Inclusive jets, forward jets, Mueller Navelet jets and jet gap jet: tests of QCD evolution at colliders

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Al Mueller's 70th Birthday Celebration, October 23-25 2009

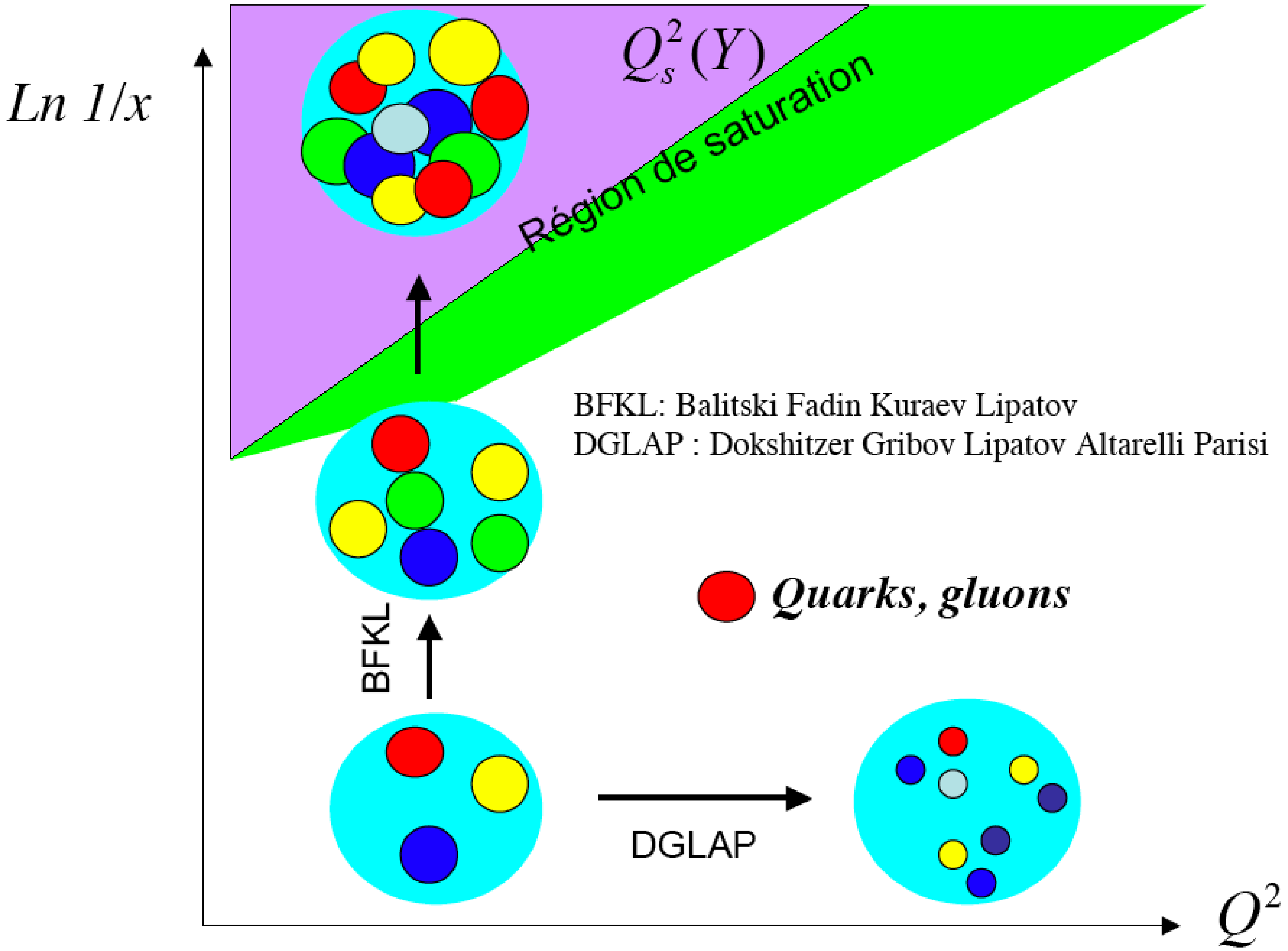
Contents:

- HERA, Tevatron and LHC
- Jet measurements
- Forward jets at HERA
- Mueller Navelet jets at Tevatron and LHC
- Jet gap jet at Tevatron and LHC

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

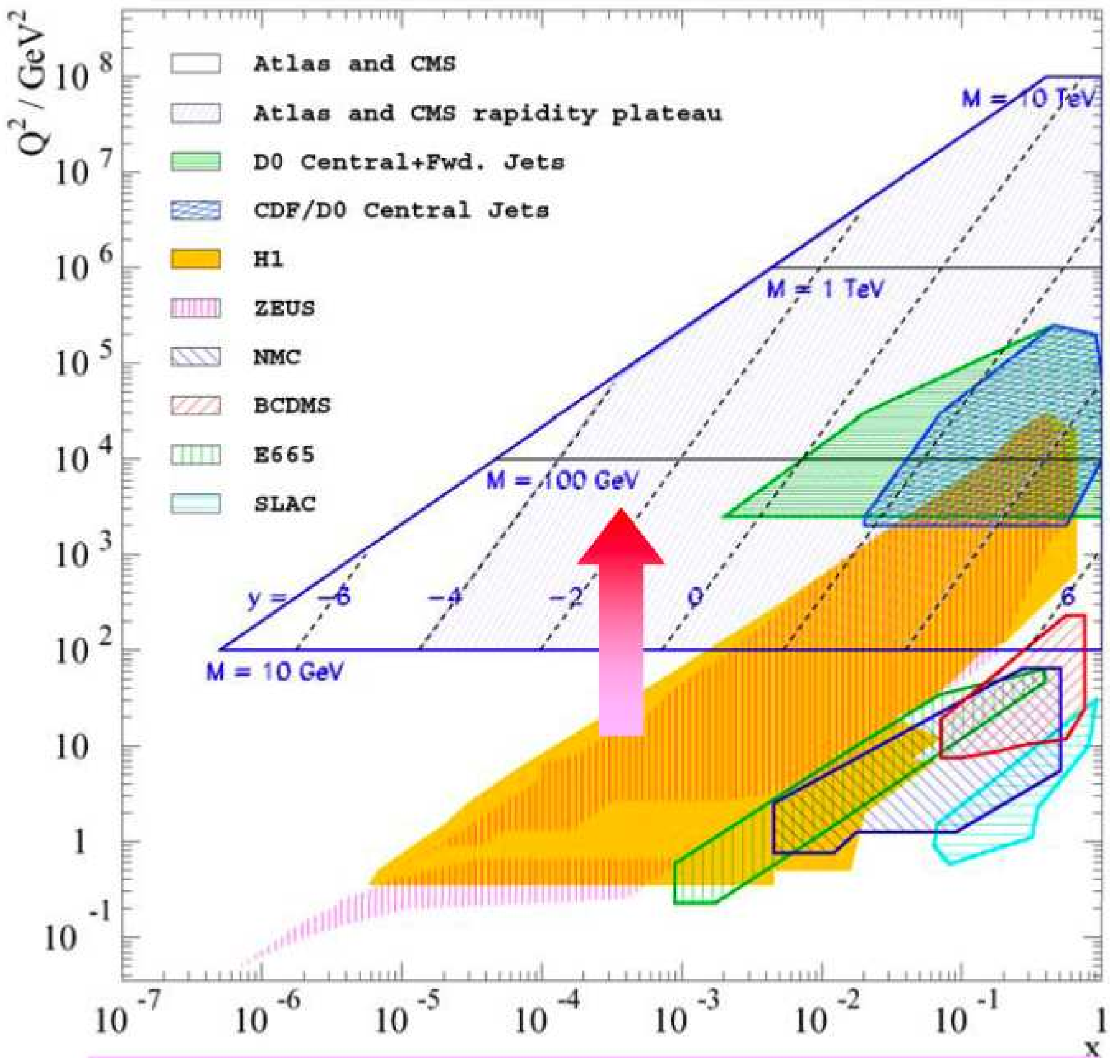
Evolution equations of QCD

- Dokshitzer Gribov Lipatov Altarelli Parisi Resums $\alpha_S \log Q^2$ terms
- Balitski Fadin Kuraev Lipatov Resums $\alpha_S \log 1/x$ terms; dipole model from Al Mueller



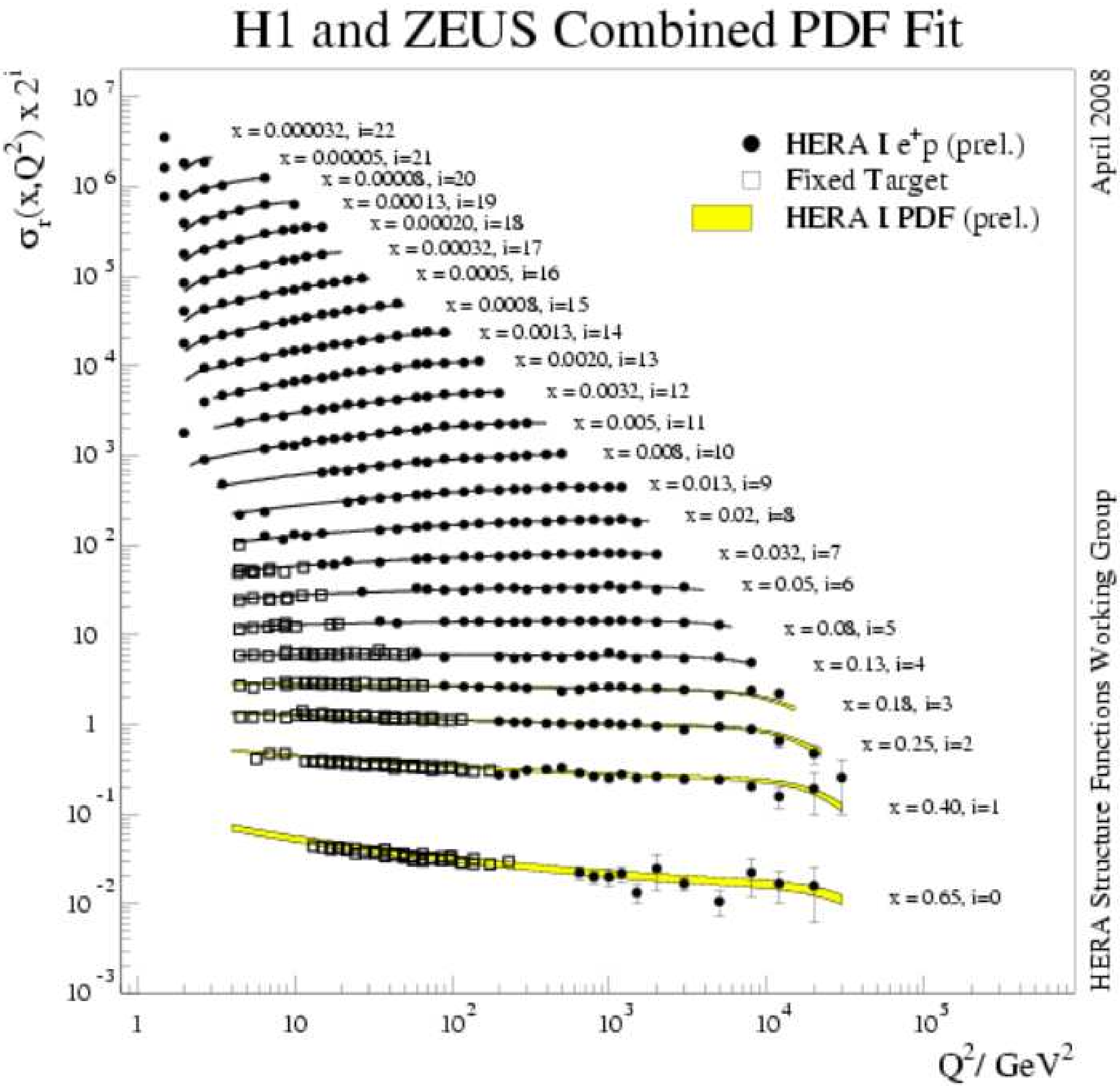
HERA, Tevatron and LHC kinematical planes

