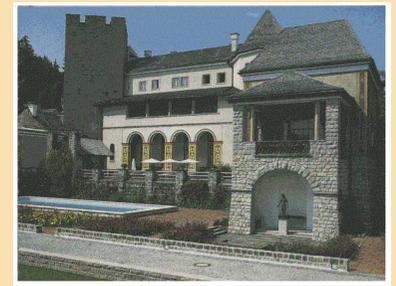


Ringberg workshop: New trends in HERA Physics 2003

Ringberg Castle, Germany

28<sup>th</sup> September - 3<sup>rd</sup> October, 2003



# Jet production in deep inelastic $ep$ scattering at HERA

from



ZEUS Collab.

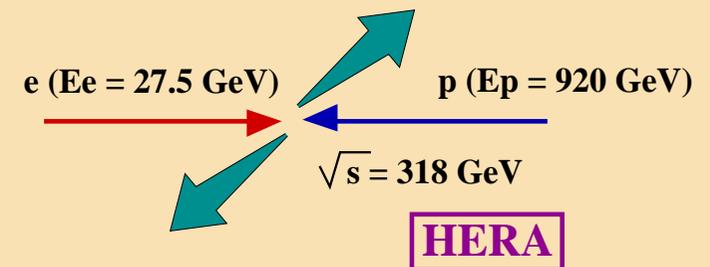
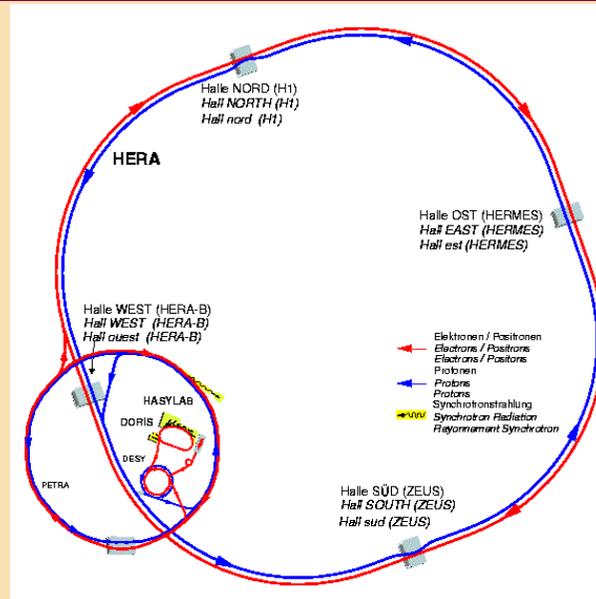


H1 Collab.

**C Glasman**  
Universidad Autónoma de Madrid



at





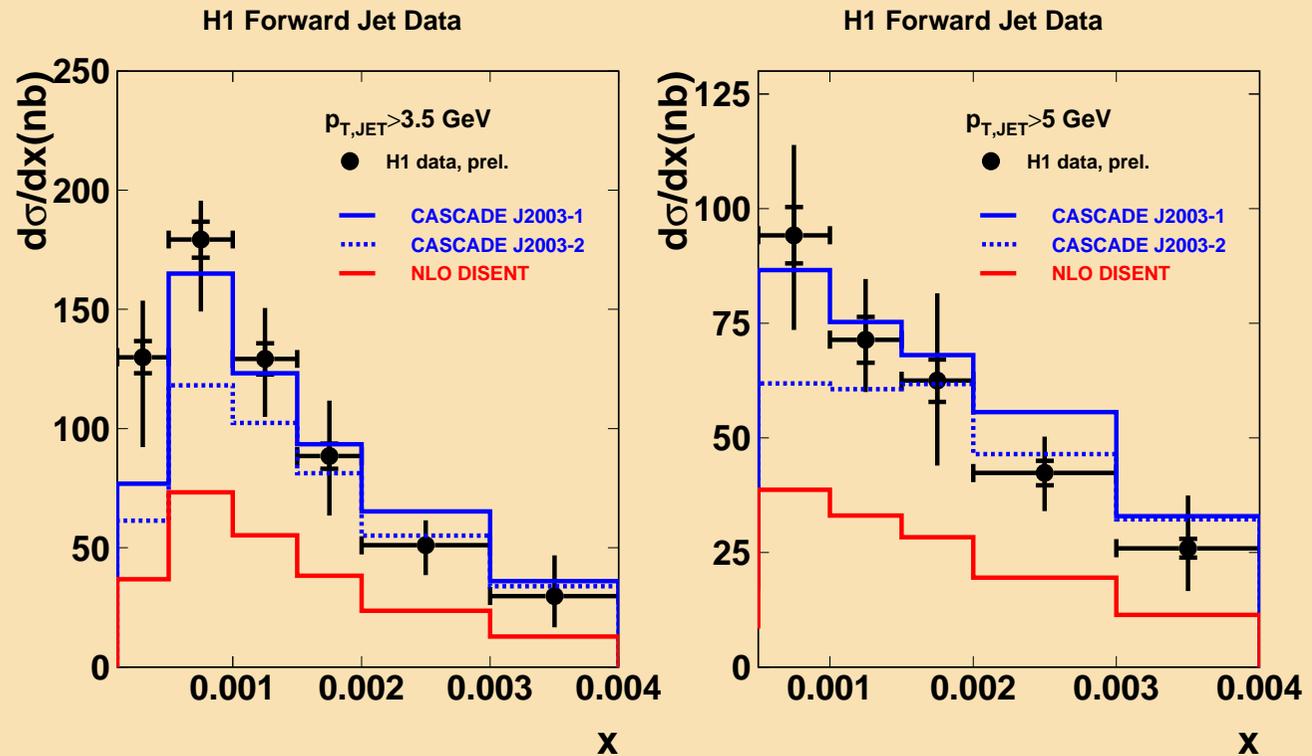
# Jet production in neutral current deep inelastic $ep$ scattering

- A wealth of data from fixed target and collider experiments has allowed an accurate determination of the proton PDFs
- ⇒ **Measurements of jet production in NC DIS provide**
  - a sensitive test of the pQCD predictions of the short-distance structure
  - a determination of the strong coupling constant  $\alpha_s$
- To perform stringent tests of the pQCD calculations and precise determinations of  $\alpha_s$  use observables for which the predictions are directly proportional to  $\alpha_s$ :  
**jet cross sections in the Breit frame, jet substructure**
- **Small experimental uncertainties:**
  - jets with relatively high transverse energy (uncertainty on jet energy scale)
  - kinematic region in  $(Q^2, x)$  and jet variables (small detector corrections)
  - ratios of cross sections (partial cancellation of systematic uncertainties)
- **Small theoretical uncertainties:**
  - **NLO QCD calculations** (reduction of higher-order contributions)
  - **jet algorithm: longitudinally invariant  $k_T$  cluster algorithm** (Catani et al)
    - > small parton-to-hadron effects and infrared safe to all orders
    - > less ambiguities in matching the experimental and theoretical implementations
    - > suppression of beam-remnant jet
  - **Jet selection: inclusive jet production** (smaller uncertainties than for dijets)

# Jet production in neutral current deep inelastic $ep$ scattering

- At high scales ( $Q^2, E_T^{\text{jet}}$ ), calculations using the collinear approximation of the DGLAP evolution equations give a good description of the data at NLO  
 → by fitting the data with the NLO calculations → extraction of  $\alpha_s$  and gluon density

- For  $E_T^{\text{jet}} \sim Q$  and large  $\eta^{\text{jet}}$ , large discrepancies between NLO calculations and data were observed at low  $x$



- This could indicate a breakdown of DGLAP evolution and  
 → onset of BFKL effects  
 → partonic structure of virtual photon ( $(E_T^{\text{jet}})^2 > Q^2$ )  
 → large NNLO contributions at low  $Q^2$

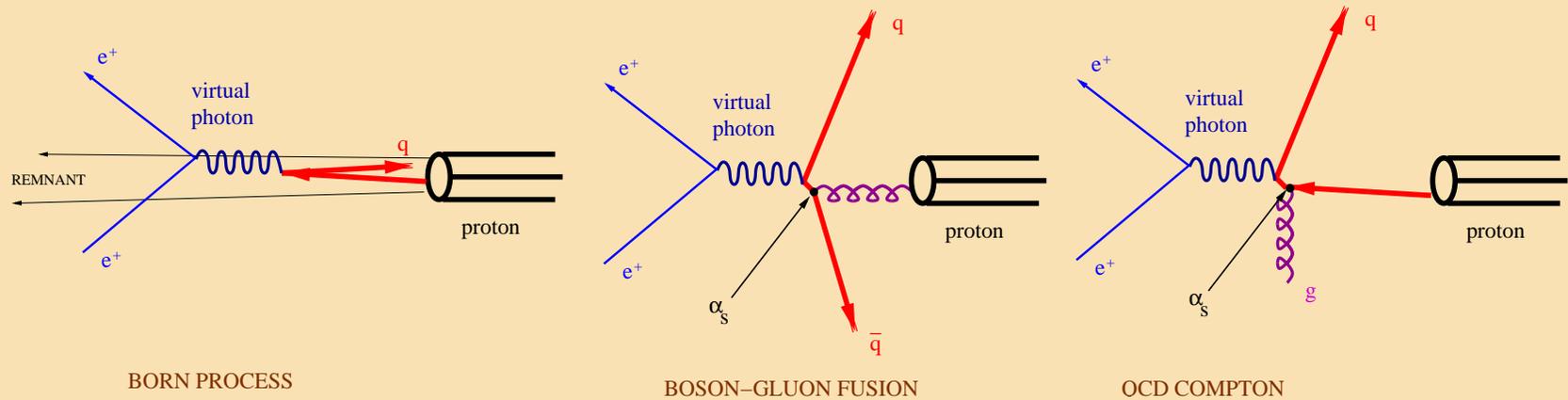
Contributed paper to EPS03

## NLO QCD calculations for jets in NC DIS

- Several NLO ( $\mathcal{O}(\alpha_s^2)$ ) programs are available for performing jet cross sections calculations → DISANT, MEPJET, DISASTER++, NLOJET
- NLO corrections
  - virtual corrections with internal particle loops
  - real corrections with a third parton in the final state
- Different methods to calculate real corrections:
  - phase space slicing method (M)
  - subtraction method (D, D++, NJ)
- Since there are two hard scales in jet production, the renormalisation and factorisation scales can be chosen as one of the two,  $\mu_R, \mu_F = Q$  or  $E_T^{\text{jet}}$
- The calculations are for jets of partons and the measurements are done at the hadron level → need to correct the calculations for hadronisation effects
- Theoretical uncertainties:
  - terms beyond NLO, which are usually estimated by varying  $\mu_R$  by factor 2
  - uncertainties on  $\alpha_s(M_Z)$  and the proton PDFs
  - uncertainty coming from the hadronisation corrections

# Jet production in the Breit frame

- In the Breit frame, the virtual boson collides head-on with the proton



- **High- $E_T$  jet production in the Breit frame:**

- suppression of the Born contribution (struck quark has zero  $E_T$ )
- suppression of the beam-remnant jet (zero  $E_T$ )
- lowest-order non-trivial contributions from  $\gamma^* g \rightarrow q\bar{q}$  and  $\gamma^* q \rightarrow qg$
- directly sensitive to hard QCD processes ( $\alpha_s$ )

- **Restriction of the phase space using only variables in Breit frame ( $E_{T,B}^{\text{jet}}, \eta_B^{\text{jet}}$ )**

- facilitates the separation of beam fragmentation and hard process in the calculations
- allows the measurement of the azimuthal distribution ( $\phi_{jet}^B$ )

# Inclusive jet cross sections in NC DIS: $d\sigma/dQ^2$



- Jets searched with  $k_T$  algorithm in the Breit frame
- At least one jet with  $E_{T,B}^{\text{jet}} > 8 \text{ GeV}$  and  $-2 < \eta_B^{\text{jet}} < 1.8$
- Kinematic range:  $Q^2 > 125 \text{ GeV}^2$  and  $-0.7 < \cos \gamma < 0.5$
- no cut applied in the laboratory frame

Phys Lett B 547 (2002) 164

## Advantages of inclusive jet cross sections in a QCD analysis:

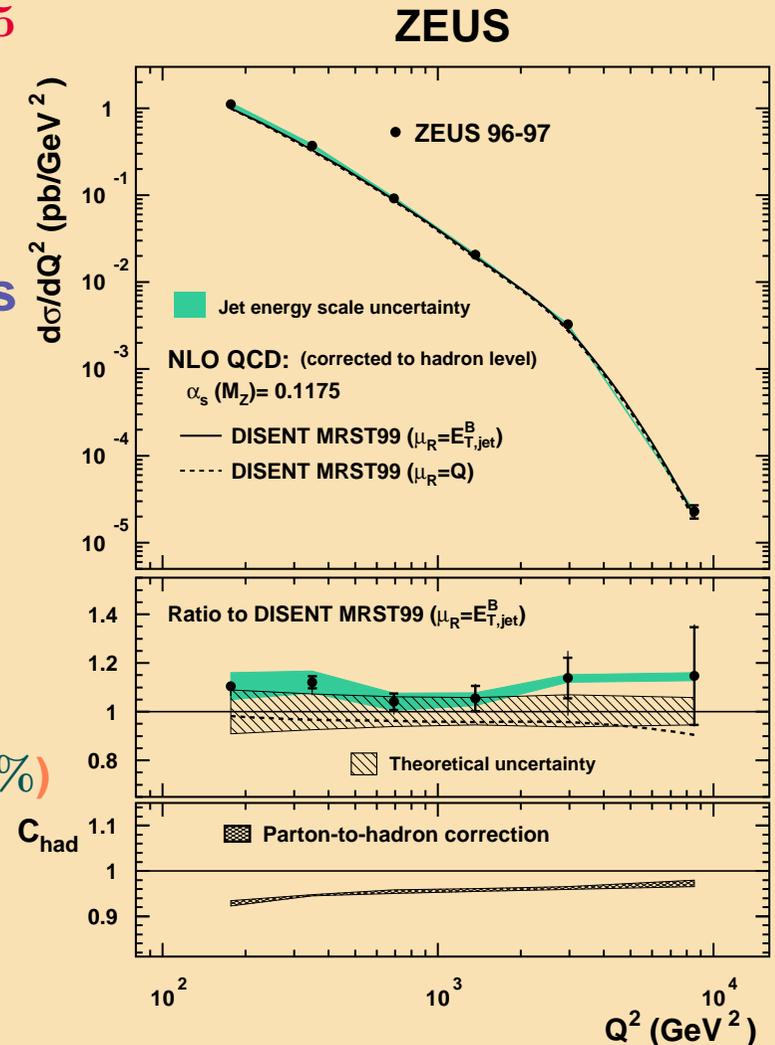
- infrared insensitivity (no dijet asymmetric cuts needed)  $\rightarrow$  wider phase-space than in dijet
- suited to test resummed calculations
- smaller theoretical uncertainties than in dijet cross sections

