ZEUS Parton Distribution Functions
- Addition of Jet Data to ZEUS QCD Fit -

HERA-LHC PDF Working Group

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- Introduction
- Putting Jet Data in the Fit
  - Procedure
  - Results
  - Extrapolation to LHC Scales
- Conclusions and Outlook

ZEUS Parton Density Function Parameterisation

- Each parton momentum distribution is parameterised in x at the starting scale $Q_0^2 = 7$ GeV^2 using an expression of the form:

$$xf(x) = p_1 x^{p_2}(1-x)^{p_3}(1+p_5 x)$$

$\rightarrow$ sensitive to low (p_2), mid (p_5) and high (p_3) x regions

- Parton densities are evolved in Q^2 using the NLO DGLAP equations, and are convoluted with coefficient functions in the Roberts-Thorne Variable Flavour Number scheme

$\rightarrow$ List of parameters is fed to an evaluation function which calculates χ^2 based on the data and theory PDFs

- The following distributions are parameterised:
  - u-valence $xu_v(x)$: $p1u, p2u, p3u, p5u$
  - d-valence $xd_v(x)$: $p1d, p2d, p3d, p5d$
  - total sea $xS(x)$: $p1S, p2S, p3S, p5S$
  - gluon $xg(x)$: $p1g, p2g, p3g, p5g$
  - $x\Delta = x(\bar{d} - \bar{u})$: $p1\Delta, p2\Delta, p3\Delta, p5\Delta$

$\Rightarrow 4 \times 5 = 20$ possible free parameters !

Parameter Constraints

- Fortunately, some parameters can be fixed ...

  Parameter constraints in latest ZEUS-O (94-00) fit:

	u_v	d_v	S	g	Δ
p_1	NO. SUM	NO. SUM	FREE	MOM. SUM	FIXED TO ZEUS-S
p_2	FREE	FIX TO p_2u	FREE	FREE	0.5
p_3	FREE	FREE	FREE	FREE	$p_3S + 2$
p_5	FREE	FREE	FIX TO 0	FREE	FIXED TO 0

$\rightarrow$ p_1u, p_1d are fixed through number sum rules and p_1g through momentum sum rule

$\rightarrow$ $p_2\Delta = 0.5$, $p_3\Delta (= p_3S + 2)$, $p_5\Delta = 0$ as per MRST

$\rightarrow$ p_2u is free BUT $p_2u = p_2d$ for convergence of fit

$\rightarrow$ $p_5S = 0$ (simplifying form of sea) since little information above $x > 0.4$

- ZEUS-O: 94-00 NC & CC DATA FROM ZEUS ONLY

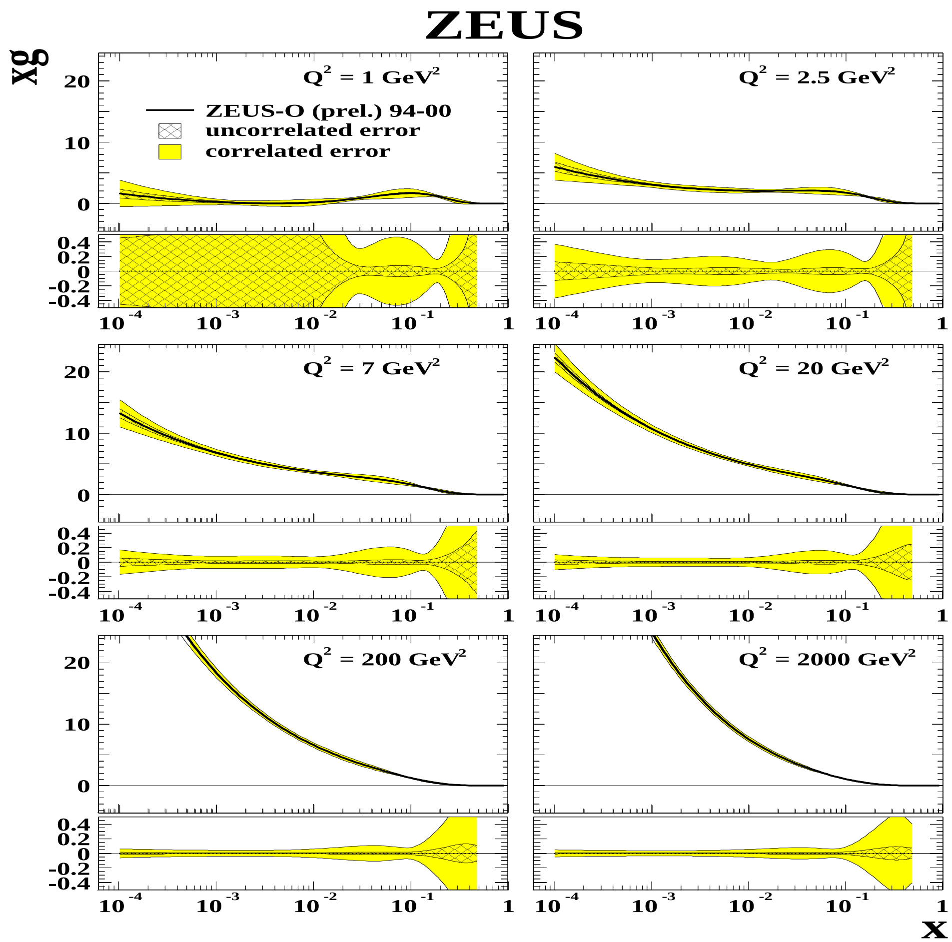
  $\rightarrow$ Uses some input from the ZEUS global (ZEUS-S) fit ($p_1\Delta$)

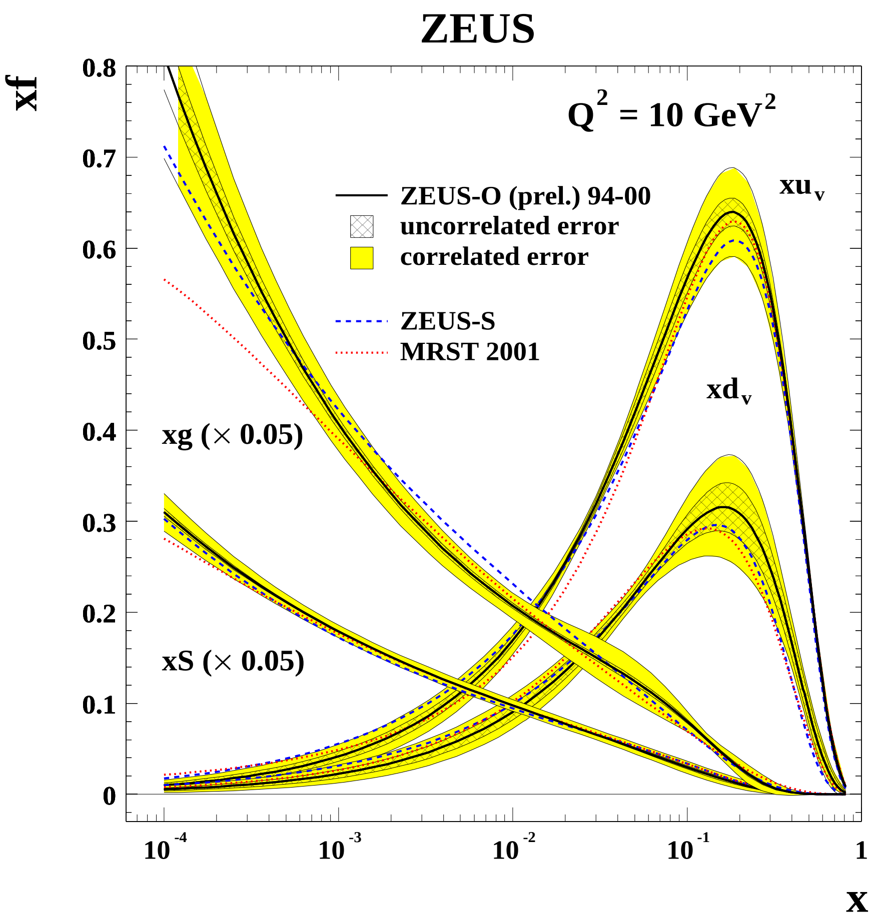
  $\rightarrow$ Valence information comes mainly from high Q^2 NC and CC data

  $\rightarrow$ Low-x sea and gluon comes from HERA F_2 data

  BUT HIGH-x GLUON IS VERY POORLY CONSTRAINED SINCE INFORMATION COMES ONLY FROM MOMENTUM SUM RULE

How Does This Show In The ZEUS-O Fits?





