Probing BFKL dynamics at hadronic colliders

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Contents:

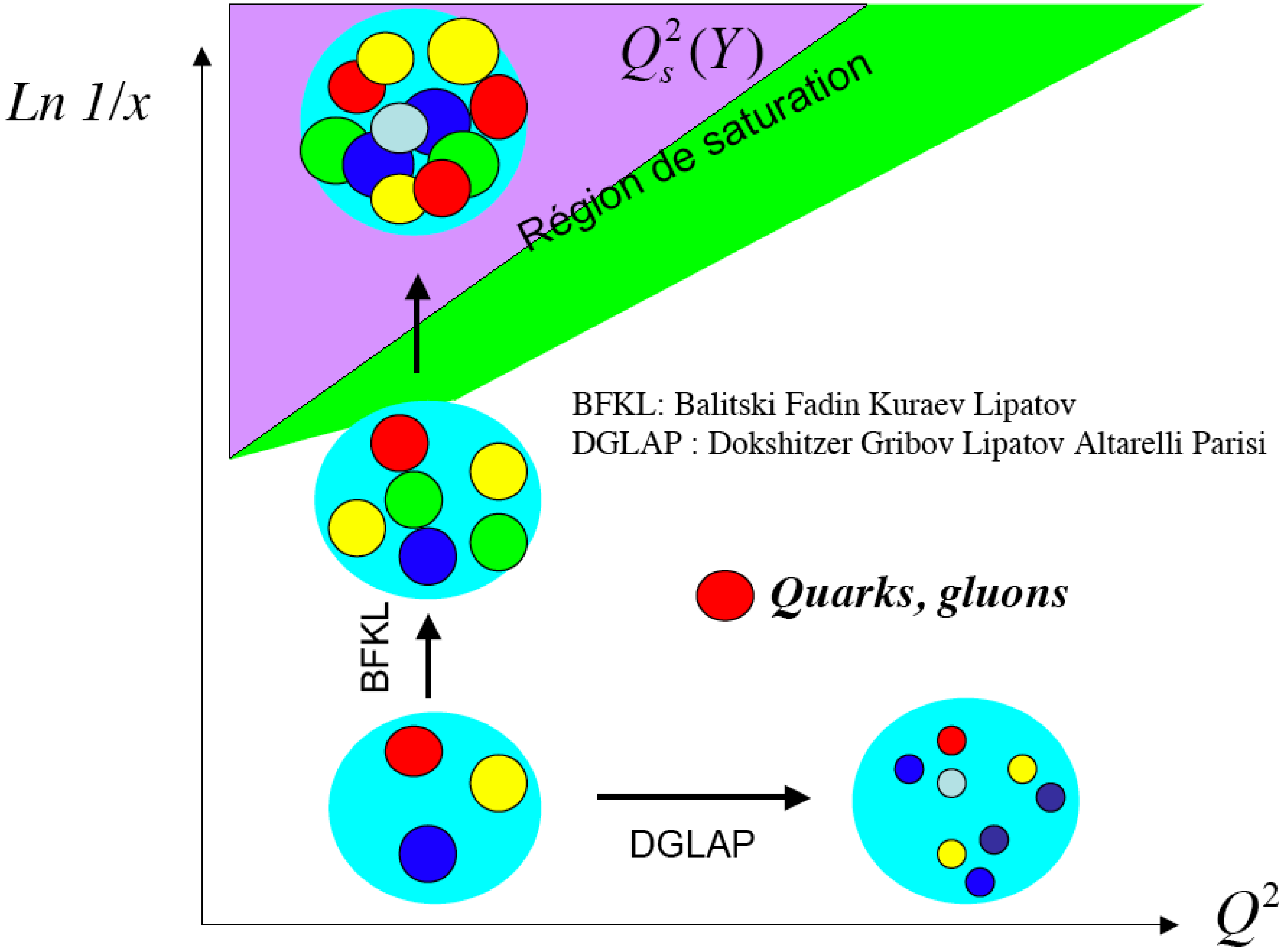
- Forward jets at HERA (short reminder)
- Jet veto (ATLAS measurement)
- Mueller Navelet jet and jet gap jets at Tevatron/LHC
- Jet gap jet in diffraction at the LHC

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

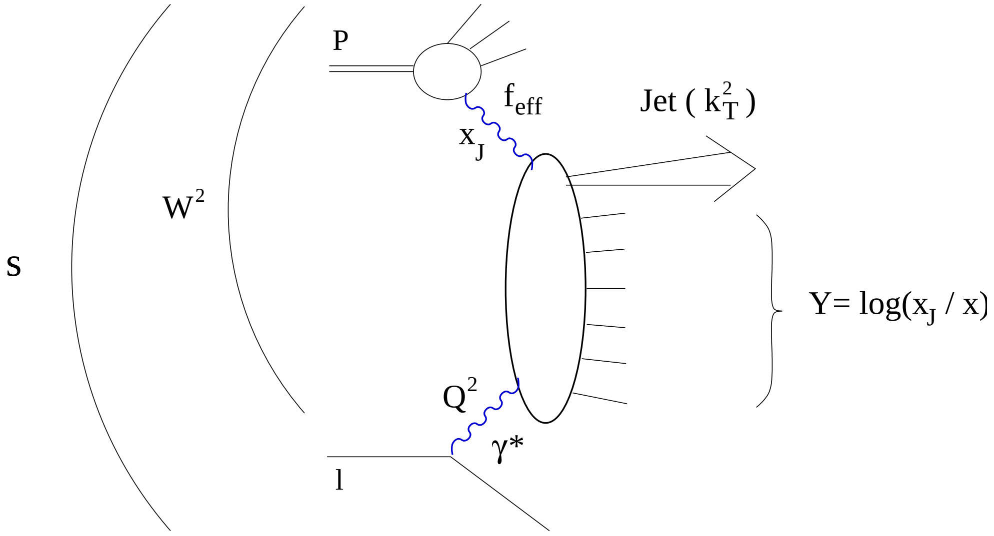
- Forward jets: Nucl. Phys. B 739 (2006) 131; Phys. Lett. B 655 (2007) 236; Eur. Phys. J. C55 (2008) 259;
- Mueller Navelet jets: Phys. Rev. D79 (2009) 034028;
- Jet Gap Jet: Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036; Phys. Rev. D 87 (2013) 034010
- Jet veto: Phys.Rev. D87 (2013) 054016

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
- C. Marquet, R. Peschanski, C. Royon: Nucl. Phys. B 739 (2006) 131; Phys. Lett. B 655 (2007) 236; Eur. Phys. J. C55 (2008) 259

BFKL NLL and resummation schemes

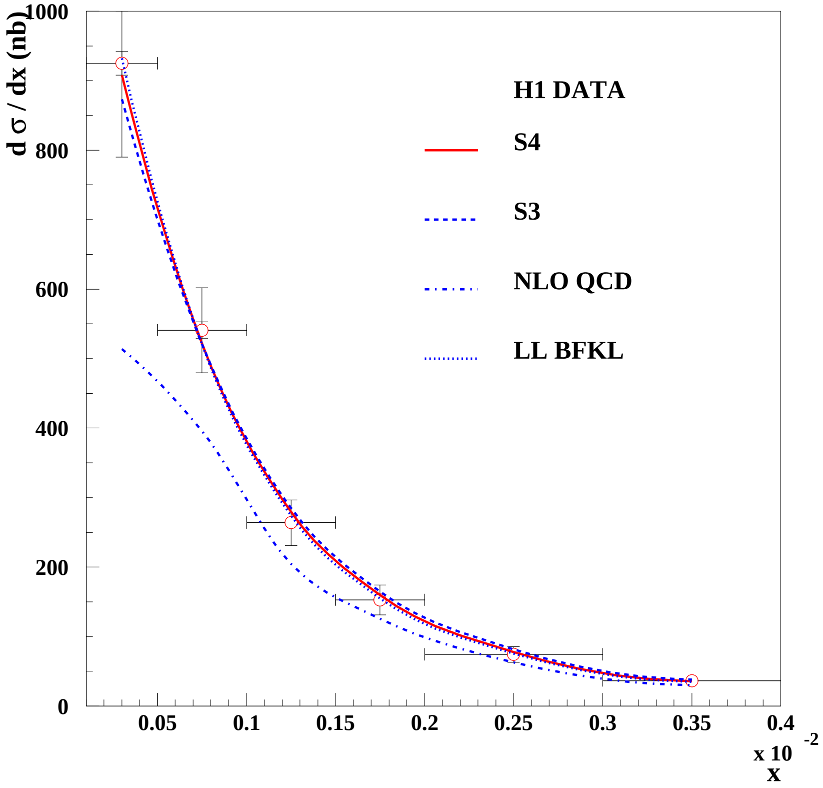
- NLO BFKL: Corrections were found to be large with respect to LO, and lead to unphysical results
- NLO BFKL kernels need resummation: to remove additional spurious singularities in γ and $(1-\gamma)$
- NLO BFKL kernel: (γ and ω associated to $\log Q^2$ and rapidity after Mellin transform)

