Probing the BFKL dynamics at hadronic colliders

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EDS Blois 2013
Saariselkä, Finland, September 9 - 13 2013

Contents:

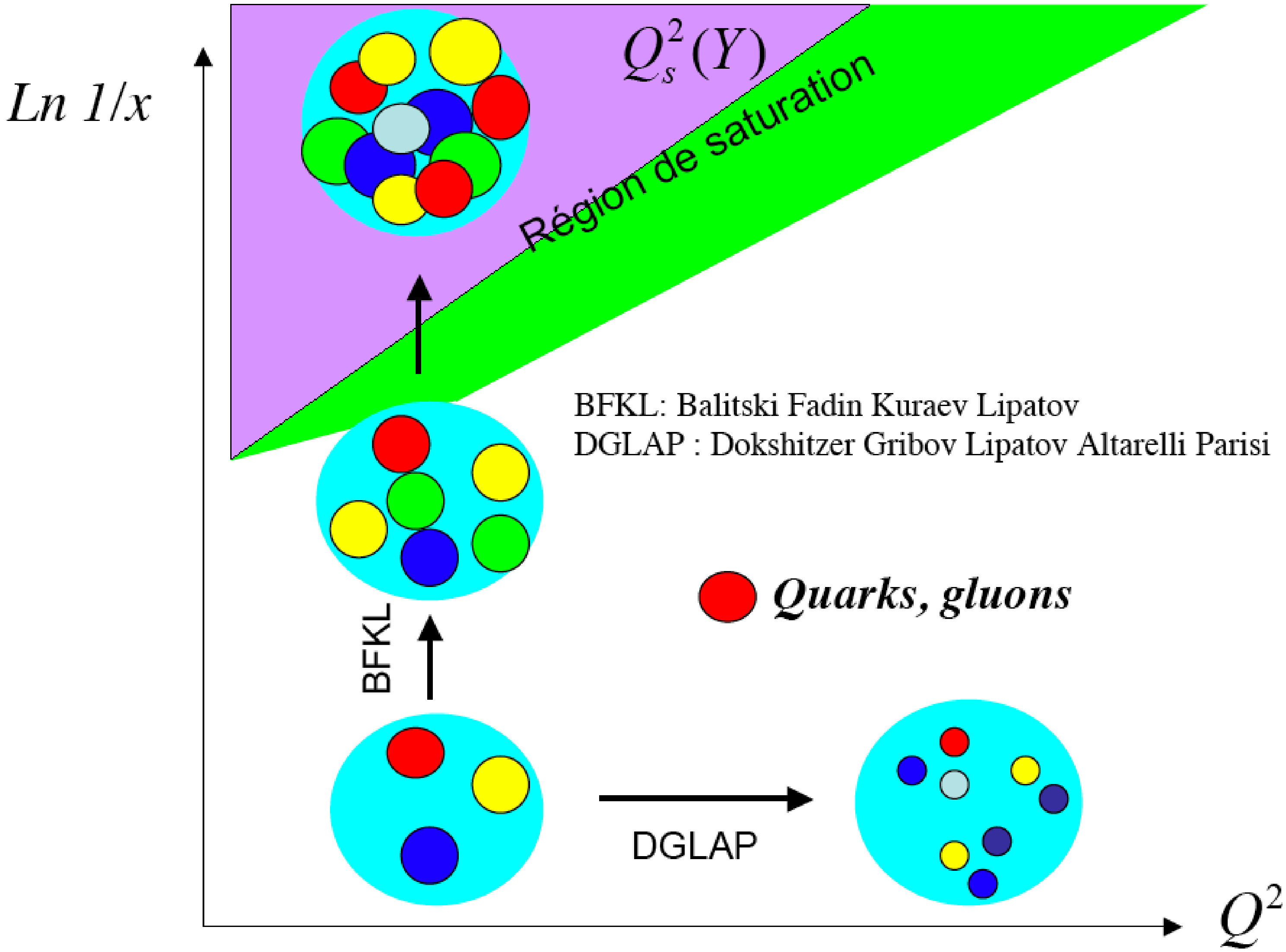
- Forward jets at HERA (short reminder)
- Mueller Navelet jet
- Jet veto (atlas measurement)
- Jet gap jet at Tevatron, LHC
- Jet gap jet in diffraction at the LHC

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

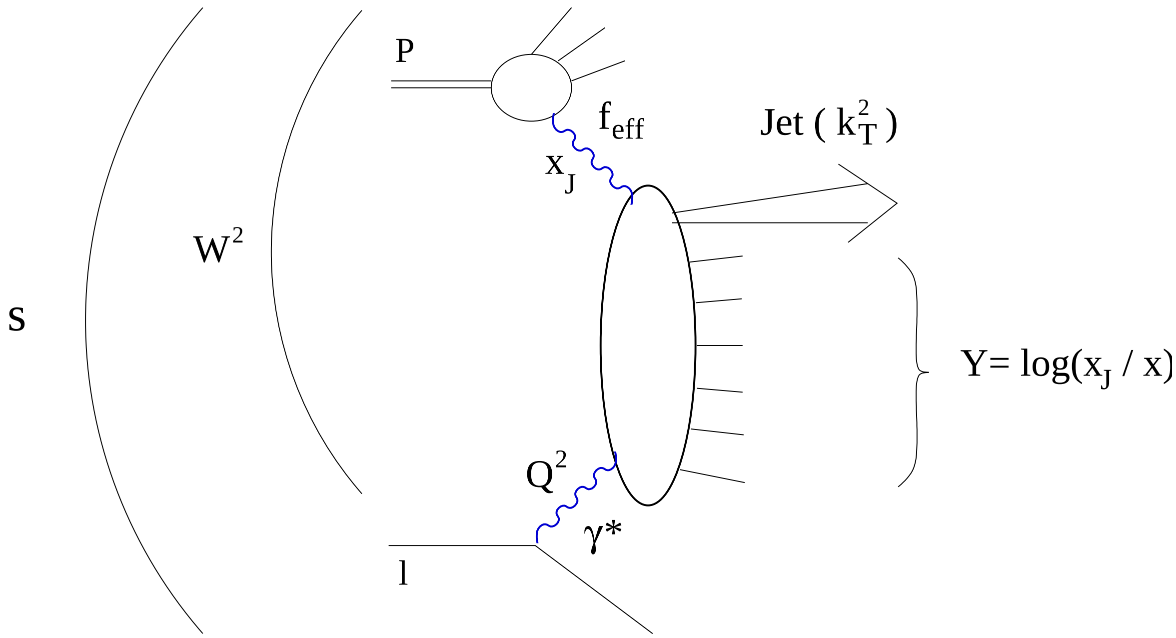
- Forward jets: Nucl. Phys. B 739 (2006) 131; Phys. Lett. B 655 (2007) 236; Eur. Phys. J. C55 (2008) 259;
- Mueller Navelet jets: Phys. Rev. D79 (2009) 034028;
- Jet Gap Jet: Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036; Phys. Rev. D 87 (2013) 034010
- Jet veto: Phys.Rev. D87 (2013) 054016

