James Stirling – Legacy for PDF Studies.

Robert Thorne

December 13th 2018

University College London

With thanks to Alan Martin

James Stirling 1953-2018

James Stirling died on 9 November 2018 following a short illness.

He left an enormous legacy in the theory and application of QCD and performed work which was central in verifying QCD as the correct theory of strong interactions, and in computing precise predictions for all types of processes at hadron colliders like the LHC

However, in this meeting we know him best for his extremely wide-ranging and influential contribution to the subject of PDFs.

James was born in Belfast, Northern Ireland, and educated at Peterhouse, Cambridge University, where he obtained his PhD in 1979.

Already during his graduate studies at Cambridge, in the early days of QCD, he contributed to the clarification of the connection between deep inelastic lepton-hadron scattering and hadron-hadron processes such as Drell-Yan production.

He then took a post-doc position at the University of Washington in Seattle, and as early as 1981 came the first studies to obtain the details of parton distributions.

THE NAIVE PARTON MODEL AND LARGE p_T SCATTERING DATA

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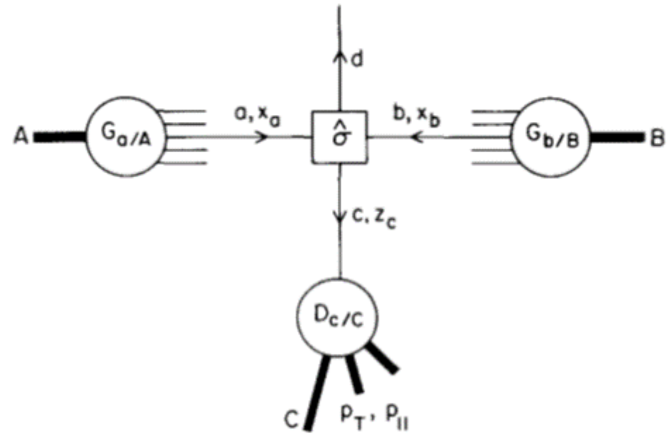
We attempt to fit FNAL data on large p_T scattering beam and trigger particle ratio using a naive QCD parton model constrained as much as possible by existing experimental input. We find that, in the context of a model with canonical gluon distributions, recent data on the production of large p_T pions by pion beams gives evidence for the presence of the three-gluon vertex. We argue, however, that there is no set of gluon distributions which is consistent with all the existing data.

Using the factorization theorem.

$$E\frac{d\sigma}{d^3p}(A+B\to C+X)=\sum_{a,b,c}\int dx_a\,dx_b\,G_{a/A}(x_a)G_{b/B}(x_b)\frac{D_{c/C}(z_c)}{z_c}$$

$$\times\left[\frac{1}{\pi}\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(s,\hat{t},\hat{u})\right].$$



Only the gluons and valence quark and generic sea quark. Also need the pion.

We use the standard two-component, valence plus sea, separation of the hadron quark distributions. The sea is taken to be SU(3) symmetric. For the proton we use

$$xG_{u_v/p}=2.0986x^{1/2}(1-x)^{2.7};$$

$$xG_{d_v/p}(x)=1.1911x^{1/2}(1-x)^{3.7},$$

$$xG_{\bar{u}/p}(x)=0.1943\,(1-x)^7,$$

With these distributions as input, the remaining unknowns are the glue distributions of the proton and pion. We choose a one-parameter representation of these distributions:

$$xG_{g/p}(x)=262.08(1+a_px^3)(1-x)^5/(84+a_p),$$

$$xG_{g/\pi}(x)=15(1+a_\pi x^2)(1-x)^2/(10+a_\pi). \qquad (3)$$

Already encounter difficulties in fitting different data sets simultaneously.

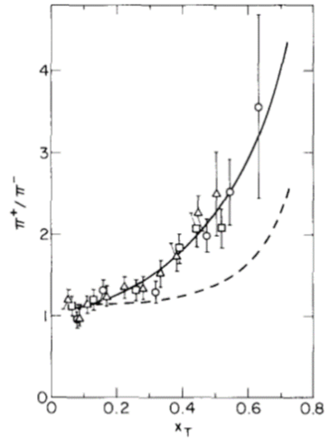


Fig. 3. The proton trigger ratio. Shown are data points from ref. [12] with canonical ($a_p = 0$; solid line) and hard glue ($a_p = 1000$; dashed line) fits in our model. Hard glue is inconsistent with the data.

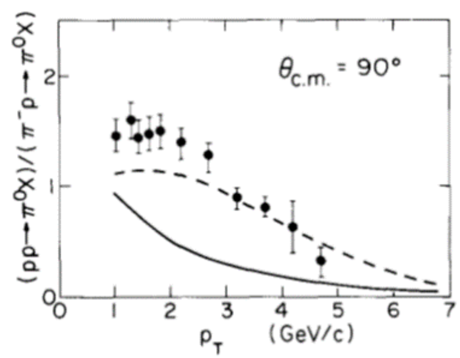


Fig. 6. The beam ratio. Shown are data points from ref. [13] with soft glue ($a_p = 0$, $a_\pi = 4$; solid line) and hard glue ($a_p = 1000$, $a_\pi = 10$; dashed line) fits. Hard glue is needed to fit the data.

Improve theory?

Any realistic model of hadron scattering arising from QCD includes several elements not considered in the simple model discussed above. Calculable leading logarithm perturbative effects introduce scaling violation through a Q^2 dependent coupling constraint, $\alpha_s(Q^2) = \frac{12}{25}\pi\,[\log(Q^2/\Lambda^2)]^{-1}$, and structure functions with Q^2 dependence given by the Altarelli–Parisi equations [14]. Here Q^2 denotes some mass scale characteristic of the hard scattering and Λ is the strong interaction scale determined from experiment. It now appears experimentally that Λ is fairly small, $\Lambda \sim 0.1$–0.3 GeV, so that logarithmic deviations from scaling are probably not significant. (Fragmentation functions, in fact, scale exactly within experimental errors.)

Significant break in trying to obtain the PDFs in detail. Next time was for very specific, and rather different, physics reasons. Typical of James' reasoning in PDF studies.

ON THE DETERMINATION OF LIMITS ON THE NUMBER OF LIGHT NEUTRINOS AND THE TOP QUARK MASS FROM W, Z PRODUCTION IN $p\bar{p}$ COLLISIONS

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The ratio of the (acceptance corrected) number of W's and Z's observed at the CERN collider is compared with the prediction of the standard model. Possible sources of error are carefully studied. A new analysis of deep inelastic data is performed in order to significantly improve the accuracy of the standard model prediction. The implications for the number of light neutrinos and the mass of the top quark are discussed.

$$R = \frac{\#(W \to e\nu)}{\#(Z \to ee)} = \frac{\sigma_W}{\sigma_Z} \frac{BR(W \to e\nu)}{BR(Z \to ee)} \equiv R_\sigma \cdot R_{BR}, \quad (1)$$

Also started very long and successful collaboration with Alan Martin - (M) and Dick Roberts - (R).

At the time some existing PDFs, and also some not very compatible data from BCDMS and NMC.

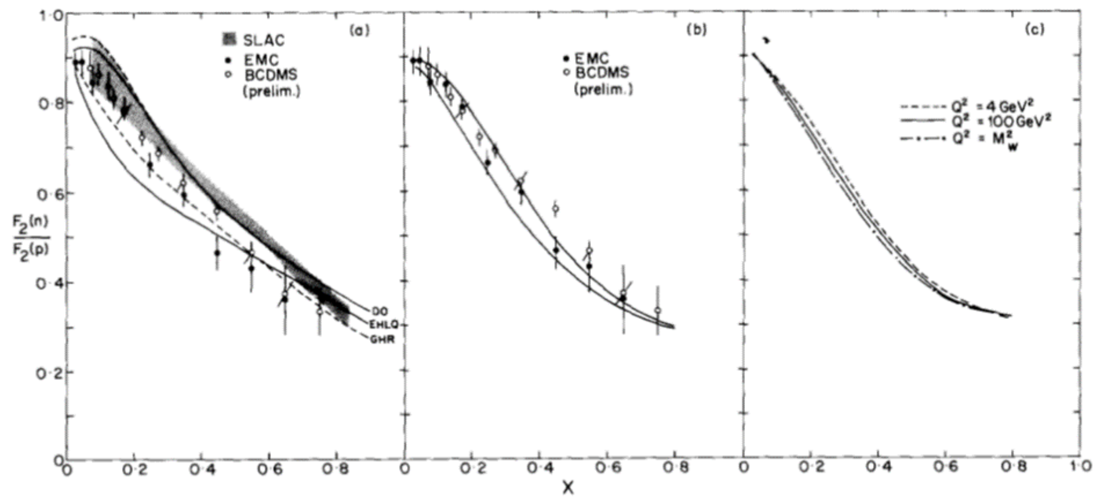

Fig. 2. The ratio F_2^n/F_2^p versus x: (a) Experimental results [9,11] compared with previous structure function parametrisations [5–7] evaluated at $Q^2 = 10$ GeV^2 (the ratio is insensitive to Q^2); (b) The shaded band shows the allowed range of our fit to EMC data [9] (solid points). For comparison we also show the preliminary BCDMS data [11] (not included in the fit); (c) The slow Q^2 evolution of the ratio (corresponding to our fit to the deep inelastic data).

Showed that improved PDFs reduced uncertainty compared to existing sets which didn't fit all data.

Gathering all the above results together, we finally conclude

$$R_\sigma = 3.36 \pm 0.09,$$

where the error represents the combined uncertainty from the parton distributions and from the W and Z masses. This is to be compared to the previously used result

$$R_\sigma = 3.25 \pm 0.2.$$

Full details of the extraction of the PDFs themselves appeared soon afterwards – first NLO fit.

Structure-function analysis and ψ, jet, W, and Z production: Determining the gluon distribution

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We perform a next-to-leading-order structure-function analysis of deep-inelastic μN and νN scattering data and find acceptable fits for a range of input gluon distributions. We show three equally acceptable sets of parton distributions which correspond to gluon distributions which are (1) "soft," (2) "hard," and (3) which behave as $xG(x) \sim 1/\sqrt{x}$ at small x. J/ψ and prompt photon hadroproduction data are used to discriminate between the three sets. Set 1, with the "soft"-gluon distribution, is favored. W, Z, and jet production data from the CERN collider are well described but do not distinguish between the sets of structure functions. The precision of the predictions for σ_W and σ_Z allow the collider measurements to yield information on the number of light neutrinos and the mass of the top quark. Finally we discuss how the gluon distribution at very small x may be directly measured at DESY HERA.

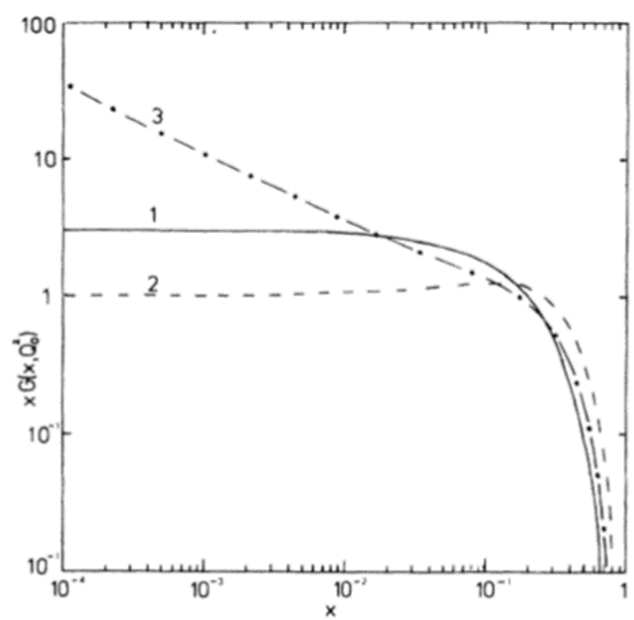

FIG. 1. The starting gluon distributions at $Q_0^2 = 4$ GeV^2 for the three parametrizations: 1 is the "soft" gluon, 2 the "hard" gluon, and 3 the "$1/\sqrt{x}$" gluon.

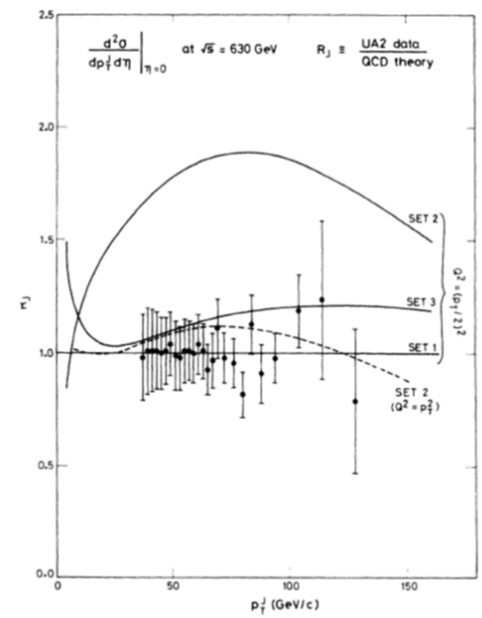

FIG. 15. The ratio of the UA2 data (Ref. 24) and the QCD prediction using set-1 distributions with the scale $Q = \frac{1}{2}p_T$. Also shown (solid curves) are the predictions of the set-2 and set-3 distributions with the same scale $Q = \frac{1}{2}p_T$ normalized to the set-1 prediction, and the set-2 prediction with the scale $Q = p_T$ (dashed curve).

Template of comparisons to different data types, and interesting predictions for precision physics set in place.

