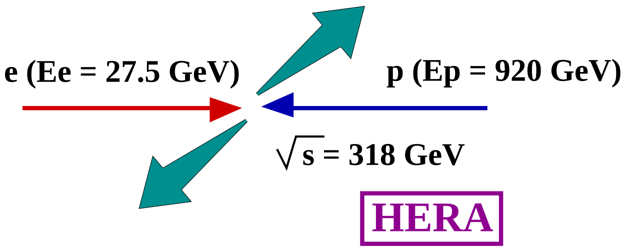
Krakow, EPS 2009

July 16th, 2009

PDFs at HERA

Juan Terrón (Universidad Autónoma de Madrid, Spain)



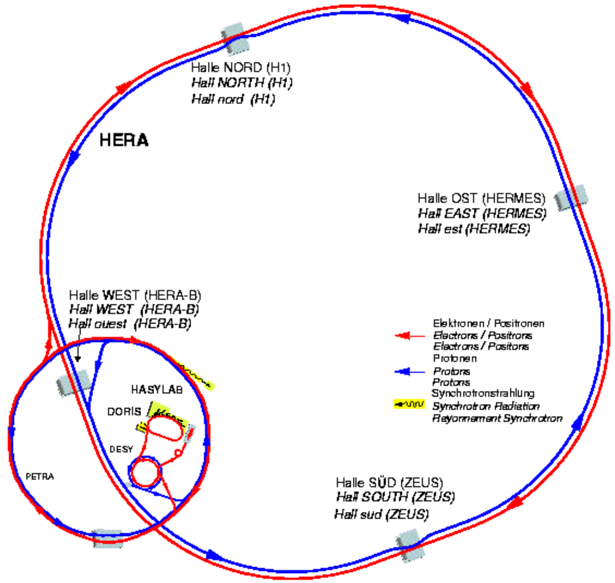
H1 and ZEUS Collaborations

- **Outline**

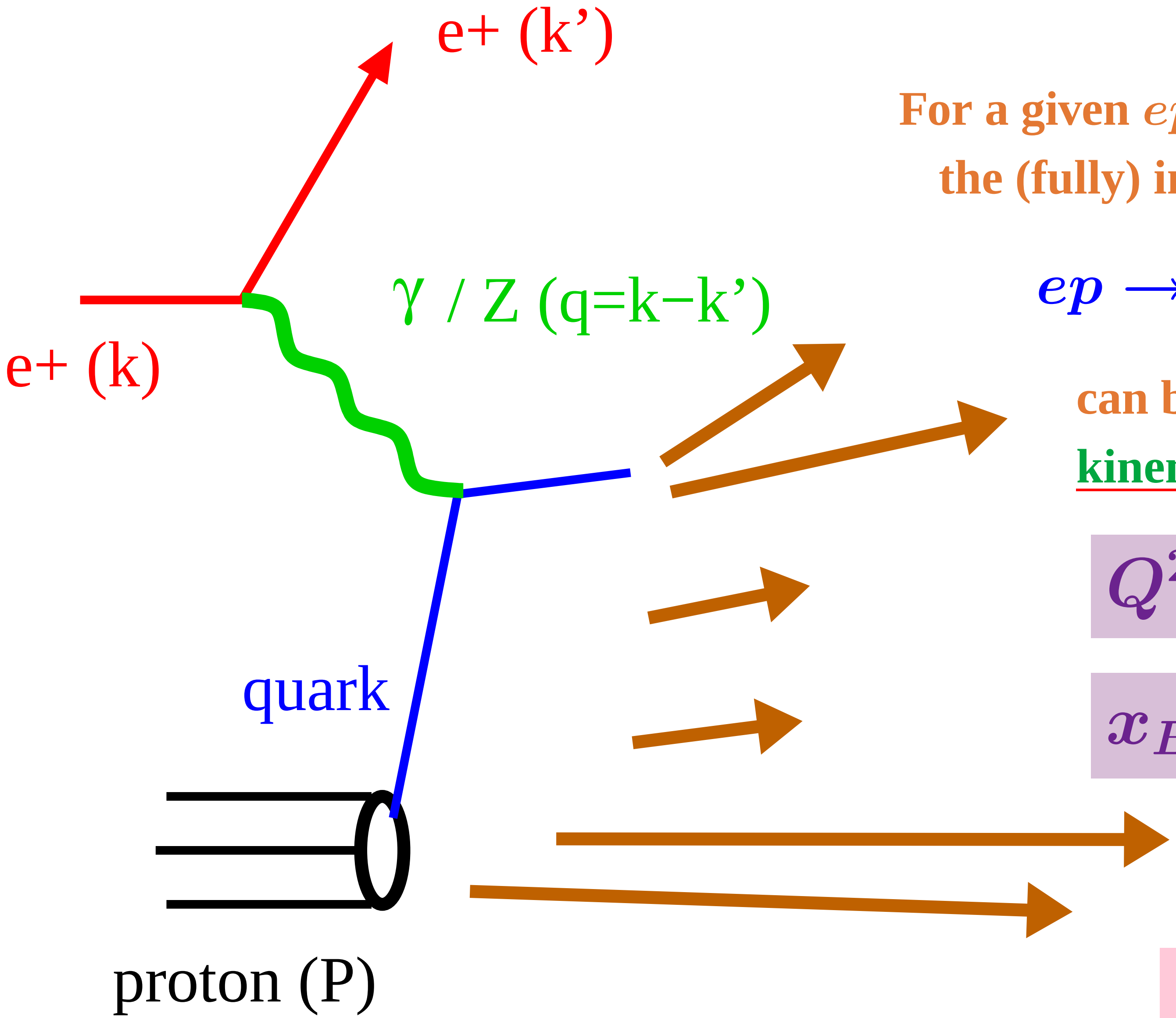
→ A Precision Measurement of the Inclusive ep Scattering Cross Section at HERA by H1; **H1PDF2009**

→ ZEUS09 PDF fit including HERA-II NC/CC e^-p and CC e^+p and HER/MER/LER data; **ZEUS 2009 PDF**

→ Jet cross sections and constraints on the proton PDFs



Kinematics of Neutral Current Deep Inelastic Scattering



For a given ep centre-of-mass energy, $\sqrt{s}$, the (fully) inclusive cross section for

$$ep \rightarrow e + \mathrm{X}$$

can be described by two independent kinematic variables, e.g.

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

$$x_{Bj} = Q^2/(2P \cdot q)$$

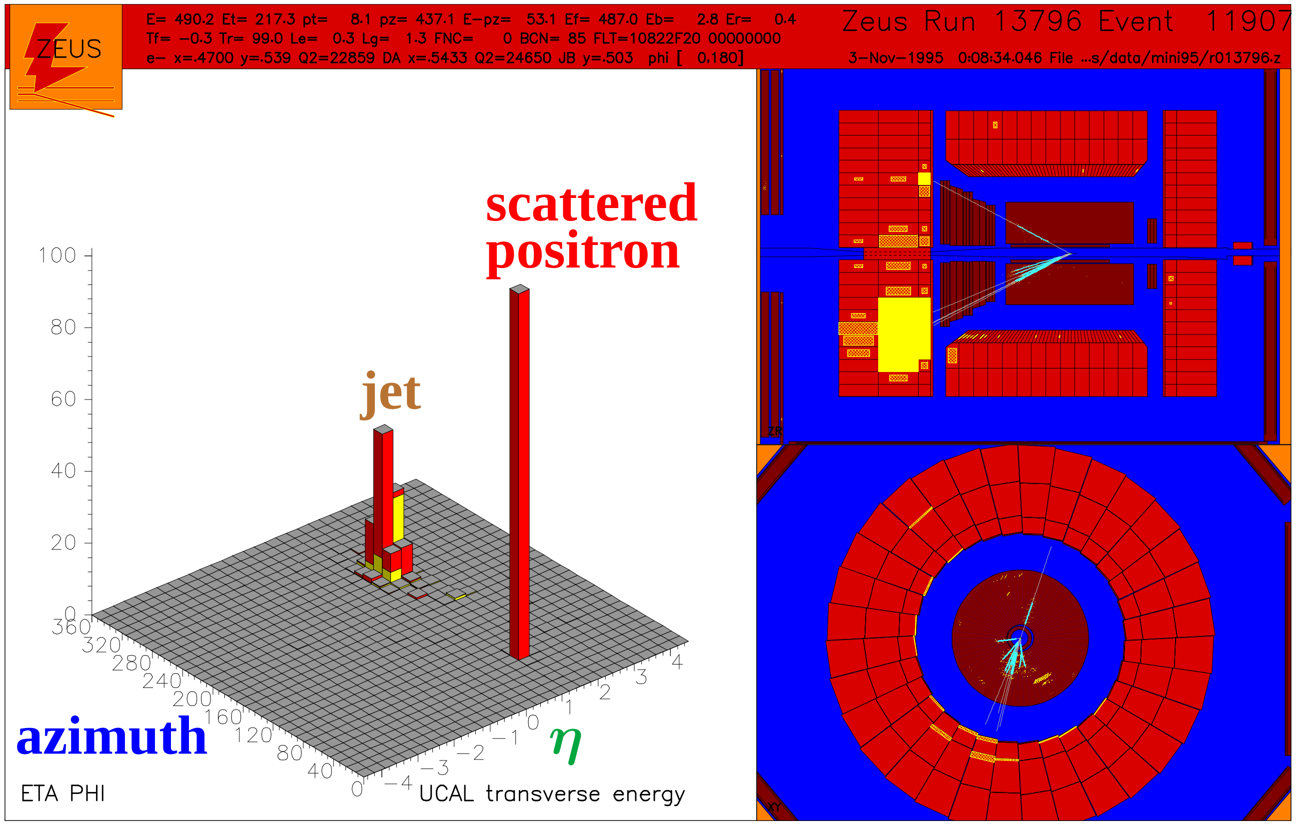
$\rightarrow$ Inelasticity variable

$$y = Q^2/(x_{Bj} s)$$

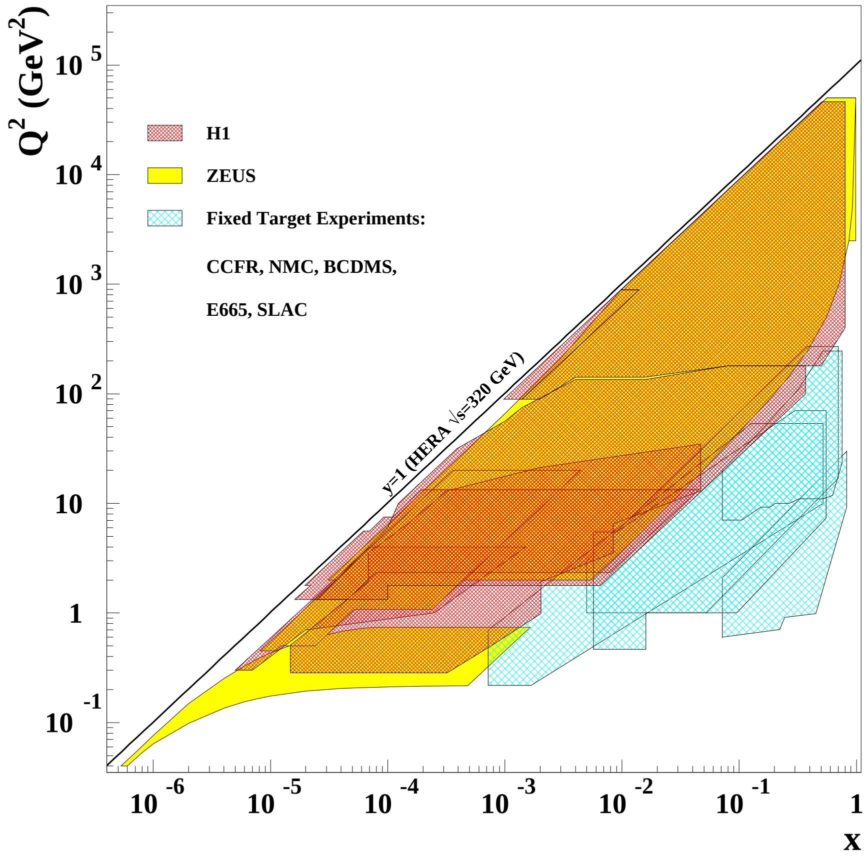
Neutral Current Deep Inelastic Scattering

