Photon and proton structure - overview

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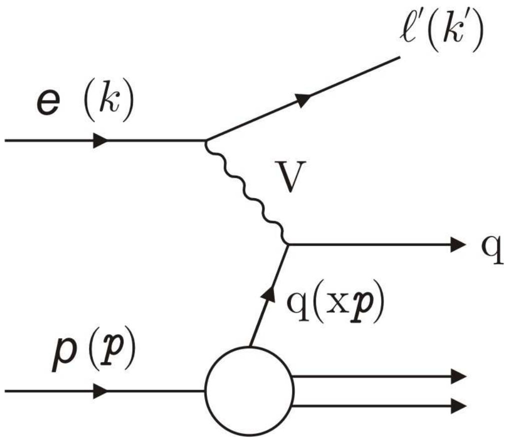
Oxford

- Warsaw to Paris
- Proton PDFs
- Photon PDFs
- Common ground – γp dijets
- Outlook

From Warsaw 2005 to Paris 2007

- Photon2005
  - new photon PDFs (AFG04, CJK, SAL)
  - ZEUS proton PDF fit (F_2 + jets)
  - $F_2(\gamma)$ data from LEP2 (L3)
  - data from HERA
    - CC DIS cross-sections with polarised $e^{+/-}$ beams
    - $F_2(cc)$ & $F_2(bb)$ (H1 using vertex detector impact parameters)
  - NNLO splitting fcns for $F_2(\gamma)$ (Vogt et al)
- Photon2007
  - further LEP2 measurements (leptonic SF from L3, $\gamma^*\gamma \to \bar{b}b$ ALEPH)
  - data from Tevatron Run-II on proton PDF constraints
  - 3 talks on polarised DIS from COMPASS (Stolarski, Reggiani, Schill)
  - promise of complete HERA-II data-sets
  - progress and challenges on theory questions

Deep Inelastic Scattering at HERA



Neutral Current $ep \to eX,\quad$ V= γ or Z^0

Charged Current $ep \to \upsilon X,\quad$ V= $W^{\pm}$

Kinematics

$Q^2 = -(k-k')^2 \qquad x = \dfrac{Q^2}{2p.q} \qquad y = \dfrac{p.q}{p.k} \qquad q = k - k'$

$s = (k+p)^2 \qquad Q^2 = sxy \qquad Y_{\pm} = 1 \pm (1-y)^2$

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

$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2}{4\pi x}\frac{M_W^4}{(Q^2+M_W^2)^2}\left[Y_+ F_2^{CC}(x,Q^2) \mp Y_- xF_3^{CC}(x,Q^2)\right]^{\dagger}$$

$$F_2^{NC} \simeq \sum_i e_i^2 x(q_i + \overline{q}_i) \ \ (\gamma \text{ only}); \quad F_2^{CC} = \sum_i x(q_i + \overline{q}_i); \quad xF_3^{CC} = \sum_i x(q_i - \overline{q}_i)$$

$q_i(x,Q^2)$ - momentum density of quark flavour i in proton

† F_L has been ignored

Proton PDF Q^2 evolution

Parton densities evolve in Q^2 with homogeneous DGLAP eqns

$$\frac{\partial \Sigma}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\left(\Sigma \otimes P_{qq} + g \otimes P_{qg}\right)$$

$$\frac{\partial g}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\left(\Sigma \otimes P_{gq} + g \otimes P_{gg}\right)$$

$$\frac{\partial q_f^{NS}}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} q^{NS} \otimes P_{qq}$$

PDFs related to physical quantities by coefficient functions

$$\frac{F_2(x,Q^2)}{x} = \sum_f e_f^2 q_f \otimes C_f + \overline{e}^2 g \otimes C_g$$

various factorisation schemes, most popular now is $\overline{\text{MS}}$

- P_{ij} and C_i given by QCD, now to NNLO

- $xf(x,Q_0^2) = p_1 x^{p_2}(1-x)^{p_3}(1+p_4 x)$, typical PDF parameterisation at Q_0^2

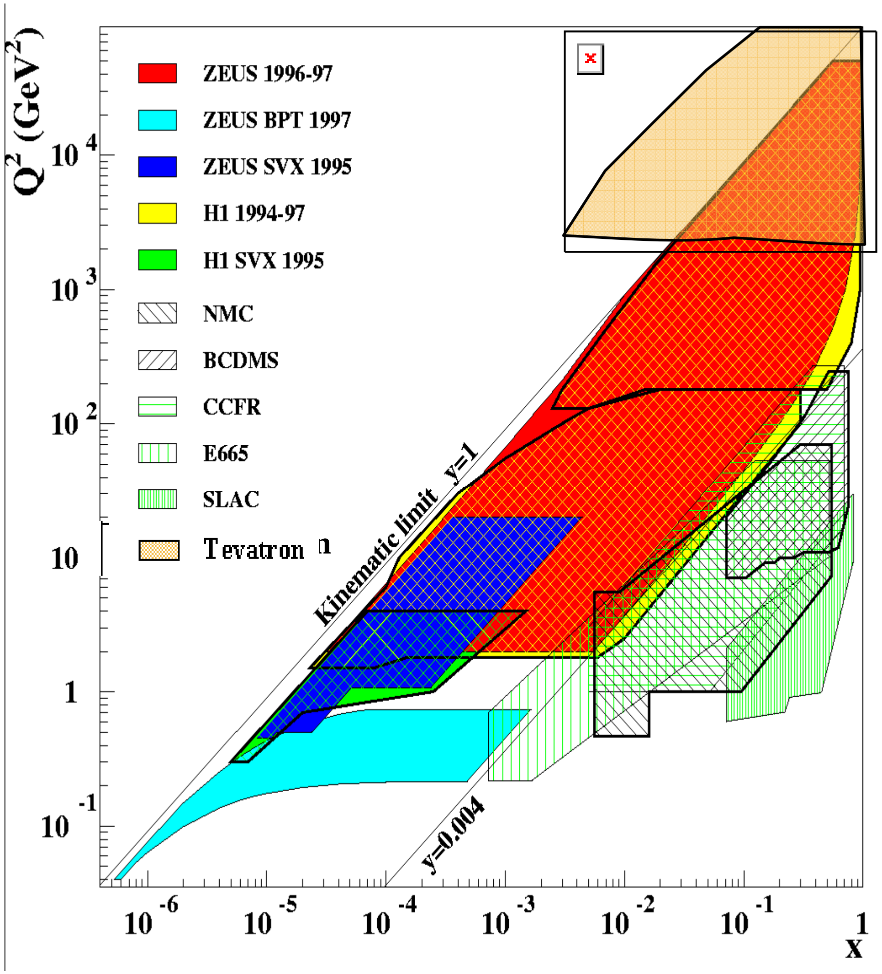
For a global fit, using sum-rule constraints, ~12 free parameters

