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# Jet physics in $ep$ collisions

Experimental results from H1 and ZEUS collaborations

- Photoproduction of jets with high transverse momenta.
- Inclusive jets and dijets in DIS.
- Jets and determination of  $\alpha_s$ .
- Jet cross sections in CC DIS.
- Forward jet production in DIS.
- Three-jet production in DIS.
- Summary

ISMD-2006

XXXVI International Symposium on Multiparticle Dynamics

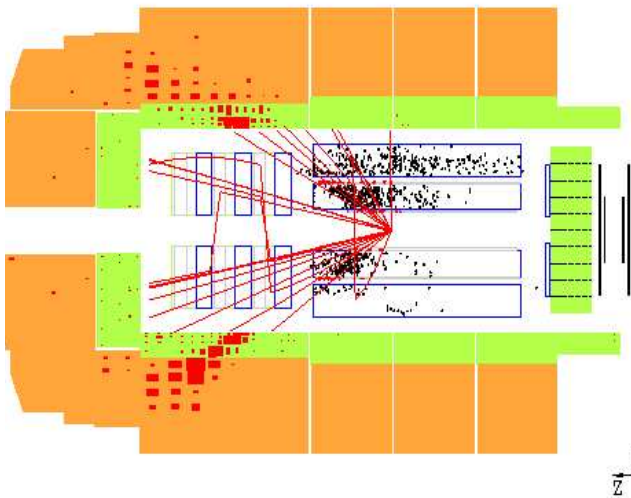
Rio de Janeiro, Paraty, August 2-8, 2006

# INTRODUCTION

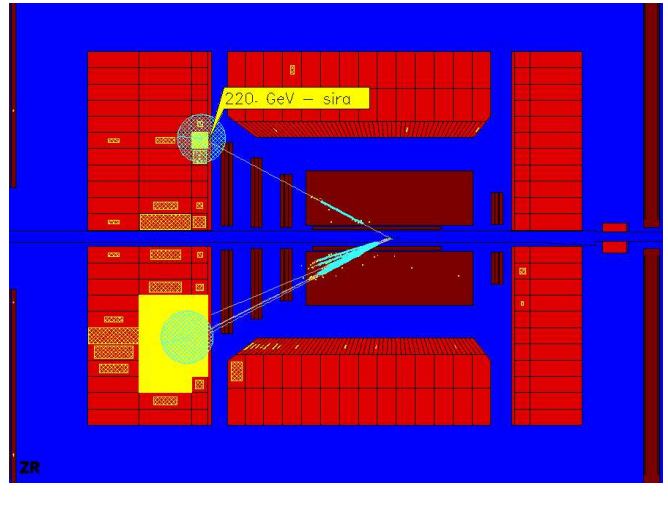
**HERA** is a lepton-proton collider located in Hamburg, Germany

Proton energy  $E_p = 920 \text{ GeV}$ .

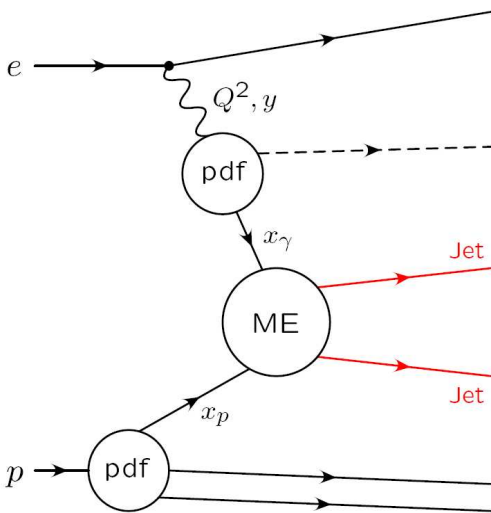
Electron (positron) energy  $E_e = 27.6 \text{ GeV}$



H1 detector



ZEUS detector



4-mom. transfer  $Q^2 = -(k - k')^2$

Bjorken variable  $x_{Bj} = \frac{Q^2}{2p \cdot q}$

Inelasticity  $y = \frac{p \cdot q}{p \cdot k}$

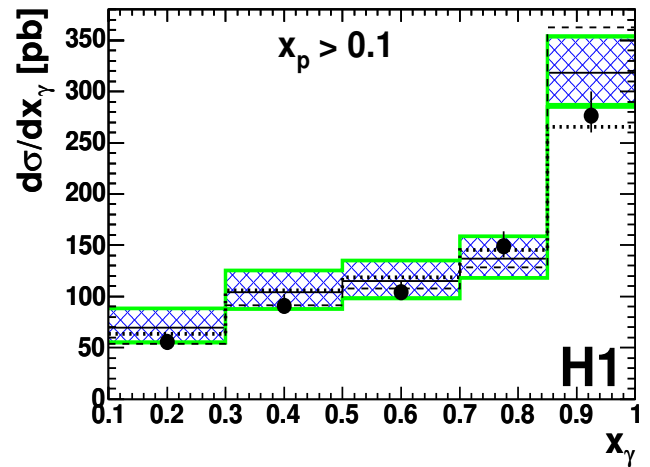
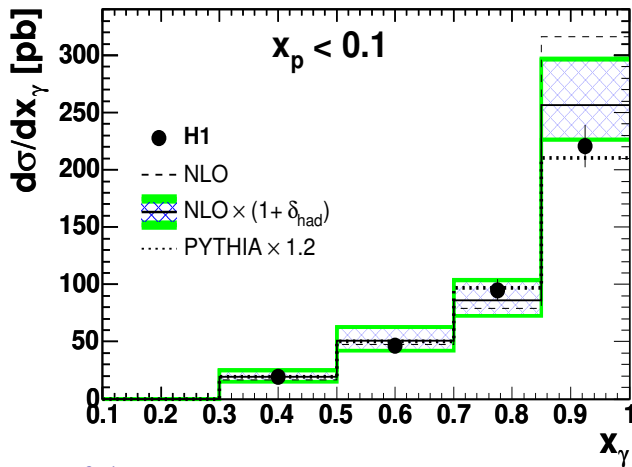
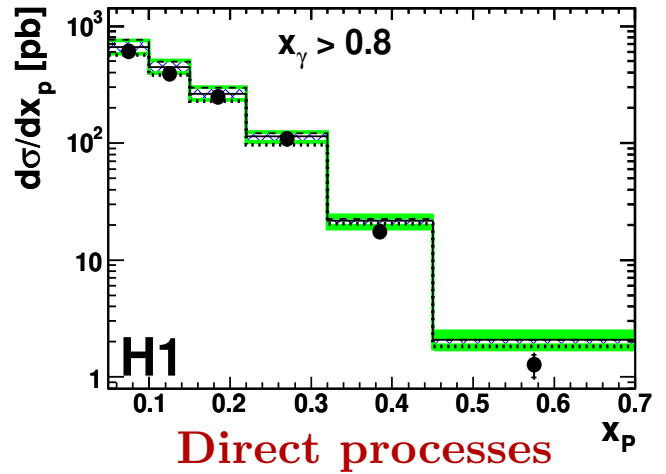
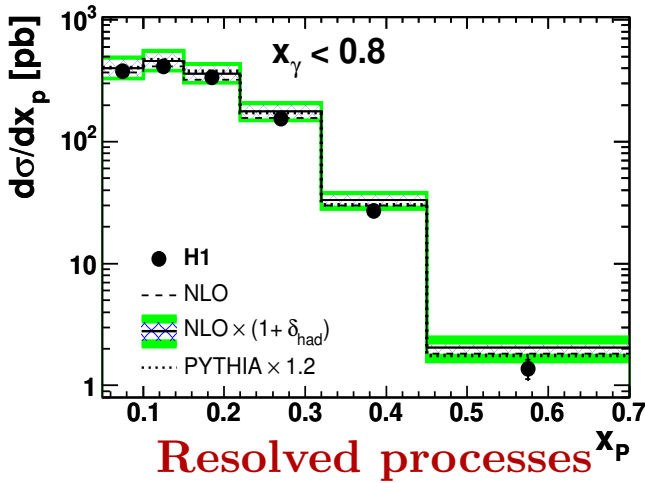
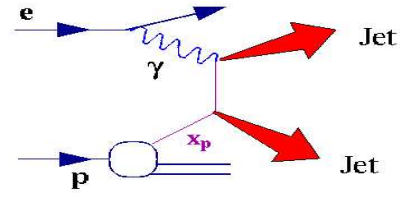
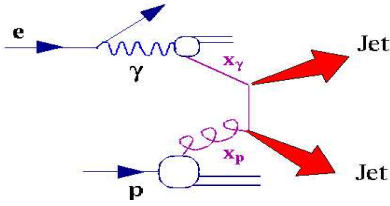
Pseudorapidity  $\eta = -\ln \tan \frac{\theta}{2}$

**Photoproduction:**  $Q^2 \approx 0 \text{ GeV}^2$

**DIS:**  $Q^2 \gg 1 \text{ GeV}^2$

In the leading order  $x_\gamma$  and  $x_p$  are longitudinal photon and proton momentum fractions entering the hard interaction.

# PHOTOPRODUCTION OF DIJETS WITH HIGH $P_t$



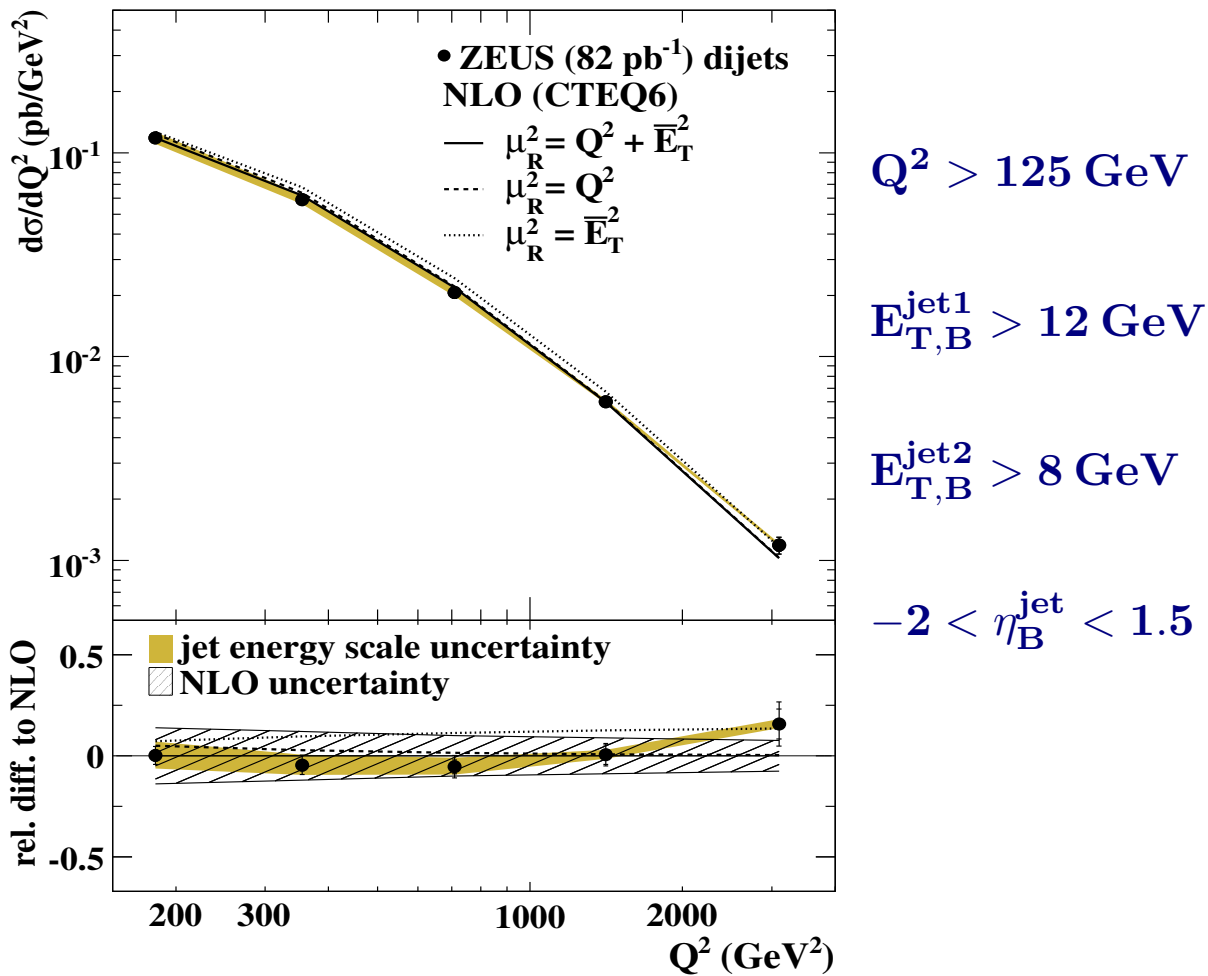
70 % of gluon induced events

Photon-gluon fusion

Photon-quark scattering

- Both the NLO QCD calculation and the PYTHIA MC calculation provide a reasonable description of the data;
- These data, combined with inclusive DIS cross section measurement, helps to extract proton parton density functions with improved precision.

