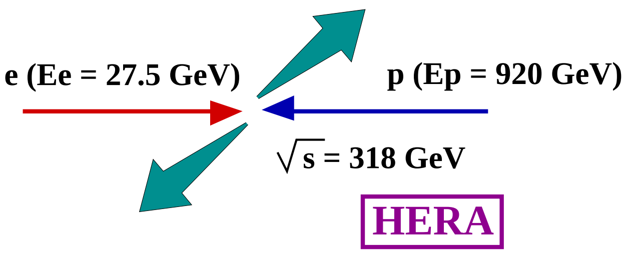
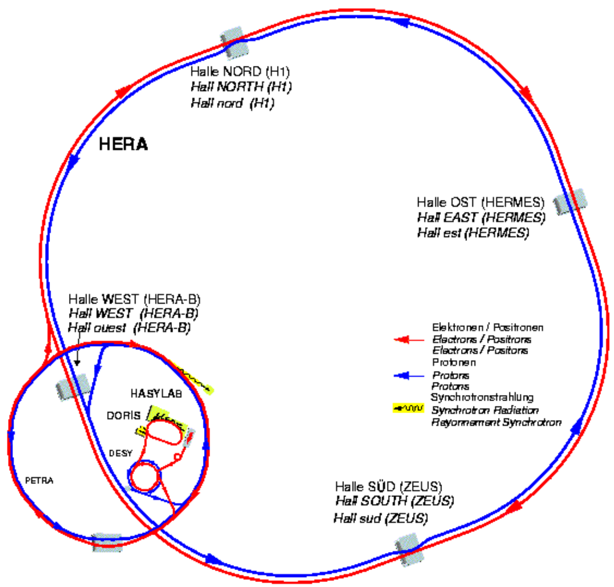
Madison, DIS 2005

April 27th, 2005

# PROTON PDFS USING STRUCTURE FUNCTION AND JET DATA FROM ZEUS

Juan Terrón (Universidad Autónoma de Madrid, Spain)




## ZEUS Collaboration

# Determination of the proton PDFs

- **Observables used in the fits to determine the proton PDFs:**

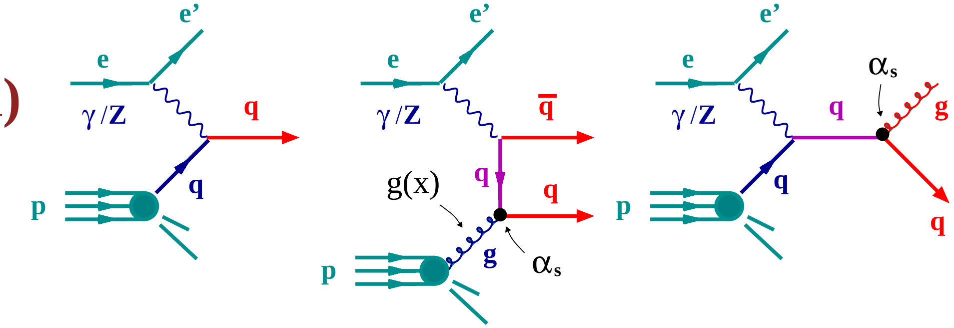
$\longrightarrow$ **Inclusive measurements of deep inelastic $lN$ scattering**

- **Advantages:**

$\longrightarrow$ **inclusive (only final-state lepton is tagged)**

$\Rightarrow$ **no QCD corrections associated to the final-state signature (lepton!)**

$\Rightarrow$ **no hadronisation corrections associated to the final-state signature (lepton!)**




**Quark-Parton Model** **Boson-Gluon Fusion** **QCD Compton**

- **Disadvantages:**

$\longrightarrow$ **the gluon distribution contributes indirectly through higher-order terms**

- **Observables based on jets have hardly been used (except jet production in $p\bar{p}$ at TeVatron)**

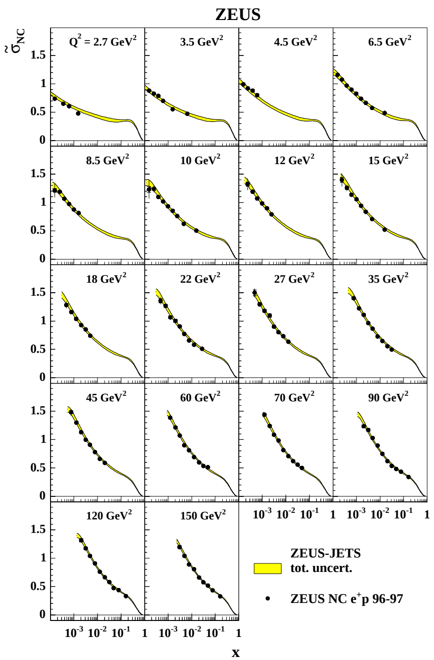
$\longrightarrow$ **large QCD corrections and hadronisation corrections**

- **That's the past! NOW there are measurements of jet cross sections at HERA**

$\Rightarrow$ **directly sensitive to the gluon density in the proton**

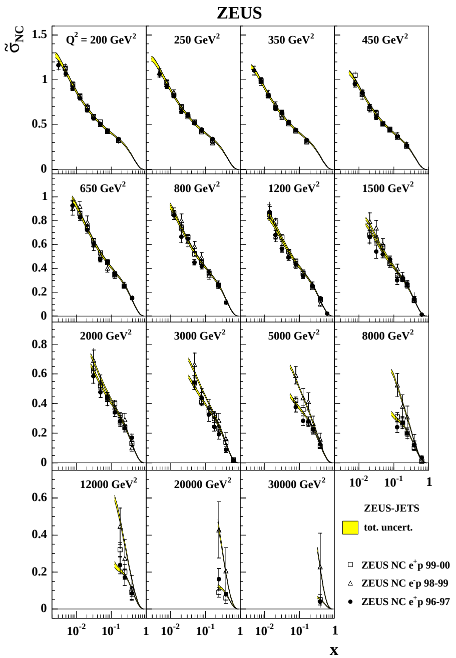
$\Rightarrow$ **with small experimental and theoretical (terms beyond NLO, hadronisation) uncertainties!**

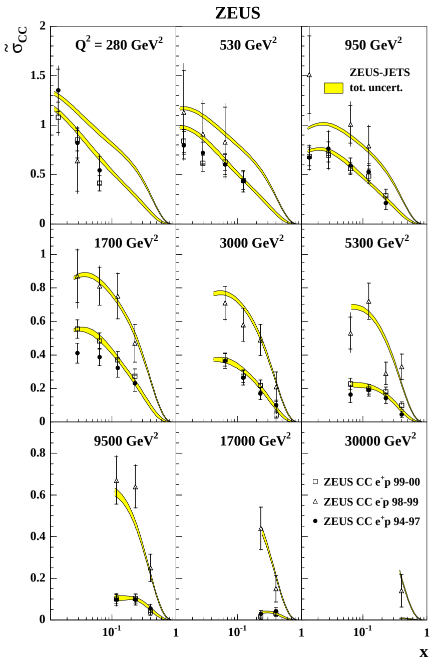
# Determination of PDFs using structure function and jet data from ZEUS



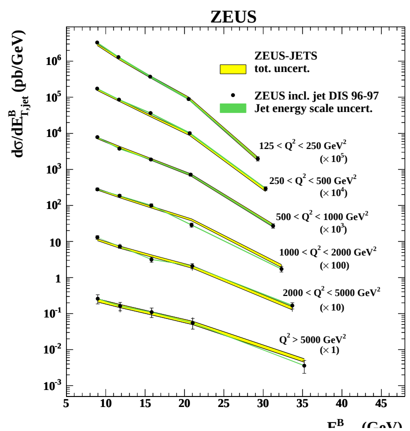

## low-$Q^2$ NC DIS

## high-$Q^2$ NC DIS

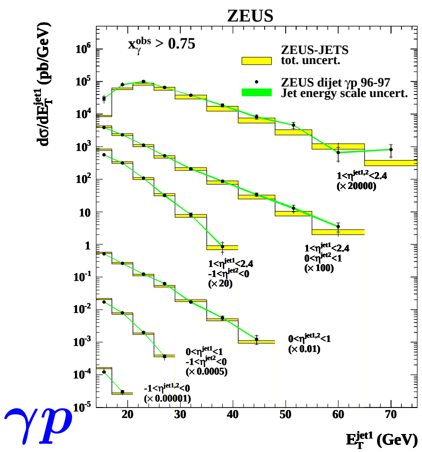



## high-$Q^2$ CC DIS



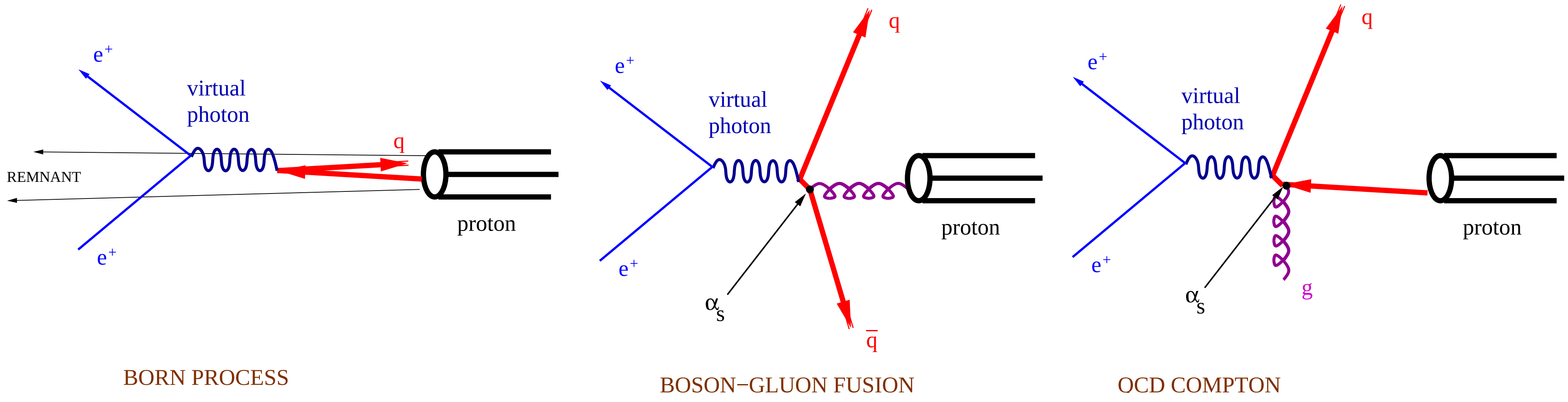

## Jets NC DIS




## Jets $\gamma p$

- **Determination of the proton PDFs using inclusive measurements of NC and CC DIS $e^{\pm}p$ in a large level arm of $x$ and $Q^2$ $\Rightarrow$ $6.3 \cdot 10^{-5} < x < 0.65, 2.7 < Q^2 < 30000$ GeV$^2$ and measurements of jet cross sections in NC DIS and $\gamma p$ collisions from ZEUS only (!)**
- **Sufficient sensitivity to determine the proton PDFs within a single experiment**

