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BENCHMARK CROSS SECTIONS FOR $p\bar{p}$ COLLISIONS AT 1.8 TeV

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ABSTRACT

High-energy $p\bar{p}$ collisions provide many quantitative tests of the Standard Model. Of particular interest are "hard scattering" processes, which test not only Standard Model matrix elements and higher order perturbative corrections, but also the distributions of quarks and gluons in the colliding hadrons. We present detailed comparisons of data from the CERN $S\bar{p}pS$ collider with theory, incorporating up-to-date parton distributions derived from recent deep inelastic scattering data. Encouraged by the excellent agreement between data and theory at $\sqrt{s} = 630$ GeV, we present a complete set of "benchmark" predictions for the FNAL $p\bar{p}$ collider at $\sqrt{s} = 1.8$ TeV.

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1. Introduction

The CERN $p\bar{p}$ collider has provided some of the most fundamental tests of the Standard Model – from quantitative tests of perturbative QCD to precision measurements in the electroweak sector. The level of agreement has led to quite stringent limits on ‘new physics’ beyond the Standard Model. One consequence of this is that, based on the comparison between theory and experiment at 630 GeV , precise predictions can be made for many cross sections which will soon be accurately measured at the Fermilab $p\bar{p}$ collider at 1.8 TeV . In most cases it is possible to estimate the uncertainties in the predictions, for example from parton distributions and higher order QCD corrections. Such ‘benchmark’ cross sections can then form the starting point for looking for deviations from the standard predictions.

In two earlier papers [1,2] we have derived sets of parton distributions, based on detailed fits to the most recent deep inelastic μN and νN scattering data. We have discussed in particular the uncertainties in the quark and gluon distributions. From this study have emerged ‘standard’ sets of distributions, which can be regarded as ‘best fits’ to a wide variety of deep inelastic data. These distributions, then, form the basic input for $p\bar{p}$ (or pp) collider phenomenology.

Our comparisons between theory and experiment have already included some $p\bar{p}$ cross sections at 630 GeV . In this paper we present predictions for a variety of cross sections for $p\bar{p}$ collisions at 1.8 TeV . For obvious reasons we restrict our attention to those processes for which ‘experimentally corrected cross sections’ can be derived, and as far as possible, for which next-to-leading order QCD corrections are known. This includes, for example, the total cross section for W production and decay into $l\nu$, but we exclude cross sections for processes such as bottom quark production, which depend sensitively on the fragmentation process, detector cuts etc. Data on all the processes we consider (with the exception of top quark production) have already been presented by the UA1 and UA2 collaborations at 630 GeV .

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 region – gives very similar predictions to set MRS1.

The more recent MRSE and MRSB sets [2] have similar (soft) gluon distributions but were constructed to take into account the significant differences in the values of $F_2^{\mu p}$ measured by the EMC and BCDMS collaborations. The latter data became available subsequent to the MRS analysis of [1]. Roughly speaking, the $u_V + d_V$ quark distribution is bigger at small x in MRSB by order 10% (see Fig.4 of reference [2]). Set MRSE is a slightly updated version of MRS1 – the predictions are essentially identical and will not be distinguished here. In reference [2] we argued that Drell-Yan data favour the MRSB distributions, although the available data are not adequate enough to provide a definitive answer. We may therefore regard set MRSB, with $\Lambda_{\overline{MS}} = 200 \text{ MeV}$, as the ‘optimum’ set of distributions, being compatible with all the relevant data. In this paper we therefore use the MRSB distributions for our benchmark cross sections.

It is important to point out that it will be difficult to use $p\bar{p}$ cross section data to discriminate between the MRSB distributions and familiar ‘standard’ distributions, such as those of Duke and Owens [3]. To illustrate this, Fig.1 shows the distributions of MRSB together with the ratio of DO1 to MRSB as a function of x for two representative values of Q . In the region of x relevant for collider physics phenomenology ($x \sim O(10^{-1})$) the differences are in fact not large. We should emphasize that our different sets of parton distributions do not represent *extreme* values for quark or gluon distributions. Rather they represent roughly central values for the particular set of deep inelastic data fitted. To give

an example, there are no deep inelastic data at very large x and so the parton distributions in this region are simply a reasonable extrapolation from lower x . The theoretical uncertainty on a cross section sensitive to large x parton distributions is therefore very large. Fortunately, all of the cross sections we consider depend on parton distributions at values of x for which deep inelastic data exist, albeit at generally lower values of Q^2 .

