VERTEX DETECTORS FOR ULTRA HIGH ENERGY HADRON SPECTROMETERS

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The importance of detailed high resolution studies of the vertex region in hadron processes arises principally from the need to detect and study the production of new flavor particles such as Charm, Bottom, . . . etc. This can either be regarded as part of the particle-identification problem at the VBA in the same way as we need to identify strangeness, leptons, etc., or if the physics is still interesting, as a means to search for new flavors and their associated spectroscopies. The ground state particles are expected to have lifetimes in the range 10^{-14}-10^{-12} sec and masses ~ 5 GeV for bottom etc. with associated decay lengths ranging from ~ 150 μm (P/M = 50, $\tau = 10^{-14}$ sec) to ~ 15 cm (P/M = 500, $\tau = 10^{-12}$ sec).

The production vertex is expected to be very complex due to

(a) Many associated pions, kaons, etc. in addition to new flavor particles.

(b) Pair production of new flavors followed by high multiplicity decay

or:

(c) Cascade decays down the flavor chain, i.e.,

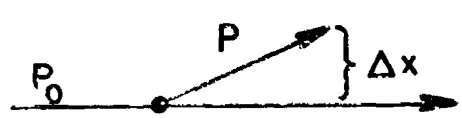
Bottom → Charm → Strangeness, etc.

In general there will be the problem of selecting those events containing new flavor particles from the background and subsequently to correctly assign the downstream particles to their vertex or origin (at least three possibilities!). To achieve this selection and association in a situation where the background of multiparticle production is very high requires the direct observation of the new flavor decay vertices.

At the VBA, we should not ignore the more esoteric possibility of observing free quarks which could either be unit charged and decay with lifetimes $\sim 10^{-13}$ sec (Pati and Salam) or fractionally charged and stable. There is also the chance to observe completely unexpected phenomena and the general approach must be to maximize the information available on all events.

Properties Required for a Vertex Detector

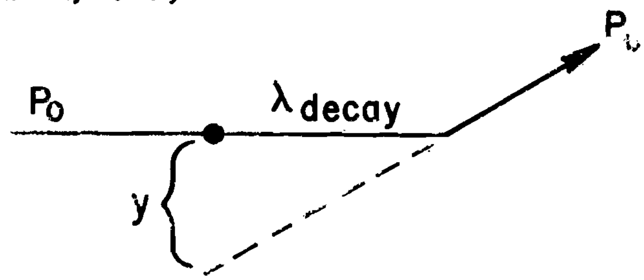
(a) Spacial resolution. Studies have been made of the problem of optically resolving the decay vertices from each other and from neighboring tracks. In general, the problem is independent of the momentum of the incident particle since the detection efficiency is governed by the transverse separation of the vertices from the other tracks in the event rather than the longitudinal separation. In simple terms the transverse separation is given by



$$\Delta x \simeq \frac{p_\perp}{M} \cdot \tau c$$

and for $(p_\perp/M) \simeq \frac{1}{2}$, $\Delta x \simeq 15$ μm for $\tau \sim 10^{-13}$ sec.

One could argue that the event be detected (rather than have separately resolved vertices) if one large angle track from the decay does not project back to the main vertex, i. e.,



$$y \sim \frac{p_{\perp i}}{M_i} \tau \quad \text{i. e.,} \sim (3-10)\,\tau$$

or ~ 100 μm for $\tau \sim 10^{-13}$ sec.

We should clearly aim for the first situation, i. e., to have a detector able to resolve the decay vertices from the surrounding tracks. To a first approximation the resolution required is ~ 1 μm for $\tau \sim 10^{-14}$ sec, 10 μm for $\tau \sim 10^{-13}$ sec, etc., and is independent of the beam momentum. Of course, because of the variable nature of the background associated tracks, the production and kinematics, the exponential decay distribution there remains some efficiency for the detection of particles with $\tau \sim 10^{-14}$ sec using a detector with resolution 10 μm, etc.; however, these simple pictures give a guide to the resolutions required.

(b) New flavor cross sections and lifetimes; rates and trigger considerations. The current estimates for Charm lifetimes are ~ 5×10^{-13} sec and for Bottom ≥ 10^{-13} sec corresponding to resolution in the region ≲ 50 μm and ≃ 10 μm. Cross-section estimates at 20 TeV ($\sqrt{s}$ = 200) taken from Babcock et al. are ~ 100 μb for charm and ~ 1 μb for pp→bb+x; m_b = 5 GeV. If we accept the charm interpretation of the beam dump experiments indicating σ Charm ~ 40-100 μb at 400 GeV ($\sqrt{s} = 27.4$) we might expect somewhat larger cross sections than currently predicted for new flavor production at the VBA. An apparent rule is that each new flavor is produced at a few per cent of the previous new flavor

$$\frac{\sigma_s}{\sigma_{ns}} \simeq \frac{\sigma_{ch}}{\sigma_{st}} \simeq \frac{\sigma_b}{\sigma_{ch}} = \ldots \text{ few } \%.$$

The small cross sections expected for heavy new flavor particle production coupled with the complex nature of the events has serious consequences for the design of the detection system. All detectors searching the microbarn and sub-microbarn level require some form of triggering either on-line or off-line. Several trigger possibilities exist, e.g.,

(1) To trigger on strange particle production in a particular kinematic situation. This will usually represent a trigger cross section of order 1 mb.