# Inclusive Production of High-$E_T$ Jets in NC DIS in the Breit Frame




- **In the Breit frame the virtual boson collides head-on with the proton**
- **High-$E_T$ jet production in the Breit frame**

  **$\longrightarrow$ suppression of the Born contribution (struck quark has zero $E_T$)**

  **$\longrightarrow$ suppression of the beam-remnant jet (zero $E_T$)**

  **$\longrightarrow$ lowest-order contributions from**

  - **Boson-gluon fusion process** $\boxed{\gamma^* g \longrightarrow q\bar{q}}$
  - **QCD-Compton process** $\boxed{\gamma^* q \longrightarrow qg}$

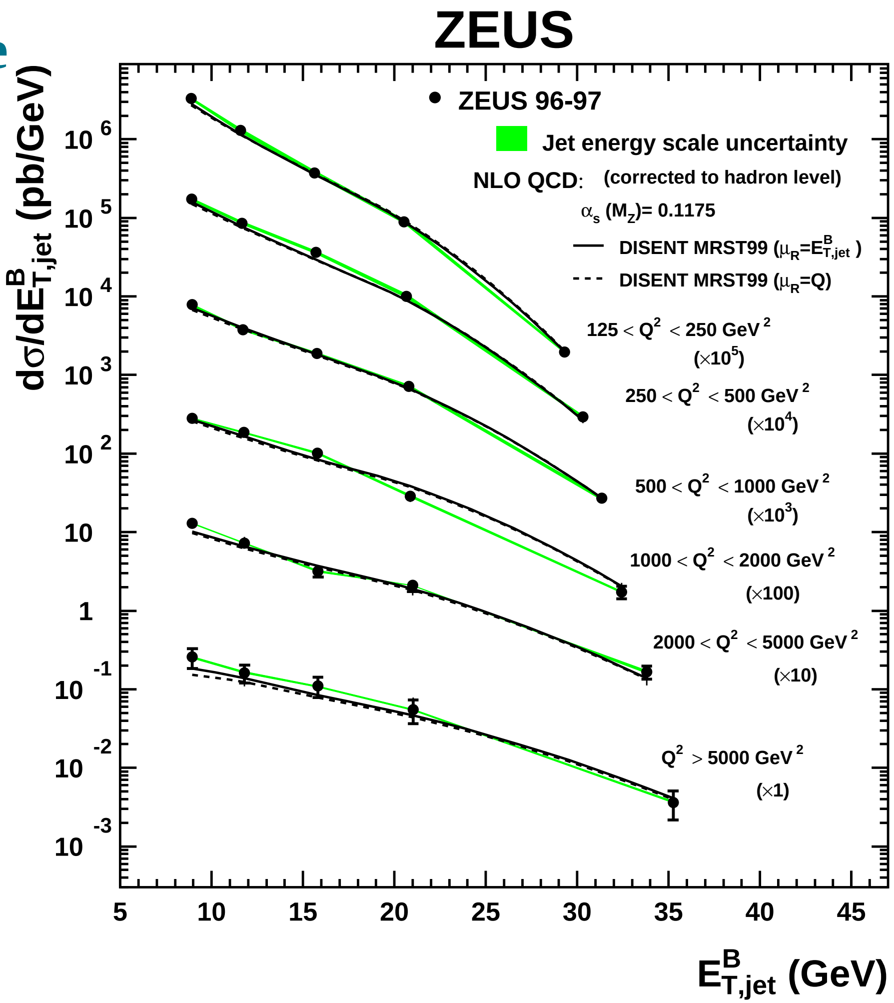
**$\Rightarrow$ directly sensitive to $\alpha_s$ and the gluon density in the proton**

# Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV$^2$

- Measurement of inclusive jet cross sections in the kinematic region defined by $Q^2 > 125$ GeV$^2$ and $-0.7 < \cos\gamma < 0.5$ for jets with $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$ where $\cos\gamma = \frac{(1-y)xE_p - yE_e}{(1-y)xE_p + yE_e}$
- Jets identified using the longitudinally invariant $k_T$ cluster algorithm in the Breit frame
- Inclusive jet production: smaller uncertainties than for dijet production
- Small experimental uncertainties:

  $\longrightarrow$ jet energy scale (1% for $E_{T,jet} > 10$ GeV)

  $\Rightarrow$ $\sim \pm 5\%$ on the cross sections

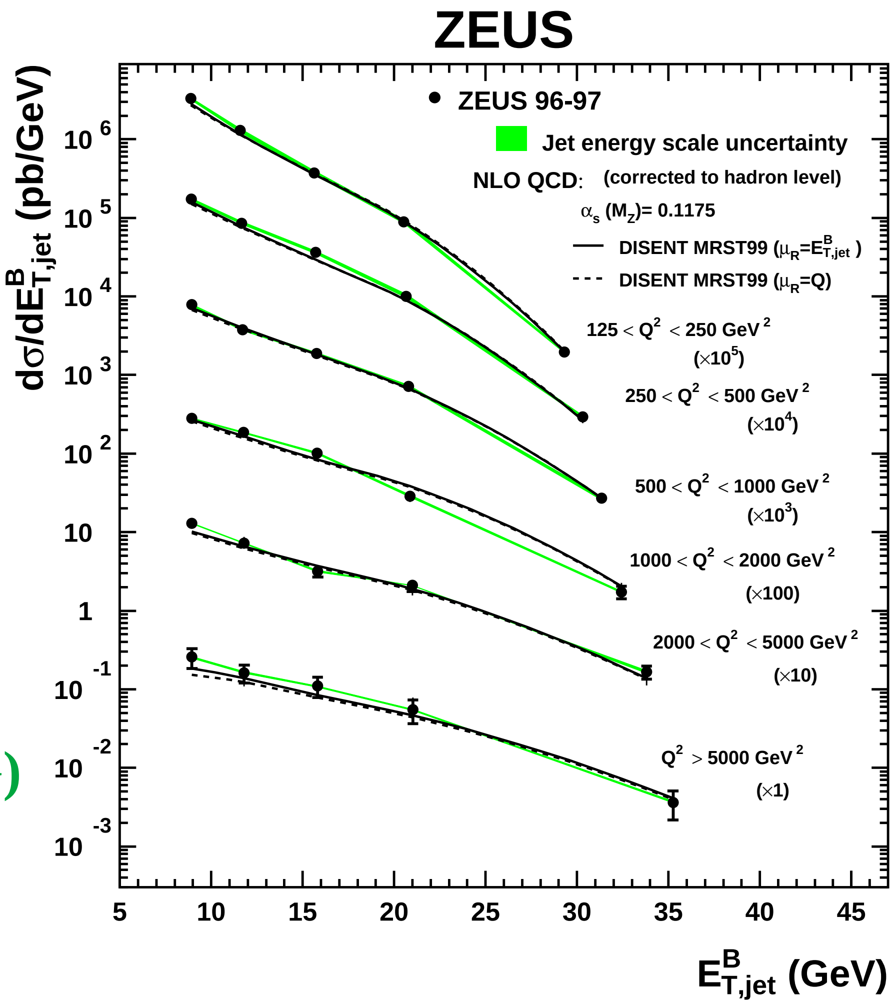



- Small parton-to-hadron corrections ($C_{had}$): $< 10\%$

  $\longrightarrow$ $< 5\%$ for $Q^2 > 250$ GeV$^2$ except for lowest-$E^B_{T,jet}$ point

# Inclusive Jet Cross Sections in NC DIS at $Q^2 > 125$ GeV$^2$

- Several NLO QCD ($\mathcal{O}(\alpha_s^2)$) programs are available for performing jet-cross-section calculations: MEPJET, DISENT, DISASTER++, NLOJET

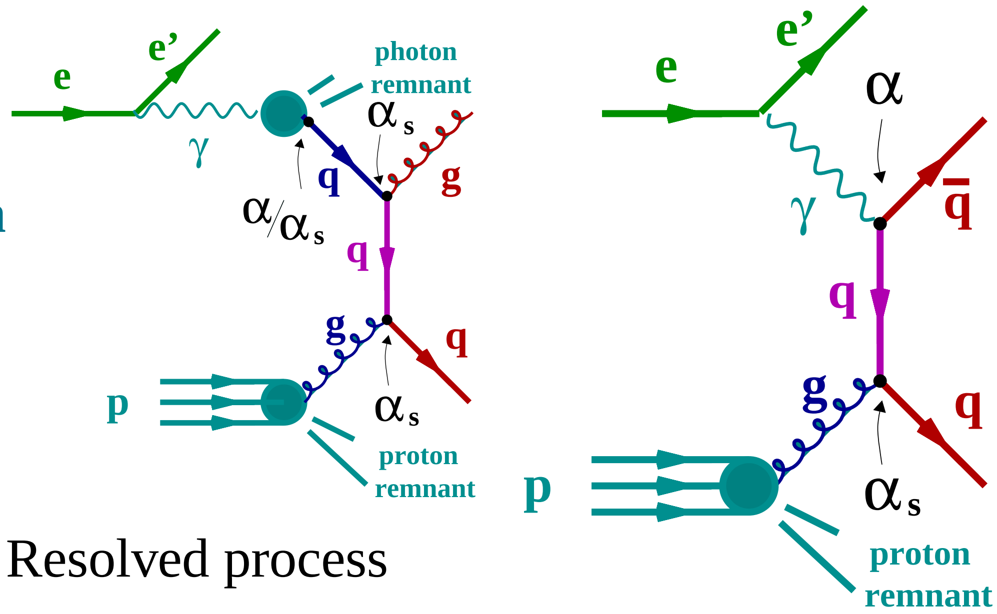



- Small theoretical uncertainties:
  - → higher-order terms (> NLO); varying $\mu_R$ between $\frac{1}{2} \cdot E^B_{T,jet}$ and $2 \cdot E^B_{T,jet}$ ⇒ $\pm 5\%$
  - → hadronisation corrections; variance of $C_{had}$ values (ARIADNE, LEPTO-MEPS, HERWIG) ⇒ $< 1\%$