2. W and Z Production

We begin by considering W and Z cross sections. These are most sensitive to quark distributions, and so it is sufficient to consider the differences between sets MRSE and MRSB. Fig.2 shows the theoretical predictions for 630 GeV and 1.8 TeV respectively. The average measured values from the UA1 and UA2 collaborations [4,5] are displayed, together with a preliminary value for the W cross section at 1.8 TeV from the CDF collaboration [6]. The theoretical uncertainties are from several sources: (a) the larger quark distributions in MRSB are reflected in weak boson cross sections which are some 10% larger, (b) the leptonic branching ratios are sensitive to the (unknown) top quark mass, (c) the exact $O(\alpha_s^2)$ QCD corrections have not yet been calculated and could easily change the cross sections by order 10%, and (d) the uncertainty in the W and Z masses leads to non-negligible uncertainties in the production cross sections. The effect of each of these uncertainties is displayed in the figures. Notice that, numerically, the effects of (a), (b) and (c) are roughly similar.

A related quantity is the *ratio* R of the W and Z cross sections times leptonic branching ratios. We have already presented a detailed discussion of this question in an earlier paper. The conclusion was that the parton distribution uncertainty is greatly reduced at 1.8 TeV compared with 630 GeV , because smaller x values (where different flavour quark distributions are more equal) are probed. Fig.3 is an updated version of a similar figure in reference [2]. The recently calculated $O(\alpha_s)$ corrections to the heavy quark parts of the W and Z total decay

widths have been included [7], and in fact are responsible for the abrupt threshold behaviour around $m_t = M_Z/2$. A preliminary value of R has been reported by the CDF collaboration [6], but the errors are presently too large to make a comparison with the predictions in Fig.3 meaningful. We stress again that an accurate measurement of R will be one of the most important measurements for the Fermilab collider.

It should be mentioned that W and Z cross sections for $\sqrt{s} = 1.8 \text{ TeV}$ have also recently been calculated in reference [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 ($c\bar{s} \rightarrow W^+$ compared with $c\bar{c} \rightarrow Z^0$) and the effects of this can be seen in the value of R . In the MRS sets, the charm quark is evolved from zero at $Q^2 = 4 \text{ GeV}^2$. The resulting distribution is in good agreement with deep inelastic data on the $c\bar{c}$ component of F_2 , and we believe therefore that the MRS charm provides a good description. We shall return to this point in a future paper.

The production of W and Z bosons with large transverse momentum is another important test of the Standard Model. The leading order processes ($q\bar{q} \rightarrow Wg$, $qg \rightarrow Wq$) are proportional to α_s and directly involve the gluon distribution. A detailed phenomenological analysis, based on the MRS1 and MRS2 parton distributions, has been performed in reference [9]. Fig.4 shows a similar comparison of the theoretical prediction using the MRSB set with data from UA1 and UA2 [10,11]. The agreement is quite reasonable, given the size of the errors on the data. The UA1 data is perhaps a little high. As discussed in reference [9] the theoretical predictions include part (the non-singlet contribution) of the complete $O(\alpha_s^2)$ QCD correction. It was estimated that this introduces a $O(\pm 20\%)$ theoretical uncertainty. There is in addition a comparable uncertainty from using the different MRS distributions, which arises from a combination of different $\Lambda_{\overline{MS}}$ values and slightly different quark and gluon distributions. Compared with the measurement uncertainties, these theoretical uncertainties are