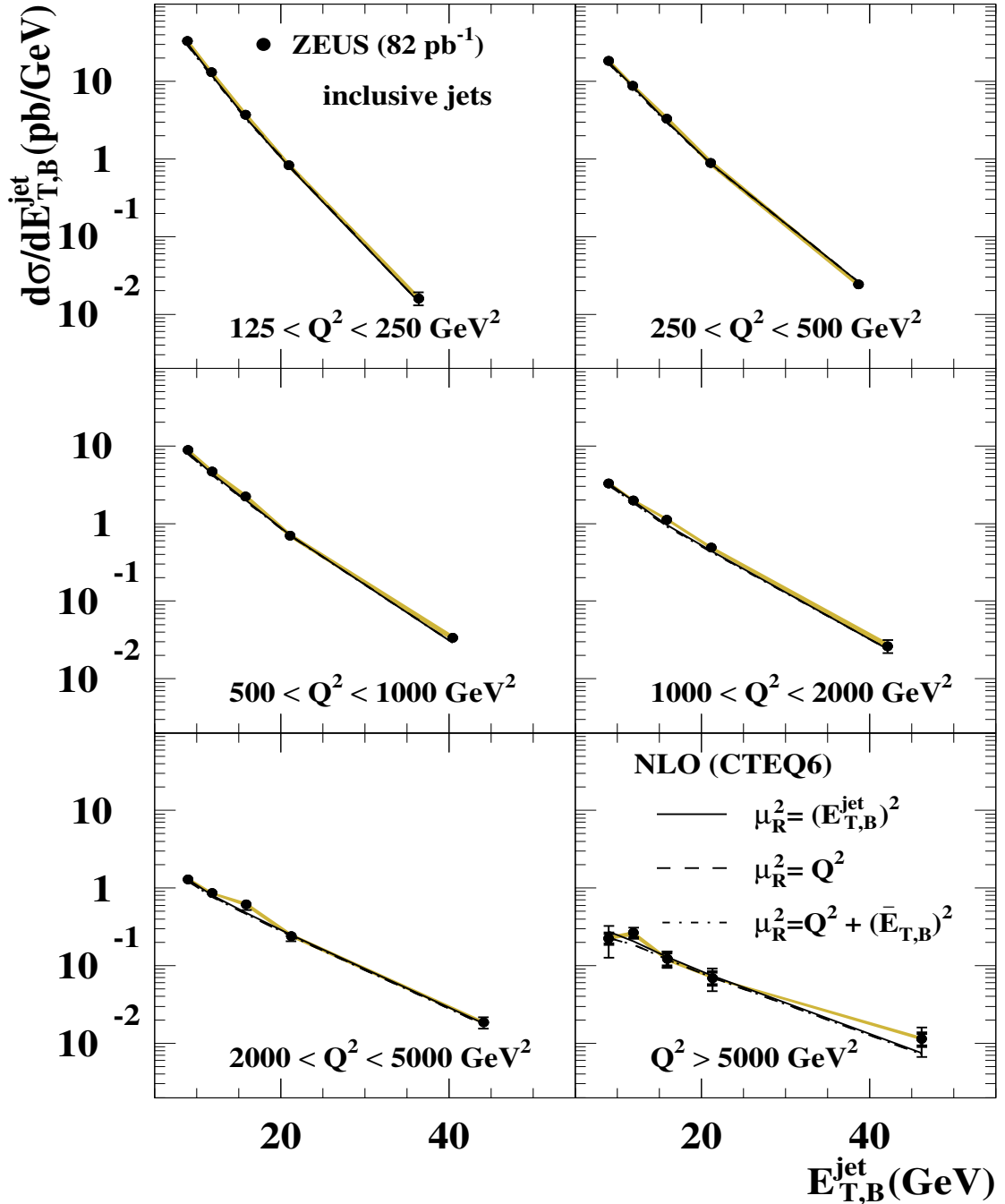
## DIJETS IN DIS



- The largest contribution to theoretical uncertainties ( $\pm 20\%$ ) comes from  $\mu_R$ .
- The largest contributions to systematic uncertainty come from uncertainty in absolute energy scale ( $\pm 10\%$ ) and correction factor for detector effects  $\pm 8\%$
- The theoretical uncertainties are dominated.

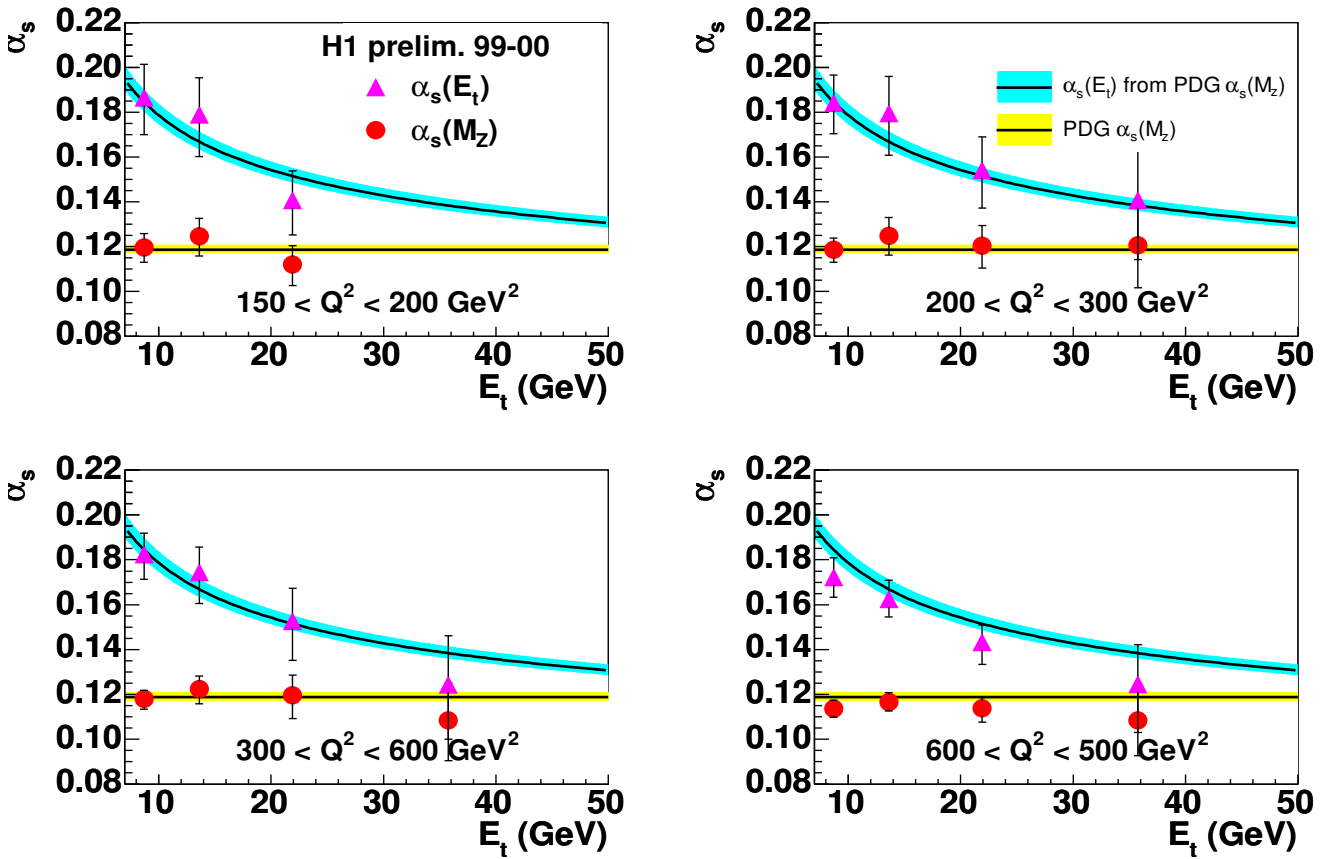
**INCLUSIVE JETS IN DIS**

**ZEUS**

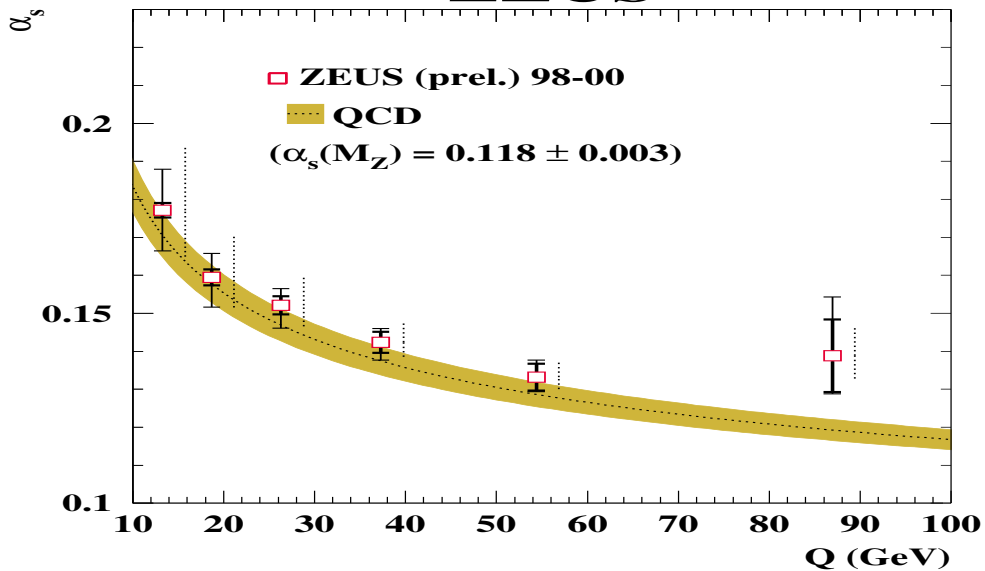


- $E_{T,B}^{\text{jet}}$  - Jet transverse energy in the Breit frame.
- The data are well described by the NLO QCD.
- The measurements are very precise and relevant for improving determination of the gluon density.

