# Parton Densities and Determination of $\alpha_s$ from ep Collisions


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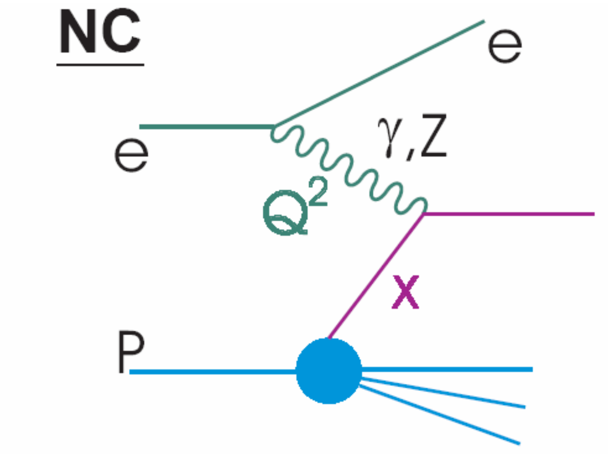
**Lake Louise Winter Institute 2007**

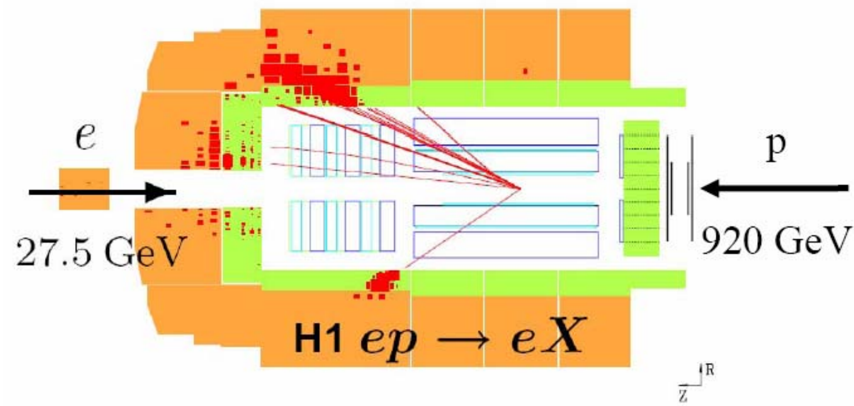
- **Deep Inelastic Scattering at HERA**
- **Structure Functions and Parton Densities**
- **Determination of $\alpha_s$**
- **Summary and outlook**

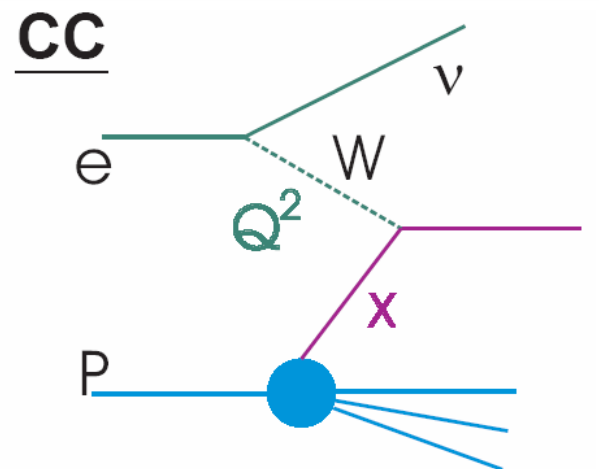
**HERA at DESY: ep collider $\sqrt{s} = 319$ GeV, HERA I 130 pb$^{-1}$,**
**HERA II longitudinally polarized $e^{\pm}$ 350 pb$^{-1}$ (so far), stops 2007 June 30**

