Inclusive and multi-jet results from HERA

Robin Devenish (Oxford)

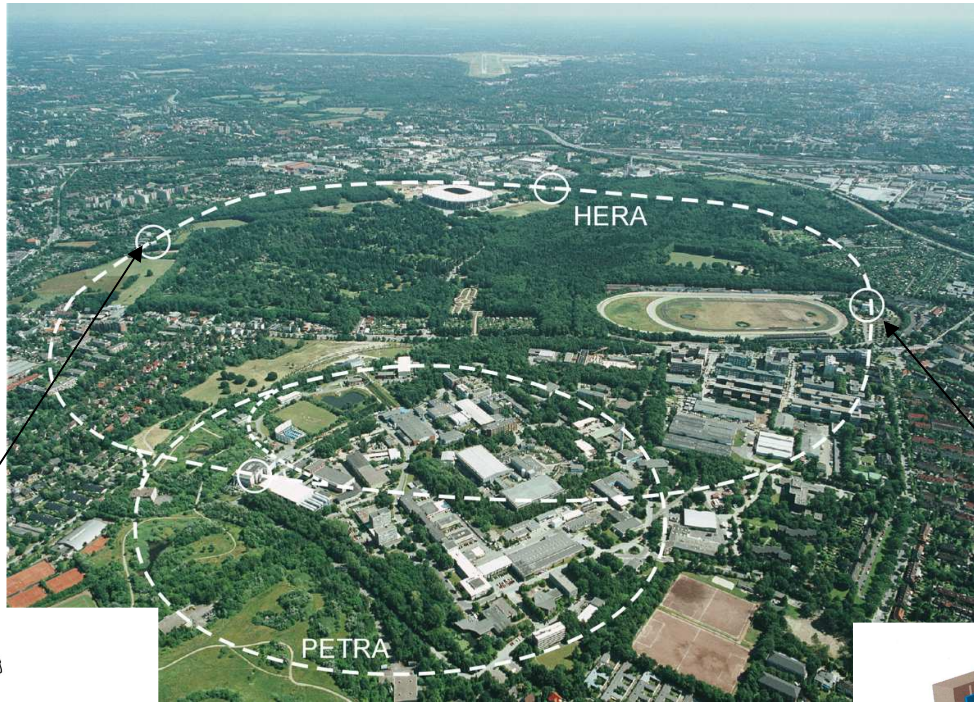
For the H1 and ZEUS Collaborations

- Introduction
- Inclusive jets
- Multi-jets
- Summary

Introduction

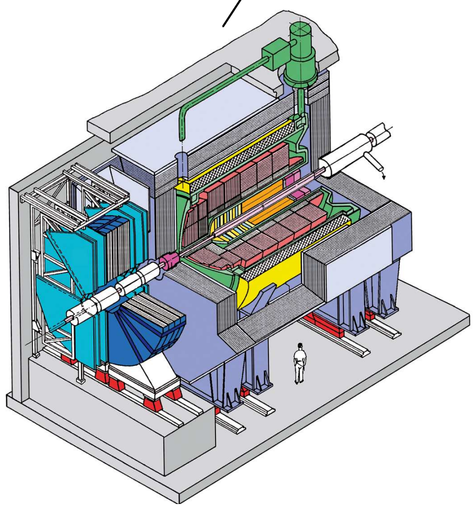
HERA & detectors

e-p collider
$e^{+/-}$ 27.5 GeV
p 920 GeV
E_{cm}= 318 GeV

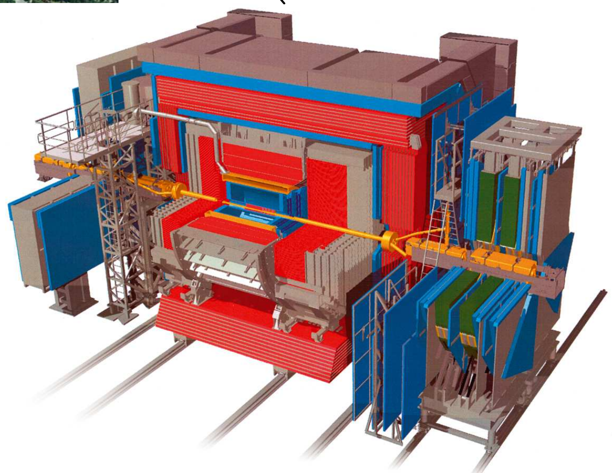


Circumference
~ 11 km

H1 detector
LAr Cal.



ZEUS detector
U/Scint. Cal.



Parton dynamics

- Jets at HERA

$e + p \rightarrow e' + j_1 + X$ inclusive jet production (a)

$e + p \rightarrow e' + j_1 + j_2 + X$ di-jet production (b,c)

- Photoproduction: $Q^2 < 1\ \mathrm{GeV}^2$

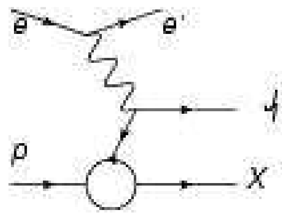
- DIS for jet studies: $125 < Q^2 < 20000\ \mathrm{GeV}^2$ (ZEUS)

  $5 < Q^2 < 100\ \mathrm{GeV}^2$ (H1 low Q^2)

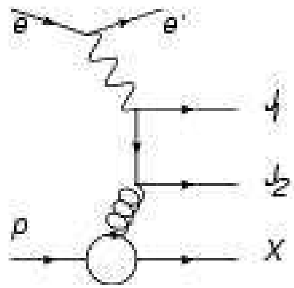
  $150 < Q^2 < 15000\ \mathrm{GeV}^2$ (H1 high Q^2)

- Difference between photoproduction and DIS?
  - resolved (hadronic) γ^* significant only for γp
  - direct γ^* component for both
  - hard scales: Q^2 (DIS jets)

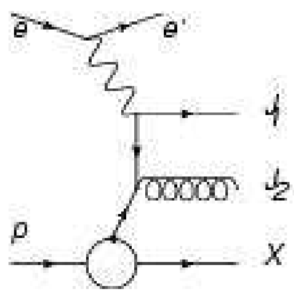
    E_T^{jet} (γp jets)



(a)



(b)



(c)

Jet algorithms

- Particle variables: E_T^i, η^i, ϕ^i (with respect to beamline)

- Calculate a distance measure between pairs
  - $d_{ij} = \min((E_T^i)^2, (E_T^j)^2) \cdot [(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2] / R^2$ k_T algorithm
  - $d_{ij} = \min((E_T^i)^{-2}, (E_T^j)^{-2}) \cdot [(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2] / R^2$ anti-k_T algorithm
  - plus distance to the beam $d_i = (E_T^i)^2$ or $d_i = (E_T^i)^{-2}$, respectively

  The parameter R is usually set equal to unity

- Cluster: find smallest of all objects $\{d_{ij}, d_i\}$
  - d_{kl} smallest $\rightarrow$ combine objects i and j
  - d_k smallest $\rightarrow$ object k is a jet and removed
  - iterate until all objects assigned

- Both measures are collinear and infrared safe
  - difference is in shape of cone in $\eta - \phi$ plane
  - anti-k_T jets are more uniformly circular

More on jet algorithms

- Cone algorithms - popular at hadron colliders
  - objects with $E_T > E_T^{cut}$ are the jet 'seeds'
  - objects with $E_T < E_T^{cut}$, within cone radius R about seed $\sqrt{(\eta_{seed} - \eta_i)^2 + (\phi_{seed} - \phi_i)^2} < R$ added to the jet
  - $E_T^{jet}, \eta^{jet}, \phi^{jet}$ are E_T weighted averages
  - gives circular shape - but seeds not 'safe' to all orders in pQCD

- Seedless Infra-red Safe (SIScone) algorithm solves seed problem
  - find 'stable' cones of radius R for given set, S, of initial objects with cone axis coincident with total momentum direction of S
  - $\tilde{p}_t$ is scalar sum of p_t of objects within cone, discard cones with $\tilde{p}_t < p_{t,\min}$
  - merge or split overlapping cones if $\sum p_t(\text{shared}) > f \times \tilde{p}_t(\text{min})$
  - for ZEUS jets $f = 0.75$ and $\tilde{p}_t(\text{min}) = 0$

Inclusive Jets

1. NC
2. Photoproduction

NC event selection (ZEUS)

- $E_p = 920$ GeV, $E_e = 27.5$ GeV, $\int Ldt = 81.7 \pm 1.8\ \text{pb}^{-1}\ (e^- p + e^+ p)$

  $E_e^{'}, \theta_e$ measured from Calorimeter cells, Q^2 calculated using double angle

  γ_h (in QPM angle of scattered quark) reconstructed from hadronic final-state
- Event selection cuts: ($E = \sum_i E_i, P_z = \sum_i p_z^i$ summed over CAL cells)

  $E_e^{'} > 10$ GeV; $|Z_{vertex}| < 34$ cm; $38 < E - P_Z < 65$ GeV

  $Q^2 > 125\ \text{GeV}^2$; $|\cos\gamma_h| < 0.65$
- Jet reconstruction in Breit frame, then boosted to *ep* (HERA) frame

  $E_{T,lab}^{jet}, \eta_{lab}^{jet}$ for each jet
- Require: $E_{T,lab}^{jet} > 2.5$ GeV, with at least one jet with $E_{T,lab}^{jet} > 8$ GeV

  and $-2 < \eta_{lab}^{jet} < 1.5$ (reject events with $\eta_{lab}^{jet} < -2$)
- Acceptance correction factors $\sim 1 - \varepsilon$ with $\varepsilon < 0.1$