## Extraction of $\alpha_s$ from inclusive jet cross sections



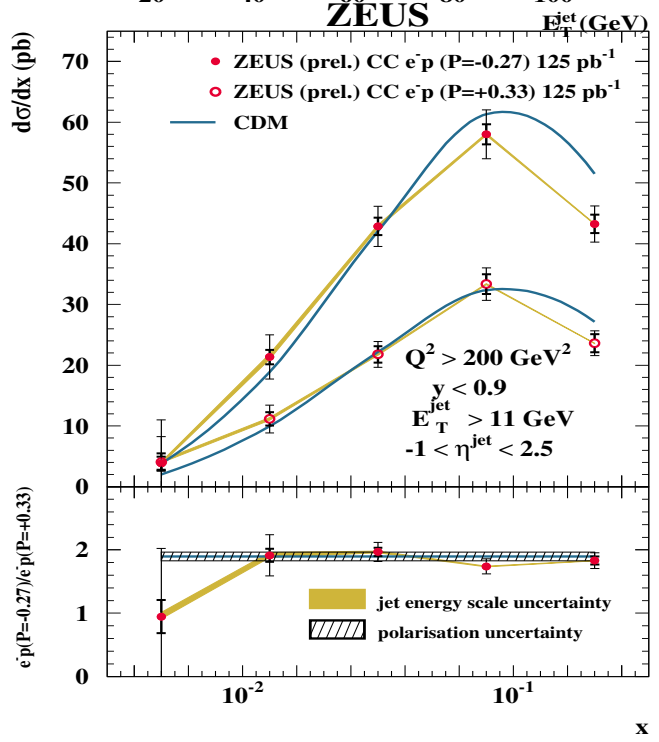
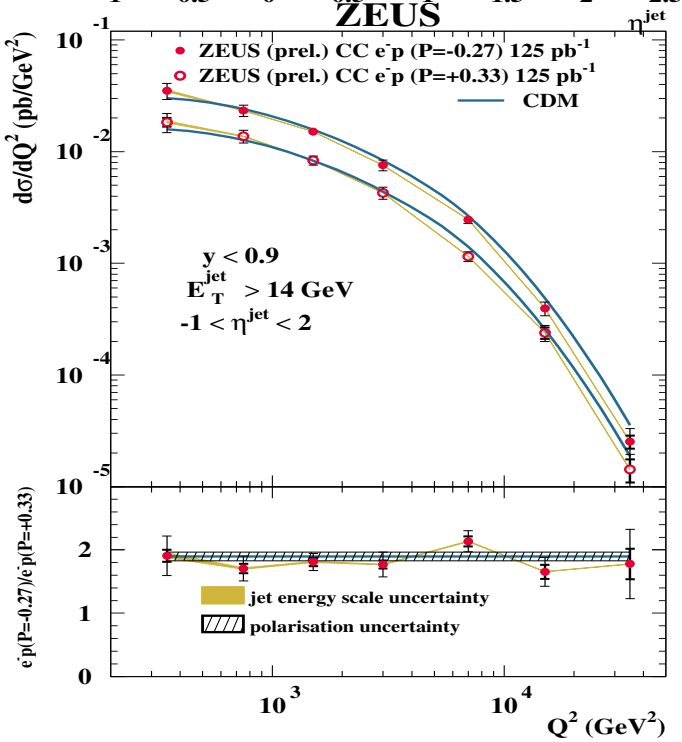
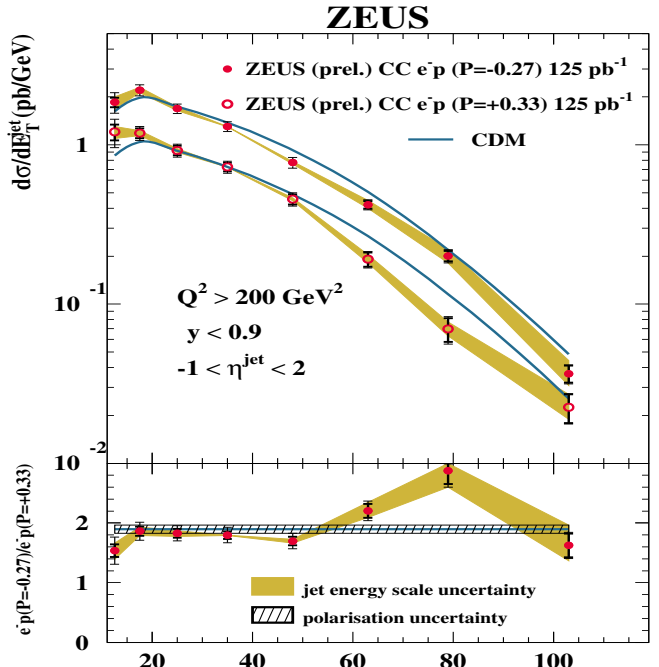
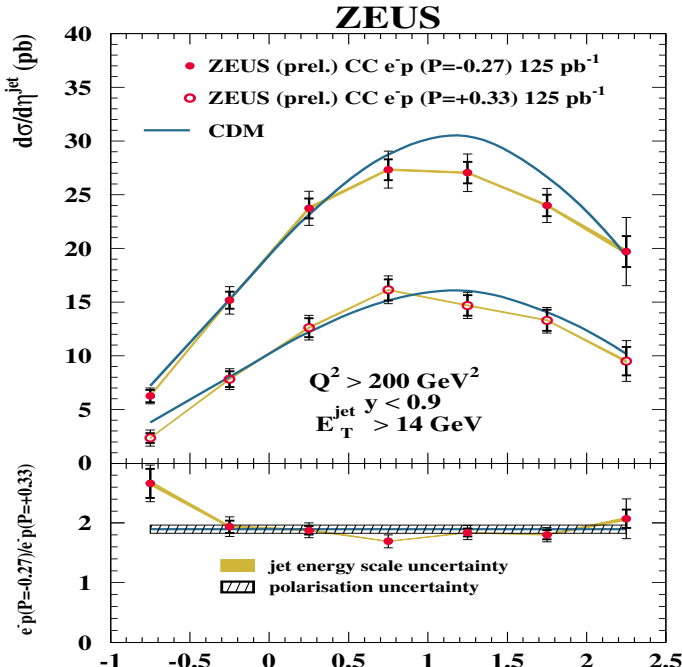
## ZEUS



- **H1 value**       $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\text{exp}) \pm 0.0047(\text{th})$
- **ZEUS value**       $\alpha_s(M_Z) = 0.1196 \pm 0.0025(\text{exp}) \pm 0.0023(\text{th})$
- **World average**       $\alpha_s(M_Z) = 0.1187 \pm 0.0020(\text{exp})$

# JET CROSS SECTION IN CC EVENTS

## Measurements with lepton polarised beams (HERA II !)



$\sigma_{\text{jets}}^{\text{neg}} = 71.3 \pm 1.2(\text{st}) \pm 3.6(\text{sys}) \pm 0.3(E_{\text{scale}})\text{pb}$   
 $\sigma_{\text{jets}}^{\text{pos}} = 38.7 \pm 1.2(\text{st}) \pm 2.0(\text{sys}) \pm 0.2(E_{\text{scale}})\text{pb}$

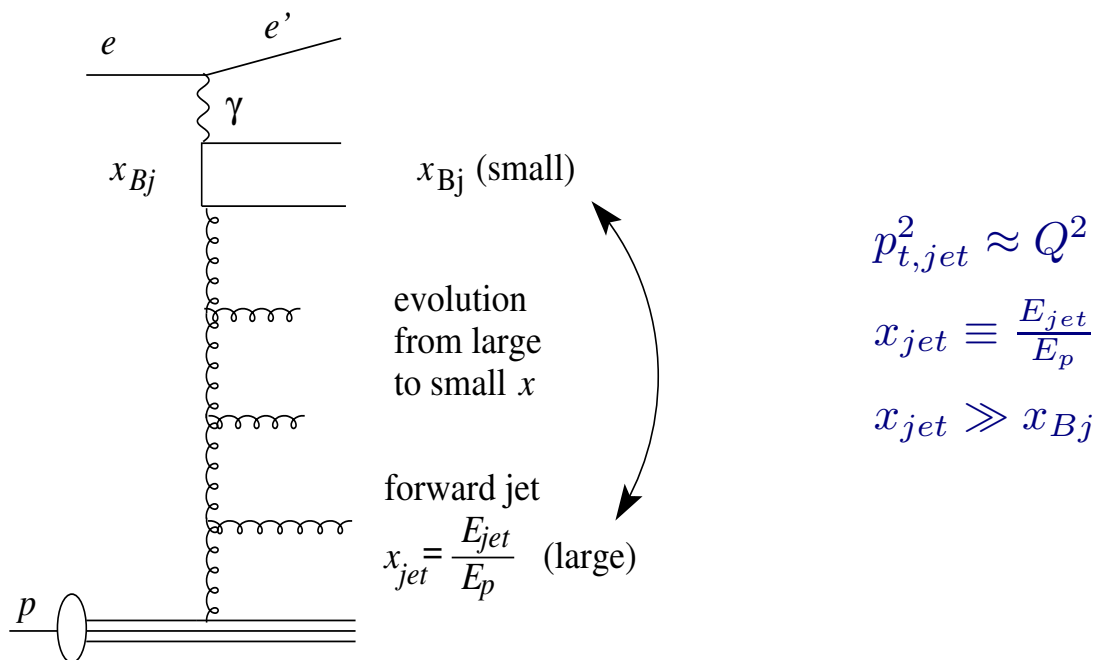
$\sigma_{\text{MC}}^{\text{neg}} = 75 \text{ pb}$   
 $\sigma_{\text{MC}}^{\text{pos}} = 40 \text{ pb}$

## FORWARD JET PRODUCTION IN DIS

QCD calculations based on DGLAP evolution scheme are successful in describing of strong rise of  $F_2(x_{Bj}, Q^2)$  with decreasing  $x_{Bj}$  over large  $Q^2$  range.

Is there regions with different parton dynamics?

- **DGLAP**  $\Rightarrow$  neglects  $\ln(1/x)$  terms, strong  $k_t$  ordering.
- **BFKL**  $\Rightarrow$  no  $k_t$  ordering.



### QCD MODELS

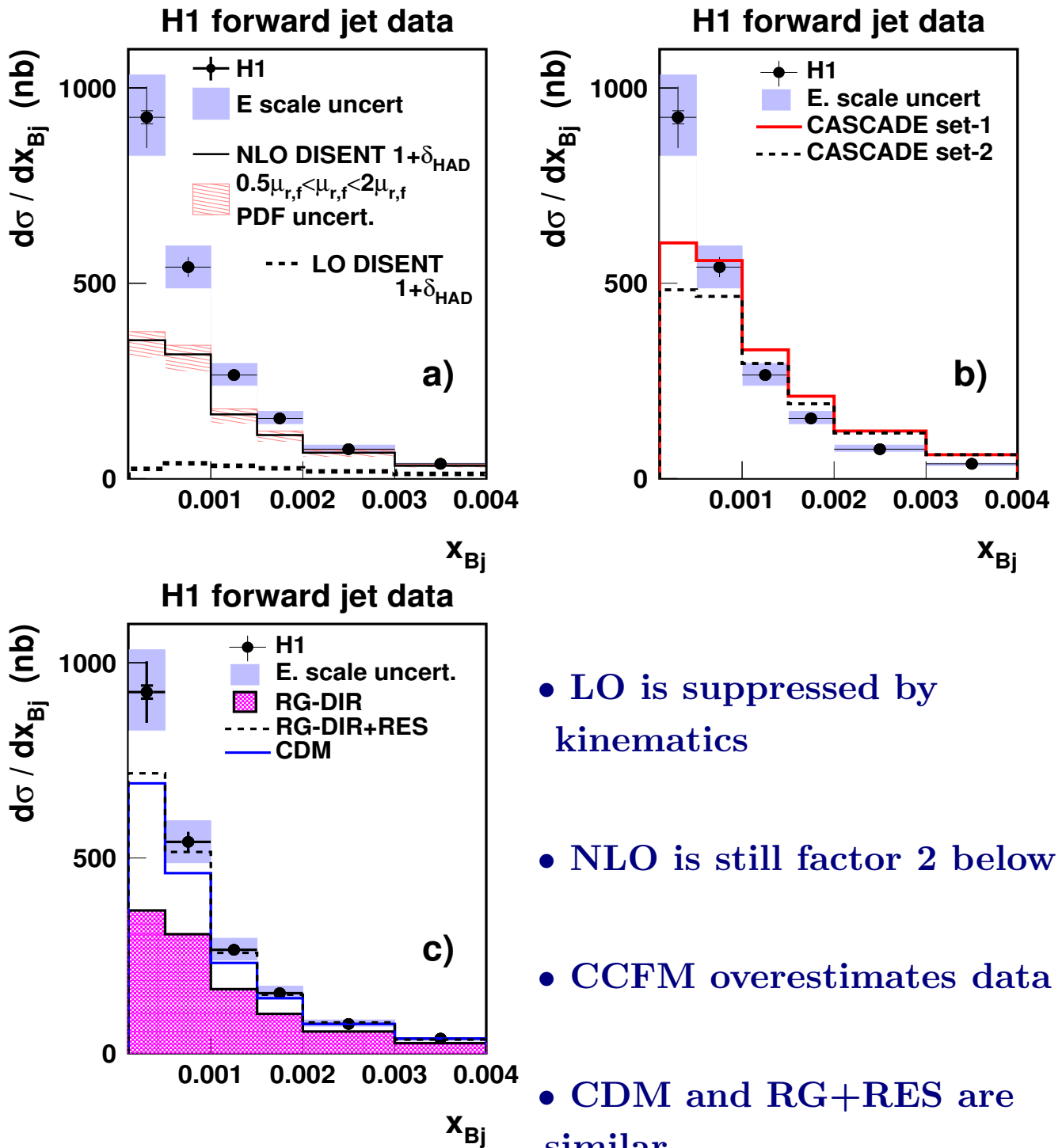
- **RAPGAP** MC LO + resolved and direct processes
- **DJANGO** with CDM
- **CASCADE** based on CCFM

