Report of the Strong Interactions Theoretical Issues Working Group

R. K. Ellis
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

Strong interaction issues for the next decade are identified. Rather than testing QCD, the important issues are the measurement of strong interaction quantities which are necessary to achieve the other physics goals of the laboratory.

1 QCD in the 1990's

There are two types of QCD investigations which can be carried out at the Tevatron in the 1990's. The first of these can be characterised as the measurement of quantities useful for engineering purposes, which are necessary for the full exploitation of the Tevatron collider and the SSC. An example of this would be the measurement of parton distribution functions. The second type is the investigation of hadronic matter in special situations. As examples of this second type of activity, there is the investigation of nuclear matter, higher twist effects and the polarisation of the gluon spin in the proton.

Whilst there is room for both of these activities in a complete program, it is my feeling that the second of these activities is of lesser importance than the first and that it therefore has a lower priority in the allocation of the resources of the laboratory. In the following article I shall give a summary of some of the topics relating to the first type of investigation. This report is not an exhaustive discussion. It is merely a report of some of the topics which were discussed by the QCD working group at Breckenridge. The members of the QCD working group were P. Aurenche, E. L. Berger, S. Brodsky, R. K. Ellis, B. Fletcher, V. Khoze, C. S. Kim, D. Lichtenberg, G. Miller, J. Owens, E. Predazzi, J. Pumplin, J. W. Qiu, I. Sarcevic, G. Sterman, M. Strickman, W. K. Tung, and C. P. Yuan.

2 The ratio of W and Z production cross sections

The ratio R of the cross sections $(W \to l\nu)$ and $(Z \to l^+l^-)$ at a $p\bar{p}$ collider provides a precision test which is sensitive to several parameters of the standard model[1]. The experimentally measured ratio for the observed leptonic decays can be expressed as follows,

$$R = \frac{\sigma(p\bar{p} \to W)B(W \to l\nu)}{\sigma(p\bar{p} \to Z)B(Z \to l^+l^-)} = R_\sigma \cdot R_{BR}, \tag{1}$$

where R_{BR} is given by,

$$R_{BR} = \frac{B(W \to l\nu)}{B(Z \to l^+l^-)} = \frac{\Gamma(W \to l\nu)}{\Gamma(W \to \text{all})}\frac{\Gamma(Z \to \text{all})}{\Gamma(Z \to l^+l^-)}. \tag{2}$$

The value of R_{BR} can be obtained from the measured R after inclusion of theoretical information on the ratio R_σ. Within the context of the standard model the value of R_{BR} depends on the mass of the top quark through the total W width, if the decay $W \to t\bar{b}$ is kinematically allowed. It also depends on the number of massless neutrino species through the total Z width. The presently quoted values[2,3] for this ratio are

$$\begin{aligned} R = &\quad 10.35 + 1.5 - 1.0(\text{stat}) \pm 0.3(\text{syst}) : \quad UA2 \\ R = &\quad 10.3 \pm 0.8(\text{stat}) \pm 0.5(\text{syst}) : \quad CDF. \end{aligned} \tag{3}$$

These values are shown plotted in Fig. 1, compared with theoretical predictions from Martin, Roberts and Stirling[4].

The measurement of the ratio R will continue to be of interest through the next decade, although the particular features of the standard model which it tests will change as a consequence of results forthcoming from other experiments. The limits set on the top-quark mass by R_{BR} have the advantage that they do not depend on any assumption about the semi-leptonic branching ratio of the top quark. If we assume that the width of the Z has been accurately measured by the e^+e^- colliders SLC and LEP, $p\bar{p}$ colliders offer a unique opportunity to measure the width of the W. Note however that the increase of the number of massless neutrinos from 3 to 4 increases the ratio R by 7%. The measurements quoted above are statistically limited by the number of produced Z's. In the future a measurement of the ratio R sensitive to fractions of a massless neutrino will be possible. This should provide a nice confirmation of the results from e^+e^- annihilation.

