Probing the BFKL dynamics at hadronic colliders

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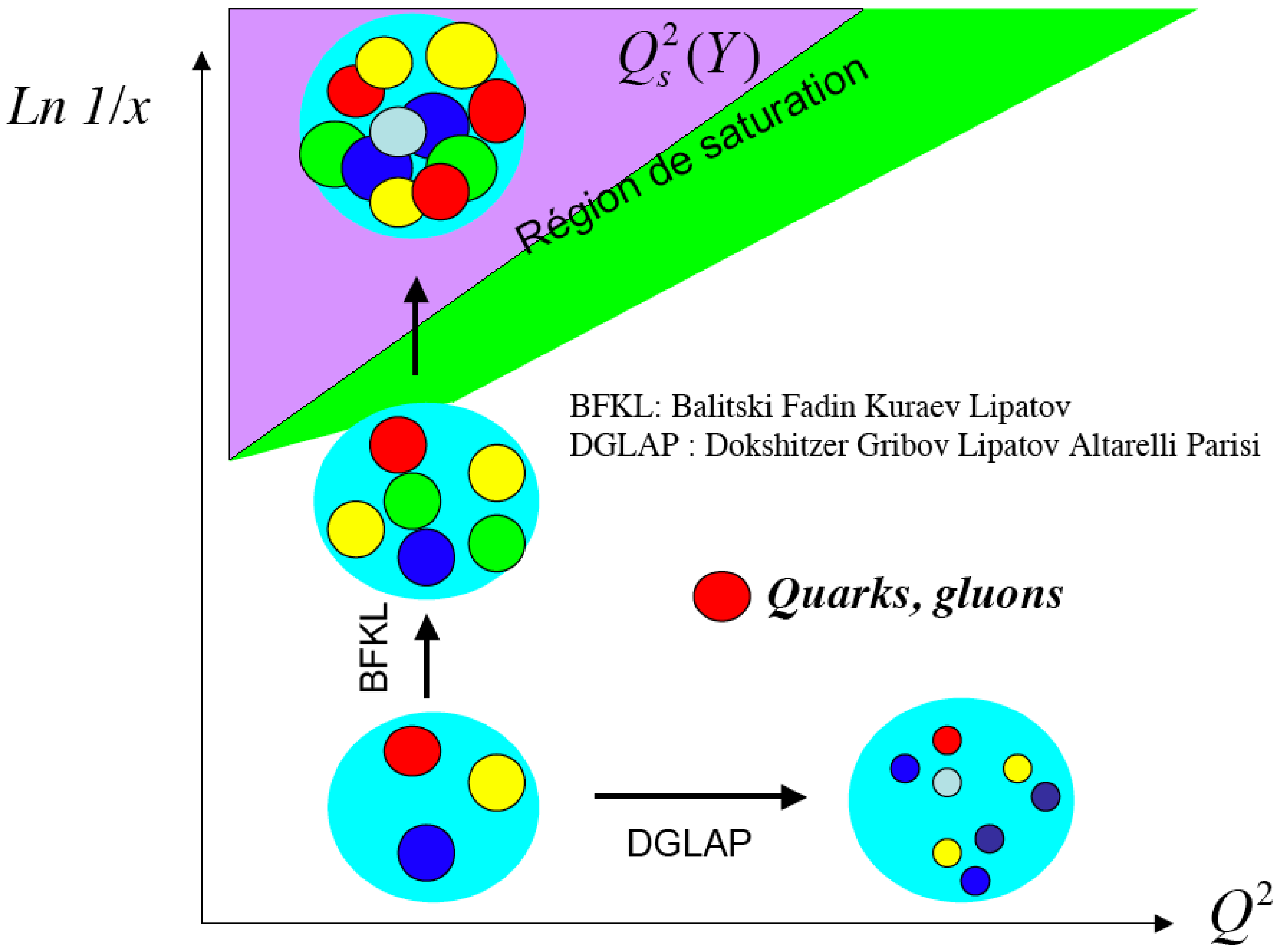
Contents:

- 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

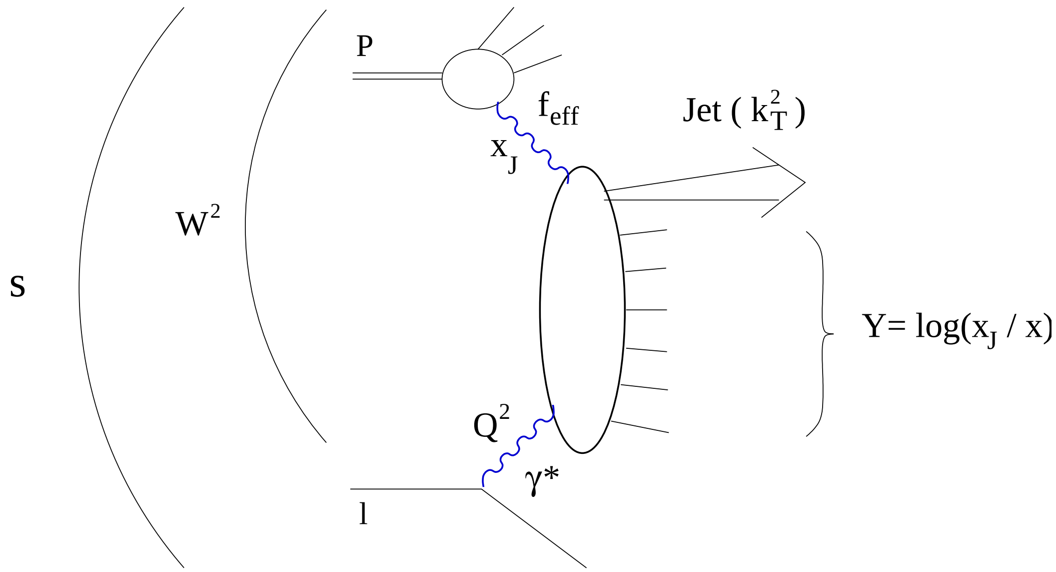
Work done in collaboration with D. Werder, O. Kepka, C. Marquet, R. Peschanski, M. Trzebinski, Y. Hatta, G. Soyez, T. Ueda, R. Zlebcik,...
Work in progress with D. Colferai, F. Deganutti, T. Raben, S. Schlichting