- Inclusive jet cross sections in NC DIS in the Breit frame provide direct sensitivity to the gluon density in the proton with small experimental and theoretical uncertainties

# Dijet Photoproduction

- Production of jets in $\gamma p$ collisions has been measured via $ep$ scattering at $Q^2 \approx 0$
- At lowest order QCD, two hard scattering processes contribute to jet production $\Rightarrow$




Resolved process

Direct process

- pQCD calculations of jet cross sections

$$\sigma_{2jet} = \sum_{a,b} \int_0^1 dy\, f_{\gamma/e}(y) \int_0^1 dx_\gamma\, f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) \int_0^1 dx_p\, f_{b/p}(x_p, \mu^2_{Fp})\ \hat{\sigma}_{ab\rightarrow jj}$$

longitudinal momentum fraction of $\gamma/e^+$ ($y$), parton $a/\gamma$ ($x_\gamma$), parton $b$/proton ($x_p$)

$\rightarrow f_{\gamma/e}(y) =$ flux of photons in the positron ($WW$ approximation)

$\rightarrow f_{a/\gamma}(x_\gamma, \mu^2_{F\gamma}) =$ parton densities in the photon (for direct processes $\delta(1-x_\gamma)$)

$\rightarrow f_{b/p}(x_p, \mu^2_{Fp}) =$ parton densities in the proton

$\rightarrow \sigma_{ab\rightarrow jj}$ subprocess cross section; short-distance structure of the interaction

# Dijet Photoproduction

- **Measurements of dijet photoproduction provide**

$\longrightarrow$ **direct sensitivity to $\alpha_s$ and gluon density in the proton**

- **However, resolved processes are also sensitive to both the quark and gluon densities in the photon**

$\longrightarrow$ **Photon structure: information on quark densities from $F_2^\gamma$ in $e^+e^-$; gluon density poorly constrained!**

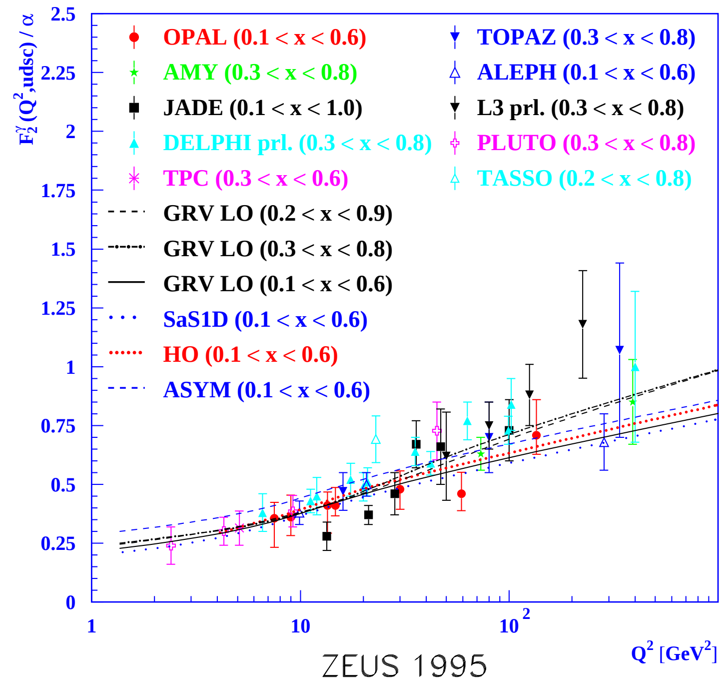
- **To suppress the dependence on the photon PDFs**

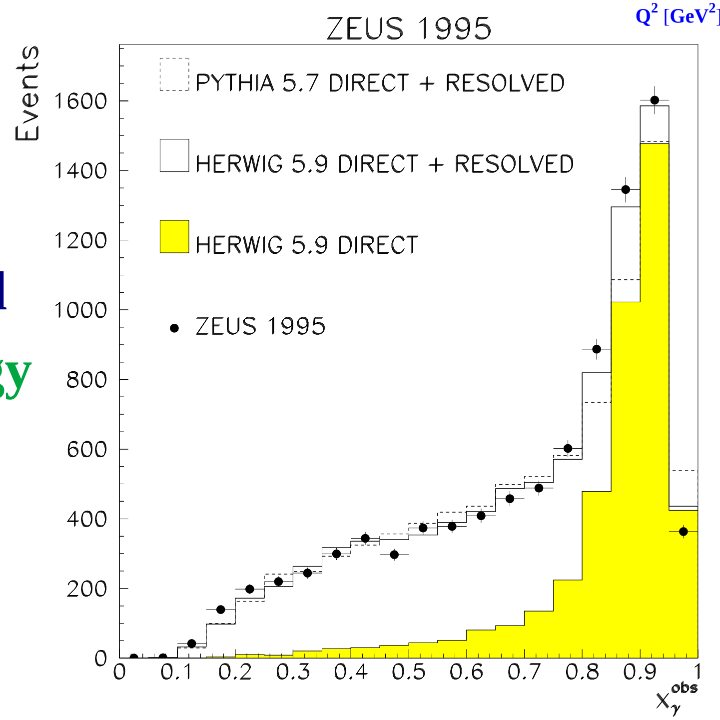
$\longrightarrow$ **measurements restricted to the region where direct processes dominate**

$\Rightarrow$ **Observable to separate the contributions from resolved and direct processes: the fraction of the photon's energy participating in the production of the dijet system**

$$x_\gamma^{obs} = \frac{1}{2E_\gamma} \sum_{i=1}^{2} E_T^{jet_i} e^{-\eta^{jet_i}}$$

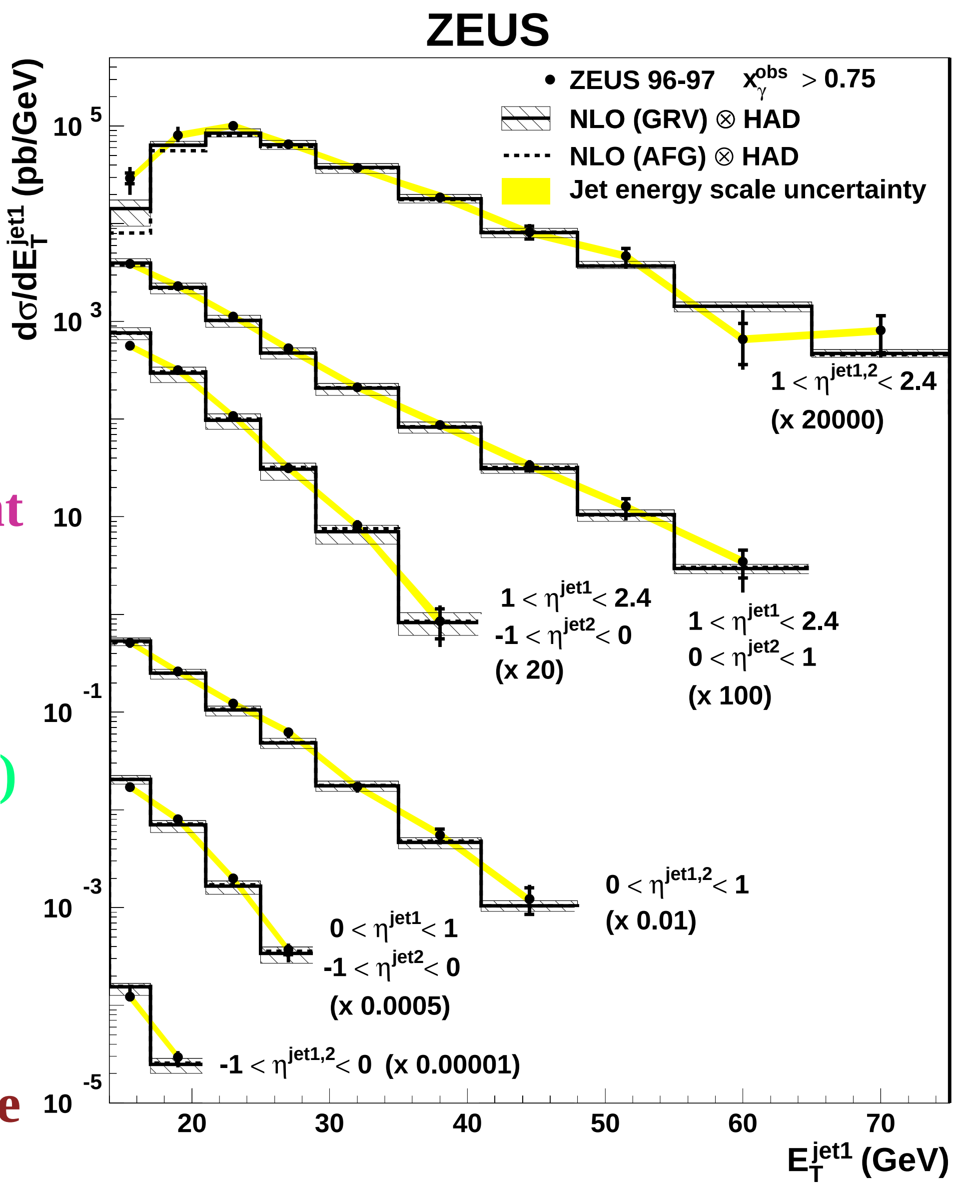
$\longrightarrow$ **Direct-process-enriched region:** $x_\gamma^{OBS} > 0.75$



