Hadronic Final States and QCD

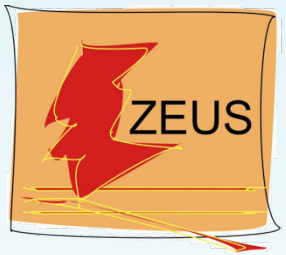
Jet cross sections and α_s in DIS and photoproduction at HERA

DIS09, Madrid, 26th–30th April 2009

Claire Gwenlan (University of Oxford, STFC Advanced Fellow)
on behalf of the ZEUS collaboration

Outline

- motivation
- jet cross section measurements
- strong coupling, α_s



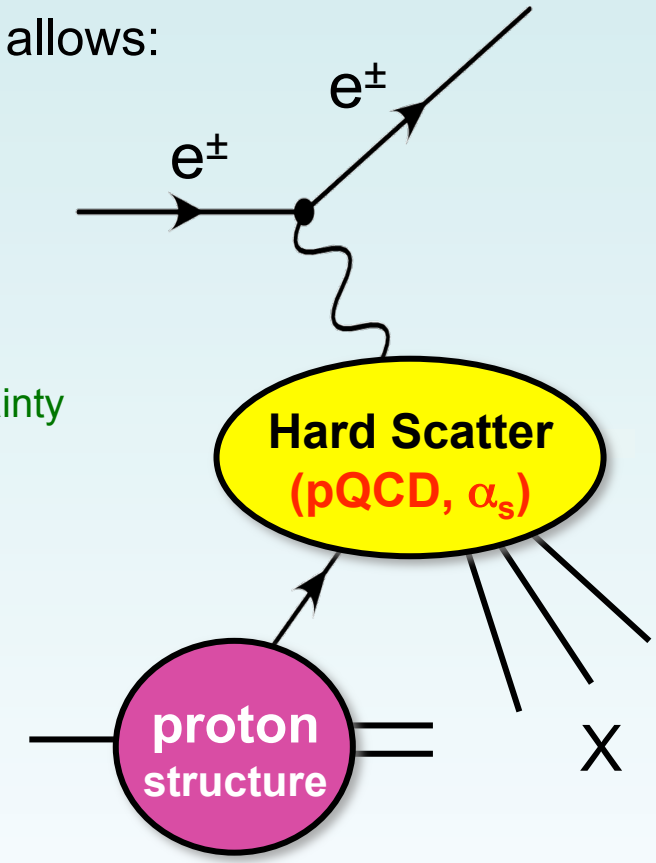
 = new for DIS09

Motivation

HERA $e^{\pm}p$ collider:− an ideal environment for precision studies of QCD

Study of **jets** in the **Hadronic Final State** at HERA allows:

- stringent tests of our understanding of **pQCD**
  - factorisation, perturbative expansion, PDF universality
- constraints on **proton** (and photon) structure
- extractions of **QCD parameters** (α_s, …)
  - in regions of small experimental and theoretical uncertainty



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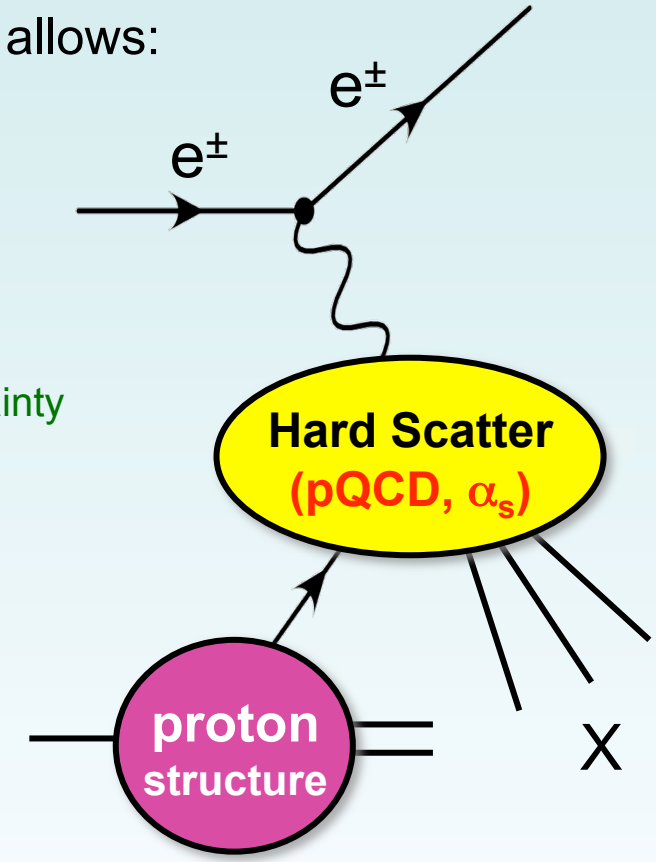

new from ZEUS since DIS08:

- **inclusive jets in neutral current DIS**
  (**×2.5** increase in statistics c.f. most recent studies)
- **two new extractions of α_s from jet data**
  (NC DIS inclusive jets; **re-analysis** of published γp)

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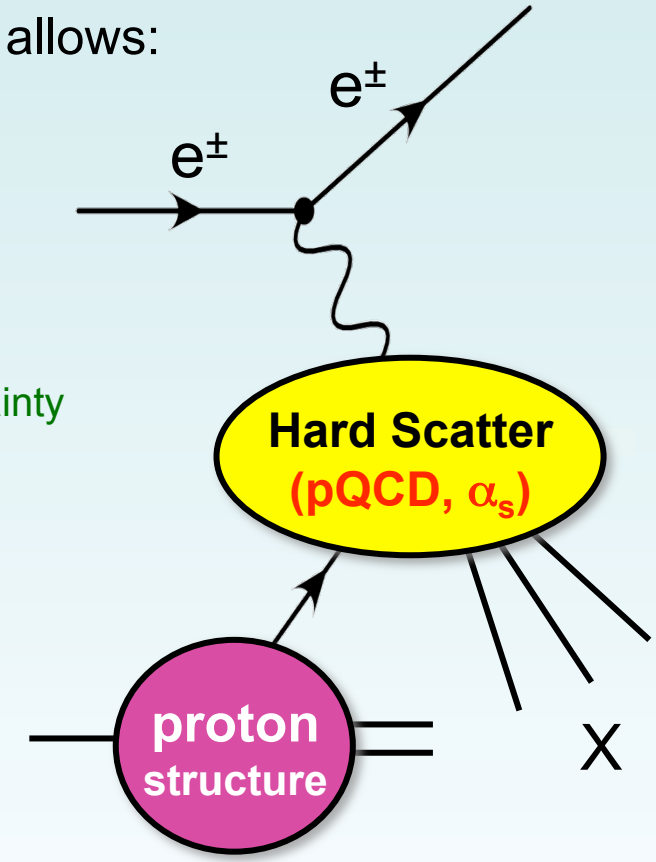
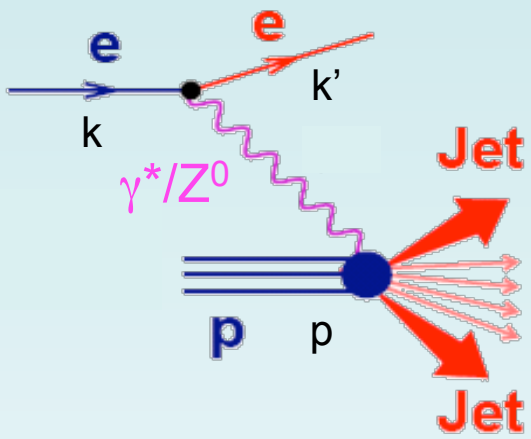


presented here:

- **jet cross sections in neutral current DIS**
  (**new inclusive jet** cross sections; **dijets**)
- **two new extractions of α_s from jet data**
  (NC DIS inclusive jets; **re-analysis** of published γp)

Jet production at HERA

Neutral Current (NC): γ or Z^0 exchange



Kinematic Variables:

- 4-momentum transfer ('resolution'): $Q^2 = -q^2 = -(k-k')^2$
- Bjorken scaling variable: $x = Q^2/2p.q$
- inelasticity: $y = p.q/p.k$

related via: $Q^2 = sxy$

[where $\sqrt{s}$ = CoM energy: $s = (k+p)^2$]

Broadly, two main processes:

- **Deep Inelastic Scattering** (DIS): $Q^2 \gg 1$ GeV^2
- **Photoproduction** (γp): $Q^2 \approx 0$ GeV^2 ← quasi-real **photon** exchange

Jet cross section (DIS):

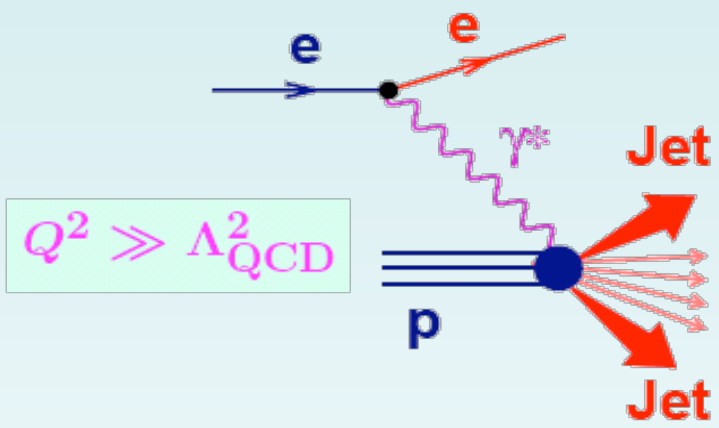
$$\sigma = \sum_n \alpha_s^n \cdot \sum_{a=q,\bar{q},g} f_a \otimes \hat{\sigma}_a^{(n)}$$

$\hat{\sigma}_a$: perturbatively calculable **subprocess cross section**

f_a: **proton PDF** (long-distance, experimentally determined)

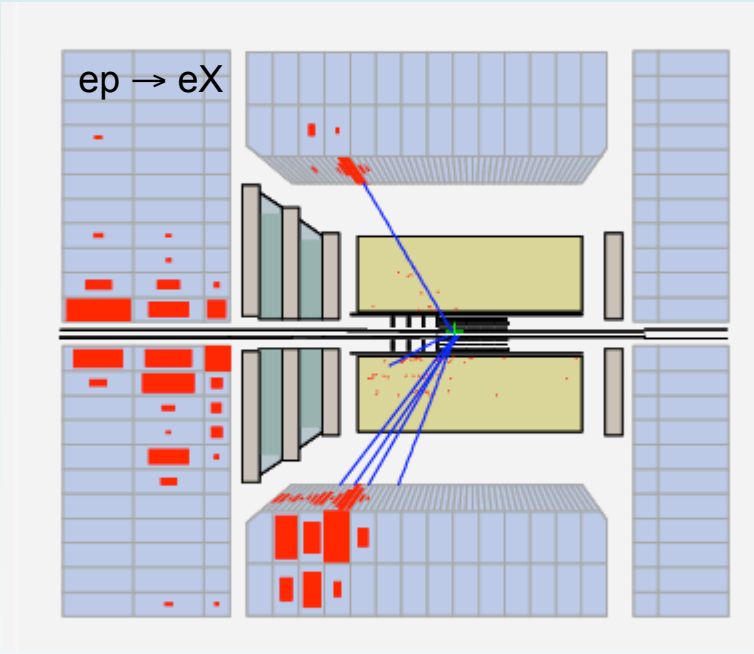
γp: need **photon** PDF too

Jet cross sections in NC DIS



NC deep inelastic scattering (DIS)