### Small experimental uncertainties:

- $\rightarrow$  uncorrelated uncertainties (5%)
- $\rightarrow$  absolute energy scale,  $\pm 3$  (1)% for low (high)  $E_{T,B}^{\text{jet}}$  ( $\mp 5\%$ )

### Small theoretical uncertainties:

- $\rightarrow$  higher orders (5%)
- $\rightarrow$  proton PDFs (3%)
- $\rightarrow$   $\alpha_s(M_Z)$  (5%)
- $\rightarrow$  parton-to-hadron corrections ( $< 10\%$ ; uncertainty  $< 1\%$ )



# Inclusive jet cross sections in NC DIS: $d\sigma/dE_{T,B}^{\text{jet}}$



- Jets searched with  $k_T$  algorithm in the Breit frame
- At least one jet with  $E_{T,B}^{\text{jet}} > 8 \text{ GeV}$  and  $-2 < \eta_B^{\text{jet}} < 1.8$
- Kinematic range:  $Q^2 > 125 \text{ GeV}^2$  and  $-0.7 < \cos \gamma < 0.5$
- no cut applied in the laboratory frame

Phys Lett B 547 (2002) 164

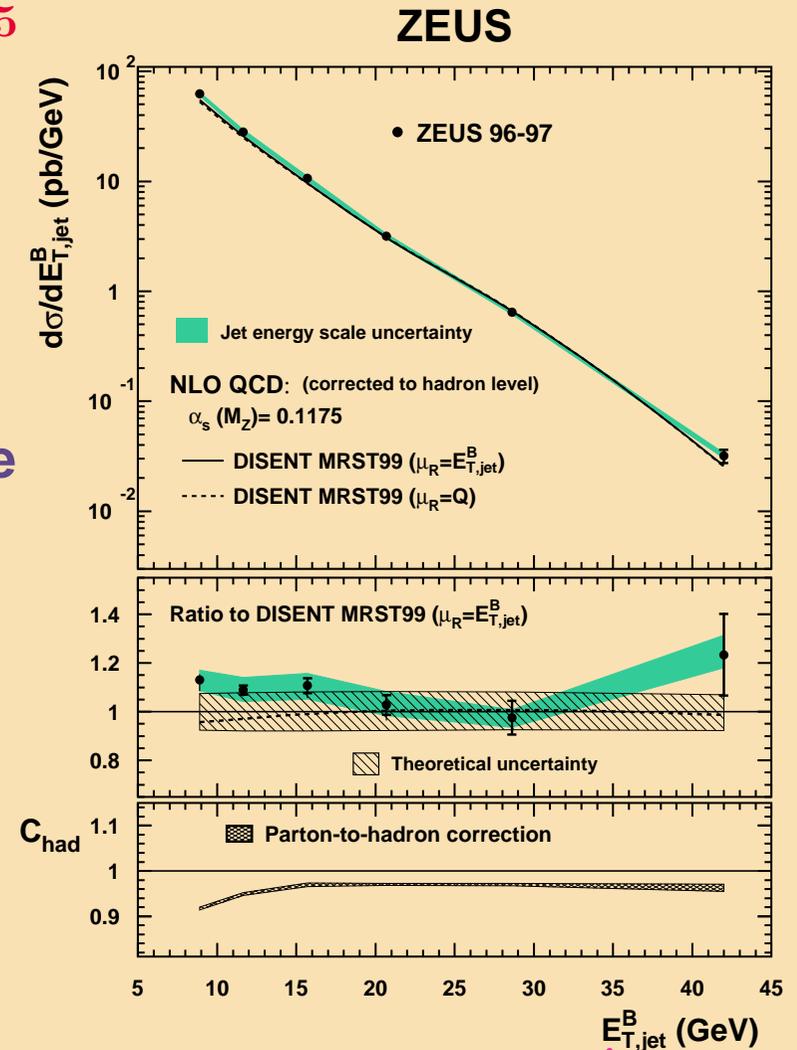
## ● Comparison to NLO predictions (DISSENT):

- $\mu_R = E_{T,B}^{\text{jet}}$  and  $\mu_F = Q$
- $p$  PDFs: MRST99

→ The measured inclusive jet cross sections are well described by the predictions at high  $Q^2$  and at high  $E_{T,B}^{\text{jet}}$

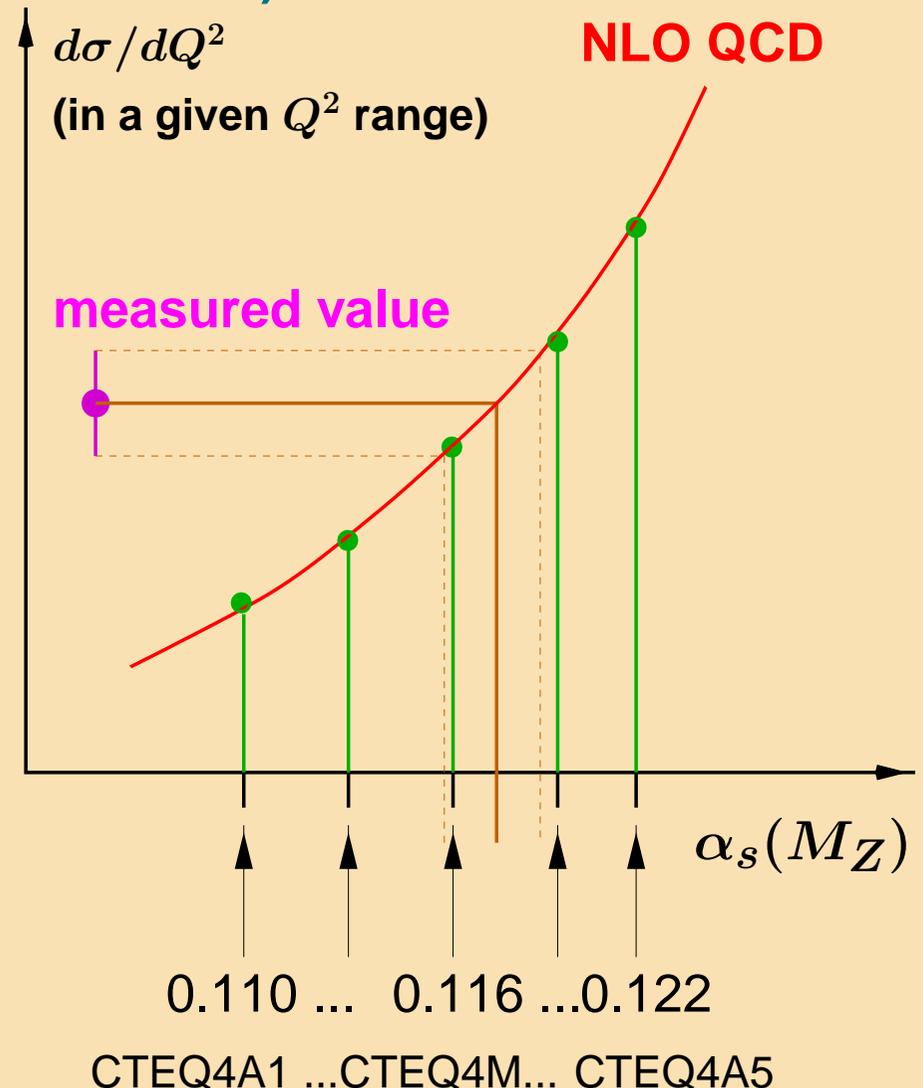
→ At low  $Q^2$  and low  $E_{T,B}^{\text{jet}}$ , the measurements of inclusive jet cross sections are above the calculations by  $\sim 10\%$ , of the same size as the theoretical uncertainties

→ Extraction of  $\alpha_s$  from these measurements restricted to high  $Q^2$  and  $E_{T,B}^{\text{jet}}$



# Inclusive jet cross sections and determination of $\alpha_s(M_Z)$

- **NLO QCD calculations of inclusive jet cross sections depend on  $\alpha_s(M_Z)$  through**
  - matrix elements ( $\hat{\sigma} \sim A \cdot \alpha_s + B \cdot \alpha_s^2$ )
  - proton PDFs ( $\alpha_s(M_Z)$  value assumed in evolution)
- To take into account the correlation, the NLO QCD calculations were performed using various sets of proton PDFs which assume different values of  $\alpha_s(M_Z)$
- The calculations were then parametrised as a function of  $\alpha_s(M_Z)$  in each region of  $Q^2$  of the measurements
- From the measured value of  $d\sigma/dQ^2$  in each  $Q^2$  region, the value of  $\alpha_s(M_Z)$  and its uncertainty were extracted



# Inclusive jet cross sections and determination of $\alpha_s$



- The inclusive jet cross section  $d\sigma/dQ^2$  for  $Q^2 > 500 \text{ GeV}^2$  has been used to extract  $\alpha_s(M_Z)$

$$\rightarrow \alpha_s(M_Z) = 0.1212 \pm 0.0017 \text{ (stat.) } \begin{matrix} +0.0023 \\ -0.0031 \end{matrix} \text{ (exp.) } \begin{matrix} +0.0028 \\ -0.0027 \end{matrix} \text{ (th.)}$$

Phys Lett B 547 (2002) 164

(H1 result:  $\alpha_s(M_Z) = 0.1186 \pm 0.0030 \text{ (exp.) } \begin{matrix} +0.0039 \\ -0.0045 \end{matrix} \text{ (th.) } \begin{matrix} +0.0033 \\ -0.0023 \end{matrix} \text{ (PDF)}$   
(for  $Q^2 > 150 \text{ GeV}^2$ )

Eur Phys J C 19 (2001) 289

- Experimental uncertainties:

→ jet energy scale (1% for  $E_T^{\text{jet}} > 10 \text{ GeV}$ )

- Theoretical uncertainties:

→ terms beyond NLO ( $\Delta\alpha_s(M_Z) = 3\%$ )

→ uncertainties proton PDFs ( $\Delta\alpha_s(M_Z) = 1\%$ )

→ hadronisation corrections ( $\Delta\alpha_s(M_Z) = 0.2\%$ )

- Consistent with other determinations of  $\alpha_s$  and the PDG

→ **Very precise determination of  $\alpha_s(M_Z)$ !**

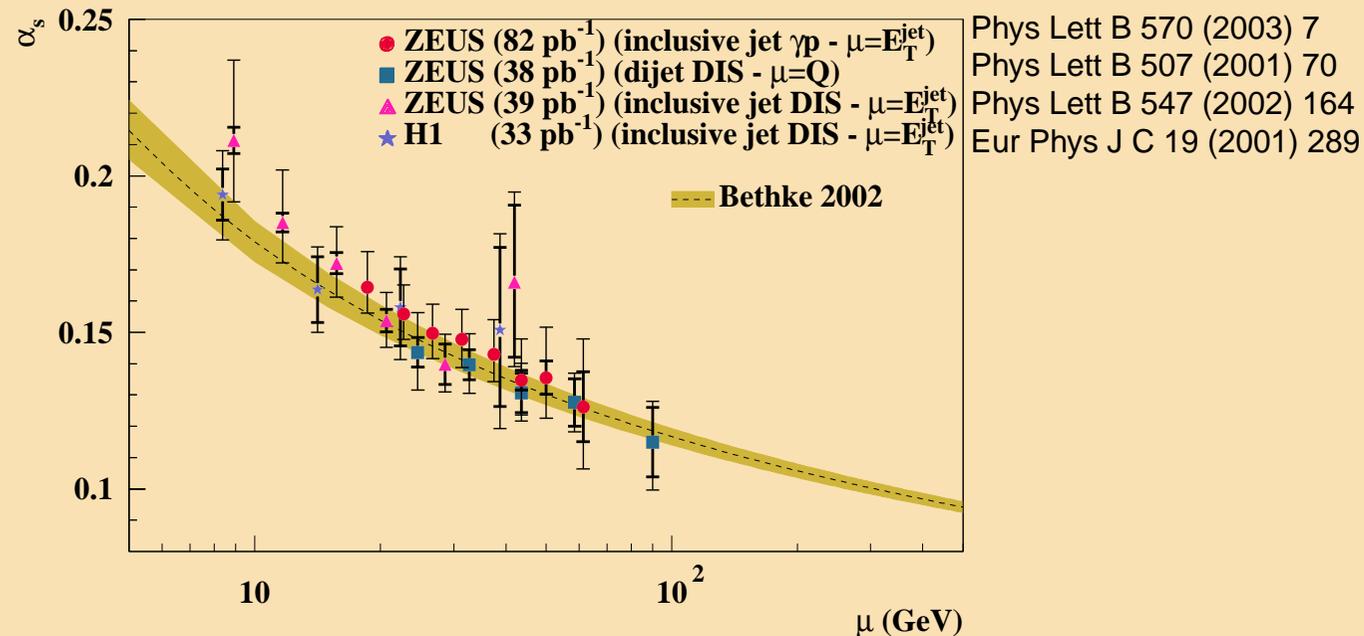
→ Further precision depends upon further experimental and theoretical improvements



# Test of the energy-scale dependence of $\alpha_s$



- The QCD prediction for the energy-scale dependence of  $\alpha_s$  has been tested by determining  $\alpha_s$  from the measured differential cross sections at different scales
  - from the measured  $d\sigma/dE_{T,B}^{\text{jet}}$  in each  $E_{T,B}^{\text{jet}}$  region,  $\alpha_s(E_{T,B}^{\text{jet}})$  was extracted
- The measurements are consistent with the running of  $\alpha_s$  predicted by QCD over a large range in  $E_{T,B}^{\text{jet}}$



- Compilation of H1 and ZEUS determinations of  $\alpha_s(\mu)$  using measurements of jet production in NC DIS and photoproduction
  - test of the scale dependence of  $\alpha_s$  between  $\mu = 8.4$  GeV and 90 GeV



# Inclusive jet $d\sigma/dE_{T,B}^{\text{jet}}$ in different $\eta_{\text{LAB}}^{\text{jet}}$ regions at low $Q^2$

- Jets searched with  $k_T$  algorithm in the Breit frame
- At least one jet with  $E_{T,B}^{\text{jet}} > 5 \text{ GeV}$  and  $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.8$
- Kinematic range:  $5 < Q^2 < 100 \text{ GeV}^2$

Phys Lett B 542 (2002) 193

## H1 Inclusive Jets

### ● Experimental uncertainties:

- uncorrelated uncertainties (5 – 10%)
- absolute energy scale,  $\pm 3\%$  ( $\mp 10 - 15\%$ )

