Parton Densities and Determination of α_s from ep Collisions

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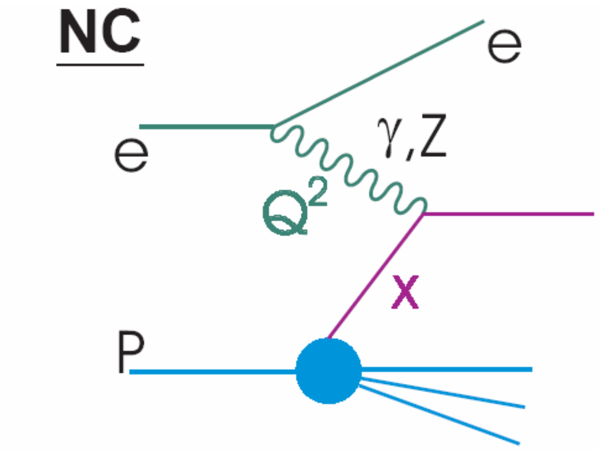
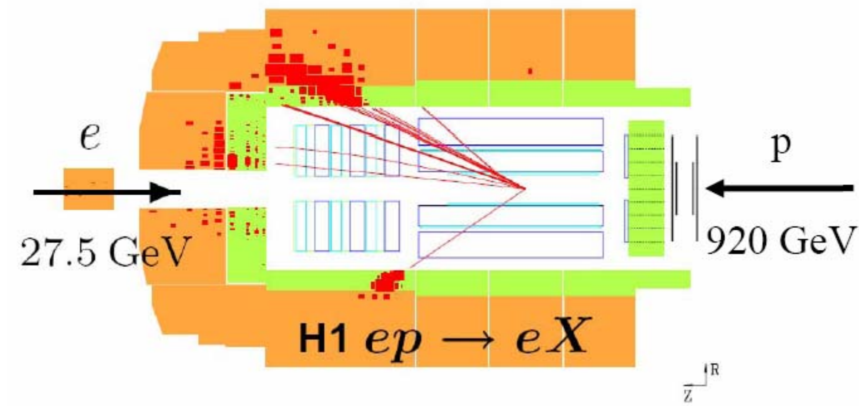
- **Deep Inelastic Scattering at HERA**
- **Structure Functions and Parton Densities**
- **Determination of α_s**
- **Summary and outlook**

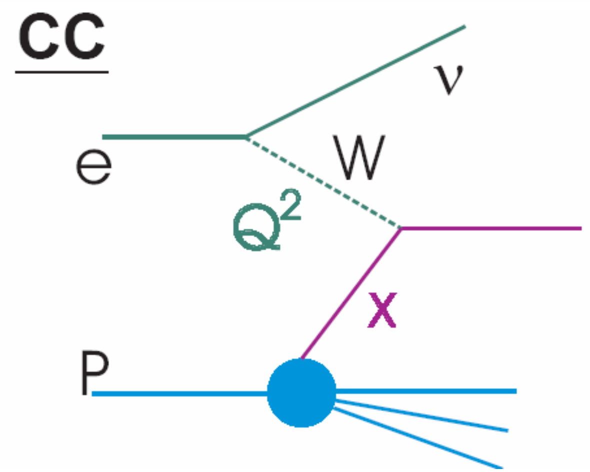
HERA at DESY: ep collider $\sqrt{s}$ = 319 GeV, HERA I 130 pb^{-1},
HERA II longitudinally polarized $e^{\pm}$ 350 pb^{-1} (so far), stops 2007 June 30

