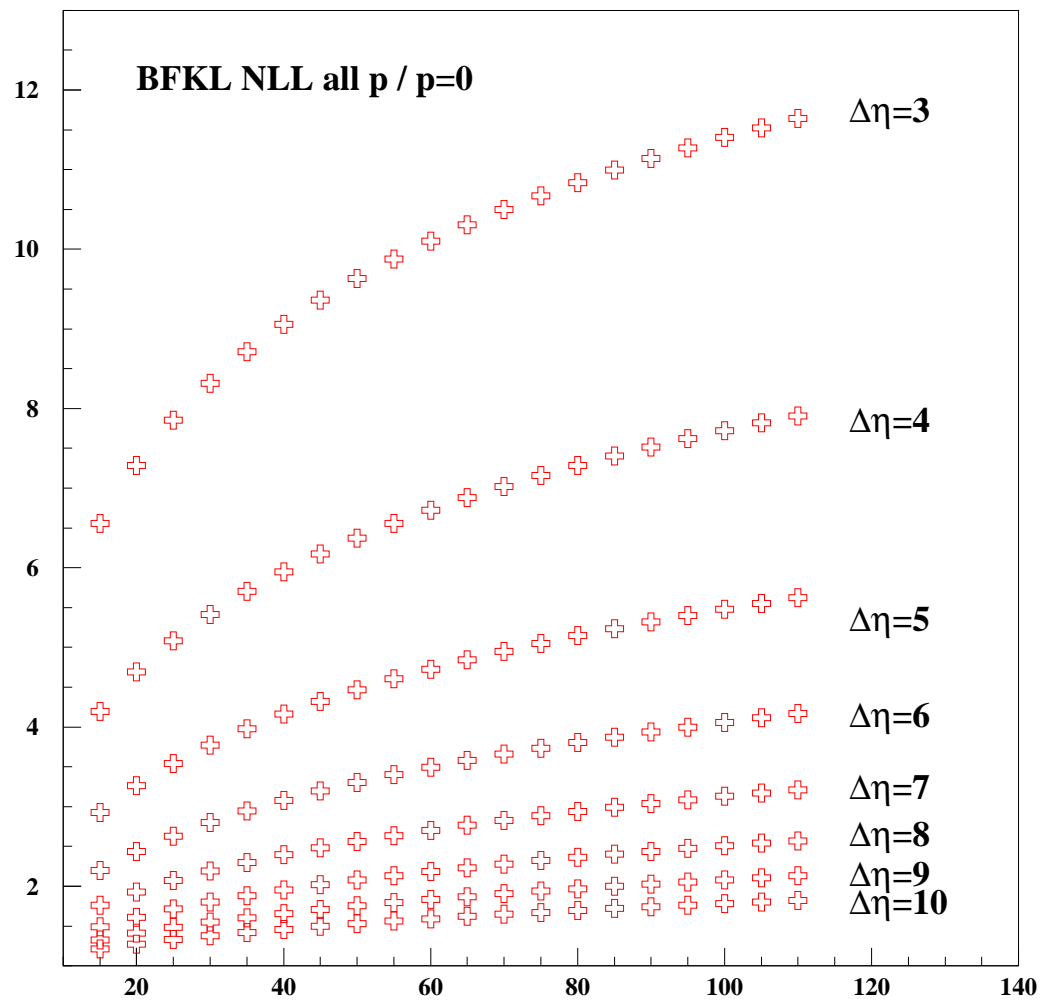
where S is the survival probability (0.1 at Tevatron, 0.03 at LHC)

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

- α_S : 0.17 at LL (constant), running using RGE at NLL
- **BFKL effective kernel χ_{eff} :** determined numerically, solving the implicit equation: $\chi_{eff} = \chi_{NLL}(\gamma, \bar{\alpha} \chi_{eff})$
- **S4 resummation 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 $\chi^2 \sim 0.1$)

BFKL formalism: resummation over conformal spins

- Study of the ratio $\frac{d\sigma/dp_T(\text{all } p)}{d\sigma/dp_T(p=0)}$
- Resummation over p needed: modifies the p_T and $\Delta\eta$ dependences...

