Scaling violations in inclusive jet photoproduction at HERA and the measurement of α_s

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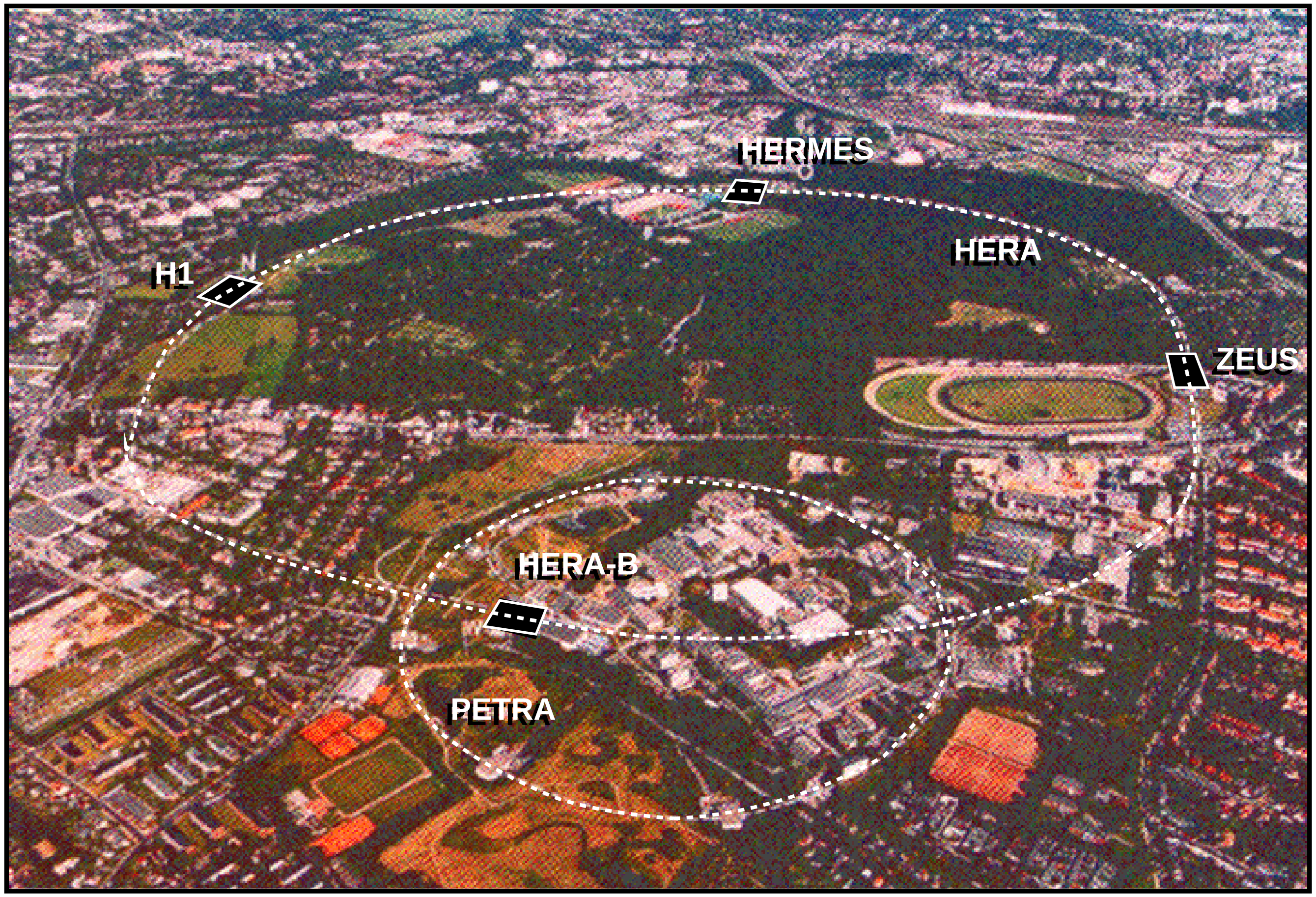
On behalf of the ZEUS Collaboration

Introduction

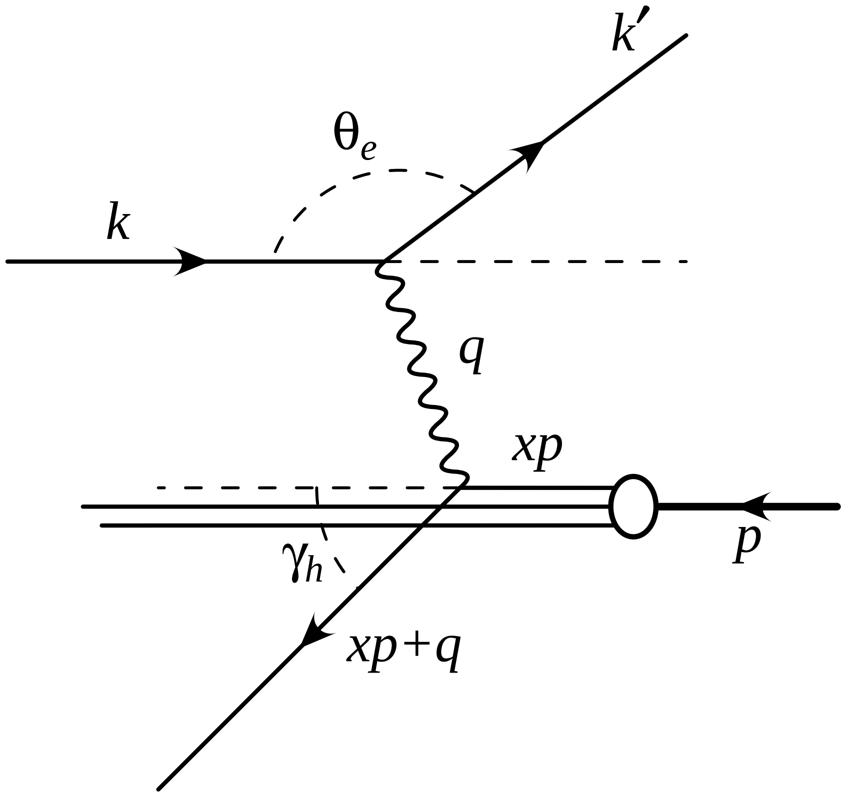
- The HERA collider provides a unique laboratory for the study of the hadronic final state, completing the coverage from e^+e^- to $p\bar{p}$.
- Jet data are now very precise at high transverse energy where non-perturbative effects are small
  ➡ precision tests of our understanding of QCD and the extraction of QCD parameters.
- The parton model predicts cross sections that scale with the centre-of-mass energy.
- QCD predicts scaling violations due to the evolution of hadron parton density functions and the running coupling constant
  ➡ not yet directly observed in photoproduction.