Deep Inelastic Scattering at HERA

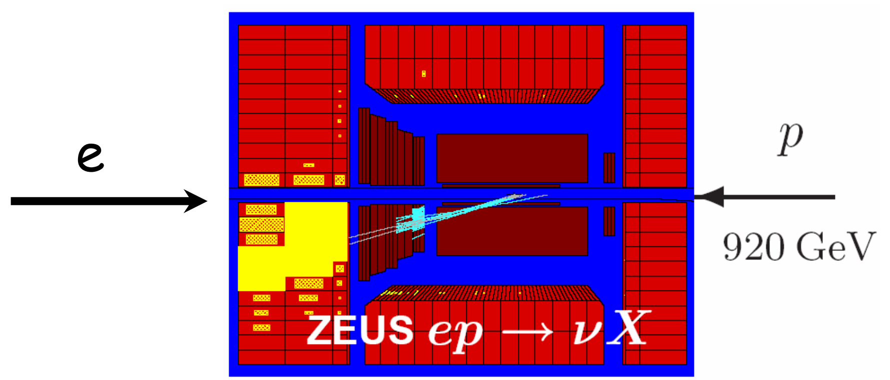


neutral current DIS

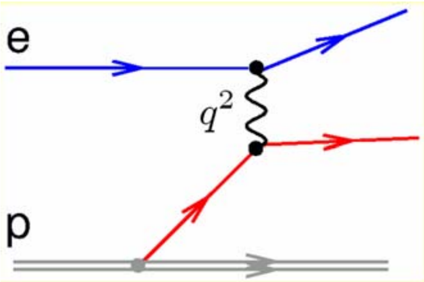




charged current DIS

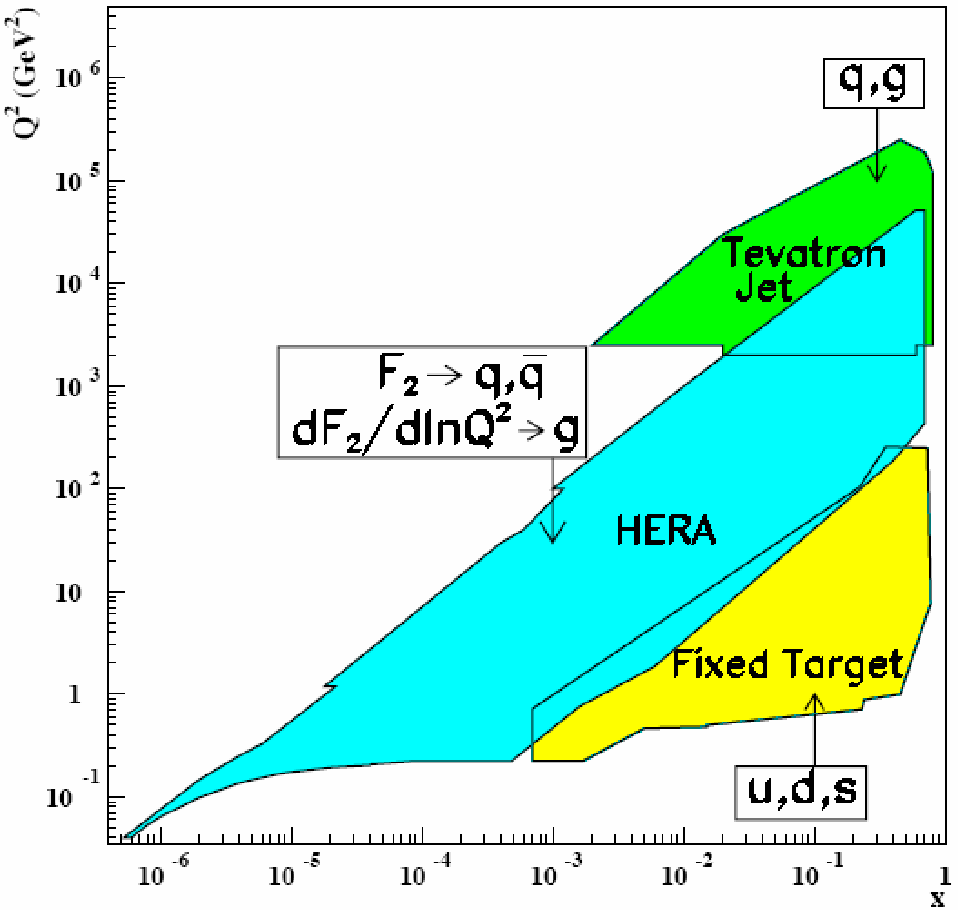


Precise measurements of the scattered charged lepton (E_e scale at 1% level)
and hadronic final state (E_h scale at 1 - 4% level)
in the H1 and ZEUS detectors



HERA kinematic plane

- Center of mass energy $\sqrt{s}$ = 319 GeV
- Four momentum transfer $Q^2 = -q^2$
  virtuality of the exchanged boson
  ($0 < Q^2 < 10^5$ GeV^2)
- Bjorken $x = Q^2/p{\cdot}q$
  Quark Parton Model – fraction of the proton momentum carried by the struck quark
  ($10^{-6} < x < 1$)
- Inelasticity $y = Q^2/xs$



Kinematics can be reconstructed from the scattered electron or/and hadronic final state

HERA – large range in x and Q^2

HERA – most important source of data on proton structure

Inclusive neutral current cross section

$$\frac{d^2\sigma_{NC}(e^{\mp}p)}{dx\,dQ^2} \propto Y_+ F_2 + y^2 F_L \pm Y_- x F_3, \qquad Y_\pm = 1 \pm (1-y)^2$$

- **F_2^{em}** **dominates in most phase space** $F_2 = F_2^{em} + \Delta(\gamma Z, Z)$
- **F_L** **contributes at high y**
- **F_3** **parity violating SF, important at high Q^2 ($Q^2 > m_Z^2$), dominated by γZ interference**
- **Structure functions F_i ➡ parton distribution functions (PDF)**

Quark-parton model ➡ scaling, no dependence of SF on Q^2

PDF probability to find a parton in a fast moving proton with a fraction x of the proton momentum

$$F_2^{em}(x,Q^2) = x\sum e_q^2\,(q(x)+\bar{q}(x)), \qquad F_L(x,Q^2)=0$$

$$xF_3^{\gamma Z}(x,Q^2) \sim x\sum e_q a_q (q(x)-\bar{q}(x))$$ ➡ sensivity to **valence quark PDFs**

Structure functions and QCD

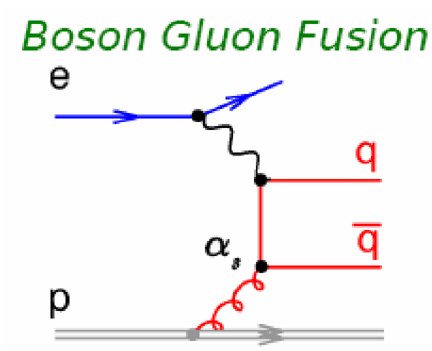
- **QCD processes lead to logarithmic scaling violations** ($\partial F_2 / \partial \ln Q^2 \neq 0$)

- **Factorization theorem: SF are convolution of universal scale-dependent PDFs $f_{a/p}(x, \mu_f^2)$ and process dependent calculable in pQCD** (as power series of $\alpha_s(\mu_r)$) **coefficient functions** C_i^a

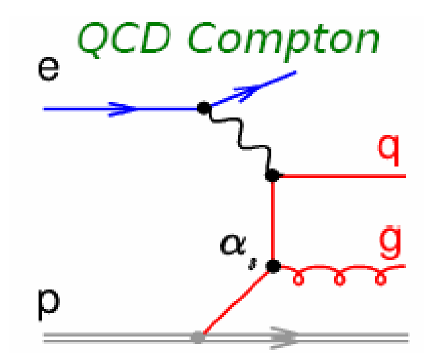
$$F_i(x, Q^2) = \sum_{a=g,q,\bar{q}} C_i^a \otimes f_{a/p}$$

