Study of Inclusive Jets Production in ep Interactions at HERA

Mónica Luisa Vázquez Acosta

Universidad Autónoma de Madrid

On behalf of the ZEUS & H1 Collaborations

Jet physics at HERA

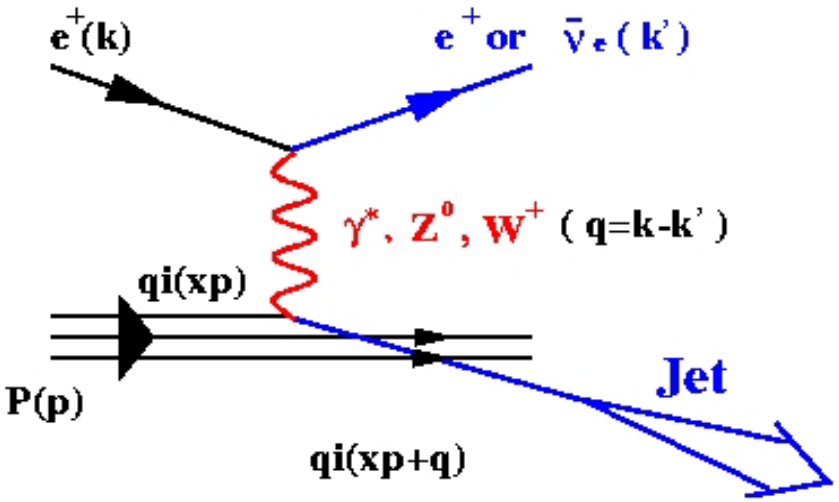
- ✓ The HERA collider provides a unique laboratory for the study of the hadronic final state

- ✓ Jet data are very precise at high transverse energy where the experimental uncertainties and non-perturbative effects are small. This allows
  - ❑ Precision tests of perturbative QCD
  - ❑ Constrains on proton and photon parton distribution functions
  - ❑ Study the size of the theoretical uncertainties for further improvements
  - ❑ Extraction of QCD parameters where the uncertainties are small

- ✓ Study of subprocesses proportional to α_s or higher powers

- ✓ Explore the low Q^2 transition region where non-perturbative effects become important

HERA Kinematics



- Negative squared 4-momentum transfer

$$Q^2 \equiv -q^2 = (k - k')^2$$

- Bjorken scaling variable

$$x \equiv \frac{Q^2}{2p \cdot q}$$

- Deep Inelastic Scattering: $\boxed{Q^2 >> 1\,\mathrm{GeV}^2}$

Neutral Current: $e^+p \to e^+\,X\,(\gamma, Z^0)$

Charged Current: $e^+p \to \bar{\nu}_e\,X\,(W^\pm)$

- Photoproduction: $\boxed{Q^2 \sim 0\,\mathrm{GeV}^2}$

- Inelasticity

$$y \equiv \frac{p \cdot q}{p \cdot k}$$

- Total hadronic centre-of-mass energy

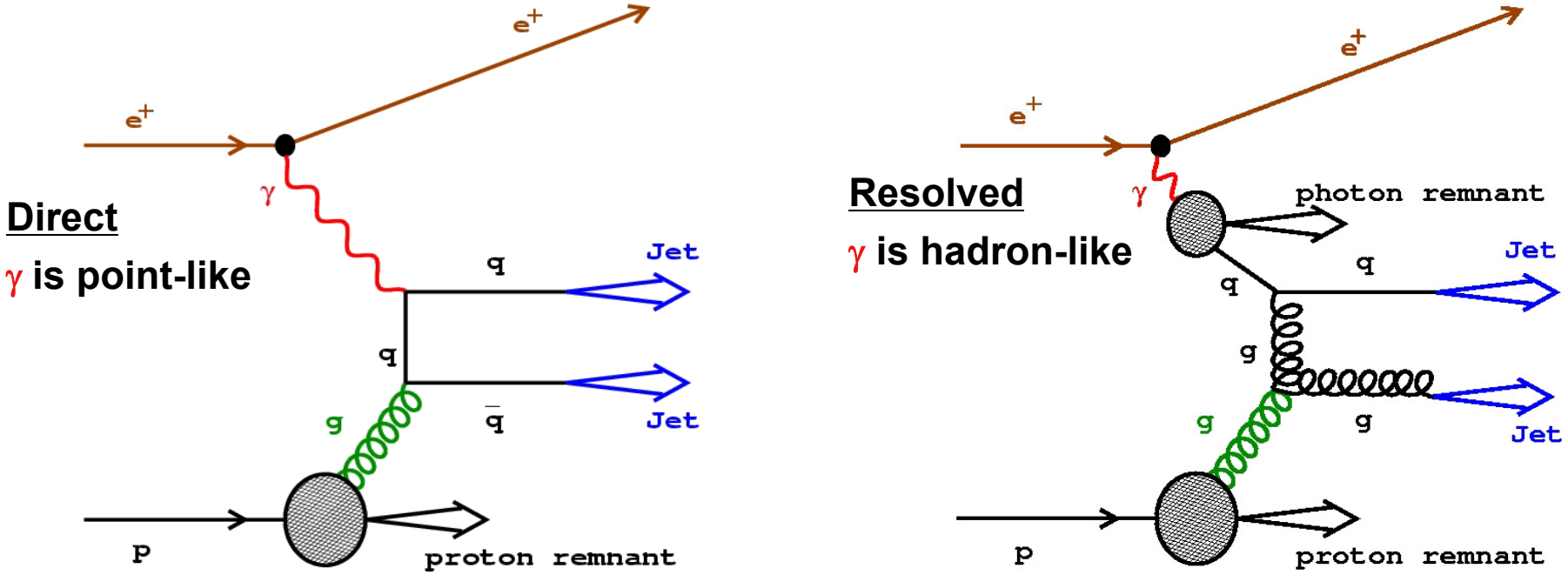
$$W^2 \equiv (q + p)^2 = ys - Q^2$$

Inclusive Jet Photoproduction at HERA

- In photoproduction the photon has low virtuality, at HERA $Q^2 \sim 10^{-3}$ GeV^2

  ⇒ the high transverse energy jets provide a hard scale

- High E_T jet production is described up to $O(\alpha\,\alpha_s)$ in the SM by



Inclusive jet production does not restrict the phase space of the second jet

⇒ reduced theoretical uncertainties in the NLO QCD predictions

⇒ the information of the event kinematics is reduced

Inclusive Jet Cross Sections in Photoproduction
ZEUS Collaboration - hep-ex/0212064