The HERA collider



- HERA is the only lepton-hadron colliding beam machine.
- 1998-2000, 27.5 GeV leptons on 920 GeV protons, $\sqrt{s} = 318\mathrm{GeV}$.

HERA kinematics



- Kinematic variables...
  - ▷ (Negative) squared 4-momentum transfer

$$Q^2 = -(k - k')^2.$$

  - ▷ Bjorken scaling variable

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

  - ▷ Inelasticity

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

- Total hadronic centre-of-mass energy,

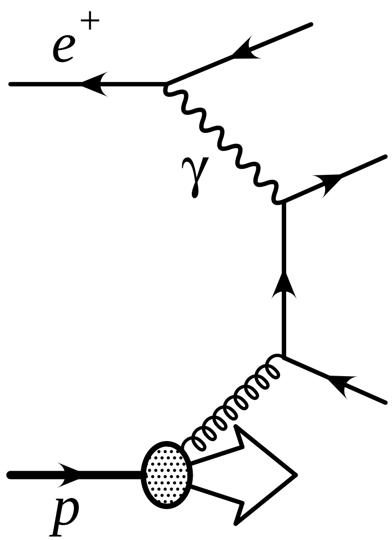
$$W^2 = (q + p)^2 = ys - Q^2$$

- For photoproduction, $Q^2 \sim 0\ \mathrm{GeV}^2$, $W^2 \approx ys$

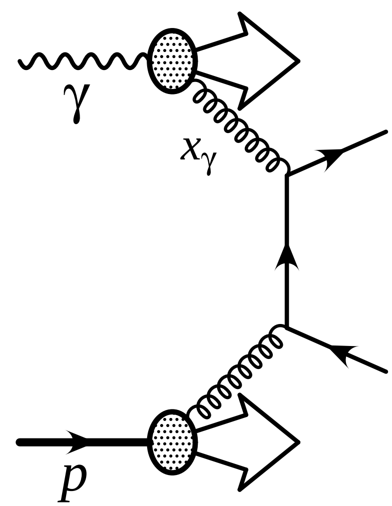
Photoproduction at HERA

- In photoproduction the photon has a very low virtuality, at HERA $\sim 10^{-3}$ GeV^2
  ⇒ perturbatively calculable when there is a hard scale provided by high transverse energy jets.
- To $\mathcal{O}(\alpha\alpha_s)$, two types of process contribute to the high E_T jet production.

Direct



Resolved



- At Leading order picture, two jets, balanced in E_T, back-to-back in ϕ.
- Different hadronic centre-of-mass energies, $W_{\gamma p}$ are accessible within the same data set.

Why single inclusive jet production?

- For perturbativly calculable cross sections, need an infrared and collinear safe jet algorithm ➡ K_T algorithm in the inclusive mode.
- Fixed order calculations available at NLO – $\mathcal{O}(\alpha\alpha_s^2)$.
  ➡ predict dijet cross sections, but large renormalisation scale uncertainty due to restriction of phase space for the second highest transverse energy jet.
- Inclusive jet production does not restrict the phase space of the second jet, or even require it to be within the detector acceptance,
  ➡ Smaller renormalisation scale uncertainty, more reliable QCD predictions but at the cost of less information on the event kinematics.

Next-to-leading order prediction

- NLO calculation here from Klasen, Kleinwort and Kramer, using the phase space slicing method to cancel the infrared and collinear divergences.
  - ▷ Two loop $\alpha_s(M_Z) = 0.1175$.
  - ▷ Renormalisation and factorisation scales $\mu_F = \mu_R = E_T^{\rm jet}$.
  - ▷ MRST99 proton, and GRV photon.
- Parton level NLO corrected to hadron level using PYTHIA.
- Theoretical uncertainties shown
  - ▷ Corrections due to terms beyong NLO, estimated from scale variation $\frac{1}{2}E_T^{\rm jet} < \mu_R < 2E_T^{\rm jet}$
  - ▷ Photon and proton PDF's – AFG-HO (photon) and MBFIT (proton).
  - ▷ $0.1125 < \alpha_s(M_Z) < 0.1225$.
  - ▷ Hadronisation (HERWIG) $<$2.5%.
- Indicated as shaded band.

