

Fast Track Finding using Radially Pointing Scintillating Fibers

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ABSTRACT: A detector layout using O(cm) long, radially pointing, scintillating fibers at large radius is investigated. Such a geometry allows discrimination between high and low p_T particles based on their angle of incidence and because high p_T particles deposit large ionization in one fiber, while low p_T particles deposit small ionization in many fibers. A pixelated array of these fibers provides a phi-z projection of particle trajectories, from which the track parameters can be calculated. The simulated track parameter resolutions are presented, and some of the unique detector and electronics issues associated with such a design are discussed.

KEYWORDS: Track trigger; scintillating fiber.

Introduction

Collider detectors for an upgraded LHC (SLHC [1]) will need to find tracks at the trigger level despite a complicated environment polluted by many hits “piled-up” from multiple interactions. Such a “tracking trigger” could be used to confirm an e or μ hypothesis by comparing the track p_T to the muon chamber measurement or to the calorimeter energy measurement for electron candidates. Availability of tracking at the trigger level would also be useful to measure isolation, and reject the otherwise enormous background from non-isolated, semileptonic b and c decays.

A layout that has potential for track triggering is described here. It uses short scintillating fibers oriented to point radially, as opposed to a longitudinal geometry [2]. The radial geometry simplifies discrimination between low and high p_T particles because they give different patterns of light yield; a high p_T particle produces a large light signal in only a few fibers, while a low p_T particle produces small light signals in many fibers. As shown in Fig. 1, two layers of these fibers could be arranged, and mirrored, to allow both to be readout by a common layer of electronics situated between them. This simplifies concentration of their data and matching of hit positions between the two layers. Track parameters can be calculated directly from these hits.

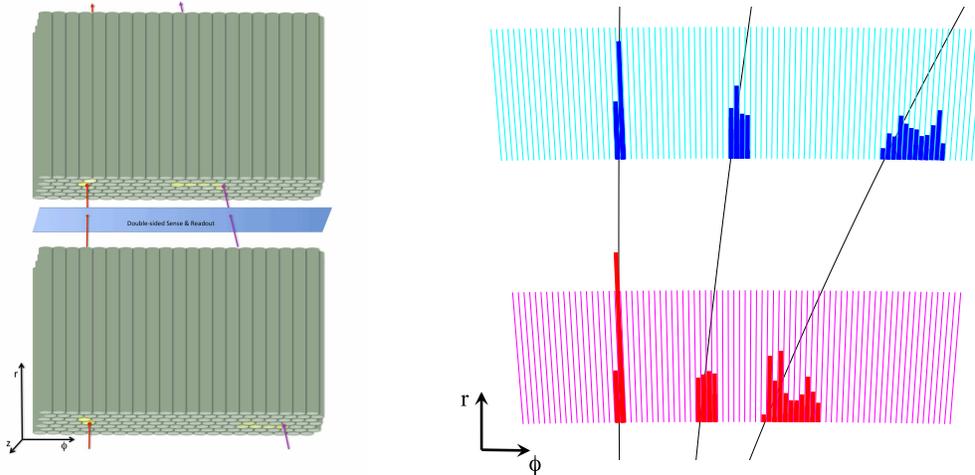


Figure 1. Left: A cartoon illustrating the studied layout having two layers of radially pointing fibers with double-sided readout between. The trajectories of two particles, one high and one low p_T , are shown for illustration. Right: An $r\phi$ view of a section of the layout with simulated signals from three particles with $p_T = 30, 10,$ and $3 \text{ GeV}/c$.

Simulated Performance

The performance of this type of geometry was studied using a sample layout arranged as follows. Fibers, 5 cm long and $1 \times 1 \text{ mm}^2$ in cross-section, are arranged into two concentric cylindrical layers with inner radii of $r_1 = 100 \text{ cm}$ and $r_2 = 110 \text{ cm}$. The 5 cm gap between them is envisioned to contain the photodetectors and electronics for both layers. The length of these cylinders is set to 4 m, which corresponds to $|\eta| < 1.4$. The fibers are assumed to point exactly radially, so they project to the origin in $r\phi$ but not in z . Each fiber is assumed to be readout independently via a $1 \times 1 \text{ mm}^2$ silicon photomultiplier, SiPM [3]. These are recently developed devices that use avalanche photo-diodes operating in Geiger mode. Proportional photon counting is achieved by using a large

number of sub-pixels, in parallel, within each $1 \times 1 \text{ mm}^2$ pixel, so its signal is proportional to the number of sub-pixels that are lit by one or more photons. Because the fiber readout is pixelated in the ϕz plane, I dub each fiber+SiPM channel as a “fixel”.