Systematic uncertainties

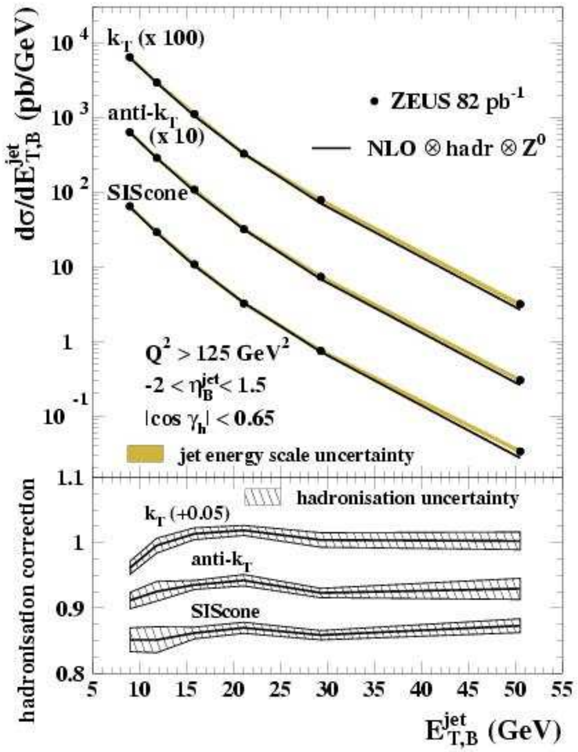
- Jet energy scale uncertainty $\pm 1\%$, $E_T > 10$ GeV; $\pm 3\%$ for smaller E_T

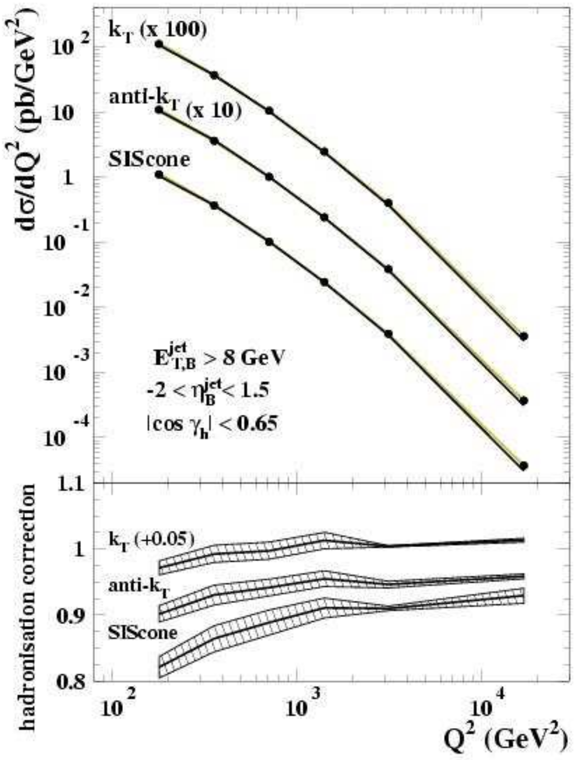
  $\Rightarrow$ 5% uncertainty on cross-sections
- Detector acceptance corrections < $\pm 3\%$ from difference in using ARIADNE or LEPTO-MEPS
- Variation of selection cuts within resolution: $< \pm 3\%$
- Uncertainty in boost to Breit frame (use electron track) < $\pm 1\%$
- Uncertainty in $E_e^{'} < \pm 1\%$

  Apart from jet energy, add other uncertainties in quadrature

- Uncertainty in luminosity $\pm 2.2\%$ - but not added

NC inclusive jets vs NLO QCD

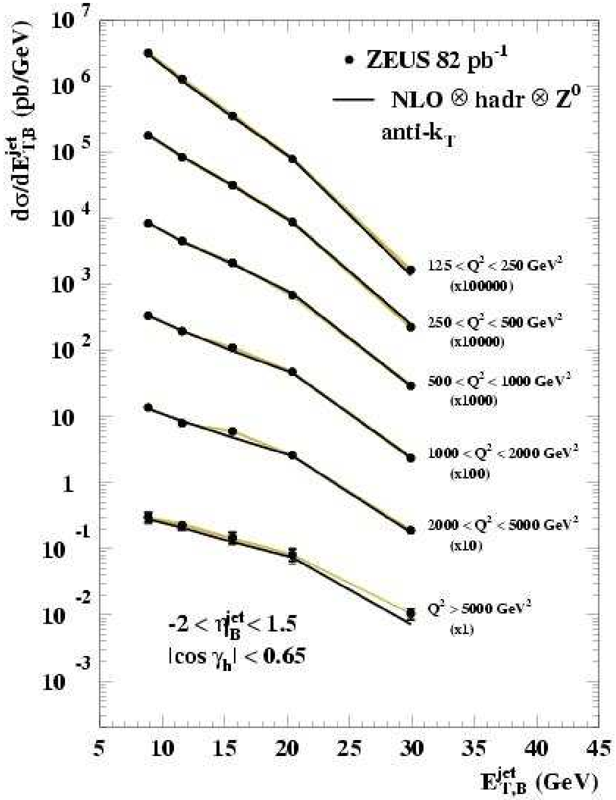


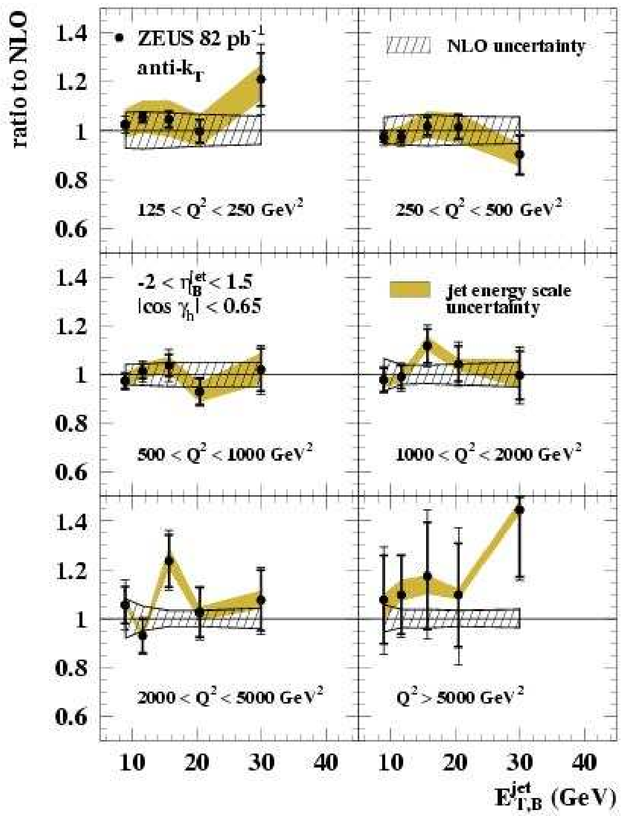


Comparison of ZEUS data using k_T, anti-k_T and SIScone jet algorithms. Good agreement between the measurements over 5 orders of magnitude, and with NLO QCD (DISENT calculation)

NB: Z^0 exchange not in NLO codes, allowed for using MC events

NC jets vs E_T (anti-k_T)