very small. This means, for example, that there is no way in which the prediction at $\sqrt{s} = 630 \text{ GeV}$ could be adjusted to go through the highest p_T^W data point from UA1. Fig.4 also shows the prediction for $\sqrt{s} = 1.8 \text{ TeV}$. By and large the same comments apply, except that the $qg \rightarrow Wq$ contribution is more important. This can be seen in Fig.5(b), which shows the subprocess decomposition at the two energies as a function of p_T^W . The two subprocesses contribute roughly equally at the higher energy. This implies that the ‘non-singlet’ approximation for the higher order corrections is less valid and it is therefore important that the *complete* higher order corrections be calculated. Due to lack of statistics, there are at present no published data on Z production at large transverse momentum. The theoretical predictions for the two $p\bar{p}$ collider energies are shown in Fig.6. The same comments as for W production apply.

3. Drell-Yan Production

It was emphasised in reference [2] that Drell-Yan cross sections provide a way of distinguishing different quark distributions. Fig.7 shows the lepton pair cross section at $y = 0$ as a function of the pair mass for the two $p\bar{p}$ collider energies. The data point at 630 GeV is from the UA1 collaboration [12]. Again the larger quark distributions in MRSB give larger cross sections. It would be informative to have a more accurate measurement of this quantity at both energies, although the absence of the $O(\alpha_s^2)$ corrections should again be taken into account.

4. Prompt Photon Production

Prompt photon production at large transverse momentum is at present the only *precision* test of perturbative QCD at hadron colliders. The most precise comparisons are with fixed target data at lower energy. However both UA1 [13] and UA2 [14] collaborations have presented corrected data on the transverse momentum distribution at $\eta = 0$ which is in good agreement with the theoretical predictions.

Fig.8 shows the comparison of data with theory at 630 GeV , again using the MRSB distributions. Care must be taken in taking the comparison too far, since isolation cuts have been imposed on the experimental events. This affects only the measurements at smaller values of p_T^γ , and could well explain why the theory falls below the data in this region. Note that we have used the leading order theoretical cross section with the scale $Q = p_T/2$ – chosen to reproduce numerically the exact next-to-leading order corrected cross section of Aurenche et al. [15], with the effects of photon isolation included. Fig.8 also shows the predictions for $\sqrt{s} = 1.8 \text{ TeV}$, using the same Q scale. Preliminary data from the CDF collaboration [16] is included, and appears to be in reasonable agreement with the prediction.

We have also computed the direct photon cross sections using the other MRS sets of parton distributions. We find that in the relevant p_T^γ regions, the cross sections differ only by about $\pm 20\%$. The differences arise from a combination of different quark distributions, different gluon distributions, and different values of $\Lambda_{\overline{MS}}$ in the strong coupling constant. Combining the parton distribution uncertainty with the residual theoretical uncertainties from the higher order corrections, we could reasonably include a theoretical $\pm 30\%$ error on the benchmark cross section.

It is again interesting to consider the decomposition of the cross section in terms of the annihilation ($q\bar{q} \rightarrow \gamma g$) and Compton ($qg \rightarrow \gamma q$) subprocesses. This

is illustrated in Fig.5(c) for the two collider energies. As expected, the Compton process is more important at the same p_T^γ at the higher energy.

5. Jet Production

Jet production at large transverse momentum in $p\bar{p}$ collisions provides one of the most significant tests of perturbative QCD. We have already demonstrated the excellent agreement between theory and data from both the UA1 [17] and UA2 [18] collaborations [1]. This is illustrated again in Fig.9, where now the predictions for $\sqrt{s} = 1.8 \text{ TeV}$ are also displayed. Preliminary data from the CDF collaboration [19] are shown and are already in good agreement with the prediction. We should stress that these are leading order comparisons only. The QCD scale has been set to $Q = p_T^J/2$ to optimise the agreement with the UA2 data at $\sqrt{s} = 630 \text{ GeV}$. As we have already discussed [1], the scale uncertainty, the parton distribution uncertainty and the uncertainty in the normalisation of the data are all at the $\pm 50\%$ level. Theoretical calculations of the complete next-to-leading order perturbative QCD corrections are under way [20], and will presumably reduce the *theoretical* uncertainty somewhat. The subprocess decomposition for the jet p_T distribution is shown in Fig.5(a). Notice that at both $p\bar{p}$ energies, quark-gluon scattering accounts for about 50% of the cross section across the measured p_T range. The other half is mainly gluon-gluon scattering at small p_T and mainly quark-quark scattering at larger p_T . The latter of course, dominates the cross section as the kinematic limit $p_T = \sqrt{s}/2$ is approached.