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

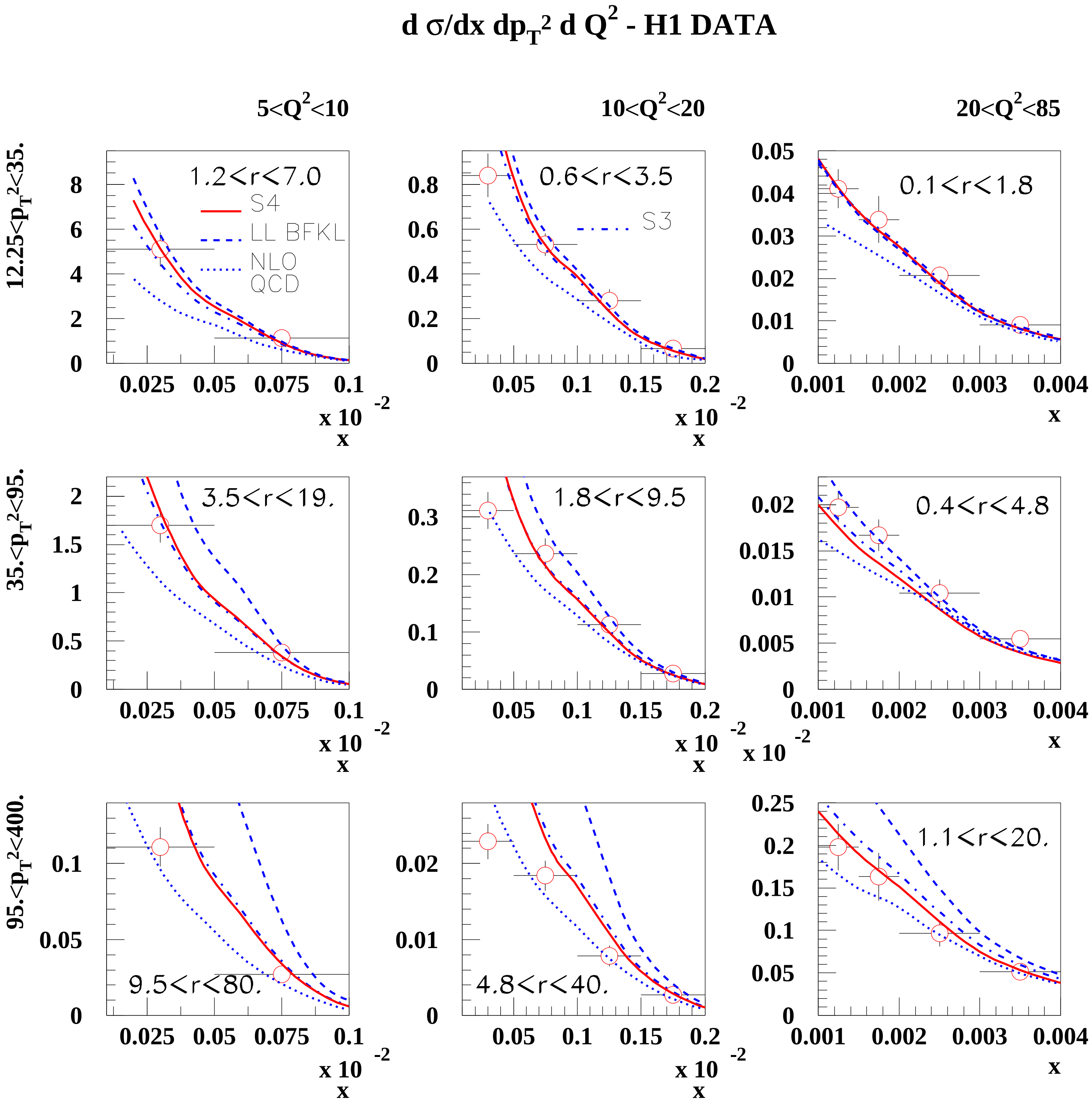
- $\chi_1(\gamma)$: calculated, NLO BFKL eigenvalues (Lipatov, Fadin, Camici, Ciafaloni)
- $\chi^{(0)}$ and $\chi_1(0)$: ambiguity of resummation at higher order than NLO, different ways to remove these singularities, not imposed by BFKL equation, Salam, Ciafaloni, Colferai; use resummation schemes S3 and S4 from Salam et al.
- Transformation of the energy scale: $\gamma \to \gamma - \omega/2$ (Salam) needed for F_2 but not for forward jet cross sections (the problem is symmetric contrary to F_2)
- BFKL NLL full calculation available (no saddle point approximation): resolution of implicit equation performed by numerical methods
- Exact gluon kinematics introduced (R. Peschanski et al.) to mimic the NLL impact factor effects

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
- Scale dependence: variation of the scale between $2Qk_T$, $Qk_T/2$, Q^2, k_T^2: $\sim 20\%$ difference
- BFKL higher corrections found to be small (We are in the BFKL region, cut on $0.5 < k_T^2/Q^2 < 5$)