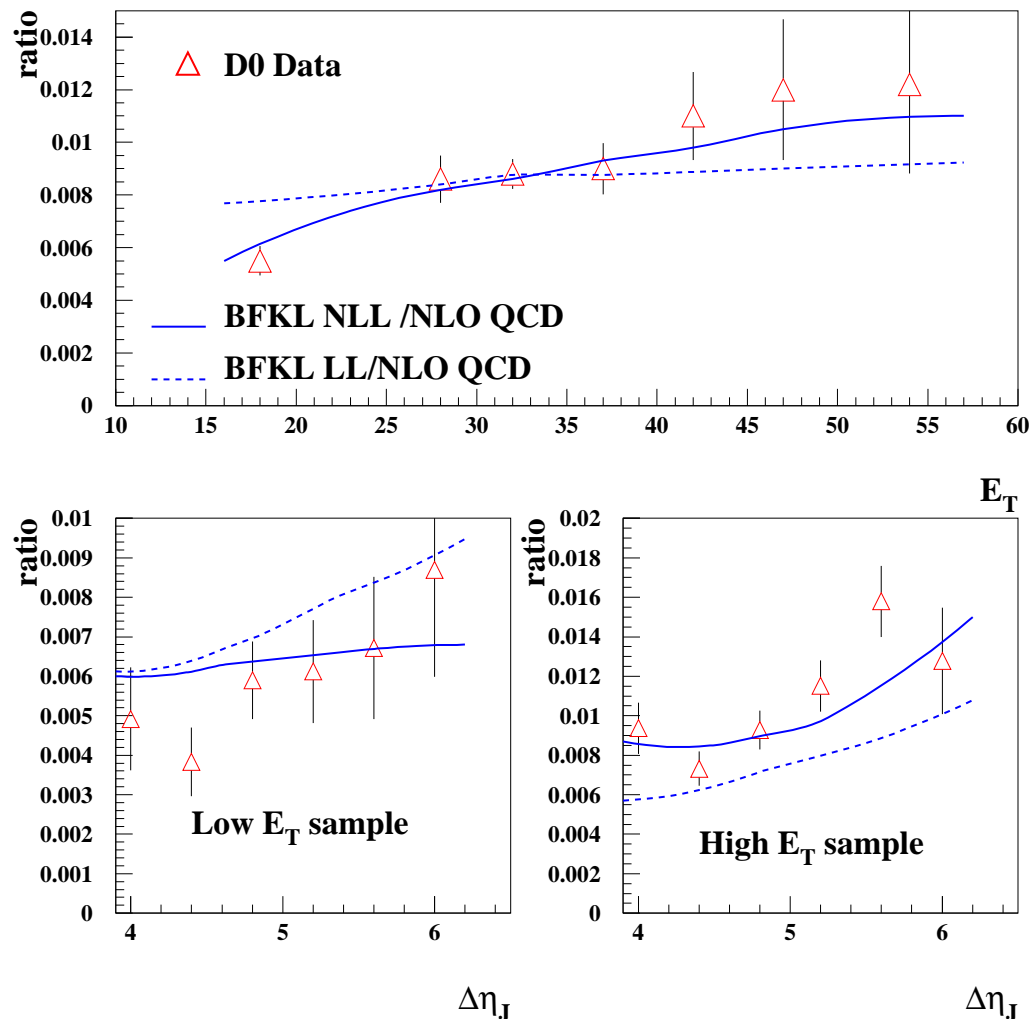


Comparison with D0 data

- **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:**

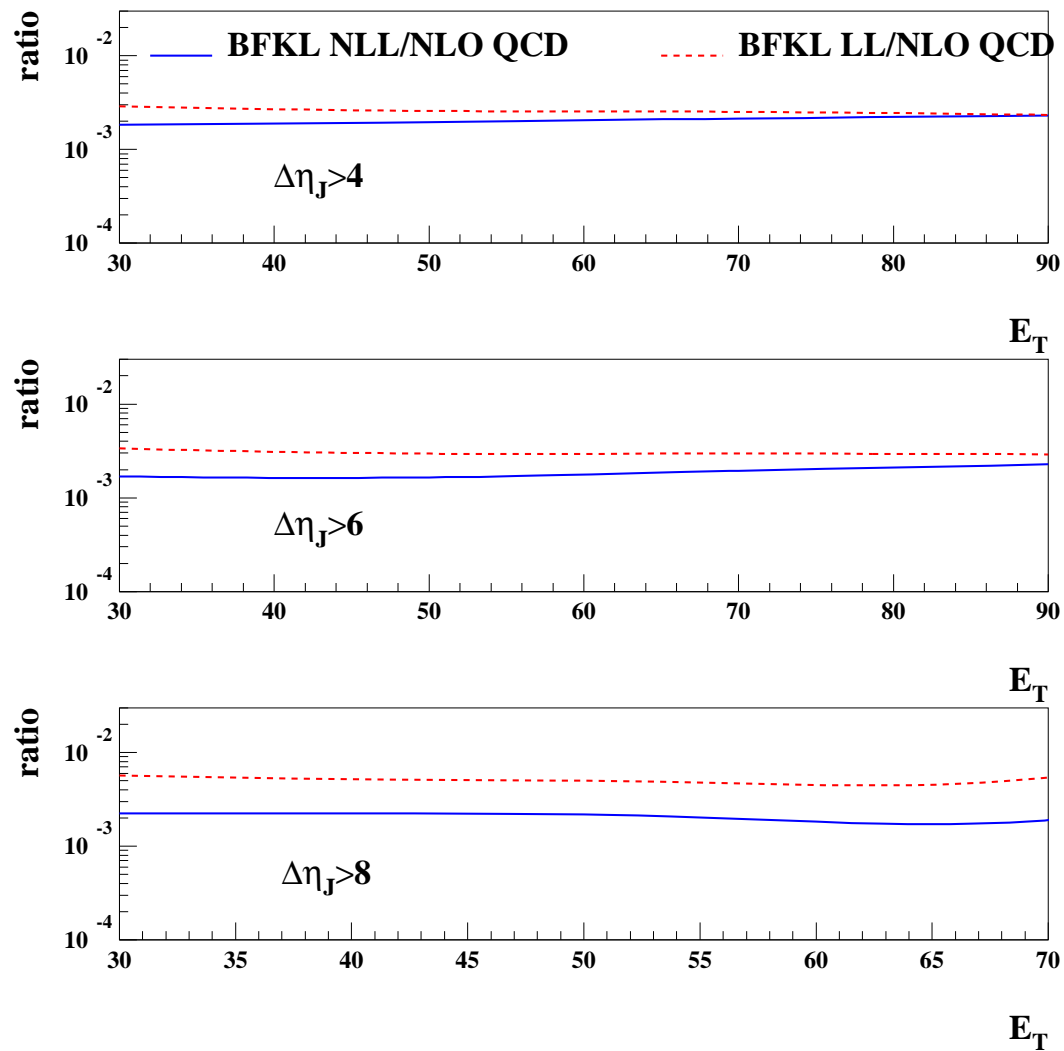
$$\text{Ratio} = \frac{\text{BFKL NLL Herwig}}{\text{Dijet Herwig}} \times \frac{\text{LO QCD NLOJet}++}{\text{NLO QCD NLOJet}++}$$

