Would like averaged HERA structure function data.

All published (at the time) charm structure function data.

Direct high-\( x \) data on \( F_{LL} \) replacing CCFR.

NuTeV and CHORUS data on \( F_{LU} \) replacing CCFR.

New CDFII and D0II high-\( p_T \) jet data.

HERA inclusive jet data (in DIS).

CDFII and D0II data on \( \Phi p/(Z)_{0}p \) for \( \Phi > 0 \).

CDFII and D0II data on \( d\phi/(Z)_{0}d\phi \) for \( d\phi > 0 \).

First data sets only.

D0II data for \( \p_{T} < 20 \) GeV and \( 35 \) GeV \(< \p_{T} < 45 \) GeV. D0II data in two different \( \p_{T} \) bins – 25 GeV \(< \p_{T} < 35 \) GeV and 35 GeV \(< \p_{T} < 45 \) GeV. CDFII lepton asymmetry data in two different \( \p_{T} \) bins. Affects other partons.

NuTeV and CCFR dimuon data included directly. Leads to a direct constraint on NuTeV and CCFR high-\( x \) data on \( F_{LL} \).

MSTW08 – New data included.
Major changes in theory/approach:

Implementation of updated heavy-flavour VFNS, particularly at NNLO. Already used in MRST06 NNLO distributions, but not in official NLO sets. (Already used a general MSTW08 implementation of updated heavy-flavour VFNS, particularly at NNLO. ALready use in


Inclusion of NNLO corrections. Allows easy inclusion of new jet data from both Tevatron and HERA.

Improved nuclear corrections, De Florian and Sassot obtained from NLO partons.

Change in definition of $\alpha_S$ — same as QCDNUM, Pegasus. No $\alpha_D$ parameter.

Improved fast NLO — fast perturbative QCD calculations Kluge, Rabbertz, Wobisch.

Inclusion of fastNLO, De Florian and Sassot obtained from NLO partons.

W, Z and $\gamma^*$ data using Vrap and FEWZ.
This is a genuine theory uncertainty. Changes of up to 2% in "MRST2006" (unofficial). Compare MRST2004 to unofficial "MRST2006" because they use older data. Pre-2006 NLO different but ok, GM-VFNS.

Use pre-2006 NNLO, not approximated too much, but different. Use examples: CTEG959, CTEG959. Compare only to CTEG959 in MRST99. Impacts on LHC and Tevatron predictions.

GM-VFNS – Response to Plenary (Nadolsky).
Using similar sort of reasoning MRST used reasoning of $\chi^2$ to take a value such that every data set remains roughly within its $90\%$ confidence limit compared to the best global fit.

$0.1 = L$ for $CTEQ6$ eigenvector $\psi$. Some sets somewhat outside $90\%$ confidence limits. Some sets $\chi^2$ that every data set remains roughly within its $90\%$ confidence limit.
Similarly for the 68% C.L. region.

Recale by a factor $\frac{\chi^2}{\chi^0}$ since this is often deviates from 1.

For data set $n$ is evaluated at the global minimum.

$\chi^2$ is the most probable value of the $\chi^2$-distribution.

$$\frac{1}{N} \frac{(N^2 - 1)}{2} \left( \frac{\chi^2}{\chi^0} \right) = (N^2 - 1) \frac{\chi^2}{2}$$

where the probability density function is

$$\chi^0 = \left( \frac{\chi^2}{\chi^0} \right) \left( \frac{\chi}{N^2 - 1} \right) \frac{\chi^2}{2} \int_{\chi^0}^{\infty} d\chi$$

$\chi^0$ is the 90th percentile of the $\chi^2$-distribution with N-1 d.o.f. i.e.

$$\left( \frac{\chi^2}{\chi^0} \right) > \frac{\chi^2}{2}$$

Define 90% C.L. region for each data set $n$ (with $N^2$ data points) as

Explained below (Watt DIS08)
For eigenvector 13, for example, the change in $\chi^2$ for the most sensitive data sets is shown.

For each determine the point in $\Delta \chi^2_{\text{global}}$ at which the appropriate confidence level limit is reached in each direction.
Plot this for all datasets for a given eigenvector.

