SUMMARY OF DIS 98

John ELLIS
Theoretical Physics Division, CERN
CH - 1211 Geneva 23

ABSTRACT

A personal selection is made of some of the hot topics debated at this conference, including examples of using our knowledge of QCD to make electroweak measurements, structure functions at low $x$ in the light of the corrections to the leading BFKL behaviour recently calculated, diffraction, the existence of one or more Pomerons and whether it/they may have a well-defined structure function, some issues in hadronic final states and polarized structure functions, and the interesting events at large $Q^2$ and $x$ and with isolated leptons and missing transverse energy. Finally, some of the prospects for future deep-inelastic scattering facilities are reviewed, and the interested community encouraged to organize itself to advocate their approval.

Summary Talk Presented at the
Sixth International Workshop on Deep-Inelastic Scattering and QCD
Brussels, April 1998
1 Why Are We Here?

Since there have been many excellent reviews of the parallel sessions at this conference, my talk is not so much a fair summary, more a set of personal perspectives. Almost the first question I was asked on arrival in Brussels was: “Why are you here?” I turn the question around by asking: “Why are we here?” The answers were in fact provided by George Sterman at the end of DIS 97. We are here to search for new physics – in his words: “We must use the QCD we know well to investigate new physics”, and to understand better QCD and nucleon structure – in his words: “Pursue the QCD we do not know well”.

It is worth remembering that the primary motivations for high-energy \( ep \) colliders – first CHEEP in 1978 and subsequently HERA – were to search for new physics. Among the topics proposed for these accelerators were: probing electroweak neutral currents (now starting at HERA), measuring charged currents (well on its way), producing the \( W^\pm \) and \( Z^0 \) (apparently starting) and \( ep \) collisions with polarized \( e^\pm \) beams (not yet undertaken at HERA). The physics interest in the early proposals was focussed on large \( Q^2 \).

However, as we have all been happy to discover, a funny thing happened on the way to large \( Q^2 \) – in fact several, including low-\( x \) structure functions and diffraction, which generated much of the discussion at this meeting. Large-\( Q^2 \) events also generated much discussion at DIS 97, though their excitement here has been somewhat diminished.

In this talk, I start by reviewing some of the ways in which we may use the QCD we know well in the searches for new physics. Then I wander through the garden of QCD we do not know well, plucking a few flowers that please me, before turning to large \( x \) and \( Q^2 \) and finally commenting on some future prospects.

2 Examples of Using QCD

The understanding of QCD for fixed-target deep-inelastic scattering has now advanced to a detailed stage, enabling precision electroweak measurements to be made. We heard at this meeting of a new measurement of \( \sin^2 \theta_W \) in deep-inelastic \( \nu N \) scattering:\n
\[
\sin^2 \theta_W = 0.2253 \pm 0.0019 \pm 0.0010
\]

which can be interpreted as a measure of the \( W^\pm \) mass:

\[
m_W = 80.26 \pm 0.11 \text{ GeV}
\]

The fact that the extracted value of \( m_W \) depends on both \( m_t \) and \( m_H \) warns us that this is an indirect measurement, which can be compared with the prediction:

\[
m_W = 80.333 \pm 0.040 \text{ GeV}
\]
made on the basis of precision electroweak data from LEP and SLD [4]. When combined with
the earlier CCFRR measurement [5], the error in (2) is reduced to 0.105 GeV, among the most
precise available measurements, and having significant impact on the global electroweak fit [4].

On the other hand, measurements of the $W^{\pm}$ mass using charged-current events at HERA [3]
still have some way to go:

$$m_W = 78.6^{+2.5+3.3}_{-2.9-3.0} \text{ GeV}$$ (4)

Will HERA at high luminosity eventually be able to impact significantly the global fit
to electroweak parameters? Including the NuTeV result, the latest global fit yields [3]

$$m_H = 66^{+74}_{-39} \text{ GeV}$$ (5)

with a nominal 95 % confidence-level upper limit of 215 GeV, if no allowance is made for
possible systematic errors. It is striking that the most likely range for the Higgs mass is that
within reach of LEP searches! Unfortunately, the Higgs production cross section at HERA is
not very encouraging.

Another example of the use of QCD is in predicting parton-parton luminosity functions for
the Tevatron and the LHC. For example, the most recent analysis of data from HERA and
elsewhere enable the gluon-gluon luminosity to be fixed with a precision [4]

$$\Delta \left( \tau \frac{dL_{gg}}{d\tau} \right) < 10\%$$ (6)

for $\sqrt{\tau} \sim 10^{-2}$ as relevant for Higgs production at the LHC, if the estimate (3) is correct.
Likewise, the uncertainty in the gluon-quark luminosity [4]

$$\Delta \left( \tau \frac{dL_{gq}}{d\tau} \right) < 10\%$$ (7)

for $\sqrt{\tau} \sim 10^{-1}$ as relevant single-top production at the Tevatron. Thus structure function
measurements enable the discovery prospects of hadron-hadron colliders to be assessed reliably.