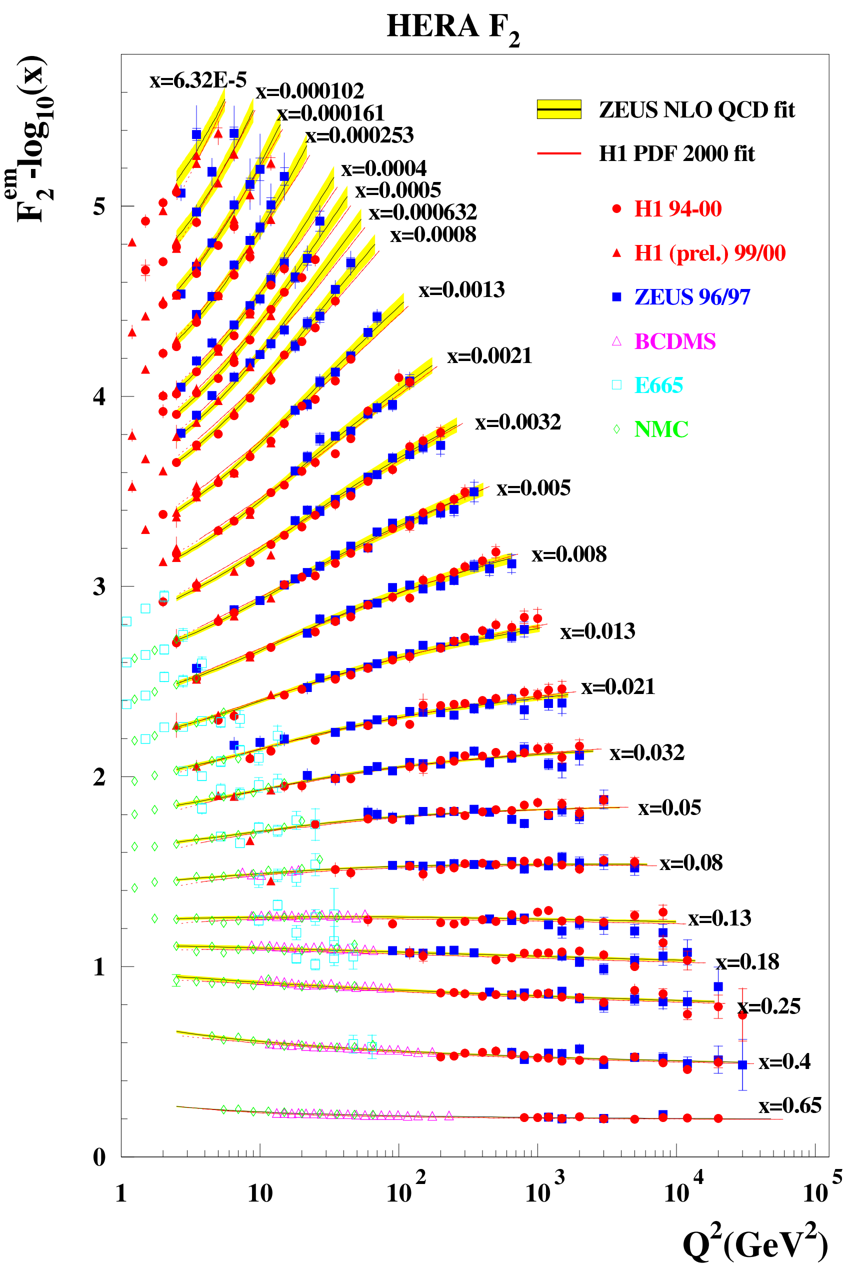
Data for proton structure

- deep inelastic scattering
  - fixed target
  - HERA
- jets (ep, γp, $\bar{p}$p)
- $\bar{p}p \to W^{\pm}X,\ Z^0 X$
  - leptonic decay asymmetries
- heavy flavour
  - ep $\to$ eQ$\bar{Q}$X (γ-g fusion)

Talks by
Kupco – Tevatron jets
Lancaster – W, Z

Perez
Overview of proton PDFs





F_2^p data

HERA

E_e 27.5, E_p 920 (820) GeV

Physics luminosity:

HERA-I (1992 – 2000)
~ 140 pb^{-1} (mainly e^+p)

HERA-II (2003 – 2007)
~ 400 pb^{-1} (e+/-, P+/-)
21 pb^{-1} (E_p 460, 575 GeV)

(2005 only 140 pb^{-1})

← now probing large x and Q^2

getting at the glue in the proton - g^p

- Scaling violations $\dfrac{\partial F_2}{\partial \ln Q^2} \sim xg$

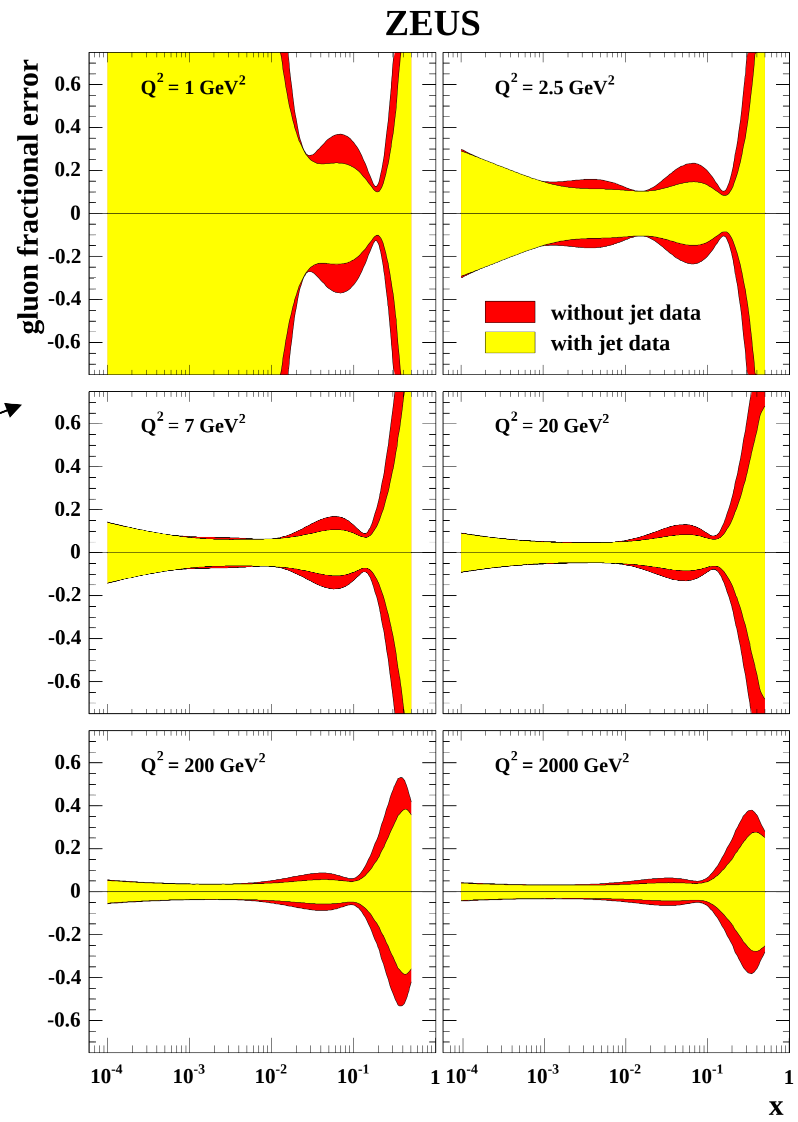
particularly at low x

- jet data (ep, γp, p$\bar{\text{p}}$)

- example from ZEUS-jets fit

constraint at larger x

- heavy flavour production (?)