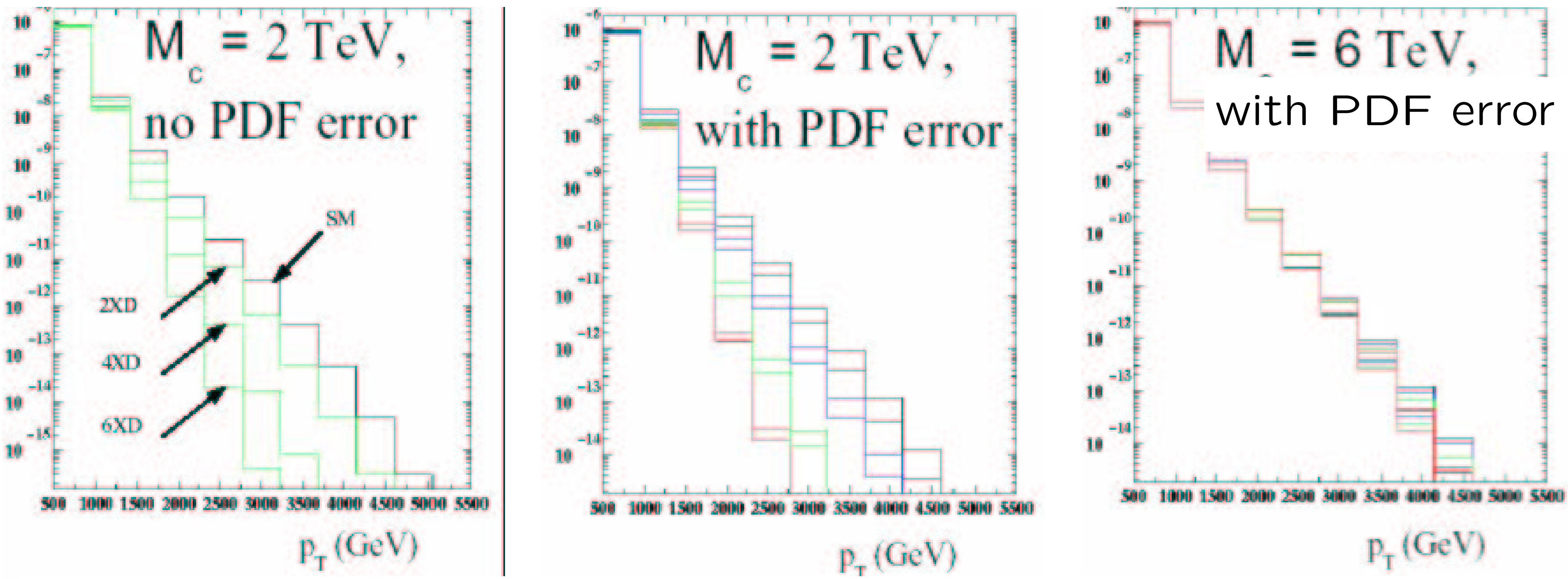
- Mid-to-high x gluon not well constrained

  $\rightarrow$ because there is no data directly sensitive to high-x gluon in ZEUS-O fit

Effect of PDF Uncertainties on LHC Predictions

- Large PDF uncertainties (and in particular the gluon) has potentially serious consequences for the LHC
  → dominant uncertainty in production rates for many processes at LHC

EXAMPLE: Two-jet cross sections at the LHC sensitive to compactification scale of extra dimensions (M_C) :- Ferrag et al.



- Discovery reach reduced from $M_C \sim 5$ TeV → ~ 2 TeV
  → PDF uncertainty comes mainly from large gluon uncertainty at high-x

What Can We Do ?

ADD JET DATA.....

We have added data from two distinct papers (both 1996-1997 data):

- INCLUSIVE JET DEEP INELASTIC SCATTERING
(ZEUS Coll., Phys. Lett. B547 (2002) 164)

  KINEMATIC REGION: $\rightarrow$ $Q^2 > 125$ GeV^2, $E_{\mathrm{T}}^B > 8$ GeV, $-2 < \eta^B < 1.8$
  - 9 cross sections available: differential in Q^2, E_T^B, η^B and double differential in E_T^B in 6 bins of Q^2

- TWO-JET PHOTOPRODUCTION AT HIGH-ET
(ZEUS Coll., Eur. Phys. J C23 (2002) 4)

  KINEMATIC REGION: $\rightarrow$ $Q^2 < 1$ GeV^2, $E_{\mathrm{T}}^{jet1,2} > 14, 11$ GeV, $-1 < \eta^{jet1,2} < 2.4$
  - 12 cross sections available: double differential in E_{T} in 6 bins of $\eta^{jet1,2}$ (and for $x_\gamma < 0.75$ and $x_\gamma > 0.75$)

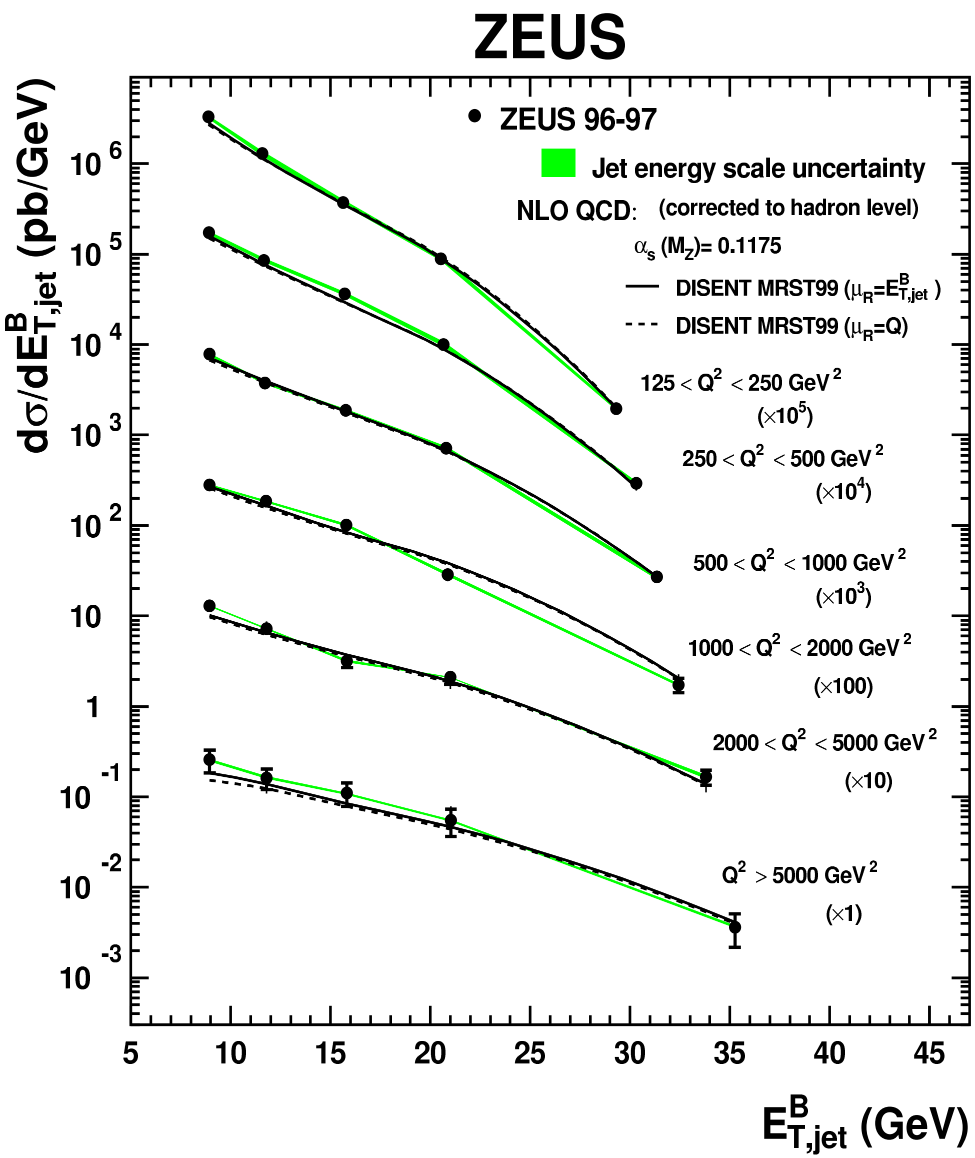
We have made a careful choice of cross sections most suitable for use in the ZEUS QCD fit $\longrightarrow$