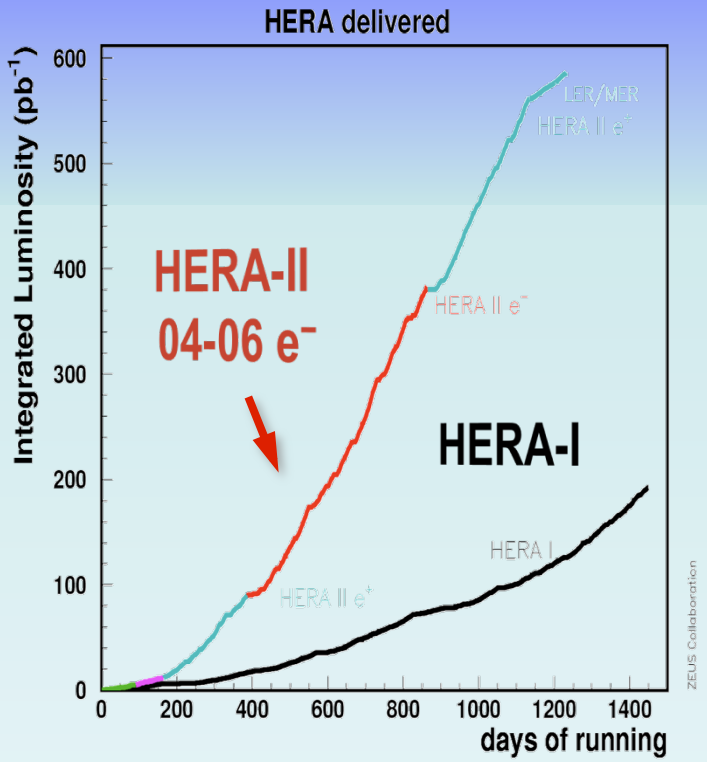
$$ep \longrightarrow e + \mathrm{Jet}\ (+\mathrm{Jet}) + X$$



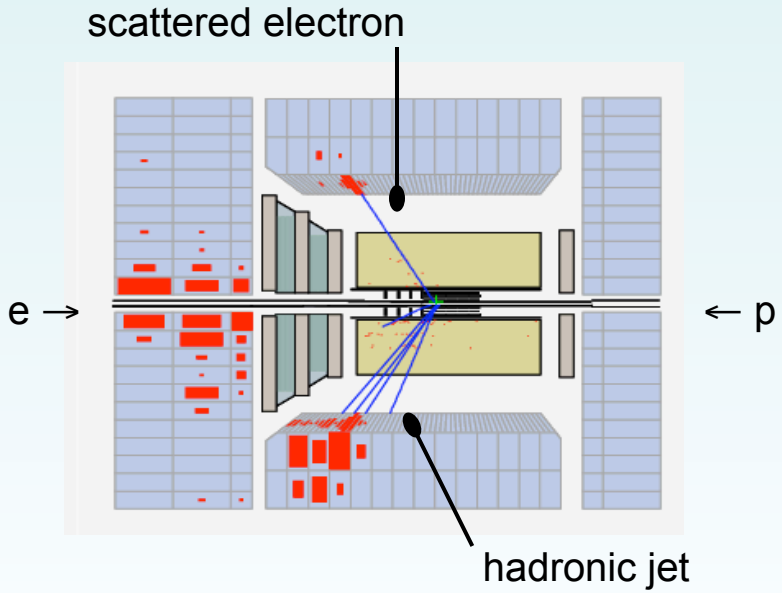
Data selection

event samples ($\sqrt{s}$ = **319 GeV**):

1. **inclusive jet** NC DIS analysis:
   - HERA-II 05−06 e^-p **(188 pb^{-1})**
2. **dijet** NC DIS analysis:
   - HERA-I 98−00 + II 04−05 e^-p **(209 pb^{-1})**



NC DIS event in the ZEUS detector



phase space: ↙ no Z^0

- $Q^2 > 125$ GeV^2 dijet: $Q^2 < 5000$ GeV^2
- $|\cos(\gamma_{had})| < 0.65$
- jet selection (in Breit frame; defined next):
  - inclusive: ≥ **1** jet with $E_{T,Breit} > 8$ GeV
  - dijet: ≥ **2** jets with $E_{T,Breit1(2)} > 12(8)$ GeV
  - $-2 < \eta_{Breit} < 1.5$

* γ_{had} ≡ angle of scattered quark (in QPM)

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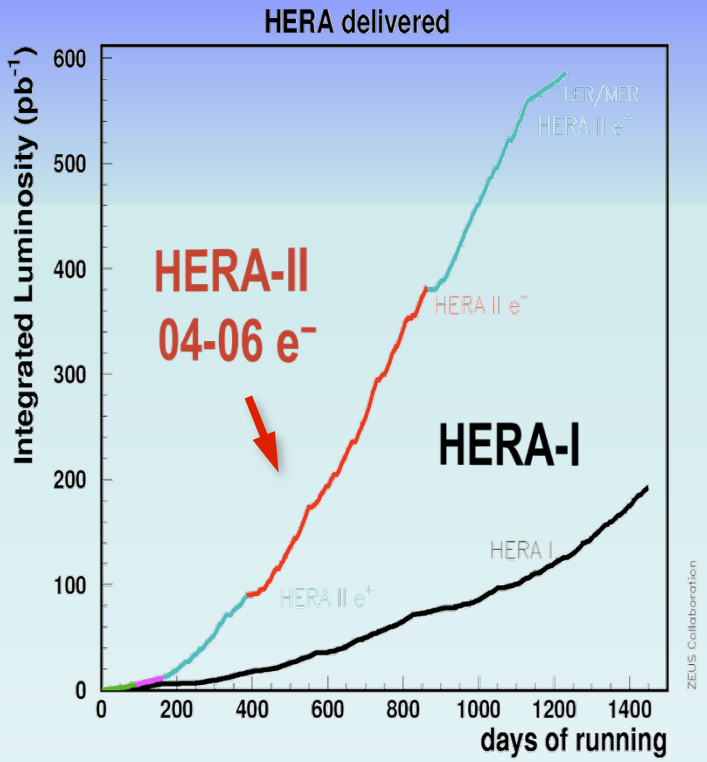

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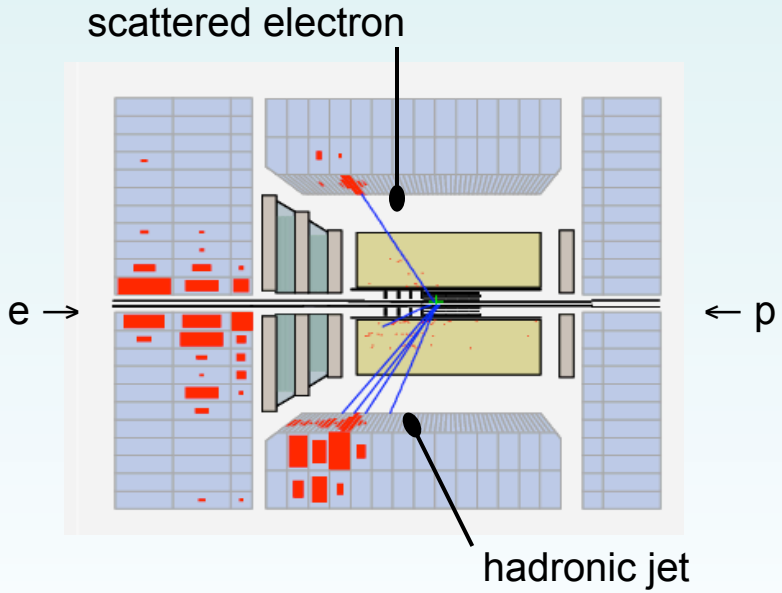


experimental uncertainties:

- **statistical:** typically **1−5%**
- **systematic: jet energy scale*** dominates (1−3%) ➔ **5−10%** on cross sections
  [next important: model uncertainty for acceptance corrections (ARIADNE vs. LEPTO)]

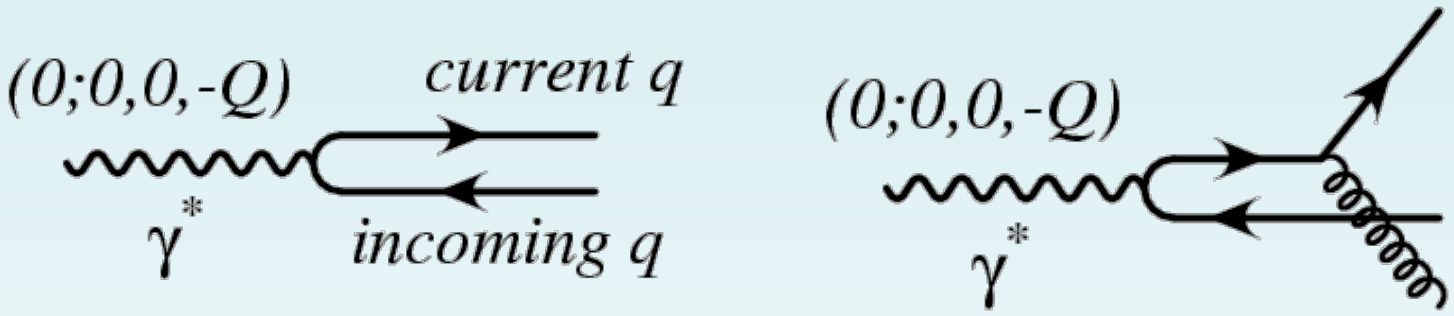
* from **energy balance** with scattered electron

Jet reconstruction and the Breit frame

Jet reconstruction: k_T−algorithm in longitudinally−invariant inclusive mode (R=1)

infra-red and collinear safe jet definition

Breit frame:− virtual boson collides head-on with struck quark from proton



Born level **O(α_s): qγ* → qg**

requirement of high-transverse-energy jets in the **Breit frame**:

- Born level contribution suppressed ➔ struck quark back-scattered with zero-E_T
- lowest order (non-trivial) contributions, O(α_s) ➔ two high−E_T jets (well separated from p remnant)

➔ directly sensitive to **hard QCD sub-process** at O(α_s) (and higher orders)

NLO QCD theory

comparison of **measurements** to **O(α_s^2)** QCD calculations:

- NC DIS differential **jet** cross sections calculated at **NLO** using **DISENT**:
  - **proton PDFs**: **ZEUS−S** (global PDF fit) dijet: **CTEQ6**
  - value of $\alpha_s(M_Z) = 0.118$; calculated at two loops
  - **renormalisation scale**: $\mu_R = E_{T,B}$ of each jet dijet: $\mu_R = \sqrt{Q^2+\overline{E}_{T,B}^2}$
    [default choices; other scales also investigated]
  - **factorisation scale**: $\mu_F = Q$ ↓ not necessary for dijet due to restricted Q^2 range
  - corrections for **hadronisation** and **Z^0** effects applied
- sources of theoretical **uncertainty** considered:
  - **terms beyond NLO**: variation of scale μ_R by (conventional) factors of {½ ,2}
  - **pPDFs**: using the provided eigenvector error PDF sets (exp. sources only)
  - **$\alpha_s(M_Z)$:** using two additional sets of PDFs with different $\alpha_s(M_Z)$
  - modelling of **parton shower**: two different Monte Carlos (CDM vs. MEPS)
  - **factorisation scale**: variation of μ_F by factors of {½ ,2} → negligible

  → variation of μ_R **dominates** → typically 5−20%; other sources mostly small

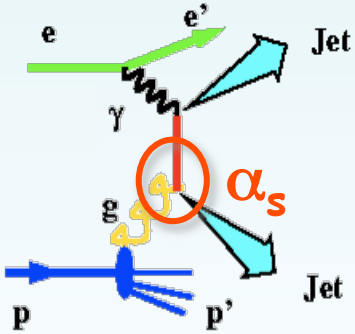
Inclusive jets cross sections

ZEUS-prel-09-006

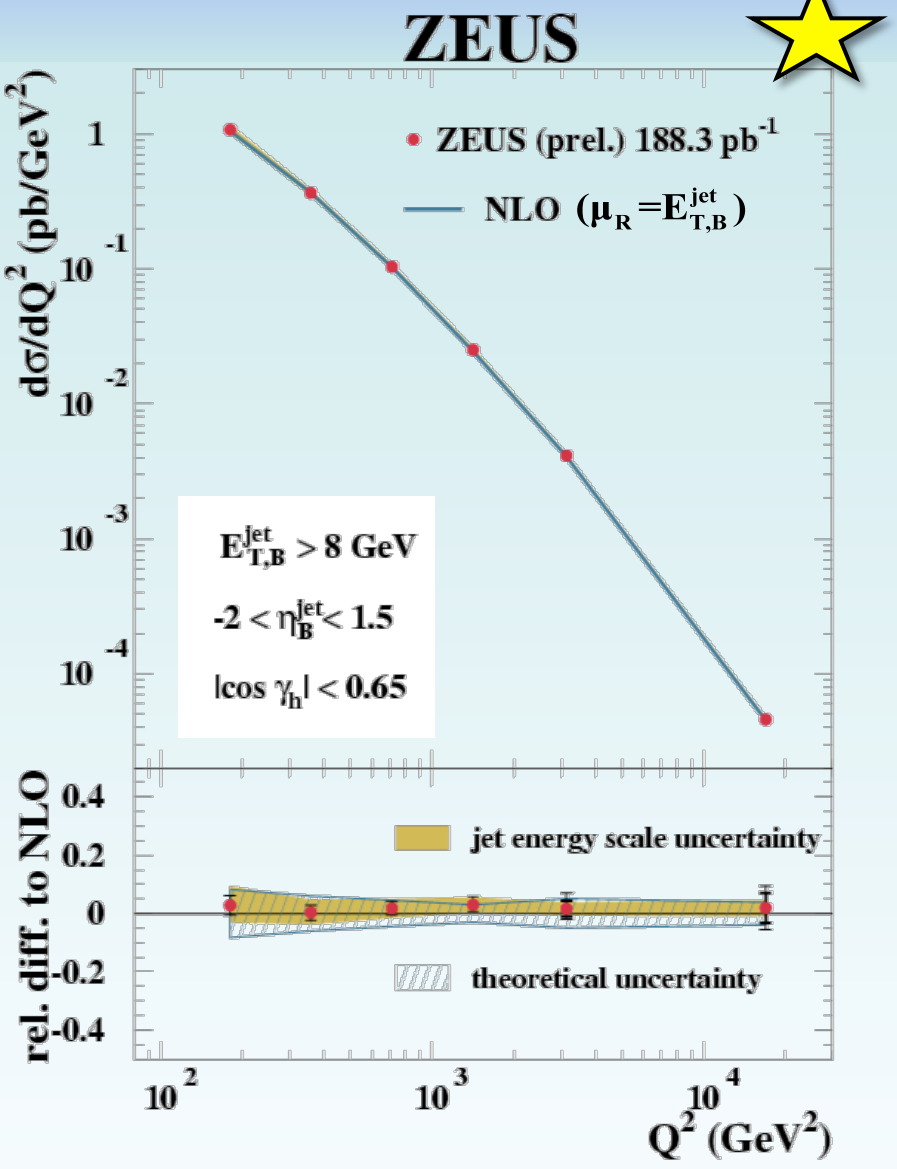
HERA-II 05−06 (188 pb^{-1}) : **50k events**
➔ **×2.5** increase c.f. most precise HERA-I

shown:− single-differential **inclusive jet** NC cross section as a function of **Q^2**:

- **good description** of data by **NLO QCD** over **many orders of magnitude** in the cross section (for both $\mu_R = E_{T,B}$ and Q)
- smaller **theoretical uncertainty** than dijet ... **but** still **dominates** over experimental, except at highest Q^2
- also sensitive to the **strong coupling α_s:**



cross section for
$Q^2 > 500$ GeV^2
used to extract
$\alpha_s(M_Z)$ (see later)



Inclusive jet cross sections

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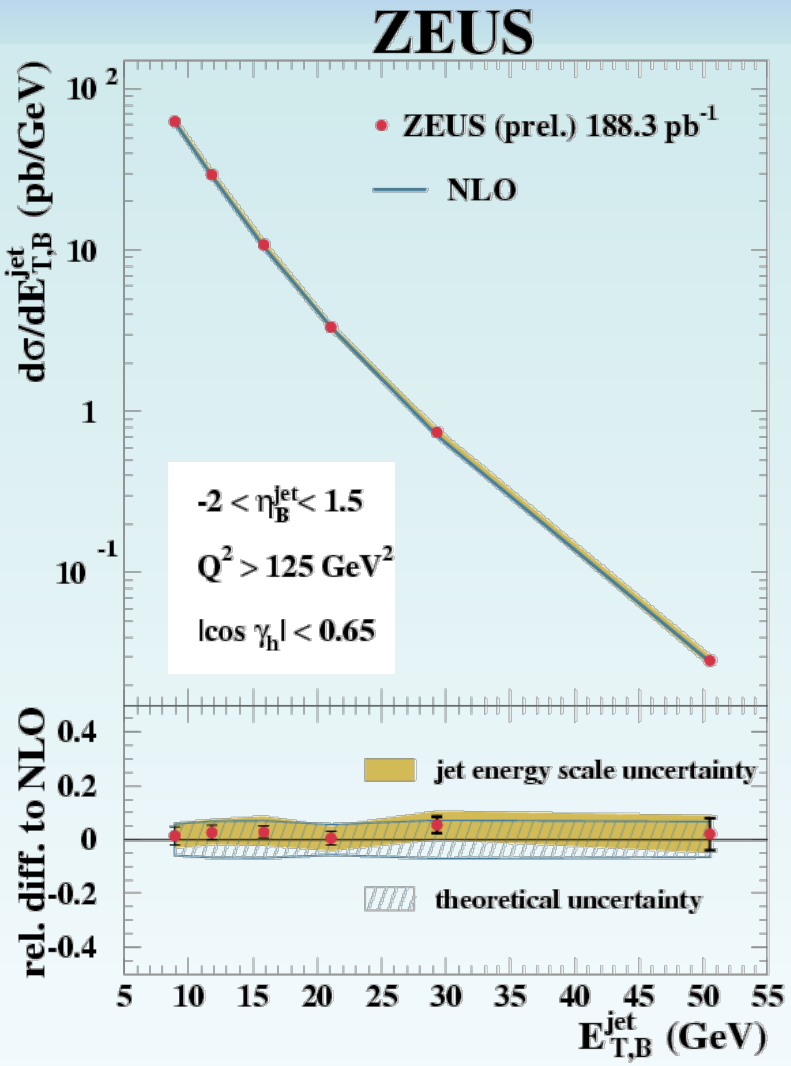
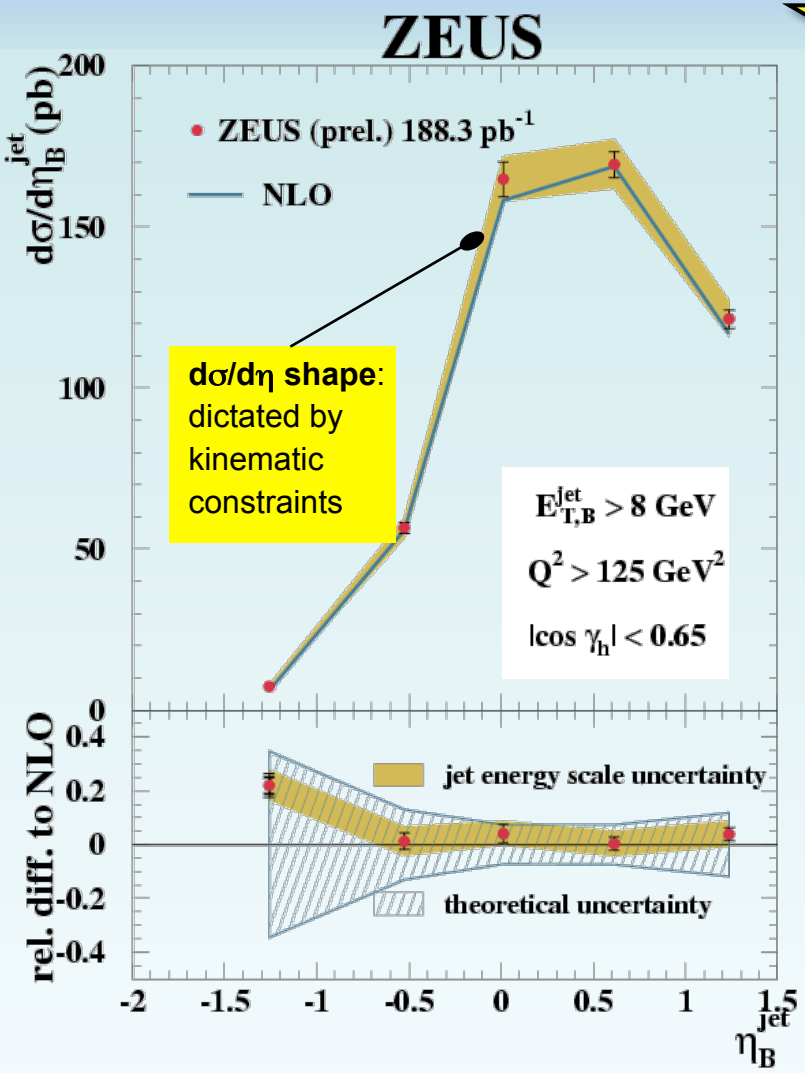
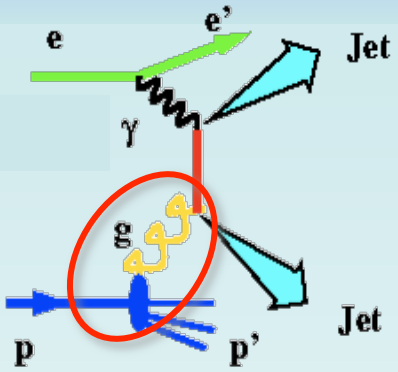




single-differential in jet observables $E_{T,B}$ and η_B ➔ good description of all data by **NLO QCD**