Typical choice for renormalization and factorization scales $\mu_r = \mu_f = Q$

- **Evolution of PDFs in μ_f described in pQCD by the DGLAP equations**



dominates at small Q^2
depends on α_s and
gluon PDF

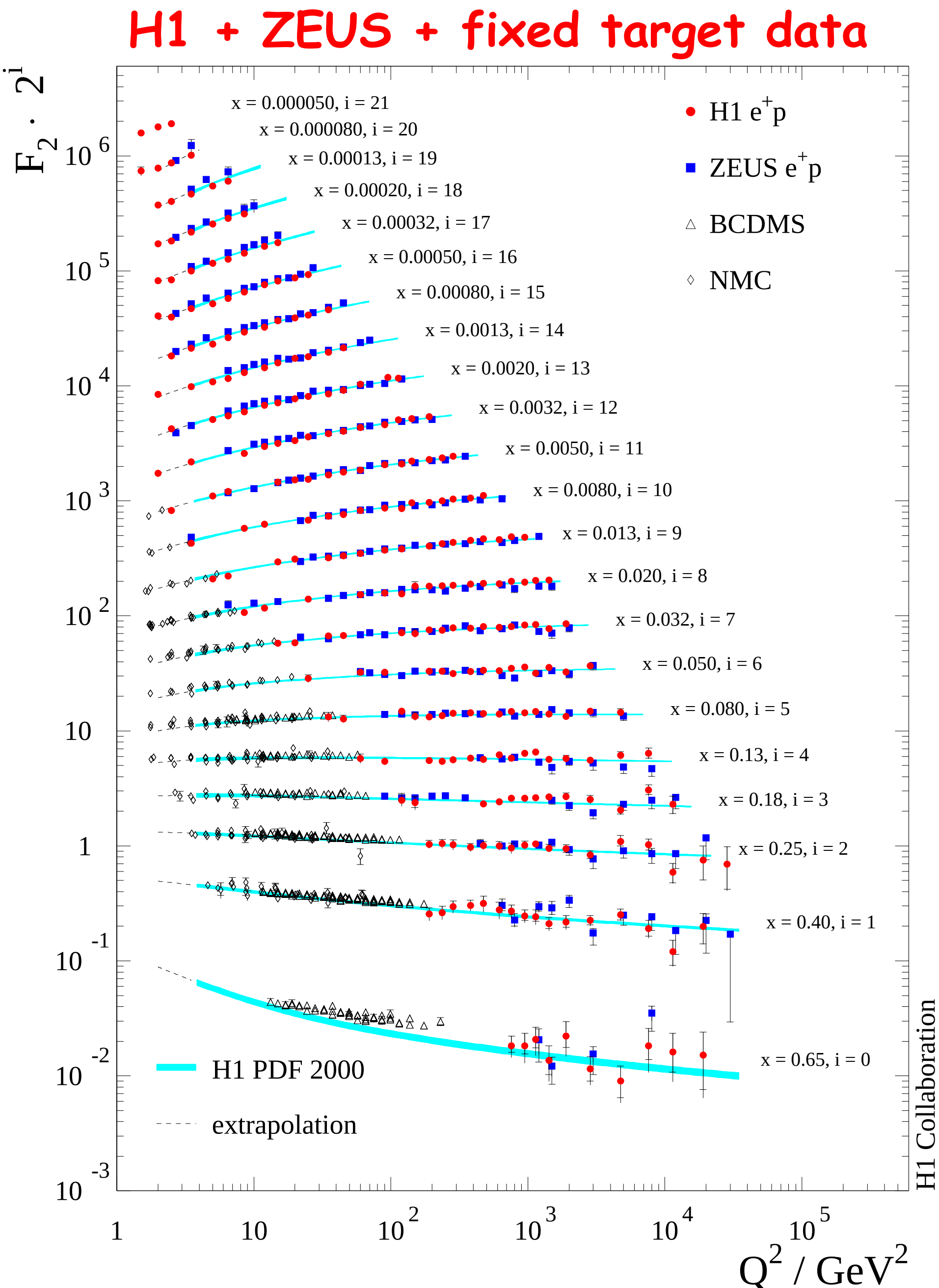


domiantes at large Q^2
depends on α_s
and quark PDFs

At leading order QCD processes BGF and QCDC give rise to scaling violations of F_2 and production of jets in the final state

→ **Sensivity to α_s and quark/gluon densities in the proton**

$F_2(x,Q^2)$ measurements at HERA – textbook results



$$F_2^{em}(x,Q^2) \sim x\sum_q e_q^2(q+\bar{q})$$

Strong constraint on $u, \bar{u}$

$$\frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_s[P\otimes g + P\otimes F_2]$$

Good constraint on g and α_s

HERA I data measured with ~ 2-3% precision over huge kinematic range:

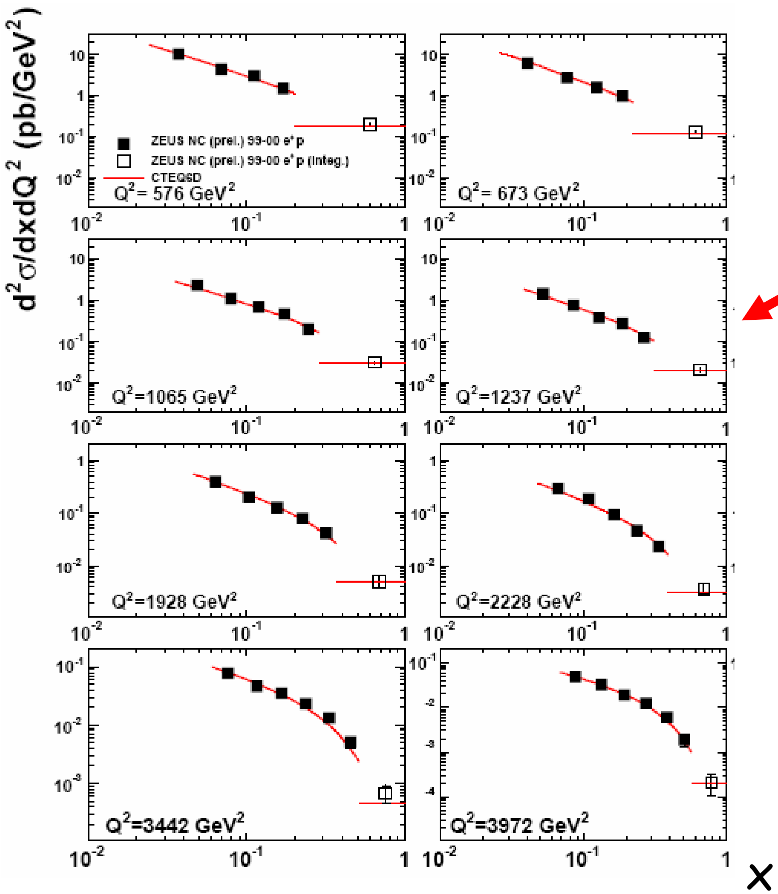
- **strong scaling violation at low x**
- **very well described by QCD fits**

HERA II – more data
(~3 times e^+p, ~10 times e^-p)
→ better accuracy at large Q^2 and x

Measurement of high-x NC cross sections at HERA

Limited DIS data on cross sections at high-x and high Q^2
(fixed target exp. F_2 up to x=0.75, H1 and ZEUS F_2 up to x=0.65) → **PDFs poorly determined at high-x**

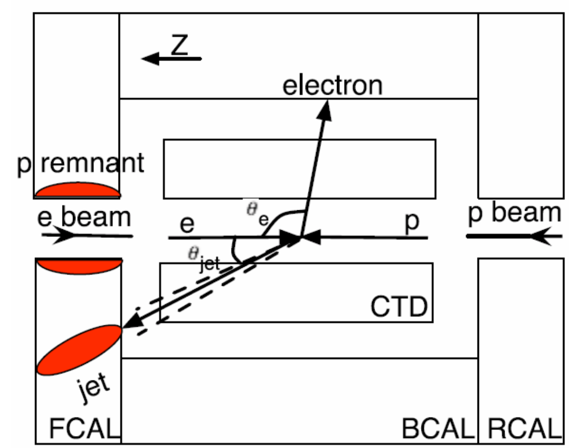
ZEUS – NC DIS cross sections up to x =1



Impact on high-x PDFs

Comparison to SM predict. at NLO (CTEQ6D)