- Reasonable description using BFKL NLL formalism



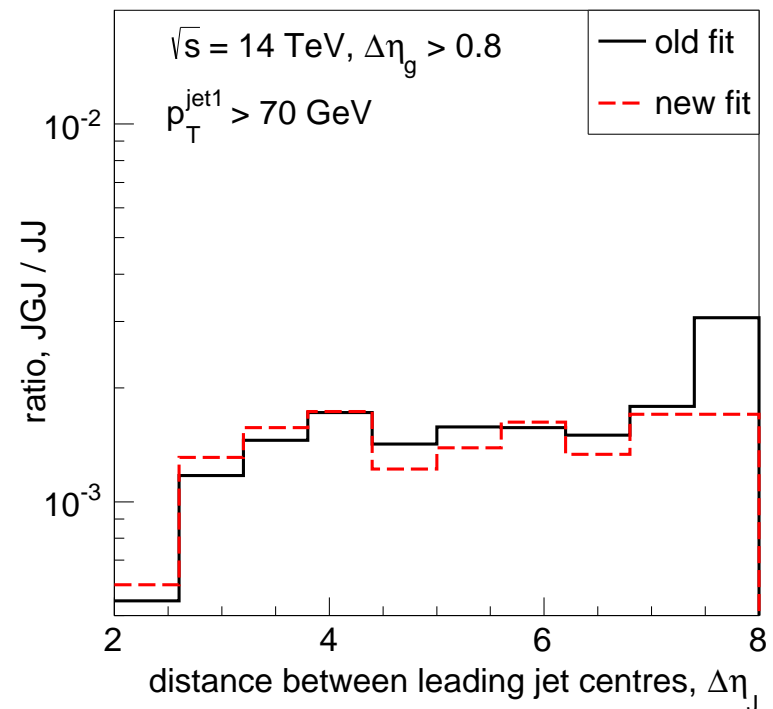
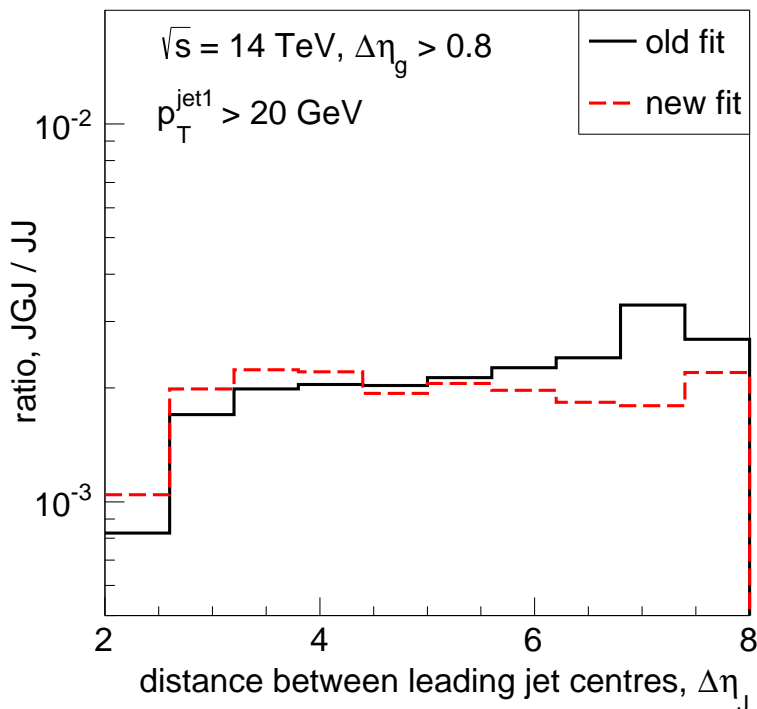
Predictions for the LHC