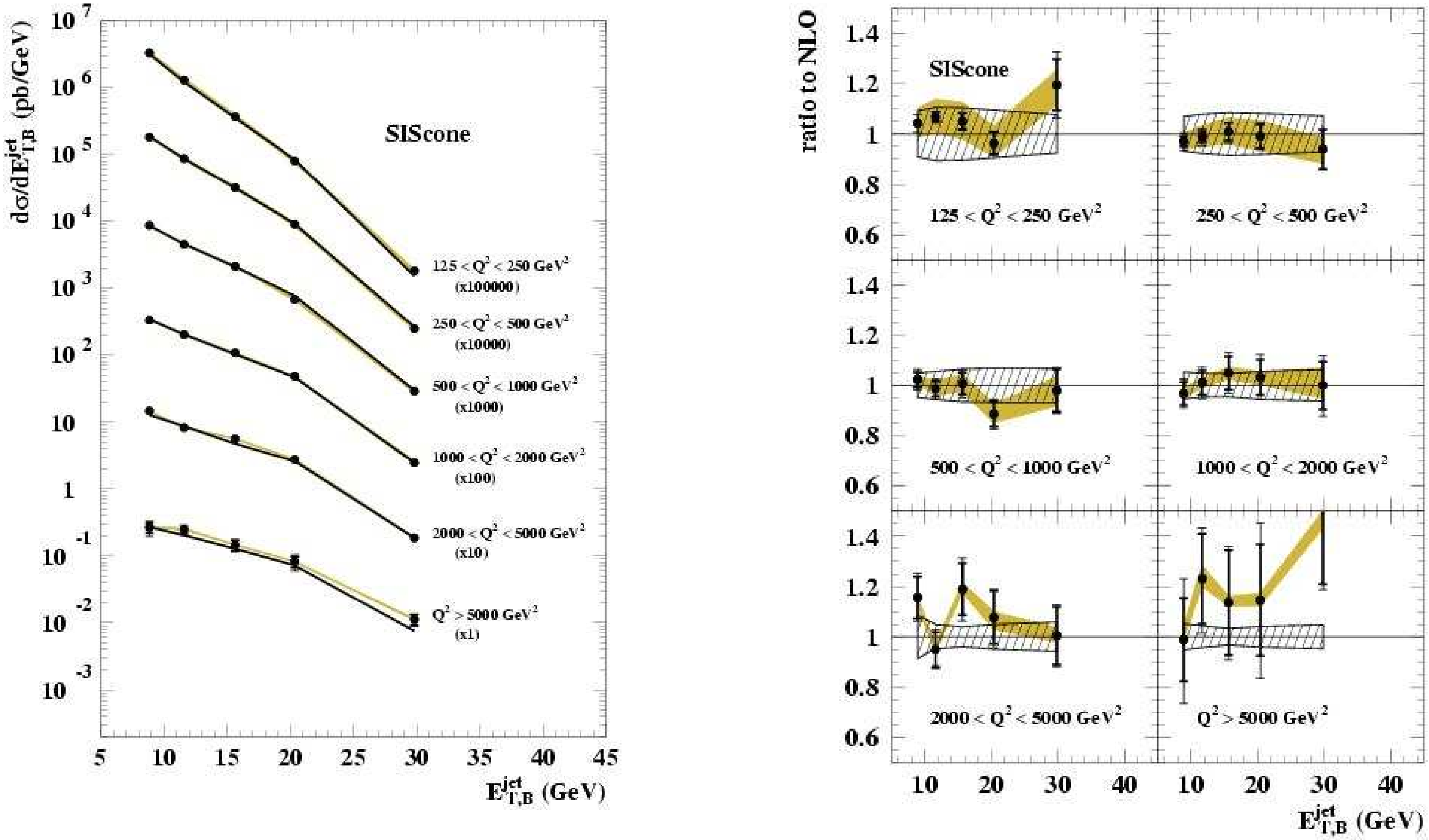




$d\sigma / dE_{T,B}^{jet}$ in bins of Q^2, anti-k_T algorithm and ratios to NLO QCD

As Q^2 increases, $d\sigma / dE_{T,B}^{jet}$ decreases less rapidly with $E_{T,B}^{jet}$

NC jets vs E_T (SIScone)



$d\sigma / dE_{T,B}^{jet}$ in bins of Q^2, SIScone algorithm and ratios to NLO QCD

Uncertainty somewhat larger for SIScone than anti-k_T at low Q^2 and $E_{T,B}^{jet}$

α_S from DIS inclusive jets

- Use measured $d\sigma/dQ^2$ with $Q^2 > 500$ GeV^2
- NLO DISENT calculations with 5 $\alpha_S(M_Z)$: 0.115, 0.117, 0.119, 0.121 and 0.123 corresponding ZEUS-S PDF sets
- In each Q^2 bin parameterise $\alpha_S(M_Z)$ dependence of DISENT prediction using

  $$[d\sigma/dQ^2(\alpha_S(\mathrm{M}_Z))] = C_1^i\alpha_S(\mathrm{M}_Z) + C_2^i\alpha_S^2(\mathrm{M}_Z)$$
- C_1^i, C_2^i determined by χ^2 fit to NLO calculations
- Finally $\alpha_S(\mathrm{M}_Z)$ determined by χ^2 fit to measured $d\sigma/dQ^2$ values

- Uncertainties on $\alpha_S(\mathrm{M}_Z)$ values:
  - repeat calculation for each systematic check on $d\sigma/dQ^2$ measurements
  - largest experimental uncertainty: jet energy scale ($\pm$2%)
  - largest theoretical uncertainty: terms beyond NLO ($\pm$1.5%); PDF ($\pm$0.7%)
  - hadronisation: k_T $\pm$0.8%; anti-k_T $\pm$0.9%; SIScone $\pm$1.2%
- Cross checked using other PDF sets: CTEQ6.1; MSTW2008

ZEUS results for α_S (NC Jets)

Method	Value	Stat. error	Exp. Error	Theory error
k_T	0.1207	+/- 0.0014	+0.0035 -0.0033	+0.0022 -0.0023
anti-k_T	0.1188	+/- 0.0014	+0.0033 -0.0032	+0.0022 -0.0022
SIScone	0.1186	+/- 0.0013	+0.0034 -0.0032	+0.0025 -0.0025

Results are good agreement with each other

Precision comparable to α_S measurements from e^+e^- at LEP

Also in good agreement with:

HERA average: 0.1186 +/- 0.0051 (Glasman, DIS 2005)

World average: 0.1184 +/- 0.0007 (Bethke, 2009)

Jets in Photoproduction

ZEUS γp: event selection & uncertainties

- $E_p = 920$ GeV, $E_e = 27.5$ GeV, $\int L dt = 188.5 \pm 4.9$ pb^{-1} $(e^- p)$

- Event selection

  $p_T^{miss} / \sqrt{E_T^{tot}} < 2\sqrt{\text{GeV}}$; total missing $p_T \ll E_T^{tot}$ total event E_T

  remove DIS events with identified scattered electron

- Sample has $Q^2 < 1$ GeV^2 with median $Q^2 \approx 10^{-3}$ GeV^2

  require $0.2 < y < 0.85$; y is inelasticity, estimated using $y_{JB} = (E - p_z)/2E_e$

- Require at least one jet with $E_{T,lab}^{jet} > 17$ GeV and $-2 < \eta^{jet} < 1.5$

- Uncertainties

  - Jet energy scale $\pm 1\% \Rightarrow$ uncertainty on cross-sections: $\pm 5\%$ low E_T^{jet} $\nearrow$ $\pm 10\%$ high E_T^{jet}
  - Detector acceptance corrections < $\pm 4\%$ from difference in using PYTHIA or HERWIG
  - Uncertainty in luminosity $\pm 2.6\%$ - but not added

Uncertainties in NLO calculation

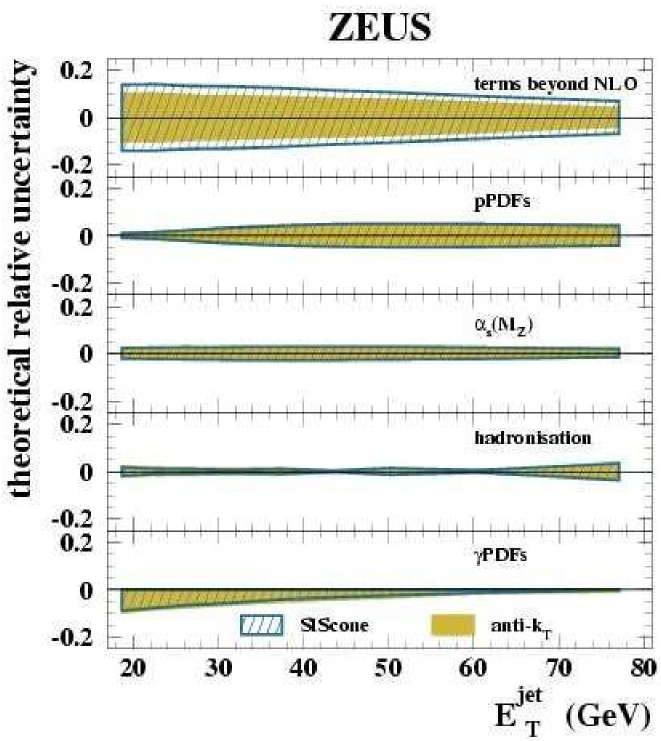
Calculation from Klasen, Kleinwort & Kramer.

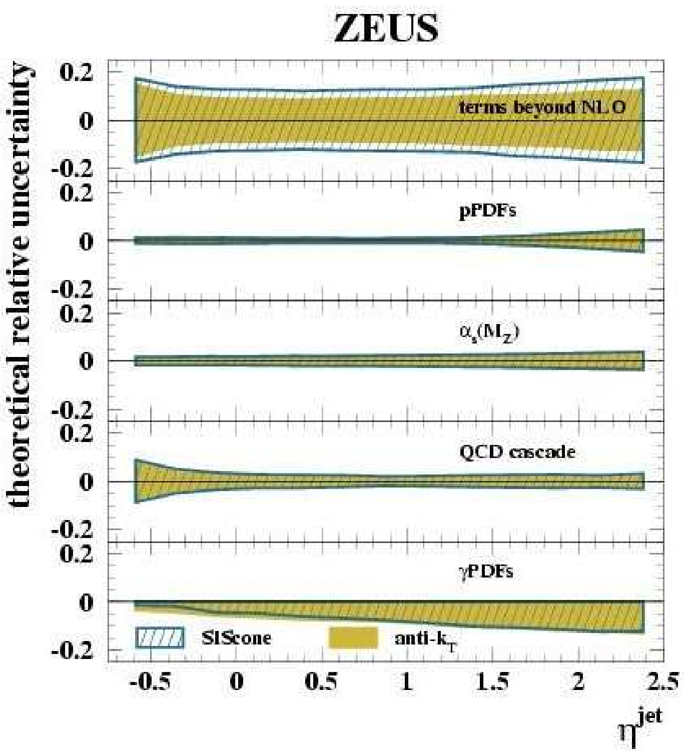
$n_f = 5$; $\mu_R = \mu_F = E_T^{jet}$; $\Lambda_{\overline{MS}}^{(5)} = 226$ MeV; PDFs: proton, ZEUS-S; photon GRV-HO