Inclusion of Inclusive DIS Jet Data

- INCLUSIVE JET DEEP INELASTIC SCATTERING
  (ZEUS Coll., Phys. Lett. B547 (2002) 164)

  We have chosen to use only the 6 cross sections differential in E_T^B in bins of Q^2. This avoids correlations between cross sections with same events

  30 NEW DATA POINTS $\longrightarrow$

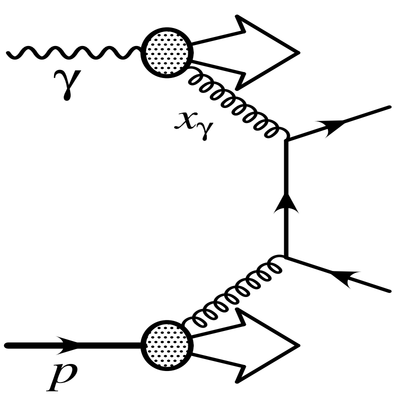


Inclusion of Photoproduction Jet Data

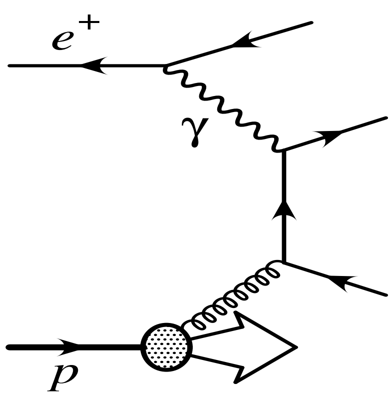
- TWO-JET PHOTOPRODUCTION AT HIGH-ET
  (ZEUS Coll., Eur. Phys. J C23 (2002) 4)

  We have chosen only the 6 cross sections at high x_γ
  (to avoid complications from uncertainty in photon structure)

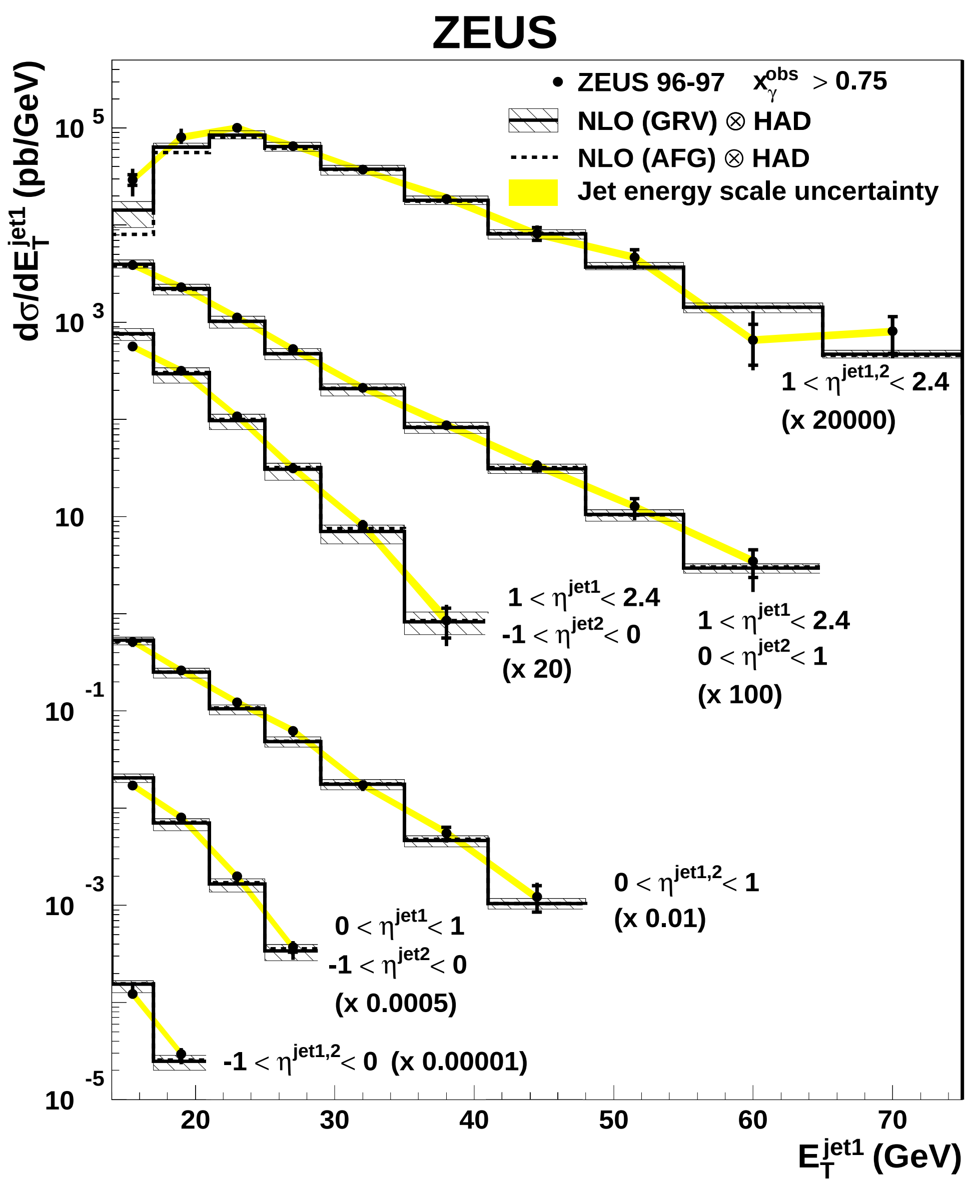
  38 NEW DATA POINTS $\longrightarrow$



$x_\gamma < 0.75$



$x_\gamma > 0.75$



Addition of Jet Data

FIRST STAGE:

- Use NLO program to produce grid (in x, μ_F^2) of weights giving the perturbatively calculable part of cross section

  $\rightarrow$ Each weight is uniquely identified by x, μ_F^2 and σ bins as well as parton ID

INCLUSIVE DEEP INELASTIC SCATTERING JET DATA

$\rightarrow$ NLO PROGRAM: DISENT

- SCALES: $\mu_R = E_{\mathrm{T}}^{jet}$, $\mu_F = Q$

$\rightarrow$ Grids are 200 $\times$ 200 in (x, Q^2)

TWO-JET PHOTOPRODUCTION DATA

$\rightarrow$ NLO PROGRAM: FRIXIONE-RIDOLFI

- SCALES: $\mu_R = \mu_F = E_{\mathrm{T}}/2$ where E_T is summed tranverse energy of final state partons
- PHOTON PDF: AFG-MC PH

$\rightarrow$ Grids are 200 $\times$ 200 in $(x, (E_T/2)^2)$

GRID Reproduction of the NLO Predictions

- We placed on ourselves, the requirement that the cross sections from the NLO programs should be reproducible to within $\sim 1\%$

DIS INCLUSIVE JET CROSS SECTIONS

$\longrightarrow$ All six double differential cross sections are reproducible to within 0.05% !!!