3 Structure Functions at Low $x$

These certainly appear in the category that we do not know well. The metaphysical question
that awaits a definitive answer is: to BFKL [8] or not to BFKL ? that is, are the structure
functions dominated by diffusion in $k_T$, without strong ordering, in which case one should
resum $\Sigma(\alpha_s \ln \frac{1}{x})^n$, or does the DGLAP ordering in $k_T$ still dominate, in which case one should
resum $\Sigma(\alpha_s \ln Q^2)^n$ ? In the former case, one has the following generic high-energy cross-section
formula [8]:

$$\sigma_{AB} \sim \int \frac{e^{E(Q_1,Q_2,Y)}}{\sqrt{4\pi D Y}} : D = \frac{7\alpha_s}{2\pi} N_c \xi(3)$$ (8)
with the leading high-energy behaviour of the kernel $E$ for fixed scales $Q_1, Q_2$ as $Y \to \infty$ given by the BFKL Pomeron intercept:

$$\alpha_P(Q_1 Q_2) = 1 + \frac{4 N_c \ln 2}{\pi} \alpha_s$$  \hfill (9)

After heroic calculations by Fadin and Lipatov [10], supported by Camici, Ciafaloni [11] and others [12, 13], we now know the leading corrections to the kernel:

$$E(Q_1, Q_2, Y) \simeq [\alpha_P(Q_1 Q_2) - 1] [1 - 6.5 \alpha_s] Y + \left( \frac{1}{5} \alpha_s^5 \right) Y^3 + \frac{\ln^2 Q_1/Q_2}{\Delta D Y}$$  \hfill (10)

The factor $[1 - 6.5 \alpha_s]$ in the first term indicates that the leading-order Pomeron intercept (9) is strongly modified \footnote{The second term in (10), which breaks naive Regge behaviour, is estimated to be small in accessible kinematic ranges [1].}. Does this mean that the strong growth (9), (10) is actually uncalculable with present techniques? and if quantitative predictions are impossible, how relevant is the qualitative physics of BFKL, namely the absence of strong ordering in $k_T$?

Naively, the first correction in (10) makes the leading $\ln(1/x)$ “hard” Pomeron even softer than the old non-perturbative “soft” Pomeron, which is discouraging. However, about a half of the correction is due to phase-space effects that could in principle be resummed [11]. The fact that non-leading terms would surely be important had been emphasized previously [14]. Nevertheless, to my mind, there is hope for some quantitative understanding, if more exact results become available. So far, we have NLO (and leading $1/N_f$ [13]) calculations for all deep-inelastic moments, and NNLO calculations for a few non-singlet moments. Can we hope for a full NNLO calculation before the LHC?

The reaction [16]: “Now we know why we never saw BFKL” may be too rapid. Perhaps we can, if we are clever. Promising avenues for seeing the qualitative BFKL physics may be provided by the forward jets in deep-inelastic scattering, and by hadron-hadron collisions, as discussed later. A particularly clean place to search for BFKL effects is in $\gamma^*\gamma^*$ collisions. Estimates [17] are that during 1998 each LEP experiment could see between a few and a few dozen events in the interesting kinematic range, depending whether the “soft” Pomeron or leading-order BFKL dominates. The results may be a hot topic for DIS 99.

Despite the mixed fortunes of leading-order BFKL, many fancier theoretical ideas are circulating. There has been progress in calculating the three-gluon-exchange kernel for the odderon [18]: why not also the four- and N-gluon kernels? Progress has also been made in calculating $2 \to 4$ transition vertices. These and other aspects of BFKL dynamics can be tackled using conformal-field-theory techniques and SL(2,$R$) symmetry. There is also a fascinating equivalence to condensed-matter models of spin chains – albeit with a non-compact spin: $|s^2| = s(s + 1) < 0$ – opening the way to attacks using the theory of integrable systems, the Bethe Ansatz, etc. [19]. In the continuum limit of very many gluons, this spin chain becomes formally equivalent to a non-compact non-linear \( \sigma \) model that has affinities with the theory of black holes in string theory [20]. This is all very elegant, but does it have any connection with practical reality?
One kinematic range where there may be a discrepancy with naïve DGLAP \( \ln Q^2 \) evolution is at low \( x \) and \( Q^2 \) \cite{21}: could this be due to saturation of the parton density? According to the normal leading-order evolution equations,

\[
\frac{\partial F_2}{\partial \ln Q^2} \propto x \ g(x, Q^2) \tag{11}
\]

However, if there is saturation at small \( k_T^2 \): \( \sigma_{in} \simeq R_0^2 \), one would find \cite{9}

\[
\frac{\partial F_2}{\partial \ln Q^2} \propto R_0^2 Q^2 \tag{12}
\]

which is compatible with the data. However, one should be careful, and exhaust the conservative options before jumping to conclusions. It has been pointed out \cite{22} that one can (more or less) fit the data by varying \( g(x, \text{low } Q^2) \), without changing significantly \( g(x, \text{high } Q^2) \), as shown in Fig. 1. However, the required low-\( Q^2 \) gluon distribution is valence-like, and one still needs a low-\( x \), low-\( Q^2 \) \( \bar{q}q \) sea that is independent of the gluons. These ideas do not shock me, and they can perhaps be tested by studying vector-meson production \cite{9}, which is sensitive to the gluon distribution in this kinematic range. Alternative interpretations might include the NNLO perturbative QCD corrections that remain to be calculated, and the possible contribution of \( F_L \) should be better understood.

4 Diffraction

HERA is now providing us with a wealth of data on diffraction, sharpening the perennial question: Are there one, two or many Pomerons? \cite{23} The “soft” Pomeron that is assigned responsibility for the rises in the \( K^+p, pp, \bar{p}p, \pi p \) and \( \gamma p \) cross sections: \( \sigma \sim s^4 \) would have
intercept $\alpha_P(0) = 1 + \epsilon \simeq 1.08$. Asymptotically, any rise must eventually respect the Froissart bound imposed by unitarity: $\sigma < c (\ln s)^2$. However, the theoretical limiting coefficient $c$ is relatively large, so this bound may be irrelevant at present energies. There is, however, evidence that single soft-Pomeron exchange is not adequate, for example in single diffraction [24]. According to a simple factorizing Regge-pole picture, one would expect

$$\sigma_{SD} \sim s^{2\alpha_P(0)-2} \sim s^{2\epsilon}$$

(13)

but the data lie far below this estimate, and correspond to an approximately constant fraction of the total cross section. This observation is suggestive of saturation effects (multiple soft-Pomeron exchange) already, long before the Froissart bound enforces it.