Eigenvector number 13.

Highly inconsistent. 90% confidence level for each direction.

In this case the best fits for the two sets are constrained in one direction by E866 Drell-Yan data and in the other.

Plot this for all data sets for a given eigenvector.

Distance = $\sqrt{\Delta \chi^2}$
At input scale $Q^2 = 1$ GeV$^2$

This eigenvector contributes most to the high-$x_s$ sea quark uncertainty, but also a variety of other quarks.

Fractional contribution to uncertainty from eigenvector number 13

MSTW 2008 NLO PDF fit (68% C.L.)
As a simpler example, eigenvector number 9 constrained most by H1 and ZEUS data on $d\nu_n/F_{\pi}^{E665}$ and $d\nu_n/F_{\mu}^{E866/NuSea}$.

**Distance = $|\Delta \chi^2_{\text{global}}|$**

MSTW 2008 NLO PDF fit
At input scale $Q_0^2 = 1 \text{ GeV}^2$.

Fractional contribution to uncertainty from eigenvector number 9.

Not surprising this eigenvector contributes most to the gluon uncertainty.
In practice should give a conservative estimation of uncertainties.

**Eigenvector number**

![Diagram with eigenvector numbers and tolerance values](image)

**MSTW 2008 NLO PDF Fit**

There are asymmetries, average, and large variations, and approach repeated for all 20 eigenvectors to determine uncertainty on each.
Normalisation Uncertainties

Previously (and still for CTEQ) the normalisation of each data set was determined by the best fit – and then fixed. Really seems to be a separate issue.

In practice normalisation uncertainty uncertainty was determined from ratios: \( p - n \). Eigenvectors since some very sensitive (size of quarks) others insensitive (size of gluons) \( x \) (except high-\( x \) gluon where only a small part of total uncertainty). Largey independent of \( x \) for all partons. However now well-determined. Would be difficult to account for in tolerance for normalisation uncertainties.

Technical difficulties in including this feature in uncertainties. CTEQ argue that this is part of the reason for large tolerance. Really seems to be a problem in uncertainties.

Now implement procedure of allowing normalisations of all sets to vary while performing scans over eigenvectors.
Comparison of full uncertainty and that from ignoring normalization uncertainties (other than in best fit). Also shown (blue), alternative approach for including normalization uncertainties (more efficient in fit)...
Determining uncertainty eigenvectors due to better parameterisation in $W$-asymmetry data and new neutrino structure function data.

Mainly changed by new $J_{\text{fact}}$ equation different type of shape. Overall $\hat{D}(x)$ now chooses a...
Eventhough one dataset constrains each eigenvector limit, doesn't mean others don't contribute. Tevatron jet data instead of Run I softens gluon at high $x$ significance but impact signficantly on constraint. Inclusion of Run II Tevatron jets are never main. Even though one data set constrains...
Unlike CT09C, we do not find good consistency between fits to Run I and Run II jet data — though 90\% uncertainty bands overlap.

Little change in conclusions if CDF II \( k_T \)-algorithm or midpoint algorithm data used.
Significant difference to CTEQ fitting to same data. At small $x$ assume shape of different parametrisation. Input sea quarks is the same (consistent with mass suppression) whereas CTEQ have input sea quarks is the same (consistent with mass suppression) whereas CTEQ have different parametrisation. To assumption of fixed fraction of sea.
Generally larger uncertainties from normalization uncertainties and more flexible parameterizations.

Tolerance for eigenvectors generally smaller.

Change in shapes of gluon due to lower.

Comparison to MRST2006 PDFs.

Uncertainties due to $\alpha_S$ variation.

0.119 $\leftrightarrow$ 0.117.

Other changes partly due to lower production and neutrino data.

by anyone in uncertainty sets.

Down from Tevatron vector boson.

DIS0918
Comparison to CTEQ6.6 at NLO.

CTEQ $x$ small-x. CTEQ strange now larger at $Q^2$. Feeds into parametrization. Runs I jets (input $Q^2$) and small-$x$ (input $x$) CTEQ gluon larger at high-$x$.
Central values. Currently differ somewhat in some
on gluon. Extra constraints from Tevatron W, Z and high-\(p_T\) jet data, Drell-Yan data etc.
Particularly important for quark flavour decomposition and impacts on quark distribution at \(Q^2\); DIS092.