Terms beyond NLO: vary scale μ between $E_T^{jet}/2$ and $2E_T^{jet}$

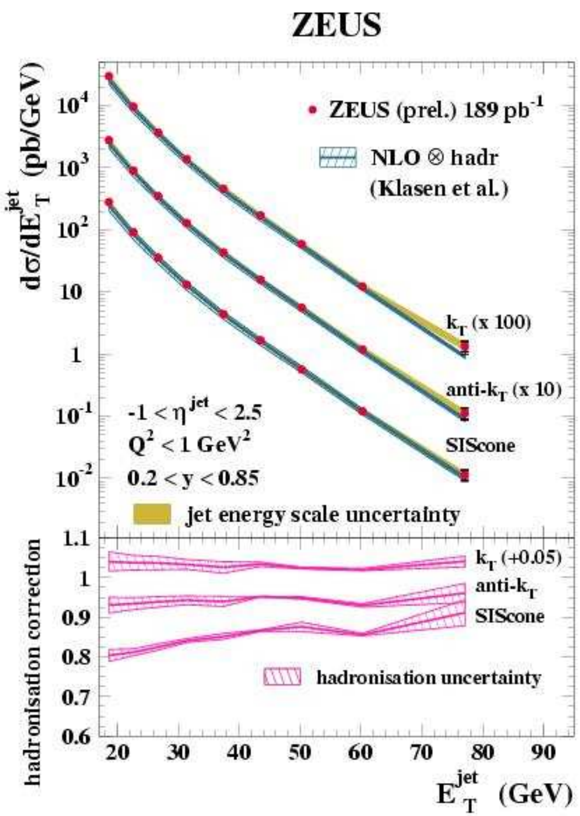
PDF uncertainty: proton, repeat with 22 sets from ZEUS-S (covering exp. uncertainties)

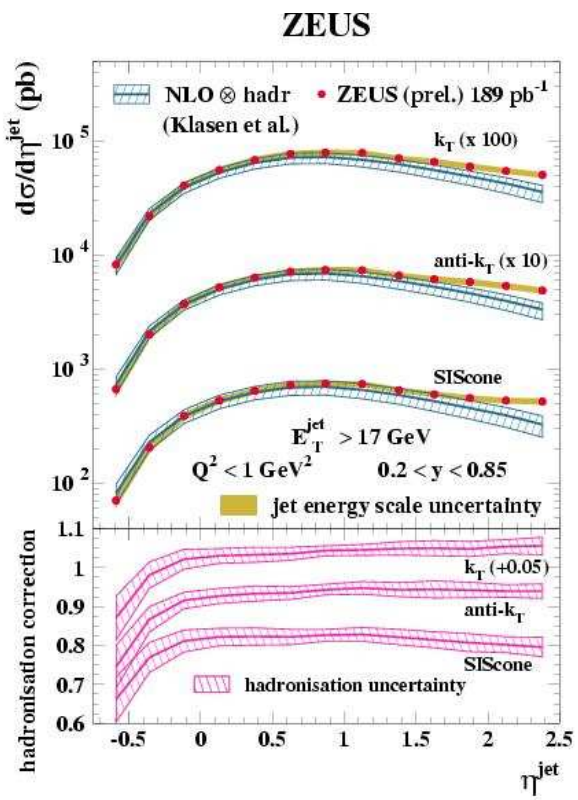
photon, replace GRV-HO with AFG04





Photoproduction jets vs NLO QCD





Comparison of ZEUS data using k_T, anti-k_T and SIScone jet algorithms.
Good agreement between the measurements over 4 orders of magnitude, and with NLO QCD (Klasen, Kleinwort and Kramer)

α_S from photoproduction inclusive jets

- Use measured $d\sigma/dE_T^{jet}$ with $21 < E_T^{jet} < 71$ GeV
- NLO calc (Klasen, Kleinwort & Kramer) with 5 $\alpha_S(M_Z)$: 0.115, 0.117, 0.119, 0.121 and 0.123
  corresponding ZEUS-S proton PDFs and GRV-HO for the photon
- Similar technique (now wrt E_T^{jet})
  $[d\sigma/dE_T^{jet}(\alpha_S(\mathrm{M}_Z))] = C_1^i\alpha_S(\mathrm{M}_Z) + C_2^i\alpha_S^2(\mathrm{M}_Z)$
- C_1^i, C_2^i determined by χ^2 fit to NLO calculations
- Finally $\alpha_S(\mathrm{M}_Z)$ determined by χ^2 fit to measured $d\sigma/dE_T^{jet}$ values

- Uncertainties on $\alpha_S(\mathrm{M}_Z)$ values:
  - repeat calculation for each systematic check on $d\sigma/dQ^2$ measurements
  - largest experimental uncertainty: jet energy scale ($\pm 1.7\%$)
  - largest theoretical uncertainty: terms beyond NLO (2 - 3%);
    proton PDF ($\pm 0.7\%$); photon PDF (~2.4%)
  - hadronisation: k_T $\pm 0.5\%$; anti-k_T $\pm 0.4\%$; SIScone $\pm 0.2\%$

Results for α_S (Photoproduction Jets)

Method	Value	Exp. Error	Theory error
k_T	0.1208	+0.0024	+0.0044
		-0.0023	-0.0033
anti-k_T	0.1200	+0.0024	+0.0043
		-0.0023	-0.0032
SIScone	0.1199	+0.0022	+0.0047
		-0.0022	-0.0042

Results are good agreement with each other

Precision comparable to α_S measurements from e^+e^- at LEP

Also in good agreement with:

HERA average: 0.1186 +/- 0.0051 (Glasman, DIS 2005)

World average: 0.1184 +/- 0.0007 (Bethke, 2009)

Note that exp. errors smaller than for DIS, but theory uncertainty is larger

Multi jets

1. Dijets in DIS (ZEUS)
2. Multijets in DIS (H1)

NC event selection (ZEUS) dijet

- $E_p = 920$ GeV, $E_e = 27.5$ GeV, $\int Ldt = 203\ \text{pb}^{-1}\ (e^- p),\ 171\ \text{pb}^{-1}(e^+ p)$

  $E_e^{'}, \theta_e$ measured from Calorimeter cells, Q^2 calculated using double angle
- Event selection cuts: ($E = \sum_i E_i, P_z = \sum_i p_z^i$ summed over CAL cells)

  $E_e^{'} > 10$ GeV, $|Z_{vtx}| < 30$ cm, $P_{T,miss}/\sqrt{E_T} < 2.5\ \text{GeV}^{1/2}$, $38 < E - P < 65$ GeV

  $125 < Q^2 < 20000\ \text{GeV}^2$; $0.2 < y < 0.6$, where $y = Q^2/x_{Bj}s$

- Jet reconstruction (k_T) in Breit frame, then boosted to *ep* (HERA) frame

  $E_{T,lab}^{jet}, \eta_{lab}^{jet}$ for each jet
- Require: $E_{T,lab}^{jet} > 2.5$ GeV, with at least one jet with $E_{T,lab}^{jet} > 8$ GeV

  and $-2 < \eta_{lab}^{jet} < 1.5$ (reject events with $\eta_{lab}^{jet} < -2$)
- Acceptance correction factors $\sim 1 - \varepsilon$ with $\varepsilon < 0.1$

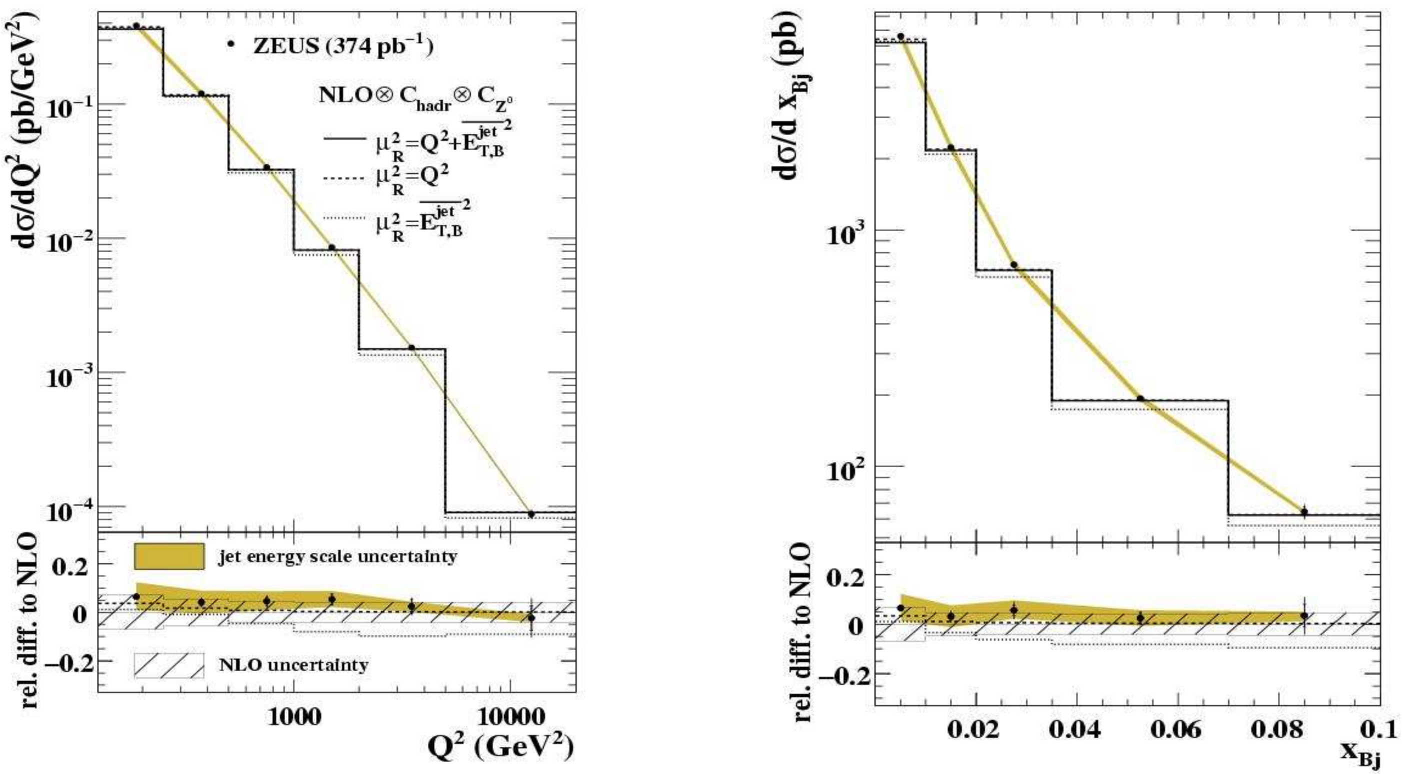
Systematic uncertainties (dijet)