# Deep Inelastic Scattering at HERA

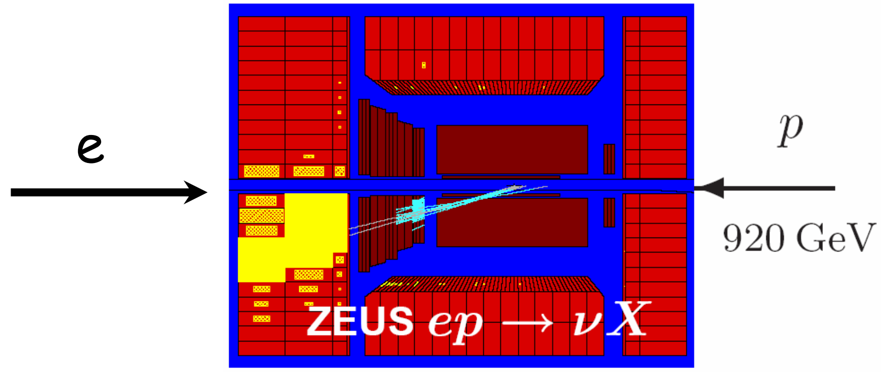



neutral current DIS



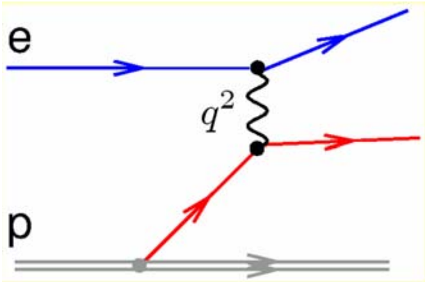




charged current DIS

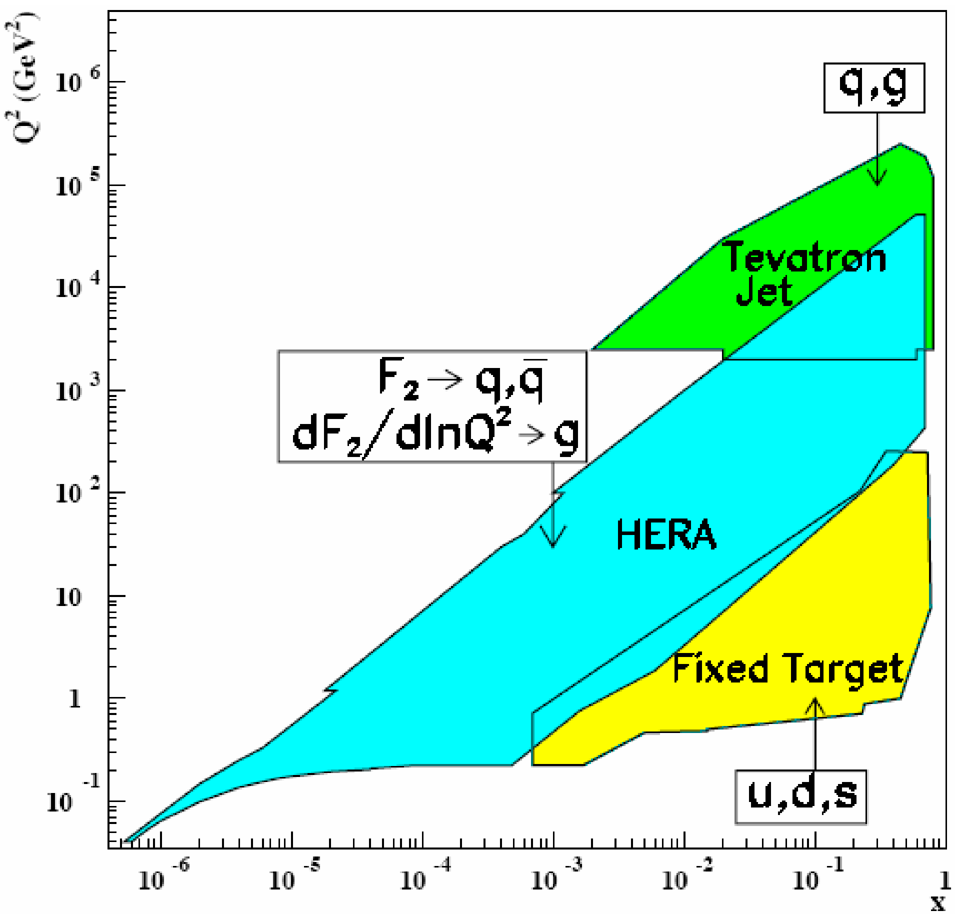



**Precise measurements of the scattered charged lepton** ($E_e$ scale at 1% level)
**and hadronic final state** ($E_h$ scale at 1 - 4% level)
**in the H1 and ZEUS detectors**

# HERA kinematic plane




- Center of mass energy $\sqrt{s}$ = 319 GeV
- Four momentum transfer $Q^2 = -q^2$
  virtuality of the exchanged boson
  $(0 < Q^2 < 10^5 \text{ GeV}^2)$
- 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** $\quad F_2 = F_2^{em} + \Delta(\gamma Z, Z)$
- **$F_L$ contributes at high y**
- **$F_3$ parity violating SF, important at high $Q^2$ ($Q^2 > m_Z^2$), dominated by $\gamma Z$ 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

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

$$x F_3^{\gamma Z}(x,Q^2) \sim x\sum e_q a_q (q(x) - \bar{q}(x))$$ ➔ sensivity to valence quark PDFs

# Structure functions and QCD

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

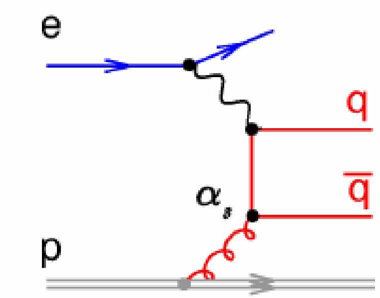
- **Factorization theorem**: **SF are convolution of universal scale-dependent PDFs $f_{a/p}(x, \mu_f^2)$ and process dependent calculable in pQCD** (as power series of $\alpha_s(\mu_r)$) **coefficient functions** $C_i^a$

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

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

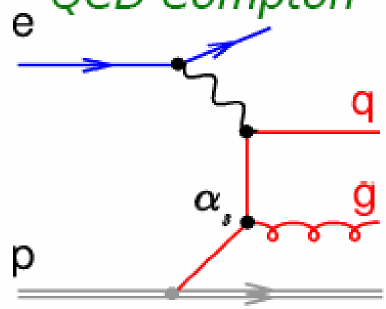
- **Evolution of PDFs in $\mu_f$ described in pQCD by the DGLAP equations**