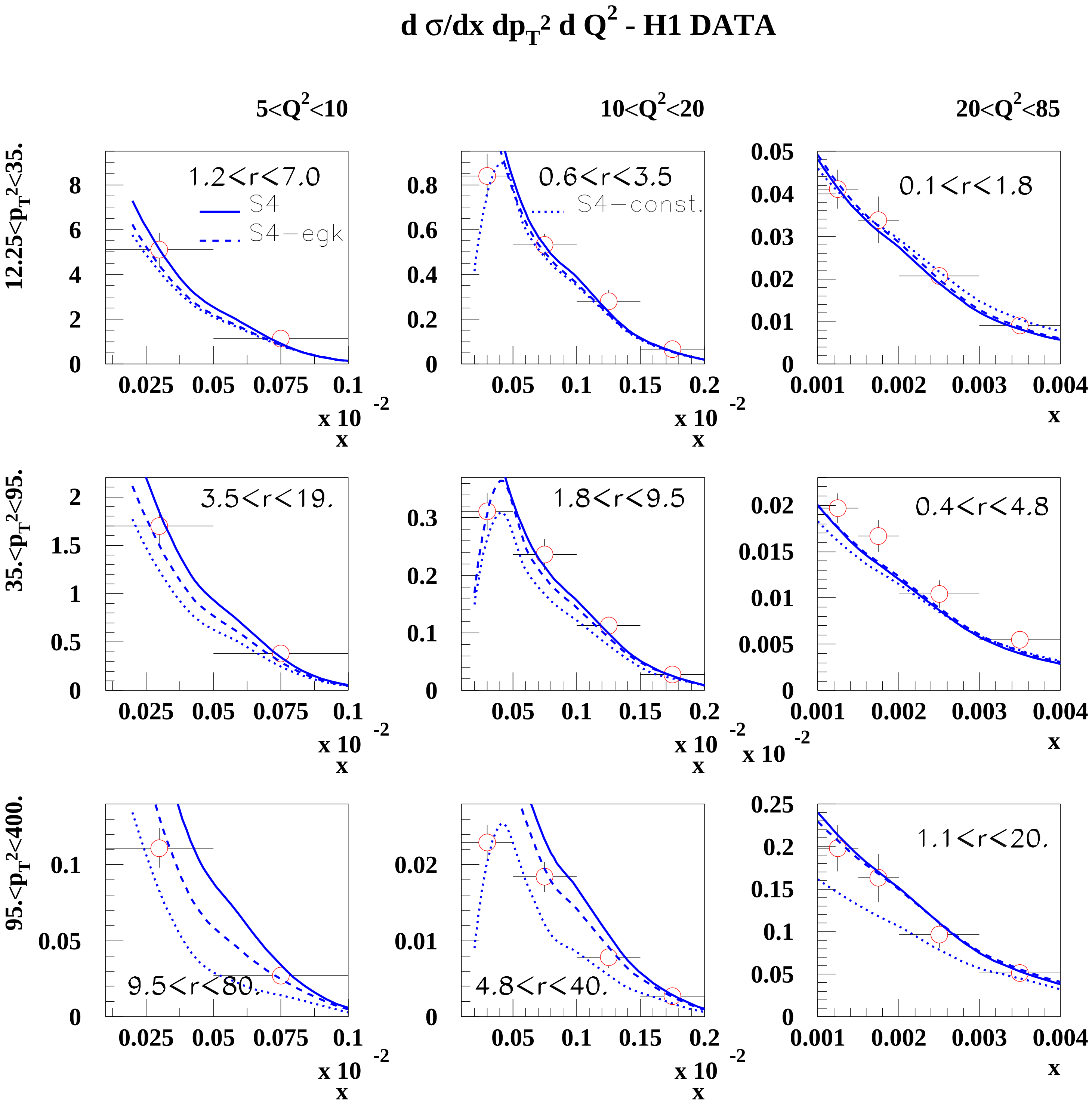


Comparison with H1 triple differential data



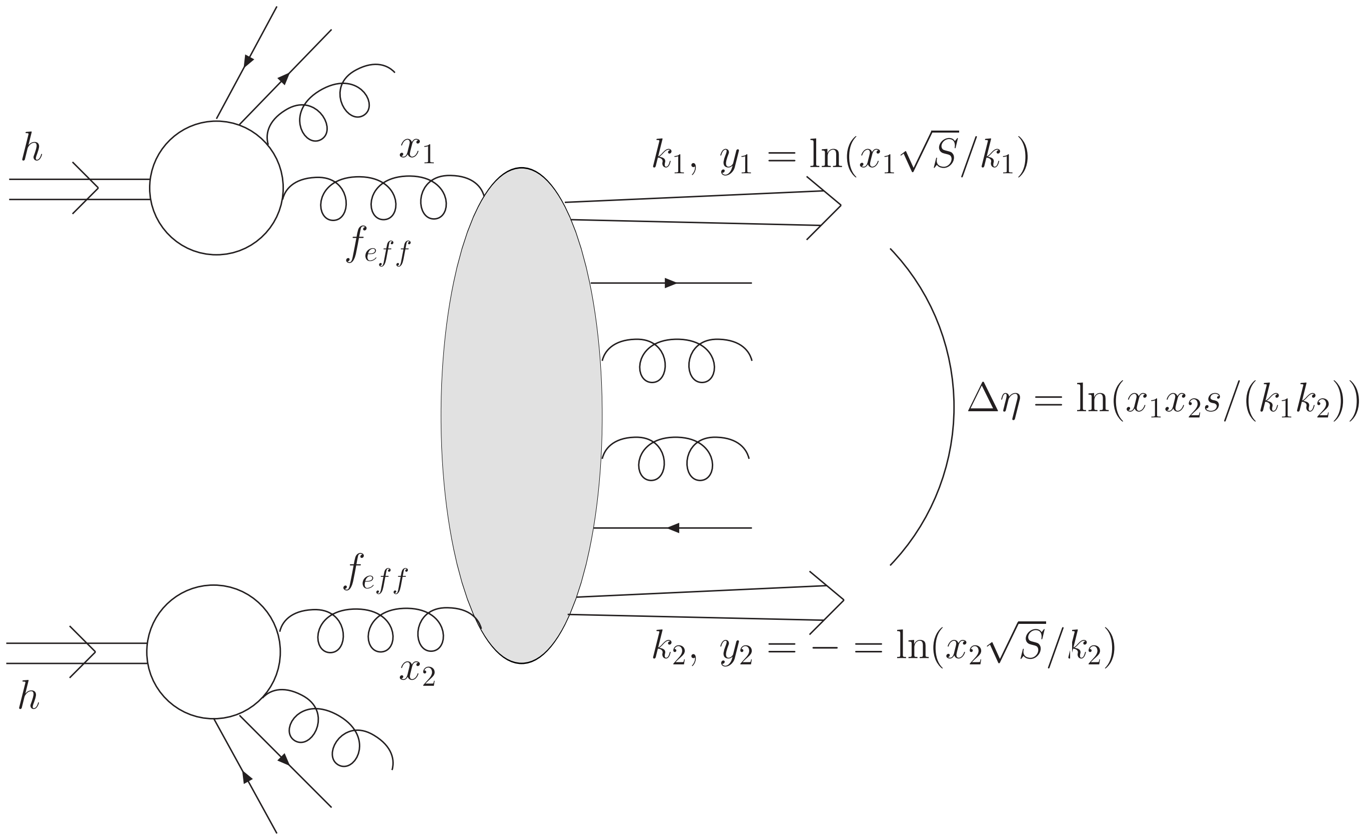
Comparison with H1 triple differential data

Study of dependence on impact factor



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:
- C. Marquet, C. Royon: Phys. Rev. D79 (2009) 034028

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:

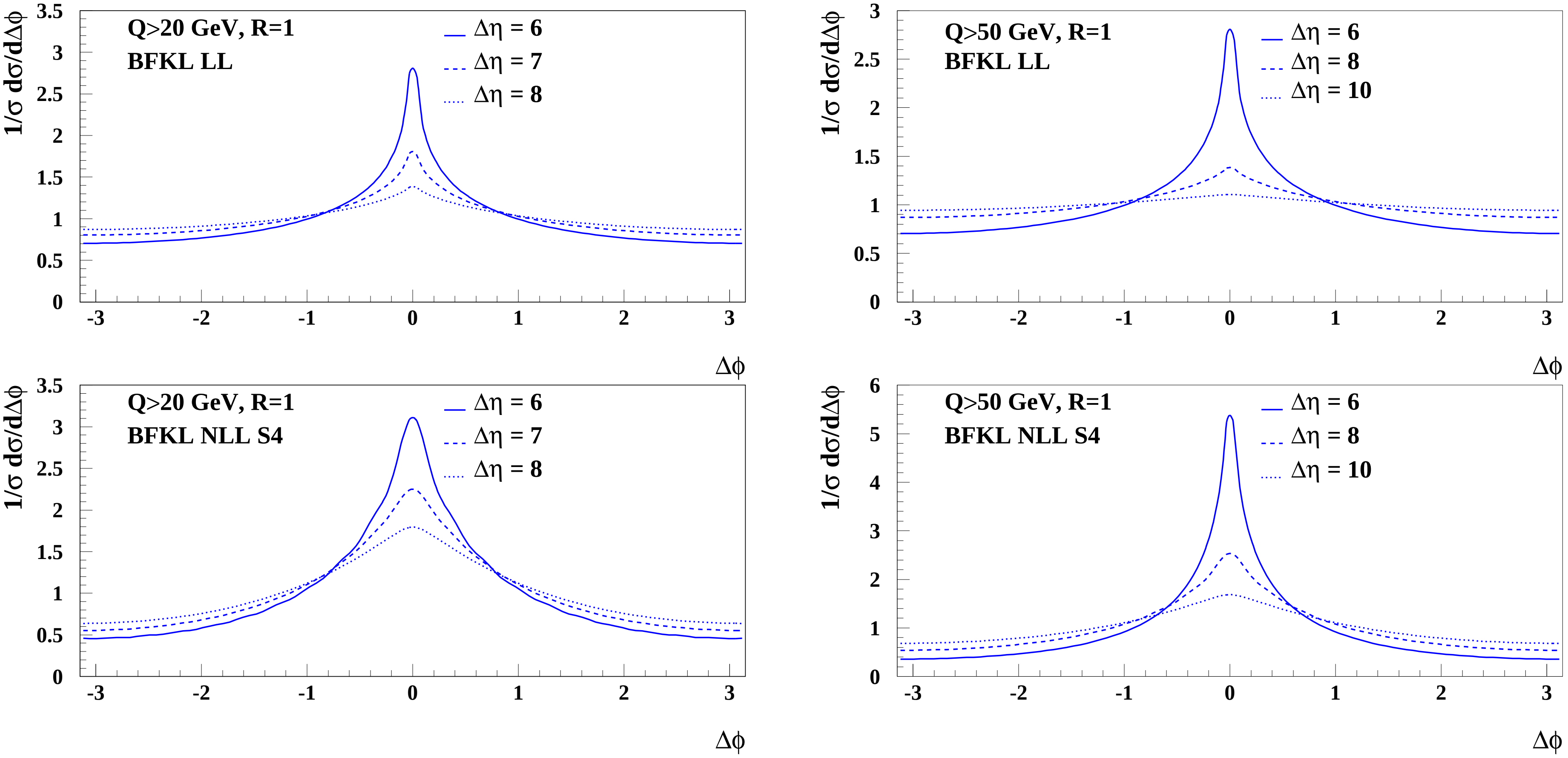
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Bigg/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