Topology of high-x DIS event



High Q^2 – 100 % acceptance for a reconstr. of the scattered electron

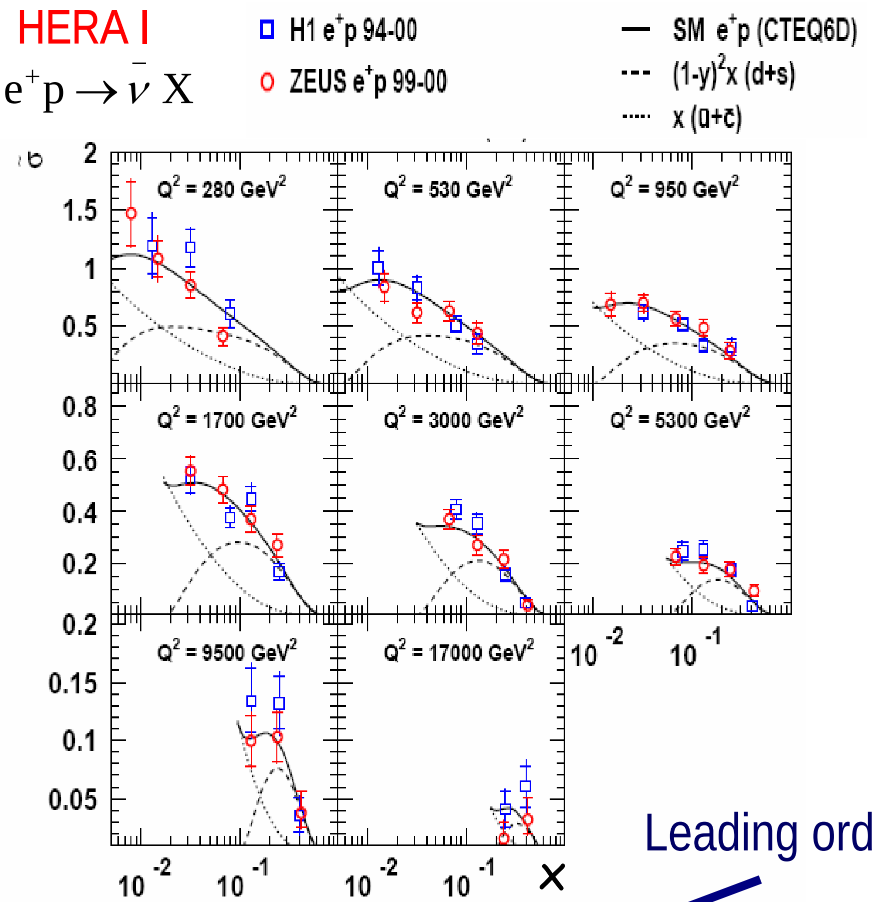
Not too high x, measure x from jet measure $d^2\sigma / dx\, dQ^2$

For $x > x_{Edge}$ measure $\dfrac{\int_{x_{Edge}}^{1} \dfrac{d^2\sigma}{dx\, dQ^2}}{1 - x_{Edge}}$

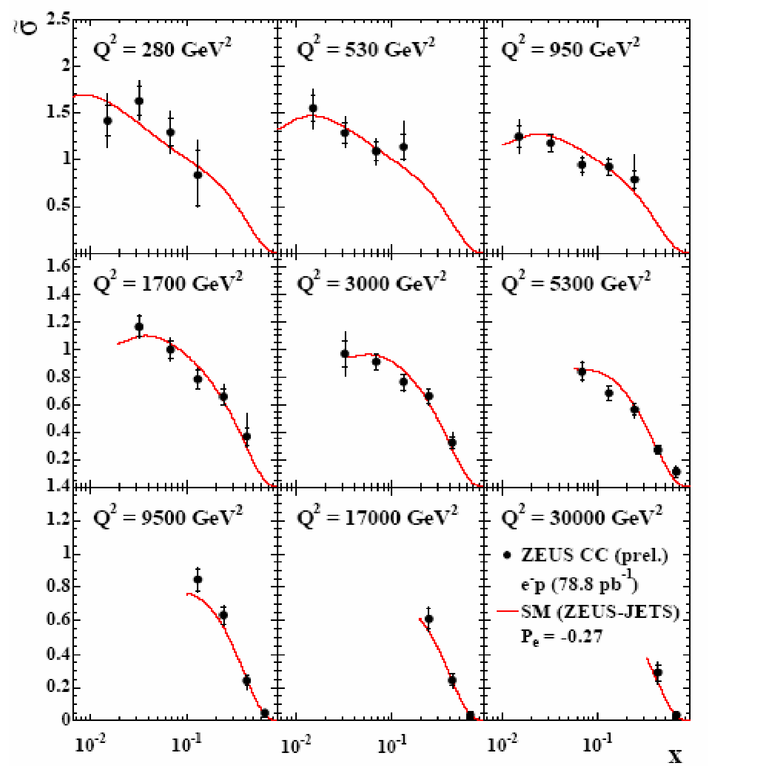
Charged current cross sections

$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2} \propto (1\pm P)\,G_F^2 \frac{M_W^4}{x(Q^2+M_W^2)^2}\,\bar{\sigma}_{CC}(e^{\pm}p)$$

HERA I $e^+p \to \bar{\nu}\, X$



Polarized HERA II data (ZEUS, P_e = -0.27), $e^-p \to \nu\, X$



Leading order relations

$$\bar{\sigma}_{CC}(e^+p) \propto x(\bar{u}+\bar{c}) + x(1-y)^2(\mathbf{d+s+b})$$

$$\bar{\sigma}_{CC}(e^-p) \propto \mathbf{x(u+c)} + x(1-y)^2(\bar{d}+\bar{s}+\bar{b})$$

constraint on d_v density at large x

constraint on u_v density at large x

At large Q^2 and large x HERA can disentangle quark flavours

Determination of parton densities at HERA

- **Parametrizaton of x dependence of PDFs at starting scale Q_0^2**
  (constraints: sum rules, flavour composition of sea quarks, behaviour of the valence u and d quarks at low x …)

