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Robert Thorne

September 17th 2019

University College London

With thanks to Alan Martin

Late 1990s – an expanded collaboration.

Parton distributions: a new global analysis

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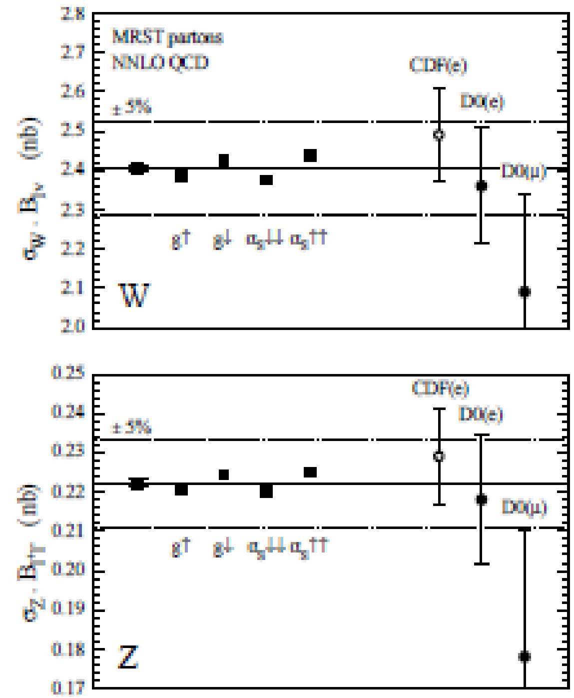
Abstract. We present a new analysis of parton distributions of the proton. This incorporates a wide range of new data, an improved treatment of heavy flavours and a re-examination of prompt photon production. The new set (MRST) shows systematic differences from previous sets of partons which can be identified 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”.

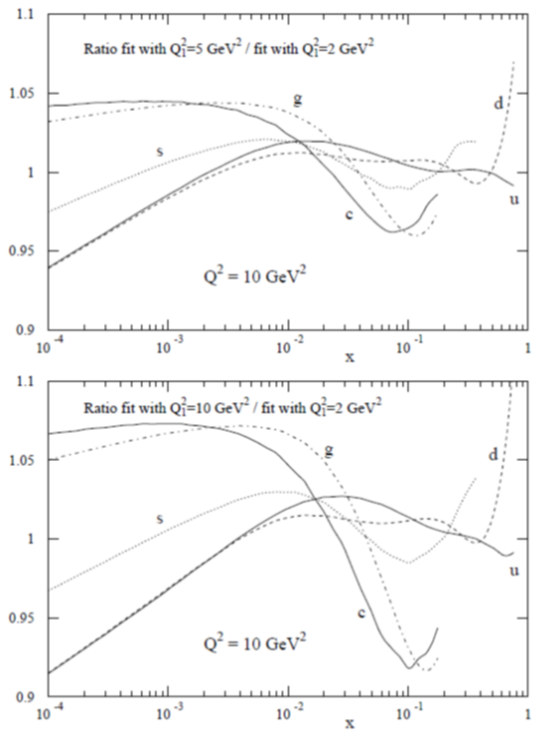


Fig. 20. The parton distributions at $Q^2 = 10\ \mathrm{GeV}^2$, compared with the default MRST partons, obtained by making $Q_1^2 = 5\ \mathrm{GeV}^2$ and $Q_1^2 = 10\ \mathrm{GeV}^2$ cuts in Q^2 to the data included in the fits

