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SOLENOIDAL DETECTOR NOTES

EVENT SIMULATION AND TRACK RECONSTRUCTION IN THE SDC EXPERIMENT

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Event Simulation and Track Reconstruction in the SDC Experiment

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The proposal for the SDC experiment has placed substantial emphasis on charged particle tracking. This paper will describe event simulation and track reconstruction studies, focussing on three topics: measurement of isolated leptons from the decay of a Higgs boson; track reconstruction inside QCD jets; and identifying b quark jets with secondary vertices in top quark events.

1. INTRODUCTION

The proposal for the SDC experiment [1] at the SSC includes a large central charged particle tracking system in a 2 Tesla solenoidal magnetic field. The tracking system will contribute substantially to a number of physics measurements, including:

* lepton identification in conjunction with calorimeter or muon system
* electron charge
* muon momentum measurement
* jet multiplicity, fragmentation properties
* secondary vertexing to identify tau leptons and b quark jets
* calorimeter cross calibration.

The system performance goals [2] include:

* fully hermetic coverage within $|\eta| < 2.5$
* Transverse momentum resolution: $\sigma(p_t)/p_t < 20\%$ at 1 TeV
* Efficiency $> 98\%$ for isolated tracks and $> 90\%$ for tracks in jets with $p_t \leq 500$ GeV
* Capability to tag b quark jets from t decay with $> 25\%$ efficiency and high purity using secondary vertices.

Achieving these goals will require a system with higher precision and granularity than previous HEP experiments, over a large angular region. In addition, the system needs to be robust to radiation damage in the SSC environment, consist of a minimum amount of material (to minimize electron bremstrahlung and photon conversions), and the total cost cannot be excessive.

1.1. Event Simulation

Considerable effort has been devoted to event simulation and track reconstruction, in order to demonstrate that the system options considered can meet these goals. Simulation has also been useful for optimizing certain design parameters such as the number and placement of layers and studying the effect of material.

The simulations have been performed using the SDCSIM program, which combines several Monte-Carlo generators (ISAJET, PYTHIA, HERWIG and a single particle generator), detector simulation using the GEANT 3.14 framework, and event reconstruction (discussed below). The GEANT routines transport particles through the detector, simulating decays and interactions with the material. The detailed simulation of the individual subsystems is handled by user-written routines, which convert the deposited energy into raw data banks.

Since the 16 ns beam crossing interval is less than the response times of some detector elements, it is important to simulate additional beam crossings, as well as additional inelastic events in the same crossing. We simulate the standard SSC luminosity (L=10^{33}/cm^2/sec) with a Poisson distribution of mean 1.6 background events for four previous and two crossings after the event of interest, and scale the number of background events to study performance at other luminosities. Note that the GEANT simulation is rather slow, taking more than an hour per event on a 25 MIP processor at 10 times the design luminosity.

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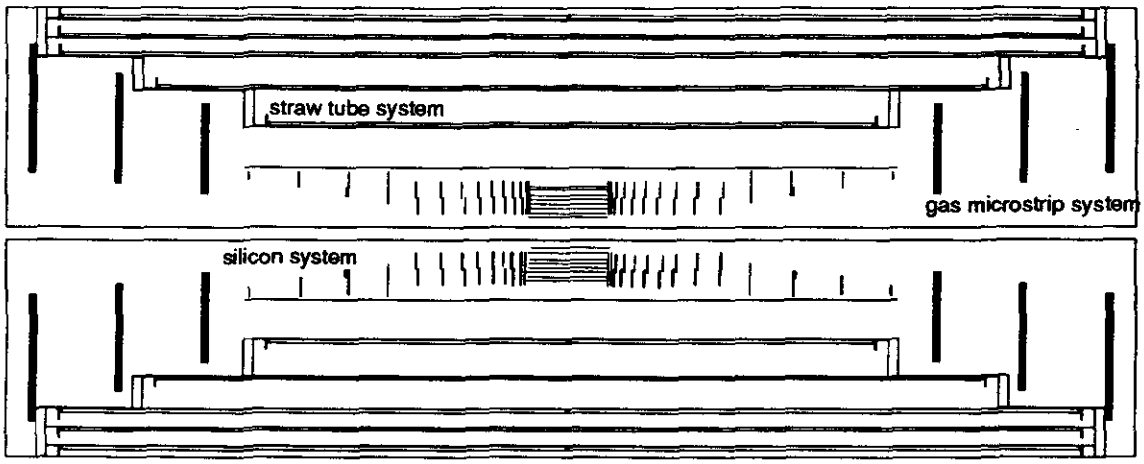

Figure 1. GEANT representation of the SDC tracking system in a x-z cut view. The system shown is the silicon/straw tube/gas microstrip option described in the text.