- **Evolution of initial PDFs in Q^2 within NLO DGLAP formalizm**

- **Convolution of PDFs with coefficient functions** → predictions for structure functions/cross sections

- **Fit to measured structure functions/NC and CC cross sections**
  (evaluation of correlated syst. errors by Offset (ZEUS) or Hessian (H1) method)

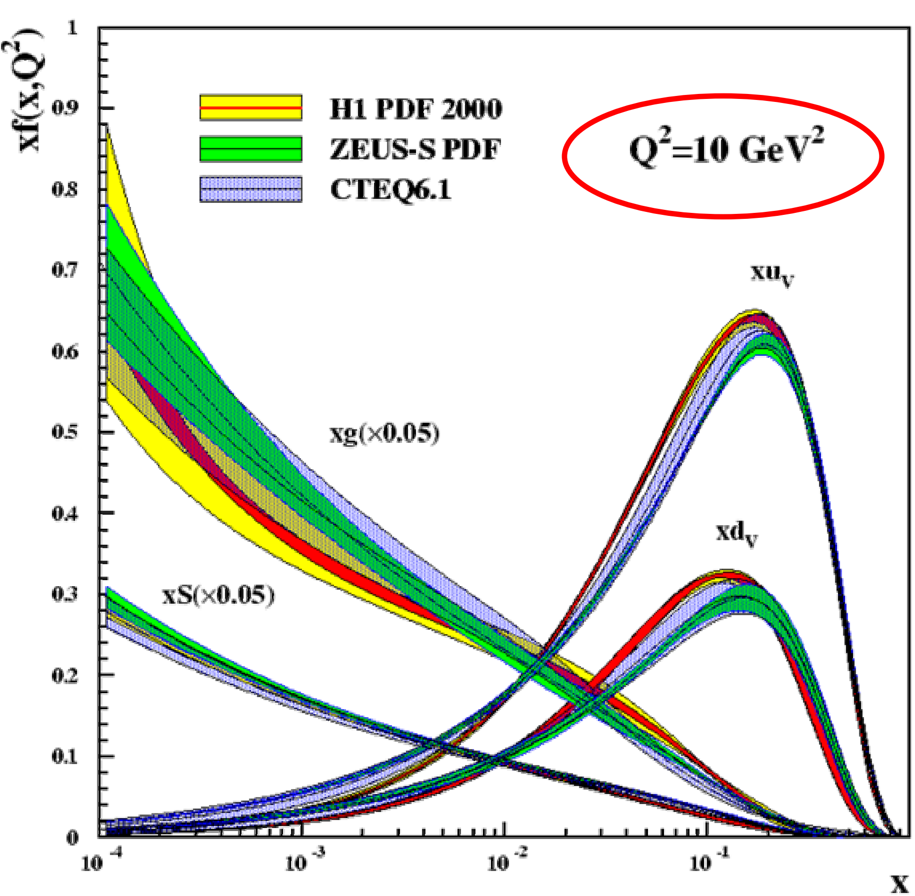
Analyses from the HERA data only

Low Q^2 NC inclusive σ → low x sea and g (from $dF_2/d\ln Q^2$)

High Q^2 NC&CC inclusive σ → valence quark densities

Jet production data → constrain the gluon at mid to high x

- Systematic uncertainties well understood
- No complications from nuclear corrections necessary for fixed target νFe and μD data
- No sensivity to higher twists
- No assumption on strong isospin



Parton distributions

from NLO QCD fits of H1 and ZEUS:

- **F2 data from own experiment**
- **CC cross sections** (constr. on u, d at high x)
- **ZEUS – fixed target DIS data** included to improve the precision of valence quarks PDFs

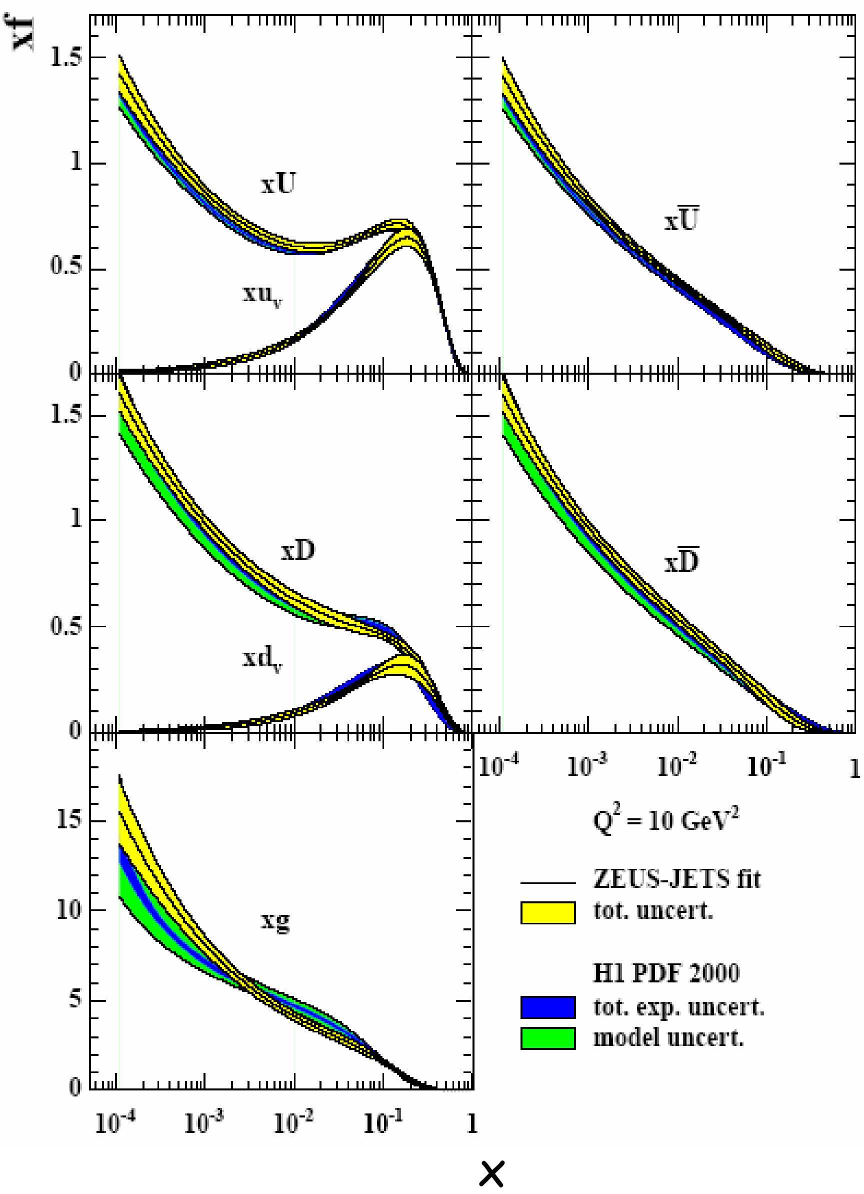
- H1 and ZEUS parton densities agree within uncertainties (also agreement with global fits CTEQ and MRST)
- Strong increase of gluon and sea quark PDFs at low x (reflects the rise of F_2)
- Different shapes of the H1 and ZEUS gluon densities (but gluon at low x and Q^2 not well constrained, also limited sensivity at high x)