- **Neutral Current DIS event candidate**

  $Q^2 \sim 24000$ GeV^2 and $x_{Bj} \sim 0.5$



- **Coverage of kinematic plane (Q^2,x_{Bj})**



Neutral Current Deep Inelastic Scattering

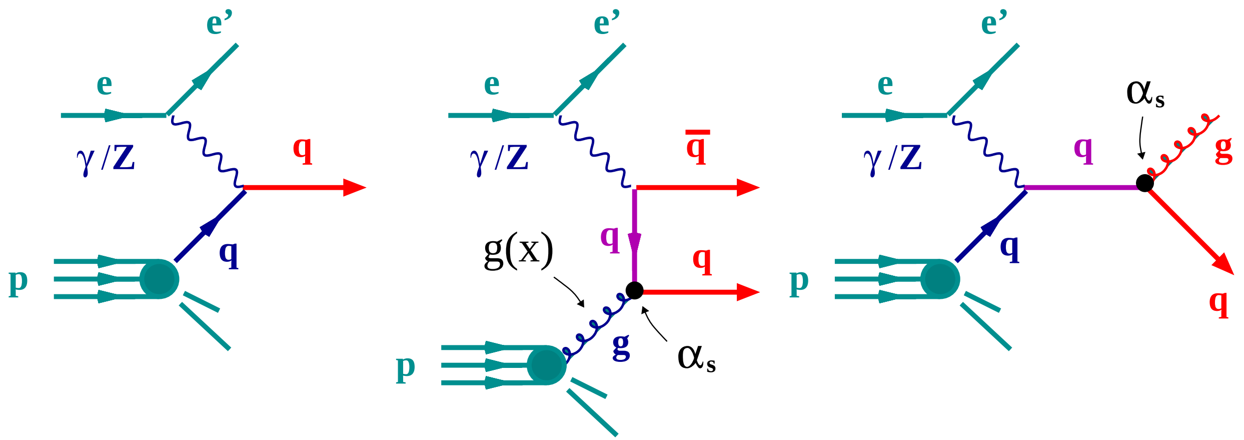
- **Inclusive process $e^{\pm}p \rightarrow e^{\pm} + X$**

$$\frac{d\sigma(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot \left(Y_+ \cdot F_2(x,Q^2) - y^2 \cdot F_L(x,Q^2) \mp Y_- \cdot xF_3(x,Q^2) \right)$$

Dominant (for F_2) **High y** (for F_L) **High Q^2** (for xF_3)

where $Y_{\pm} = 1 \pm (1-y)^2$

- **Structure functions of the proton (F_2, F_L, F_3) and QCD**
  - $\rightarrow F_2 \sim x \sum_i e_i^2 \cdot (q_i(x,Q^2) + \bar{q}_i(x,Q^2))$ **for** $Q^2 \ll M_Z^2$
  - $\rightarrow$ **the longitudinal structure function $F_L = 0$ in the quark-parton model**
  - $\rightarrow$ **parity-violating term F_3 is small for $Q^2 \ll M_Z^2$**

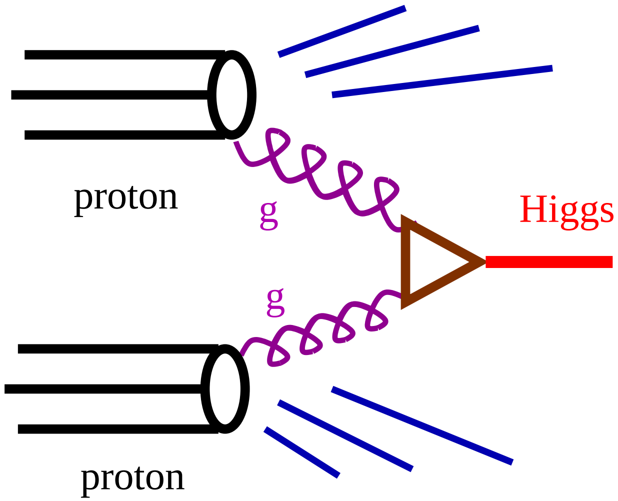


Quark-Parton Model **Boson-Gluon Fusion** **QCD Compton**

Clean probe of the Parton Distribution Functions in the Proton
$q_i(x,Q^2)$, $\bar{q}_i(x,Q^2)$
$g(x,Q^2)$

Universality (and usefulness) of Proton PDFs

$$\sigma_{pp\to H(W,Z,\ldots)+X} = \sum_{a,b} \int_0^1 dx_1\, f_{a/p}(x_1,\mu_F^2) \int_0^1 dx_2\, f_{b/p}(x_2,\mu_F^2)\;\hat{\sigma}_{ab\to H(W,Z,\ldots)}$$



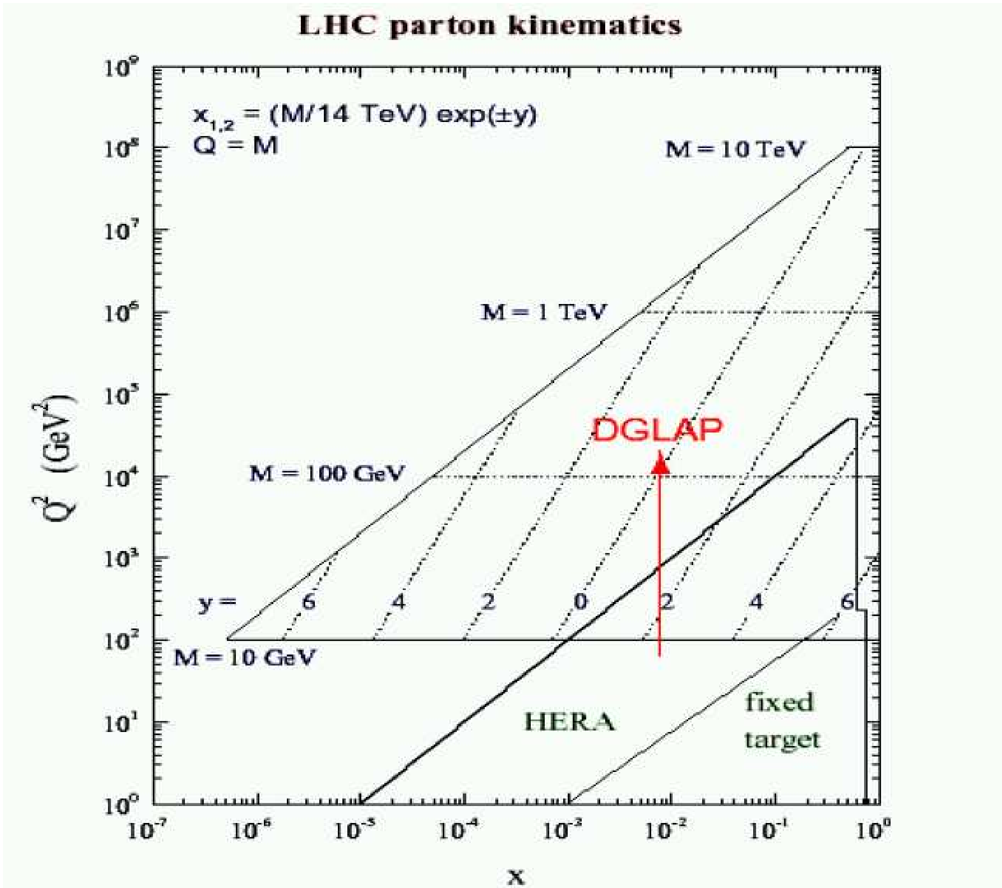
σ_H sensitive to gluon distribution at

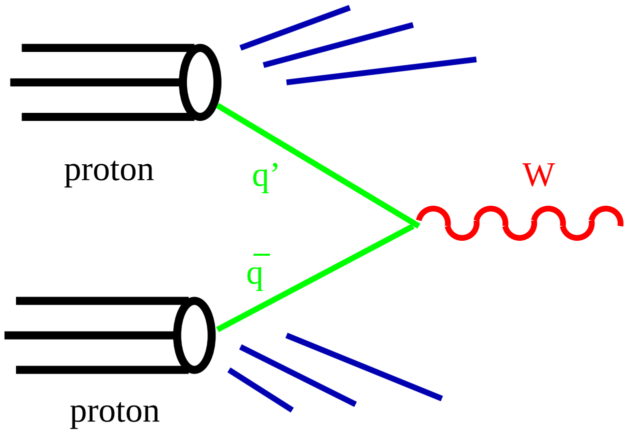
$x \sim \frac{M_H}{\sqrt{s}} \sim 8 \cdot 10^{-3}$

and $\mu_F^2 \sim M_H^2 \sim$

~ 13000 GeV^2

(for $M_H = 115$ GeV)





σ_W sensitive to sea distribution at

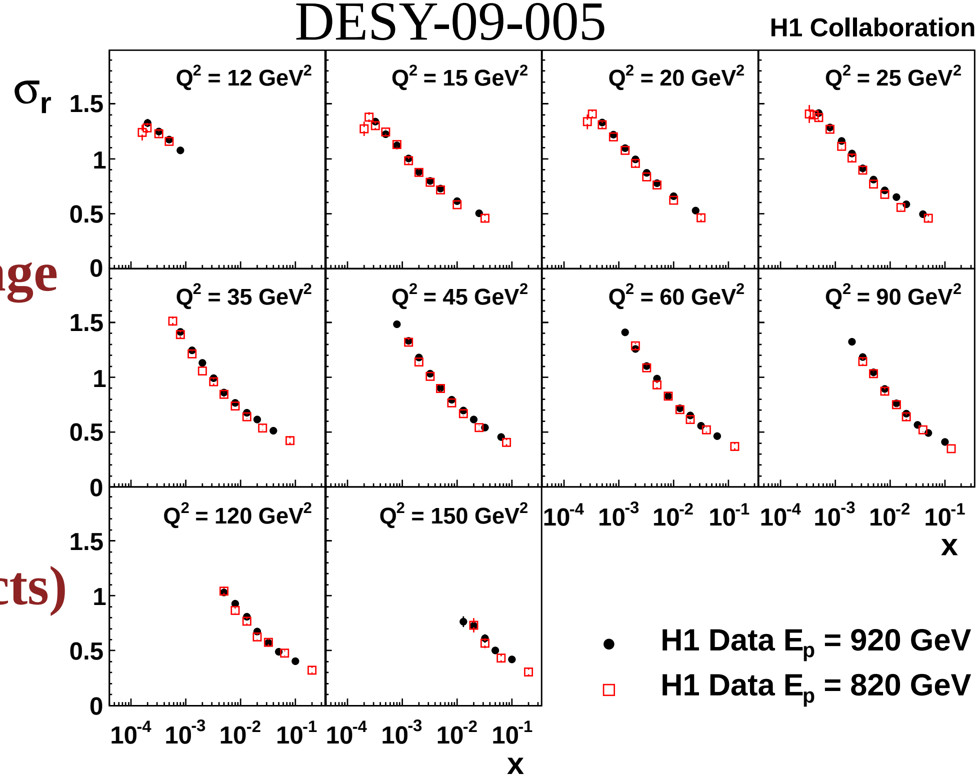
$x \sim \frac{M_W}{\sqrt{s}} \sim 6 \cdot 10^{-3}$

and $\mu_F^2 \sim M_W^2 \sim 6400$ GeV^2

Precision Measurement of Inclusive NC DIS by H1 Collaboration

- New measurement of the doubly-differential reduced cross section $\sigma_r = (2\pi\alpha^2 Y_+/xQ^4)^{-1} d\sigma_{ep}^{NC}/dxdQ^2$ for the reaction $e^+p \to e^+ + X$ over the range $12 < Q^2 < 150$ GeV^2, $2 \cdot 10^{-4} < x < 0.1$ using $\mathcal{L} = 22$ pb^{-1} of data taken with $E_p = 920$ GeV
- Analysis restricted to $y < 0.6$ (small F_L effects)
- Very good control over all essential measured detector quantities: $\delta E'_e/E'_e \sim 0.2 - 1\%$, $\delta E_{HFS}/E_{HFS} \sim 2\%$, extra efficiency uncertainties $\sim 0.3 - 0.5\%$

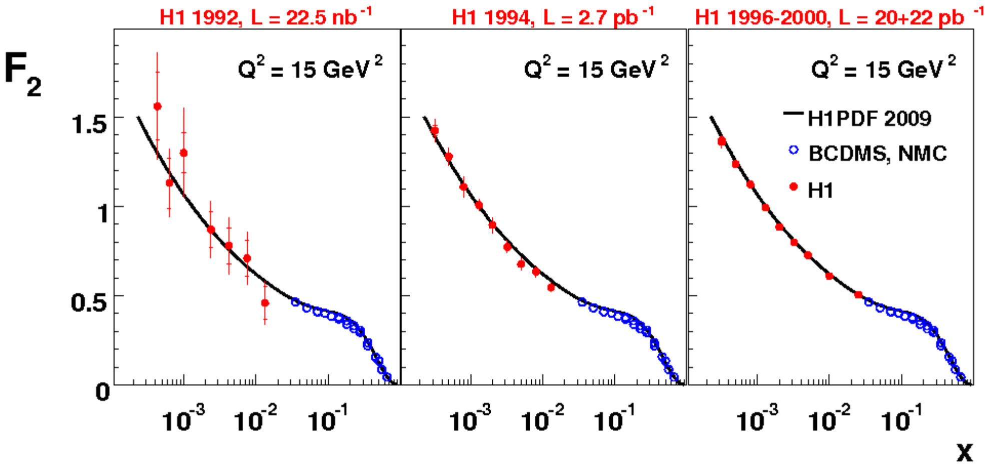
DESY-09-005



- Comparison to previous measurements using data taken with $E_p = 820$ GeV (after correction for a small Q^2-dependent bias): good agreement; uncertainties reduced by a factor two! $\longrightarrow$ Average of both sets of measurements taking into account bin-to-bin correlated uncertainties (σ_r corrected to $E_p = 920$ GeV for $y < 0.35$)

