DIS 96–97. Theory/Developments

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Abstract. Recent developments in the QCD understanding of DIS are reviewed, as well as theoretical attempts to accommodate the HERA anomalous e^+p events.

INTRODUCTION

It was in dark 70's when the USSR was intact and whales did not enjoy full scale protection. Back then a prominent Soviet solid state physicist Sergey V. Maleev, returning from summer vacation, brought to his home institution in Leningrad a "Whaler's Book". He had found it in a little village high up, deep in the Pamir Mountains. The book contained, among other informative things, a formula for calculating the volume of the catch. It ran

$$V = \pi R^2 L . \tag{1}$$

After having defined the dimensions R and L, the author continued:

> "Here π is an empirical constant which, for *Greenland whales*, equals approximately 3.14".

Since then "π for Greenland whales" has become a proverb in our department.

I recalled this true story when reading an email message from José Repond who stressed that the organisers of DIS 97 are expecting a coverage of theoretical attempts to explain the "HERA anomaly".

Let me start by complaining about the splitting of the "Theory" subject into "Theory/Phenomenology" and "Theory/Developments". Physical Theory is a theory of Physical Phenomena. Therefore theoretical developments aim at a better understanding of Phenomenology, either directly or indirectly (we are not talking "theoretical theory" here). Given this definition, it is still worth specifying two types, or rather two stages, of a physical theory:

Phenomenological Theory (PT) and Theoretical Phenomenology (TP).

The distinction between the two is clear:

PT is characterised by relative equilibrium. It has an intrinsic logic of self-deployment, internal beauty, and relates to Phenomenology on a "predict-check out-feed back" basis.

TP is rather turbulent. For an insider, it is about a painful search for new principles to accommodate some "out-of-hand" piece of Phenomenology. For an outsider it is an easy target for ridicule, simply because the initial ideas and constructions are bound to look naive, cumbersome, unnatural.

TP may mark a transition period to a new PT, or a breakthrough in an existing one. Remember an outburst of ideas (open colour, 3 GeV weak bosons, etc.) which followed the discovery of J/ψ. At the same time, it very well may be (and rather so often is) leading nowhere, and with no-one to blame.

Here "the stakes we are gambling are frighteningly high". What makes TP so vulnerable is that it emerges and develops as a Theory of a *single* Phenomenon (see Eq. (1)).

We shall discuss both: recent advances in QCD as Phenomenological Theory, and an explosive Theoretical Phenomenology triggered by the recent HERA anomaly.

QCD

What makes the problem of DIS at very small x-Bjorken so difficult is its similarity to high-energy hadron-hadron interactions. The latter subject was intensively discussed in 1960-70 and won the reputation of being one of the most difficult and controversial "almost solvable" problems in elementary particle physics, which it remains nowadays.

With the advent of QCD some key phenomena of high energy scattering have become less mysterious, at a qualitative level: (almost) constant total cross section (vector gluons), (almost) finite transverse momenta of hadrons in minimum bias events (asymptotic freedom), fast decaying hadron form factors (internal quark structure), and the like. However, we have not come any closer to the solution of the problem of high energy hadron scattering which is intrinsically a large-distance phenomenon. QCD in its present naive (quark-gluon; perturbative) form may provide some hints but cannot address such a problem quantitatively.

The x-dependence of parton densities in normal hadrons is not perturbatively predictable. It never was, neither for moderate nor for small values of x. Perturbative QCD took responsibility for the *scaling violation* pattern, i.e. for Q^2-evolution of parton distributions. At the same time it has to rely on a

non-perturbative initial input containing full (arbitrary) x-dependence which one determines phenomenologically from hard processes at some momentum transfer scale Q_0.

The BFKL resummation programme aims exactly at this blind spot, as it attempts to *derive* from first principles the x-dependence of parton distributions, specifically at very small x. Is this a perturbative problem in the first place? The answer is, strictly speaking, no.

A convincing argument is an argument that the part presenting it finds convincing. Given this definition, it becomes clear why critical voices that spoke at previous DIS workshops of the little relevance of the "BFKL Pomeron" to the HERA F_2 remained unheard: the criticism relied on convincing arguments. Now the position of advocates of the thesis "interesting but irrelevant" has strengthened, since they've got respectable publications to refer to.

We start from the paper by A.H. Mueller entitled:

"Limitation on using the operator product expansion
at small values of x",   [hep-ph/9612251].

Mueller has explicitly found the boundary function $x_0(Q^2)$ "such that for Bjorken-x values below x_0 the operator product expansion breaks down with significant non-perturbative corrections occuring in the leading twist coefficient and anomalous dimension functions due to diffusion to small values of transverse momentum".

The author considers first forward high-energy scattering of two tiny-size hadrons (onia) with characteristic radii $R \ll 1$fm. Onium-onium scattering can be treated perturbatively as a hard process with an intrinsic hard scale $k_0 = R^{-1} \gg \Lambda_{\mathrm{QCD}}$. Such a treatment was developed by Mueller some years ago. It was based on describing multiplication of soft gluons in the Fock states of the colliding hadrons, followed by an interaction between two small-x gluon-partons.