### ● Comparison to LO/NLO predictions (DISENT):

- $\mu_R = E_{T,B}^{\text{jet}}$ ,  $Q$  and  $\mu_F = Q$
- $p$  PDFs: CTEQ5L/M

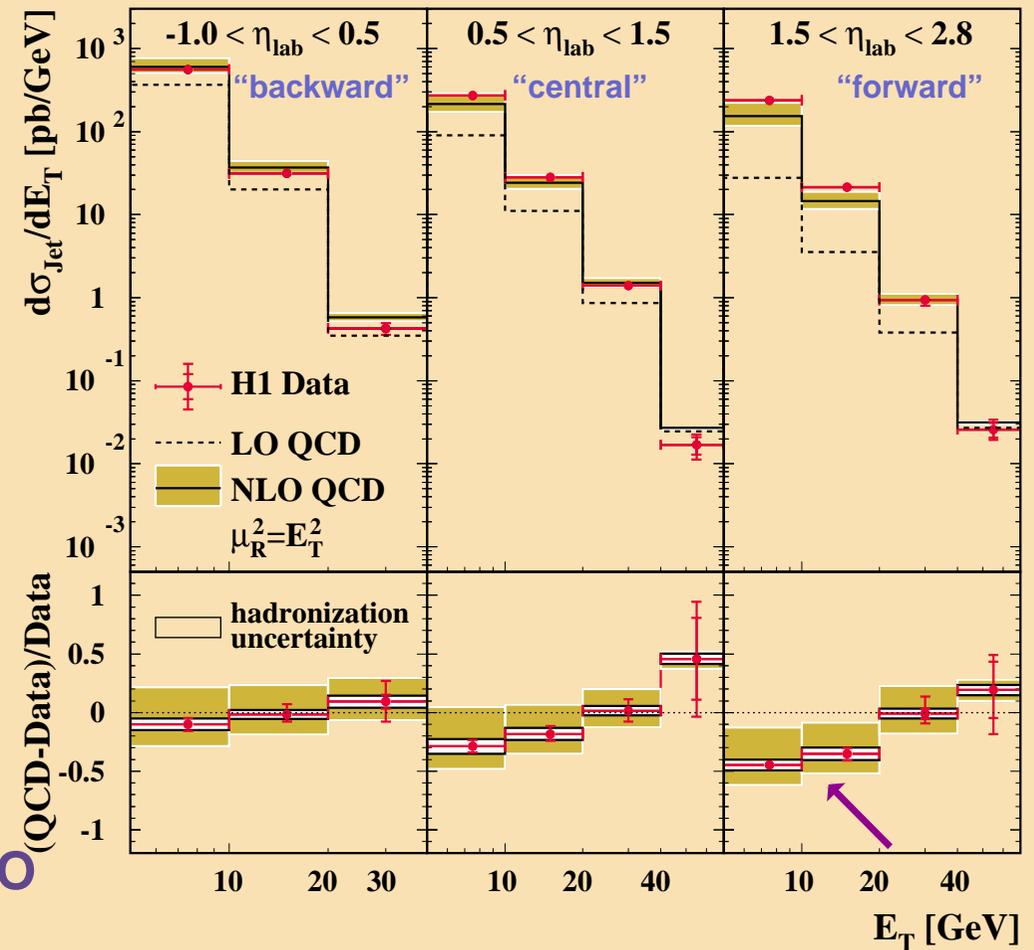
### ● Theoretical uncertainties:

- higher orders (20 – 30% at low  $E_{T,B}^{\text{jet}}$ , 10% at high  $E_{T,B}^{\text{jet}}$ )
- parton-to-hadron corrections (5 – 10%; uncertainty 5%)

### ● Good agreement between data and NLO in “backward” and “central” regions

### ● Large NLO corrections for low $E_{T,B}^{\text{jet}}$ and in “forward” region → NLO/LO $\sim 5$

### ● NLO predictions below data for $E_{T,B}^{\text{jet}} < 20 \text{ GeV}$ in “forward” region

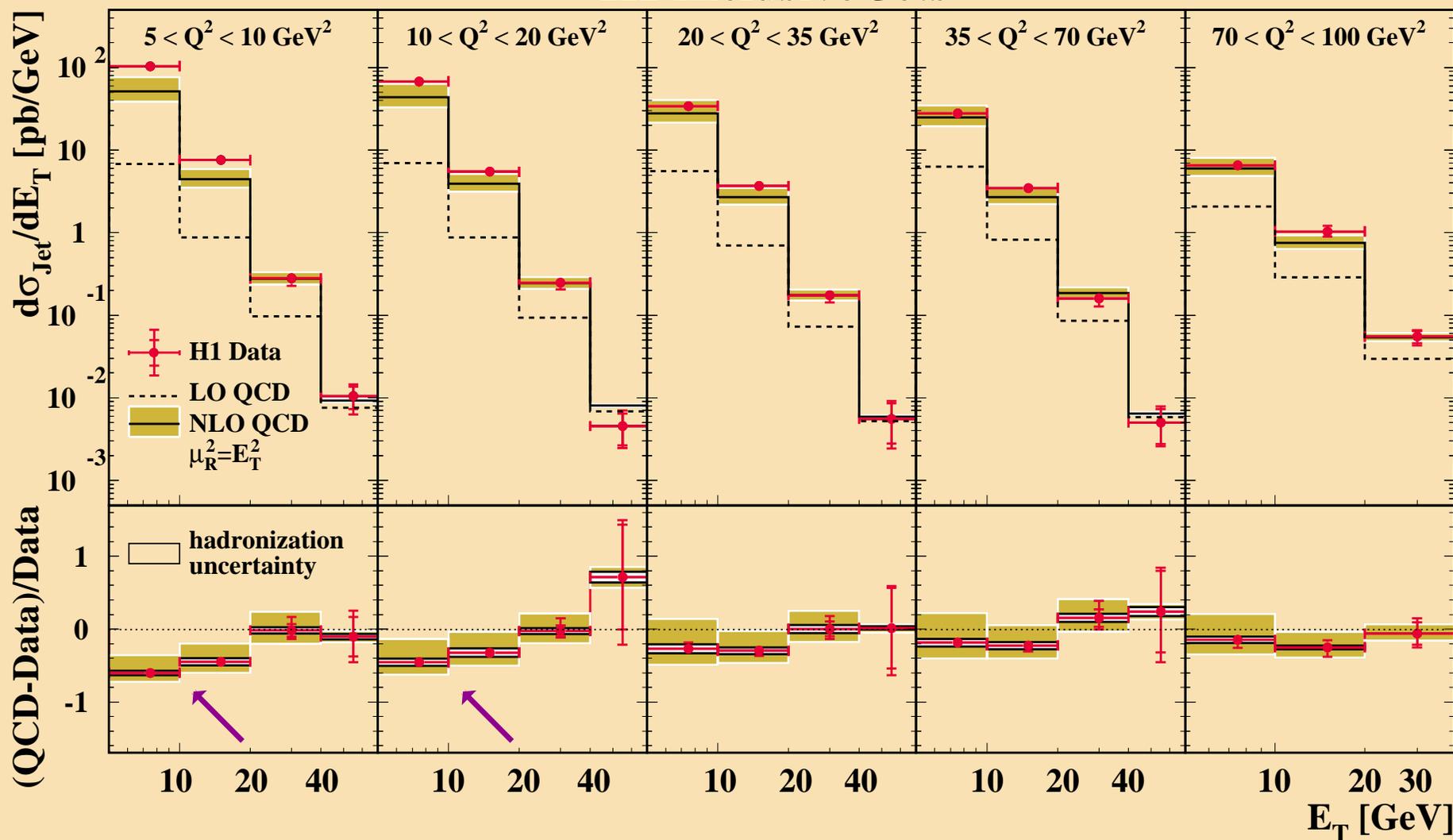




# Inclusive jet $d\sigma/dE_{T,B}^{\text{jet}}$ in different $Q^2$ regions for $1.5 < \eta_{\text{LAB}}^{\text{jet}} < 2.8$

Phys Lett B 542 (2002) 193

## H1 Inclusive Jets

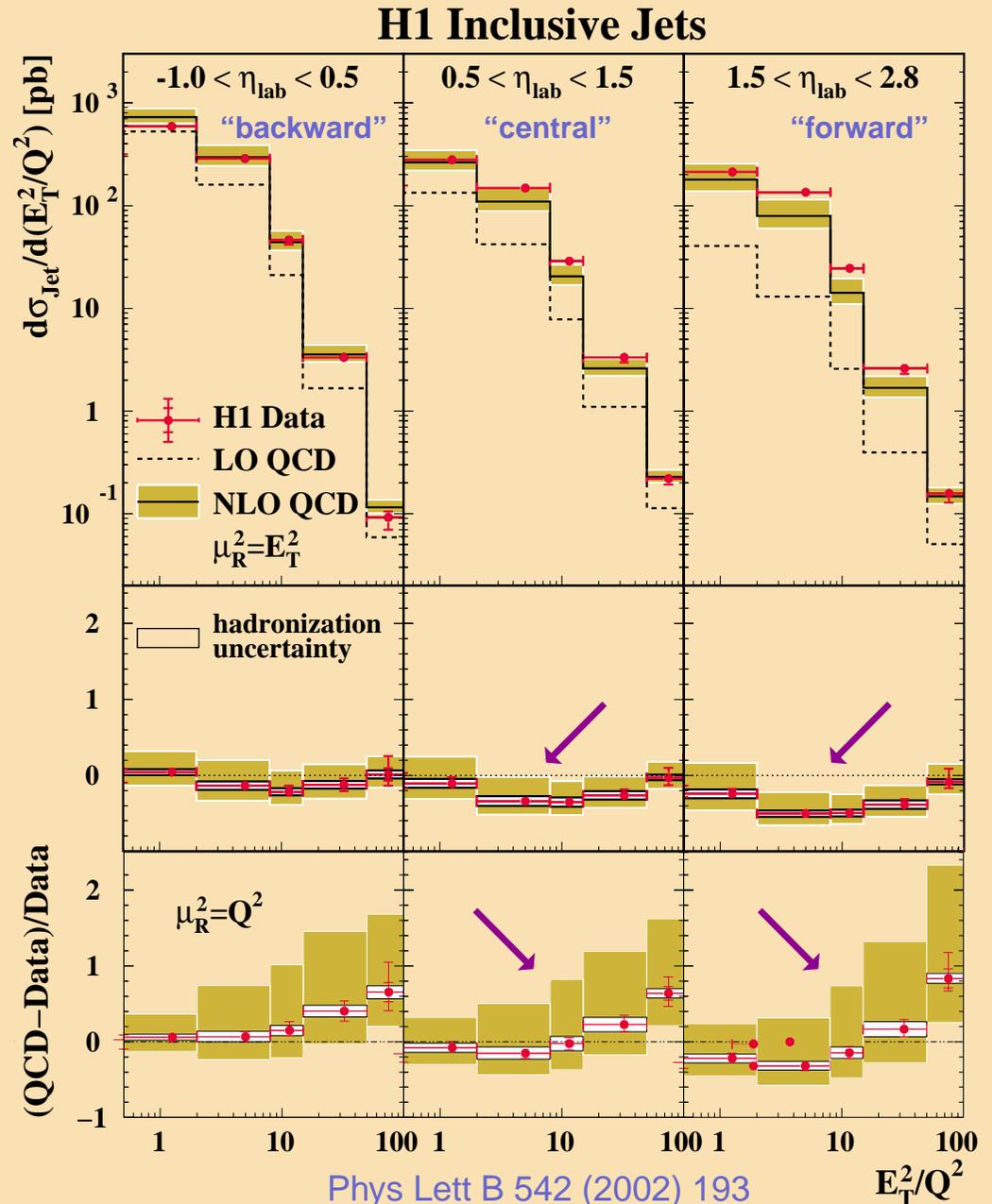


- NLO predictions up to 50% lower than the data in regions where the NLO corrections are largest



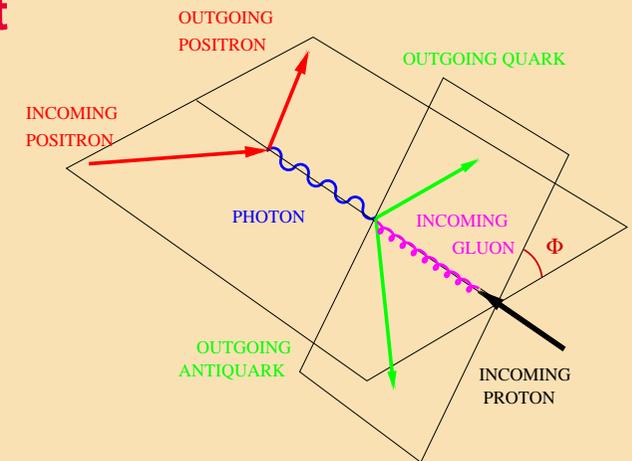
# $d\sigma/d(E_{T,B}^{\text{jet}}/Q)^2$ : interplay of the two hard scales

- “Backward” region well described by NLO
  - NLO predictions lower than the data in “central” and “forward” regions for  $2 < (E_{T,B}^{\text{jet}}/Q)^2 < 50$ 
    - regions dominated by small values of  $(E_{T,B}^{\text{jet}})^2$  and  $Q^2$
  - NLO calculations with  $\mu_R = Q$ 
    - disagreement for large  $(E_{T,B}^{\text{jet}}/Q)^2$  (small  $Q^2$ )
- Improved calculations are needed to understand jet production at low  $Q^2$

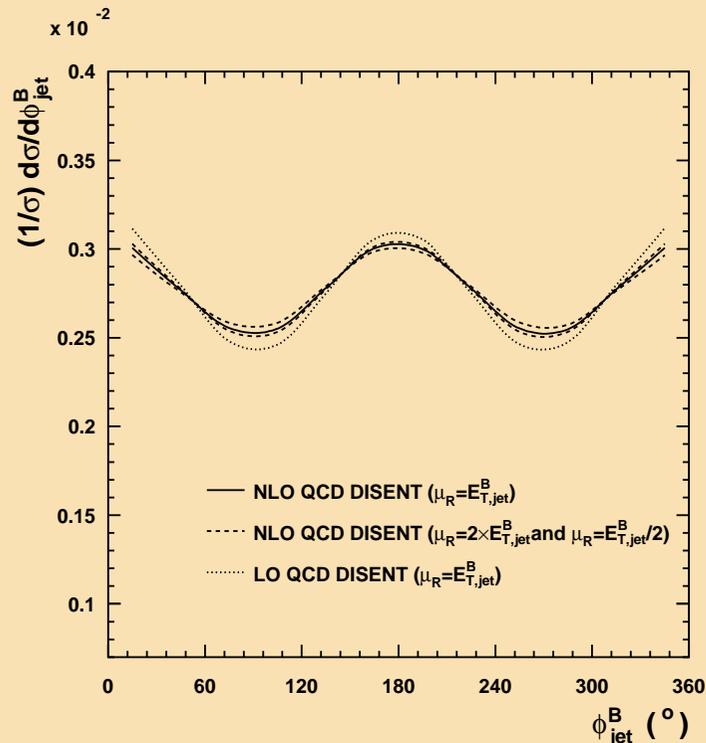


# Azimuthal distribution of jets in NC DIS

- The distribution of the azimuthal angle  $\phi_{\text{jet}}^B$  in the Breit frame between the lepton scattering plane and the plane defined by the jet and the incoming proton direction is expected to be non-uniform due to perturbative QCD effects and insensitive to non-perturbative effects