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



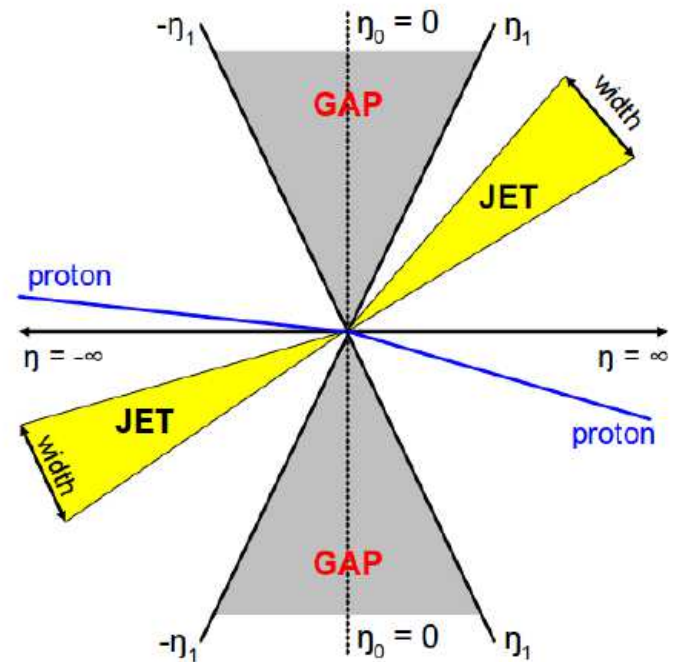
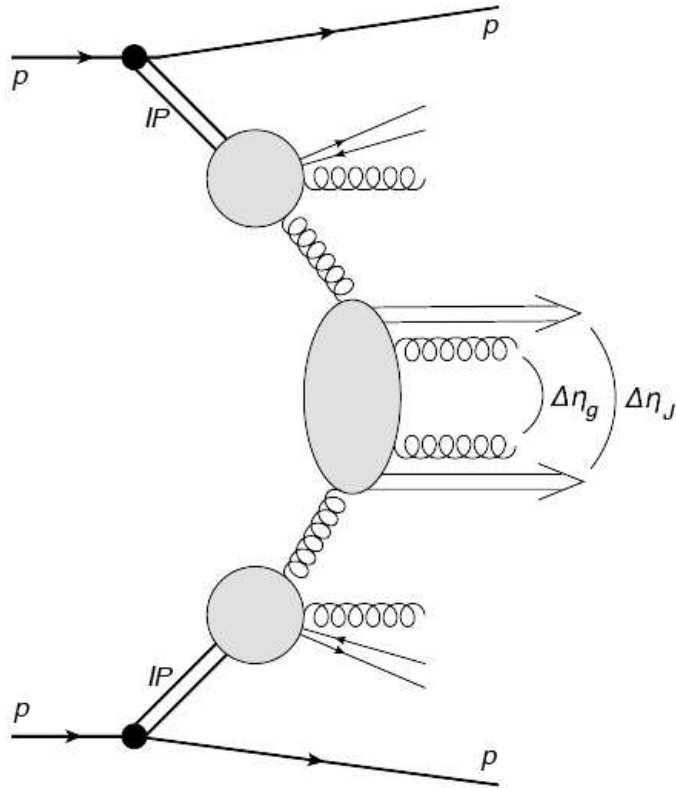
A better prediction of the Mueller-Tang cross section

- The previous BFKL NLL polynomial fit implemented in Herwig was performed at Tevatron energies (before the LHC): need to be redone at higher p_T in order to avoid any extrapolation
- Perform again the polynomial fit at the LHC energy: Maciej, Paula, polynomial parameters given in ArXiv:1504.06271
- New parametrisation leading to similar results as the previous one