- Kinematical plane at HERA, Tevatron and LHC in (x, Q^2) compared to fixed target experiments
- Jets at HERA and Tevatron are complementary to HERA to constrain PDFs



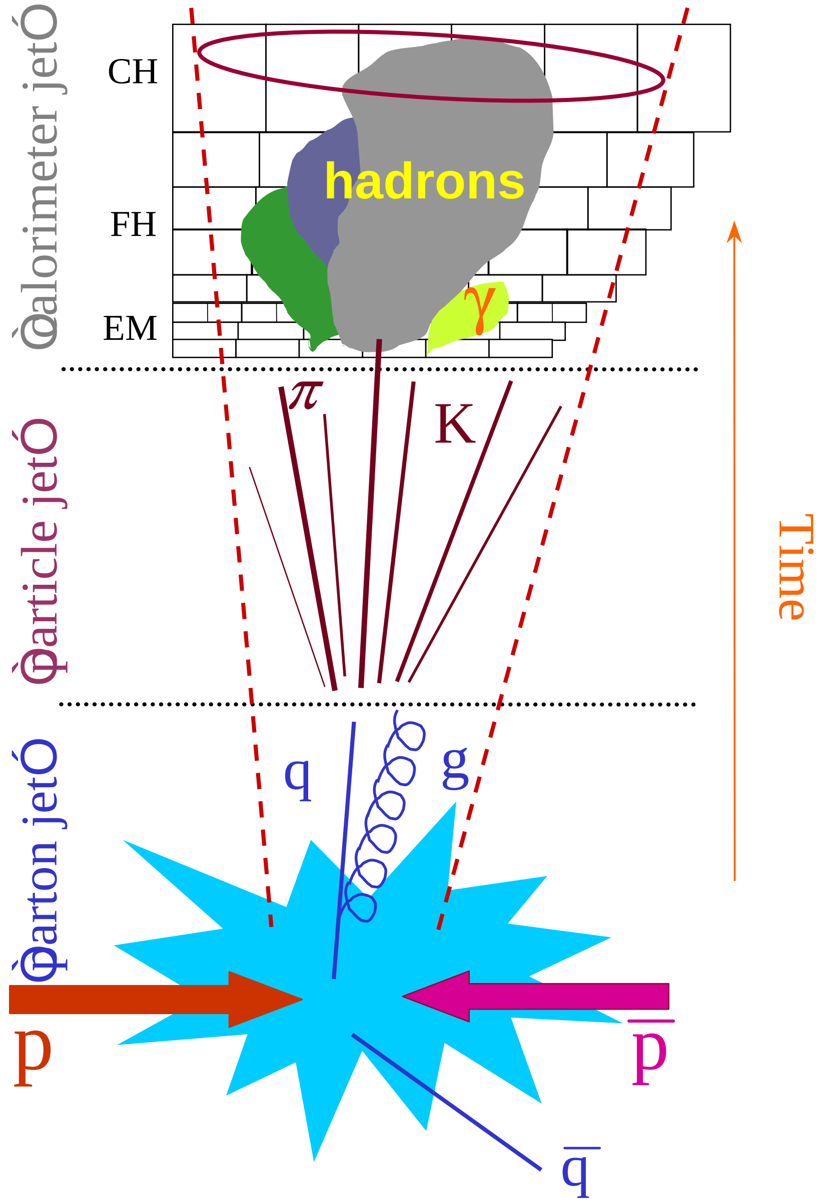
F_2 measurements at HERA

DGLAP leads to a good description of the F_2 HERA data



Jets at the Tevatron (and the LHC)

Dominant uncertainty: Determination of jet energy scale in calorimeter: use γ+jet at Tevatron, Z+jets at LHC



Jet energy scale measurement

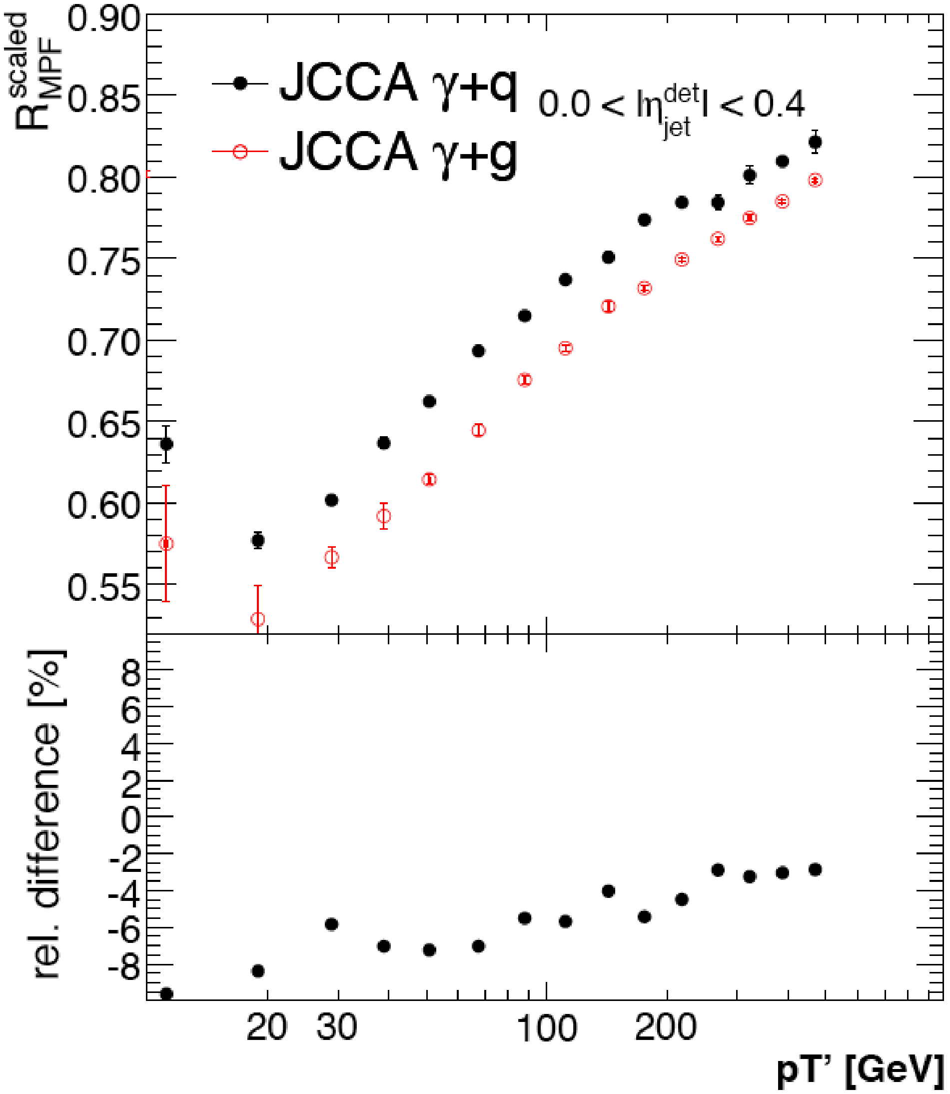
- Jet energy scale measurement (D0):

$$E_{jet}^{corr} = \frac{E_{jet}^{uncorr.} - Off}{Show \times Resp}$$

- Basic JES: use p_T balance in γ+jet events
- Off: offset corrections, related to uranium noise, pile-up..., Determined using zero-bias data
- Show: Showering corrections, takes into account the energy emitted outside of jet cone because of detector, dead material...,
- Resp: Jet response
  - η dependent corrections: equalise calorimeter response
  - Jet response, obtained using p_T balance in $\gamma+$ jet events, cross check using $Z+$ jet event
  - Differences between quark and gluon jets

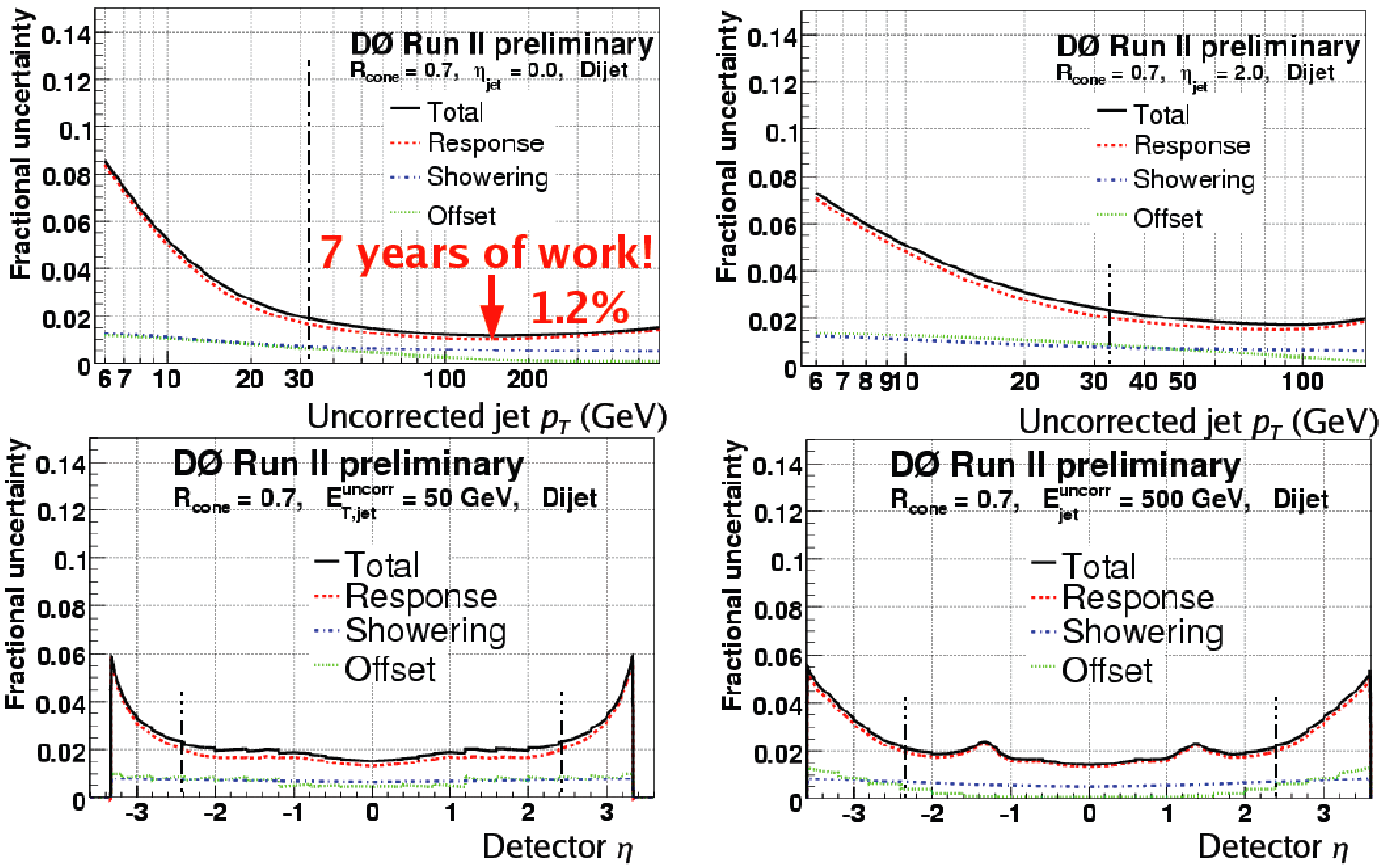
Differences between quark and gluon responses

- Different quark and gluon jet responses (studied in response between quark and gluon using the γ+jet and inclusive jet samples)
- Means different corrections depending on physics: QCD jets (gluon dominated), $t\bar{t}$ events (quark dominated)...