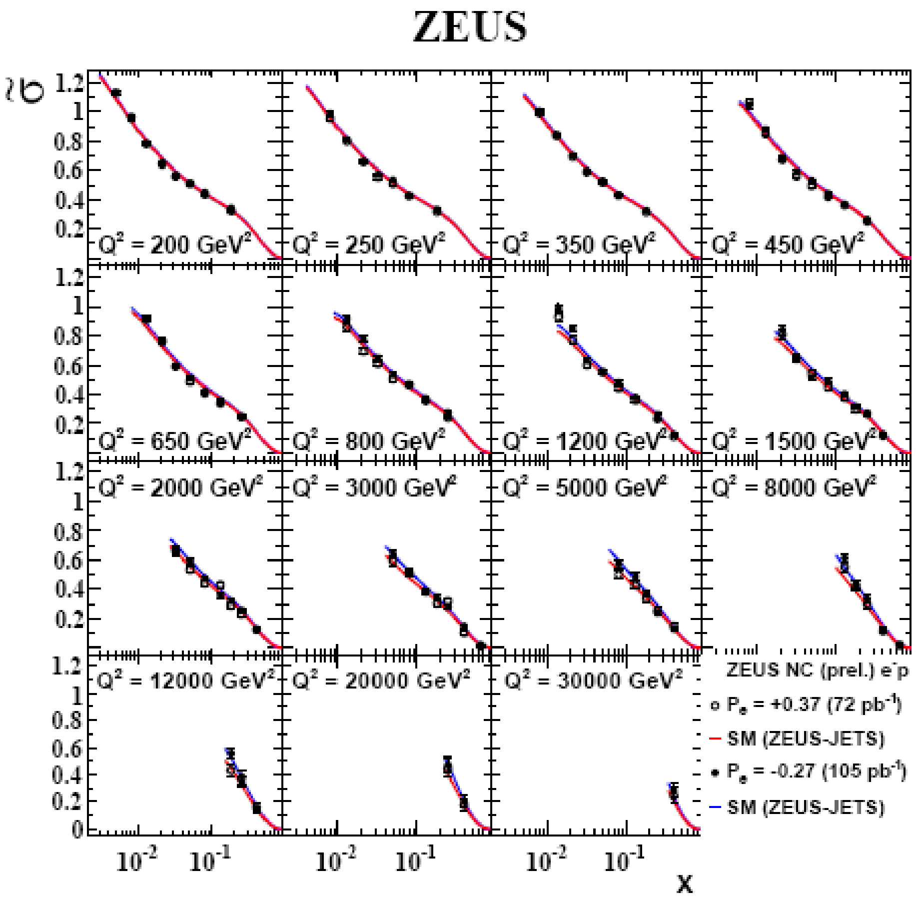


see also talk by Jiminez

New data from HERA-II

- Quick look at
  - high Q^2 NC cross-sections
  - high y cross-sections
  - charm production

Reduced cross section for polarised electrons



$$\tilde{\sigma}^{\pm} = F_2(x,Q^2) \mp \frac{Y_-}{Y_+} \cdot x F_3(x,Q^2)$$

$$F_2(x,Q^2) = F_2^{\gamma} + P_e a_e \chi_Z F_2^{\gamma Z}$$

P⁻ (L) > P⁺ (R) **(a_e = -0.5)**

Measured cross sections are in good agreement with SM predictions over whole kinematic region

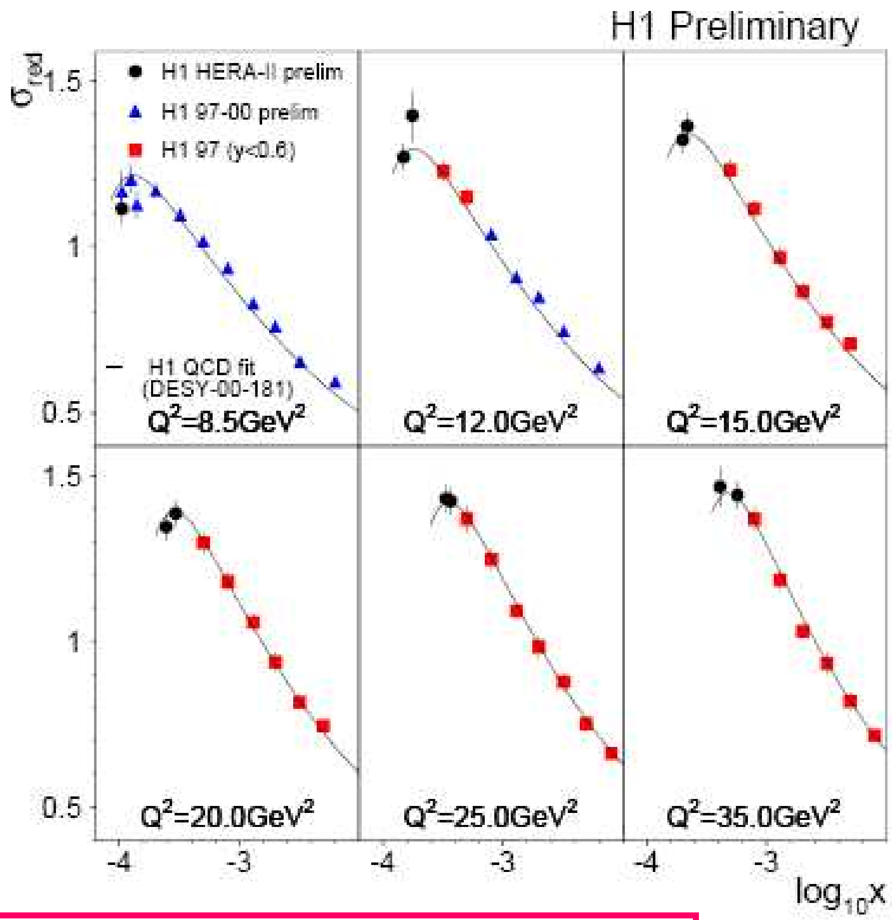
e⁻ (R) ~ 71.8 pb-1 @ Pe ~ +29.7 %
e⁻ (L) ~ 105.4 pb-1 @ Pe ~ -27.0 %