The layout is simulated to determine the resolution and assess the potential for reducing combinatorics. Monte Carlo generated charged particles are propagated through a 3.8 T solenoidal magnetic field (based on CMS [4]) and hit fibers are identified. For simplicity of calculation, fibers with a square cross-section are used; circular fibers should provide somewhat better resolution from hit sharing between neighbors. Signals are generated based on an assumed yield of 10 photoelectrons per mm of pathlength, convolved with a 5% Landau tail and \sqrt{N} smearing [5]. This simulation accounts for geometry and combinatorics, but it is a parametric rather than full simulation in that it ignores several effects. Conversions, secondary interactions, and multiple scattering within the fibers are not included. Electronic noise is not modeled, but it is not expected to be significant.

Clustering is performed to identify and reconstruct particle trajectories. This step searches each layer for linearly contiguous groups of lit fibers, as illustrated in Fig. 2(b). Clusters in the inner and outer layer are paired by simple projection. Combining the endpoints from the paired clusters completely specifies the 3D track parameters, assuming production at the origin. While the track parameters are determined only from the four endpoints, the line of hit fibers connecting them makes the cluster finding in a dense environment significantly more robust than if only those endpoints were present. This is illustrated by the simplicity of visually identifying tracks in Fig. 2(a), which gives encouragement that the same task could be accomplished with a simple hardware algorithm.

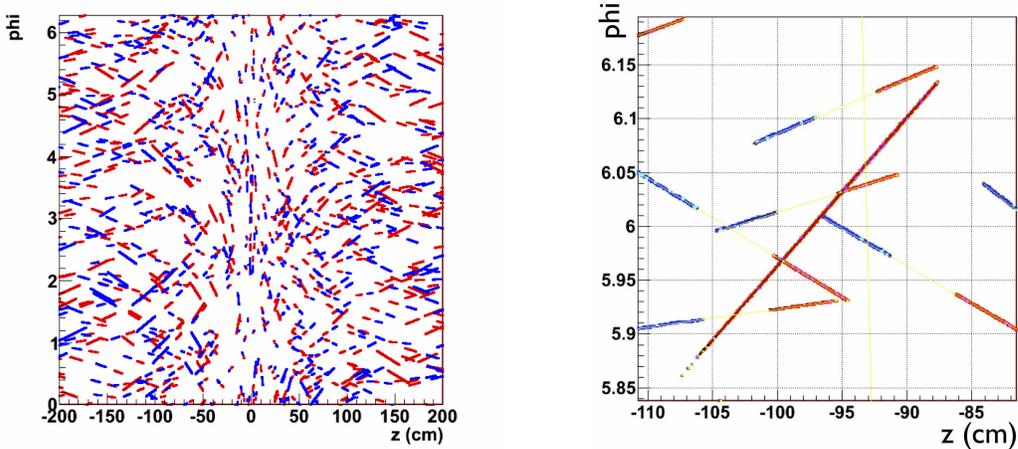


Figure 2. Left: A ϕ vs z view of a simulated event with 200 piled-up pp interactions. The red (blue) squares correspond to lit fibers from the inner (outer) layer, from which linear clusters are formed. Right: A zoomed view of the same event. The yellow lines show reconstructed trajectories of paired clusters.

High and low p_T particles can be discriminated based on the light yield from individual fibers. Low p_T particles are bent by the B field so they traverse the fibers at a high angle and deposit light in multiple fibers along a range of ϕ ; the light in any individual fiber is rather small. High p_T particles, by contrast, enter nearly perpendicular in the ϕ direction, and they give large light

yield in only a few fibers at a localized ϕ . If all the fibers pointed at the origin in both the ϕ and z directions, then a very high p_T particle would give a large light level in only a single fiber. The fact that the layout considered does not have z -projecting fibers complicates this slightly, but it is simple to sum over z to determine, for each cluster, the peak amount of light at a single ϕ . This is called the *peak phi charge*, and it is correlated with p_T . Figure. 3(a) shows this correlation for the lower peak phi charge of the two clusters in a pair. Applying a cut on this quantity in the trigger level should provide a coarse, but fast, track p_T threshold. For example, requiring more than 250 photoelectrons is efficient for high p_T but rejects most tracks with $p_T < 5$ GeV.