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}

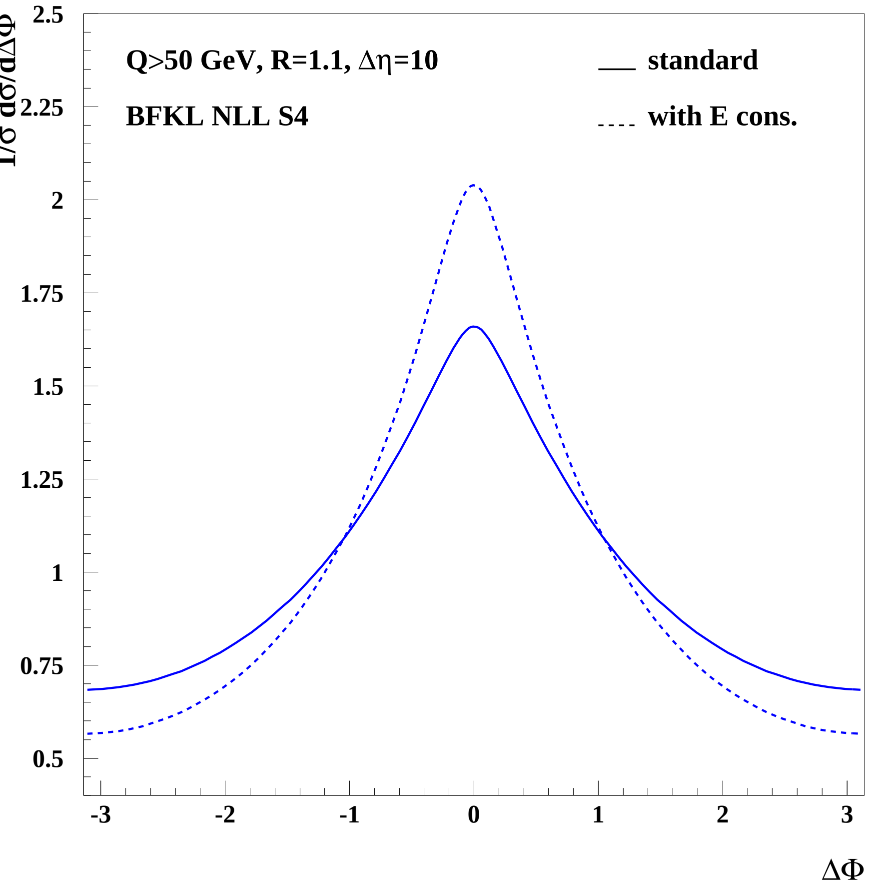
$$
\begin{aligned}
y_{eff} \quad = \quad & \Delta\eta \ \left(\int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right) \\
& \left(\int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right)^{-1}
\end{aligned}
$$

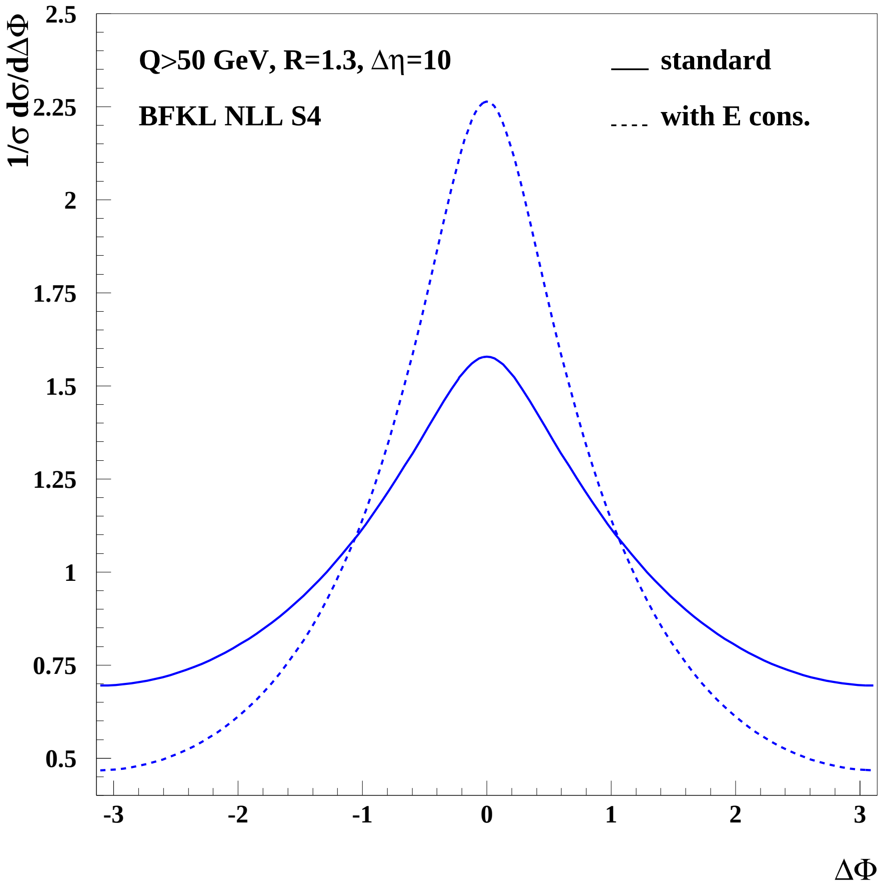
where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \rightarrow 3$ contribution to the $hh \rightarrow JXJ$ cross-section at order α_s^3, and $d\sigma^{LL-BFKL}$ is the LL-BFKL result

- 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

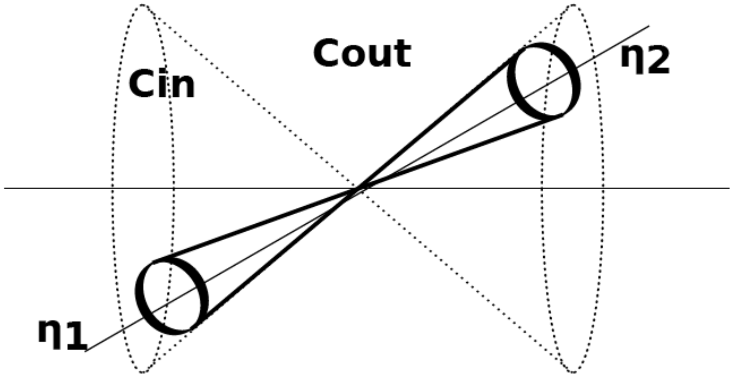
Mueller Navelet cross sections: energy conservation effect in BFKL

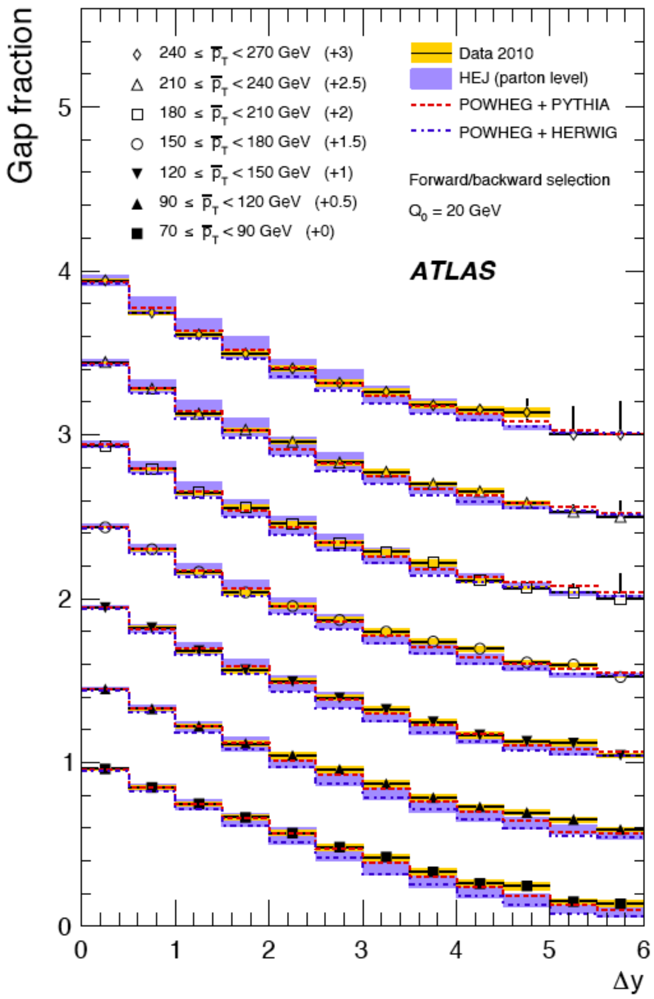
- Effect of energy conservation on BFKL dynamics
- Large effect if jet p_T ratios not close to 1: goes closer to DGLAP predictions, needs jet p_T ratio $<$ 1.1-1.15