Looking for BFKL/saturation effects

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



Forward jet measurement at HERA

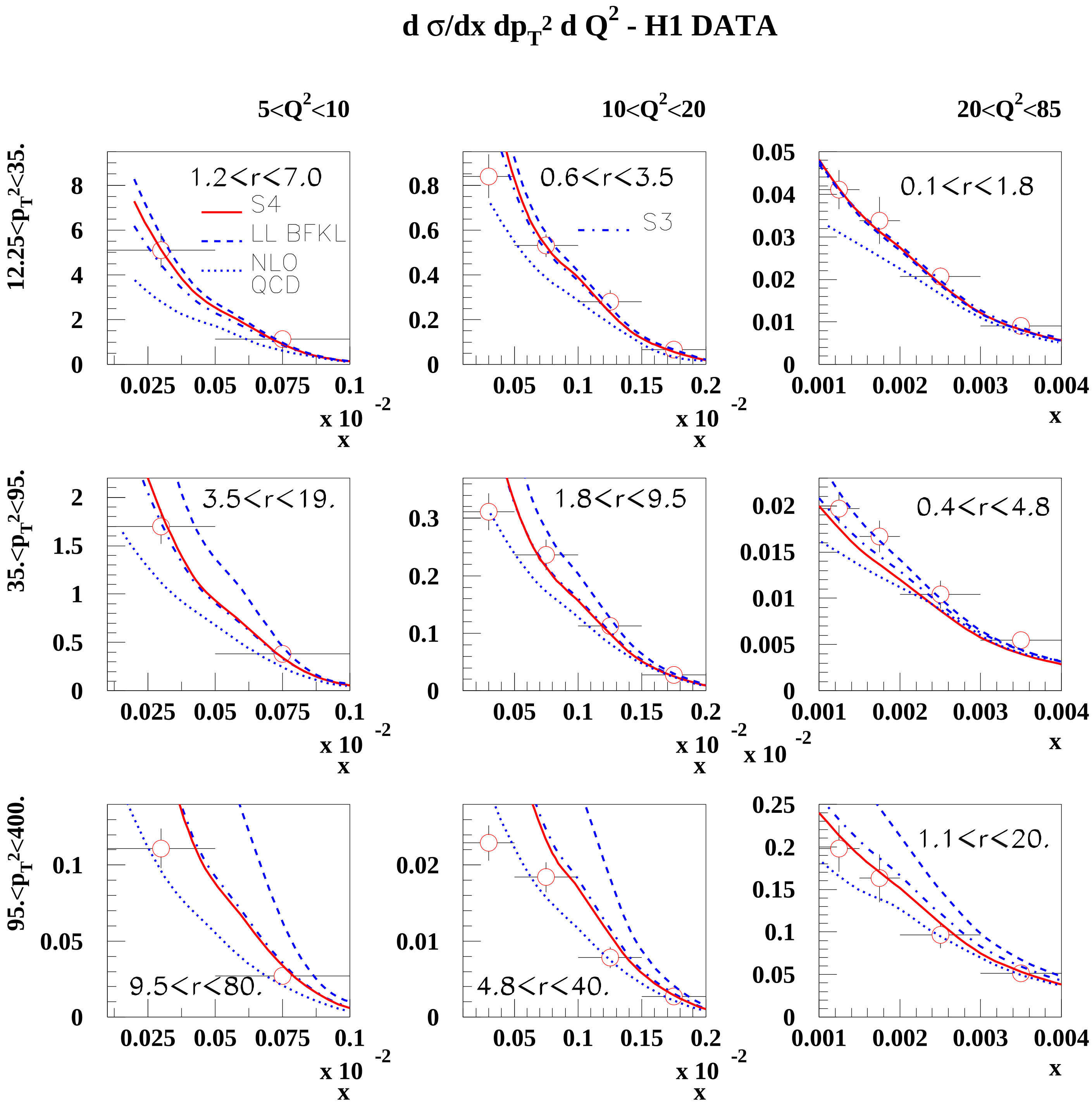


- Full BFKL NLL calculation used for the BFKL kernel, available in S3 and S4 resummation schemes to remove the spurious singularities (modulo the impact factors taken at LL)
- Equation:

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

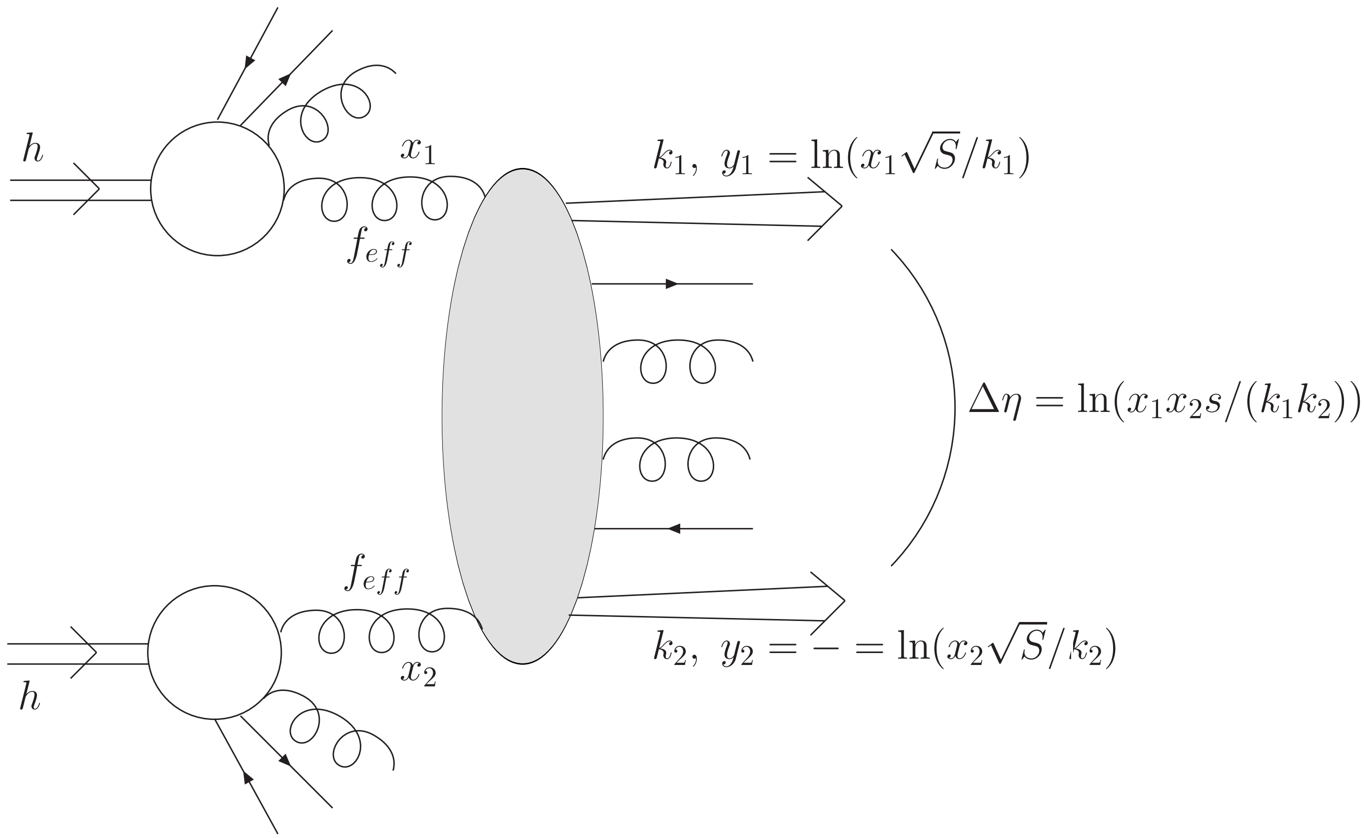
- Implicit equation: $\chi_{eff}(\gamma, \alpha) = \chi_{NLL}(\gamma, \alpha, \chi_{eff}(\gamma, \alpha))$ solved numerically (Nucl. Phys. B 739 (2006) 131; Phys. Lett. B 655 (2007) 236; Eur. Phys. J. C55 (2008) 259)

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

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:

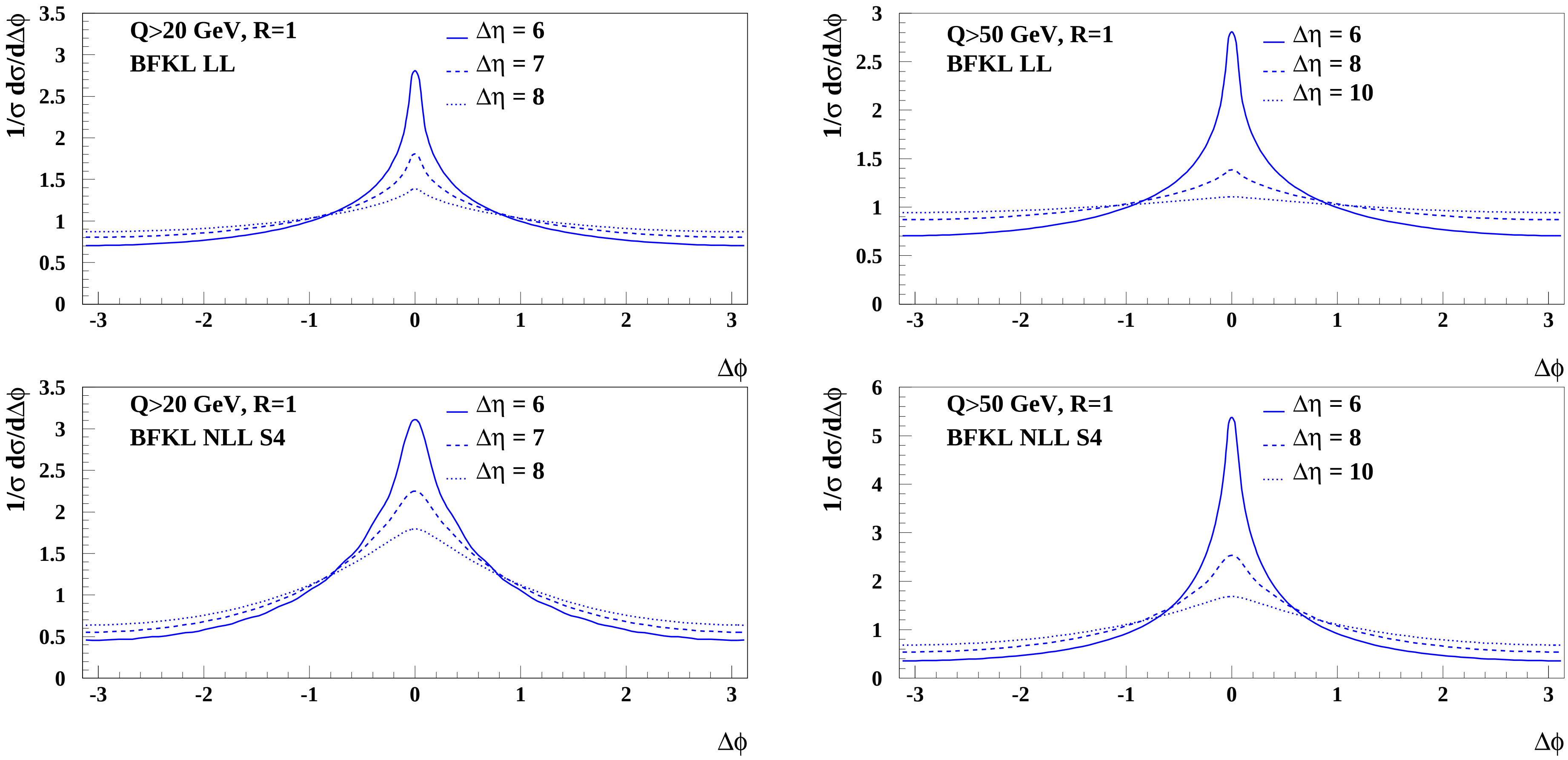
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Bigg/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

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%



- C. Marquet, C.R., Phys. Rev. D79 (2009) 034028
- Mueller Navelet jets at NLL and saturation effects: Study in progress with F. Deganutti, T. Raben, S. Schlichtling

Effect of energy conservation on BFKL equation

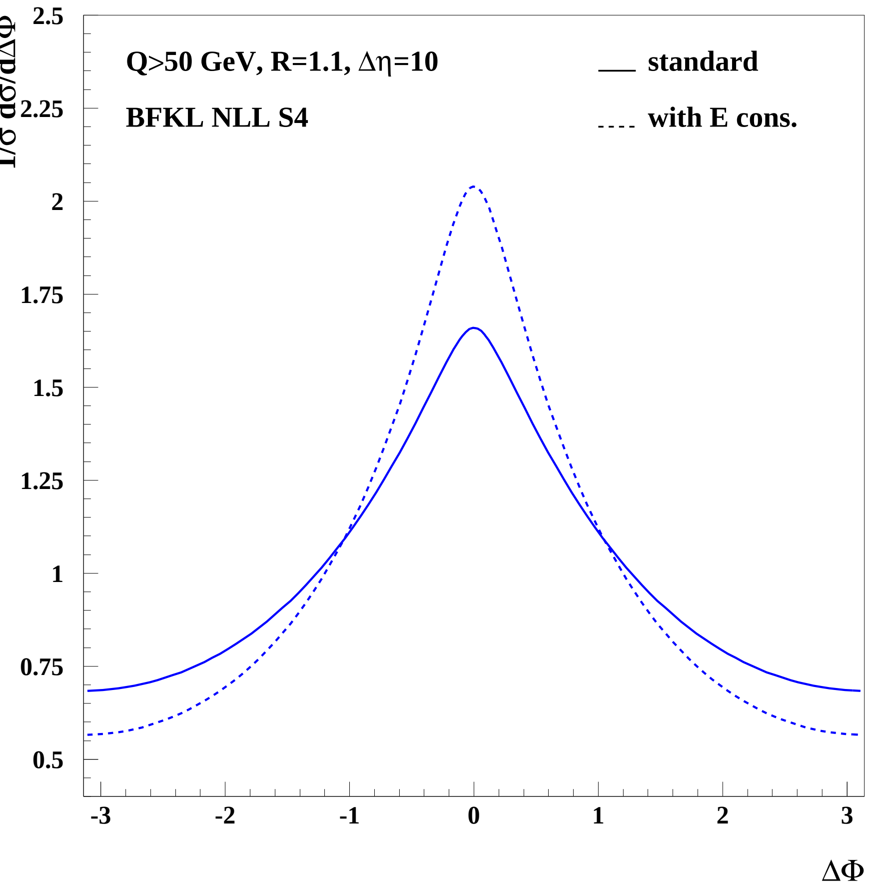
- BFKL cross section lacks energy-momentum conservation since these effects are higher order corrections
- Following Del Duca-Schmidt, we substitute $\Delta\eta$ by an effective rapidity interval y_{eff}

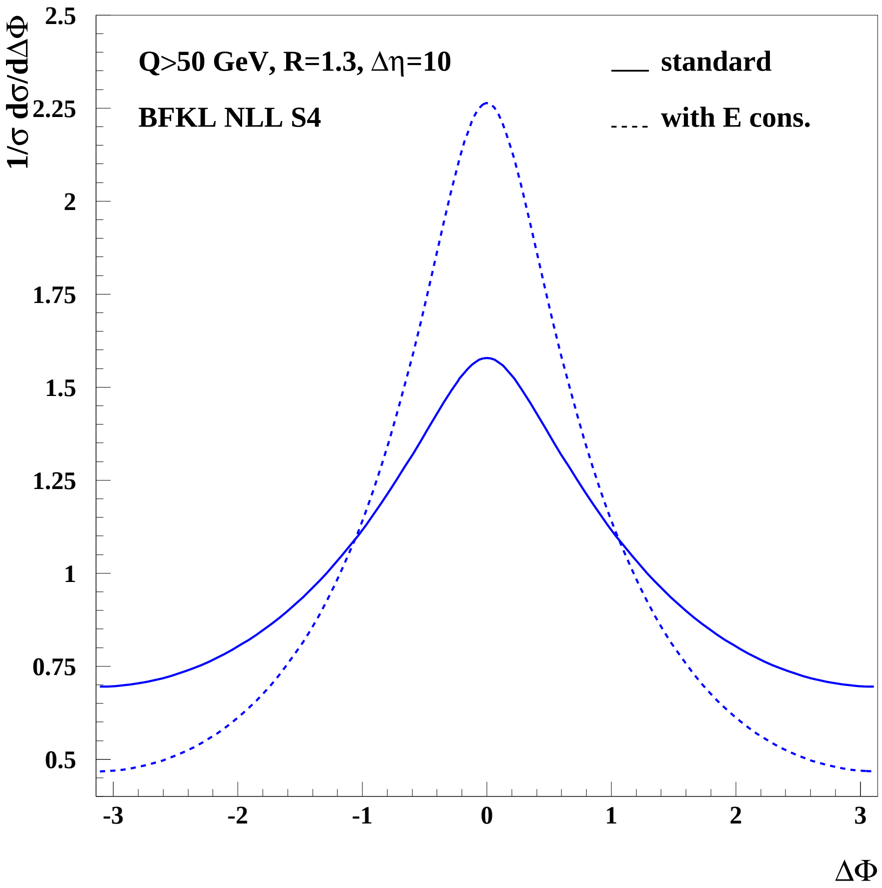
$$y_{eff} = \Delta\eta \left(\int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right) \left(\int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right)^{-1}$$

  where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \to 3$ 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