Looking for BFKL/saturation effects

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



Forward jet measurement at HERA



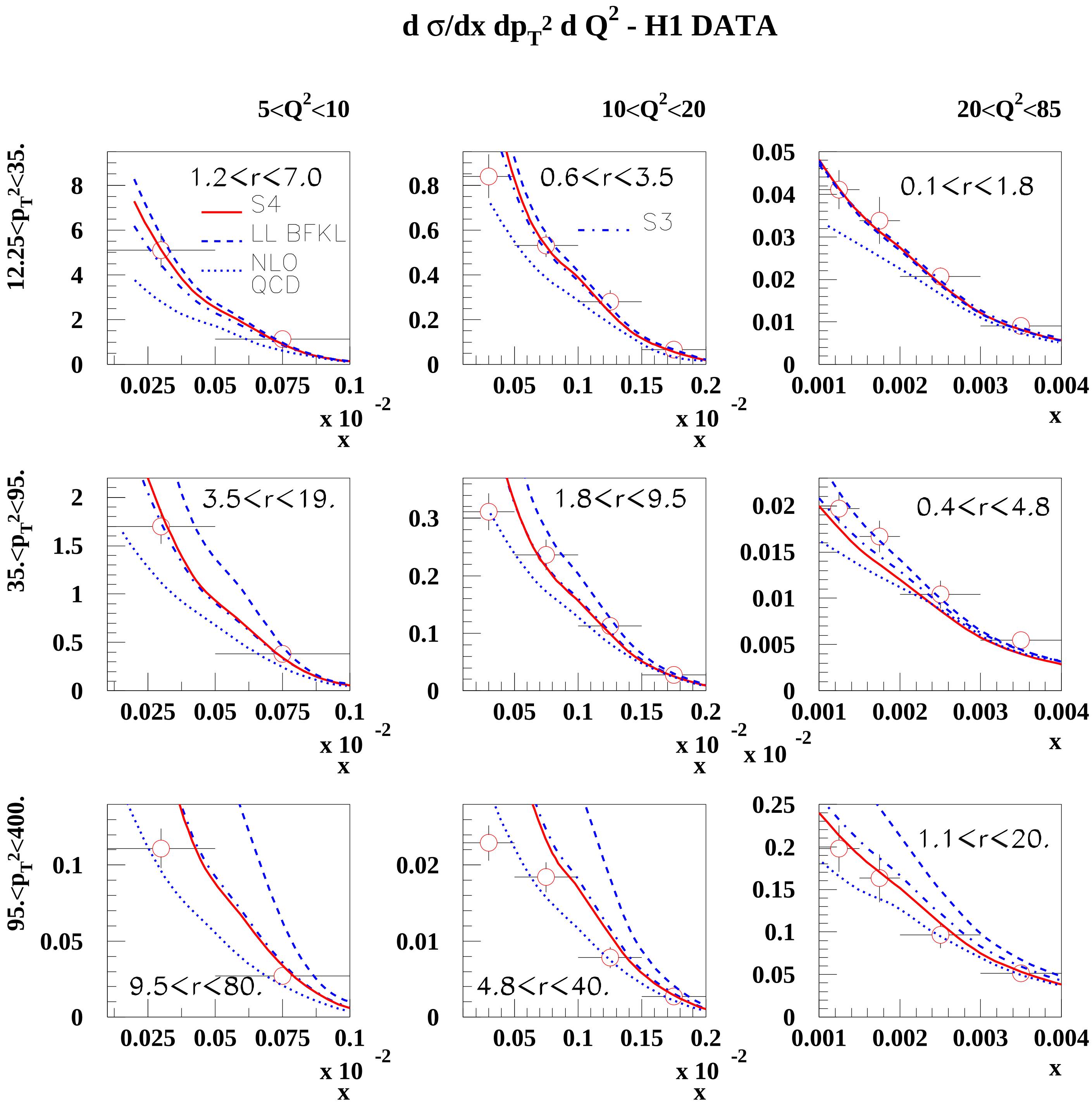
- Full BFKL NLL calculation used for the BFKL kernel, available in S3 and S4 resummation schemes to remove the spurious singularities (modulo the impact factors taken at LL)
- Equation:

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

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

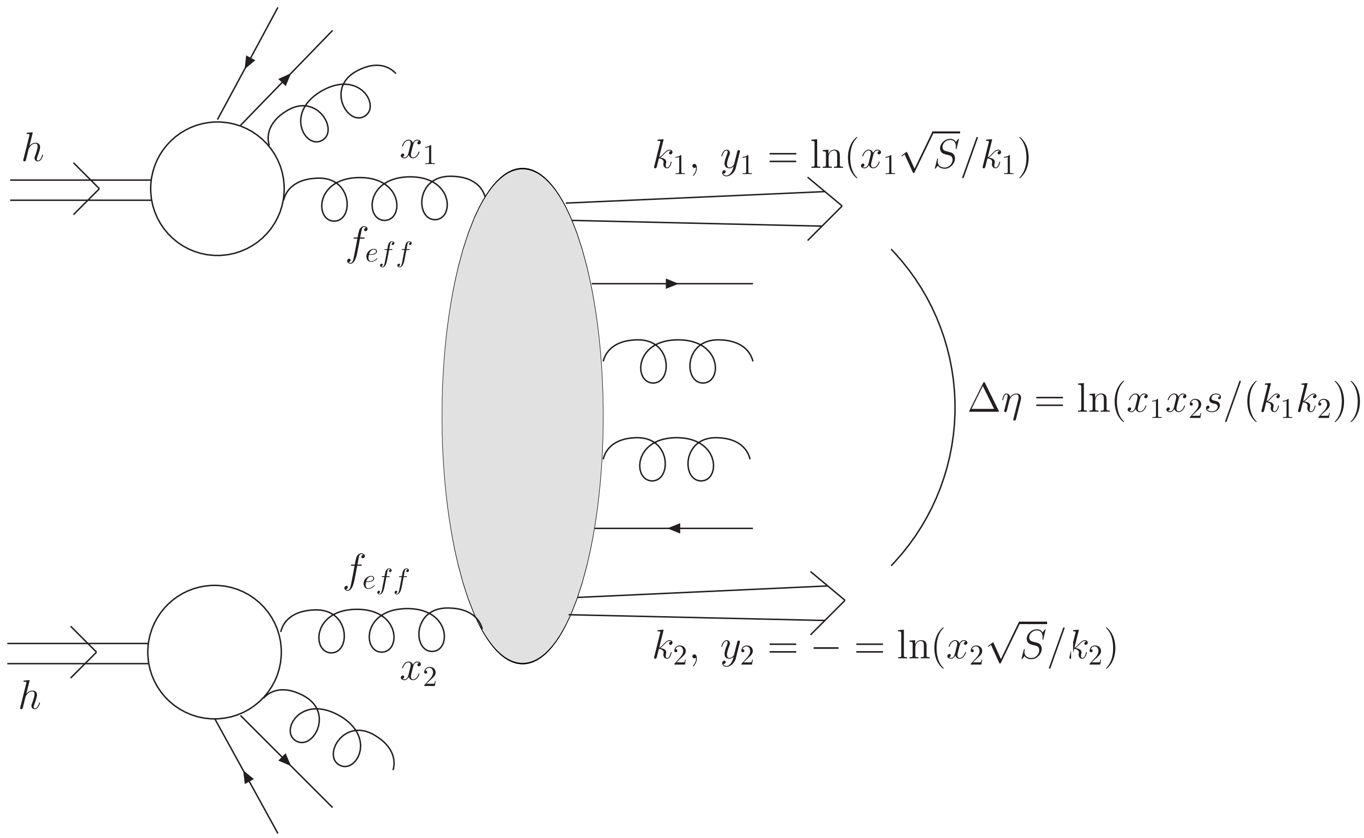
- Implicit equation: $\chi_{eff}(\gamma, \alpha) = \chi_{NLL}(\gamma, \alpha, \chi_{eff}(\gamma, \alpha))$ solved numerically

