Future Directions for QCD*

James D. Bjorken
Stanford Linear Accelerator Center, Stanford, California 94309

ABSTRACT

New directions for exploring QCD at future high-energy colliders are sketched. These include jets within jets, BFKL dynamics, soft and hard diffraction, searches for disoriented chiral condensate, and doing a better job on minimum bias physics. The new experimental opportunities include electron-ion collisions at HERA, a new collider detector at the C0 region of the TeVatron, and the FELIX initiative at the LHC.

I. INTRODUCTION

This talk is not meant to be a comprehensive overview of QCD. The emphasis here is simply on those aspects of QCD theory and phenomenology most relevant to the Snowmass mission, namely, (1) new-facility opportunities, (2) new, relatively unexplored, directions in QCD theory and/or experiment, and (3) the difficult areas of QCD which need to be data driven, but where the data is insufficient.

Before entering into these somewhat specific and perhaps idiosyncratic topics, it must be put on the record that a large core region of theory and phenomenology is in quite good shape, and quite mature. The QCD Lagrangian has been "tested" so incisively that few if any theorists now challenge the correctness of the QCD Lagrangian (this includes yours truly). Yes, α_s runs. The parton structure of hadrons and much of hard-collision phenomenology are well understood. Extrapolation to the higher energies and new facilities can be done with confidence, at least at the level needed for design purposes.

However, there are many fundamental issues in QCD which are not in good shape. Quite a few involve the low-energy nonperturbative sector, *e.g.* the question of confinement, and do not meet the criteria for inclusion in this talk as outlined in the first paragraph. My views of some of these are covered in another talk, given at the SLAC Summer Institute this year[1].

The QCD physics issues which will be discussed in the next section include

- Fractal final-state phase space
- Black quarks
- Soft and hard diffraction
- The chiral phase: disoriented chiral condensate
- Underlying-event and minimum-bias physics.

In Section III we discuss these topics in the context of physics opportunities at new machines and/or new facilities at old machines.

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II. PHYSICS

A. Fractal final-state phase space

The final-state phase space in the high-energy, high-p_t limit of strong interactions is fractal[2]. By this we mean that the QCD branching structure of parton cascades leads to jets within jets within jets$\ldots$ Each jet extends the phase-space region into which hadrons are produced. Because of the self-similar nature of the parton cascade, this leads to an anomalous dimension of the phase space.

To get some more concrete appreciation for what the above words are supposed to mean, consider a typical Fermilab Tevatron multijet final state, with the jets well scattered in the lego plot. In the detector most of these jets will be at small angles. But suppose that the system were produced at large angles instead. Then in the lego plot, with the usual Snowmass-accord definition of jets, the multijet configuration would most likely be able to be described as a mere two-jet final state. The original information of the multijet textures of the right-moving or left-moving systems would be compressed into single circles-of-radius-0.7. Clearly one should not be content with such a description. It is however easy to retrieve the original information without an overall coordinate rotation[3]. One simply introduces polar coordinates inside each Snowmass circle, trades the new polar angle in for an appropriately defined rapidity variable and replots the contents of the interior of the circle into a new lego plot. Note that the area of the new lego plot will be $2\pi \log p_t$. If jets are found in the new lego plot the process is iterated until none remain. Then the mean density of produced hadrons in this extended lego plot can be expected to be rather uniform, and therefore the total multiplicity can be expected to be proportional to the total lego area, which clearly has fractality built in.

To see this fractality clearly is a big experimental challenge. For the leading-jet systems prevalent in hadron-hadron collisions, the calorimeter resolution in the forward direction is made very good; the pixel area (in real space) near the beam axis is made small, so that *e.g.* the number of pixels per unit azimuthal angle does not depend upon distance from the beam. For the rotated jet systems, one needs to accomplish this in all directions.

Thus the frontier becomes very small pixel size, when expressed in lego variables, everywhere in the detector. In practice a $\delta\eta \times \delta\phi$ of 0.003×0.003 might be attainable for resolving charged tracks and γ's, and this would give good resolution in the first phase-space extension out to η' of about 4. This would require of order 10^6 pixels for a typical 4π detector.