\(x\) and high-\(p_T\). Currently comparable despite input flexibility in NNPDF.

\(x\) and high-\(p_T\) jet data, Drell-Yan data etc. Often comparable despite input flexibility in NNPDF.

\(x\) and high-\(p_T\). Currently comparable despite input flexibility in NNPDF.

\(x\) and high-\(p_T\). Currently comparable despite input flexibility in NNPDF.

\(x\) and high-\(p_T\). Currently comparable despite input flexibility in NNPDF.

\(x\) and high-\(p_T\). Currently comparable despite input flexibility in NNPDF.
Kinematics at LHC

Overall, new kinematic regime.

LHCb in particular probes regions of intrinsic (experimental) uncertainty due to extra powers of $\ln(1/x)$.

LHCb (LHC physics) and/or lowish mass states at LHC.

Some predictions potentially unstable, e.g. high-rapidity processes.

Possible problems at small $x$.
where $G = g + 4/9 \sum q(q + \bar{q})$

| $|y_X| < 2.5$ |

Parton luminosity uncertainties at LHC (MSTW2008NLO)

Uncertainties on parton luminosities, i.e. of fundamental rates for creation processes, are optimum for standard model particle production. Start to worsen at highest masses where sensitive to large-$x$ PDFs.

Parton Luminosity Uncertainties
Of course, will be starting the LHC running at 10 TeV rather than the full 14 TeV. Roughly 60 - 70% the full cross-sections for most standard model (including light Higgs) processes.

Ratios of parton luminosities at 10 TeV LHC and 14 TeV LHC

M^x (GeV) vs. 10^3

MSTW2008NLO

\[ Σ \]

\[ \text{Ratio of parton luminosities} \]

\[ \text{Luminosity ratio} \]
Predictions for W and Z total cross sections at the Tevatron CDF Run II with fixed order QCD and vector boson width effects, and common branching ratios. Fairly significant change from NLO to NNLO mainly due to hard cross-section correction. Other than this reasonable agreement in predictions, the disagreement with common branching ratios and common fixed order QCD predictions for Tevatron with common cross-sections W and Z predictions.
Predictions for \(W\) and \(Z\) total cross sections for LHC with common fixed order QCD and vector boson width effects, and common branching ratios. Virtually no change from MRST2006 to MRST2008. Ratio changes due to change in strange distribution. Reasonable agreement at NLO with CTEQ6.6, but systematic difference.

Increases from MRST2006 compared to MRST2004 due to changes in (NLO) or completed (NNLO) heavy flavour prescription. Virtually no change from MRST2006 compared to MRST2008. Ratio changes due to change in strange distribution. Reasonable agreement at NLO with CTEQ6.6, but systematic difference.
Uncertainty on $\sigma(W^+)$, $\sigma(W^-)$, $\sigma(Z)$, and $\sigma(DY)$ at LHC using MSTW2007NLO.

Uncertainty on $\sigma(Z)$ and $\sigma(W^+)$ grows at high rapidity. Uncertainty on $\sigma(W^-)$ grows more quickly at very high rapidity. Uncertainty on $\sigma$(less well-known down quark) depends on partons at very small $x$. 

Uncertainty on $\sigma(Z)$ grows at high rapidity. Uncertainty on $\sigma(\gamma)$ decreases quickly. Uncertainty on $\sigma(\gamma)$ is greatest as $y$ increases. Dependence on parts at very small $x$. Dependence on parts at very small $x$. Uncertainty on $\sigma(Z)$ grows at high rapidity.

Uncertainty on pdf uncertainty on $\sigma(W^+)$, $\sigma(W^-)$, $\sigma(Z)$, and $\sigma(DY)$ at LHC using MSTW2007NLO.

very small $x$. $y$ increases. $y$ increases. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Uncertainty on parts at very small $x$. Un
Extremely small uncertainty on ratios and $Z/W$. 

\[ W^+ / W^- = d_\sigma (W^+)/d_\sigma (W^-), \]

\[ A_{WW} = (d_\sigma (W^+)-d_\sigma (W^-))/(d_\sigma (W^+)+d_\sigma (W^-)) \]

\[ RWZ = d_\sigma (W^0)/d_\sigma (Z^0) \]

at LHC using MSTW2007NLO.