In the large-N_c approximation this multiplication can be described in terms of the probabilistic colour dipole picture. Dipole density, determining the interaction cross section, is governed by an evolution equation that naturally emerges in the impact parameter space. Solution of the latter proves to be equivalent to the BFKL dynamics.

The upper bound on the total interaction energy, above which the problem becomes entirely non-perturbative, reads:

$$\ln \frac{s}{M^2} = Y < Y^{\mathrm{OPE}}(k_0) = \frac{\pi}{14 N_c \zeta(3) b^2} \left(\frac{1}{\alpha_s(k_0)} \right)^3 , \quad b = \frac{11 N_c}{12\pi} - \frac{n_f}{6\pi}. \quad (2)$$

Numerically,

$$Y^{\mathrm{OPE}}(k_0) \approx \left(\frac{1}{2\alpha_s(k_0)} \right)^3 . \quad (3)$$

At the same time, the Leading-Log (BFKL) approximation comes into a conflict with the s-channel unitarity when $Y = \ln s \equiv \ln 1/x$ reaches so large a value Y^{UN} that the log-enhanced amplitude hits the limit

$$\alpha_s^2 \, x^{-\omega_0} \simeq 1 \,, \quad \omega_0 = \frac{N_c \alpha_s}{\pi} \, 4 \ln 2 \,, \tag{4}$$

with ω_0 the famous "BFKL intercept". Thus,

$$Y^{\mathrm{UN}}(k_0) \approx \frac{2}{\omega_0} \ln \frac{1}{\alpha_s(k_0)} \simeq \frac{1}{\alpha_s(k_0)} \,. \tag{5}$$

Choosing a sufficiently large k_0 scale, so as to ensure $1 \ll Y^{\mathrm{UN}} \ll Y^{\mathrm{OPE}}$, one can use onium-onium scattering as a theoretical laboratory for solving the unitarity quest within the perturbative QCD framework.

Returning to the DIS environment, we feel much less encouraged.

Here basically the same boundary (3) applies. However, dealing with DIS structure functions we have two essentially different "sizes" (hard scales) in the game: that of the virtual photon, Q, and the initial hardness scale Q_0, from which one dares to start the perturbative description. Clearly, now k_0 stands for the *minimal* of the two, that is, $k_0 \equiv Q_0$. As a result, a head-on perturbative attack on the x-dependence of DIS structure functions is allowed only for the values of x that respect

$$\ln \frac{\bar{x}}{x} < Y^{\mathrm{OPE}} \approx \left(\frac{1}{2\alpha_s(Q_0)} \right)^3 \,. \tag{6}$$

(Here $\bar{x} \sim 0.1$, according to Mueller's estimate.)

Choosing the popular 1–2 GeV for Q_0 ($\alpha_s > 0.3$) leaves little room for perturbative treatment of the small-x region. (Calculating cubes, keep in mind that when (6) is reached the uncontrollable non-perturbative physics has already taken over! Step down.)

Lifting Q_0 to, say, 5–10 GeV would help theoreticians but won't please HERA experimenters since it undermines availability of the small-x region ($Q^2 > 25$–$100 \, \mathrm{GeV}^2$).

Experimental verification of a sharp increase of parton-parton scattering cross sections with energy, as predicted by BFKL dynamics, remains a challenging task. But it seems wiser to look for keys not under a lamppost but where you lost them. In the BFKL context this means leaving in peace F_2 and addressing instead Mueller-Navelet jets and the transverse energy flow in DIS, high-p_t jets with large rapidity gap at hadron colliders, etc. (onium-onium scattering would certainly do as well).

A rare thing is more damaging to empirical science than an improper name. In perturbative QCD we may discuss BFKL approximation, BFKL equation, BFKL dynamics but should never talk "BFKL or Hard Pomeron". There are

two reasons for that. First of all, the Pomeron (Gell-Mann's name for the Gribov vacuum pole or vacuum singularity) is a reserved word. (Would you dare to use a variable RETURN in your Fortran code?) More importantly, the very term "Hard Pomeron" is nonsensical.

- **Pomeron:** a leading high-energy contribution to elastic hadron scattering amplitudes driven by the leading singularity in the t-channel (complex) angular momentum ω.

- **Hard:** determined by small distances, and therefore perturbatively controllable.

These two word simply don't merge, since the position and the nature of the leading singularity in ω is entirely off the books of perturbative QCD!

One may generate the BFKL evolution to look for increase in cross sections, but should not refer to the *power* ansatz (4) as a QCD (PQCD) prediction.

To avoid confusion we'd better switch from a "BFKL (Hard) Pomeron" to a "BFKL (Hard) Heron", an abbreviation for the High Energy Regime of small, small distance QCD parton scattering cross sections, applicable in a limited range of $\ln 1/x$.

The non-perturbative nature of the "BFKL intercept" has been (convincingly) demonstrated by G. Camici and M. Ciafaloni in

"Model (In)dependent Features of the Hard Pomeron"   [hep-ph/9612235].