(2) To trigger on direct lepton production, i.e., a muon or an electron directly produced. The trigger cross section will be $\simeq 10^{-14}\sigma(\pi) \simeq 50\ \mu b$ + background.

(3) To trigger on some characteristic correlation, e.g., a "jet" trigger using a hadron calorimeter downstream. The trigger cross sec ion will depend on the jet definition and the jet $p_\perp$ etc.

Various trigger cross sections can be chosen; however, clearly the choice of trigger determines the kind of physics under study. We do not consider this in any detail but merely note that one can conceive of (a) very loose triggers where a large quantity of data is stored for off-line analysis, or (b) rather selective tight triggers, such as high $p_{\perp}$ jets for example, where the trigger cross section is small and the physics selection is on-line. The choice of trigger in addition to the physics aims will influence the choice of vertex detection technique. Important parameters for the detector which determine the triggering possibilities and hence the range of physics available are clearly:

(a) Overall data rate. How many interactions per second can one tolerate in the detector.

(b) Memory time. Which essentially determines the overall rate and the sophistication possible in the trigger.

(c) Dead time. For how long is the detector dead following a trigger.

A high overall data rate is necessary to study processes with very small cross sections; however, we also require either a very short dead time for data acquisition followed by off-line selection or a very small trigger cross section if the dead time is significant.

Clearly the memory time must be such as to allow the trigger condition to be applied.

Finally, as a requirement for any vertex detector at TeV energies, it is clear that multitrack efficiency is essential.

We now consider the performance of detectors currently in use or under development.

Current Technology and Its Use

(a) Nuclear Emulsion. Emulsions have been around for a long time and the properties are well known. The search for Charm has recently revived interest in the technique since it is the highest resolution detector available. Resolution is in the submicron range (grain size ~ 0.5-1.0 μm) with grain densities on minimum ionizing particle tracks ~ 200/mm. Very useful as an exploratory technique but not suitable for studies of low cross-section phenomena. Disadvantages arise from the complete absence of time resolution and consequent difficulties in associating events with downstream spectrometer information

(b) High resolution bubble chambers. A high resolution hydrogen bubble chamber will be used next year to search for charmed particle tracks at the SPS. The properties of the chamber are given in Table I.

The spacial resolution is only limited by optical considerations which represents a fundamental limitation for all dynamic visual detectors. Thus bubbles grow according to diameter $d \propto \sqrt{t}$ from a critical radius $\lesssim \lesssim 1$ μm. The delay between the event and the flash is chosen to allow the bubbles to grow sufficiently to be optically resolved. The optical resolution is related to the depth of field D (in the chamber) through $\mathrm{Res} = 0.61\sqrt{\lambda D}$ where λ is the wavelength. The resolution chosen for the CERN high resolution chamber is 20 μm corresponding to D a depth of field of 2 mm. This depth has to contain the beam and secondary particles leaving this band go quickly out of focus. The bubble chamber has the positive feature that the bubbles continue to grow and if necessary a second picture can be taken of the same event with worse resolution but a larger depth of field, e.g., 100 μm and 5 cm. If we wish to achieve resolutions in the 1 μm region then the field is ~ 5 μm, i.e., we have "microscope" optics. The problem is to contain the beam within a 5 μm region of the chamber. This is probably impractical and it would seem not possible to design a chamber using classical optics which will have resolution better than ~ 10 μm. Higher optical resolution can be obtained if holographic techniques can be exploited.

If we consider now the accuracy with which we can find the center of a bubble (bubble centers should be on the particle trajectory to better than 1 μm) then this is typically 10-20% of the diameter which is in the region of 1 μm. Thus measured reconstructed events could (we should call this precision to avoid confusion with optical resolution defined above) have effective resolution ~ 1 μm.

There is also a limit on the bubble density arising from the density of δ-rays in hydrogen (or the medium) having energy greater than the minimum energy required for bubble nucleation. In hydrogen this appears in the region of 300-1000 bubbles/cm.

In the existing conventional chamber the rate is expected to be 30-100 Hz with chamber diameter ~ 20 cm. The maximum visible track length in hydrogen is therefore ~ 30 meters/sec corresponding to a maximum rate ~ 1 event/mb/sec. (The present chamber is only expected to run at ~ 30 meters/sec.)