The inclusive cross section

- Cross section for all jets,

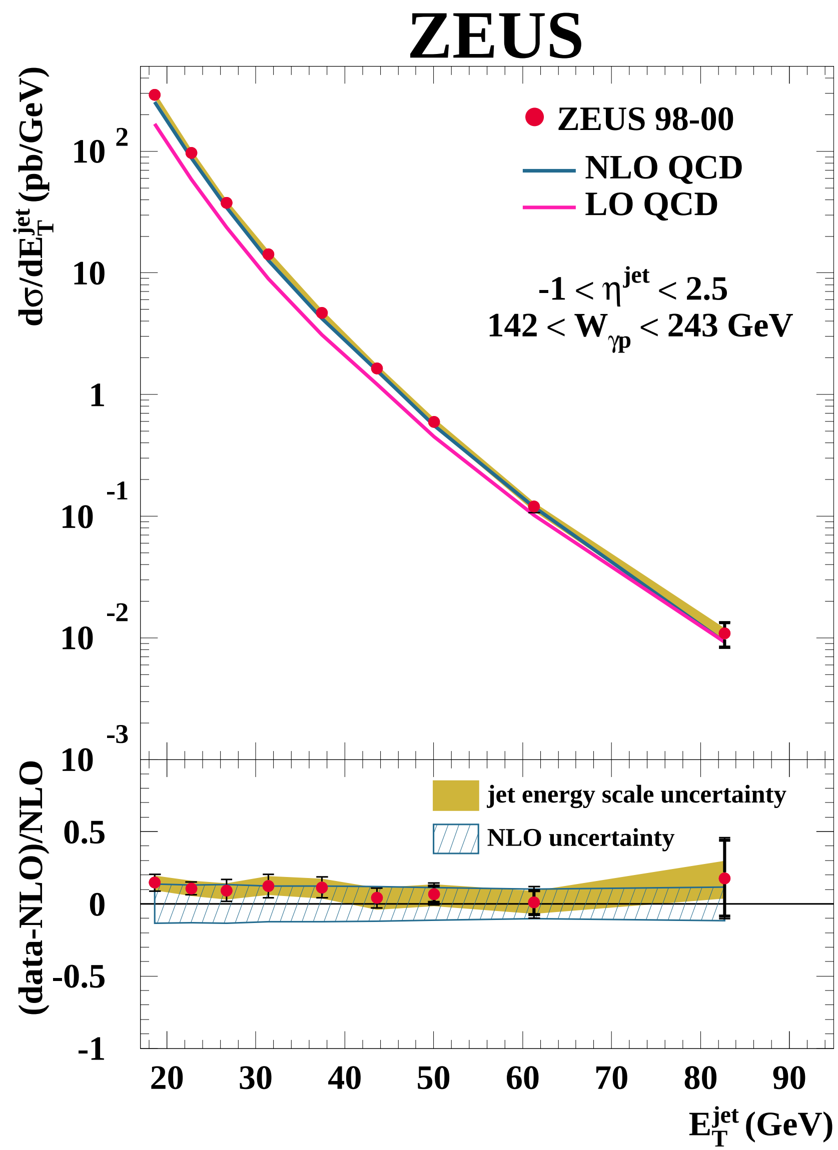
  $17 < E_T^{\rm jet} < 95$ GeV, $\quad -1 < \eta^{\rm jet} < 2.5$

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

- For $E_T^{\rm jet} < 45$ GeV, resolved processes dominant.

- Small theoretical uncertainties...
  - ▷ Renormalisation scale $\sim 10\%$,
  - ▷ Photon and proton pdfs $\sim 5\%$,
  - ▷ $\alpha_s \sim 8\%$ at low $E_T^{\rm jet}$.

- Good agreement of NLO with the data over many orders of magnitude.



Scaling violations

- With the scaling hypothesis, the scaled jet invariant cross section

$$(E_T^{\mathrm{jet}})^4 E^{\mathrm{jet}} \frac{\mathrm{d}^3\sigma}{\mathrm{d}p_X^{\mathrm{jet}}\,\mathrm{d}p_Y^{\mathrm{jet}}\,\mathrm{d}p_Z^{\mathrm{jet}}}$$

as a function of

$$x_T \equiv \frac{2E_T^{\mathrm{jet}}}{W}$$

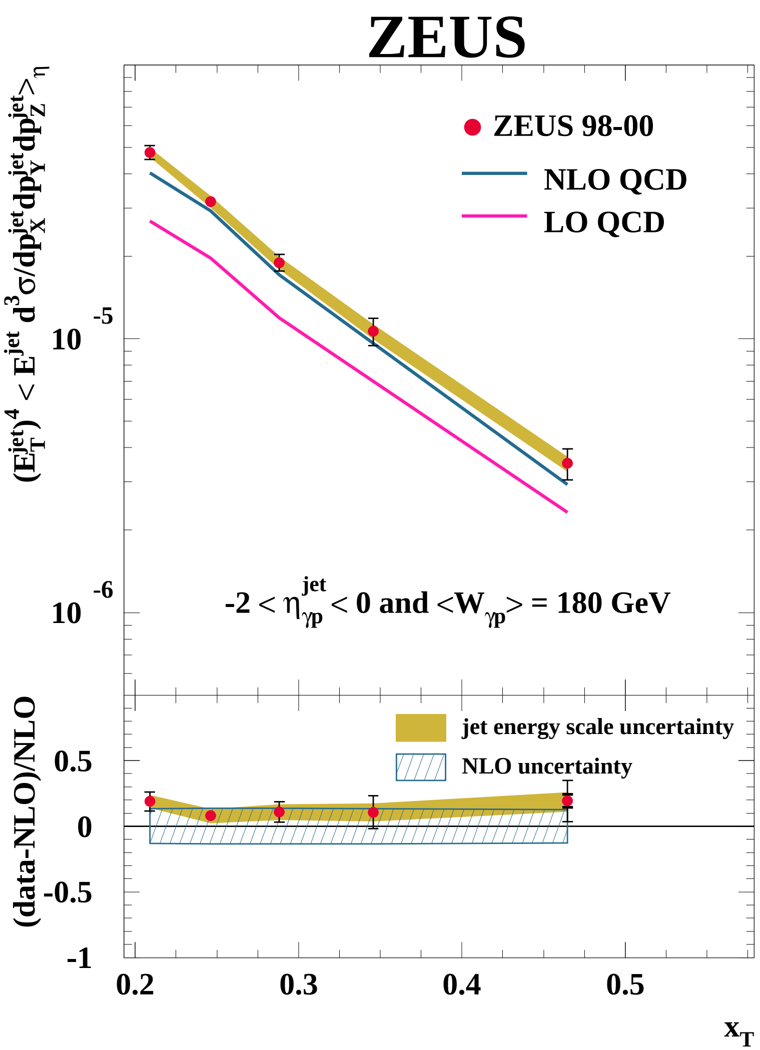
should be independent of $W_{\gamma p}$ ⇒ take ratio of the cross sections in distinct ranges of $W_{\gamma p}$ ...