*Boson Gluon Fusion*




dominates at small $Q^2$
depends on $\alpha_s$ and
gluon PDF

*QCD Compton*



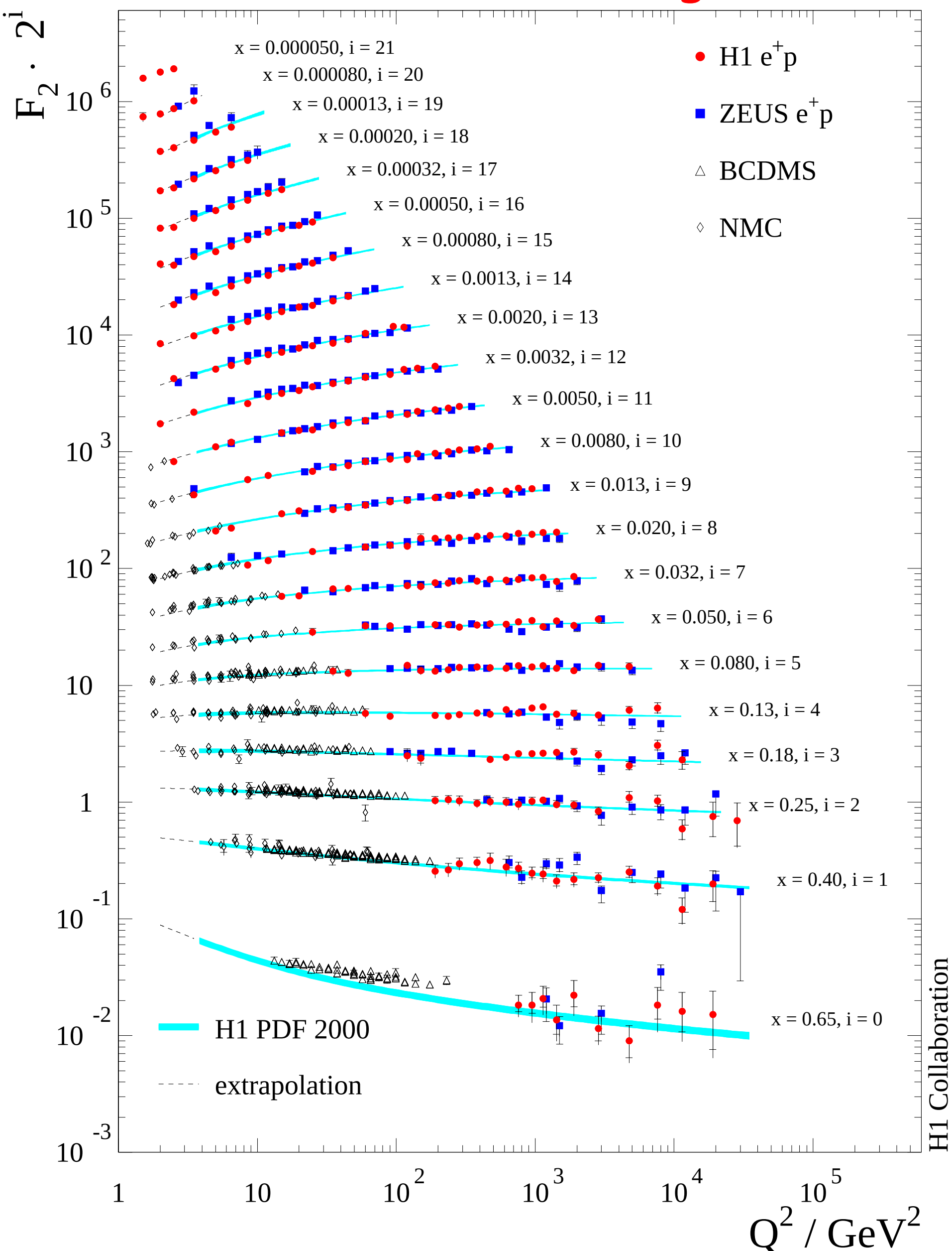

domiantes at large $Q^2$
depends on $\alpha_s$
and quark PDFs

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 $\alpha_s$ and quark/gluon densities in the proton**

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

## H1 + ZEUS + fixed target data




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

**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 $\alpha_s$**

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

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

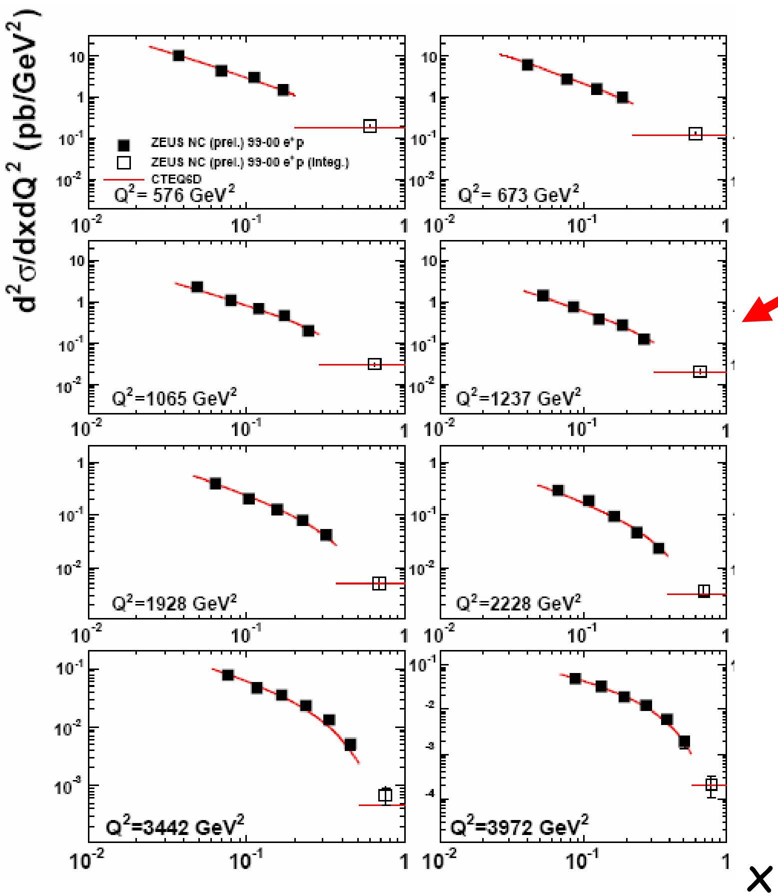
HERA II – more data
(~3 times $e^+p$, ~10 times $e^-p$)
→ better accuracy at large $Q^2$ and x