The strategy adopted in the paper was to look at the sensitivity of the leading singularity to the behaviour of the QCD coupling in the infrared, outside the perturbative domain. The second C&C paper

"K-Factorization and Small-x Anomalous Dimensions"   [hep-ph/9701303]

dealt with the $q\bar{q}$ subleading contribution to the BFKL evolution "with particular emphasis on running coupling effects". In agreement with the Mueller result the authors find that the next-to leading BFKL equation is consistent "at leading twist level, provided the effective variable $\alpha_s(t)\ln 1/x$ is not too large".

With account of the running coupling, the BFKL equation for the t-channel partial wave $f(t)$ with the angular momentum ω can be written as

$$ f(t) = f_0(t) + \frac{N_c \alpha_s(t)}{\pi\,\omega} \int dt'\, K(t,t')\, f(t')\,, \qquad t = \ln\frac{k^2}{\Lambda^2}\,,\ \ t' = \ln\frac{k'^2}{\Lambda^2}\,, \quad (7) $$

with k, k' transverse momenta of gluons in the BFKL "ladder". In terms of the spectral representation for the kernel,

$$ K(t,t')\ =\ \int \frac{d\gamma}{2\pi i}\, \chi(\gamma)\, \exp\left\{(\gamma - \tfrac{1}{2})(t - t')\right\}\,, $$

the spectral function $\chi(\gamma) = \chi(1 - \gamma)$ has a minimum $\chi_{\min} = \chi(\frac{1}{2})$. The critical point $\gamma = \frac{1}{2}$ generates the singularity in ω one is looking for.

The integral equation (7) is collinear safe. Therefore, in the vicinity of this critical point, its kernel can be expanded as

$$K(t,t') \;=\; \chi(\tfrac{1}{2}) \left(1 + \tfrac{1}{2}\frac{\chi''(\tfrac{1}{2})}{\chi(\tfrac{1}{2})} + \dots \right) \delta(t - t')\,,$$

thus reducing (7) to a differential second order equation

$$f(t) - f_0(t) \;=\; c\frac{\alpha_s(t)}{\omega}\left(1 + a^2 \partial_t^2 \right) f(t)\,,$$

with a, c some constants. The *homogeneous* equation for $f(t)$ is a Schrödinger equation,

$$\hat{H}(t)f(t) = \epsilon(\omega)\,f(t)\,, \quad \hat{H}(t) = \partial^2 + V(t)\,,$$

with the "potential"

$$V(t) \;=\; \text{const}\,\frac{\omega}{\alpha_s(t)}\,.$$

It is the lowest spectral value of ϵ of this one-dimensional quantum mechanical problem that determines the leading singularity of the partial wave in ω (the "Pomeron intercept" ω_0).

For large positive values of t the "potential" is well defined and grows, due to asymptotic freedom, like $\alpha_s(t)^{-1} \propto t$. This information however is insufficient for solving the eigenvalue problem, the obstacle being our ignorance about the region of small positive and negative t (confinement, non-perturbative domain; you name it).

If we decide to *freeze* the coupling below some $t = t_0$, the Schrödinger equation acquires a continuum spectrum (similar to the $\alpha_s =$const case), and the leading singularity remains a cut in the complex ω-plane.

If instead we decide to *switch off* abruptly gluon interactions at some low scale, we get a potential well (with an infinitely sharp left wall). The spectrum becomes discrete, and the leading singularity is a pole (followed by an infinite set of subleading poles).

Playing around with the shape of an effective α_s in the origin you may change the position of the QCD Pomeron and even its nature. An explicit solution of the Schrödinger problem constructed by Camici and Ciafaloni embodies the Pomeron singularity into the reflection coefficient for scattering in the well potential. They conclude that the "nature and location [of the Pomeron are determined by] soft hadronic interactions".

Dixi.

A long-awaited analysis of the next-to-leading corrections to the BFKL evolution was reported by V.S. Fadin, M.I. Kotsky and L.N. Lipatov in

"Gluon pair production in the quasi-multi-Regge kinematics"
[hep-ph/9604267].

In BFKL language an exchanged t-channel (reggeized) gluon is called "Reggeon" and a real s-channel gluon — a "Particle". Beyond the leading $(\alpha_s \ln 1/x)^n$ approximation virtual corrections emerge to the PPR and RRP vertices, as well as to the gluon Regge trajectory. These corrections were calculated by Fadin, Fiore, Kotsky and Quartarolo in 1995–96. Now an analysis of the most technically difficult contribution due to production of two gluons (Particles) with comparable energies has been finalised. Together with a $q\bar{q}$ production channel (Camici and Ciafaloni) all the bits and pieces are ready.

According to the 10th Commandment of Theoretical Physics, "Only when you can explain it in 3 minutes, have you got a result: neither God nor Landau will listen to you any longer". From this point of view, the FKL paper is not yet a result, though it marks a major breakthrough in the subject. Pieces still have to be assembled and looked into, to verify explicitly how the coupling in the BFKL equation runs, and how much the next-to-leading correction affects the rate of energy growth.