Sampa Bhadra, DIS2007 11

ZEUS Preliminary

details in talk by Petrukin

H1 – σ_r at high y



N. Raicevic DIS 2007, 16-20 April, 2007

$$\sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

- HERA-II data points

based on 96pb^{-1}

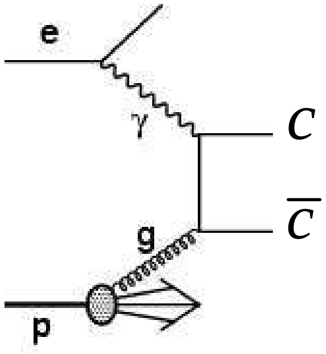
$Q^2 = sxy$

so, for fixed s and Q^2

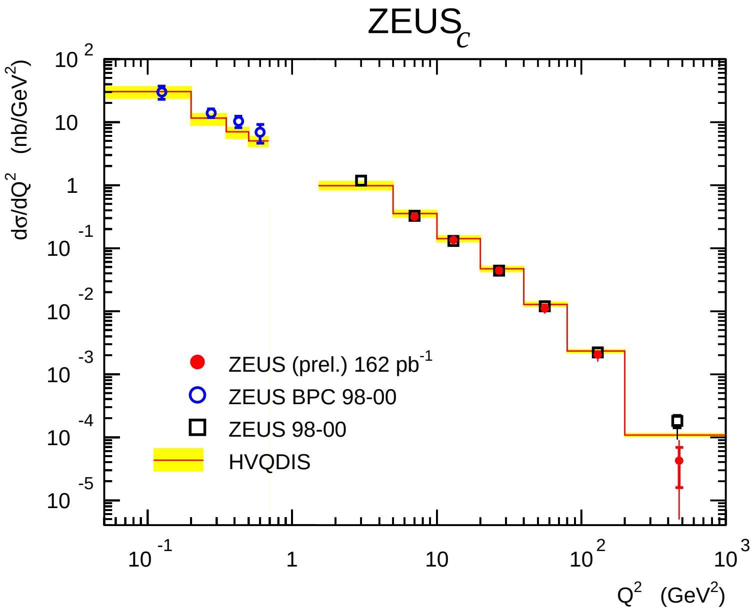
high y $\leftrightarrow$ low x

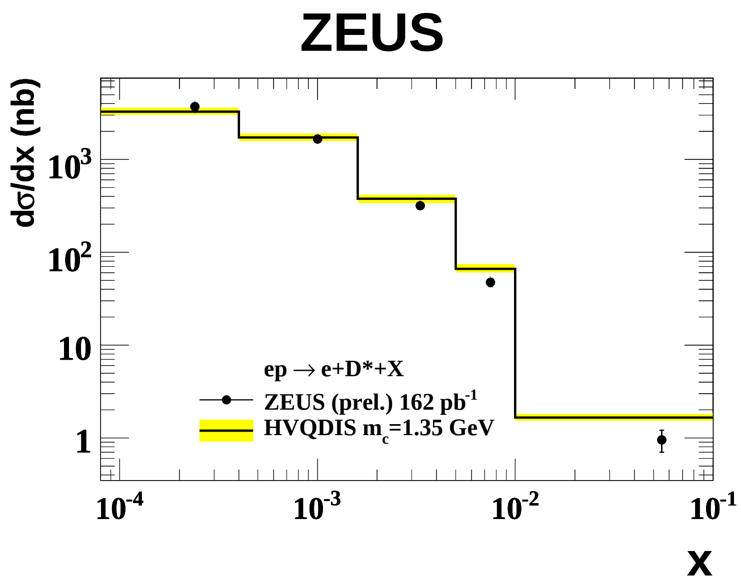
'Warm up' for F_L

g^p from charm production in DIS



- dominant process is photon-gluon fusion
- NLO calculation for cross-sections – HVQDIS
- HERA data not yet used directly in PDF determination but agreement using HERA gluons is good
- HVQDIS requires FFNS – work needs to be done to reconcile this with high Q^2 ZM-VFNS





see also talk by Boenig

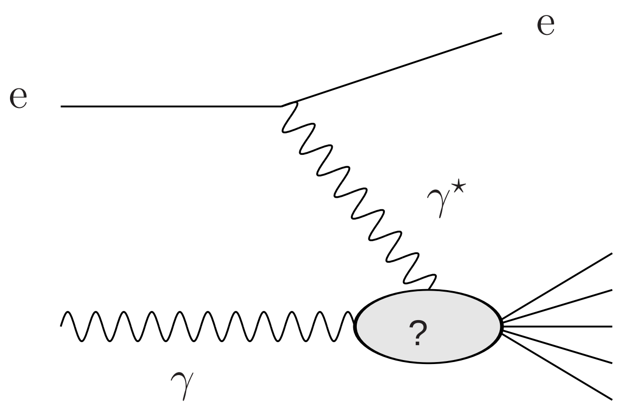
Summary on proton PDFs

- Principal players are:

  H1, ZEUS, CTEQ, MSTW (MRST), Alekhin
- Sophisticated methods for handling experimental uncertainties
- Still a lot of HERA-II data to come (high x and Q^2)
- Combined QCD-EW fits (talk by Stella)
- Work on combining the H1 and ZEUS data (F_2 and other data) is underway – smaller overall errors and the definitive HERA PDFs

  (some early ideas in the HERA-LHC workshop)
- More high precision data from the Tevatron to come
- NNLO for the inclusive processes already in use
- More work to be done on including more jet data and charm(?) to help constrain the gluon (and on NNLO calculations)
- For details, Emmanuelle Perez later in this session

$\gamma^*\gamma$ to X -- DIS on a photon target



Similar variables to proton DIS -

x, y, Q^2 - but more difficult to measure

$$Q^2 = 2E_{beam}E_{tag}(1-\cos\theta_{tag})$$

$$x = \frac{Q^2}{Q^2+W^2}, \quad W^2 = \left(\sum_i p_i^{hads}\right)^2$$

$$y = 1 - \frac{E_{tag}}{E_{beam}}\cos^2\left(\frac{\theta}{2}\right)$$

$$\frac{d^3\sigma}{dxdydQ^2} = \frac{2\pi\alpha^2}{Q^4x}\left[Y_+F_2^\gamma(x,Q^2) - y^2F_L^\gamma(x,Q^2)\right]\Phi_\gamma(x,y)$$

Φ_γ is the flux of photons radiated by the untagged beam electron

since $y \ll 1$, the contribution of F_L^γ is neglected

photon PDF Q^2 evolution

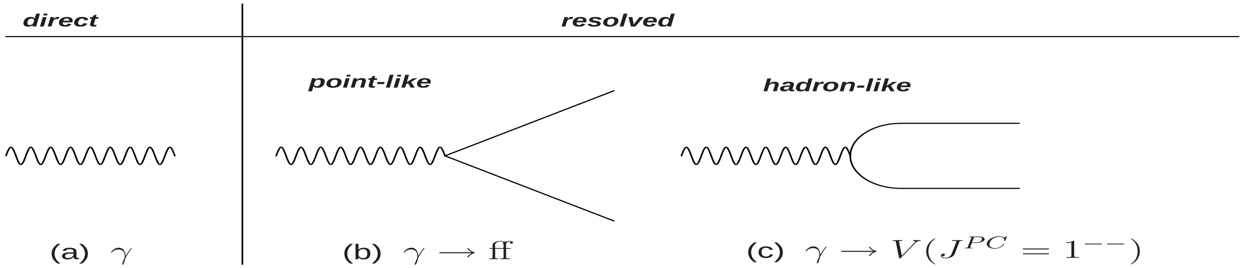


diagram from Nisius Phys. Rep.

