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Jet physics in ep collisions

Experimental results from H1 and ZEUS collaborations

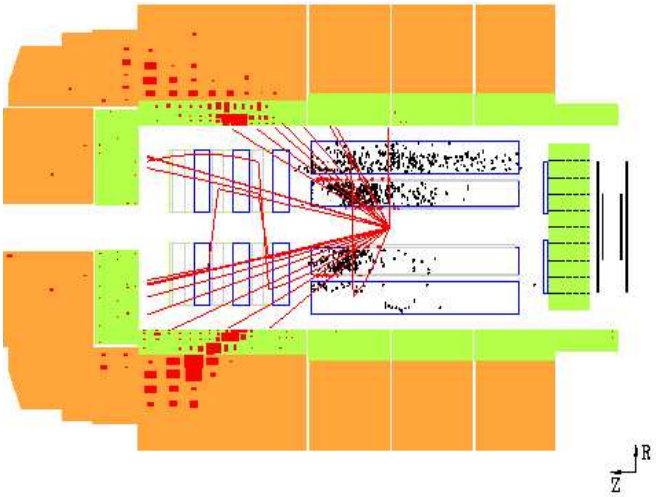
- **Photoproduction of jets with high transverse momenta.**
- **Inclusive jets and dijets in DIS.**
- **Jets and determination of α_s.**
- **Jet cross sections in CC DIS.**
- **Forward jet production in DIS.**
- **Three-jet production in DIS.**
- **Summary**

ISMD-2006
XXXVI International Simposium on Multiparticle Dynamics
Rio de Janeiro, Paraty, August 2-8, 2006

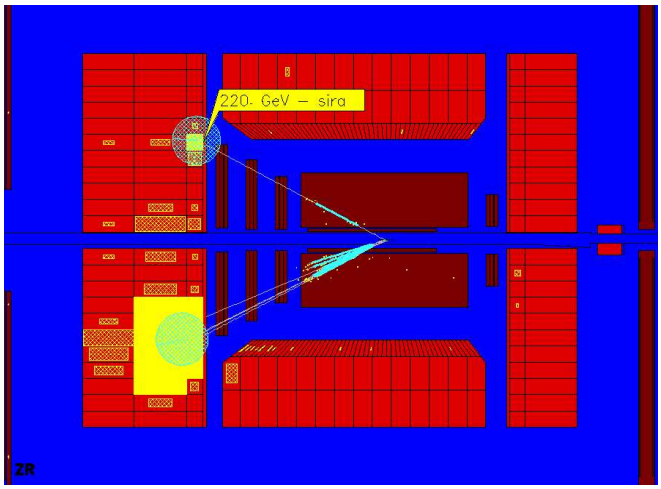
INTRODUCTION

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

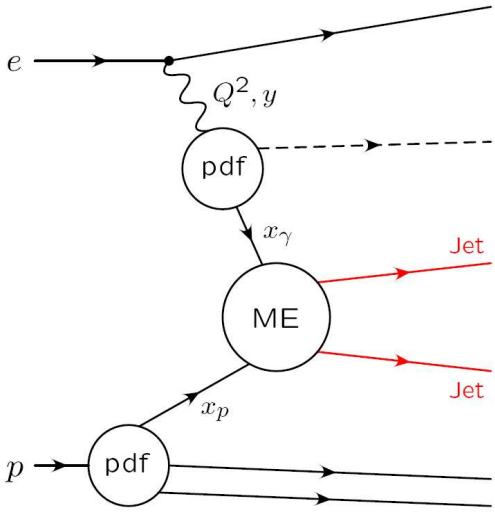
Proton energy $E_p = 920\,GeV$.
Electron (positron) energy $E_e = 27.6\,GeV$



H1 detector



ZEUS detector



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

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

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

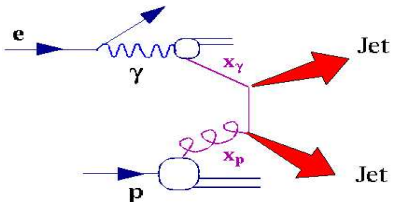
Pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$

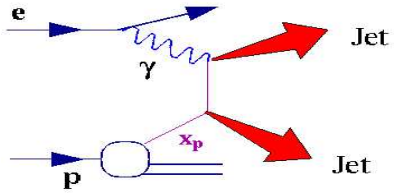
Photoproduction: $Q^2 \approx 0\,GeV^2$

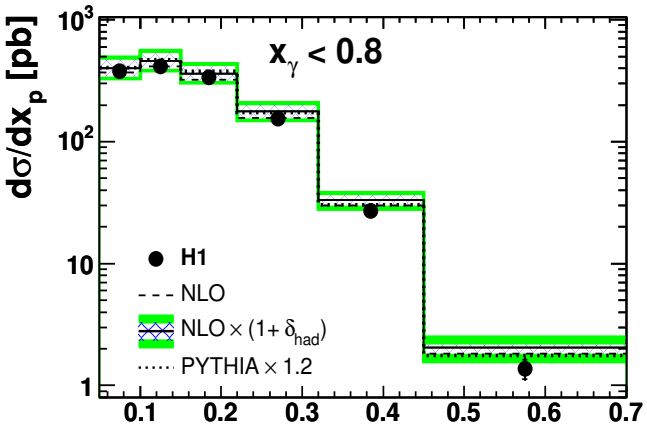
DIS: $Q^2 \gg 1\,GeV^2$

In the leading order x_γ and x_p are longitudinal photon and proton momentum fractions entering the hard interaction.