This problem of premature saturation can be visualized more clearly in the impact-parameter picture advocated here by Mueller [9]. The $S$ matrix for elastic $pp$ scattering as a function of the impact parameter $b$ is related to observable cross sections by

$$\sigma_{tot} = 2 \int d^2 b [1 - S(b)]$$

$$\sigma_{el} = \int t d^2 b [1 - S(b)]^2$$

$$\sigma_{inel} = \int d^2 b [1 - S^2(b)]$$

(14)

It has been known since the old ISR days that at high energies $S(b)$ is small as $b \rightarrow 0$, and that the increasing cross section is due mainly to expansion in the impact-parameter profile.

The rate at which the cross section for any given process will rise is determined by the part of the profile which dominates. For example, it has been suggested that the single-diffraction cross section may be dominated by intermediate values of $b$ where $0 \ll S(b) \ll 1$. Saturation is reflected in the importance of multi-Pomeron exchange, in which additional particle production fills in an erstwhile rapidity gap.

As was also recalled here by Mueller [9], it has been proposed [25] that one could probe the impact parameter profile in aligned-jet production in the reaction $\gamma^* + p \rightarrow M_x + p$. Defining

$$F(x,b) = \int d^2 p \ e^{ip \cdot b} \sqrt{d\sigma_{SD}/d^2 p}$$

(15)

the suggestion is to look at

$$\Delta_{eff} \equiv \frac{d}{d \ln 1/x} \ln F(x,b)$$

(16)

where $x^{-1}$ takes the place of $s$ in high-energy $pp$ scattering. If the saturation idea is correct, one would expect $\Delta_{eff}$ to be relatively small when $b \rightarrow 0$.

Large-mass diffraction $\gamma^* + p \rightarrow M_x + p$ can also be used to probe Pomeron structure in more subtle ways. Let us consider a two-gluon ladder-exchange model for the Pomeron: then the transverse size of the $\gamma^*$ state probed is determined by the transverse momentum $k_T$ of the
softest gluon. We may write:
\[
d\sigma_{SD} \propto \frac{dk_T^2}{Q^2} \left[1 - S(k_T, b, Y \equiv \ln(1/x_P))\right]^2 d^2b \, dx_P
\] (17)

In the lowest-order two-gluon model
\[
1 - S \propto x_P \frac{G(x_P, k_T^2)}{k_T^2}
\] (18)

where \(G(x_P, k_T^2)\) is the gluon density as a function of the longitudinal momentum fraction \(x_P\) and the transverse momentum \(k_T\). One might naively expect on the basis of (18) to find dominance by low \(k_T \sim \Lambda_{QCD}\). However, as already mentioned, the data on high-energy hadron scattering suggest that \(S \ll 1\) for \(b \to 0\) and small \(k_T\). Hence, and for other reasons [26], the diffractive \(\gamma^* + p \to M_x + p\) process may get important contributions from regions where \(k_T > \Lambda_{QCD}\). This “semihard” Pomeron may lead to faster cross-section growth than the “soft” Pomeron.

This discussion indicates that there is just one Pomeron, but that it comes in many guises. The Pomeron is not a simple Regge pole, as could also be seen from the previous discussion of BFKL, the historical discussion of cuts and unitarity, and the rich harvest of data from HERA and elsewhere. The Pomeron exists in a multi-parameter space – these include \(b\) and \(k_T\) in the two-gluon approximation alone, but many more parameters would be needed to characterize multi-gluon exchange. These may be characterized by different rates of energy growth, and a fortiori different slopes: the striking new data [27] indicating that the Pomeron is essentially flat in \(\gamma + p \to J/\psi + p\) may be particularly helpful in unravelling the two-gluon component. A complete understanding will require a joint campaign by many experiments: HERA, the Fermilab Tevatron collider, the LHC, ⋯.

What does this discussion tell us about the concept [28] of the “Pomeron structure function” \(f_{q,g}^P(\beta)\)? The idea that there may be such universal distributions \(f_{q,g}^P(\beta)\) of partons in the Pomeron is very appealing phenomenologically. However, it is questionable theoretically: unlike the \(\pi\), there is no nearby, identifiable particle state, and we have just argued that the Pomeron comes in many guises, so that the concept of a universal structure function looks implausible. Moreover, there are experimental indications from hadron-hadron collisions that factorization into a product of universal distributions breaks down [24].

On the other hand, the Pomeron structure function idea provides an attractive description of H1 data [31] on the \(F_2^{D(3)}\) diffractive structure function in electroproduction. These are well described by parton distribution functions in the Pomeron with a dominant hard gluon at low \(Q^2\). This is softened by the DGLAP equations as \(Q^2\) increases, providing a pattern of scaling violations similar to those seen in the data.

A number of authors have proposed an alternative \(\gamma^*\)-dissociation picture [31], according to which inelastic diffraction is viewed as a convolution of a photon light-cone wave function \(\Psi\), an eikonal gluon scattering kernel, and a proton structure function \(\Phi\).\footnote{There are also related colour-dipole models [32].} This type of model has
been used to predict and to fit diffractive data from H1 and ZEUS [31]. There was considerable
discussion at this meeting of a recent comprehensive fit [33] with a phenomenological model of
this type. This model has several components: transverse $\bar{q}q$ production $F_{T\bar{q}q}$ which is important
at medium $\beta$, transverse $\bar{q}qg$ production $F_{T\bar{q}qg}$ which has an importance at small $\beta$ controlled by
an exponent $\gamma$: $F_{T\bar{q}qg} \propto (1 - \beta)^\gamma$, longitudinal $\bar{q}q$ production $\Delta F_{\bar{q}q}^L$ which is important at large
$\beta$, and a higher-twist contribution $\Delta F_{q'q}$.