- Jet energy scale uncertainty $\pm 1\%$, $E_T > 10$ GeV; $\pm 3\%$ for smaller E_T

  $\Rightarrow$ 5% uncertainty on cross-sections
- Detector acceptance corrections < $\pm 3\%$ from difference in using ARIADNE or LEPTO-MEPS
- Variation of selection cuts within resolution: $< \pm 3\%$
- Uncertainty in boost to Breit frame (use electron track) < $\pm 1\%$
- Uncertainty in $E_e^{'} < \pm 1\%$

  Apart from jet energy, add other uncertainties in quadrature
- Uncertainty in luminosity $\pm 2.2\%$ - but not added

ZEUS NC dijets vs NLO QCD



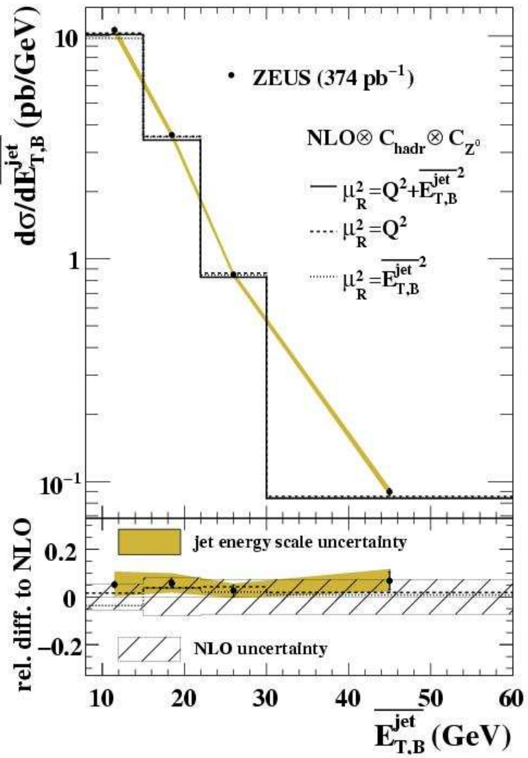
$$Cuts:\ E_{T,B}^{jet} > 8\ \text{GeV};\quad M_{jj} > 20\ \text{GeV};\quad -1 < \eta_{LAB}^{jet} < 2.5$$

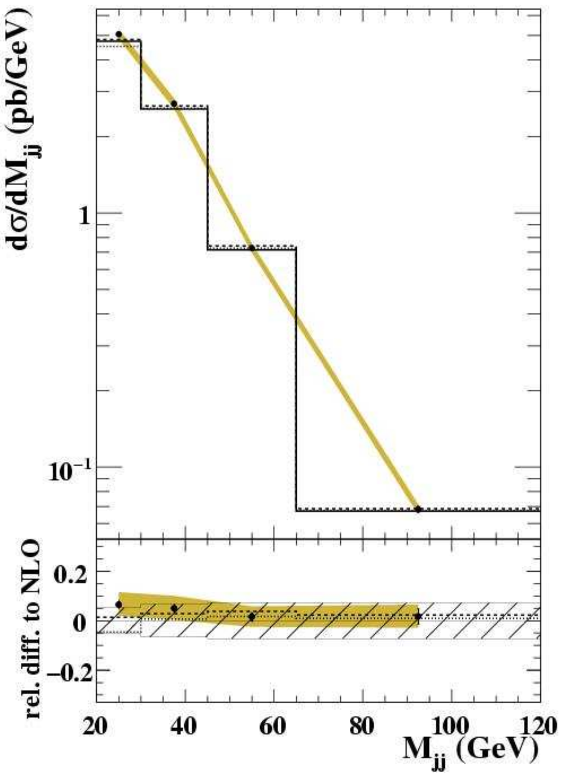
$$0.2 < y < 0.6;\quad 125 < Q^2 < 20000\ \text{GeV}^2$$

NB: Z^0 exchange not in NLO codes, allowed for using MC events

Very good agreement between measurement and NLO QCD (NLOJET++)

ZEUS dijets II



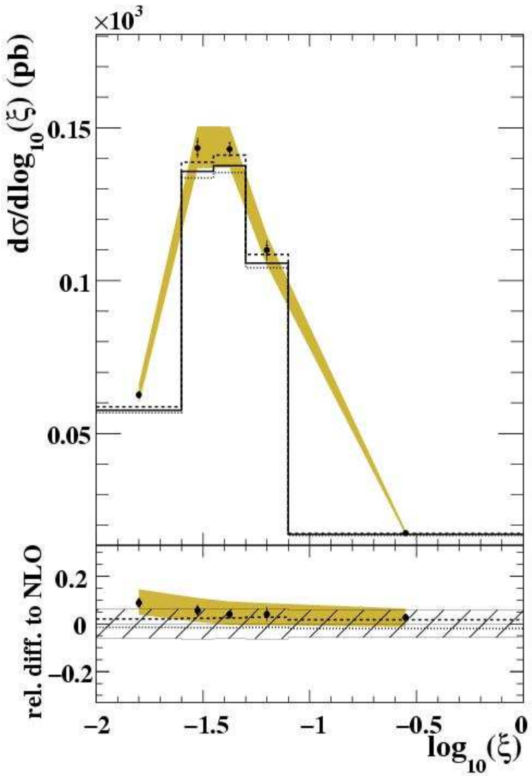


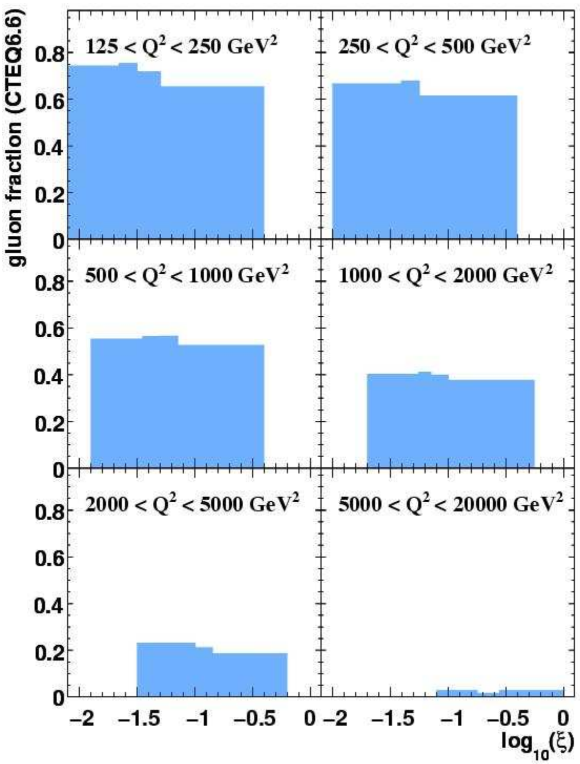
$\overline{E_{T,B}^{jet}}$: mean jet E_T; M_{jj}: dijet invariant mass (no surprises)

NLO: $\overline{\text{MS}}$ $n_f = 5$; $\mu_F = Q$; $\mu_R^2 = Q^2 + \overline{E_{T,B}^{jet}}^2$; $\alpha_S(M_Z) = 0.118$

CTEQ6.6 proton PDF; NLOJET calc. checked against DISENT

ZEUS dijets III





$\xi = x_{Bj}(1 + M_{jj}^2 / Q^2)$; variable sensitive to details of the NLO matrix elements

RH figure shows the fraction of dijet events initiated by a gluon from the proton

75% in lowest Q^2 bin ($125 < Q^2 < 250$ GeV^2) to ~5% for largest ($5000 < Q^2 < 20000$ GeV^2)