Parton densities evolve in Q^2 with inhomogeneous DGLAP eqns

$$\frac{\partial \Sigma^\gamma}{\partial \ln Q^2} = k_q + \frac{\alpha_s}{2\pi}\left(\Sigma^\gamma \otimes P_{qq} + g^\gamma \otimes P_{qg}\right)$$

$$\frac{\partial g^\gamma}{\partial \ln Q^2} = k_g + \frac{\alpha_s}{2\pi}\left(\Sigma^\gamma \otimes P_{gq} + g^\gamma \otimes P_{gg}\right)$$

$$\frac{\partial q_f^{NS}}{\partial \ln Q^2} = \sigma_f^{NS} k_q + \frac{\alpha_s}{2\pi} q^{NS} \otimes P_{qq}, \quad \sigma_f^{NS} = (e_f^2 - 1)/n_f$$

P_{ij} and k_i calculated from QCD & QED - P_{ij} to NNLO (Vogt et al 2005)

Sasaki this session

photon PDFs

- PDFs related to physical quantities by coefficient functions

$$\frac{F_2^\gamma(x,Q^2)}{x} = \sum_f e_f^2 q_f \otimes C_f + \bar{e}^2 g^\gamma \otimes C_g + C_\gamma$$ (C_γ is the direct photon term)

various factorisation schemes, $\overline{\mathrm{MS}}$ and DIS_γ

- PDFs parameterised using a 'valence like' functional form

$$xf^\gamma(x,Q_0^2) \sim x^a(1-x)^b$$ (a, b are fit parameters)

using VMD connection $f^\gamma = \kappa \frac{4\pi\alpha}{\mathrm{f}_\rho^2} f^\pi$, with κ determined from the fit

- Number of free parameters in 'global photon' fit in range 2 - 6
  far fewer than for proton, but then much less data

Data for photon structure

- inclusive $e^+e^- \to e^+e^- X$
  - $\gamma^*\gamma \to X$
  - PETRA, TRISTAN, LEP
- jets $\gamma p \to jjX$ (HERA)
- Other possibilities
  - $\gamma^*\gamma \to jjX$ (LEP)
  - $\gamma^*\gamma \to \gamma jX$ (LEP)
  - $\gamma^*\gamma \to Q\bar{Q}X$ (LEP)
  - $\gamma p \to \gamma jX$ (HERA)
  - $\gamma p \to c\bar{c}X$ (HERA)

- Note that access to small x_γ is limited

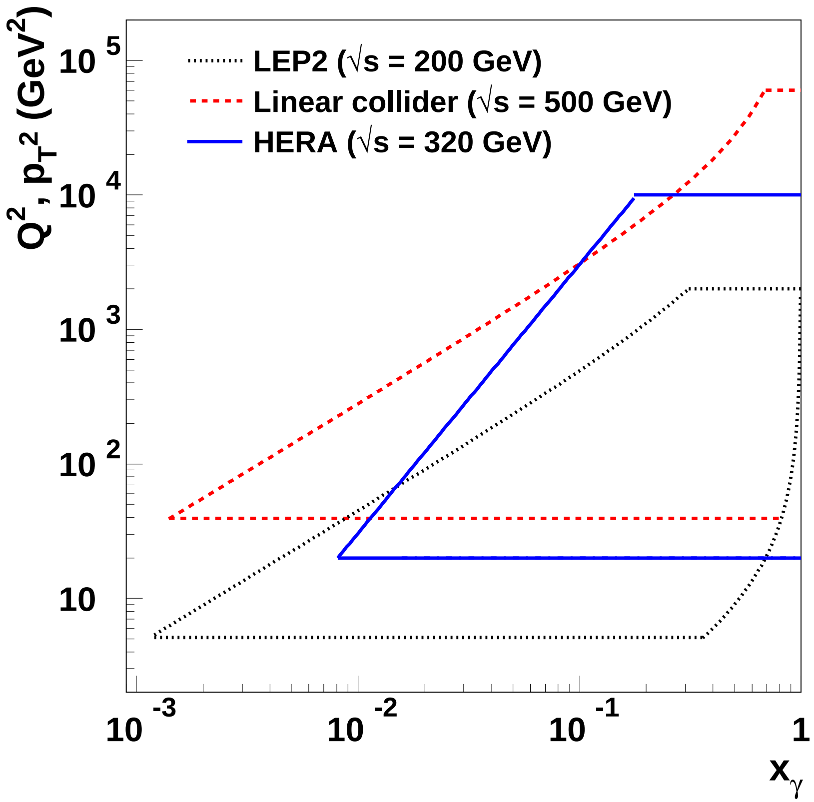


diagram from Butterworth & Wing, Rep. Prog. Phys.