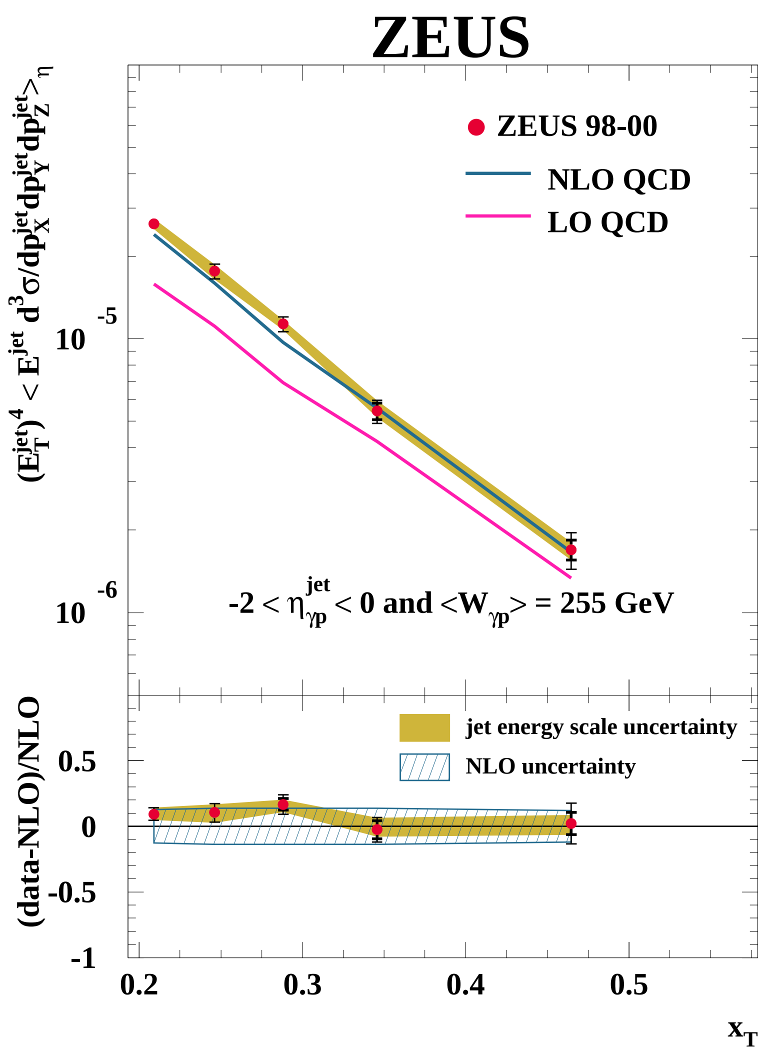
$$169 < W_{\gamma p} < 191 \text{ GeV} \quad - \quad \text{mean } W_{\gamma p} = 180 \text{ GeV}$$

$$240 < W_{\gamma p} < 270 \text{ GeV} \quad - \quad \text{mean } W_{\gamma p} = 255 \text{ GeV}$$

- Unfold for different photon flux at each $W_{\gamma p}$ in the ratio.
- Restrict jets to $-2 < \eta_{\gamma p}^{\mathrm{jet}} < 0$ in the γp centre-of-mass frame.