→ clean test of perturbative QCD



- LO pQCD prediction for unpolarised NC DIS at  $Q^2 \ll M_Z^2$

$$\rightarrow d\sigma/d\phi_{\text{jet}}^B = A + B \cdot \cos(\phi_{\text{jet}}^B) + C \cdot \cos(2\phi_{\text{jet}}^B)$$

- In  $\gamma^* q \rightarrow qg$  the outgoing  $g(q)$  preferentially appears at  $\phi = 0(\pi)$
- In  $\gamma^* g \rightarrow q\bar{q}$  the  $\phi$  dependence is dominated by the  $\cos 2\phi$  term

- For an inclusive jet measurement

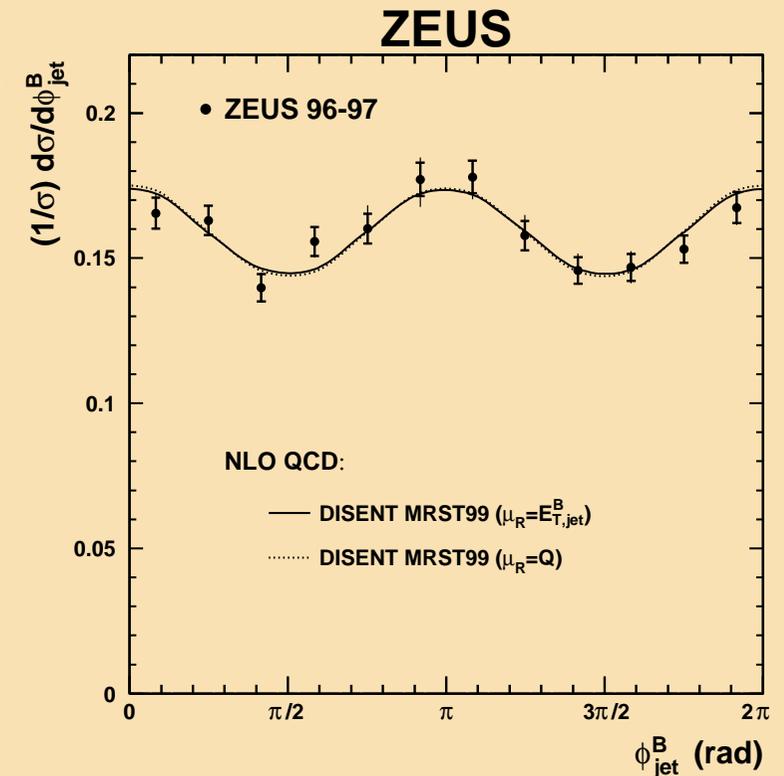
$$\rightarrow d\sigma/d\phi_{\text{jet}}^B = A + C \cdot \cos(2\phi_{\text{jet}}^B)$$

# Azimuthal distribution of jets in NC DIS



- **Measurement of the normalised inclusive jet cross section  $(1/\sigma)d\sigma/d\phi_{\text{jet}}^B$** 
  - Jets searched with  $k_T$  algorithm in the Breit frame
  - At least one jet with  $E_{T,B}^{\text{jet}} > 8 \text{ GeV}$  and  $-2 < \eta_B^{\text{jet}} < 1.8$
  - Kinematic range:  $Q^2 > 125 \text{ GeV}^2$  and  $-0.7 < \cos \gamma < 0.5$
  - no cut applied in the laboratory frame to avoid distortions of the azimuthal distribution by kinematic effects
- **Clear enhancements at  $\phi_{\text{jet}}^B = 0$  and  $\phi_{\text{jet}}^B = \pi$** 
  - **Small experimental uncertainties**
  - **Negligible parton-to-hadron corrections**
  - **Small theoretical uncertainties:**
    - terms beyond NLO ( $\pm 1\%$  on the amplitude of the modulation of the distribution)
    - other uncertainties (eg intrinsic  $k_T$  of partons in the proton) are smaller
- **NLO QCD calculations ( $\mathcal{O}(\alpha_s^2)$ ) using  $\mu_R = E_{T,B}^{\text{jet}}$  (or  $\mu_R = Q$ ),  $\mu_F = Q$  and the MRST99 pPDF sets describe the measurements very well**
  - **precise test of the perturbative QCD prediction for the azimuthal distribution**

Phys Lett B 551 (2003) 226



# Azimuthal distribution of jets in NC DIS: $Q^2$ dependence



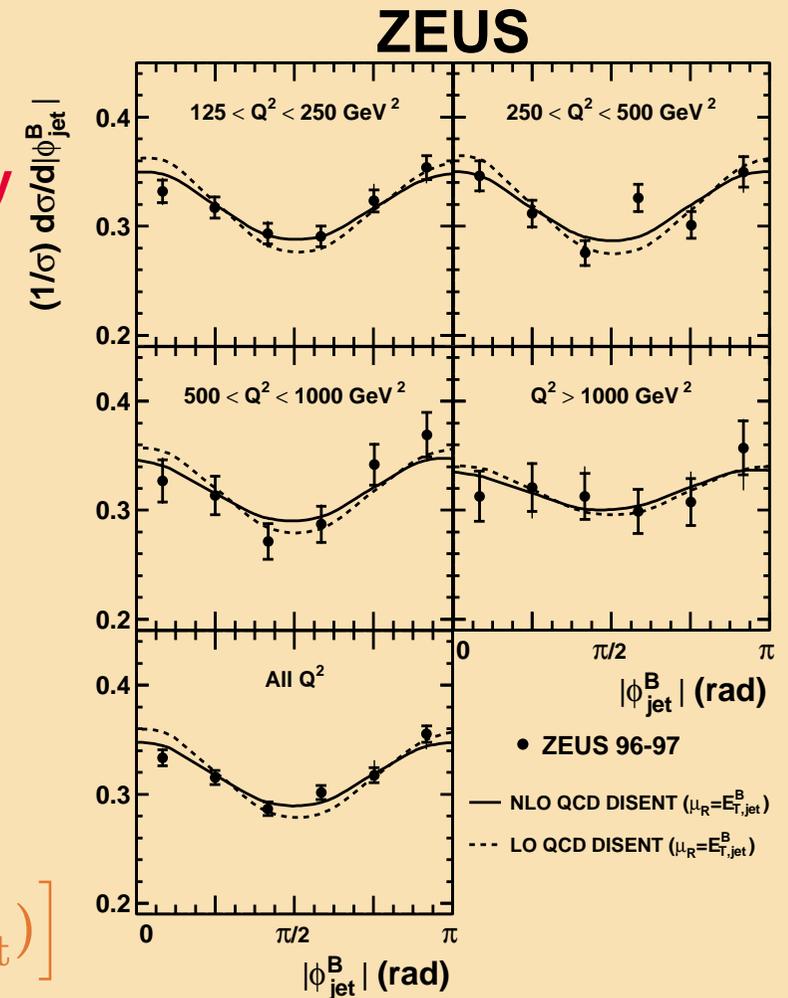
- Measurement of the normalised inclusive jet cross section  $(1/\sigma)d\sigma/d|\phi_{\text{jet}}^B|$  in different regions of  $Q^2$  Phys Lett B 551 (2003) 226

- NLO QCD calculations describe the data well
- LO QCD predicts a larger asymmetry, particularly at low  $Q^2$

- The asymmetry is predicted to decrease as  $Q^2$  increases due to the progressive decline of the  $\gamma^*g \rightarrow q\bar{q}$  process

- To quantify the asymmetry and its dependence on  $Q^2$ , a fit was performed to the data and QCD calculations using the functional form

$$\rightarrow \frac{1}{\sigma} \frac{d\sigma}{d|\phi_{\text{jet}}^B|} = \frac{1}{\pi} \left[ 1 + f_1 \cos(\phi_{\text{jet}}^B) + f_2 \cos(2\phi_{\text{jet}}^B) \right]$$



# Azimuthal distribution of jets in NC DIS: $Q^2$ dependence



$$\rightarrow \frac{1}{\sigma} \frac{d\sigma}{d|\phi_{\text{jet}}^B|} = \frac{1}{\pi} \left[ 1 + f_1 \cos(\phi_{\text{jet}}^B) + f_2 \cos(2\phi_{\text{jet}}^B) \right]$$

Phys Lett B 551 (2003) 226

- Fitted values of  $f_1$  and  $f_2$  as functions of  $Q^2$  and for the entire sample ( $Q^2 > 125 \text{ GeV}^2$ )

$$\rightarrow f_1(\text{Data}) = -0.0273 \pm 0.0144 \text{ (stat.)} \begin{matrix} +0.0121 \\ -0.0099 \end{matrix} \text{ (syst.)}$$

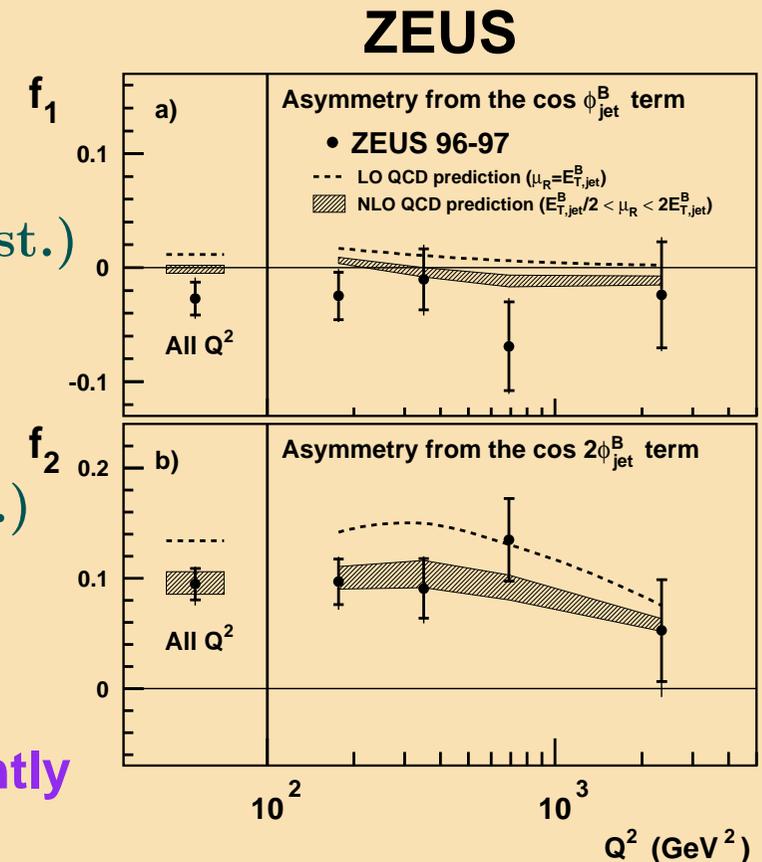
$$\rightarrow f_1(\text{NLO QCD}) = -0.0003 \begin{matrix} +0.0025 \\ -0.0044 \end{matrix} (\mu_R - \text{scale})$$

$$\rightarrow f_2(\text{Data}) = 0.0947 \pm 0.0143 \text{ (stat.)} \begin{matrix} +0.0068 \\ -0.0133 \end{matrix} \text{ (syst.)}$$

$$\rightarrow f_2(\text{NLO QCD}) = 0.0984 \begin{matrix} +0.0074 \\ -0.0131 \end{matrix} (\mu_R - \text{scale})$$

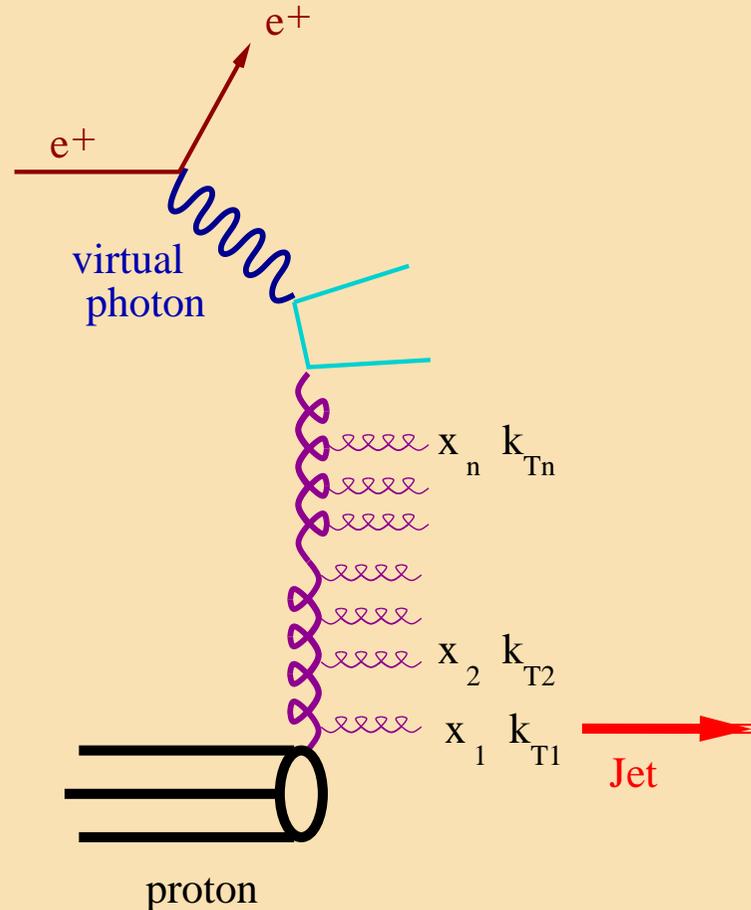
- For  $f_1$ , the observed asymmetry tends to be slightly larger and more negative than that of the NLO
- The NLO QCD calculations of  $f_2$  are in good agreement with the measured values

→ Precise test of pQCD prediction for the azimuthal asymmetry



## Parton evolution at low $x$

- At low  $x$ , dijet data may be used to gain insight into parton dynamics



- The evolution of the PDFs with  $\mu_F$  is described by the DGLAP evolution equations
- The DGLAP equations sum the leading powers of  $\alpha_s \log Q^2$  in the region of strongly-ordered transverse momenta
  - $Q^2 \gg k_{Tn}^2 \gg \dots \gg k_{T2}^2 \gg k_{T1}^2$
  - (LLA: strong  $k_T$ -ordered parton cascade)