Inclusive DIS data → gluon PDF contributes indirectly to the cross section, determined from scaling violation ($dF_2 / d\ln Q^2$)

Direct contribution of the gluon PDF to jet cross sections (BGF) → inclusion of jet data in NLO QCD fits

Parton distributions

QCD fits within single experiments
ZEUS-JETS and H1 PDF 2000



ZEUS-JETS fit

HERA I data:

NC&CC inclusive DIS cross sections

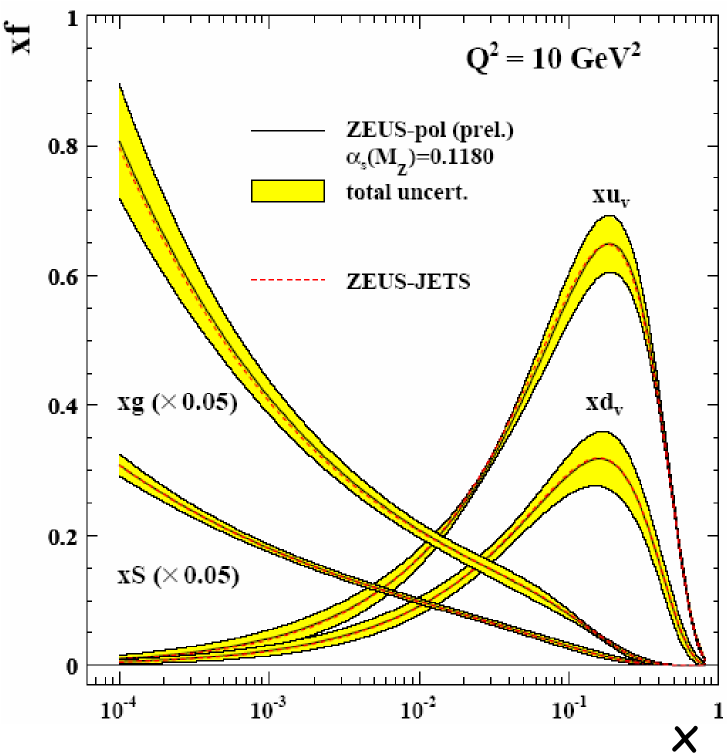
+ jet cross sections (inclusive jets in DIS and dijets in photoproduction ($Q^2 = 0$, $x_\gamma > 0.75$))

- reduced uncertainty of the gluon density in the region $0.01 < x < 0.4$ (factor ~2)
- H1 and ZEUS PDFs agree within uncertainties but some diffrences in shapes exist
- Differences due to different analysis methods and a difference at the level of the data sets
- Simultaneous determination of PDFs and α_s

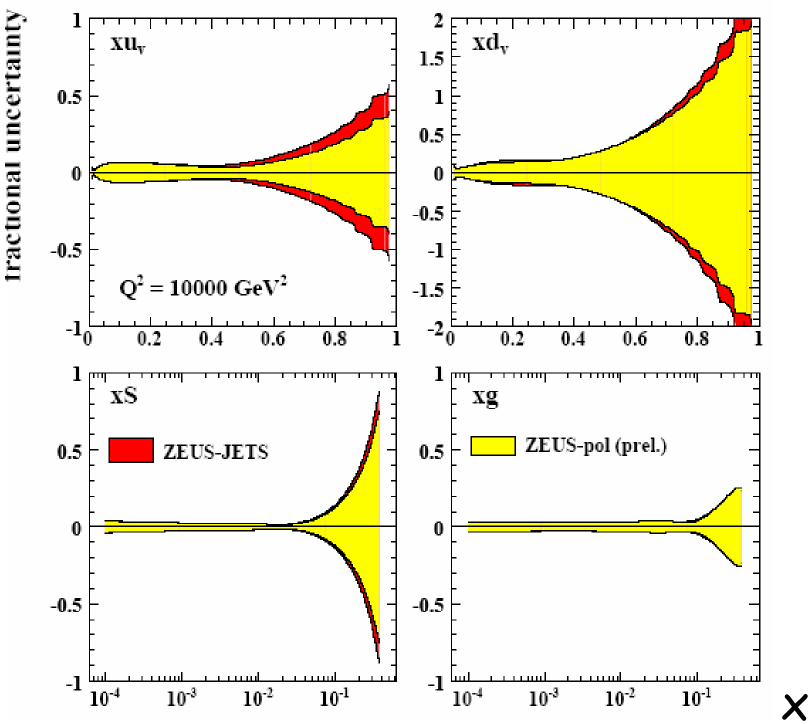
QCD fits with HERA II polarized data

Electroweak and QCD analysis based on ZEUS-JET fit using inclusive DIS and jet data from HERA I and HERA II polarized $e^- p$ NC&CC inclusive cross sections

EW paramters fixed to SM values



ZEUS-pol (with HERA II data)
ZEUS-JETS (w/o HERA II data)



Central values of PDFs almost unchanged

Uncertainties reduced at high x (see $\mathbf{xu_V}$)
$\sigma_{NC} \sim (4u + d)$, $\sigma_{CC} (e^- p) \sim u$