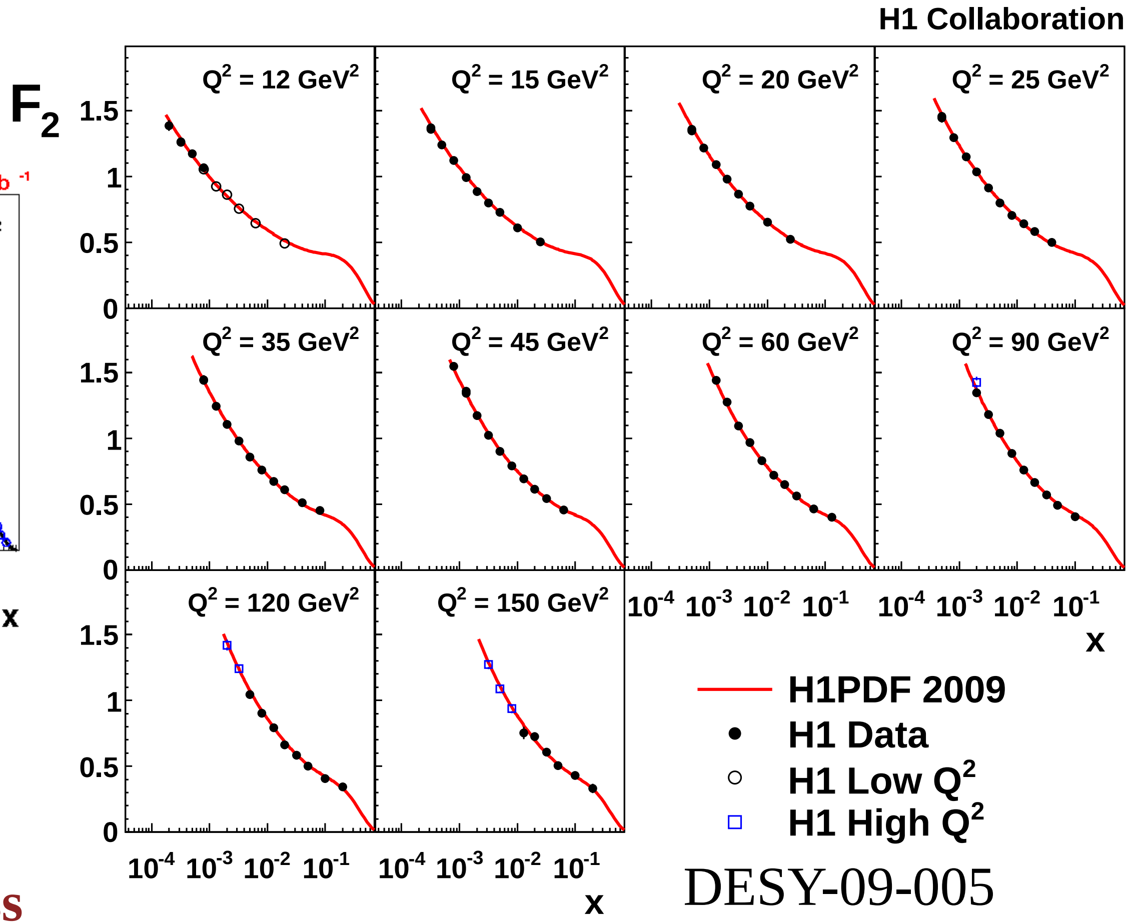
(see talk by Jan Kretzschmar)

Determination of $F_2(x, Q^2)$



- Accuracies starting from $\sim 20-30\%$, reaching $\sim 4-6\%$, last publication using 1996/97 data $\sim 2-3\%$, and finally $\sim 1.3-2\%$

(see talk by Jan Kretzschmar)



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- Extraction of F_2 from the reduced cross sections: $\sigma_r = F_2(x, Q^2) - (y^2/Y_+)F_L(x, Q^2)$ by correcting for the F_L contribution as given by the QCD fit (see later)
- Most precise measurement of F_2 in the medium-Q^2 region: total uncertainty $1.3 - 2\%$
- Steep rise of F_2 at low-x is well described by QCD fit

$\Rightarrow$ Detailed and precise information on the sea and gluon densities in the proton

$F_2(x, Q^2)$ provides...

→ **direct information on quark densities**

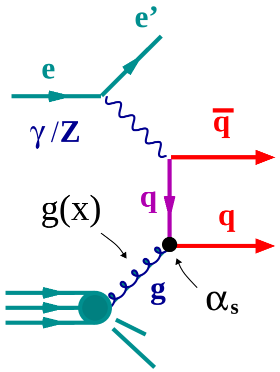
$$F_2 \sim x \sum_i e_i^2 \cdot (q_i + \bar{q}_i)$$

→ **indirect information on gluon density**

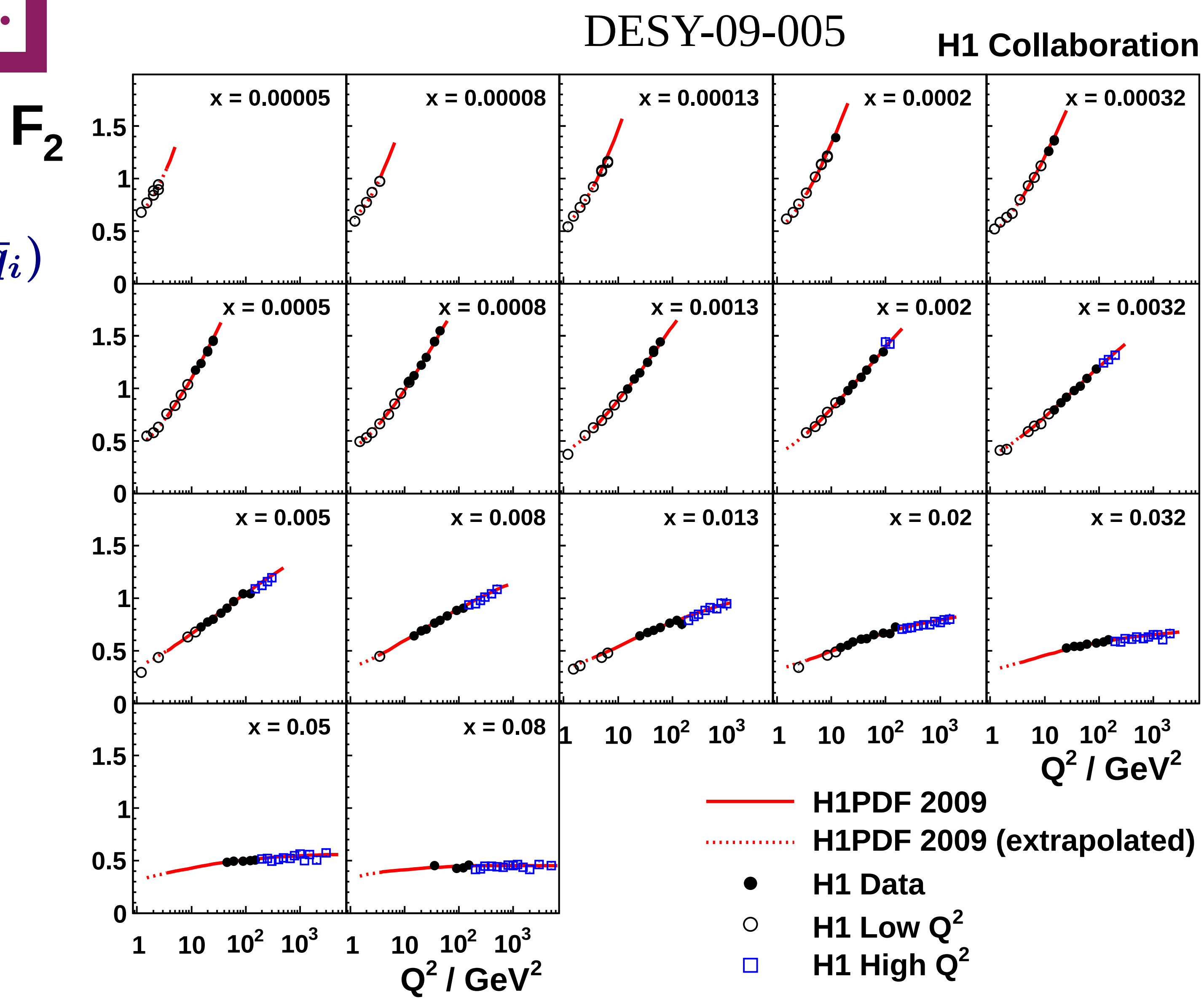
- **Large and positive scaling violations at low x**

  dominance of BGF

  $\partial F_2/\partial \ln Q^2 \sim \alpha_s \cdot xg$



Boson−Gluon Fusion



- **Approximate scaling for $x \sim 0.1$**

Determination of the Proton PDFs: a new QCD Fit, H1PDF 2009

- Analysis using DGLAP evolution equations at next-to-leading order (NLO) in α_s

$$\frac{\partial q_i(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dz}{z} \left(\sum_j P_{q_i q_j} \cdot q_j(x/z, \mu^2) + P_{q_i g} \cdot g(x/z, \mu^2) \right)$$

$$\frac{\partial g(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dz}{z} \left(\sum_j P_{g q_j} \cdot q_j(x/z, \mu^2) + P_{gg} \cdot g(x/z, \mu^2) \right)$$

The DGLAP equations yield the proton PDFs at any value of Q^2 provided they are input as functions of x at some input scale Q_0^2

$\longrightarrow$ number sum rules and the momentum sum rule are imposed

- In order to determine the proton PDFs additional experimental information is needed on

  $\longrightarrow$ quark densities at high x $\longrightarrow$ flavour composition of the sea

- Additional data sets needed
- New QCD fit (H1PDF 2009) uses only inclusive DIS measurements by H1 $\longrightarrow$

  $\longrightarrow$ more precise data for $Q^2 < 150$ GeV^2

  $\longrightarrow$ improved theoretical treatment of heavy quarks (VFNS scheme, Roberts and Thorne)

Data set	Process	Q^2 range	
H1 combined low Q^2 1995 – 2000	e^+p NC	0.2	12
H1 combined medium Q^2 1996 – 2000	e^+p NC	12	150
H1 high Q^2 94 – 97	e^+p NC	150	30 000
H1 high Q^2 94 – 97	e^+p CC	300	15 000
H1 high Q^2 98 – 99	e^-p NC	150	30 000
H1 high Q^2 98 – 99	e^-p CC	300	15 000
H1 high Q^2 98 – 99	e^-p NC	100	800
H1 high Q^2 99 – 00	e^+p NC	150	30 000
H1 high Q^2 99 – 00	e^+p CC	300	15 000

Determination of the Proton PDFs: a new QCD Fit, H1PDF 2009

- **Parametrisation of the proton PDFs**

$\longrightarrow$ u valence (xu_V), d valence (xd_V), gluon (xg), $x\overline{U} = x\bar{u} + x\bar{c}$, $x\overline{D} = x\bar{d} + x\bar{s} + x\bar{b}$
at $Q_0^2 = 1.9$ GeV^2 by the functional form

$$xf(x) = A_p x^{B_p}(1-x)^{C_p}(1 + D_p x + E_p x^2)$$

- **Constraints on the parameters $\{A_p, B_p\}$:**

$\longrightarrow$ momentum and number sum rules $\Rightarrow A_g, A_{u_v}, A_{d_v}$

$\longrightarrow$ no sensitivity to difference on low-x behaviour of u and d valence: $B_{u_v} = B_{d_v}$

$\longrightarrow$ $B_{\overline{U}} = B_{\overline{D}}$

$\longrightarrow$ suppression of strange sea: $xs(x) = f_s x\overline{D}(x)$ with $f_s = 0.31$