# 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**

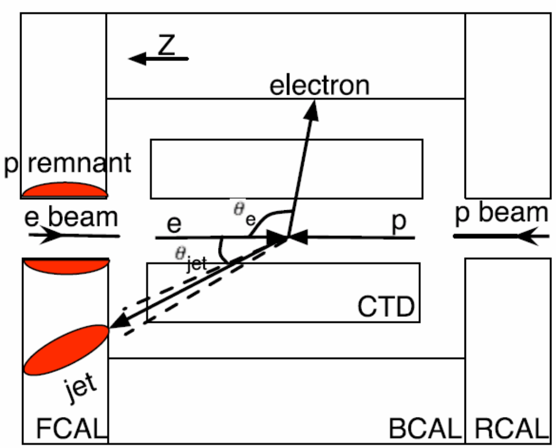
**ZEUS – NC DIS cross sections up to x =1**




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 $dQ^2$

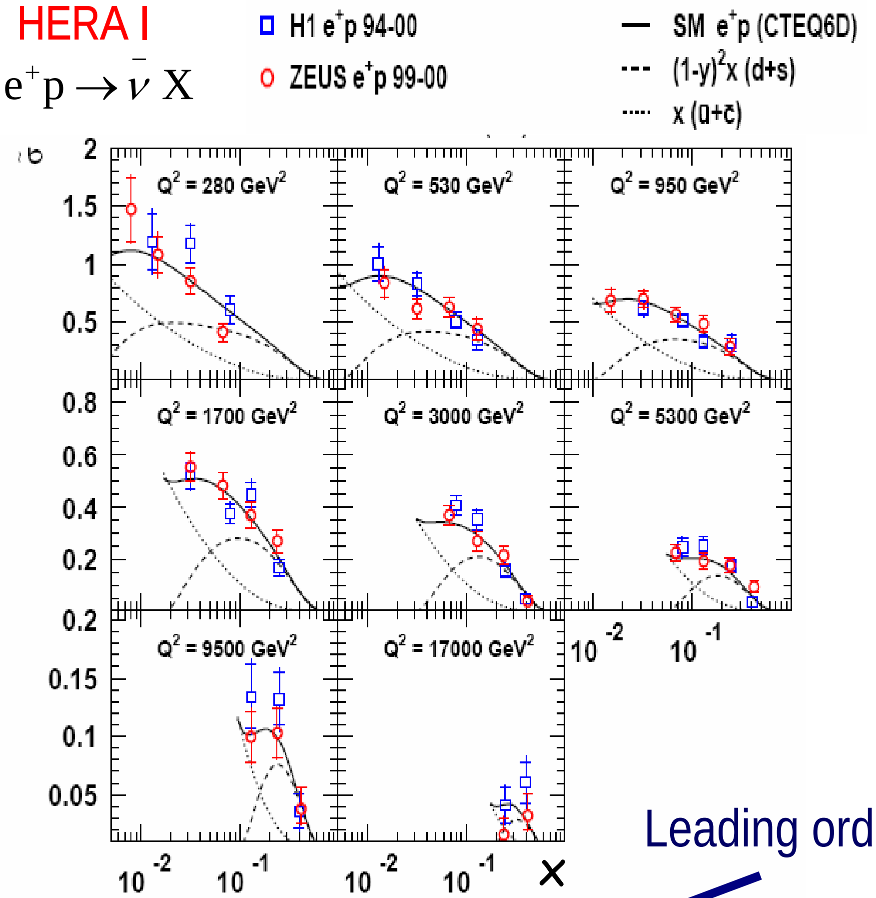
For x > $x_{Edge}$ measure $$\frac{\int_{x_{Edge}}^{1} \frac{d^2\sigma}{dx\,dQ^2}}{1-x_{Edge}}$$

# Charged current cross sections

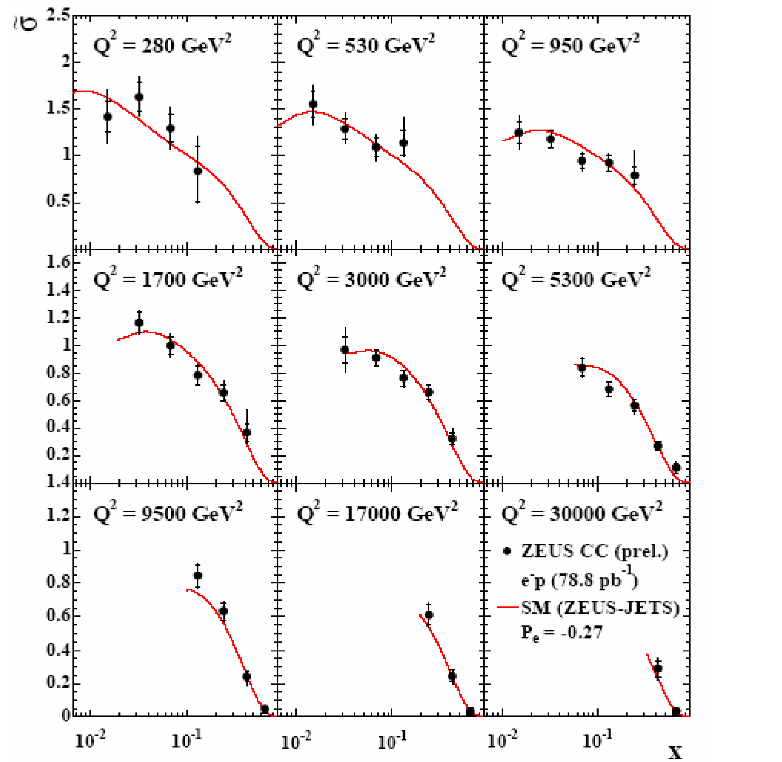
$$\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2} \propto (1 \pm P)\, G_F^2 \frac{M_W^4}{x(Q^2+M_W^2)^2}\, \bar{\sigma}_{CC}(e^{\pm}p)$$