- Cross sections for jets with

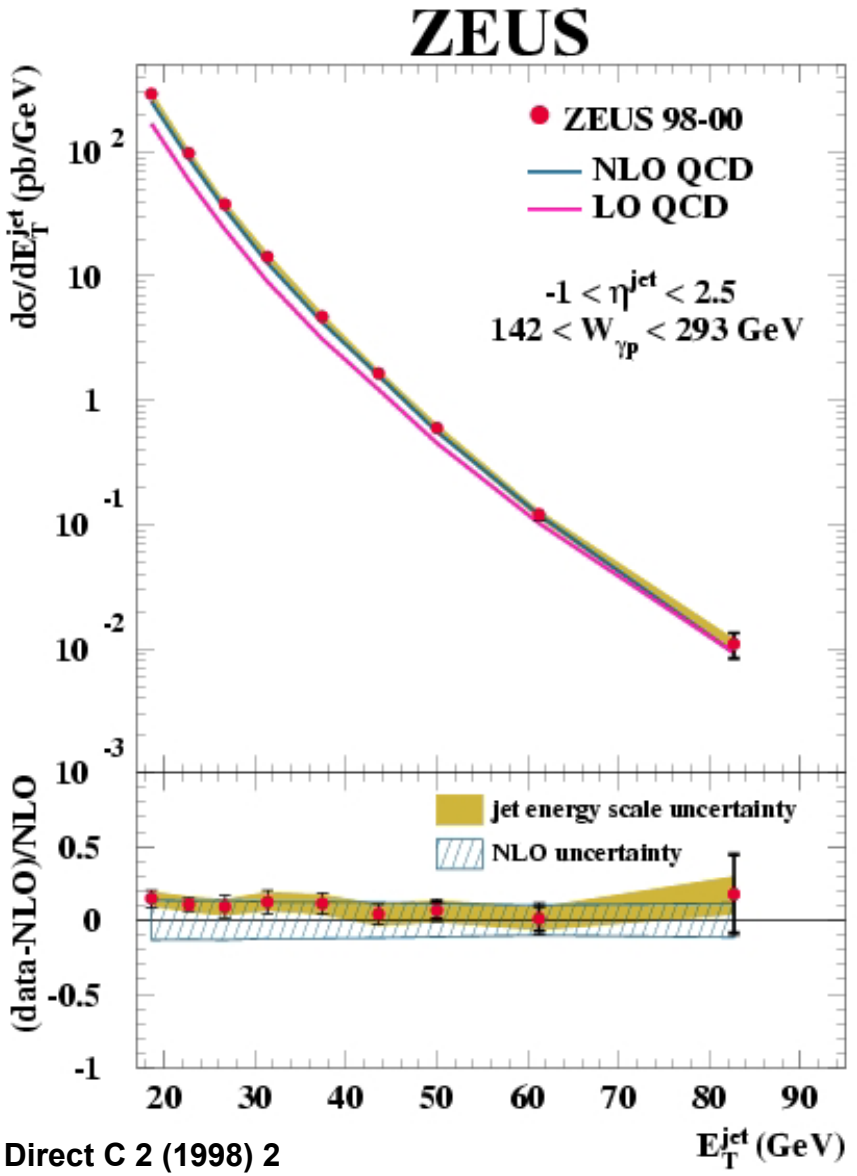
$$17 < E_T^{jet} < 95\,GeV, \; -1 < \eta^{jet} < 2.5$$

$$142 < W_{\gamma p} < 293\,GeV, \; Q^2 \leq 1\,GeV^2$$

Good agreement of **NLO QCD** calculation with the **measured cross section** over 5 orders of magnitude

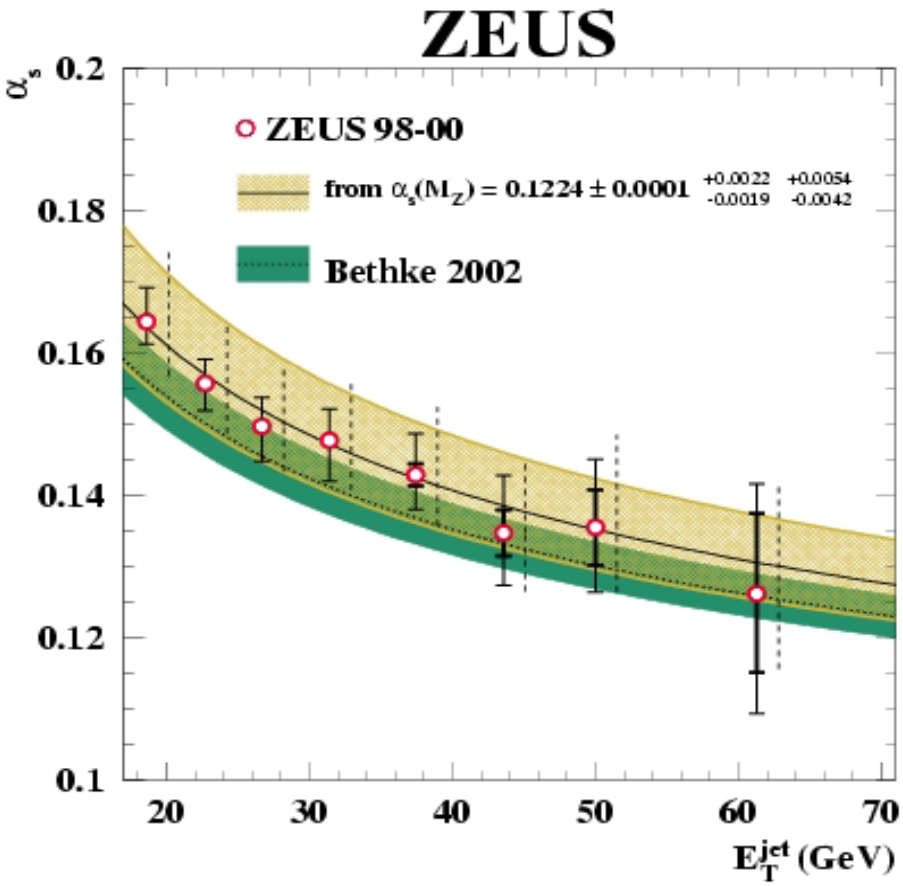
Small theoretical uncertainties

- uncertainty due to missing higher orders in the perturbative series ~10%
- photon and proton PDFs ~ 5%

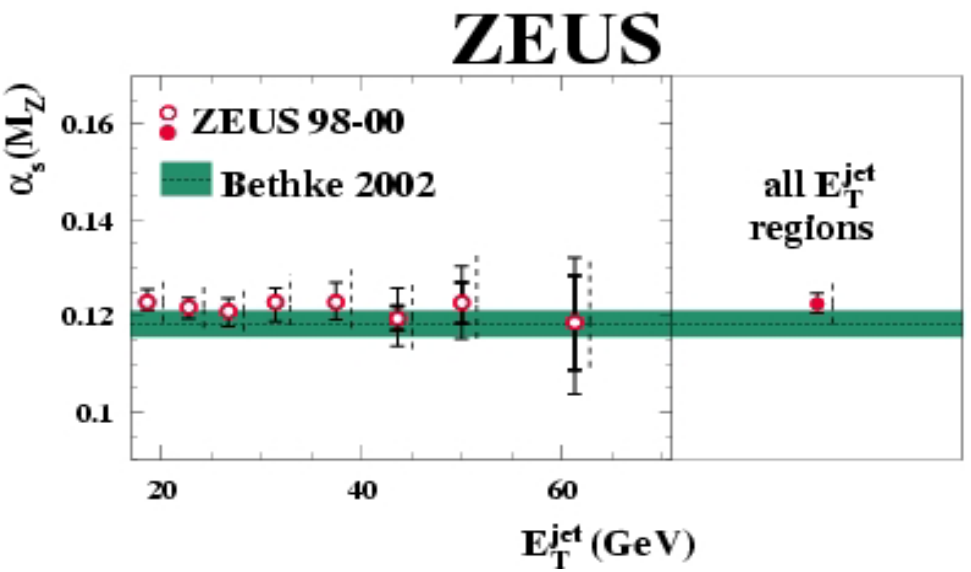


Theoretical calculation from Klasen, Kleinwort and Kramer - Eur. Phys. J. Direct C 2 (1998) 2

Measurement of α_s in Photoproduction
ZEUS Collaboration - hep-ex/0212064



Running of α_s in a single measurement



- $\alpha_s(M_Z)$ values determined from a QCD fit to $d\sigma/dE_T^{jet}$ in different E_T^{jet} regions
- Small experimental uncertainties
- Theoretical error dominates
- Consistent with recent determination of Bethke

A χ^2–fit to all the E_t^{jet} regions gives a value of $\alpha_s(M_Z)$ of:

$$\alpha_s(M_Z) = 0.1224 \pm 0.0001\,(\text{stat.})^{+0.0022}_{-0.0019}\,(\text{exp.})^{+0.0054}_{-0.0042}\,(\text{th.})$$