$\longrightarrow$ $A_{\overline{U}} = A_{\overline{D}}(1 - f_s)$ so that $\bar{d}/\bar{u} \rightarrow 1$ as $x \rightarrow 0$

$$\Rightarrow \text{10 free parameters } (\alpha_s(M_Z) = 0.1176)$$

- **Additional conditions:**

$\longrightarrow$ $F_2 \geq 0$ and $F_L \geq 0$

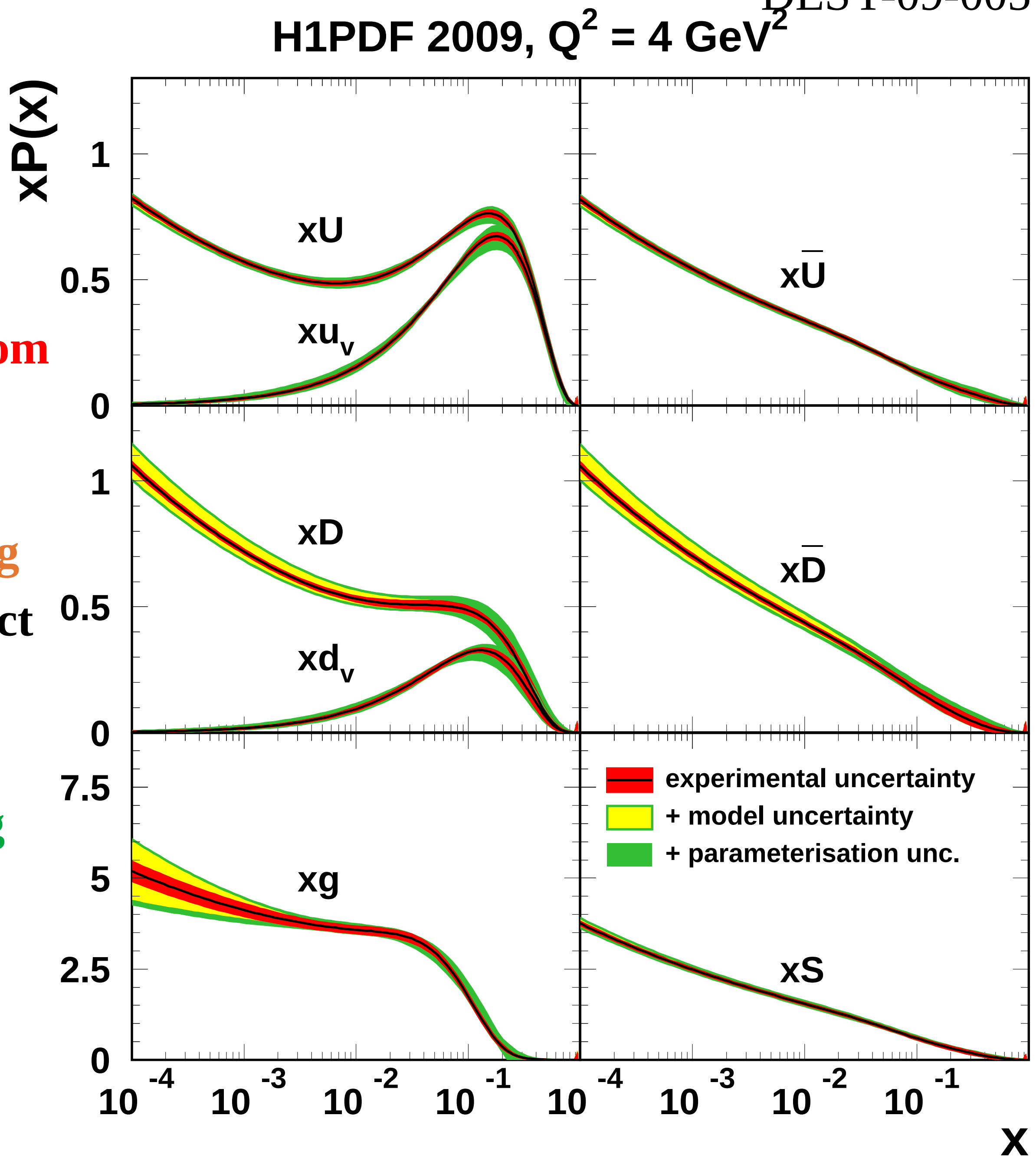
$\longrightarrow$ all PDFs ≥ 0 (but included as parametrisation uncertainty)

$\longrightarrow$ valence not too low compared to sea at high x (but included as parametrisation uncert.)

DESY-09-005

A new QCD Fit, H1PDF 2009

- Data with $Q^2 > Q^2_{\rm min} = 3.5\ {\rm GeV}^2$
- Good description of all data sets ($\chi^2/ndof = 587/644$)
- Experimental uncertainty, obtained from $\Delta\chi^2 = 1$ using the Hessian method
- Model uncertainty, obtained by varying $\rightarrow m_c, m_b, f_s, Q^2_{\rm min}, Q^2_0$ (largest effect at low x)
- New uncertainty contribution resulting from the parametrisation choice: alternative parametrisations leading to good fits but unphysical behaviour at large x are used to estimate it



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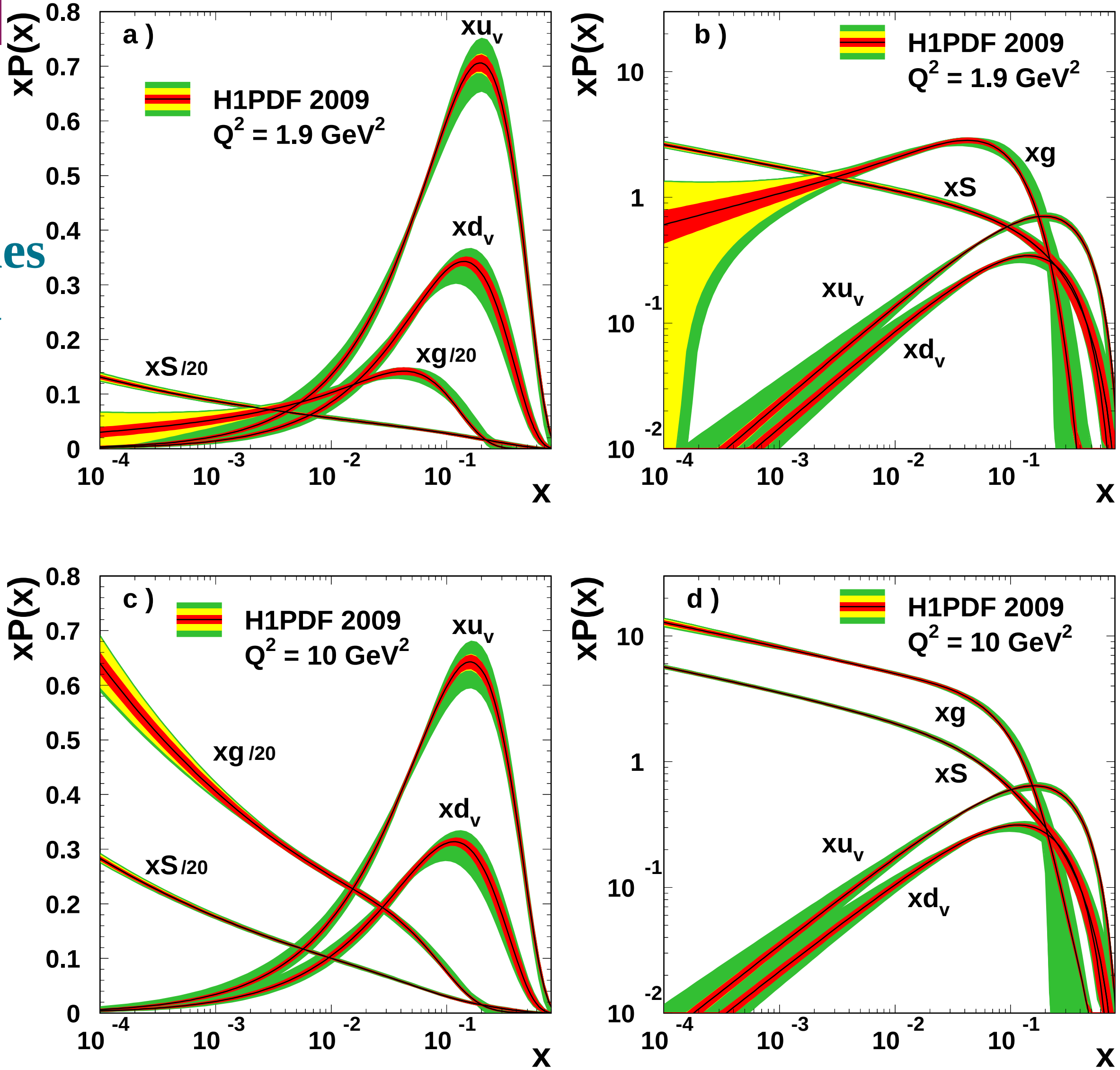
A new QCD Fit, H1PDF 2009

- Reduced uncertainties at low x with respect to previous fit (H1PDF 2000)
- Larger (and more realistic) uncertainties at high x (parametrisation uncertainty dominant)



- At $Q^2 = 1.9$ GeV^2

→ sea quarks dominate at low x

→ valence-like gluon density

- At $Q^2 = 10$ GeV^2

→ gluons dominate at low x

→ similar rise of gluons and sea quarks

Improved determination of the proton PDFs

Determination of the Proton PDFs: a new QCD fit, ZEUS09 PDF

- **Parametrisation of the proton PDFs**

$\rightarrow$ **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 $\{p_i\}$:**
  - $\longrightarrow$ **momentum and number sum rules $\Rightarrow p_{1,g}, p_{1,u_V}, p_{1,d_V}$**
  - $\longrightarrow$ **no sensitivity to difference on low-x behaviour of u and d valence: $p_{2,u_V} = p_{2,d_V}$**
  - $\longrightarrow$ **no sensitivity to flavour structure of light-quark sea: fix $p_{i,\Delta}$ consistent with Gottfried sum rule and Drell-Yan data**
  - $\longrightarrow$ **suppression of strange sea in accordance with dimuon data from CCFR-NuTeV**

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

$\Rightarrow$ 11 free parameters ($\alpha_s(M_Z) = 0.118$)

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

Determination of the Proton PDFs: a new QCD fit, ZEUS09 PDF

- Data sets used in the previous fit (ZEUS-JETS PDF, 577 data points):

$\longrightarrow$ Structure function measurements: reduced double differential cross sections in x and Q^2 for neutral (charged) current DIS e^+p and e^-p

$\longrightarrow$ Jet cross section measurements: inclusive jet production in NC DIS and dijet production in γp collisions

$\Rightarrow$ $6.3 \cdot 10^{-5} < x < 0.65, 2.7 < Q^2 < 30000$ GeV^2 and $W^2 > 20$ GeV^2

- New sets of data from HERA II running period:

  $\longrightarrow$ High Q^2 ZEUS e^-p NC and CC data from HERA II $\Rightarrow$ valence u_V at high x

  $\longrightarrow$ High Q^2 ZEUS e^+p CC data from HERA II $\Rightarrow$ valence d_V at high x

  $\longrightarrow$ Low Q^2 ZEUS NC data with $E_p = 920, 575$ and 460 GeV from HERA II $\Rightarrow$ gluon and sea at low x

- High statistics from HERA II allows an improved determination of the valence-quark distributions at high x in an only-ZEUS-based QCD fit: advantage of being free from heavy-target corrections, higher twists and isospin symmetry assumptions (which affect fixed-target DIS data used in global QCD fits)