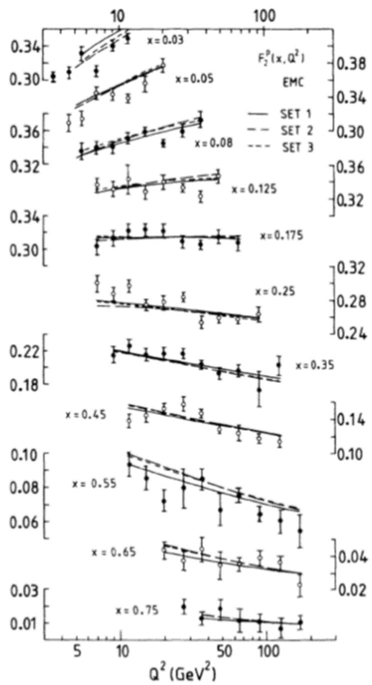

FIG. 2. F_2 proton structure function from the EMC (Ref. 7). The solid long-dashed, and short-dashed curves, respectively, correspond to sets 1, 2, and 3 of structure functions. Only those data with $Q^2 > 5$ GeV^2, $W^2 > 10$ GeV^2 were included in the fits.

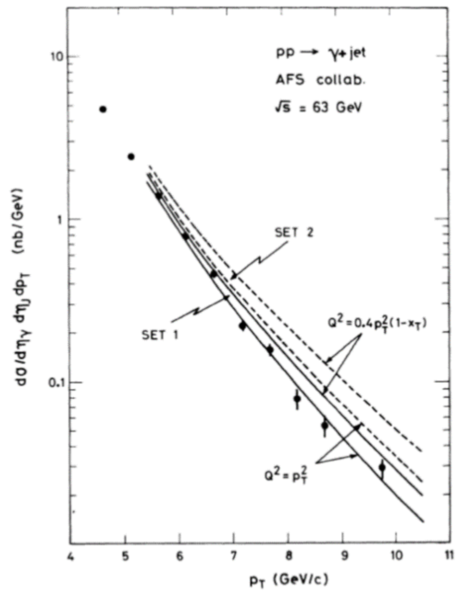

FIG. 13. The differential cross section $d^3\sigma/d\eta_\gamma d\eta_J dp_T$ for $\eta_\gamma \simeq \eta_J \simeq 0$ for $pp \to \gamma + \text{jet} + X$ at $\sqrt{s} = 63$ GeV. The data are from Ref. 22. The predictions are shown for two different choices of scale for the structure functions: $Q^2 = p_T^2$ and Q^2 equal to the optimum scale found for the inclusive process $pp \to \gamma X$ by Aurenche *et al.* (Ref. 20). In each case α_s is evaluated at the scale μ_{opt} that is given as a function of p_T.

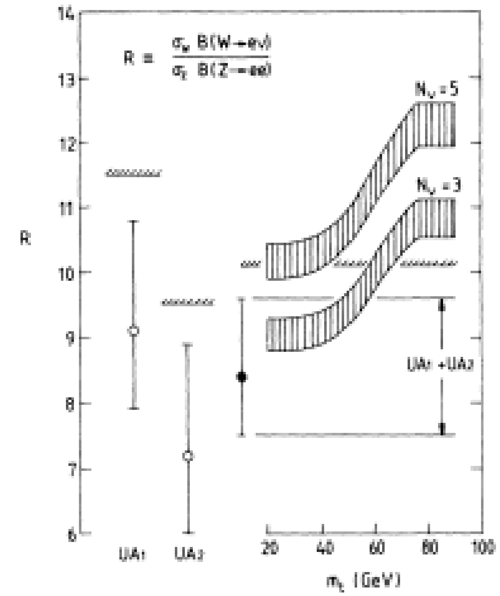

FIG. 18. Ratio of W,Z cross sections measured by the UA1 and UA2 Collaborations (Refs. 27 and 28). The average of the experimental results is also shown (solid circle). The predictions, together with their uncertainties, are as in Fig. 17.

Soon became overwhelmingly clear that not all data is always equal.

IMPLICATIONS OF NEW DEEP INELASTIC SCATTERING DATA FOR PARTON DISTRIBUTIONS

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Received 23 December 1987

We perform a next-to-leading order structure function analysis of μN and νN deep inelastic data in an attempt to resolve the disagreement between recent EMC and BCDMS measurements of F_2 for μp scattering. Equally acceptable QCD fits are obtained including either set of μN data, but a comparison with Drell–Yan data appears to favour the parton distributions derived from the BCDMS data.

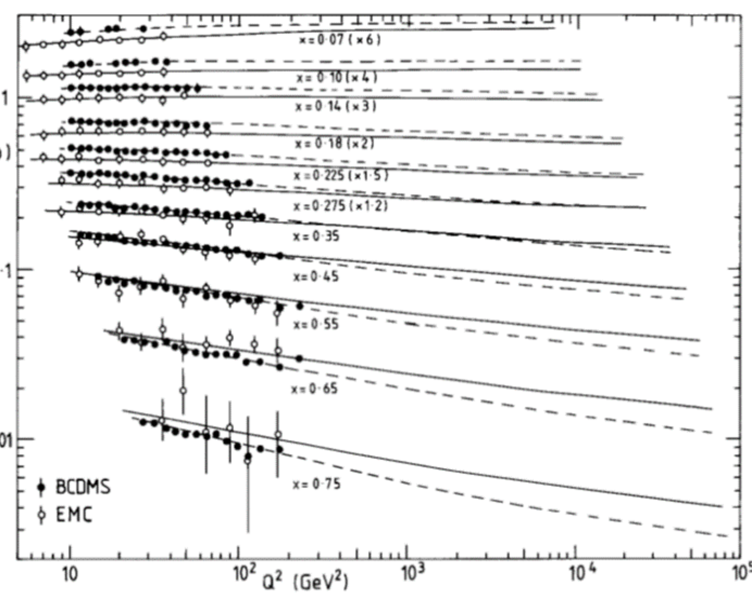

Fig. 1. The structure function $F_2(\mu p)$ as measured by EMC [2] (open circles) and by BCDMS [1] (closed dots). The continuous (dashed) curves are the result of a global fit to the EMC (BCDMS) μN data together with deep inelastic neutrino data. We fit only to data with $Q^2 > 5$ GeV^2 and $W^2 > 10$ GeV^2. We include systematic errors (not shown), and assume a 2% systematic error for $F_2(\mu p)$ of BCDMS. The curves are extended into the kinematic region accessible at HERA.

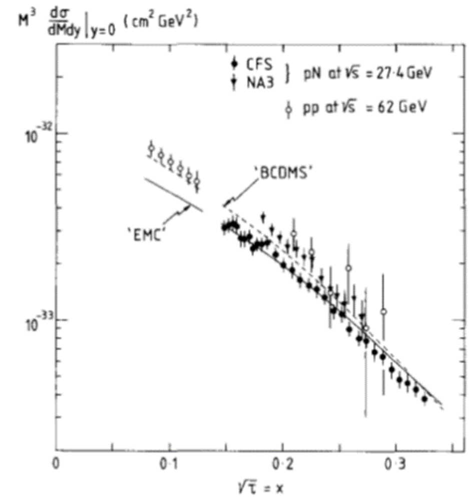

Fig. 5. A "scaling" plot of Drell–Yan production: $M^3 d^2\sigma/dM\,dy$ at $y=0$ versus $\sqrt{\tau} \equiv M/\sqrt{s}$ where M is the mass of the produced $\mu^+\mu^-$ pair. The open circles are ISR pp→μμX data [12] at $\sqrt{s}=62$ GeV. The remaining data are for pN→μμX at $p_L = 400$ MeV/c [10,11]. The continuous and dashed curves correspond to the QCD predictions obtained from the "EMC" and "BCDMS" parton distributions, respectively. For $x<0.14$ ($x>0.14$) the predictions are for pp (pN) at $\sqrt{s}=62$ ($\sqrt{s}=27.4$) GeV as appropriate for the data.

Another standard convention of PDF studies and predictions was also very quickly introduced.

Benchmark cross sections for $p\bar{p}$ collisions at 1.8 TeV

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The parton distributions we use are the MRS sets 1, 2, 3, E and B [1,2]. Details of how they are derived will not be repeated here. We can summarise by saying that five sets are available. Sets MRS1, MRS2 and MRS3 have broadly similar quark distributions but different gluons (soft glue, hard glue and a more singular ($1/\sqrt{x}$) glue respectively) and correspondingly different $\Lambda_{\overline{MS}}$ values. Set MRS2 is disfavoured by data on J/ψ hadroproduction and direct photon production. Set MRS3 was deliberately constructed to have a radically different small x gluon distribution, but for present day phenomenology—which generally does not probe the small x regions—gives very similar predictions to set MRS1.

It should be mentioned that W and Z cross sections for $\sqrt{s} = 1.8$ TeV have also recently been calculated in [8]. There is reasonable agreement with the present calculations, except for the values of R. This disagreement can be traced to the treatment of the charm quark distribution. The charm quark contributes unequally to the W and Z cross sections ($c\bar{s} \to W^+$ compared with $c\bar{c} \to Z^0$) and the effects of this can be seen in the value of R. In the MRS sets, the charm

CHARM QUARK CONTRIBUTION TO THE W AND Z CROSS SECTIONS AT $p\bar{p}$ COLLIDERS

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The ratio R of the cross sections for $p\bar{p}\to W\to \ell\nu$ and $p\bar{p}\to Z\to \ell^+\ell^-$ is one of the most important precision measurements at present day $p\bar{p}$ colliders. In previous studies we have investigated some of the theoretical uncertainties in the calculation of this ratio. We further refine the analysis by considering the uncertainty coming from the charm quark content of the nucleon. We show that data on the charm quark contribution to deep inelastic structure function F_2 are already sufficiently precise to place limits on this uncertainty, and we conclude that the charm quark uncertainty in the ratio of W and Z cross sections does not pose a serious problem. We predict that $R=10.4\pm0.1$ at $\sqrt{s}=1.8$ TeV if $N_\nu=3$ and $m_t>M_W$.

Table 1
The sensitivity of R_σ to the charm distribution.

$\sqrt{s}$ (GeV)	charm	$\Delta\sigma_W$ (nb)	$\Delta\sigma_Z$ (nb)	σ_W (nb)	σ_Z (nb)	R_σ
630	–	0	0	6.07	1.95	3.11
	$MRSB_4$	0.099	0.002	6.16	1.95	3.16
	$MRSB_8$	0.090	0.002	6.15	1.95	3.15
	DO1	0.131	0.004	6.20	1.95	3.17
	EHLQ1	0.081	0.081	6.15	1.95	3.15
1800	–	0	0	17.47	5.82	3.00
	$MRSB_4$	1.51	0.056	18.97	5.88	3.23
	$MRSB_8$	1.35	0.045	18.81	5.87	3.21
	DO1	1.69	0.081	19.15	5.90	3.24
	EHLQ1	1.48	0.049	18.94	5.87	3.23

Also the implication for very high precision Collider measurements were realised very early.

PARTON DISTRIBUTION UNCERTAINTY IN THE MEASUREMENT OF M_W IN PROTON–ANTIPROTON COLLISIONS

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We show explicitly how the value of the W boson mass, M_W, measured at the $p\bar{p}$ colliders depends on the choice of parton distributions used in the fitting procedure, and demonstrate why the error from this source (of order ±50 MeV or less) is considerably smaller than was previously believed. Recent deep inelastic muon scattering data on the structure function ratio $F_2^{\mu n}/F_2^{\mu p}$ play a key role in reducing this uncertainty on M_W.

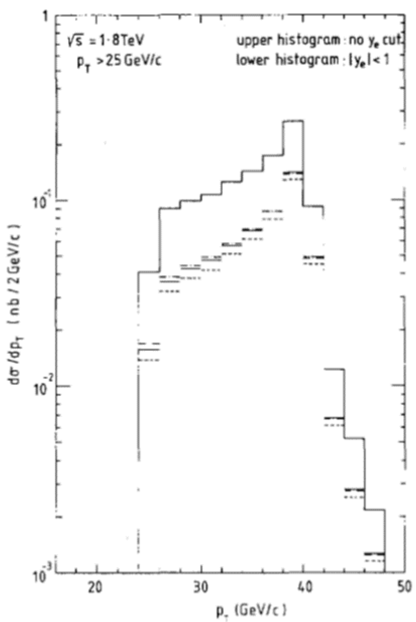

Fig. 1. Charged lepton transverse momentum (p_T) distribution for $p\bar{p}\to W(\to e\nu)+X$ at $\sqrt{s}=1.8$ TeV and with $p_T>25$ GeV/c. The upper histogram (solid lines) corresponds to no lepton rapidity cut. The lower histograms correspond to $|y_e|<1$ with the MRSB′ (solid lines), DO1 (dash-dotted lines) and EHLQ1 (dashed lines) parton distributions.

Along with the potential to improve the relevant PDFs with particular data.

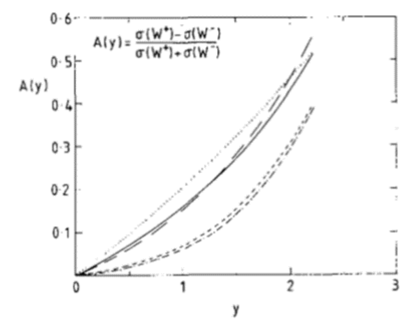

Fig. 3. Theoretical predictions for the $W^{\pm}$ charge asymmetry as a function of rapidity at $\sqrt{s}=1.8$ TeV, using the parton distributions of MRSB′ (solid line), MRSE′ (long dashed line), DO1 (dash-dotted line), DO2 (short dashed line) and EHLQ1 (dotted line).

An early interest in the implications of very low-x physics soon to be probed at HERA.