1.2. Tracking System Design

The SDC tracking system will consist of an inner silicon system and one of two options at larger radii. The baseline outer system in the technical proposal is straw tubes covering the range $|\eta| < 1.8$ and gas micro-strip tiles at intermediate angles ($1.8 < |\eta| < 2.8$). this option in shown in Figure 1. Alternatively, the outer system may consist of scintillating fibers covering the range $|\eta| < 2.3$. The choice between these alternatives will be made early next year.

The silicon system [3] will use double sided detectors with small angle stereo. It is divided into two sections: an 8 layer barrel from 9 to 36 cm radius with a length of 60 cm; and on either end an array of 13 disk layers extending to $|z| = 260$. The barrel detectors will be rectangular with 50 μm strip pitch, bonded in pairs to make 12 cm units. The disk detectors will be trapezoids with tapered strips with 50 μm maximum pitch, also bonded in pairs. With a 10 mrad stereo angle, the expected resolution of a 'coordinate' made from an axial/stereo pairing is $\sim$10 μm in $r\phi$ and $\sim$1.4 mm in z (or r). The GEANT simulation for the system uses a detailed detector geometry including dead areas, and a simplified hit model which ignores diffusion and magnetic field effects.

The straw tube system [4] will be arranged in 3 axial superlayers with 8 layers and two 3-degree stereo superlayers with 6 layers, from 80 to 160 cm radius. The 2 mm tube radius gives a maximum drift time of under 40 ns (3 beam crossings), with a predicted $r\phi$ resolution of $\sim$ 120 μm per layer, or $\sim$ 80 μm for a superlayer segment. The simulation has somewhat simplified geometry which models the straw layers as cylinders, but it uses a detailed response model including dead time and propagation delays.

The gas microstrip system [5] will have 3 superlayers from 290 cm $< |z| <$ 425 cm, each consisting of 2 axial and 2 small angle stereo layers. The tiles will be arranged in projective rings, simplifying their use in the trigger, and will have an anode pitch of 200 μm. The GEANT simulation for the system was recently completed, and was not used in the studies described below.

The scintillating fiber option [6] would use 4 superlayers of 1 mm diameter fibers between 60 and 170 cm radius. The smaller fiber diameter and fast signals give a factor of 5 to 10 lower

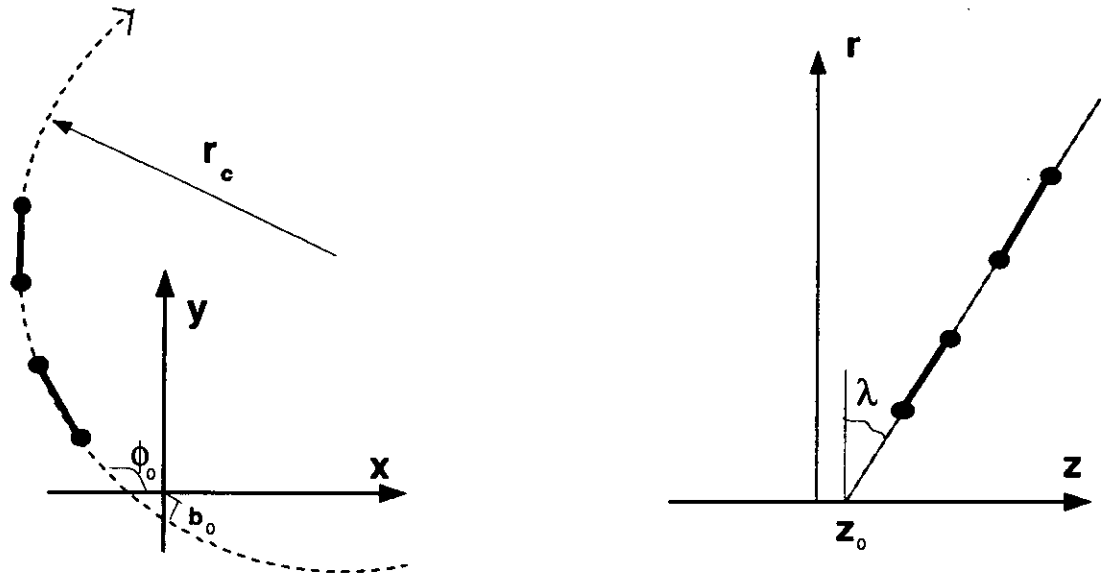

Figure 2. Definitions of the track helix parameters in the r–ϕ view (a) and the r–z view (b). The parameters are: the impact parameter b_0, the azimuth angle ϕ_0 the curvature $\rho = -q/r_c$, the z intercept z_0, and the slope $\tan\lambda$, where q is the particle charge (± 1) and r_c is the radius of curvature.

occupancy than the straw tubes, with comparable resolution. Also, with this option a separate intermediate angle detector may not be needed.