The extraction of physics from the experimental value of R relies on an accurate estimate for the theoretical ratio R_σ and its errors. The dominant theoretical uncertainties in the R_σ ratio are the value of the weak mixing angle, $\sin\theta_W$, and the parton distribution functions. The sensitivity to the parton distributions enters especially through the distribution of charm quarks and the ratio of the valence distributions of up and down quarks. At CERN energies the W and Z cross sections

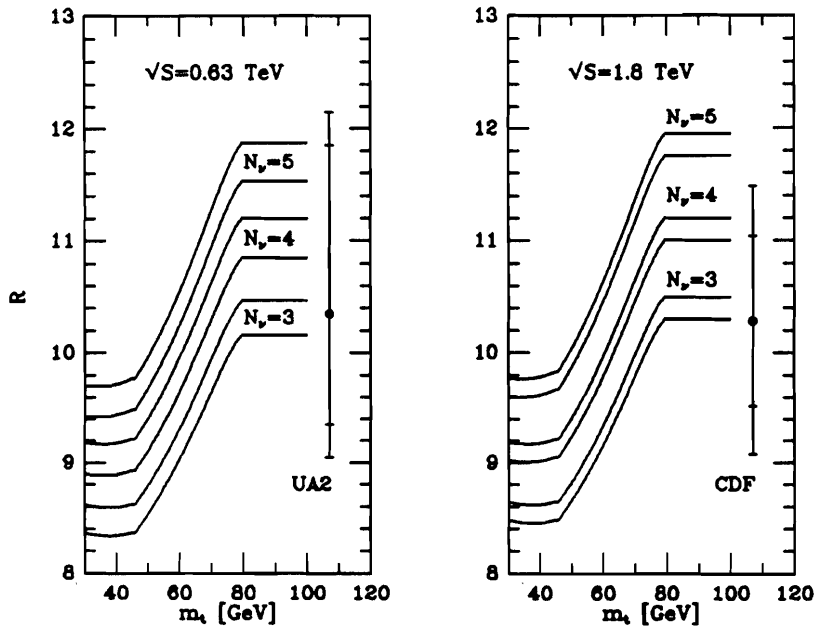

Figure 1: R-ratio compared with data

are particularly sensitive to u_v/d_v. At Tevatron energies there is a sensitivity to the charm distribution function which appears linearly in the W cross section, but quadratically in the Z cross section. There is also some sensitivity to the exact value of the masses of the W and the Z. The constraints placed on R_σ by measurements of the parton distributions are the subject of some theoretical debate. I refer the reader to the literature[4,5,6] for a complete discussion.

At Tevatron energies these uncertainties, which are individually of the order of a fraction of a percent, lead to total variations in the ratio R_σ which are of the order of 1%[4]. An estimate of the total uncertainty as evaluated by the authors of Ref. 4 is indicated by the bands in Fig. 1. In view of the experimental errors it is clear that these ambiguities are not yet crucial. In the next decade as measurements improve, these uncertainties will become more troubling. Note, however, that the argument can be turned around. If we can exclude the decay $W \to t\bar{b}$ and accept the standard model values for the vector boson decays with three massless neutrinos, the R measurement can be used to determine the parton distributions and weak mixing angle.

3 Scale dependence in QCD predictions

This is an old problem. It is well known that QCD predictions always depend on the scale at which the strong coupling is evaluated and on the scale at which the parton distributions are probed. Consider any hard process which is described by

the QCD improved parton model,

$$\sigma^H = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1,\mu) f_j(x_2,\mu) \hat{\sigma}_{ij}(x_1 p_1, x_2 p_2, \mu, \alpha_S(\mu)). \tag{4}$$

The parameter μ is arbitrary, but should not be logarithmically different from the scale of the hard process. The short-distance cross section has a perturbative expansion

$$\hat{\sigma}_{ij}(\mu, \alpha_S(\mu)) = c_n(\mu)\alpha_S^n(\mu) + c_{n+1}(\mu)\alpha_S^{n+1}(\mu) + \ldots \tag{5}$$

Since μ is an arbitrary scale, no physical result can depend on it. In practical terms this means that variations of μ are of one higher order than the perturbative calculation. For a calculation performed through α_S^{n+1} it must be true that,

$$\mu^2 \frac{d}{d\mu^2} \sigma^H = O(\alpha_S^{n+2}), \tag{6}$$

so that no matter what choice is made for μ, the corrections to an $O(\alpha_S^{n+1})$ calculation are always $O(\alpha_S^{n+2})$. This is true for all choices of scale. It is easy to be seduced by the various schemes which purport to fix the scale[7], since they apparently lead to more definite predictions. The definiteness of these predictions is only an illusion, since the uncalculated higher order terms are *a priori* of the same order no matter what the scale choice.