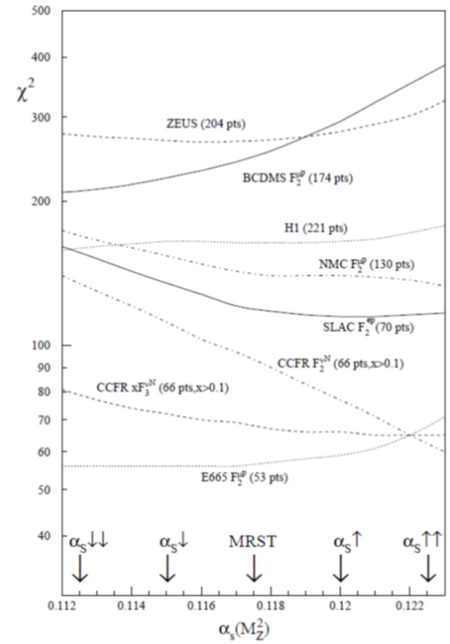


Fig. 21. The contributions to the total global fit χ^2 from the various data sets as a function of α_S. The parton set corresponding to the optimum value $\alpha_S = 0.1175$ is denoted simply MRST and is the default set of partons used throughout the paper. The four other sets, which correspond to the 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

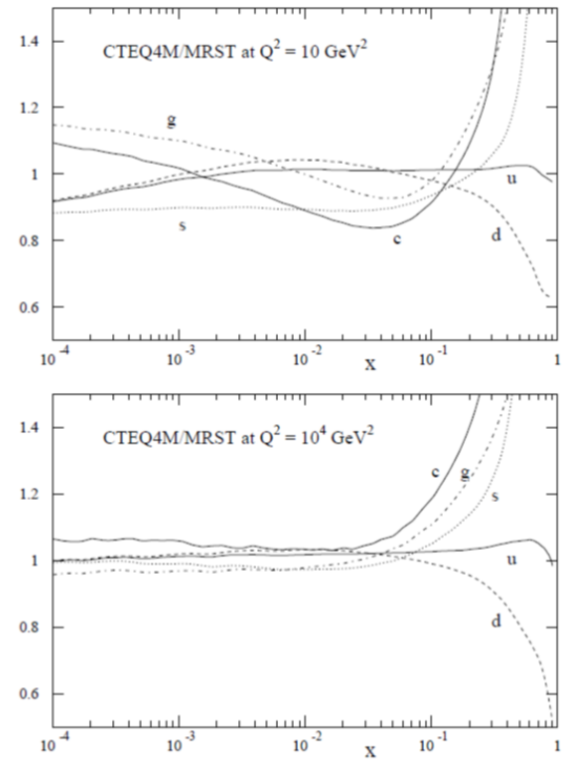
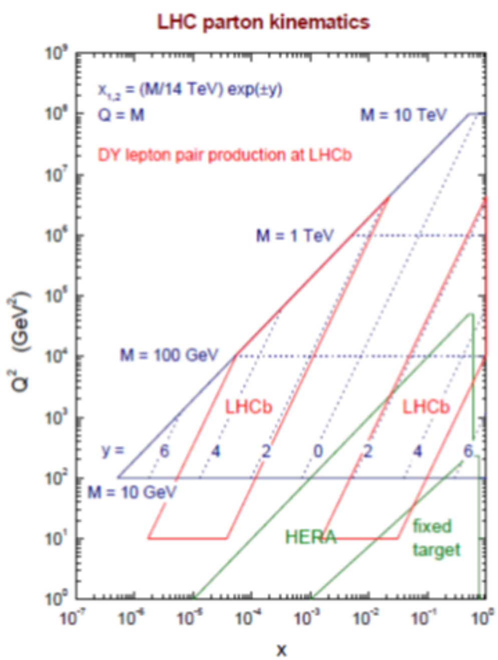


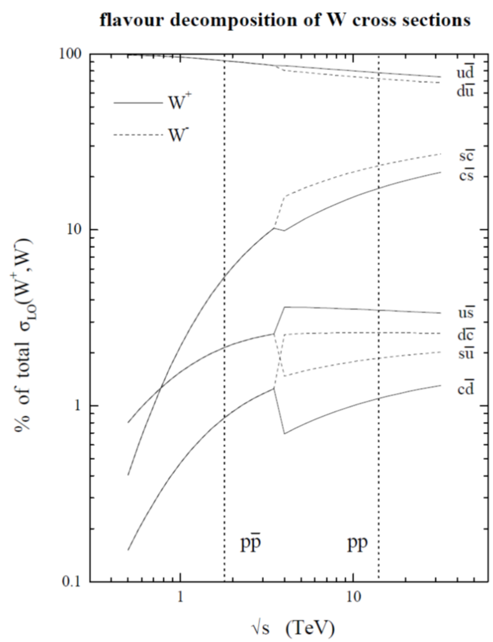
Fig. 44. Ratio of the partons of the CTEQ4M [21] set to those of the MRST set at $Q^2 = 10$ and $10^4\ \mathrm{GeV}^2$