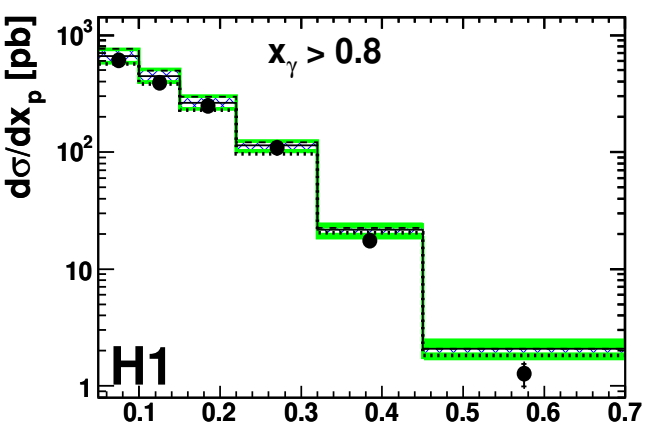
PHOTOPRODUCTION OF DIJETS WITH HIGH P_t



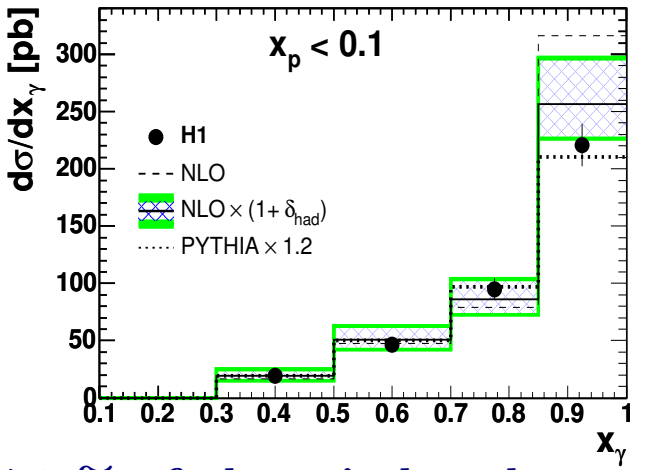


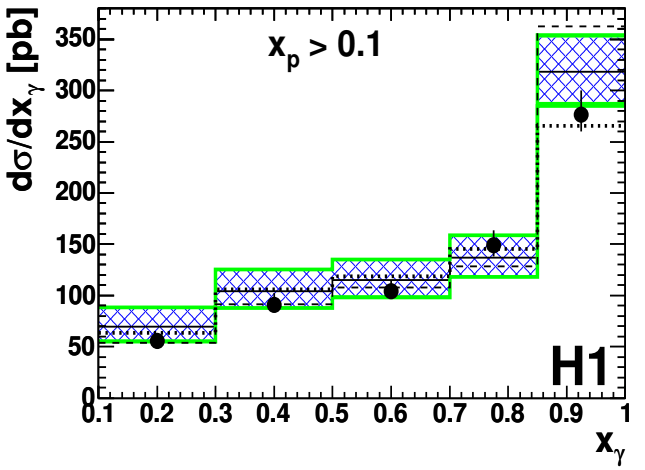


Resolved processes



Direct processes





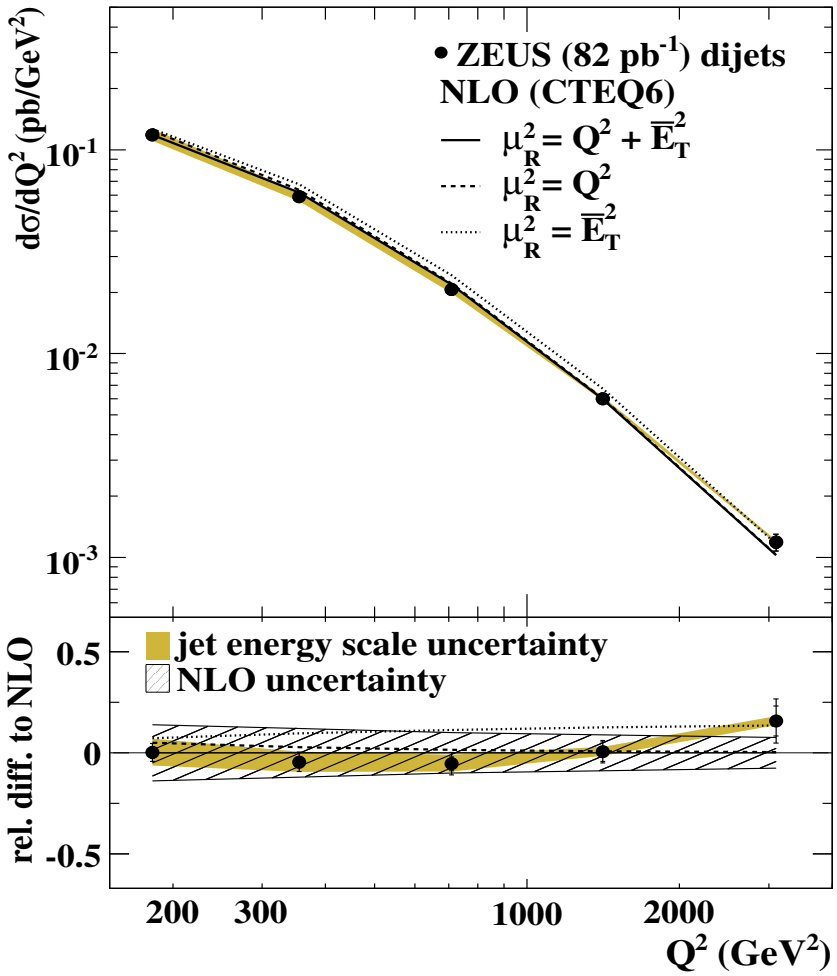
70 % of gluon induced events

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



$Q^2 > 125$ GeV

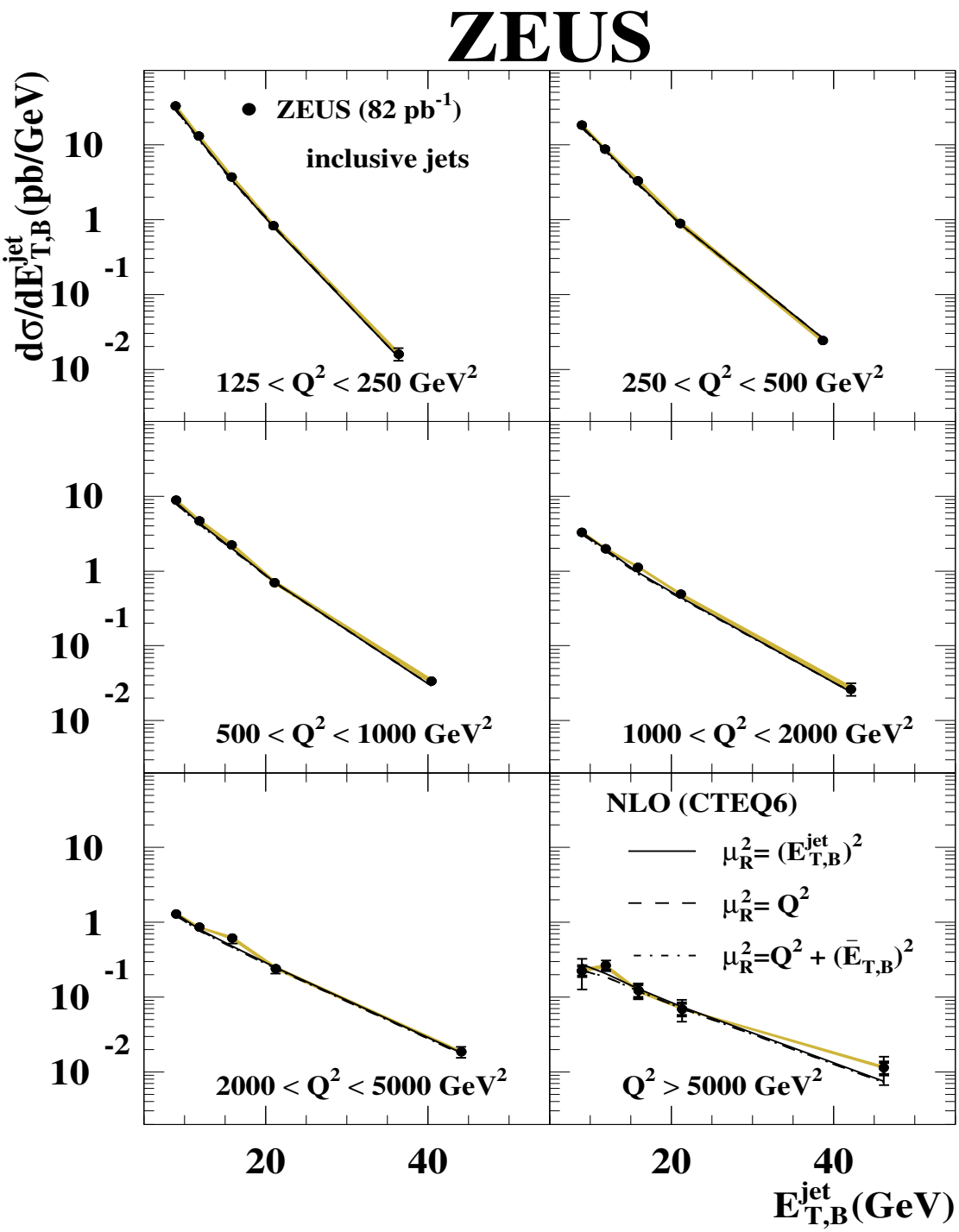
$E_{T,B}^{jet1} > 12$ GeV

$E_{T,B}^{jet2} > 8$ GeV

$-2 < \eta_B^{jet} < 1.5$

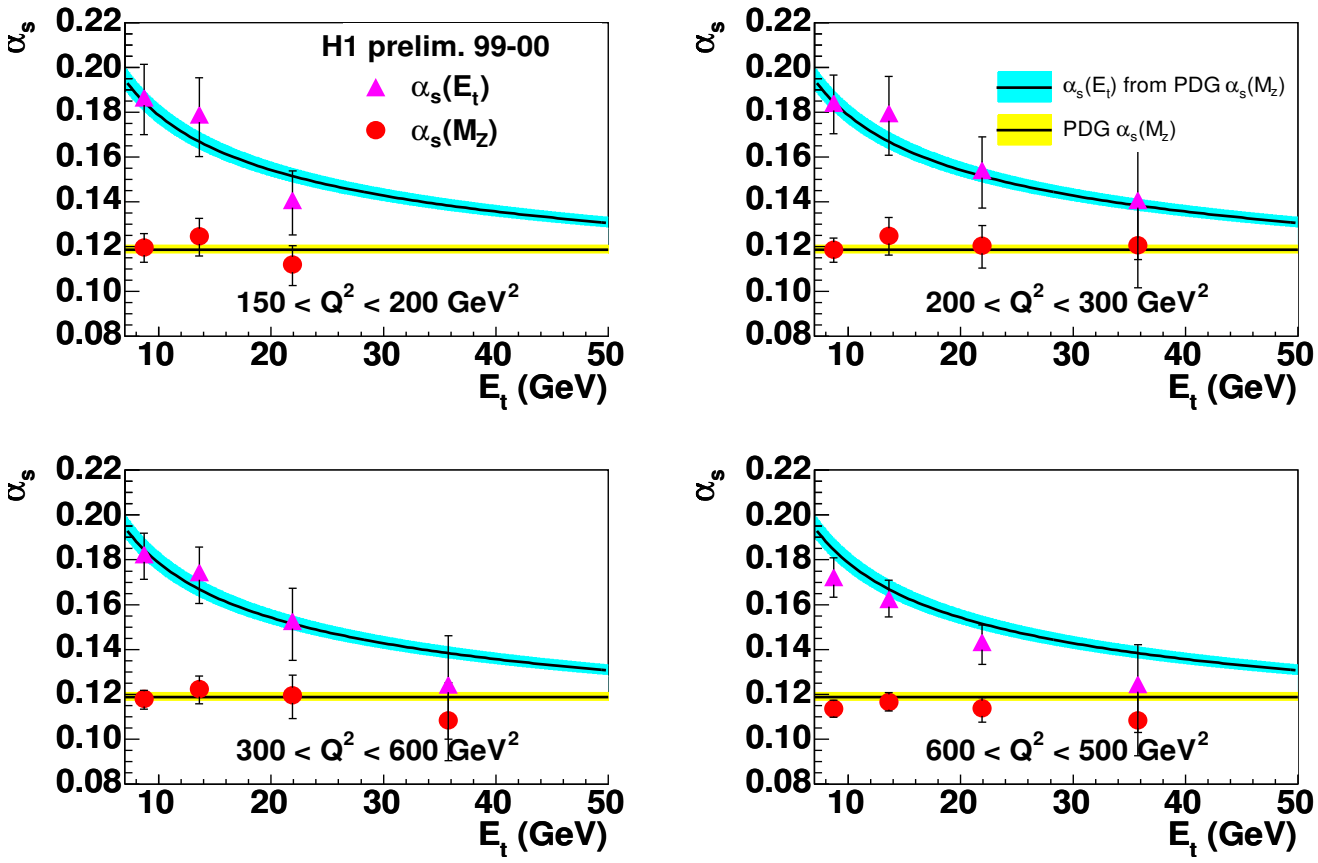
- The largest contribution to theoretical uncertainties ($\pm 20\%$) comes from μ_R.
- The largest contributions to systematic uncertainty come from uncertainty in absolute energy scale ($\pm 10\%$) and correction factor for detector effects $\pm 8\%$
- The theoretical uncertainties are dominated.

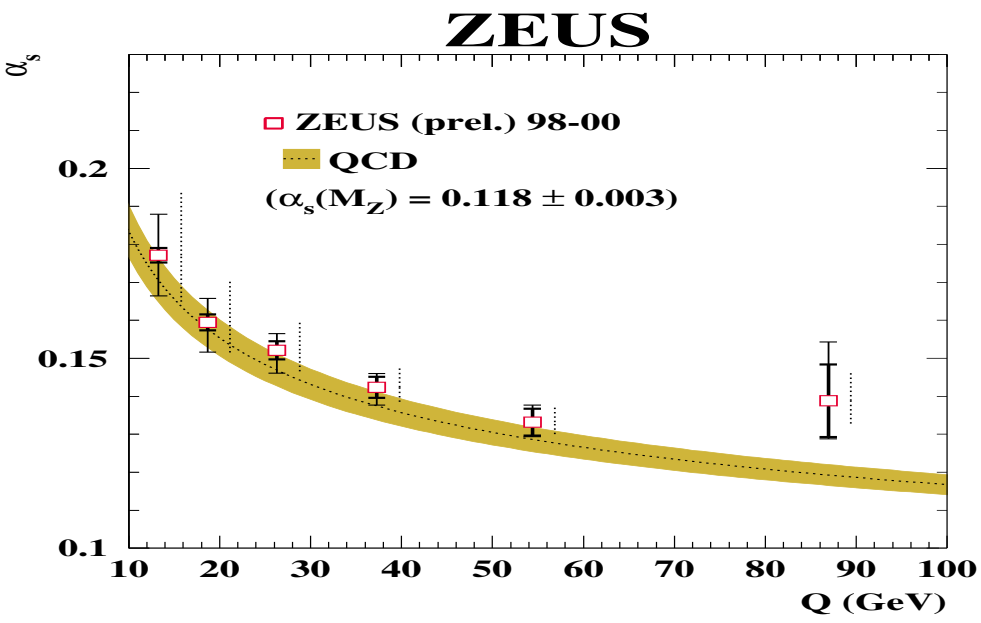
INCLUSIVE JETS IN DIS



- $E^{jet}_{T,B}$ - 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 α_s from inclusive jet cross sections