4 Large terms in Drell-Yan

The predictions of perturbative QCD are obtained by the calculation of perturbation series in the running coupling α_S. In some cases of current interest it turns out that the coefficients in these perturbation series are so large that they cast doubt on the reliability of the perturbation series. Examples of such series are the Drell-Yan process[8] at fixed-target energies and bottom-quark production at collider energies[9].

The simplest example of this behaviour is the series for the Drell-Yan process, which has been considered in detail by Sterman and collaborators[10]. The cross section for the production of a lepton pair of mass Q is given by,

$$\frac{d\sigma}{d\ln Q^2} \approx \sigma_0 \int_\tau^1 dz \frac{\mathcal{F}(\tau/z)}{z} \left[\delta(1-z) + \alpha_S \Delta^{(1)}(z) + \alpha_S^2 \Delta^{(2)}(z) + \ldots \right] \tag{7}$$

where $\tau = Q^2/S$ and $\mathcal{F}$ is determined by the flux of partons,

$$\mathcal{F}(y) = \int dx_1 dx_2 q(x_1) \bar{q}(x_2) \delta(y - x_1 x_2). \tag{8}$$

The short distance cross section is calculable in perturbation theory,

$$\Delta^{(1)}(z) = \left[a\delta(1-z) + b\left(\frac{1}{1-z}\right)_+ + c\left(\frac{\ln(1-z)}{1-z}\right)_+ + \text{non} - \text{distribution terms} \right]. \tag{9}$$

The effects of a, b and c can be large and put the reliability of perturbation theory in jeopardy. The plus distributions are defined[11] for any sufficiently smooth function f as,

$$\int_0^1 dz f(z)\Big(\frac{\ln^n(1-z)}{1-z}\Big)_+ = \int_0^1 dz\,(f(z)-f(1))\frac{\ln^n(1-z)}{(1-z)} \tag{10}$$

The distribution terms in $\Delta^{(2)}(z)$ are also known[12]. Note that the effect of the plus distribution terms depends both on the size of the coefficients b and c and on the form of the flux function $\mathcal{F}$ in the vicinity of the threshold.

Sterman has presented partial results on a systematic procedure for the resummation of all distribution terms. The summation is formally singular, because of the growth of the running coupling at low Q^2. This sensitivity to soft gluon effects is a higher twist effect. It is suppressed by powers of Q^2 but must be regulated by a cut-off on soft gluon effects. By varying the soft gluon cut-off one can obtain an estimate of the reliability of the QCD prediction. The extension of this technique to other processes involving incoming hadrons is an important outstanding problem.

5 Bottom quark production

The production of bottom quarks in hadronic reactions figures largely in the future plans of the Laboratory. From a practical point of view bottom-quark production tests our understanding of the production of heavy objects. In addition, bottom production can provide a background to top-quark signals. The planning of b-quark experiments for the SSC and Tevatron depends both on expected rates and on rapidity and transverse momentum distributions for bottom quarks.

The result for the invariant cross section for the production of a heavy quark of mass m may be written as,

$$\frac{d\sigma}{dy_3 dy_4 d^2p_T} = \frac{\alpha_S^2(\mu)}{s^2}\sum_{ij} x_1 f_i(x_1,\mu) x_2 f_j(x_2,\mu)\overline{\sum}|M_{ij}|^2\,, \tag{11}$$

where f_i are the parton distribution functions and $|M_{ij}|^2$ is the square of the invariant matrix element. Energy momentum conservation fixes the values of x_1 and x_2,

$$x_1 = \frac{m_T}{\sqrt{S}}(e^{y_3}+e^{y_4}),\;\; x_2 = \frac{m_T}{\sqrt{S}}(e^{-y_3}+e^{-y_4}), \tag{12}$$

if we know the value of the p_T and rapidities of the outgoing heavy quarks (y_3 and y_4). The transverse mass is defined by $m_T^2 = m^2 + p_T^2$. Thus at collider energies the production of bottom quarks is dominated by the gluon-gluon fusion mechanism because of the size of the gluon distribution functions. At high energies $S \gg m^2$ simple perturbation theory is no longer correct. Evidence of the breakdown of simple perturbation theory is presented below.