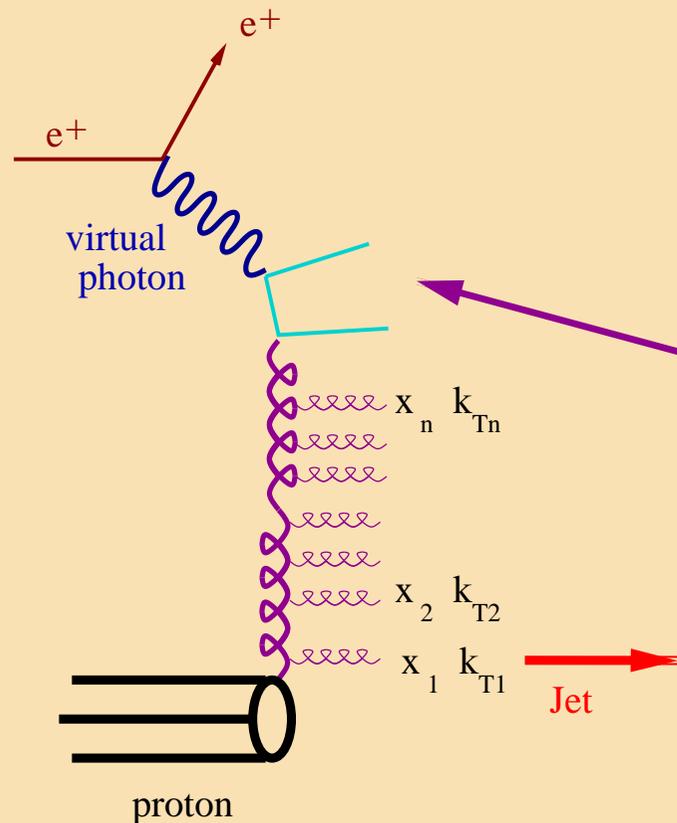
→ successful description of jet production at large scales

- DGLAP approximation expected to break down at low  $x$  → when  $\log Q^2 \ll \log 1/x$ , terms proportional to  $\alpha_s \log 1/x$  become important and need to be summed

- The BFKL equations accomplish this:
  - the integration is taken over the full  $k_T$  phase space of the gluons
  - no  $k_T$  ordering

## Parton evolution at low $x$

- The CCFM parton evolution with angular-ordered parton emission is equivalent to the BFKL approach for  $x \rightarrow 0$  and reproduces the DGLAP evolution at large  $x$
- Do the properties of the dijet system depend on the dynamics of the ladder?
  - $k_T$  ordered or unordered evolution of cascade
- Possible deviations from the DGLAP approach can be tested at small  $x$ , where strong  $k_T$ -ordering of the exchanged parton cascade is no longer strictly fulfilled



- At small  $x$ : parton emission along the exchanged gluon ladder increases with decreasing  $x$ 
  - not included in DGLAP: additional contributions have to be included when predicting cross sections at low  $x$
  - the two outgoing hard partons are no longer balanced in transverse momentum: excess of events with the hard partons no longer back-to-back in azimuth



# Triple differential cross section: $d\sigma/dQ^2 dx dE_T^*$

- Jets searched with  $k_T$  algorithm in the  $\gamma^*p$  cms frame
- At least two jets with  $E_T^* > 5$  GeV,
  - $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$  and  $E_{T,\text{max}}^* > 7$  GeV
- Kinematic range:  $5 < Q^2 < 100$  GeV<sup>2</sup> and  $10^{-4} < x < 10^{-2}$

- Comparison to NLO predictions (DISENT):

→  $\mu_R^2 = \bar{E}_T^{*2}$  and  $\mu_F^2 = 70$  GeV<sup>2</sup>

→  $p$  PDFs: CTEQ6M

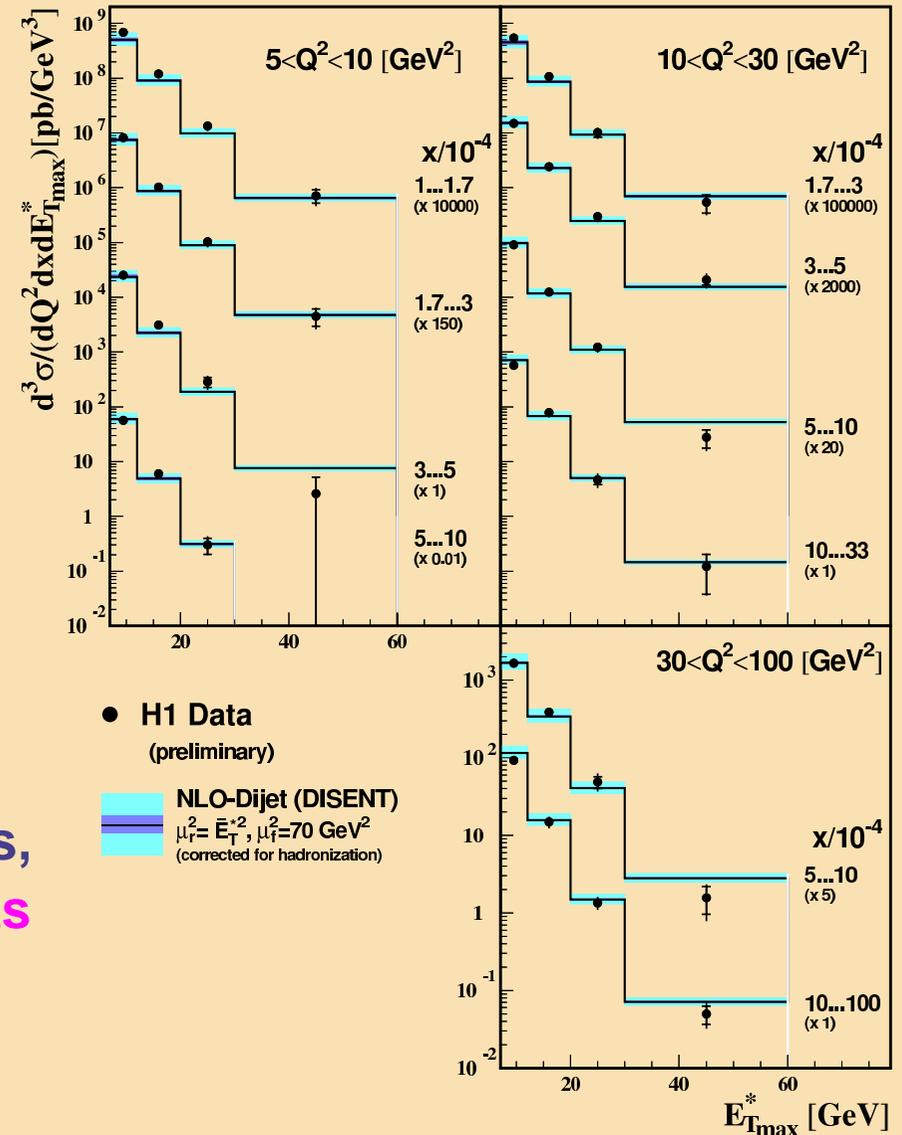
- Theoretical uncertainties:

→ higher orders (20%)

→ parton-to-hadron corrections (10%)

- Good agreement between data and NLO calculations within the present uncertainties, even at small values of  $E_{T,\text{max}}^*$  where effects due to small- $x$  dynamics should be most prominent

Contributed paper to EPS03





# Triple differential cross section: $d\sigma / dQ^2 dx |\Delta\eta^*|$

- Jets searched with  $k_T$  algorithm in the  $\gamma^*p$  cms frame
- At least two jets with  $E_T^* > 5$  GeV,  
 $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$  and  $E_{T,\text{max}}^* > 7$  GeV
- Kinematic range:  $5 < Q^2 < 100$  GeV<sup>2</sup> and  
 $10^{-4} < x < 10^{-2}$

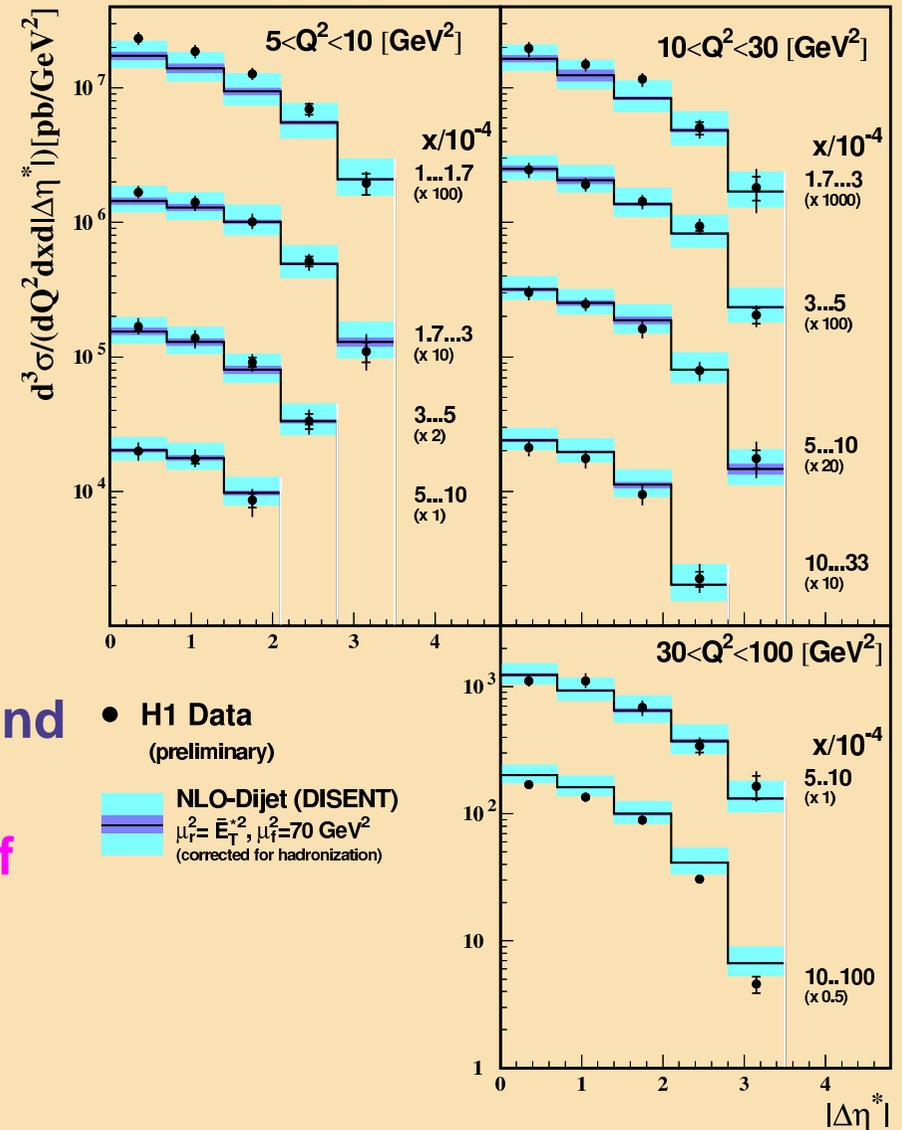
- Comparison to NLO predictions (DISJET):

→  $\mu_R^2 = \bar{E}_T^{*2}$  and  $\mu_F^2 = 70$  GeV<sup>2</sup>

→  $p$  PDFs: CTEQ6M

- No significant disagreement between data and NLO calculations within the uncertainties, small deviations observed at small values of  $x$ ,  $Q^2$  and  $|\Delta\eta^*|$

Contributed paper to EPS03





# Azimuthal jet separation

- Measurement of the azimuthal separation,  $\Delta\phi^*$ , of the two hardest jets in the  $\gamma^*p$  cms

- DGLAP:  $\Delta\phi^* \neq \pi$  can occur due to higher order effects

- BFKL and CCFM: number of events with  $\Delta\phi^* < \pi$  should increase due to partons entering the hard process with large  $k_T$

→ A significant fraction of events observed at small azimuthal separation

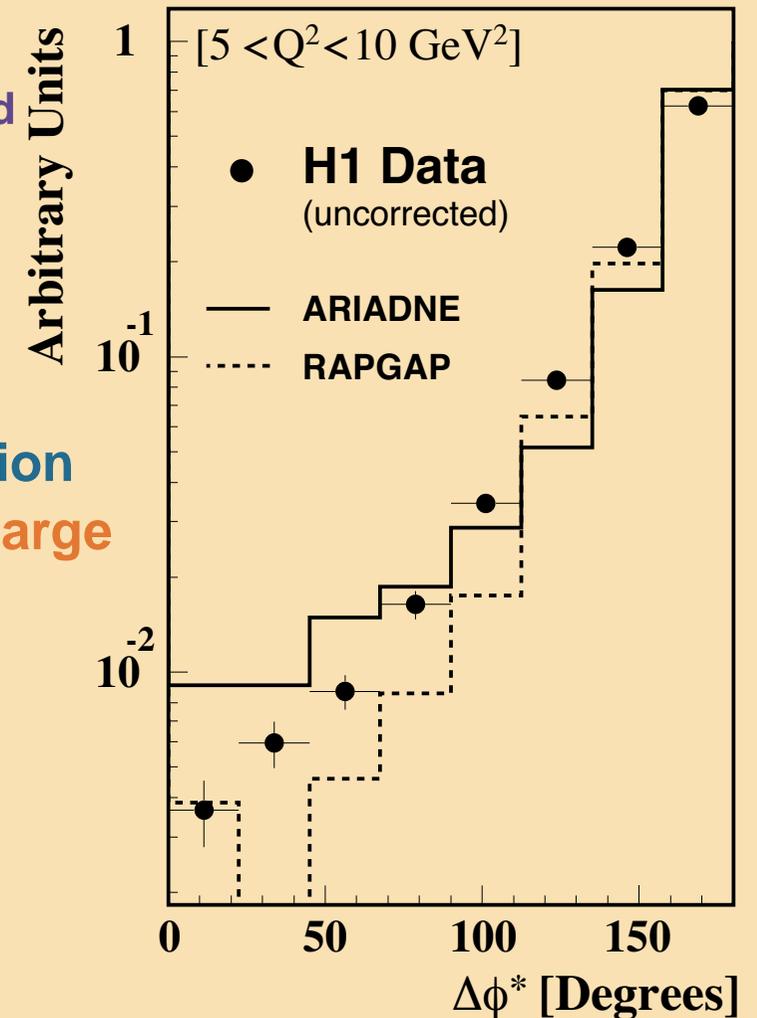
- The measurement of a multi-differential cross section as a function of  $x$ ,  $Q^2$  and  $\Delta\phi^*$  is difficult due to large migrations