Bethke: hep-ex/0211012

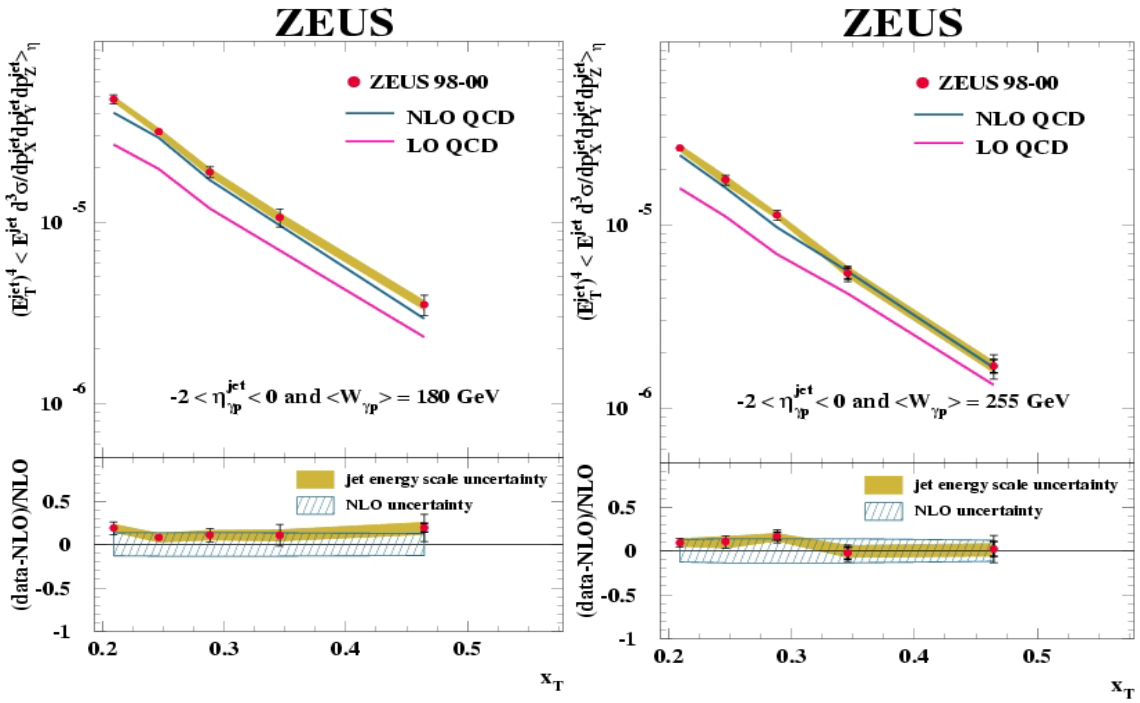
Scaling Violations in Photoproduction
ZEUS Collaboration - hep-ex/0212064

Scaling hypothesis: the scaled jet invariant cross section

$$\left(E_T^{jet}\right)^4 \cdot \left\langle E^{jet} \cdot \frac{d^3\sigma}{dp_x^{jet}\, dp_y^{jet}\, dp_z^{jet}} \right\rangle_\eta$$

averaged over $-2 < \eta_{\gamma p}^{jet} < 0$ as a function of $x_T \equiv \frac{2E_T^{jet}}{W}$

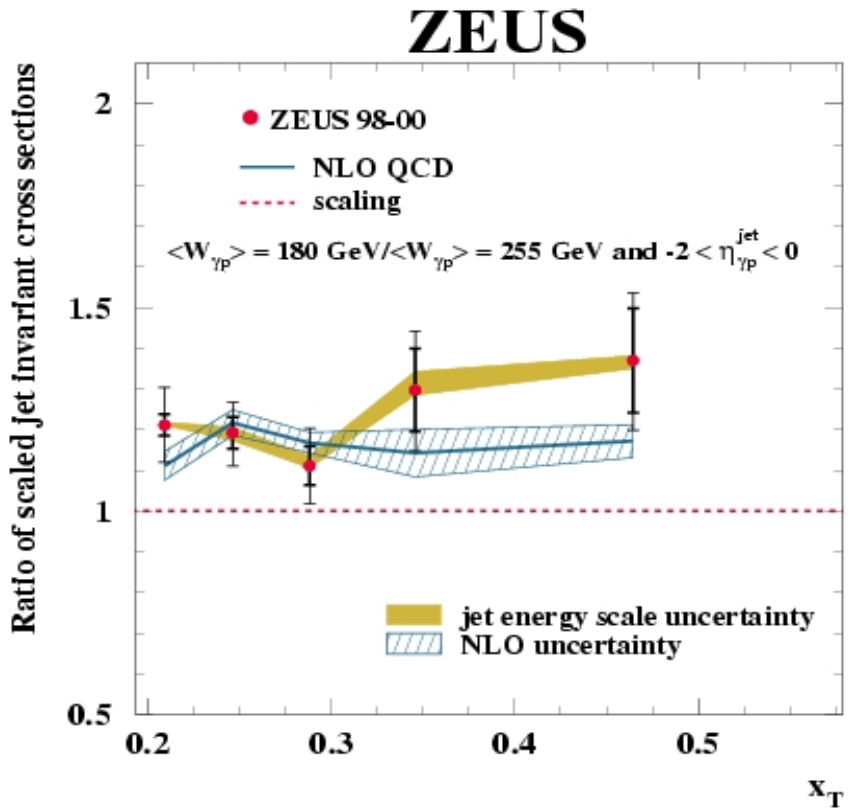
should be independent of $W_{\gamma p}$



$169 < W_{\gamma p} < 191$ GeV $\qquad$ $240 < W_{\gamma p} < 270$ GeV

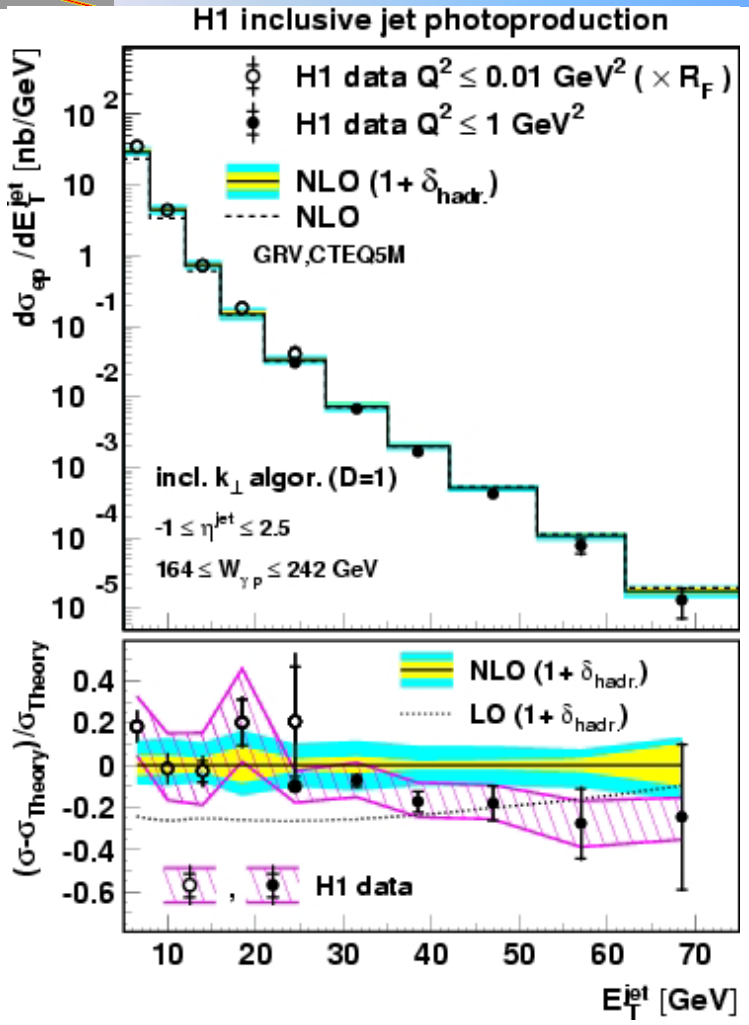
Effectively equivalent to running with two different beam energies