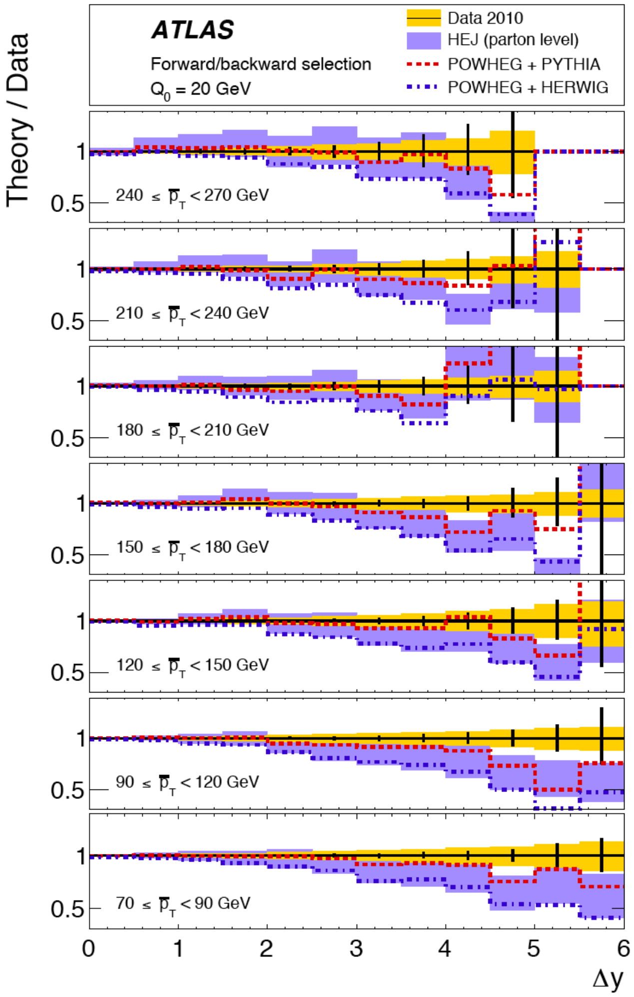
ATLAS "jet veto" measurement: sign of BFKL?





- 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

Comparison with QCD calculation

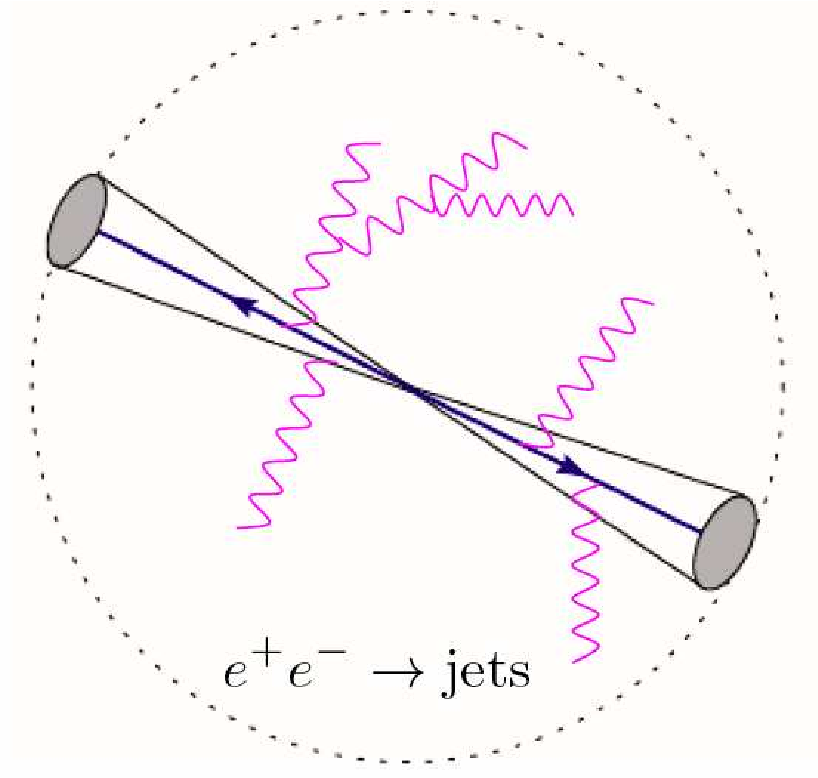


- The standard NLO and parton shower approach (POWHEG + pythia or herwig) fails to describe data

$$\frac{(d\sigma^{2\to2}+d\sigma^{2\to3})_{p_{T_3}<E_{out}}}{d\sigma^{2\to2}+d\sigma^{2\to3}}$$

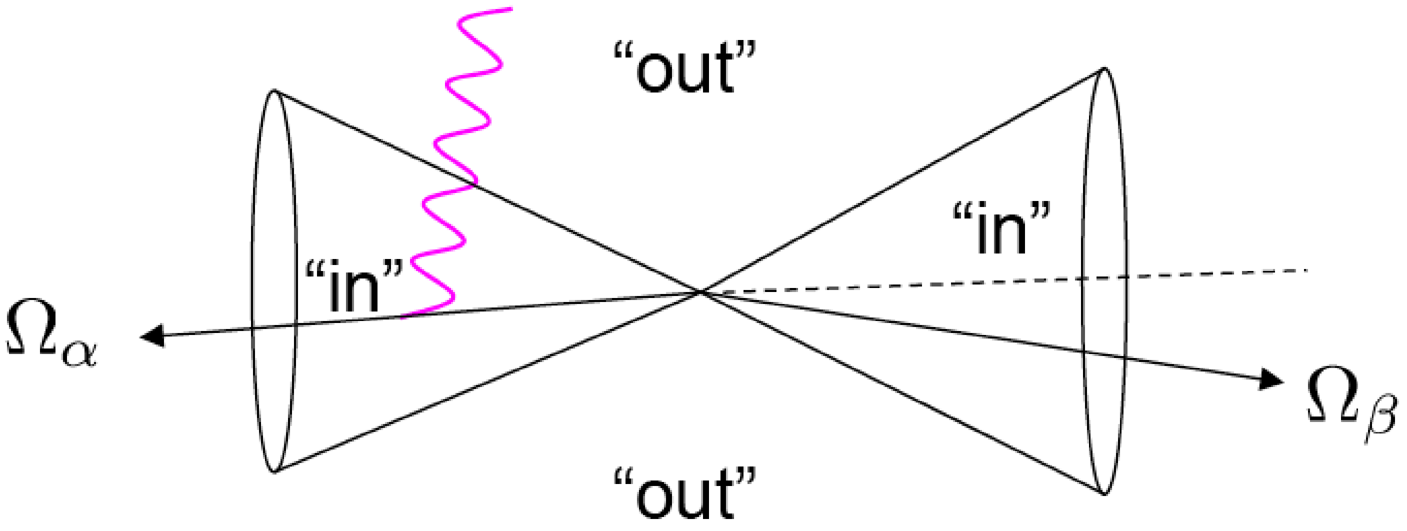
- BFKL resummation (HEJ Monte Carlo) also fails to describe data
- Both approaches miss the resummation of soft gluons at large angles