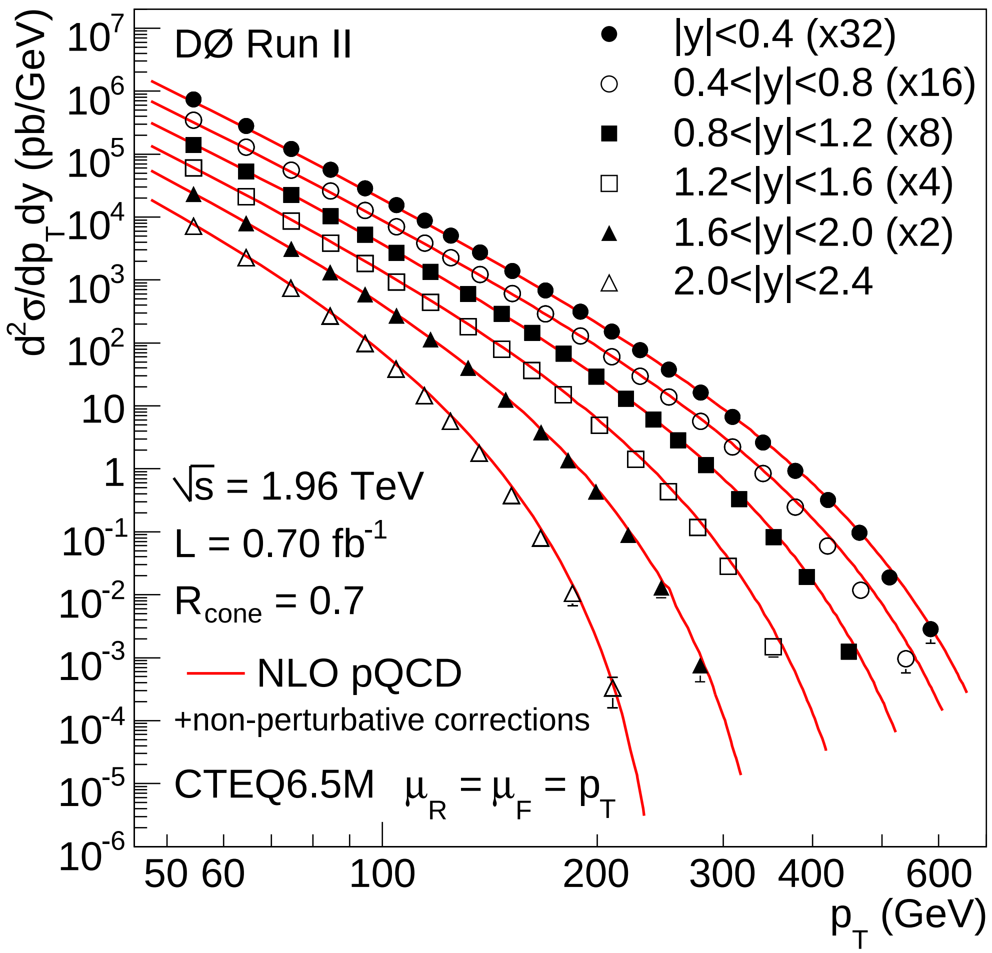
Jet Energy Scale in D0

- "Standard" JES determined using γ+jet
- Corrections for JES for QCD jets obtained using inclusive jet sample and p_T balance between dijets
- Uncertainties of the order of 1.2% for central jets and $p_T \sim 100$ GeV



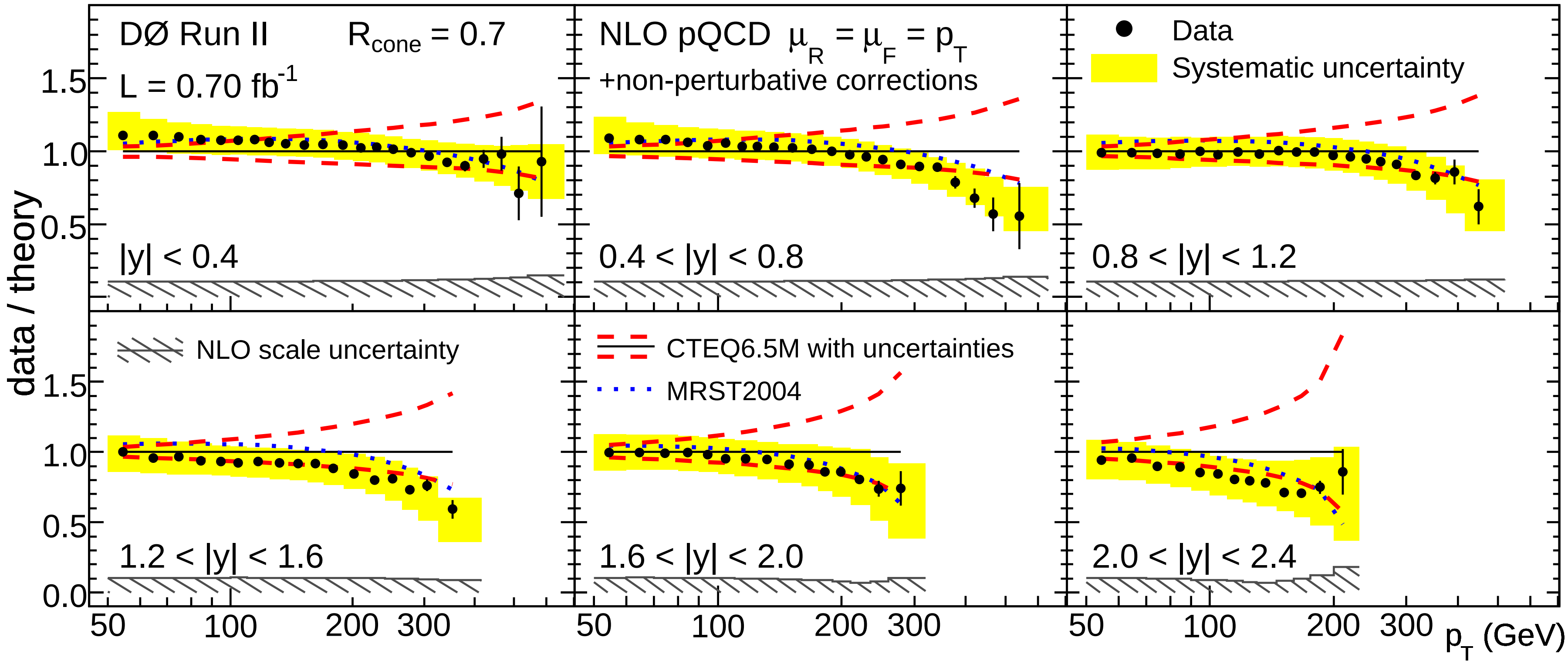
Jet cross section measurements at the the Tevatron (D0)

- Measurement of the inclusive jet cross section using 0.7 cone algorithm in a p_T range 50-700 GeV and a rapidity up to 2.4 (D0)
- Corrections up to hadron level
- Comparison with NLO QCD calculation (CTEQ6.5M for D0, CTEQ6.1 for CDF with uncertainties $\sim$ two times larger): Good agreement over six orders of magnitude



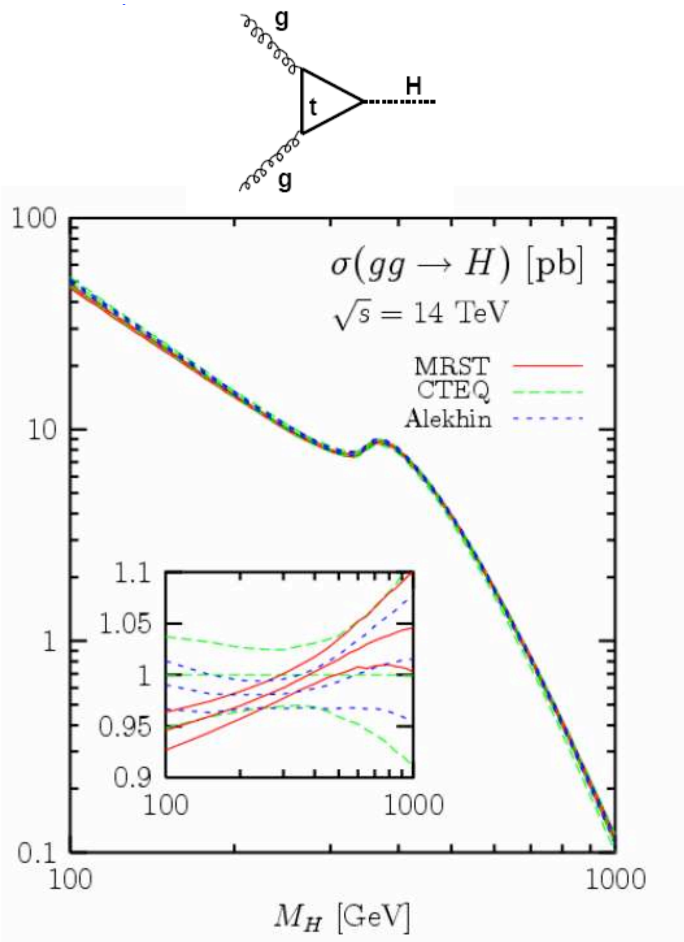
Data over Theory (D0)

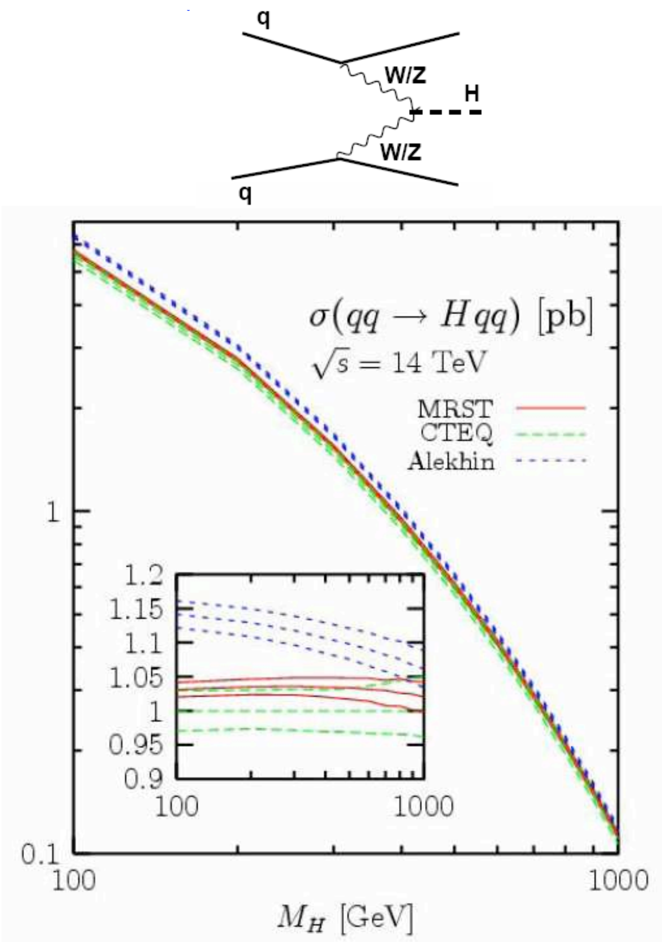
- Good agreement between data and theory within uncertainties
- Data allow to constrain further PDFs, further lower band from CTEQ
- Similar results for CDF



How do PDF uncertainties affect LHC potential?