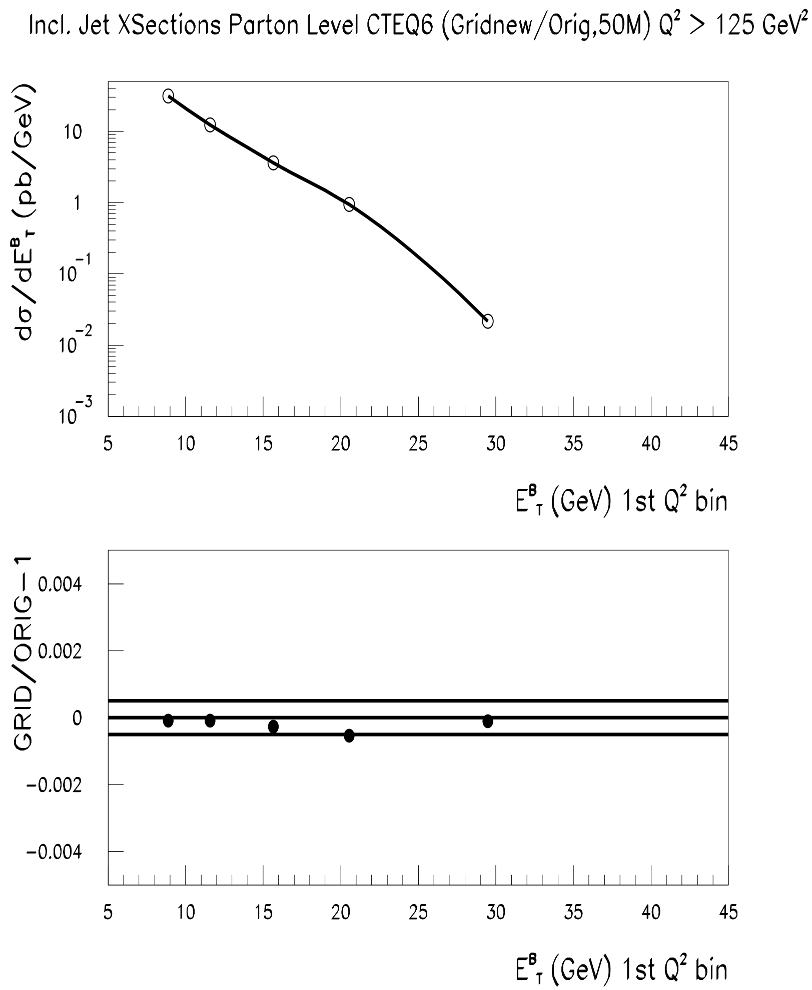
THIS IS A FACTOR OF 20 BETTER THAN WE ORIGINALLY REQUIRED!

Typical example is shown opposite $\longrightarrow$

γp TWO-JET CROSS SECTIONS

$\longrightarrow$ All high-x_γ cross sections reproducible to within $\sim 1\%$ (& usually within 0.5%)

SATISFIES OUR REQUIREMENT



Addition of Jet Data

SECOND STAGE:

- In the QCD fit program, convolute NLO weights with ZEUS PDFs (evaluated using the evolution program QCDNUM) to give predicted cross sections according to:

$$\mathrm{d}\sigma_{\mathrm{jet}} = \Sigma_{a=q,\bar{q},g} \int \mathrm{d}x f_a(x,\mu_F^2) \mathrm{d}\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_F^2) \times (1+\delta_{had})$$

→ where $\hat{\sigma}_a(x,\alpha_s(\mu_R),\mu_F^2)$ is the weight

→ where $f_a(x,\mu_F^2)$ is the PDF for parton a at x and scale μ_F

NOTE that the parton-level predictions were multiplied by the hadronisation corrections quoted in the relevant papers. The inclusive DIS jet cross sections were also multiplied by correction factors for Z^0 exchange.

- Add relevant terms to the χ^2
- Treatment of uncertainties (see "correlated systematics" talk):

→ UNCORRELATED: statistical and uncorrelated systematic

→ CORRELATED: calorimeter energy scale and luminosity determination

Where Might These Data Have An Impact?

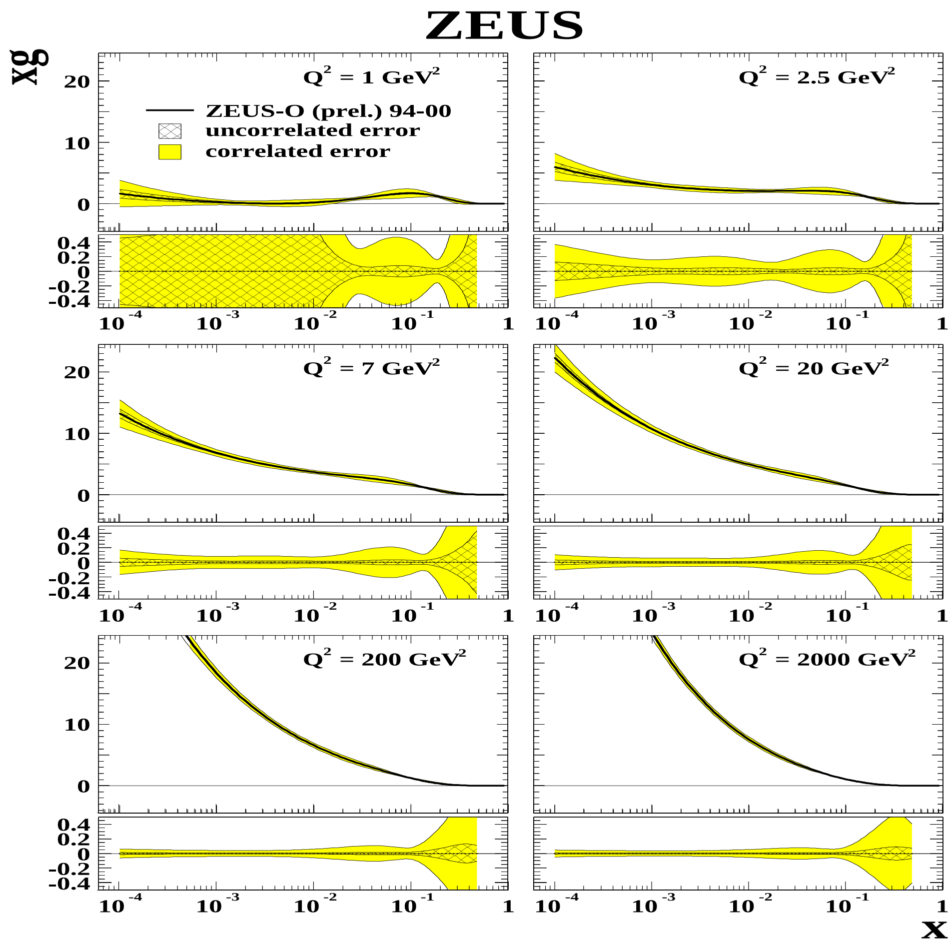
- Both the inclusive jet DIS and the two-jet photoproduction data have Bjorken-x values of $\sim 0.01 - 0.1$
  $\rightarrow$ expect some impact on the mid-to-high-x gluon
  $\rightarrow$ may also expect some impact on the mid-to-high-x sea ?