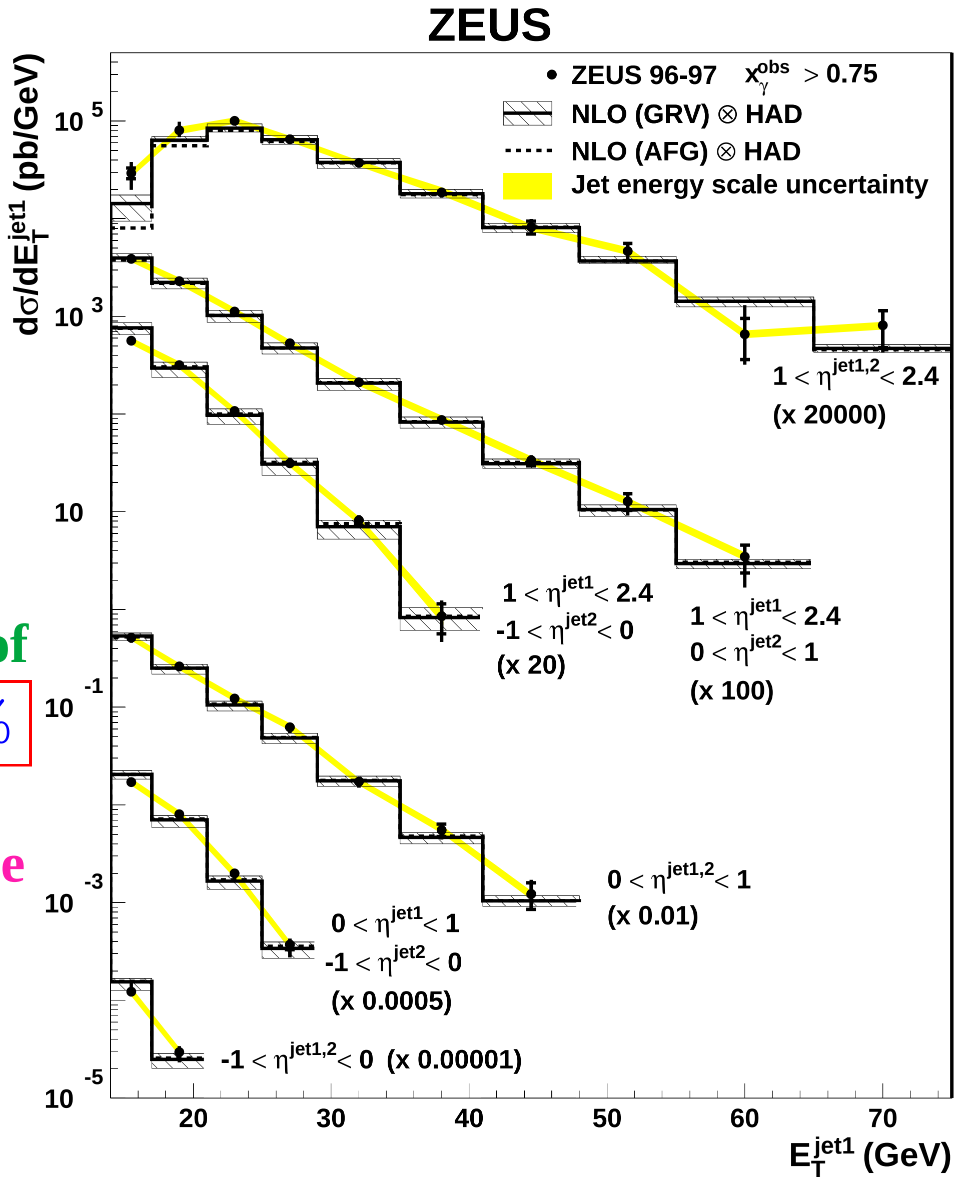
# Dijet Photoproduction Cross Sections for $x_\gamma^{obs} > 0.75$

- Measurement of the differential cross section section $d\sigma/dE_T^{jet,1}$ for dijet events with
  $E_T^{jet,1} > 14$ GeV, $E_T^{jet,2} > 11$ GeV,
  $-1 < \eta^{jet} < 2.4$ (both jets) and $x_\gamma^{obs} > 0.75$
  in the kinematic region
  $Q^2 < 1$ GeV$^2$ and $134 < W_{\gamma p} < 277$ GeV
- Jets identified using the longitudinally invariant $k_T$ cluster algorithm in the laboratory frame
- Small experimental uncertainties:
  → jet energy scale (1% for $E_{T,jet} > 10$ GeV)
  ⇒ $\sim \pm 5\%$ on the cross sections
- Small parton-to-hadron corrections ($C_{had}$):
  → $< 10\%$ except at the edges of phase space



# Dijet Photoproduction Cross Sections for $x_\gamma^{obs} > 0.75$

- Several NLO QCD ($\mathcal{O}(\alpha\alpha_s^2)$) programs are available for performing jet-cross-section calculations: Klasen & Kramer, Harris & Owens, Aurenche et al, Frixione & Ridolfi
- Small theoretical uncertainties:
  $\longrightarrow$ higher-order terms ($>$ NLO); varying $\mu_R$ between $\frac{1}{4} \cdot E_T^{sum}$ and $E_T^{sum} \Rightarrow \pm 10\%$
  $\longrightarrow$ hadronisation corrections; half the spread of $C_{had}$ values (PYTHIA, HERWIG) $\Rightarrow 2-3\%$
- Dijet cross sections in photoproduction provide direct sensitivity to the gluon density in the proton with small experimental and and theoretical uncertainties



# Determination of the proton PDFs

- Parametrization of the proton PDFs

→ $u$ valence ($xu_V$), $d$ valence ($xd_V$), gluon ($xg$), total sea ($xS$) and $x\Delta = x(\bar{d} - \bar{u})$ at $Q_0^2 = 7$ GeV$^2$ by the functional form

$$xf(x) = p_1 x^{p_2} (1-x)^{p_3} (1 + p_4 x)$$

- Constraints on the parameters $\{p_i\}$:
  - → momentum and number sum rules ⇒ $p_{1,g}, p_{1,u_V}, p_{1,d_V}$
  - → no sensitivity to difference on low-$x$ behaviour of $u$ and $d$ valence: $p_{2,u_V} = p_{2,d_V}$
  - → no sensitivity to flavour structure of light-quark sea: fix $p_{i,\Delta}$ consistent with Gottfried sum rule and Drell-Yan data
  - → suppression of strange sea in accordance with dimuon data from CCFR-NuTeV
- The results of the fit are not sensitive to reasonable variations of these assumptions

→ it is possible to extract a flavour-averaged sea distribution from ZEUS data alone

- Heavy quarks: variable flavour-number scheme of Roberts and Thorne

⇒ 11 free parameters ($+\alpha_s$ when free; otherwise $\alpha_s(M_Z) = 0.118$)

- Evolution of the PDFs with the energy scale: DGLAP equations at NLO ($\overline{MS}$ scheme)

# Inclusion of jet cross sections in a fi t of the proton PDFs

- In contrast with the evaluation of the structure functions from the evolved PDFs,

$\longrightarrow$ the calculation of jet cross sections at NLO requires much more CPU time: $\mathcal{O}(10)$ hours per PDF set $\Rightarrow$ Unaffordable in a fit of the proton PDFs

- Deconvolution of the PDFs and $\alpha_s$ from the matrix elements in the calculations

  $\longrightarrow$ construction of grids such that the calculations for the jet cross sections can be performed sufficiently fast (and accurately) $\Rightarrow \mathcal{O}(1 \text{ second})$ per PDF set!

$$\sigma_{jet}(\text{bin i}) = \sum_{n=1,2} \sum_{a=q,\bar{q},g} \sum_j \sum_k f_a(\xi_k, Q_j^2) \cdot \alpha_s^n(Q_j^2) \cdot G_{i,a,n,\xi_k,Q_j^2}$$

$\longrightarrow G_{i,a,n,\xi_k,Q_j^2}$ grid of weights in the "$(x = \xi, Q^2)$" plane for a given bin of the cross section ($i$), parton species ($a$) and order ($n$); typical size in $(\xi, Q^2) \longrightarrow 100 \times 100$

$\Rightarrow$ jet-cross-section calculations can be performed for ANY PDF set and ANY value of $\alpha_s$ in a fast way and with an accuracy better than $0.5\%$

# Determination of the proton PDFs

- **Data sets used in the fit (577 data points):**

$\longrightarrow$ **Structure function measurements: reduced double differential cross sections in $x$ and $Q^2$ for**

- **neutral current DIS $e^+p$ and $e^-p$**
- **charged current DIS $e^+p$ and $e^-p$**

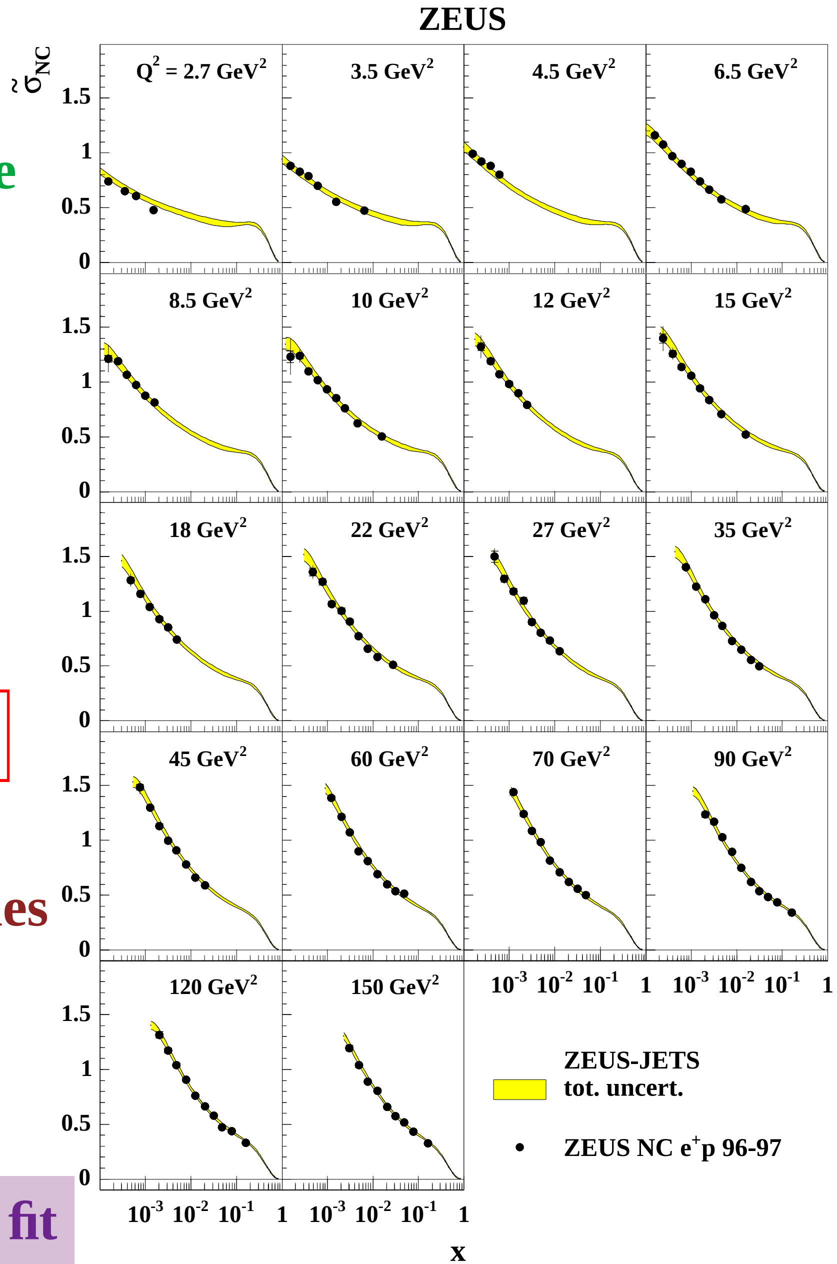
$\longrightarrow$ **Jet cross section measurements:**

