NEW RESULTS FROM JET PHYSICS AT HERA

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2nd HERA-LHC Workshop
June 2006

OVERVIEW

- **Hard jets at HERA**
- **New jet results from HERA**
  - ZEUS inclusive jets at Q^2 and α_s (… and the positive effects on PDFs)
  - H1 inclusive jets at high Q^2 and α_s
  - ZEUS dijets at high Q^2 (and the PDFs)
  - H1 multijets at high Q^2 and α_s
  - H1 dijets in photoproduction
  - ZEUS multijets in photoproduction
    (not shown here, see talk in this workshop by T. Namsoo)
- **Summary on α_s from jets at HERA**
- **(HERA) jet physicists wish-list**

HARD JETS AT HERA "why, what and how" ...

"HERA provides a unique laboratory for the study of the hadronic final state"

Jet production cross section:

$$\sigma = \sum_{m=1}^{2} \alpha_s^m(\mu_r) \sum_{a=q,\bar{q},g} f_a(\eta,\mu_f) \otimes \hat{\sigma}(x_{Bj}/\eta,\mu_r,\mu_f)$$

Series expansion in powers of α_s

f_a: parton a density (long distance, determined from experiment)

$\hat{\sigma}$: sub-process cross section (short distance, calculable in pQCD)

Study of jets in the hadronic final state allows:

- stringent tests of our understanding of QCD (pQCD, factorisation, PDF universality)
- extraction of QCD parameters $\rightarrow$ fit data with NLO QCD $\Rightarrow$ extract α_s
- constraints on proton (and photon) parton distributions
- highlight areas that require further theoretical input/understanding, …

Tools:

- excellent understanding of detector (jet-energy-scale known to 1-3%)
- jet algorithm: k_T clustering (infra-red/collinear safe, small corrections,..)
- selection criteria: jets at high-E_T/Q^2, asymmetric cuts,…
- observables proportional to α_s (e.g. Breit frame in DIS, ratios, …)
- NLO QCD calculations (e.g. DISENT, NLOJET++)
  - scale $\mu_{r,f}$ = Q, E_T (or some combination), correct to hadron level with PS models, up-to-date PDFs

many measurements dominated by theory uncertainties: scale, hadronisation, α_s, PDFs

REMEMBER: importance of jet physics for LHC (background to all searches, understanding of detector/calibration/tools etc.)

HERA KINEMATICS

- Negative four-momentum transfer squared:

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

- Bjorken scaling variable:

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

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- Inelasticity:

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

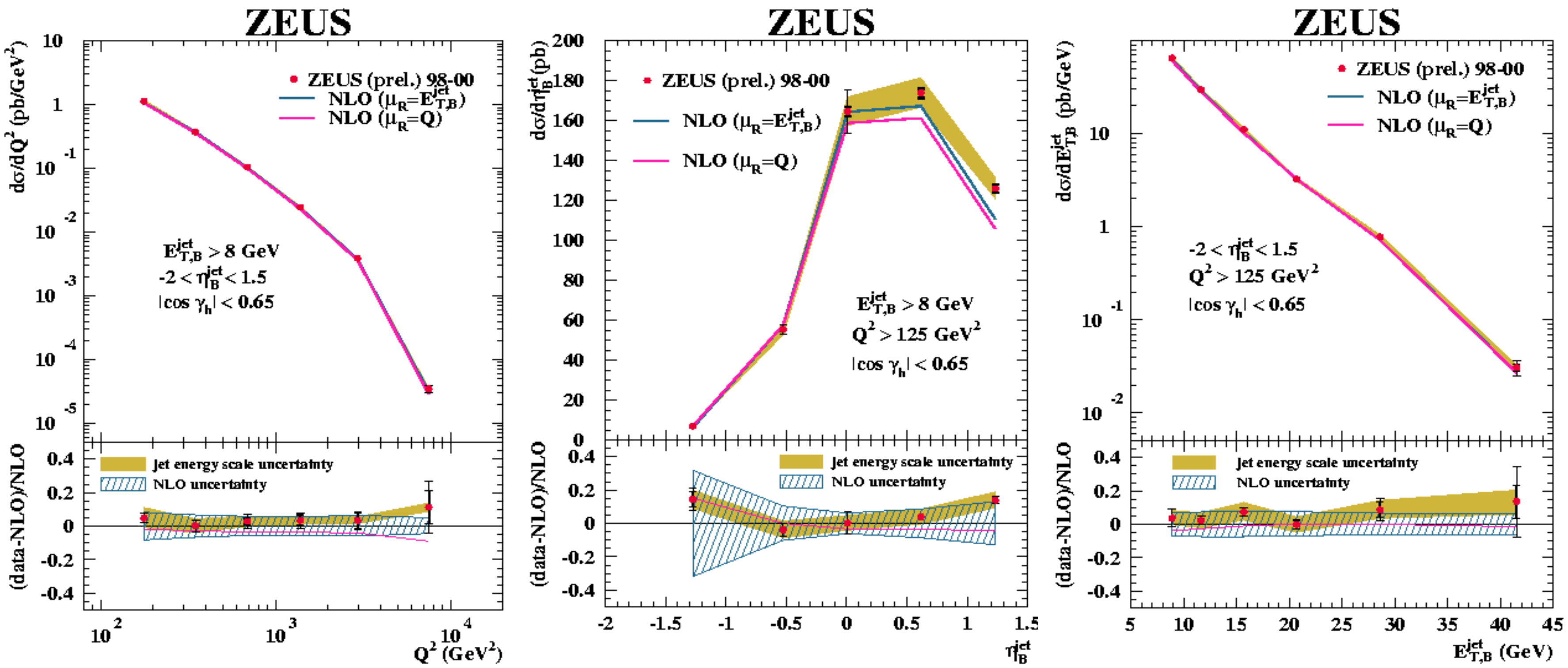
Only need two out of three variables since $Q^2 = sxy$

ZEUS INCLUSIVE JETS AT HIGH Q^2

`Simple' measurement – take PDFs/α_S as given

Phase Space:
$Q^2 > 125\ GeV^2$
$E_T(Breit) > 8\ GeV$
$-2 < \eta(Breit) < 1.5$
$|\cos\gamma_h| < 0.65$

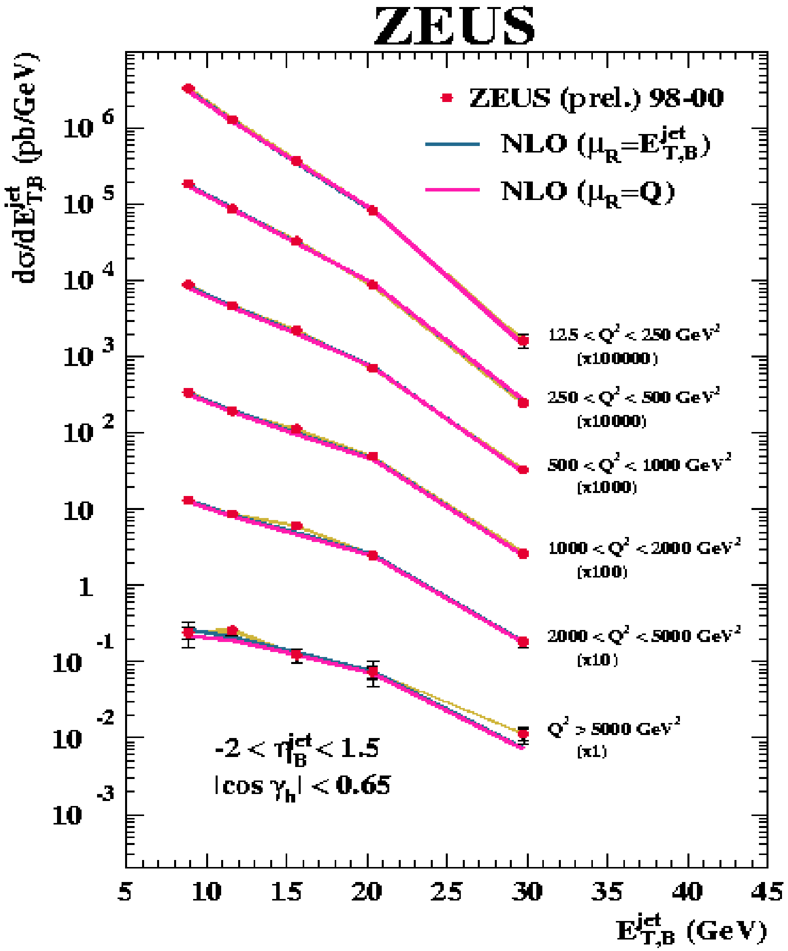
- **Tests**: understanding of pQCD, factorisation, PDF universality,…
- **Data**: 82 pb^{-1} e^+p data from 98-00
- **Aims**: extraction of strong coupling, use data in QCD fits for PDF constraints