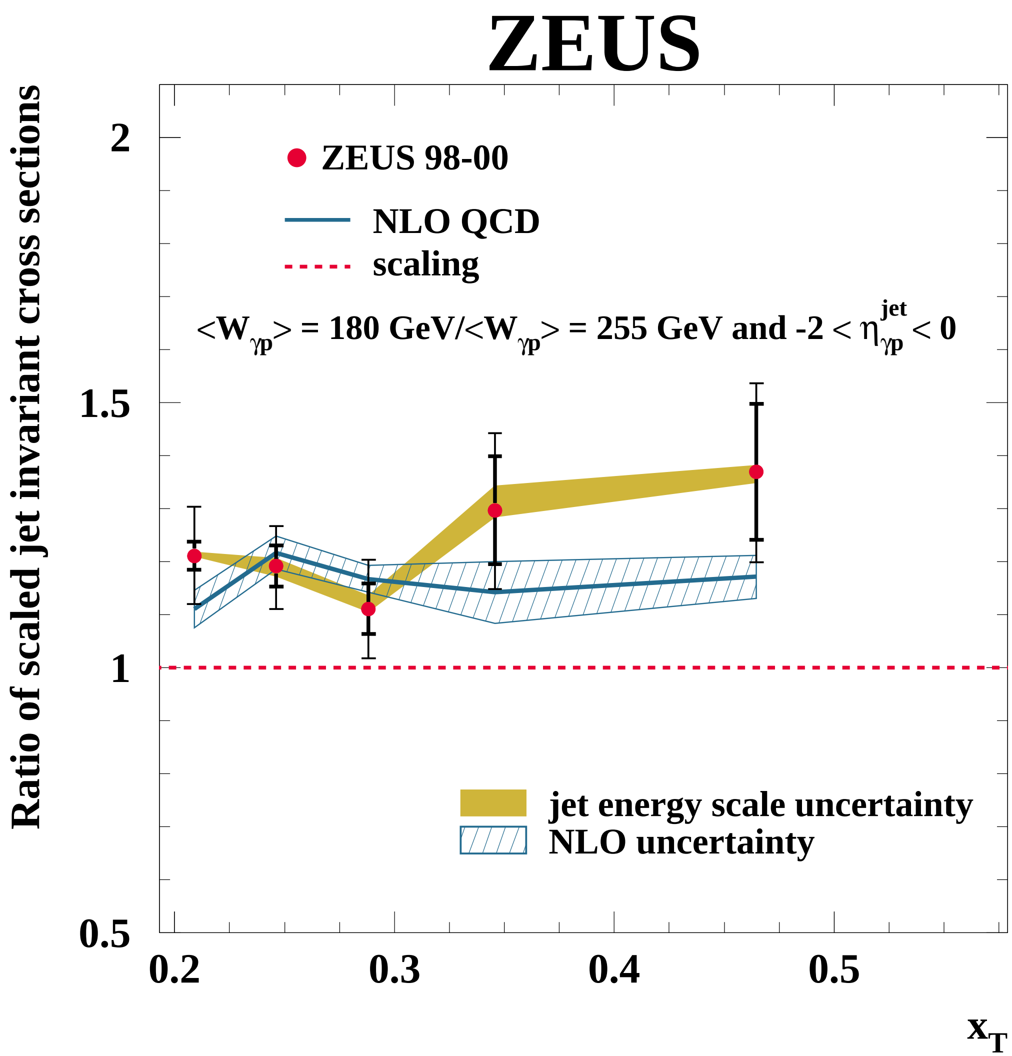
The scaled cross section





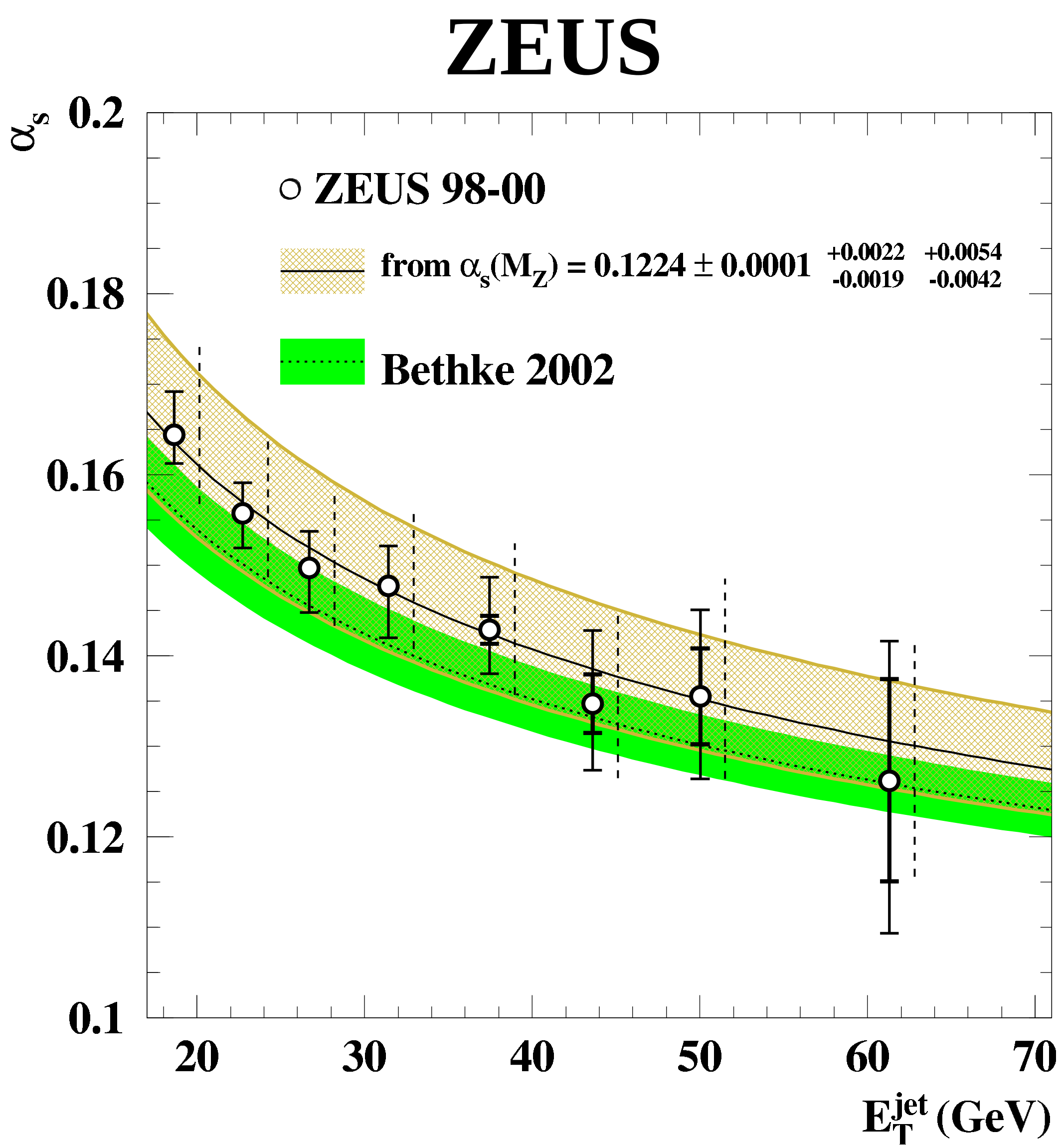
- NLO consistent with the data.

Scaling violations (contd.)



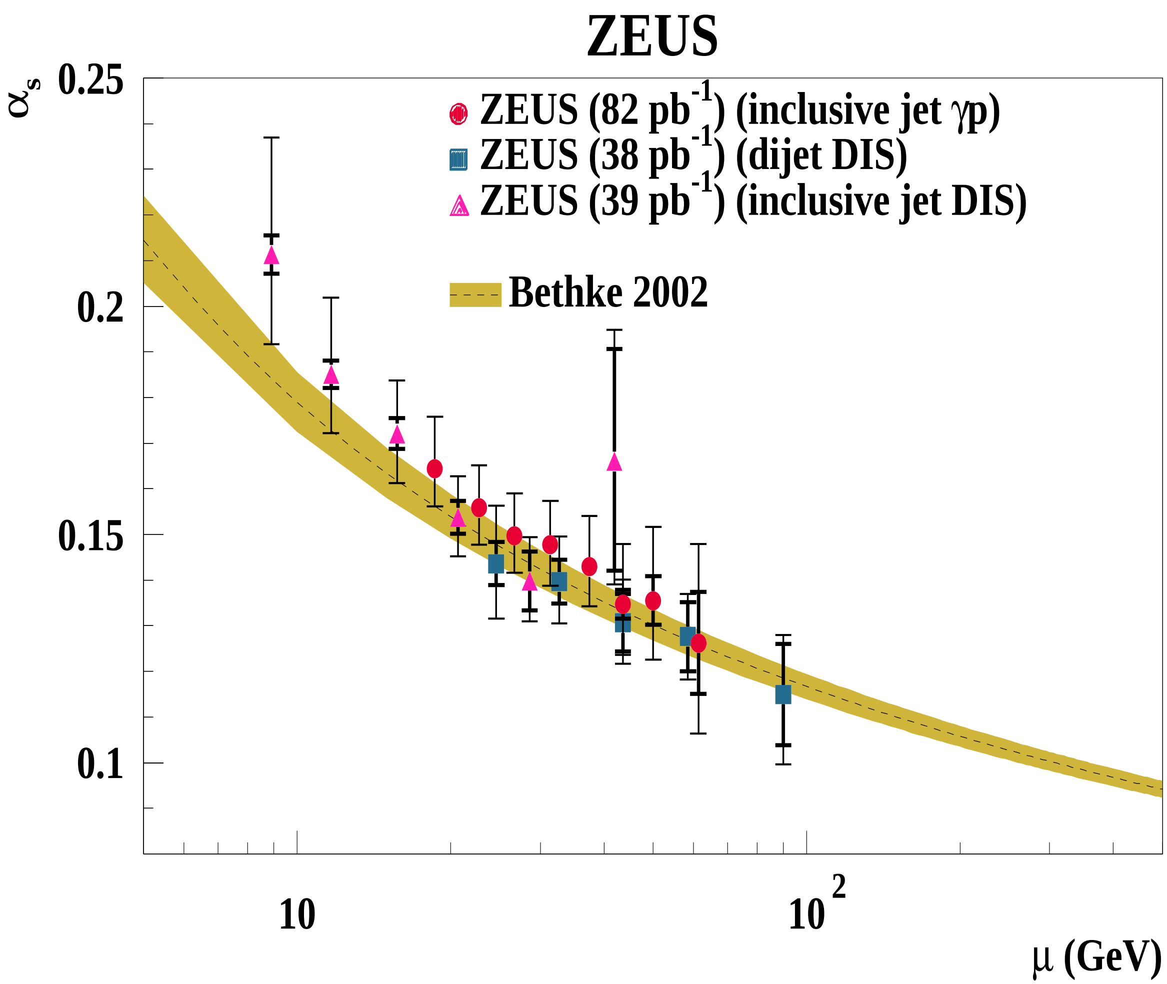
- Ratio of cross sections, $< W_{\gamma p} >= 180$ GeV with respect to $< W_{\gamma p} >= 255$ GeV.
- Theoretical uncertainties reduced...
  - ▷ Renormalisation scale $\sim$ 2.5%,
  - ▷ Photon, proton pdfs $\sim$ 5%, 0.3%,
  - ▷ $\alpha_s \sim$ 4%.
- NLO consistent with data.
- First observation of scaling violations in jet photoproduction.