HERA I

$e^+p \rightarrow \bar{\nu}\, X$




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




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**

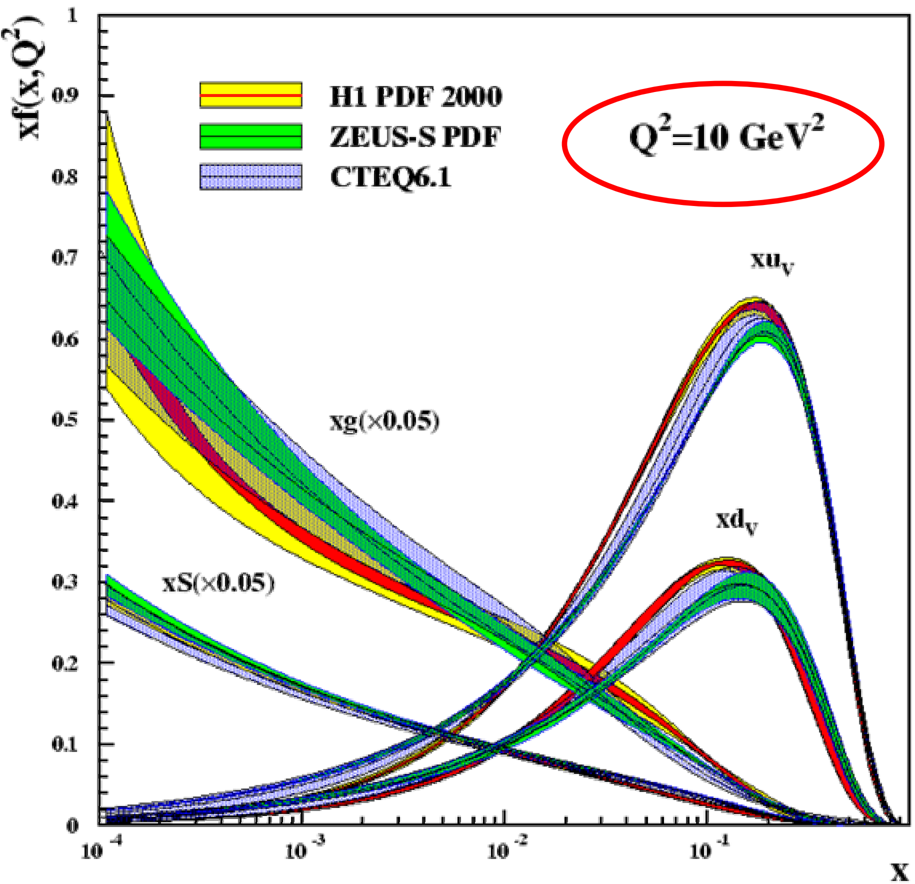
Low $Q^2$ NC inclusive $\sigma$ → low x sea and g (from $dF_2/d\ln Q^2$)

High $Q^2$ NC&CC inclusive $\sigma$ → 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 $\nu$Fe and $\mu$D data
- No sensivity to higher twists
- No assumption on strong isospin