Various Leading Log Approximations (LLA) are known to overestimate particle multiplication. Therefore damping of the predicted energy growth by the NL effects is a safe bet. Some specific *physically motivated* NL corrections, in particular those stemming from kinematical effects, energy conservation, etc.), can be studied numerically with a help of an appropriate model.

In the paper by G. Bottazzi. G. Marchesini, G.P. Salam and M. Scorletti

"Structure functions and angular ordering at small x" [hep-ph/9702418]

special emphasis is given to angular structure of the final state glue. Their evolution picture reduces to the standard BFKL one in the LLA, but embodies essential subleading effects originating from the angular ordering, the latter being a consequence of QCD coherence. Analytic and numerical analysis has shown that due to the angular ordering the characteristic function $\chi(\gamma)$ gets modified, $\gamma_{crit} > \frac{1}{2}$, the diffusion is reduced (the tendency competing with the running $\alpha_s(k_\perp)$ that should drag the system towards smaller transverse momenta), and the singular x-behaviour becomes softer.

An important thing is that the BMSS study sets a framework for a forthcoming theoretical analysis of the final state structure. It is worth remembering that the standard evolution equations designed to predict *inclusive* cross sections (DGLAP, BFKL) exploit inclusive cancellations between real and virtual contributions from unresolved partons and therefore are not suited, generally speaking, for describing the structure of final states. To make a long (and old) story short, in hard processes the final states are dominated by those partons which *do not contribute* to the hard cross section (soft accompanying radiation). Perturbative predictions for final particle multiplicities, spectra,

correlations etc. are Double-Logarithmic while the evolution of the basic cross sections is a Single-Log problem:

$$F^{LLA}(x; Q^2, Q_0^2) = \sum_n a_n(x) \left(\alpha_s \ln \frac{Q^2}{Q_0^2} \right)^n , \qquad \text{DGLAP, Infrared safe;}$$

$$F^{LLA}(x; Q_1^2, Q_2^2) = \sum_n b_n(Q_1^2/Q_2^2) \left(\alpha_s \ln \frac{1}{x} \right)^n , \qquad \text{BFKL, Collinear safe.}$$

Now that you are convinced that there have been major developments in the field of small-x physics since Rome-96, let me mention that this subject was far from the only object of theoretical curiosity and labour. In particular, a spectacular number of theoretical papers was devoted to diffractive and quasi-diffractive particle production. Apologising for not having covered this and other QCD related topics in this talk, let me mention just one (the "most theoretical") paper of the diffraction pool.

We started our discussion from the paper from Columbia University. The closing one comes from British Columbia. It was written by Canadian physicists I. Halperin and A. Zhitnitsky and is entitled

"Hard diffractive electroproduction, transverse momentum distribution and QCD vacuum structure"   [hep-ph/9612425].

This study lends a hope, if not a firm support, to those aiming at QCD phenomenology of diffractive processes. Elastic QCD scattering amplitudes were long known to exhibit the perturbative asymptotic regime only at very high momentum transfer, $Q^2 =$50–100 GeV^2. The authors analysed diffractive electroproduction of longitudinally polarised ρ-mesons within the QCD sum rule technology based on non-perturbative ITEP/OPE vacuum condensates. They have found that, in a marked contrast with the notorious property of elastic scattering, ρ-production shows a surprisingly low onset of the asymptotics starting at $Q^2 \simeq$10 GeV^2.

On this optimistic note we leave Phenomenological Theory.

HERA ANOMALY

We turn to an outburst of theoretical activity that followed the anomalous HERA events. Some personal data are due: I am not a big fan of supersymmetry ("interesting but irrelevant"), good old QCD providing enough headaches, to worry too much about any *newer* physics.

The decision not to play truant and to dive into the subject has come with the recognition that a reasonable part of the audience will probably have the same information background that I had, namely

1. Something weird is going on in e^+p at HERA at the highest Q^2.

2. *Its* mass is 200 GeV.

3. The probability of *it* being a statistical fluctuation is 1%.

What follows is an outsider's view on theoretical attempts to accommodate the HERA anomaly.

The theoretical discussion of leptoquarks (cards on the table!) has at least a 20-year (parabolic?) history displayed in Fig. 1. (The following statistics may fluctuate within a 15% margin, depending on the database and search pattern chosen.)
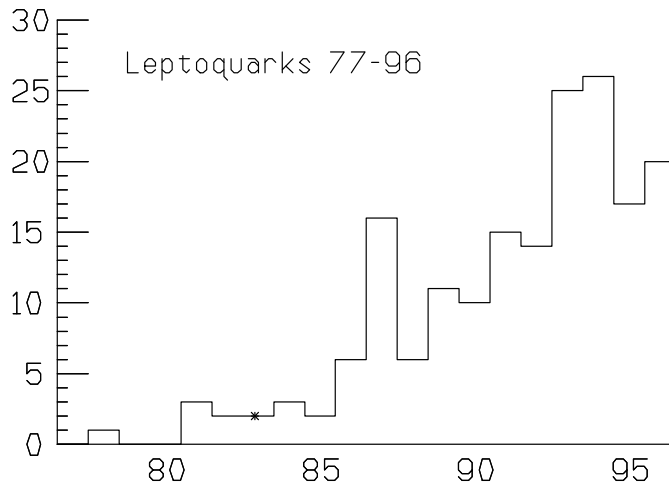

FIGURE 1. Statistics of leptoquark papers, 1977–1996. The 1983 point marks the first title/abstract that responded to "leptoquark" and "HERA" simultaneously.