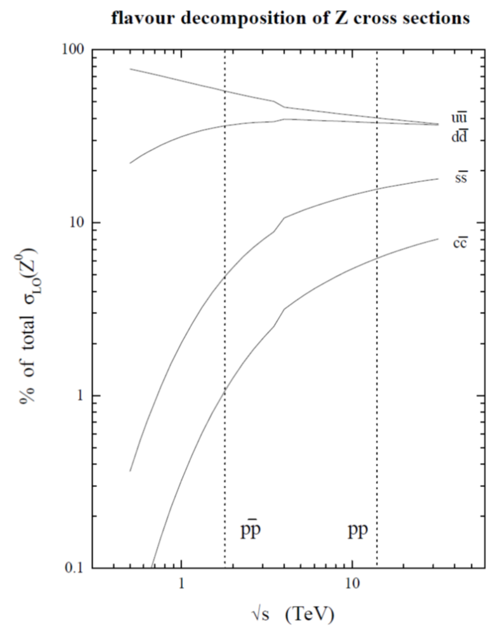
Parton Distributions and the LHC: W and Z Production

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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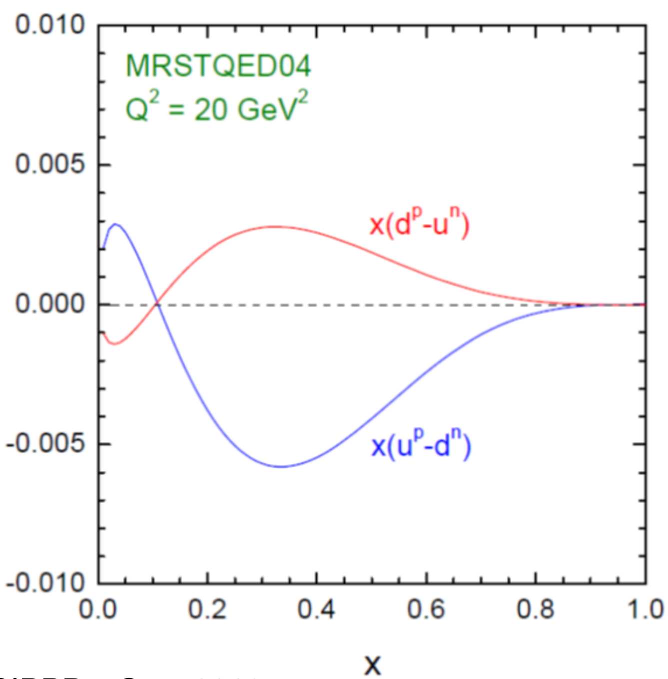
Abstract

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.

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

Update of Parton Distributions at NNLO

A.D. Martin[a], W.J. Stirling[a], R.S. Thorne[b,1] and G. Watt[b]

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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.