More information from ratios including $\frac{Z}{W}$, $\frac{W^-}{W^+}$ and $\frac{W^0}{Z^0}$. 

\[ y = 0 \quad x = 1 \quad \forall x \quad 0 \quad \forall x \quad \text{is} \quad \text{extreme small uncertainty on ratios} \]

One of most useful inputs to PDFs.

Extremely small uncertainty on $W/Z$ and $W^+/W^-$. 

\[ A_W = (d_\sigma (W^+)-d_\sigma (W^-))/(d_\sigma (W^+)+d_\sigma (W^-)) \]

\[ y = 0 \quad x = 1 \quad \text{range of extrapolation of valence} \]

\[ 900 \quad 0 \quad \text{is} \quad \text{very large even just experimental sources} \]

Cleaner experimentally.

Uncertainty on $A_W$ 

Including ratios from different PDF extractions.

Differences in different PDF quarks. 

$\text{Extremely small uncertainty on ratios}$. 

\[ (Z)_\sigma / (W)_\sigma = Z_W \]

\[ (W^+_\sigma + W^-_\sigma) / (W^-_\sigma - W^+_\sigma) = A_W \]

\[ R_W = d_\sigma (W)/d_\sigma (W) ]\]

\[ R_W = d_\sigma (W^-)/d_\sigma (W^-) \]

\[ R_W = d_\sigma (W^+)/d_\sigma (W^+) \]

... with very little data.
Again very interesting for early data.

Significantly more difference in this from other PDFs, including MRST.

Quoted uncertainty for ratio very small, i.e. $\approx 0.8\%$.

Predictions for $W^+$ and $W^-$ cross-sections with common branching widths effects, and common fixed order QCD and vector boson branching ratios for LHC with common

Predictions for $W^+$ and $W^-$ cross-sections at the LHC.
Also consider implications for new physics from updated PDFs.

In MSTW2008

Also consider implications for new physics from updated PDFs.
Leads to competitive looking uncertainties.

Determining uncertainties by scanning over fit quality to different data sets, as with eigenvectors.

Preliminary – Uncertainties on PDFs and $\alpha_S$.
PDFs and coupling are correlated. Additional uncertainty from $(\frac{Z}{\bar{c}W}) S x$ uncertainties.

Changes within, or close to within, initial uncertainties.

More evolution. Slightly larger change in $(\frac{Z}{\bar{c}W}) S x$ change in $(\frac{Z}{\bar{c}W}) S x$.

Expected gluon–anti–gluon feeds into evolution of quarks, but

Gluon feeds into evolution of quarks, but

correlation. Variation of gluon largely expected gluon–anti–gluon variation for quantities depends on how $(\frac{Z}{\bar{c}W}) S x$.

Of fit already worse than best fit. PDF uncertainties at limits of $(\frac{Z}{\bar{c}W}) S x$ uncertainties.

Can also look at PDF changes and
Predictions at NNLO for $Z$ production for different allowed values of $M_Z$ and their uncertainties. Cross sections with MSTW 2008 NNLO PDFs.

Total uncertainty envelope of set of uncertainties increases by up to 50% at LHC. Largely due to effect of PDFs.

Uncertainties.

Predicitons at NNLO for $Z$ production for $Z$ DIS0932.
Predictions at NNLO for Higgs production for different allowed $\alpha_s(M_Z)$ values and their uncertainties.

Values and their uncertainties:

Increases by a factor of 2−3 (up more than down) at LHC. Direct $\alpha_s$ dependence mitigated somewhat by anti-correlated small-$x$ gluon asymmetry feature of minor problems in fit to HERA data. At Tevatron intrinsic gluon uncertainty dominates.

Higgs ($M_H = 120 \text{ GeV}$) with MSTW 2008 NLO PDFs.
Can extend study to a range of Higgs masses. Sees same features, i.e., intrinsic PDF uncertainties most important at Tevatron and increases with mass (high-x gluon). Consistently more PDF-\(g_s\) anti-correlation in downwards direction.