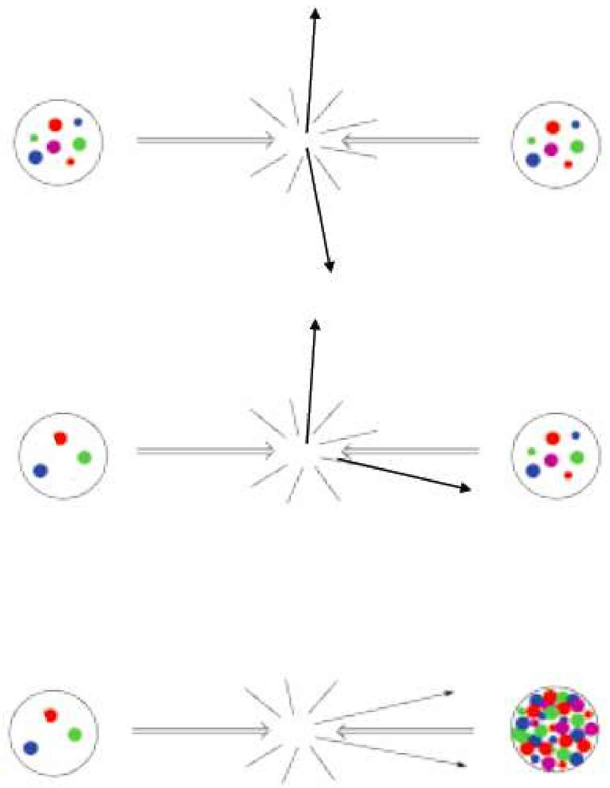
Saturation effects at the LHC: Use pA data

- Saturation effects: need to go to low x, jets as forward as possible on the same side
- Compare pp and pA runs in order to remove many systematics

final state : $k_1, y_1 \quad k_2, y_2$

$$x_p = \frac{k_1\, e^{y_1} + k_2\, e^{y_2}}{\sqrt{s}} \qquad x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}}$$

scanning the wave functions:



$$x_p \sim x_A < 1$$

central rapidities probe moderate x

x_p increases | x_A ~ unchanged

$$x_p \sim 1, x_A < 1$$

forward/central doesn't probe much smaller x

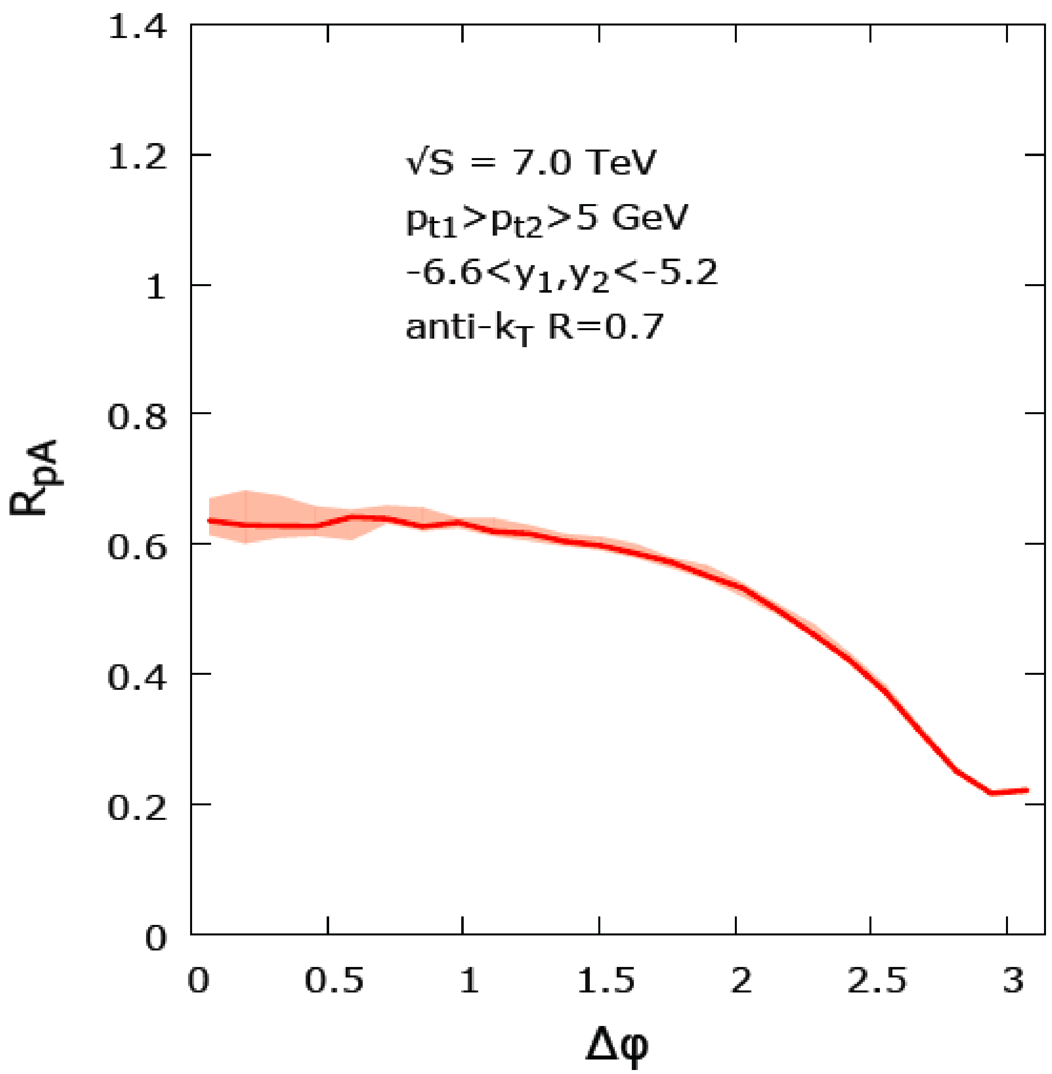
x_p ~ unchanged | x_A decreases

$$x_p \sim 1, x_A << 1$$

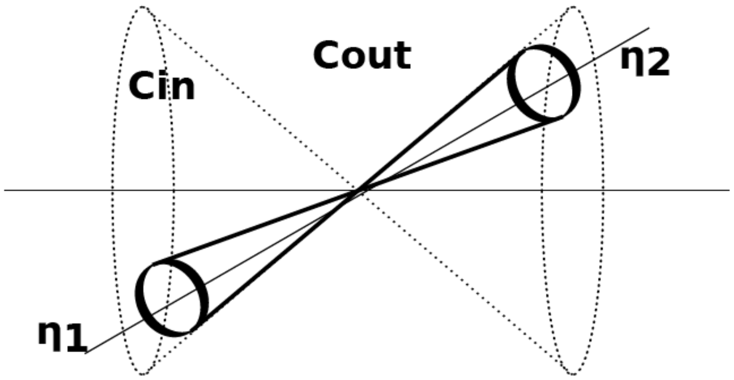
forward rapidities probe small x

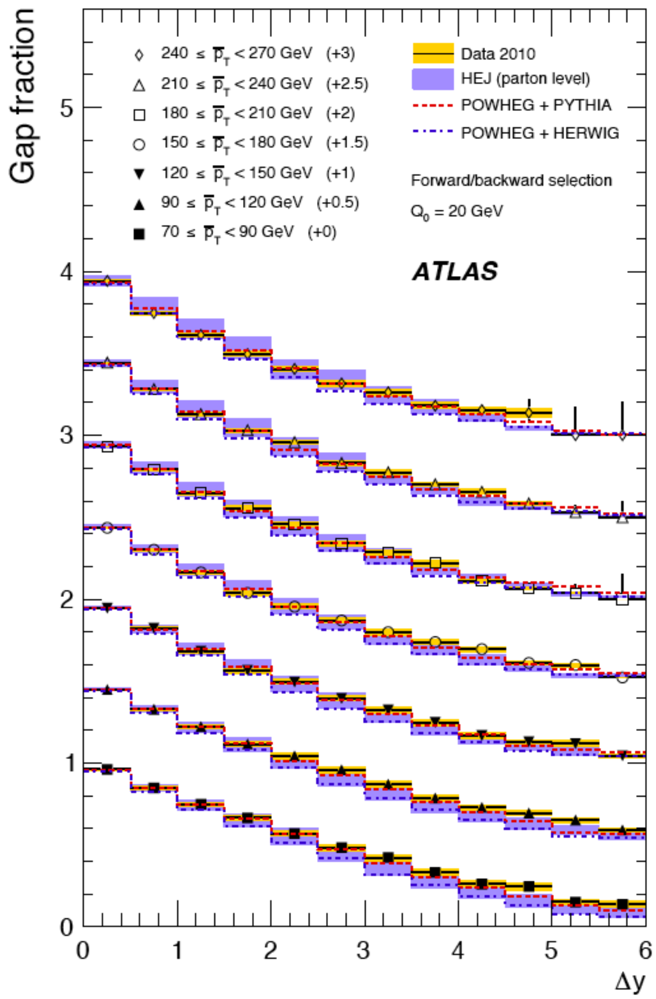
Saturation effects at the LHC

- Suppression factor between pp and pA runs: estimated to be 1/2 in CASTOR acceptance
- Important to get CASTOR in pA and low lumi pp data
- Study performed by Cyrille Marquet et al.