H1 multijets in DIS

Low Q^2 $5 < Q^2 < 100$ GeV^2 $L = 43.5$ pb^{-1}

High Q^2 $150 < Q^2 < 15000$ GeV^2 $L = 350$ pb^{-1}

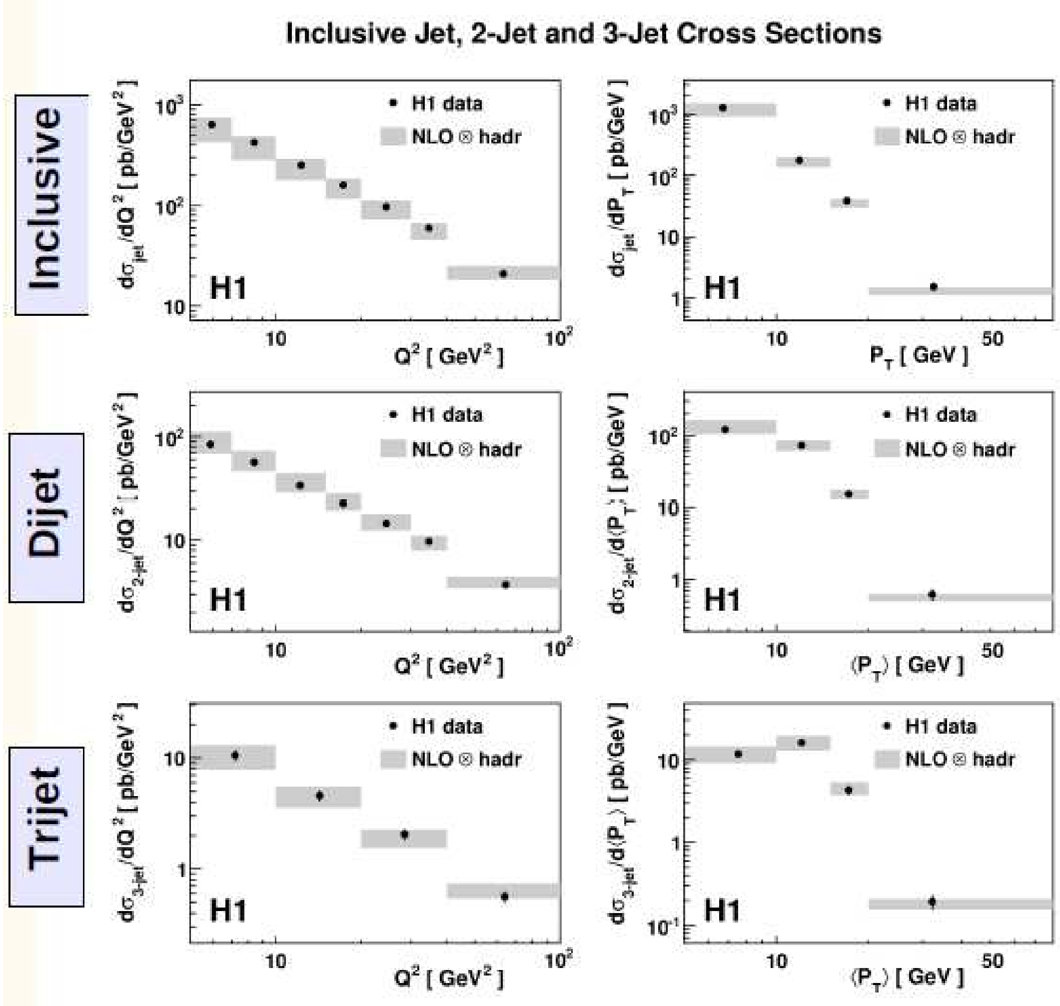
H1 Low Q^2 DIS jets

Inclusive and multijet cross sections as functions of Q^2 and p_T

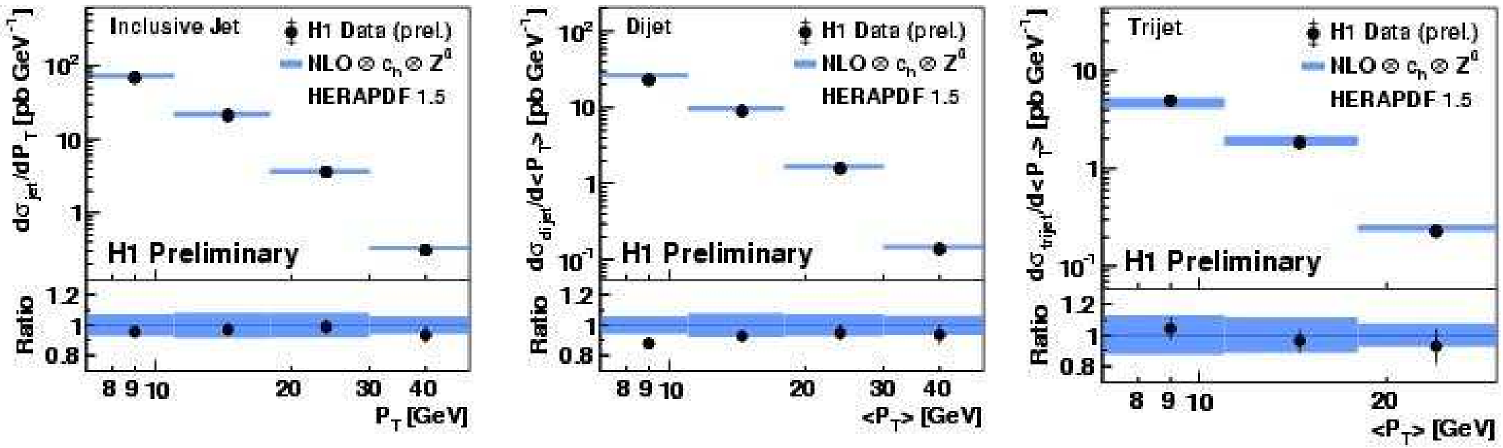
Note vertical log scale

Theoretical uncertainty is larger than experimental at low Q^2

Trend of data well described by NLO QCD



High Q^2 Selection



$\int L dt = 350\ \text{pb}^{-1}$; k_T jet algorithm in Breit frame

$150 < Q^2 < 15000\ \text{GeV}^2$; $0.2 < y < 0.7$; $-1.0 < \eta_{lab}^{jet} < 2.5$

Inclusive jets: $7 < p_{B,T}^{jet} < 50$ GeV

Dijets and trijets: $7 < p_{B,T}^{jet} < 50$ GeV; $M_{ij} > 16$ GeV

Data corrected for detector effects and QED radiation

NLO corrected for hadronisation and Z^0 exchange (NLOJet++)

using HERAPDF1.5; $\alpha_S(M_Z) = 0.118$; $\mu_r = \mu_f = \sqrt{(Q^2 + p_T^2)/2}$

Uncertainty in NLO: vary μ_r, μ_f by factor of 2

Inclusive jet cross-sections

$\int Ldt = 350 \text{ pb}^{-1}; \;\; \Delta L / L = 2.5\%$

Phase space:

$150 < Q^2 < 15000 \text{ GeV}^2;$

$0.2 < y < 0.7; \;\; -1.0 < \eta_{lab}^{jet} < 2.5$

Inclusive jets: $7 < p_T^{jet} < 50$ GeV

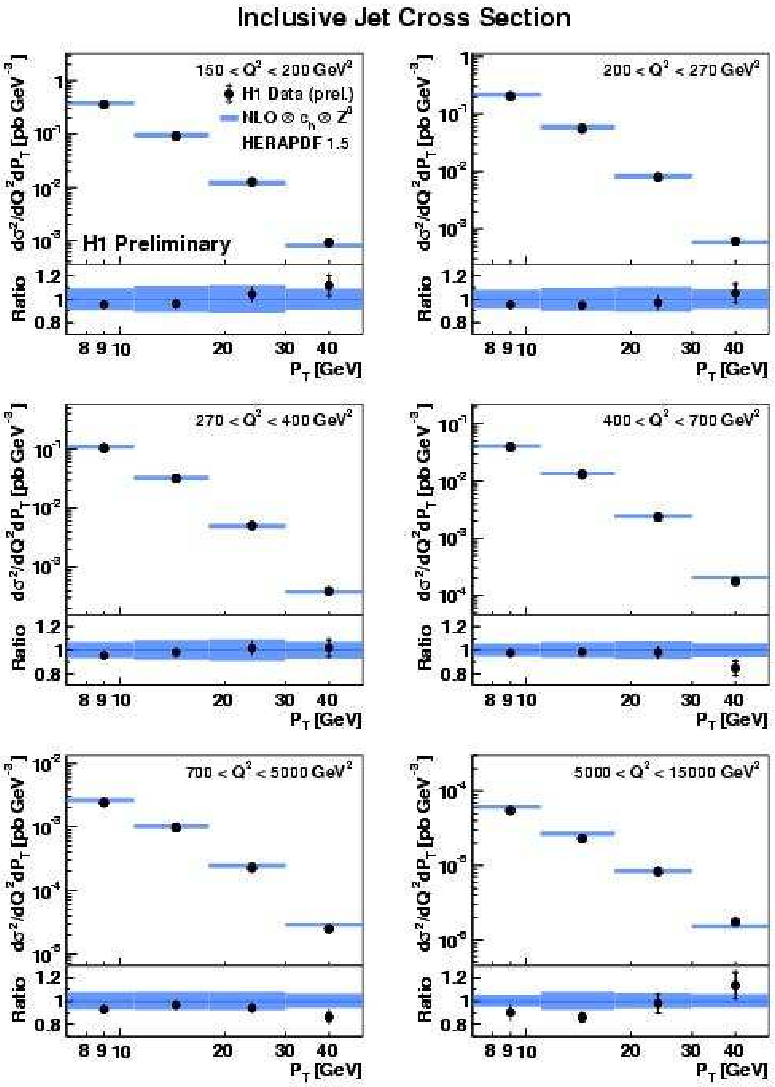
Data well described by NLO over a large range of Q^2 and p_T