Past year's monthly statistics contains a prominent October bin (6 papers out of 20 total; 1% probability for this being a statistical fluctuation, I gather). Following 1+2 papers in January-February, the March–97 peak yields *more* theoretical papers than the integrated 1996, with a similar density in the first third of April. A list of 29 theoretical leptoquark/HERA-anomaly papers that appeared on the hep bulletin board before the Chicago Conference is assembled for your convenience at the end of this contribution.

Not that it was such a great joy to go through a couple of dozen of preprints, many apparently having been written overnight. At the end of the day, however, I found that forced journey quite satisfactory. First of all, if you enjoy reading scientific papers written with passion, some papers on the list are worth your attention even if you are not an expert in the field. More importantly, I learned how much we actually know from experiment about Standard Model (SM) physics, the knowledge that leaves so little room for going wild with our creative imagination.

The logic of the following short presentation was designed mainly with the help of the papers by K.S. Babu, C. Kolda, J. March-Russell and F. Wilczek

[9], J. Kalinowski, R. Rueckl, H. Spiesberger and P.M. Zerwas [8], J. Blümlein [7], and G. Altarelli, J. Ellis, S. Lola, G.F. Giudice and M.L. Mangano [4].

A   Contact interaction

The starting point is to address the positron-quark interaction amplitude $e^+q \to e^+q$ as a trouble-maker. The standard procedure for parametrising unconventional physics consists of writing down an effective point-like interaction Lagrangian involving some new large momentum scale Λ. In our case there may be 8 a priori independent scales parametrising 16 options:

$$\mathcal{L} = \sum_{i,j=L,R} \frac{4\pi}{(\Lambda_{ij}^q)^2} \, \eta_{ij}^q \, (\bar{e}_i \gamma_\mu e_i)(\bar{q}_j \gamma_\mu q_j) \, . \tag{8}$$

Left/Right (L/R) options for the lepton and quark brackets give 2^2, $q = u/d$ another 2, and then for each of 8 scales there is a sign factor $\eta = \pm 1$.

Comments are due:

- A *scalar* effective interaction is strongly vetoed by the non-observation of helicity violating pion decays, therefore only vector currents in (8).

- Existing OPAL+CDF limits on Λ_{ij}^q are typically $\Lambda \sim 0.8 - 3$ TeV, depending on the channel.

- The strongest constraints come from Atomic Parity Violation [9]. For example, the Cesium nucleus ($Z = 55$, $N \approx 78$) was predicted to have the Standard Model total weak charge $Q_W^{SM} = -73.12 \pm 0.09$ which fits well with the observed $Q_W^{exp} = -71.04 \pm 1.81$. Our contact interaction contributes to it as

$$\Delta Q_W = -2 \left[C_{1u}(2Z + N) + C_{1d}(Z + 2N) \right], \tag{9}$$

  where

$$C_{1q} = \frac{\sqrt{2}\pi}{G_F} \left\{ \frac{\eta_{RL}^q}{(\Lambda_{RL}^q)^2} - \frac{\eta_{LL}^q}{(\Lambda_{LL}^q)^2} - \frac{\eta_{LR}^q}{(\Lambda_{LR}^q)^2} + \frac{\eta_{RR}^q}{(\Lambda_{RR}^q)^2} \right\} .$$

  A *single* term in (8) with $\Lambda < 3$ TeV would produce $\Delta Q_W = \pm 20$, the resulting value being 10σ off.

- The possibility of a *conspiracy* between different helicity contributions is not excluded. Moreover, it has been argued by Ann E. Nelson [18] to be quite natural, from inside the GUT scenario.

- An actual fit to the Q^2-distribution of HERA events based on the contact interaction was performed in [4]. It includes the less experimentally restricted scales Λ_{LR}^{-d}, Λ_{RL}^{+d}, Λ_{LR}^{+u} and Λ_{RL}^{+u} and looks acceptable though not particularly spectacular.

B New exchange boson

Now we are in a position to introduce more dynamics into the discussion —
a new particle (boson) exchange as a model for the $e^+ q \to e^+ q$ blob.