(c) The high pressure streamer chamber. The high pressure streamer chamber operated this year at Fermilab contains 90% Ne/10%

hydrogen at ~25 atmospheres. Successful operation was achieved with track widths ~150-200 μm/(effective resolution) limited by the diffusion of the seed electrons away from the particle trajectory before the application of the high voltage pulse. A program to improve the resolution by using ~100 atmospheres argon and a CO_2 laser to induce streamer formation is underway and should reach $\lesssim$ 50 μm. The resolution is ultimately limited by purely optical considerations as for the bubble chamber; i.e., the depth of field to contain the beam and the detected secondary particles is related directly to the resolution.

The advantage of the technique is clearly in terms of rate. The existing chamber is ~4 cm long, so that 10^6 particles per second (memory ~1 μsec) will yield a basic event rate of ~10 events/mb/sec, i.e., about two orders of magnitude greater than the current bubble chamber experiment. The disadvantages of having a heavy nucleus target are the presence of nuclear fragments which can cause obscuration of the production vertex and the possibility of secondary interactions simulating decays, although the latter will be a negligible background to those events where a pair of decays are detected.

The advantages of a high data rate can only be realized if a suitably selective trigger can be found. Thus for the streamer chamber experiment the use of a direct muon trigger improves the signal-to-noise by a factor ~30, but this is offset by the fact that ~90% of the triggers are in the walls of the pressure vessel. The problems of the trigger are essentially related to the use of film as a recording medium so that the dead time of the system is determined by the camera wind-on dead time. Film has the advantage of good resolution so that images down to ~5 μm can be recorded. In principle one can use large arrays of C. C. D.'s to achieve the same resolution (by adjusting the optical demagnification factor) and hence reduce the dead time of the system.

A development which significantly improves the resolution of the streamer chamber is the Laser Induced Streamer Chamber (LISC). In this development (Los Alamos-Yale collaboration), a chamber will be constructed using up to ~ 100 atmospheres of argon gas (much less thermal diffusion of the "seed" electrons) and to grow the streamers by laser illumination of the chamber. With such a chamber a resolution (track width) should be achievable in the region of 20-50 μm.

(d) High Resolution Drift Chambers. The question naturally arises what is the ultimate resolution achievable with a mini-TCP drift chamber system. Lanius et al. are constructing (have constructed ?) a target chamber assembly for use at CERN consisting of an argon drift chamber with 20 μm wires at 20 μm spacing. The resolution is limited by the diffusion of the electrons during the drift distance to the wires. Of course, the resolution is in one dimension only--normal to the wire direction. No depth of field problems exist and presumably very high rates can be achieved. This development looks extremely promising.

Future Possibilities and Developments

A future development which would remove the depth of field limitation would be the application of holography to both the bubble chamber and the streamer chamber. We are not aware if any fundamental reasons why such systems should not substantially improve the resolution and extend the depth of field.

Possible future developments of specific techniques are:

(a) The development of single shot standing wave ultrasonic helium bubble chambers. In principle this is possible and allows the construction of a bubble chamber of sensitive depth $\sim \frac{1}{4}\lambda$ where λ is the wavelength of the sound in helium ($\lambda \sim 2$ cm for $\sim 10^4$ Hz). Hydrogen would be much more difficult because of the large pressure swings required and the consequent mechanical problems of the piezo electric transducer design. The difficulty with such high rates will be the bubble recompression (although this would probably be achievable for the extremely small bubbles ($\lesssim 10$ μm) required for high resolution work) and the diffusion of heat away from the site of a recompressed bubble. The latter have time constants of ~ milliseconds so that to prevent the renucleation of bubbles on old tracks it would be necessary for rates above ~ 1 kilohertz to have a liquid flow sufficient to move the bubbles away from the pressure antinodes between cycles to a reasonable fraction of the sound velocity! Clearly a development program is needed to establish this technique. If successful however we might have very high rate, high resolution helium chambers as possible vertex detectors for the future.

(b) The development of the Laser Induced Streamer Chamber could proceed in several interesting directions. Modern laser technology might allow operation of a streamer chamber with liquid densities. Based on our present incomplete knowledge, such a chamber would require energy densities of some tens of joules per cm^2 and pulse widths of some tens of picoseconds. If the technical problems of such a device could be solved, the expected resolution would be of the order of 1 micron.

Another direction in the development of the streamer chamber would be to attempt to record the data by the illumination of the chamber by a second laser beam and photographing the light scattered from the streamers. Such a development would allow holographic recording and thus much larger sensitive depths at high resolution than would be possible with direct imaging.

Table I. CERN High Resolution Bubble Chamber 1979.

Diameter	20 cm	
Depth	3.5 cm	
Rate	$\geq$ 30 Hz	
Resolution (aimed at)	~20 μm;	precision ~2.3 μm
Liquid	Hydrogen	
Walls out of Lexan		
Trigger	Interaction trigger $\geq$ 50% events in H_2	