1.3. Track Reconstruction

Figure 2 shows a hypothetical track helix in two views, to define the five track parameters: impact parameter (b_0), azimuth (ϕ_0), curvature ($\rho = -q/r_c$), z intercept (z_0) and slope ($\tan\lambda$). Raw data are first reconstructed locally in each subsystem to form "coordinates" and/or "segments" (coordinates with direction), which are then combined to reconstruct tracks.

To avoid algorithm dependent conclusions, three different track reconstruction algorithms have been used. One, a segment clustering algorithm, reconstructs tracks in the silicon inner tracker, and extends to other subsystems in the fitting stage. This will be discussed further below. A second uses a road following algorithm starting with the outer silicon layers to extend tracks inwards and outwards, refitting each time a hit is added. A third segment binning algorithm divides segments from all systems into curvature, ϕ and $\tan\lambda$ bins, and fits all combinations of segments in each bin to form tracks. The first two rely heavily on the pattern recognition capability of the silicon system. All three make some implicit vertex constraint in the track reconstruction, so observing particles (such as K_s and λ) which decay within the system will be quite difficult. Note that none of the algorithms are fully optimized for the complex SSC events.

As an example, in the segment clustering algorithm, pairs of segments (each composed of a pair of coordinates in adjacent silicon layers) are compared separately in two 2-dimensional spaces. In the barrel section, these are the (ρ, ϕ_0) and $(z_0, \tan\lambda)$ views shown in Figure 2, whereas in the forward detectors, a different linear combination of parameters is used [7]. Pairs of segments which match in both views, based on a χ^2 test which includes multiple scattering, are clustered together to form a track candidate. For very close tracks (as within a jet), clusters which merge can either be broken apart after clustering or sorted out

during clustering. The five helix parameters are obtained for each track candidate with an iterated least squares fit. The track is then extended to pick up missing hits or segments in the other systems and refit.

2. PHYSICS PERFORMANCE

The tracking simulation studies have focussed primarily on three physics processes: the four lepton decay of a Higgs boson, QCD jets, and high p_t b-quark jets from top decays. These studies are summarized in the following sections.

2.1. Higgs decays to four leptons

The capability to efficiently detect a final state with four leptons (electrons or muons) will be crucial to discover an ultra-rare particle such as the Higgs boson, in a relatively background free channel. As well as observing a signal, it will be important to measure properties accurately such as the width and angular distribution. This process emphasizes strongly the importance of a very high isolated track efficiency over a large angular range, and also the rejection of backgrounds such as misreconstructed tracks, hadrons faking electrons, and photon conversions. Electrons present a challenge, since they can undergo bremsstrahlung within the system, changing their momenta. Since we would require the momentum to match the energy measured in the calorimeter to reject pions, it is quite important to be able to measure the momentum with the inner silicon system and a beam constraint, before most of the brelmstrahlung has taken place [8]. The resulting efficiency for the standard cut ($0.8 < E/p < 1.4$) is just above 95%.

The simulation study reported here [9] assumed a Higgs mass of 300 GeV and used the decay modes $H^0 \rightarrow Z^0 Z^0 \rightarrow e^+e^-\mu^+\mu^-$ and $\mu^+\mu^-\mu^+\mu^-$, with all four leptons within $|\eta| < 2.5$. The ISAJET Monte-Carlo was used to generate the Higgs events and the background events corresponded to various luminosity were generated with PYTHIA. The efficiency for tracks with $p_t > 10$ GeV (mainly the leptons) is above 99% averaged over $|\eta| < 2.5$, with about 0.03 false tracks with $p_t > 5$ GeV per event. To achieve this, it has been important to optimize layer positions, minimize dead area, and maintain enough layers for robust track finding.

