FULL ACCEPTANCE PHYSICS AT THE LHC

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This paper reviews the detector concept and the physics menu of a full acceptance detector at a hadron collider. As an example, the set-up of the FELIX experiment, proposed for the LHC, is described. The primary mission of FELIX is QCD: to provide comprehensive and definitive observations of a very broad range of strong-interaction processes.

1 Introduction

A full acceptance detector at the Large Hadron Collider (LHC), planned at CERN, has to be optimized for studying the structure of individual events over the entire phase space. Particle production extends to very small forward angles and most of the energy flow is contained in the extreme forward cones below 1 mrad (Figure 1).

The particle production at three hadron colliders (FNAL,LHC and a possible supercollider) is illustrated in Figure 2. The larger the centre-of-mass energy, the further forward the acceptance has to be extended for large momentum particles. Consequently, long straight sections ($\pm$ 100 m for LHC) with strong magnetic fields are needed to separate the beams to allow the detection of neutral particles between the beams and to sweep forward charged particles out of the beams. The principle is illustrated in Figure 3 for the LHC case. The machine quadrupoles focussing the beams have then to be placed, further upstream behind the beam separating dipoles resulting in large beta-values and lower luminosities. This is the reason why high luminosity experiments are not compatible with full acceptance detectors. However, the detection of very forward diffractive protons, a few hundred meters upstream, is not so much influenced by the central experimental lay-out and these "Roman Pots" should be integrated in each experiments.

We discuss the principle lay-out of a full acceptance detector, using the FELIX [1] experiments as an example. FELIX will observe and measure all charged particles, from the central region all the way out to diffractive protons which have lost only 0.2% of their initial energy.

The FELIX design involves the coordinated arrangement of three distinct

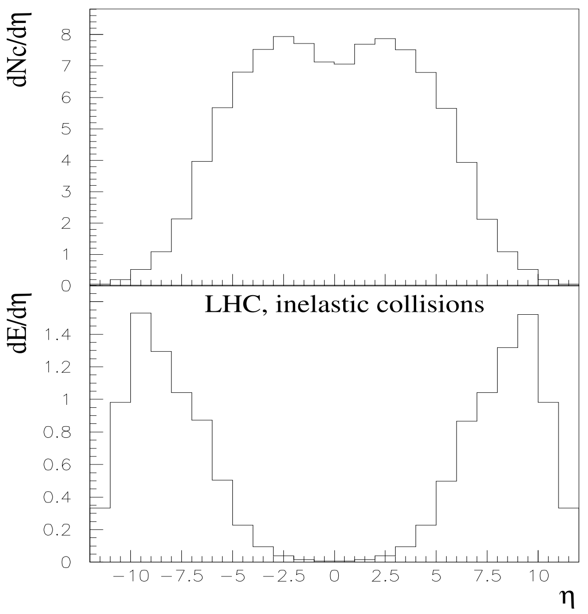

Figure 1: The pseudorapidity distribution of charged particles and of the energy-flow at $\sqrt{s}$ =14 TeV.

systems: the magnetic architecture responsible for getting the beams through the I4 straight section, the tracking system, and the calorimetry. Each system must be complete in its own right, without compromising the characteristics of the other systems. The magnetic apertures must not be limiting apertures of either the tracking or calorimeter systems. There must be sufficient physical space for both tracking and calorimetry. The calorimeters must be physically large enough to have good resolution, and must not interfere with either the tracking or the magnetic systems. All of this requires a lot of space, and the detector must be carefully integrated into the design of the machine. Full acceptance cannot be achieved by "adding on" to central detectors optimized for high p_T physics. Here FELIX is fortunate. The decision to split the RF cavities at I4, moving them to ± 140 m from the interaction point (IP), combined with the fact that FELIX's "low" luminosity permits the focusing quadrupoles to be moved more than 120 m from the IP, provides the necessary longitudinal space. I4 is also ideal from the point of view of transverse space. The beams are separated by 42 cm at the location of the RF cavities, providing