Might such a capability be useful beyond QCD? It seems to me that the answer is affirmative. For example, one might search for rapidity gaps in transverse, extended phase space.

For example consider a W produced at $p_t = 800\ GeV$ decaying symmetrically into two jets. The separation of the jet cores is 0.2 radians; in the extended phase-space the jet cores will appear at $\eta' = 2$ (Fig. 1). And there will be a rapidity gap in the extended-phase-space lego plot. This feature may be useful for production of color-singlet objects which are even more interesting than a W.

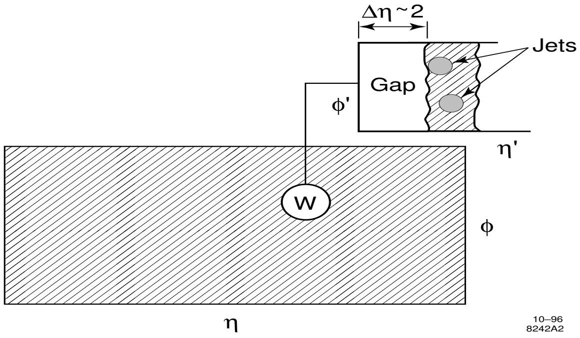

Figure 1: Extended phase-space for high-p_T W production.

B. Black Quarks

Quark-parton interactions at a large, fixed momentum scale Q increase in strength as the center-of-mass energy increases, despite the phenomenon of asymptotic freedom. The Rutherford form of the parton-parton interaction is modified by a positive power of cms energy, perhaps as large as 0.8. This could well lead to a novel regime of strong-interaction phenomena in a kinematic regime naively expected to be under control via QCD perturbation theory.

The formalism underlying this involves the exchange of a ladder built from gluons, the so-called "hard Pomeron" or "BFKL Pomeron"[4]. A very clean prototype process is the interaction of two spacelike virtual photons with each other at extreme cms energy. The interaction of the two small color dipoles via one gluon exchange is enhanced by extra gluon emission, and the expectation is, in the limiting case of large Q^2 and very large s, that there are no residual soft effects[5]. This is in contrast to the situation in ep interactions, where the "aligned-jet" mechanism probably dominates the small-x physics[6]. In this case the important fluctuations of the virtual photon into quark-antiquark are those which create a large dipole-moment and small internal p_t of the $q\bar{q}$ system. While the configuration is improbable at large Q^2, the interaction with proton, when it occurs, is strong, leading to scaling behavior and good phenomenological results. In collisions of two virtual photons, however, the "alignment" has to occur twice, once for each photon, and therefore the cross-section falls as Q^{-4}, while the perturbative piece scales as Q^{-2}. Numbers are being provided by Brodsky, Hautmann and Soper[5]; beyond $10\ GeV^2$ the perturbative piece begins to dominate (Fig. 2).

Typical BFKL final states are multijet; in the $\gamma^*\gamma^*$ case their p_t are all supposed to be of order Q, and the mean rapidity spacing of the gluon jets is inversely correlated (roughly) with the exponent of the rise with energy of the cross section:

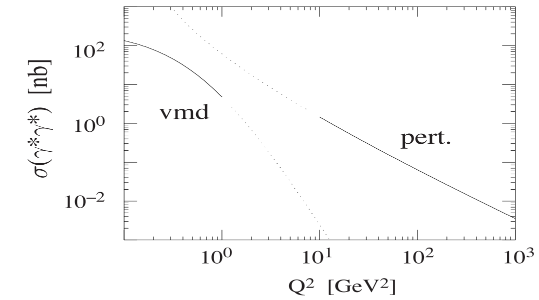

Figure 2: Estimated $\gamma^* - \gamma^*$ cross sections versus Q^2.

$$0.4\,\Delta\eta = \frac{12\alpha_s \Delta\eta}{\pi\, \ell n\, 2} \sim 1 \quad \text{or} \quad \Delta\eta \sim 2.5\ . \tag{1}$$

In hadron-hadron collisions, the same phenomenon occurs, with gluons or quarks, not virtual photons, as projectiles. As emphasized by Mueller and Navelet[7], there should be leading jets with p_t of order Q, the generic p_t scale, to define the scale of the BFKL process. And again there should be a multijet structure in between the leading jets, with mean rapidity spacing again of order 2.5.