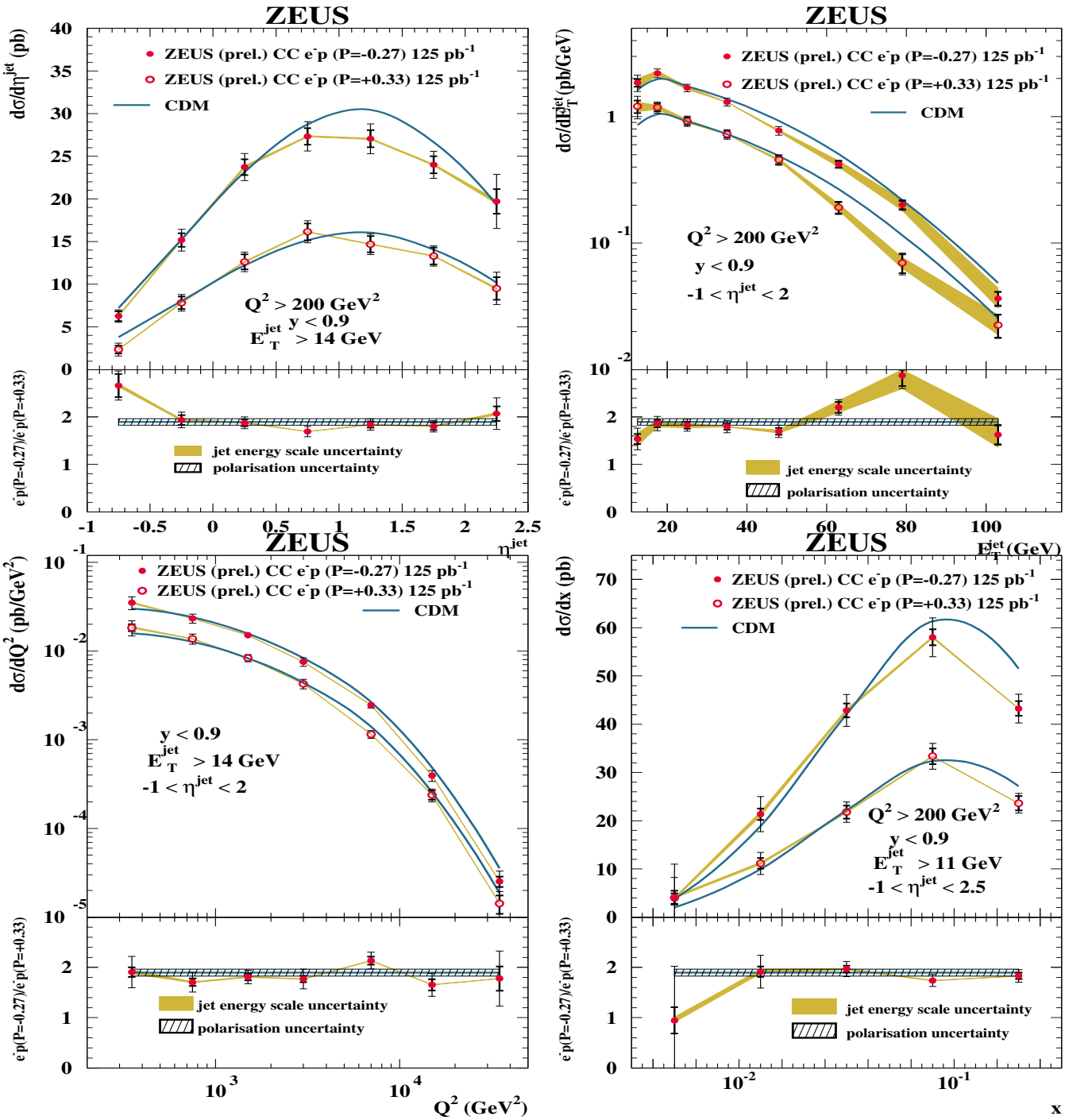




- **H1 value** $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\mathrm{exp}) \pm 0.0047(\mathrm{th})$
- **ZEUS value** $\alpha_s(M_Z) = 0.1196 \pm 0.0025(\mathrm{exp}) \pm 0.0023(\mathrm{th})$
- **World average** $\alpha_s(M_Z) = 0.1187 \pm 0.0020(\mathrm{exp})$

JET CROSS SECTION IN CC EVENTS

Measurements with lepton polarised beams (HERA II !)



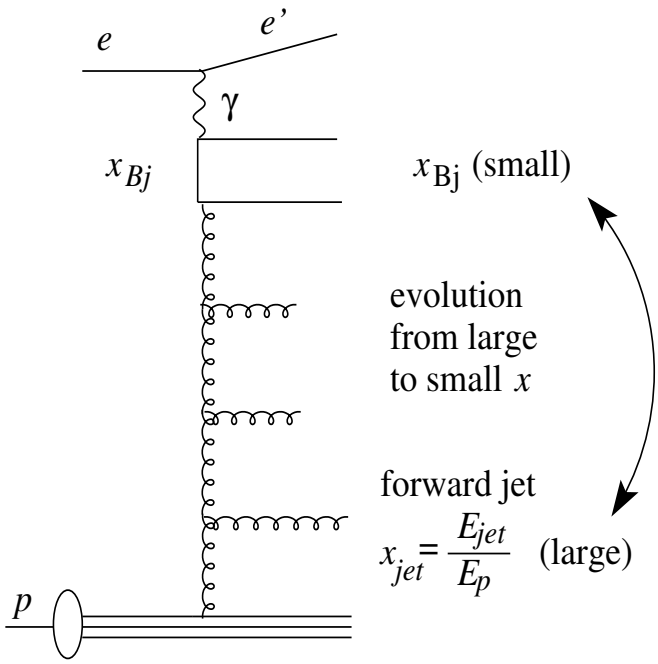
$$\sigma^{neg}_{jets} = 71.3 \pm 1.2(st) \pm 3.6(sys) \pm 0.3(E_{scale})pb \qquad \sigma^{neg}_{MC} = 75\,pb$$
$$\sigma^{pos}_{jets} = 38.7 \pm 1.2(st) \pm 2.0(sys) \pm 0.2(E_{scale})pb \qquad \sigma^{pos}_{MC} = 40\,pb$$

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.**



$$p^2_{t,jet} \approx Q^2$$

$$x_{jet} \equiv \frac{E_{jet}}{E_p}$$

$$x_{jet} \gg x_{Bj}$$

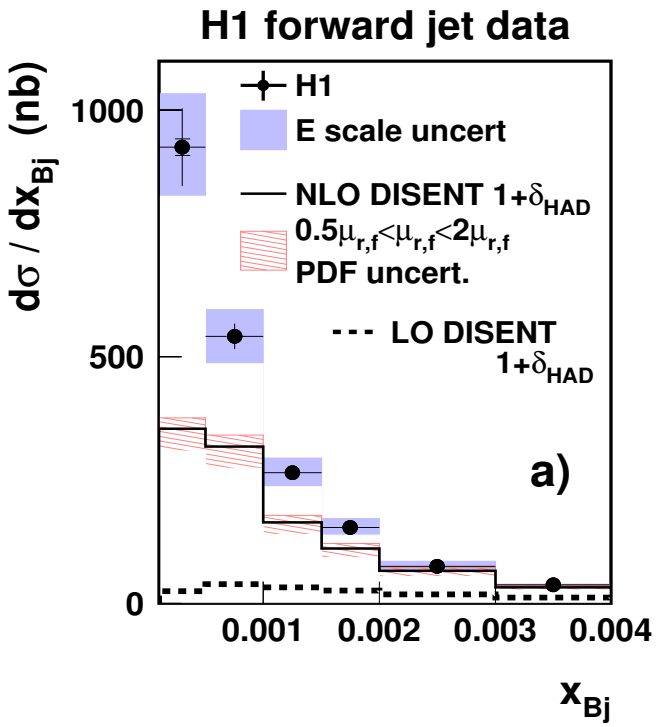
QCD MODELS

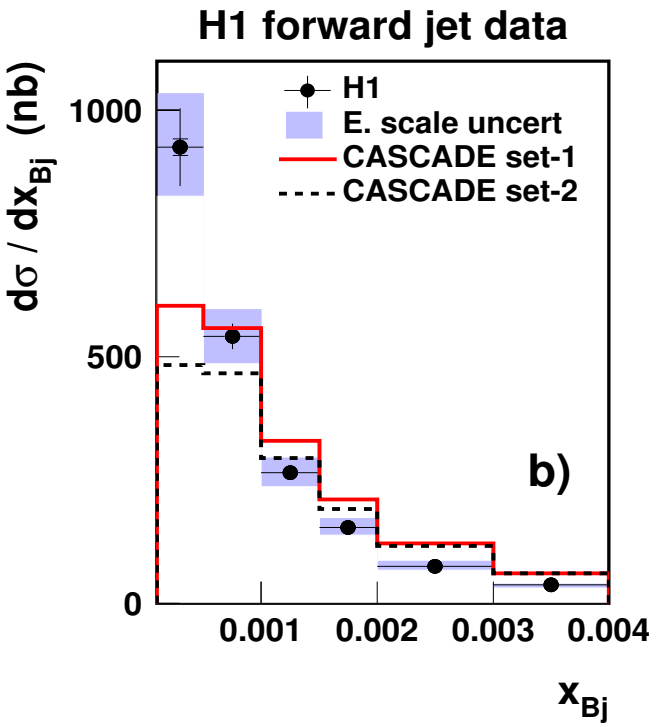
- **RAPGAP MC LO + resolved and direct processes**
- **DJANGO with CDM**
- **CASCADE based on CCFM**

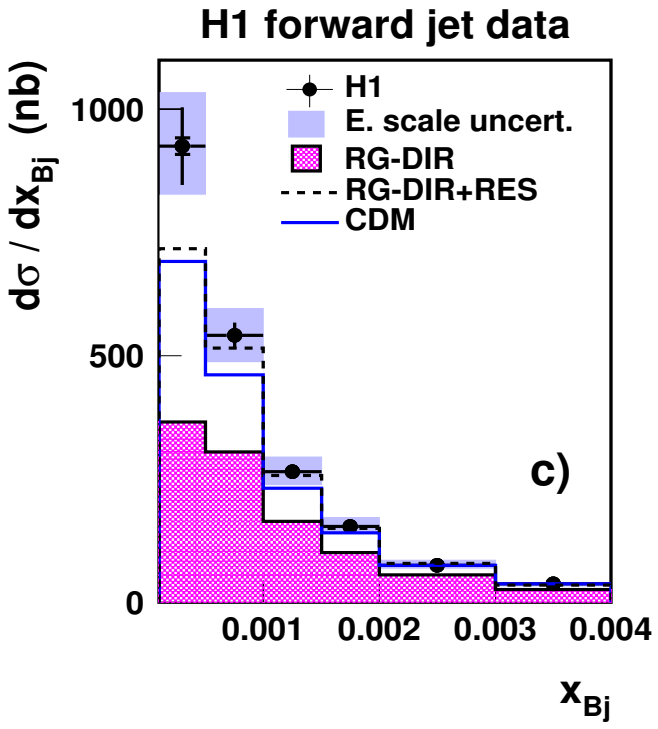
$LO(\alpha_s)$ and $NLO(\alpha_s^2)$ calculated by DISENT (μ_r = average of p_t^2)