6. Top Quark Production

Finally, we consider top quark production cross sections. There is now substantial evidence that (at least in the standard six quark model), the top quark mass lies in the range $O(50 \text{ GeV}) < m_t < O(200 \text{ GeV})$. It is therefore important to be able to make precise predictions for the production cross sections at both the CERN and FNAL $p\bar{p}$ colliders. A realistic appraisal of top quark production in $p\bar{p}$ collisions has already been presented in reference [21]. A new development since then has been the calculation of the next-to-leading order corrections to the leading order processes $gg \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ [22]. It is now possible to make more precise theoretical predictions for the production cross sections. One advantage of including the next-to-leading order corrections is that the QCD scale dependence is much reduced. This is illustrated in Fig.10, where the $t\bar{t}$ cross sections are calculated as a function of the QCD scale, with and without the higher order corrections. These corrections reduce, but do not eliminate, the scale dependence. It has become fashionable to choose as ‘optimal’ the scale at which the cross section curve is stationary. This is generally close to the scale at which the higher order corrections vanish (see Fig.10). There is however no rigorous proof that this is indeed the best choice. It is evident from Fig.10 that there is still a scale uncertainty of order say 30%. In the calculations which follow we shall use the optimal scale ansatz. Empirically we find that the optimal scale is related to the top quark mass by the approximate formula:

$$Q_{opt} = \frac{m_t}{5} \left(1 + \frac{m_t}{100 \text{ GeV}} \right)$$

for top quark masses in the 50 – 200 GeV range at both collider energies. Also shown in Fig.10 is a scale which illustrates the dependence on the parton distributions for $m_t = 50 \text{ GeV}$. Sets MRSB, MRSE and MRS3 evidently give very similar predictions while the harder gluon and larger $\Lambda_{\overline{MS}}$ value of (disfavoured) set MRS2 give a cross section some 40% larger.

The resulting total cross sections $p\bar{p} \rightarrow t + X$ are shown in Fig.11. The contribution from $W \rightarrow tb$ (including the $O(\alpha_s)$ corrections in the production and the decay) is also shown. This latter prediction is slightly less uncertain than the quark and gluon fusion contributions since it can be normalised to the cross section for W production and decay into leptons. For $m_t < M_Z/2$ there is also a very small contribution to the cross section from $Z \rightarrow t\bar{t}$. This has been omitted from Fig.11.

Fig.12 shows the subprocess decomposition for the $t\bar{t}$ part of the cross section. As expected, the gluon induced processes are more important at the higher collider energy for the same top quark mass. The qg subprocess is higher order, contributing only at $O(\alpha_s^3)$. Notice that even though the cross section at $\sqrt{s} = 1.8 \text{ TeV}$ has a large gluon contribution, the uncertainty is not as large as one might expect since the gluon is probed at x values of order 0.1. In this region there is some (indirect) constraint from deep inelastic scattering [1]. Finally we should mention that top quark cross sections for $p\bar{p}$ colliders have also been computed in reference [23]. There is approximate agreement between the two calculations, given that different parton distributions have been used.

7. Conclusion

In summary, then, we have presented a set of ‘benchmark’ predictions for a variety of cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8 \text{ TeV}$. The reliability of the predictions is based on the fact that excellent agreement between theory and data is obtained at $\sqrt{s} = 630 \text{ GeV}$. Our predictions provide a starting point for investigating possible differences between theory and data at the Fermilab $p\bar{p}$ collider.