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Parton distributions at small x

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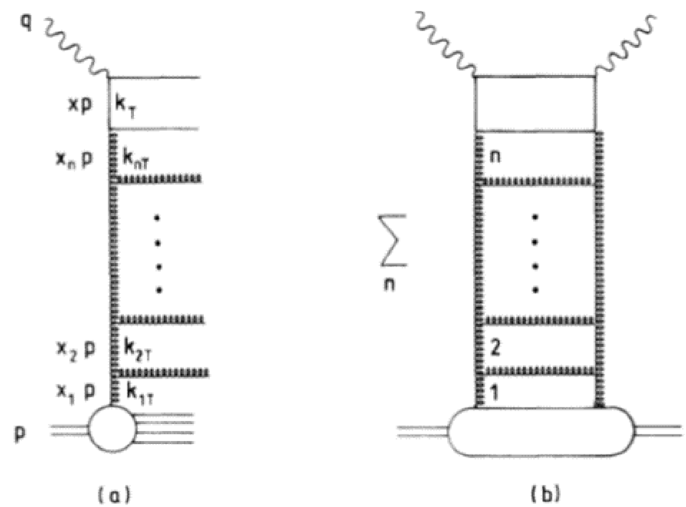
We perform a next-to-leading-order QCD analysis of the recent data for deep-inelastic lepton-nucleon scattering and related processes, in which we pay particular attention to the forms of the parton distributions at very small x. We discuss in detail, and we incorporate in the analysis, the theoretical QCD results leading to the singular $x^{-1/2}$-type behavior of the gluon and sea-quark distributions, as well as the modifications due to shadowing effects. We find the QCD shadowing corrections are significant for $x \lesssim 10^{-3}$ even though the parton distributions are below their saturation limit. We give predictions for the structure functions F_2 and F_L accessible at the DESY ep collider HERA, and for W and Z production up to the energies of the CERN Large Hadron Collider and the Superconducting Super Collider. We discuss the possibility of experiments at these colliders probing the parton distributions in the very-small-x region.

Look at suggestions from different ways of ordering gluon ladder - DGLAP or BFKL.



Also look at possible beyond leading twist contributions, e.g shadowing.

And, most importantly, implications for other processes.

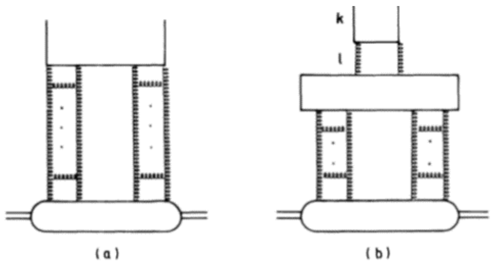


FIG. 5. Diagrams giving rise to shadowing corrections to the evolution equation, (36), for the sea-quark distributions.

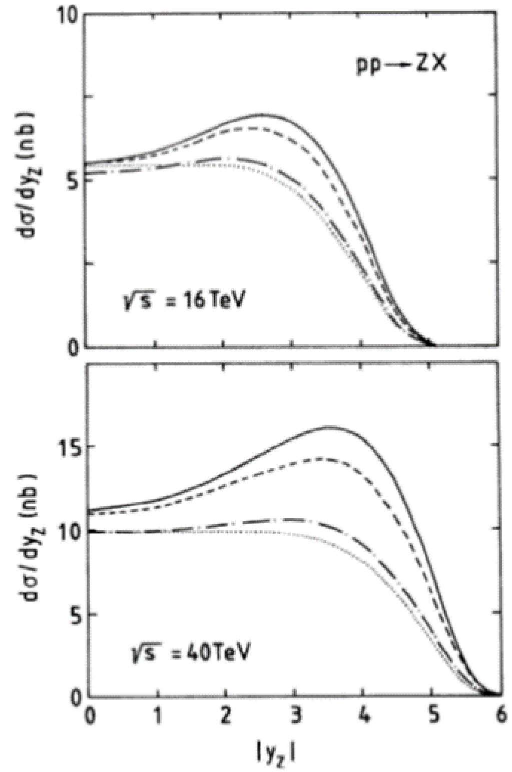


FIG. 16. The rapidity distribution of Z bosons produced in pp collisions at $\sqrt{s}=16$ TeV and $\sqrt{s}=40$ TeV as predicted by the B_- and B_0 sets of partons. The unshadowed B_- prediction is shown as a solid line, shadowing with $R=5$ GeV^{-1} as a dashed line, and shadowing with $R=2$ GeV^{-1} as a dot-dashed line. The dotted line is the B_0 prediction. The details of observing the produced Z by its $\mu^+\mu^-$ decay mode are discussed in Ref. 36.

Scale dependence of $\Lambda_{\overline{MS}}$ from deep inelastic scattering

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Precision measurements of $\Lambda_{\overline{MS}}$ from deep inelastic scattering traditionally use a fixed renormalization scale $\mu=Q$. This is in contrast to measurements in e^+e^- annihilation, where "scale dependence" is an important source of uncertainty on the value of $\Lambda_{\overline{MS}}$. We extend our previous determination of $\Lambda_{\overline{MS}}$ to allow for different scale choices. We find that our previous value of $\alpha_s(M_Z)=0.109^{+0.004}_{-0.005}$ becomes $\alpha_s(M_Z)=0.109^{+0.007}_{-0.008}$ when a reasonable variation of scale is included. We discuss the implications of this result for recent attempts to obtain information on the scale of supersymmetry from coupling constant unification.

A very early investigation of the scale dependence we are now discussing again.

Already knew that $\mu \sim Q$ was most sensible, but also preferred.

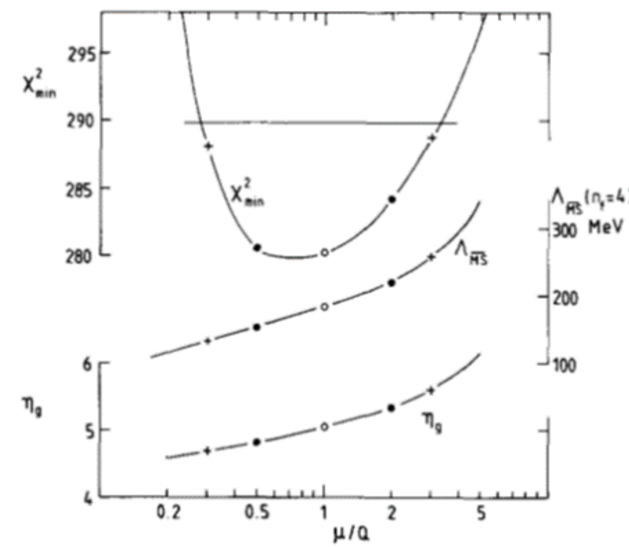

Fig. 1. The effect of changing the scale from $\alpha_s(Q)$ to $\alpha_s(\mu)$ in the NLO structure function analysis. The upper curve shows the optimum value, $\chi^2_{min}(\mu)$, of χ^2 obtained in fitting to the BCDMS and CDHSW deep-inelastic structure function data (for different choices of μ), simultaneously with WA70 prompt photon data. The horizontal line is at $\chi^2_+ \equiv$ [minimum value of $\chi^2_{min}(\mu)$] + 10. The lower curves are the values of $\Lambda^{(4)}_{\overline{MS}}$ and the exponent η_g, of $(1-x)$ in the gluon distribution, obtained in these fits. The open circles correspond to the conventional fit with $\mu=Q$ (essentially the B_0 fit of ref. [12]).

James was also interested in expanding the range of knowledge if possible.

Parton distributions for the pion extracted from Drell-Yan and prompt photon experiments

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We determine the parton distributions of the pion from a consistent next-to-leading-order analysis of several high-statistics $\pi^{\pm}N$ experiments including both Drell-Yan and prompt photon production.

$$xV_\pi = A_V x^\alpha (1-x)^\beta ,$$
$$xS_\pi \equiv 2x(u+\bar{d}+\bar{s}) = A_s(1-x)^{\eta_s} ,$$
$$xg = A_g(1-x)^{\eta_g} ,$$

And linking to other sources of available information.

Very early lattice comparison.

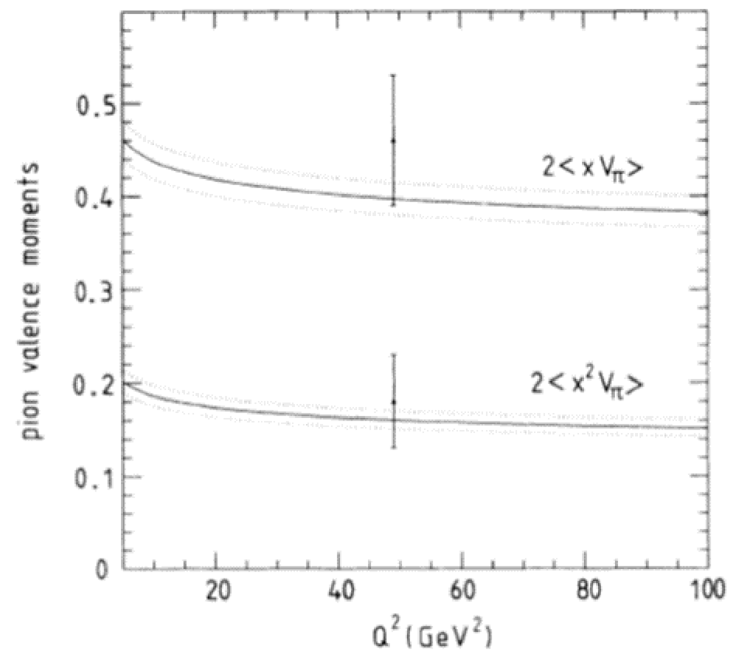

FIG. 11. The first two moments of the pion valence distribution (solid lines) as predicted from the fit to the Drell-Yan data of NA10 compared with the predictions of lattice QCD [15]. The uncertainty in the valence parameters marks out the regions bounded by the dotted lines.

New improved data provides evidence for changes in PDFs.

New information on parton distributions

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(Received 5 May 1992; revised manuscript received 28 August 1992)

New data on structure functions from deep-inelastic scattering provide new information on parton distributions, particularly in the $0.01 < x < 0.1$ interval. This has important implications for predictions for the DESY ep collider HERA and for present and future high-energy hadron colliders. We present the results of updated fits to all available precision structure function and related data. We focus in particular on two issues: (a) the increase in the sea-quark distributions at small x implied by new F_2 data from the New Muon Collaboration, and its implications for other processes, and (b) the evidence for SU(2)-symmetry breaking in the light-quark sea. We show that although good fits can be obtained with or without this symmetry breaking, more physically reasonable parton distributions are obtained if we allow $\bar{d} > \bar{u}$ at small x. With the inclusion of the latest deep-inelastic data we find $\alpha_s(M_Z) = 0.111^{+0.004}_{-0.005}$. We also show how W, Z, and Drell-Yan production at $\bar{p}p$ colliders can give information on parton distributions.

PACS number(s): 13.60.Hh; 12.38.Bx; 13.15.Dk

$$xg(x, Q_0^2) = A_g\, x^{\delta_g}\, (1 + \gamma_g x)\, (1 - x)^{\eta_g}$$

$$xS \equiv 2x\, (\bar{u} + \bar{d} + \bar{s})$$
$$= A_S\, x^{\delta_s}\, (1 + \epsilon_S x^{1/2} + \gamma_S x)\, (1 - x)^{\eta_S}$$

$$2\bar{s} = 0.2\ S,$$

$$2\bar{d} = 0.4\ S + \Delta,$$

$$2\bar{u} = 0.4\ S - \Delta,$$

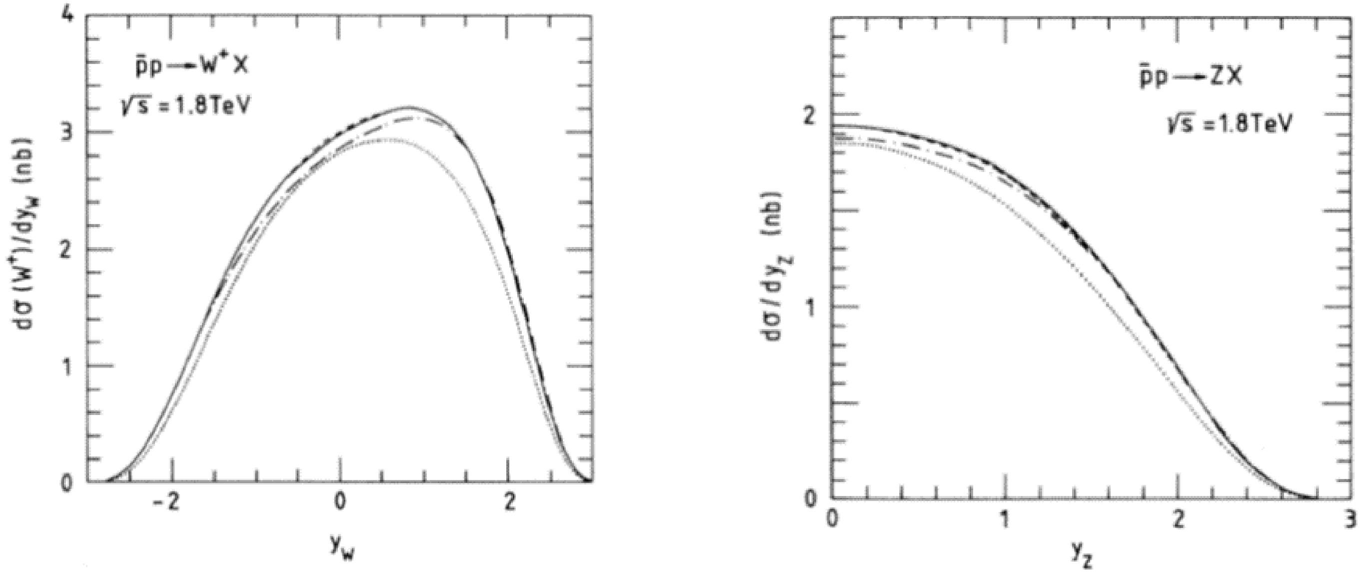
with

$$x\Delta \equiv x\, (\bar{d} - \bar{u}) = A_\Delta\, x^{\eta_\Delta}\, (1 - x)^{\eta_S}.$$

TABLE III. Description of the deep-inelastic data for the three sets of partons shown in terms of χ^2.