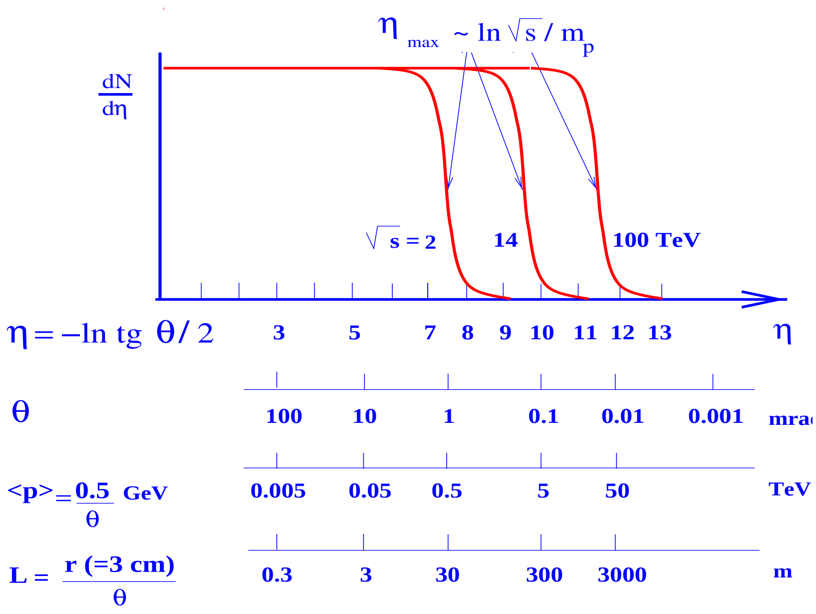

Figure 2: Particle production for different center-of-mass energies.

room for zero degree calorimetry. Since the existing infrastructure, including the ALEPH solenoid, can be re-used with minimal modifications, I4 is clearly a superb location for a full acceptance detector. (The central part of FELIX, which nicely fits into the existing cavern, and the extensions upstream into the forward regions, are shown in Figure 4.)

Nevertheless, the task of integrating a detector with genuinely full acceptance into the available space at I4 is not trivial. The FELIX Letter of Intent [1] outlines how it can be done, using well-understood magnets and compact detectors, for a comparatively modest price: we estimate a cost of about 25 MCHF for the machine magnets and the infrastructure, and about 50 MCHF for the detector outlined here and presented in more detail in the FELIX LoI.

2 The FELIX detector

We now introduce the major features of the FELIX design. More details can be found in the FELIX LOI [1]. FELIX will implement a “kissing scheme” in

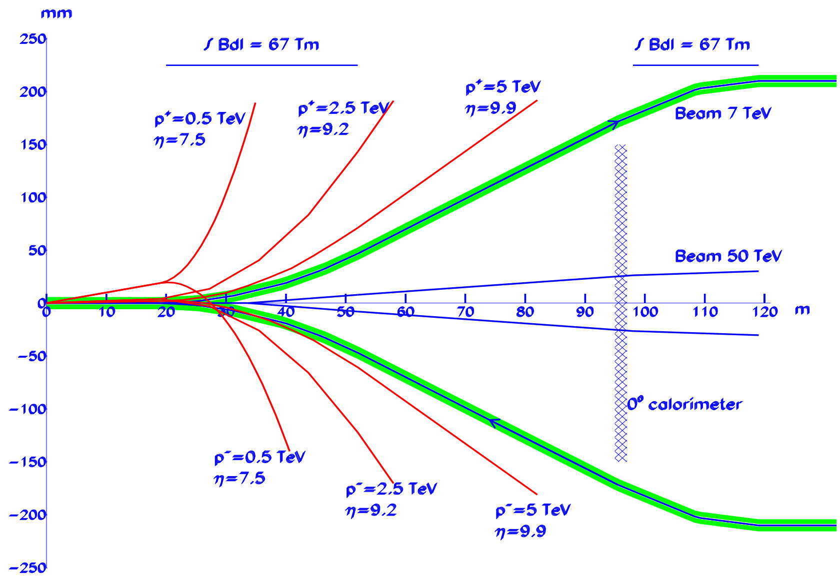

Figure 3: Some particles trajectories in the strong forward magnets together with the beam separation. Neutral are detected in the 0^o calorimeter.