The running of α_s at HERA



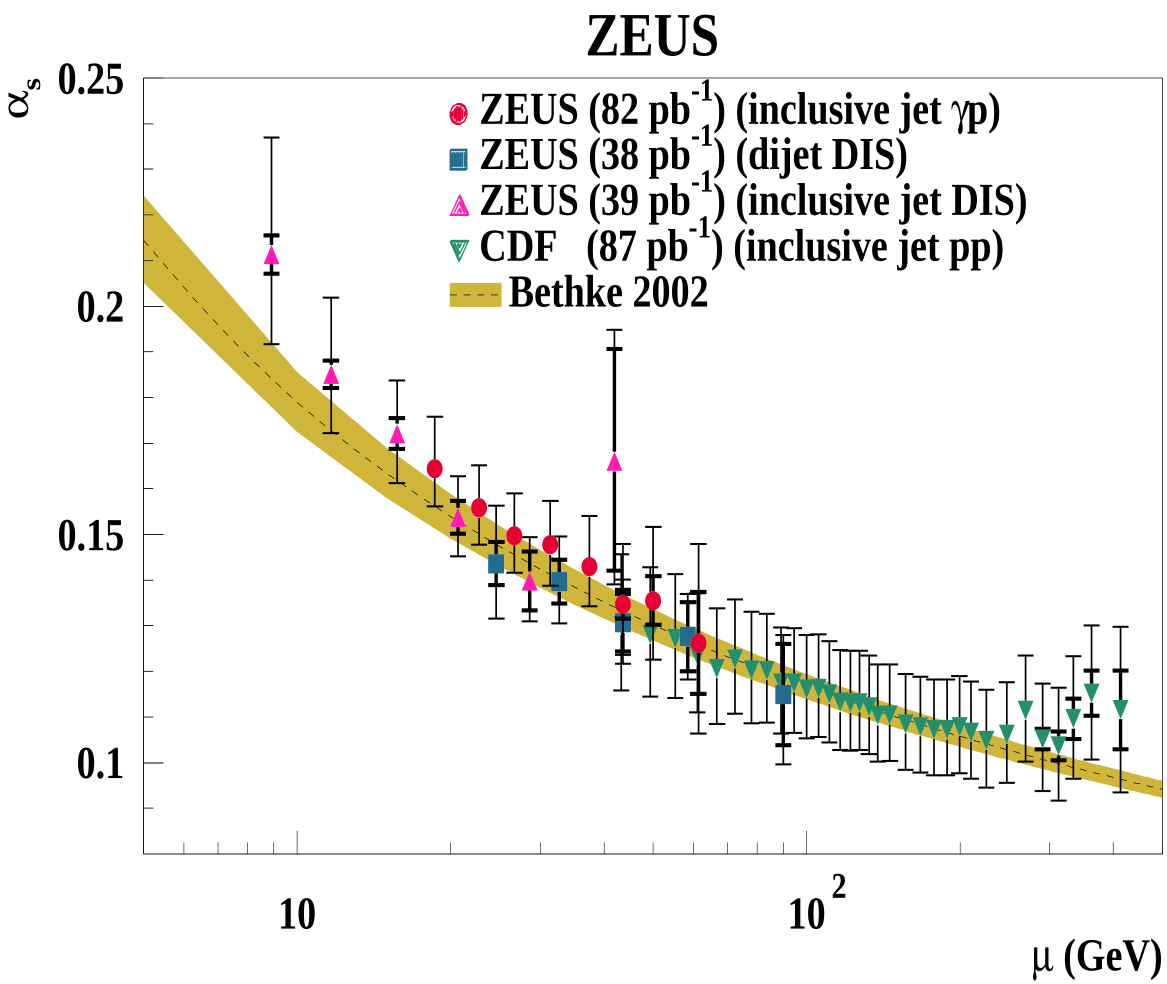
- Extract α_s in each $E_T^{\rm jet}$ bin using the MRST99 pdf sets.
- Clear running of α_s in a single measurement.

The running of α_s



- Spans the overlap region of existing ZEUS data.
- Running seen over an order of magnitude in scale variation from ZEUS data alone.