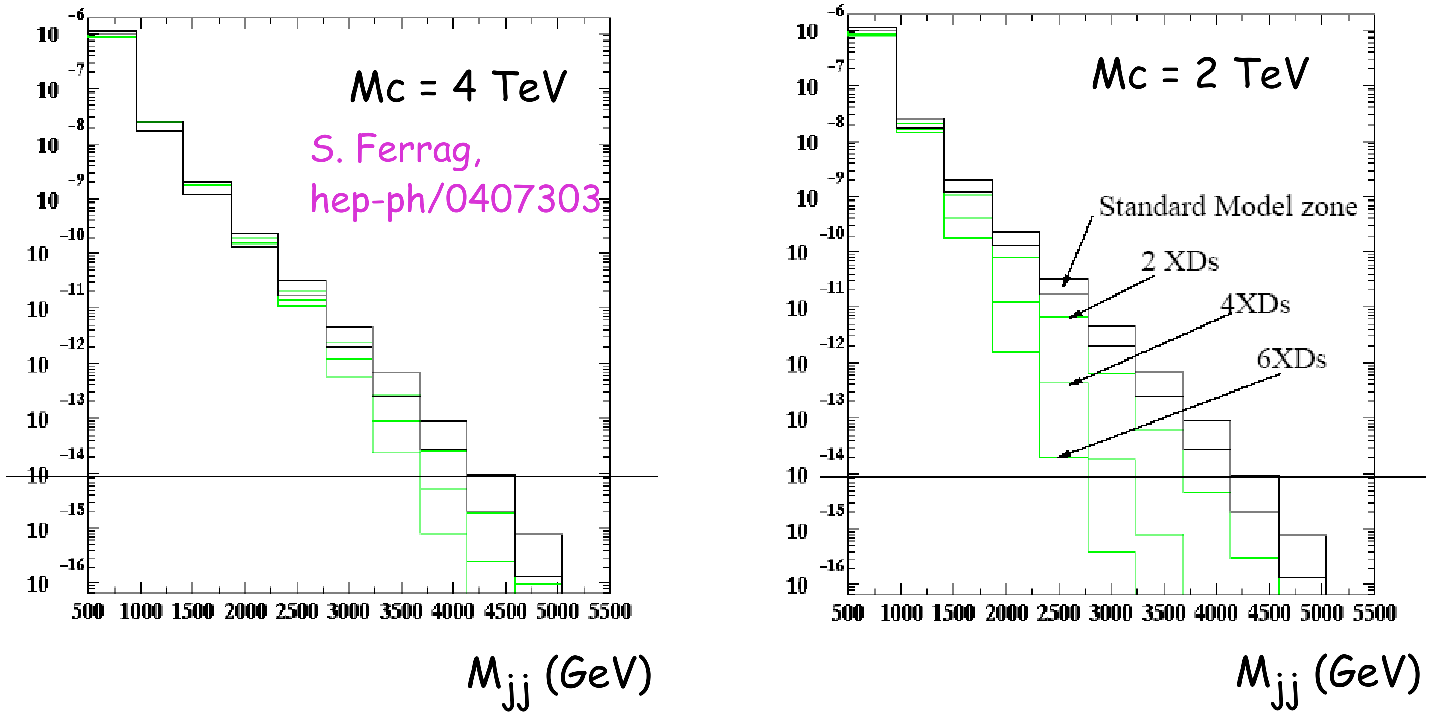
- How do PDF uncertainties affect LHC discovery potential on Higgs boson as an example?
- Cross sections (signal and background) are known within 10%, no strong impact on cross section calculation to produce heavy object (Higgs)
- Higher uncertainties due to NLO calculation: for example, for Higgs events at 120 GeV, NNLO effects are of the order of 9% (for Z^0, 4%)





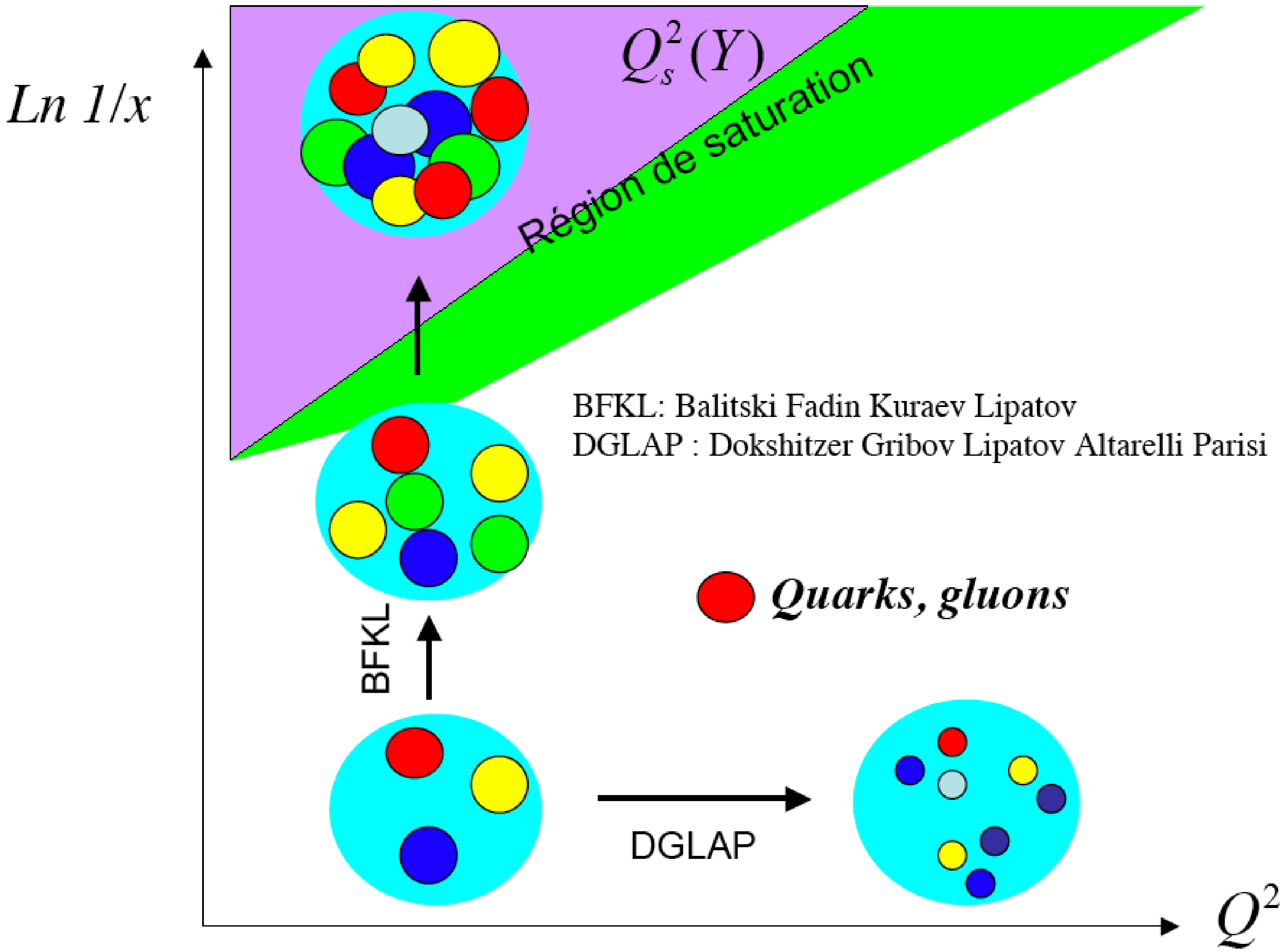
How do PDF uncertainties affect LHC potential?

- PDF uncertainties have an impact on searches (higher dimensions. SUSY...), single top searches because of the background uncertainty
- An example: $qqqq$ contact interactions for two compactification scales: Look for excess in dijet mass spectrum
- Warning: No JES uncertainty considered in this study

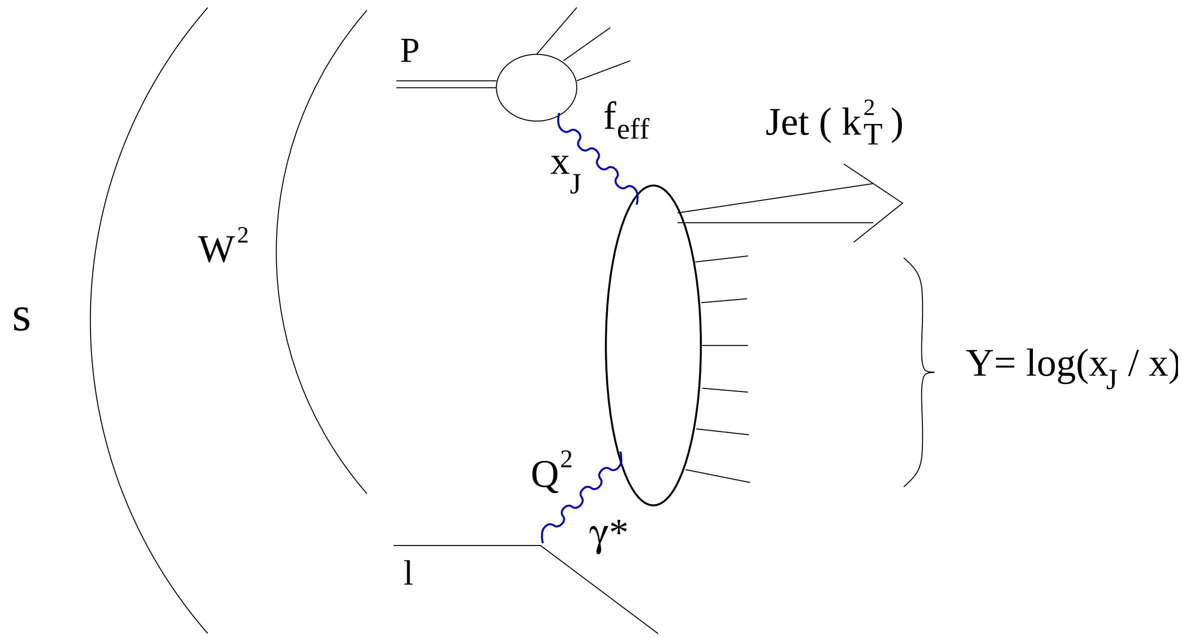


Looking for BFKL/saturation effects

At low x, looking for BFKL effects (x-resummation)



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 calculation

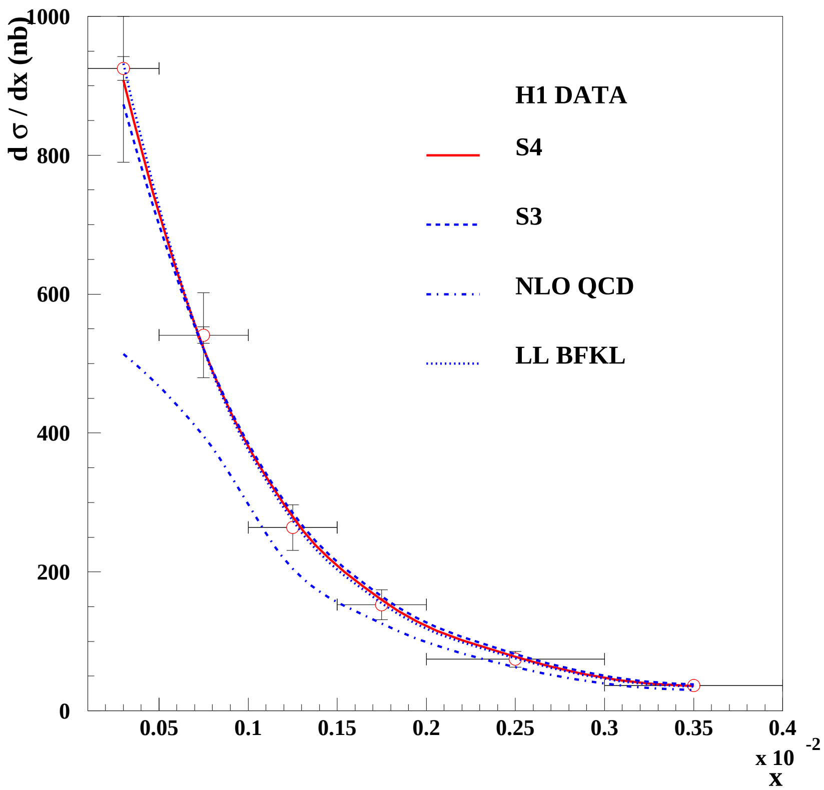
- Full BFKL NLL calculation used for the BFKL kernel (available in S3 and S4 resummation schemes to remove the spurious singularities of BFKL kernel), modulo the impact factors taken at LL
- Equation:

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

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

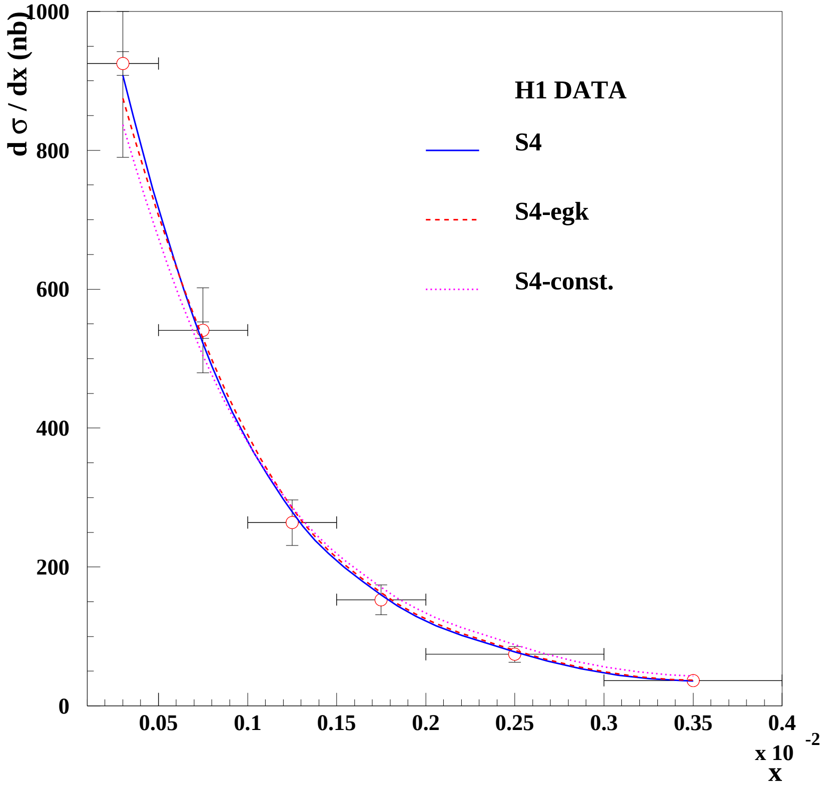
Fit results

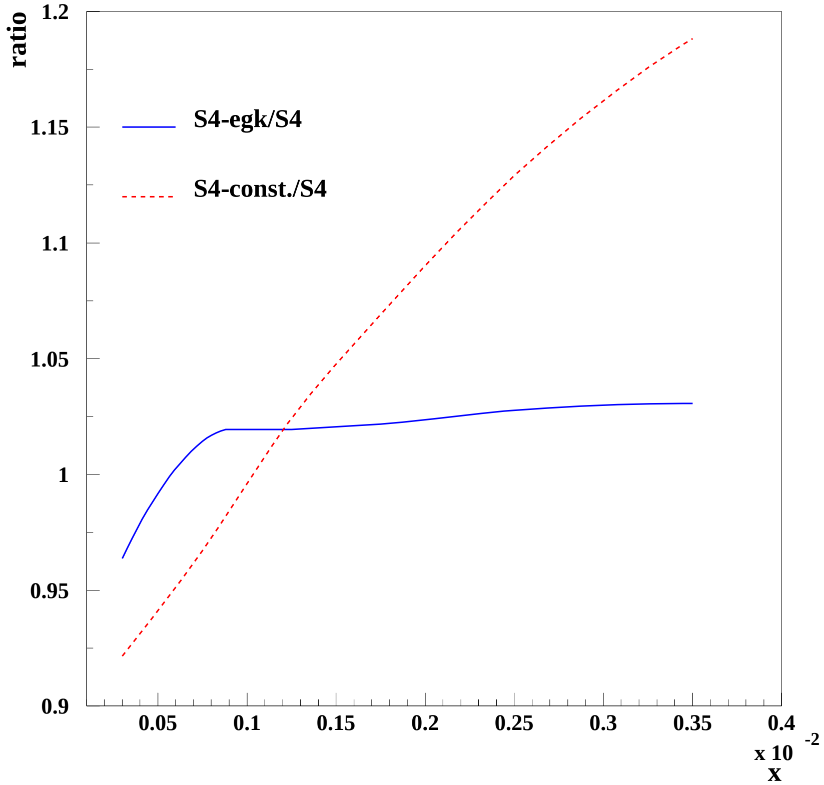
- Fit of NLL BFKL calculation to the H1 $d\sigma/dx$ data: one single parameter, normalisation of cross section
- Good description of H1 data using BFKL LL and BFKL NLL formalism, DGLAP-NLO fails to describe the data
- Scale dependence: variation of the scale between $2Qk_T$, $Qk_T/2$, Q^2, k_T^2: $\sim 20\%$ difference
- BFKL higher corrections found to be small (We are in the BFKL-LL region, cut on $0.5 < k_T^2/Q^2 < 5$)



Dependence on impact factor

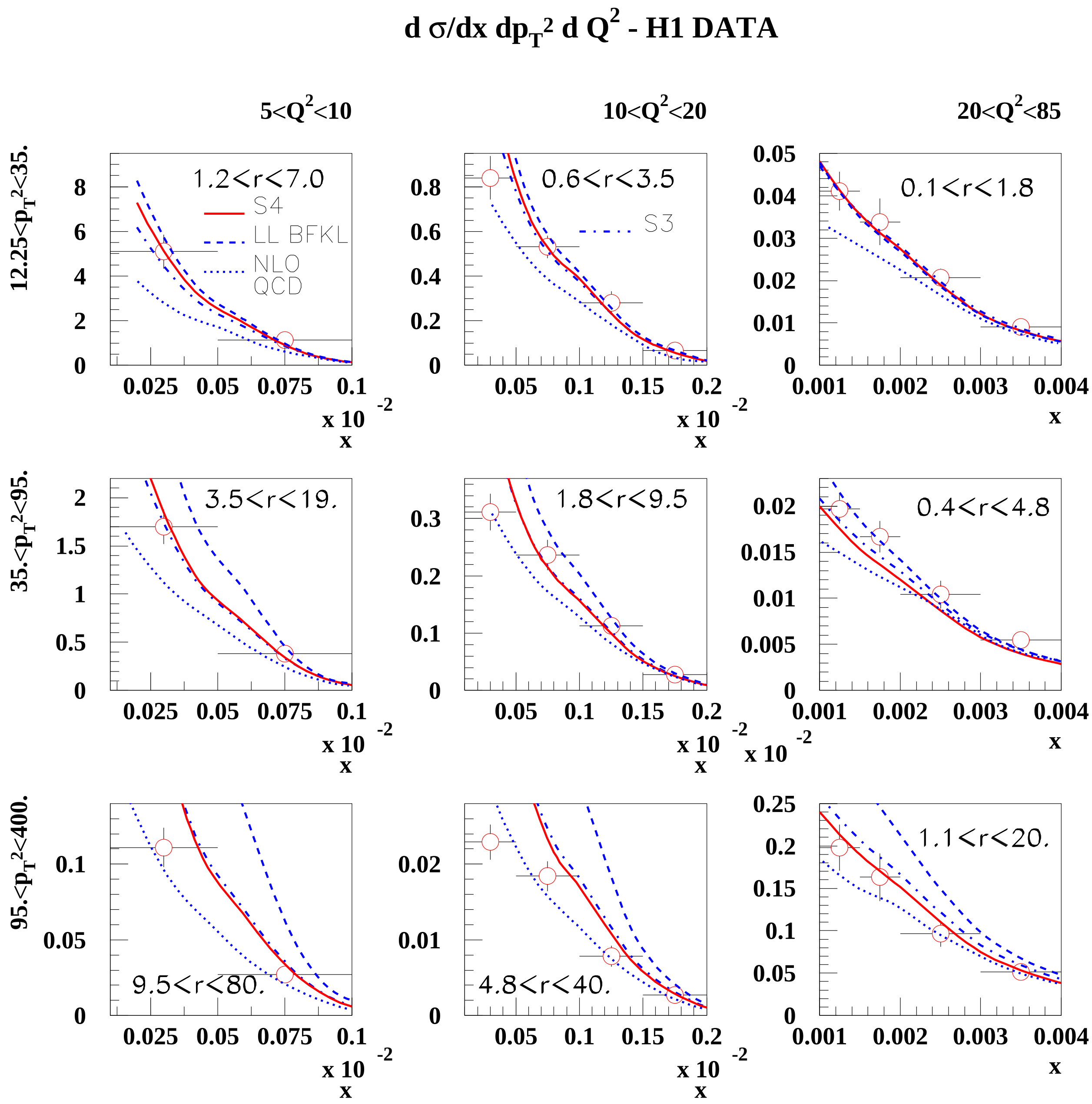
- Impact factor not yet fully known at NLL
- Variation of impact factor, 3 studies: $h_T,\ h_L(\gamma)$ at LO; $h_T,\ h_L(1/2)$ constant; implement the higher-order corrections in the impact factor due to exact gluon kinematics in the $\gamma^* \to q\bar{q}$ transition (see C.D. White, R. Peschanski,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





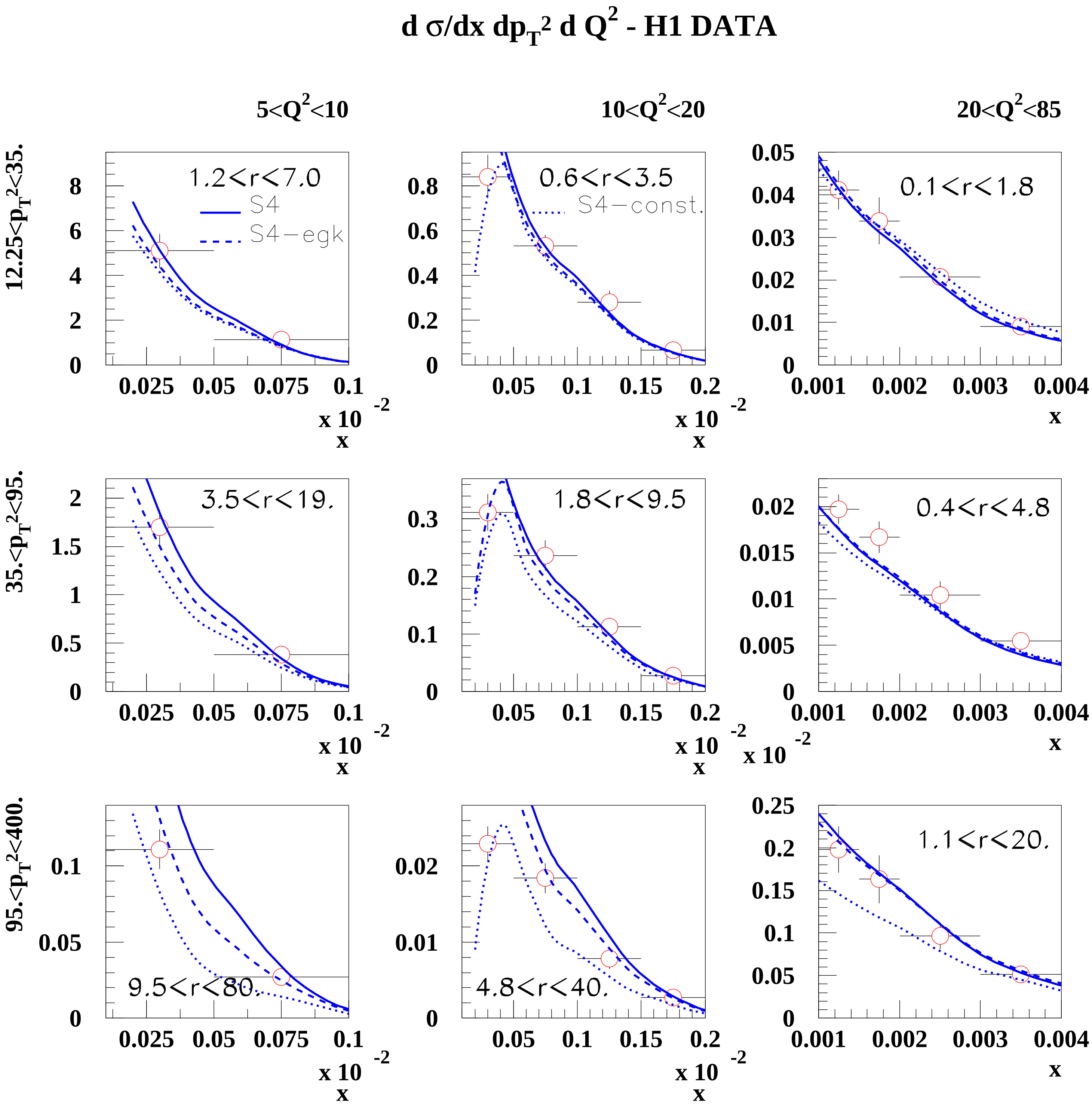
Comparison with H1 triple differential data