Comparison with H1 triple differential 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:

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:

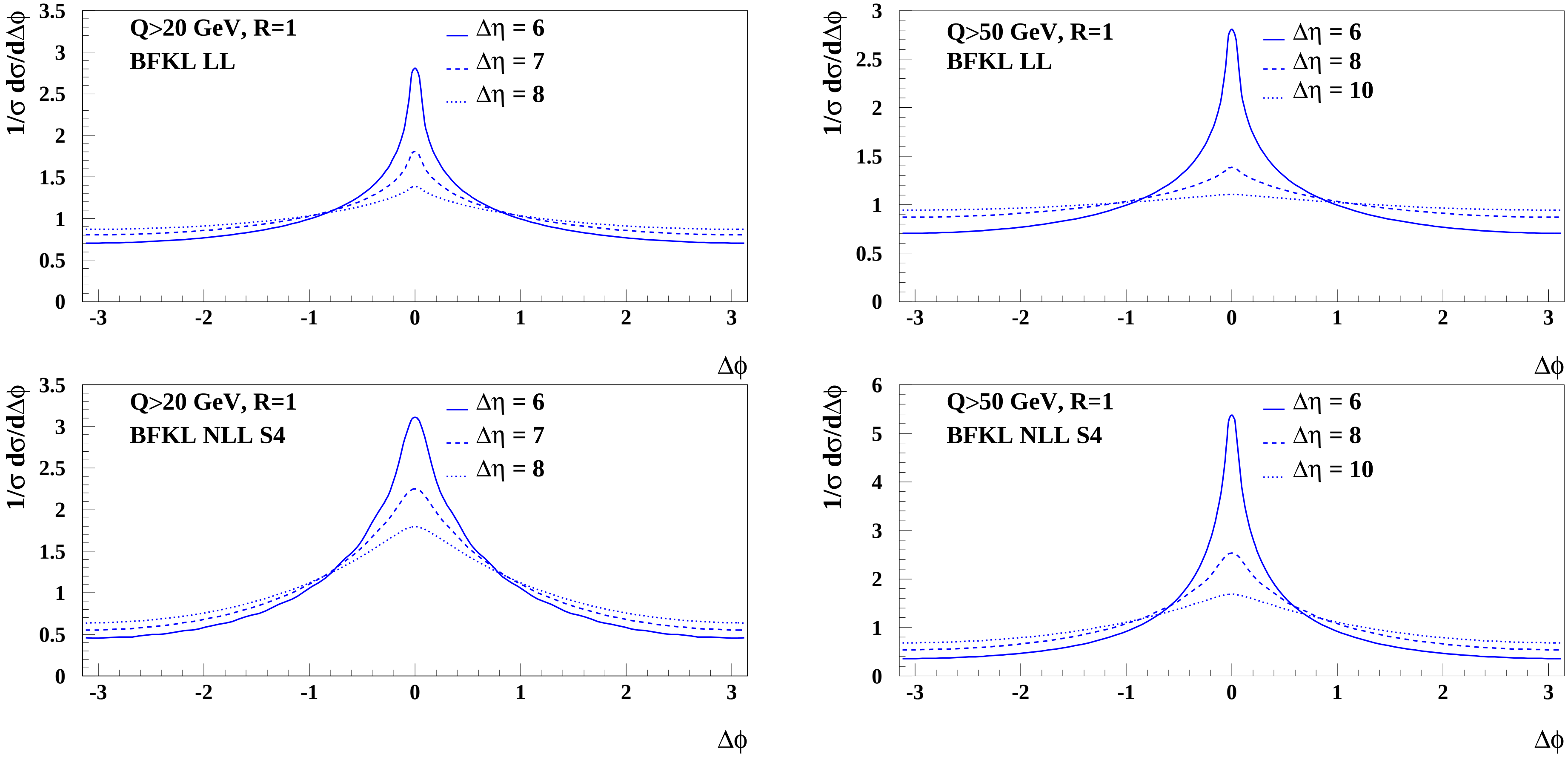
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Bigg/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

where

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

Mueller Navelet jets: $\Delta\Phi$ dependence

- $1/\sigma d\sigma/d\Delta\Phi$ spectrum for BFKL 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