- **inclusive jet production in NC DIS**
- **dijet production in $\gamma p$ collisions**

$\Rightarrow$ $6.3 \cdot 10^{-5} < x < 0.65, 2.7 < Q^2 < 30000$ GeV$^2$

$\longrightarrow$ $W^2 > 20$ GeV$^2$

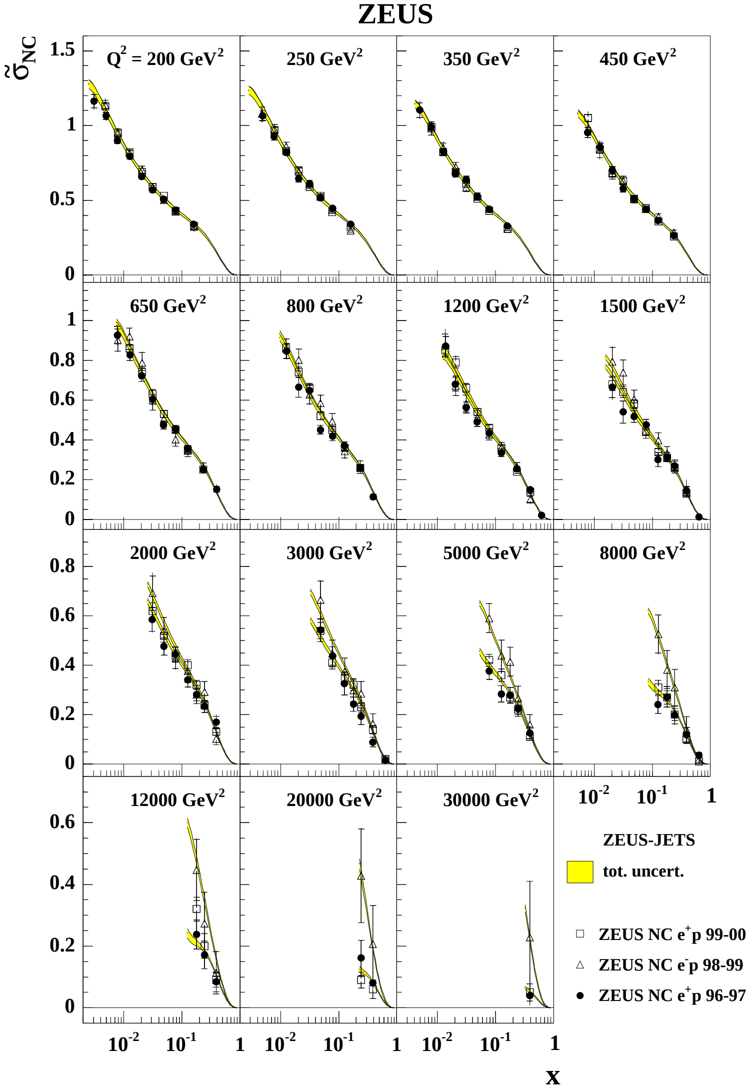
- **Full account of correlated experimental uncertainties using the offset method**
- **A good description of the data is obtained:** $\chi^2 = 470$ **for 577 data points**