$LO(\alpha_s)$  and  $NLO(\alpha_s^2)$  calculated by **DISENT** ( $\mu_r =$  average of  $p_t^2$ )



# FORWARD JET PRODUCTION IN DIS

Forward JET:  $\theta_{\text{jet}} < 20^\circ$  and  $x_{\text{jet}} = E_{\text{jet}}^*/E_p > 0.035$

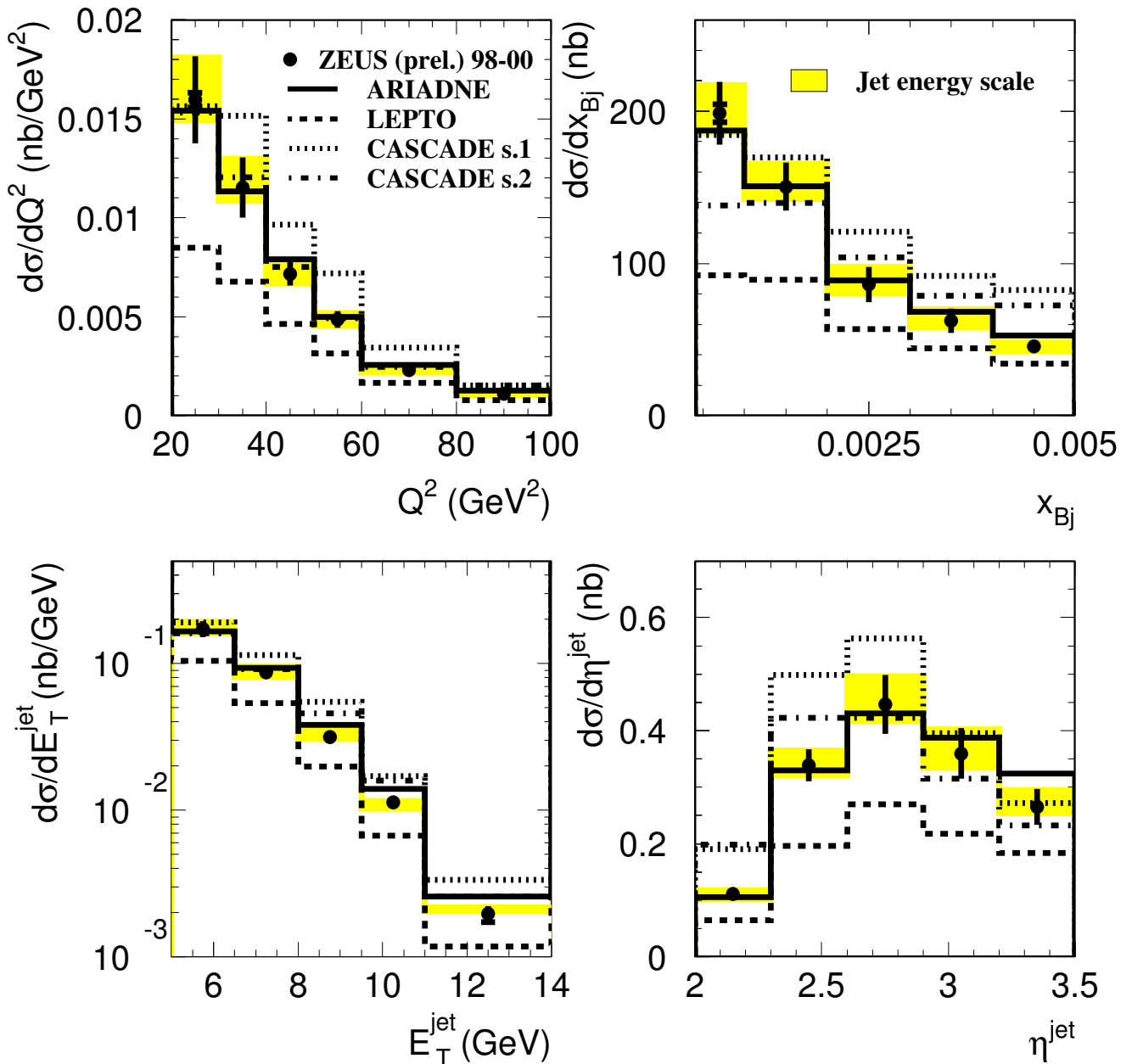


- LO is suppressed by kinematics
- NLO is still factor 2 below
- CCFM overestimates data
- CDM and RG+RES are similar

# FORWARD JET PRODUCTION IN DIS

Very forward jet:  $2 < \eta_{\text{jet}} < 3.5$

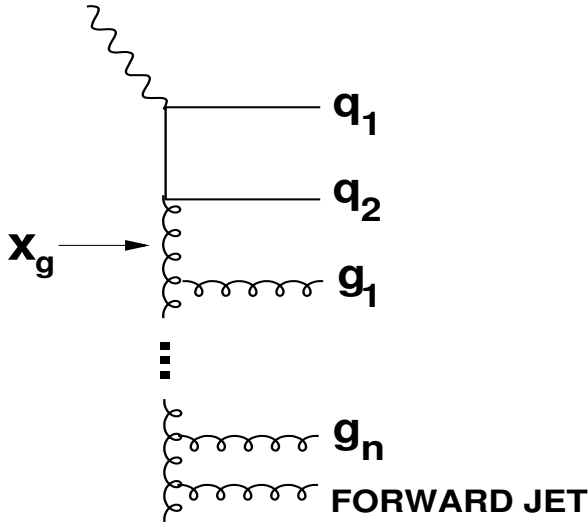
## ZEUS



Generators which suggest ordering in  $k_t$  describe data with forward jet unsatisfactory.

# FORWARD JET PRODUCTION IN DIS

$$\eta_{\text{fwdjet}} > \eta_{\text{jet2}} > \eta_{\text{jet1}} > \eta_e$$



$\eta_{\text{jet1}}$

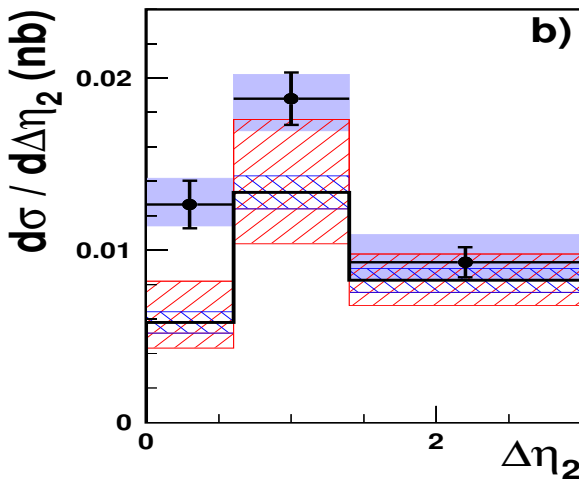
$$\Delta\eta_1 = \eta_{\text{jet2}} - \eta_{\text{jet1}}$$

$\eta_{\text{jet2}}$

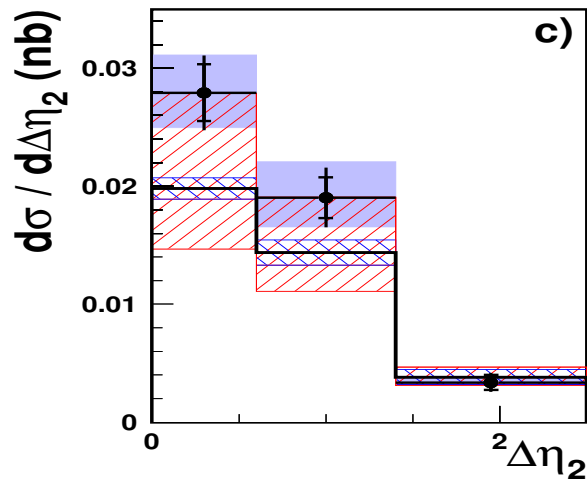
$$\Delta\eta_2 = \eta_{\text{jetfwd}} - \eta_{\text{jet2}}$$

$\eta_{\text{fwdjet}}$

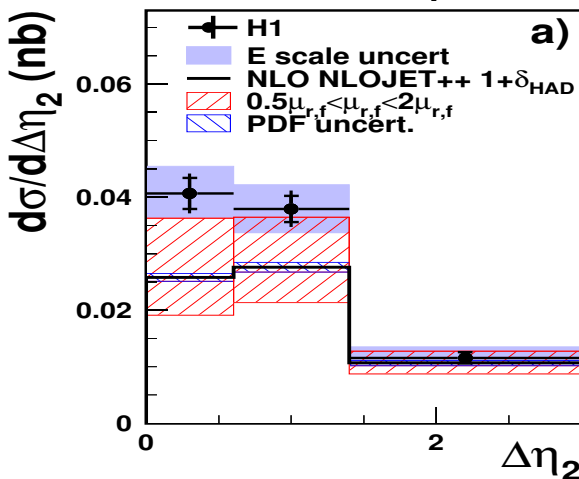
$\Delta\eta_1 < 1$



$\Delta\eta_1 > 1$



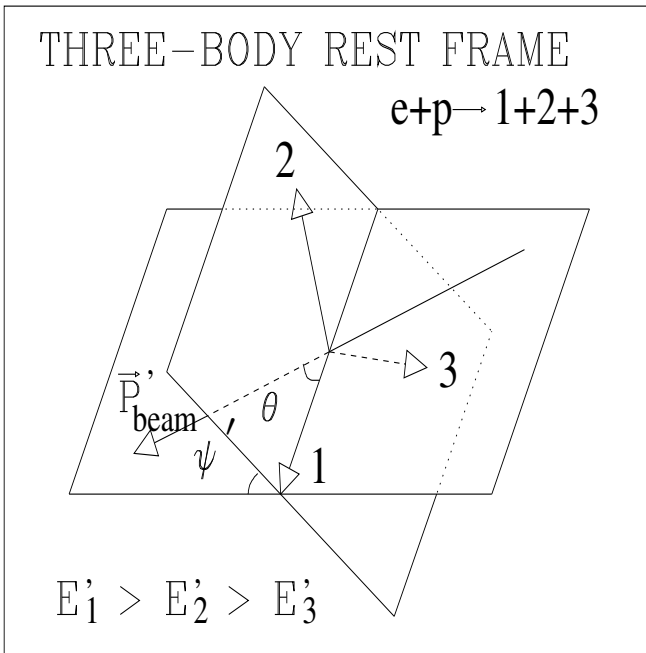
All  $\Delta\eta_1$



$\Delta\eta_1 < 1 \Rightarrow$  small  $x_g$ ,  
more radiation.

$\Delta\eta_2 < 1 \Rightarrow$  jet from  
gluon radiation

## THREE-JET PRODUCTION IN DIS



$E_t^* > 4 \text{ GeV} \quad (\gamma^* p \text{ CM})$

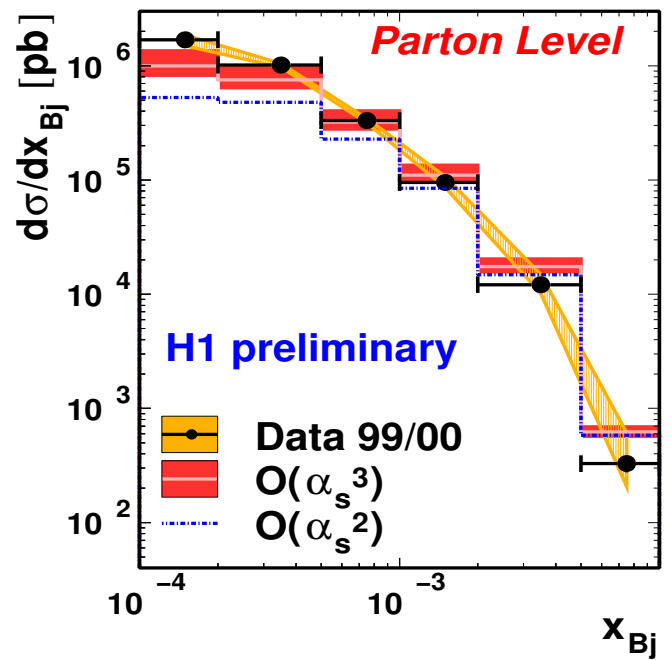
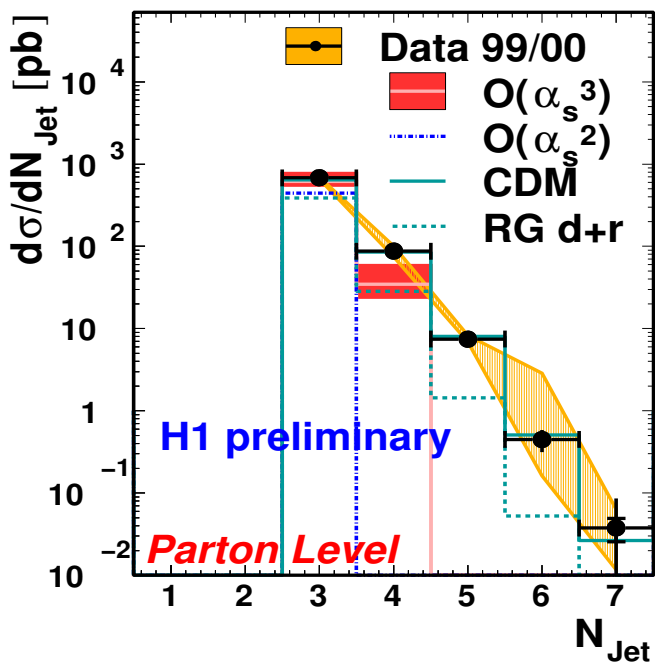
Any jet  $\Rightarrow \quad -1 < \eta_{\text{jet}} < 2.5$