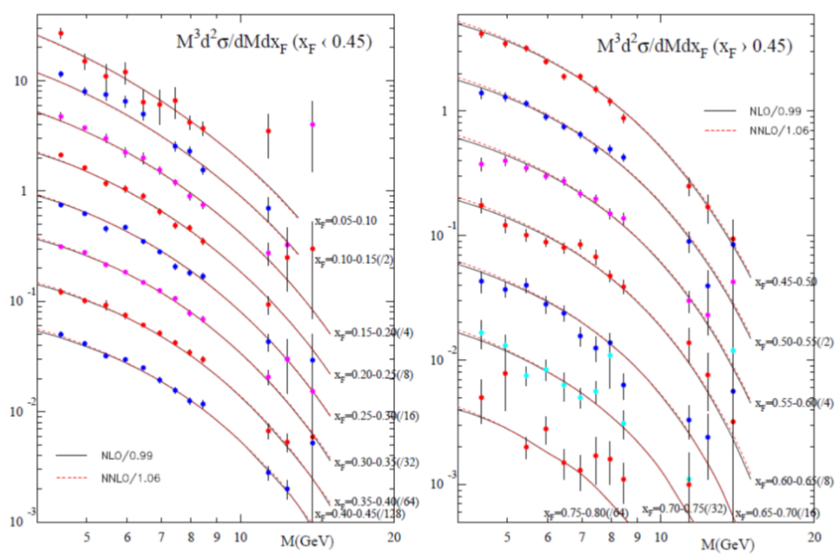

Figure 7: Comparison of the NLO and NNLO Drell–Yan cross sections with the data.

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