PARAMETER SUMMARY

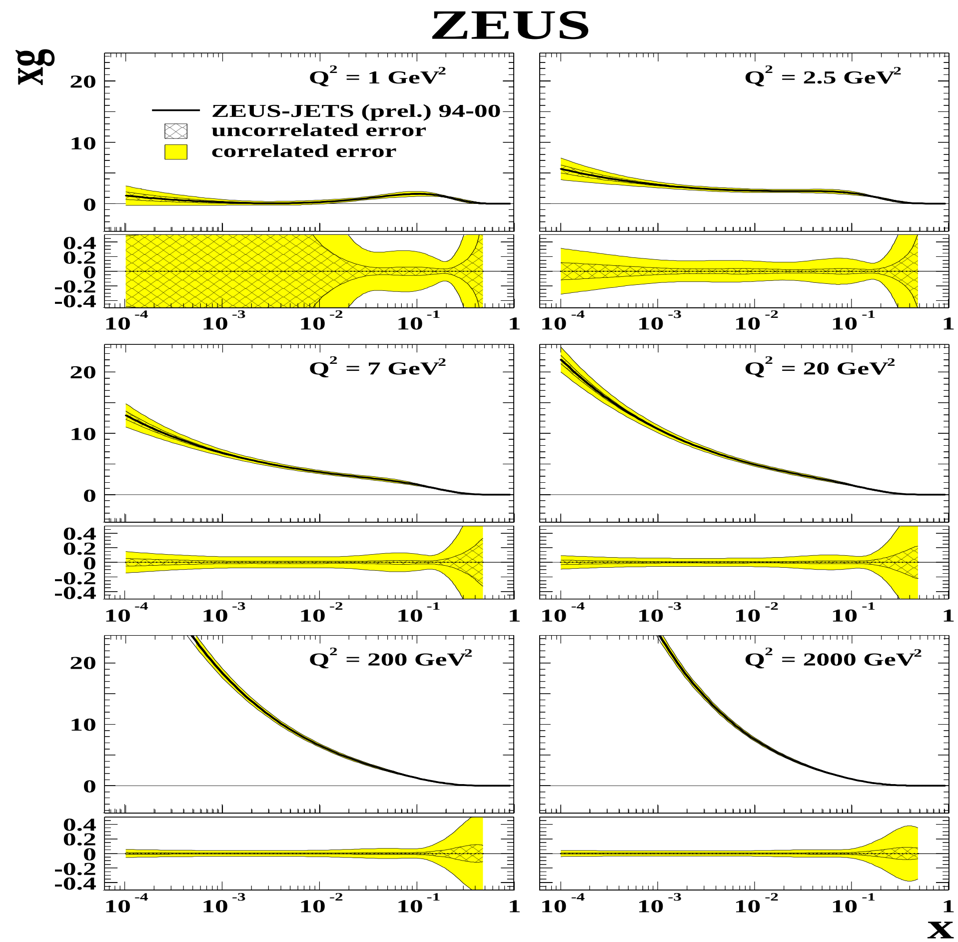
	u_v	d_v	**S**	**g**	Δ
p_1	NO. SUM	NO. SUM	FREE	MOM. SUM	FIXED TO ZEUS-S
p_2	FREE	$p_2 d = p_2 u$	FREE	FREE	0.5
p_3	FREE	FREE	FREE	FREE	$p_3 S + 2$
p_5	FREE	FREE	FIXED $= 0$	FREE	FIXED TO 0