HERA jet data and the gluon

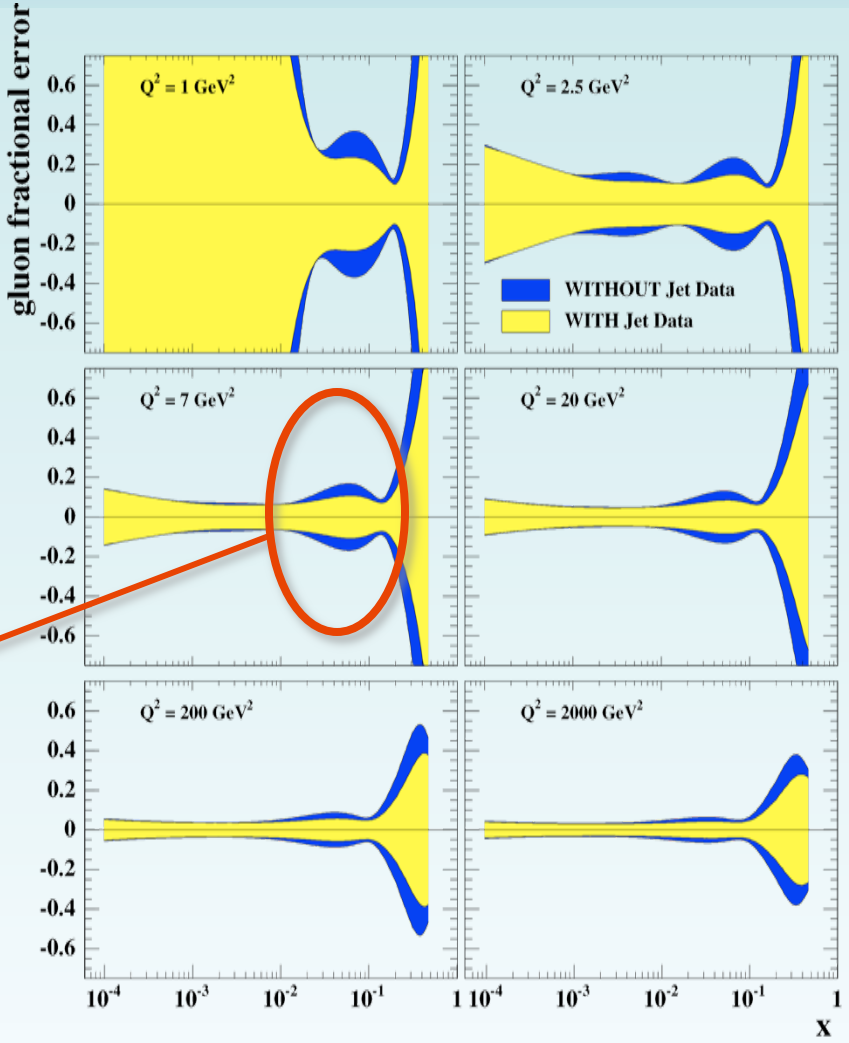
HERA jets:
also sensitive to **gluon** (and **quark**) content of proton
γp: also to photon structure



- **NC DIS inclusive** and **γp jet** cross sections included in a previous **ZEUS NLO QCD fit**, (together with more inclusive data)
  [Eur Phys J **C42** (2005) 1]

➔ **gluon uncerts. substantially reduced** (medium-to-high-x)

same analysis: also a precise α_s determination

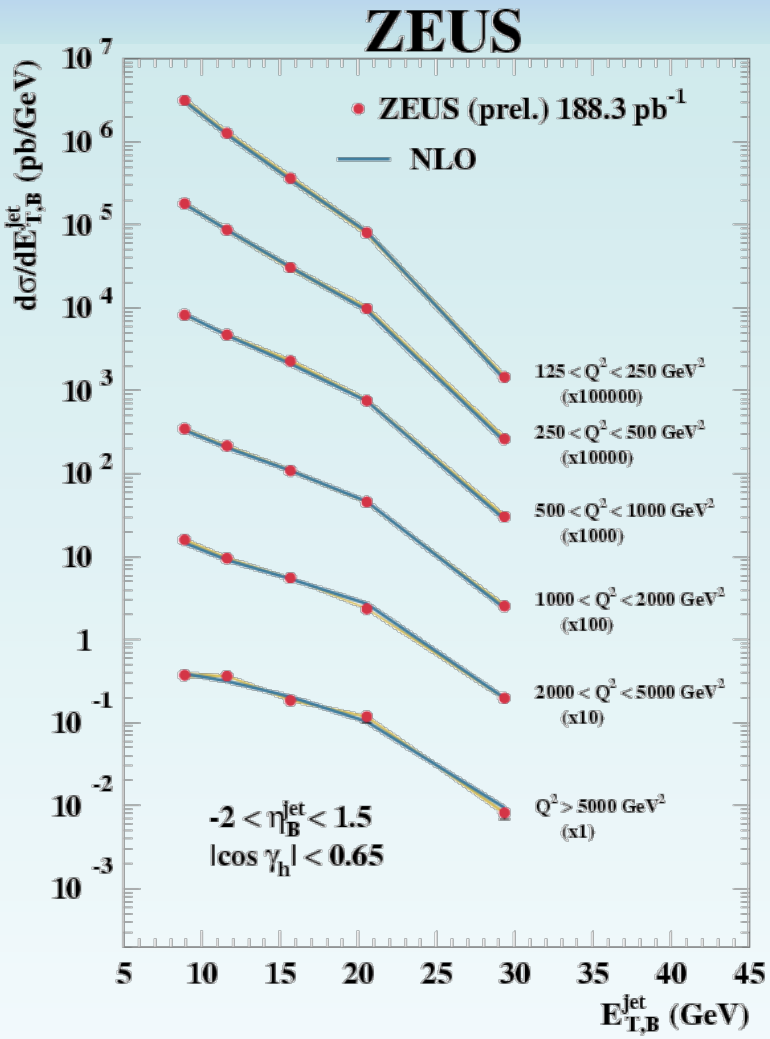


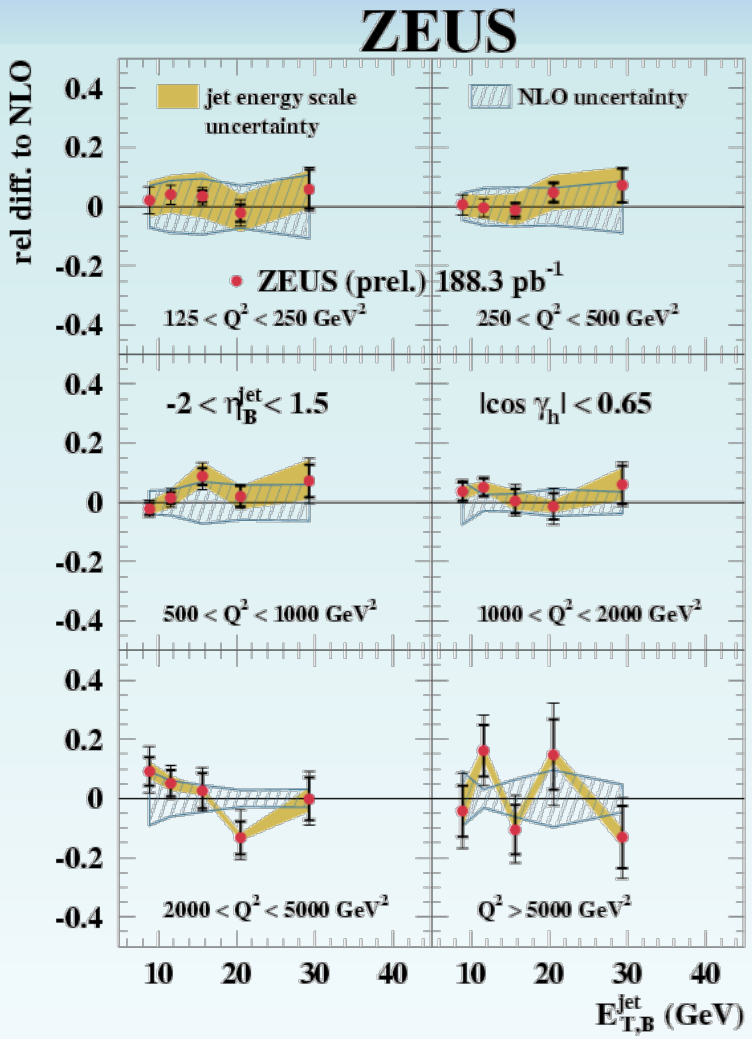
Proof of Principle:

… jet cross sections from **only** 40 pb^{-1} used
➔ **now** have the new NC DIS **inclusive jets**

Inclusive jet cross sections

ZEUS-prel-09-006





double-differential NC DIS **inclusive jet cross sections**, as a function of $\mathbf{E_{T,B}}$ in bins of $\mathbf{Q^2}$

➔ **same** kinematic region as **NC DIS** measurement used in ZEUS QCD fit; **× 4.5** increase in statistics

Dijet cross sections

ZEUS-prel-07-005

HERA-I 98−00 + HERA-II 04−05 (209 pb^{-1})
➔ **×2.5** luminosity c.f. HERA-I alone