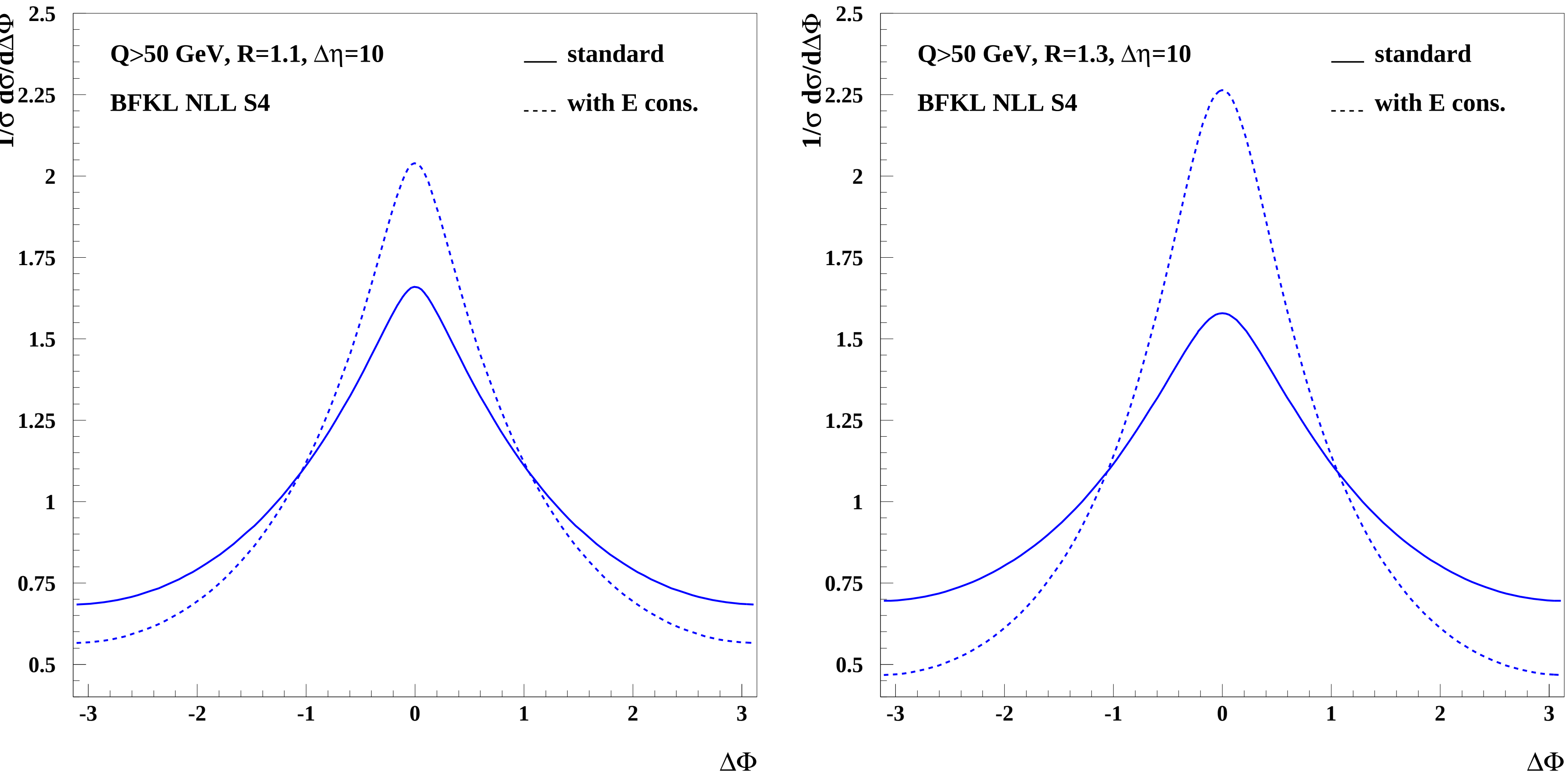
- BFKL cross section lacks energy-momentum conservation since these effects are higher order corrections
- Following Del Duca-Schmidt, we substitute $\Delta\eta$ by an effective rapidity interval y_{eff}

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

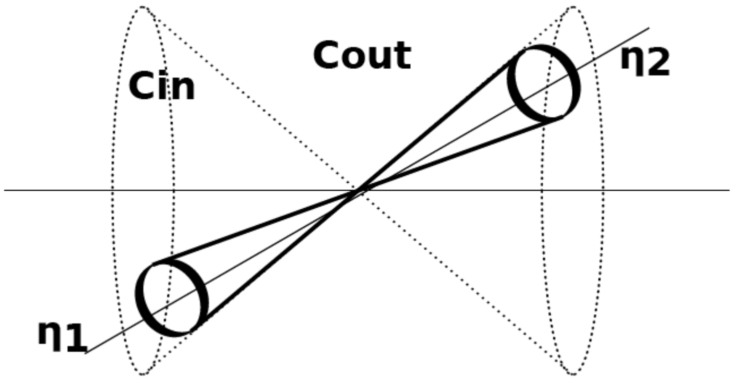
  where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \to 3$ contribution to the $hh \to JXJ$ cross-section at order α_s^3, and $d\sigma^{LL-BFKL}$ is the LL-BFKL result
- To compute $d\sigma^{O(\alpha_s^3)}$, we use the standard jet cone size $R_{cut} = 0.5$ when integrating over the third particle's momentum

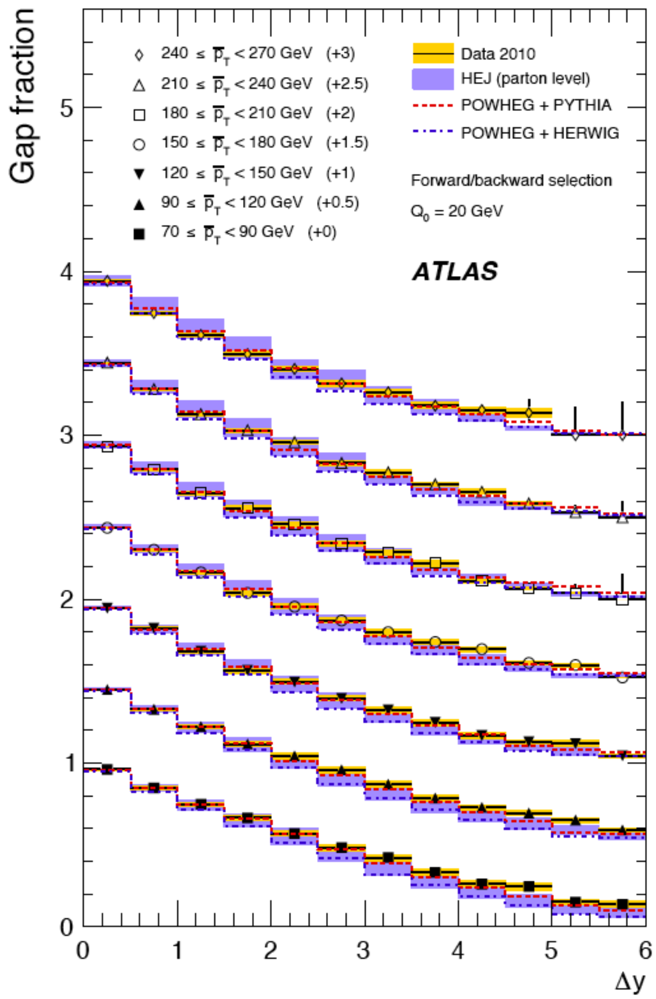
Mueller Navelet cross sections: energy conservation effect in BFKL