One jet  $\Rightarrow \quad -1 < \eta_{\text{jet}} < 1.3$

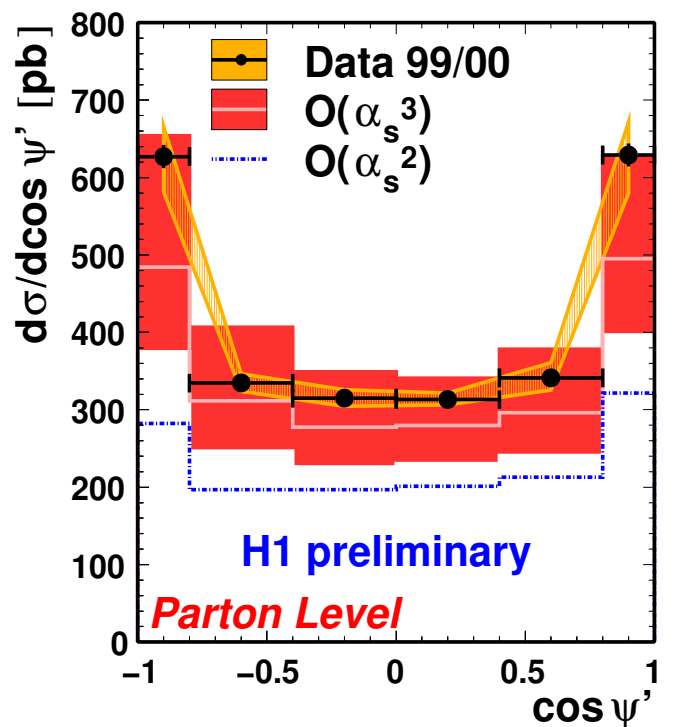
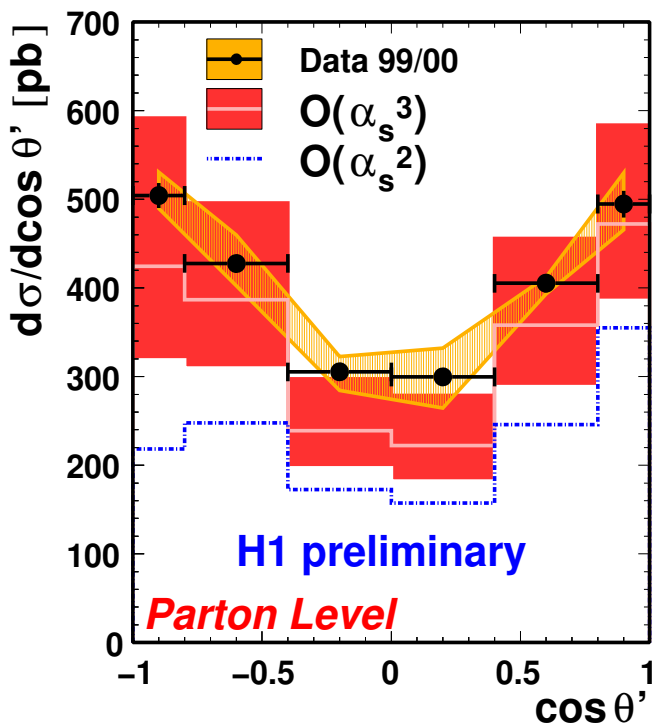
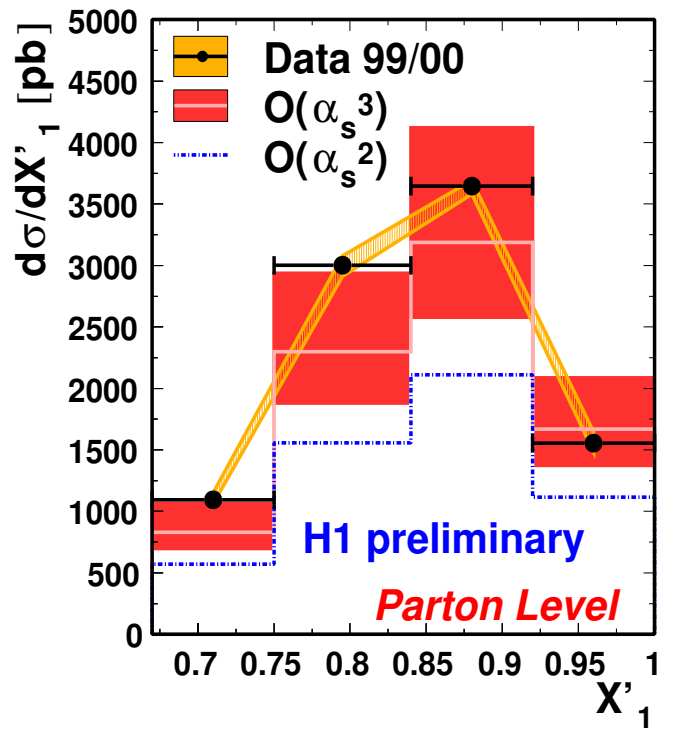
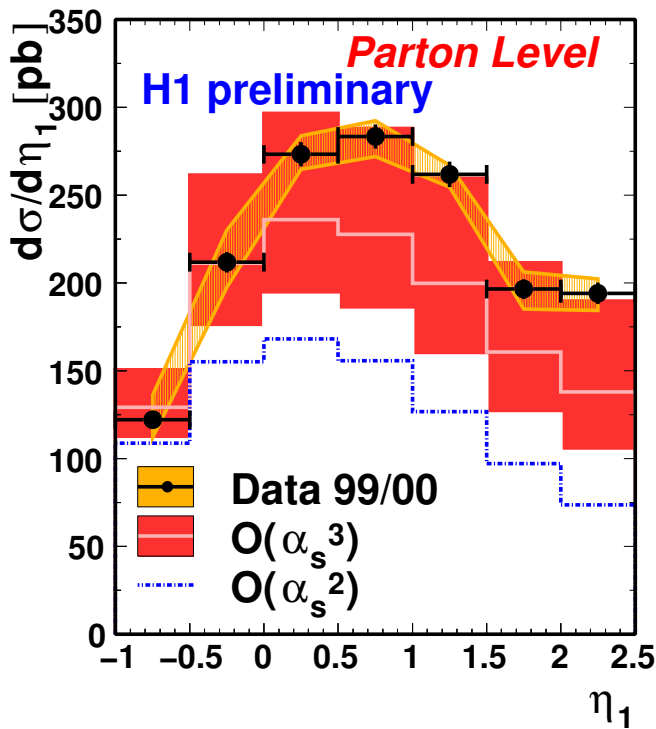
RAPGAP  $\mu^2 = Q^2 + p_t^2$

DIANGO  $\mu^2 = Q^2$

NLOJET++ program was used for LO and NLO calculations.



## THREE-JET PRODUCTION IN DIS



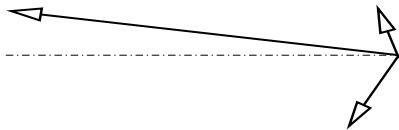
- NLO prediction improves the situation dramatically.
- Difference in normalisation is 18%.

# THREE-JET PRODUCTION IN DIS

Forward JET:  $\theta_{\text{jet}} < 20^\circ$  and  $x_{\text{jet}} = E_{\text{jet}}^*/E_p > 0.035$

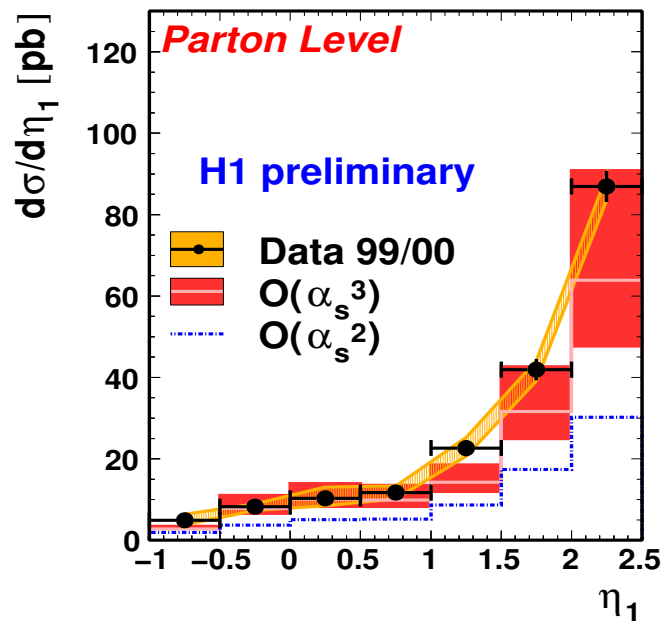
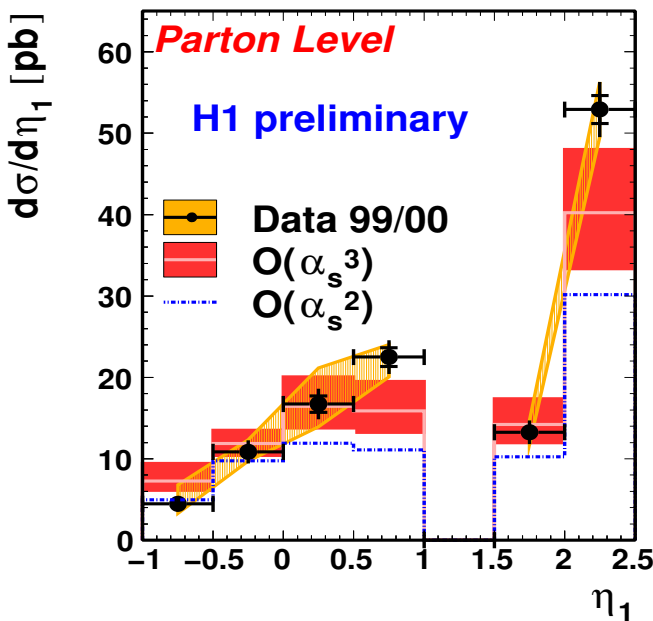
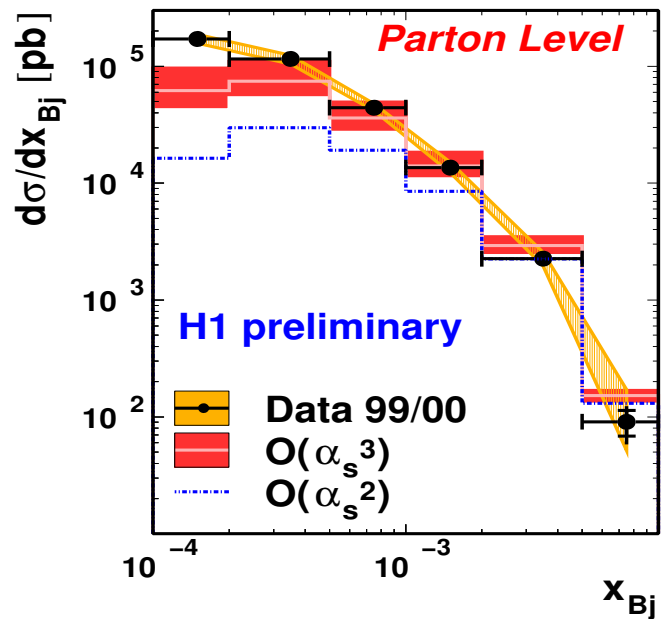
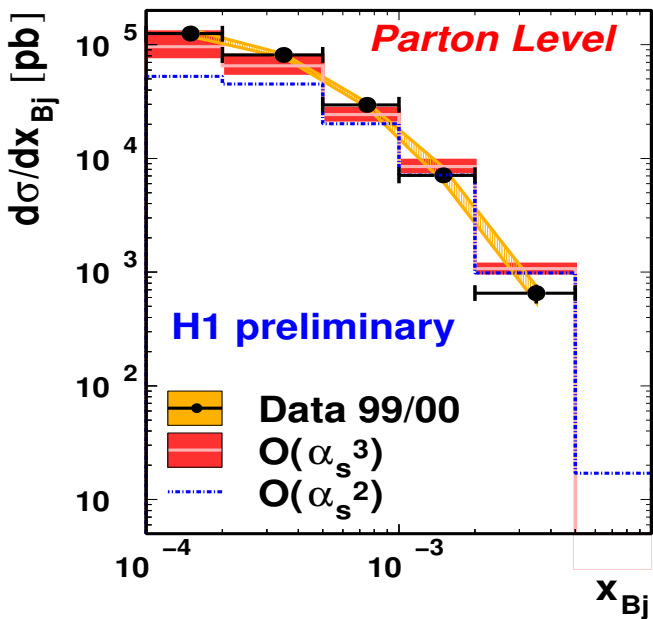
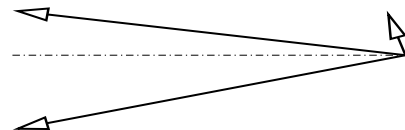
Two central jets