We used this model first to fit the ZEUS 1994 data [34], as shown in Fig. 2. We found a good
fit with a relatively high value of $\gamma$ and with different Pomeron intercepts $\alpha_P > 1$ for the leading
term and the higher-twist contribution $\Delta F_{T\bar{q}q}$ This should not be shocking, given the previous
discussion of the complicated internal structure of the Pomeron. This ZEUS fit also provided
a match to the H1 1994 data that was qualitatively reasonable [33], though not perfect. We
have also made fits optimized to the H1 1994 data directly. We find two fits, one with low
$\gamma$ (Fig. 3) and one with a higher value (Fig. 4). The solution with the low value corresponds
to the singular gluon distribution proposed by H1, whereas the high-$\gamma$ fit resembles more the
ZEUS fit. Again, both of the H1 fits are not too dissimilar from the ZEUS data, but there is
a suggestion that ZEUS sees less $Q^2$ growth. One may ask whether the two collaborations are
necessarily measuring exactly the same thing, in view of their different procedures for event
selection.

We think it is too early to conclude that the data require a singular gluon structure function
in the Pomeron. Further iteration is required to understand better the different experimental
event selections and their modelling. Perhaps studies of hadronic final states will help resolve
these issues?

5 Hadronic Final States

One should always remember that the pseudorapidity $\eta$ (related to the final-state angle $\theta$) is
not the same as the rapidity $y$. The original ZEUS diffractive event selection was based on a
pseudorapidity cut [26], which tends to impose a lower cutoff on the virtuality of the quark
exchanged between the $\gamma^*$ and the Pomeron. This tends to bias one away from the “Pomeron
structure function” region, and to select semi-hard Pomeron events. This effect should perhaps
still be considered in relation to the H1 event selection. Nowadays, ZEUS base their event
selection on a subtraction of the large-$M_x$ background. Several models – short-range order,
triple-Regge, parton showers [35] – suggest that this background should fall off exponentially:
$\exp(-b M^2_x/W^2)$, where $b \sim 1$ to 2. ZEUS fits this exponent to their data, and then subtracts
the background. This procedure may give problems in the largest-$M_x$ bin, but not for lower
$M_x$, and should not depend strongly on $Q^2$. Ideally, one would tag diffractive events with a
forward spectrometer, but the statistics is limited. Nevertheless, this subsample may be used
to help tune Monte Carlos, and will in the future provide more useful information.

Diffractive event shapes were a hot topic at DIS 98, with the key issue being whether they
are similar to $e^+e^-$ events [36]. Theoretically, there is no particular reason to expect this, since
Figure 2: Fit of two-gluon exchange model to 1994 ZEUS data on diffraction [33].
Figure 3: Fit of two-gluon exchange model to H1 data, corresponding to a hard initial gluon distribution in the Pomeron [33].
Figure 4: Fit of two-gluon exchange model to H1 data, corresponding to softer initial gluons and similar to the ZEUS fit shown in Fig. 2 [33].
the pattern of perturbative gluon radiation in $\gamma^* P \rightarrow \bar{q} q g$ may differ from that in $e^+ e^- \bar{q} q g$, there may also be a contribution with the Pomeron coupling directly to a gluon, and there could be important non-perturbative effects. H1 reports that their diffractive sample has significantly lower thrust $T$ and higher sphericity $S$, whereas the ZEUS longitudinal spectrometer data do not have significantly lower $T$ and higher $S$. However, the ZEUS data have $T$ and $S$ values not very different from H1, and they find that this difference is reduced if they imitate the H1 event selection.

In addition to perturbative contributions, $T$ and $S$ could receive contributions from non-perturbative remnants of the $\gamma^*$ and/or the Pomeron. Theorists should make more detailed calculations of these and other effects on event shapes, and experimentalists should devise more selective searches for these possible remnants [37].

Another topic of interest here was the forward-jet cross section, proposed as a probe of BFKL dynamics. ZEUS has reported an excess [38] compared to DGLAP-based models, though the colour-dipole ARIADNE model does describe them. A naive parton-level BFKL prediction lay far above the data. However, it has been pointed out that phase-space corrections reduce significantly the naive BFKL parton-level prediction [39], as shown in Fig. 5. Parton-hadron corrections are small in ARIADNE, but are difficult to evaluate in the BFKL picture. One of the problems here is to implement correctly the cancellations between virtual and real corrections, in the absence of $k_T$ ordering and incorporating correctly the kinematic constraints on the gluon $k_T$. Perhaps there will be progress on this before DIS 99?
Searches for BFKL effects have also been active in \(^{\bar{p}p}\) collisions at Fermilab \([40]\). Here there is lots of phase space, and an azimuthal angular decorrelation between high-\(p_T\) jets is a promising signature. However, the probabilities of rapidity gaps between two high-\(p_T\) jets at fixed \(\Delta \eta \geq 1\) has the disappointing feature that

\[
P^{\text{gap}}(630 \text{ GeV}) \sim 3 P^{\text{gap}}(1800 \text{ GeV}) \tag{19}
\]

This may mean that asymptopia has not yet been reached. Fortunately, there is sufficient kinematic range at Fermilab to extend the study to larger \(\Delta \eta\). If this fails, one can always look forward to the LHC \([41]\), the ultimate accelerator for studying diffraction \([42]\).