# Parton distributions




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

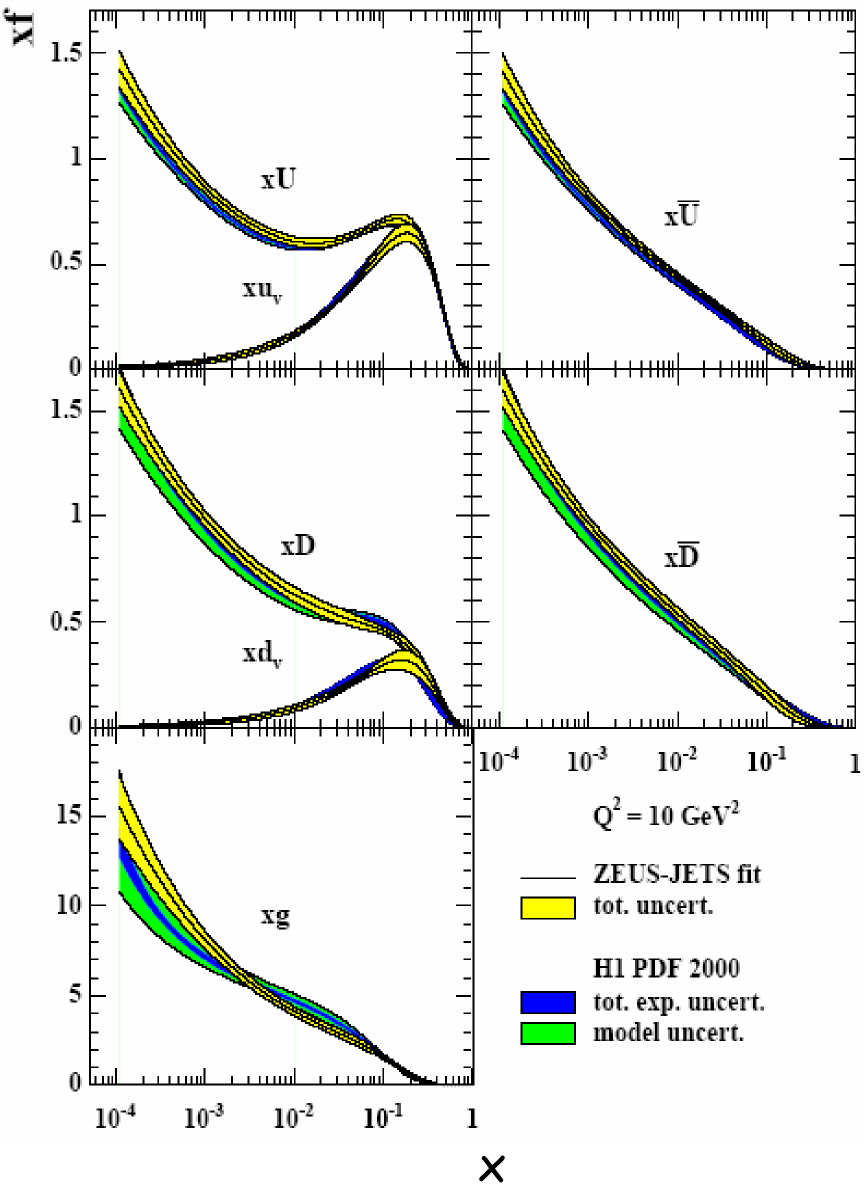
**from NLO QCD fits of H1 and ZEUS:**

- **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)

# 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**

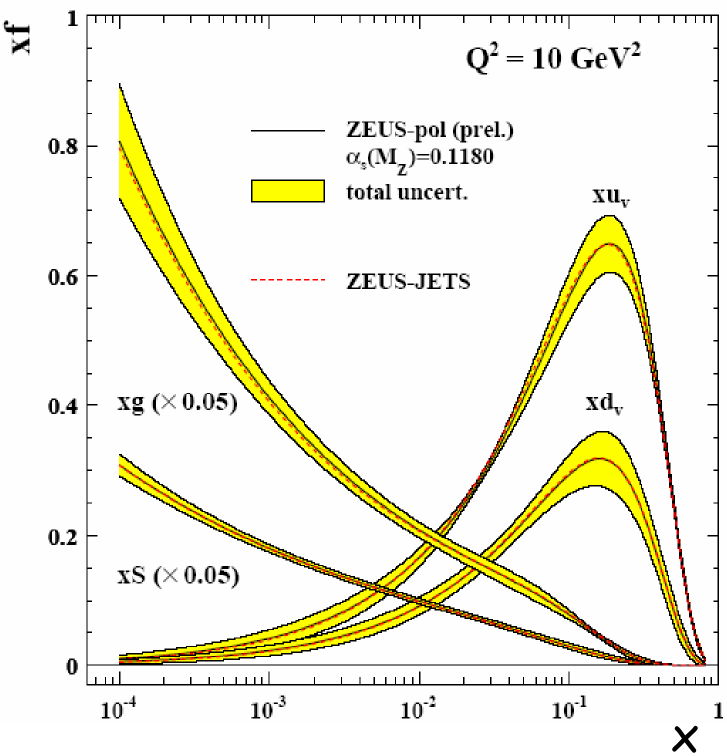
**+ jet cross sections** (inclusive jets in DIS and dijets in photoproduction ($Q^2 = 0$, $x_\gamma > 0.75$))