In order for the multijet phenomenon to occur (and presumably the BFKL energy dependence as well!) very large s/Q^2 is therefore necessary. A naive estimate of when the quark-quark cross section gets large (the "black-quark threshold") is

$$\sigma \sim \frac{4\pi\,\alpha_s^2}{Q^2}\left(\frac{s}{Q^2}\right)^{0.4} \approx \frac{2\pi}{Q^2} \tag{2}$$

or

$$\sqrt{s} \sim 100\, Q\ . \tag{3}$$

The bottom line is that very large subenergies are preferred.

C. Rapidity Gaps

The presence of rapidity gaps in soft hadron-hadron collision processes is an old story: this is the physics of elastic scattering and diffraction dissociation. If, however, quarks can get "black", then one can anticipate a new class of diffractive processes that are intrinsically short-distance. In addition there are hard diffractive processes induced by color-singlet two-gluon exchange (or electroweak-boson exchange) which also can lead to final states containing both rapidity gaps and jets, even without invoking the BFKL strong interaction.

The study of hard diffraction (rapidity gaps and jets in the same final state) is in its infancy. It was proposed by Ingelman and Schlein[8], and dijets in single diffractive dissociation have been found by Schlein and collaborators in the UA8 experiment[9]. Since then rapidity gaps between coplanar dijets have been observed in $p\bar{p}$ collisions by D0 and CDF[10], and gaps are seen as an important final state in deep inelastic ep collisions at HERA[11].

So there are many such hard diffractive processes, some characterized by a semisoft momentum transfer across the rapidity gap (UA8, HERA) and others by a large momentum transfer (CDF, D0). Sorting it all out will be a major program for the future. The soft and semisoft diffraction is arguably a consequence of the blackness of the constituent quark. It is a central question whether BFKL blackness of partons is in fact just a smooth extrapolation to smaller scales of the observed blackness of constituent quarks, or whether they are distinct phenomena. The answer to this question will have to be data driven.

There is a lot which still needs to be done experimentally to study well the various forms of hard (and for that matter semisoft and soft) diffraction. Roman-pot detectors in both beam directions to catch leading particles should be a standard supplement to every modern barrel detector at colliders. At present there is only the beginning of a realization of the value of this simple addition to the instrumentation. In addition, for the optimal study of BFKL phenomena, there should be good detection capability at large pseudorapidity (4 to 7 at the TeVatron, and 4 to 9 at the LHC) to identify the BFKL-Mueller-Navelet tagging jets as well as to validate the presence of rapidity gaps. The need for this large-acceptance capability is even less appreciated; I have advocated its importance for some time[12] and can only report my total state of frustration.

In the shadowy world of diffractive phenomena, nuclei as targets or projectiles are very valuable, since they are a way of tuning the degree of blackness present in the collision process. The A-dependence of the small-x behavior in electroproduction, for example, provides strong evidence for the aligned-jet picture of the dynamics at fixed-target energies. A-dependence studies would be an especially valuable tool at HERA energies, where there is clear evidence for onset of new behavior, either BFKL or its precursor, in the structure function F_2. The high observed gluon density in the nucleon presages a much higher gluon density in nuclei. The recent workshop studies at DESY[13] show that even for Al and certainly for Pb the gluon density $xG(x)$ should be large enough to exhibit saturation effects at attainable energy.