ZEUS-prel-09-010

A new QCD fit, ZEUS09 PDF

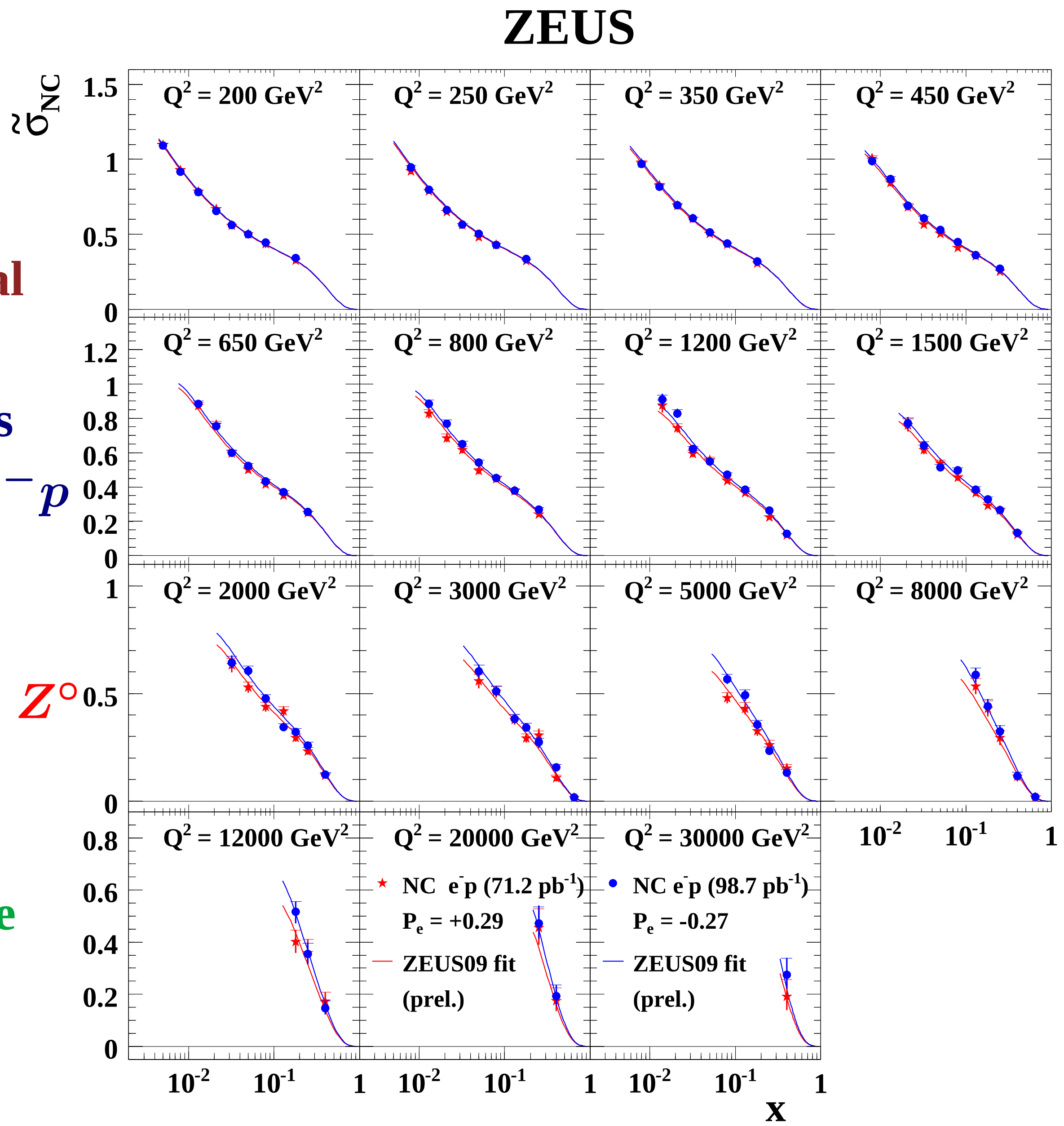
- QCD fit to 1060 data points: good description of all data sets, $\chi^2/ndof = 0.97$
- Full account of correlated experimental uncertainties using the offset method
- Comparison of the QCD-fit predictions to reduced cross sections for NC DIS e^-p with longitunally polarised e^- beams

$\longrightarrow$ constrain valence u_V at high x

$\longrightarrow$ Polarisation dependence due to $\gamma^* - Z^\circ$ interference and Z° contribution (significant only at high Q^2)

$\longrightarrow$ Confirmation of the predictions of the electroweak sector of the SM in a space-like process

ZEUS High Q^2 NC DIS e^-p data



A new QCD fit, ZEUS09 PDF

- Charged Current DIS: $ep \to \nu + X$
- Cross-section formulae in LO QCD

$$\frac{d\sigma(e^-p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\eta_W^2 \cdot \sum_i (u_i + (1-y)^2 \bar{d}_i)$$

where $\eta_W = M_W^2/(Q^2 + M_W^2)$

- Comparison of the QCD-fit predictions to reduced cross sections for CC DIS e^-p with longitunally polarised e^- beams (multiplicative factor $1-P$ for e^-)

$$\tilde{\sigma}_{CC} = (G_F^2 \eta_W^2/2\pi x)^{-1} d\sigma/dxdQ^2$$

$\longrightarrow$ Sensitivity to flavour composition

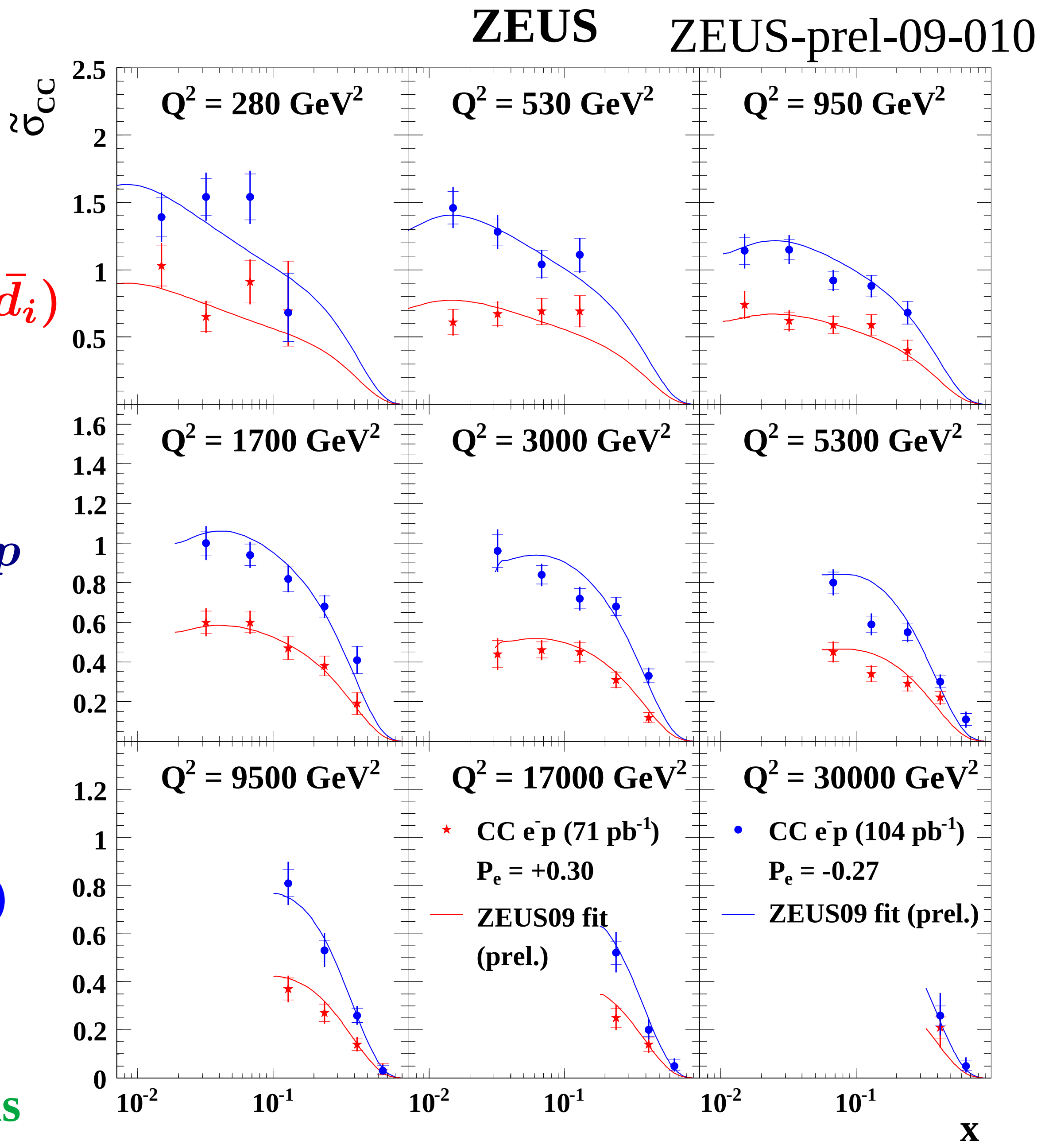
$$\tilde{\sigma}(e^-p) = x(u + c + (1-y)^2(\bar{d} + \bar{s}))$$

$\longrightarrow$ Sensitivity to valence quarks

$\tilde{\sigma}(e^-p) \to xu_V$ (high-x)

$\longrightarrow$ Confirmation of electroweak predictions

ZEUS High Q^2 CC DIS e^-p data



A new QCD fit, ZEUS09 PDF

- Charged Current DIS: $ep \to \nu + X$
- Cross-section formulae in LO QCD

$$\frac{d\sigma(e^+p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\eta_W^2 \cdot \sum_i (\bar{u}_i + (1-y)^2 d_i)$$

where $\eta_W = M_W^2/(Q^2 + M_W^2)$

- Comparison of the QCD-fit predictions to reduced cross sections for CC DIS e^+p with longitudinally polarised e^+ beams (multiplicative factor $1+P$ for e^+)

$\tilde{\sigma}_{CC} = (G_F^2 \eta_W^2/2\pi x)^{-1} d\sigma/dxdQ^2$

$\to$ Sensitivity to flavour composition

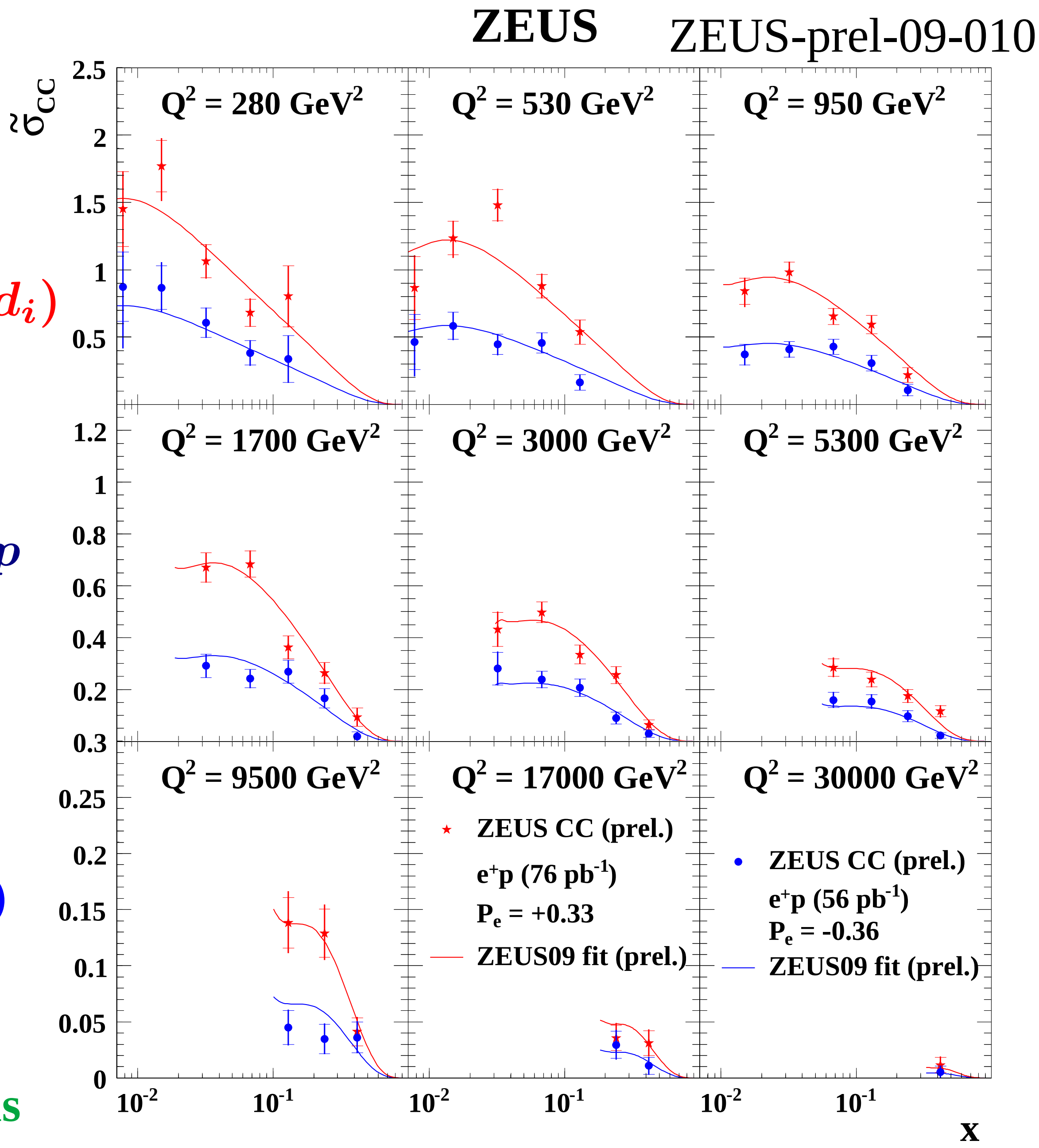
$\tilde{\sigma}(e^+p) = x(\bar{u} + \bar{c} + (1-y)^2(d+s))$

$\to$ Sensitivity to valence quarks

$\tilde{\sigma}(e^+p) \to x(1-y)^2 d_V$ (high-x)