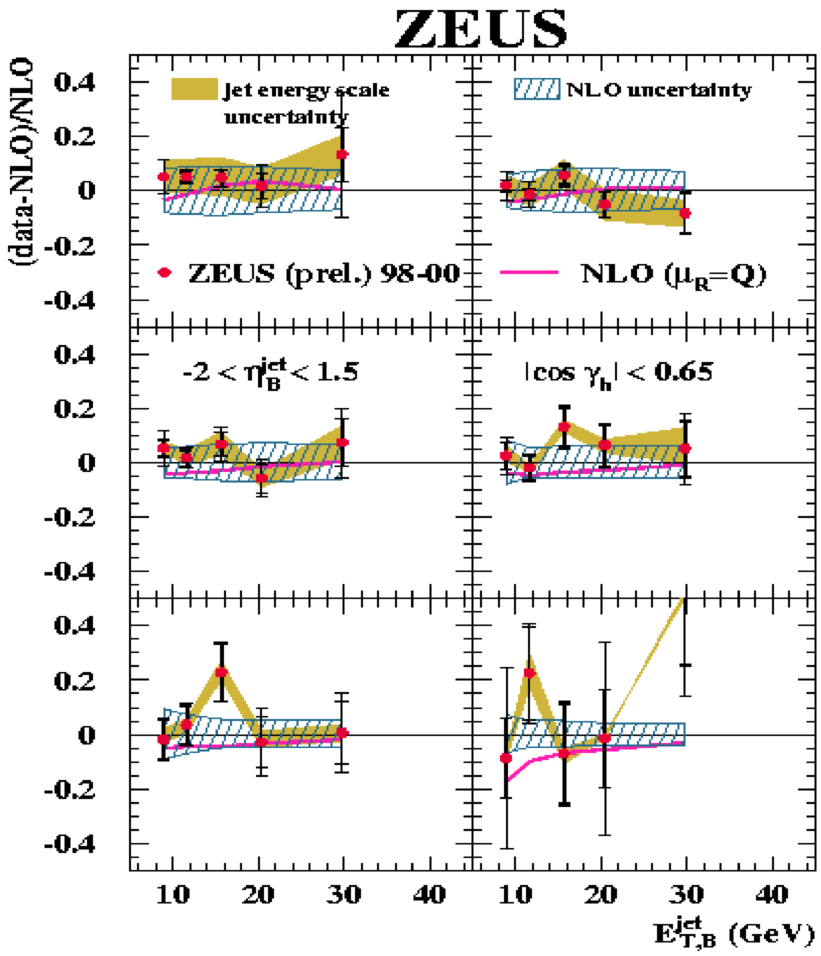


- Data well described by NLO theory (DISENT, CTEQ6M)
- Uncertainties mostly dominated by scale variation effect ($1/2\mu_{r,f} < \mu_{r,f} < 2\mu_{r,f}$)

ZEUS INCLUSIVE JETS

Also double-differentially, comparison to NLO





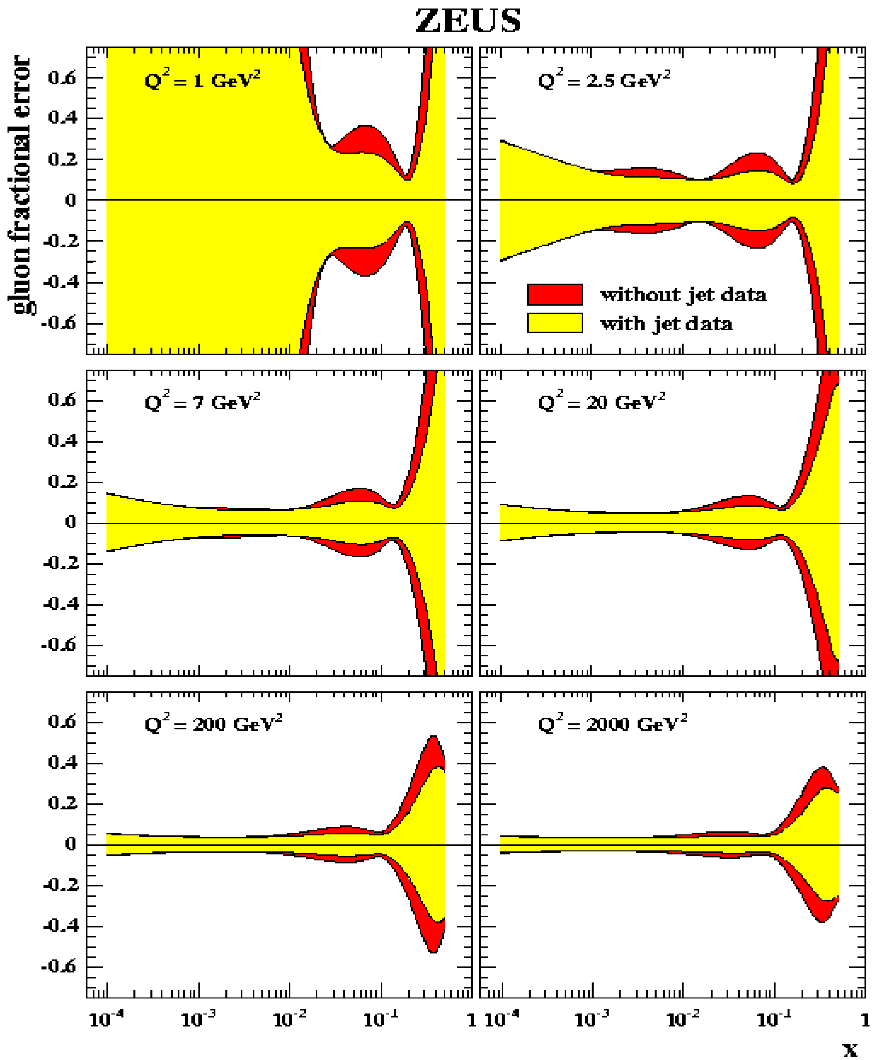
E_T and Q^2 dependence → PDF information
(use data in QCD fits as 96/97 measurement)

Ratio with NLO QCD: data well described

REMINDER: PDFs VIA INCL. JETS

Aim: reduction of gluon error via BGF process

- Structure functions alone leave large uncertainty of PDFs (especially gluon) at high momentum fractions
- Jet data provide access to this regime
- (Technically demanding) inclusion of jet data in QCD fits leads to significant improvement of gluon uncertainty at medium and high momentum fractions
- **Data sets (both 96-97 ZEUS data):**
  - DIS inclusive jets (predecessor to this analysis!)
  - Dijets in photoproduction
- **Future plans**: include **new** high-Q^2 98-00 ZEUS inclusive and dijets (see later)
- Programs like FASTNLO provide systematic way of using jet data in fits



α_s *FROM ZEUS INCLUSIVE JETS*

in bins of E_T and combined

Single differential cross sections in Q^2 and E_T(Breit) used to extract α_s in each cross section bin

measured cross section point

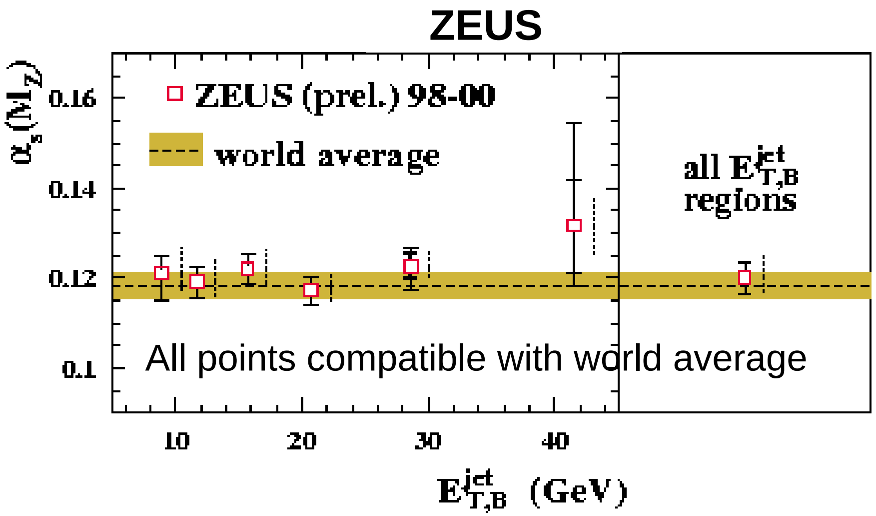
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

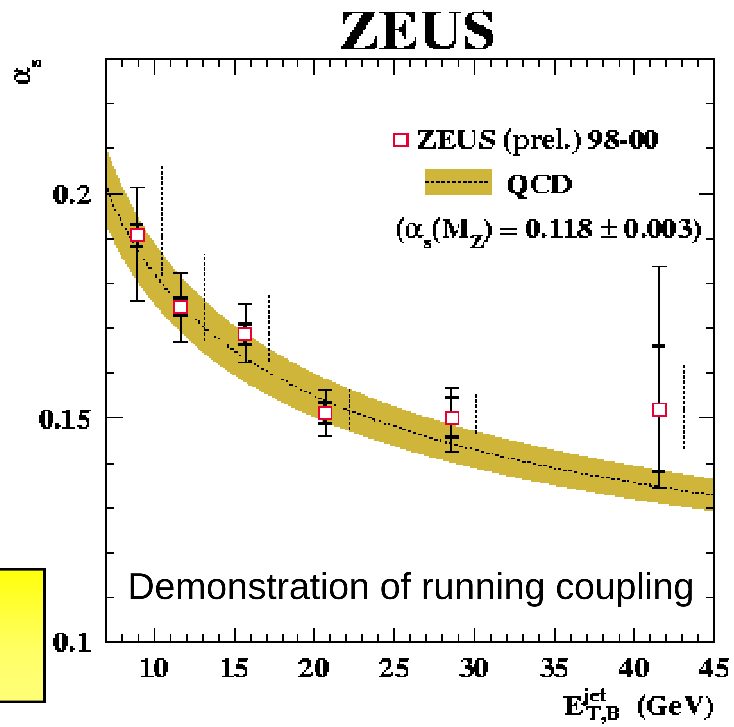
parameterisation

NLO QCD predictions

PROCEDURE:

- use set of proton PDFs with different $\alpha_s(M_Z)$ e.g. MRST99
- parameterise α_s dependence of cross section prediction using function: $\sigma(\alpha_s(M_Z))=A_i\, \alpha_s(M_Z) + B_i \,.\, \alpha_s^2(Mz)$
- extract value of α_s from measured cross section



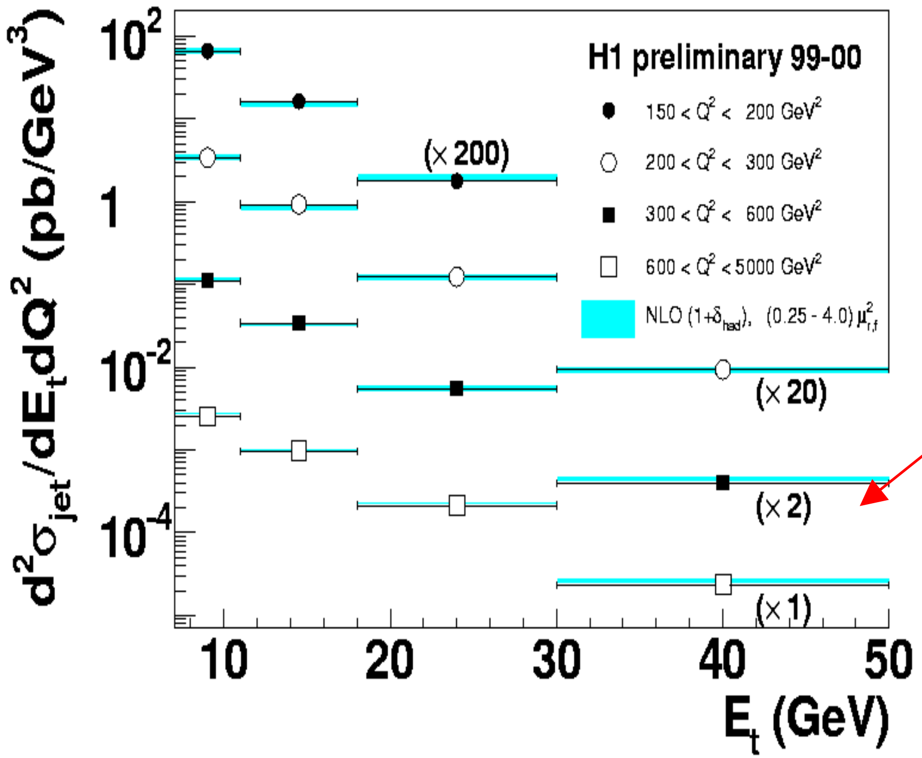


ZEUS inclusive jets (best value for Q^2 > 500 GeV^2):
$\alpha_s(M_Z)$ = 0.1196±0.0025(exp.)±0.0023(theory)

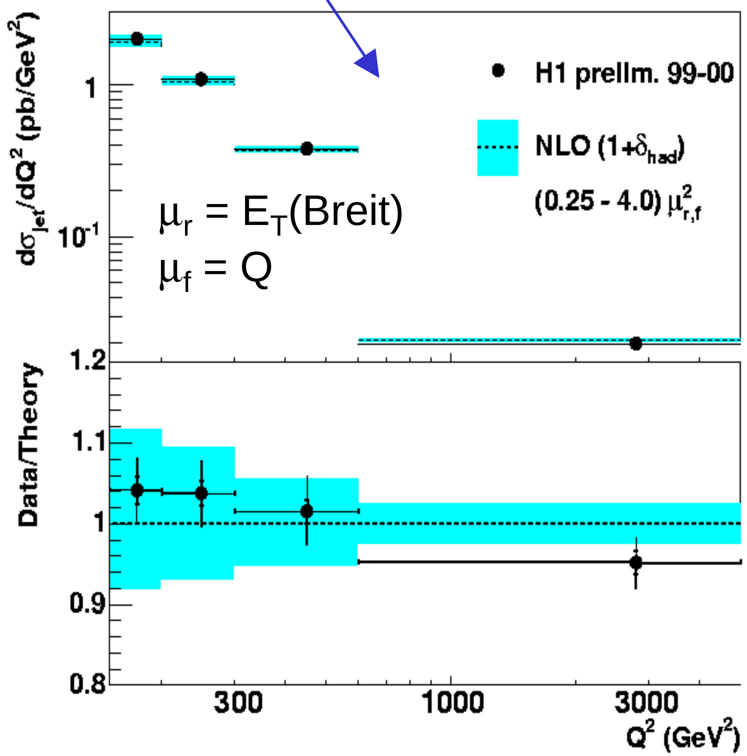
c.f. world average: $\alpha_s(M_Z)$ = 0.1187±0.0020

H1 INCLUSIVE JETS AT HIGH Q^2

As function of E_T in bins of Q^2



- Data: 61.3 pb^{-1} from 99-00 e^+p data
- Phase Space (similar to ZEUS analysis):
  - $150 < Q^2 < 5000$ GeV^2
  - $0.2 < y < 0.6$
  - E_T(Breit) > 7 GeV
  - $-1.0 < \eta_{Lab} < 2.5$
- Cross sections:
  - Single differential in E_T(Breit) and Q^2
  - Double differential in E_T(Breit) and Q^2

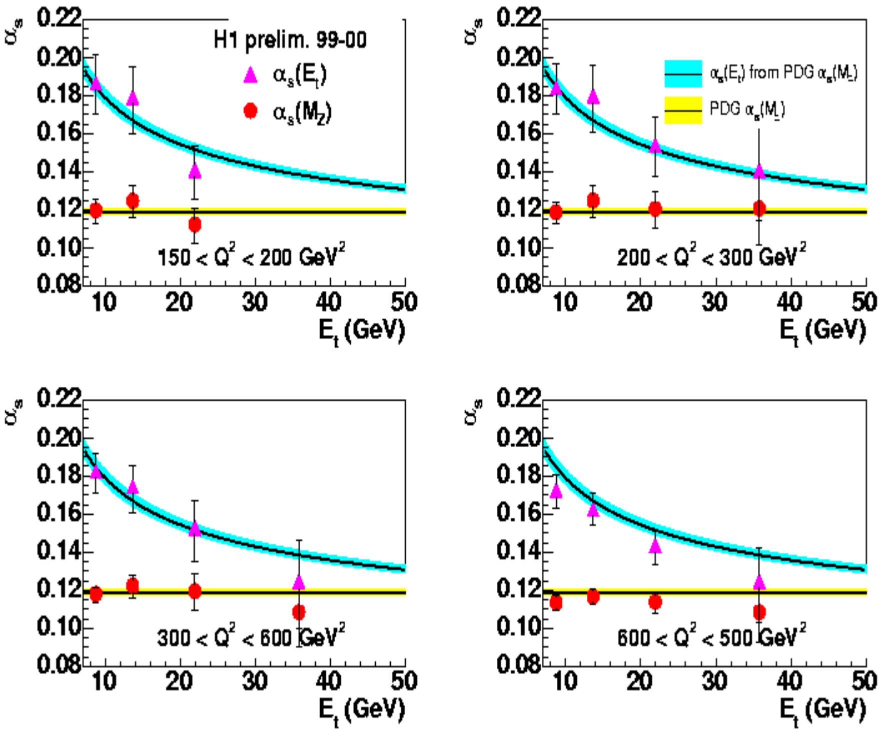


- Very good agreement of data and NLO QCD (NLOJET++, CTEQ5M1) within all uncerts.
- Uncertainty dominated by scale variation effect