FORWARD JET PRODUCTION IN DIS

Forward JET: $\theta_{jet} < 20^o$ and $x_{jet} = E^*_{jet}/E_p > 0.035$



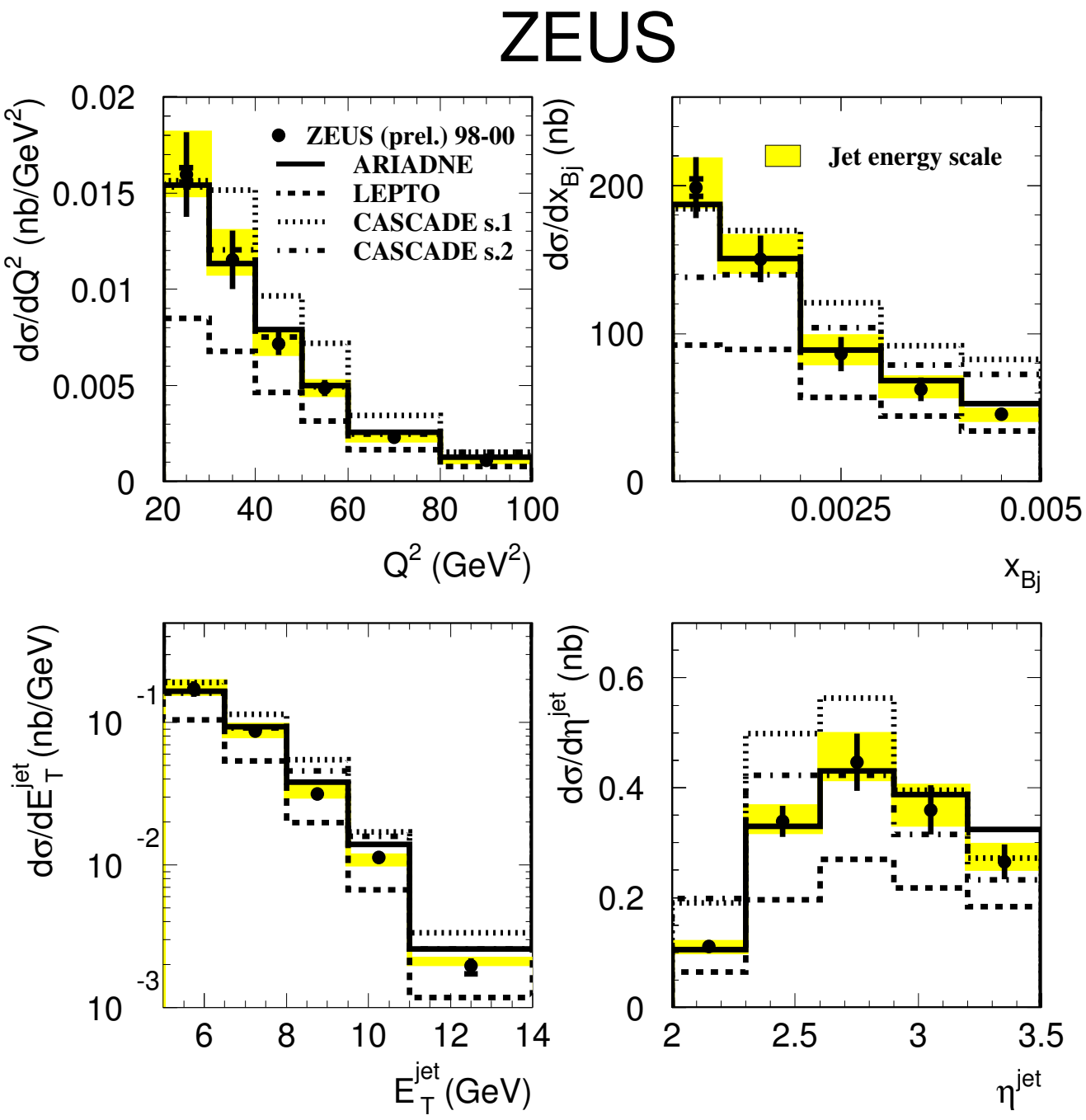




- **LO is suppressed by kinematics**
- **NLO is still factor 2 below**
- **CCFM overestimates data**
- **CDM and RG+RES are similar**

FORWARD JET PRODUCTION IN DIS

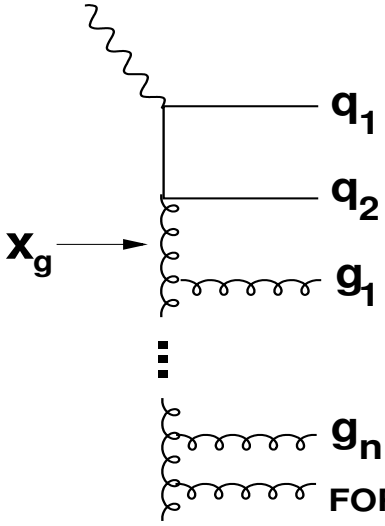
Very forward jet: $2 < \eta_{\mathrm{jet}} < 3.5$



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

FORWARD JET PRODUCTION IN DIS

$$\eta_{\mathrm{fwdjet}} > \eta_{\mathrm{jet2}} > \eta_{\mathrm{jet1}} > \eta_{\mathrm{e}}$$



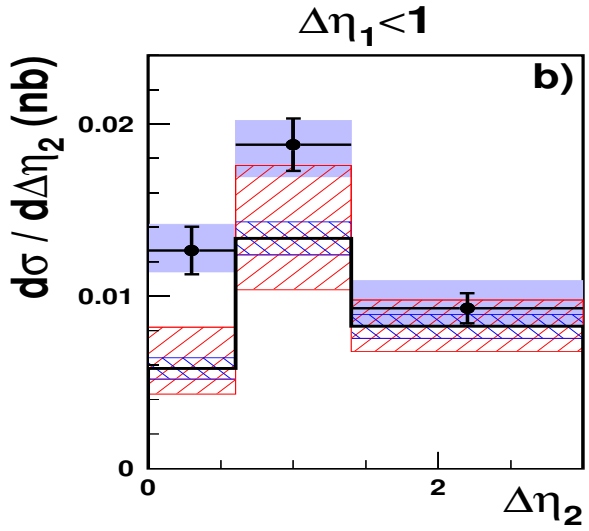
η_{jet1}

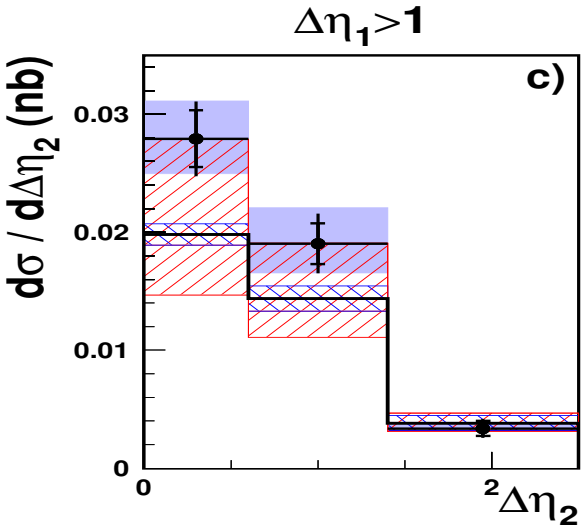
$\Delta\eta_1 = \eta_{\mathrm{jet2}} - \eta_{\mathrm{jet1}}$

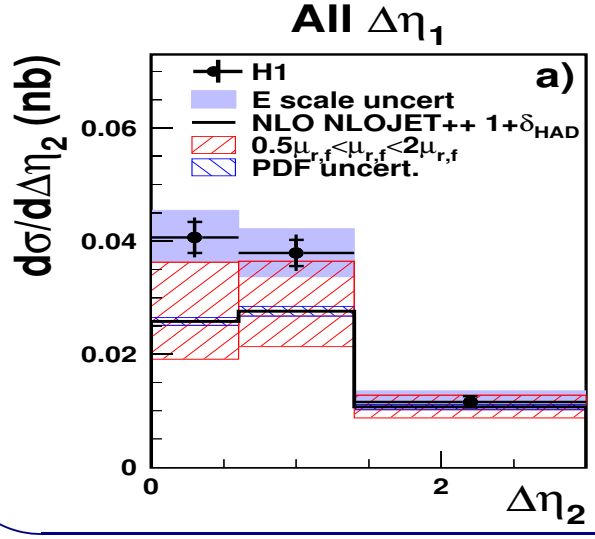
η_{jet2}

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

η_{fwdjet}



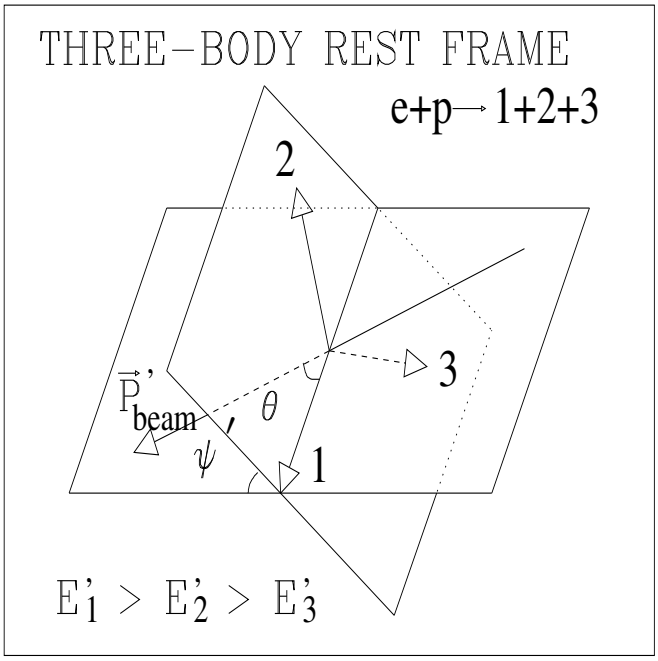




$\Delta\eta_1 < 1 \Rightarrow$ small x_g, more radiation.

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

THREE-JET PRODUCTION IN DIS



$E_t^* > 4\,\mathrm{GeV}$ $(\gamma^* p$ CM)

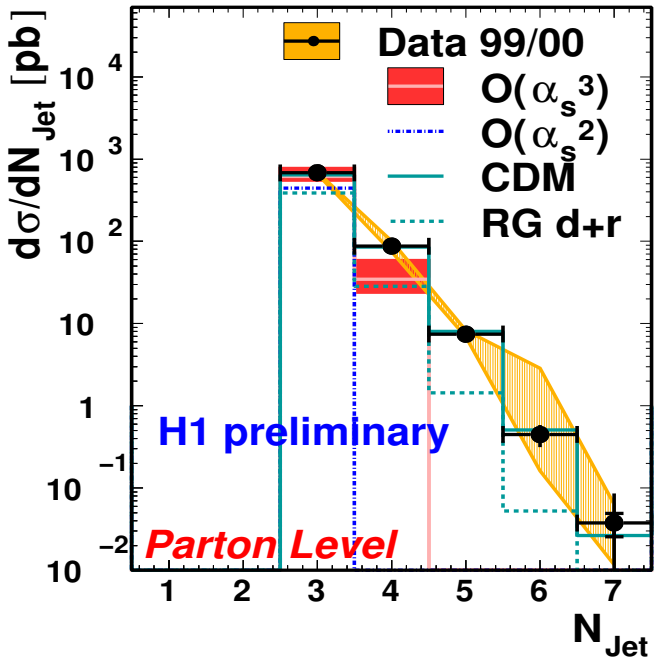
Any jet $\Rightarrow$ $-1 < \eta_{jet} < 2.5$