$\to$ Confirmation of electroweak predictions

ZEUS High Q^2 CC DIS e^+p data



A new QCD fit, ZEUS09 PDF

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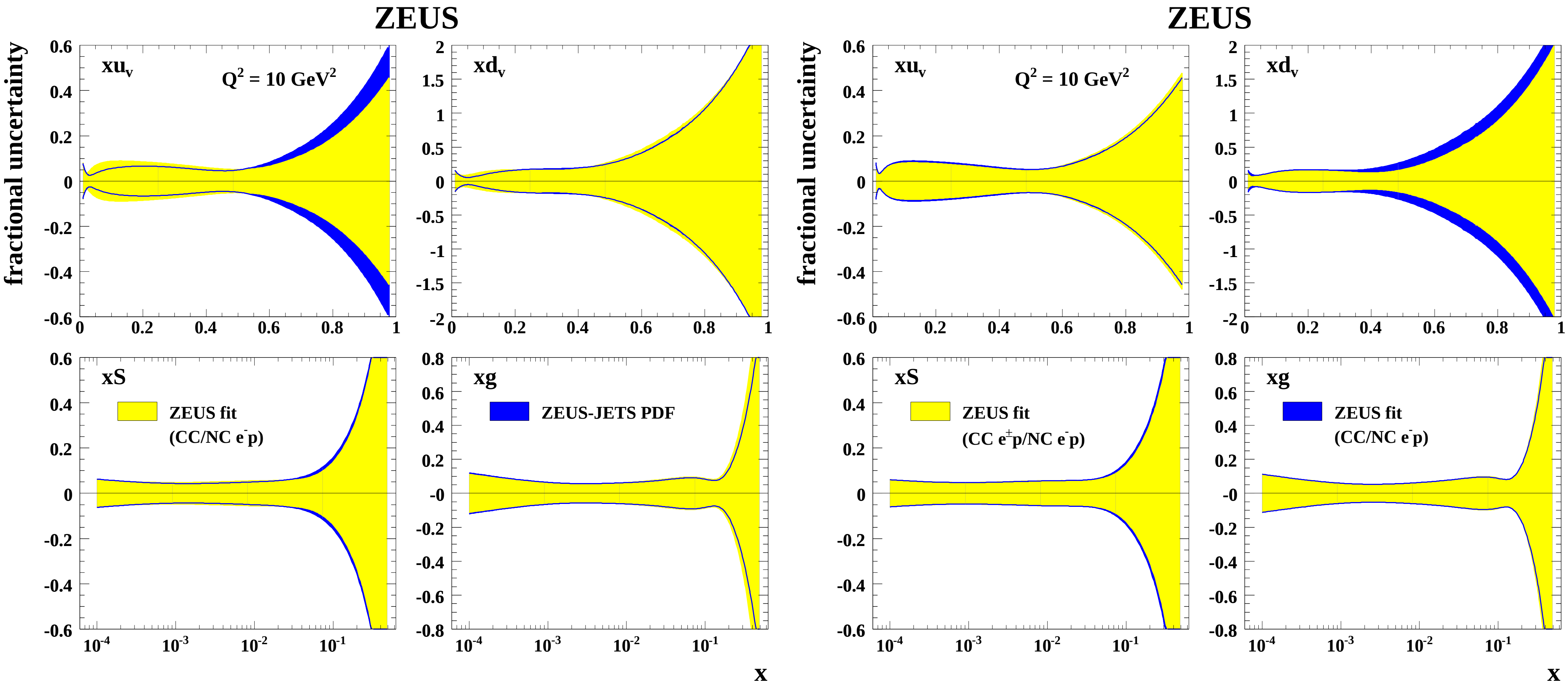

→ Inclusion of High Q^2 ZEUS e^-p NC and CC data from HERA II ⇒ valence u_V at high x

→ High Q^2 ZEUS e^+p CC data from HERA II ⇒ valence d_V at high x

A new QCD fit, ZEUS09 PDF

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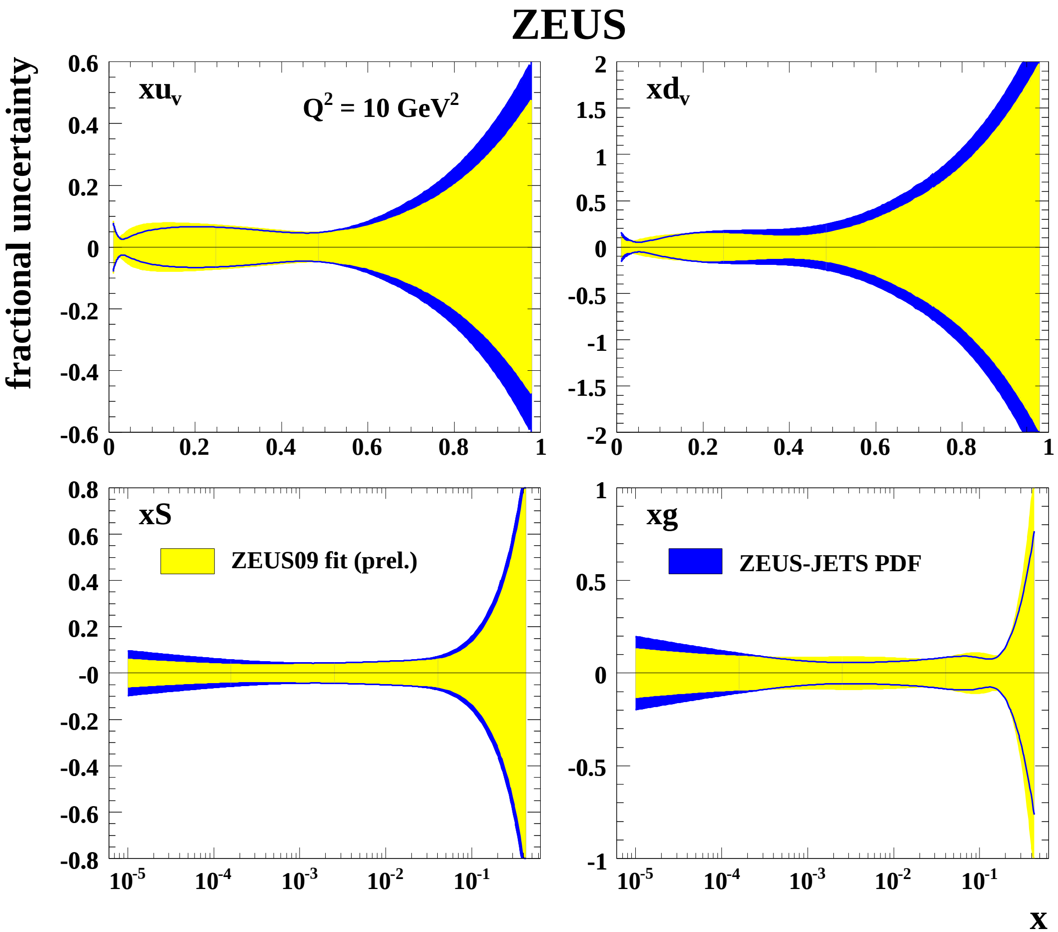
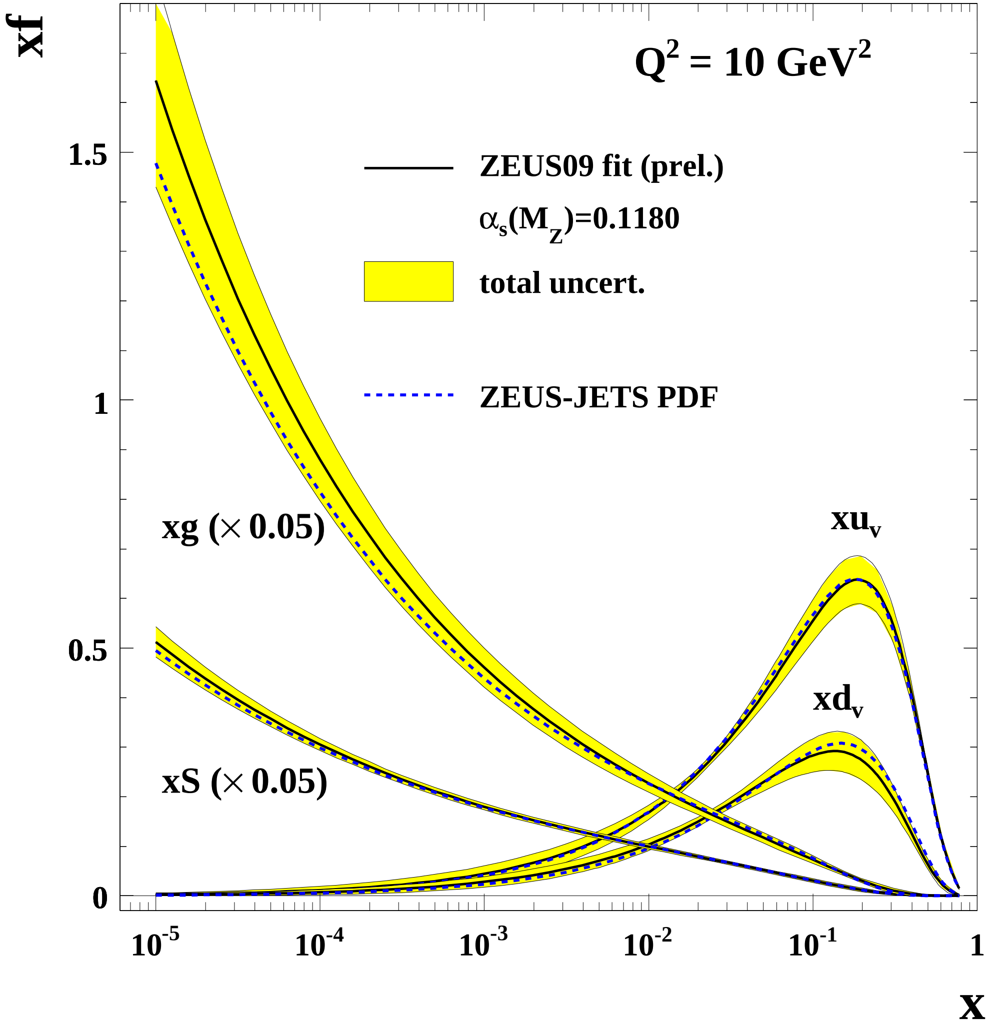
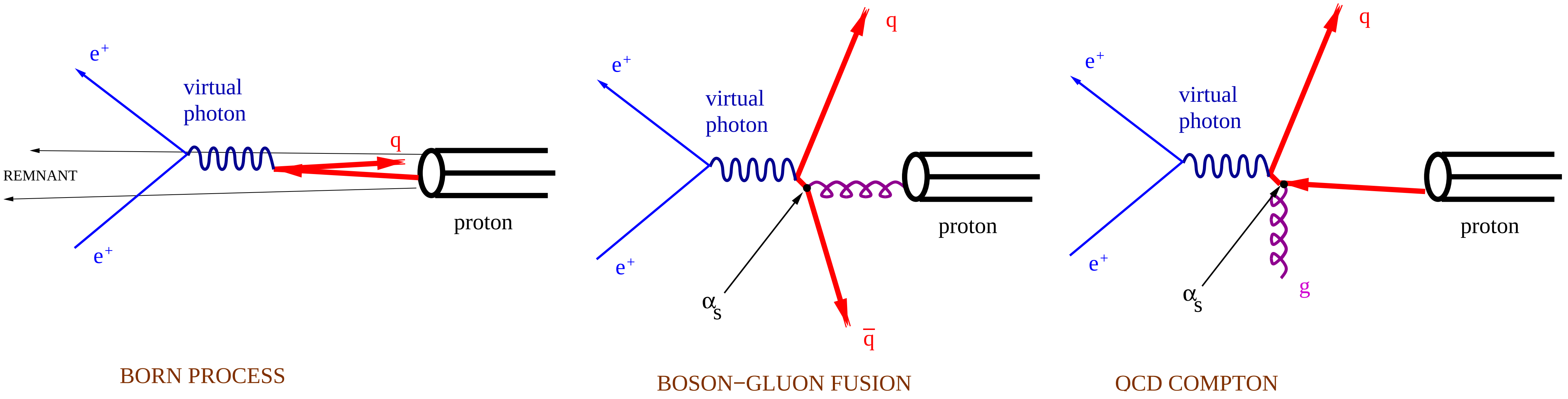




→ Inclusion of High Q^2 ZEUS e^-p NC and CC data, High Q^2 ZEUS e^+p CC data and Low Q^2 ZEUS NC data with $E_p = 920$, 575 and 460 GeV from HERA II

Improved determination of u_V, d_V at high x free from nuclear corrections, etc.