- Triple differential cross section: Keep the normalisation from the fit to $d\sigma/dx$ and predict the triple differential cross section; scale uncertainty of the order of 20%
- Good description over the full range



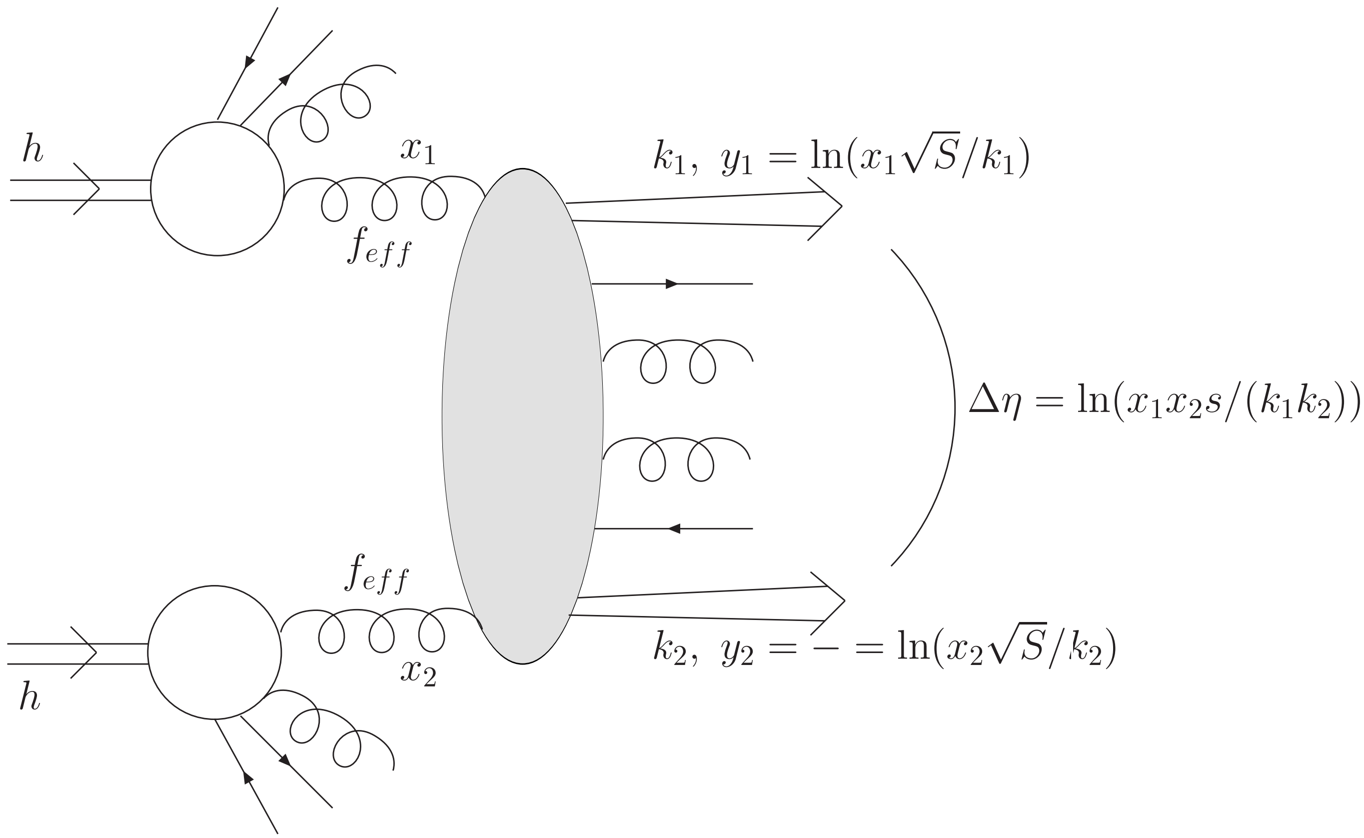
Comparison with H1 triple differential data

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:

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:

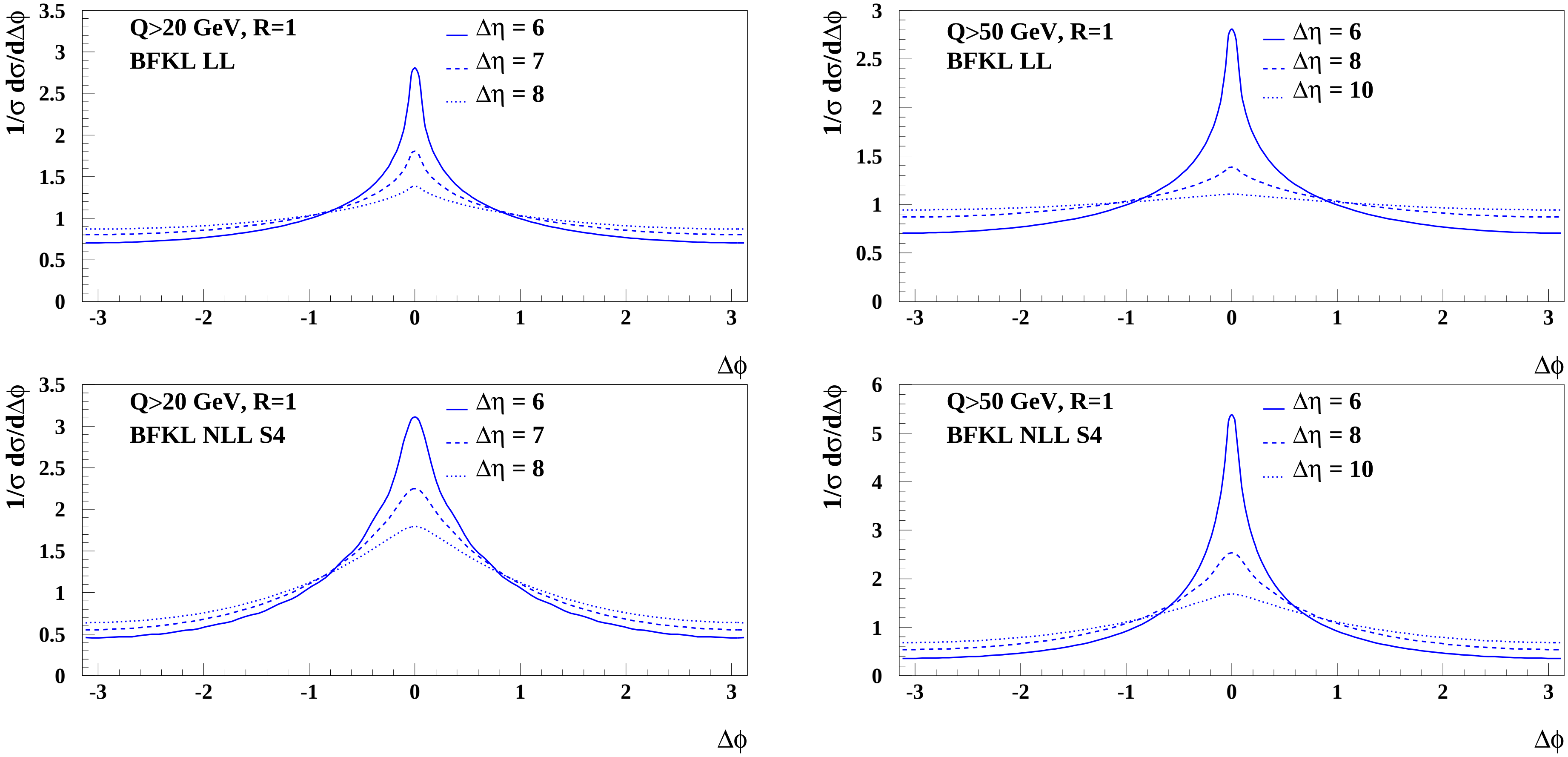
$$
2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \bigg/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)
$$

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 $\Delta\eta$
- Measurement being done at CDF, to be performed at LHC



Effect of energy conservation on BFKL equation

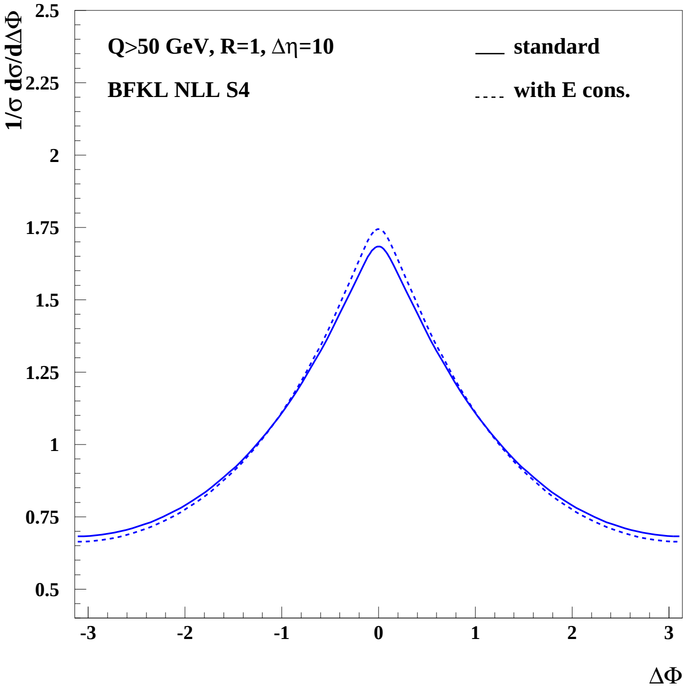
- BFKL cross section lacks energy-momentum conservation since these effects are higher order corrections
- Following Del Duca-Schmidt, we substitute $\Delta\eta$ by an effective rapidity interval y_{eff}

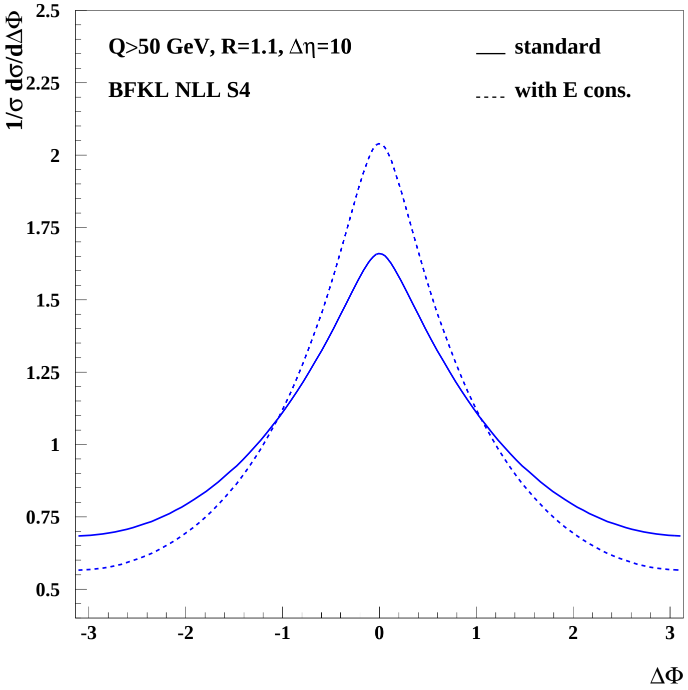
$$y_{eff} = \Delta\eta \left(\int d\phi \cos(p\phi) \frac{d\sigma^{O(\alpha_s^3)}}{d\Delta\eta dy dQ dR d\Delta\Phi} \right)^{-1} \int d\phi \cos(p\phi) \frac{d\sigma^{LL-BFKL}}{d\Delta\eta dy dQ dR d\Delta\Phi}$$