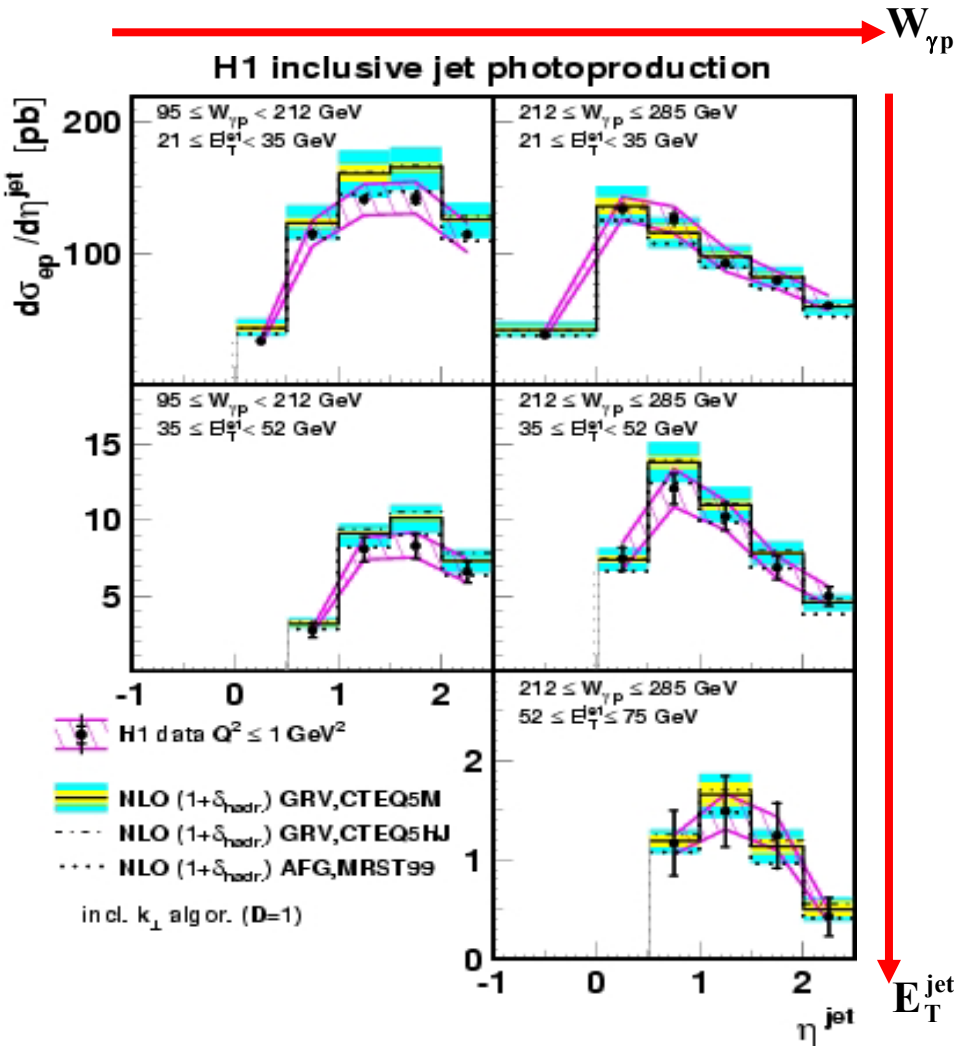
NLO QCD calculations are consistent with the data



- Theoretical uncertainties reduced
- Scaling violation due to: parton evolution and running of α_s
- First observation of scaling violations in jet photoproduction

Inclusive Jet Cross Sections in PHP
H1 Collaboration - hep-ex/0302034





- **Agreement with NLO QCD very good**
- **All predictions obtained using different proton (MRST99,CTEQ5) and photon (GRV,AFG) PDFs agree with the data**

Theoretical calculation from Frixione, Ridolfi - Nucl. Phys. B 507 (1997) 315

Comparison of γp with pp
H1 Collaboration - hep-ex/0302034

Scaled cross section: independent of energy up to scaling violations

$$S(x_T) \equiv \frac{E_T^3}{2\pi} \frac{d^2\sigma}{dE_T\, d\eta}\,;\; x_T \equiv \frac{2E_T}{W_{\gamma p}}$$

$x_T < 0.2$

⇨ shape similar for γp and $p\bar{p}$

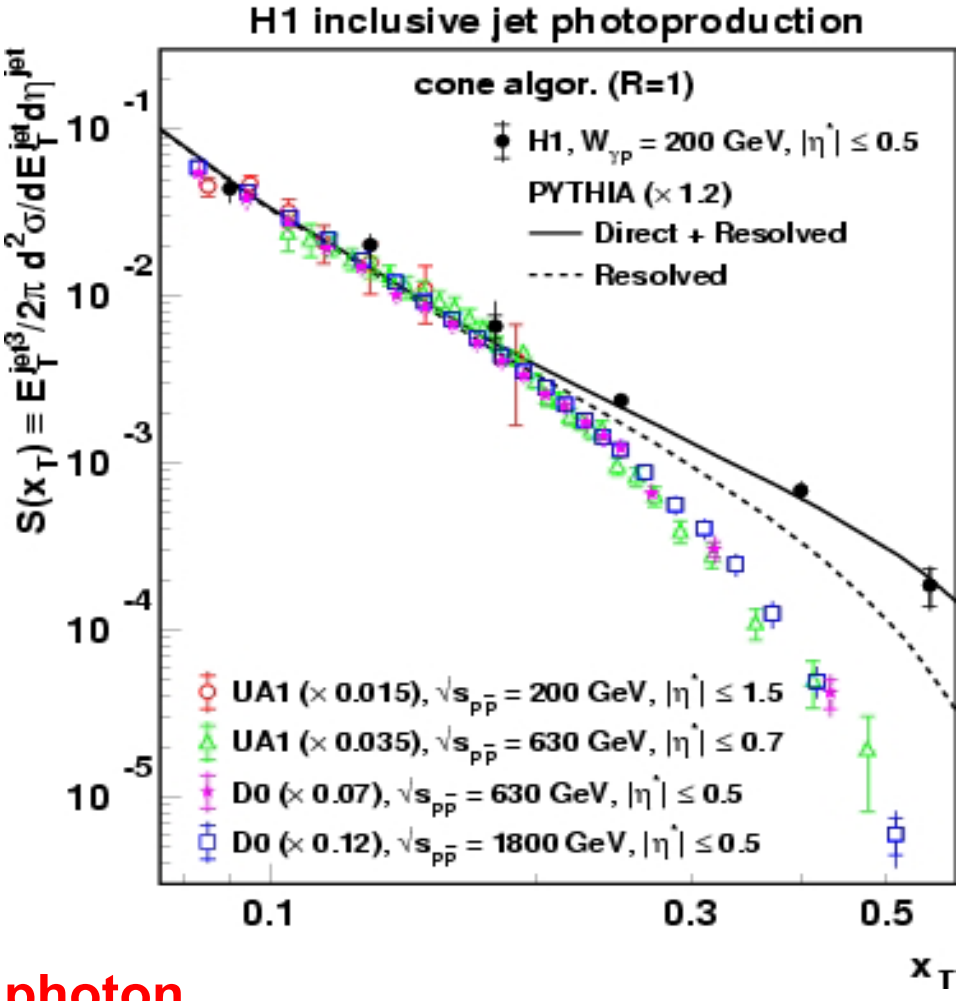
⇨ resolved photon ~ hadron

$x_T > 0.2$

⇨ γp harder than $p\bar{p}$ spectrum

- enhanced quark density in the resolved photon w.r.t. a hadron
- dominance of direct

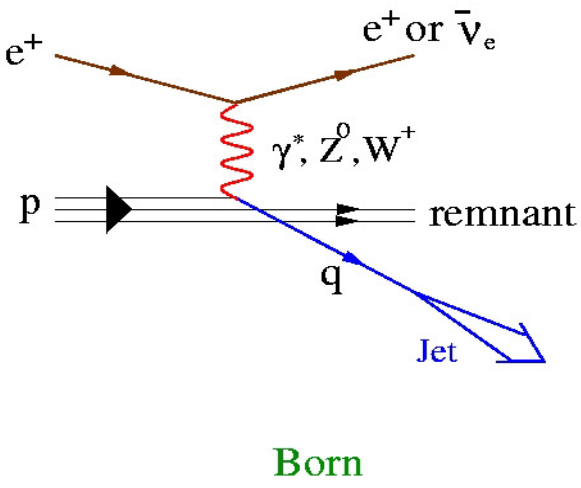
⇨ point-like photon



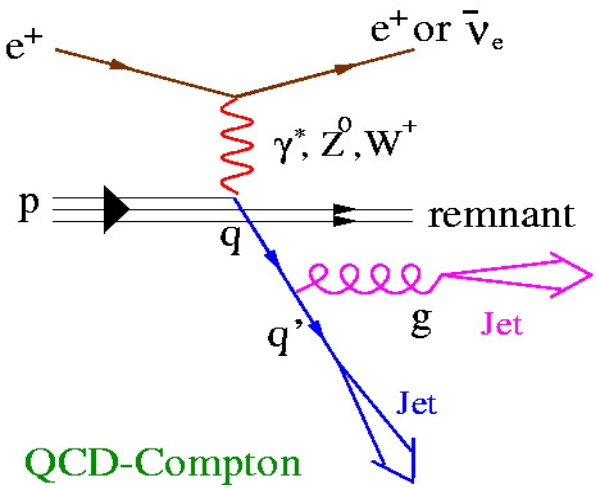
⇨ **Confirmation of the dual nature of the photon**