High-E_T Jet Production 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)**

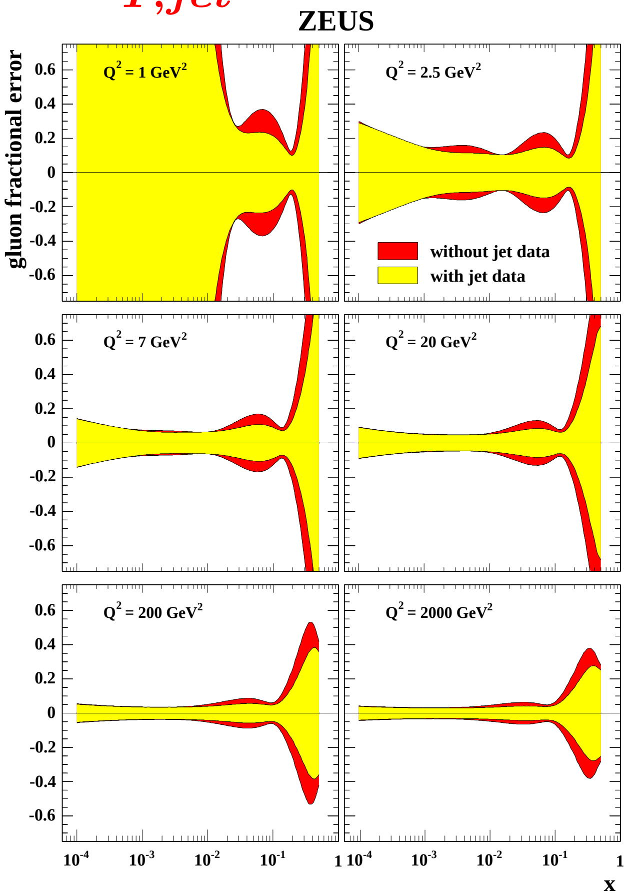
$\longrightarrow$ **suppression of the beam-remnant jet (zero E_T)**

$\longrightarrow$ **lowest-order non-trivial contributions from $\gamma^* g \rightarrow q\bar{q}$ and $\gamma^* q \rightarrow qg$**

$\Rightarrow$ **directly sensitive to hard QCD processes (α_s) $\Rightarrow$ gluon density**

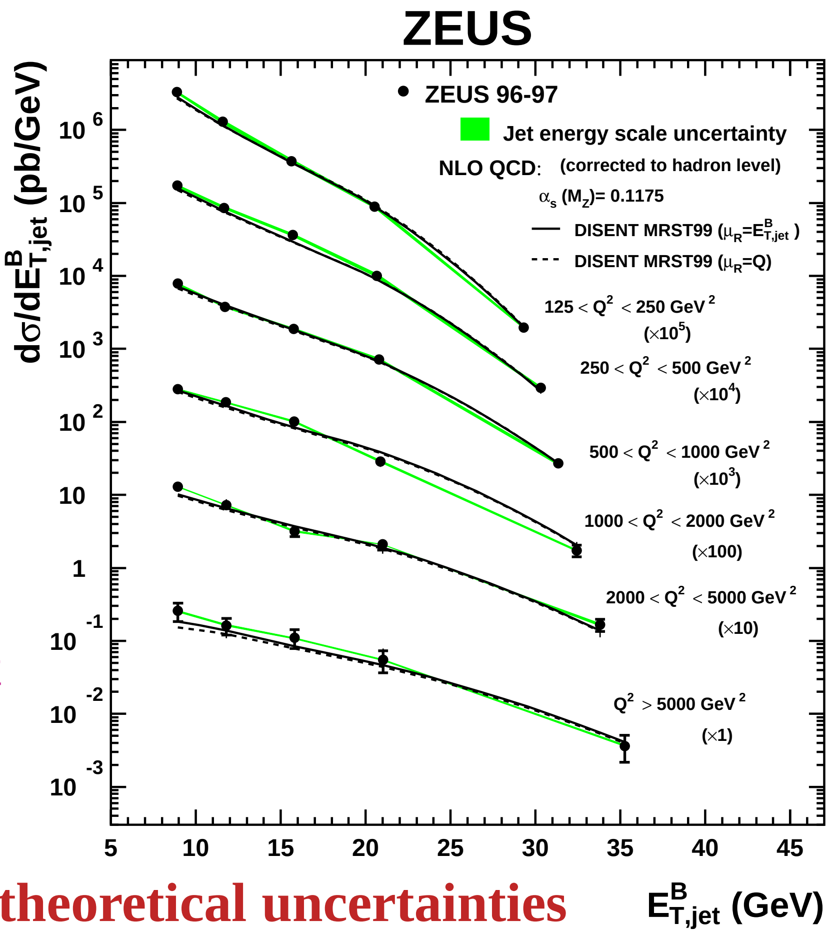
Improving the gluon distribution: jet data

- 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 $-2 < \eta^B_{jet} < 1.8$



$$\cos\gamma = \frac{(1-y)xE_p - yE_e}{(1-y)xE_p + yE_e}$$

- Longitudinally invariant k_T cluster algorithm in the Breit frame



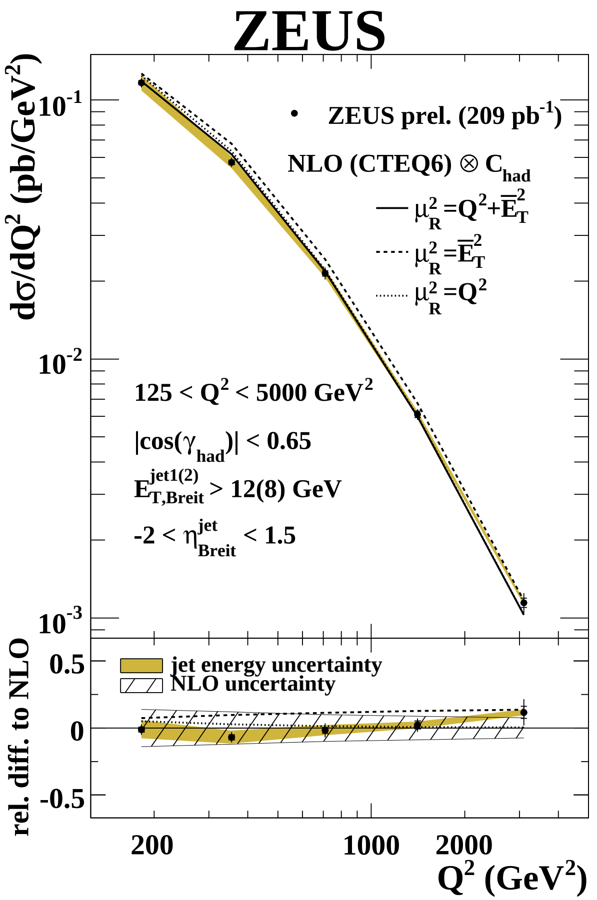
- Small experimental and theoretical uncertainties

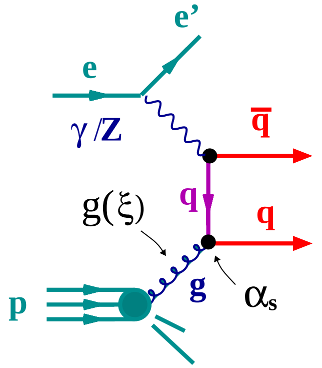
← Comparison of gluon distributions from fits with and without jet data: constrain on the gluon density in the range 0.01-0.4

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

→ **Sizeable reduction of the gluon uncertainty**

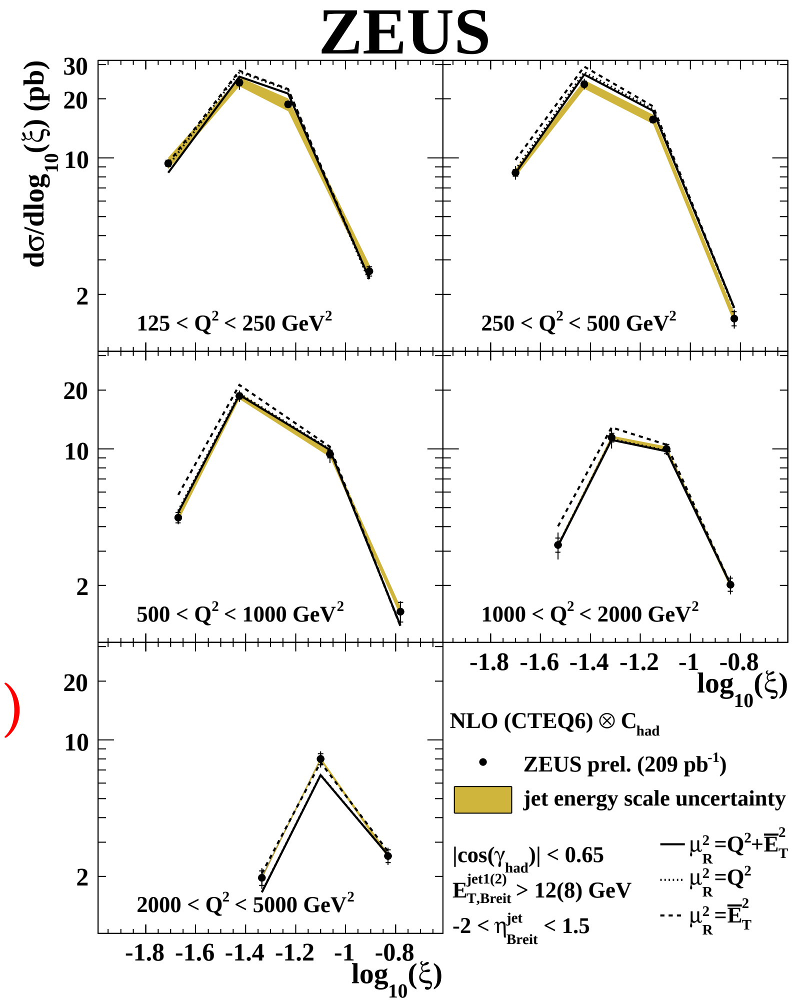
Dijet cross sections from HERA I+HERA II





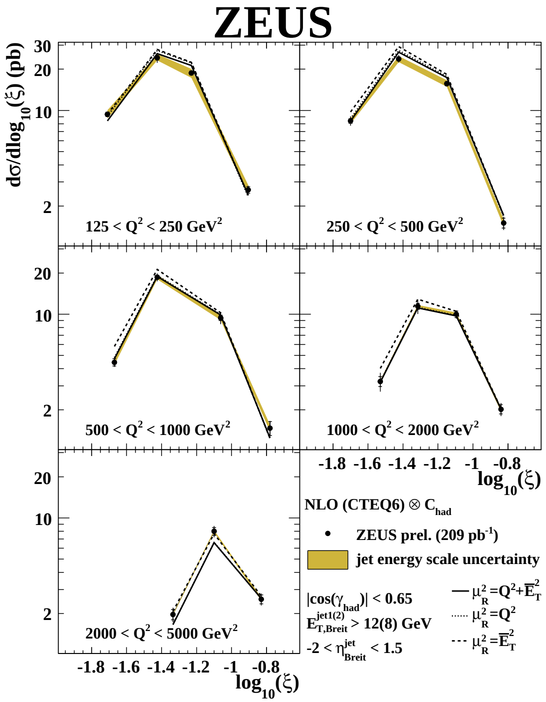
Boson−Gluon Fusion

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

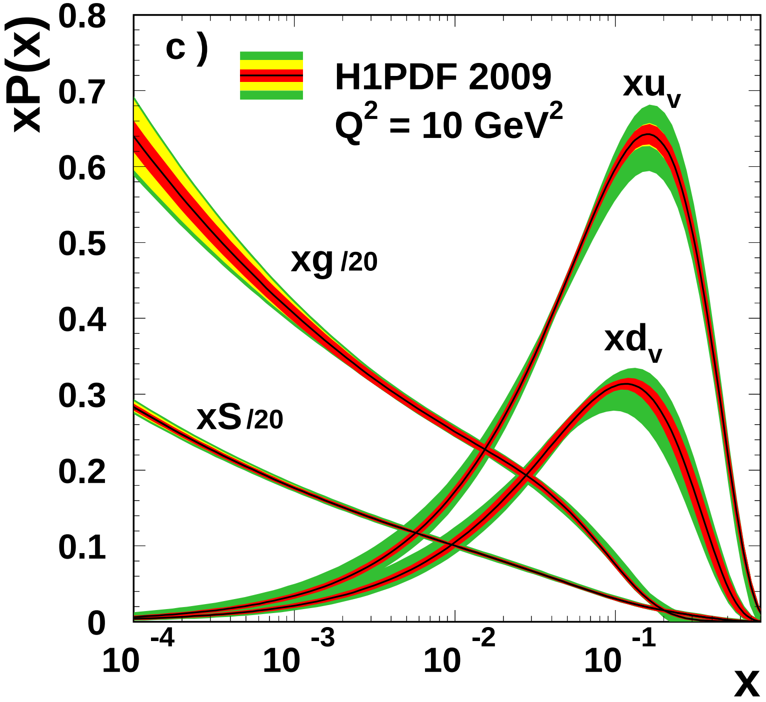


- **Measurement of dijet cross sections in NC DIS for $125 < Q^2 < 5000$ GeV^2 and $|\cos\gamma| < 0.65$ for dijets with $E_{T,Breit}^{jet1(2)} > 12(8)$ GeV and $-2 < \eta_{jet}^B < 1.5$ using HERA I and (04/05) HERA II data, $\mathcal{L} = 209$ pb^{-1} → increased statistical precision**
- **Good description by NLO pQCD using CTEQ6 PDFs; further constrain on gluon density**