The study of rapidity gaps with ion projectiles at HERA would be an especially useful way to sort out the various theoretical scenarios on the diffractive mechanisms in electroproduction. For example most models have anticipated that the typical diffracted mass would be of order Q. The newest data clearly show a contribution from diffracted masses large compared to Q. In the aligned-jet picture, the former piece comes from elastic scattering of the slower quark or antiquark from the nucleon ($A^{2/3}$), while the latter piece would be diffraction dissociation ($A^{1/3}$). Other models will I am sure differ from this expectation and, no matter what, the progress will need to be data driven.

It seems to me that an e-ion capability at HERA is a most natural upgrade path, one that flows naturally from the major contribution of the present HERA program to strong-interaction physics, and one which will surely be very productive and will help to complete the story which HERA has so successfully initiated.

In any case the bottom line is that the A-dependence studies remain of great value at collider energies: $e - A$ at HERA, and $p - A$ at RHIC and LHC.

And the bottom lines for rapidity-gap physics are for me whether the "new" BFKL physics is a smooth extension of the strong-coupling physics of the constituent quarks, whether soft and hard diffraction are smoothly connected, and what role (if any) the chiral limit of QCD plays in these issues. It is possible that these issues may turn out to be not distinct, but really just the same.

D. The Chiral Phase in QCD; Disoriented Chiral Condensate

The up and down quarks are at short distances almost massless. This implies that QCD has a nearly exact $SU(2) \times SU(2)$ symmetry corresponding to separate isospin rotations of left-handed and right-handed quarks. This symmetry is spontaneously broken. There is a vacuum condensate (like the Higgs condensate) and the pions emerge as collective (Goldstone-boson) modes of the condensate. In the perfect symmetry limit the pions would be massless.

Given the mechanism of spontaneous symmetry breakdown, much of the long-distance, low-energy limit of the theory is rather well determined, in particular the low-energy limit of the interactions of the pions with matter and with each other. This is codified in the "chiral effective Lagrangian," with the degrees of freedom being constituent quarks and pions. The validity of this effective theory extends from zero energy up to a mass scale of 500-1000 MeV[14].

It is a challenge for QCD theorists to derive the existence of this chiral phase from first principles. There is evidence from the lattice calculations that a chiral condensate forms, but the mechanism remains unclear. There is also an interesting line of work by Shuryak, Diakonov, and others which argues that the chiral symmetry breaking mechanism can be traced to the presence of instantons in the QCD vacuum[15]. This idea is discussed more in my SLAC Summer Institute talk[1].

But while everyone (theorists) talks about the QCD vacuum, hardly anyone (experimentalists) tries to do something about it. For the last three years some of us have banded together to do a test/experiment at the Tevatron collider (T864 (MiniMax)) to search for something called disoriented chiral condensate (DCC)[16].

What is DCC? It is a conjectured piece of strong-interaction vacuum with an unusual orientation of its chiral order parameter. The vacuum condensate associated with the $SU(2) \times SU(2) = 0(4)$ chiral-symmetry spontaneous breaking is a chiral four-vector $(\sigma, \vec{\pi})$ which in normal vacuum points in the sigma direction. But inside a hot fireball shell created in a high-energy collision, the chiral orientation need not be the same. If it is different, *e.g.* points in the π^0 direction, then this piece of wrongly oriented vacuum will eventually decay into true vacuum with emission of a semiclassical pulse of π^0's. In other events the chiral order parameter might point in a charged-π direction and only charged pions will be found in the final state.

The experimental signature is large event-to-event fluctuations of the fraction of produced pions which are neutral. One finds

$$f = \frac{N_{\pi^0}}{N_{\pi^0} + N_{\pi^+} + N_{\pi^-}} \tag{4}$$

$$\left(\frac{dN}{df}\right)_{\rm DCC} = \frac{1}{2\sqrt{f}} \tag{5}$$

$$\left(\frac{dN}{df}\right)_{\rm Generic} \approx \delta\left(f - \frac{1}{3}\right) \ . \tag{6}$$

There are other possible signatures as well. DCC which is produced at large transverse velocity may be easiest to find. Or cutting on low transverse momentum or groups of pions with low relative transverse momentum are other possibilities.