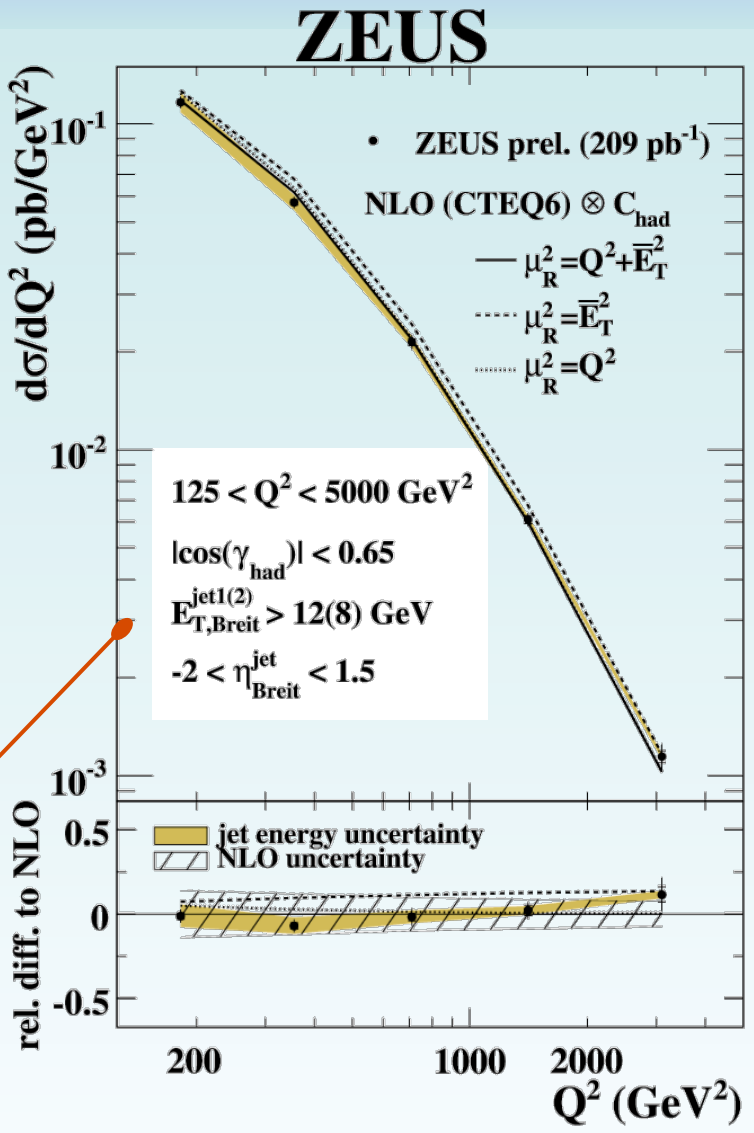
[N.B. results with full HERA-II (04−07) statistics coming soon!]

shown:− single-differential NC **dijet** cross section as a function of $\mathbf{Q^2}$:

Comparison to NLO QCD (with various scale choices):

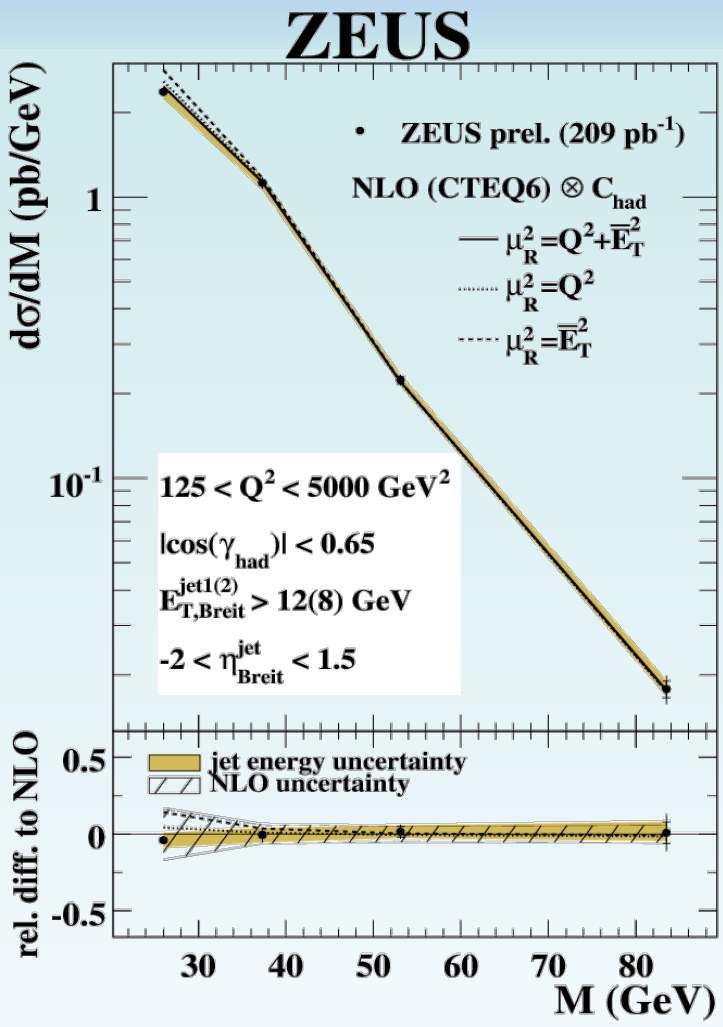
- data **well described** by **NLO QCD** across measured range
  - − overall best description with $\mu_R=\sqrt{Q^2+\overline{E}_T^2}$ (Q^2 also good)
- theoretical uncertainties **dominate**
  - ➔ μ_R scale variation (terms beyond NLO)

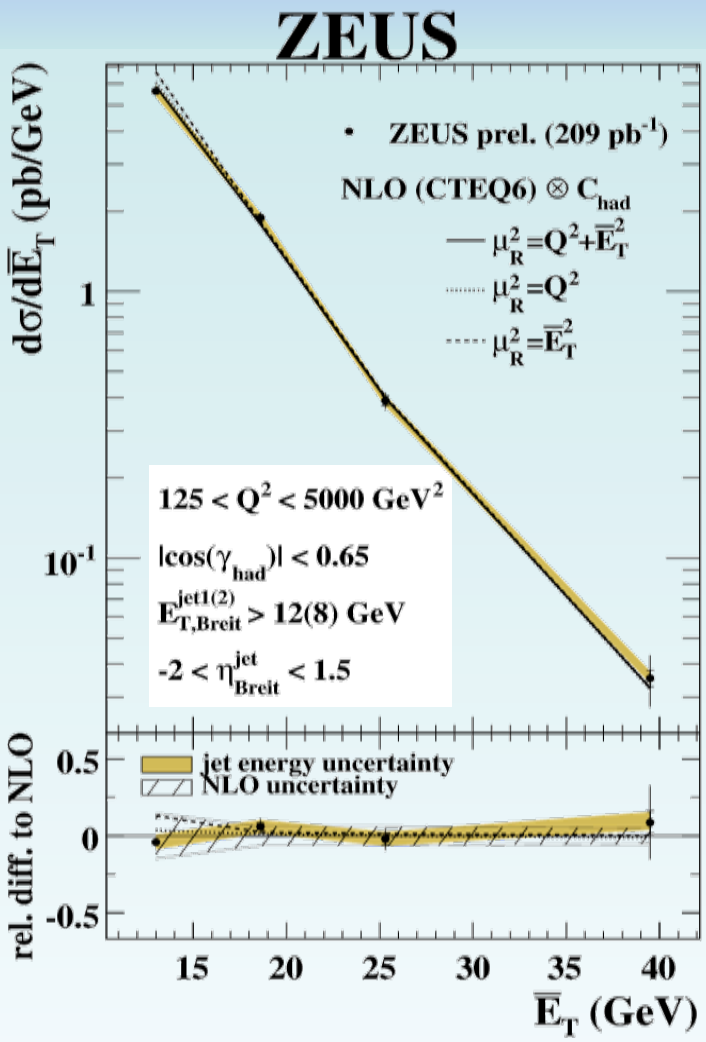
note asymmetric cut on jet-E_T cut: ➔ infra-red safety



Dijet cross sections

ZEUS-prel-07-005



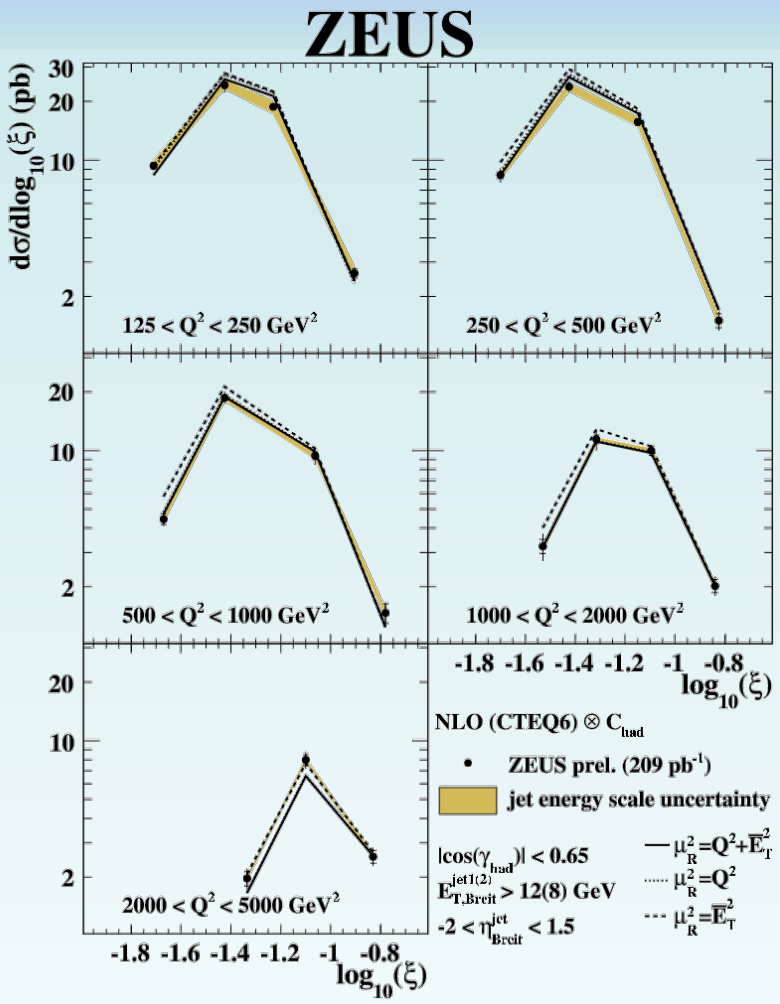


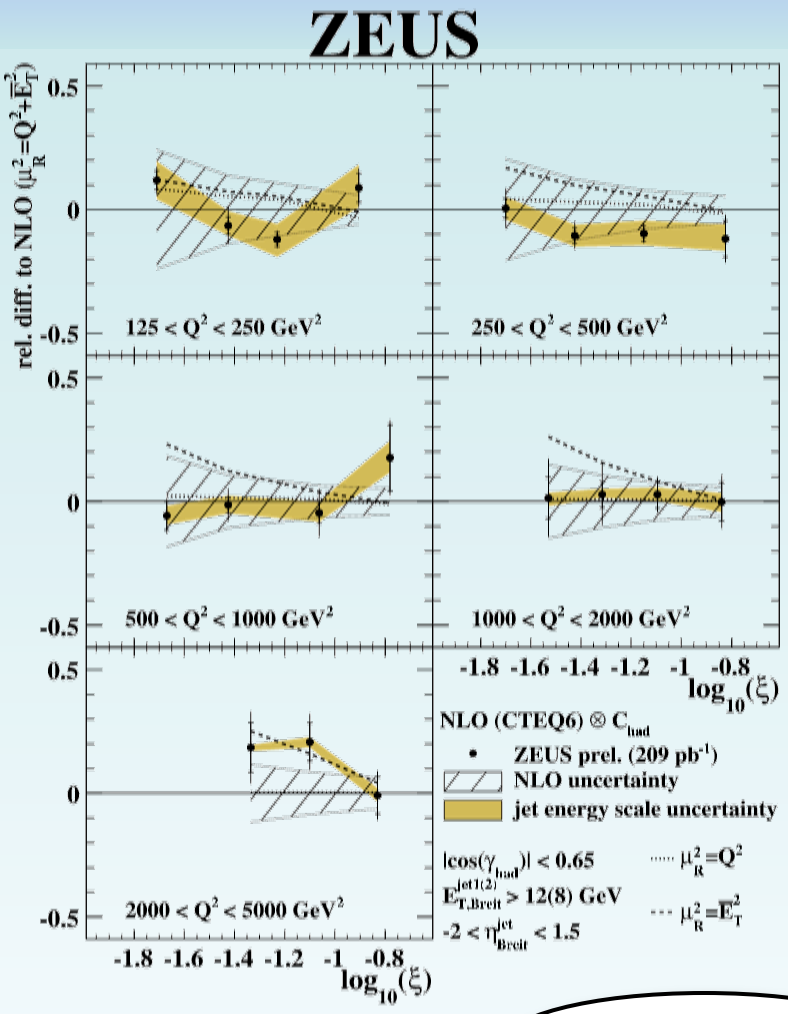
single-differential, as functions of M_{jj}, $\bar{E}_T$ ➔ sensitive to the **matrix element** in the perturbative calculations