Measurement		No. of data	χ^2 D$_0$	S$_0$	D$_-$
BCDMS	$F_2^{\mu p}$	142	153	144	148
NMC[a]	$F_2^{\mu p}$	73	100	101	100
NMC[a]	$F_2^{\mu D}$	73	78	83	78
EMC	F_2^n/F_2^p	10	3	3	3
BCDMS	F_2^n/F_2^p	11	5	7	5
NMC	F_2^n/F_2^p	11	17	20	17
CDHSW	$F_2^{\nu N}$	84	59	53	60
CDHSW	$xF_3^{\nu N}$	94	53	56	56
CCFR[a]	$F_2^{\nu N}$	81	36	34	37
CCFR[a]	$xF_3^{\nu N}$	79	25	30	25

Again look at predictions and introduce philosophy of global fits.



We stress the importance of examining *all* processes that involve the parton distributions. We have considered several cases where there are direct connections between features of deep-inelastic scattering and of hadronic reactions. For example, the *ratio* of the W and Z cross sections in $\bar{p}p$ collisions is tied to the *ratio* n/p of the structure functions at $x \sim M_V/\sqrt{s}$, while the *asymmetry* of the $W^\pm$ rapidity distributions is governed by the *slope* of the n/p ratio at that x value. The *magnitude* of the W cross section is rigidly constrained by the *size* of F_2 at $x \sim M_W/\sqrt{s}$ and so the cross sections at the CERN Super Proton Synchrotron (SPS) collider are already tightly constrained by the previous structure function measurements at $x \sim 0.13$, while those at the Fermilab collider are influenced by the new NMC measurement of F_2 around $x \sim 0.04$. Likewise, in the future predictions at LHC and/or SSC will be based on structure function measurements at HERA in the region $x \sim 0.005$.

This involved reacting quickly to new important data.

PHYSICAL REVIEW D VOLUME 50, NUMBER 11 1 DECEMBER 1994

Parton distributions of the proton

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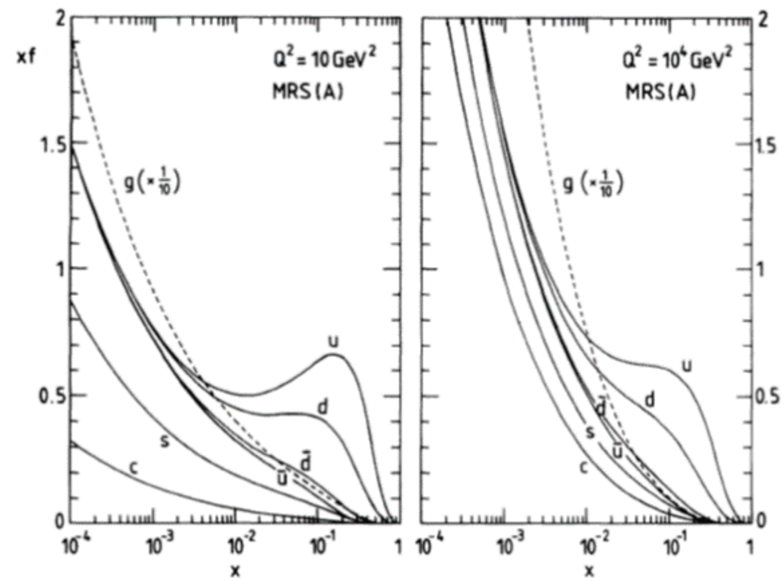
(Received 8 June 1994)

To obtain improved parton densities of the proton, we present a new global analysis of deep-inelastic and related data including, in particular, the recent measurements of F_2 at DESY HERA, of the asymmetry of the rapidity distributions of $W^\pm$ production at the Fermilab $p\bar{p}$ collider and of the asymmetry in Drell-Yan production in pp and pn collisions. We also incorporate data to determine the flavor dependence of the quark sea distributions. We find that the behavior of the partons at small x is consistent with the precocious onset of BFKL leading $\ln(1/x)$ dynamics. We discuss the ambiguities remaining in the gluon distribution. We present improved predictions for W boson (and t quark) production at the Fermilab $p\bar{p}$ collider.

TABLE I. Experimental data used to determine the MRS parton distributions. The last column gives an indication of the main type of constraint imposed by a particular set of data.

Process/experiment	Leading-order subprocess	Parton determination
DIS ($\mu N \to \mu X$) BCDMS, NMC $F_2^{\mu p}, F_2^{\mu n}$	$\gamma^* q \to q$	Four structure functions→ $u+\bar{u}$, $d+\bar{d}$, $\bar{u}+\bar{d}$, s (assumed$=\bar{s}$), but only $\int xg(x)dx \simeq 0.5$ [$\bar{u}-\bar{d}$ is not determined]
DIS ($\nu N \to \mu X$) CCFR (CDHSW) $F_2^{\nu N}, xF_3^{\nu N}$	$W^* q \to q'$	
$\mu N \to c\bar{c}X$ F_2^c, EMC	$\gamma^* c \to c$	$c \approx 0.1 s$ at Q_0^2
$\nu N \to \mu^+\mu^- X$ CCFR	$W^* s \to c$ $\hookrightarrow \mu^+$	$s \approx \frac{1}{2}\bar{u}$ (or $\frac{1}{2}\bar{d}$)
DIS (HERA) F_2^{ep} (H1,ZEUS)	$\gamma^* q \to q$	λ ($x\bar{q} \sim xg \sim x^{-\lambda}$, via $g \to q\bar{q}$)
$pp \to \gamma X$ WA70 (UA6)	$qg \to \gamma q$	$g(x \approx 0.4)$
$pN \to \mu^+\mu^- X$ E605	$q\bar{q} \to \gamma^*$	$\bar{q} = \cdots (1-x)^{\eta_S}$
$pp, pn \to \mu^+\mu^- X$ NA51	$u\bar{u}, d\bar{d} \to \gamma^*$ $u\bar{d}, d\bar{u} \to \gamma^*$	$(\bar{u}-\bar{d})$ at x=0.18
$p\bar{p} \to WX(ZX)$ UA2, CDF, D0	$ud \to W$	u, d at $x_1 x_2 s \simeq M_W^2 \to$ $x \approx 0.13$ CERN $x \approx 0.05$ Fermilab
$\to W^\pm$ asym CDF		slope of u/d at $x \approx 0.05$



Also making and comparing predictions for the most important PDF dependent cross sections.

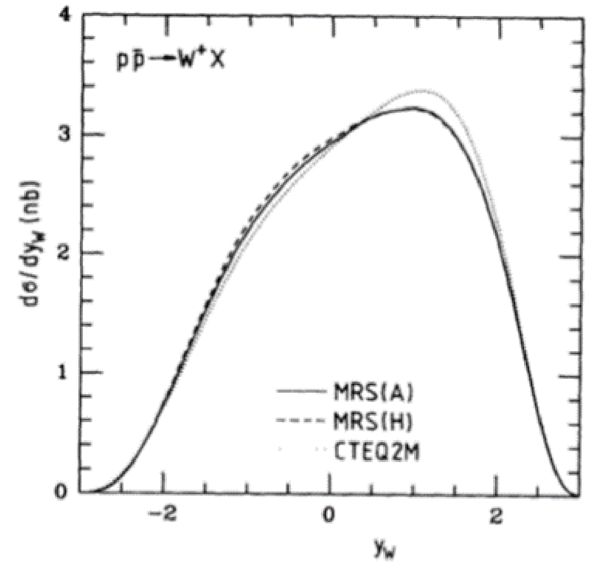
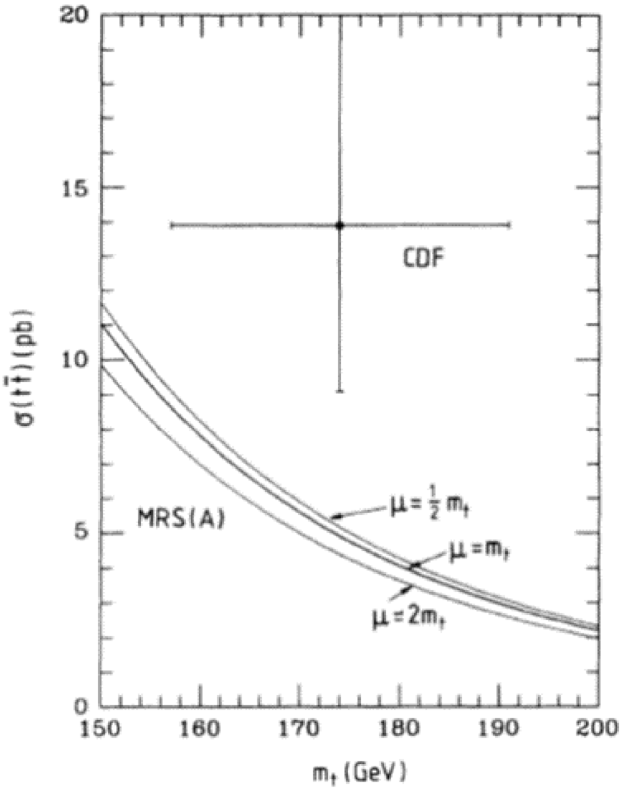


FIG. 20. Next-to-leading-order predictions for W^+ rapidity distribution in $p\bar{p}$ collisions at $\sqrt{s}$=1.8 TeV from the MRS(A,H) and CTEQ2M partons.



Data was now providing complimentary PDF and α_S information.

The α_S dependence of parton distributions

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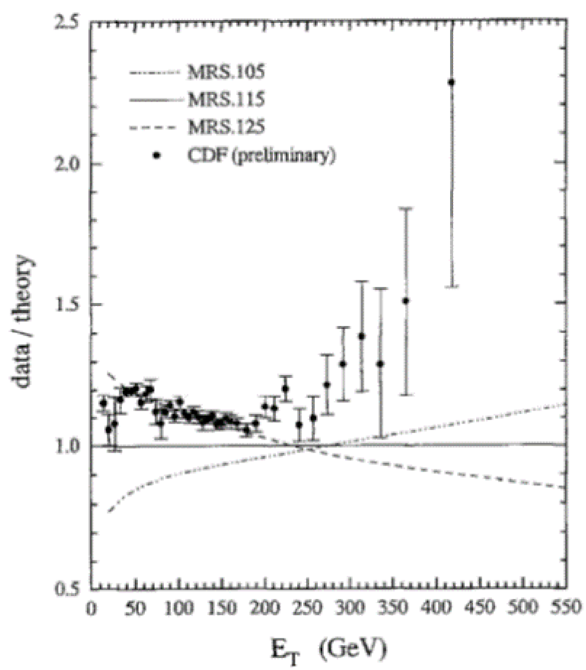
Editor: P.V. Landshoff

Abstract

We perform next-to-leading order global analyses of deep inelastic and related data for different fixed values of $\alpha_S(M_Z^2)$. We present sets of parton distributions for six values of α_S in the range 0.105 to 0.130. We display the (x, Q^2) domains with the largest parton uncertainty and we discuss how forthcoming data may be able to improve the determination of the parton densities.



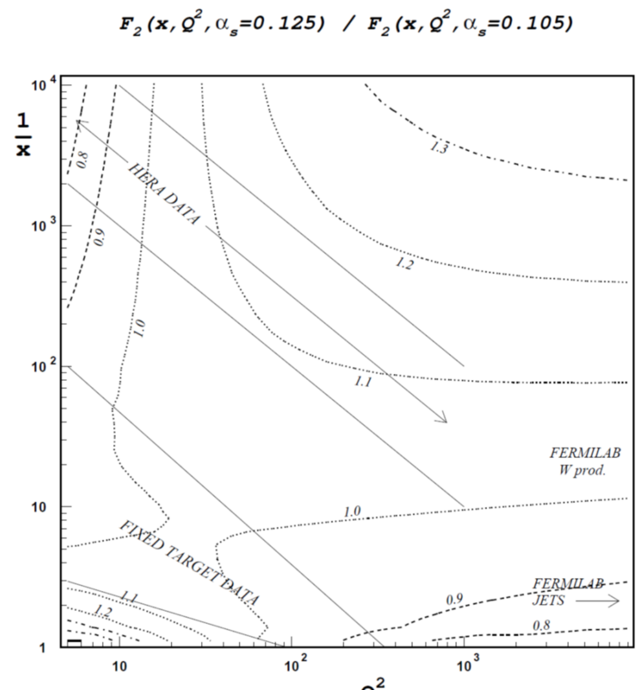


Fig.3

As always James was extending the range of his interests, particularly if there was a promising PhD student to work with.

Spin-dependent parton distributions from polarized structure function data

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Received: 6 June 1994/In revised form: 25 July 1994

Polarized parton distributions in the nucleon

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(Received 2 January 1996)

The distribution of the spin of the nucleon among its constituents can be parametrized in the form of polarized parton distribution functions for quarks and gluons. Using all available data on the polarized structure function $g_1(x,Q^2)$, we determine these distributions at both leading and next-to-leading order in perturbation theory. We suggest three different, equally possible scenarios for the polarized gluon distribution, whose x dependence is found to be only loosely constrained by current experimental data. We examine various possibilities of measuring polarized parton distributions at future experiments. [S0556-2821(96)01811-5]

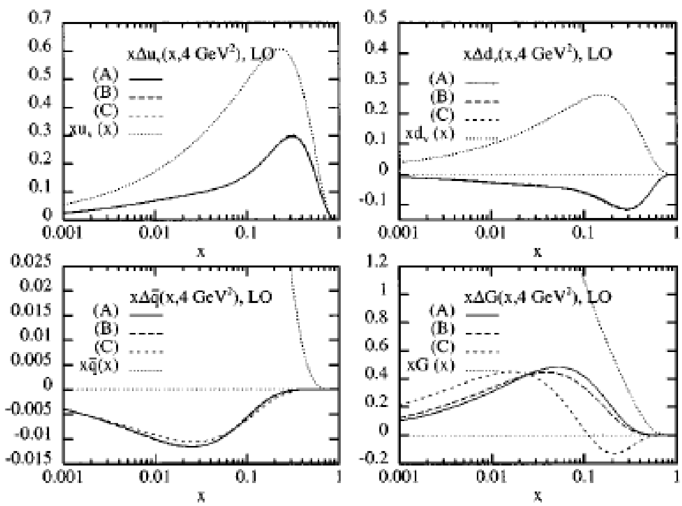

FIG. 1. Leading order polarized parton distributions as described in the text at $Q_0^2=4$ GeV^2 compared to the unpolarized distributions of [16].