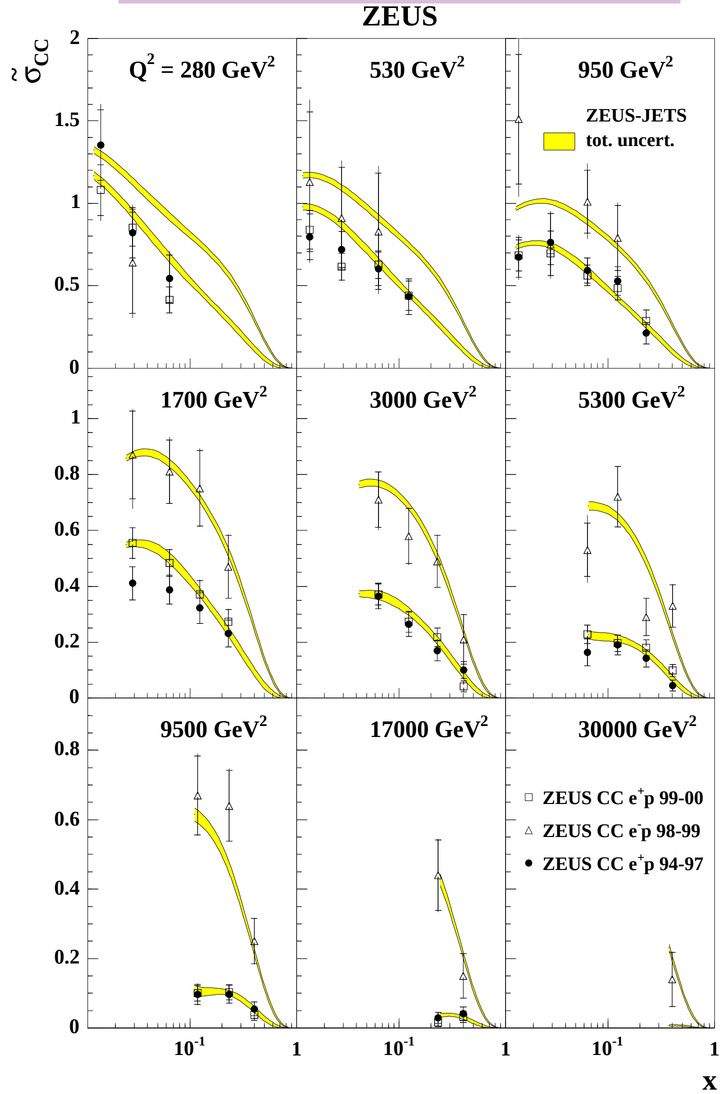

**Low-$Q^2$ NC DIS $e^+p$ data vs ZEUS-JETS fit**

# High-$Q^2$ NC and CC DIS $e^{\pm}p$ data vs ZEUS-JETS fit

## High-$Q^2$ NC DIS $e^{\pm}p$



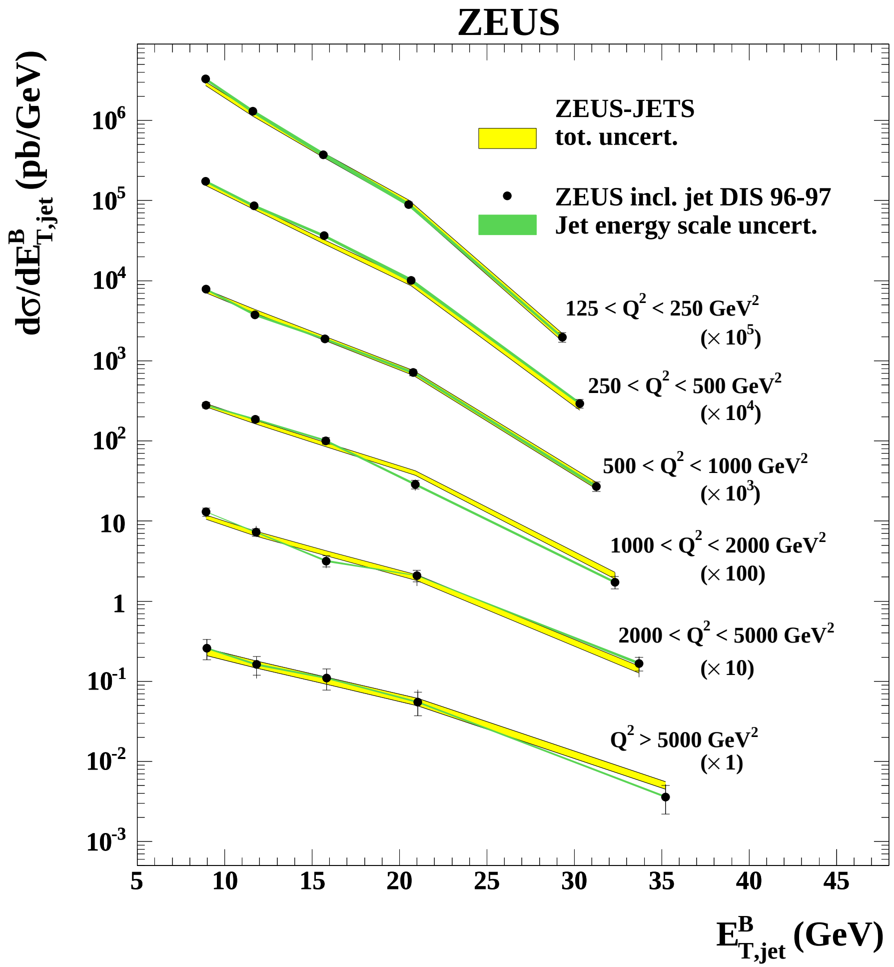

## High-$Q^2$ CC DIS $e^{\pm}p$



# Jet cross sections vs ZEUS-JETS fit

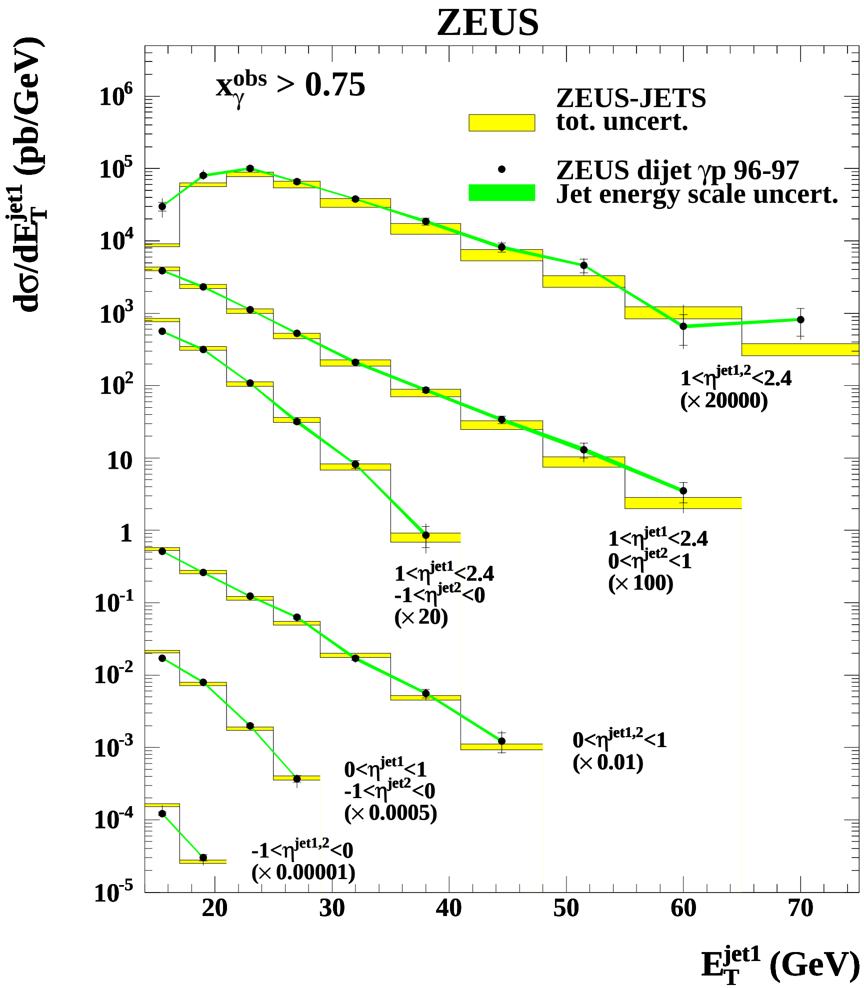
## Inclusive Jet Production in NC DIS $e^+p$

$Q^2 > 125$ GeV$^2$, $E^B_{T,jet} > 8$ GeV




## Dijet Production in $\gamma p$ collisions

$E_T^{jet,1(2)} > 14\ (11)$ GeV, $x_\gamma^{obs} > 0.75$

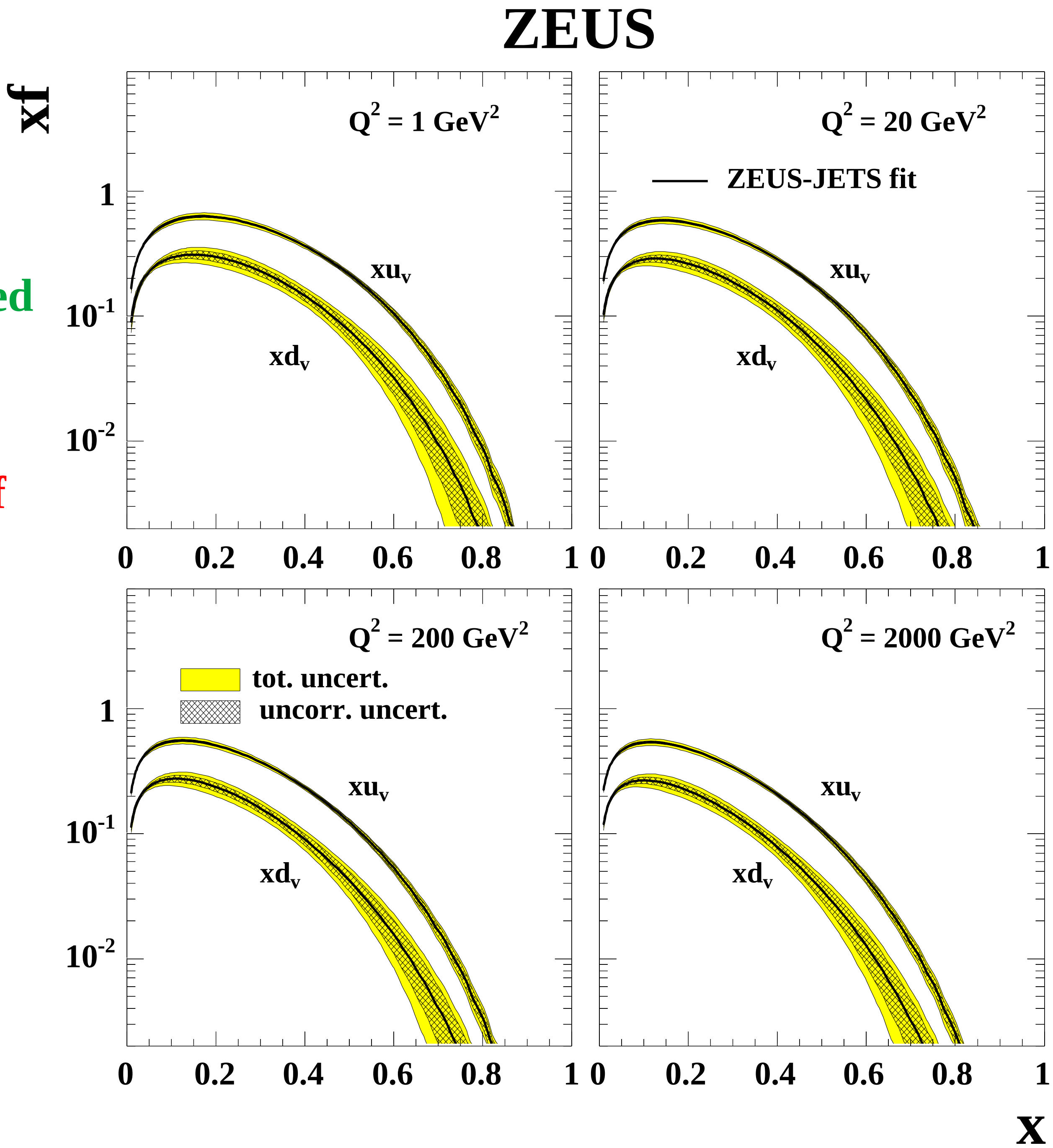


## Valence distributions

- Precision of the valence quark distributions

→ at high-$x$ not as well constrained as in global PDF fits which include fixed-target DIS data

→ competitive + the advantage of being free from heavy-target corrections, higher twists and isospin-symmetry assumptions



# Gluon and sea distributions

- Precision of the gluon and sea distributions

$\longrightarrow$ at low-$x$: as well determined as in global PDF fits which make use of HERA data

$\longrightarrow$ at higher-$x$: the uncertainty of the gluon has been reduced by the addition of jet data

- Model uncertainties in PDFs:

$\longrightarrow$ variation of $Q_0^2$ in the range $4 < Q_0^2 < 10$ GeV$^2$

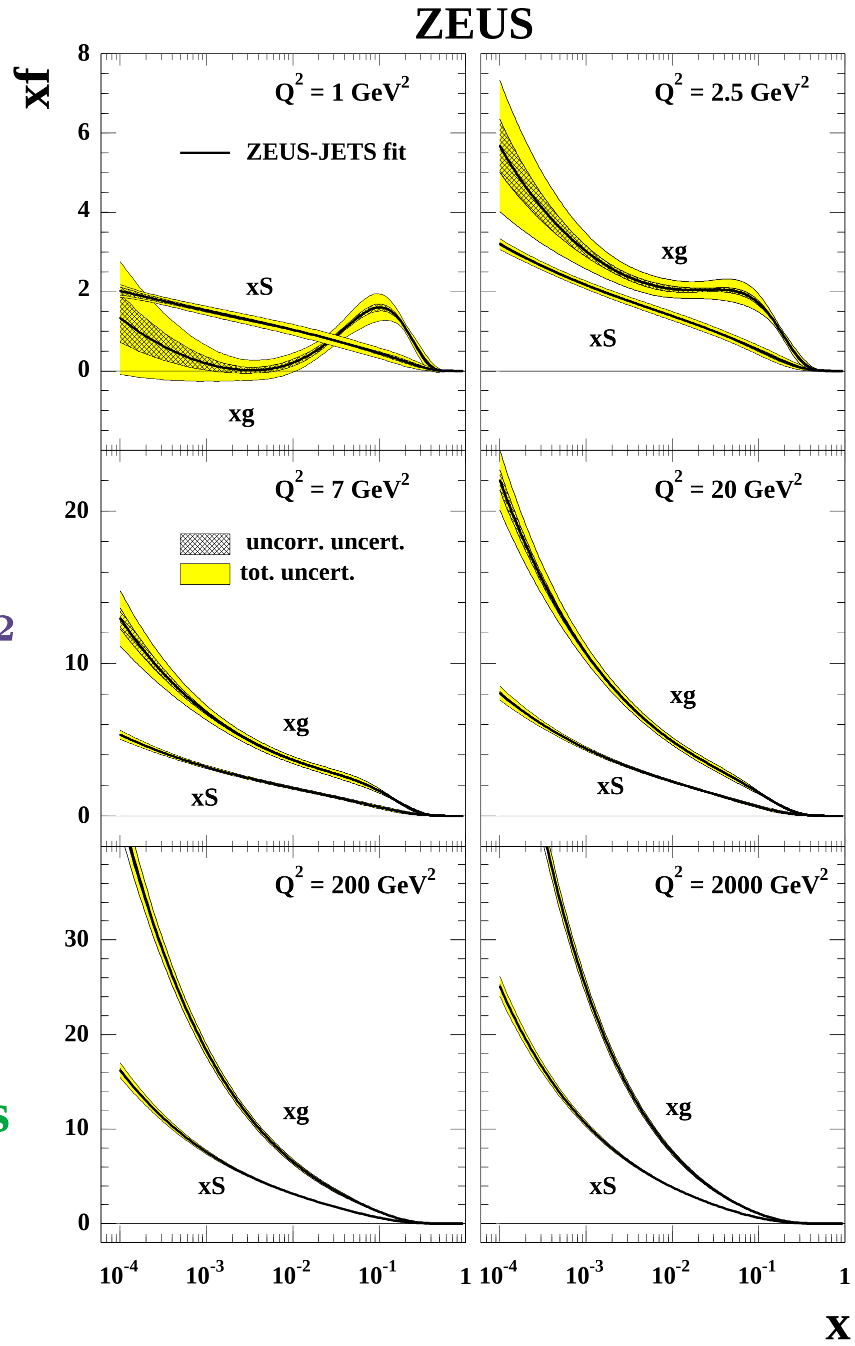
$\longrightarrow$ modification $(1 + p_4 x) \longrightarrow (1 + p_5 \sqrt{x})$ in parametrizations of valence quarks