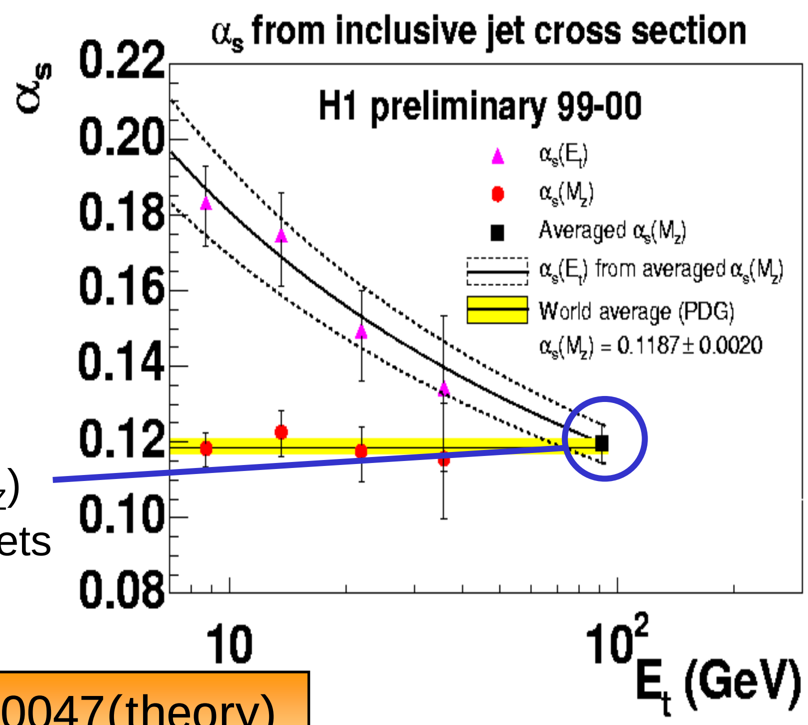
  N.B. $\mu_r=E_T$(Breit) (shown) gives smaller uncert. than $\mu_r=Q$

H1 INCLUSIVE JETS

extraction of strong coupling



- Coupling $\alpha_s(M_Z)$ [also $\alpha_s(<E_T>)$] extracted from double differential cross section in E_T(Breit) and Q^2 (15 data points) and single differential cross section in E_T(Breit)
  - all single measurements consistent



- 15 double differential points used for average $\alpha_s(M_Z)$
- Result consistent with world average + ZEUS incl. jets
- Theory error dominates (effect of higher orders)

H1 inclusive: $\alpha_s(M_Z) = 0.1197 \pm 0.0016(\text{exp}) \pm 0.0047(\text{theory})$

c.f. ZEUS inclusive: $\alpha_s(M_Z) = 0.1196 \pm 0.0025(\text{exp}) \pm 0.0023(\text{theory})$

ZEUS DIJETS AT HIGH Q^2

Motivation

IDEA:

- PDFs characterized by variables Q^2 and ξ (proton momentum fraction)
- In dijet events:

$$\xi = x_{Bj} \cdot \left(1 + \frac{M_{jj}^2}{Q^2}\right)$$

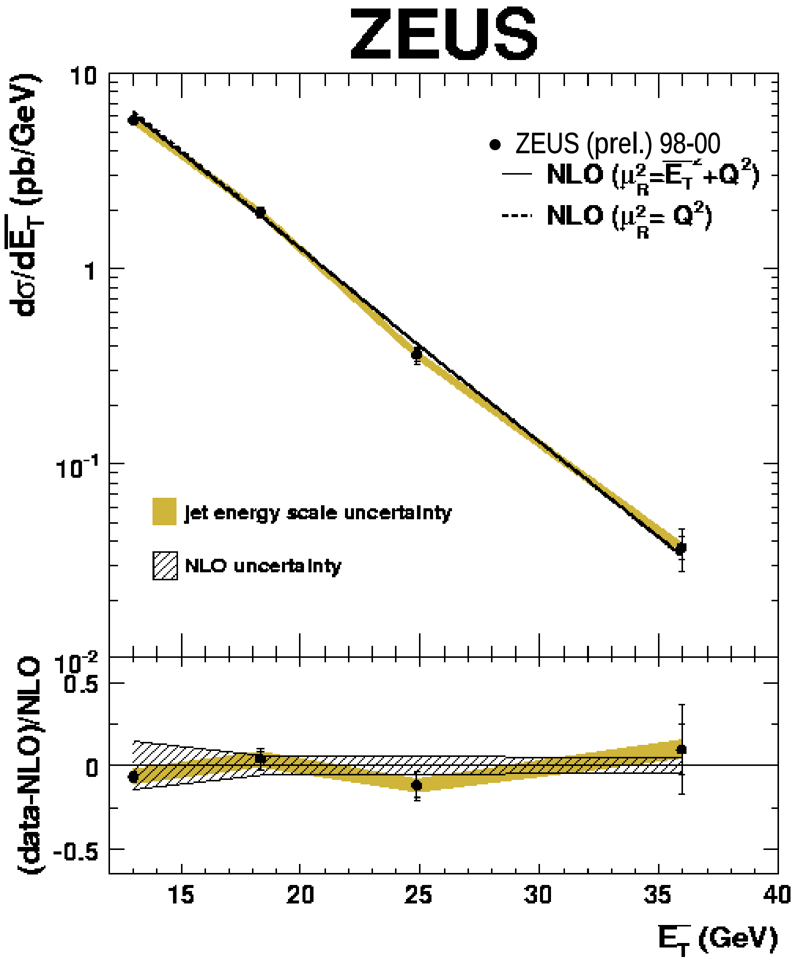
→ use dijets at high Q^2 from large 98-00 data sample (82 pb^{-1}) to obtain theoretically safe and precise information about PDFs (gluon at high ξ!)

ANALYSIS:

- Phase Space:
  - $125 < Q^2_{DA} < 5000$ GeV^2
  - $|\cos\gamma_{had}| < 0.65$
- Jet Selection
  - $-2.0 < \eta_{Breit} < 1.5$
  - $E_{T,1(2)} > 12$ (8) GeV
- Compare to NLO QCD (DISENT, CTEQ6)

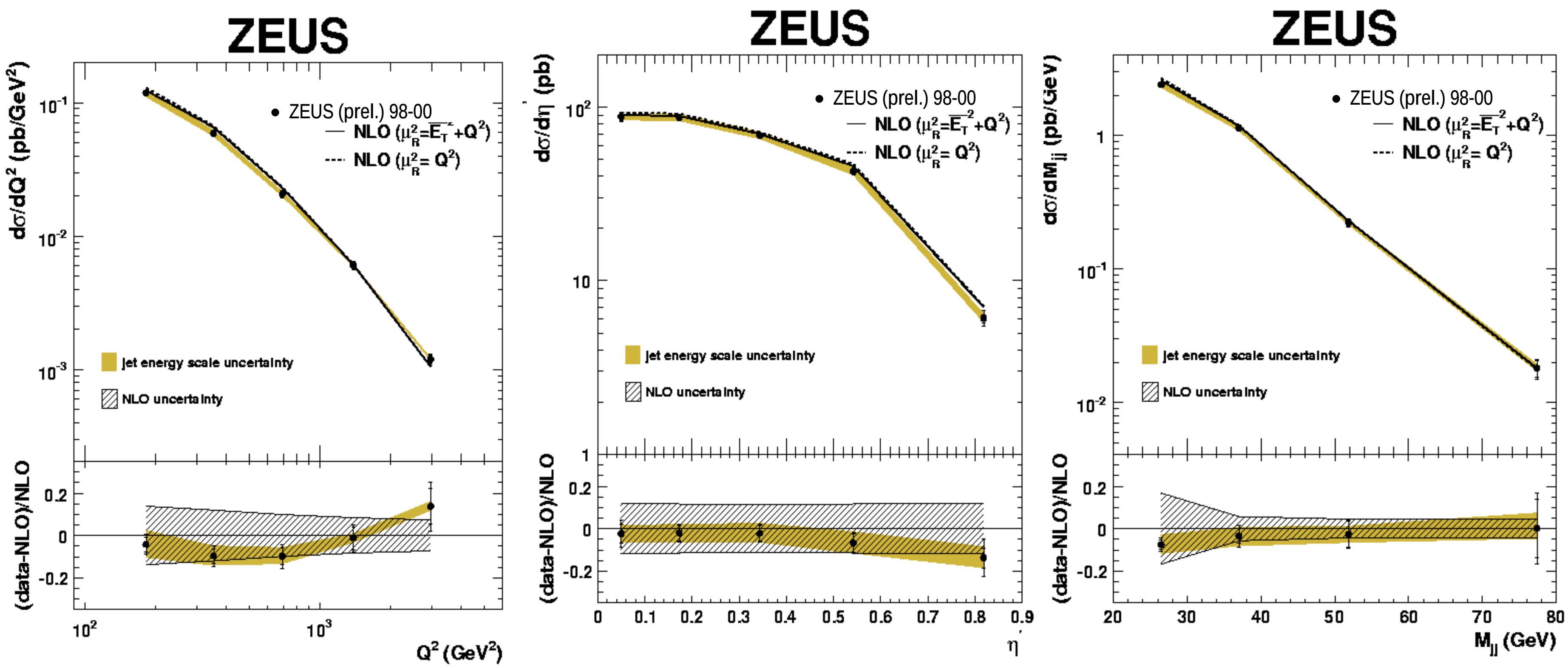
EXAMPLE: mean E_T of dijets

→ well described by NLO QCD !