F_2^γ data

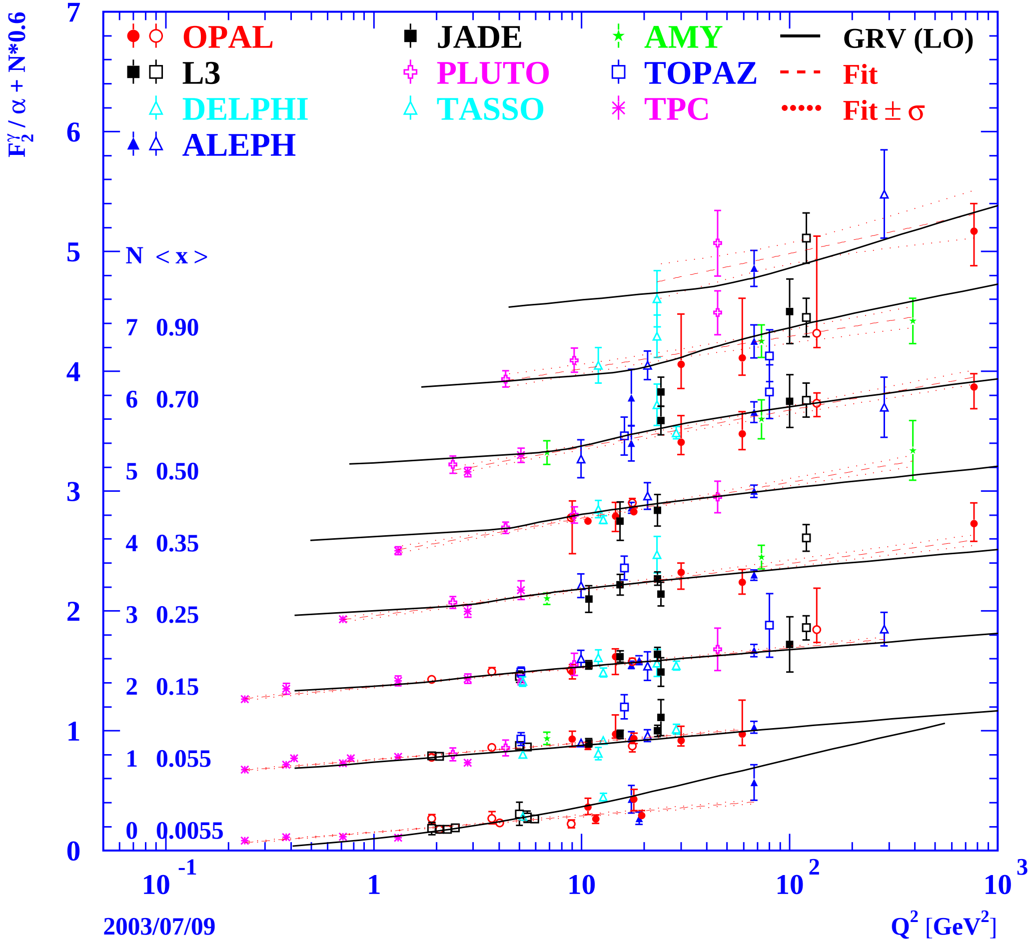


figure from Nisius, Phys. Rep.

Difficult !

Compare $F_2(p)$ on p6:

- lower precision

- smaller range in $\ln Q^2$

but

Provides the dominant input for photon PDF determination

Photon PDFs

- New at time of PHOTON2005
  - almost all LEP data and improved heavy flavour treatments
- AFG04 (update of AFG-HO 1994) Aurenche, Fontannaz, Guillet
  - $F_2(\gamma)$ data from PETRA, TRISTAN and LEP
- CJK04 Cornet, Jankowski, Krawczyk
  - $F_2(\gamma)$ data from PETRA, TRISTAN and LEP
  - checks on compatibility of LEP data
  - different gluon
- SAL – perhaps the most ambitious Slominski, Abramowicz, Levy
  - $F_2(\gamma)$ data from PETRA, TRISTAN and LEP
  - HERA dijet photoproduction, and low x $F_2(\gamma)$ from Gribov factorisation

- Older GRV-HO (1992) and AFG-HO, still in use
  - did not use LEP data

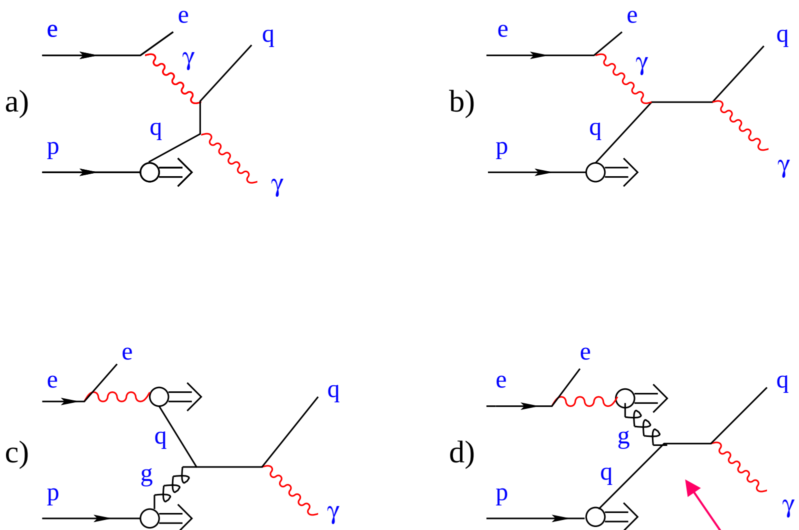
Other processes for photon PDFs

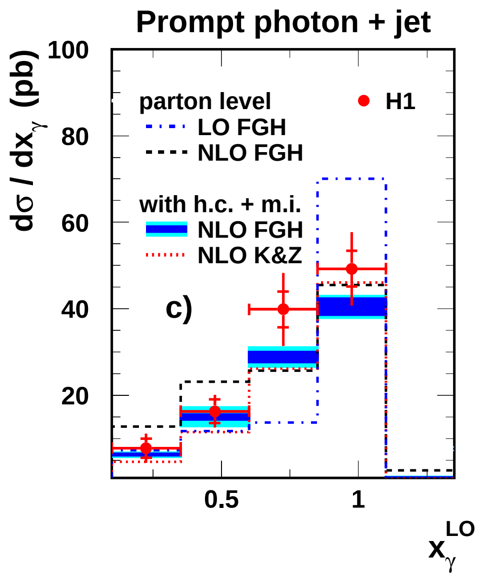
- Other processes with jets and/or hard FS photons
  - $\gamma p \to \gamma jX$ (perhaps for the future)
  - $\gamma p \to jjX$ (more on this - again)
  - talk by Grindhammer on HERA processes

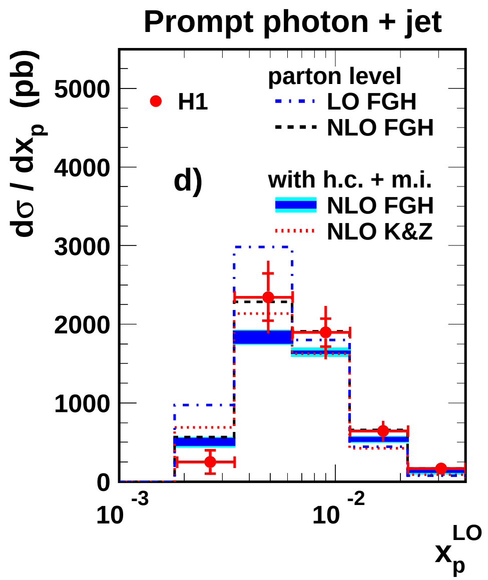
- getting at the photon glue
  - $F_2(\gamma)$ scaling violations – lack of data at low x and small $\ln Q^2$ range
    also masked by scaling violation of pointlike $\gamma \to q\bar{q}$ term
  - $\gamma^* \gamma \to \bar{b}b$ (LEP) talk by Finch (generated a lot of discussion!)
    also reference in his talk to LEP $\gamma^* \gamma \to \bar{c}c$ (experiments agree with each other and with NLO calculation) – sensitivity to photon PDF
    probably masked by uncertainty in charm mass.