$\longrightarrow$ choice of constraints in parametrization of sea

$\longrightarrow$ tighter cuts on jet data; $E_{T,jet}^{B} > 10$ GeV in NC DIS and $E_T^{jet,1} > 17$ GeV in $\gamma p$

$\longrightarrow$ parton-to-hadron corrections to jet cross sections

$\longrightarrow$ residual uncertainty due to photon PDFs used in the dijet calculations (AFG $\longrightarrow$ GRV)



# Gluon and sea distributions

- **Precision of the gluon and sea distributions**

→ at low-$x$: as well determined as in global PDF fits which make use of HERA data

→ at higher-$x$: the uncertainty of the gluon has been reduced by the addition of jet data

- **Model uncertainties in PDFs:**

→ variation of $Q_0^2$ in the range $4 < Q_0^2 < 10$ GeV$^2$

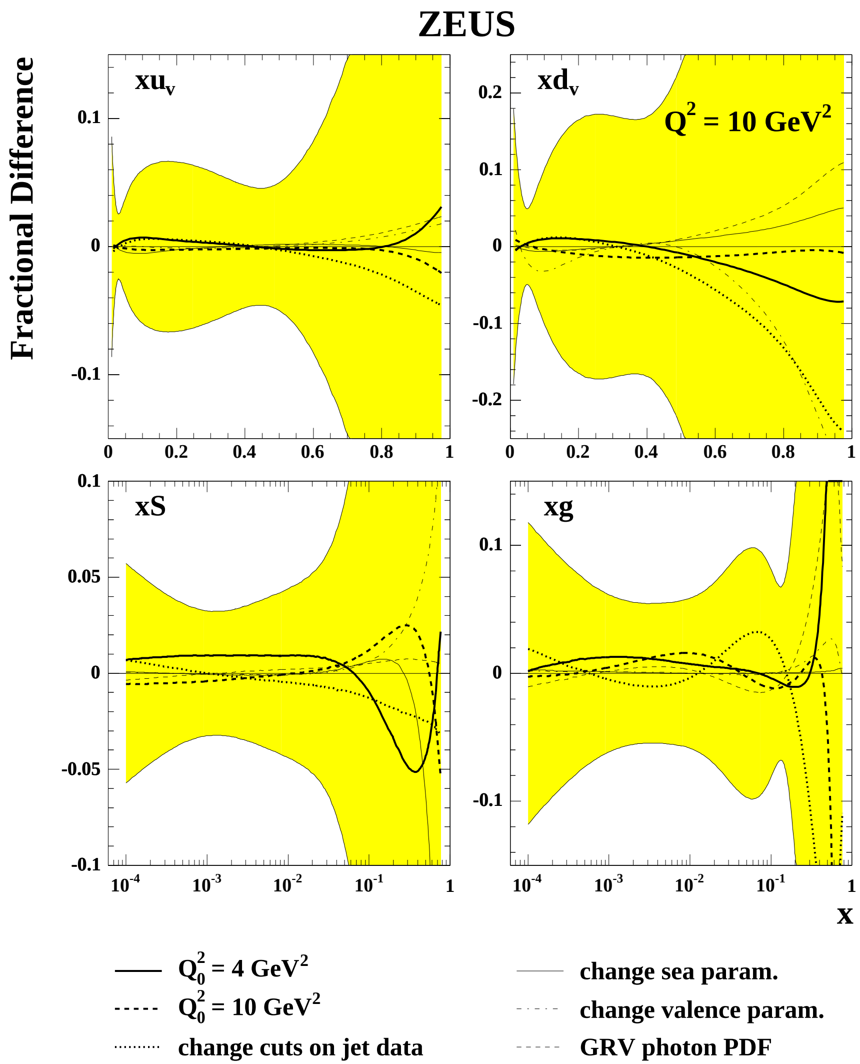
→ modification $(1 + p_4 x) \rightarrow (1 + p_5 \sqrt{x})$ in parametrizations of valence quarks

→ choice of constraints in parametrization of sea

→ tighter cuts on jet data; $E_{T,jet}^B > 10$ GeV in NC DIS and $E_T^{jet,1} > 17$ GeV in $\gamma p$

→ parton-to-hadron corrections to jet cross sections

→ residual uncertainty due to photon PDFs used in the dijet calculations (AFG → GRV)




⇒ Effects much smaller than the experimental uncertainties

# Improving the gluon distribution: jet data

- Comparison of gluon distributions from fits with and without jet data

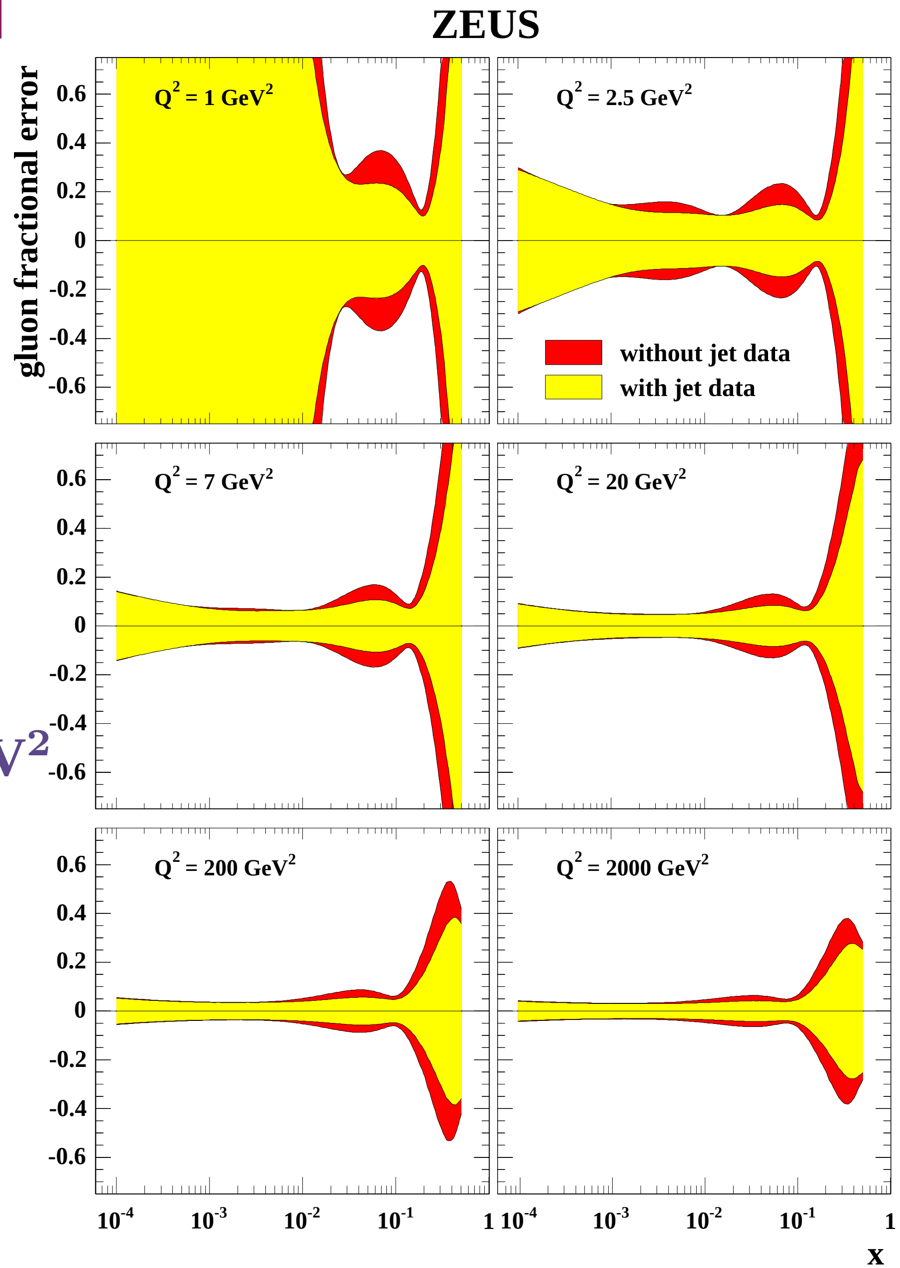
→ no significant change of the shape: no tension between jet and inclusive data

→ the jet cross sections constrain the gluon density in the range $0.01 - 0.4$

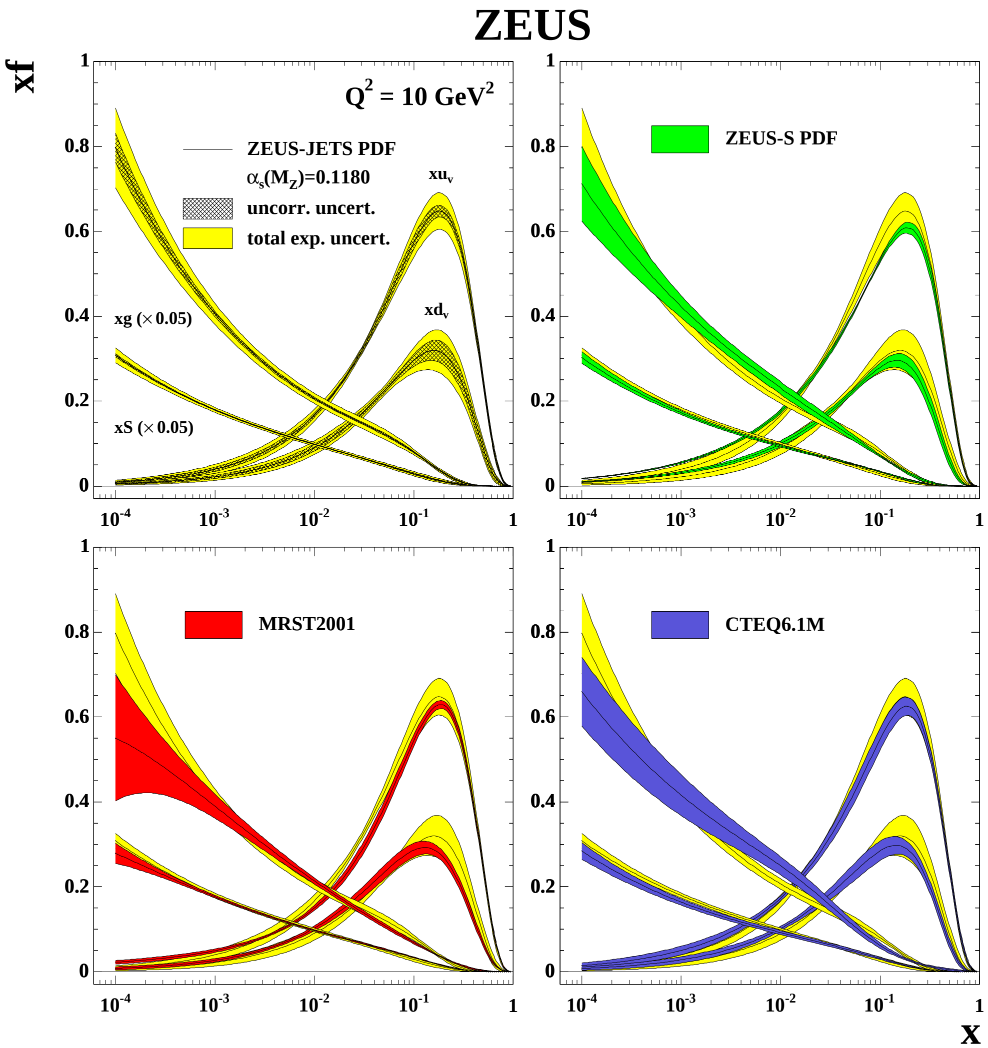
→ **Sizeable reduction of the gluon uncertainty**