A.D. Martin[1], W.J. Stirling[2], R.S. Thorne[3], G. Watt[3,a]

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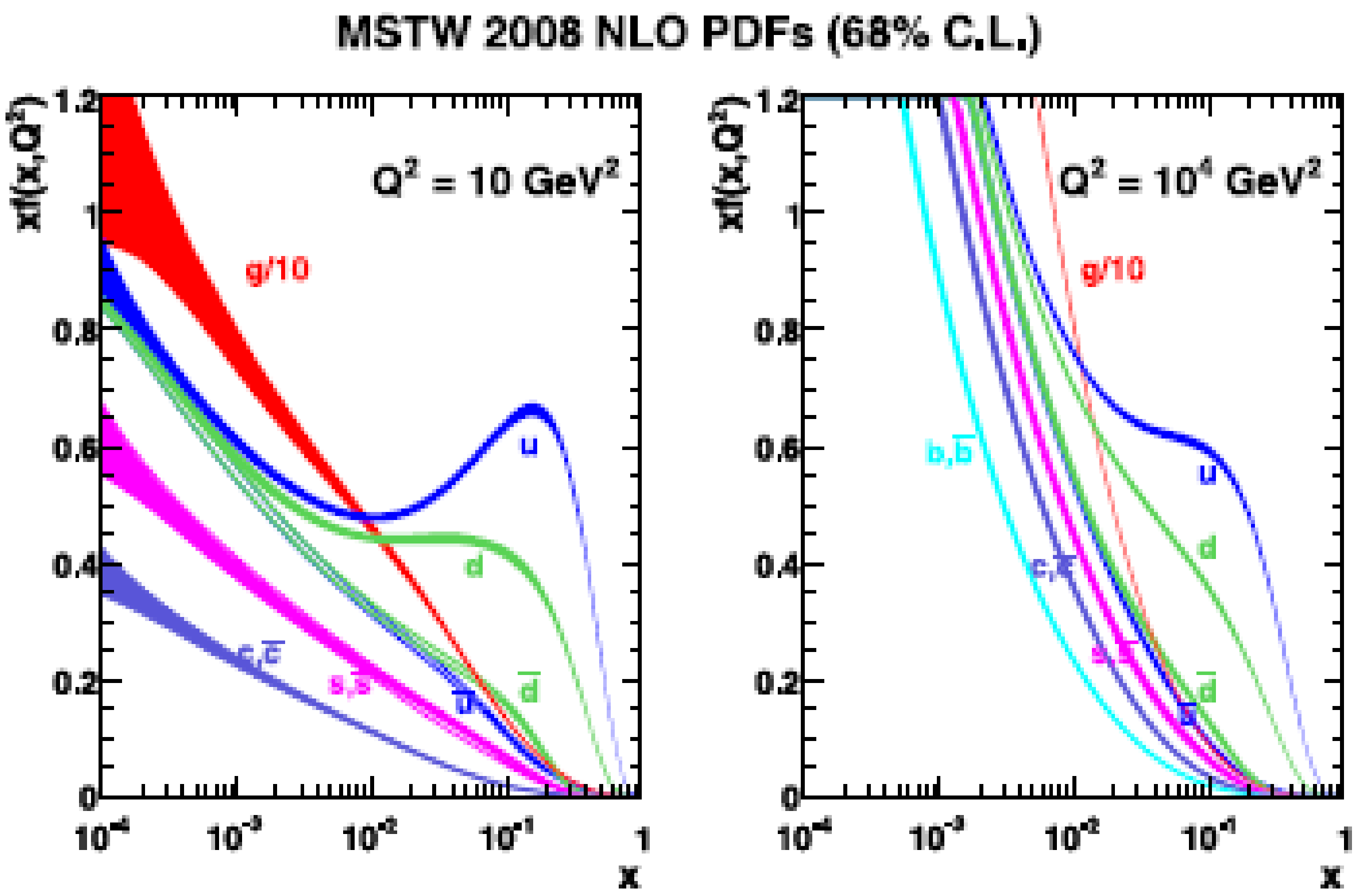
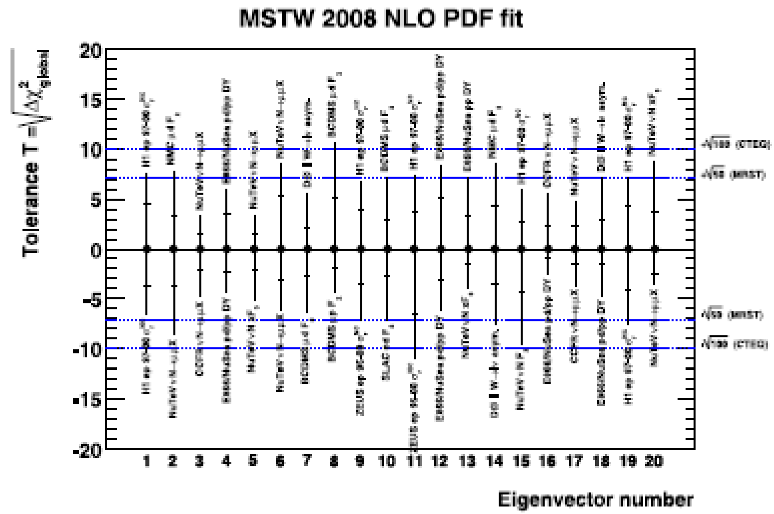