We have three options to address:

t-channel exchange, $e^+ \to e^+ + X$, $q + X \to q$. This sort of X has long
been known as Z'. The combined D0+CDF exclusion limit for direct
production of such an animal in $q + \bar{q} \to Z' \to e^+ + e^-$, $\mu^+ \mu^-$ is too high,
$M_{Z'} > 650$ GeV. Moreover, this mechanism would obviously provoke a
similar signal in the $e^- p$ HERA sample as well, a reportedly unwanted
feature.

u-channel. Here the interaction sequence is $e^+ \to q + X$, $q + X \to e^+$.
In this case, however, the $e^- p$ DIS would yield a much larger number of
anomalous events. In this channel the interaction becomes resonant, and
the crossing relation

$$\sigma(e^- p) \sim \frac{M_X}{\Gamma_X} \sigma(e^+ p)$$

would produce about 10^3 $e^- p$ events at present statistics, given a typical
$\Gamma \sim 10$ MeV.

s-channel production is the only viable option. In this (as well as the u-
channel) case the exchanged boson obviously has both lepton and quark
numbers, a *leptoquark* (LQ).

C LQ quantum numbers

The LQ is a colour triplet like a quark, bears weak $SU(2)$ isospin and may
be a scalar or a vector boson (leaving aside higher spins $J > 1$ for the sake of
renormalizability of a future Phenomenological Theory).

The leptoquark fermion number may be either $F = 0$ or $F = 2$. The setup
$F = 0$, $J = 0$ seems to be preferred.

$F = 0$. The fermion number $F = 2$ means merging the positron with an *anti-
quark* parton from the proton, LQ= $e^+ \bar{q}$. Such an option is ruled out.
At large $x \sim 0.5$ where the game in being played, the sea is suppressed
by a factor 50(200) with respect to the valence d(u) quarks. Therefore,
by the previous argument, one would expect *at least* a few events (if not
more) in the cross channel, $\overline{LQ} = e^- q$ in which the valence quarks par-
ticipate. Moreover, the sea suppression drives the value of the coupling
λ quantifying the strength of the LQℓq interaction to dangerously large
values to explain the observed signal.

$J = 0$. The situation with the LQ spin is not as obvious [7]. Still, the $J = 1$ option seems to balance on the brink of being excluded experimentally. LQs can be produced in pairs at the Tevatron via gluon exchange $q + \bar{q} \to g \to \text{LQ} + \overline{\text{LQ}}$. The leptoquark production cross section has been limited by D0 as $\sigma < 0.4$ pb. This translates into the upper limit for the vector LQ mass, $M_{LQ}^{J=1} > 240(215) \, \text{GeV}$. A weaker restriction of $215 \, \text{GeV}$ emerges when the *maximal conspiracy* between production via the normal QCD-charge and a potential anomalous colour coupling is allowed [9]. At the Tevatron [4] the production cross section of the *scalar* LQ was estimated as $\sigma \simeq 0.2$ pb, with $J = 1$ overshooting by a factor 10.

This does not mean that the situation with $J = 0$ LQ is rosy. The scalar leptoquark is also (and hopefully will remain) under severe pressure from the Tevatron. The combined CDF+D0 exclusion limit for the LQ mass is

$$M_{LQ} \ < \ 190 \, (143) \, \text{GeV} \,, \qquad \text{for } B(\text{LQ} \to e^+ + q) = 1 \, \left(\tfrac{1}{2}\right) .$$

This brings us to an intriguing subject of decay channels other than $e^+ + q$.

A neutrino does not look easy to accommodate. An up-quark scenario $e^+ + u \to \text{LQ}$ calls for a weird object (system) with electric charge $+5/3$ to accompany $\bar{\nu}_e$ substituted for e^+ in the final state. The $e^+ + d \to \text{LQ}$ channel looks fine, at first sight, since one might expect a LQ decaying into $\bar{\nu}_e + u$. However, by examining the $SU(2)$ doublet structure of the coupling one observes that the LQ must couple to both left and right leptons: the $e_L^+ \, d_L$ combination to produce, the $(\bar{\nu})_R \, u_R$ to decay. This pattern, once again, is forbidden by pion decays.

It is worth noticing that an apparent difficulty with the neutrino may be good news, since no clear signal was reported in the Charged Current (CC) DIS.

D Special offer: squark

An R-parity violating SUSY object — squark — as a LQ candidate seems to offer a natural qualitative explanation for some of the above-mentioned peculiarities and troubles. Namely, it is ready to explain an absence of signal in $e^- p$ and CC-$e^+ p$ collisions and has room for decreasing the branching into $e^+ q$.

$R = (-1)^{3B+L+2J}$ is $+1$ for normal particles (quarks, leptons, electroweak bosons) and -1 for their SUSY-partners. Within the R-parity-respecting scenario sparticles are produced in pairs. Lifting off this requirement allows an R-parity-violating coupling of a squark to a lepton and a quark, the one we are looking for. The first thing to mention is that normal R-conserving SUSY decays of such an object can be employed to push down the $e^+ q$ branching, thus softening the Tevatron mass boundary.

Eight distinctive final state signatures for squark production were found and listed in [22]. Depending on the nature of the lightest *neutralino* (one among *photino* $\tilde{\gamma}$, *zino* $\tilde{Z}$ and two *Higgsinos* $\tilde{H}_0$; what a language!) they involve high-$P_\perp$ e^+/e^- and/or missing $P_\perp$ and different numbers of jets.