Jet energy scale 1% $\Delta E / E$

$\rightarrow \Delta\sigma/\sigma \sim 2-5\%$

Exp. uncertainties ~4-8%

about half theory uncertainty



NLO/data

Predictions for

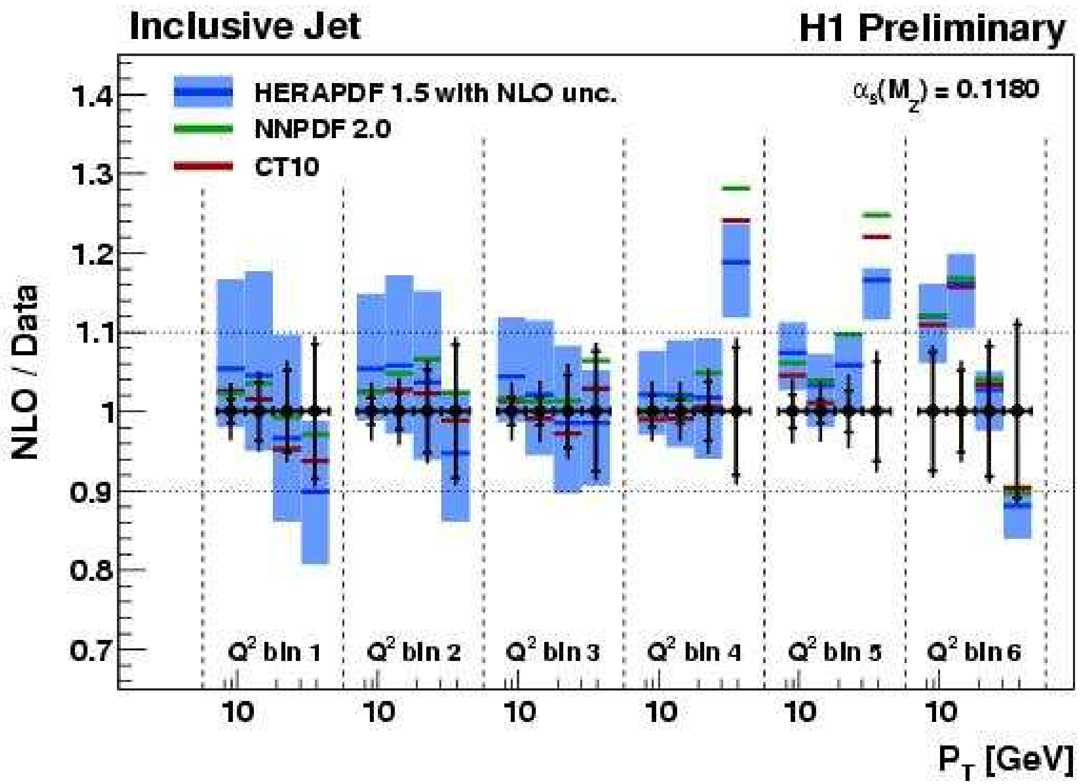
three PDF sets

Q^2 bins:

as in previous plot

Different x regions

for xg and xf probed



Some potential discrepancies at large Q^2 and large p_T

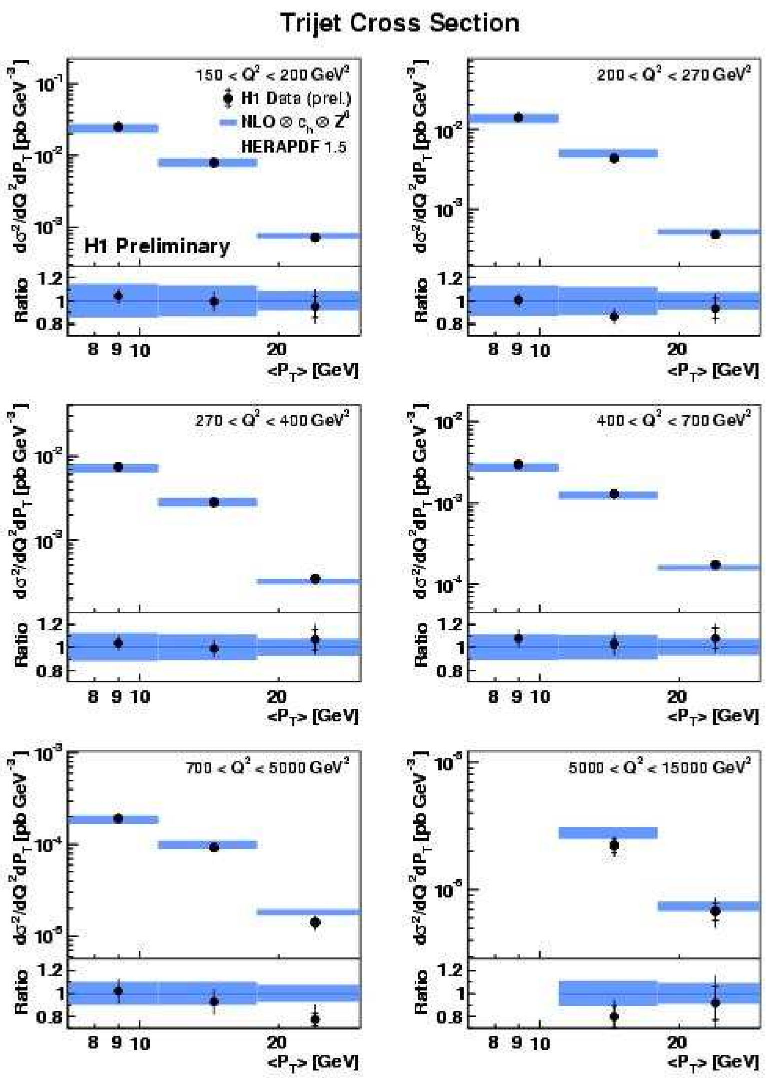
But shows potential of jet data to constrain proton PDF in global fits

Trijet cross-sections (H1)

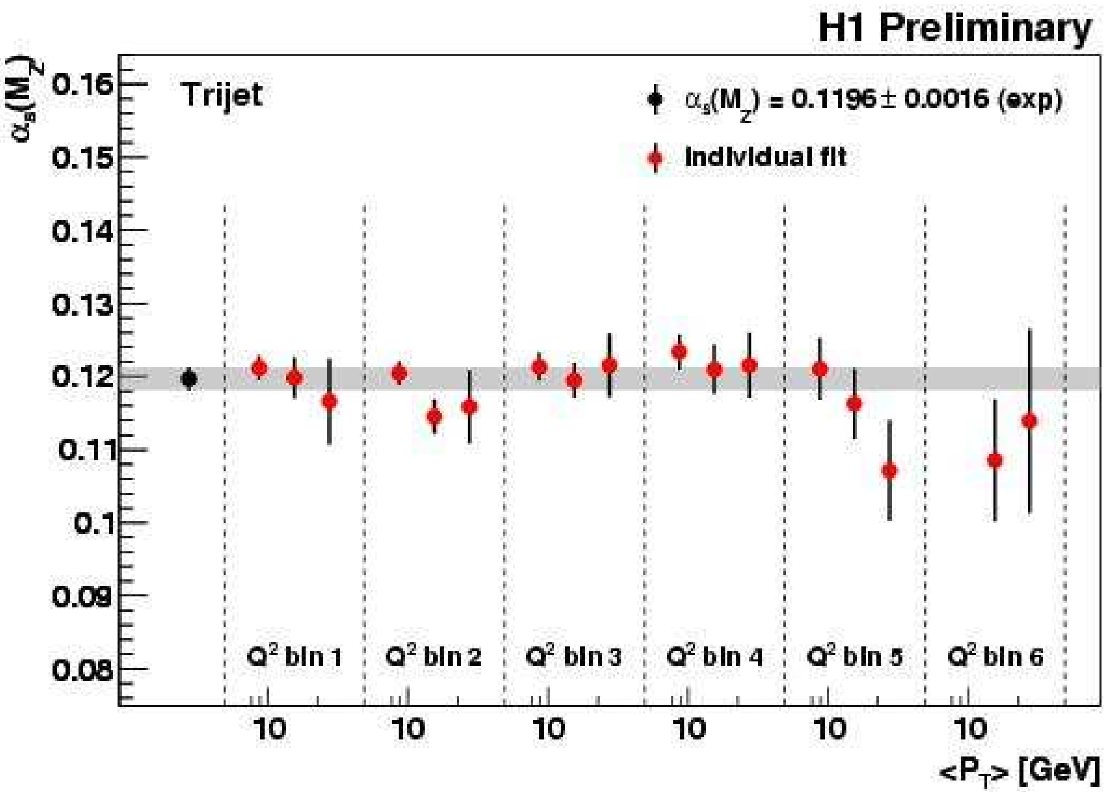
First double-differential
tri-jet cross-sections
at large Q^2

Exp. uncertainty:
~ 6% low $\langle p_T \rangle$
~ 15% high $\langle p_T \rangle$

Overall very good
agreement with NLO QCD



H1 trijets α_S measurement



Individual fits on all data points in Q^2 and $<p_T>$

Grey band shows experimental uncertainty of the simultaneous fit

Individual fit errors uncorrelated only; PDF, hadronisation uncert. not shown

α_S from jets (H1)

Inclusive Jet:

$$\alpha_s(M_Z) = 0.1190 \pm 0.0021\ (\text{exp.}) \pm 0.0020\ (\text{pdf})\ ^{+0.0050}_{-0.0056}\ (\text{th.})$$