Jets in Deep Inelastic Scattering

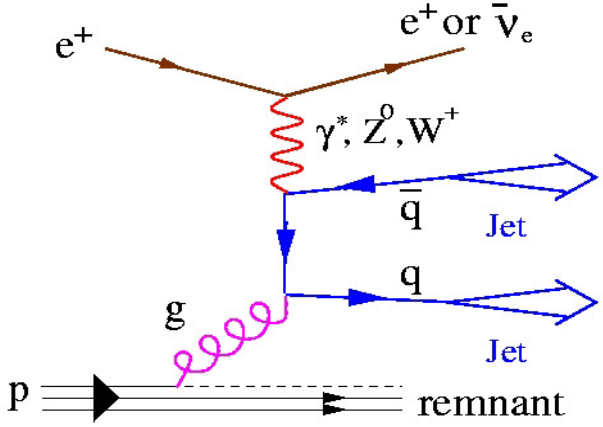
Jet production in DIS $e^+ p \rightarrow e^+ (\bar{\nu}_e) + \text{jet(s)} + X$ **is described in the SM** $O(\alpha_s)$ **by**



Born

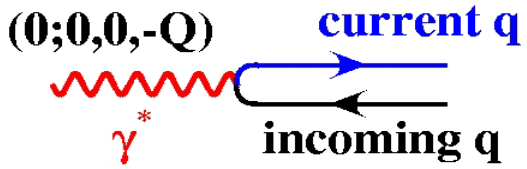


QCD-Compton

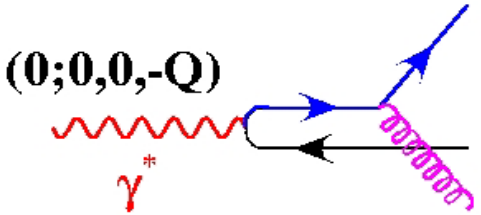


Boson-gluon fusion

Breit Frame



Born



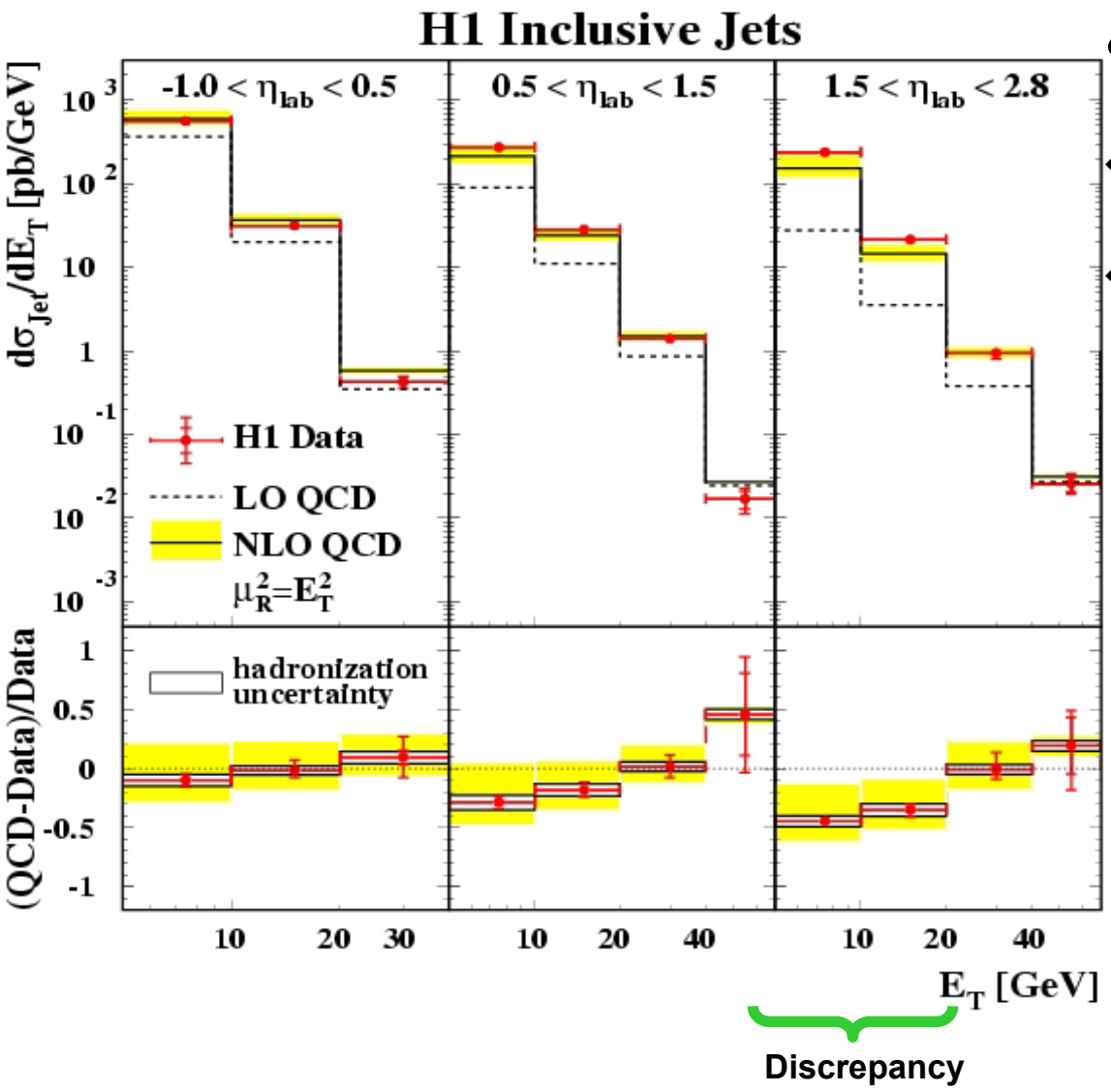
QCD-Compton

Jets with high E_T in the Breit frame:

- **Supress Born contribution** (the current quark has no E_T)
- **Lowest order contributions QCD-Compton and boson-gluon fusion**
- **Directly sensitive to QCD subprocesses at** $O(\alpha_s)$

Inclusive jets in NC DIS at low Q^2
H1 Collaboration - hep-ex/0206029

Backward Central Forward



- Low Q^2 region ($5 < Q^2 < 100\ GeV^2$)

❖ At large virtualities $Q^2 \geq 125\ GeV^2$ data agrees well with NLO QCD predictions