- 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



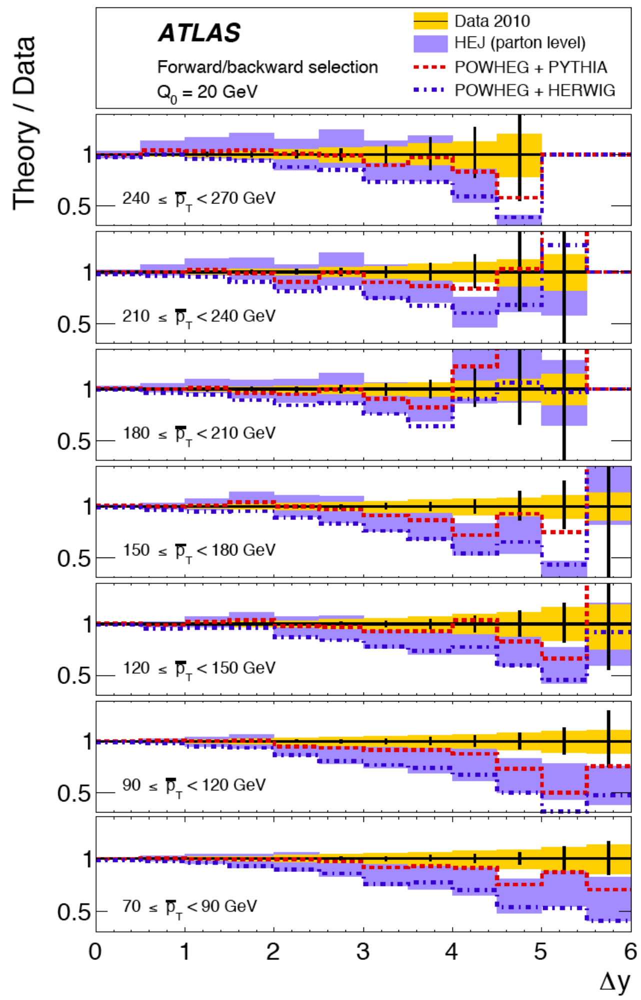
ATLAS "jet veto" measurement: sign of BFKL?





- 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 jet veto / total dijet events

Comparison with QCD calculation

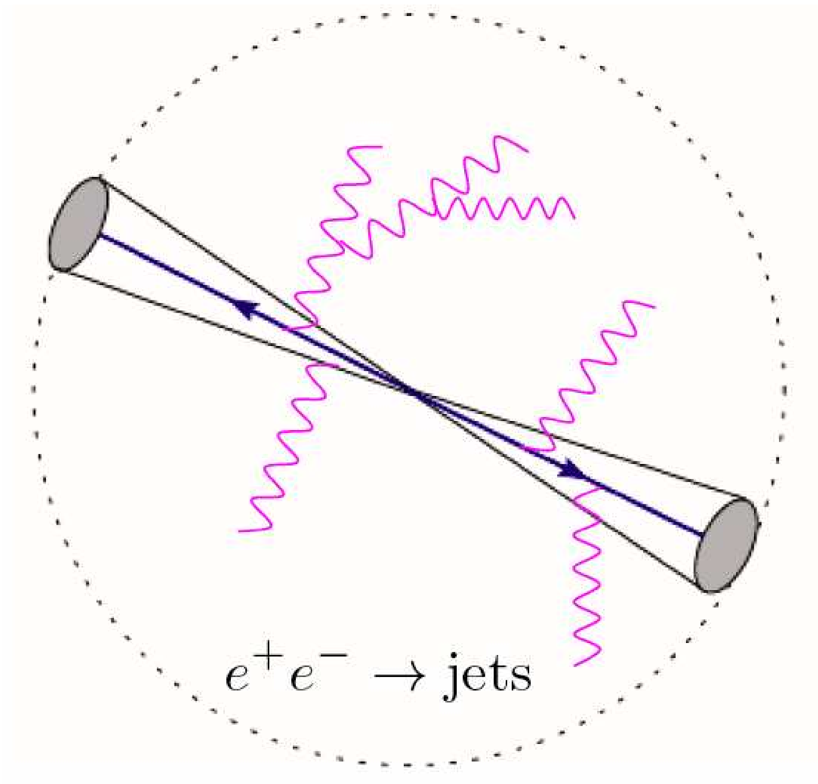


- The standard NLO and parton shower approach (POWHEG + pythia or herwig) fails to describe data

$$\frac{(d\sigma^{2\to 2} + d\sigma^{2\to 3})_{p_{T_3} < E_{out}}}{d\sigma^{2\to 2} + d\sigma^{2\to 3}}$$

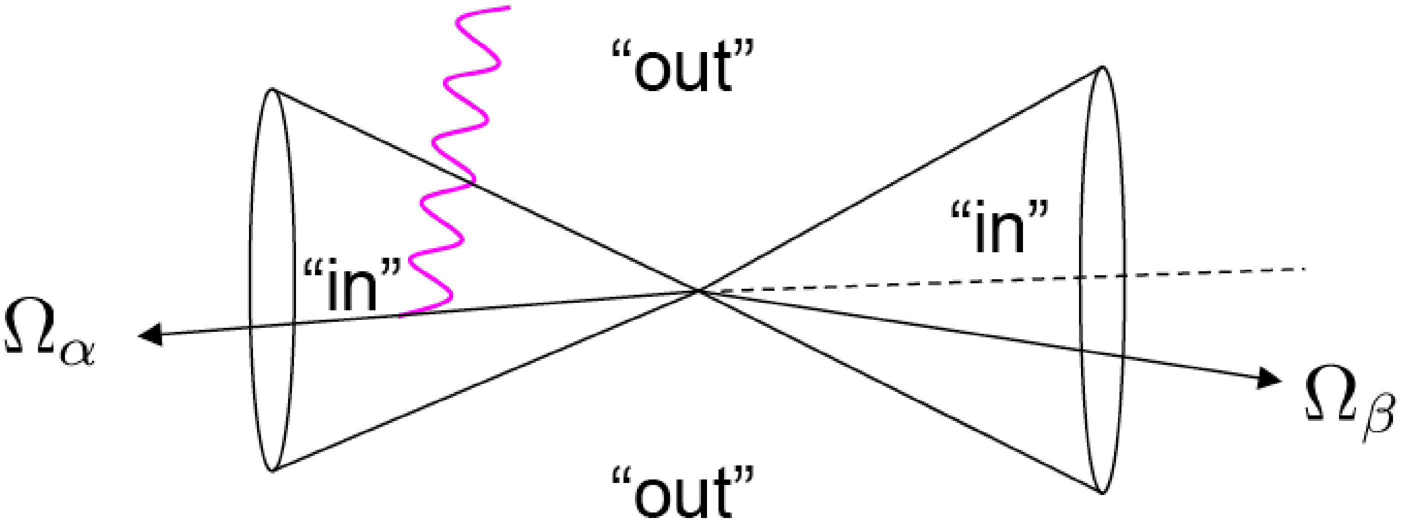
- BFKL resummation (HEJ Monte Carlo) also fails to describe data
- Both approaches miss the resummation of soft gluons at large angles