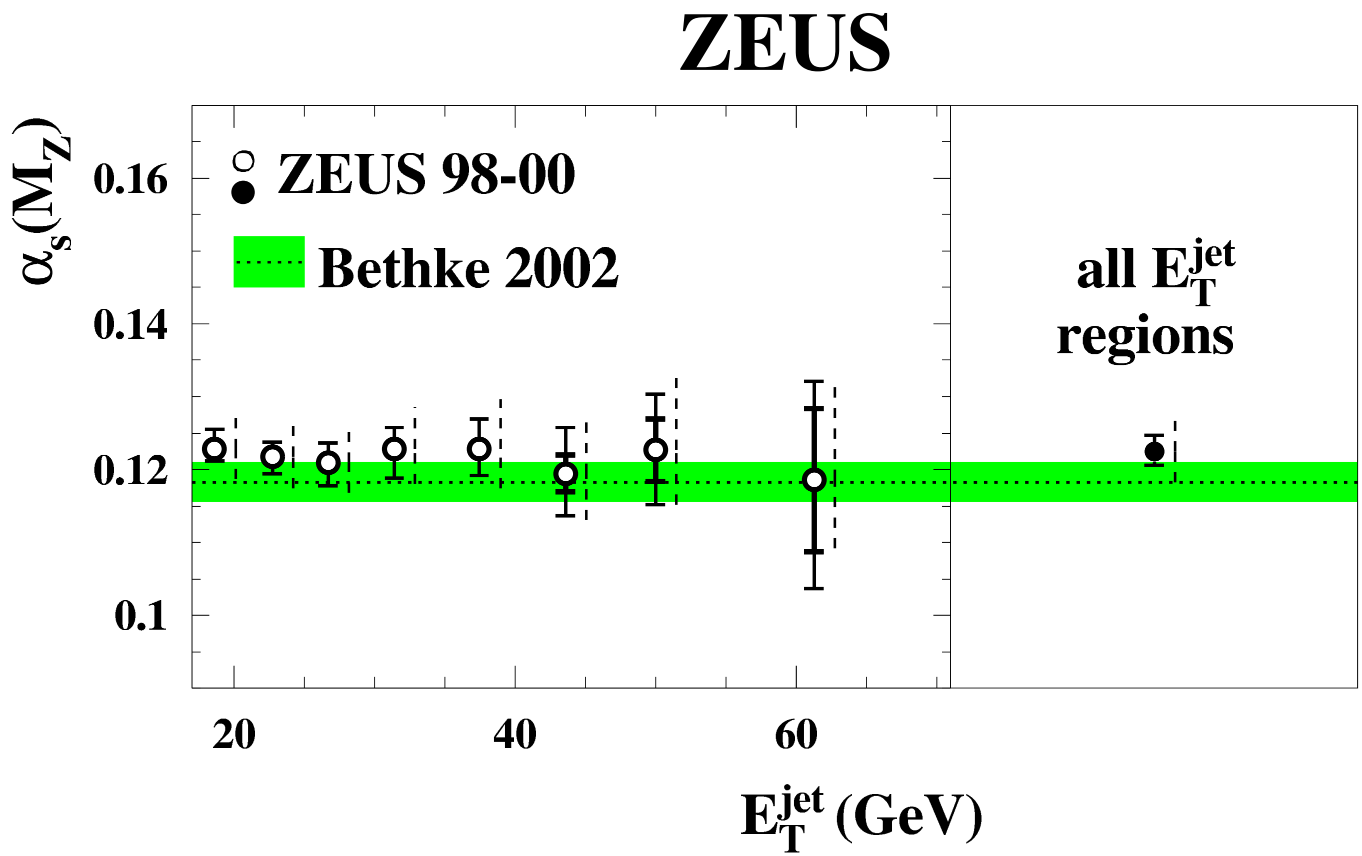
The running of α_s



- Spans the overlap region of existing ZEUS data.
- Running seen over an order of magnitude in scale variation from ZEUS data alone.

- Including CDF data, see α_s running with scale variation well over an order of magnitude.