$$1 < \eta_{\text{jet}} < 1$$



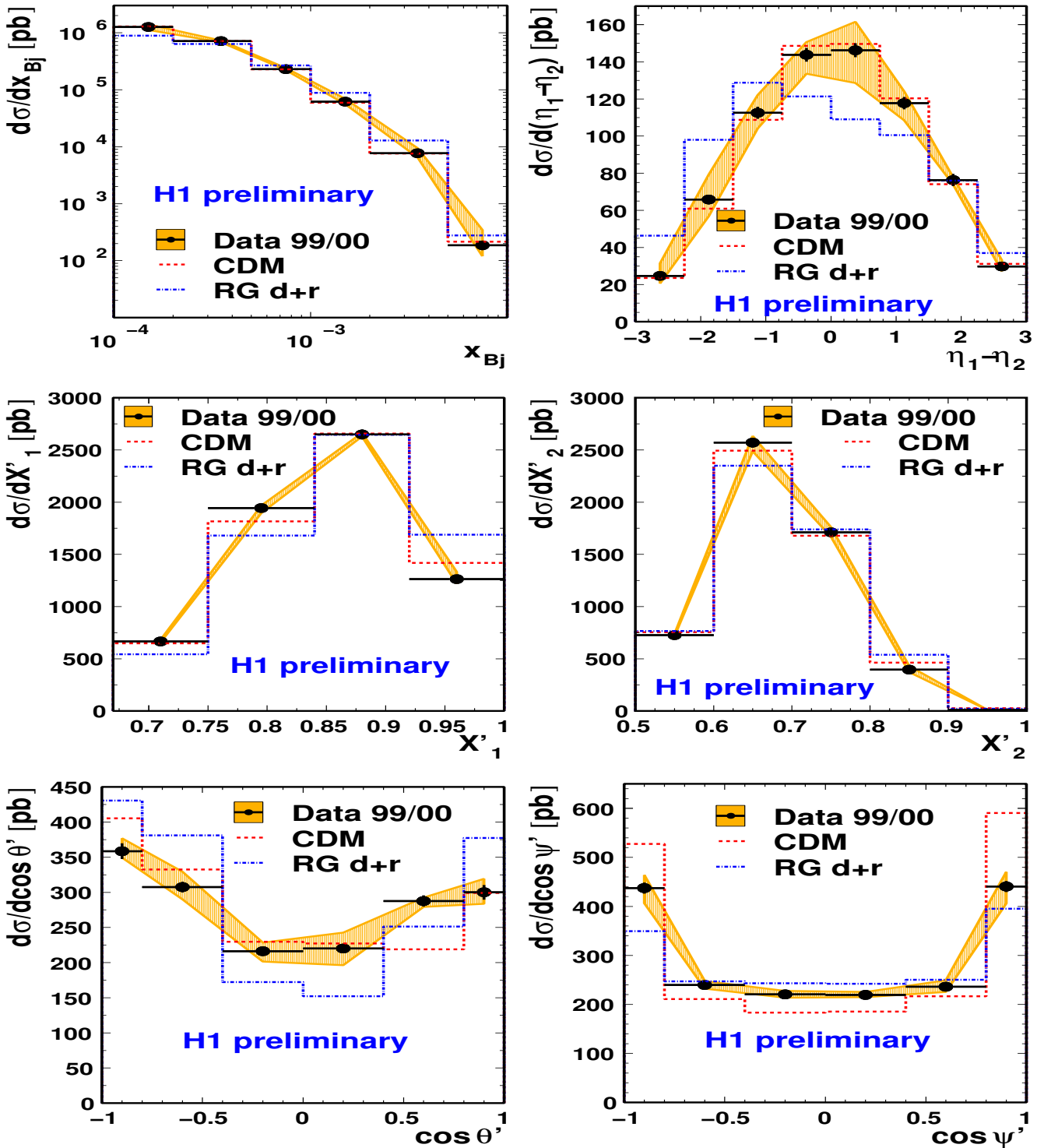
Two forward jets

$$\eta_{\text{jet}} > 1$$



# THREE-JET PRODUCTION IN DIS

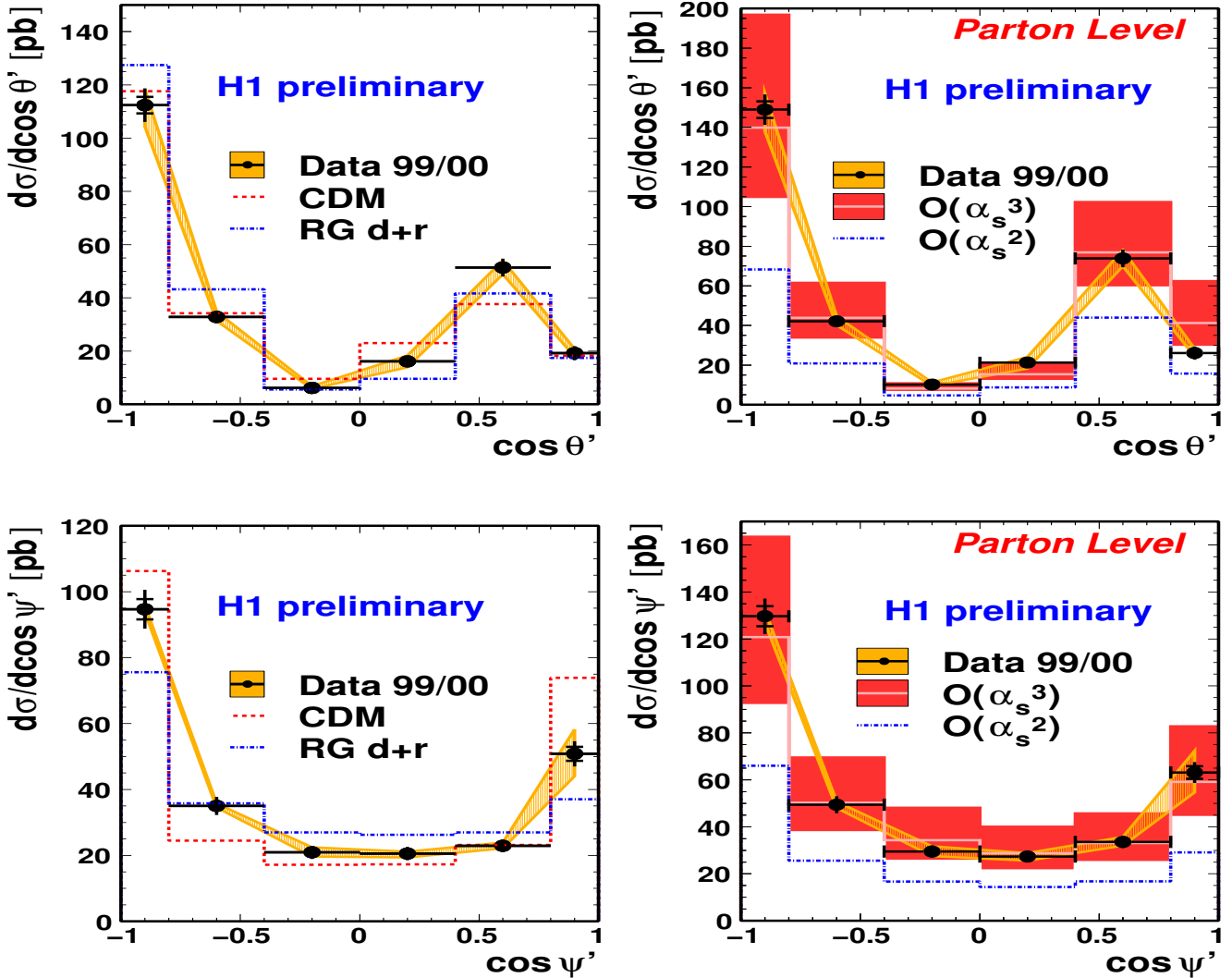
## Comparison to LO Monte Carlo



Generators with non-ordered gluon radiation describe data satisfactory.

## THREE-JET PRODUCTION IN DIS

Comparison to LO MC and NLO for two forward jets



- NLO ( $\alpha_s^3$ ) — Great improvement in all regions.
- Three-jet events in DIS with at least one radiated hard gluon in addition to the two partons from hard BGF process are ideally suited to study gluon radiation at low  $x$ .

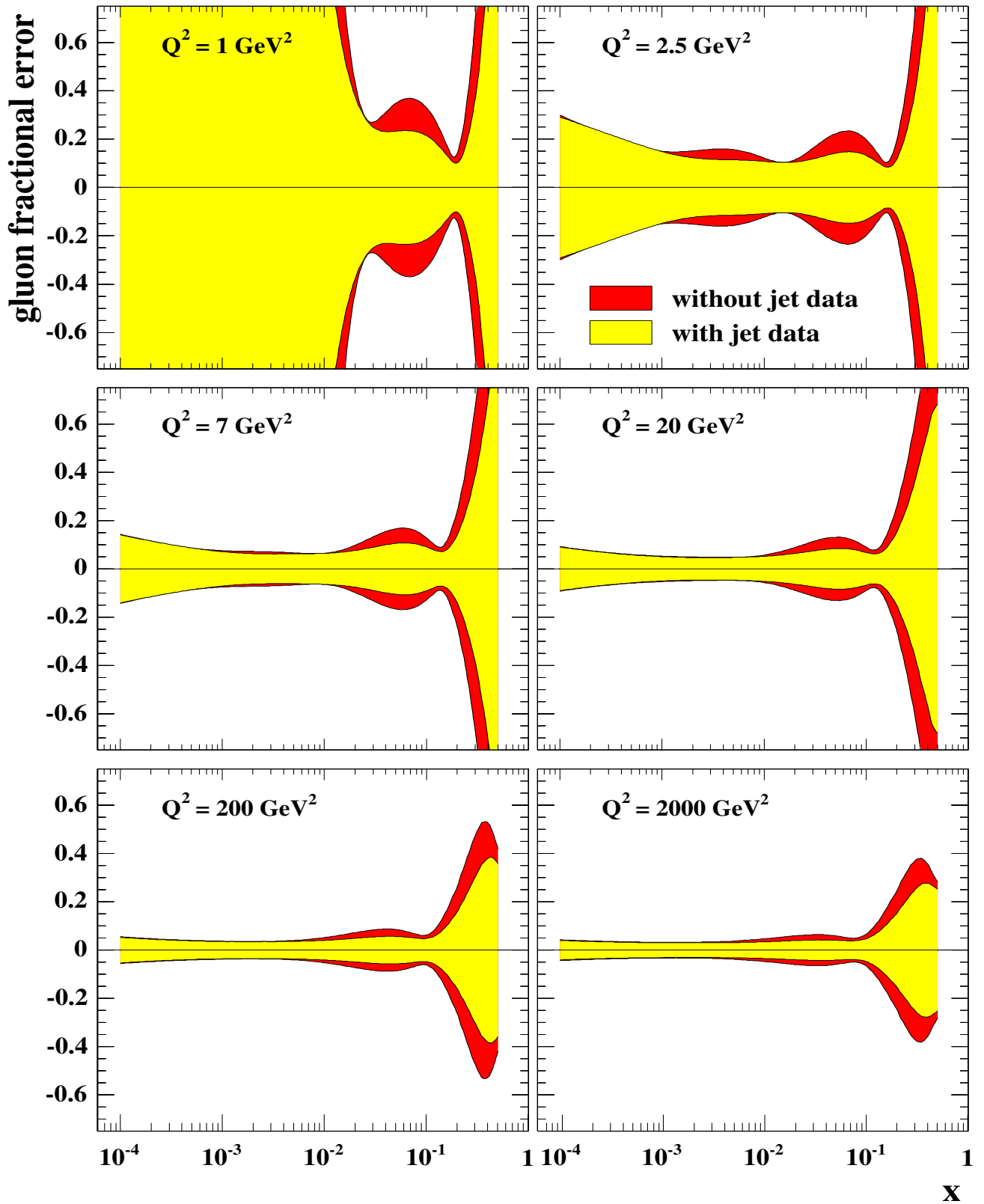


## SUMMARY

- Considerable progress in measurements and understanding of jets are achieved at HERA;
- Considerable progress in theoretical calculations and reliable predictions are achieved;
- Good understanding of pQCD and precise measurements of cross sections allow to extract  $\alpha_s$  with excellent accuracy.
- In many regions theoretical uncertainties are dominated by scale variation effects.