In this study, a pair Z^0 bosons were required to be reconstructed to make a Higgs candidate. All pairs of opposite sign tracks from same type leptons were used to calculate an invariant mass, which was required to be within 10 GeV of the Z^0 mass. The muon pair masses, shown in Figure 3a, do not include the muon system in the track fit. The resolution from the simulation is approximately that obtained by parametric calculations, and the Z^0 peak is reconstructed with close to its natural width. The electron pair masses are better measured with the electromagnetic calorimeter, so the study used the calorimeter resolution to smear the generated energies, but used the directions and efficiency from tracking. The capability to make a tight cut on the Z^0 masses, though not essential for the 300 GeV Higgs, could be very important in more background dominated scenarios such as a lower mass Higgs decay where one of the Z^0s would be virtual.

For events with two Z^0 candidates, the reconstructed four-lepton invariant mass distribution is shown in Figure 3b, at standard (10^{33}) luminosity and 6 times higher. The resolution of the Higgs peak was unchanged at the higher luminosity. The overall reconstruction efficiency from tracking is approximately 84% at nominal luminosity and falls to about 75% at 6 times nominal.

2.2. Tracking within jets

Reliable track finding inside jets will be important for identifying heavy quark jets with secondary vertices, for identifying leptons near or inside jets, and for measuring the properties of jets at the SSC. The latter is crucial since the fluctuations in the fragmentation process pose the main backgrounds to rarer objects such as photons, electrons, muons and taus.

Due to the high track density in the core of

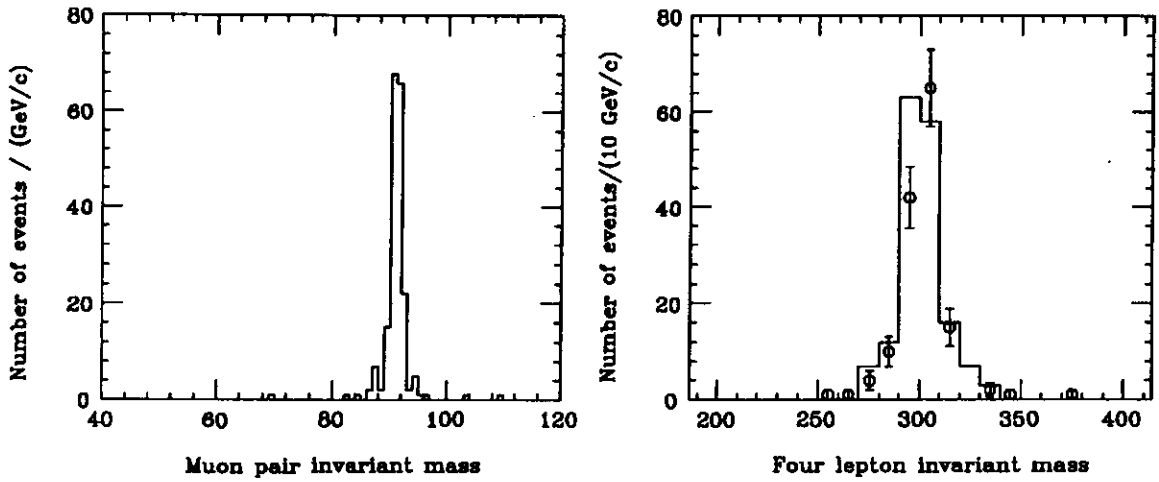

Figure 3. a) Di-muon invariant mass in $H^0 \rightarrow Z^0 Z^0 \rightarrow e^+e^-\mu^+\mu^-$ events with $M_{H^0} = 300$ GeV at nominal SSC luminosity. b) Four lepton invariant mass distribution for events with two Z^0 candidates (see text). The histogram and circles are for 10^{33} and $6 * 10^{33}$ luminosity, respectively.

jets, the demands are higher compared with isolated leptons both on the system (the granularity for multi-track separation) and the reconstruction algorithm. The efficiency within jets has been studied with the segment clustering algorithm for the silicon and straw tube option and with the road following algorithm for the silicon and scintillating fiber option. Two jet events were generated using ISAJET with minimum transverse momenta of 50, 100, 200 and 500 GeV. The jet kinematics for each event were reconstructed by clustering stable Monte-Carlo particles within an η-ϕ cone with radius $R \equiv \sqrt{(\Delta\eta^2 + \Delta\phi^2)} \leq 0.5$. The reconstruction efficiency for tracks inside jets is shown for the two cases in Figure 4. The segment clustering algorithm has a somewhat higher efficiency at modest p_t but falls off at higher values of jet p_t when compared with the road following algorithm, though the comparison is complicated since both the systems and algorithms were different.