Gluon emission at large angles



- Resummation of soft gluon emissions at large angle not taken into account in parton showers
- Resummation of soft emissions performed in e^+e^- case: when $p_T \gg E_{out}$, one can resum the soft logarithms $(\alpha_S \log p_T/E_{out})^n$ while requiring that the energy flow into the region between the jets is less than E_{out}

Banfi Marchesini Smye equation



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

$$\partial_\tau P_\tau(\Omega_\alpha,\Omega_\beta) = -\int_{C_{out}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})} P_\tau(\Omega_\alpha,\Omega_\beta)$$
$$+ \int_{C_{in}} \frac{d^2\Omega_\gamma}{4\pi} \underbrace{\frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})}} \Big(P_\tau(\Omega_\alpha,\Omega_\gamma) P_\tau(\Omega_\gamma,\Omega_\beta) - P_\tau(\Omega_\alpha,\Omega_\beta) \Big)$$

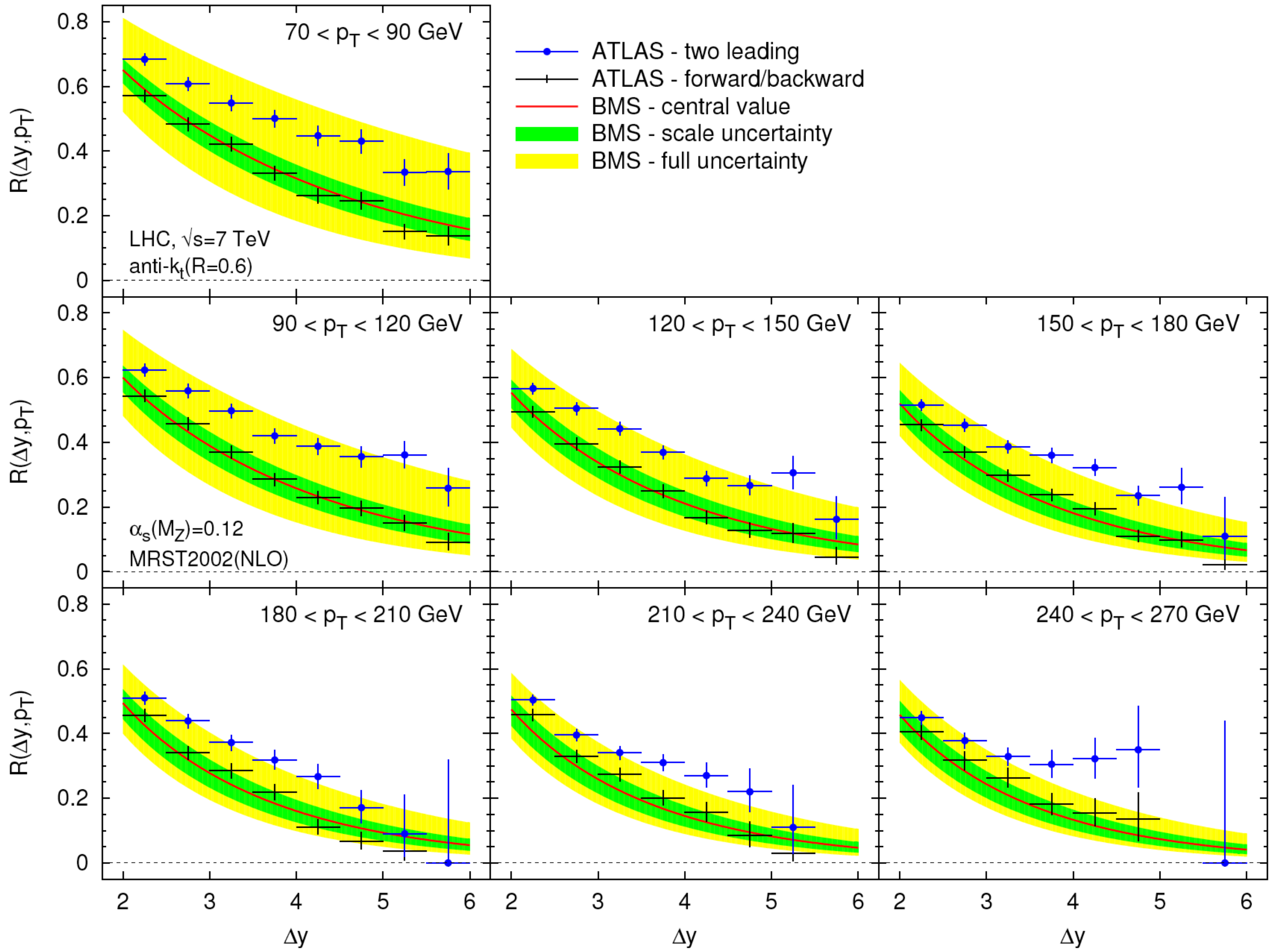
Sudakov logs

non-global logs

differential probability for the soft gluon emission

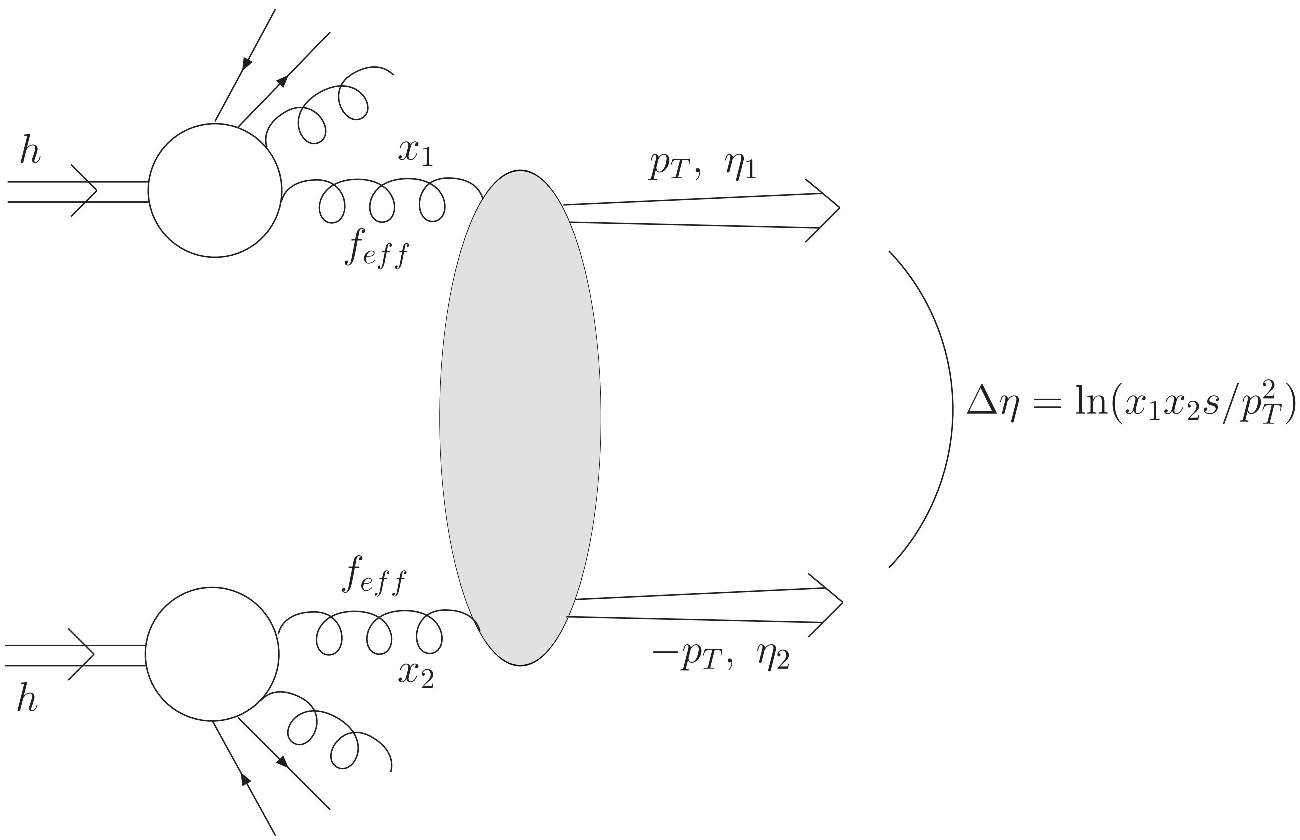
- Numerical solutions are available (Hatta and Ueda, 2009)

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

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

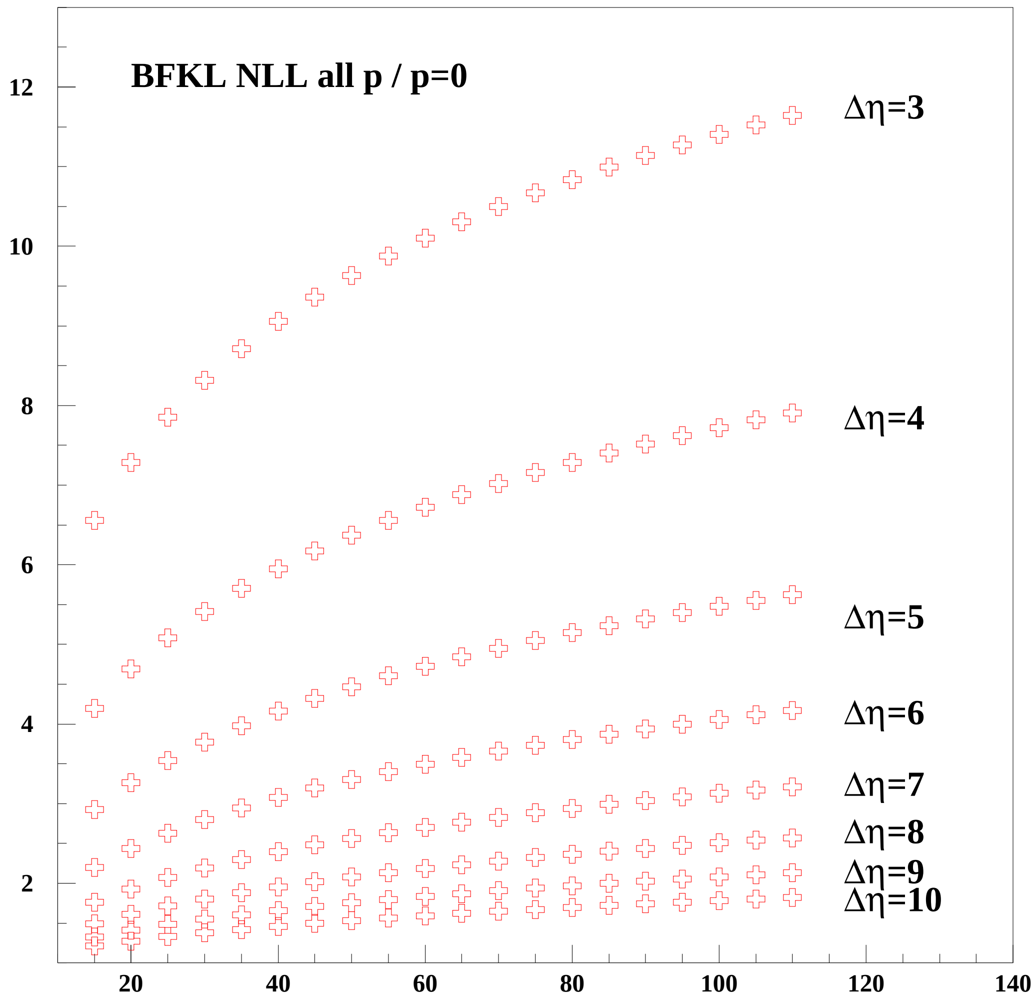
where S is the survival probability (0.1 at Tevatron, 0.03 at LHC)