Minimal SUSY extension of the SM can be supplied with an abundance of R-violating structures:

$$W_{\bar{R}} = \lambda_{ijk} L_i L_j e_k^c + \lambda'_{ijk} L_i Q_j d_k^c + \lambda''_{ijk} u_i^c d_j^c d_k^c \,. \tag{10}$$

Capital L and Q stand for the left $SU(2)$-doublet lepton and quark fields. Little e, d and u are right lepton and quark (up/down) singlets; superscript c marks a conjugated field (antiparticle). Finally, i, j, k are flavour generation indices, running from 1 to 3. Each field in (10) is a *superfield*. This means that each letter may be taken to represent either a normal particle or its super-partner. In particular, the second term of this Lagrangian contains the combination $\lambda'_{111} \, e_L^- \, \tilde{u}_L \, d_R^c$, the one responsible for the process $e_R^+ d_R \to \tilde{u}_L$. Similarly, the couplings λ'_{121} and λ'_{131} would produce in $e^+ d$ collisions $\tilde{c}$ and $\tilde{t}$ squarks respectively. Thus we are talking about scalar SUSY-partners of the upper quark fields as potential leptoquarks produced in positron-d-quark collisions.

Good old physics interferes again to veto the first generation scenario involving $\tilde{u}$. Normal SUSY interaction may virtually transfer a d-quark into a spair $d \to \tilde{d} + \tilde{g}$. The new R-violating coupling λ'_{111} then causes the squark decay $\tilde{d} \to u + e^-$. This opens up a possibility of neutrinoless double β-decay (put two neutrons close to each other and let their internal d-quarks exchange a virtual gluino).

The HERA event rate implies $\lambda' > 0.03$. At the same time, an experimental limit on $0\nu\,2\beta$-decay translates into a much smaller value

$$|\lambda'_{111}| \; < \; 7 \cdot 10^{-3} \left(\frac{m_{\tilde{q}}}{200\,\mathrm{GeV}} \right)^2 \left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}} \right)^{\frac{1}{2}} \,.$$

The $\tilde{c}$ and $\tilde{t}$ options remain open. What is interesting (and may become a crucial turning point for upgrading the leptoquark TP into a PT, see above) is that each of the two scenarios predicts new discoveries "around the corner" [4]. Thus, the $\tilde{c}$-scenario provokes FCNC-forbidden decays $K^+ \to \pi^+ \nu\bar{\nu}$ not far below the present experimental limit, new effects in $D^0 \leftrightarrow \bar{D}^0$ mixing, $D^0 \to e^+ e^-$ and $D^+ \to \pi^+ e^+ e^-$ decays. The $\tilde{t}$-scenario, in turn, may cause a potentially large contribution to the ρ-parameter.

Under scrutiny are FCNC, CC-universality, neutrino masses, rare decays, mixing, etc. The first impression is somewhat worrying. Experimental information about the 2nd and the 3rd generations, though not as extensive as for the 1st, severely restricts off-diagonal *products* of λ'- couplings. In particular, $\lambda'_{i12}\lambda'_{i21}$ (ΔM_K and ϵ_K), $\lambda'_{i13}\lambda'_{i31}$ (ΔM_B), $\lambda'_{11k}\lambda'_{21k}$ and $\lambda'_{1j1}\lambda'_{2j1}$ ($\mu\mathrm{Ti} \to e\mathrm{Ti}$),

$\lambda'_{1j1}\lambda'_{2j2}$ ($K_L \rightarrow \mu e$). The list can be continued. It looks as if we must have only one coupling to explain the HERA anomalous events, and forbid all the others. The question of "naturalness" comes to mind.

The R-violating Lagrangian (10) possesses another conceptual problem. It contains, together with the λ'-sector, λ- and λ''-terms that violate FCNC and cause proton decay, respectively. This problem was addressed by R. Barbieri, Z. Berezhiani and A. Strumia in [28]. They argue that the GUT initial conditions may provide peace and calm down here by suppressing the unwanted couplings, in a long course of evolution from the GUT scale, in a more or less natural way.

Also under focus are virtual LQ effects in e^+e^- collisions (typically at the 1% level, [8]), prospects for LEP-2 and NLC studies [6], [16], [21], and an e^+D option at HERA. Results of the first calculations of QCD corrections to the Born LQ production amplitudes have also been reported [19], [24].

Highly non-orthodox solutions of the HERA puzzle were suggested by Stephen Adler ($SU(4)$-preons) [1] and Alan White (Sextet Quark Model) [27]. I am not in a position to provide you with a constructive criticism of these ideas or to praise them. Nevertheless, a word of caution is due. There is a strong chance that intrinsic ties between the electroweak and QCD sectors of the SM are much deeper that we used to think they are. (Remember a mysterious pion, a point-like Goldstone from the electroweak point of view, and a loosely bound $q\bar{q}$ pair for QCD.) Therefore, watch out and be ready for surprises.