❖ At low virtualities discrepancies are seen and are studied in more detail

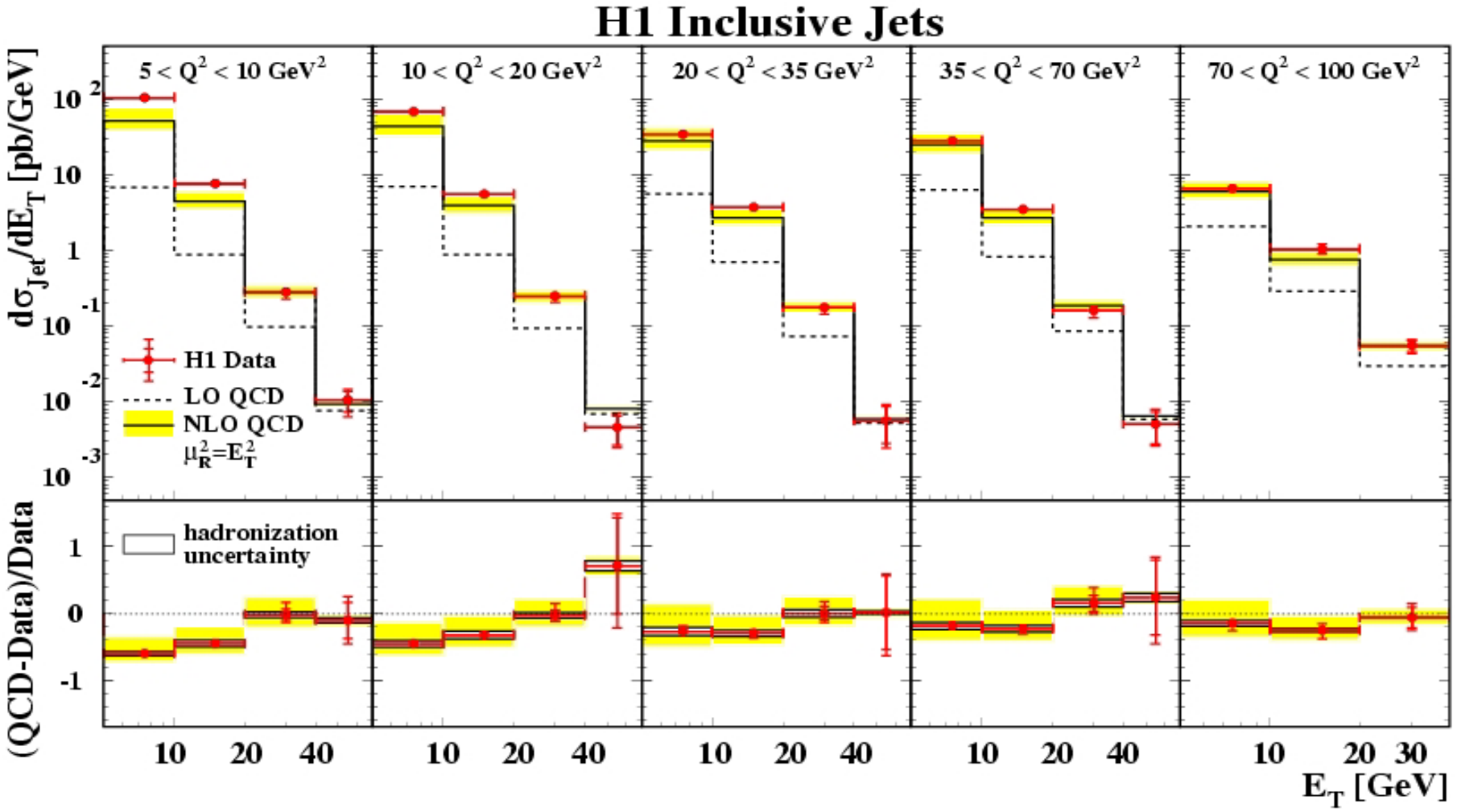
➢ Good agreement of NLO QCD with data in backward and central regions

➢ Large NLO corrections for low E_T and in the forward region: NLO/LO~5

NLO predictions below data for E_T < 20 GeV in the forward region

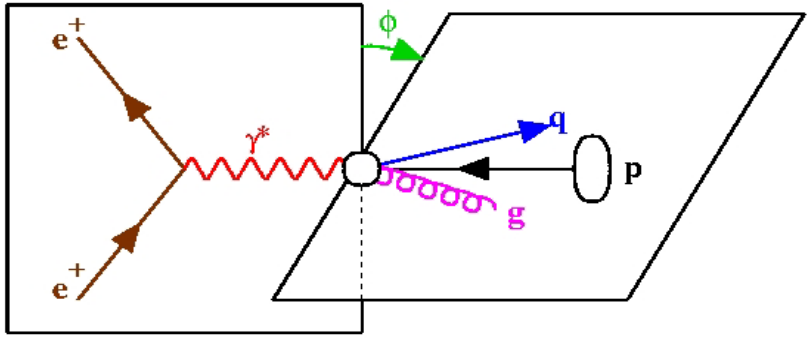
Inclusive jets in NC DIS: forward region
H1 Collaboration - hep-ex/0206029

Forward region: $1.5 < \eta^{lab} < 2.8$



NLO predictions up to 50% lower than data where NLO corrections are largest

Azimuthal asymmetry of jets in NC DIS
ZEUS Collaboration - hep-ex/0210064



No jet cuts in the laboratory frame

- $E^B_{T,jet} > 8\,GeV, -2 < \eta^B_{jet} < 1.8$
- $Q^2 > 125\,GeV^2, -0.7 < \cos\gamma < 0.5$

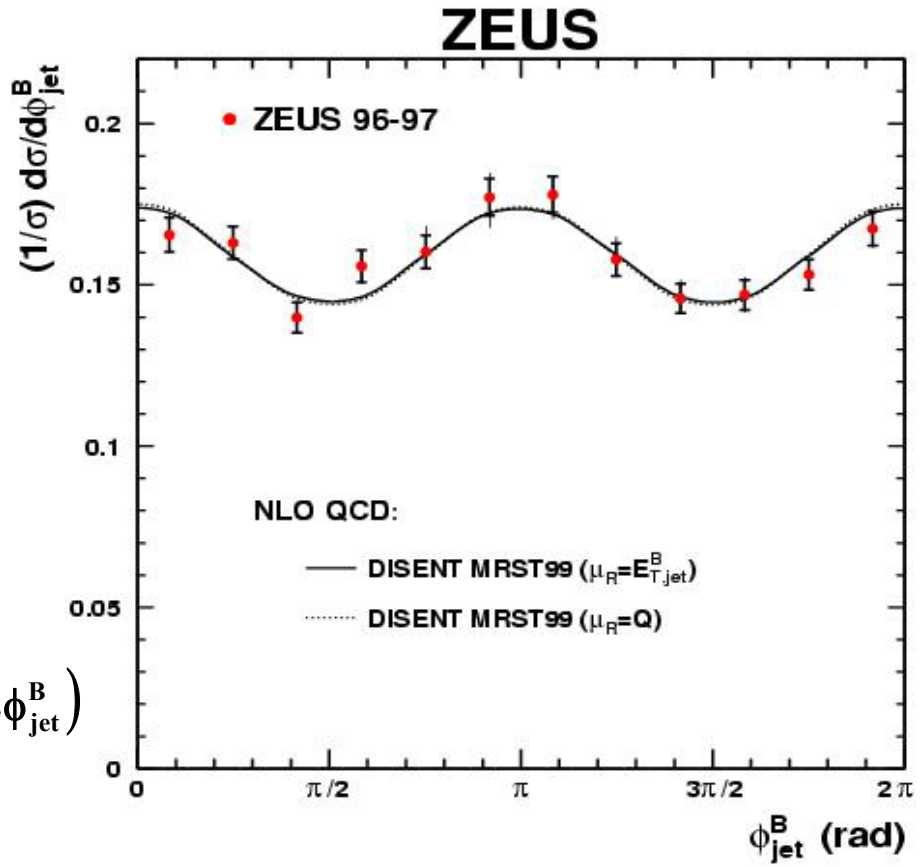
- Distribution of the azimuthal angle in the Breit frame between the lepton scattering plane and the plane defined by the jet and the incoming proton direction

- LO pQCD predicts for NC DIS at $Q^2 << M_Z^2$

$$\frac{d\sigma}{d\phi^B_{jet}} = A + B\cdot\cos\left(\phi^B_{jet}\right) + C\cdot\cos\left(2\phi^B_{jet}\right)$$