ZEUS DIJETS AT HIGH Q^2

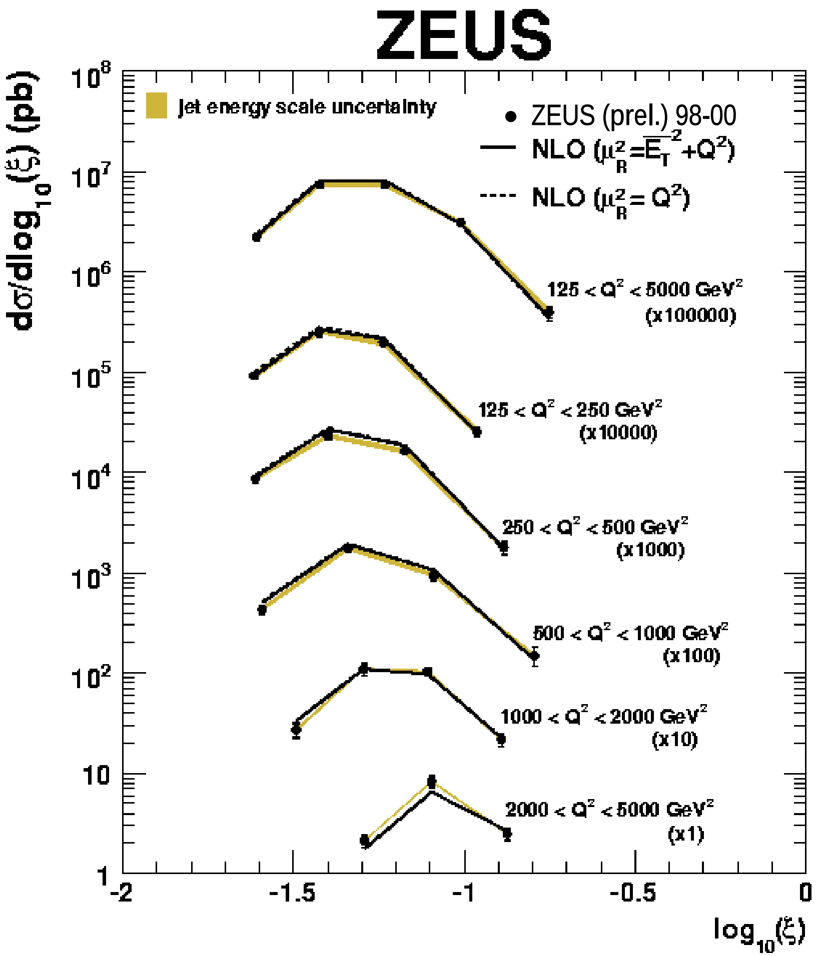
More single-differential results

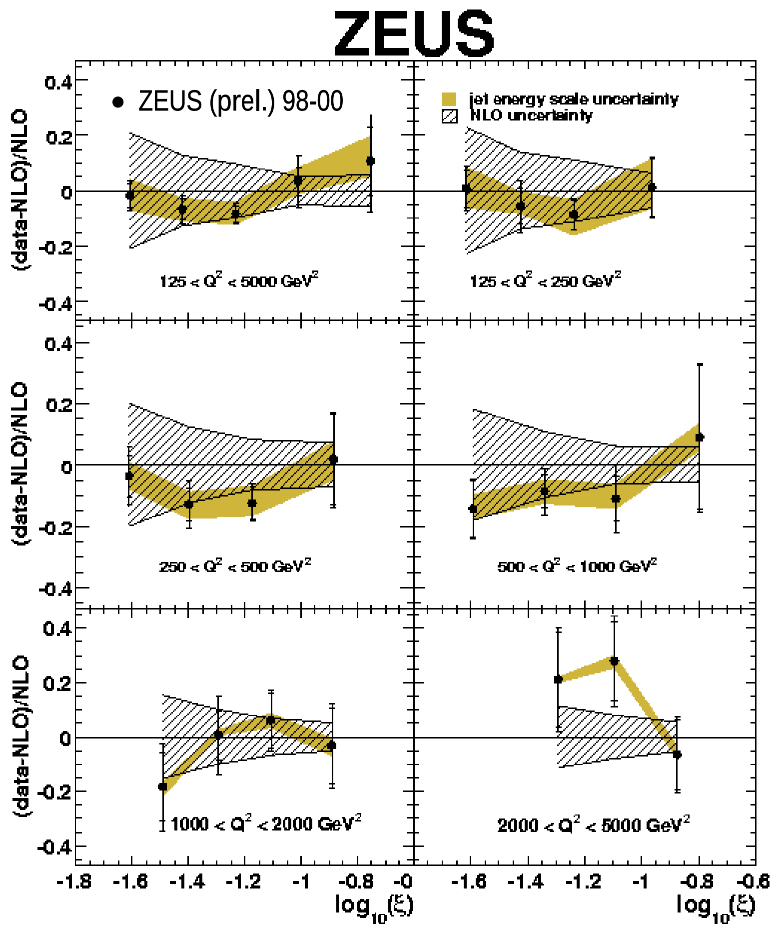


- Data nicely described by NLO theory corrected to hadron level
- Theoretical uncertainties almost everywhere larger than experimental uncertainties
  $\rightarrow$ dominating contribution from scale variation to estimate higher-order effects

ZEUS DIJETS AT HIGH Q^2

double-differential measurement: log(ξ) in Q^2 bins

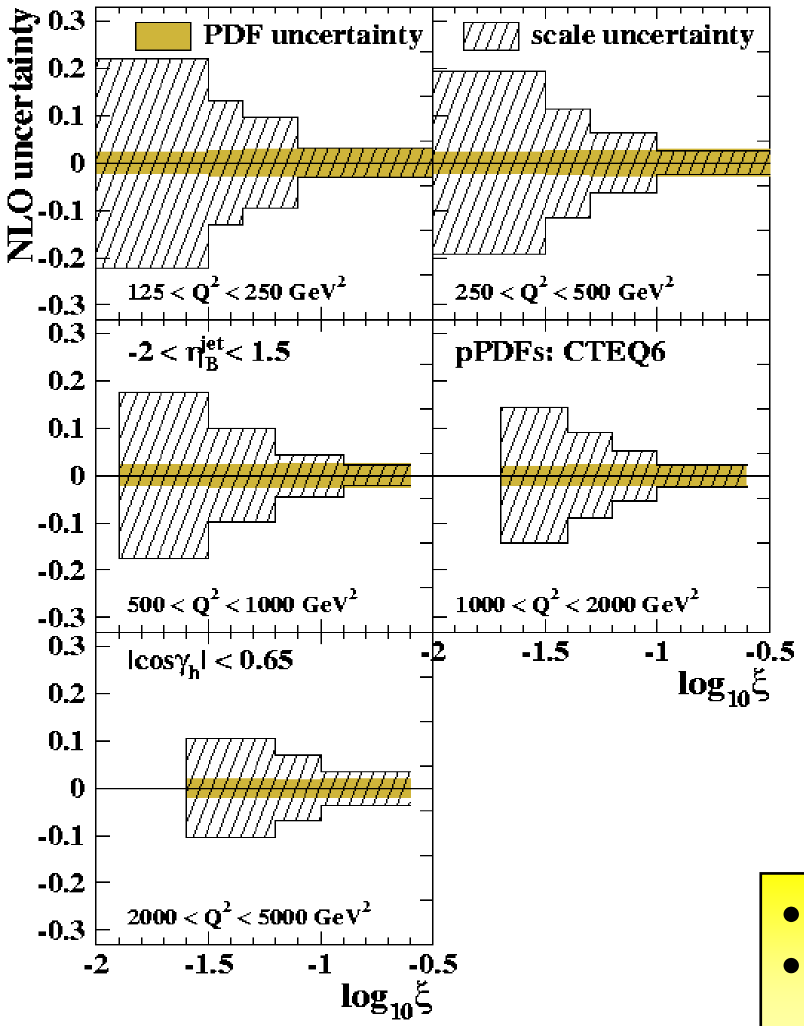




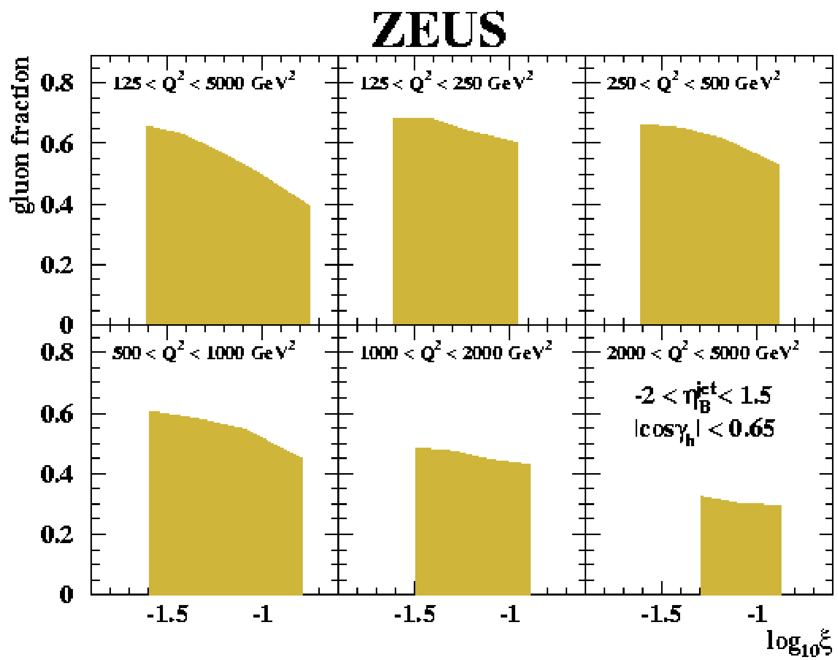
- Also double-differential data well described by NLO QCD
- Still large theoretical uncertainties; at high Q^2, statistics getting low

ZEUS DIJETS AND POTENTIAL FOR PDFs

theory uncertainty and gluon fraction



- scale uncertainty 5-20%, large at small ξ
- PDF uncertainty ≤3%, significant at high ξ



- gluon fraction decreases with increasing ξ and Q^2
- still substantial gluon contribution → use in NLO QCD fits of PDFs.