➔ data well described by **NLO QCD** ➔ validity of description of **dijet dynamics** by pQCD at O(α_s^2)

Dijet cross sections

parton momentum fraction:
$\xi = x_{Bj}(1+M_{jj}^2/Q^2)$





ZEUS-prel-07-005

double-differential cross sections as a function of **$\log_{10}(\xi)$** in different **Q^2** bins:

➔ reasonable description by **NLO QCD** ➔ sensitivity to **scale** and proton **PDFs** (next slide)

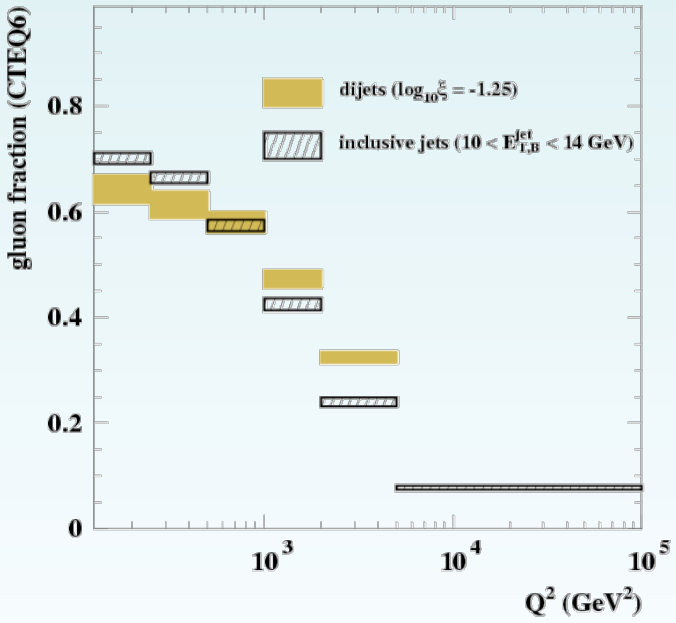
HERA dijets and the gluon

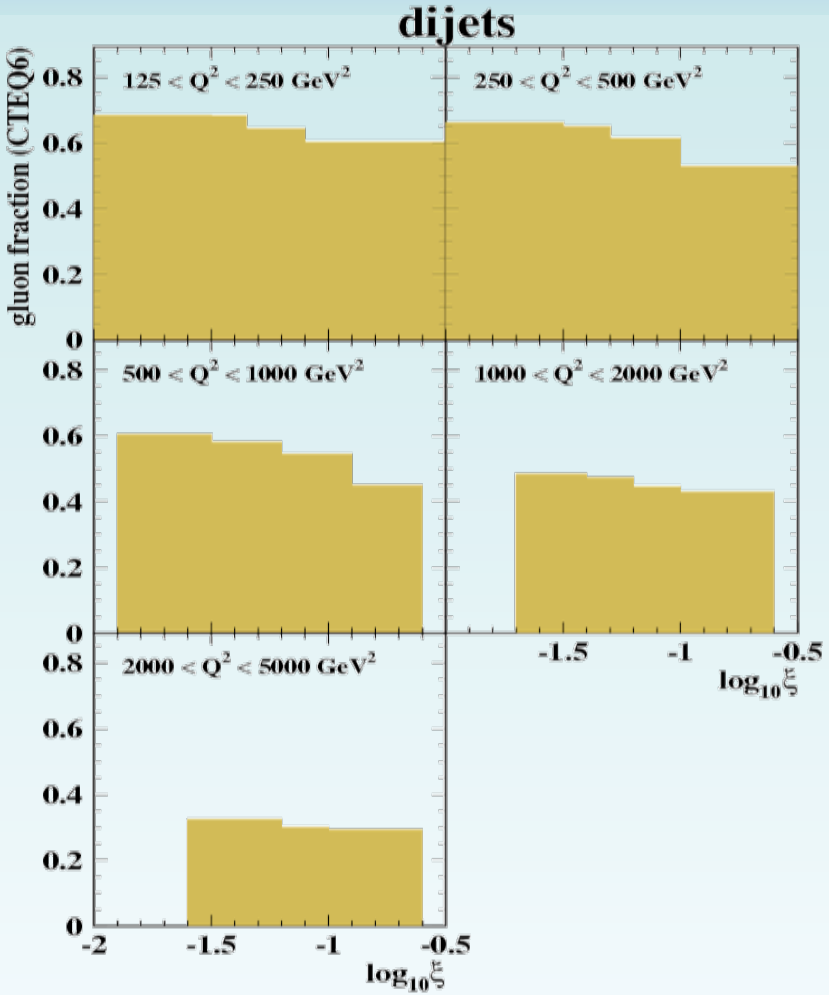
parton momentum fraction:
$\xi = x_{Bj}(1 + M_{jj}^2 / Q^2)$

NC DIS **inclusive jet data** previously shown to constrain the **gluon PDF**

double-differential dijet NC cross sections:

- **gluon** contribution **at least 30%**, even at highest Q^2, ξ (larger contribution than for inclusive in some regions of phase space)





gluon-induced fraction of the dijet cross section

HERA dijets and the gluon

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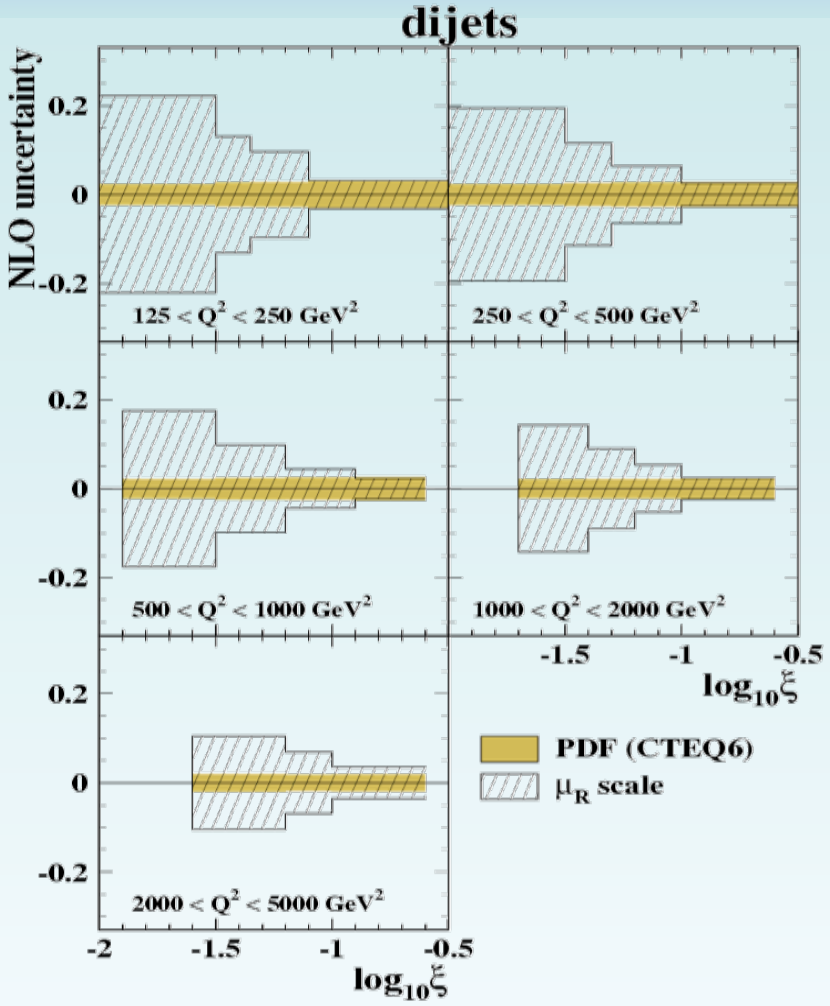
double-differential dijet NC cross sections:

- **gluon** contribution **at least 30%**, even at highest Q^2, ξ (larger contribution than for inclusive in some regions of phase space)
- **uncertainties:**
  - μ_R **scale** uncertainty decreases at high Q^2, ξ
  - **PDF** uncertainty approximately constant and **non-negligible**

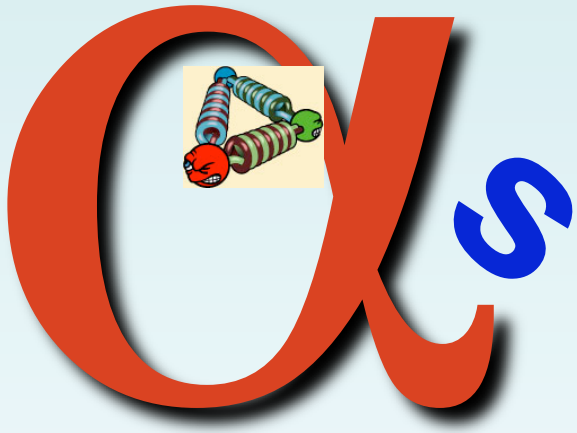
➔ potentially significant constraints on **gluon**

plus, results including rest of **HERA-II (+06-07)** data **coming soon** ➔ further ×**2** luminosity!



theoretical uncertainties from μ_R scale + PDFs

extraction of the strong coupling α_s



HERA jets and α_s

α_s: a **fundamental** parameter of QCD ➔ but **must** be determined experimentally