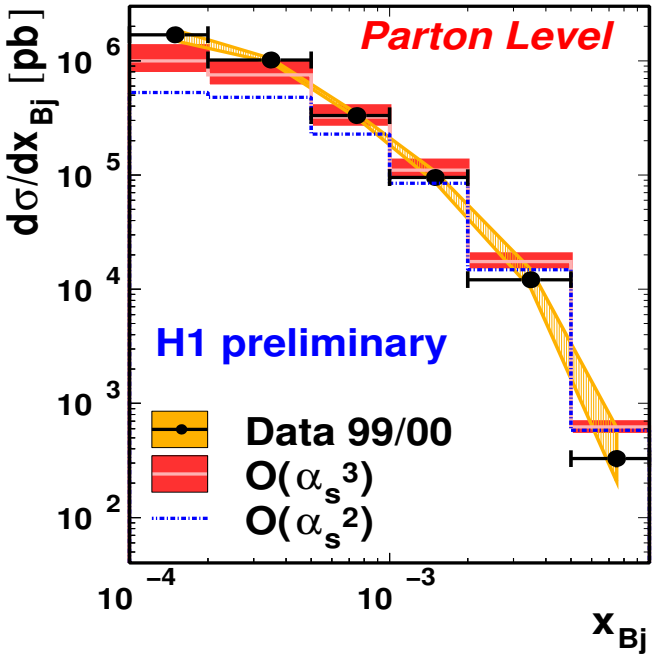
One jet $\Rightarrow$ $-1 < \eta_{jet} < 1.3$

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

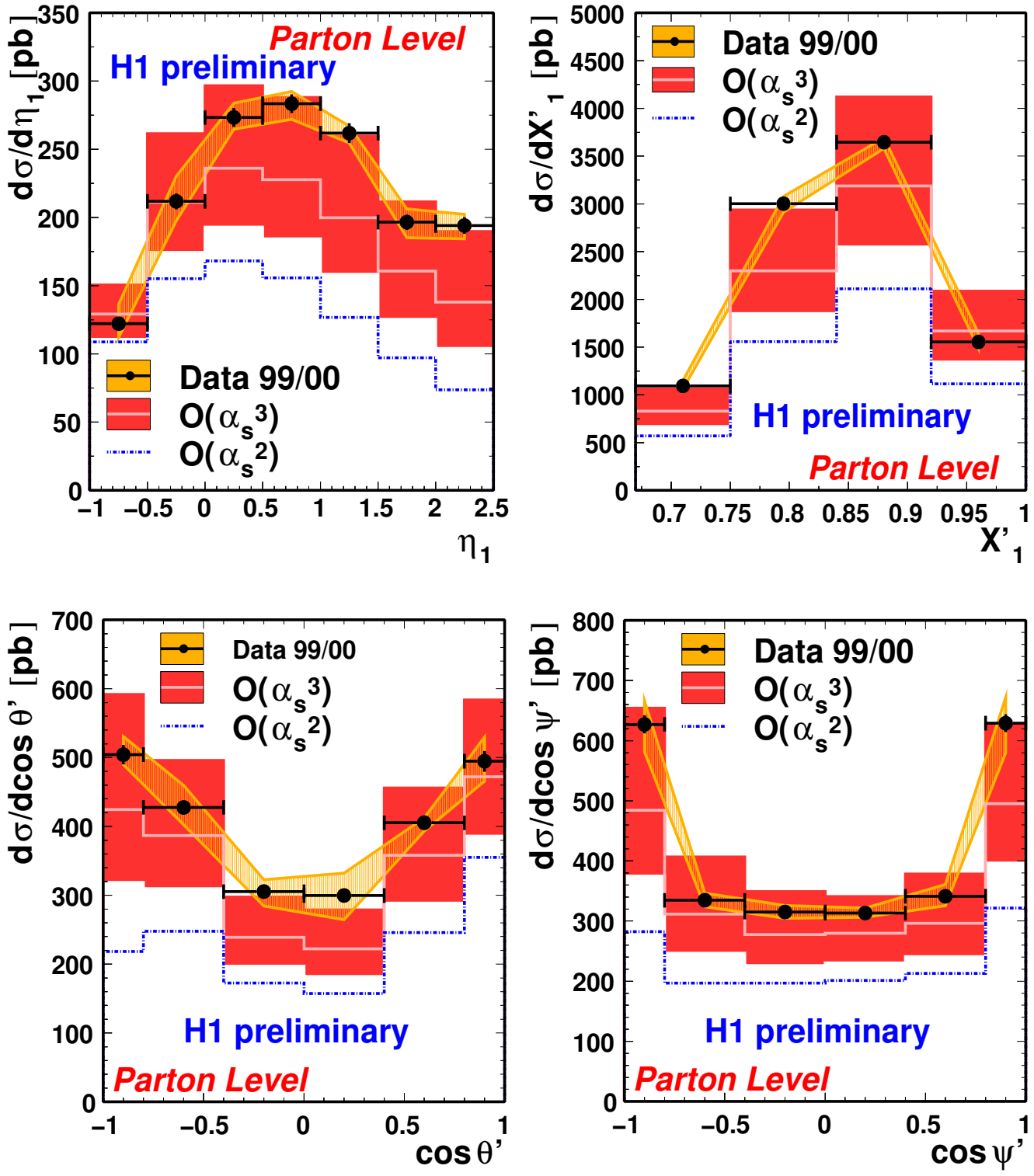
DIANGOH $\mu^2 = Q^2$

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





THREE-JET PRODUCTION IN DIS

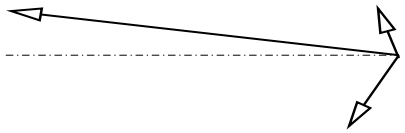


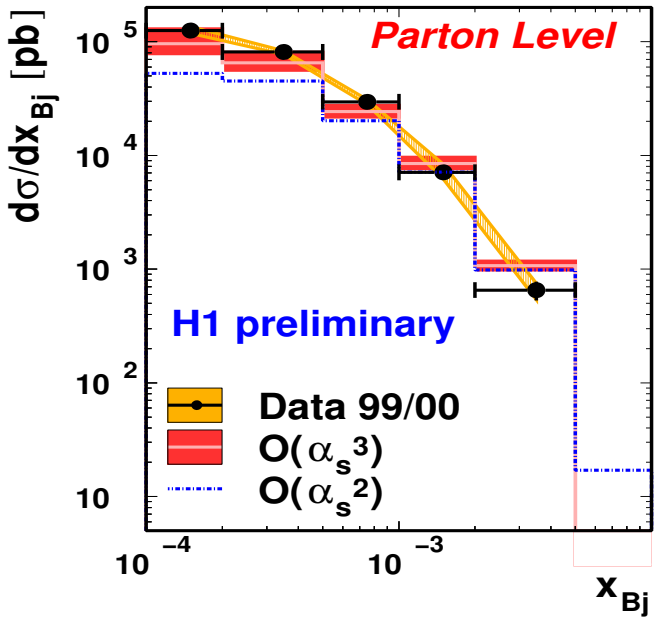
- NLO prediction improves the situation dramatically.
- Difference in normalisation is 18%.