- 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 $\alpha_s$

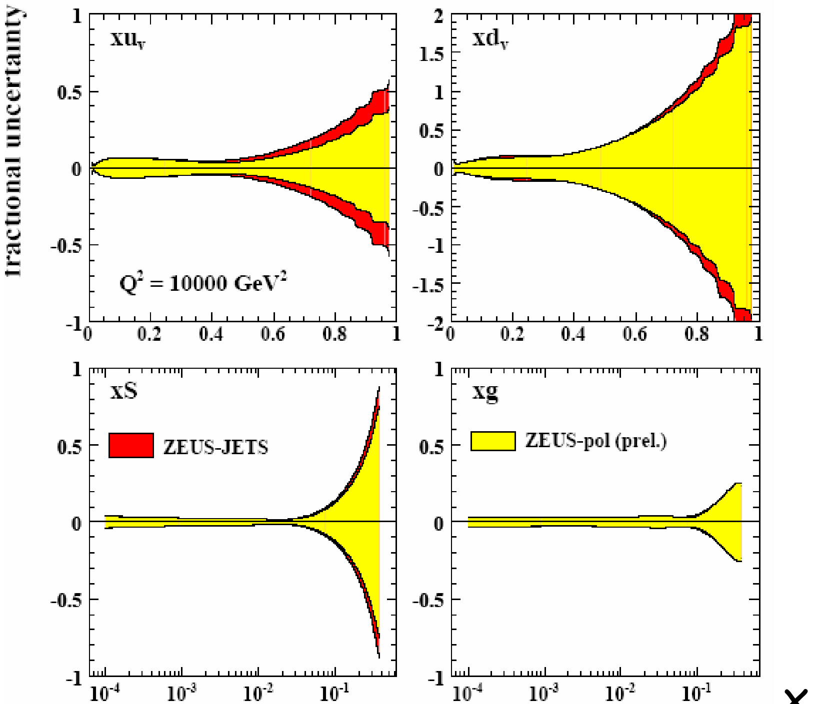
# QCD fits with HERA II polarized data

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

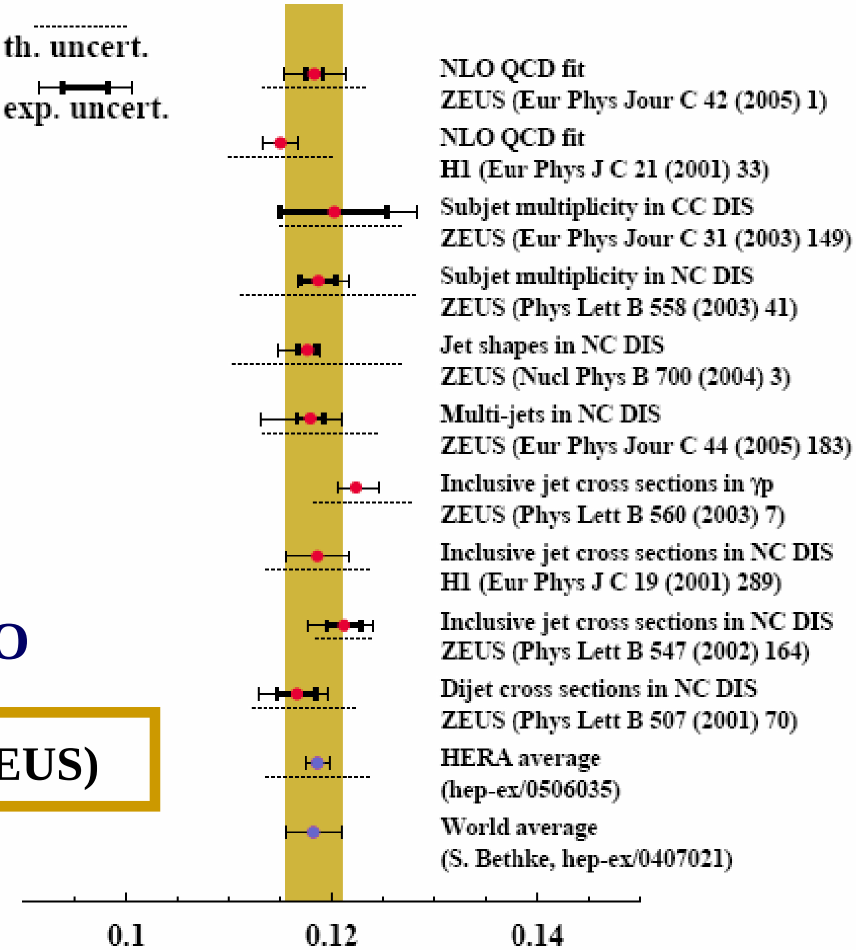
Uncertainties reduced at high x ( see $\mathbf{xu_V}$)
$\sigma_{NC} \sim (4u + d)$, $\sigma_{CC}(e^- p) \sim u$

# Determination of $\alpha_s$ at HERA

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

**$\alpha_s = 0.1186 \pm 0.0011(\text{exp}) \pm 0.005(\text{th})$ ( 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 $Q^2$

# $\alpha_s$ determination from jets

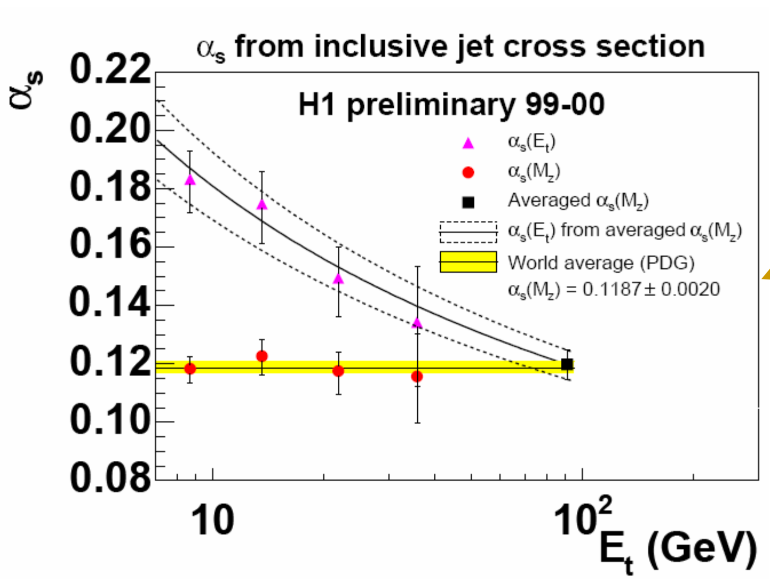
$\alpha_s(M_Z)$ extracted from different. jet cross sec. $d\sigma/dE_{T,B}$ and $d\sigma/dQ^2$ measured in Breit Frame