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}

Sudakov logs

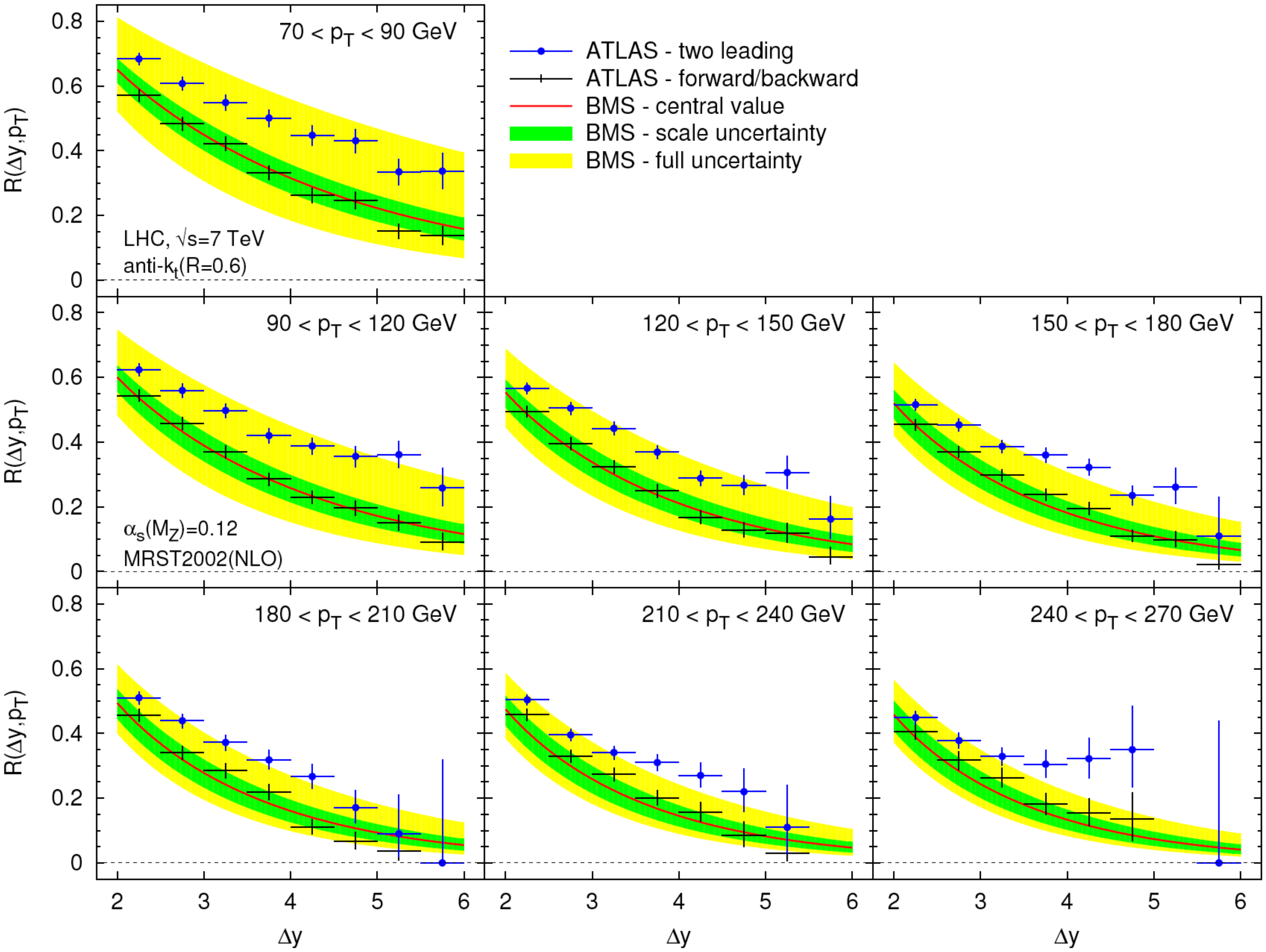
$$\partial_\tau P_\tau(\Omega_\alpha,\Omega_\beta) = -\int_{\mathcal{C}_{out}} \frac{d^2\Omega_\gamma}{4\pi}\frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})}P_\tau(\Omega_\alpha,\Omega_\beta)$$

$$+\int_{\mathcal{C}_{in}} \underbrace{\frac{d^2\Omega_\gamma}{4\pi}\frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})}}_{\text{differential probability for the soft gluon emission}}\Big(P_\tau(\Omega_\alpha,\Omega_\gamma)P_\tau(\Omega_\gamma,\Omega_\beta)-P_\tau(\Omega_\alpha,\Omega_\beta)\Big)$$

non-global logs

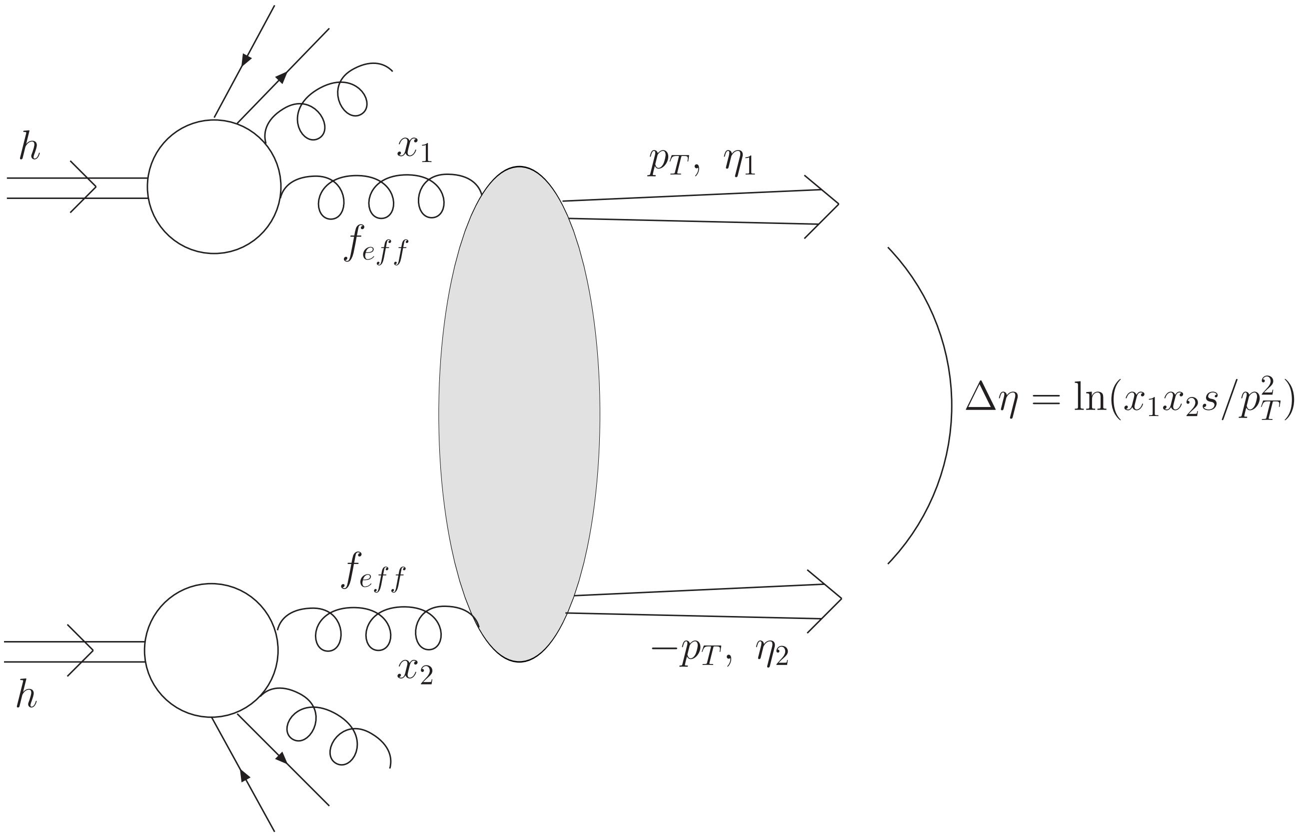
- Numerical solutions are available (Hatta and Ueda, 2009)

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)
- O. Kepka, C. Marquet, C. Royon, Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036