- The ratio

$$\rightarrow S = \frac{\int_0^\alpha N_{2\text{jet}}(\Delta\phi^*, x, Q^2) d\Delta\phi^*}{\int_0^\pi N_{2\text{jet}}(\Delta\phi^*, x, Q^2) d\Delta\phi^*}, \quad \alpha = \frac{2}{3}\pi$$

is better suited to test small- $x$  effects

Contributed paper to EPS03



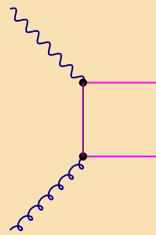


# $x$ and $Q^2$ dependence of $S$

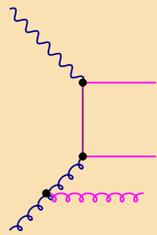
- Measurement of the  $S$  distribution as a function of  $x$  in bins of  $Q^2$
- The data rise towards low  $x$ , especially at low  $Q^2$
- Comparison to NLO-dijet predictions (DISSENT):
  - the calculations are several standard deviations below the data and show no rise towards low  $x$

Contributed paper to EPS03

DISSENT:



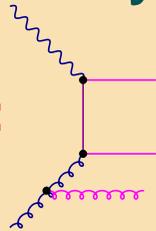
no  $k_T$



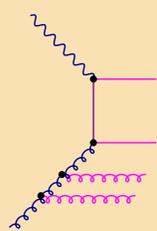
$k_T$

- Comparison to NLO-3jet predictions (NLOJET):
  - accurate description of the data at large  $Q^2$  and large  $x$
  - fail to describe the increase towards low  $x$ , especially at low  $Q^2$

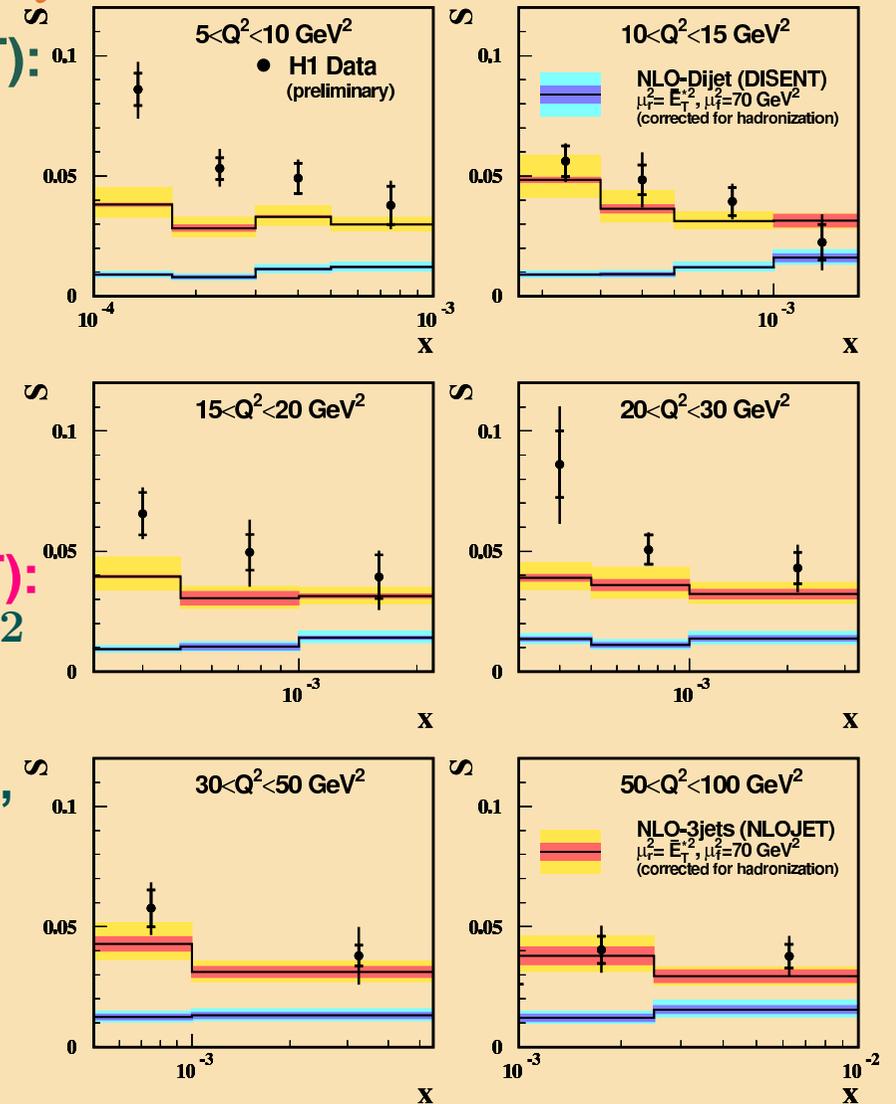
NLOJET:



$k_T$



$k_T$





# $x$ and $Q^2$ dependence of $S$

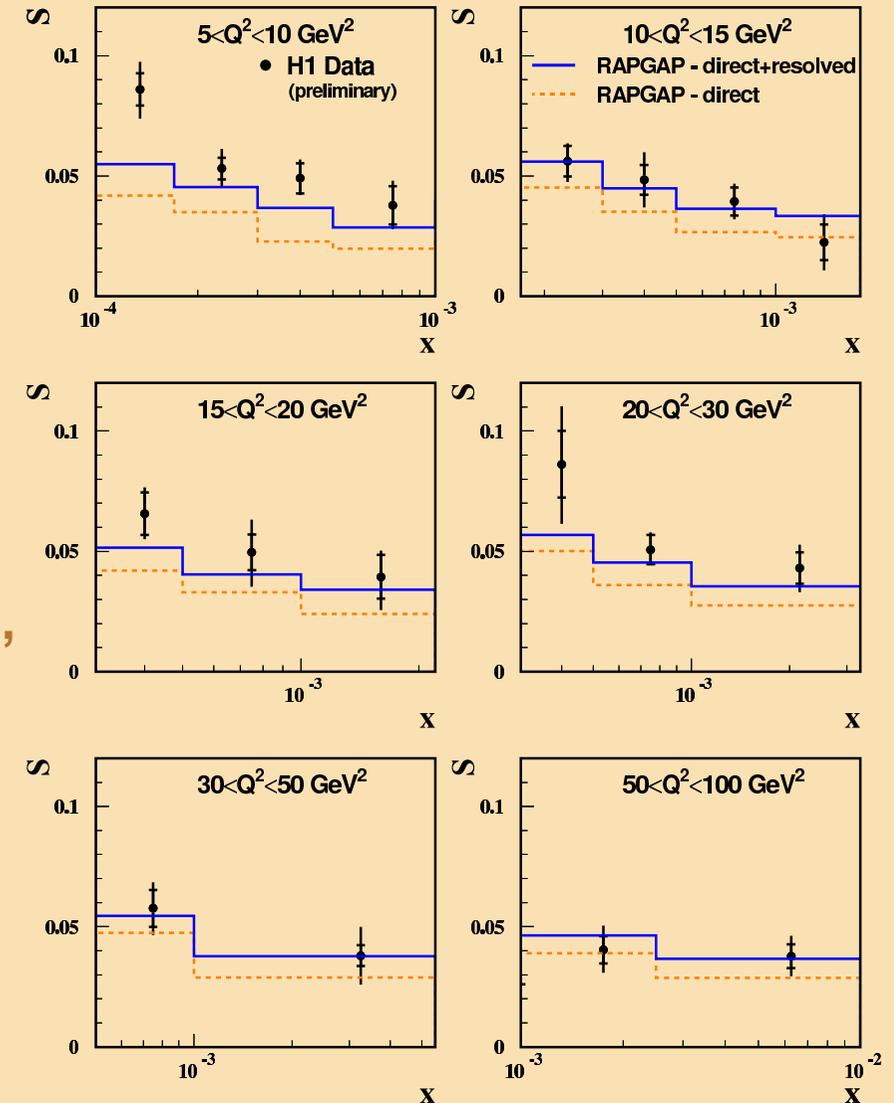
- Measurement of the  $S$  distribution as a function of  $x$  in bins of  $Q^2$

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→ A useful comparison is only provided by models which incorporate higher order effects beyond NLO

- Comparison to RAPGAP predictions (DGLAP approach):

- good description of data at large  $Q^2$  and large  $x$
- fail to describe the increase towards low  $x$ , especially at low  $Q^2$
- improved description of data when incorporating resolved photons, but still prediction too low at low  $x$





# $x$ and $Q^2$ dependence of $S$

- Measurement of the  $S$  distribution as a function of  $x$  in bins of  $Q^2$

- If the observed discrepancies are due to the influence of non- $k_T$ -ordered parton emissions, models based on the color dipole model or the CCFM evolution equations, may provide a much better description of the ratio  $S$

- Comparison to CDM predictions (ARIADNE):

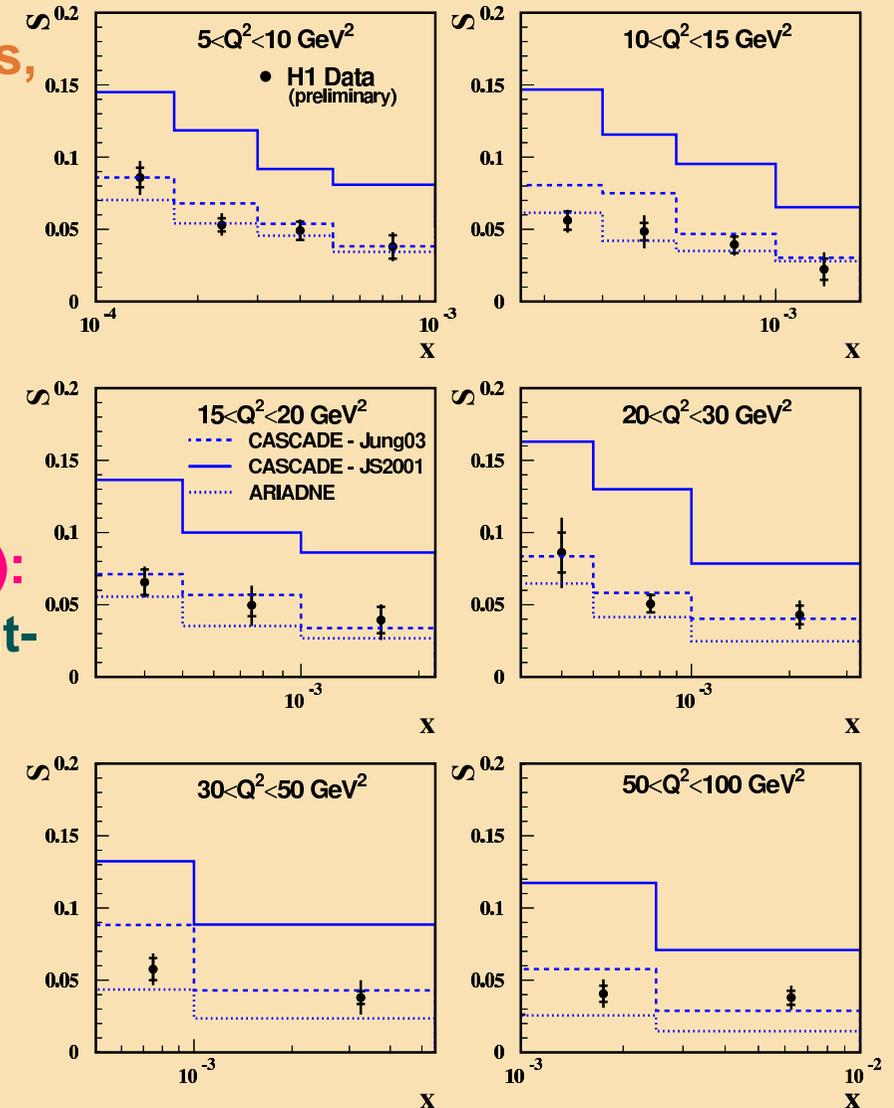
- good description of data at low  $x$  and  $Q^2$
- fail to describe the data at high  $Q^2$

- Comparison to CCFM predictions (CASCADE):
- the prediction using JS2001 lies significantly above the data

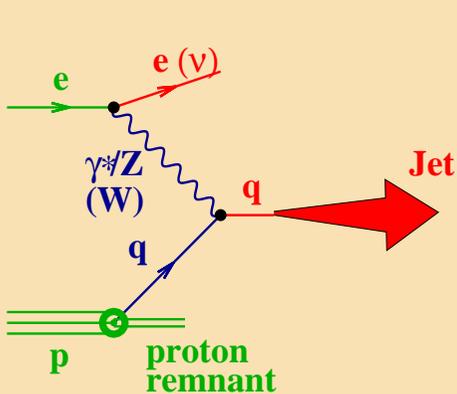
- the prediction using the set 2 of Jung2003 closer to the data

- The measurement of the ratio  $S$  is sensitive to the details of the unintegrated gluon distribution

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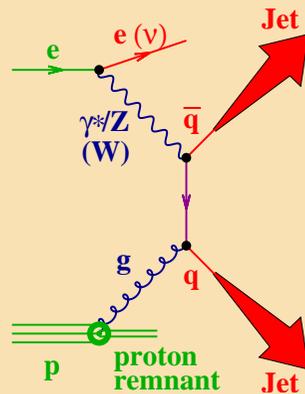
# Multijet production in NC DIS



jet production in the QPM:

$$\gamma^* \rightarrow q$$

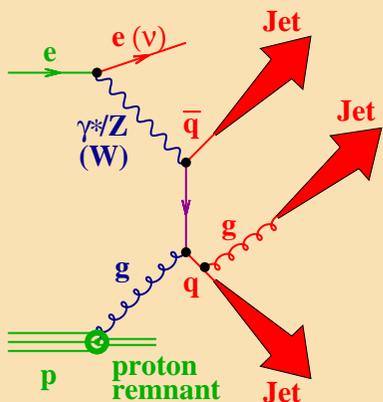
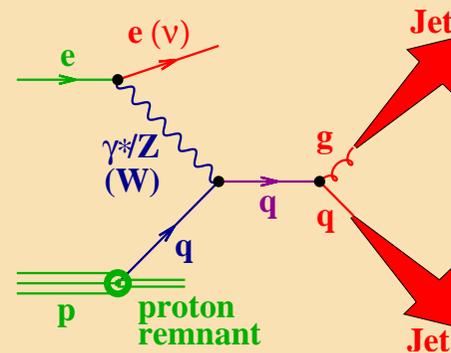
one-jet events



jet production at  $\mathcal{O}(\alpha_s)$ :

$$\gamma^* g \rightarrow q\bar{q}, \gamma^* q \rightarrow qq$$

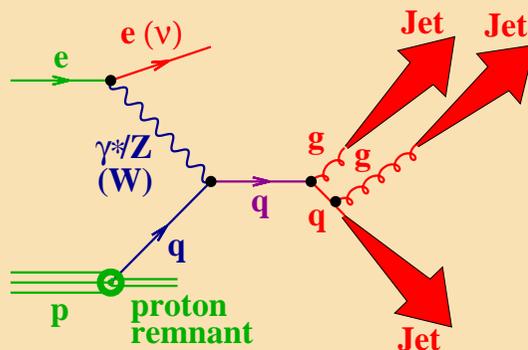
two-jet events



jet production at  $\mathcal{O}(\alpha_s^2)$ :

$$\gamma^* g \rightarrow q\bar{q}g, \gamma^* q \rightarrow qgg$$

three-jet events



→ Events with three jets can be seen as dijet processes with additional gluon radiation or splitting of a gluon in a  $q\bar{q}$  pair