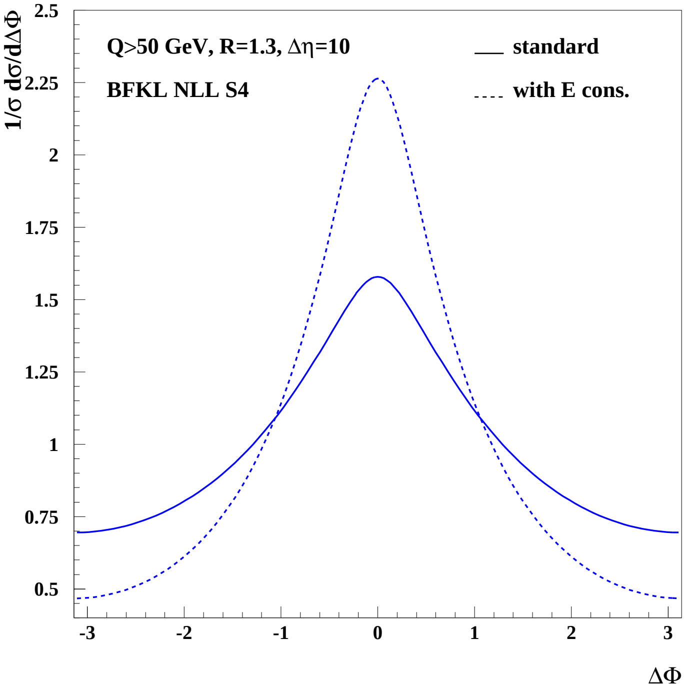
where $d\sigma^{O(\alpha_s^3)}$ is the exact $2 \to 3$ contribution to the $hh \to JXJ$ cross-section at order α_s^3, and $d\sigma^{LL-BFKL}$ is the LL-BFKL result

- 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

Effect of energy conservation on BFKL equation

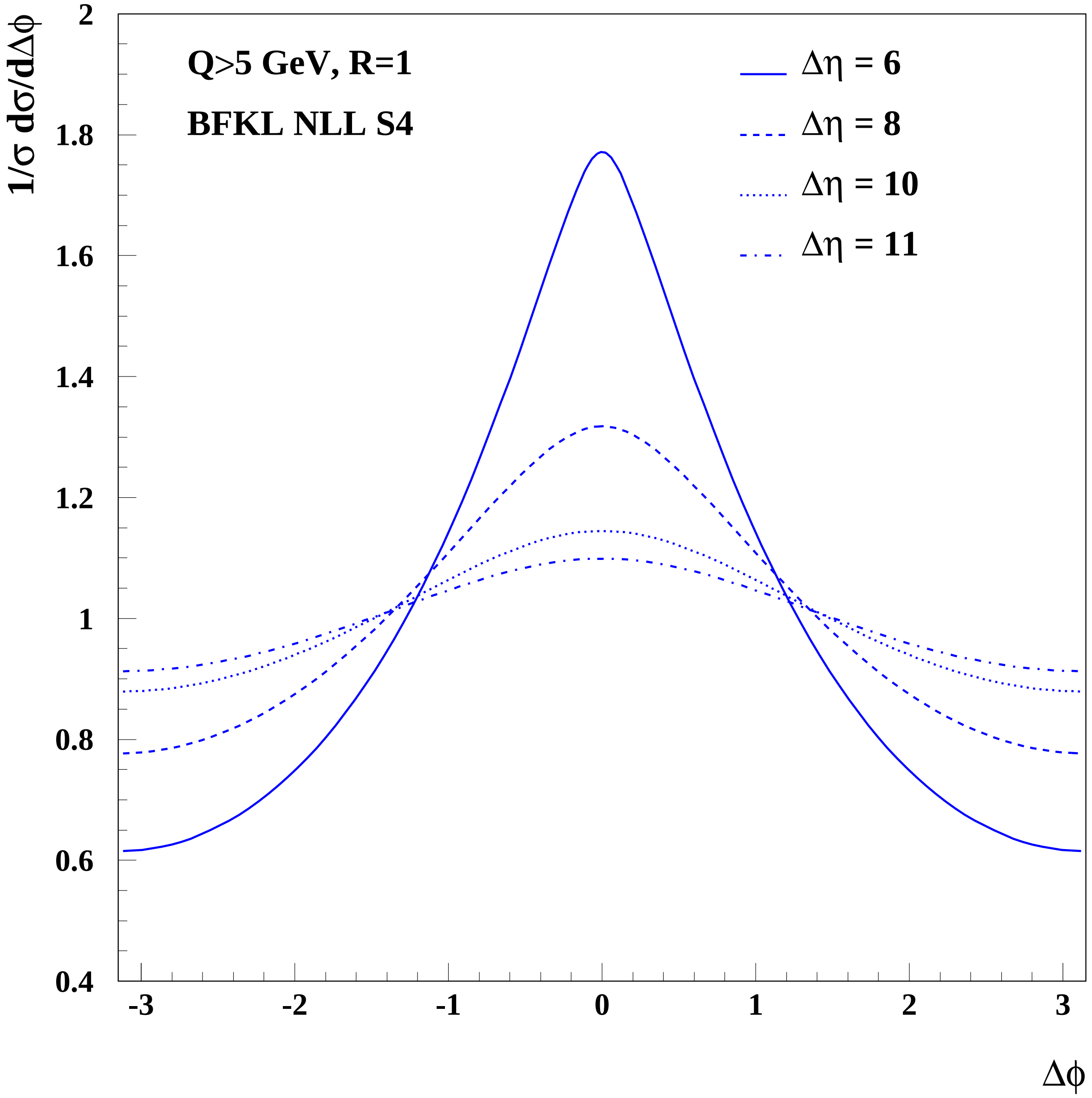




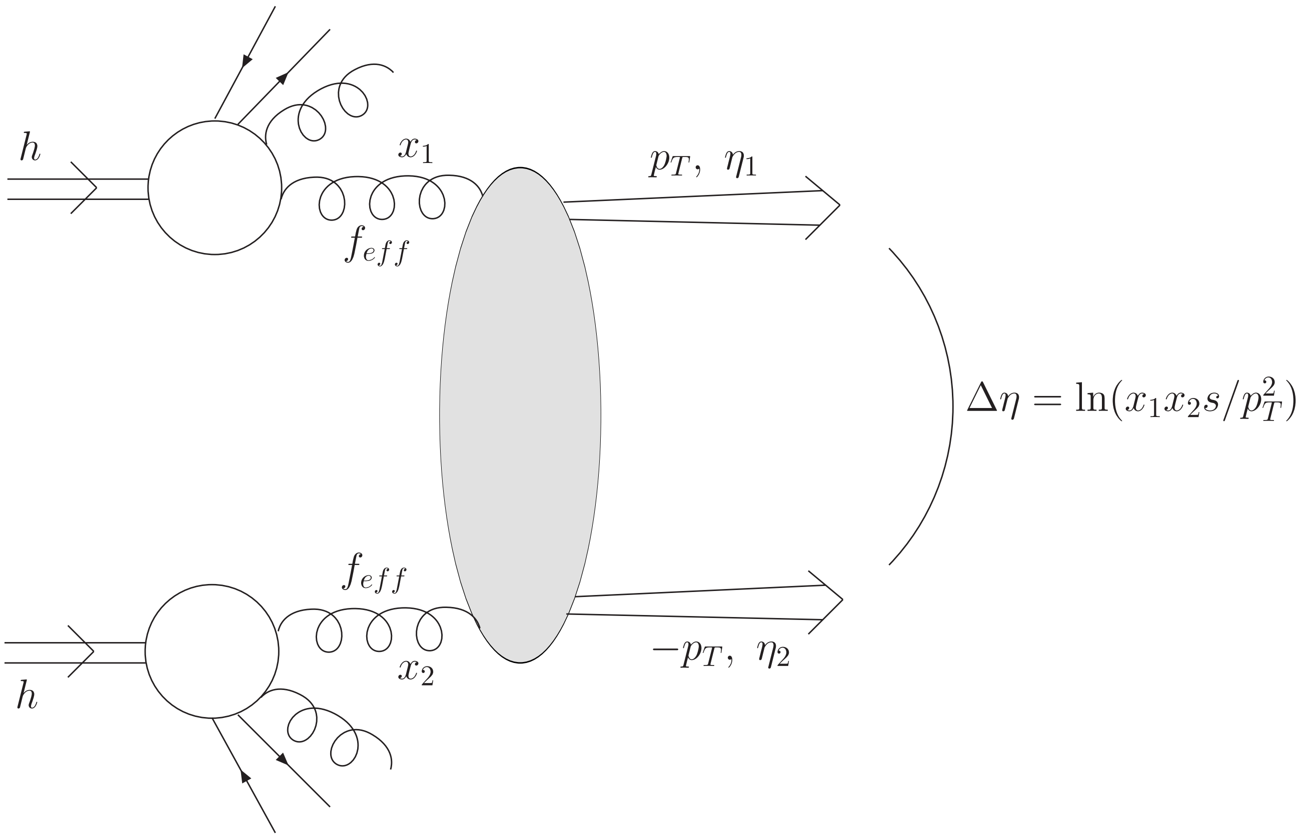


Mueller Navelet jets in CDF

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



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

$$\frac{d\sigma^{pp\to XJJY}}{dx_1 dx_2 dp_T^2} = \mathcal{S} f_{eff}(x_1, p_T^2) f_{eff}(x_2, p_T^2)$$

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

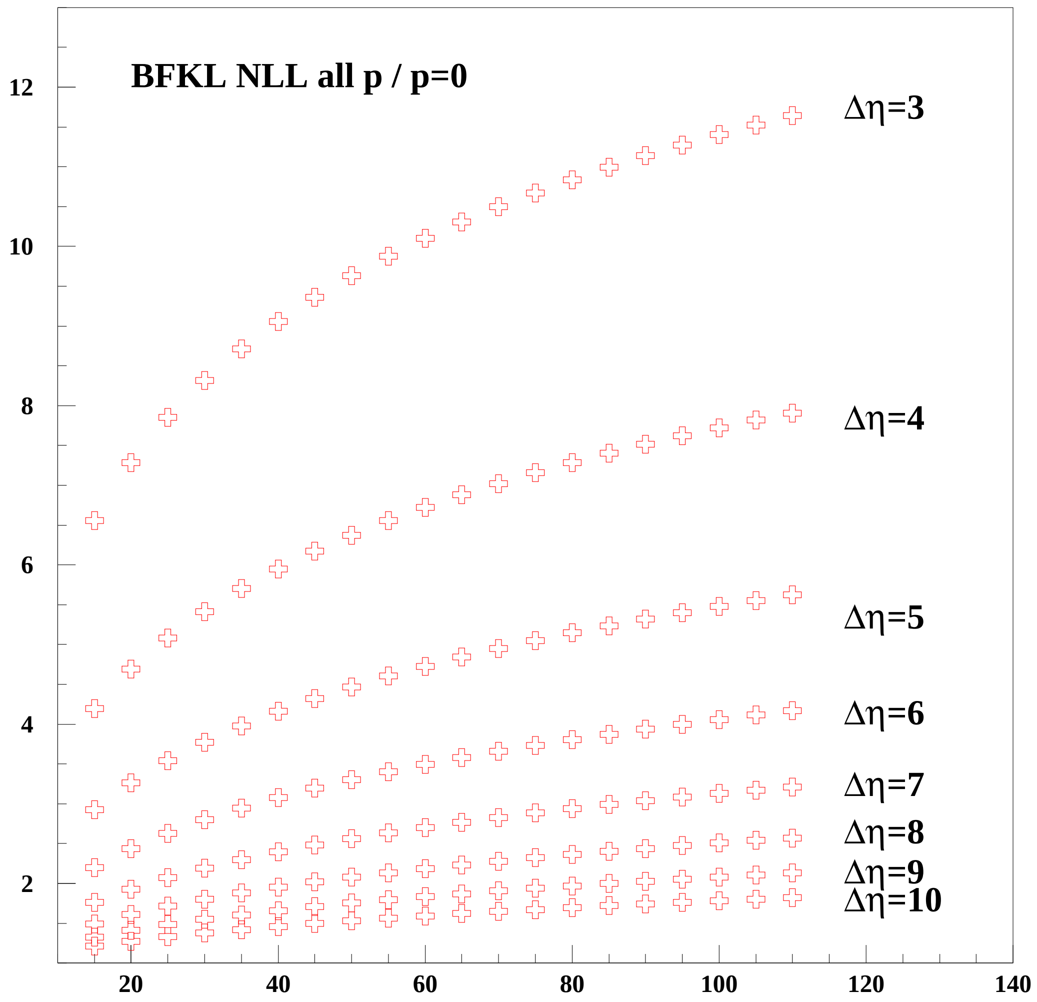
$$\frac{d\sigma^{gg\to gg}}{dp_T^2} = \frac{1}{16\pi} \left| A(\Delta\eta, p_T^2) \right|^2$$