2.3. b-jet tagging in top quark events

Identifying b-quark jets may be quite important for studying the properties of the top quark, by reducing the non-top background substantially, and also reducing combinatoric background in measuring the top quark mass [9]. This can be done with non-isolated leptons with of order 5–10% efficiency; in this case the b-quark charge is measured, but the semileptonic decay is not as useful for directly measuring the top mass. Alternatively, the tracking system can be used to search for secondary vertices from the b and c decay cascade. This requires high efficiency and little confusion for track finding in jets of typically 100 GeV, and resolution on the transverse impact parameter substantially less than $c\tau \simeq 350$ μm for the B mesons. The impact parameter resolution (σ_{b_0}) for the proposed system is about 100 μm at p_t =1 GeV and 10 μm at high p_t.

The efficiency for 'tagging' a b quark jet with secondary vertices was studied with the GEANT simulation and full event reconstruction using a simple algorithm, which was to count the number of reconstructed tracks in a jet which have significant impact parameters. ISAJET was used to generate b and "generic" jets separately, and tracks were reconstructed with the combined silicon and straw system. Tracks with measured $p_t > 0.8$ GeV and χ^2/DOF < 5 which were within $\Delta R < 0.5$

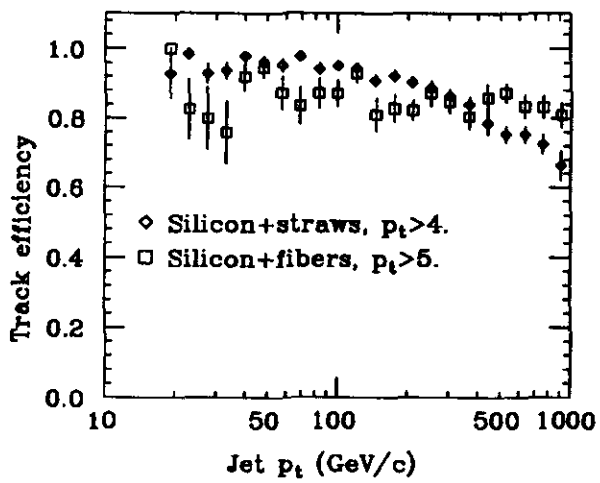

Figure 4. Overall track finding efficiency within jets as a function of the jet transverse momentum, for two detector configurations. Two different algorithms were used (see text).

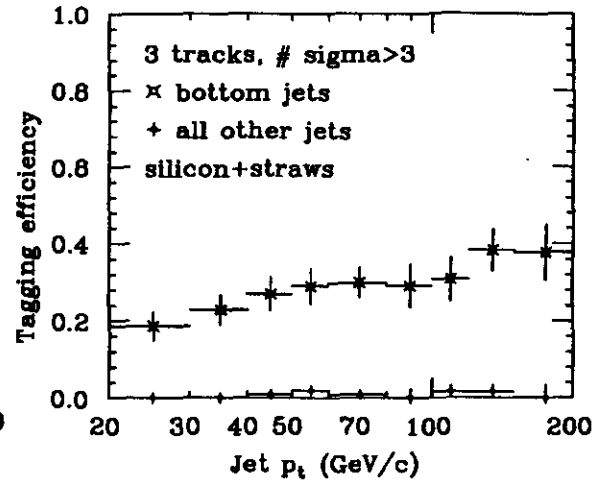

Figure 5. Efficiency for identifying b-quark jets compared with non-b-quark jets using secondary vertices, with the algorithm described in the text. The background rejection ratio is about 30:1.

to a jet axis were considered.

A typical tagging criterion is to require 3 or more tracks in a jet to have $b_0 > 3\sigma_{b_0}$, where σ_{b_0} is the impact parameter error from the fit, and the sign of b_0 is defined to be positive for tracks originating from a vertex displaced along the jet direction. Figure 5 shows the efficiency for tagging b-quark and non-b-quark jets with this requirement. The tagging efficiency is typically 25–30% for the b jets, and below 1% for the non-b jets. The use of this requirement has been investigated for top quark mass and branching ratio measurements [10]. With rather simple event selection requiring a high p_t isolated lepton and at least 3 jets, requiring that one of them is identified as a b-quark jet reduces the non-top background to a negligible level. Also, knowing which jet is the b in these event enhances the ability to look for non-standard decays of the top via a charged Higgs boson.

3. SUMMARY

In summary, the GEANT simulations have been quite useful for studying design issues for the SDC tracking system. The pattern recognition capability has been shown to be quite robust, even in complicated SSC events at higher than the design luminosity. Two factors which make this possible are a reliance on local pattern recognition for reconstructing coordinates and segments; and a heavy reliance on the precision and low occupancy of the silicon inner tracker.

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