Let me finish this non-expert review with a citation which has unintentionally demonstrated how rapidly our field is actually developing: "... possible backgrounds come from the production and decay of top quark pairs..." [4]. It did not take long for the t-quark to develop into a "background" for some newer and ever more exciting phenomena.

The grip of the Standard Model remains tight. New physics? May be, it is about time. In a near future we will learn whether the DIS-97 Chicago assembly marked a peak of a historic, or rather hysteric, period in elementary particle physics.

Anomaly related papers on the hep bulletin board 1997

28. The high-Q^2 Hera anomaly and supersymmetric unification,
    Riccardo Barbieri, Zurab Berezhiani, Alessandro Strumia   [04275]

27. Electroweak-Scale Excess Cross-Sections in the Sextet Quark
    "Standard Model", Alan R. White   [04248]

26. e^+e^- Annihilation into Hadrons at LEP2 in the Presence of
    the Anomalous DESY Positron-Jet Event Phenomenon,
    S. Jadach, B. F. L. Ward, Z. Was   [04241]

25. Stops in R-parity Breaking Model for High-Q^2 Events at HERA,
    T. Kon, T. Kobayashi   [04221]

24. QCD aspects of leptoquark production at HERA,
    C. Friberg, E. Norrbin, T. Sjöstrand   [04214]

23. HERA high Q^2 events as indications of excited leptons with
    weak isotopic spin 3/2, B. A. Arbuzov   [03460]

22. R-Parity Violating Supersymmetry at HERA,
    Herbi Dreiner, Emanuelle Perez, Yves Sirois   [03444]

21. Supersymmetry with R-Parity Breaking: Contact Interactions
    and Resonance Formation in Leptonic Processes at LEP2,
    J. Kalinowski, R. Rueckl, H. Spiesberger, P. M. Zerwas   [03436]

20. Formation and Decay of Scalar Leptoquarks/Squarks in ep
    collisions, T. Plehn, H. Spiesberger, M. Spira, P. M. Zerwas   [03433]

19. QCD Corrections and the Leptoquark Interpretation of the
    HERA High Q^2 Events, Z. Kunszt, W. J. Stirling   [03427]

18. Contact Terms, Compositeness, and Atomic Parity Violation,
    Ann E. Nelson   [03379]

17. Four-Fermion Effective Interactions and Recent Data at HERA,
    Nicola Di Bartolomeo, Marco Fabbrichesi   [03375]

16. Leptoquark production at LEP2, Costas G. Papadopoulos   [03372]

15. Like-Sign Dileptons at the Fermilab Tevatron Revisited in
    the Light of the HERA High-Q^2 Anomaly,
    D. Choudhury, S. Raychaudhuri   [03369]

14. Bounds on Contact Interactions from LEP1 Data and the
    High-Q^2 HERA Events, M. C. Gonzalez-Garcia, S. F. Novaes   [03346]

13. Constraints on Leptoquark Masses and Couplings from Rare
    Processes and Unification, G. K. Leontaris, J. D. Vergados   [03338]

12. Much Ado About Leptoquarks: A Comprehensive Analysis,
    JoAnne L. Hewett, Thomas G. Rizzo   [03337]

11. Removing flavor changing neutral interactions from leptoquark
    exchange, M. Suzuki   [03316]

10. Contact Interactions and high-Q^2 events in e^+p collisions at HERA,
    V. Barger, Kingman Cheung, K. Hagiwara, D. Zeppenfeld   [03311]

 9. Comments on the high-Q^2 HERA anomaly
    K.S. Babu, Christopher Kolda, John March-Russell,
    Frank Wilczek   [03299]

 8. Leptoquark/Squark Interpretation of HERA Events: Virtual
    Effects in e+e- Annihilation to Hadrons,
    J. Kalinowski, R. Rueckl, H. Spiesberger, P. M. Zerwas   [03288]

 7. On the Expectations for Leptoquarks in the Mass Range
    of O(200 GeV), J. Blümlein   [03287]

 6. What Can We Learn About Leptoquarks At LEP200?
    Michael A. Doncheski, Stephen Godfrey   [03285]

 5. High Q2-Anomaly at HERA and Supersymmetry,
    H. Dreiner, P. Morawitz   [03279]

 4. Pursuing interpretations of the HERA large-Q2 data,
    G. Altarelli, J. Ellis, S. Lola, G. F. Giudice, M. L. Mangano   [03276]

 3. Rapidity Gap of Weakly Coupled Leptoquark Production in
    ep Collider, T. K. Kuo, Taekoon Lee   [03255]

 2. R-Parity Violation at HERA?
    Debajyoti Choudhury, Sreerup Raychaudhuri   [02392]

 1. SU(4) Preonic Interpretation of the HERA Positron-Jet Events,
    Stephen L. Adler   [02378]

 0. Scalar Leptoquark Pair Production at the CERN LHC: Signal and
    Backgrounds, B. Dion, M. de Montigny, L. Marleau, G. Simon   [01285]