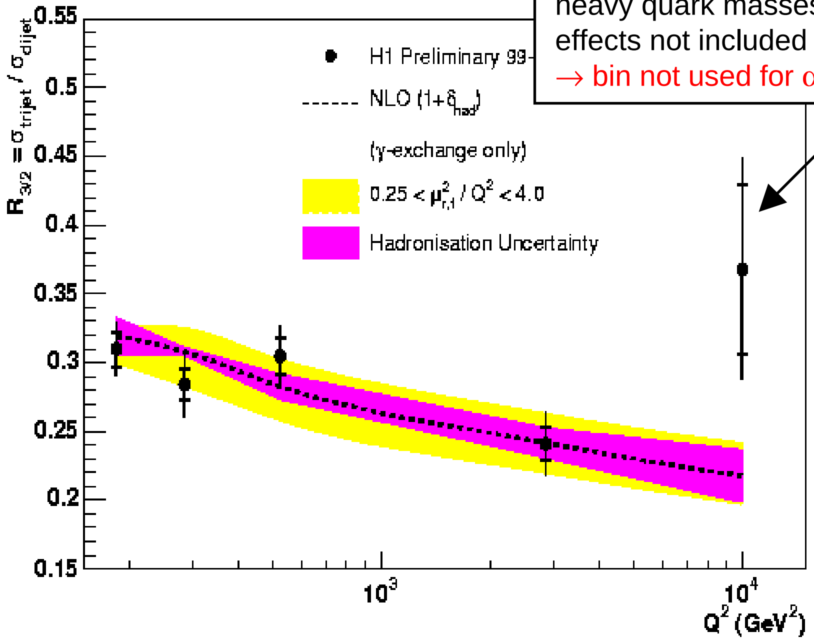
H1 MULTIJETS AT HIGH Q^2

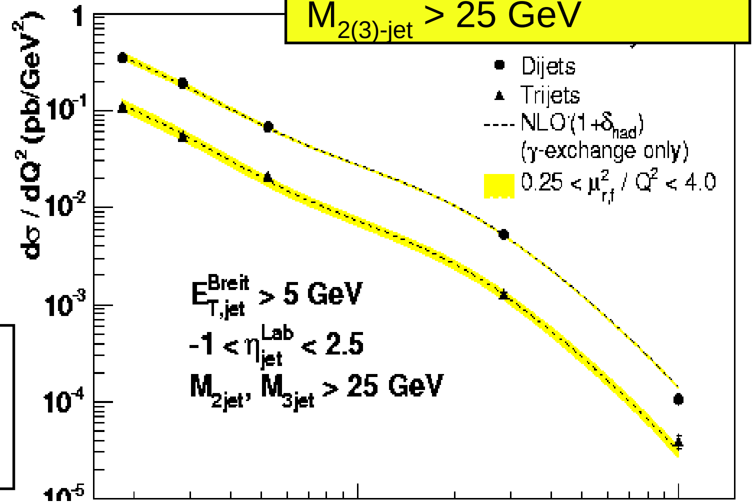
Di- and trijets from 99-00 data

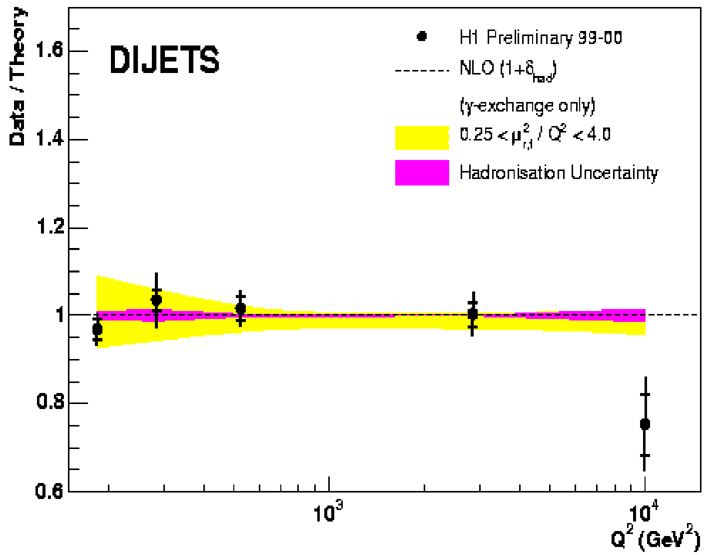
Phase Space:
150 < Q^2 < 15000 GeV^2
0.2 < y < 0.6
E_T(Breit) > 5 GeV
-1 < η_{Lab} < 2.5
$M_{2(3)\text{-jet}}$ > 25 GeV

- Analysis of di- and trijet events in large e^+p data sample from 99-00 (65.4 pb^{-1})
  (analysis similar to ZEUS DESY-05-019)
- NLO QCD (NLOJET++) gives excellent description
- In 3/2-jet ratio theoretical+experimental uncerts. (partly) cancel → use this quantity to extract α_s

Discrepancy in last bin due to heavy quark masses and EW effects not included in NLOJET
→ bin not used for α_s extraction

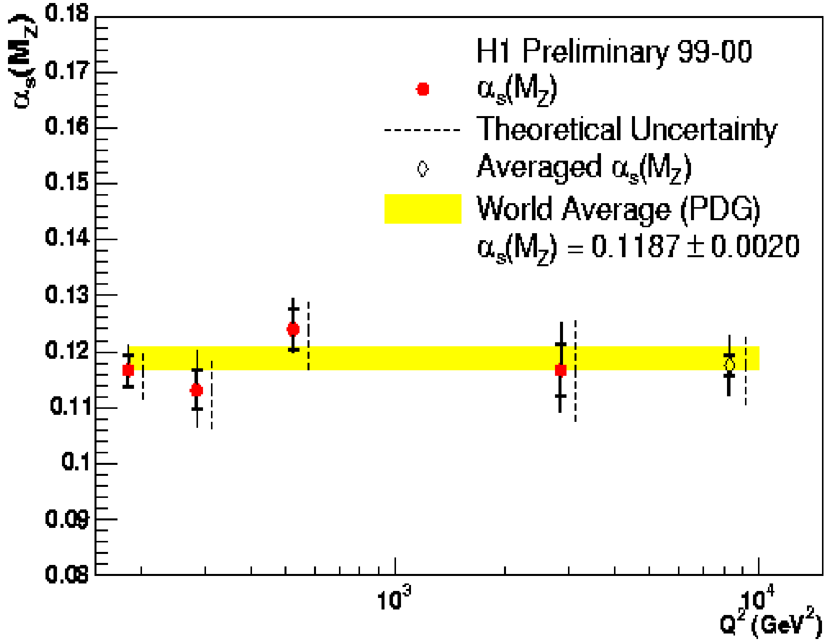




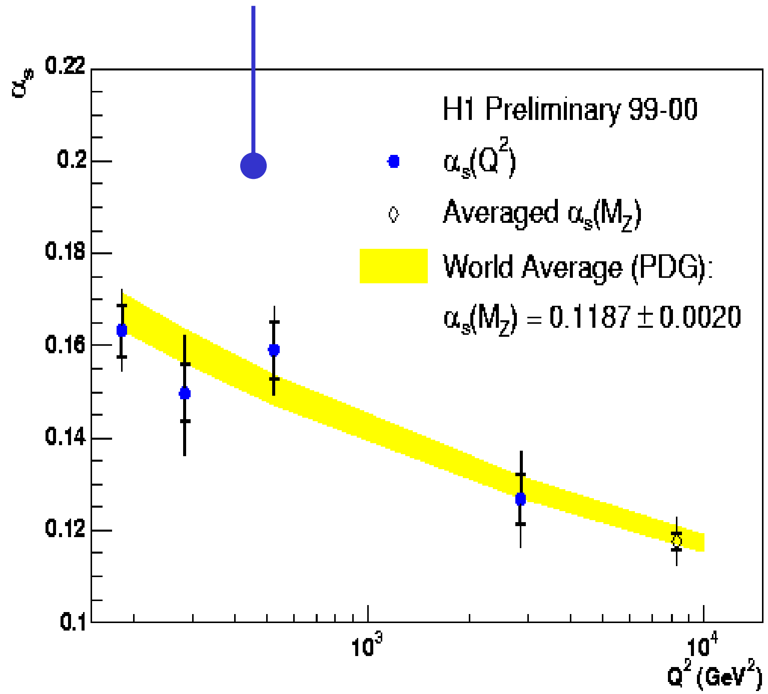


H1 MULTIJETS AT HIGH Q^2

Strong coupling from di- and tri-jets



- $\alpha_s(M_Z)$ extracted from 3/2-jet ratio as a function of Q^2
  - Single data points compatible with each other and with world average
- Nice demonstration of running coupling