A more precise quantity is the peak phi charge divided by the phi width of the cluster. This takes advantage of both the charge effect just described and the fact that low p_T particles will light fibers over a larger phi range. The result is shown as a function of p_T for paired clusters in Fig. 3(b). If this quantity could be calculated within the front end electronics, it would provide a powerful foundation for a track trigger.

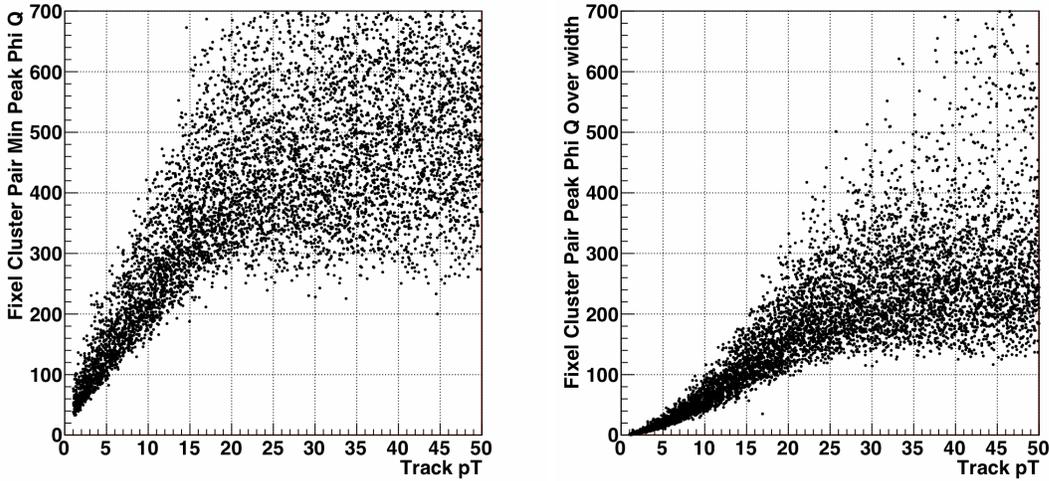


Figure 3. Left: The peak light yield, summed over z , at any given phi address for each cluster pair is plotted as a function of p_T . Right: The peak light yield divided by cluster phi width for each cluster pair vs p_T . These should be simple quantities to calculate at the trigger level and provide rejection of particles with p_T below about 5 to 10 GeV.

The track parameters can also be directly calculated from the end points of the two clusters in a matched pair, assuming that the particle originates from the origin. The resolutions obtained within the parameteric simulation are $\sigma_{z_0} = 3.3$ mm, $\sigma_\eta = 0.0025$, $\sigma_{\phi_0} = 0.01$, and $\sigma_C \approx 1 \times 10^{-4}$ cm. The resolution functions contain non-gaussian tails at the 1/mil level due to split clusters. If the light in a fiber falls below threshold, a long cluster can be mistakenly reconstructed as two shorter clusters, due to the resulting gap. This happens mostly for very low p_T particles, which traverse the fibers with little more than 1 mm of path length and so have relatively low light yields. (An example of this is the left end of the long, 45° cluster in Fig. 2(b).) Some of these bad clusters can be flagged based on inconsistency between cluster length and total charge, but that will not identify cases where a few fixels are lost at the end of a long cluster from particles with p_T below about 1 GeV.

Triggering

This detector layout is most useful if it can be used at the trigger level to identify high momentum tracks and calculate the momentum sum of nearby tracks, i.e., the isolation energy, in a $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$ cone around a high p_T candidate. The η and ϕ_0 resolutions are well below the typical cone size of $\Delta R = 0.3$. The curvature resolution, though of course p_T dependent, is sufficient for calculating such an isolation sum. The z_0 resolution can help to limit contamination of the isolation sum from particles originating from different pp interactions, which should be spread along z in a luminous region with width of order 10 cm. At high luminosity, such contamination makes calorimeter based isolation requirements, which could not be z restricted, essentially useless.