which the two beams are brought together at 0^o in the horizontal plane and then returned to the same inner or outer arc (See Figure 5). To accomplish this, we need some 67 T-m to first bring the beams together (D2 magnets), and then another 67 T-m (D1 magnets) to make them parallel. This has to be accomplished within the 120 m available. Both sets of magnets must be superconducting machine dipoles. The D1 magnets must also have large bores, to accommodate both beams and to provide acceptable tracking and calorimetry apertures.

In order to avoid parasitic beam-beam interactions and long-range tune shift effects, the beams will collide with a vertical crossing angle of ± 0.5 mrad. To do this while optimizing the match of the magnetic architecture to tracking and calorimetry, we propose to re-use the existing UA1 magnet, split longitudinally into two halves and equipped with new coils. We will also build two 5 meter long, 2 T warm dipole (D0) magnets.

The magnetic architecture is completed by the re-use of the existing ALEPH solenoid, which is well-matched with the use of the UA1 magnet.

An important feature of this overall design is that the strengths of the

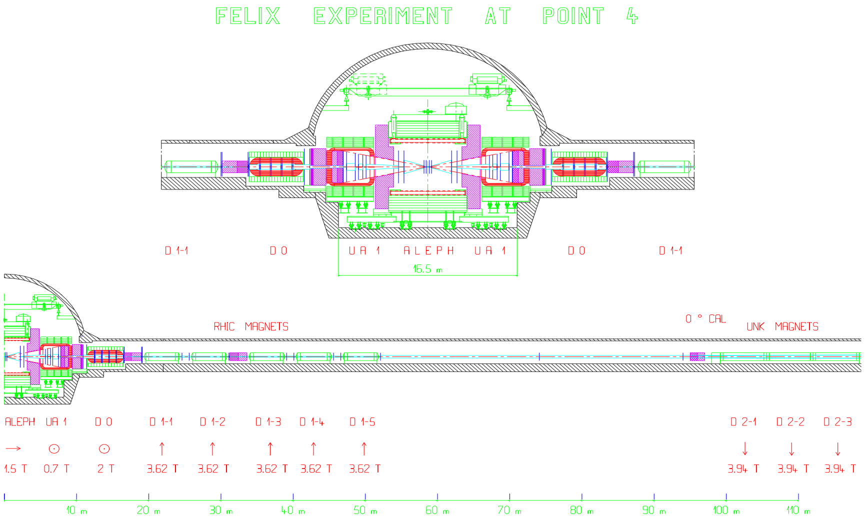

Figure 4: Sketch of the FELIX experiment in central and very forward region.

magnetic fields increase in the forward direction, always well-matched to the typical momenta of the particles, resulting in momentum resolution which is reasonably uniform over all of phase space.

Some 50 tracking stations, located as far as 430 m from the IP, are needed to ensure full acceptance and uniform resolution. The positions of most of the stations (vertical lines) are indicated in Figure 5. FELIX will instrument radially outward, emphasizing compact, near-beam tracking. How close we will approach the beams depends on the location. In general, we will use Roman pot detectors to aggressively approach the beams wherever the location is accessible and the pot mechanical structure does not interfere with other tracking or calorimetry. Elsewhere, we propose to use fixed-radius tracking, approaching to within 2.5 cm of the beams. The acceptance for charged particles as a function of pseudorapidity and their momenta is almost 100% over the entire phase space.