This theoretical picture is also motivated by cosmic-ray events (Centauro, anti-Centauro) seen in mountaintop and balloon-borne emulsion chambers[17]. In the Chacaltaya events, it is claimed that groups of hadrons which exhibit the Centauro-like behavior also have low relative transverse momentum, perhaps in line with the above picture, which suggests that the hadrons are emitted at late proper times from a large emitting area.

Our test/experiment T864 was proposed in April 1993, and is now completed. This is not the occasion to describe it in any detail. Suffice it to say that we have recorded about 8 million events, and have initiated the data analysis. We have found a promising analysis technique[18] which utilizes ratios of bivariate factorial moments (standard tools of the trade in the multiparticle-dynamics community) to finesse many (not all) of the serious efficiency problems faced in such a search—especially ours, which uses unsophisticated apparatus of small acceptance.

It is still very early in the analysis. Thus far we see no evidence for spectacular events *a la* Centauro and JACEE, although we need to do more work to assess the level of significance. The factorial-moment method shows consistency with generic pion production, with a DCC admixture limited to something like 10 to 20 percent of the generic production (although it is too early to really quote numbers).

No matter what comes out, we have learned a lot about how to go about searching for DCC, and believe that the search can and should be done with better detectors and improved analysis technique. We stand ready to help others make the search. At present there is a growing interest within the nuclear-physics, heavy-ion community in searching for DCC. I hope this might happen in the high-energy community as well.

E. Underlying-event and Minimum-bias Physics

The physics of mundane, minimum-bias events, and the underlying-event portion of high-p_t multijet events is definitely not a glamour subject. Nevertheless it is a topic which is important in its own right as well as having serious engineering value in the interpretation of the high-p_t, high glamour physics.

The data base in electron-positron collisions is by now quite complete, and the theoretical descriptions relatively mature. But even for this case there are new challenges appearing, especially in the analysis of $WW \rightarrow q\bar{q}q\bar{q}$ final states at LEP II. One cannot superpose the final-state hadron distributions from two independent W decays, because the hadronization of each jet pair occurs simultaneously in overlapping regions of space. Many of the final-state-interaction properties are nonperturbative in origin and will be a challenge to QCD phenomenology. And the stakes are high; namely, accurate measurement of the W mass[19].

But the situation is the worst in hadron-hadron collisions[20]. The main minimum-bias data base at collider energies is limited to UA(1), where a small band of analysts carry on valiantly an analysis of that old data, and UA(5)—a nonmagnetic streamer-chamber experiment with low gamma-ray efficiency—which nevertheless to this day remains one of the most serious sources of real information. There is a small amount of data from our much-too-modest predecessor experiment at C0, E(735). CDF and D0 have poor capability at transverse momenta under 400 MeV, greatly hampering meaningful minimum-bias analyses. In addition, D0 of course does not have magnetic analysis, also a serious limitation. Much of the minimum-bias physics at collider energies is reduced to Monte-Carlo cocktails, the quality of which, for an outsider like me, is hard to digest. Of course, the creators do a great service to the field. Nevertheless what is really assumed? What is the real data base that is used, and what are the limits of applicability? Were a real hadron-hadron minimum-bias data base to suddenly appear, how well would those codes really do?

With the great investment being made in learning about the rare processes, it would seem especially prudent to make at least some modest investment toward understanding the more common processes. To do that job well requires a community of interest able to mount a dedicated effort with specialized detectors that have low-p_t sensitivity, acceptance large enough to observe the final-state energy (not E_T) distribution, along with some particle identification. Such detectors should acquire a large database commensurate with modern data-acquisition capabilities. It is with despair that I note that there is insufficient interest within this country for this to happen. It is not only a pity that this is the case, it is bad science.

