PROTON PDFS USING STRUCTURE FUNCTION AND JET DATA FROM ZEUS

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Determination of the proton PDFs

- Observables used in the fits to determine the proton PDFs:
  - Inclusive measurements of deep inelastic $l \bar{N}$ scattering

  - Advantages:
    - Inclusive (only final-state lepton is tagged)
    - No QCD corrections associated to the final-state signature (lepton!)
    - No hadronisation corrections associated to the final-state signature (lepton!)

  - Disadvantages:
    - 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)
  - Large QCD corrections and hadronisation corrections

  - That’s the past! NOW there are measurements of jet cross sections at HERA
    - Directly sensitive to the gluon density in the proton
    - With small experimental and theoretical (terms beyond NLO, hadronisation) uncertainties!
Determination of PDFs using structure function and jet data from ZEUS

- Determination of the proton PDFs using inclusive measurements of NC and CC DIS $e^\pm p$
  in a large level arm of $x$ and $Q^2 \Rightarrow 6.3 \cdot 10^{-5} < x < 0.65, 2.7 < Q^2 < 30000 \text{ GeV}^2$
  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

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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
  - $\rightarrow$ suppression of the Born contribution (struck quark has zero $E_T$)
  - $\rightarrow$ suppression of the beam-remnant jet (zero $E_T$)
  - $\rightarrow$ lowest-order contributions from
    - Boson-gluon fusion process $\gamma^* g \rightarrow q\bar{q}$
    - QCD-Compton process $\gamma^* q \rightarrow qg$

$\Rightarrow$ 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 $E_{T,jet}^B > 8$ GeV and $-2 < \eta_{jet}^B < 1.8$
  where $\cos \gamma = \frac{(1-y) x E_p - y E_e}{(1-y) x E_p + y E_e}$

- 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:
  - jet energy scale (1% for $E_{T,jet} > 10$ GeV)
  - $\Rightarrow \sim \pm 5\%$ on the cross sections

- Small parton-to-hadron corrections ($C_{had}$): $< 10\%$
  - $< 5\%$ for $Q^2 > 250$ GeV$^2$ except for lowest-$E_{T,jet}^B$ point
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 ($>\text{NLO}$); varying $\mu_R$
  
  between $\frac{1}{2} \cdot E^B_{T,\text{jet}}$ and $2 \cdot E^B_{T,\text{jet}} \Rightarrow \pm 5\%$

  → hadronisation corrections; variance of $C_{\text{had}}$ values (ARIADNE, LEPTO-MEPS, HERWIG)

  $\Rightarrow < 1\%$

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

- pQCD calculations of jet cross sections

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

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)

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

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

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

- Measurements of dijet photoproduction provide
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

- 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
  measurements restricted to the region where
direct processes dominate

⇒ 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

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

- Direct-process-enriched region: $x_{\gamma}^{OBS} > 0.75$
Dijet Photoproduction Cross Sections for $x_{\gamma}^{\text{obs}} > 0.75$

- Measurement of the differential cross section $d\sigma/dE_{T,1}^{\text{jet}}$ for dijet events with $E_{T,1}^{\text{jet}} > 14$ GeV, $E_{T,2}^{\text{jet}} > 11$ GeV, $-1 < \eta^{\text{jet}} < 2.4$ (both jets) and $x_{\gamma}^{\text{obs}} > 0.75$ 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**: 
  - higher-order terms (> NLO); varying $\mu_R$ between $\frac{1}{4} \cdot E_T^{\text{sum}}$ and $E_T^{\text{sum}}$ ⇒ $\pm 10\%$
  - hadronisation corrections; half the spread of $C_{\text{had}}$ values (PYTHIA, HERWIG) ⇒ $2 - 3\%$

- 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 ($x u_V$), $d$ valence ($x d_V$), gluon ($x g$), total sea ($x S$) and $x \Delta = x (\bar{d} - \bar{u})$
  - at $Q_0^2 = 7 \text{ GeV}^2$ 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 \( \Rightarrow p_{1,g}, p_{1,u_V}, p_{1,d_V} \)
  - 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
  \( \Rightarrow 11 \text{ free parameters} (+ \alpha_s \text{ when free; otherwise } \alpha_s(M_Z) = 0.118) \)

- Evolution of the PDFs with the energy scale: DGLAP equations at NLO ($\overline{MS}$ scheme)
Inclusion of jet cross sections in a fit of the proton PDFs

- In contrast with the evaluation of the structure functions from the evolved PDFs, 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
  $\Rightarrow$ construction of grids such that the calculations for the jet cross sections can be performed sufficiently fast (and accurately) $\Rightarrow$ $\mathcal{O}(1$ second$)$ per PDF set!

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

$G_{i,a,n,\xi_k,Q_j^2}$ 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 ($\xi, Q^2$) $\rightarrow$ 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%
Determinations of the proton PDFs

- Data sets used in the fit (577 data points):
  - Structure function measurements: reduced double differential cross sections in $x$ and $Q^2$
    - Neutral current DIS $e^+p$ and $e^-p$
    - Charged current DIS $e^+p$ and $e^-p$
  - Jet cross section measurements:
    - Inclusive jet production in NC DIS
    - Dijet production in $\gamma p$ collisions

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

  $W^2 > 20 \text{ GeV}^2$

- 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 $e^+ p$

$Q^2 > 125 \text{ GeV}^2$, $E_{T,jet}^B > 8 \text{ GeV}$

Dijet Production in $\gamma p$ collisions

$E_{T,jet}^{1(2)} > 14 (11) \text{ GeV}$, $x_{\gamma}^{obs} > 0.75$
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
  - 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 \(Q^2_0\) in the range \(4 < Q^2_0 < 10 \text{ GeV}^2\)
  - 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; \(E_{T,jet}^B > 10 \text{ GeV in NC DIS}\) and \(E_{T,jet,1}^p > 17 \text{ GeV in } \gamma p\)
  - parton-to-hadron corrections to jet cross sections
  - residual uncertainty due to photon PDFs used in the dijet calculations (AFG → GRV)
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- Model uncertainties in PDFs:
  - variation of \(Q_0^2\) in the range \(4 < Q_0^2 < 10 \text{ GeV}^2\)
  - 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; \(E_{T,jet}^B > 10 \text{ GeV}\) in NC DIS and \(E_{T,jet}^{jet,1} > 17 \text{ GeV}\) in \(\gamma p\)
  - parton-to-hadron corrections to jet cross sections
  - residual uncertainty due to photon PDFs used in the dijet calculations (AFG \(\rightarrow\) GRV)

\(\Rightarrow\) 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
Proton PDFs using structure function and jet data from ZEUS

Comparison of proton PDFs

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

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**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 $\gamma^*(g \rightarrow q\bar{q})$ (coupled to gluon density) and via $\gamma^*(q \rightarrow qg)$ (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:

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

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

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

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

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

- 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 \( \rightarrow \text{direct sensitivity to } \alpha_s \text{ and the gluon density in the proton and small experimental and theoretical uncertainties} \)
  \[ \Rightarrow \text{sizeable reduction of the uncertainty of the gluon density in the mid- to high-} \times \text{ region} \]
  \[ \Rightarrow \text{precise determination of } \alpha_s \text{ from HERA data alone} \]

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