### 6 Polarized Structure Functions

Some impressive new data sets were presented at this meeting. The HERMES collaboration has presented new data on \(g_1\), as well as on hadronic final states that enable the valence and sea polarized-quark distributions \(\Delta u_V, \Delta d_V\) and \(\Delta\text{(sea)}\) to be extracted \([44]\). The SMC has presented their new definitive data on \(g_1^P\) and \(g_1^D\) \([45]\). The E155 collaboration \([46]\) has presented preliminary data on \(g_1^P, D\) with very small statistical errors:

\[
\Delta_{\text{stat}} \epsilon_{0.9} \epsilon_{0.014} dx \ g_1^{P,D}(x) \sim 0.002
\]

Here the challenge will be to control the systematic errors down to a comparable level. Questions were raised about the nuclear corrections to the assumed superposition of \(D\) and \(^4\text{He}\) components in the \(^6\text{Li}\) target, but in my view the QCD evolution and the small \(x\) extrapolation will be larger issues for attempts to extract \(\Gamma_p, D \equiv \int_0^1 dx \ g_1^{P,D}(x)\) from these data \([47]\).

The new SMC numbers for these quantities are \([45]\):

\[
\Gamma_p(10 \text{ GeV}^2) = 0.120 \pm 0.005 \pm 0.006 \pm 0.014 \tag{20}
\]

\[
\Gamma_D(10 \text{ GeV}^2) = 0.019 \pm 0.006 \pm 0.003 \pm 0.013 \tag{21}
\]

where the theoretical errors associated with QCD evolution and extrapolation are listed last. The central value \([20]\) has been decreased somewhat by a recalibration of the muon-beam polarization. The CERN data are quite compatible with the Bjorken sum rule \([45]\):

\[
\int_0^1 dx \left[ g_1^P(x, Q^2) - g_1^n(x, Q^2) \right] \big|_{Q^2=5\text{GeV}^2} = 0.173^{+0.024}_{-0.012} \tag{22}
\]

However, the SMC data alone indicate strong discrepancies with the naïve singlet sum rules: \(\Gamma_p\) is off by 3.1\(\sigma\), \(\Gamma_D\) by 3.5\(\sigma\). The new SMC results may be combined with previous data to extract \([47]\) a new world average value of the singlet matrix element:

\[
\Delta \Sigma = 0.27 \pm 0.05 \tag{23}
\]
Figure 6: Values of the total quark contribution to the proton spin extracted from various sets of data on polarized lepton-nucleon scattering, showing the improved consistency as higher-order perturbative QCD corrections are included [47].
Note that the consistency between the different data is much improved \cite{47} by including the higher-order perturbative corrections, as seen in Fig. 6.

The SMC has presented here NLO perturbative QCD fits to their new data and those previously available \cite{18}. Independent moment-space and \((x, Q^2)\)-grid fitting programs give very similar results. They have compared two fashionable renormalization schemes: the conventional MS scheme and the so-called Adler-Bardeen (AB) scheme in which a gluonic correction is subtracted:

\[
\widetilde{\Delta}q|_{AB} = \Delta q - \frac{\alpha_s}{2\pi} \Delta G \tag{24}
\]

These schemes should yield similar \(g_1^{p,D}(x, Q^2)\) and \(\Delta G(x, Q^2)\), though they will of course yield different \(\Delta q(x, Q^2)\). The fit values of \(\Delta G\) are

\[
\text{MS} : \Delta G = 0.25^{+0.29}_{-0.22} \tag{25}
\]

\[
\text{AB} : \Delta G = 0.99^{+1.17+0.42+1.43}_{-0.31-0.22-0.45} \tag{26}
\]

Note that the systematic errors have not yet been evaluated in the MS scheme. There are indications that \(\Delta G\) may be positive, though the two determinations \(\text{(25)}, \text{(26)}\) are compatible with zero at the 1(2)-\(\sigma\) level. Moreover, it is important to note that, although the central values in \(\text{(25)}, \text{(26)}\) look rather different, they are compatible with each other at the 1-\(\sigma\) level. Encouragingly, the two fits give rather similar values of the singlet axial-current matrix element:

\[
\text{MS} : a_0 = 0.19 \pm 0.05 \pm 0.04 \tag{27}
\]

\[
\text{AB} : a_0 = 0.23 \pm 0.07 \pm 0.19 \tag{28}
\]

Each of the values \(\text{(27)}, \text{(28)}\) is also quite compatible with the estimate \(\text{(23)}\) based on the moments \(\Gamma_1^{p,n}\). Therefore the proton spin puzzle is still with us.

However, we still do not know whether (in the AB scheme) it is due to \(\Delta s < 0\) and \(\Delta G \sim 0\), or to \(\Delta s \sim 0, \Delta G > 0\). The need to measure \(\Delta G\) is as great as ever, and even higher on the experimental agenda. Some insight into this may come from including E155 data in a global fit, but there will still be concerns about the systematic errors in combining data from different experiments. It might be possible to obtain some information from \(Q^2\) variations within the E155 data set. Their 10.5\(^o\) spectrometer data have yet to be analyzed, though they have less statistics than the lower-angle, lower-\(Q^2\) data. The first direct information on \(\Delta G\) should come from COMPASS \cite{49}, measuring the \(\bar{c}c\) (and possibly charged hadron-pair) production asymmetry in polarized \(\mu N\) scattering:

\[
\delta(\Delta G/G) \sim 0.1 \text{ to } 0.05 \tag{29}
\]

starting in the year 2000, and from the polarized RHIC option \cite{50}, measuring \(\gamma^+\) jet and dijet production asymmetries:

\[
\delta(\Delta G/G) \sim 0.1 \text{ to } 0.03 \tag{30}
\]

\(^{3}\)There have also been interesting, more precise data on \(g_2\) \cite{10}.