Determination of α_s at HERA

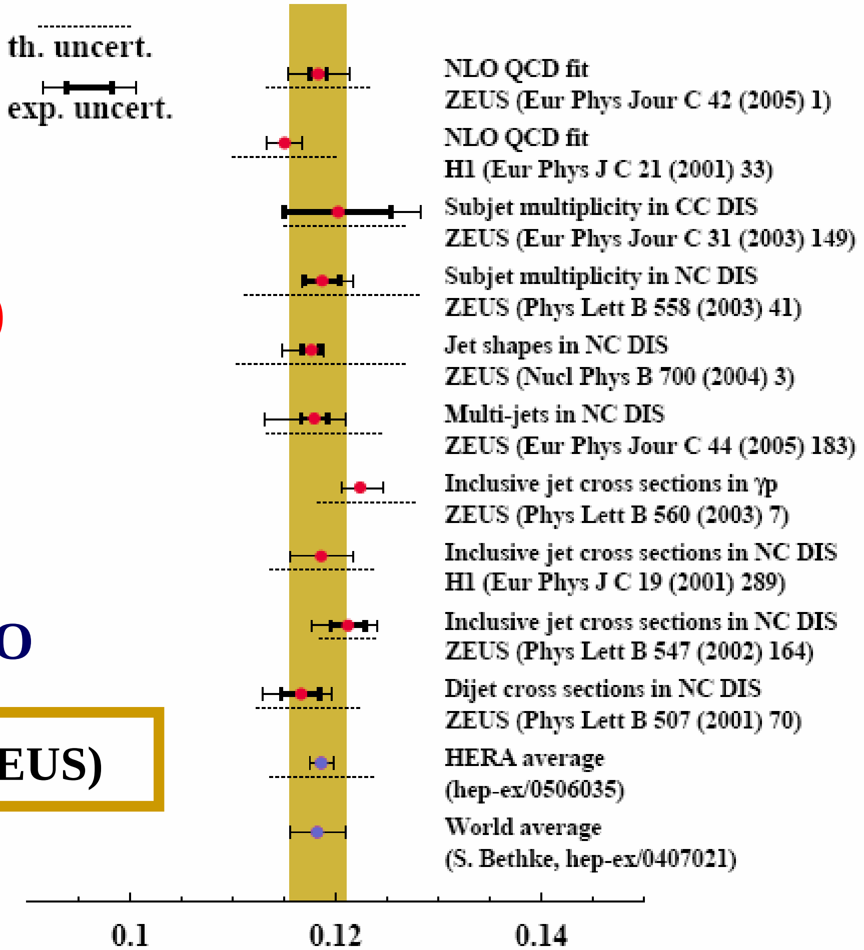
- $\alpha_s(M_Z)$ determined at HERA from a variety of measurements
  - Scaling violation of F_2 (indirect sensivity to α_s)
  - Jet measurements (cross sections and jet properties, direct sensivity to α_s)
- $\alpha_s(M_Z)$ values are all in good agreement
- **Combined $\alpha_s(M_Z)$ value determined to NLO**

$$\alpha_s = 0.1186 \pm 0.0011(\text{exp}) \pm 0.005(\text{th}) \text{ (H1 + ZEUS)}$$

- **Compatible with the world mean**

  0.1182 ± 0.0027 (Bethke 2004)
- **With competitive precision**
- **Dominant theoretical error**
- **Included in a more recent world average**

  0.1189 ± 0.0010 (Bethke 2006)



The $\alpha_s(M_z)$ values from H1 and ZEUS analyses contributing to the HERA average in comp. with the world average (Bethke 2004)

New high precision measurements of jet production in NC DIS at high Q^2

α_s determination from jets

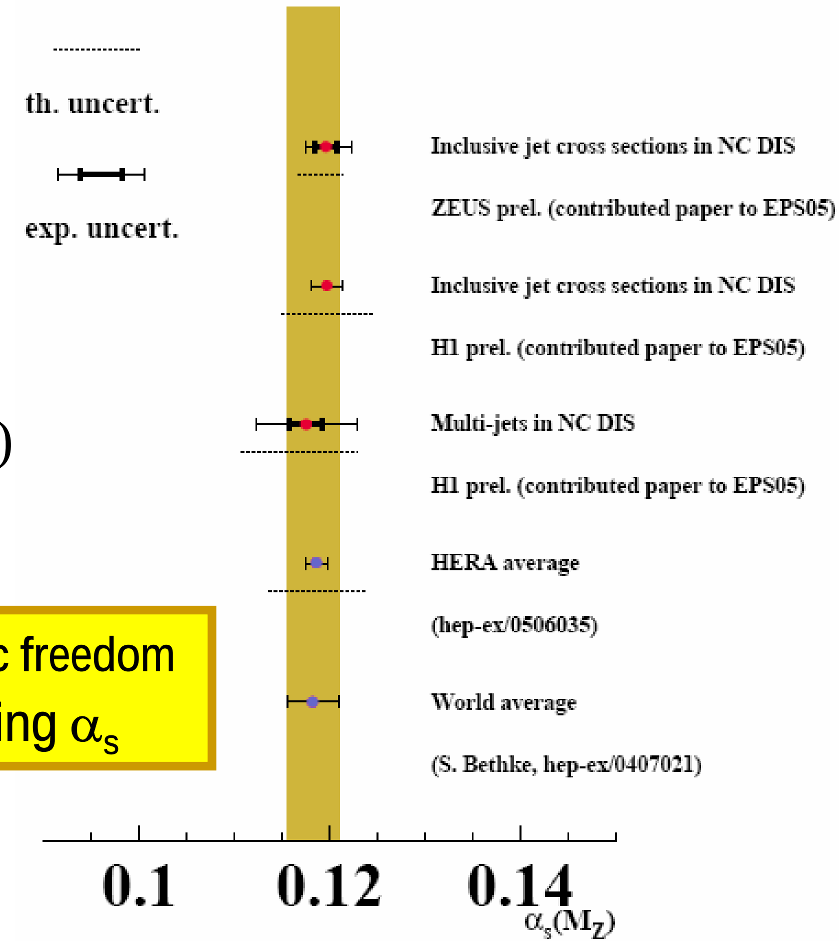
$\alpha_s(M_Z)$ extracted from different. jet cross sec. $d\sigma/dE_{T,B}$ and $d\sigma/dQ^2$ measured in Breit Frame