The results on bottom production at collider energies all come from the UA1 collaboration at CERN[13]. Fig. 2 displays the experimental cross section for

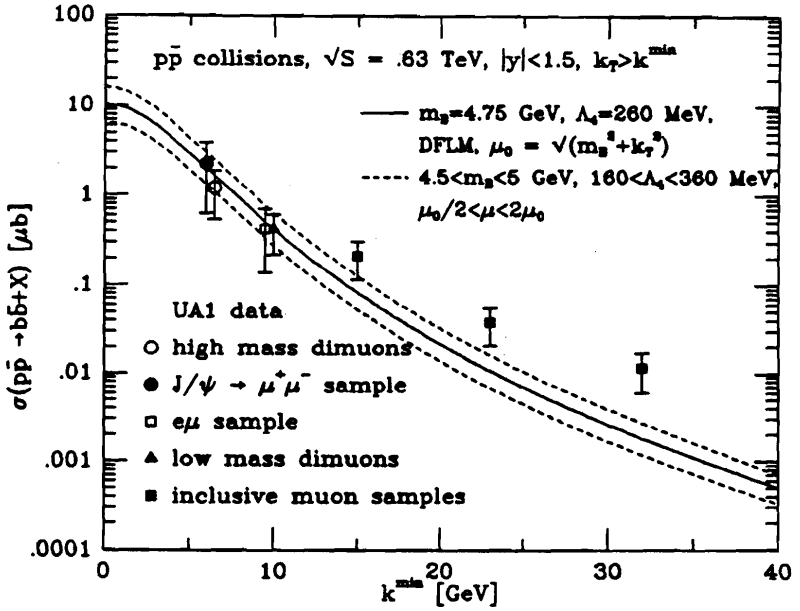

Figure 2: Bottom quark production at CERN energy compared with data.

production at $k_T > k_{min}$ compared with theory[9]. The agreement with theory is fair although some discrepancy is observed at large k_{min}. For the planning of experiments at even higher energies it is important to have an estimate of cross sections. As indicated above, this requires a knowledge of the form of the gluon distribution function at even lower values of x. At such small values of x the gluon distribution function is unknown. In view of the large uncertainties we have chosen to make the simplest estimate possible for the cross section, using a scaling form for the gluon distribution function. This estimate of bottom production cross section is shown in Fig. 3. Also shown is the measurement of the total cross section from the UA1 collaboration. The large effect of the higher orders means that simple perturbation theory, Eq. 11, is not applicable in this kinematic region. Further theoretical work is needed.

6 The reach of the Tevatron for top-quark discovery

The precision measurements of the Z-boson mass which have become available this summer[14,15] together with the low energy neutrino scattering data have further tightened the constraints on the top-quark mass in the standard model. The actual upper limit is somewhat dependent on the interpretation of the low energy neutrino scattering data, but a value of the order of 200 GeV would appear to be excluded on the basis of present data[16] if the minimal standard model is correct.

Note however that some current theoretical ideas[17] on the source of Elec-

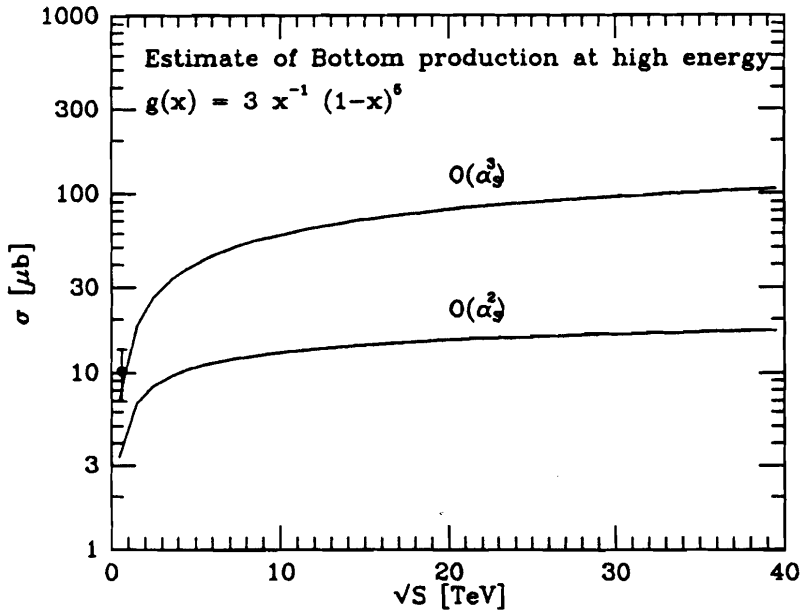

Figure 3: Estimate of cross section for bottom quark production.

troweak symmetry breaking link the weak scale $v \approx 250$ GeV, with the mass of the top quark, suggesting that an even heavier top quark would be preferred by this scheme. We shall therefore discuss the potentiality of the Tevatron to discover a top quark up to about 300 GeV.