---

14
at $x = 0.02$ to 0.3, also in the same year. The interesting E156 proposal to measure $\bar{c}c$ production in polarized $eN$ scattering at SLAC has not been approved, to my personal regret. This would be a fitting continuation of the outstanding SLAC polarization programme, and I would like to be convinced if there are urgent particle-physics arguments why it should not be accepted.

The ultimate weapon for determining the polarized gluon distribution would be the measurement of dijets, $Q^2$ evolution, etc., using polarized $e$ and $p$ beams at HERA \[\text{17}\]. This would be unequalled for measurements at low $x$ and high $Q^2$, for evaluating sum rules, etc., but may have to wait until beyond 2005.

7 Large $x$ and $Q^2$

We have seen at this meeting that the conventional perturbative QCD DGLAP evolution describes deep-inelastic data perfectly (almost) everywhere. A global fit \[\text{22}\] yields

$$\alpha_s(M_Z) = 0.1175 \pm 0.003 \pm ?$$

(31)

where the question mark reflects my perplexity, in view of the fact that different data sets favour different central values of $\alpha_s$: e.g., relatively small for BCDMS and relatively large for SLAC and CCFR. Moreover, $\gamma/Z^0$ interference is seen clearly at HERA \[\text{4}\]. These successes give us confidence that the error of extrapolation to large $x$ and $Q^2$ at HERA is $\leq 7\%$.

Is there an experimental excess \[\text{52}\] at large $Q^2$? The answer is yes, everywhere, both in neutral currents and in charged currents, both in ZEUS and H1 data, as seen in the Table.

|        | $Q^2 > 15000$ GeV$^2$: 22 vs 15±2 | $Q^2 > 7500$ GeV$^2$: 41 vs 28±8 |
|--------|---------------------------------|---------------------------------|
| HI     | $M = 200\pm12.5$ GeV: 8 vs 3±0.5 | $Q^2 > 15000$ GeV$^2$: 9 vs 5±3  |
|        | $Q^2 > 35000$ GeV$^2$: 2 vs 0.3±0.02 | $Q^2 > 20000$ GeV$^2$: 0.3 vs 1  |
| ZEUS   | $Q^2 > 30000$ GeV$^2$: 1 vs 0.06 | $Q^2 > 30000$ GeV$^2$: 1 vs 0.06 |

None of these excesses is significant by itself, and they are probably not significant when all taken together. Nevertheless, these numbers are intriguing. Please do not listen too closely to those who tell you the previous excesses have now gone away. There are still excesses, and even the much-maligned 1997 data do not exhibit any deficits.

\[\text{4}\] How long will it be before H1 and ZEUS offer us interesting determinations of $\sin^2 \theta_W$?
Figure 7: Scatter plot of isolated lepton + missing transverse energy events reported by H1, compared with calculations of Standard Model sources [55].

We have all had a lot of fun with the large $Q^2$ and $x$ data during the past year [53], which also taught the community a great deal. We learnt how to compile constraints from HERA and other experiments on leptoquarks and on squarks with R-violating interactions. Many new analyses at LEP and Fermilab [54] were stimulated: the latter, in particular, make life almost impossible for leptoquarks coupling to the first or second generations. On the other hand, there is still scope for a third-generation leptoquark, or for an R-violating squark (which may in general have competing R-conserving decays into jets and missing energy). We have also learnt to compile constraints on contact interactions, ranging from atomic-physics parity violation upwards in energy. New analyses of Drell-Yan lepton-pair production at Fermilab [54] and of $e^+e^- \rightarrow \bar{f}f$ at LEP have also been stimulated.

Very possibly, the large $x$ and $Q^2$ events are not harbingers of new physics beyond the Standard Model. However, there is still plenty of phase space to be explored in future runs, starting with the expected forthcoming increase in $e^-p$ luminosity, and continuing with the luminosity upgrade from 2000 onwards.

There was discussion here of HERA events with isolated leptons and missing $p_T$ [53]. H1 reports five $\mu^\pm$ and one $e^-$ event, as seen in Fig. 7. Four of the $\mu^\pm$ events and the $e^-$ event resemble kinematically $W^\pm$ production, whereas the remaining $\mu^\pm$ event looks more like heavy-flavour production: however, H1 expects the rate for this background to be very small. ZEUS reports $4e^\pm$ events that look (more or less) like $W^\pm$ production, compared with expectations of $3.5 \pm 0.4$ $e^\pm$ and $1.3 \pm 0.2$ $\mu^\pm$ events from $W^\pm$ production and backgrounds. Twenty years after high-energy $ep$ colliders were proposed, the HERA experiments seem finally to be detecting the $W^\pm$. 
8 Future Prospects

There is an active programme of experiments in the years ahead. HERA will operate with an $e^-$ beam and hopefully at a larger luminosity in 1998 and 1999. There is a major luminosity upgrade planned to start in 2000. Run II of the Fermilab Tevatron collider will start in 2000, and a subsequent Run III at higher luminosity is planned to last until the LHC comes on the horizon. COMPASS and polarized RHIC will start taking data in 2000.