An important consideration is the occupancy within the tracking detectors. High particle densities close to the beam pose a significant pattern recognition problem. Each tracking station should thus have sufficient resolution and re-

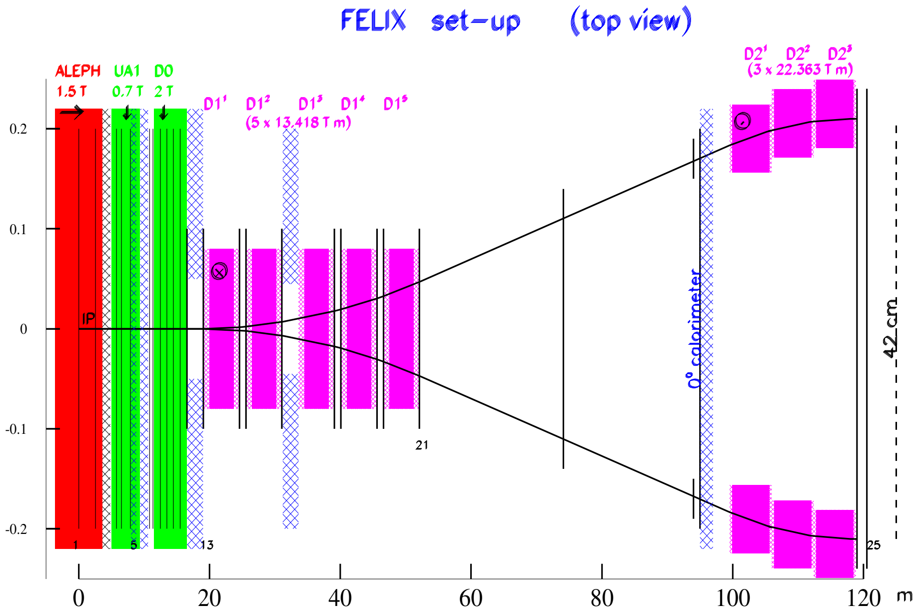

Figure 5: The top view of the FELIX detector. The different magnets, calorimeters (hatched areas), tracking stations (vertical lines) and the beam trajectories in the horizontal plane are indicated.

dundancy to be able to locally reconstruct track segments. Track segments are then matched, station-to-station, resulting in a very powerful spectrometer.

These considerations lead to a common conceptual design for most FELIX tracking stations, based on two technologies: Si pixel detectors out to radii of about 8 cm, supplemented by Gas Electron Multiplier (GEM) chambers at larger radii. We are also exploring the possibility of using GEM as the basis for very compact micro-TPC's. A conceptual design for a "standard" fixed-radius tracking station is shown in Figure 6. The same technologies will be used for a compact microvertex detector.

FELIX proposes four calorimeters on each side of the IP to provide complete electromagnetic and hadronic calorimetry for angles $\theta < 0.2$ radian, that is, for $|\eta| > 2.3$. The coverage of the calorimeters is illustrated in Figure 7. The interplay with the magnets and tracking systems is illustrated in Figure 4.

The calorimeters must have superb energy and spatial resolution, and must provide the information needed to identify neutrons, electrons and gammas. This must be done in limited space, and in a high-radiation environment.

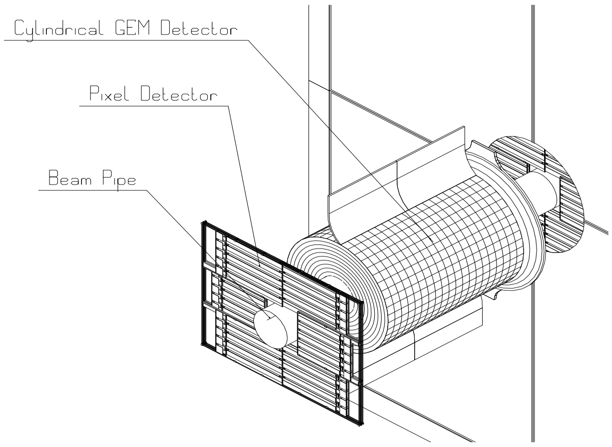

Figure 6: A schematic view of a tracking station based on Si pixel detectors and a micro-TPC. Note that several large-area GEM chambers have been removed to improve visibility of the micro-TPC.

These considerations determine the structure of the calorimeters, the choice of sampling materials and the kinds of photodetectors and front end electronics which can be used for the readout.