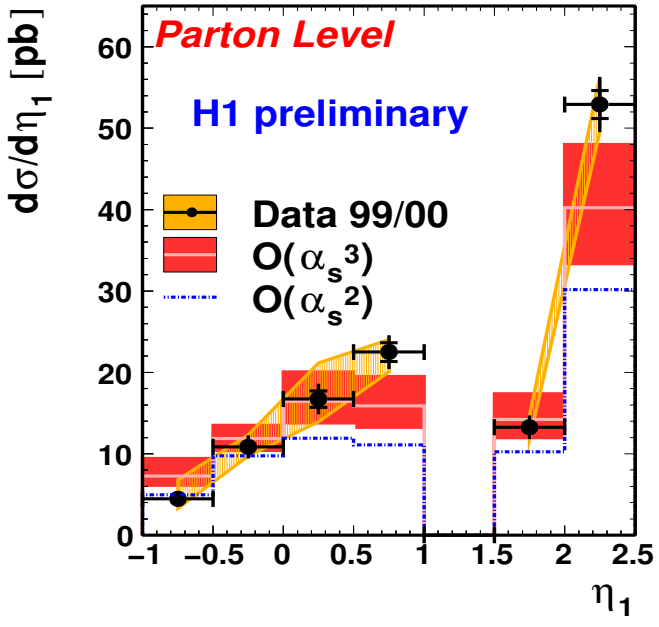
THREE-JET PRODUCTION IN DIS

Forward JET: $\theta_{jet} < 20^o$ and $x_{jet} = E^*_{jet}/E_p > 0.035$

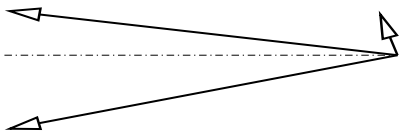
Two central jets
$-1 < \eta_{jet} < 1$

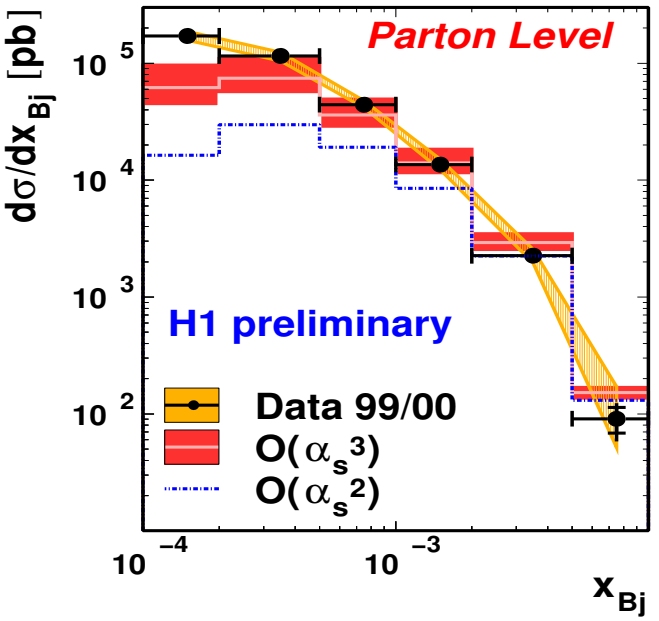


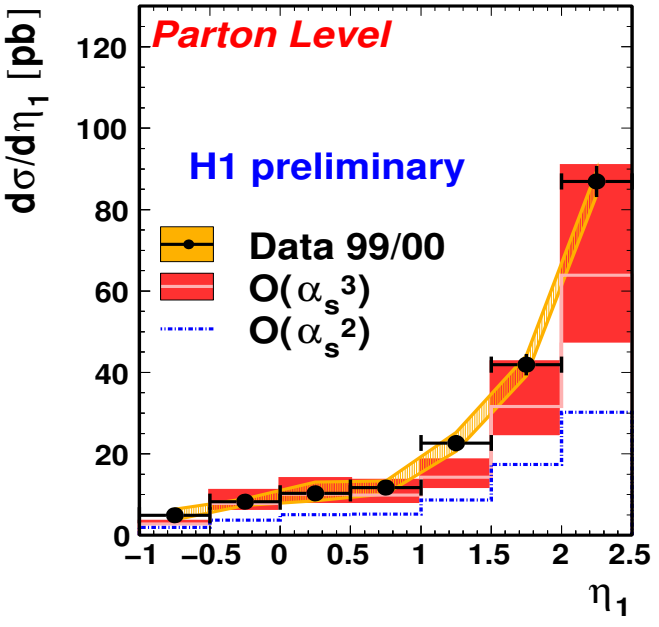




Two forward jets
$\eta_{jet} > 1$

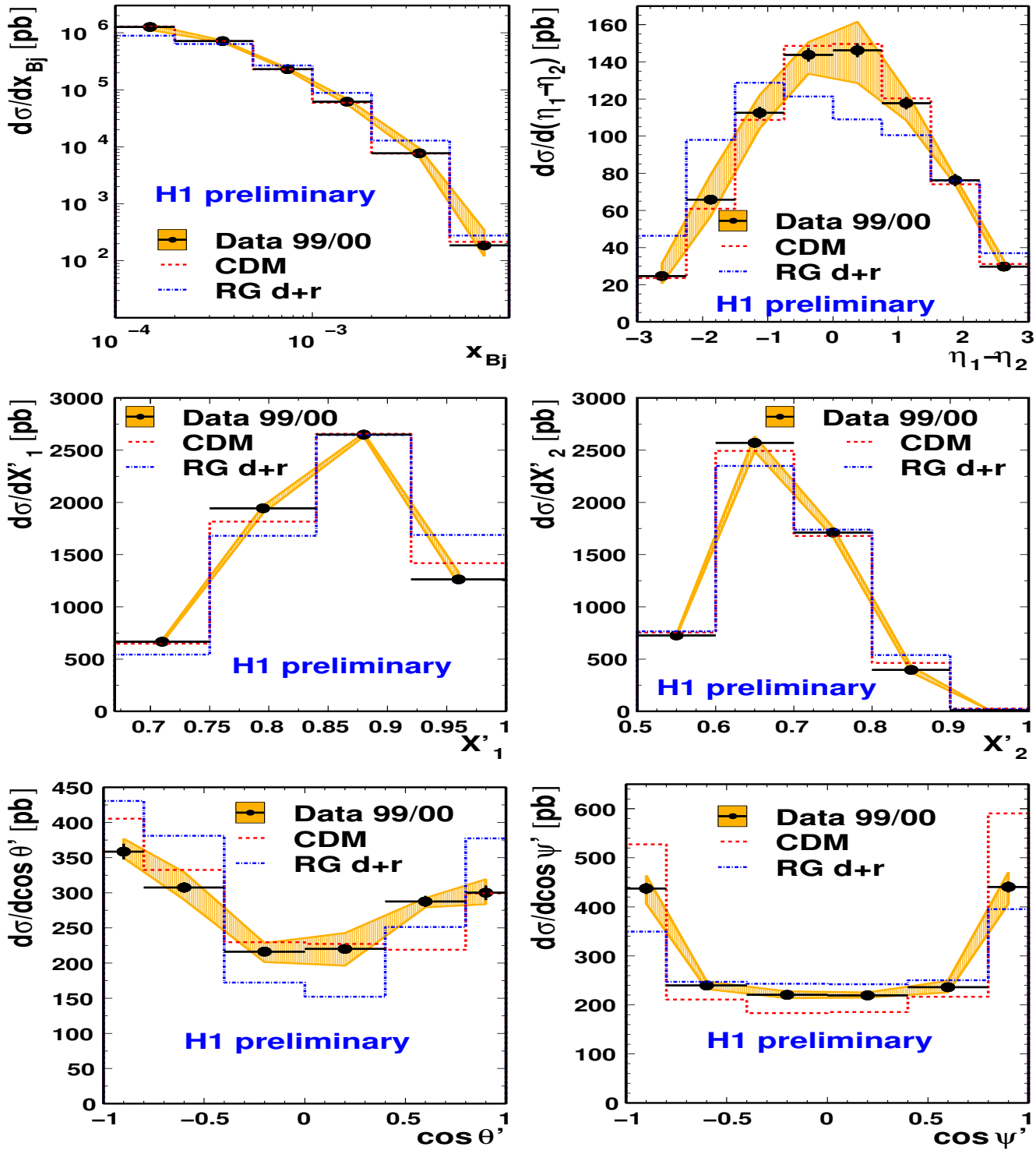






THREE-JET PRODUCTION IN DIS

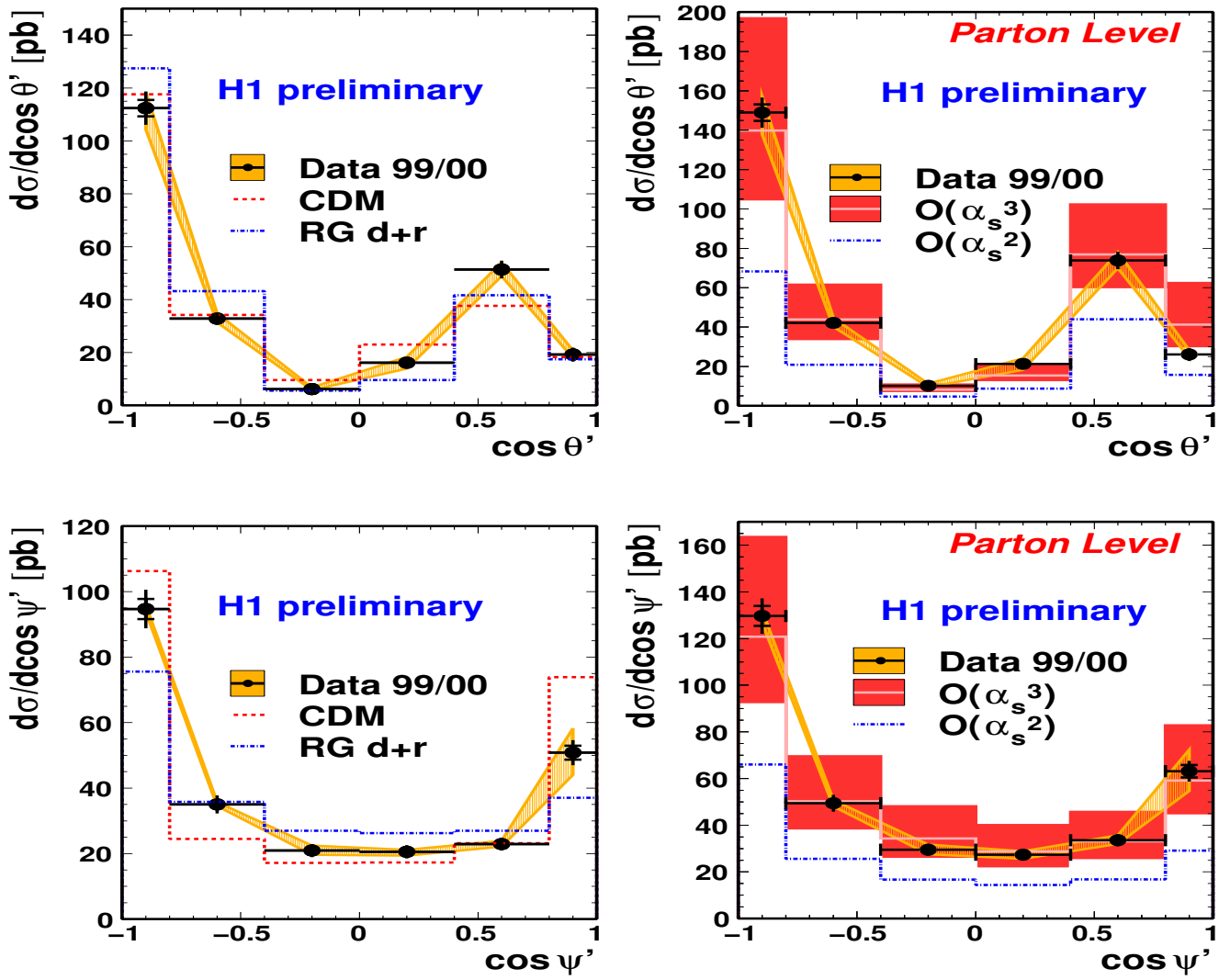
Comparison to LO Monte Carlo



Generators with non-ordered gluon radiation describe data satisfactory.

THREE-JET PRODUCTION IN DIS

Comparison to LO MC and NLO for two forward jets

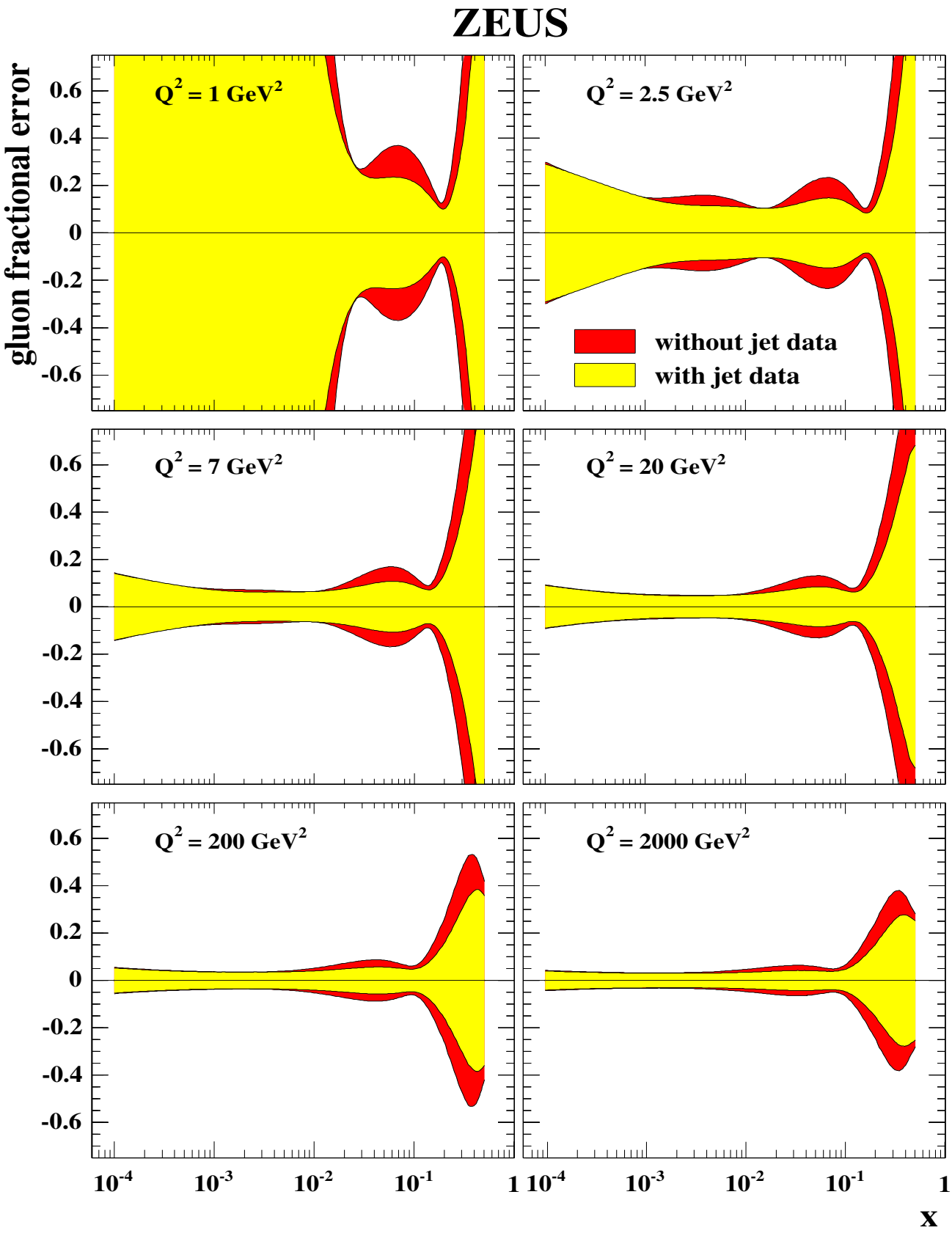


- **NLO (α_s^3) — Great improvement in all regions.**
- **Three-jet events in DIS with at least one radiated hard gluon in addition to the two partons from hard BGF process are ideally suited to study gluon radiation at low x.**