γp to γjX - H1

HERA-I 109 pb^{-1}





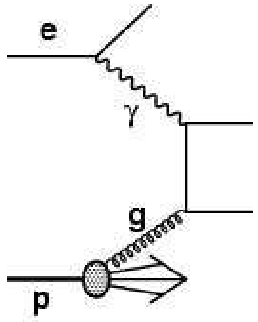


NLO calculations:
FGH – Fontannaz, Guillet, Heinrich
K&Z – Krawczyk & Zembrzuski
AFG-HO photon, MRST2 proton PDFs

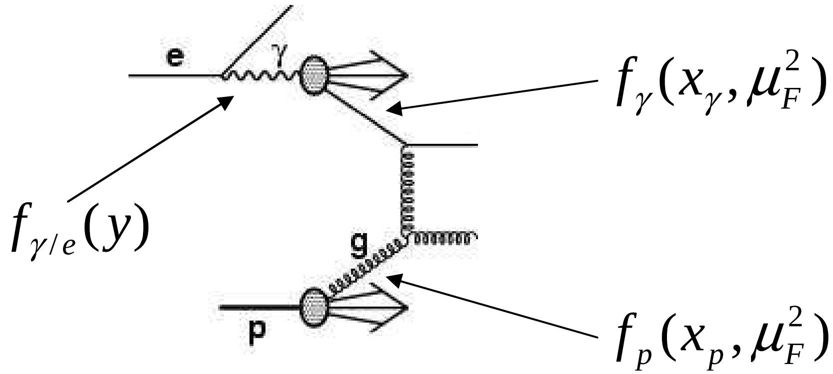
in principle sensitivity to resolved γ

similar measurements by ZEUS (talk by Brownson)

γp to jjX – important for both *p* & γ PDFs



direct



resolved

hard scale provided by $E_T^{jet} > 20$ GeV

$$d\sigma_{ep}(resolved) = \int dy f_{\gamma/e}(y) \int dx_p dx_\gamma f_p(x_p,\mu_F^2) f_\gamma(x_\gamma,\mu_F^2) d\hat{\sigma}_{ab}(x_p,x_\gamma,\mu_R^2)$$

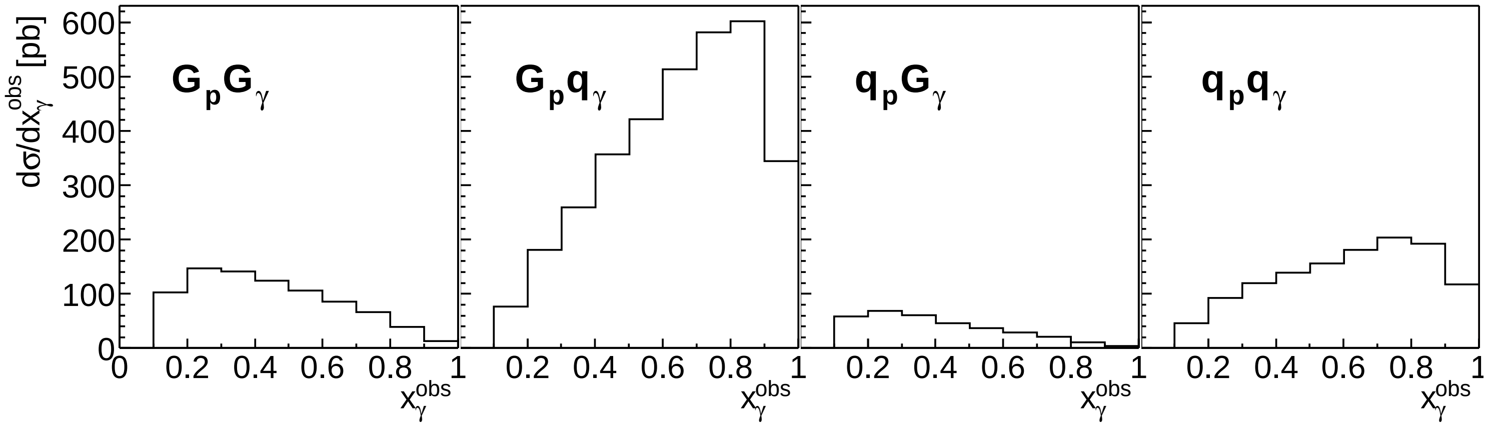
with LO estimators for x_γ and x_p :

$$x_\gamma^{obs} = \frac{E_T^{j1} e^{-\eta^{j1}} + E_T^{j2} e^{-\eta^{j2}}}{2yE_e}; \qquad x_p^{obs} = \frac{E_T^{j1} e^{\eta^{j1}} + E_T^{j2} e^{\eta^{j2}}}{2E_p}$$

$x_\gamma^{obs} > 0.75$ 'direct enriched', $x_\gamma^{obs} < 0.75$ 'resolved enriched'