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FIGURE CAPTIONS

1. The MRSB parton distributions of the proton [2] at $Q = 10 \text{ GeV}$ and 80 GeV (where $xS = xu_{sea} = x\bar{u}_{sea} = \dots$). We also show the ratio of the distributions of set 1 of Duke and Owens [3] to the MRSB distributions.
2. The $W (\rightarrow e\nu)$ and $Z (\rightarrow e^+e^-)$ cross sections in $p\bar{p}$ collisions at 630 GeV and 1.8 TeV calculated using the parton distributions of reference [2], with $N_\nu = 3$ assumed in computing the $Z \rightarrow e^+e^-$ branching ratio. The errors corresponding to an uncertainty of $\Delta M = \pm 1 \text{ GeV}$ in the weak boson masses and to possible $O(\alpha_s^2)$ corrections are indicated. The average of the UA1 and UA2 measurements [4,5] at 630 GeV and the CDF measurement [6] at 1.8 TeV are shown.
3. The ratio of the $W (\rightarrow e\nu)$ and $Z (\rightarrow e^+e^-)$ cross sections at 630 GeV , and at 1.8 TeV , calculated using the parton distributions of reference [2] for $N_\nu = 3$ and 5. The error shown at the right of the curves at 630 GeV indicates the range of values obtained using the various acceptable MRS sets of parton distributions. The dashed lines at 1.8 TeV correspond to $R_\sigma = \sigma_W/\sigma_Z = 3.28 \pm 0.05$, the error arising partly from the ± 0.005 uncertainty in $\sin^2 \theta_W$ and partly from $\Delta M_{W,Z} = \pm 1 \text{ GeV}$. The combined UA1 [4] and UA2 [5] measurements and 90% c.l. upper limit are shown at 630 GeV .
4. The p_T distributions for W production in $p\bar{p}$ collisions at 630 GeV and 1.8 TeV calculated using the MRSB parton distributions [2] compared to UA1 [10] and UA2 [11] data at 630 GeV .
5. The subprocess decomposition of the cross sections as a function of p_T for (a) jet production, (b) W production and (c) prompt γ production in $p\bar{p}$ collisions at 1.8 TeV and 630 GeV calculated using the MRSB distributions.
6. The p_T distribution for Z production at 630 GeV and 1.8 TeV calculated

using the MRSB parton distributions.

7. The production of Drell-Yan l^+l^- pairs of mass m in $p\bar{p}$ collisions at 630 GeV and 1.8 TeV calculated using the parton distributions of reference [2]. The UA1 measurement [12] at 630 GeV is shown.
8. The p_T distribution of direct photons produced in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1.8$ TeV compared to UA1 [13], UA2 [14] and CDF [16] data.
9. The jet p_T distribution at $\eta = 0$ in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1.8$ TeV calculated using the MRSB distributions with scale $Q = p_T^J/2$, and compared with UA1 [17], UA2 [18] and CDF [19] data.
10. The scale dependence of the $p\bar{p} \rightarrow t\bar{t}X$ cross section at $\sqrt{s} = 1.8$ TeV calculated using the MRSB parton distributions for $m_t = 50, 100, 150$ GeV . The effect of using MRS2, MRS3 and MRSE distributions is indicated on the curve for $m_t = 50$ GeV . The dashed curve is the leading order prediction for $m_t = 50$ GeV .
11. The cross sections for top quark production in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1.8$ TeV arising from the sum of the $O(\alpha_s^3)$ corrected $2 \rightarrow 2$ $t\bar{t}$ production subprocesses (continuous curves) and from $W \rightarrow t\bar{b}, \bar{t}b$ (dashed curves) as a function of m_t . MRSB parton distributions [2] are used.
12. The subprocess decomposition for $t\bar{t}$ production in $p\bar{p}$ collisions at 1.8 TeV and 630 GeV . Note that QG can only arise from $2 \rightarrow 3$ subprocesses ($qg \rightarrow t\bar{t}q$).

Fig. 1

Fig. 2

$$R \equiv \sigma_W B(W \rightarrow e\nu) / \sigma_Z B(Z \rightarrow ee)$$

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12