Gluon Distribution

WITHOUT JETS



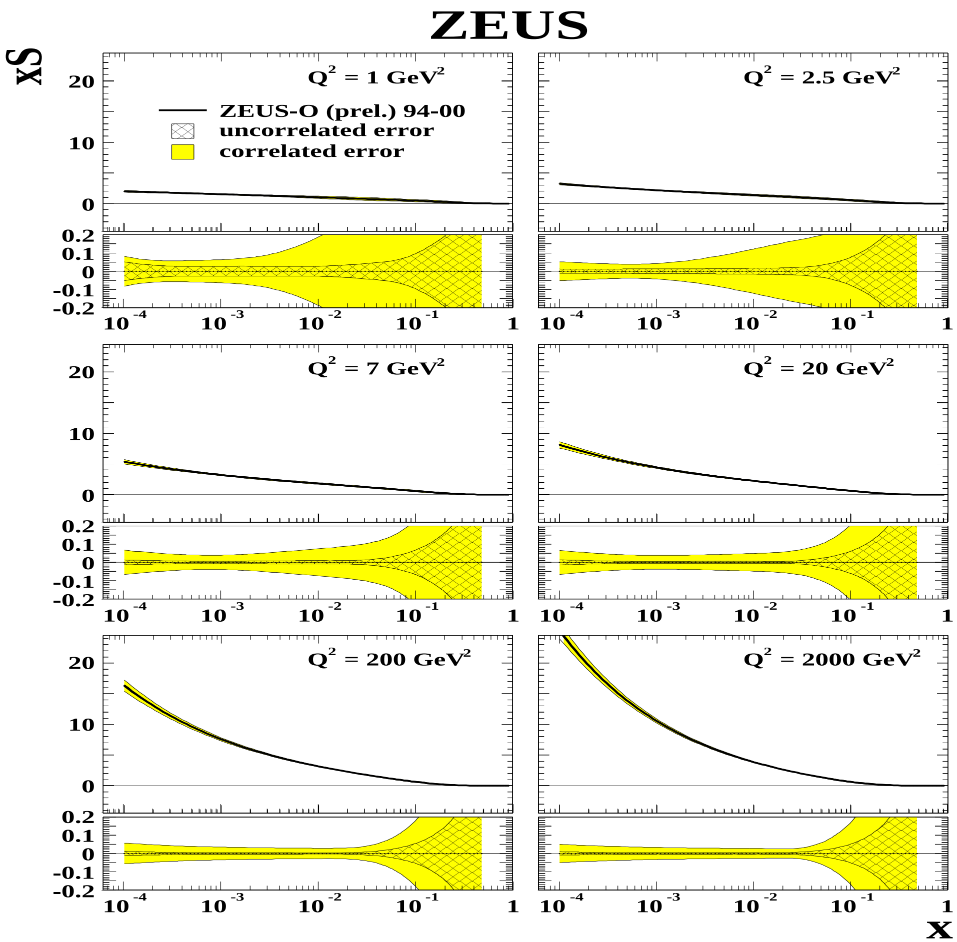
WITH JETS



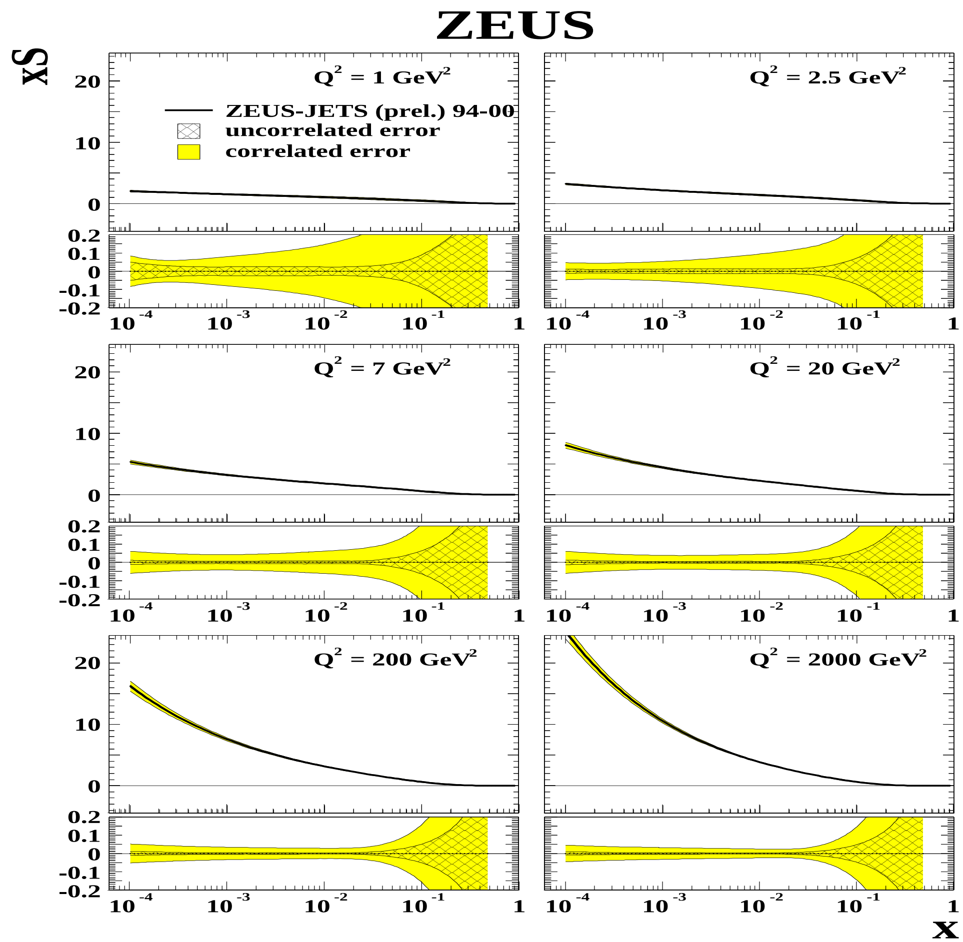
- Significant improvement to constraint on gluon PDF at mid-to-high-x when jet data added!!!

Sea Distribution

WITHOUT JETS



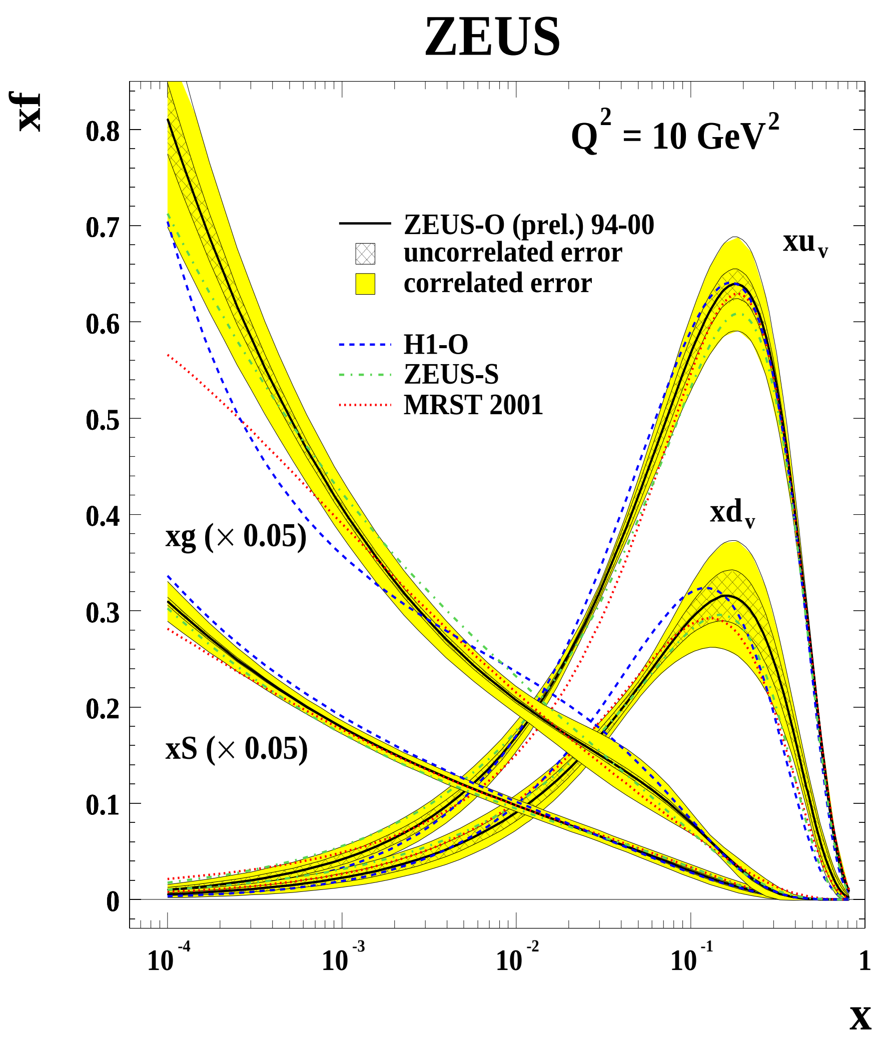
WITH JETS



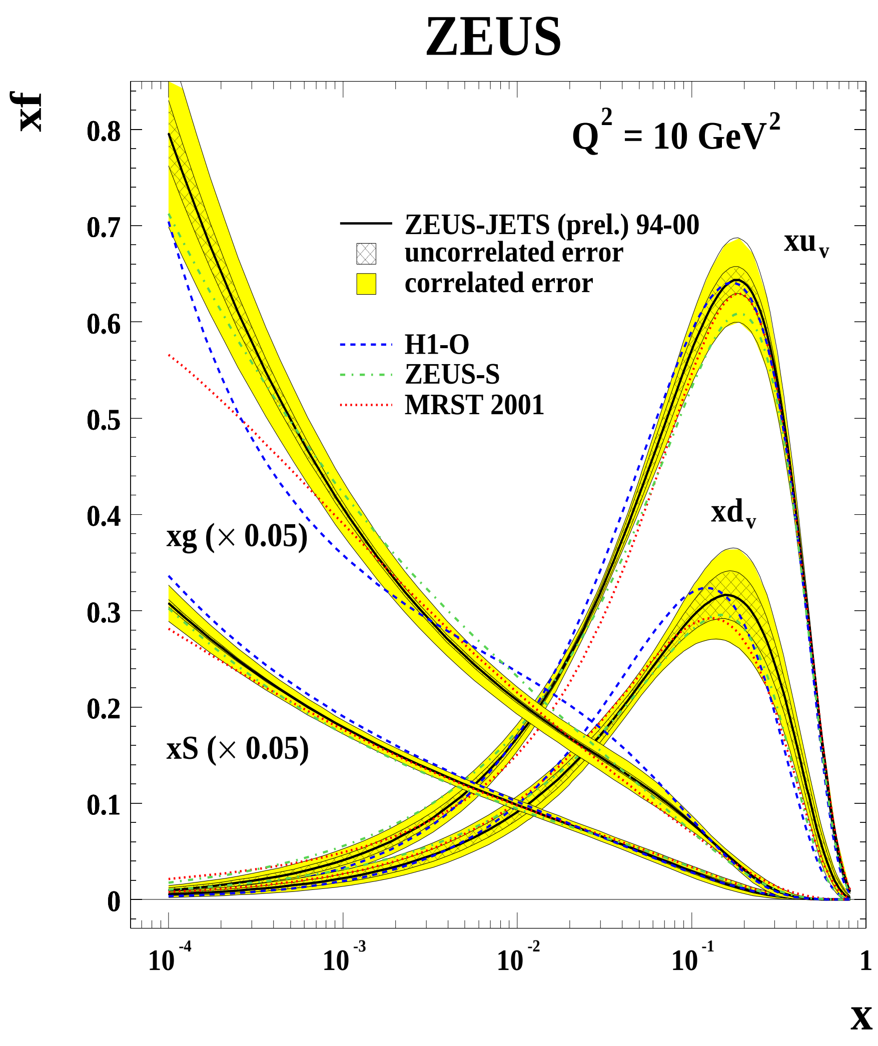
- Some effect on the sea distribution also → only really noticeable at low Q^2