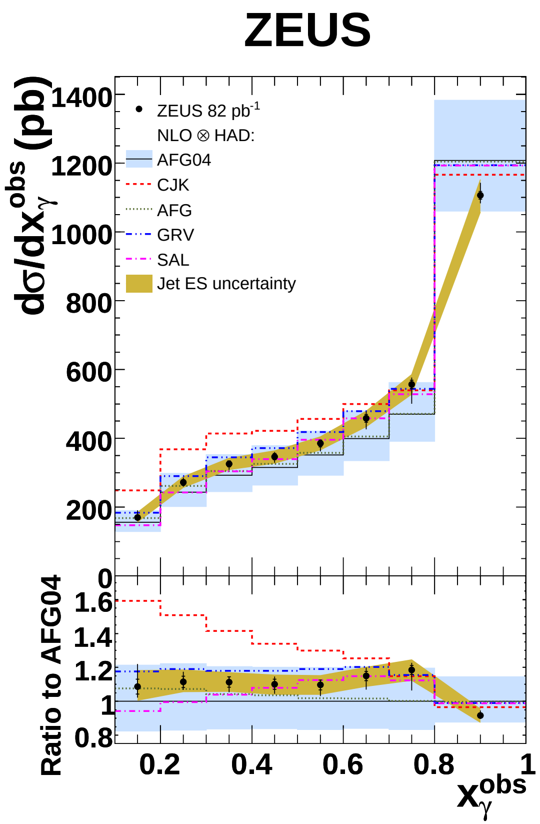
proton PDFs photon PDFs

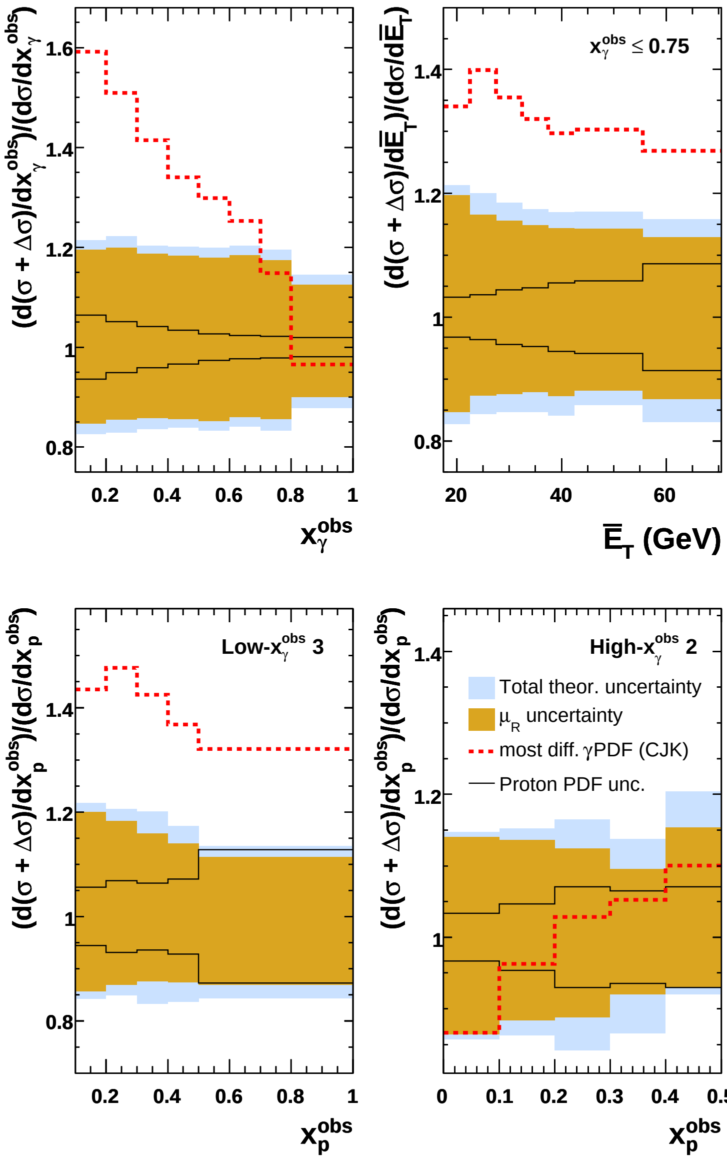
Sensitivity to PDFS



- From SAL
  - contribution to cross-section as function of x_γ^{obs}
  - Frixione-Ridolfi NLO code, CTEQ5M proton PDFs & SAL photon PDFs
  - E_T in the range 14 – 17 GeV
  - shows sensitivity to combinations of proton and photon PDFS
  - notice the dominance of G_p (g^p)

γp to jjX (ZEUS & H1- details in talk by Bussey)





Uncertainties

shaded band from μ_R up to 20%

full line is propagation of ZEUS-JETS PDF fit errors large at large x_p^{obs}

82 pb^{-1} HERA-I data

$E_T^{jet1} > 20$ GeV, $E_T^{jet2} > 15$ GeV

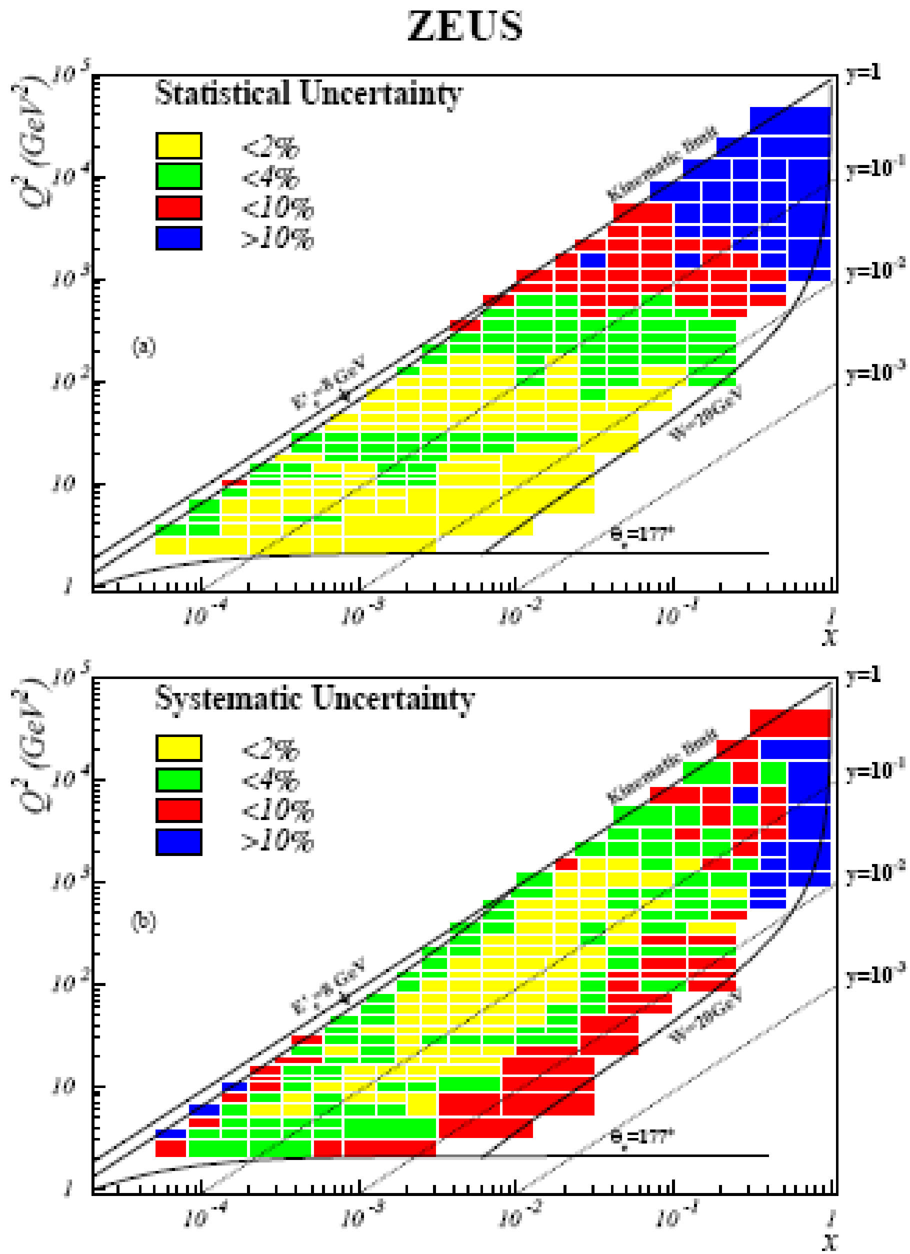
$-1 < \eta^{jet1,1} < 3$

ZEUS 96/97 $F_2(p)$

statistical and
systematic uncertainties

- $30\ \mathrm{pb}^{-1}$ at $\sqrt{s} = 300$ GeV
  data taken 1996/7
  published 2001
- high statistics F_2^p
  already systematics limited
  over central region of
  kinematic plane

- now have ~ 10× luminosity
  will give significantly improved
  results at very high Q^2 and x



Outlook

- Many interesting talks to come in this session

- A lot of high statistics measurements are in progress
  - many results presented here are from HERA-I data
  - HERA-II will extend measured region at large *x* and Q^2
  - already some very precise data from Tevatron Run-II
  - for both larger luminosity allows access to higher jet E_T
  - but systematics limit HERA and Tevatron measurements

- On the theory side
  - good news is that NNLO calculations are available for $F_2(p)$ and on the way for $F_2(\gamma)$
  - bad news is that promise of sensitivity of jet measurements to proton and photon PDFs is limited by scale uncertainties (at NLO)
  - real and urgent need for NNLO jet calculations