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

- α_S: 0.17 at LL (constant), running using RGE at NLL
- BFKL effective kernel χ_{eff}: determined numerically at NLL by 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: 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...:



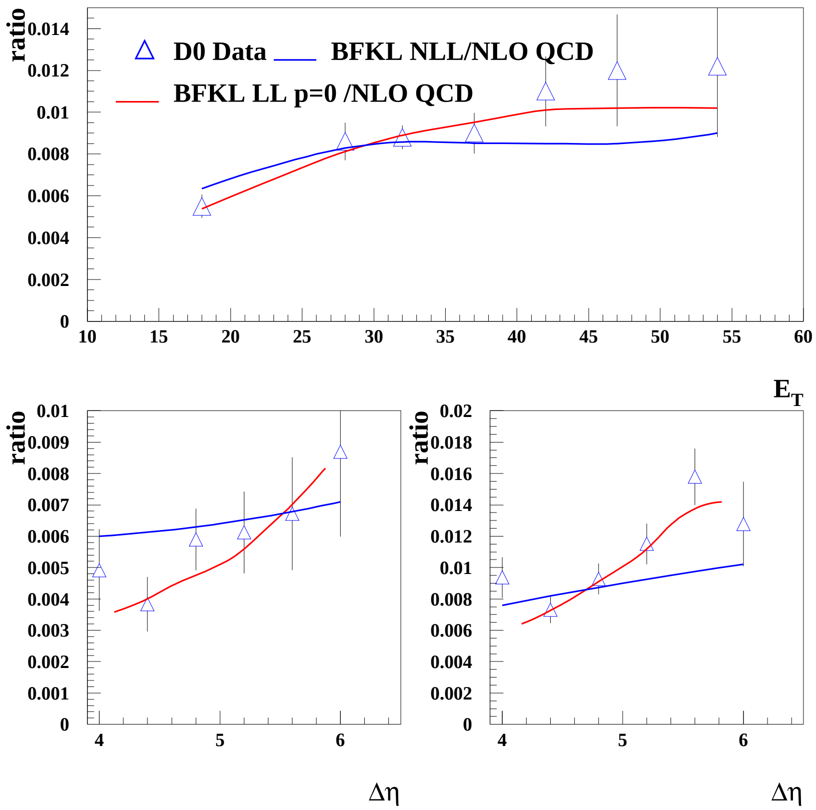
Comparison with D0 data

- 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:

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

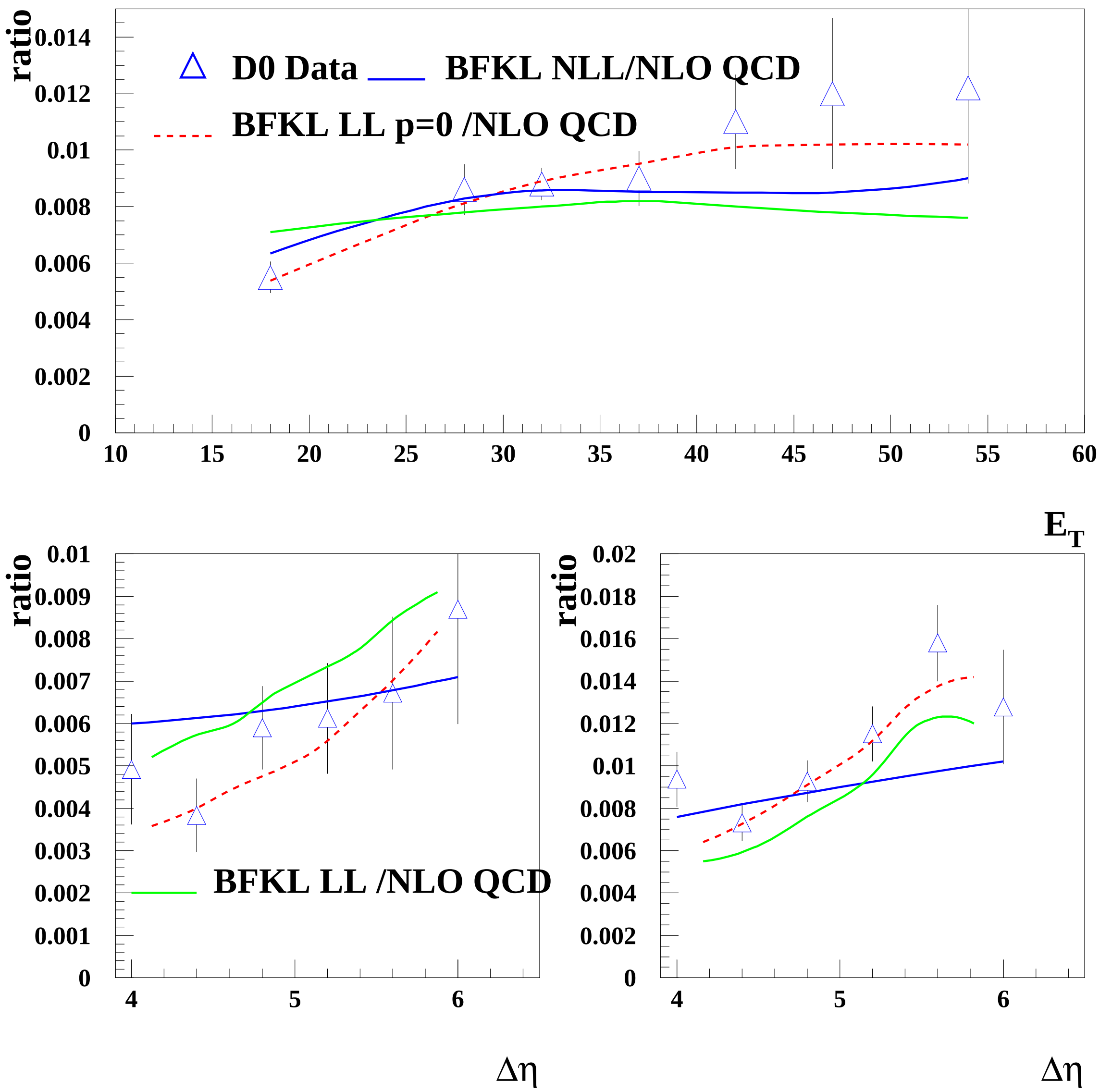
LO and NLO QCD results are obtained using NLOJet++

- Good agreement with LL (p=0) BFKL calculation (better at high p_T than with Lonnblad, Cox, Forshaw due to NLO QCD calculation), reasonable description of BFKL NLL formalism



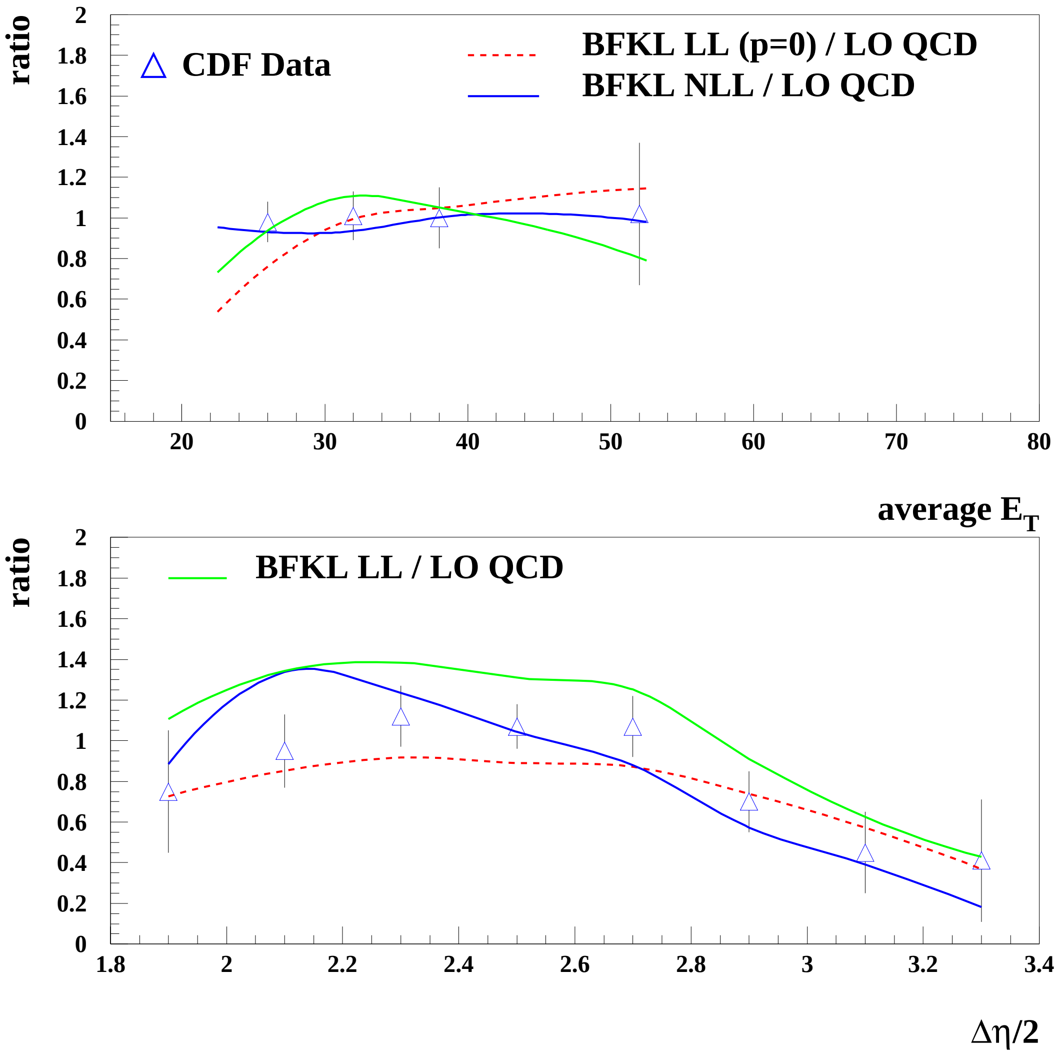
Comparison with D0 data

BFKL NLL leads to a better description than BFKL LL



Comparison with CDF data

- Measurement of jet gap jet cross section ratio as a function of average E_T of the two leading jets, and the rapidity interval between the two leading jets divided by 2, the gap between jets being between -1 and 1 in rapidity
- BFKL NLL calculation leads to a better description than LL



Conclusion

- DGLAP describes nicely the structure function, jet data at HERA, jets data at the Tevatron
- Dedicated final states needed to look for BFKL effects
- Forward jets at HERA: BFKL NLL leads to a nice description of HERA data
- Mueller-Navelet jets at Tevatron, LHC: Look for jet angular decorrelation, measurement being performed in CDF
- Jet gap jet: Clean tests of BFKL resummation, needs also different conformal spins to be resummed

Happy birthday!

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More personally, Al was one of the referees for my PhD and habilitation theses