The UA1 endwall calorimeter, which is expected to have a radiation dose of less than 5 Mrad for 10 years running, is a sampling calorimeter based on plastic scintillators and wavelength shifting fibers. The very forward (D0, D1 and Zero Degree calorimeters) see much higher radiation levels, and will thus be "spaghetti"-type calorimeters, based on either thin capillaries filled with liquid scintillator or on quartz fibers. All three very forward calorimeters consist of a preshower detector, an EM calorimeter, and two hadron calorimeter sections. They are similar in construction, differing only in their overall dimensions.

3 Physics Overview

The heart of the FELIX physics agenda is QCD: FELIX will be the ultimate QCD detector at the LHC.

Surprisingly, the need for such a detector is not obvious to many members of the high energy community. In part, this may be because of the success of the interplay between theory and experiment in the case of electron-positron collisions. The cleanliness of the process, together with the low event rate and full-acceptance capability of the detectors, has led to an especially fruitful interaction between the QCD aspects of that experimental program with the

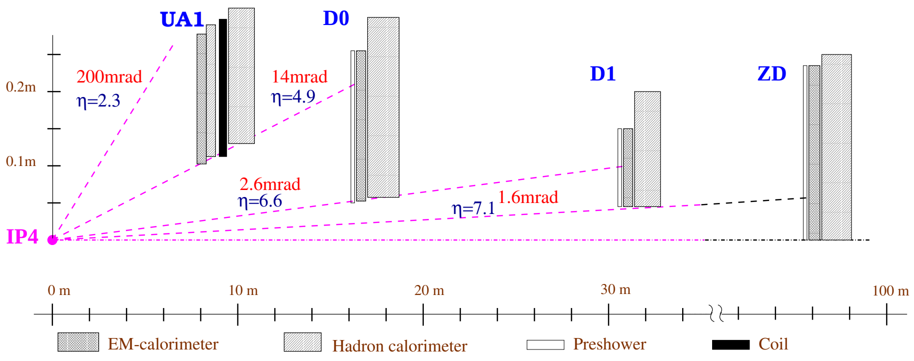

Figure 7: Schematic view of FELIX forward calorimetry.

remainder.

The case of hadron-hadron collider physics is quite different. The high-p_T, low cross section physics is accessed by highly selective triggers. The phase-space acceptance of the detectors is largely limited to the central rapidity region. Full acceptance has not been attained since the bubble-chamber era of fixed-target physics. Therefore the basic data base is much more limited.

This situation is all the more serious because of the great variety in event classes for hadron-hadron collisions. There are soft collisions with large impact parameters; angular momenta of tens of thousands instead of the unique $J = 1$ of the e^+e^- world. Central collisions produce much higher multiplicities than are seen in e^+e^- annihilation. There are the diffraction classes of events, with and without jet activity, that comprise several to tens of percent of typical subsamples (if seen in full acceptance) and which present a major challenge to theory. There are poorly understood strong Bose-Einstein-like correlations seen at very low p_T and low relative p_T in hadron-hadron collisions which do not occur in e^+e^- collisions. But at collider energies this is only based on one sample of low-p_T data from UA1, because until now no other detector has had the measurement capability. Finally, there is little if any data in the forward fragmentation regions, where cosmic ray experiments insistently claim that anomalies exist.

Given this richness of phenomena, and given the importance of QCD to the interpretation of the new-physics data expected to emerge from the LHC, it is clearly very important to improve the data-base with an LHC detector and experimental group fully dedicated to the observation and interpretation of as broad a range of QCD phenomena as possible. This is of course the mission of the FELIX initiative.

Many of these new opportunities in QCD physics at the LHC are not well known, and the FELIX collaboration has accordingly placed high priority in in providing a description of them in the FELIX LoI. We briefly summarize a few of the main themes here.

3.1 Parton densities can be measured to extremely small x, below 10^{-6}

The parton densities at small x are themselves a very important thing to measure. Up to now HERA has provided data down to x values of order 10^{-4} for Q^2 in the perturbative domain of several GeV^2. FELIX will have the capability to extend these measurements to x values below 10^{-6} via observation of dileptons, low-mass dijets, and low-mass jet-photon systems carrying large longitudinal momenta. In this regime one expects (especially for proton-ion collisions) the breakdown of the usual DGLAP/BFKL evolution-equation formalism and significant nonlinear effects to be observed.