Norm. Inclusive Jet (Eur. Phys. J C65, 363):

$$\alpha_s(M_Z) = 0.1195 \pm 0.0010\ (\text{exp.}) \pm 0.0018\ (\text{pdf})\ ^{+0.0049}_{-0.0036}\ (\text{th.})$$

Dijet:

$$\alpha_s(M_Z) = 0.1146 \pm 0.0022\ (\text{exp.}) \pm 0.0021\ (\text{pdf})\ ^{+0.0044}_{-0.0045}\ (\text{th.})$$

Norm. Dijet (Eur. Phys. J C65, 363):

$$\alpha_s(M_Z) = 0.1155 \pm 0.0009\ (\text{exp.}) \pm 0.0017\ (\text{pdf})\ ^{+0.0042}_{-0.0031}\ (\text{th.})$$

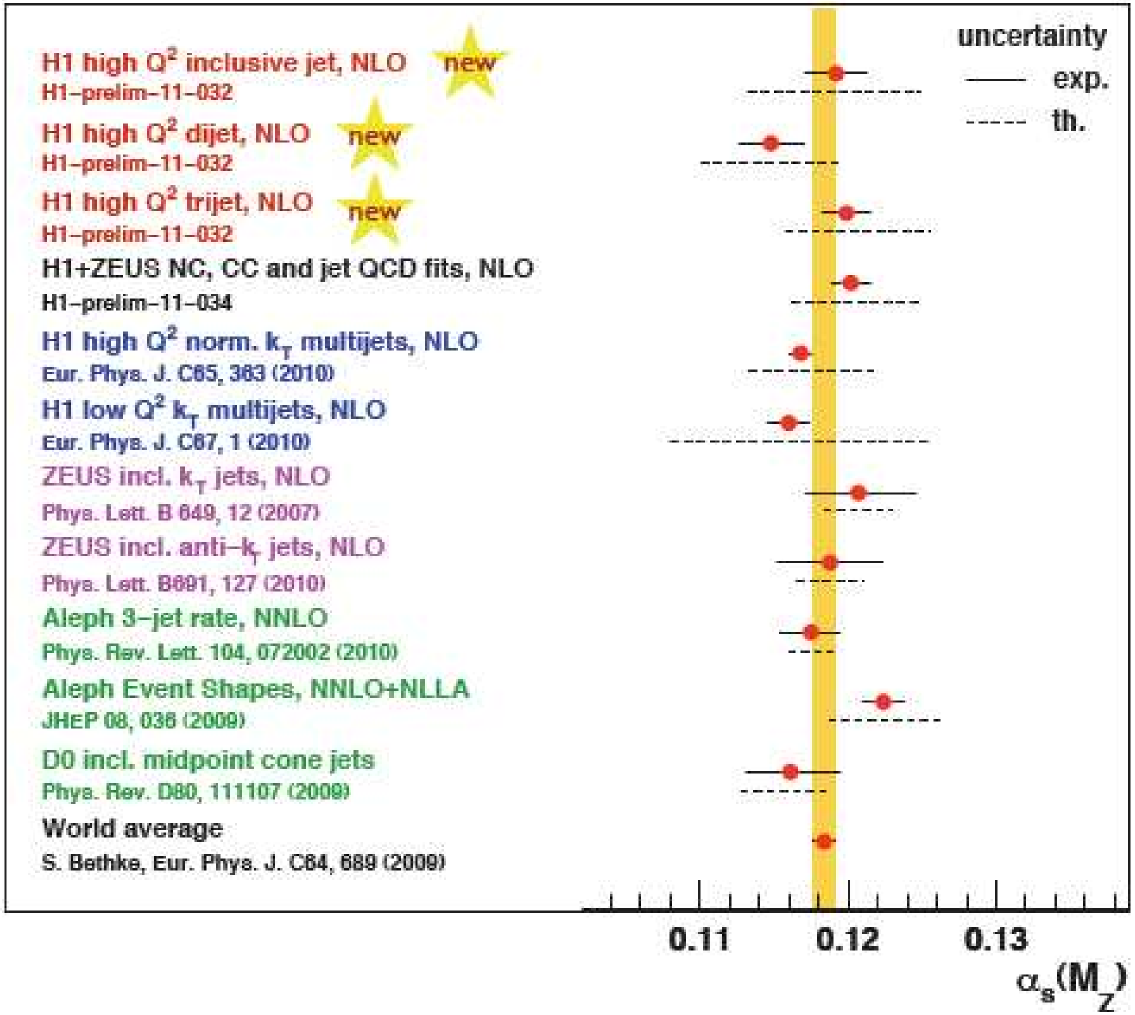
Trijet:

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016\ (\text{exp.}) \pm 0.0010\ (\text{pdf})\ ^{+0.0055}_{-0.0039}\ (\text{th.})$$

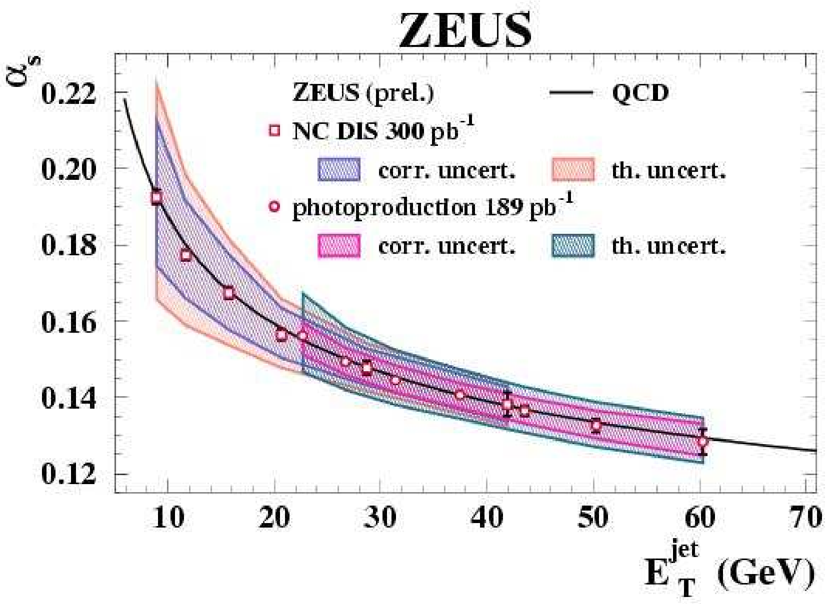
Norm. Trijet (Eur. Phys. J C65, 363):

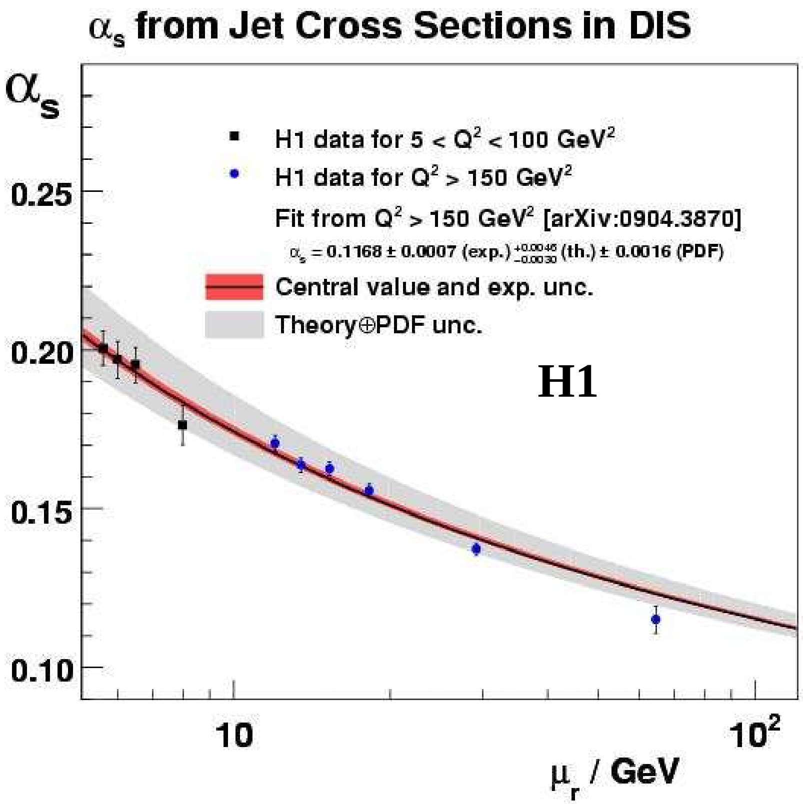
$$\alpha_s(M_Z) = 0.1172 \pm 0.0013\ (\text{exp.}) \pm 0.0009\ (\text{pdf})\ ^{+0.0052}_{-0.0031}\ (\text{th.})$$

α_S – comparison



Running α_S





- Inclusive k_T jet algorithm for both ZEUS and H1
- ZEUS shows α_S as function of E_T^{jet} on a linear scale
- H1 shows α_S as function of μ_r on a log scale

Summary

- QCD very thoroughly probed at HERA by H1 and ZEUS
  - large p_T jets the key experimental tool
  - different jet algorithms used
  - different detectors
  - different methods of reconstruction
- Results from the two experiments in very good agreement
- Competitive measurements of $\alpha_S(M_Z)$

- NNLO QCD estimates or calculations eagerly awaited...