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

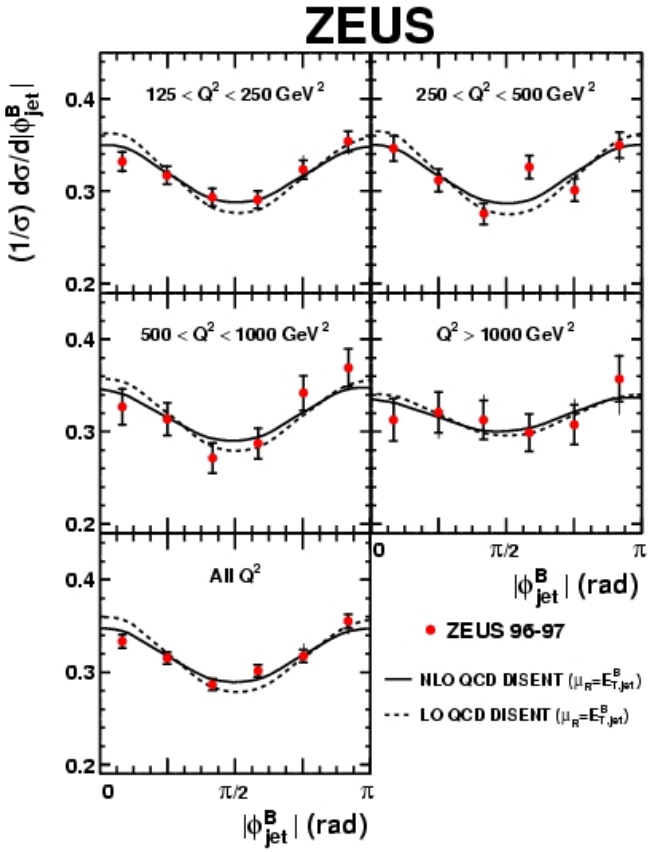
- For an inclusive jet measurement: $\frac{d\sigma}{d\phi^B_{jet}} = A + C\cdot\cos\left(2\phi^B_{jet}\right)$



Normalised cross section

- Small experimental and theoretical uncertainties
- NLO QCD calculations describe the measurements very well

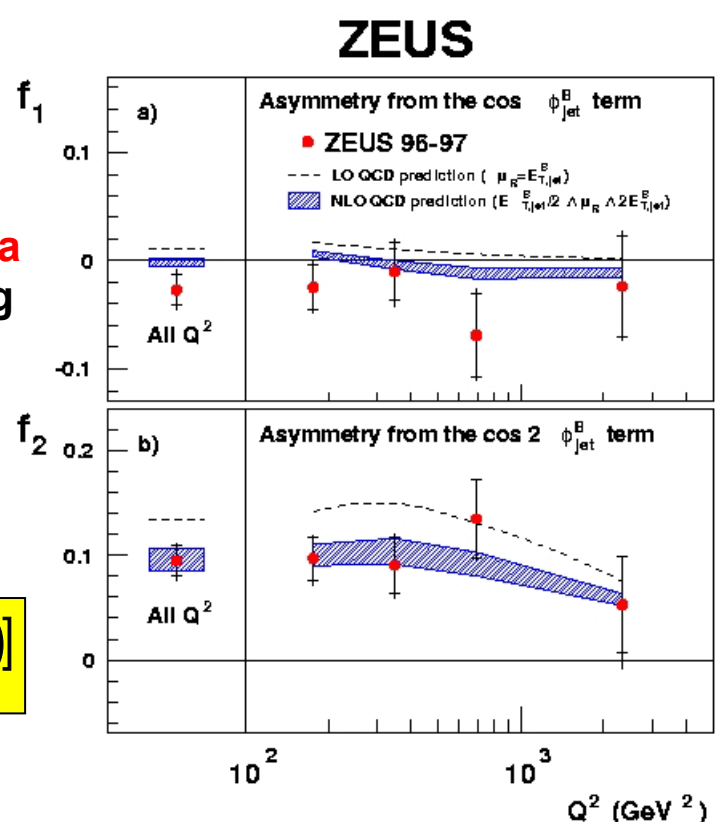
Azimuthal asymmetry of jets in NC DIS
ZEUS Collaboration - hep-ex/0210064



To **quantify the asymmetry** and the dependence with Q^2

⇒ a **fit** was performed to the **data** and the **QCD calculation** using the functional form

$$\frac{1}{\sigma}\frac{d\sigma}{d|\phi^B_{jet}|} = \frac{1}{\pi}\left[1 + f_1 \cdot \cos\left(\phi^B_{jet}\right) + f_2 \cdot \cos\left(2\phi^B_{jet}\right)\right]$$



- f_1 is consistent with 0
- f_2 decreases with Q^2

Normalised inclusive jet cross section folded about π

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

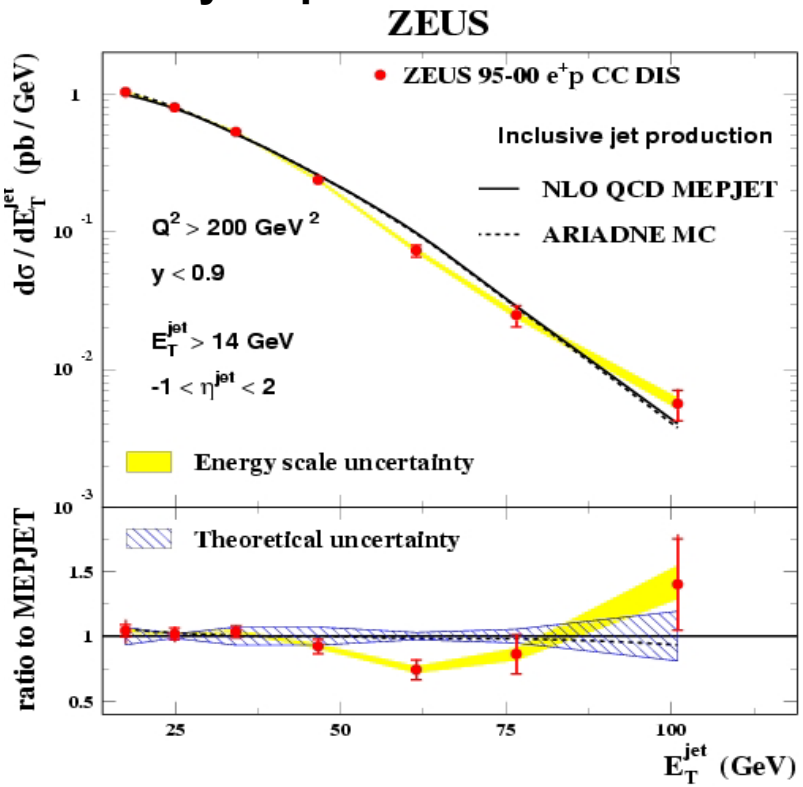
- **NLO QCD describes the data well**
- **LO QCD predicts a larger asymmetry at low Q^2**

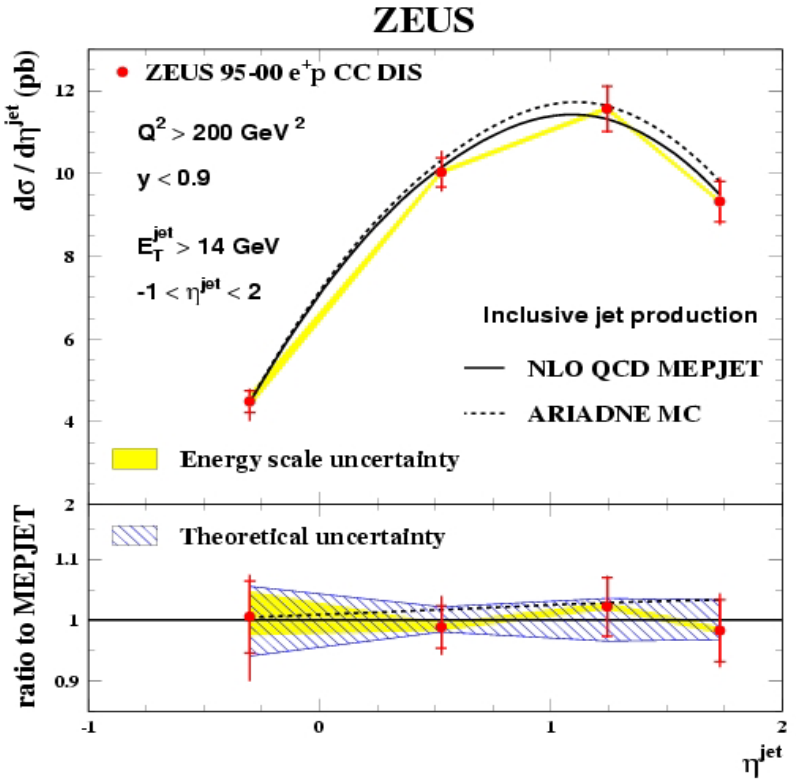
Precise test of pQCD prediction for the azimuthal asymmetry