The cross section for the production of a top quark with a mass in the range $50 < m < 330$ GeV is shown in Fig. 4. The cross section is shown plotted for $\sqrt{S} = 0.63, 1.8$ and 3.6 TeV in order to illustrate the relative rates at different energies. For a top quark with a mass above the W mass, the CERN collider becomes much less competitive. Doubling the energy of the Tevatron to $\sqrt{S} = 3.6$ TeV, increases the production cross section by at least an order of magnitude.

The present limits on the top quark mass are shown in Table. 1. In the region around the W and Z masses the most promising discovery channel occurs when both the t and the $\bar{t}$ decay semi-leptonically. The presence of the top quark is signalled by the observation of an electron and a muon. The combined branching ratio to this channel is 1.5% so that a sample of 100 pb^{-1} and a detector with perfect acceptance we get 1050, 90 or 24 events for a mass of 100, 150 or 200 GeV respectively. The branching ratio is six times bigger into W + jets channel, which is expected to become cleaner as the top mass increases and the decay jets become stiffer. Therefore for higher masses these event numbers can be multiplied by six. I conclude that 100 pb^{-1} at $\sqrt{S} = 1.8$ TeV should be sufficient to cover the range up to $m_t = 200$ GeV.

Table 1: Limits on the masses of the top and b' quark

Experiment	Limits [GeV] (95% Confidence level)	Signal
UA1[18]	$m_t > 53$	Single muon +2 jets
UA1[18]	$m_{b'} > 41$	Single muon +2 jets
UA1[19]	$m_t > 46$	Dimuon events
UA2[20]	$m_t > 67$	Electron + jets
UA2[20]	$m_{b'} > 53$	Electron + jets
CDF[21]	$40 < m_t < 77$	Electron + jets
CDF[22]	$28 < m_t < 72$	Electron + muon
KEK (Amy)[23]	$m_t > 30.4, m_{b'} > 29.8$	Isolated lepton
SLC(Mark II)[24]	$m_t > 38.5, m_{b'} > 43$	Event shape

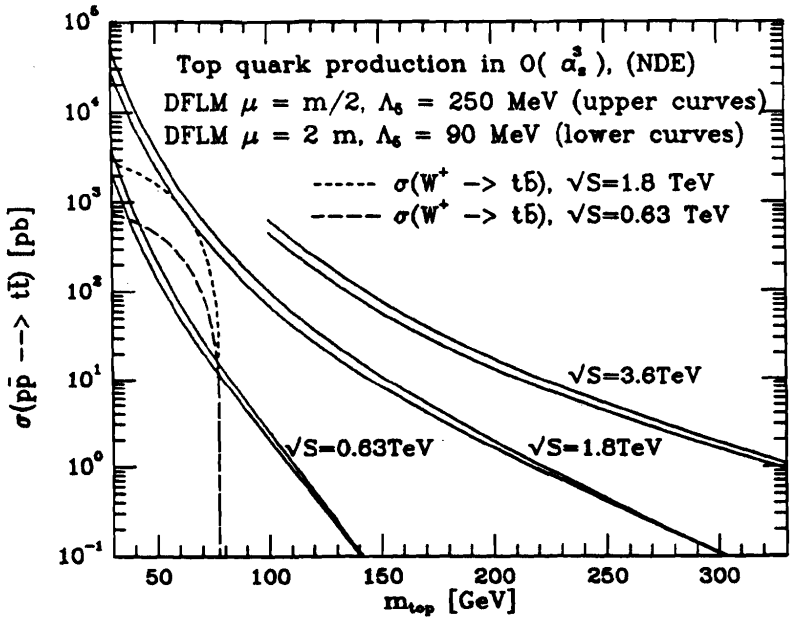

Figure 4: Cross section for top quark production

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