# BACKUP SLIDES

# ZEUS



## QCD MODELS

- **RAPGAP.** MC uses LO MEPS. Direct and resolved processes. HERACLES simulates QED-radiation effects;
- **LEPTO.** MEPS interfaced HERACLES via DJANGO;
- **ARIADNE.** Color Dipole Model;
- **CASCADE.** MC CCFM with two PDF sets;
- **PYTHIA.** MEPS. Direct and resolved PS in LL;
- **HERWIG.** Uses cluster model for hadronisation;
- **JETSET.** The hadronization of the final state. LUND model.
- **DISENT.** Program for (1+1)- and (2+1)-jet events in DIS. LO ( $\alpha_s$ ) and NLO ( $\alpha_s^2$ );
- **NLOJET++.** Can calculate (2+1)- and (3+1)-jet DIS cross sections at LO ( $\alpha_s^2$ ) and NLO ( $\alpha_s^3$ );

Uncertainties are due to a scale choice for renormalisation  $\mu_r$  and factorisation  $\mu_f$ .

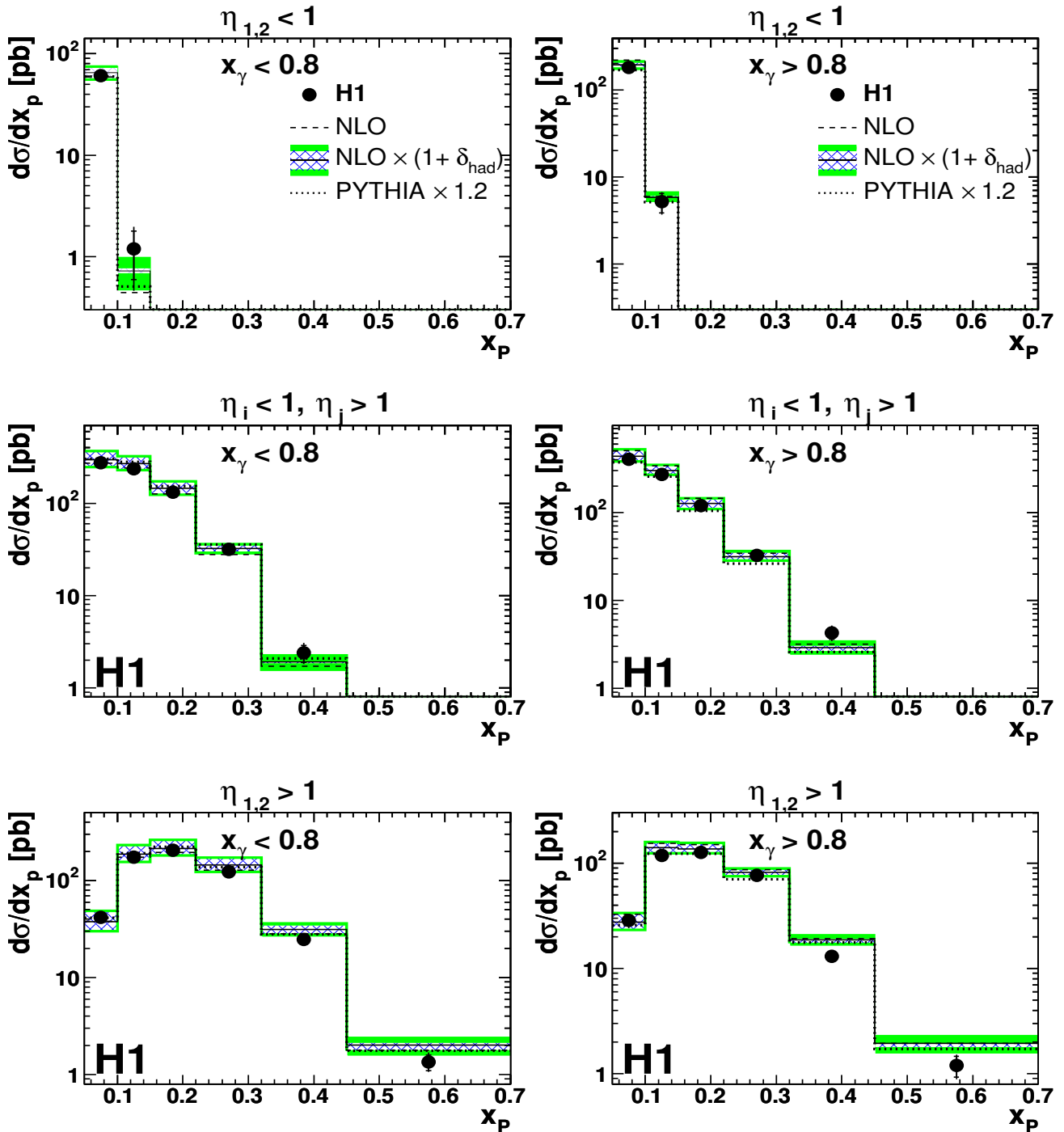
Most often:

$$\mu_r = \mu_f \text{ and } \mu_r^2 = Q^2 \text{ or } \mu_r^2 = P_t^2 \text{ or } \mu_r^2 = Q^2 + P_t^2$$

Calculation with factor two up and one half down for estimate of uncertainty.

# PHOTOPRODUCTION OF DIJETS

- "Forward", "Backward" and "Mixed" topologies:



- Pseudorapidity of two jets are sensitive to the momentum distribution of the interacting partons.

# PHOTOPRODUCTION OF DIJETS WITH HIGH $P_t$

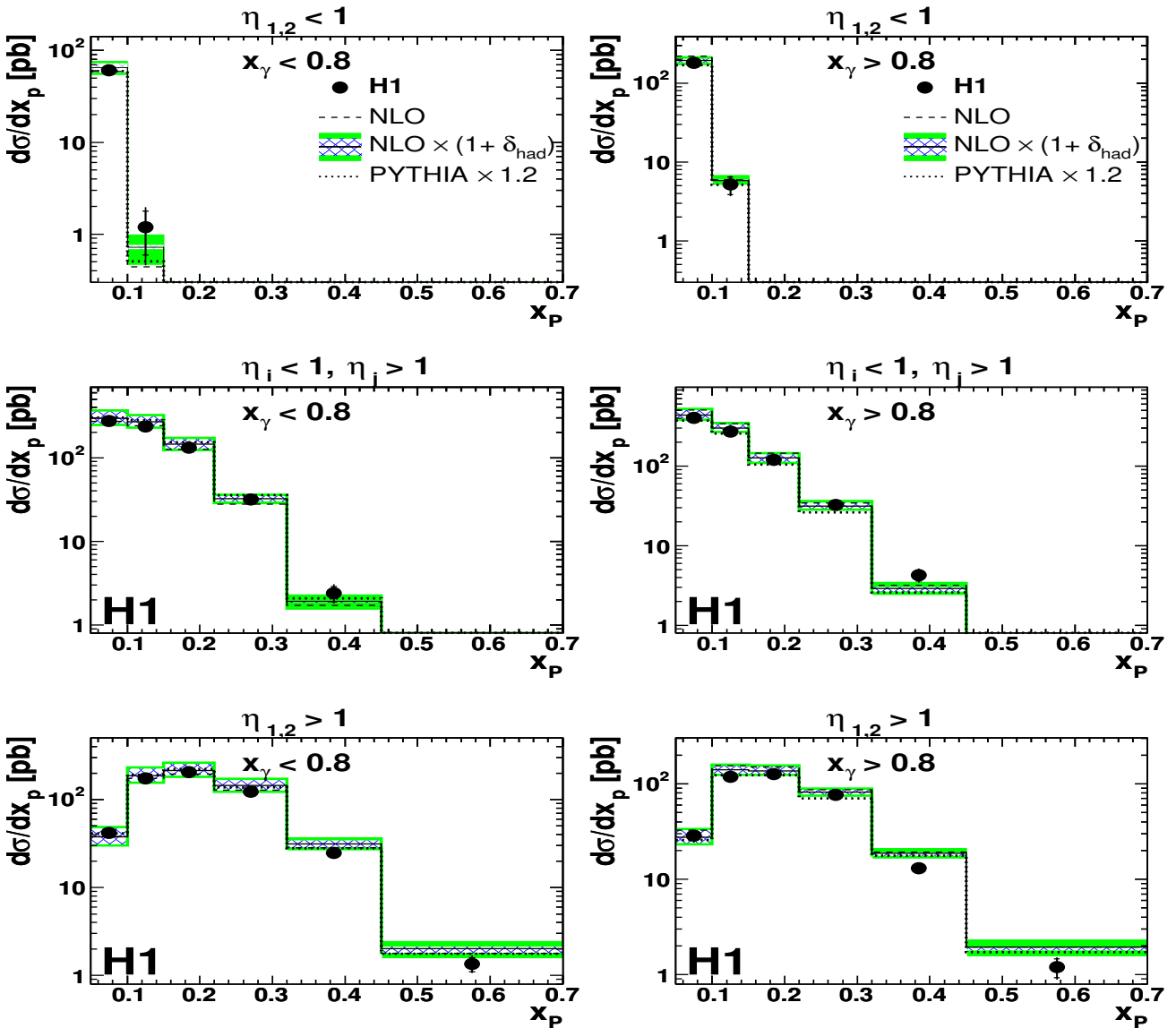
For jet reconstruction inclusive  $k_t$  algorithm was used.

$$Q^2 < 1 \text{ GeV}^2 \quad E_{t,max} > 25 \text{ GeV} \quad E_{t,scnd} > 15 \text{ GeV}$$