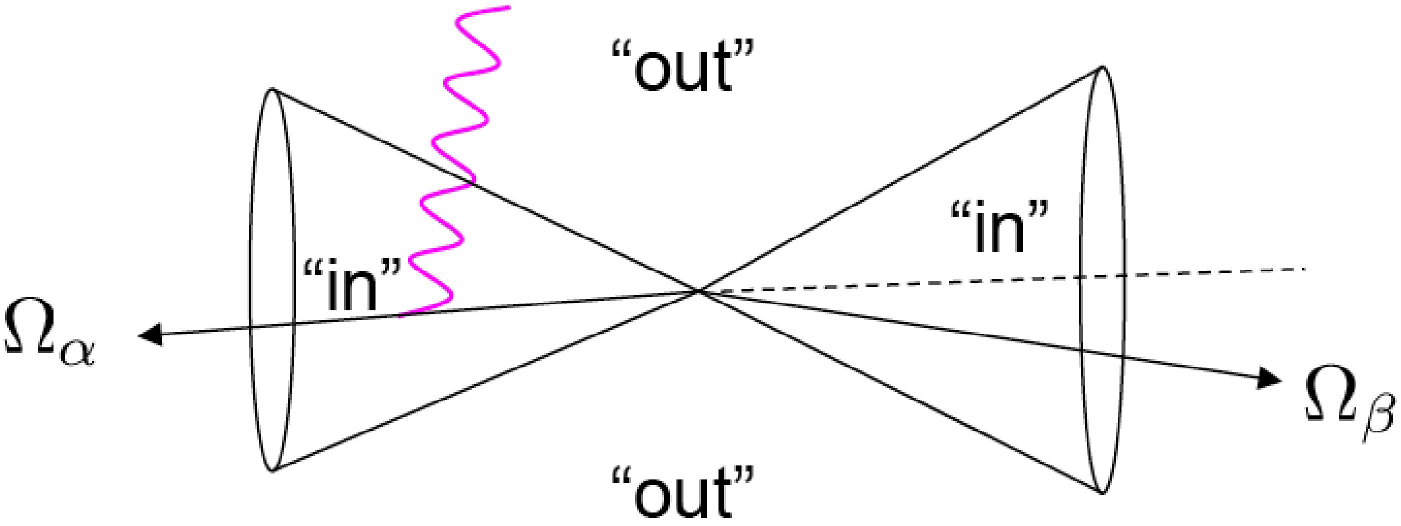
One aside: ATLAS "jet veto" measurement: sign of BFKL?