→ Direct tests of QCD beyond LO:

$$\sigma_{3\text{jet}} \propto \alpha_s^2$$

# Dijet and three-jet cross sections in NC DIS: $d\sigma/dQ^2$



- Jets searched with  $k_T$  algorithm in the Breit frame
- At least two jets with  $E_{T,B}^{\text{jet}} > 5 \text{ GeV}$  and  $-1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5$
- Kinematic range:  $10 < Q^2 < 5000 \text{ GeV}^2$ ,  $0.04 < y < 0.6$  and  $\cos \gamma < 0.7$
- Events with  $M^{3j}(M^{\text{jj}}) > 25 \text{ GeV}$  were selected

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- Comparison to NLO ( $\mathcal{O}(\alpha_s^2)$  and  $\mathcal{O}(\alpha_s^3)$ ) predictions (NLOJET):

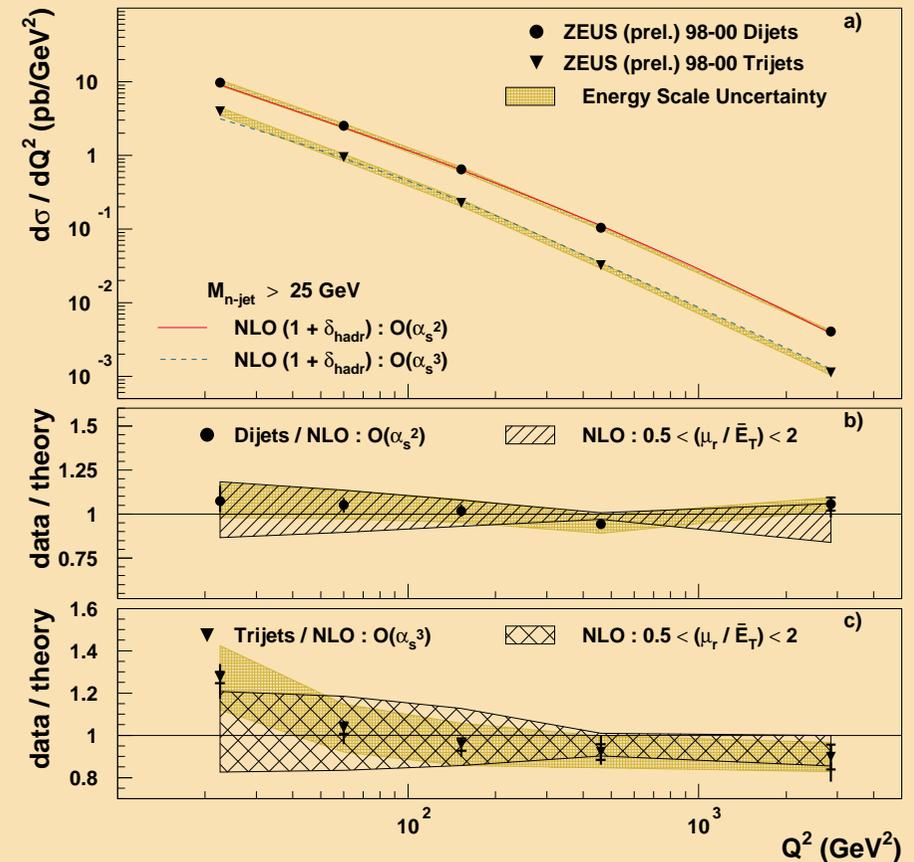
$$\rightarrow \mu_R = \mu_F = \bar{E}_T$$

$\rightarrow p$  PDFs: CTEQ6

- The measured dijet and three-jet cross sections are well described by the predictions

$\rightarrow$  Potentially useful observable to make an accurate determination of  $\alpha_s$

## ZEUS



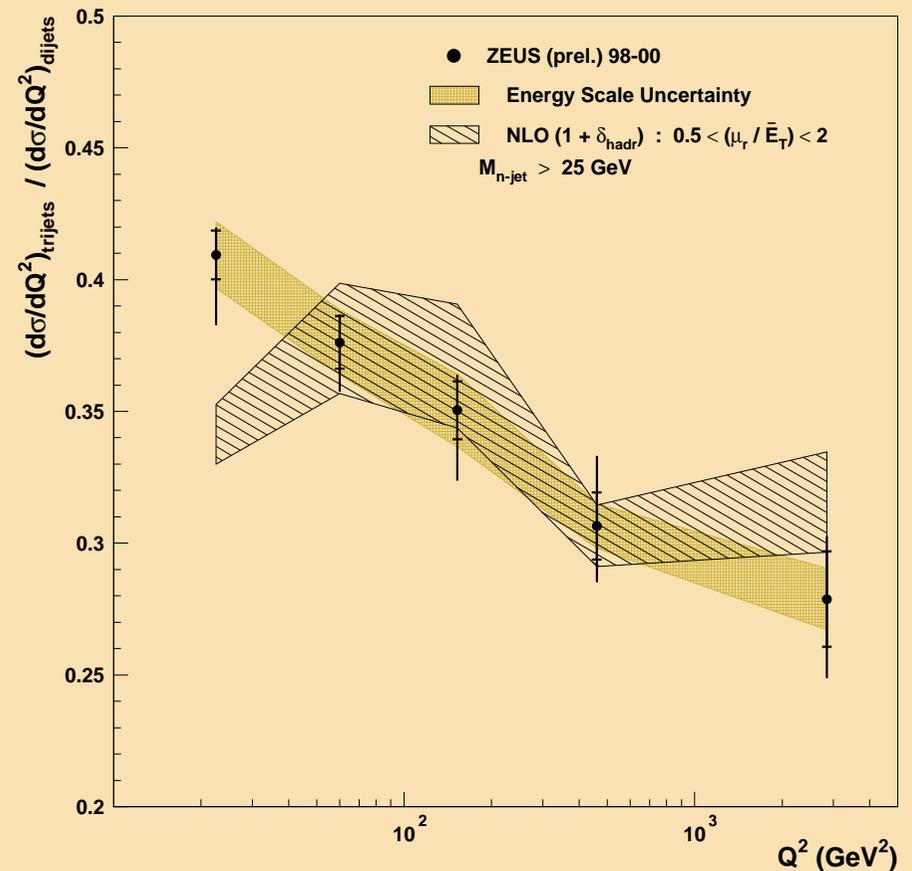
# $Q^2$ dependence of the dijet to three-jet cross section ratio



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- Measurement of the dijet to three-jet cross sections ratio as a function of  $Q^2$
- Many experimental and theoretical uncertainties cancel out in the ratio  
→ more accurate test of color dynamics
- The measured ratio is well described by the NLO calculations for  $Q^2 > 50 \text{ GeV}^2$

## ZEUS

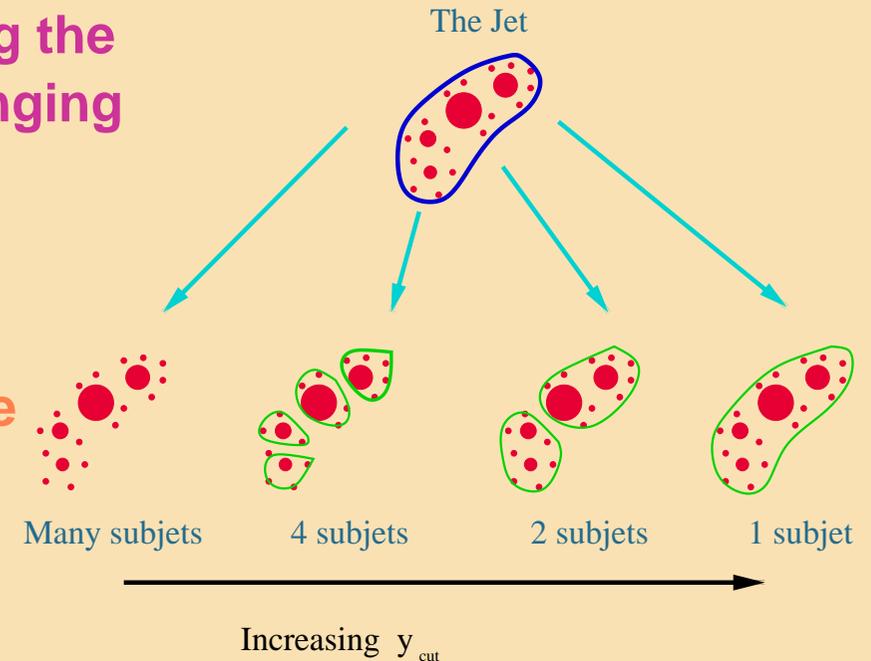


## Internal structure of jets

- The investigation of the **internal structure of jets** gives insight into the **transition** between a **parton** produced in a hard process and the experimentally observable jet of hadrons
- The **internal structure of a jet** is expected to **depend mainly** on the **type of primary parton**, quark or gluon, from which it originated and to a **lesser extent** on the particular **hard scattering process**
- **QCD predictions:**
  - At sufficiently **high**  $E_T^{\text{jet}}$ , where fragmentation effects become negligible, the **jet structure** is expected to be driven by **gluon emission off the primary parton**, and therefore, **calculable by pQCD**
  - **Gluon jets** are predicted to be **broader than quark jets** due to the **larger colour charge of the gluon**
- The **lowest non-trivial-order** contribution to the jet substructure is given by  $\mathcal{O}(\alpha\alpha_s)$  calculations for  $ep$  in LAB frame
  - **Measurements of jet substructure** provide a stringent test of pQCD calculations directly beyond LO

## Internal structure of jets: subjet multiplicity

- Subjets are resolved within a jet by reapplying the  $k_T$ -cluster algorithm on all the particles belonging to the jet until for every pair of particles the quantity  $d_{ij}$  is above  $d_{\text{cut}} = y_{\text{cut}} \cdot (E_T^{\text{jet}})^2$
- All remaining clusters are called subjets
- The subjets structure depends upon the value chosen for the resolution parameter  $y_{\text{cut}}$



- In pQCD, the mean subjet multiplicity,  $\langle n_{\text{subjet}} \rangle$  is calculated as the ratio of the cross section for  $n_{\text{subjet}} - 1$  subjets over that of the inclusive jet production

$$\langle n_{\text{subjet}} - 1 \rangle = \frac{\sigma_{n_{\text{subjet}}-1}(E_T^{\text{jet}})}{\sigma_{\text{jet}}(E_T^{\text{jet}})} \approx \frac{A_{n_{\text{subjet}}-1} \cdot \alpha_s + B_{n_{\text{subjet}}-1} \cdot \alpha_s^2}{C_{\text{jet}} + D_{\text{jet}} \cdot \alpha_s}$$

# $y_{\text{cut}}$ dependence of $n_{\text{subject}}$



- Jets searched with  $k_T$  algorithm in the LAB frame
- At least one jet with  $E_T^{\text{jet}} > 15 \text{ GeV}$  and  $-1 < \eta^{\text{jet}} < 2$
- Kinematic range:  $Q^2 > 125 \text{ GeV}^2$

Phys Lett B 558 (2003) 41

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- Small experimental uncertainties for

$$y_{\text{cut}} \geq 10^{-2}$$

- fragmentation model dependence:  $< 3\%$
- jet energy scale:  $\sim 1\%$

- Small corrections for  $y_{\text{cut}} \geq 10^{-2}$

- Data (detector effects):  $< 10\%$
- NLO (parton-to-hadron effects):  $< 17\%$  for  $E_T^{\text{jet}} > 25 \text{ GeV}$

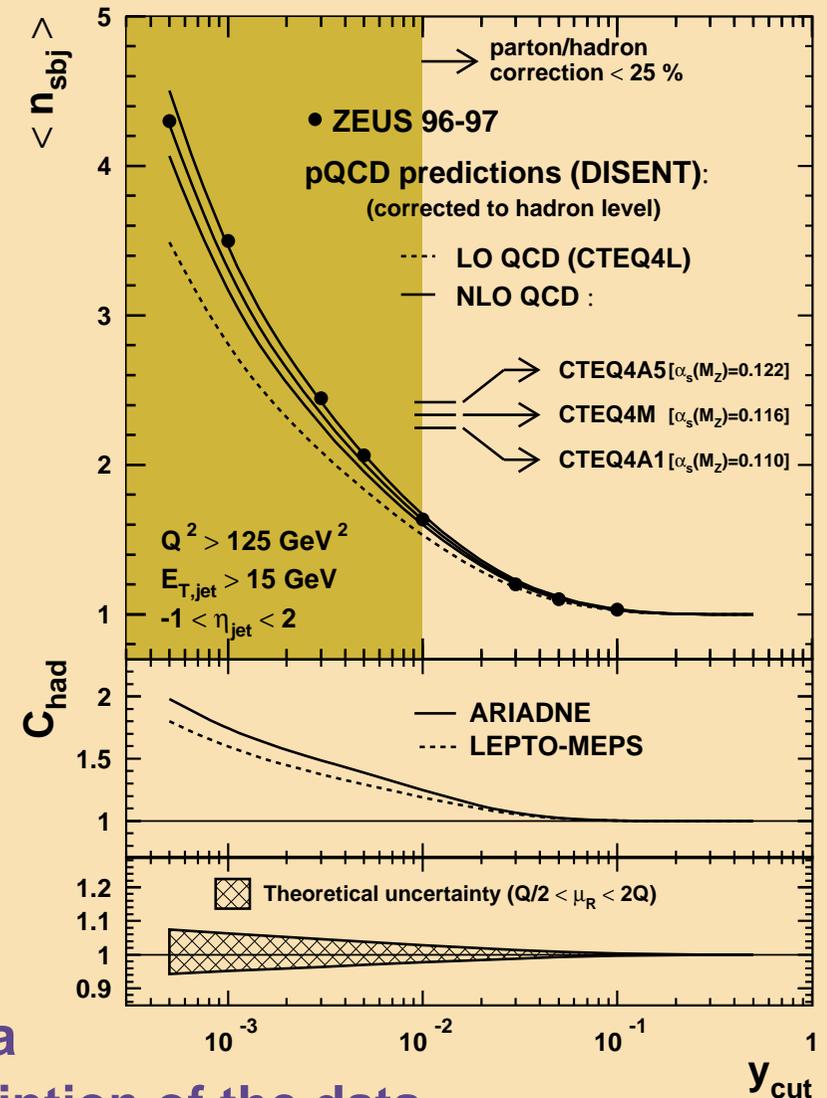
- Comparison to LO/NLO predictions (DISENT):

$$\rightarrow \mu_R = \mu_F = Q$$

$$\rightarrow p \text{ PDFs: CTEQ4L/M}$$

- Comparison with QCD calculations:

- The LO calculations fail to describe the data
- The NLO calculations provide a good description of the data



# $E_T^{\text{jet}}$ dependence of $n_{\text{subject}}$



Phys Lett B 558 (2003) 41

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● The mean subjet multiplicity at a fixed value of  $y_{\text{cut}}$ ,  $\langle n_{\text{subject}}(y_{\text{cut}} = 10^{-2}) \rangle$ , decreases as  $E_T^{\text{jet}}$  increases: the jets become more collimated

● This observable is sensitive to  $\alpha_s$

● The sensitivity of  $\langle n_{\text{subject}}(y_{\text{cut}} = 10^{-2}) \rangle$  as a function of  $E_T^{\text{jet}}$  to the value of  $\alpha_s(M_Z)$  is seen by comparing the measurement to QCD calculations using three different values of  $\alpha_s(M_Z)$

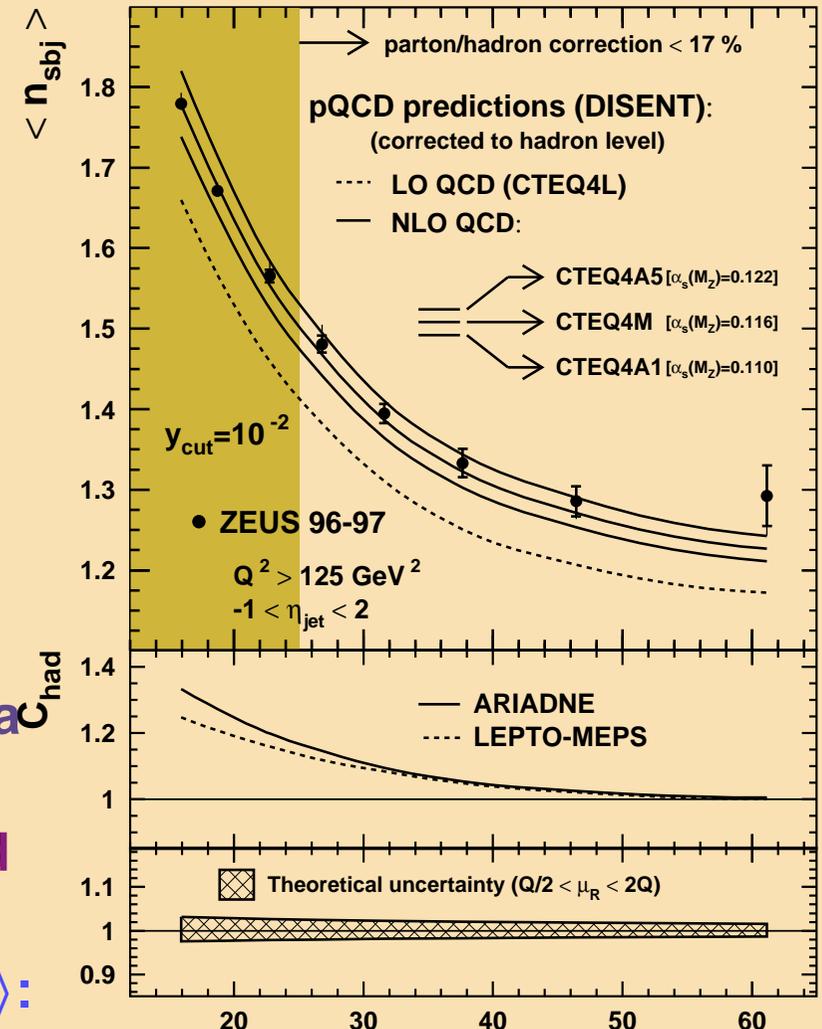
● Comparison with QCD calculations:

→ The LO calculations fail to describe the data

→ The NLO calculations provide a good description of the data: thus, it can be used to determine  $\alpha_s(M_Z)$  for  $E_T^{\text{jet}} > 25 \text{ GeV}$

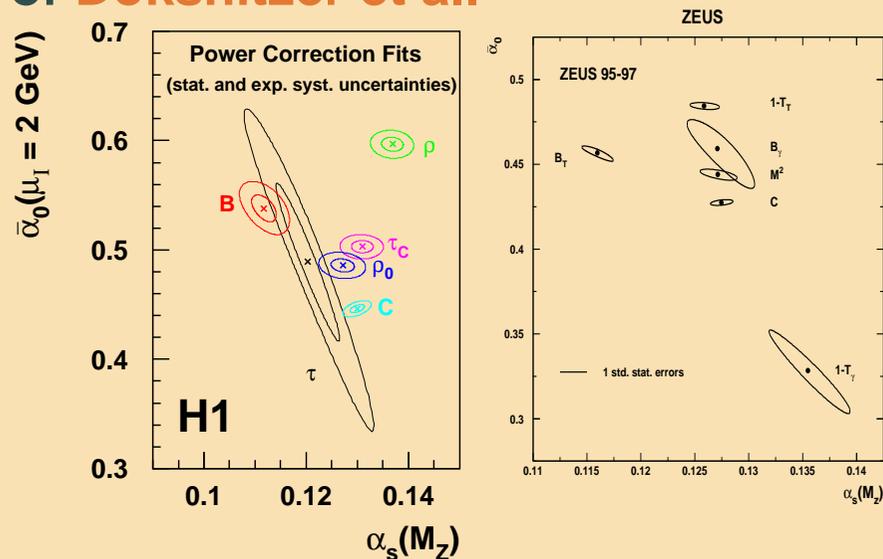
→ Extraction of  $\alpha_s$  from  $\langle n_{\text{subject}}(y_{\text{cut}} = 10^{-2}) \rangle$ :

→  $\alpha_s(M_Z) = 0.1187 \pm 0.0017 \text{ (stat.) } \begin{matrix} +0.0024 \\ -0.0009 \end{matrix} \text{ (exp.) } \begin{matrix} +0.0093 \\ -0.0076 \end{matrix} \text{ (th.) } E_{T,\text{jet}} \text{ (GeV)}$



## Event shapes

- Extraction of  $\alpha_s$  from measurements of event shape variables (**thrust, jet broadening**) is complementary to the one from jet cross sections
- Event shape variables are particularly sensitive to the details of the non-perturbative effect of hadronisation
- Recently, new developments on the model of power-law corrections have prompted revived interest in the understanding of hadronisation within the framework of pQCD
- In this type of analysis, the data are compared to a model prediction which consists of a combination of NLO QCD calculations and the theoretical expectations of the power corrections, characterised by an effective coupling  $\bar{\alpha}_0$
- Previous results give support to the concept of **power corrections** in the approach of **Dokshitzer et al.**



- but a large spread in the fitted values for  $\alpha_s$  suggested higher orders QCD needed
- resummed NLL calculations matched to NLO, are now available
- and it is possible to study event shape distributions instead of only mean values



## Event shape distributions: thrust

- A suitable frame in which to study event shapes at HERA is the Breit frame

→ the separation between the current jet and the proton remnant is maximal

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- Measurement of event shape distributions for  $14 < Q < 200$  GeV and  $0.1 < y < 0.7$ :

→ thrust  $\tau$  and  $\tau_c$ , jet broadening  $B$ , jet mass  $\rho$  and  $C$  parameter are defined for particles in the current hemisphere ( $\eta < 0$ )

→ jet rates are defined using the  $k_T$  algorithm for all hadrons in both hemispheres

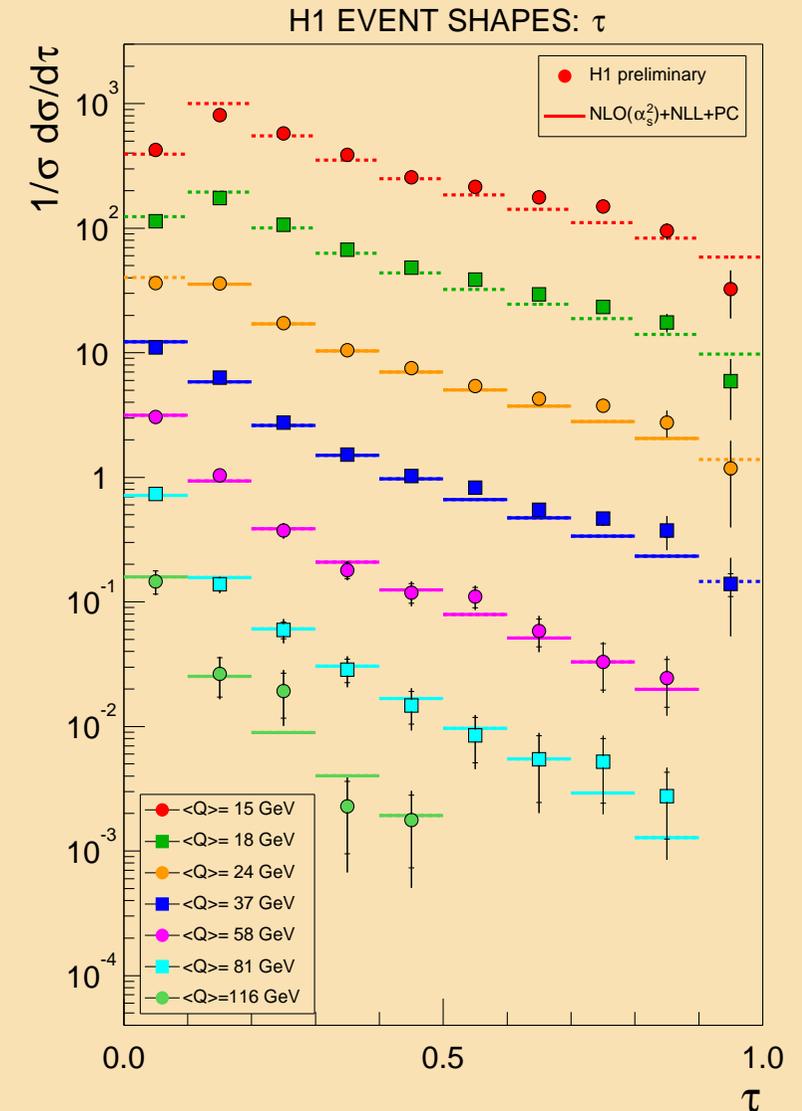
- Example: corrected measured distribution for thrust and fitted theory prediction

- Theory:

- DISASTER++ (CTEQ5M1 pPDFs)
- resummation matched to NLO and power corrections
- $\chi^2$  fit to data
- free parameters:  $\alpha_s(M_Z)$  and  $\bar{\alpha}_0$

- A good description of the data by the QCD predictions is obtained at high  $Q^2$

- The description of the data at low  $Q^2$  is poorer

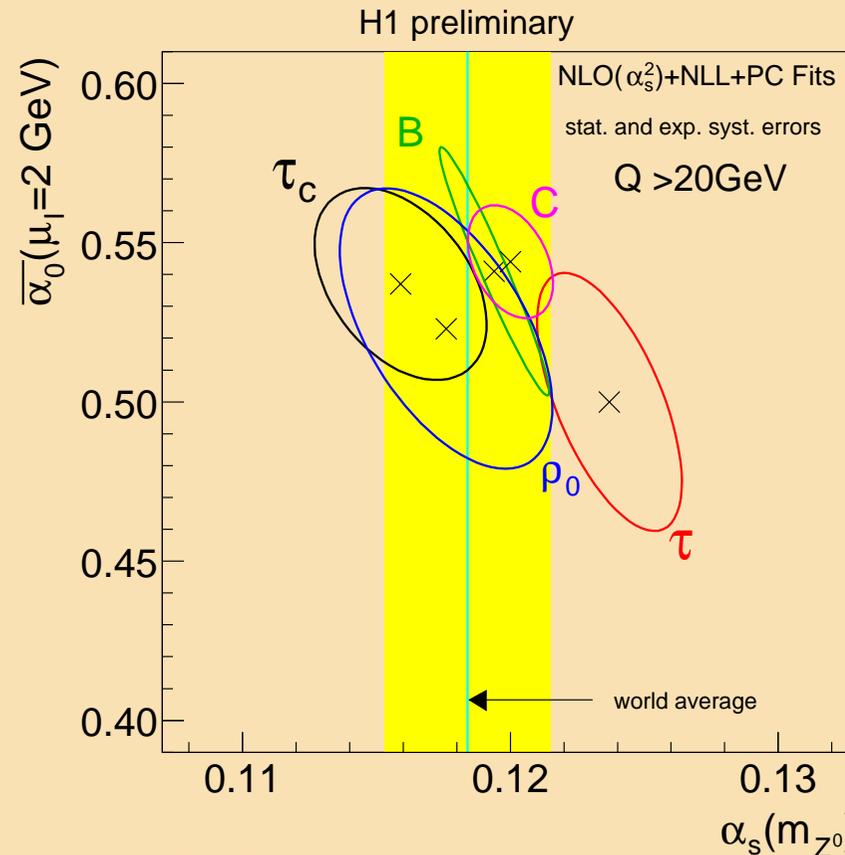




# Test of the power corrections model

- The  $1\sigma$  contours of the results of  $\bar{\alpha}_0$  and  $\alpha_s$ :

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- Negative correlation coefficient between  $\alpha_s$  and  $\bar{\alpha}_0$  found for all variables
- Universal non-perturbative parameter  $\bar{\alpha}_0 = 0.5$  at the 10% level in agreement with previous results but with smaller spread
- Sizeable theoretical uncertainty coming from higher orders ( $\sim 5\%$  for both  $\bar{\alpha}_0$  and  $\alpha_s$ , as large as experimental uncertainty)



# Conclusions



## ● HERA has become a unique QCD-testing machine due to

→ at large scales:

— considerable progress in understanding and reducing uncertainties led to

very precise measurements of the

fundamental parameter of the theory

— the use of observables resulting from jet algorithms leads to determinations of  $\alpha_s$  as precise as those from more inclusive measurements (eg  $\tau$  decay)

⇒ Improved calculations needed for better accuracy

→ at low  $x$  and low  $Q^2$ :

— considerable progress in understanding the mechanisms for parton emission has been achieved

— interplay of DGLAP  $\leftrightarrow$  BFKL  $\leftrightarrow$  CCFM dynamics has still to be fully worked out

⇒ Further progress needs more experimental and theoretical work