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 α_s with excellent accuracy.**
- **In many regions theoretical uncertainties are dominated by scale variation effects.**

BACKUP SLIDES


ZEUS
gluon fractional error
Q^2 = 1 GeV^2
Q^2 = 2.5 GeV^2
Q^2 = 7 GeV^2
Q^2 = 20 GeV^2
Q^2 = 200 GeV^2
Q^2 = 2000 GeV^2
without jet data
with jet data
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

QCD MODELS

- **RAPGAP. MC uses LO MEPS. Direct and resolved processes. HERACLES simulates QED-radiation effects;**
- **LEPTO. MEPS interfaced HERACLES via DJANGOH;**
- **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 (α_s) and NLO (α_s^2);**
- **NLOJET++. Can calculate (2+1)- and (3+1)-jet DIS cross sections at LO (α_s^2) and NLO (α_s^3);**

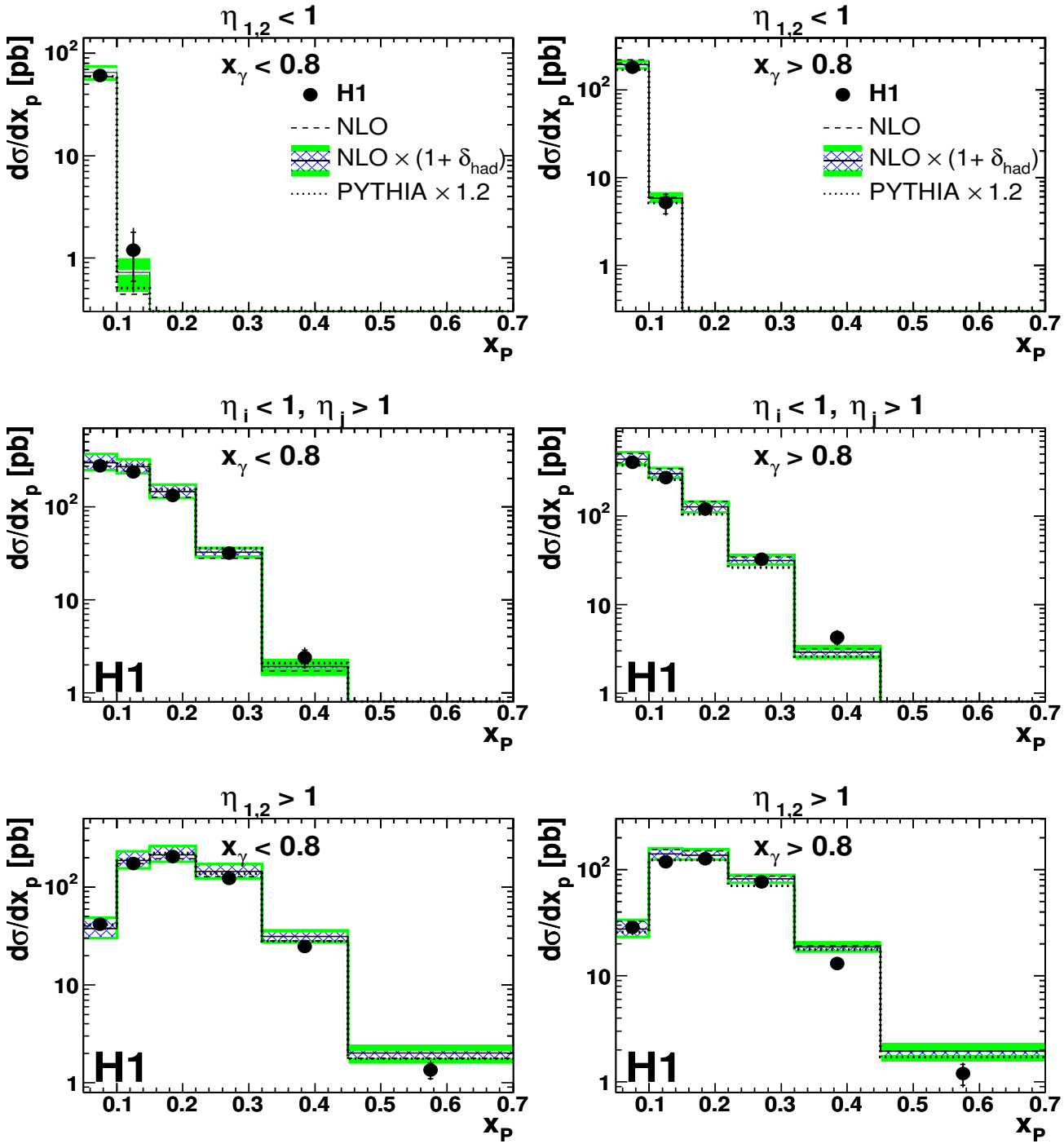
Uncertainties are due to a scale choice for renormalisation μ_r and factorisation μ_f.

Most often:

$\mu_r = \mu_f$ and $\mu_r^2 = Q^2$ or $\mu_r^2 = P_t^2$ or $\mu_r^2 = Q^2 + P_t^2$
Calculation with factor two up and one half down for estimate of unceraitnties.

PHOTOPRODUCTION OF DIJETS

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



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

PHOTOPRODUCTION OF DIJETS WITH HIGH P_t

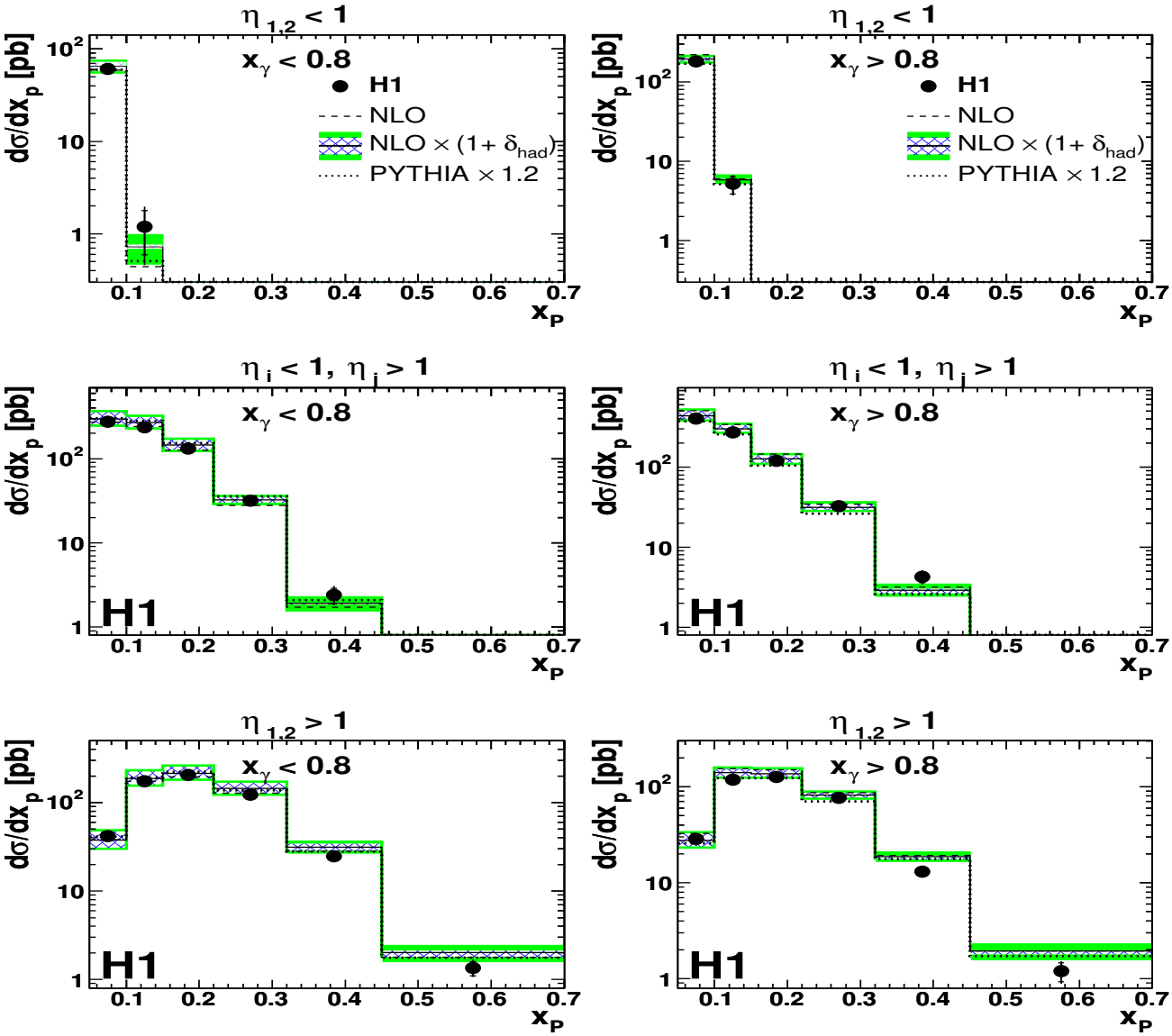
For jet reconstruction inclusive k_t algorithm was used.