Roughly constant at LHC with coupling effect large.
Conclusions

New algorithm for uncertainties. No fixed $\sigma$ uncertainties leads to uncertainties at LHC at least about 1.3, and up to 3 - 4 times bigger. Correlations vitally important.

Full study of correlated PDF and $\sigma$ uncertainties leads to uncertainties at LHC at least central rapidity $1 - 2\%$, though asymmetries can add constraints to PDFs.

Very precise predictions for $Z$ and $W$ results at the LHC. Total cross-sections and $\sigma$ uncertainties on $s + t$ feed into other partons.

New uncertainties on $s$, larger small-$x$ gluon — impacts on Higgs predictions. Slightly different shape for $p_T$ and jet data included. Smaller high-$p_T$ jet, larger small-$x$ gluon — impacts on Higgs predictions.

Change in best fit values of $(Z\gamma)/S\chi$ variation. At NLO $0.117$ compared to $0.119$ in MRST06 set. At NNLO $0.120$ compared to $0.121$ in unofficial.

New run II CDF and $W$ jets now fit using fastNLO. Important constraints on quarks — constraining for $LHC$ at least 1.3, and up to 3 - 4 times bigger. Correlations vitally important. New algorithm for uncertainties. No fixed $\sigma$ uncertainties leads to uncertainties at LHC at least about 1.3, and up to 3 - 4 times bigger. Correlations vitally important.
Still lack of compatibility some places, e.g. high-\(x\) gluon.

\[
\chi^2 = 1.
\]

not using tolerance uncertainty approach,
compatibility using dynamical.

Latter have greater uncertainty.

Comparison of normal and benchmark sets shown.

Comparison only.

cuts only.

to DIS data with conservative.

of obtaining PDFs by fitting.

HERA-LHC Workshop exercise.

Can investigate by repeating.
Strange itself has some non-insignificant mass, and this should qualitatively lead to suppression compared to light sea quarks up and down. 

When $c$ and $t$ turn on they evolve like massless quarks, but always lag behind.

$\Theta$ some suppression at all $x$ for finite $Q^2$.

Do not expect exact correspondence, but very good except $c + \bar{c}$ more suppressed at $Q^2 = 1 \text{GeV}^2$ and evolved through $\approx 7 - 8$ times input scale similar to $s + s$ at $Q^2 = 1 \text{GeV}^2$.

$\Theta$ (Implication for $s + s$ from recent HERMES data).

$\Theta$ 0.1. $x \sim 0.1$.
Some evidence for positive strangeness momentum asymmetry, but only just more than one-sigma.
Note that different parameterisations lead to very different types of uncertainty, particularly on small $x$ gluon.
Clearly seen for up valence and anti-up distributions.

Note that MSTW 2008 and NNPDF sets sometimes differ significantly in central values, though.

Noteworthy that MSTW2008 and NNPDF differ significantly in central values, though.
Also information about difference in p and distributions from ratio of $M + u$ jets to $W + u$ jets.

Also information about difference in $M$ and some dependence on cuts.

Fairly insensitive to scale choice of calculation and some dependence on cuts.

Also information about earliest data. Absolute rates give information on gluon as well, but not so easy to understand in

earliest data.
Perturbative Stability at the LHC

Using MRST PDFs

Now have QCD calculations at LO, NLO and NNLO in the coupling constant $\alpha_s$ for $W, Z, \gamma \gamma$ production. Good stability in predictions for $W, Z$ and $\gamma \gamma$ cross-sections for very high virtualities. Becomes worse at lower scales where large and large threshold $\ln(s/M^2)$ terms appear in expansion (equivalent to $\ln(1-x)$ terms) and large and large $\ln(1-x)$ terms.

Quality of fit to various combinations of jet data by CTET and with restricted gluon parameterization.

### Quality of fit to various combinations of jet data by MSTW

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<th>$x_{	ext{F}}$</th>
<th>$n_{	ext{jet}}$</th>
<th>$\chi^2$</th>
<th>$\text{CDF} (1100 \text{ ps})$</th>
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