The extration of $\alpha_s(M_Z)$

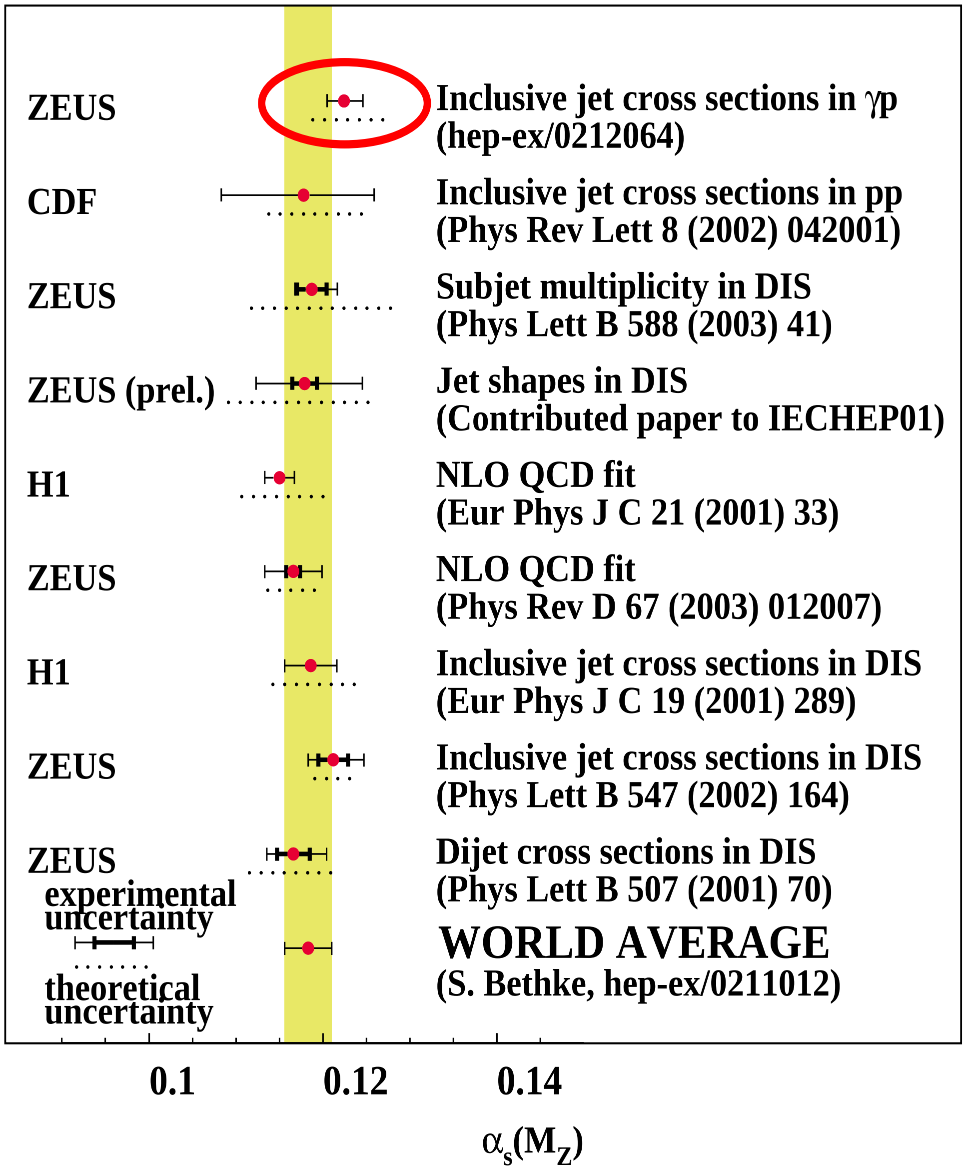


- Running the coupling back to the Z^0 mass...

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

- Small experimental uncertainties.
- Consistent with recent fit of Bethke, theory error still dominates.

Comparison with other measurements



- Consistent with all recent measurements.
- Small experimental uncertainties ⇒ very competitive.

The QCD β function

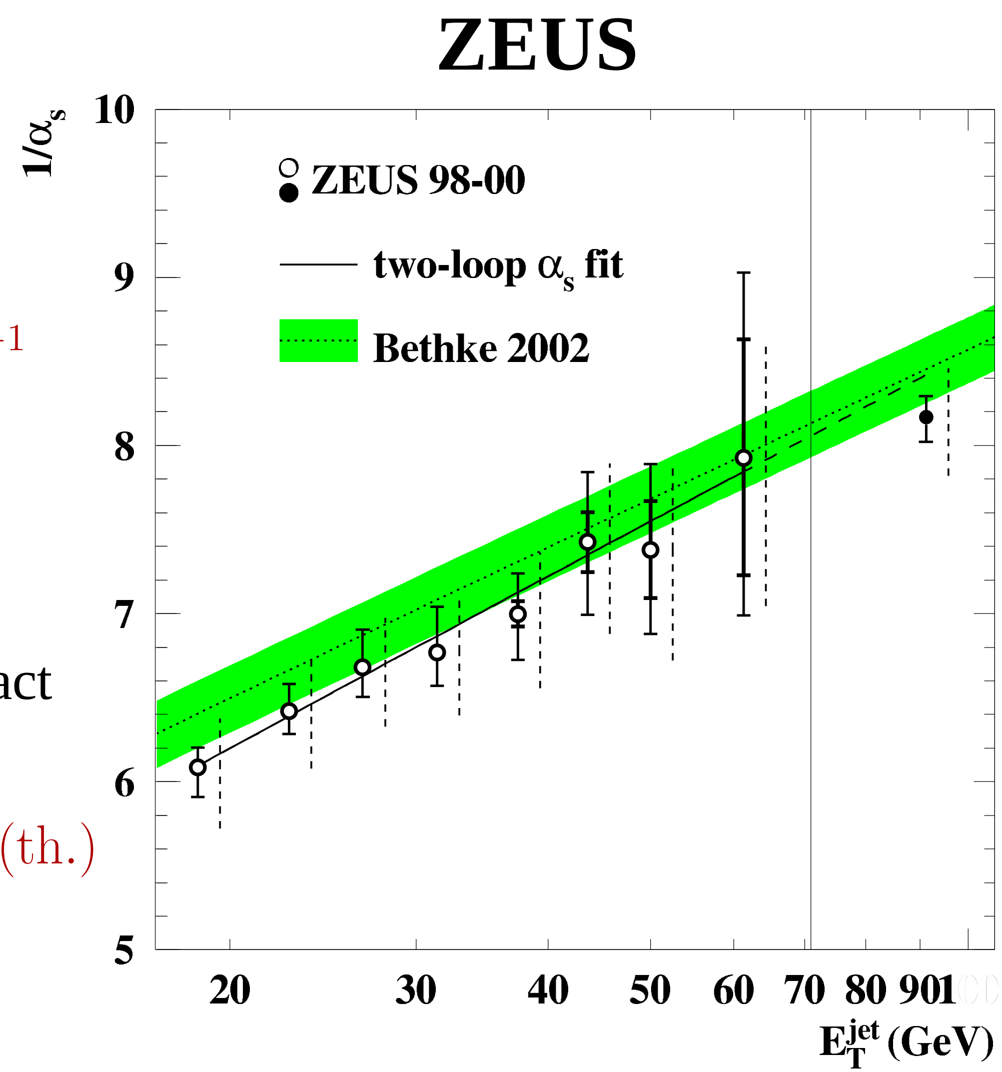
- To two-loop order

$$\alpha_s^{-1}(E_T) = \frac{\beta_0}{2\pi}\ln(E_T/\Lambda)\times \left[1 - \frac{\beta_1}{\beta_0^2}\frac{\ln(\ln(E_T/\Lambda))}{\ln(E_T/\Lambda)}\right]^{-1}$$

- $\beta_0 = 11 - \frac{2}{3}n_f$
- Taking $\beta_1 = (19\beta_0 - 107)/2$, extract β_0...

$$\beta_0 = 8.53 \pm 0.22(\text{stat.})^{+0.56}_{-0.53}(\text{exp.})^{+1.34}_{-0.82}(\text{th.})$$

- (cf. QCD $\beta_0 = 7.67$ for $n_f = 5$).



Conclusions

- The inclusive single jet photoproduction cross section has been measured with high precision.
- The theoretical uncertainties on the NLO predictions are small, and the calculation is able to reproduce the measured cross section over many orders of magnitude.
- Scaling violations have been seen in jet photoproduction for the first time.
- The value of the QCD coupling, α_s, has been extracted from photoproduction data for the first time with a precision comparable with the world average, and it's running behaviour clearly seen.
- Looking forward to improved theoretical predictions to match the existing data, and the increased precision data, at even higher transverse energy, expected from HERA II.