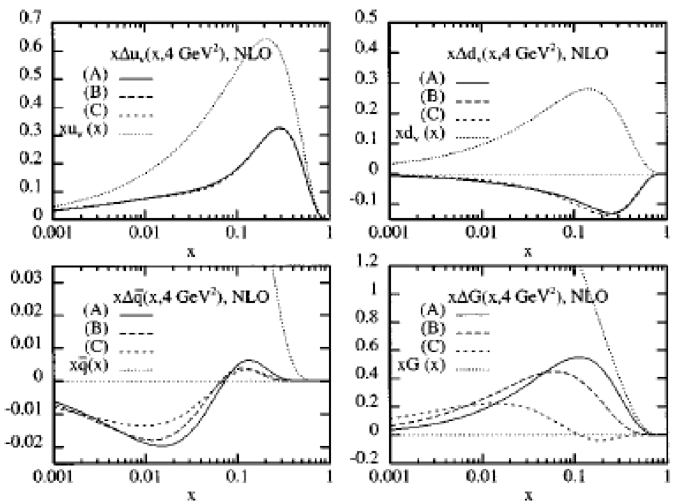

FIG. 2. Next-to-leading order polarized parton distributions as described in the text at $Q_0^2=4$ GeV^2 compared to the unpolarized distributions of [7].

Also investigating different implications for small x physics.

Analytic approaches to the evolution of polarised parton distributions at small x

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Editor: P.V. Landshoff

Abstract

The Q^2 evolution of polarised parton distributions at small x is studied. Various analytic approximations are critically discussed. We compare the full evolution with that obtained from the leading-pole approximation to the splitting functions, and show that the validity of this approximation depends critically on the $x \to 0$ behaviour of the starting distributions. A new analytic solution which is valid at small x is obtained, and its domain of applicability is discussed.

We have also shown that the evolution of the polarised gluon distribution is sensitive to the shape of this distribution in the large-x region. This observation raises doubts on the possibility of determining the gluon polarisation from the evolution of g_1 in the small-x region. It furthermore demonstrates the need for complementary measurements of $\Delta G(x)$ (e.g. from J/Ψ-production or direct-γ measurements).

Dijet production at hadron-hadron colliders in the Balitskii-Fadin-Kuraev-Lipatov approach

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(Received 3 July 1997)

The production in high-energy hadron collisions of a pair of jets with large rapidity separation is studied in an improved Balitskii-Fadin-Kuraev-Lipatov (BFKL) formalism. By recasting the analytic solution of the BFKL equation as an explicit order-by-order sum over emitted gluons, the effects of phase space constraints and the running coupling are studied. Particular attention is paid to the azimuthal angle decorrelation of the jet pair. The inclusion of subleading effects significantly improves the agreement between the theoretical predictions and recent preliminary measurements from the D0 Collaboration. [S0556-2821(97)05021-2]

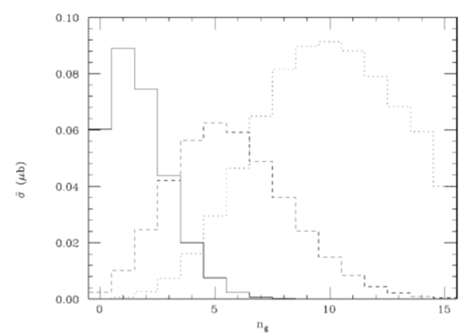

FIG. 3. The contributions to the subprocess cross section $\hat{\sigma}$ for dijet production from different numbers of emitted (i.e., resolved) gluons n_g, for $\Delta=1$ (solid histogram), 3 (dashed), 5 (dotted), running α_s, $P_T=20$ GeV and $\mu=1$ GeV.

A new, expanded collaboration.

Parton distributions: a new global analysis

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[2] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX
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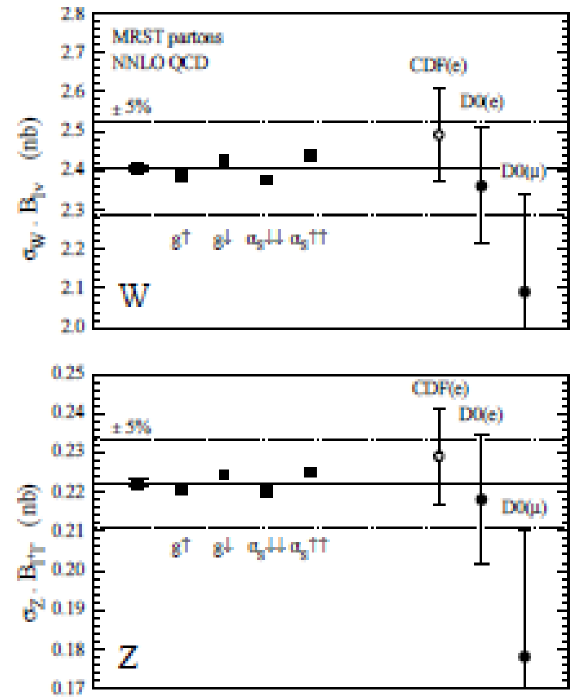
Abstract. We present a new analysis of parton distributions of the proton. This incorporates a wide range of new data, an improved treatment of heavy flavours and a re-examination of prompt photon production. The new set (MRST) shows systematic differences from previous sets of partons which can be identified with particular features of the new data and with improvements in the analysis. We also investigate the sensitivities of the results to (i) the uncertainty in the determination of the gluon at large x, (ii) the value of $\alpha_S(M_Z^2)$ and (iii) the minimum Q^2 cut on the data that are included in the global fit.

The types of data sets were ever expanding. Could now start to make some attempts at investigating “model uncertainties”.

Table 4. The χ^2 values for the DIS data included in the three global fits which resulted in the parameter values listed in Table 1

Data set	No. of data pts	MRST	MRST($g\uparrow$)	MRST($g\downarrow$)
H1 ep	221	164	166	161
ZEUS ep	204	269	273	258
BCDMS μp	174	248	239	264
NMC μp	130	141	148	142
NMC μd	130	101	107	104
SLAC ep	70	119	104	135
E665 μp	53	59	54	56
E665 μd	53	61	62	61
CCFR $F_2^{\nu N}$	66	93	102	92
CCFR $F_3^{\nu N}$	66	68	69	67
NMC n/p	163	186	192	174



Detailed studies of a number of types of variation, e.g. cuts, $\alpha_S(M_Z^2)$ ....
Comparison with the "Competition".

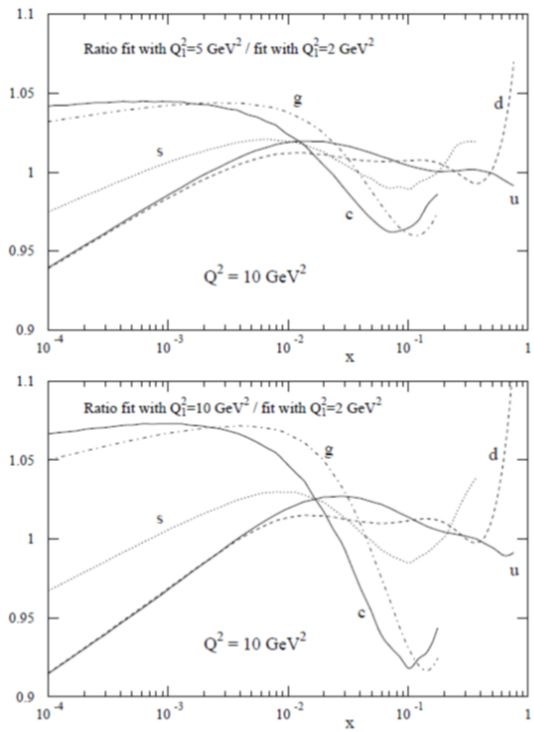


Fig. 20. The parton distributions at $Q^2 = 10\ \mathrm{GeV}^2$, compared with the default MRST partons, obtained by making $Q_1^2 = 5\ \mathrm{GeV}^2$ and $Q_1^2 = 10\ \mathrm{GeV}^2$ cuts in Q^2 to the data included in the fits

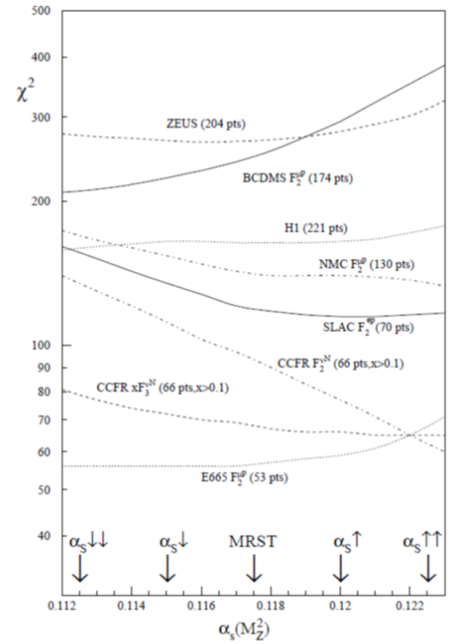


Fig. 21. The contributions to the total global fit χ^2 from the various data sets as a function of α_S. The parton set corresponding to the optimum value $\alpha_S = 0.1175$ is denoted simply MRST and is the default set of partons used throughout the paper. The four other sets, which correspond to the adjacent values of α_S indicated by arrows, are used for comparison purposes. The χ^2 values for the CCFR data are obtained from the statistical error and an additional 1.5% 'systematic' error added in quadrature

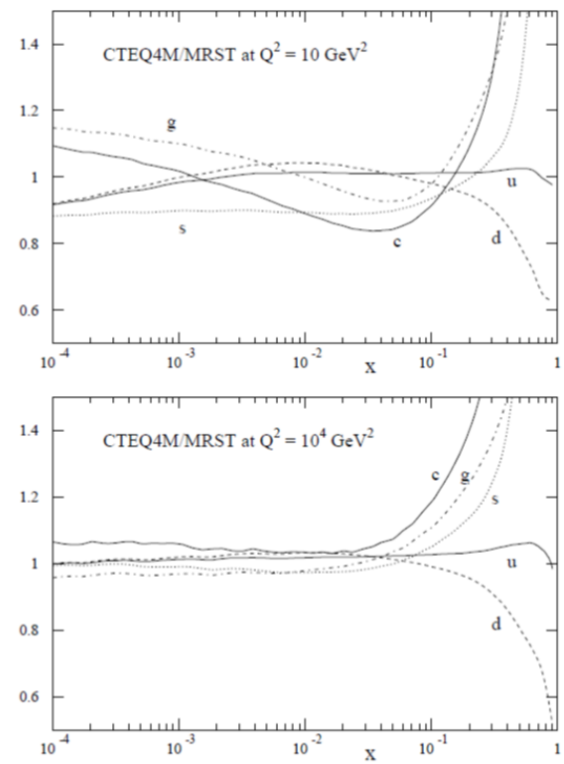
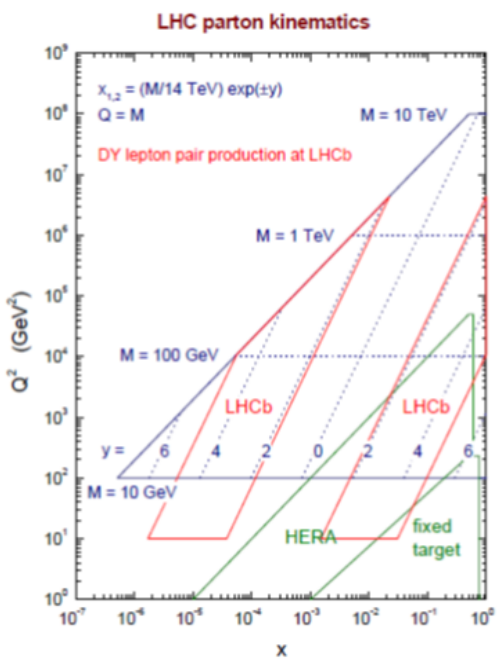


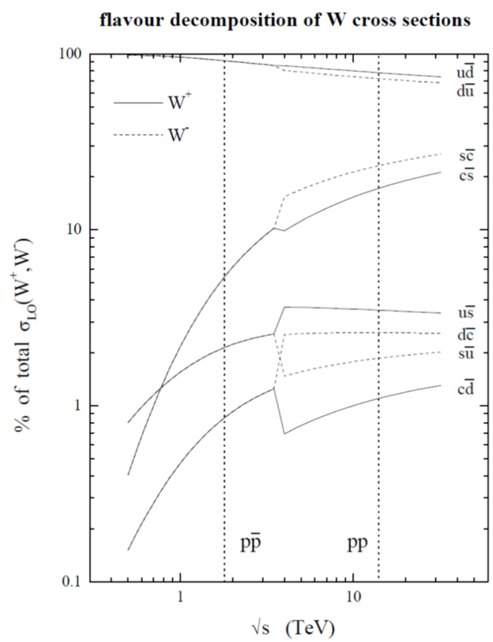
Fig. 44. Ratio of the partons of the CTEQ4M [21] set to those of the MRST set at $Q^2 = 10$ and $10^4\ \mathrm{GeV}^2$

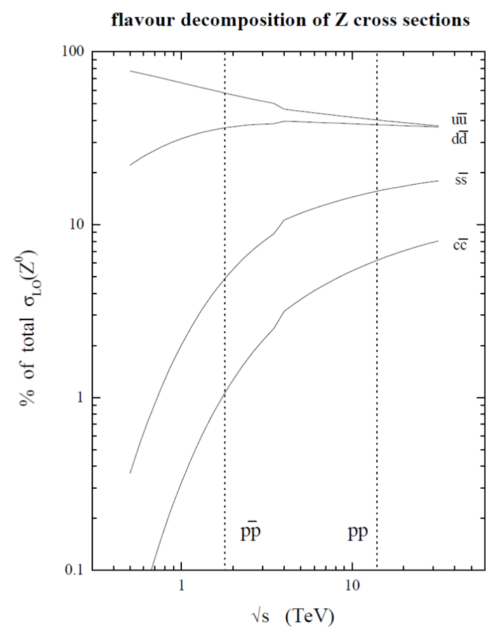
Parton Distributions and the LHC: W and Z Production

A. D. Martin[a], R. G. Roberts[b], W. J. Stirling[a,c] and R. S. Thorne[d]

Further updates led to a detailed prediction study, and the first appearance of a familiar plot (devised by James and shown using updated version).