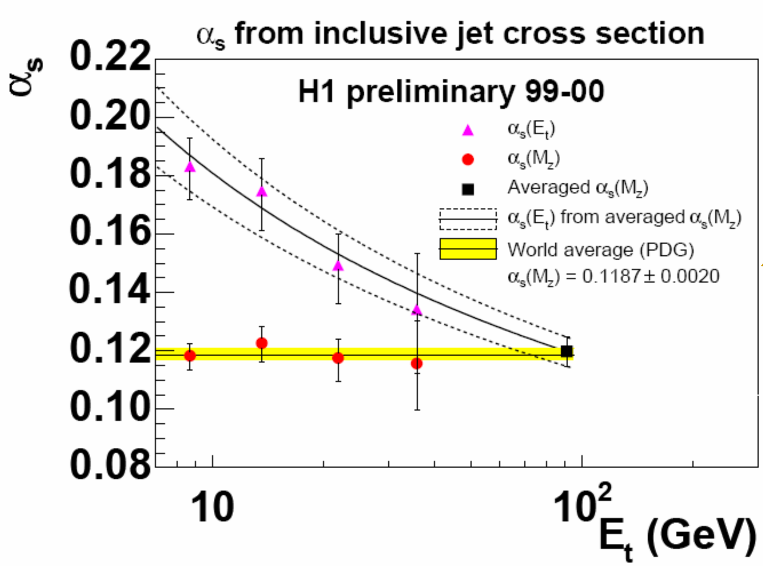
$$0.1197 \pm 0.0016(\text{exp.}) \pm^{0.0046}_{0.0048} (\text{th.})$$

H1

$$0.1196 \pm 0.0011(\text{stat.}) \pm^{0.0019}_{0.0025} (\text{exp.}) \pm^{0.0029}_{0.0017} (\text{th.})$$

ZEUS





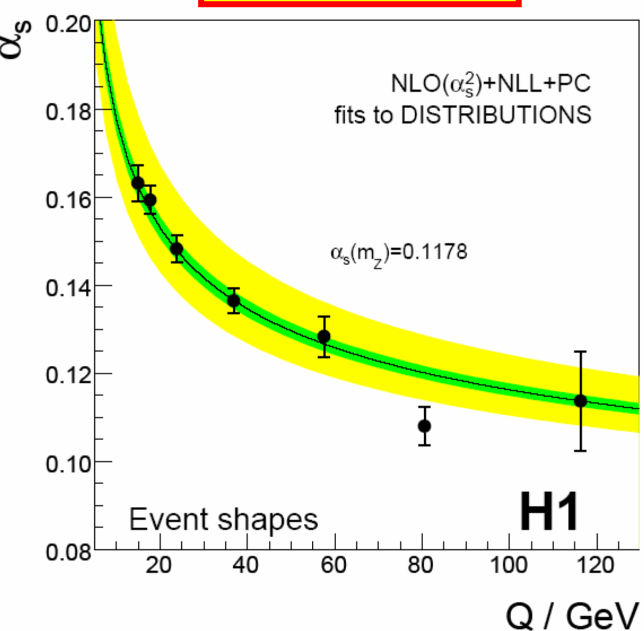
Asymptotic freedom running α_s

Mesurements not yet included in the HERA average

α_s from event shapes

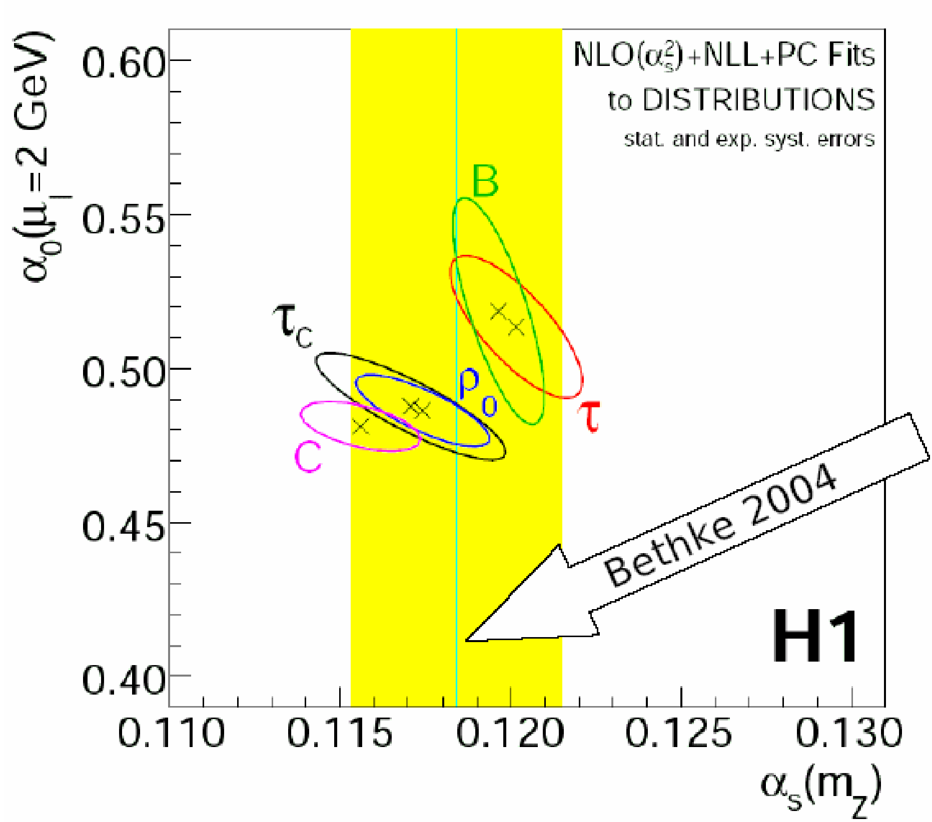
- **Variables calculated from the 4-vectors of all hadronic final state particles describing topological features of DIS events**
- **Larger statistics compared to jet samples due to semi-inclusive nature of ev. shapes**
- **Reduced exp. systematic uncertainties from hadronic energy scales**
- **Larger hadronization effects**

running α_s



QCD description : **NLO(α_s^2)+ soft gluon resummation at NLL**

Hadronization : Dokshitzer-Webber **power corrections** (PC, α_0 – effective strong coupling constant in the infrared regime)



$$\alpha_s(M_Z) = 0.1198 \pm 0.0013(\text{exp.}) \pm^{0.0056}_{0.0043} (\text{th.})$$

Summary & outlook

- **Data from HERA are fundamental to our understanding of the partonic composition of the proton and of QCD**
- Parton density functions extracted from HERA data only with the precision of a few % over most of the x range
- **Determination of α_s from scaling violation and jet data compatible and competitive with the world average**
- Precise measurements of PDFs at HERA important for predicting standard QCD cross sections at LHC

Expected improvement in parton density determination:

- **higher precision of inclusive cross section measurements (** HERA I + HERA II data**)**
- **combination of H1 + ZEUS experimental data**
- **direct measurements of longitudinal structure function $F_L \sim \alpha_s xg(x)$**
  (low energy run E_p= 460 GeV, L ~ 10 pb^{-1})
- **inclusion of charm and beauty data (F_2^{cc} and F_2^{bb}) in QCD fit**
- **NNLO QCD fits**