Used dynamical tolerance for the first time.



Also extended parameterisation for e.g. gluon.

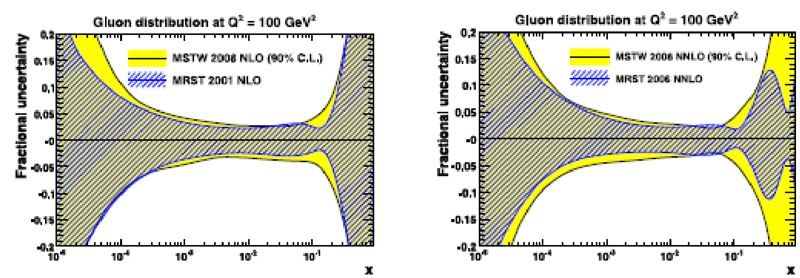


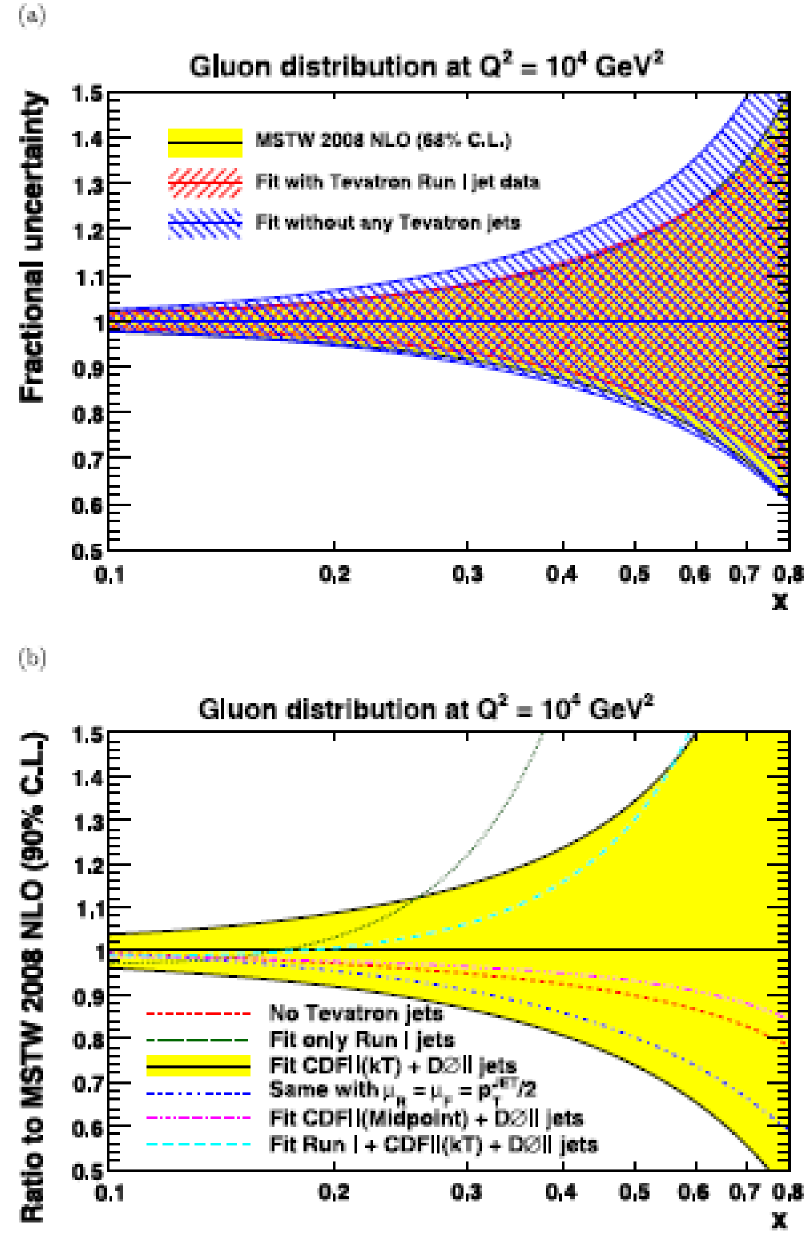
Fig. 17 The fractional uncertainty on the gluon distribution at $Q^2 = 100$ GeV^2 (**a**) from the MSTW 2008 NLO fit compared to that from the MRST 2001 NLO fit [16] and (**b**) from the MSTW 2008 NNLO fit compared to that from the MRST 2006 NNLO fit [21]

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**

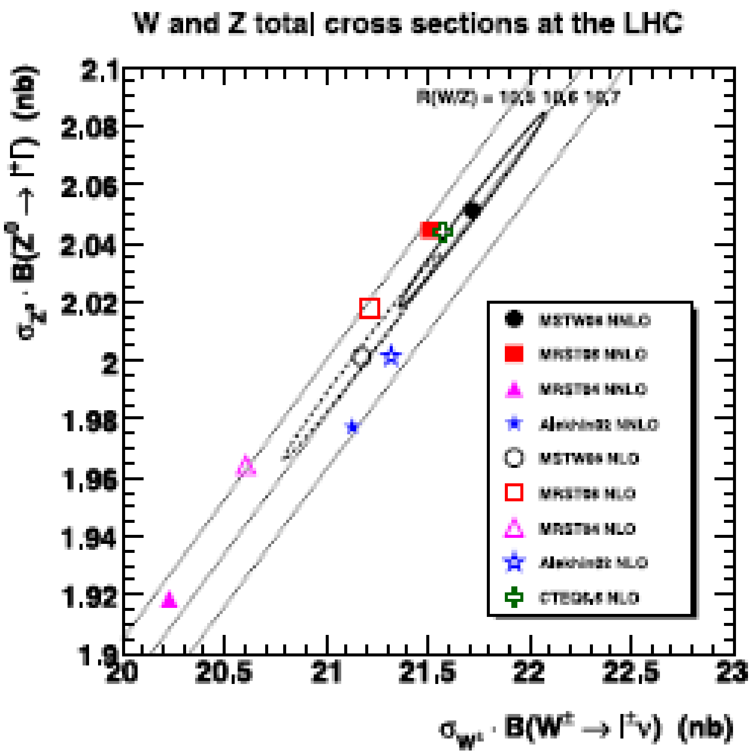
Studies of various issues such as inclusion of jets or not.