Parton distributions incorporating QED contributions

A.D. MARTIN[a], R.G. ROBERTS[b], W.J. STIRLING[a] AND R.S. THORNE[c,1]

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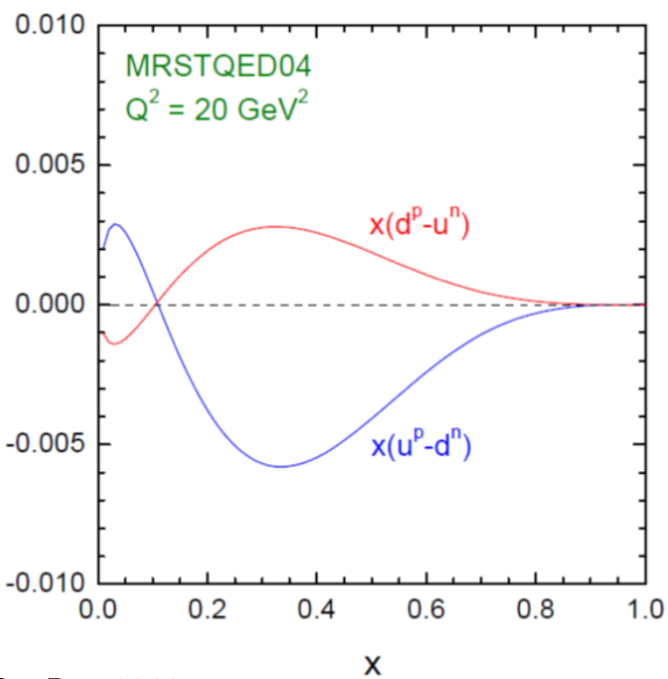
Abstract

We perform a global parton analysis of deep inelastic and related hard-scattering data, including $\mathcal{O}(\alpha_{\rm QED})$ corrections to the parton evolution. Although the quality of the fit is essentially unchanged, there are two important physical consequences. First, the different DGLAP evolution of u and d type quarks introduces isospin violation, i.e. $u^p \neq d^n$, which is found to be unambiguously in the direction to reduce the NuTeV $\sin^2\theta_W$ anomaly. A second consequence is the appearance of photon parton distributions $\gamma(x,Q^2)$ of the proton and the neutron. In principle these can be measured at HERA via the deep inelastic scattering processes $eN \to e\gamma X$; our predictions are in agreement with the present data.

First inclusion of QED in available PDFs.

Modelled photon input from evolution from low-Q^2 valence quarks.

Similar in principle to modern version.



Isospin asymmetry in valence quarks automatically in right direction to reduce NuTeV anomaly.

$$R^- = \frac{\sigma^\nu_{NC} - \sigma^{\bar\nu}_{NC}}{\sigma^\nu_{CC} - \sigma^{\bar\nu}_{CC}}$$
$$= \frac{1}{2} - \sin^2\theta_W - \left(1 - \frac{7}{3}\sin^2\theta_W\right)\frac{[S^-]}{[V^-]}.$$

Update of Parton Distributions at NNLO

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[b] Department of Physics and Astronomy, University College London, WC1E 6BT, UK

Abstract

We present a new set of parton distributions obtained at NNLO. These differ from the previous sets available at NNLO due to improvements in the theoretical treatment. In particular we include a full treatment of heavy flavours in the region near the quark mass. In this way, an essentially complete set of NNLO partons is presented for the first time. The improved treatment leads to a significant change in the gluon and heavy quark distributions, and a larger value of the QCD coupling at NNLO, $\alpha_S(M_Z^2) = 0.1191 \pm 0.002(\text{expt.}) \pm 0.003(\text{theory})$. Indirectly this also leads to a change in the light partons at small x and modifications of our predictions for W and Z production at the LHC. As well as the best-fit set of partons, we also provide 30 additional sets representing the uncertainties of the partons obtained using the Hessian approach.

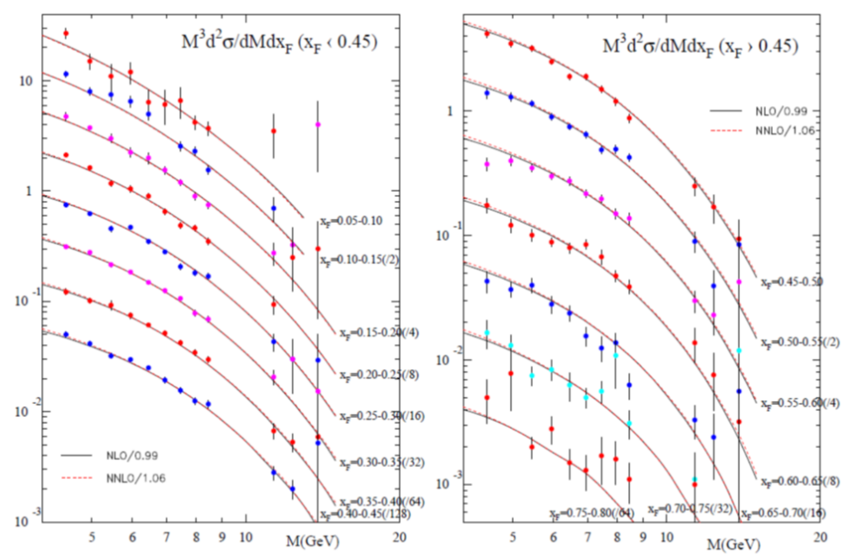

Figure 7: Comparison of the NLO and NNLO Drell–Yan cross sections with the data.

First produced PDFs with approximate NNLO in 2003. OK, due to good approximations to NNLO splitting functions.

First "full" set with heavy quark threshold properly included.

Also differential distributions forDrell-Yan included.

Full dependence in both rapidity and $\alpha_S(M_Z^2)$.

Parton distributions for the LHC

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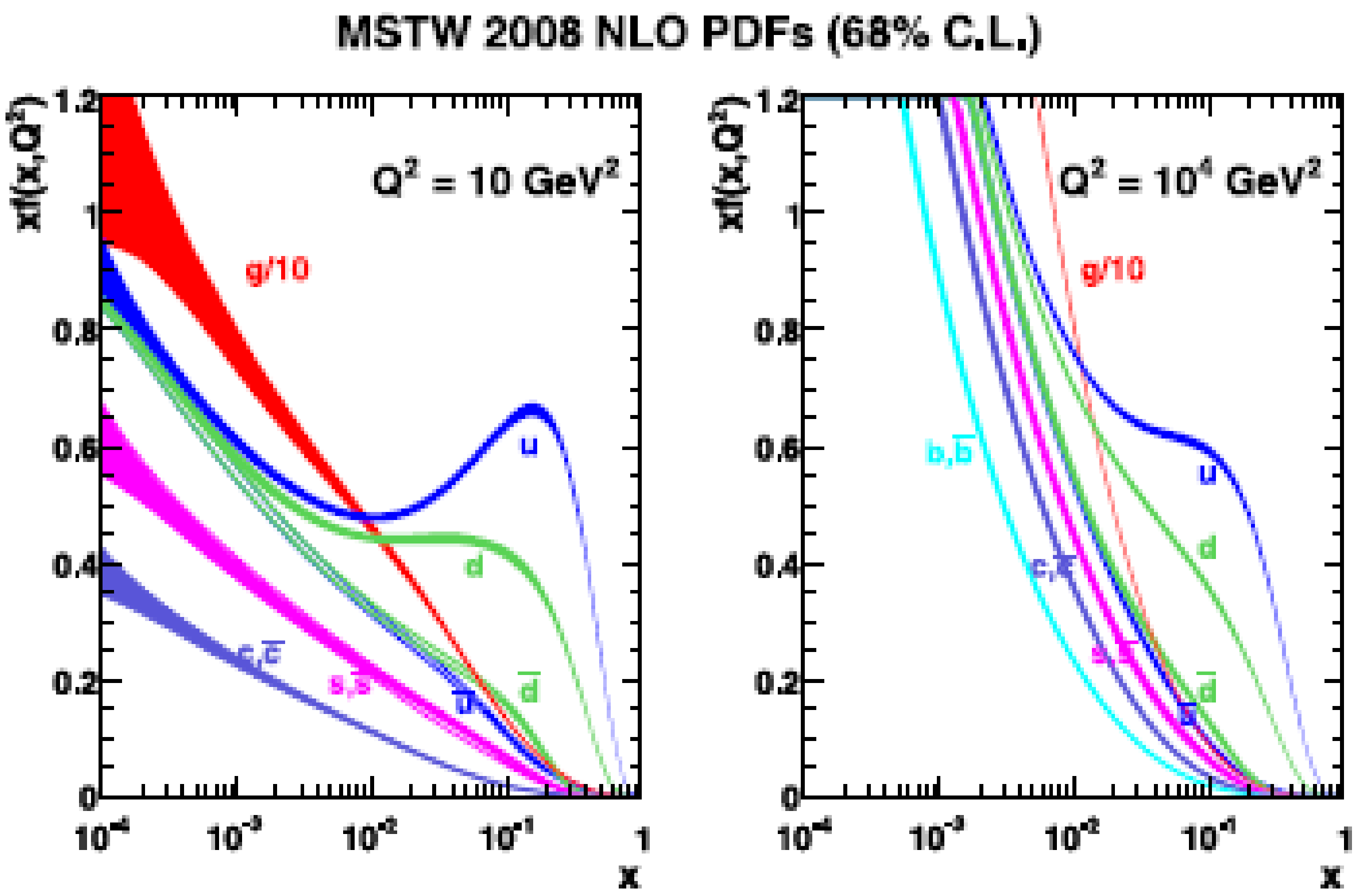


Used dynamical tolerance for the first time.

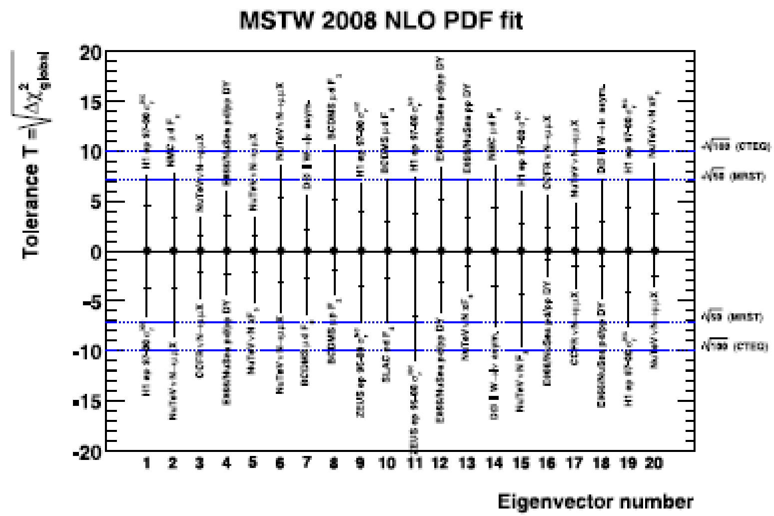


Table 2 The values of $\chi^2/N_{pts.}$ for the data sets included in the global fits. For the NuTeV $\nu N \to \mu\mu X$ data, the effective number of degrees of freedom is quoted instead of $N_{pts.}$ since smearing effects mean that nearby data points are highly correlated [39]. The details of corrections to data, kinematic cuts applied and definitions of χ^2 are contained in the text