3.2 Minijet production in hadron-hadron collisions is strongly energy dependent

The need for a vastly improved QCD data-base for hadron-hadron collisions is made even more urgent by the fact that qualitative changes are expected even in the structure of generic events because of the rapid increase with energy of gluon parton densities in the primary protons. Thanks to the measurements at HERA, this is not only the theoretical expectation but also a data-driven one. The parton densities at a $5-10$ GeV scale become so large that minijet production in central collisions may become common place, with minijet p_T large enough for reasonably clean observability. These very high parton densities create, at a perturbative short distance scale, “hot spots” in the spacetime evolution of the collision process within which there may be thermalization or other nonperturbative phenomena not easy to anticipate in advance of the data. Particle spectra themselves may evolve to something quite distinct from what has been so far observed, with strangeness, heavy flavors, and/or baryon and antibaryon production enhanced. Especially in central proton-ion collisions, where the total gluon-gluon luminosity per collision is maximized, and where the evolution of a single proton fragment is followed, one can expect this class of phenomena to be most prominent and surprises most probable.

3.3 Diffractive final states are endemic, many are important, and some are spectacular

Diffractive final states will comprise almost 50% of all final states at the LHC. The soft diffraction at very large impact parameter, which perhaps sheds light on pion-cloud or glueball physics, is at one extreme, and hard diffraction, where rapidity gaps coexist with jets, is at the other. There are a large variety of hard diffraction processes, including some with two and three rapidity gaps, which are of basic interest to study. In this class there are expected to be, for example, an extraordinary class of events where the complete event consists of a coplanar dijet accompanied by the two unfragmented beam protons detected in Roman pots, and absolutely nothing else in the detector. Certainly ATLAS and CMS can also detect such events, provided they sacrifice a luminosity factor of about 30 relative to their hard-earned peak luminosity. However, to really understand this event class, one will need, at the very least, to examine the t-distribution of the Roman-pot protons, as well as to study the generalizations of this process to the cases where one or both of the protons undergoes soft diffraction dissociation to a low mass resonance or a high mass continuum, or to a high-p_T system containing a tagging jet. Only FELIX would have such a capability.

In addition to this class of hard diffraction and very soft diffraction processes, there is another very interesting class of semihard diffractive phenomena associated with the conjectured fluctuation of the initial-state projectile into a transversely compact configuration, which therefore interacts with an unusually small cross section. Evidence for this is seen in vector-meson photoproduction at HERA, especially J/ψ production, which exhibits the expected rapid increase of cross section with energy. Also at Fermilab, diffraction dissociation of a high energy pion into dijets, with all the initial pion energy going into the dijet system, is being studied by experiment E791. Exactly the same process is available at the LHC with FELIX, as well as a similar process where one beam proton dissociates diffractively into three jets, one for each quark. The A dependence of these processes is remarkable, roughly $A^{4/3}$, because this diffractive process should occur even in central collisions, thanks to the small size of the initial configuration.

3.4 Particle production from deep within the light cone may exist and deserves careful searches

The existence of events with a very high final-state multiplicity of minijets and their associated hadrons has other implications. The products of such interactions for the most part can be expected to explode from the initially compact collision volume in all directions at the speed of light. Because of the high multiplicity density, the time of hadronization of all these degrees of freedom will be lengthened from the usual low-energy value of 1-2 fm to several fm. Up to this time of hadronization, the expanding "fireball" containing most of the partonic collision products is arguably a rather thin spherical shell, of thickness of order a fm. So even before hadronization there is a large interior volume of hundreds of fm^3, isolated from the exterior vacuum, which may evolve toward a chirally disordered vacuum. Consequently in such events there might be a large pulse of semiclassical, coherent pions of relatively low p_T emitted when this false vacuum eventually decays: disoriented chiral condensate. This is at present only a speculative possibility, although experimental searches, especially in the context of ion-ion collisions, are underway.