- Resulting value for coupling:

$$\alpha_s(M_Z) = 0.1175 \pm 0.0017(\text{stat.}) \pm 0.0050(\text{syst.}) \pm 0.0061(\text{theory})$$

- Uncertainties larger than for inclusive jets
- Systematics and theory uncertainties closer in magnitude than for (H1) inclusive jets

H1 DIJETS IN PHOTOPRODUCTION

precise multi-differential test of QCD

$$|\cos\theta^*| = |\tan(\eta_1 - \eta_1)/2|$$

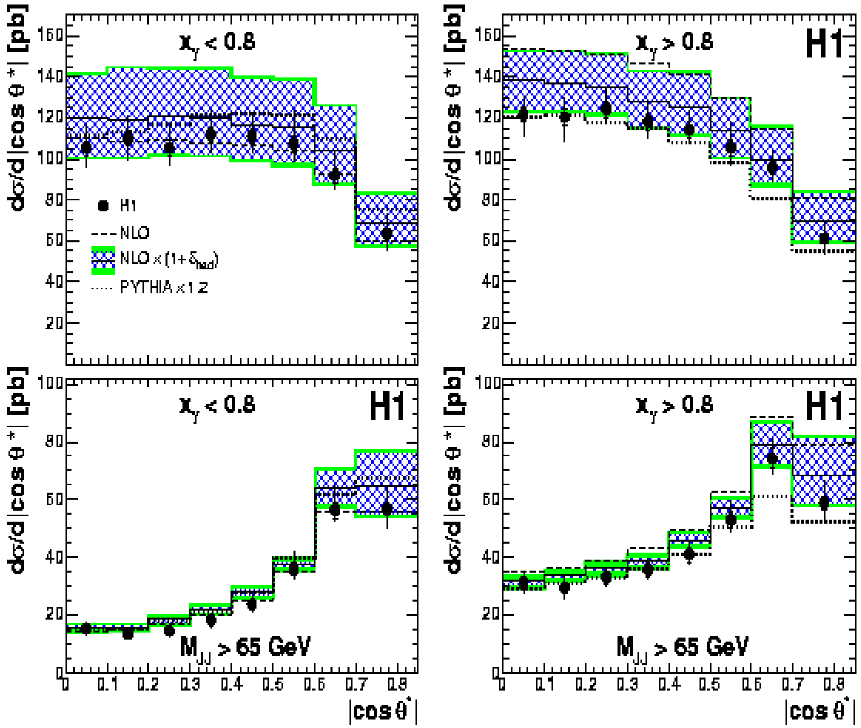
- Data set of 66.6 pb^{-1} e^+p from 99-00; large statistics allow differential measurement (14k events)
- Phase space (high-E_T jets, perturbatively "safe"):
  - $Q^2 < 1$ GeV^2; $0.1 < y < 0.9$
  - $E_T^{jet1,2} > 25$,15 GeV; $0.5 < \eta^{jet} < 2.75$
- Data might be used to exploit sensitivity to photon and proton PDFs
  - direct and resolved regimes via x_γ
  - proton momentum fractions x_p up to 0.7
  - disentangling gluon- and quark-initiated processes (Boson-Gluon-Fusion at low x_p)

$$x_\gamma = \frac{1}{2yE_e}\left(E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}\right)$$

$$x_p = \frac{1}{2E_p}\left(E_{T,1}e^{\eta_1} + E_{T,2}e^{\eta_2}\right)$$

Overall excellent demonstration of the power of pQCD

"resolved photon" enhanced — "direct photon" enhanced

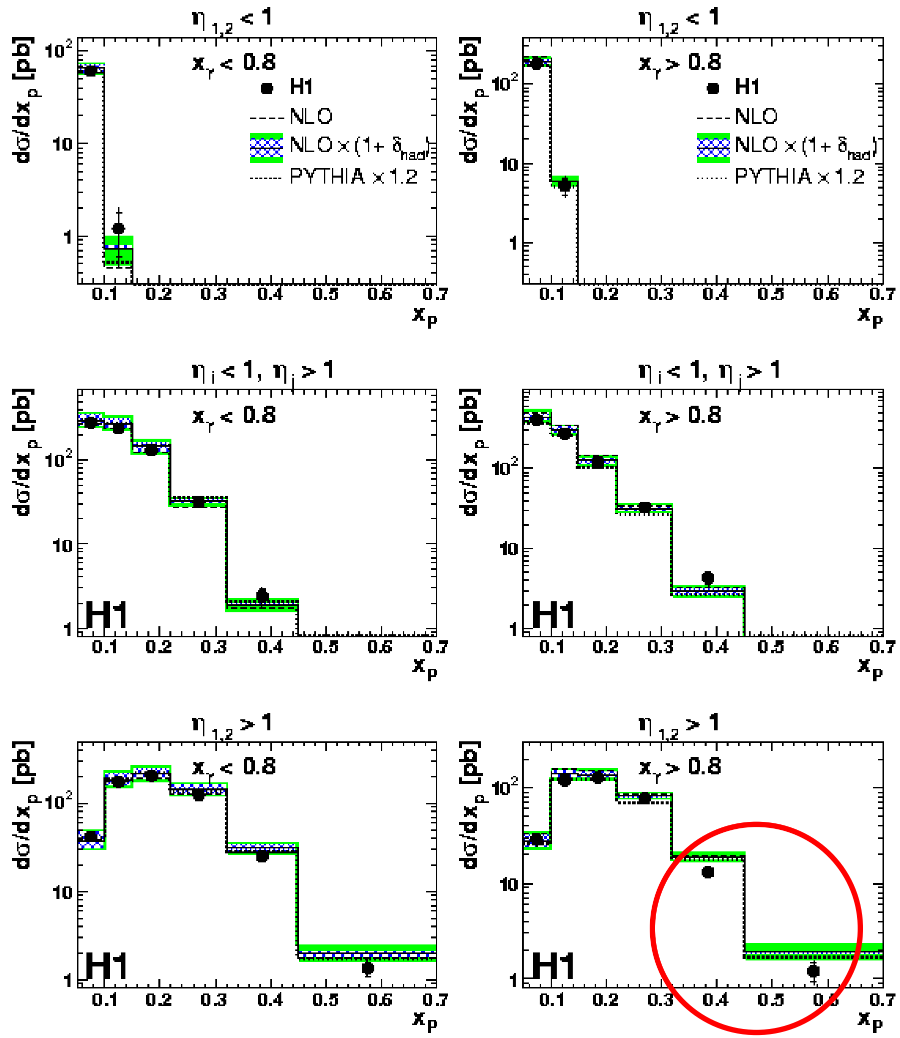


- Measurement in cosθ* gives access to dynamics of hard interaction → tests of pQCD
- High-E_T cuts suppress cross section at high cosθ*, for high M_{jj} is closer to ME expectations
- Faster rise in resolved than in direct → gluon/quark propagator spin