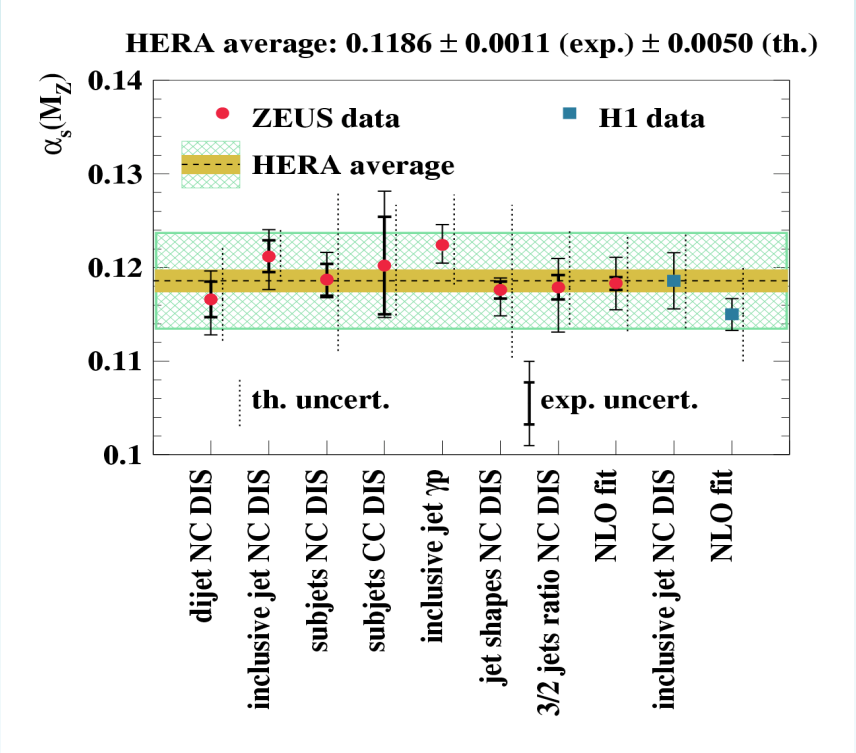
many **precise determinations** of α_s from **HERA** (from both jet observables and NLO QCD fits)

➔ just some examples shown here ➔

NEW measurements from ZEUS:

since DIS08: two **new** $\alpha_s(M_Z)$ determinations:

1. from **new** measurement of **inclusive jets** in **NC DIS** from **HERA-II**
   (cross sections shown earlier)
   ➔ improved statistical precision
   c.f. previous HERA-I analysis
2. from **re-analysis** of **HERA-I inclusive jet photoproduction** data
   ➔ reduced theoretical uncertainty c.f. previous determination using **same** data



α_s extraction from jet observables

method: based on the α_s dependence of the **perturbative QCD calculations**

pQCD calculations depend on α_s via the:

- **partonic cross section**
- proton **PDFs** (implicit; α_s assumed in evolution)

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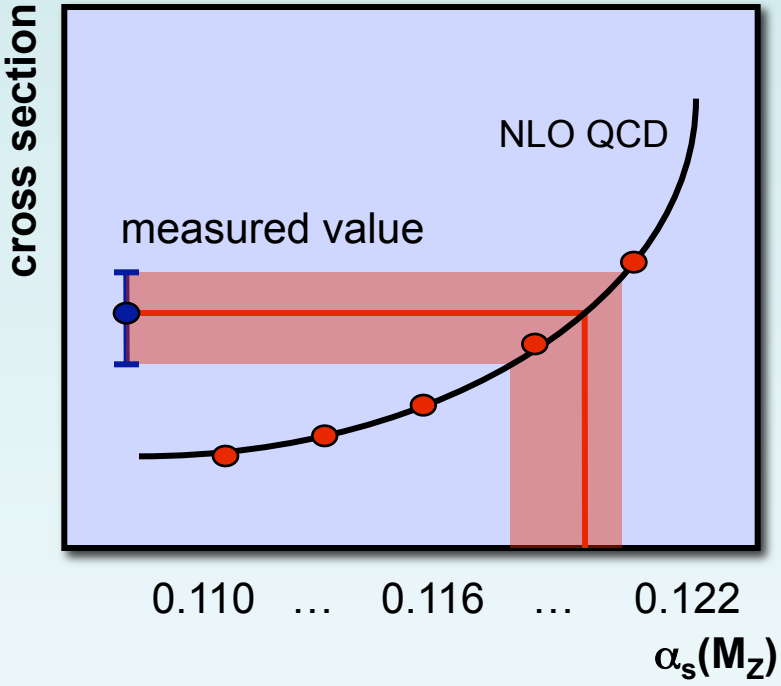
pQCD calculations depend on α_s via the:

- **partonic cross section**
- proton **PDFs** (implicit; α_s assumed in evolution)

to take into account the correlation:

- perform **NLO** calculations using various sets of proton **PDFs** (i.e. with different assumed α_s)
- as input to calc., use $\alpha_s(M_Z)$ assumed in PDF set
- parameterise α_s dependence of observable

  → $[d\sigma/dA(\alpha_s(M_Z))]^i = A_1^i\,\alpha_s(M_Z) + A_2^i\,\alpha_s(M_Z)^2$
- determine $\alpha_s(M_Z)$ and its **uncertainty** from **measured observable** (using the NLO param.)



This procedure **correctly handles** the **complete α_s dependence** of the **NLO calculations** (from matrix element and PDFs), while **preserving the correlation** between α_s and the **PDFs**

α_s from inclusive jets in NC DIS

ZEUS-prel-09-006

α_s from **new** ZEUS measurement of **inclusive jets** in **NC DIS** from **HERA-II** (188 pb^{-1})

➔ extracted from the measured **dσ/dQ^2** for $Q^2 > 500$ GeV^2 ↓ (yields smallest α_s uncert.)

$$\alpha_s(M_Z) = 0.1192 \pm 0.0009\,(\text{stat.})^{+0.0035}_{-0.0032}(\text{exp.})^{+0.0020}_{-0.0021}(\text{th.})\ \ (3.5\%\ \text{total})$$

⇧ first HERA-II α_s from ZEUS

experimental uncertainties:

- dominated by jet energy scale: ±**1.9%**

theoretical uncertainties:

- dominated by terms beyond NLO: ±**1.8%**
  (estimated using method of Jones et al. – see later)
- pPDFs (±**0.8%**), hadronisation corrections (±**0.8%**), μ_F uncertainty (**negligible**)

$\alpha_s(M_Z)$ from **HERA-II** (05−06 e$^-$p) inclusive jets in the Breit frame:
➔ very **precise determination** from ZEUS (comparable precision to e+e−)

c.f. equivalent from HERA-I: $\alpha_s(M_Z) = 0.1207 \pm 0.0014\,(\text{stat.})^{+0.0035}_{-0.0033}(\text{exp.})^{+0.0022}_{-0.0023}(\text{th.})$ (3.7% total)

➔ agreement within 1%; improved statistics for HERA-II (82 pb^{-1} → 188 pb^{-1})

α_s from inclusive jets in γp

α_s from **re-analysis** of **inclusive jets** in γp

previous publication [Phys Lett B560 (2003) 7]

HERA-I 98-00 (82 pb^{-1}): α_s extracted from $\mathbf{d\sigma/dE_T}$

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

➔ dominated by **theoretical uncertainty**

α_s from inclusive jets in γp

ZEUS-prel-08-008

α_s from **re-analysis** of **inclusive jets** in γp

previous publication [Phys Lett B560 (2003) 7]

HERA-I 98-00 (82 pb^{-1}): α_s extracted from $\mathbf{d\sigma/dE_T}$

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➔ dominated by **theoretical uncertainty**

re-analysis (same data):

− **updated** theory; new method for μ_R variation

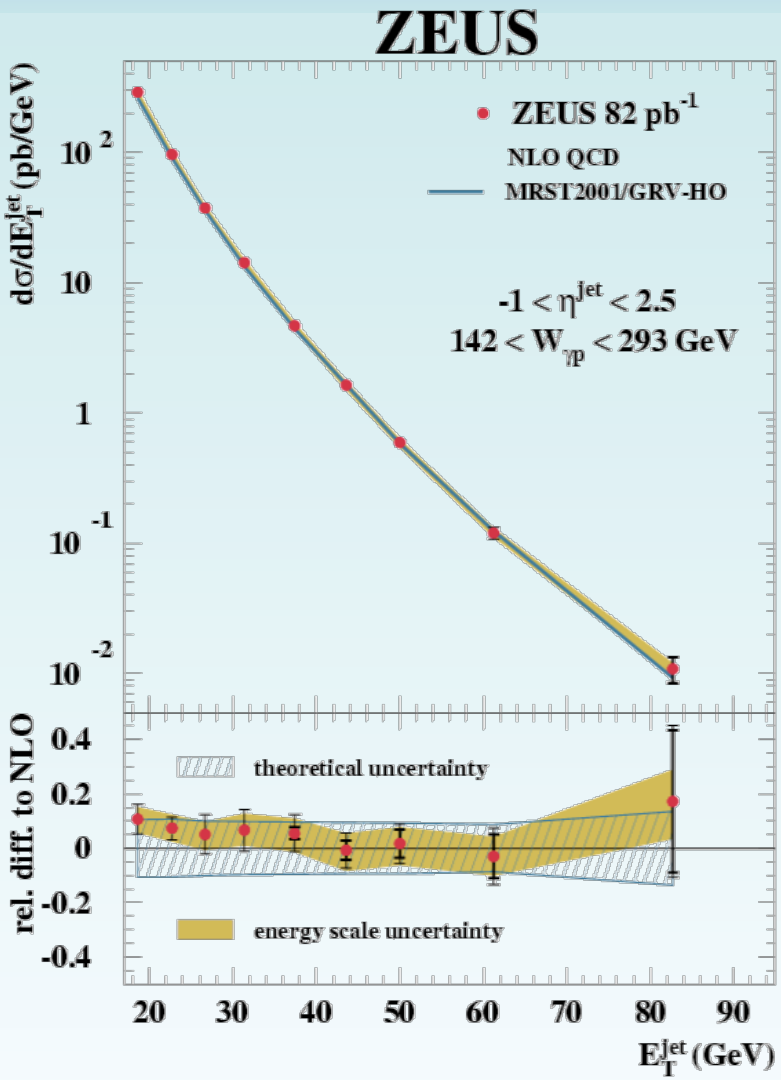
NLO QCD prediction:

− **O(α_s^2)** : Klasen, Kleinwort and Kramer

− proton PDFs: **MRST01** (previously: MRST99)

− photon PDFs: **GRV-HO**

− $\mu_R = \mu_F = E_T^{jet}$ for each jet



good description by **NLO QCD** ➚

α_s from inclusive jets in γp

ZEUS-prel-08-008

α_s from **re-analysis** of **inclusive jets** in γp

experimental uncertainties:

- dominated by jet energy scale: **±1.5%**

theoretical uncertainties:

- terms beyond NLO **(Jones et al.)**: **±2.4%**
- proton PDF (**MRST01** error sets: **±0.15%**); γPDF (AFG: **±0.7%**); hadronisation corrections (Pythia vs. Herwig: **±0.36%**); μ_F (**negligible**)