Then the LHC is scheduled to start taking data in 2005, with the capability to make $pp$, $pA$ and $AA$ collisions, where the nuclei $A$ range from Calcium to Lead. The question is whether its unique kinematic coverage down to low $x$ and/or up to large $Q^2$ will be fully exploited. The presently-approved detectors, ALICE, ATLAS, CMS and LHC-B, are not optimized for QCD studies such as diffraction. A letter of intent for an additional detector aimed at these topics has been proposed, but has not been accepted. This was not a judgement on the physics per se, but rather on the small size of the experimental community expressing initial support for FELIX, and concerns about the availability of the resources needed for the ambiguous FELIX proposal. In view of the close physics overlap between many of the subjects studied at HERA and debated hotly at this conference, many of you in the HERA community may wish to consider some LHC initiative along these lines.

HERA itself has some intriguing future options beyond the luminosity upgrade and 2005. One of these is to accelerate nuclear beams. This would address many of the interesting issues in low-$x$ and high parton-density physics, and its complementarity with the possible LHC programme should be considered carefully. There are also strong physics motivations for polarizing the HERA proton beam on a similar time scale, and enthusiasts are developing this physics case. The main hurdle to be overcome in this case is the complication and expense of accelerating a polarized proton beam: here the operation of polarized RHIC will provide valuable insight.

In the longer run, there are several interesting options for next-generation DIS machines. These include LEP $\otimes$ LHC at 67 GeV $\otimes$ 7 TeV, TESLA $\otimes$ HERA at some 500 GeV $\otimes$ 1 TeV, a muon collider with the Tevatron at some 200 GeV $\otimes$ 1 TeV, and even a proposal to use LEP-like components for collisions with a booster for the VLHC at 80 GeV $\otimes$ 3 TeV. These projects would all offer lepton-proton collisions at around 1 TeV in the centre of mass, carrying significantly further the physics of HERA.

Some of these projects are closer to realization than others. CERN has promised to take no decisions that could preclude re-installing LEP components in the LHC tunnel and realizing $ep$ collisions. DESY has chosen the axis of the TESLA linear collider so that it is tangential to the HERA ring. However, it is not planned to include $ep$ collisions in the initial TESLA project proposal. A workshop is currently being organized by ECFA and DESY to explore and develop the physics case for TESLA. The time is approaching when the physics case for the $ep$ option should also be developed.

In my view, in order to convince the rest of the physics community and our political masters
to support the major investment required for such a next-generation collider, you will need more strong arguments than the Pomeron, low-$x$ physics and diffraction, as was the case for the successful HERA project proposal. If you want one of these long-term projects to be approved, or if you favour one of the medium-term post-2005 options for HERA and/or the LHC, now is the time to build the physics case. We have all enjoyed an interesting few days here, filled with new experimental measurements and theoretical results. The next steps are to harness our enthusiasm and communicate it to a wider audience.

Acknowledgements: It is a pleasure to thank my collaborators Jochen Bartels, Klaus Geiger, Marek Karliner, Henryk Kowalski, Graham Ross, Jenny Williams and Mark Wüsthoff for sharing their insights with me: I also thank Jenny for her help in preparing this talk and Mark for his comments on the write-up. It is also a pleasure to thank the organizers for their encouragement and assistance, as well as for their efficient organization of such a fascinating meeting.

References

[1] G. Sterman, summary talk at DIS 97, preprint ITP-SB-97-43, hep-ph/9708404.
[2] J. Ellis et al., CHEEP: an ep Facility in the SPS, CERN report 78-02 (1978).
[3] NuTeV Collaboration, K.S. McFarland et al., hep-ex/9806013.
[4] LEP Electroweak Working Group, http://www.cern.ch/LEPEWWG/Welcome.html.
[5] K.S. McFarland et al., Eur.Phys.J. C1 (1998) 509.
[6] G. Howell, talk at this conference.
[7] J. Huston, S. Kuhlmann, H.L. Lai, F. Olness, J.F. Owens, D.E. Soper and W.K. Tung, preprint Fermilab-PUB-98-046-T, hep-ph/9801444.
[8] L.N. Lipatov, Sov. J. Nucl. Phys. 23 (1976) 338; E.A. Kuraev, L.N. Lipatov and V.S. Fadin, Sov. Phys. JETP 45 (1977) 199; Y. Balitskii and L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822.
[9] A.H. Mueller, talk at this conference, see also: Y.V. Kovchegov and A.H. Mueller, preprint CU-TP-889, hep-ph/9805208.
[10] V. Fadin and L. Lipatov, hep-ph/9802290.
[11] M. Camici and M. Ciafaloni, hep-ph/9803389.

M. Ciafaloni, talk at this meeting.
[12] For a review of these and other theoretical issues at this conference, see: B.Z. Kopeliovich and R. Peschanski, hep-ph/9806283.

[13] D.A. Ross, hep-ph/9804332; E. Levin, preprint TAUP 2501-98, hep-ph/9806228.

[14] J. Blümlein, V. Ravindran, W.L. Van Neerven, talk at this conference, preprint DESY 98-036, hep-ph/9806368 and references therein.

[15] J.A. Gracey, talk at this conference, preprint LTH 425, hep-ph/9805310, and references therein.

[16] R.D. Ball, discussion remark at this conference, see also: R.D. Ball and S. Forte, talk at this conference, preprint Edinburgh 98/6, hep-ph/9805315 and references therein.

[17] J. Bartels, A. De Roeck and H. Lotter, Phys. Lett. B389 (1996) 742; A. de Roeck, talk at this conference.

[18] R.A. Janik and J. Wosiek, hep-th/9802100 and talk at this conference, hep-th/9805135; M. Praszalowicz and A. Rostworowski, preprint RUB-TPII-5-98, hep-ph/9805245; M.A. Braun, preprint DESY-98-055, hep-ph/9805394.