Data set	LO	NLO	NNLO
BCDMS μp F_2 [32]	165/153	182/163	170/163
BCDMS μd F_2 [102]	162/142	190/151	188/151
NMC μp F_2 [33]	137/115	121/123	115/123
NMC μd F_2 [33]	120/115	102/123	93/123
NMC $\mu n/\mu p$ [103]	131/137	130/148	135/148
E665 μp F_2 [104]	59/53	57/53	63/53
E665 μd F_2 [104]	49/53	53/53	63/53
SLAC ep F_2 [105, 106]	24/18	30/37	31/37
SLAC ed F_2 [105, 106]	12/18	30/38	26/38
NMC/BCDMS/SLAC F_L [32–34]	28/24	38/31	32/31
E866/NuSea pp DY [107, 108]	239/184	228/184	237/184
E866/NuSea pd/pp DY [109]	14/15	14/15	14/15
NuTeV νN F_2 [37]	49/49	49/53	46/53
CHORUS νN F_2 [38]	21/37	26/42	29/42
NuTeV νN xF_3 [37]	62/45	40/45	34/45
CHORUS νN xF_3 [38]	44/33	31/33	26/33
CCFR $\nu N \to \mu\mu X$ [39]	63/86	66/86	69/86
NuTeV $\nu N \to \mu\mu X$ [39]	44/40	39/40	45/40
H1 MB 99 e^+p NC [31]	9/8	9/8	7/8
H1 MB 97 e^+p NC [110]	46/64	42/64	51/64
H1 low Q^2 96–97 e^+p NC [110]	54/80	44/80	45/80
H1 high Q^2 98–99 e^-p NC [111]	134/126	122/126	124/126
H1 high Q^2 99–00 e^+p NC [35]	153/147	131/147	133/147
ZEUS SVX 95 e^+p NC [112]	35/30	35/30	35/30
ZEUS 96–97 e^+p NC [113]	118/144	86/144	86/144
ZEUS 98–99 e^-p NC [114]	61/92	54/92	54/92
ZEUS 99–00 e^+p NC [115]	75/90	63/90	65/90
H1 99–00 e^+p CC [35]	28/28	29/28	29/28
ZEUS 99–00 e^+p CC [36]	36/30	38/30	37/30
H1/ZEUS ep F_2^{charm} [41–47]	110/83	107/83	95/83
H1 99–00 e^+p incl. jets [59]	109/24	19/24	–
ZEUS 96–97 e^+p incl. jets [57]	88/30	30/30	–
ZEUS 98–00 $e^\pm p$ incl. jets [58]	102/30	17/30	–
DØ II $p\bar{p}$ incl. jets [56]	193/110	114/110	123/110
CDF II $p\bar{p}$ incl. jets [54]	143/76	56/76	54/76
CDF II $W \to \ell\nu$ asym. [48]	50/22	29/22	30/22
DØ II $W \to \ell\nu$ asym. [49]	23/10	25/10	25/10
DØ II Z rap. [53]	25/28	19/28	17/28
CDF II Z rap. [52]	52/29	49/29	50/29
All data sets	**3066/2598**	**2543/2699**	**2480/2615**

Also extended parameterisation for e.g. gluon.

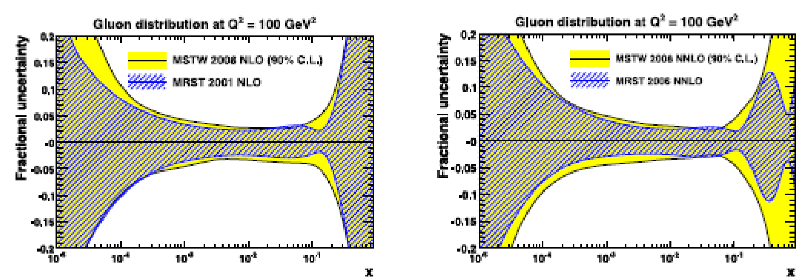
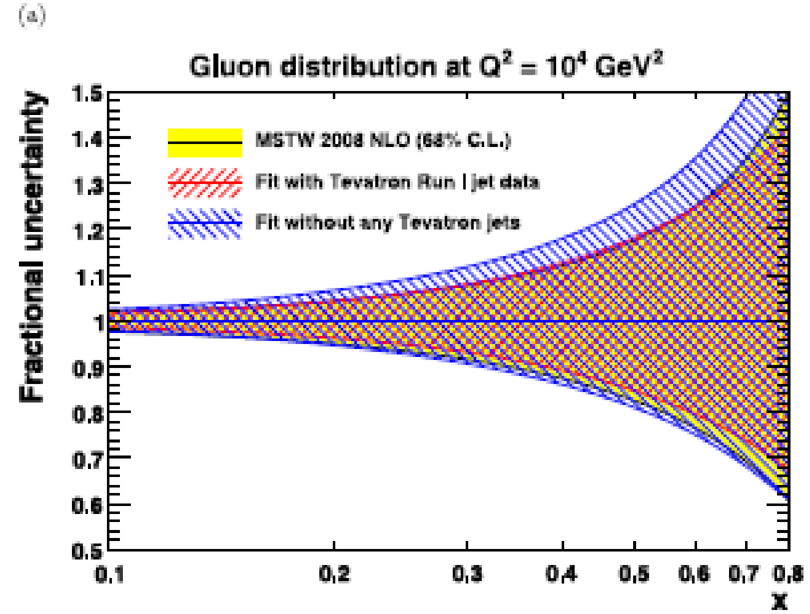
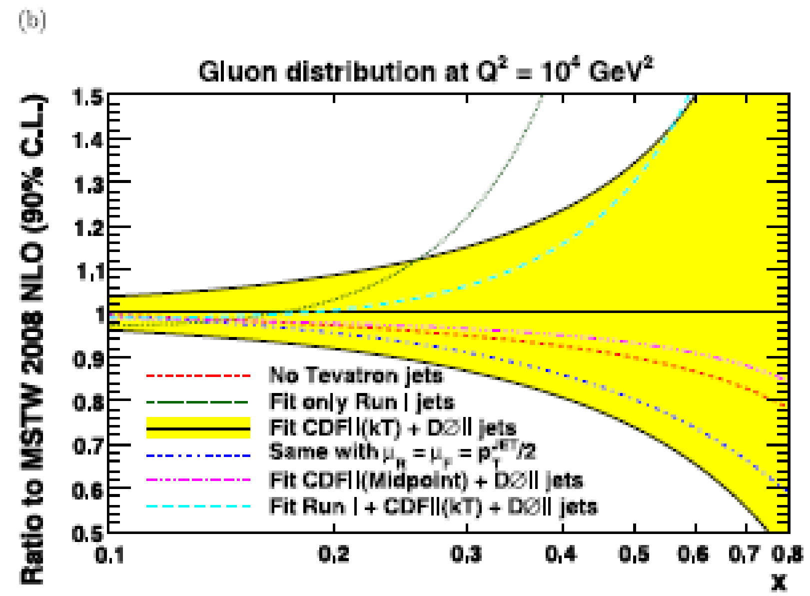


Fig. 17 The fractional uncertainty on the gluon distribution at $Q^2 = 100$ GeV^2 (a) from the MSTW 2008 NLO fit compared to that from the MRST 2001 NLO fit [16] and (b) from the MSTW 2008 NNLO fit compared to that from the MRST 2006 NNLO fit [21]

Studies of various issues such as inclusion of jets or not.

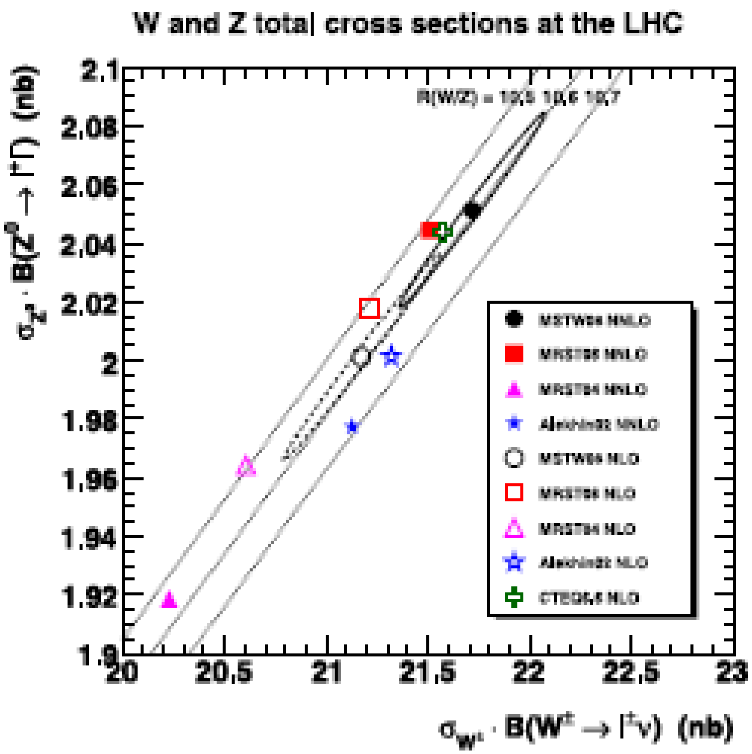
Also variation of PDFs with scale, or jet algorithm.

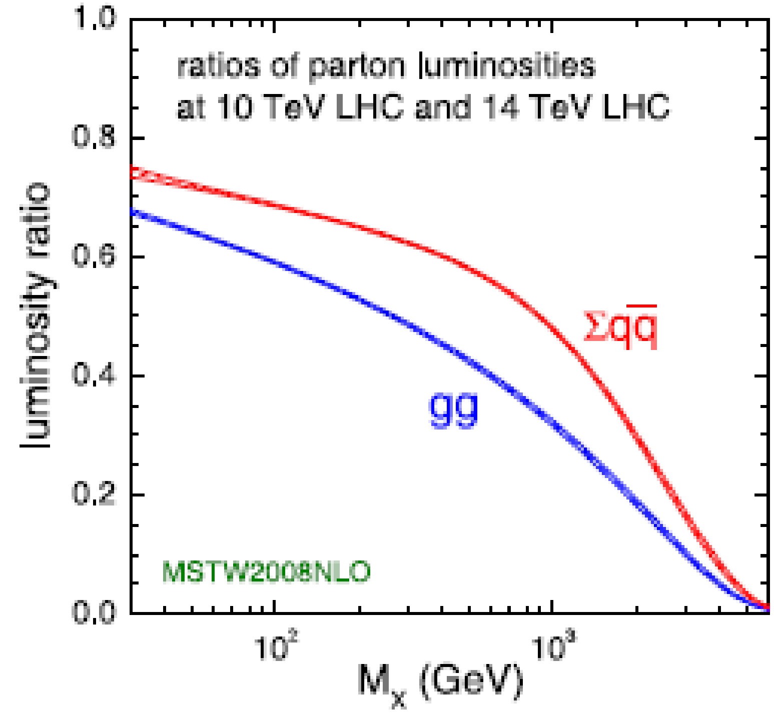




Again look at implications, and full comparison with older PDF or alternative sets.

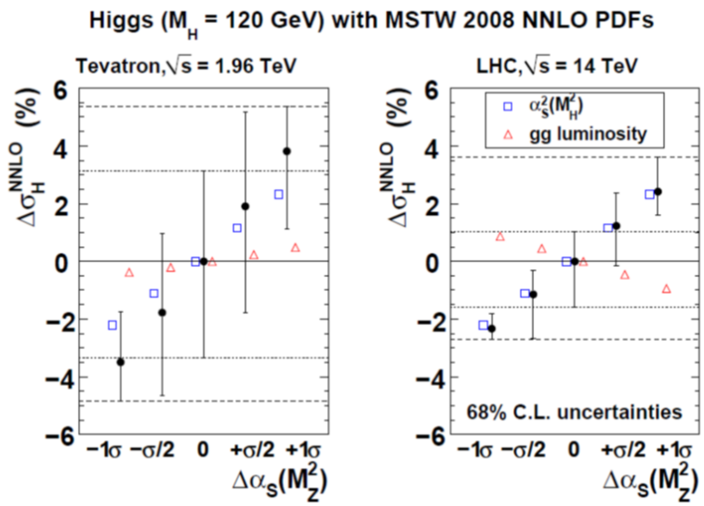
Also the first appearance of one of James' "standard" plots.

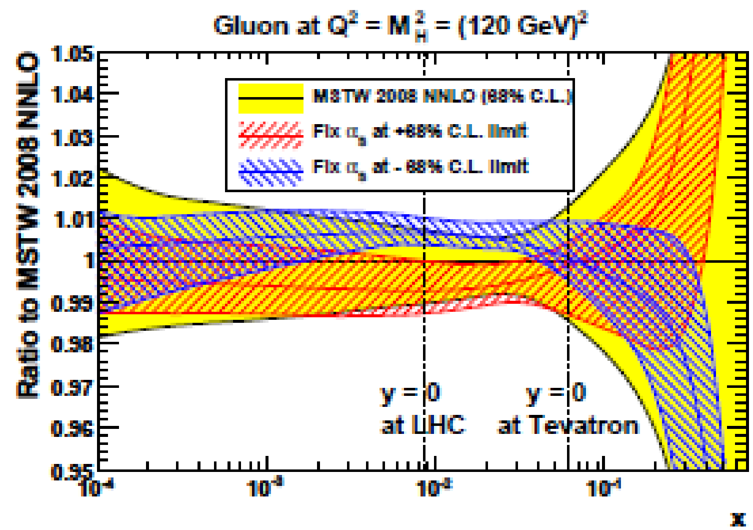




MSTW produced PDFs with $\alpha_s(m_z^2)$ uncertainties and in fine binned variations in $\alpha_s(m_z^2)$.

As always looked in detail at implications.





Also examined different flavour scheme numbers. James looked in great detail at how these affected LHC predictions.

Heavy-quark mass dependence in global PDF analyses and 3- and 4-flavour parton distributions

A.D. Martin[a], W.J. Stirling[b], R.S. Thorne[c] and G. Watt[d]

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[b] Cavendish Laboratory, University of Cambridge, CB3 0HE, UK
[c] Department of Physics and Astronomy, University College London, WC1E 6BT, UK
[d] Theory Group, Physics Department, CERN, CH-1211 Geneva 23, Switzerland

Abstract

We study the sensitivity of our recent MSTW 2008 NLO and NNLO PDF analyses to the values of the charm- and bottom-quark masses, and we provide additional public PDF sets for a wide range of these heavy-quark masses. We quantify the impact of varying m_c and m_b on the cross sections for W, Z and Higgs production at the Tevatron and the LHC. We generate 3- and 4-flavour versions of the (5-flavour) MSTW 2008 PDFs by evolving the input PDFs and α_S determined from fits in the 5-flavour scheme, including the eigenvector PDF sets necessary for calculation of PDF uncertainties. As an example of their use, we study the difference in the Z total cross sections at the Tevatron and LHC in the 4- and 5-flavour schemes. Significant differences are found, illustrating the need to resum large logarithms in Q^2/m_b^2 by using the 5-flavour scheme. The 4-flavour scheme is still necessary, however, if cuts are imposed on associated (massive) b-quarks, as is the case for the experimental measurement of $Zb\bar{b}$ production and similar processes.