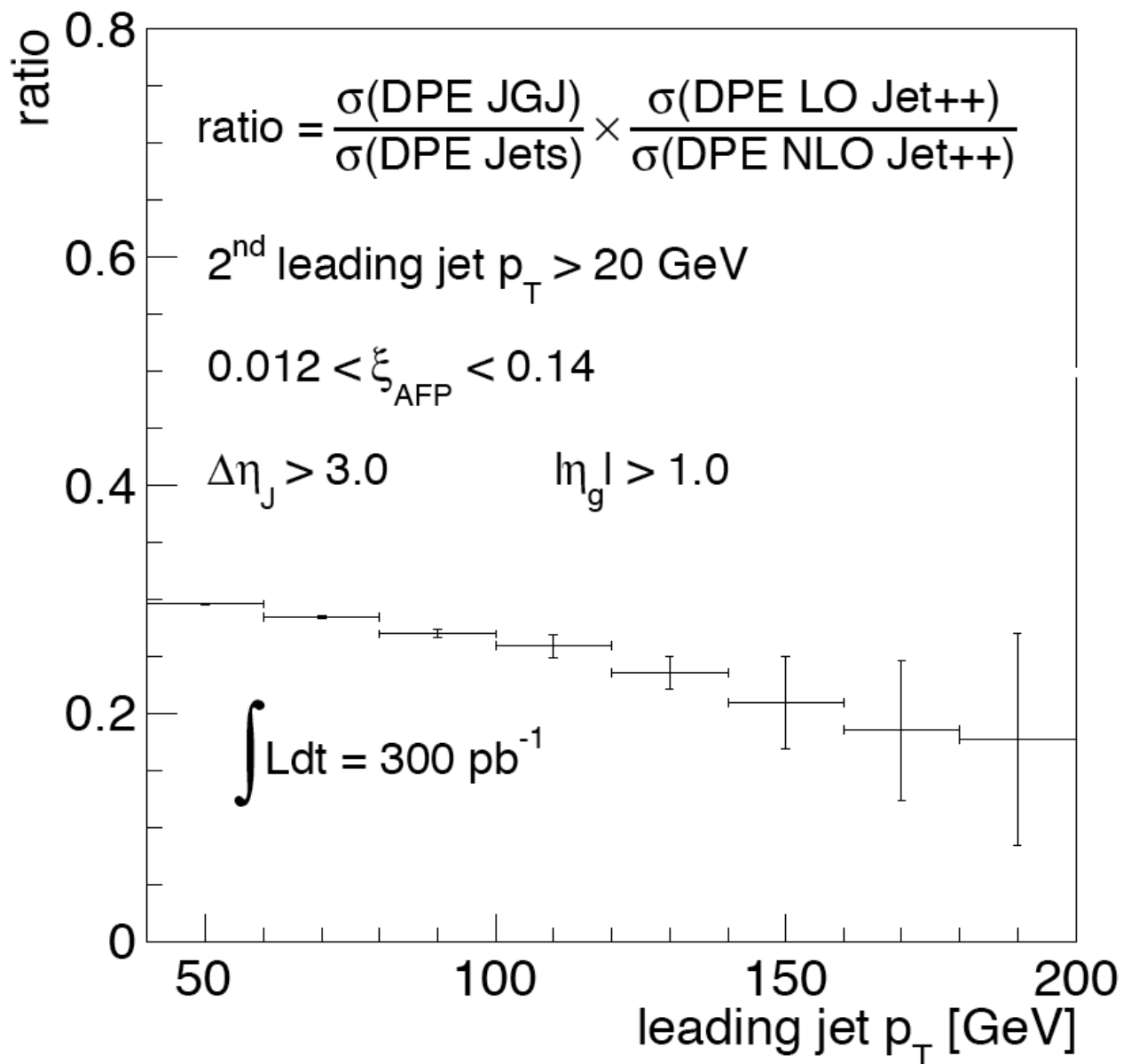
Jet gap jet events in diffraction

- 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

- Full implementation of BFKL NLL kernel for many jet processes at HERA, Tevatron and LHC
- Forward jets at HERA: DGLAP NLO fails to describe HERA data, good description of data using BFKL NLL formalism
- **Mueller Navelet jets**: Larger decorrelation expected for BFKL formalism, unfortunately suffers a lot of corrections introduced when one imposes the conservation of energy in the BFKL formalism (see Phys. Rev. D79 (2009) 034028)
- **Jet veto measurements in ATLAS**: mainly not related to BFKL resummation effects
- **Jet gap jets**:
 - NLL BFKL cross section implemented in HERWIG
 - Fair description of D0 and CDF data
 - Jet gap jet events in diffraction: clean tests of BFKL, modulo the survival probability (and its dependence on kinematics)