- 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 Smye equation



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

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

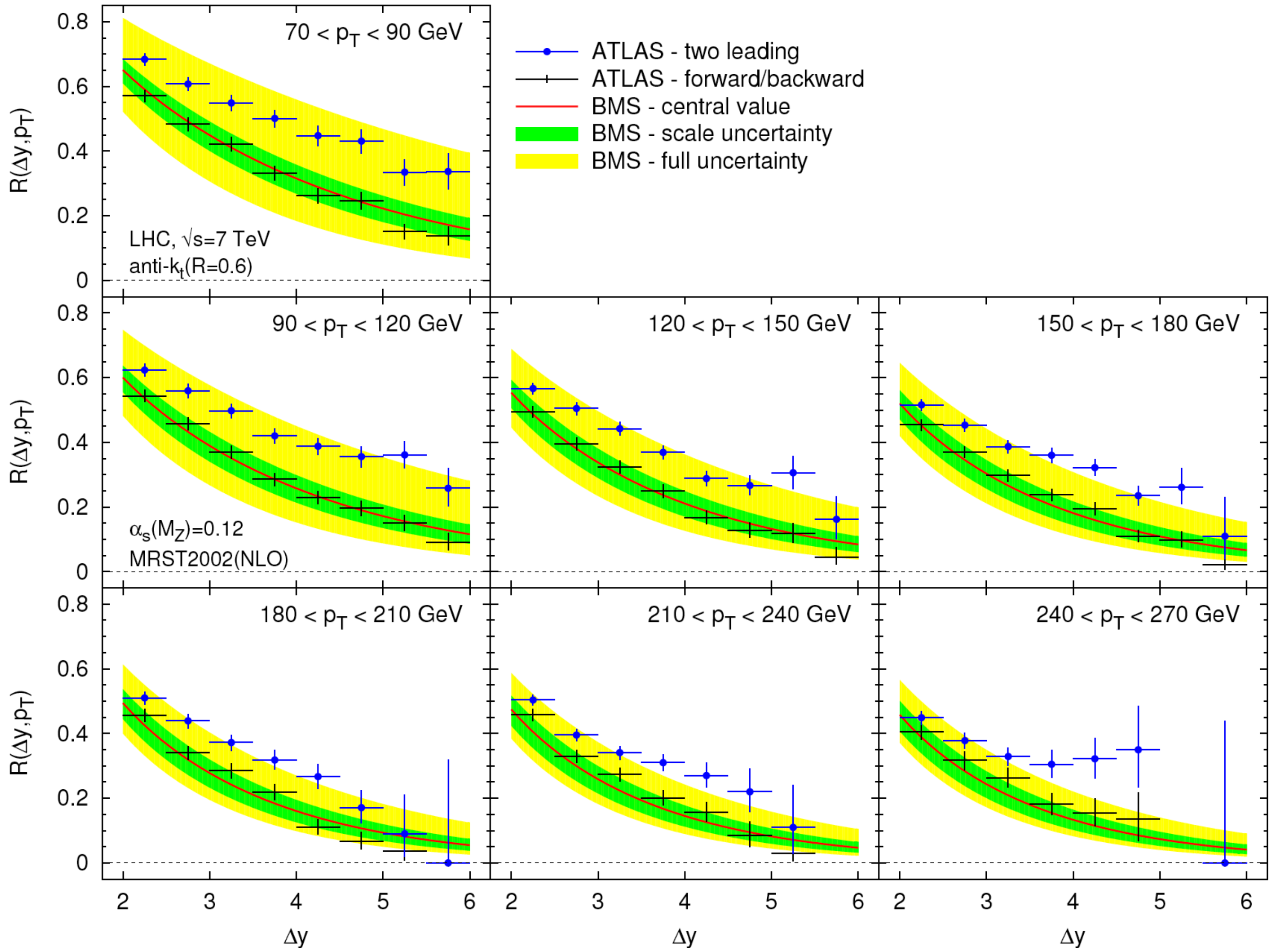
Sudakov logs

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

non-global logs

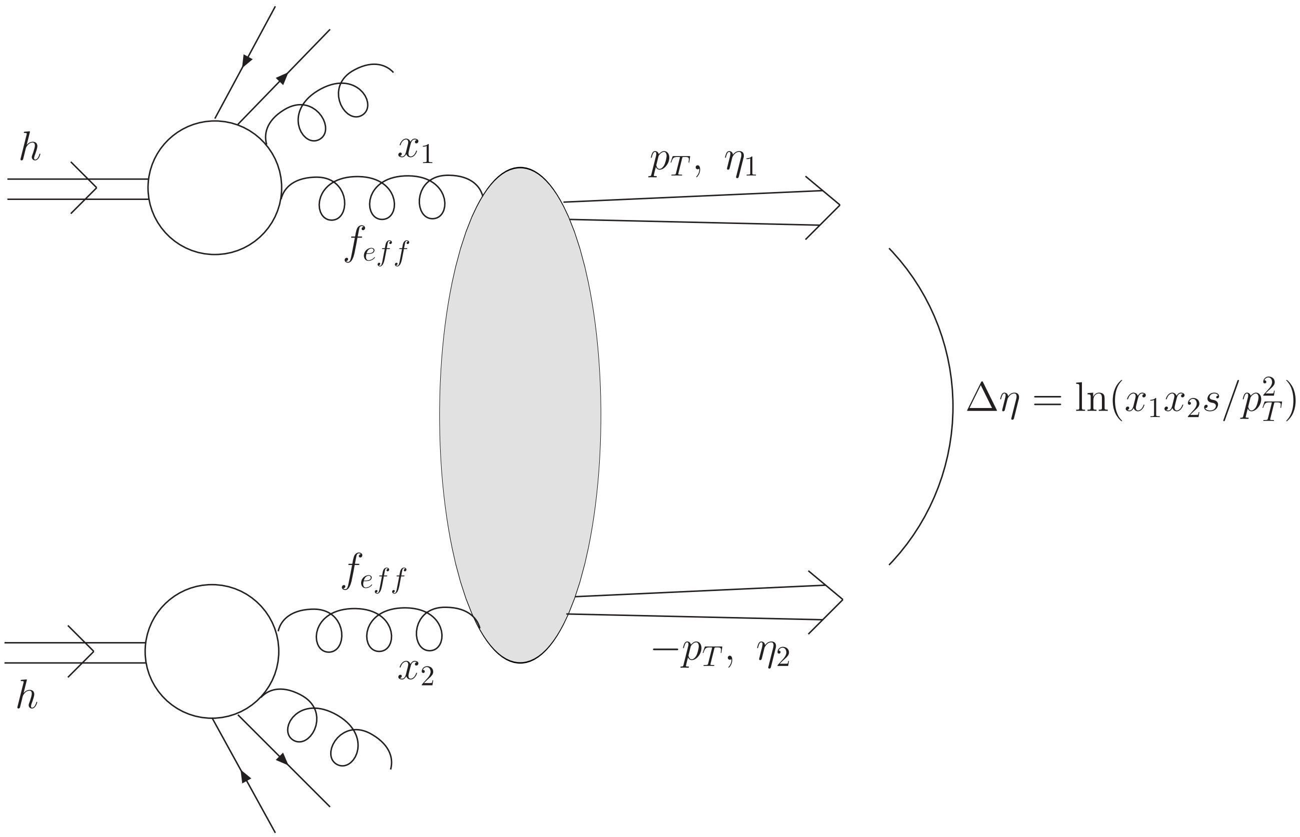
- Numerical solutions are available (Hatta and Ueda, 2009)

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)

BFKL formalism

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

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

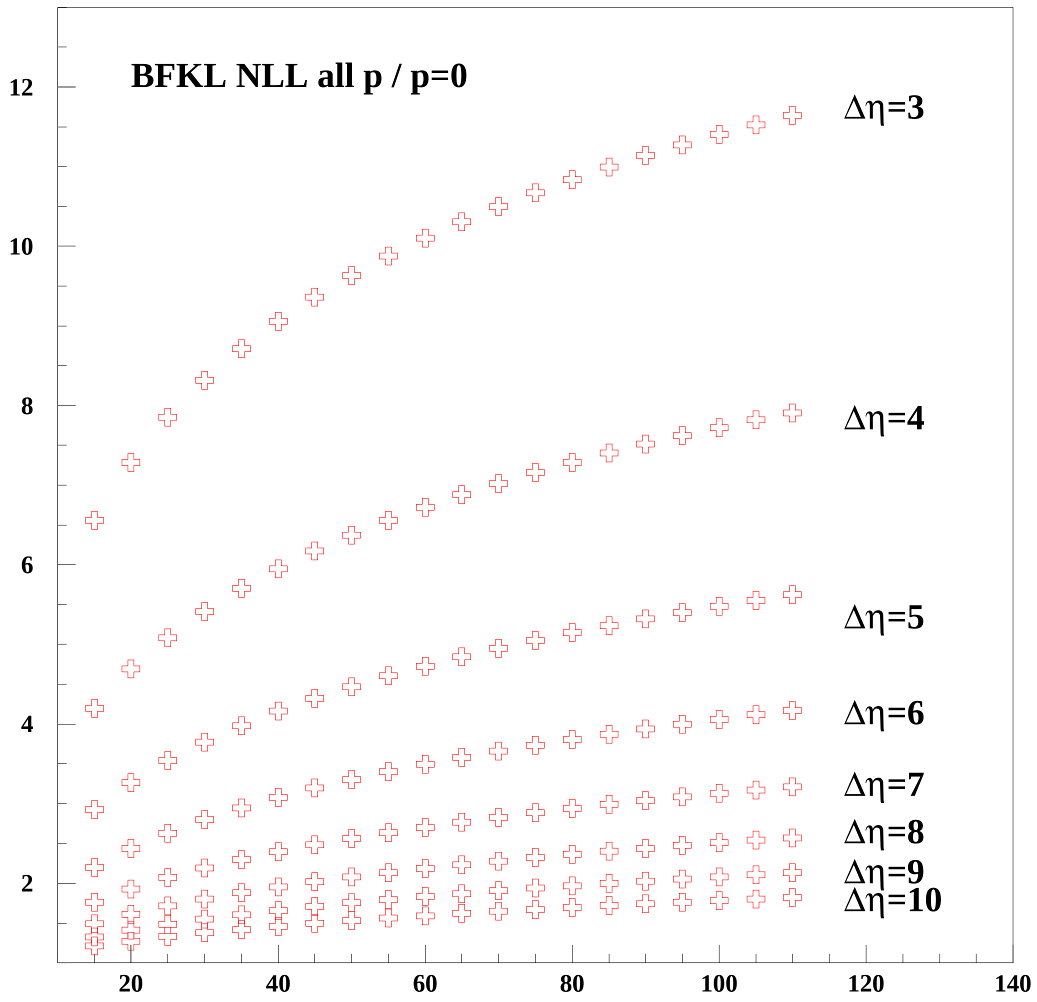
where S is the survival probability (0.1 at Tevatron, 0.03 at LHC)

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

- 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...:

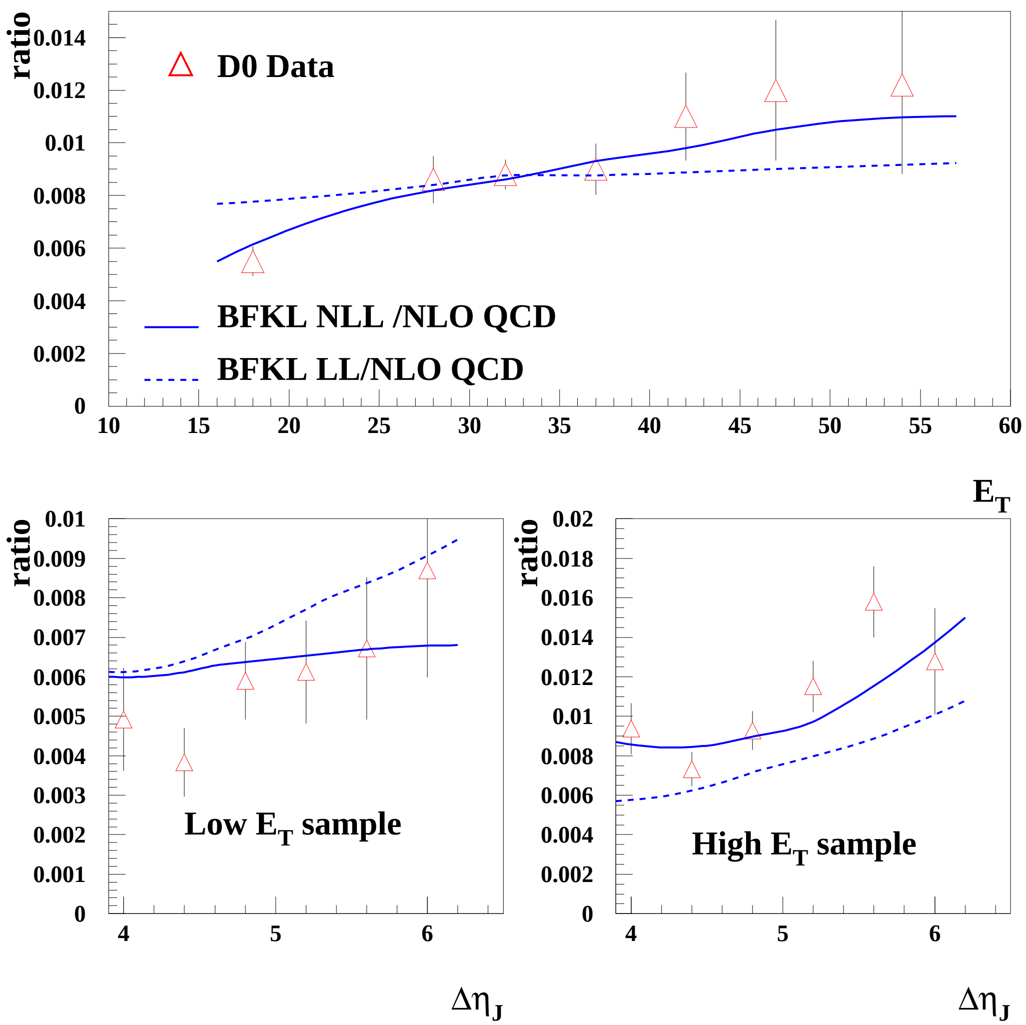


Comparison with D0 data

- 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:

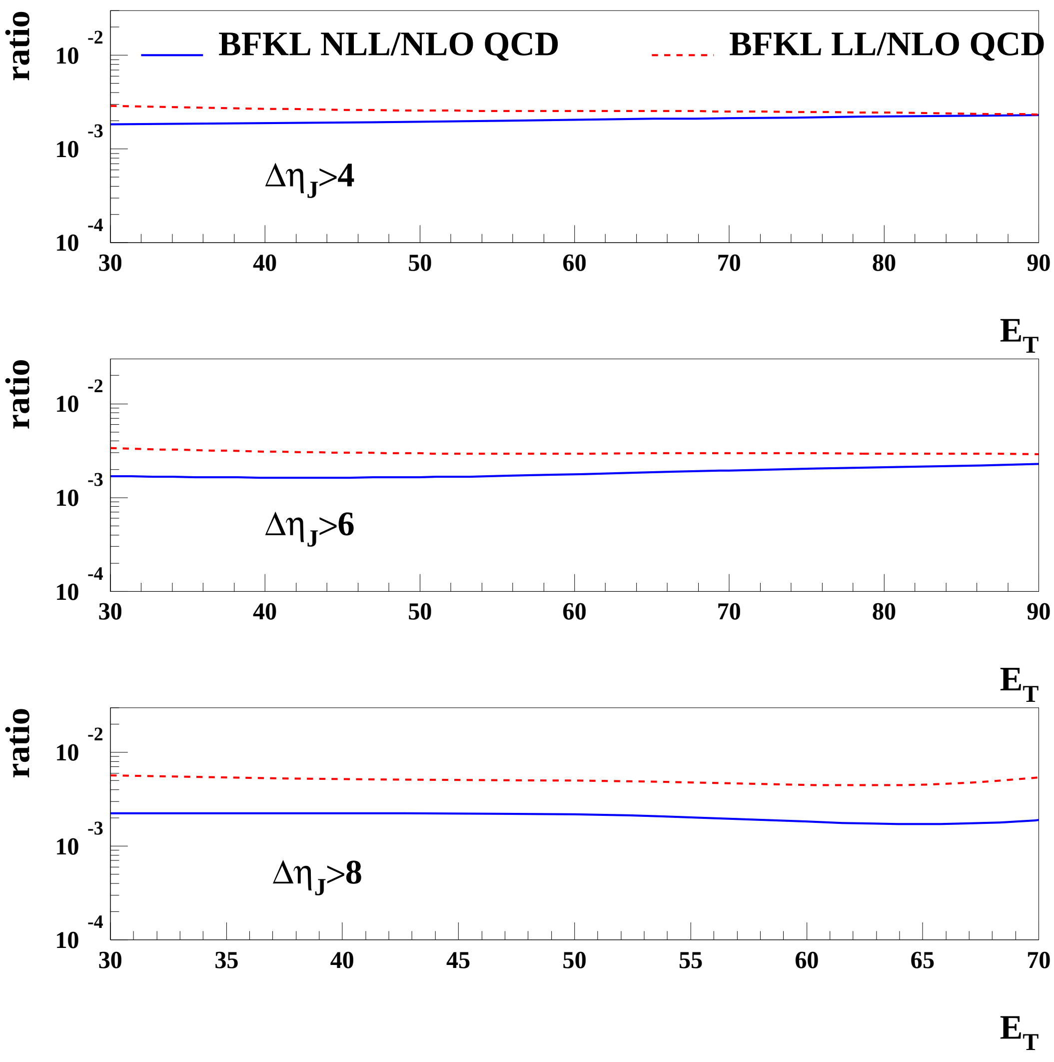
$$Ratio = \frac{BFKL\ NLL\ Herwig}{Dijet\ Herwig} \times \frac{LO\ QCD\ NLOJet++}{NLO\ QCD\ NLOJet++}$$

- Reasonable description using BFKL NLL formalism



Predictions for the LHC

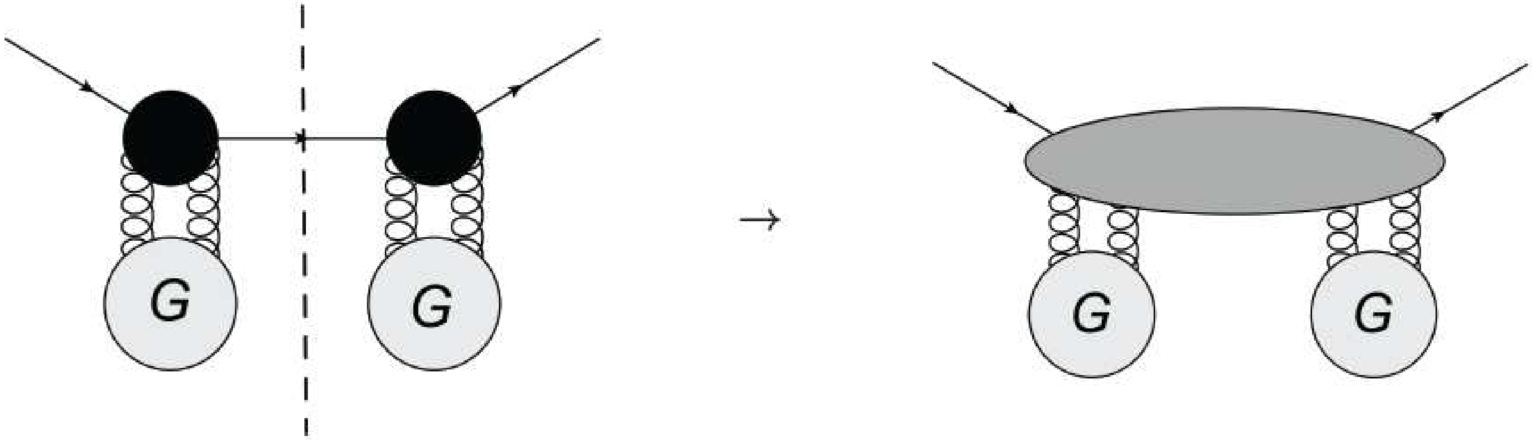
- Weak E_T and $\Delta\eta$ dependence
- Large differences in normalisation between BFKL LL and NLL predictions



- Implementation of BFKL NLL formalism including NLO impact factors
- Work done in collaboration with D. Colferai, F. Deganutti, T. Raben

Full NLL calculation (in progress)