III. MATCHING THE PHYSICS TO THE FACILITIES

A. Electron-Positron Colliders

As we have already mentioned, the decay of virtual γ and Z into jets plus gluons is well studied and can be extrapolated safely to higher energies. The main QCD phenomenon for higher energies that is not presently under study is the BFKL hard Pomeron. Ideally one wants to study the final-state hadron system in the high-energy collision of two virtual photons. For this one must tag the secondary electron and positron, which is not at all easy. But in addition one would like to see the leading hadrons and Mueller-Navelet tagging jets. While finding the electrons may be doable if care is exercised in the initial design of the final focus system, having low β^* and seeing the leading-particle hadrons looks very hard to me. Higher β^* (if the luminosity loss is tolerable) and/or a separate detector/collision region may be necessary.

B. Electron-Proton Colliders (HERA, eventually LHC?)

Options for the future of HERA are now under study. While this is an issue outside the scope of the Snowmass charge, future US participation will be influenced by the issues and the unique physics opportunities. At present the HERA program probes in powerful and unique ways the mechanisms of diffraction and the nature of the Pomeron.

One of the options for HERA is to study electron-ion collisions. To me this is a very attractive option, which would, as mentioned already in the previous section, consolidate the gains already made in understanding the nature of diffractive processes and the physics behind the rise of the deep-inelastic structure function at very small x. Together with such a program it would be very natural to increase the acceptance of the present detectors in the proton direction to more fully interpret the diffractive phenomena. This is a deficiency already apparent in the electron-proton collisions now being studied. Forward detectors, within and outside the beam-pipe acceptance, are needed to define well the rapidity gaps. The proton fragmentation, *e.g.* into tagging jets, is an important signature for BFKL dynamics as well. The deficiency in the present coverage (Fig.3) is serious, especially if one is to study at all the nuclear fragmentation.

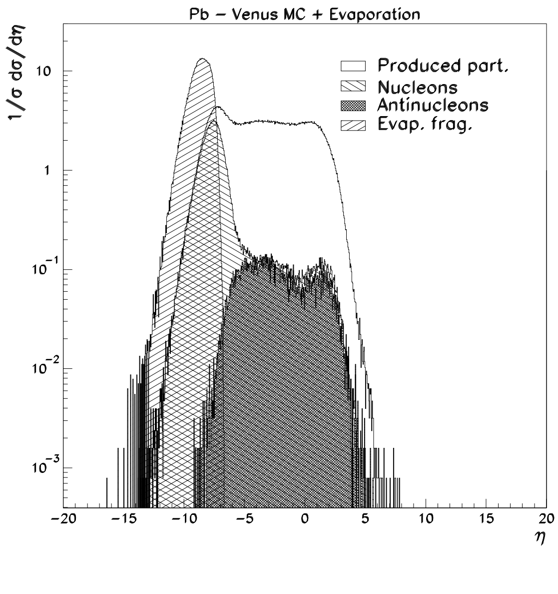

Figure 3: Hadron production spectra for $e - A$ collisions at HERA.

C. Hadron-Hadron Colliders

We have already mentioned two basic QCD frontiers in hadron-hadron collisions which impact in a most fundamental way on detector design. One is the high-granularity frontier of very small lego-pixel resolution to look in the interior of jets. Here by necessity the burden in reconstruction of jets-within-jets goes onto the electromagnetic calorimetry and the charged-particle tracking. Hadron calorimetry is almost certainly too coarse to be definitive in resolving the substructure. But I believe multijet spectroscopy can still be done without the hadron calorimetry. The price paid is some inefficiency per jet of order 20-30%, which occurs if it is lost into a lower p_t bin when too much transverse energy goes into K_L or neutrons. This strategy would of course need careful study, and even if it works in principle there is a great demand on the detector design. But, assuming the strategy is found in principle to be okay, the physical limit on resolving individual γ's or tracks would be at the few millimeter level, leading in typical detectors the possibility of exploring extended phase space to rapidities of 3 to 4. Providing this texture in all of phase space would involve an enormous number of readout channels. But it seems to me it would be valuable to instrument at least a portion of the large-angle acceptance in such a way.

Another frontier that just has to be useful is that of particle identification. There has not been a Cerenkov detector in a hadron-hadron collider since the ISR. The emergence of collider detectors to do heavy flavor physics should change that, and there may be many other useful QCD byproducts coming from that extended capability.