H1 DIJETS IN PHOTOPRODUCTION

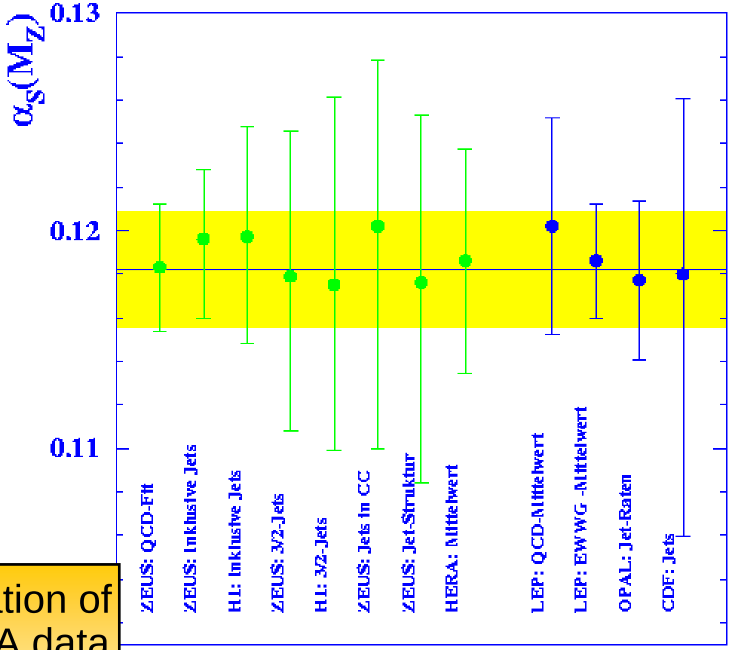
exploiting the dijet event topology

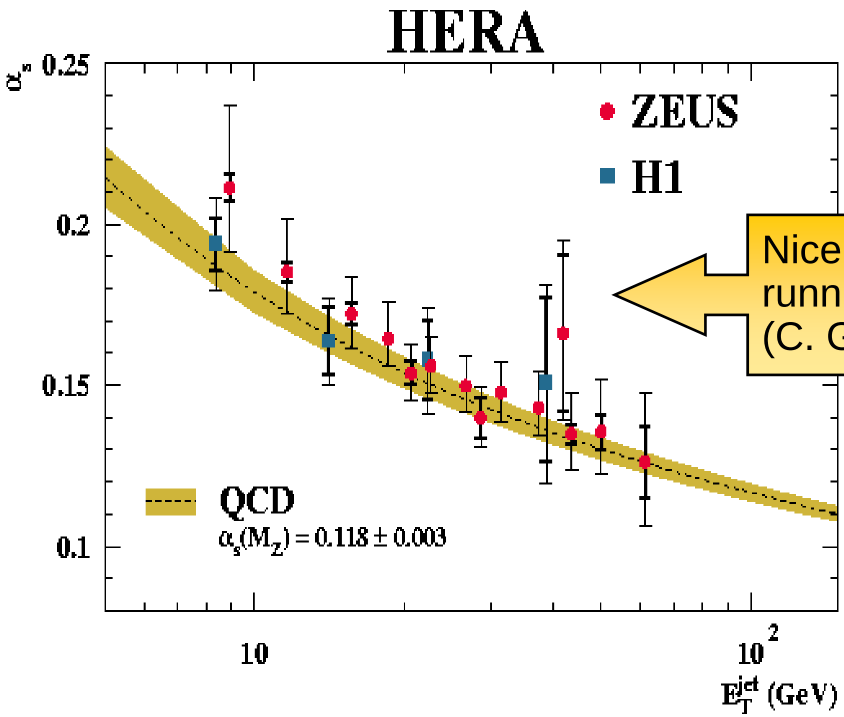
- Jet pseudorapidities sensitive to momentum distributions of incoming partons
  - → measure x_p for both jets "backwards", both jets "forward" and for one jet forward and the other backward, separately for resolved and direct
  - → learn about PDFs/dynamics?
- Data are well described in all phase space regions except for highest x_p in the direct-enhanced sample with both jets forward:
  - – insufficient parton dynamics in DGLAP-based NLO theory?
  - – underestimated PDF uncertainty at high momentum fractions?
- Data might be very useful in global fits for the proton parton densities
  - → how large is the sensitivity to the γ PDFs?



SUMMARY ON HERA α_s

Consistency of HERA/LEP/Tevatron results is an important check!





Nice demonstration of running in HERA data (C. Glasman)

Summary of new determinations of $\alpha_s(M_Z)$:

H1 inclusive:

$\alpha_s(M_Z) = 0.1197 \pm 0.0016(\text{exp.}) \pm 0.0047(\text{theory})$

H1 3/2 jets:

$\alpha_s(M_Z) = 0.1175 \pm 0.0017(\text{stat.}) \pm 0.0050(\text{syst.}) \pm 0.0061(\text{theory})$

ZEUS inclusive:

$\alpha_s(M_Z) = 0.1196 \pm 0.0025(\text{exp.}) \pm 0.0023(\text{theory})$

HERA : $\alpha_S(M_Z) = 0.1186 \pm 0.0011(\text{exp.}) \pm 0.0050(\text{theory})$
Bethke: $\alpha_S(M_Z) = 0.1182 \pm 0.0027$

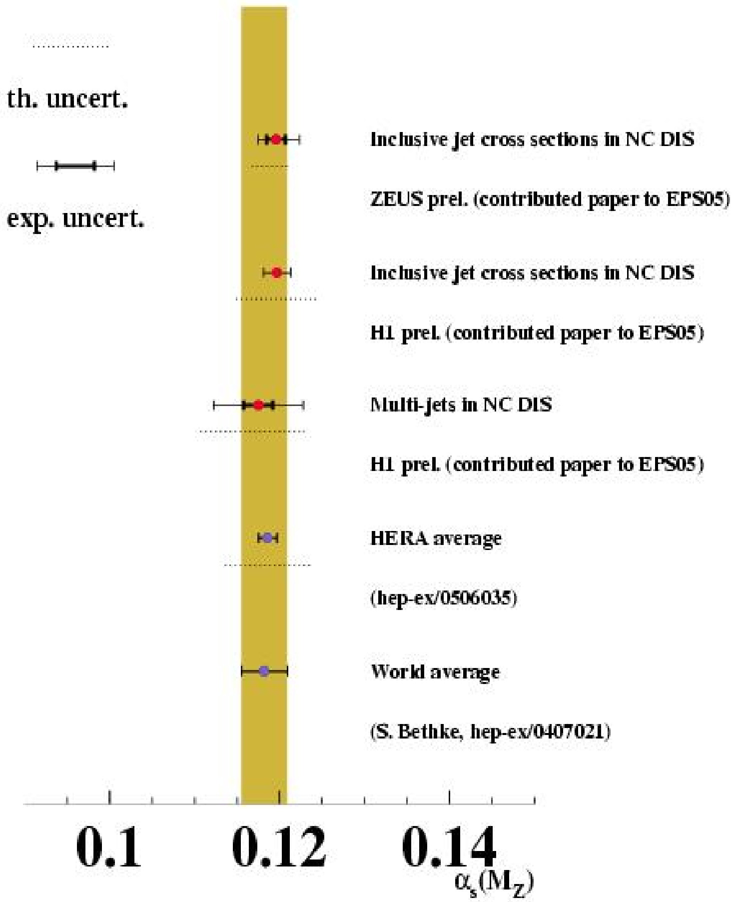
(HERA) JET PHYSICIST'S WISHLIST

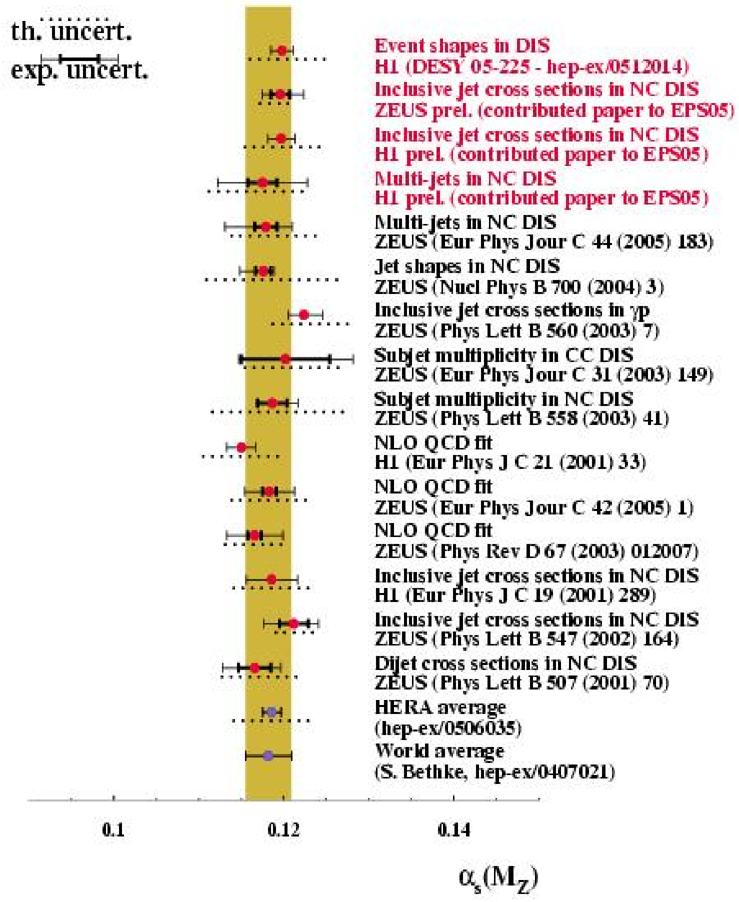
or "conclusion and outlook"

achievements:	• excellent understanding of pQCD demonstrated • concepts of factorisation/PDF universality work well… • very precise extraction of QCD parameters: - HERA average: $\alpha_S(M_Z)$=0.1186±0.0011(exp.)±0.0050(theory) - clear reduction of gluon uncertainty at medium-to-high-x via use of jet data
experimental wishes:	not much to wish for really… → we have large samples (in most fields statistics not an issue) → experimental uncertainties are well under control (luminosity, energy scale,…) BUT: some questions would profit from more data and multi-differential analyses (parton dynamics) - also (wo)man-power will be an issue → people are leaving HERA!
theoretical wishes:	… some wishes here: • often scale uncertainty dominating source of uncertainty (low Q^2, E_T, M_{JJ}) - higher orders (NNLO) would really help (coupling, PDFs) - but also an important question - which is the "true" scale (BML,…)? • hadronisation corrections of NLO theory done with LO MC programs - want NLO+PS for better consistency + as approach to NNLO → MC@NLO? (standard answer: e+e- easy, pp important, …) … but remember HERA can provide important input to LHC! • DGLAP-BFKL question: easy-to-use BFKL program would help us a lot … • …

Backups

α_s summary





HERA KINEMATICS AND JETS IN DIS

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Only need two out of three variables since $Q^2 = sxy$

Jet production in neutral current DIS at O($\alpha\alpha_s$)