Tevatron, $\sqrt{s} = 1.96$ TeV	$B \cdot \sigma^Z_{\rm NNLO}(4{\rm FS})$ (nb)	$B \cdot \sigma^Z_{\rm NNLO}(5{\rm FS})$ (nb)	$B \cdot \sigma^Z_{\rm NNLO}(5{\rm FS}, b)$ (nb)
σ^Z_0	0.2013	0.2016	0.0012
σ^Z_1	0.0409	0.0431	-0.0002
σ^Z_2	0.0063	0.0060	-0.0003
total	0.2485	0.2507	0.0008
$\Delta_b\sigma^Z$	0.0006	–	
total + $\Delta_b\sigma^Z$	0.2491	0.2507	

LHC, $\sqrt{s} = 7$ TeV	$B \cdot \sigma^Z_{\rm NNLO}(4{\rm FS})$ (nb)	$B \cdot \sigma^Z_{\rm NNLO}(5{\rm FS})$ (nb)	$B \cdot \sigma^Z_{\rm NNLO}(5{\rm FS}, b)$ (nb)
σ^Z_0	0.8083	0.8266	0.0202
σ^Z_1	0.1239	0.1322	-0.0020
σ^Z_2	0.0037	-0.0002	-0.0037
total	0.9359	0.9586	0.0145
$\Delta_b\sigma^Z$	0.0066	–	
total + $\Delta_b\sigma^Z$	0.9426	0.9586	

LHC, $\sqrt{s} = 14$ TeV	$B \cdot \sigma^Z_{\rm NNLO}(4{\rm FS})$ (nb)	$B \cdot \sigma^Z_{\rm NNLO}(5{\rm FS})$ (nb)	$B \cdot \sigma^Z_{\rm NNLO}(5{\rm FS}, b)$ (nb)
σ^Z_0	1.7472	1.8110	0.0641
σ^Z_1	0.2384	0.2557	-0.0050
σ^Z_2	-0.0047	-0.0153	-0.0107
total	1.9809	2.0514	0.0484
$\Delta_b\sigma^Z$	0.0231	–	
total + $\Delta_b\sigma^Z$	2.0040	2.0514	

Table 9: NNLO predictions for the total Z cross section (multiplied by leptonic branching ratio B) at the Tevatron and LHC using MSTW 2008 NNLO PDFs [1] as input, broken down into the α_S^n ($n = 0, 1, 2$) contributions, with $\{q = u, d, s, c;\ \alpha_S^{(4)};$ 4-flavour MSTW 2008 NNLO PDFs$\}$ in the 4FS calculation and $\{q = u, d, s, c, b;\ \alpha_S^{(5)};$ 5-flavour MSTW 2008 NNLO PDFs$\}$ in the 5FS calculation. The final column gives the contribution to the 5FS cross sections from processes where the Z couples directly to b quarks. The additional $\mathcal{O}(\alpha_S^2)$ contributions to the cross section arising from real and virtual b-quark processes, taken from Table 8, are added to the 4FS cross section in the last line of each sub-table.

Double Parton Distributions Incorporating Perturbative QCD Evolution and Momentum and Quark Number Sum Rules

Jonathan R. Gaunt[1] **and W. James Stirling**[1,2]

[1] *Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, U.K.*
[2] *Department of Physics and Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, U.K.*

ABSTRACT: It is anticipated that hard double parton scatterings will occur frequent... the collisions of the LHC, producing interesting signals and significant backgrounds t... tain single scattering processes. For double scattering processes in which the same scale $t = \ln(Q^2)$ is involved in both collisions, we require the double parton distribu... (dPDFs) $D_h^{j_1 j_2}(x_1, x_2; t)$ in order to make theoretical predictions of their rates and ... erties. We describe the development of a new set of leading order dPDFs that repre... an improvement on approaches used previously. First, we derive momentum and nu... sum rules that the dPDFs must satisfy. The fact that these must be obeyed at any sc... used to construct improved dPDFs at the input scale Q_0, for a particular choice of i... scale ($Q_0^2 = 1$ GeV^2) and corresponding single PDFs (the MSTW2008LO set). We describe a novel program which uses a direct $x-$space method to numerically integrat... LO DGLAP equation for the dPDFs, and which may be used to evolve the input dI... to any other scale. This program has been used along with the improved input dI... to produce a set of publicly available dPDF grids covering the ranges $10^{-6} < x_1$ ... $10^{-6} < x_2 < 1$, and $1 < Q^2 < 10^9$ GeV^2.

Same-sign W pair production as a probe of double parton scattering at the LHC

Jonathan R. Gaunt[1], Chun-Hay Kom[1], Anna Kulesza[2], and W. James Stirling[1]

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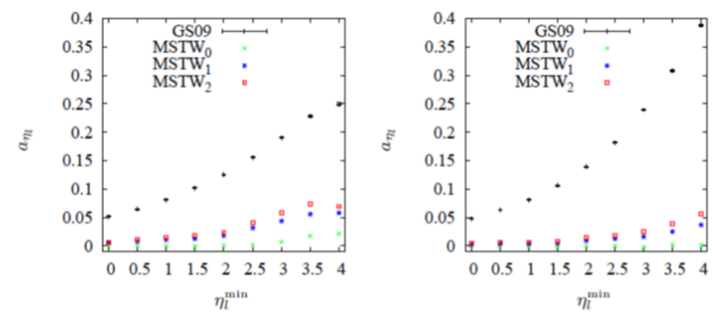
[2] Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University D-52056 Aachen, Germany

November 6, 2018

Abstract. We study the production of same-sign W boson pairs at the LHC in double parton interactions. Compared with simple factorised double parton distributions (dPDFs), we show that the recently developed dPDFs, GS09, lead to non-trivial kinematic correlations between the W bosons. A numerical study of the prospects for observing this process using same-sign dilepton signatures, including $W^\pm W^\pm jj$, di-boson and heavy flavour backgrounds, at 14 TeV centre-of-mass energy is then performed. It is shown that a small excess of same-sign dilepton events from double parton scattering over a background dominated by single scattering $W^\pm Z(\gamma^*)$ production could be observed at the LHC.



(a) Positively charged leptons (b) Negatively charged leptons

Fig. 3. Pseudorapidity asymmetry a_{η_l} for pp collisions at $\sqrt{s} = 14$ TeV evaluated using different dPDFs. No cuts are applied.

At the same time James was investigating and improving the correct theoretical framework for and phenomenological implications of double parton scattering.

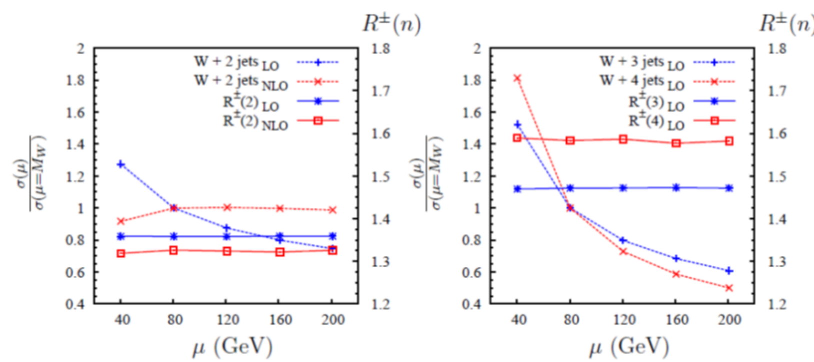
Charge asymmetry in W + jets production at the LHC

C.H. Kom and W.J. Stirling

Cavendish Laboratory, University of Cambridge, CB3 0HE, UK

Abstract

The charge asymmetry in $W^{\pm}+$ jets production at the LHC can serve to calibrate the presence of New Physics contributions. We study the ratio $\sigma(W^+ + n\text{ jets})/\sigma(W^- + n\text{ jets})$ in the Standard Model for $n \leq 4$, paying particular attention to the uncertainty in the prediction from higher-order perturbative corrections and uncertainties in parton distribution functions. We show that these uncertainties are generally of order a few percent, making the experimental measurement of the charge asymmetry ratio a particularly useful diagnostic tool for New Physics contributions.



(c) $W + 2$ jets

(d) $W + 3, 4$ jets (LO only)

Figure 2: Ratios of cross sections for $W^{\pm} + n$ jet production ($n = 0, 1, 2, 3, 4$) to the values obtained with scale $\mu = \mu_R = \mu_F = M_W$ as a function of μ. For $n = 0$, 1 and 2, the cross

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 14$ TeV
MSTW 2008 LO	1.463 ± 0.014	1.365 ± 0.011
MSTW 2008 NLO	1.422 ± 0.012	1.325 ± 0.010
MSTW 2008 NNLO	1.429 ± 0.013	1.328 ± 0.011

Table 1: Predictions for the ratio of W^+ and W^- total cross sections at the LHC at LO, NLO and NNLO pQCD, including the one-sigma (68% cl) PDF uncertainties, with $\mu_R = \mu_F = M_W$.

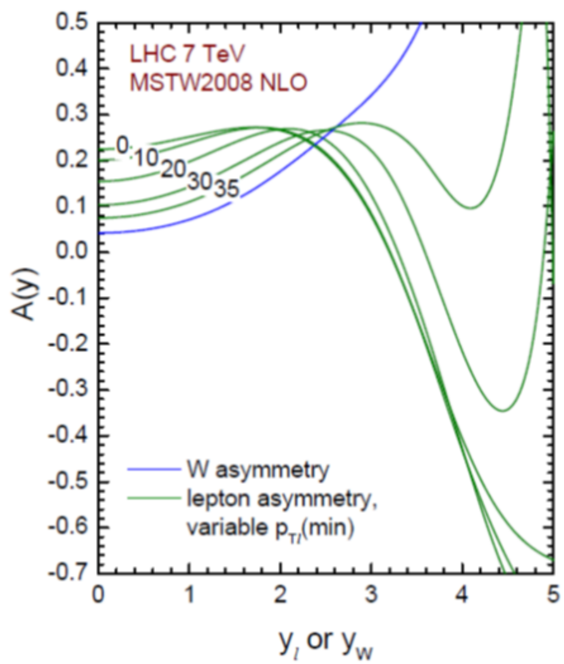
Final article with PDF determinations. As always James was asking additional questions.

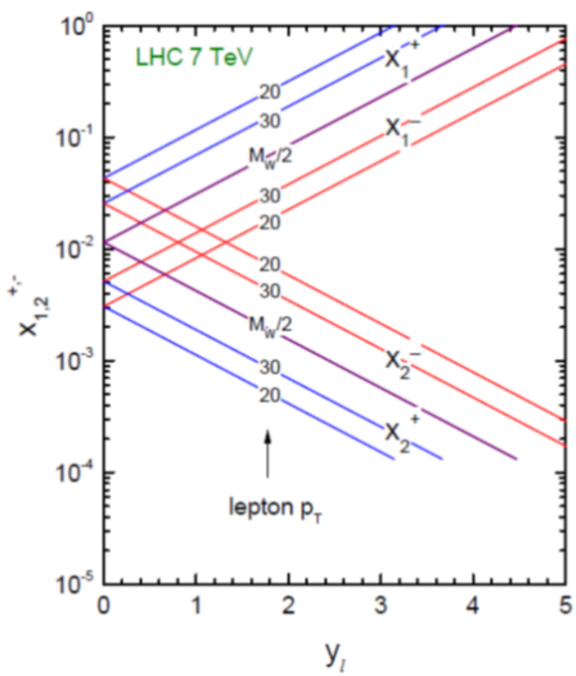
Extended Parameterisations for MSTW PDFs and their effect on Lepton Charge Asymmetry from W Decays

A.D. Martin[a], A.J.Th.M. Mathijssen[b,1], W.J. Stirling[c], R.S. Thorne[d], B.J.A. Watt[d] and G. Watt[e]

[a] Institute for Particle Physics Phenomenology, University of Durham, DH1 3LE, UK
[b] Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, Oxford, OX1 3NP, UK
[c] Cavendish Laboratory, University of Cambridge, CB3 0HE, UK
[d] Department of Physics and Astronomy, University College London, WC1E 6BT, UK
[e] Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland

Improved valence parameterisations fit lepton asymmetry better. What about interpretation and interesting predictions?





James was interested in and contributed so much to, the study of PDFs for their own sake.

(Note – I have essentially “ignored” two 500+ cited articles.)

However, also very much because they were fundamental to lots of particle physics.

Typical of his wide interests and expertise in particle physics and beyond.

He consequently made enormous contributions to the whole world of particle physics, physics and the scientific/academic world in general.

He was elected a Fellow of the Royal Society in 1999.

He played a major role in the foundation of the Institute of Particle Physics Phenomenology in 2000, and served as its first Director.

His textbook QCD and Collider Physics written with Keith Ellis and Bryan Webber has been a standard reference for more than 20 years.

In 2006 he received the national honour of CBE from the Queen for his services to science.

He moved to Cambridge in 2008 to take up the Jacksonian Professorship of Natural Philosophy in the Cavendish Laboratory, becoming Head of the Department of Physics in 2011.

In 2005 he was appointed Pro-Vice Chancellor for Research at Durham. Was twice on the UK Research Excellence Framework panels for Physics, and on STFC Science Council.

Then in 2013 he was appointed to the newly-created position of Provost, the chief academic officer, at Imperial College, London, from which he retired last August

Photograph taken at Alan's $80_{\rm th}$ birthday celebration in Durham.

James and wife Paula enjoying another of his interests.