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

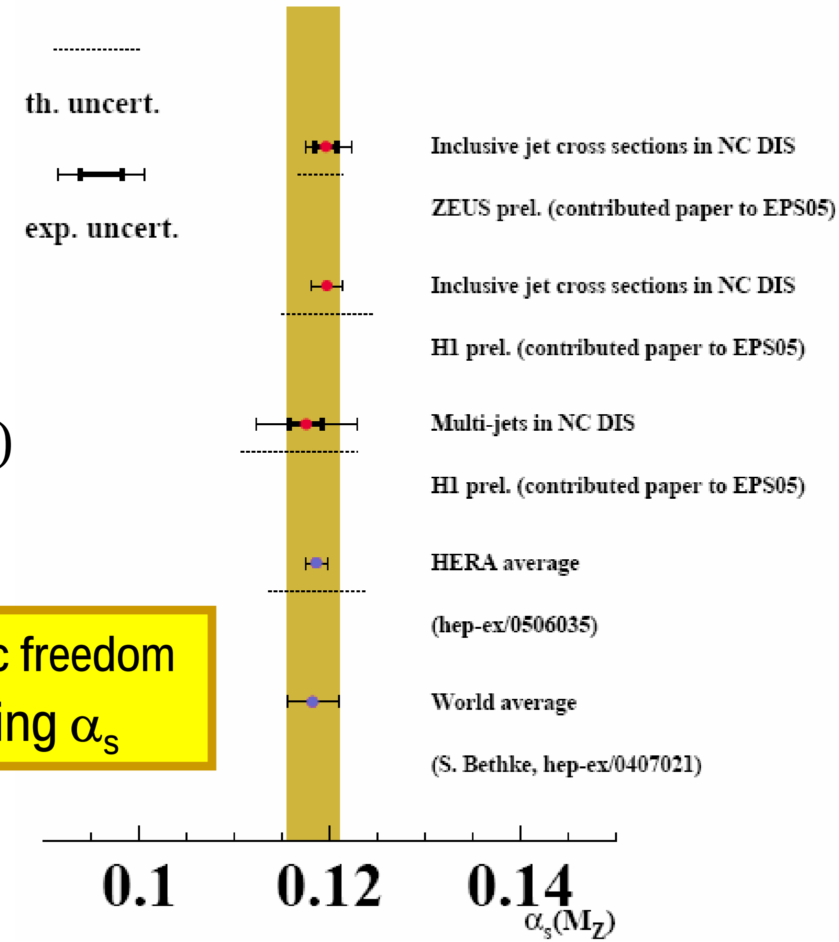
**H1**

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

**ZEUS**




Asymptotic freedom running $\alpha_s$




Mesurements not yet included in the HERA average

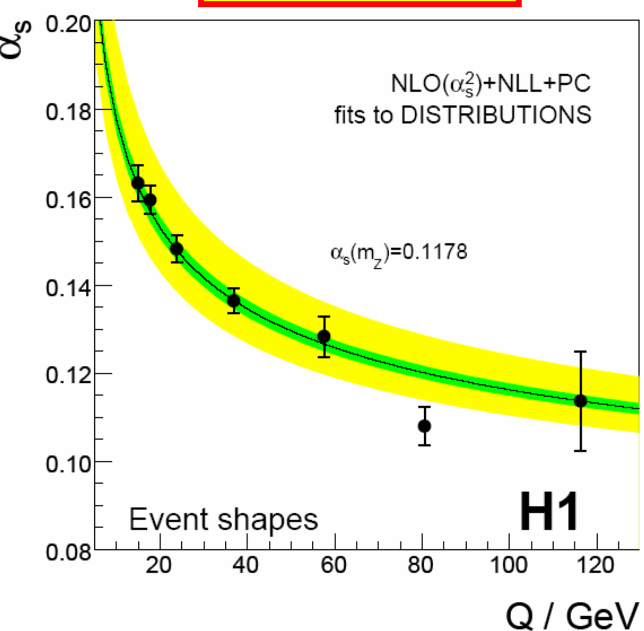
# $\alpha_s$ from event shapes

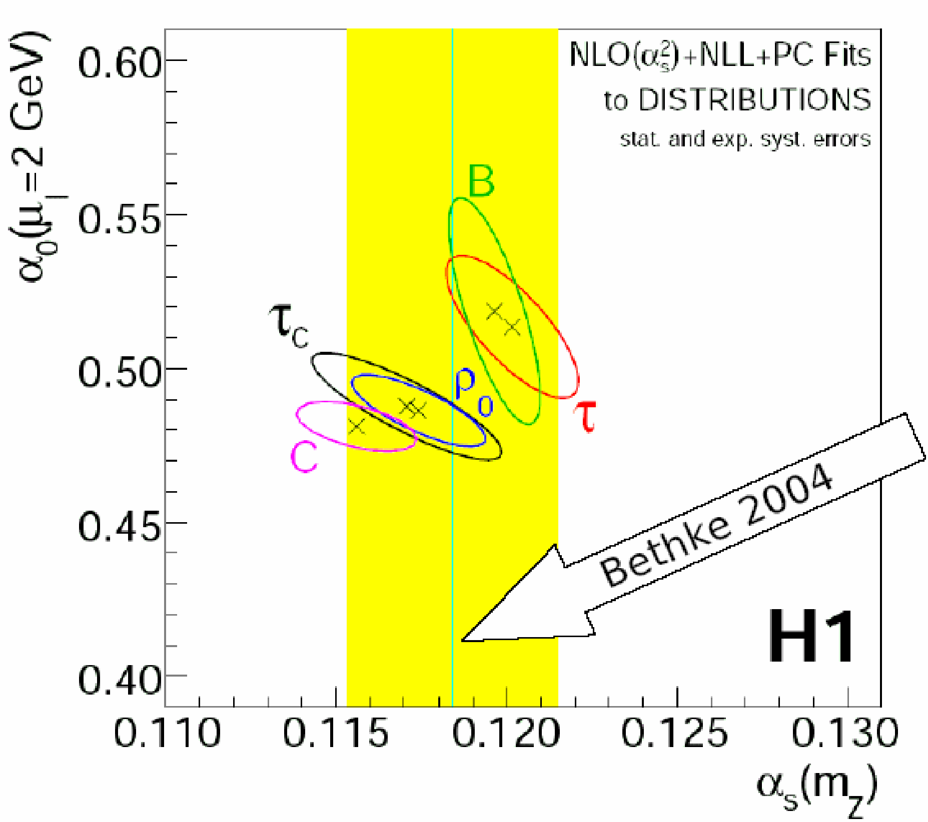
- **Variables calculated from the 4-vectors of all hadronic final state particles describing topological features of DIS events**
- **Larger statistics compared to jet samples due to semi-inclusive nature of ev. shapes**
- **Reduced exp. systematic uncertainties from hadronic energy scales**
- **Larger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

QCD description : **NLO($\alpha_s^2$)+ soft gluon resummation at NLL**

Hadronization : Dokshitzer-Webber **power corrections** (PC, $\alpha_0$ – effective strong coupling constant in the infrared regime)

running $\alpha_s$




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

# 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 $\alpha_s$ 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, $L \sim 10\ pb^{-1}$)
- **inclusion of charm and beauty data ($F_2^{cc}$ and $F_2^{bb}$) in QCD fit**
- **NNLO QCD fits**