The layout described above reserves a 5 cm region between fiber layers for sensors and electronics. The light from both fiber layers can be sensed there and easily combined. If sufficient intelligence resides in that electronics, track finding could be done locally. Information about these tracks could then easily flow in the z and ϕ directions to allow calculation of a track isolation in an $\eta\phi$ cone around any high p_T candidates. A detailed study is required to determine how such calculations could be implemented online, e.g., with lookup tables or FPGAs.

Challenges

There are several challenges that would need to be addressed for such a layout to be successful. The most obvious issue is the high channel count and associated cost. SiPM sensors have been used in HEP experiments only recently and in relatively small numbers. For example, the T2K near detector uses about 50k SiPMs for a fiber tracker [6]. The current cost for SiPMs is \$90 per channel for a few pieces [7], and \$20 per channel for the T2K order [6]. At these current prices, the considered layout would be unrealistically expensive. However, it is reasonable to expect a significant reduction in cost as this relatively new technology matures. Meanwhile, it is worth studying options for ganging fibers to reduce the channel count. This could be done with extensions of the parametric simulation.

Potential technical challenges come from the recovery time and after pulsing effects of SiPMs, e.g., a strong dependence of after pulses on the initial signal size could lead to repeated high p_T triggers. Additional effects may arise from direct interaction of particles in the SiPMs. Previous applications, which situate the SiPMs away from the scintillator via light guide fibers, are less sensitive to correlated signals produced by direct ionization in the SiPM. In the layout considered here, however, neutrons or delta rays could produce large signals within an SiPM and degrade the discrimination between high and low p_T particles. To understand these effects, a small prototype is being constructed for testing with cosmic ray muons and a beam.

A potential mechanical challenge comes from requiring the fibers to point to the beam line with sufficient precision. This may be achievable by building modules and super-modules with precise fixturing on a coordinate measuring machine, but it needs to be studied.

The fibers represent a significant amount of material, $\approx 0.3X_0$. So, they must be situated at the outermost radius of the tracking volume where the multiple scattering and secondaries produced in the fibers will not affect the inner, precision tracking. However, these effects will impact the performance of the fiber based track reconstruction. Conversions occurring within the fibers are a significant concern. Because photon trajectories are straight, such a conversion might produce a narrow cluster with a large light yield and fake the signature of a high p_T charged particle. Initial

studies of this effect indicate that the e^+e^- pairs separate sufficiently, as they pass through the two layers of fibers, to produce a distinctive cluster pattern, as long as the photon p_T is less than about 20 GeV. (A magnetic field lower than the 3.8 T assumed for this study would degrade this). One option for further suppressing this background is to distinguish the two-MIP signal, if the readout has sufficient signal resolution. Another option is to place thin and small, $1 \times 1 \text{ cm}^2$, scintillating tiles in front of the inner fiber layer to act as a “preshower” detector. These could be readout by routing a light-guide fiber through the active fiber layer to the SiPM readout. Accommodating one such fiber per square cm would displace only 1% of the active fibers in the layer. After gaining a more detailed understanding of the light yield from a prototype, the effect of conversions and such options to remediate them can be studied with a detailed simulation.

Secondary particles, either from long-lived decay (e.g., K_S) or interactions within the inner detector material, could fake the signature of a high p_T charged particle. They could enter the fibers radially and give a narrow cluster even though they are low momentum. This effect needs to be quantified with a detailed simulation study.

Conclusions

A geometry with radially pointing fibers offers some potential advantages for track triggering. It provides a simple analog quantity that is proportional to p_T , the light yield in a narrow range of fibers. It may allow easy identification of tracks with on-detector electronics because of the ambiguity reduction provided by linearly contiguous clusters. Granularity of $O(1)$ mm with radial extent of $O(10)$ cm provides sufficient resolution. Data concentration between layers and sharing across ϕ and z are simply accomplished with a common layer of electronics. Significant cost and technical challenges will need to be studied before such a layout could be implemented.

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