[19] L. Faddeev and G. Korchemsky, Phys. Lett. B342 (1995) 311; G. Korchemsky, hep-ph/9801377 and references therein.

[20] J. Ellis and N.E. Mavromatos, preprint in preparation.

[21] A. Caldwell, talk at this conference.

[22] A.D. Martin, R.G. Roberts, W.J. Stirling and R.S. Thorne, hep-ph/9803445, and talk at this conference, hep-ph/9805205; see also A.D. Martin, M.G. Ryskin and A.M. Stasto, preprint DTP/98/20, hep-ph/9806212.

[23] A. Donnachie and P.V. Landshoff, preprint DAMTP-1998-34, hep-ph/9806344, and references therein.

[24] K. Goulianos and J. Montanha, hep-ph/9805496; K. Goulianos, hep-ph/9806363, hep-ph/9806384 and references therein.

[25] B. Kopeliovich, B. Povh and E. Predazzi, Phys. Lett. B405 (1997) 361.

[26] J. Ellis and G. Ross, Phys. Lett. B384 (1996) 293; J. Ellis, G. Ross and J. Williams, preprint in preparation.
[27] T. Montero, talk at this conference;  
   for a recent review of diffractive vector-meson production, see:  
   J.A. Crittenden, [hep-ex/9806020];  
   for a recent compilation of total cross-section measurements, see: A. Bornheim, [hep-ex/9806021].

[28] G. Ingelman and P. Schlein, Phys. Lett. 152B (1985) 256.

[29] J. Whitmore, talk at this conference;  
   L. Alvero, J.C. Collins, J. Terron and J. Whitmore, [hep-ph/9805268];  
   L. Alvero, J.C. Collins and J. Whitmore, preprint PSU/TH/200, [hep-ph/9806340].

[30] H1 Collaboration, C. Adloff et al., Z. Phys. C76 (1997) 613;  
   R. Roosen, talk at this conference.

[31] N.N. Nikolaev and B.G. Zakharov, Z. Phys. C53 (1992) 331;  
   M. Genovese, N.N. Nikolaev and B.G. Zakharov, J. Exp. Theor. Phys. 81 (1995) 625, Physics Letters B380 (1996) 213;  
   N.N. Nikolaev, talk at this conference;  
   J. Bartels and M. Wüsthoff, J. Phys. G22 (1996) 929;  
   M. Diehl, Z. Phys. C66 (1996) 181;  
   E. Gotsman, E. Levin and U. Maor, Nucl. Phys. B493 (1997) 354.

[32] A. Bialas, R. Peschanski and C. Royon, preprint DAPNIA-SPP-97-30;  
   R. Peschanski, talk at this conference, [hep-ph/9805325] and references therein;  
   C. Royon, talk at this conference.

[33] J. Bartels, J. Ellis, H. Kowalski and M. Wüsthoff, preprint CERN-TH/98-67, [hep-ph/9803497];  
   H. Kowalski and M. Wüsthoff, talks at this conference.

[34] ZEUS Collaboration, talk presented by H. Kowalski at the LISHEP - LAFEX International School on High-Energy Physics, Feb. 1998;  
   K. Piotrzkowski, talk at this conference.

[35] J. Ellis, K. Geiger and H. Kowalski, Phys. Rev. D54 (1996) 5443.

[36] T. Carli, talk at this conference;  
   R. Wichmann, talk at this conference.

[37] A. Ringwald and F. Schrempp, talk at this conference, DESY 98-061, [hep-ph/9805492];  
   and references therein.

[38] M. Rivelino, talk at this conference.

[39] L. Lönnblad, talk at this conference;  
   G. Salam, talk at this conference, [hep-ph/9805322];  
   L. Orr and W.J. Stirling, talk at this conference, [hep-ph/9804431].
[40] L. Demortier, talk at this conference.

[41] L. Orr and W.J. Stirling, *Phys. Rev.* **D56** (1997) 5875.

[42] FELIX Collaboration, E. Lippmaa et al. CERN-LHCC-97-45 (1997);
   V. Avati et al., hep-ex/9801021;
   K. Eggert, talk at this conference.

[43] P.J. Mulders and T. Sloan, talk at this conference, preprint VUTH 98-17, hep-ph/9806314.

[44] K. Rith, talk at this conference.

[45] J. Cranshaw, talk at this conference;
    J. Kiryluk, talk at this conference.

[46] H. Borel, talk at this conference.

[47] M. Karliner, updating the analysis in J. Ellis and Karliner, *Phys. Lett.* **B341** (1995) 397.

[48] E. Sichtermann, talk at this conference;
    see also G. Altarelli, R.D. Ball, S. Forte and G. Ridolfi, *Acta Phys. Polon.* **B29** (1998) 1145, and references therein.

[49] G. Mallot, talk at this conference.

[50] N. Hayashi, talk at this conference, see also:
    N. Saito, hep-ex/9805003.

[51] G. Rädel, talk at this conference.

[52] T. Greenshaw, talk at this conference;
    H1 Collaboration, C. Adloff et al., *Z. Phys.* **C74** (1997) 191;
    A. Doyle, talk at this conference;
    ZEUS Collaboration, J. Breitweg et al., *Z. Phys.* **C74** (1997) 207.

[53] G. Altarelli, J. Ellis, G. Giudice, S. Lola and M. Mangano, *Nucl. Phys.* **B506** (1997) 3.

[54] I. Bertram, talk at this conference.

[55] H1 Collaboration, C. Adloff et al., preprint DESY 98-063, hep-ex/9806009.

[56] A. De Roeck, talk at this conference.