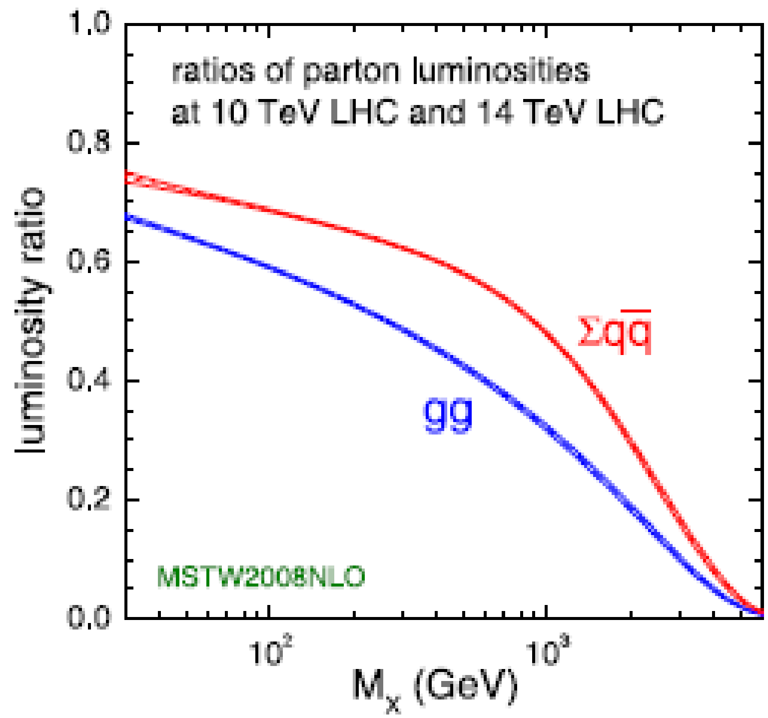
Also variation of PDFs with scale, or jet algorithm.



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

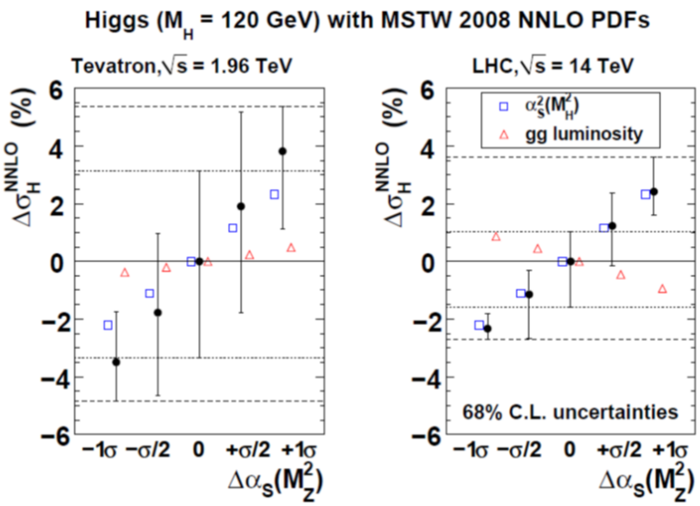
Also the first appearance of another of James' “standard” plots.