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

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

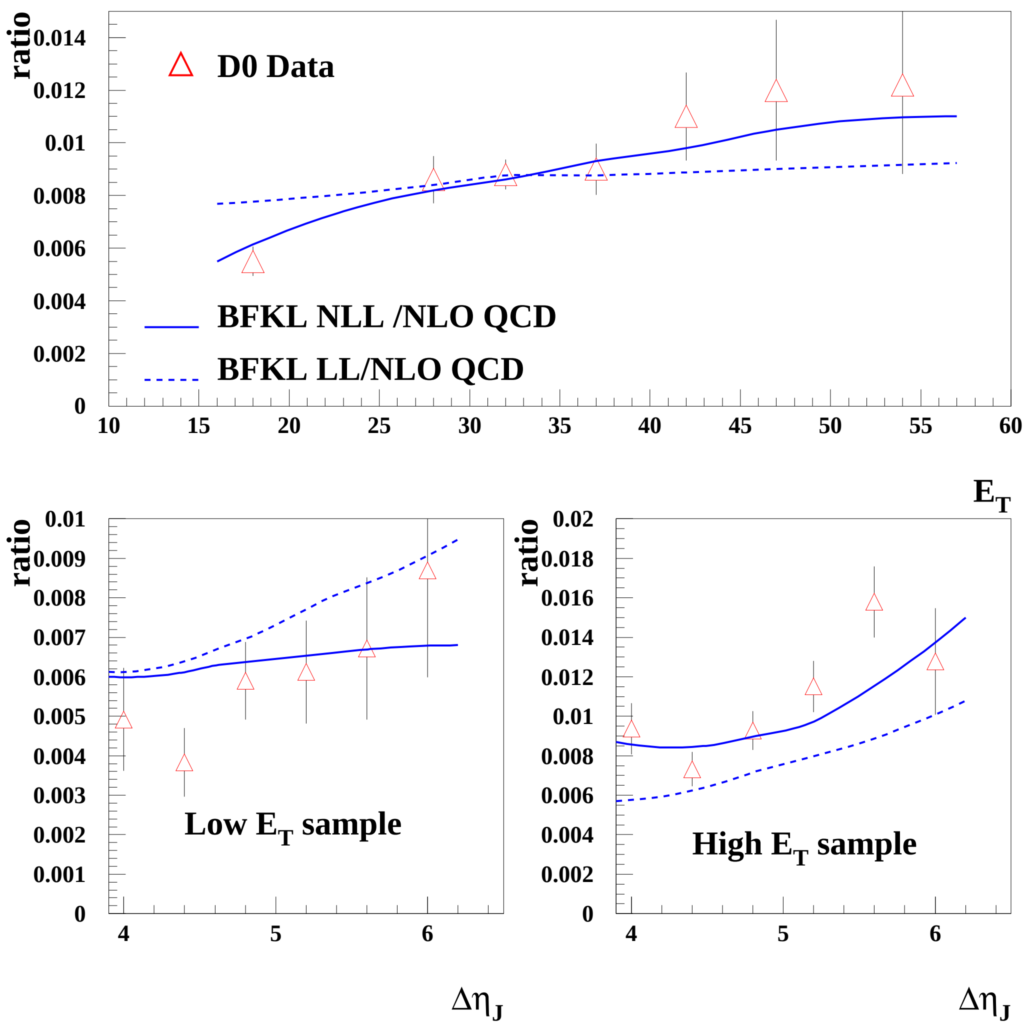


Comparison with D0 data

- 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:

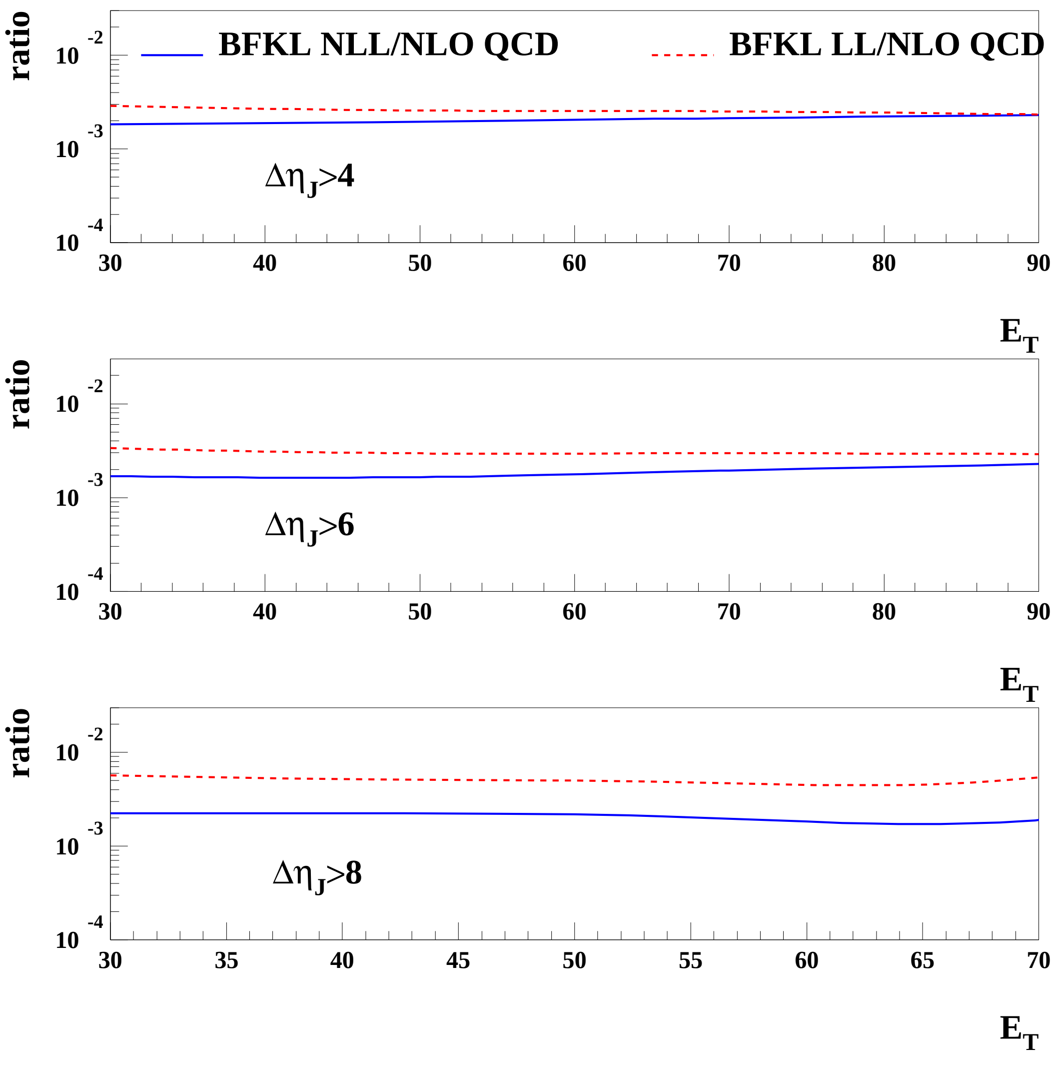
$$Ratio = \frac{BFKL\ NLL\ Herwig}{Dijet\ Herwig} \times \frac{LO\ QCD\ NLOJet++}{NLO\ QCD\ NLOJet++}$$

- 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



Conclusion

- Full implementation of BFKL NLL kernel for many jet proceeses 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 intriduced when ones imposes the conservation of energy in the BFKL formalism (see Phys. Rev. D79 (2009) 034028)
- Jet veto measurements in ATLAS: related to QCD radiation outside jets, not 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