ZEUS Fit - vs MRST/ZEUS-S/H1

WITHOUT JETS

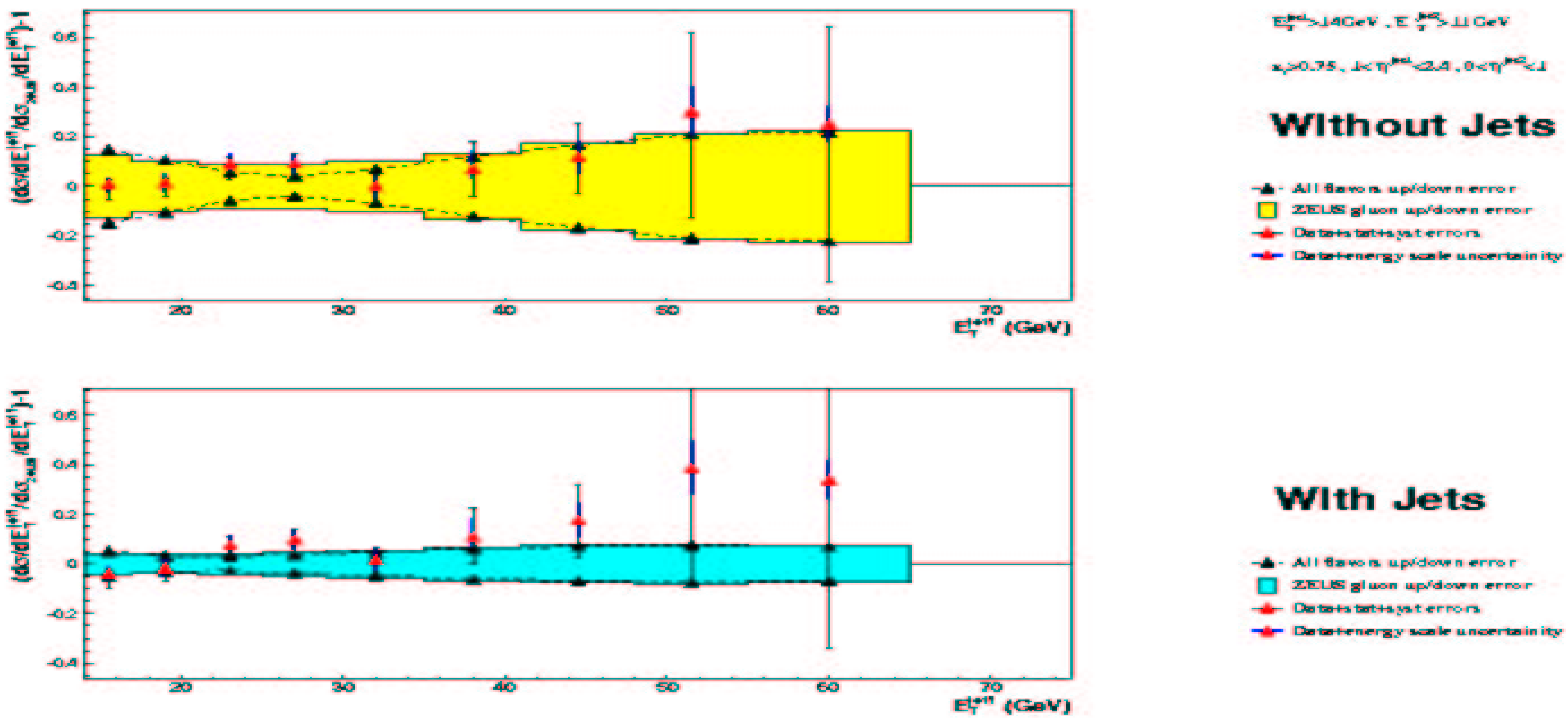


WITH JETS



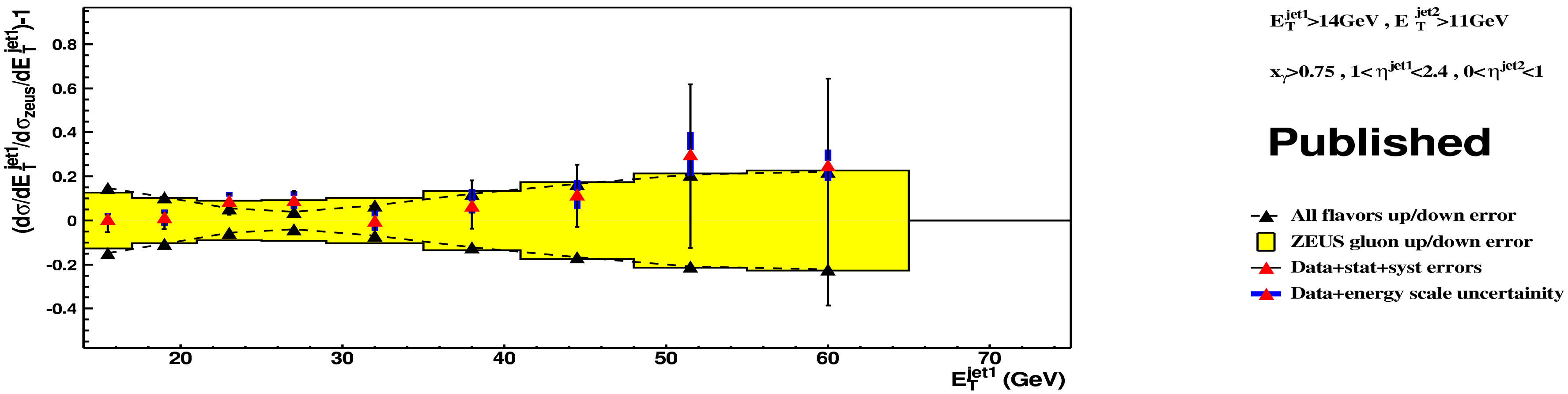
Uncertainty on Cross Section Measurement

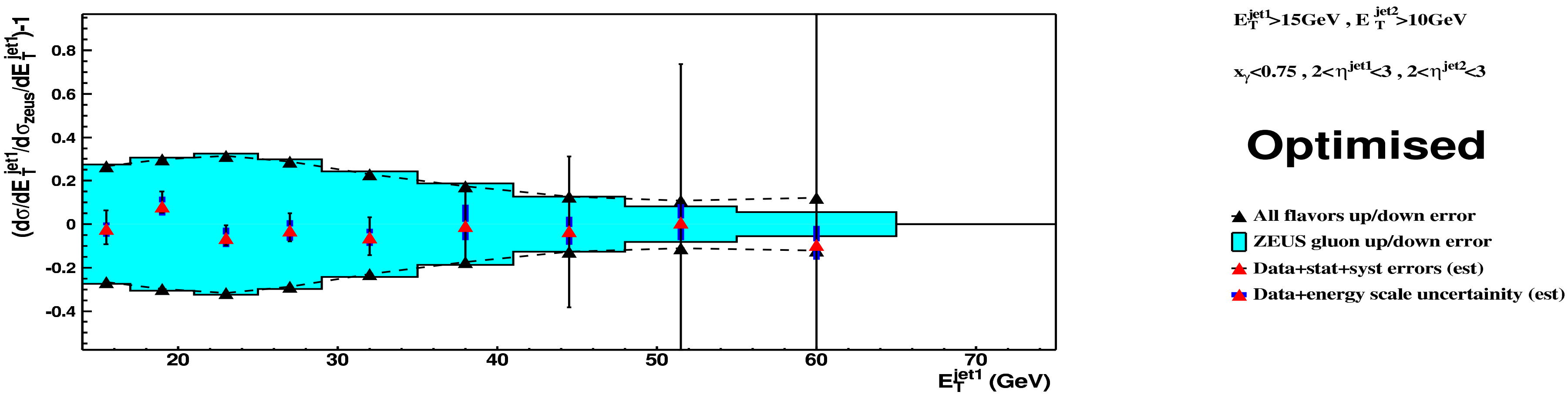
EXAMPLE: $1 < \eta^{jet1} < 2.4$, $0 < \eta^{jet2} < 1$, $x_\gamma > 0.75$



- Prediction for a typical high-E_T two-jet photoproduction cross section included in the ZEUS-JETS fit, from ZEUS-O and ZEUS-JETS PDFs
  → Reduction in uncertainty on cross section (from gluon PDF) is significant !