Yet another frontier is simply to supply the capability for studying low-p_t phenomena well; here low-p_t means down to tens of MeV per particle. Novel phenomena like DCC production or other particle production mechanisms which occur well within the light cone (instead of very near it) may leave their signature in the properties of low-p_t secondaries. So far CDF and D0 have exhibited neither the capability nor much interest in exploration in this direction.

Finally there is the issue of the extension of acceptance into the forward region. Magnetic analysis of charged particles should extend beyond the barrel-solenoid region all the way to the leading particle region. The problem of peaceful coexistence with the beam-pipe showering is a serious one, but one that I believe can be solved. And, as already mentioned, Roman-pot detectors within the beam-pipe acceptance should be designed *ab initio* into the machine lattice, not only to see the elastic and diffractive protons, but also to pick off inelastic leading hadrons which cannot be found with detectors exterior to the pipe. Again, to do all this requires an attitude by an interested community that this is indeed not only worth doing, but is a necessary adjunct to the highest priority, high-p_t program of exploratory physics.

D. Possible New Options: (CO at the TeVatron, and FELIX at LHC)

There are at present two fresh options for innovations. One is at Fermilab, where there are preliminary studies initiated by its director to explore the physics case for—and feasibility of—upgrading the C0 collision region for a major third detector. The physics focus would be on high-yield charm and bottom physics, the latter at or beyond what is needed to observe CP-violating phenomena. This is a right and proper central goal. However there is the possibility that this lead program could be supplemented with full-acceptance capability for studying some of the topics mentioned above.

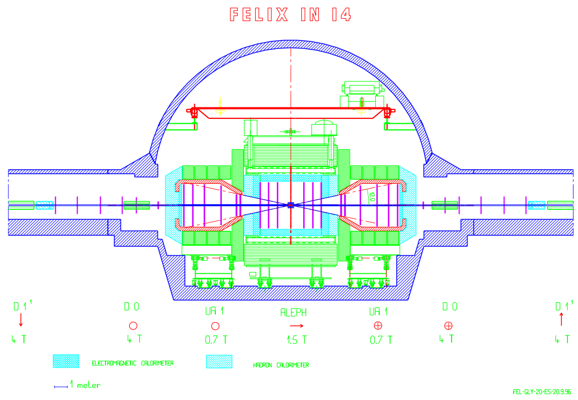

Figure 4: Layout of the FELIX detector for the LHC.

A study is underway under the leadership of Jeff Appel and Peter Garbincius. The time scale is very short, because there is a window of opportunity for doing the civil construction during a Main-Injector-commissioning shutdown. Up-to-date information is best obtained by consulting Jeff and/or Peter. Additional insight may be gleaned from the public report of Fermilab's PAC[21], which encourages nothing at C0 except heavy flavor physics. In my opinion, this attitude is deplorable.

The FELIX initiative at the LHC aims to provide a true full-acceptance detector which would be the definitive QCD facility for that program. It would be located at intersection region I4, where ALEPH now resides, and in fact would use its solenoid as its central magnet. The next magnetic stages upstream and downstream would utilize the UA1 magnet yokes (with a new coil), which are modular and "portable" (Fig. 4). Thus the central free space of $\pm$ 10 meters would be well covered by magnetic field appropriate for full magnetic analysis of charged secondaries with $\eta \leq 6$. Magnetic analysis in the region from 10 to 100 meters from the collision point would be provided by machine magnets and appropriate tracking, sufficient to provide complete rapidity coverage for the charged particles of $\eta \geq 6$, including the elastic and diffractive protons.

Because there is little cost in civil construction and magnetic/calorimetric tonnage, the main cost for the detector is measured in terms of number of readout channels. A base cost is what is needed to bring the beams together into collision. With a multiplier of two to three of this base cost, a great deal of Stage I physics could be accomplished.

More details on this initiative can be obtained from Karsten Eggert (CERN) or Cyrus Taylor (Case Western Reserve University), and by consulting the FELIX web page http://www.cern.ch/FELIX.

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