Inclusive jets in Charged Current DIS
ZEUS Collaboration - hep-ex/0306018

$$e^+ p \rightarrow \bar{\nu}_e + \text{jet} + X$$

- Test flavour changing electroweak theory and QCD in one type of events
- Analysis peformed in the laboratory frame





1. NLO QCD calculations (MEPJET)
2. Matrix elements+parton showers (ARIADNE MC)

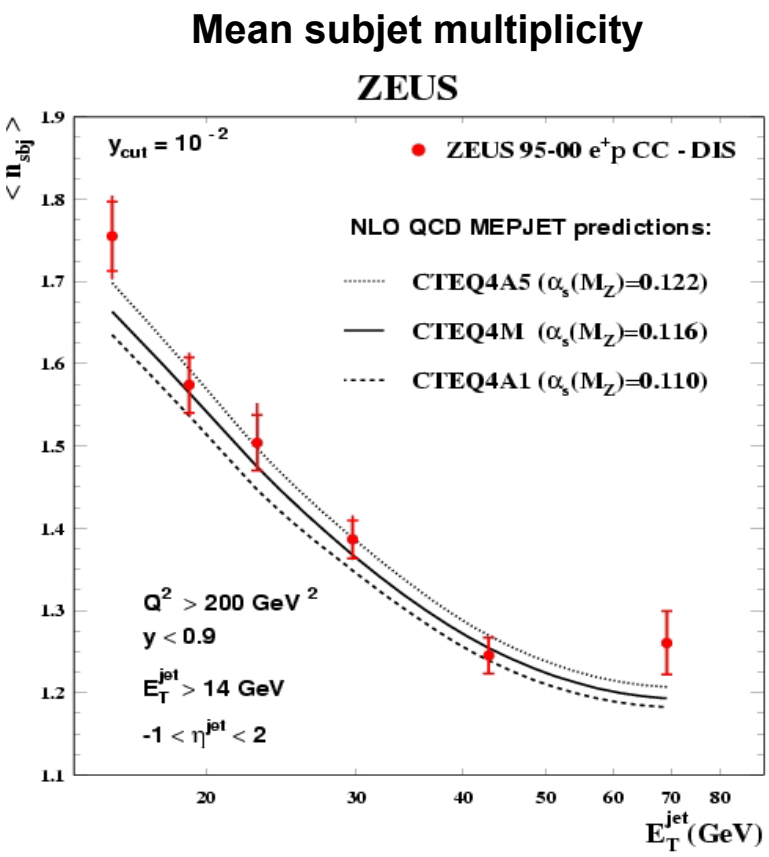
have been compared to the data

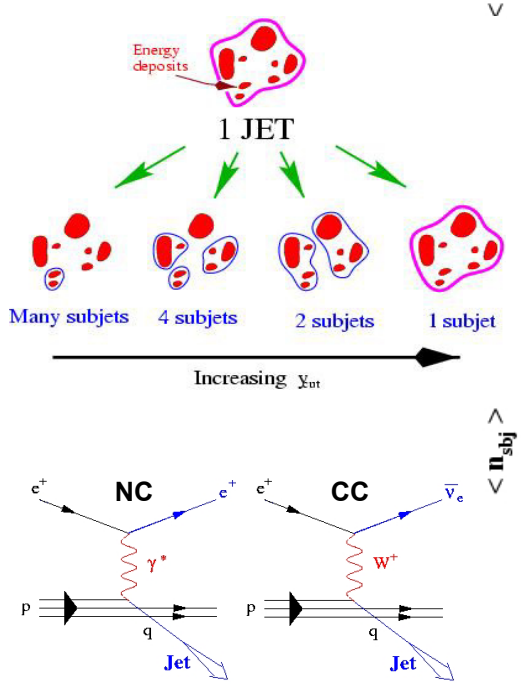
Mirkes and Zeppenfeld, Phys. Lett. B380 (1996) 205
Lönnblad, Z. Phys. C 65 (1995) 285

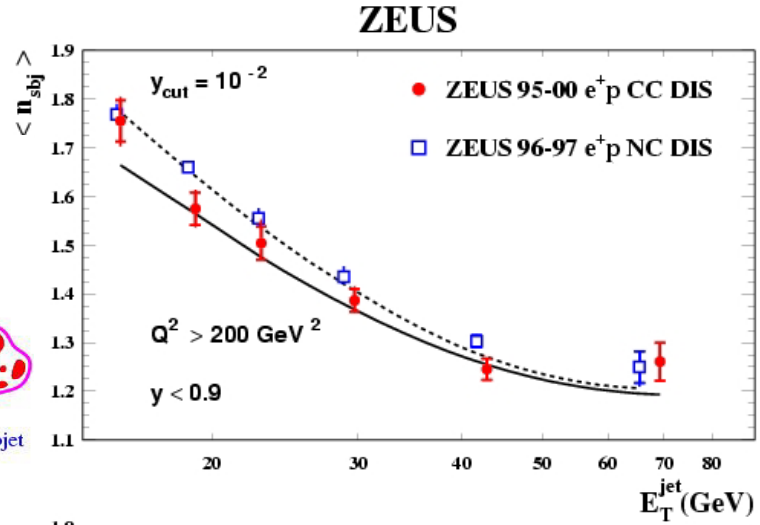
Both the NLO QCD and MC calculations describe well the data

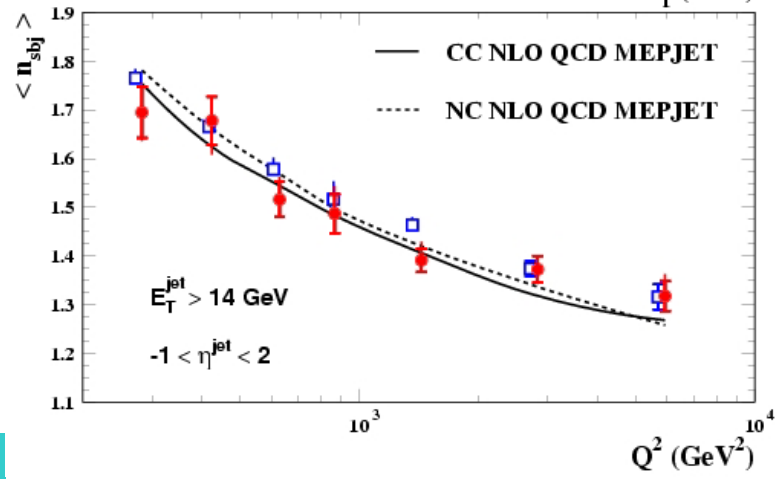
Jet Substructure of inclusive jets in CC DIS
ZEUS Collaboration - hep-ex/0306018

Mean subjet multiplicity









The measurement is sensitive to the value of $\alpha_S(M_Z)$

A χ^2–fit to the region $E_t^{jet} > 25$ GeV where the parton-to-hadron corrections are <10% gives a value of $\alpha_S(M_Z)$ of:

$$\alpha_S(M_Z) = 0.1202 \pm 0.0052\ (\text{stat.})\ ^{+0.0060}_{-0.0019}\ (\text{syst.})\ ^{+0.0065}_{-0.0053}\ (\text{th.})$$

QCD does not distinguish if W (CC) or γ (NC) is exchanged

Summary and Outlook

- ✓ HERA is now producing a wealth of precision jet data at high E_T in NC and CC deep inelastic scattering, photoproduction and the transition region.

- ✓ Many extractions of the QCD coupling constant α_s with a precision competitive with the world average. The running behaviour of α_s is clearly seen.

- ✓ At high E_T^{jet} in inclusive jet cross sections, theoretical uncertainties are small and the theoretical predictions are able to reproduce cross sections over many orders of magnitude.

- ✓ At lower Q^2 theoretical uncertainties are dominant
  ⇒ theoretical developments are needed.

- ✓ Experimental precision and coverage of data is now very good
  ⇒ time to include the HERA jet data in global PDF fits.