BFKL formalism

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

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

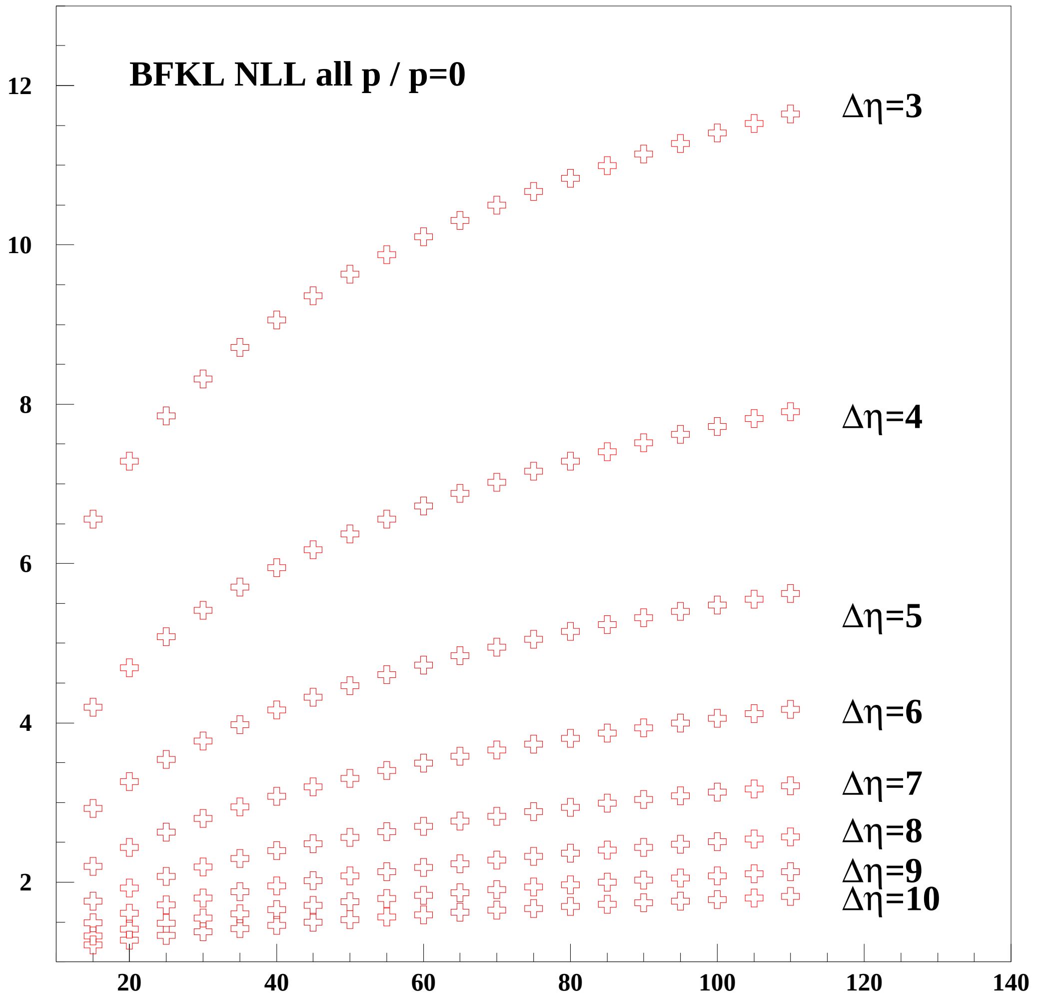
where S is the survival probability (0.1 at Tevatron, 0.03 at LHC)

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

- 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...:

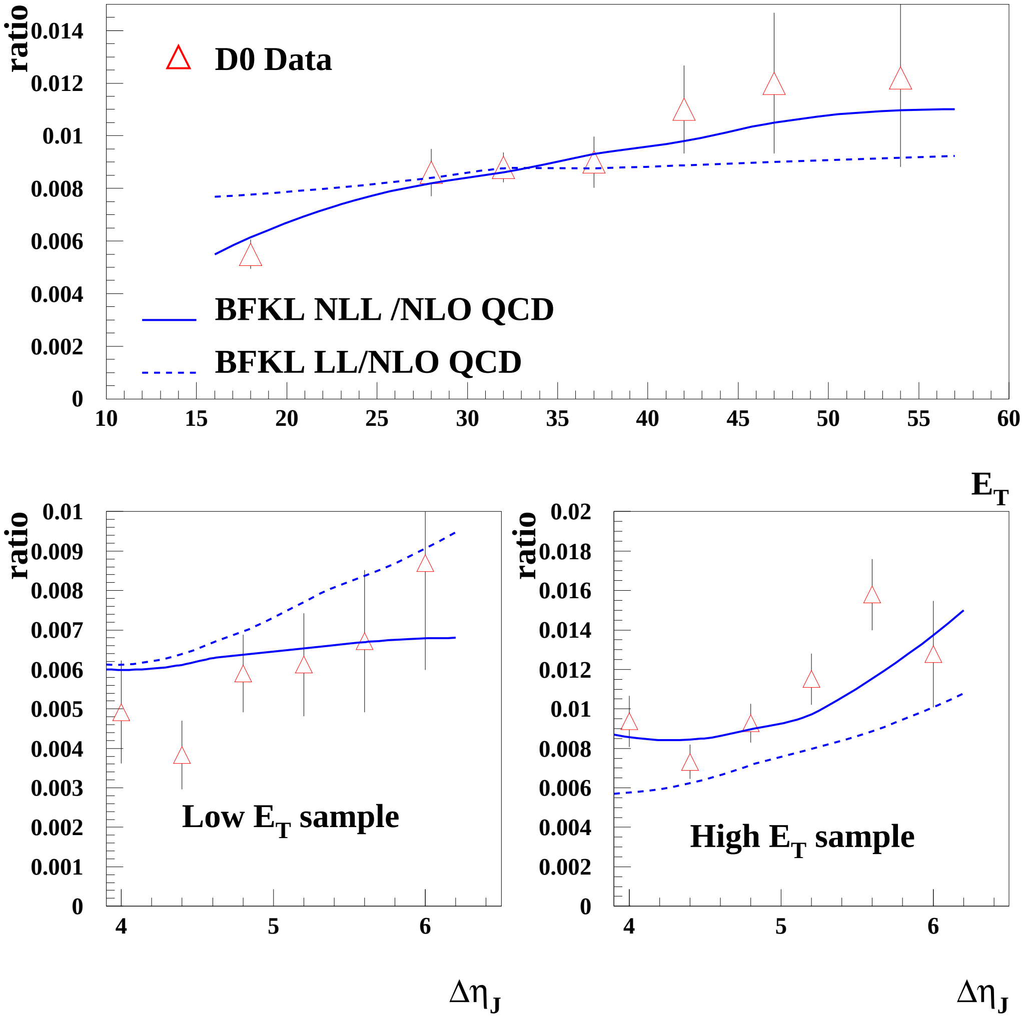


Comparison with D0 data

- 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:

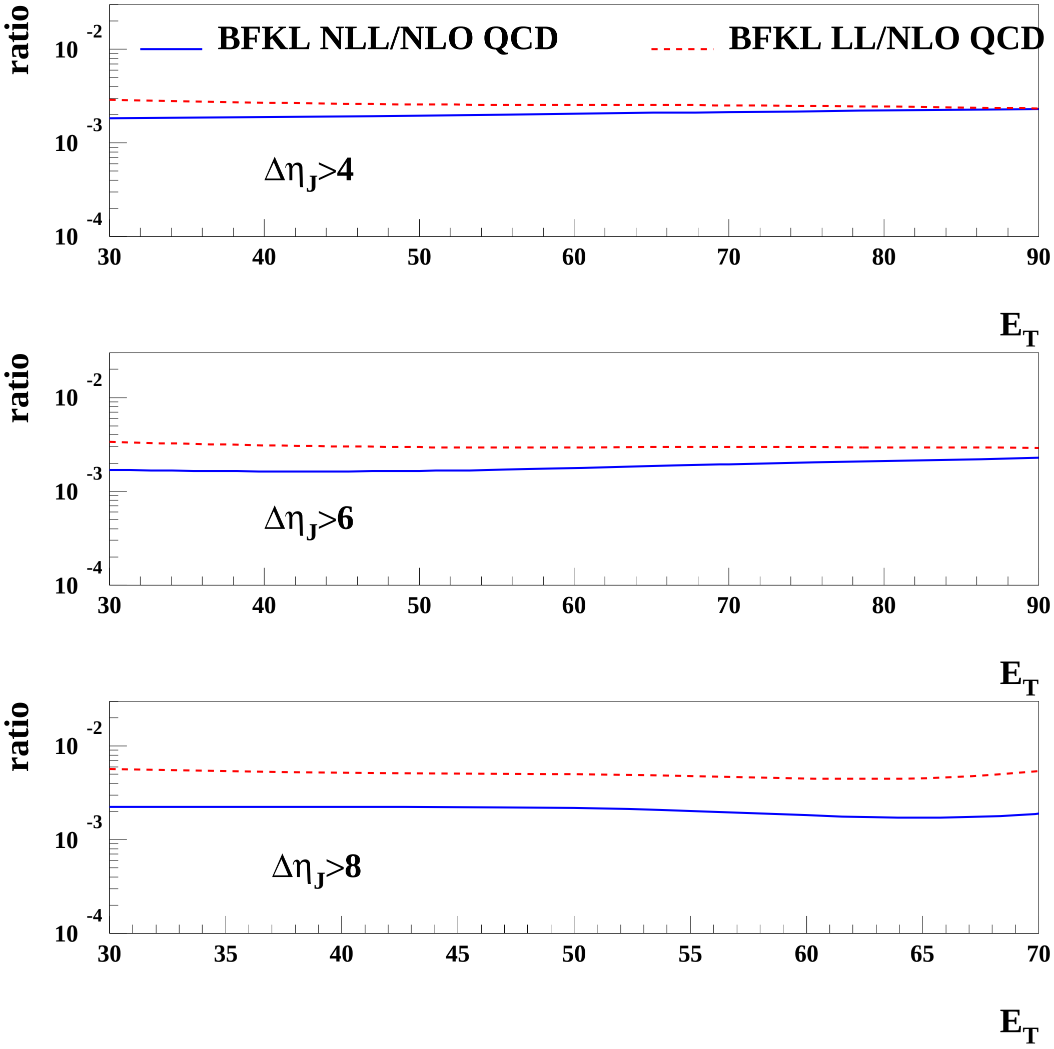
$$Ratio = \frac{BFKL\ NLL\ Herwig}{Dijet\ Herwig} \times \frac{LO\ QCD\ NLOJet++}{NLO\ QCD\ NLOJet++}$$