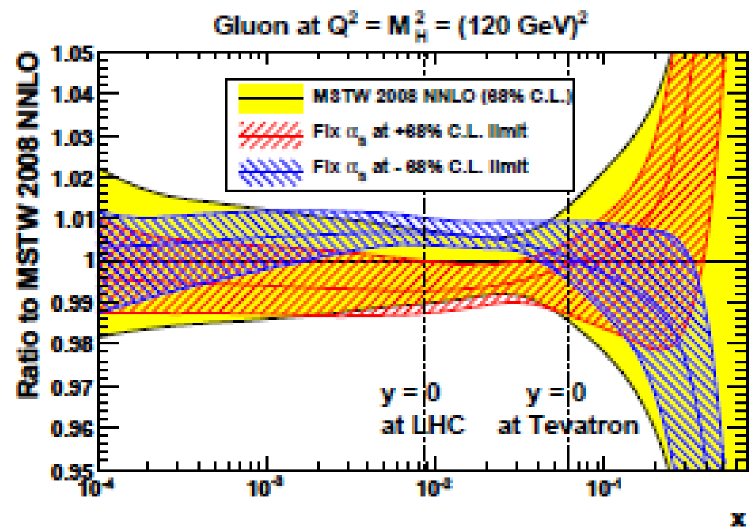




MSTW produced PDFs with $\alpha_s(m_z^2)$ uncertainties and in fine binned variations in $\alpha_s(m_z^2)$.

As always looked particularly at the 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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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)	$B \cdot \sigma^Z_{\rm NNLO}(5\mathrm{FS}, b)$ (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)	$B \cdot \sigma^Z_{\rm NNLO}(5\mathrm{FS}, b)$ (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)	$B \cdot \sigma^Z_{\rm NNLO}(5\mathrm{FS}, b)$ (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.

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

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[c] Cavendish Laboratory, University of Cambridge, CB3 0HE, UK
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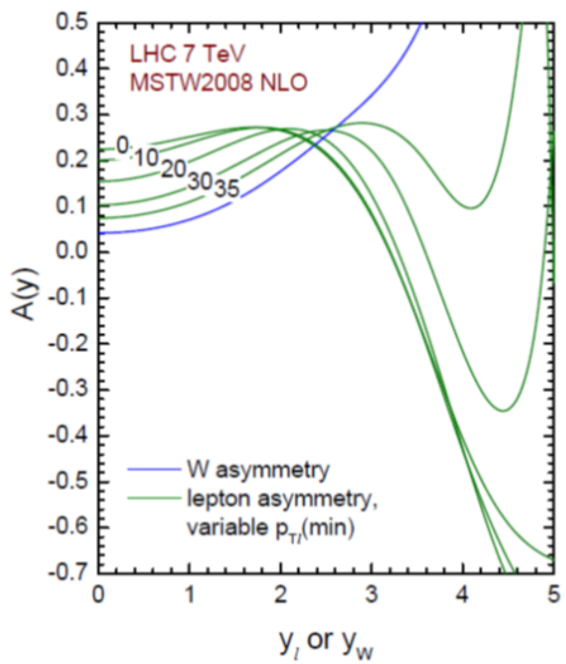
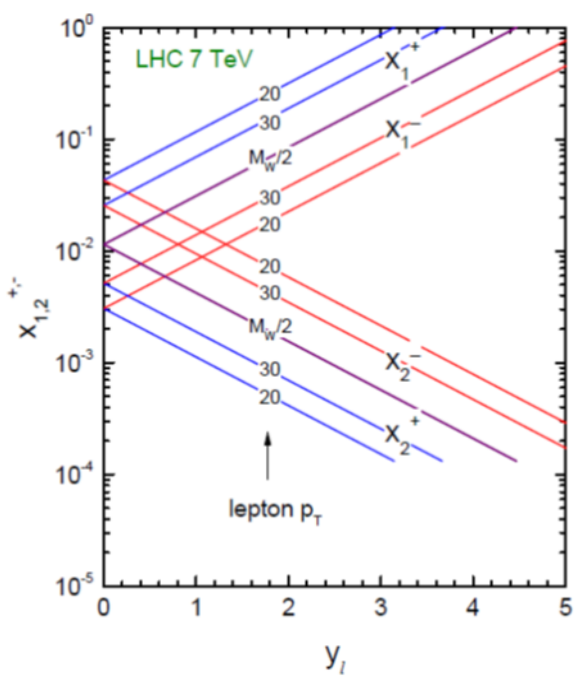
[e] Institut für Theoretische Physik, Universität Zürich, CH-8057 Zürich, Switzerland

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

Always kept up with latest developments in PDFs.

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