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

Reconstracted from hadronic final state:

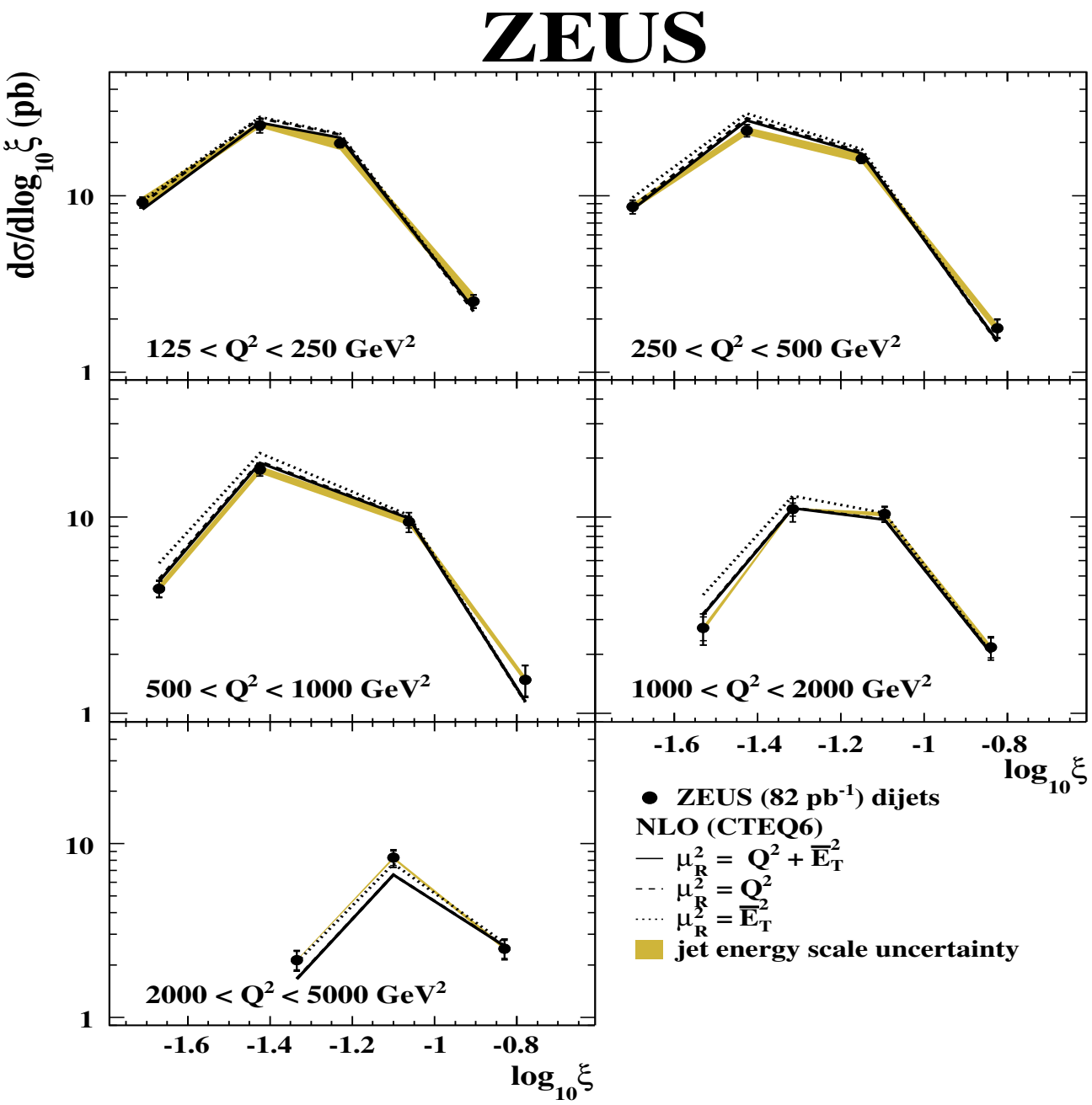
$$x_\gamma = \frac{1}{2yE_e} \cdot \sum_{i=1}^{2} E_{t,i} \cdot e^{-\eta_i}, \qquad x_p = \frac{1}{2E_p} \cdot \sum_{i=1}^{2} E_{t,i} \cdot e^{+\eta_i}$$

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



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

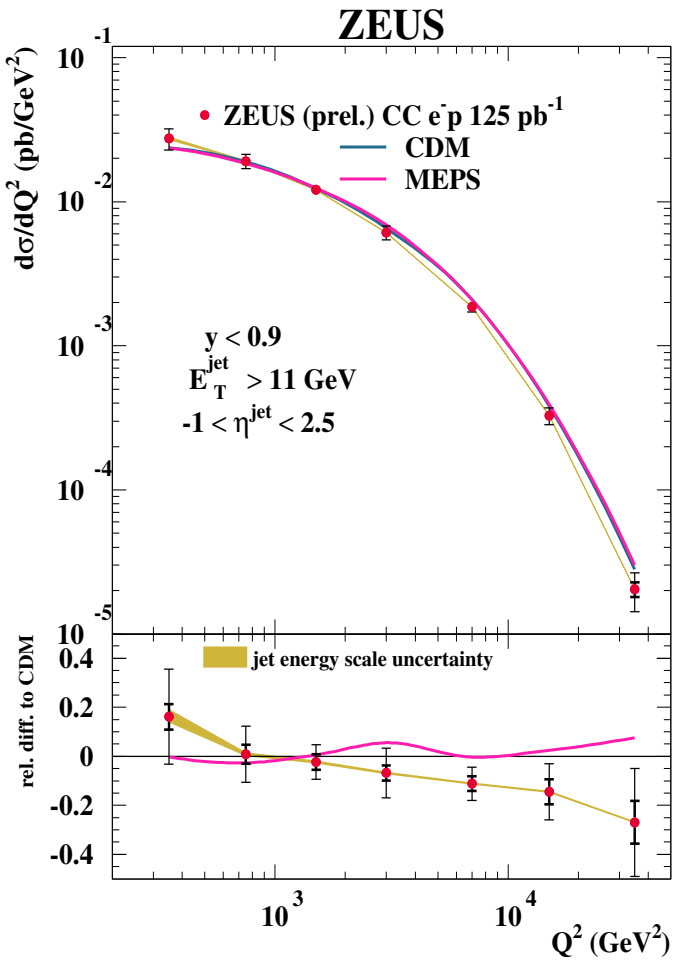
INCLUSIVE JET AND DIJET FROM DIS

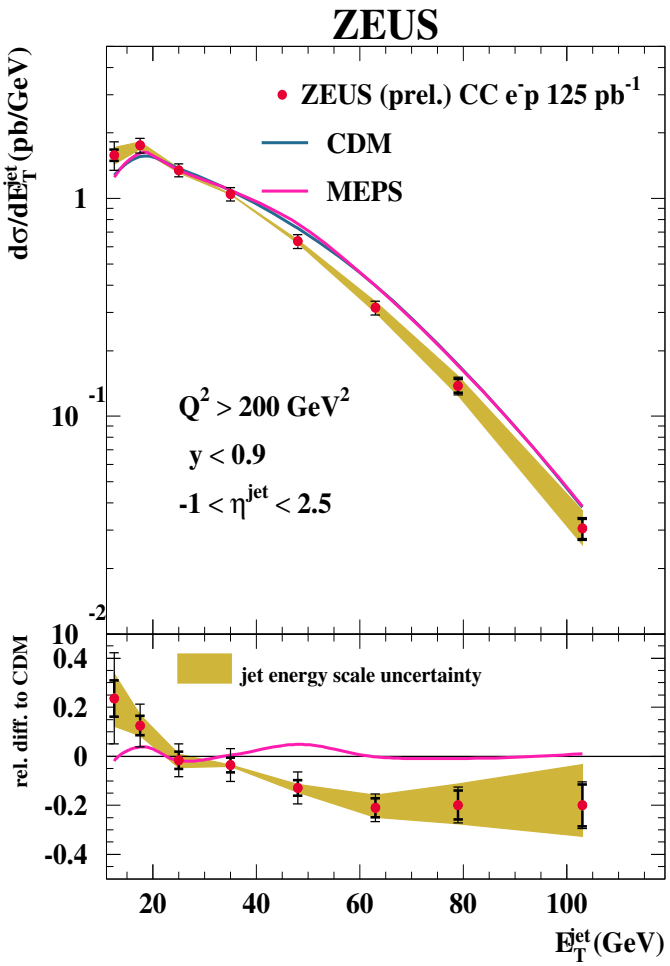


$\xi = x_{Bj}(1 + M_{jj}^2/Q^2)$ - Fraction of proton momentum taken by the interacting parton.

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

JET CROSS SECTION IN CC EVENTS



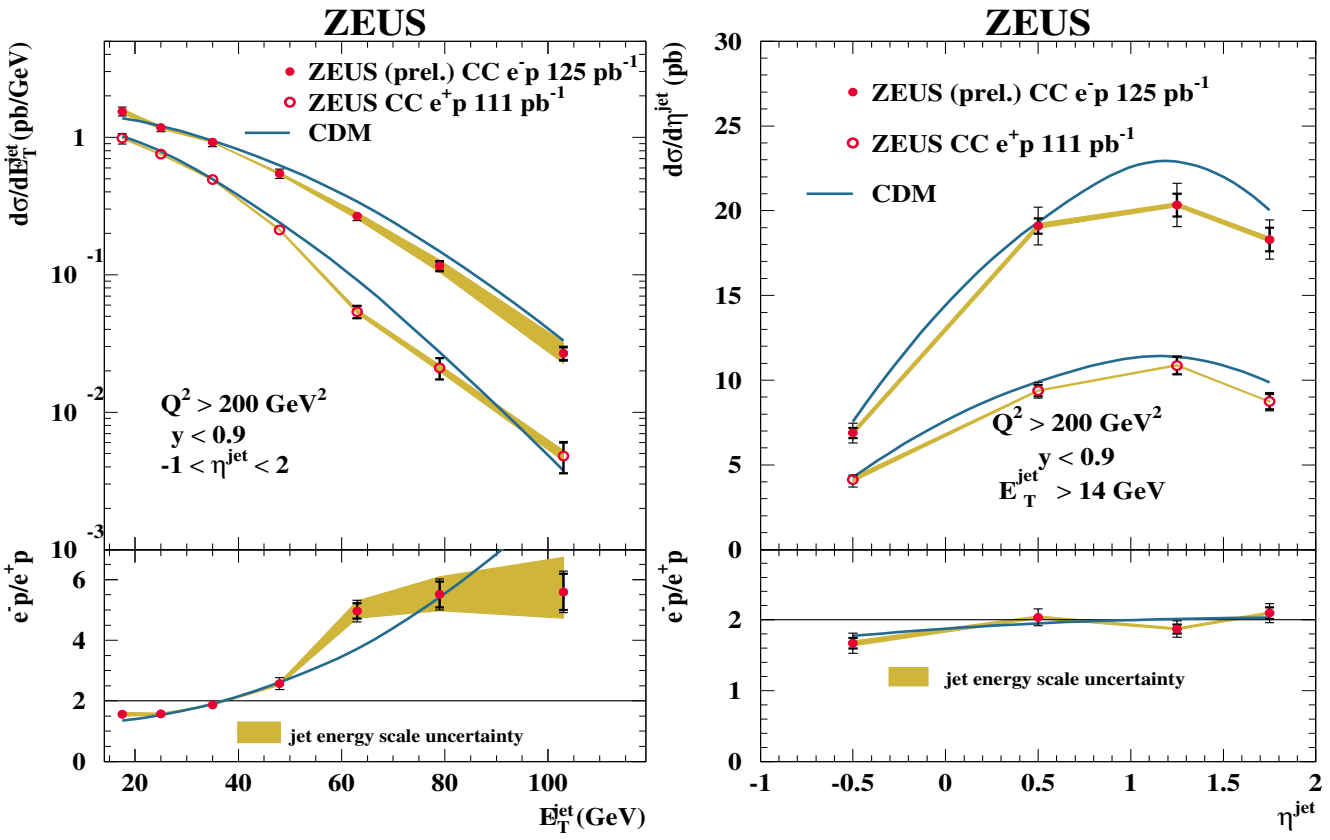


$$N_{data}^{unpol} = \frac{N_{data}^{neg}}{1-P_e^{neg}} + \frac{N_{data}^{pos}}{1-P_e^{pos}}$$

- Cross section shows a less rapidly fall-off to compare with NC DIS.
- Inclusive-jet cross section measured also as function of η^{jet} and x_{Bj}, which are well described by MC.
- The cross sections as function of Q^2 and E_T^{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^{jet} and Q^2 dependencies;
- Ratios between e^-p and e^+p cross sections are in agreement with MC.