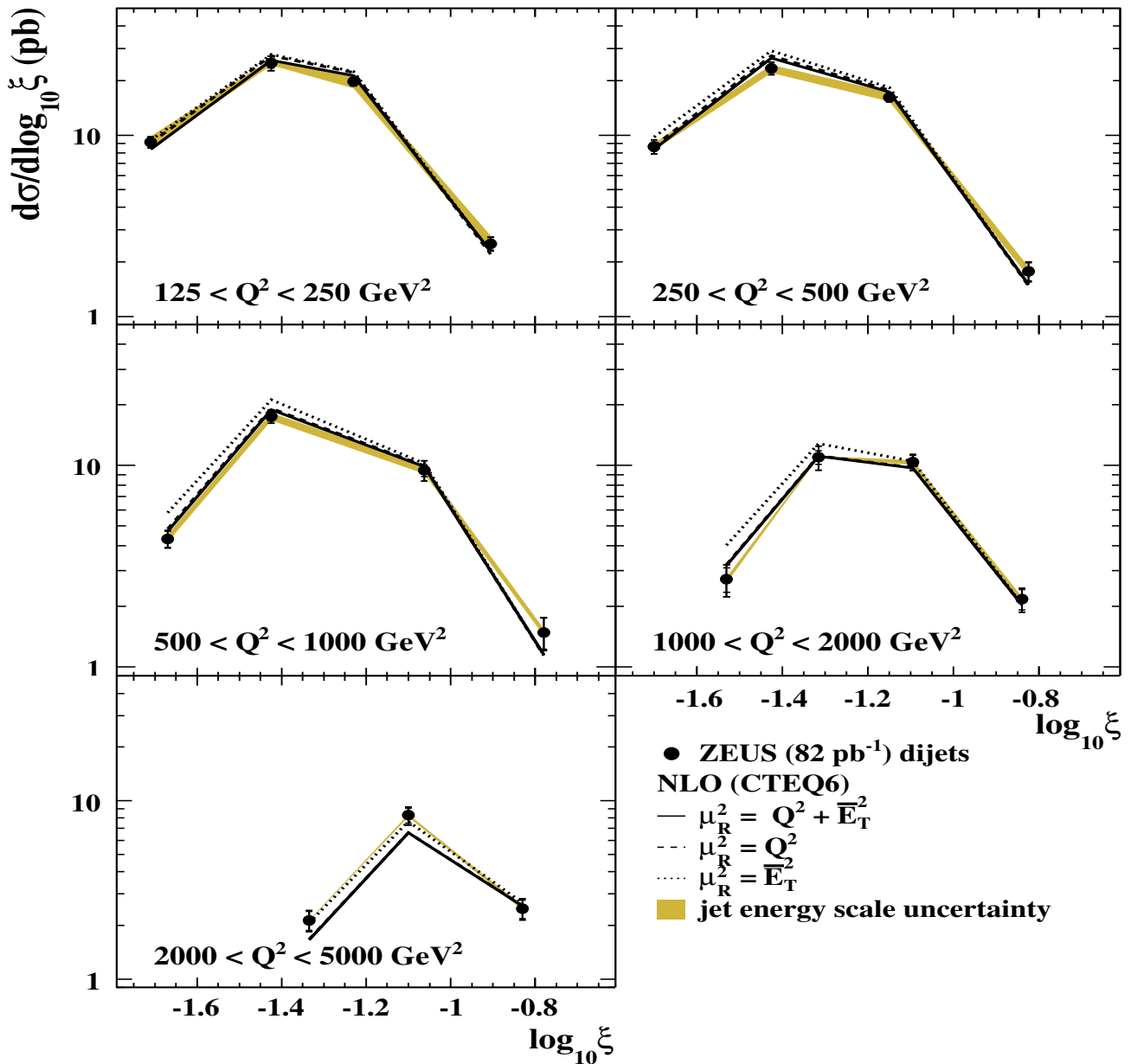
Reconstructed from hadronic final state:

$$x_\gamma = \frac{1}{2yE_e} \cdot \sum_{i=1}^2 E_{t,i} \cdot e^{-\eta_i}, \quad x_p = \frac{1}{2E_p} \cdot \sum_{i=1}^2 E_{t,i} \cdot e^{+\eta_i}$$

- "Forward", "Backward" and "Mixed" topogies:



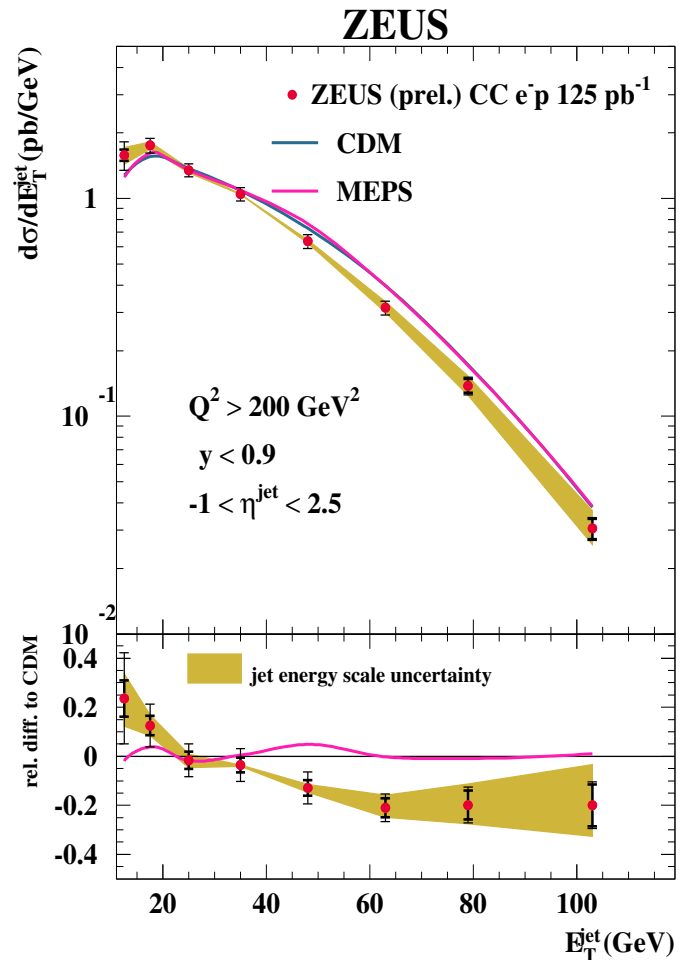
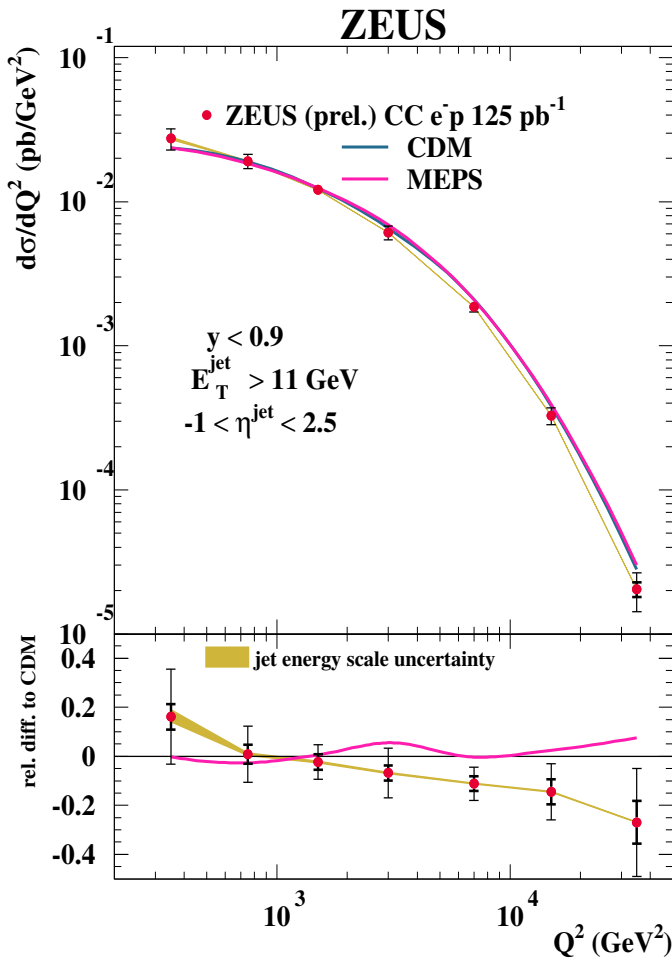
- Pseudorapidity of two jets are sensitive to the momentum distribution of the interacting partons.

**INCLUSIVE JET AND DIJET FROM DIS**
**ZEUS**


$\xi = x_{Bj}(1 + M_{jj}^2/Q^2)$  - Fraction of proton momentum taken by the interacting parton.

- Cross section in low- $\xi$  region is suppressed by requirement of two jets with high transverse momentum;
- Parton density at high  $\xi$  decreases;
- Good agreement of data with NLO description.

# JET CROSS SECTION IN CC EVENTS



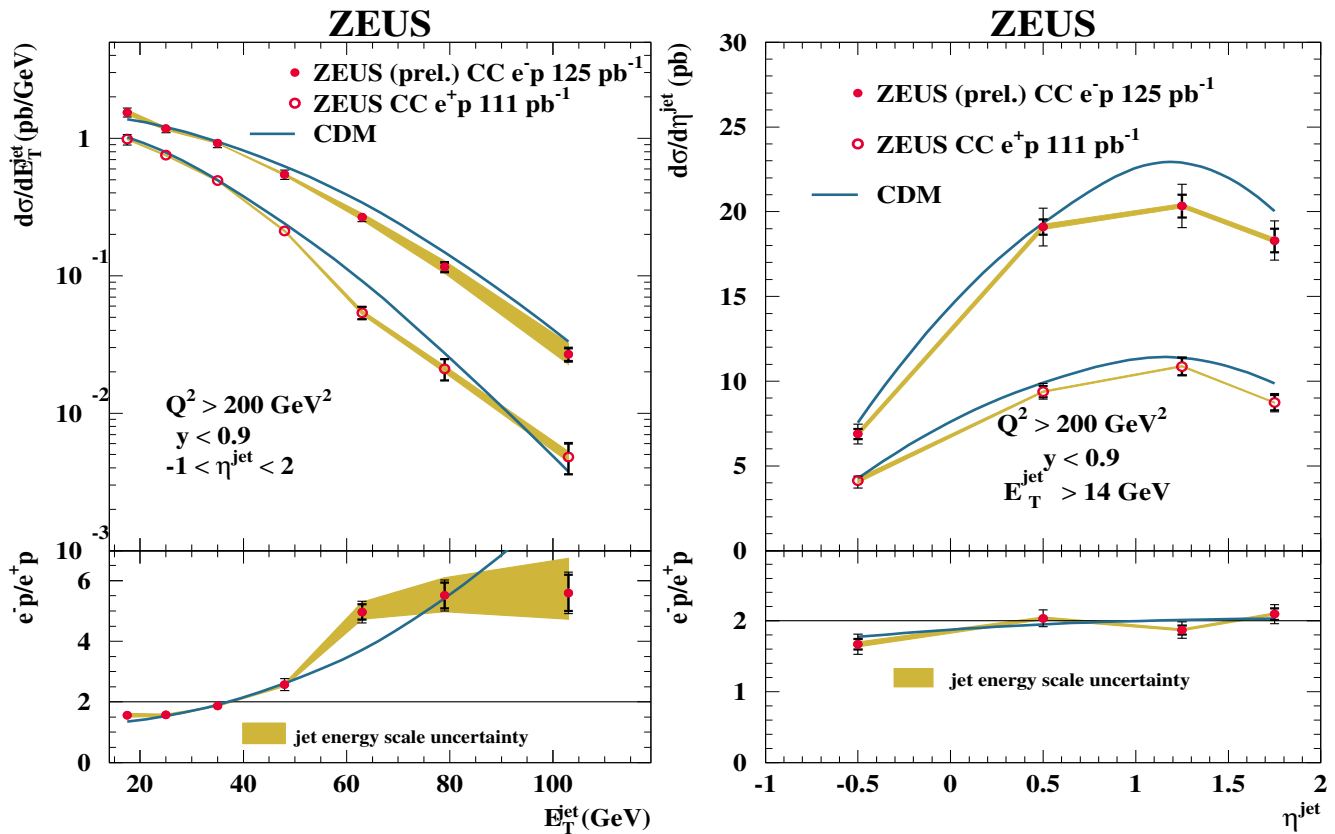
$$N_{\text{data}}^{\text{unpol}} = \frac{N_{\text{data}}^{\text{neg}}}{1 - P_e^{\text{neg}}} + \frac{N_{\text{data}}^{\text{pos}}}{1 - P_e^{\text{pos}}}$$

- Cross section shows a less rapidly fall-off to compare with NC DIS.
- Inclusive-jet cross section measured also as function of  $\eta^{\text{jet}}$  and  $x_{Bj}$ , which are well described by MC.
- The cross sections as function of  $Q^2$  and  $E_T^{\text{jet}}$  have a deviation in shape.



# JET CROSS SECTION IN CC EVENTS

## COMPARISON TO $e^+p$ DATA



- Measurement of polarised and unpolarised-corrected inclusive jet differential cross sections in CC  $e^-p$  DIS production was made with ZEUS detector for the first time;
- Inclusive jet cross sections are reasonably well described by MEPS MC;
- There are deviation in shape for  $E_T^{\text{jet}}$  and  $Q^2$  dependencies;
- Ratios between  $e^-p$  and  $e^+p$  cross sections are in agreement with MC.