More generally, one may ask: if disoriented vacuum is not what is in the interior of this quasi-macroscopic fireball, what is? If the interior "vacuum" is broken into domains of various chiral orientations, then topological obstructions might lead to production of (Skyrmionic) baryons and antibaryons of unusually low p_T. And if there is activity deep inside the light cone, no matter what it is, then this activity has eventually to be turned into emission of particles; hence a new particle production mechanism which deserves to be studied. It would seem that the only alternative available for the *absence* of new phenomena emergent from the deep interior of the light cone under these circumstances is that that region relaxes back to the true vacuum, despite its being isolated from the true vacuum by a fireball shell and despite there not being enough elapsed time for chiral orientation to be distinguished energetically from chiral disorientation.

3.5 Collisions with very high impact-parameter may probe the chiral vacuum structure

In general, the chiral vacuum condensate is distorted in the neighborhood of impurities such as an isolated proton. This is just the long-range pion cloud surrounding it. The pion-cloud structure can be probed especially well in high energy pp collisions at very large impact parameters, say 2 to 3 fm. These interactions are, because of the larger radii of interaction at the LHC, a bigger component of the cross section, and can lead to larger final-state multiplicities than found at lower energies. Perhaps here too there may be coherence in the structure of the pion emission, and this class of events may turn out to be of special interest. Again a detection capability at very low p_T, 100 MeV and less, as possessed by FELIX, is important for such studies.

3.6 New opportunities exist for tagging event classes

Together with these many novel phenomena, there will be new methods for experimentally tagging different kinds of events. The impact parameter of the collision is obviously of importance to be determined event-by-event. This is done routinely in ion-ion collisions via zero degree measurements of nuclear fragments and by the amount of transverse energy produced. At the LHC, the FELIX instrumentation in the forward direction allows a data-driven approach for attacking the problem by the former method. The large yield of minijets, strongly dependent upon impact parameter, may allow the latter method, based upon transverse energy production, to be used more effectively at the LHC (by all detector groups) because of the stronger correlation of multiplicity with impact parameter than at lower energy. A combination of both methods, unique to FELIX, is likely to be the best of all.

A second important tag available to FELIX is the choice of beam. By tagging on a leading neutron or Δ^{++} at very low t, one can reasonably cleanly isolate the one-pion-exchange contribution, and thereby replace the LHC pp collider with a somewhat lower energy, lower luminosity πp collider. In a similar spirit, and including Λ tags, one can study collisions of any combination of π, K, or p with each other. The beam-dependence of phenomena has historically been of considerable importance, and it may find important applicability, especially with respect to questions of valence-parton structure, at the LHC energy scale.

A special case of these tags is that of a photon tag in ion-ion collisions, via forward detection of the undissociated ions. The luminosity for $\gamma\gamma$ collisions is very high, and the capability of FELIX to exploit this luminosity is also very high.

Another class of tags which has been underutilized is the diffractive tag, where leading protons are detected via Roman-pots. As discussed above, this leads to a very rich stratum of up-to-now poorly-measured, poorly understood, but potentially important physics.

Finally, there may be pattern tags. The event structure in final states containing jets is dependent upon the color flow. Typically, neighboring jets in phase space are connected by a partonic color line (antenna). For quarks, one antenna line emerges from the jet, for gluons two. Along these antenna lines in phase space, hadronization and minijet production is enhanced. Recently the Tevatron collider experiments have observed these effects. In principle this technique might allow one in the future to identify in an individual multijet event quarks versus gluons, and even fully classify the event structure according to the color flow. Clearly such a pattern-analysis technique is very difficult, and needs to be data-driven. FELIX, with full acceptance, will be optimal for making the attempt.

References

1. The FELIX Collaboration. "FELIX, A Full Acceptance Detector at the LHC, Letter of Intent". CERN/LHCC 97-45, LHCC/I10, 1 August 1997. The full text of the LoI is available on the web at the FELIX webpage http://www.cern.ch/FELIX