Potential for Further Improvement

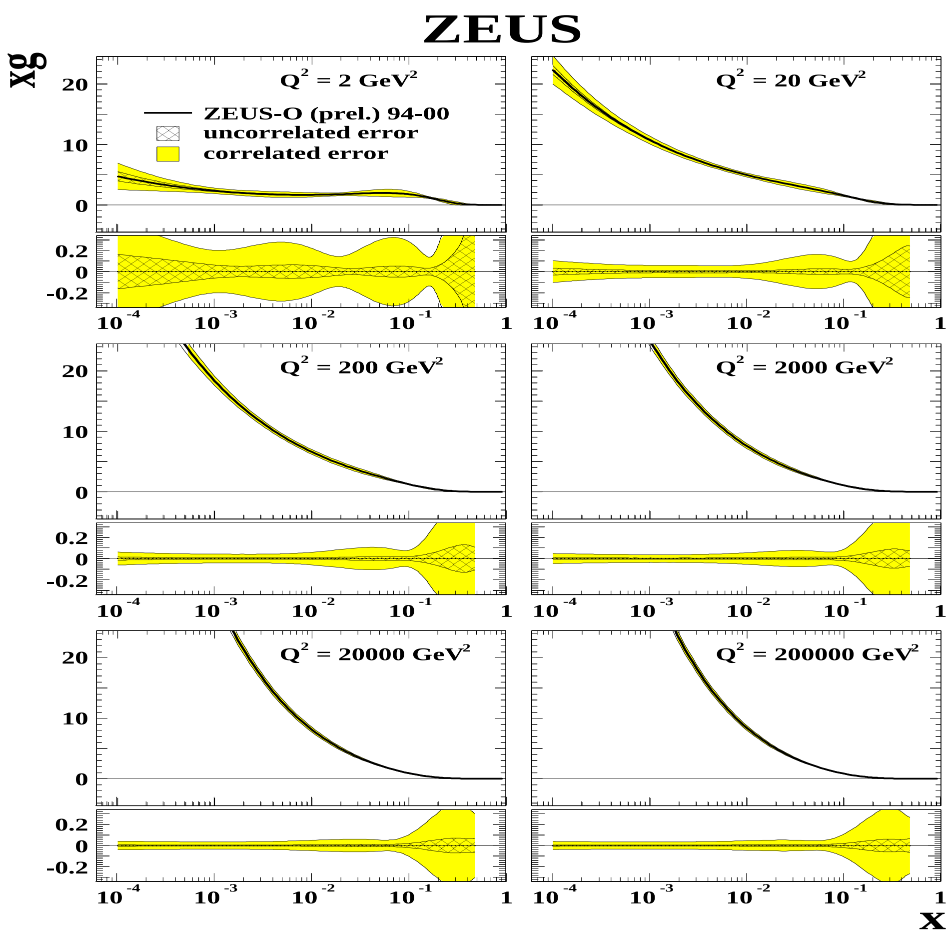




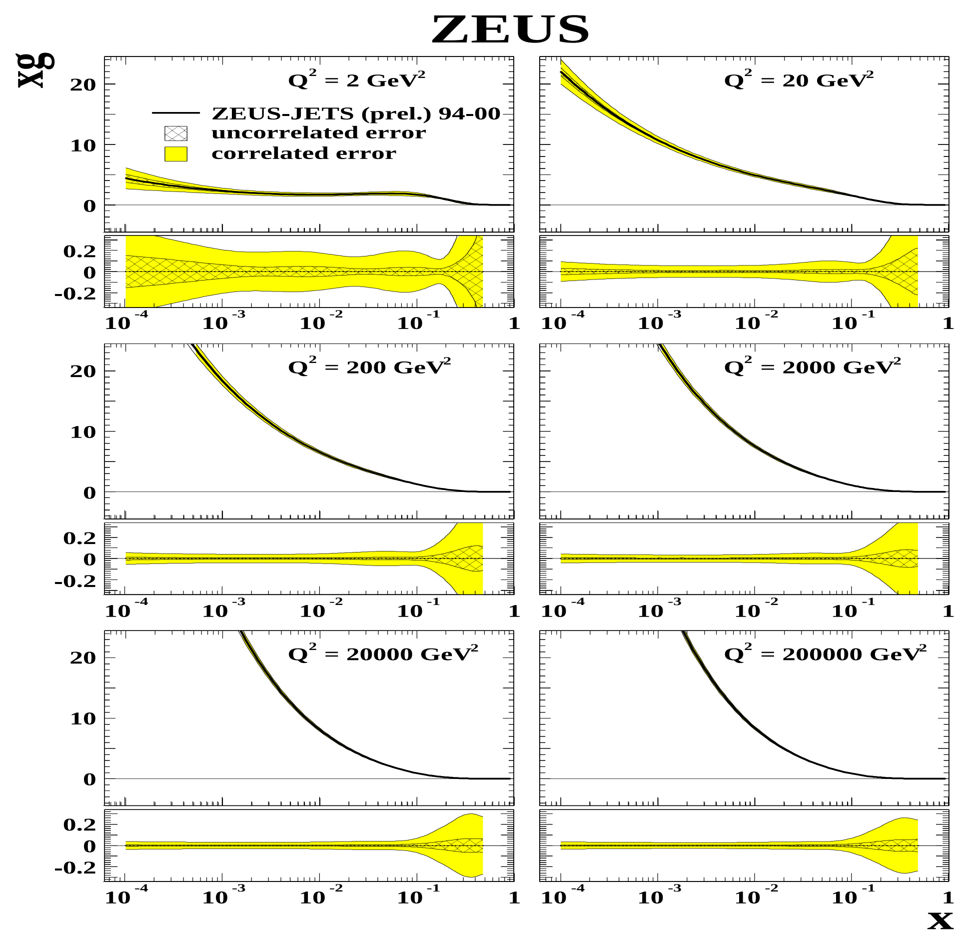
- So far, have only used 1996-1997 data $\rightarrow$ statistically limited at high-E_T (high-x)
- With rest of HERA I and HERA II data, potential to measure cross sections where sensitivity to high-x gluon is significant

Extrapolation to LHC Energies

WITHOUT JETS



WITH JETS



- Uncertainty in high-x (> 0.1) gluon can still be large, even at LHC scales
  $\rightarrow$ dominant uncertainty in production rates for many processes at LHC
- Addition of HERA jet data provides visible improvement even at LHC energies

Conclusions and Outlook

- Jet data from DIS and γp have been added to the ZEUS QCD fit
  - → This is the first time that jet data has been rigorously added in any QCD fit!
  - → The mid-to-high-x gluon is now measured using HERA data, rather than being set only by the momentum sum rule
- Addition of ZEUS jet data constrains high-x gluon significantly (PLUS a visible improvement even at LHC energies)
  - → LHC predictions become less uncertain and things will only get better!!!
- Still many interesting avenues to explore
  - → We still have more HERA I jet data to add
  - → Potential for measurement of optimised cross sections
  - → HERA II DATA !!!
- In principle, this method (modified!) can be used for LHC (and Tevatron !) jet data
  - → Inclusion of LHC high-E_T jet data in QCD fits !!!