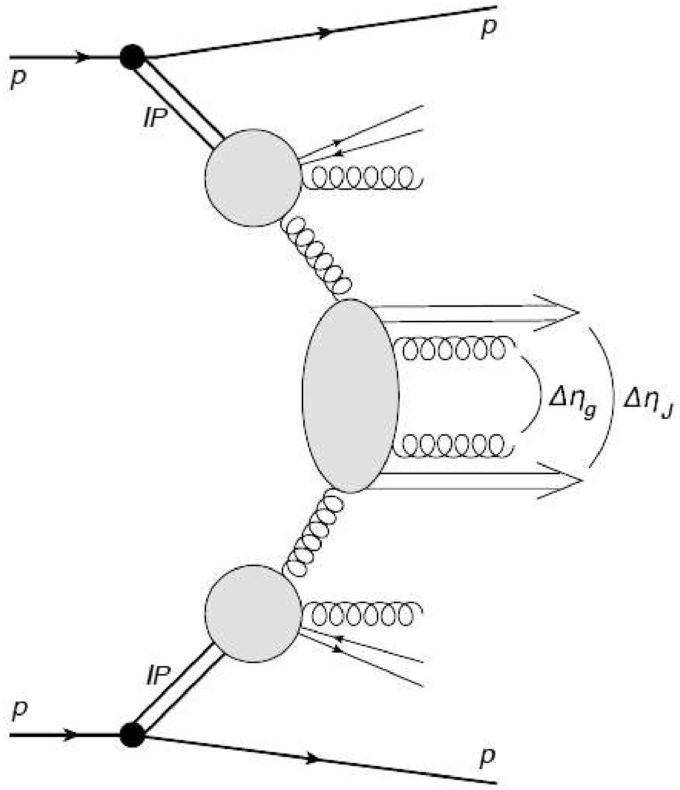
- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)
- At NLO, impact factors are much more complicated!

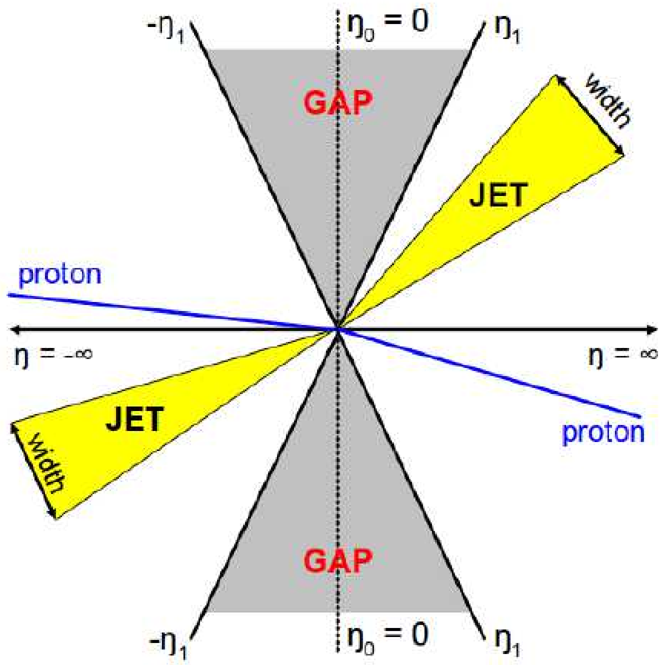


- NLL impact factors
  - Mix loop momenta (not factorized)
  - Involve jet distributions with two final states
  - Contain complicated non-analytic progress
  - Work in progress by D. Colferai, F. Daganutti, T. Raben
- Will lead to an improved parametrisation to be omplemented in HERWIG

Jet gap jet events in diffraction

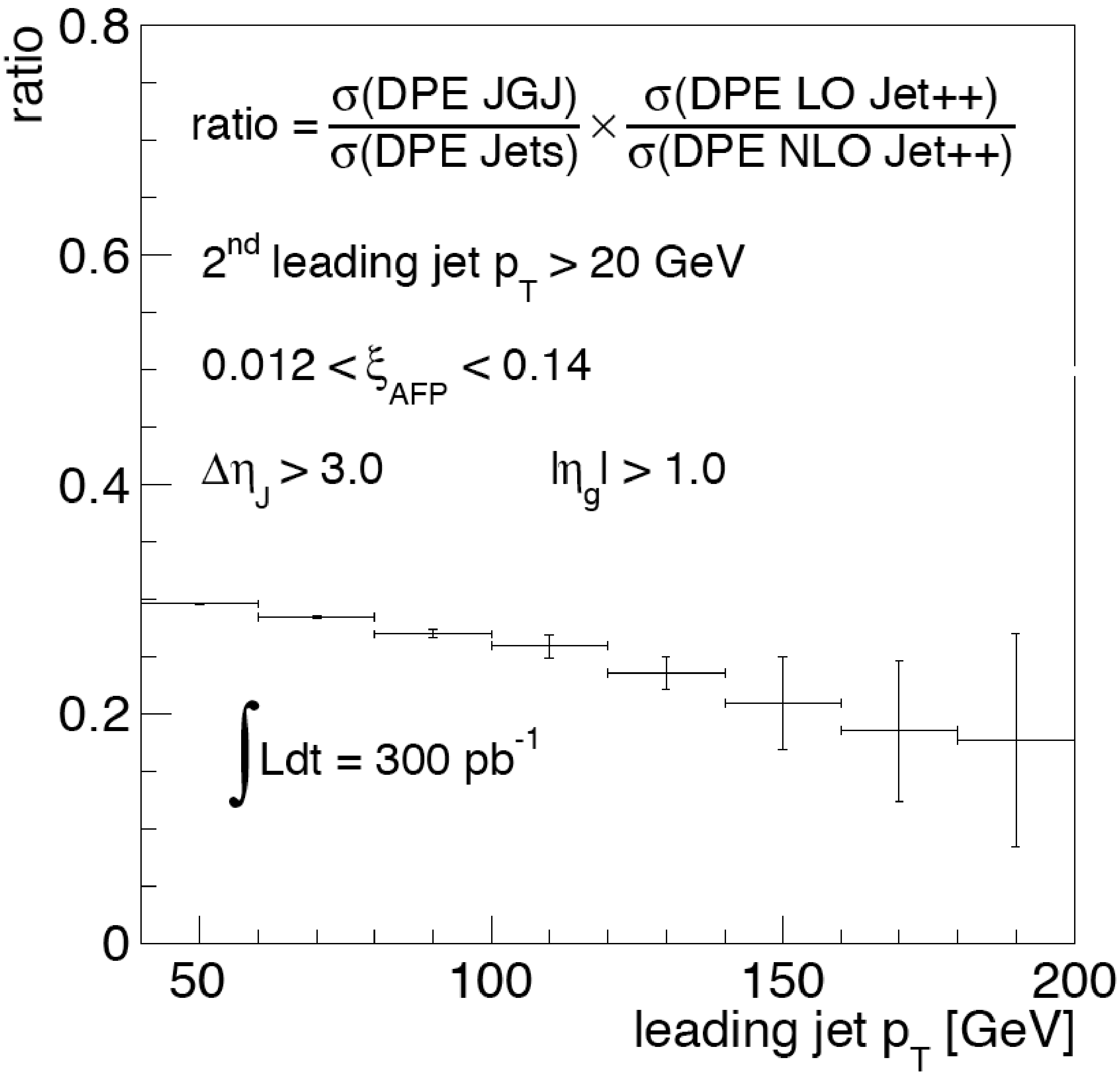
- Study BFKL dynamics using jet gap jet events
- Jet gap jet events in DPE processes: clean process, allows to go to larger $\Delta\eta$ between jets
- Reference: Gaps between jets in double-Pomeron-exchange processes at the LHC, C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D87 (2013) 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 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 higher order corrections, NLL BFKL with saturation in progress
- Jet veto measurements in ATLAS: mainly not related to BFKL resummation effects
- Jet gap jets:
  - NLL BFKL cross section implemented in HERWIG (Kernel)
  - Fair description of D0 and CDF data
  - Full NLL calculation in progress
  - Jet gap jet events in diffraction: clean tests of BFKL, modulo the survival probability (and its depndence on kinematics)