- Reasonable description using BFKL NLL formalism



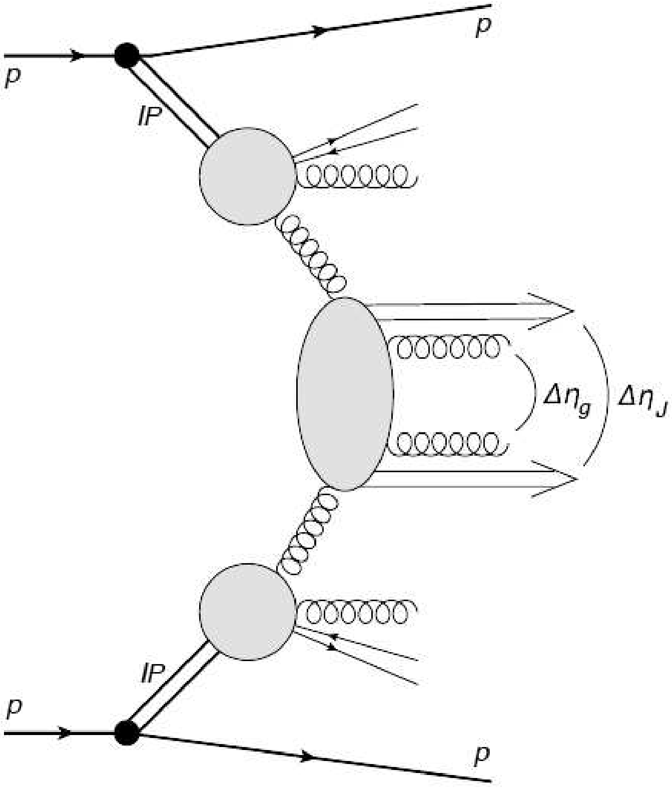
Predictions for the LHC

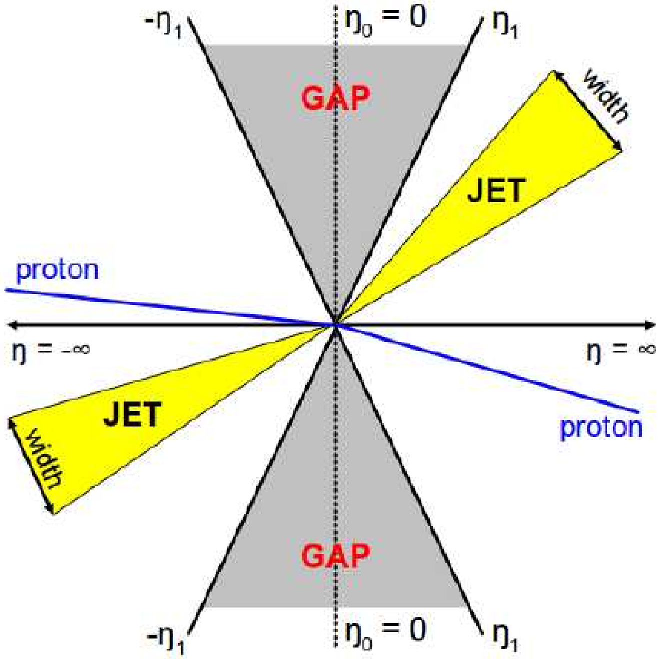
- Weak E_T and $\Delta\eta$ dependence
- Large differences in normalisation between BFKL LL and NLL predictions



Jet gap jet events in diffraction

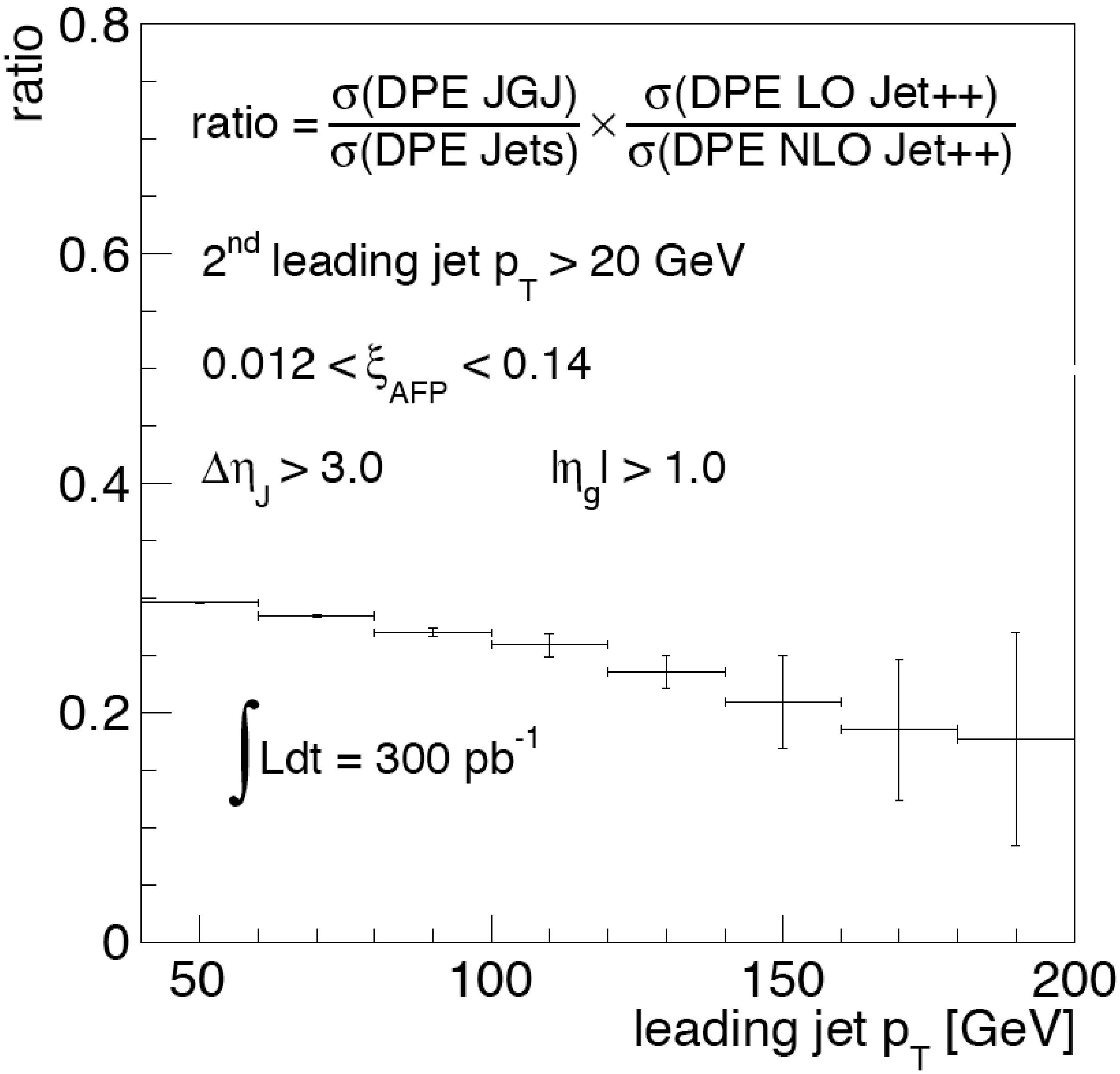
- Study BFKL dynamics using jet gap jet events
- Jet gap jet events in DPE processes: clean process, allows to go to larger $\Delta\eta$ between jets
- C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, ArXiv:1212:2059, Phys. Rev. D 87 (2013) 034010





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 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
- Jet veto measurements in ATLAS: not a clean test of BFKL resummation
- Jet gap jets:
  - NLL BFKL cross section implemented in HERWIG
  - Fair description of D0 and CDF data
  - Jet gap jet events in diffraction