μ_R variation (Jones et al. method)

- extract measured α_s
- calculate cross sections $\sigma_{\{½,2\}}$ using extracted α_s but μ_R varied by {½, 2}
- for default μ_R, find α_s values that give $\sigma_{\{½,2\}}$
- difference c.f. nominal: $\pm\Delta\alpha_s$

$\Delta\alpha_s$:− from uncertainty on predicted cross section ➔ **no** re-fitting of data

new value of $\alpha_s(M_Z)$ from ZEUS:

0.0001 change to central value from use of updated PDFs

$$\alpha_s(M_Z) = 0.1223 \pm 0.0001(\text{stat.})^{+0.0023}_{-0.0021}\ (\text{exp.})^{+0.0029}_{-0.0030}\ (\text{th.})\ \ (3.1\%\ \text{total})$$

➔ **precise** α_s determination from a **single** HERA measurement

Summary of $\alpha_s(M_Z)$ values

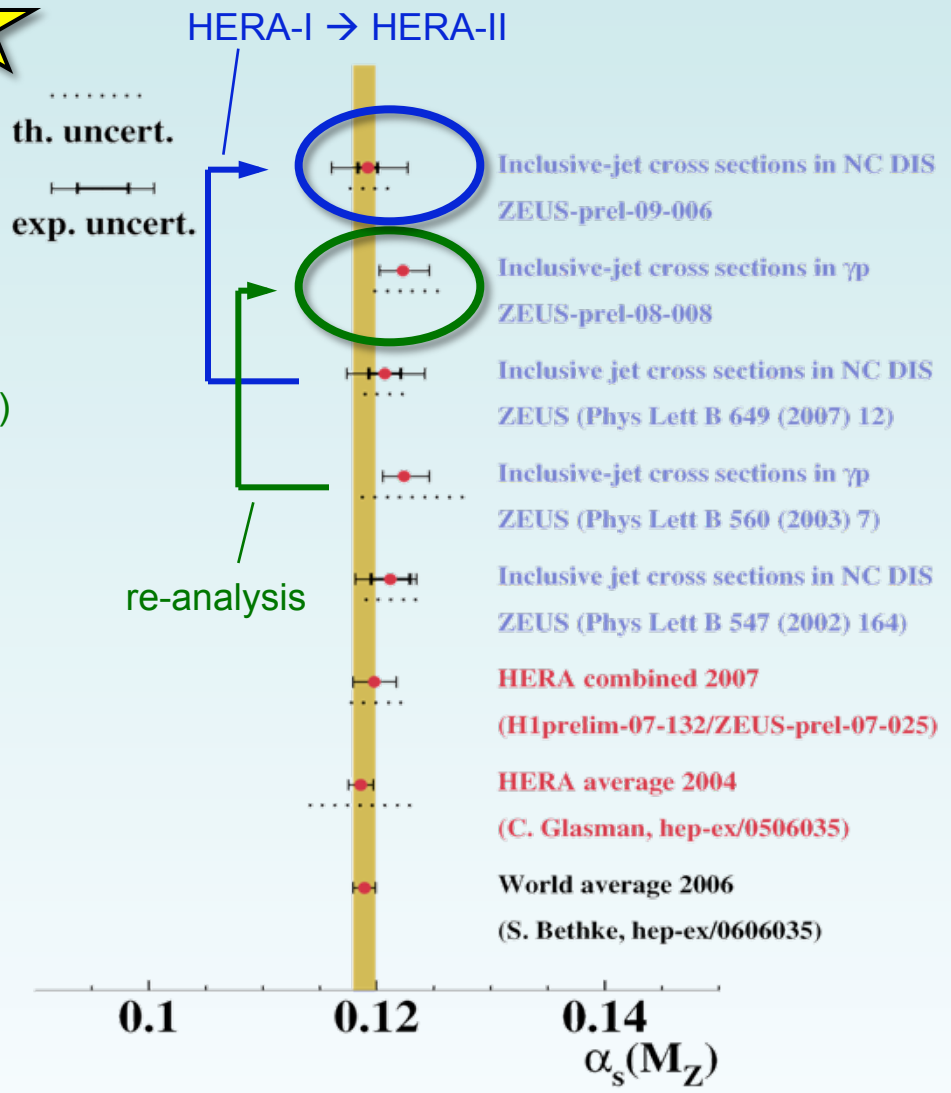
need **NNLO** to improve theoretical uncertainty

1. new **HERA-II** NC DIS incl. jets: total uncertainty **3.5%**
   c.f. HERA-I (Phys Lett B649 (2007) 12)
2. re-analysis of **HERA-I** γp incl. jets: total uncertainty **3.1%**
   c.f. previous anal. (Phys Lett B560 (2003) 7)

↑ note the competitive precision of these determinations, **from single HERA measurements**, compared to averages:

- HERA combined 2007 (**2.7%** uncert.)
  (from H1 and ZEUS inclusive jets in NC DIS; currently the highest precision HERA extraction)
- LEP (**1.7%** uncert.) [S. Kluth, EPS07]

measurements **consistent** with each other and with **world average**



Summary

» **NC DIS jet cross sections from ZEUS with HERA-II data:**

1. **new** measurement of **inclusive jets** from HERA-II (188 pb^{-1})
2. **dijets** using combined HERA-I + II (209 pb^{-1})

- **inclusive** and **dijet** data well described by **NLO QCD**
- **theoretical uncertainties** dominate (μ_R variation; or use of different scale choices)
- data sensitive to **proton PDFs** (and α_s ↓)

» **new extractions of α_s from ZEUS**

- **precise** determinations from new **inclusive jets** in **NC DIS** and re-analysis of **γp**
  - compatible with averages (HERA, LEP, world); total uncertainty **~ 3−3.5%**

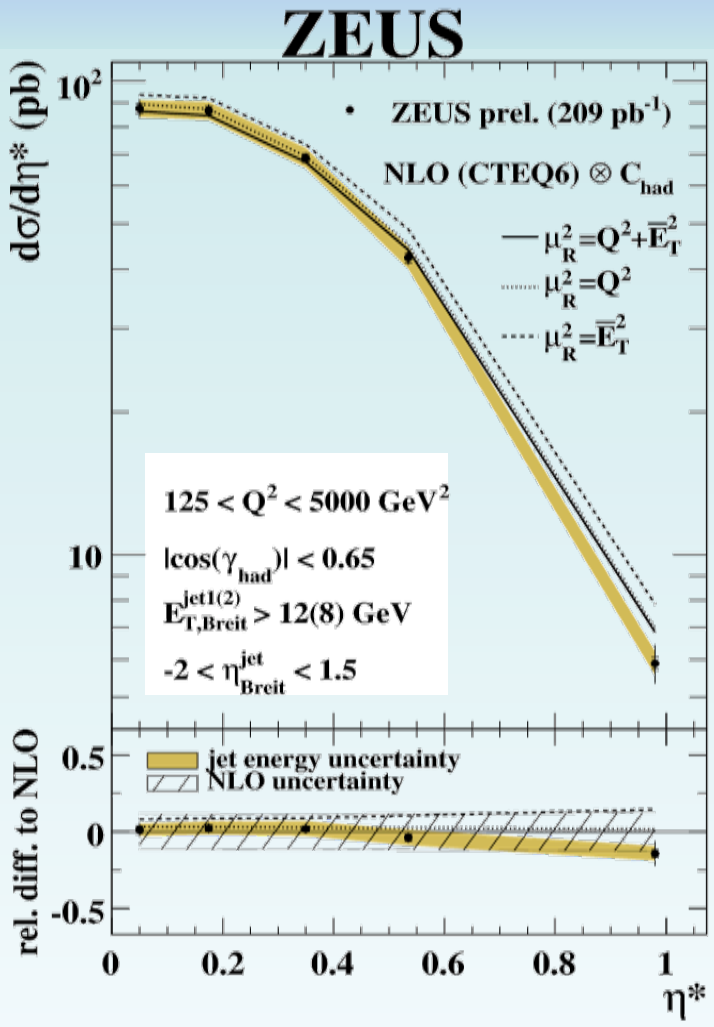
» **future:**

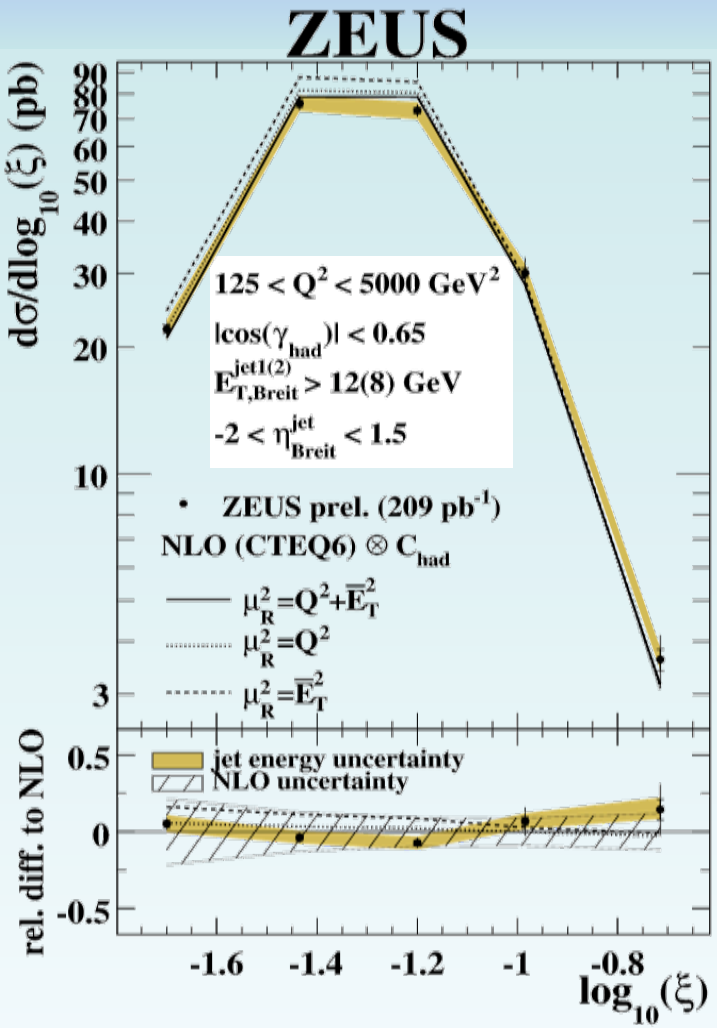
- Jets measurements with **full** HERA-II data (**coming soon**)
- HERA combinations ➔ **final word on HERA α_s**
- updates to **QCD fits** using new jet data ➔ **improvement to PDFs?**

extras

Dijet cross sections

ZEUS-prel-07-005





single-differential, as functions of $\eta^* = \frac{1}{2}(\eta^1 + \eta^2)$ and $\log_{10}(\xi)$ ➔ data well described by **NLO QCD**