Summary



H1 DESY-09-005



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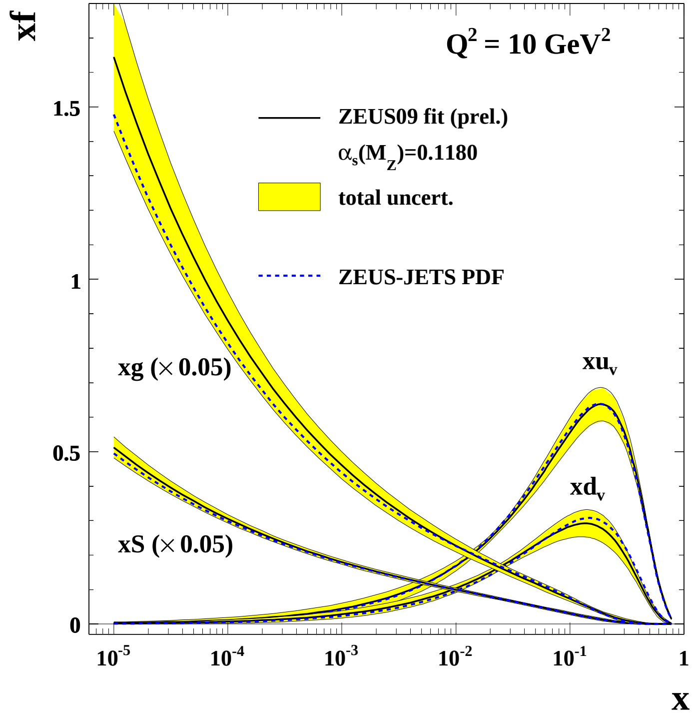
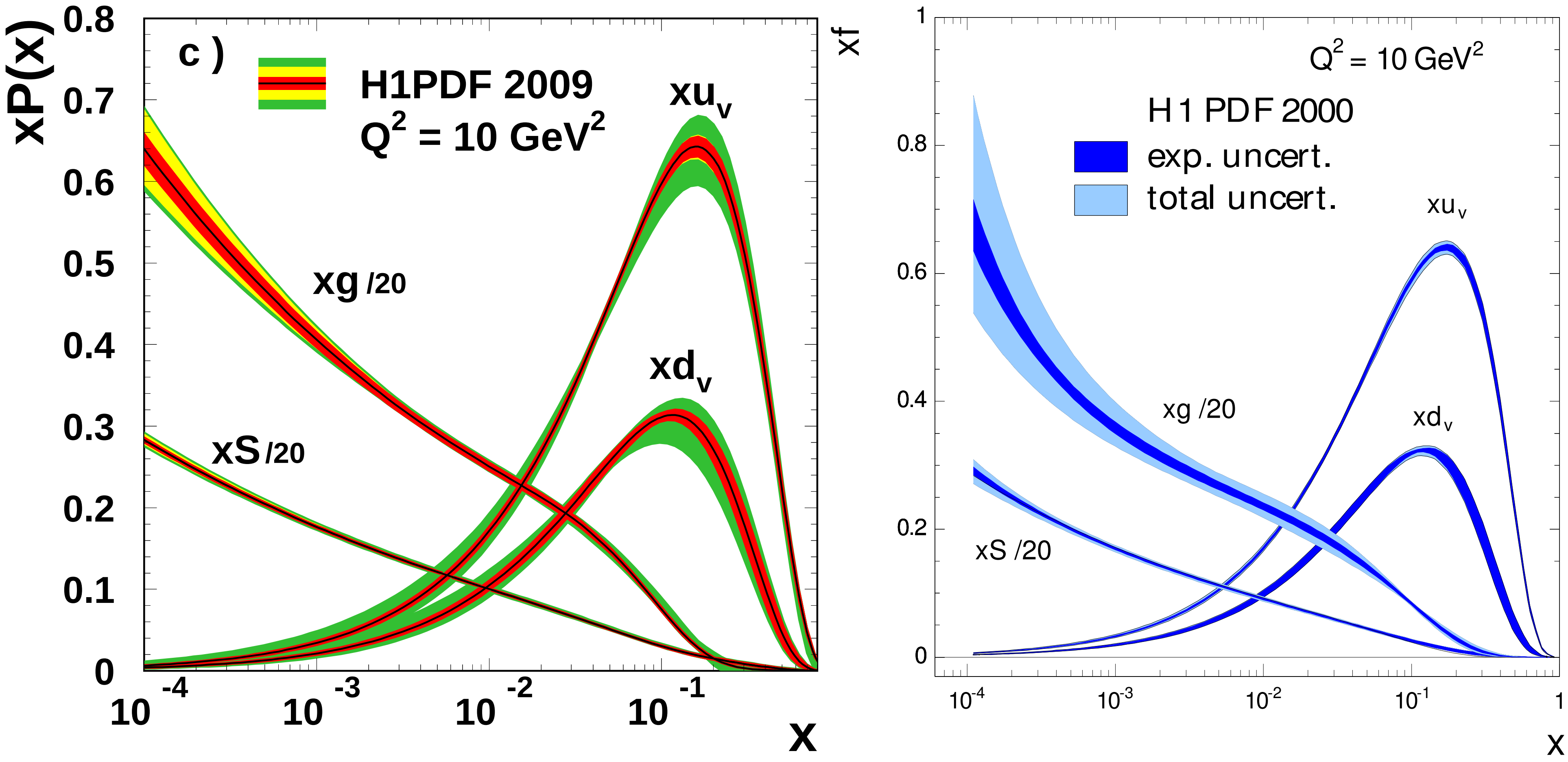


Improved determination of the proton PDFs at HERA

- **Improved determination of gluon and sea distributions at low x by including precise measurements of low Q^2 NC DIS (new H1 data with $1.3 - 2\%$ uncertainty)**
- **Improved determination of valence-quark distributions at high x free from nuclear corrections, etc by including high Q^2 NC and CC data from HERA II (new ZEUS data)**
- **Dijet cross sections in NC DIS using HERA I+II: further constrain on gluon density**

Backup Slides

Comparison of H1PDF 2009 with H1PDF 2000



- Reduced uncertainties at low x with respect to previous fit (H1PDF 2000)
- Larger (and more realistic) uncertainties at high x (parametrisation uncertainty dominant)

A new QCD fit, ZEUS09 PDF: low Q^2 data with different $\sqrt{s}$

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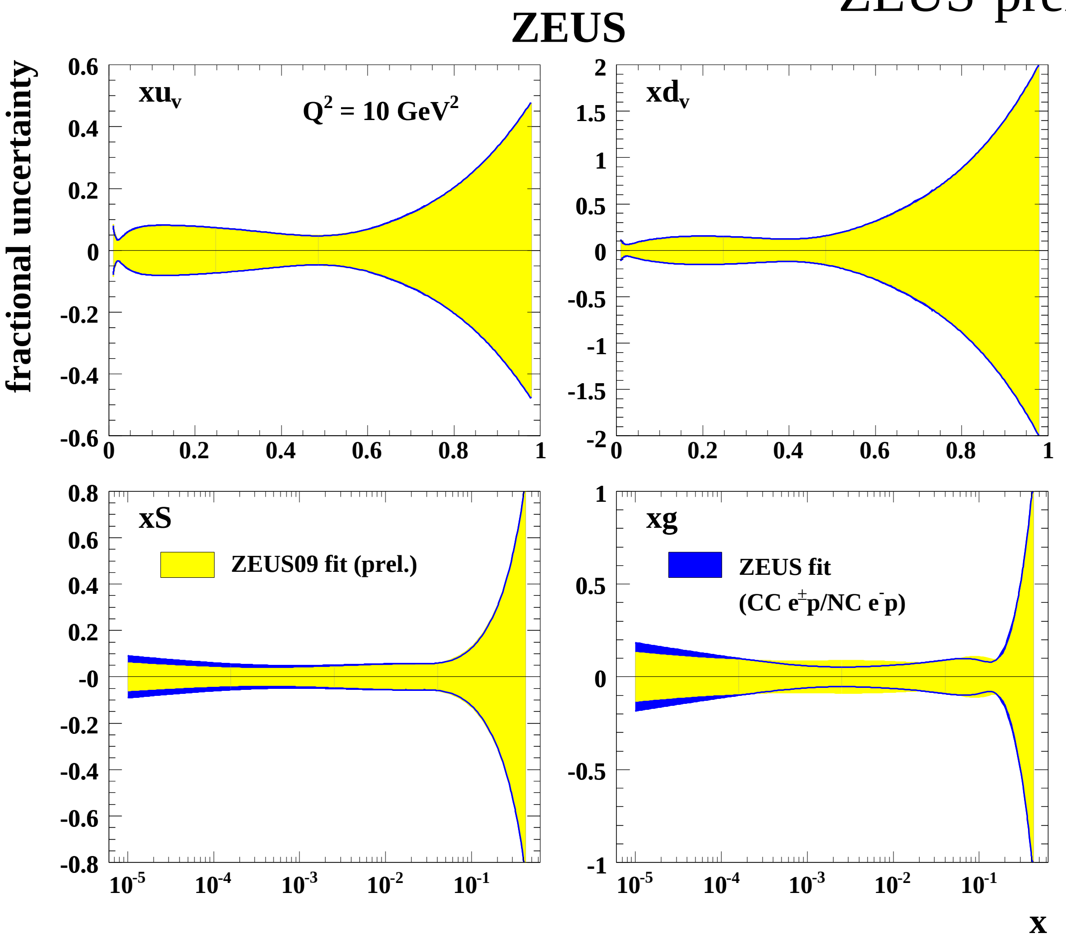
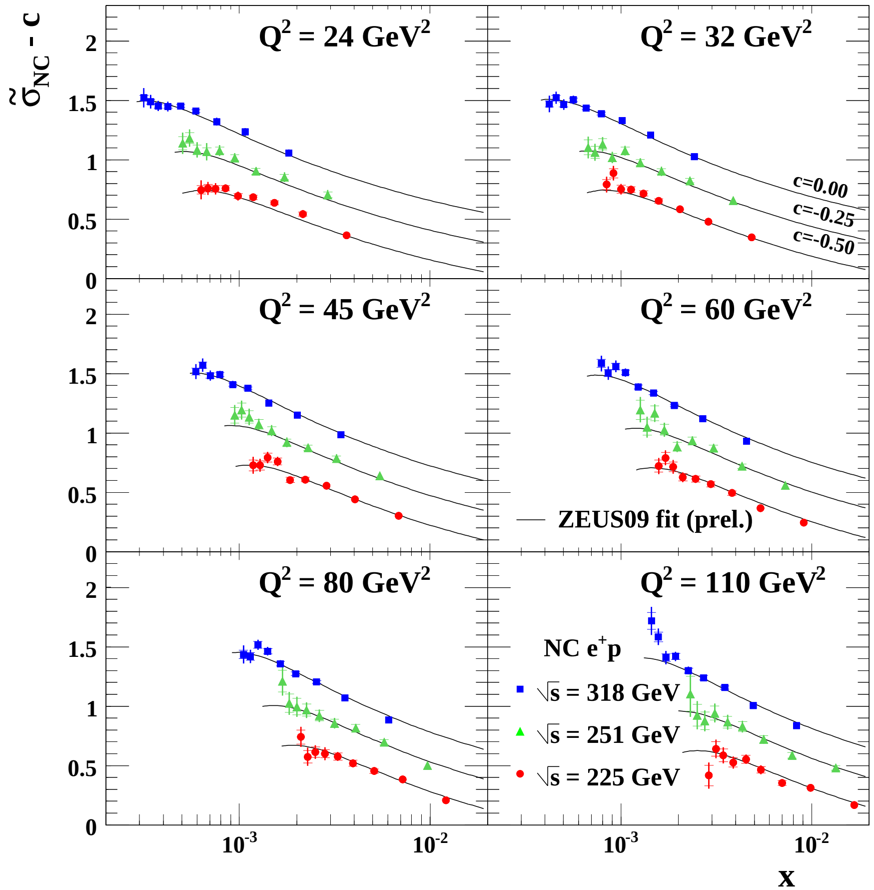


ZEUS



$\longrightarrow$ **Inclusion of Low Q^2 ZEUS NC data with $E_p = 920$, 575 and 460 GeV from HERA II ($\sqrt{s} = 318$, 251 and 225 GeV)$\Rightarrow$ gluon and sea distributions at low x**

(see talk by Burkard Reisert)