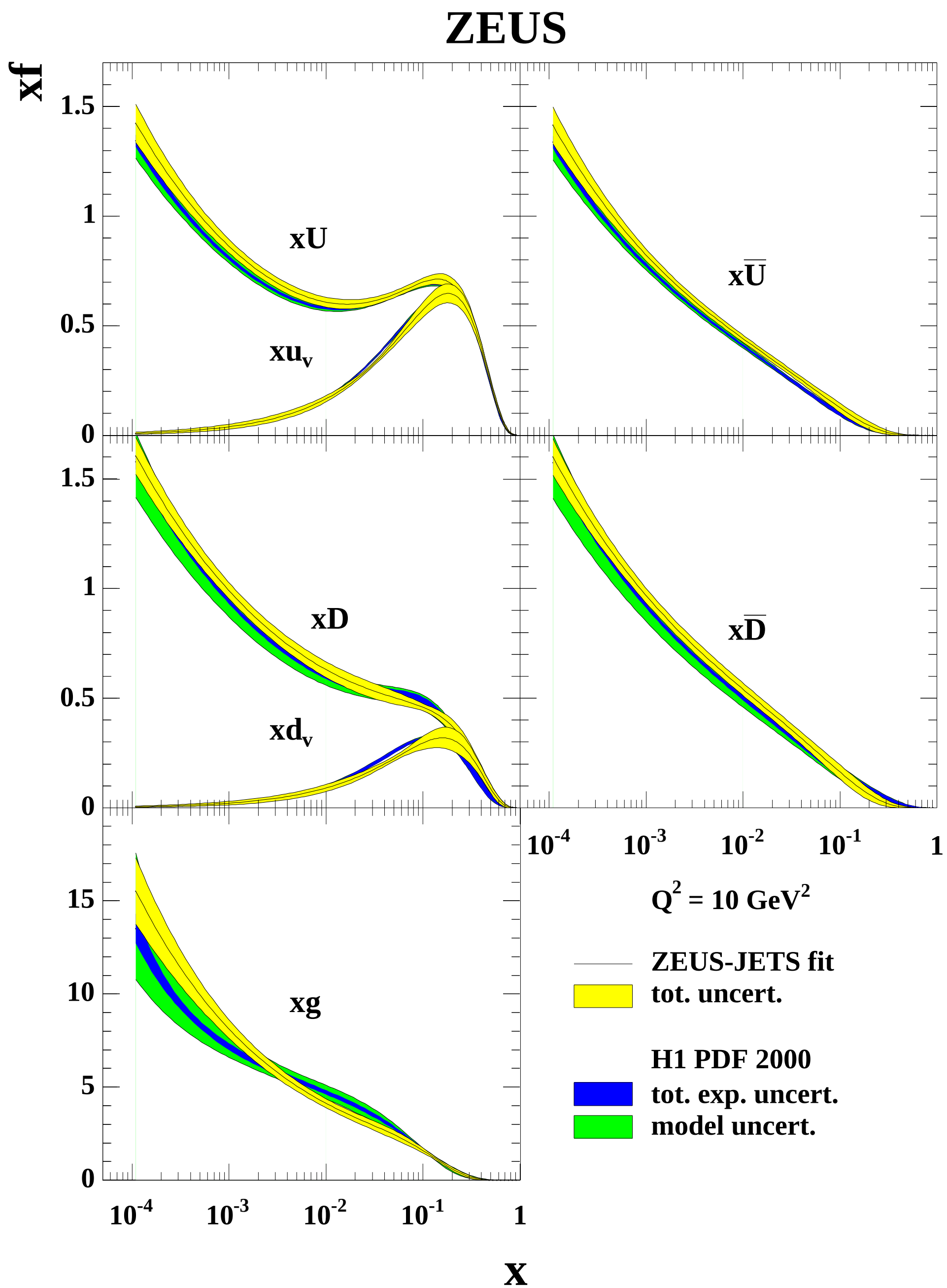
e.g. from 17% to 10% at $x = 0.06$ and $Q^2 = 7$ GeV$^2$

→ similar reduction by a factor of two in the mid-$x$ region over the full $Q^2$ range



# Comparison of proton PDFs



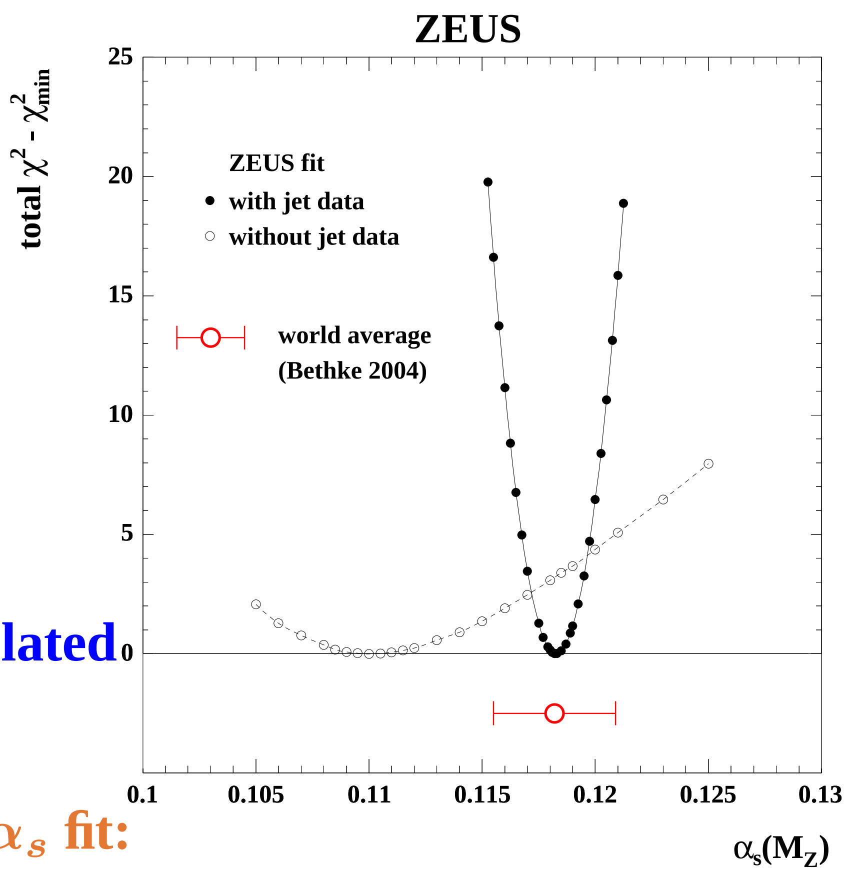




- Compatible with MRST2001 and CTEQ6.1M
- Compatible with H1 analysis

# Determination of $\alpha_s(M_Z)$

- Simultaneous determination of the proton PDFs and $\alpha_s(M_Z)$
- Jet cross sections are directly sensitive to $\alpha_s(M_Z)$
  via $\gamma^{(*)}g \to q\bar{q}$ (coupled to gluon density) and
  via $\gamma^{(*)}q \to qg$ (NOT coupled to gluon density)

$\Rightarrow$ The inclusion of the jet cross sections allows an extraction of $\alpha_s(M_Z)$ that is NOT strongly correlated to the gluon density




- Determination of $\alpha_s(M_Z)$ from the ZEUS-JETS-$\alpha_s$ fit:

$$\alpha_s(M_Z) = 0.1183 \pm 0.0007\ (\text{uncorr.}) \pm 0.0022\ (\text{corr.}) \pm 0.0016\ (\text{norm.}) \pm 0.0008\ (\text{model})$$

$+$ estimation of the uncertainty due to terms beyond NLO $\rightarrow \Delta\alpha_s(M_Z) = \pm 0.0050$

$\Rightarrow$ Precise determination $\alpha_s(M_Z) = 0.1183 \pm 0.0058$ from ZEUS data alone

$\rightarrow$ in agreement with world average $\alpha_s(M_Z) = 0.1182 \pm 0.0027$ (Bethke, 2004)

## Summary

- Due to the precision and kinematic coverage of the ZEUS measurements on structure functions and jet cross sections
  $\Rightarrow$ determination of $\alpha_s$ and the proton PDFs within a single experiment (ZEUS!) with minimal external input

- Feasibility of including rigorously jet cross-section measurements in a global fit

- Advantages of including jet cross-section measurements which have been selected according to $\longrightarrow$ direct sensitivity to $\alpha_s$ and the gluon density in the proton and small experimental and theoretical uncertainties

  $\Rightarrow$ sizeable reduction of the uncertainty of the gluon density in the mid- to high-$x$ region

  $\Rightarrow$ precise determination of $\alpha_s$ from HERA data alone

$$\alpha_s(M_Z) = 0.1183 \pm 0.0028 \text{ (exp.)} \pm 0.0008 \text{ (model)} \pm 0.0050 \text{ (th.)}$$