

Comparison of hit profiles of SLUG Simulation with CDF Data at Fermilab

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Abstract

The DICE/GEANT simulation is used to simulate and study future detectors. We have taken the ATLAS simulation package and applied the CDF (Collider Detector at Fermilab) tracking detector geometry. A hit profile comparison of the simulation results for the Central Tracking Chamber (CTC) of CDF using minimum bias events generated by PYTHIA, and the CDF data, is presented in this note.

1 Introduction

Simulation studies have become essential to design and optimize the future LHC detectors, and to develop track reconstruction methods. Within ATLAS, the DICE/SLUG package using GEANT for the detector simulation together with the PYTHIA ¹ physics simulator has been used to simulate and study the performance of detectors with Monte Carlo techniques. Because the dependence on such simulation programs has increased for the development of new detectors, we need to understand how well those simulations work using comparisons with existing physics data.

For this purpose, we have used minimum bias track data from recent runs of the Collider Detector at the Fermilab (CDF) to compare the CDF tracking detector with simulation results. In order to do this, we have included the complete geometry of the inner detector of the CDF, including its 1.41 Tesla solenoidal field, in the framework of DICE. In this note, we give a brief description of the CDF tracking detector. We then compare the track multiplicity from PYTHIA, as a function of η and p_T , with published data from CDF. After the processing of PYTHIA events through DICE, a comparison of the CTC hit profile is made.

¹There are other generators available. We have also studied the GENCL generator.

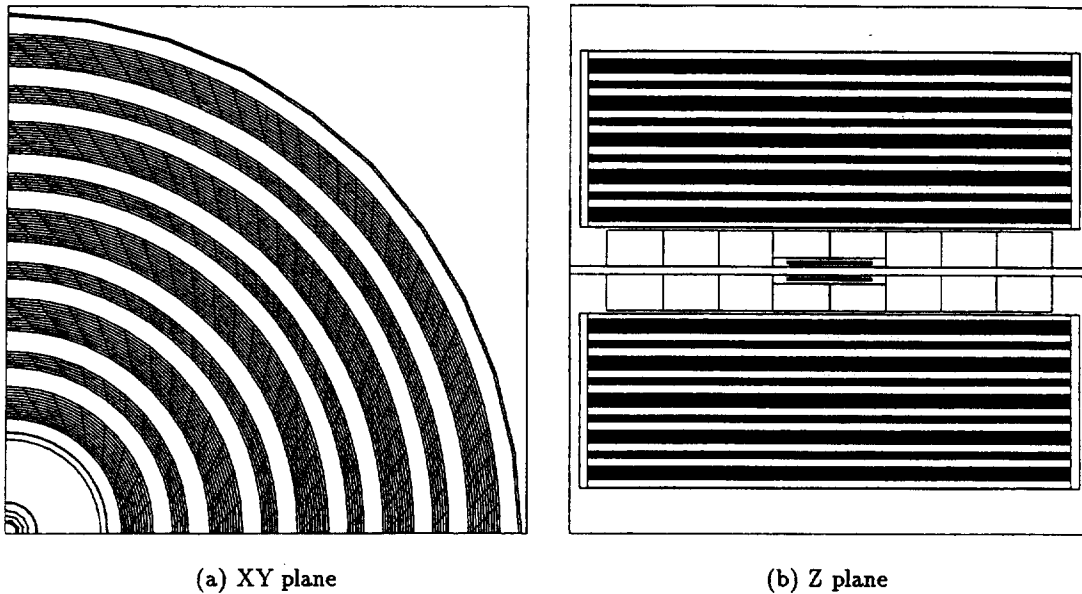


Figure 1: CDF Tracking Detector geometry, as produced by GEANT.

Number of layers	84
Number of super layers	9
Stereo angle	$0^\circ, +3^\circ, 0^\circ, -3^\circ, 0^\circ, +3^\circ, 0^\circ, -3^\circ, 0^\circ$
Number of super cells/layer	30, 42, 48, 60, 72, 84, 96, 108, 120
Number of sense wires/cell	12, 6, 12, 6, 12, 6, 12, 6, 12
Sense wire spacing	10mm in plane of wires
Radius at innermost sense wire	30.9cm
Radius at outermost sense wire	132.0cm
Gas	argon-ethane-alcohol (49.6% : 49.6% : 0.8%)

Table 1: CTC Mechanical Parameters.

2 The CDF Tracking Detector Layout

The CDF tracking detector extends to 1.4 metres in the radial direction and ± 1.5 meter in the Z direction, and consists of several components. In the simulation program, we have included realistic geometries for the beam pipe, the Silicon Vertex Detector (SVX), the Vertex Chamber (VTX), and the Central Tracking Chamber (CTC), inside a 1.41 Tesla solenoidal magnetic field. The CTC has been simulated and its hit profile is compared with the CDF data in later sections of this report.

Figure 1 shows the geometry of the Tracking Detector, as reproduced by the GEANT package. The innermost detector, immediately following the beam pipe, is the Silicon Vertex Detector (SVX), consisting of 4 layers of micro strip silicon counters, extending to 7.8cm in the R direction and 28cm in the z direction. The SVX was included in the geometry to simulate the amount and location of radiation material, not for the comparison of digitized track hits with data (due to channel-to-channel threshold variations during the 1993 run). The silicon counter has a 0.07

r.l. radial thickness.

Surrounding the SVX, the low mass Vertex Chamber (VTX) extends to 24.5cm in the radial direction and is 143cm in length. It consists of eight double time projection chambers surrounding the beam pipe and mounted end-to-end along the beam direction (z -axis). The purpose of this detector component is to provide a z -vertex determination, and the tracking for the charged particles. It is filled with argon-ethane gas. As for the SVX, this detector is modelled in the simulation as a material preceding the Central Tracking Chamber.

The most important component of the tracking detector is the Central Tracking Chamber (CTC) which occupies most of the volume within the superconducting, solenoidal 1.41 Tesla magnet coil.

The CTC is a wire chamber with 84 layers of sense wires arranged into 9 superlayers. Five of the super layers, in which the wires are parallel to the beam line, contain 12 sense wire layers each. The five axial layers are interleaved with four superlayers of stereo wires configured with angles of $\pm 3^\circ$ respect to the beam line. Each stereo layer contains 6 sense wire layers. In our simulation, the stereo angles were ignored since they have no influence on the resulting hit profile. Table 1 presents a brief description of the mechanical parameters of the CTC detector.

3 The Optimization of the PYTHIA generator

A proper comparison of CDF data with any physics generator requires that in the range of published CDF data, the generator is in reasonable agreement. Published data are [3] and [4].

In the range $|\eta| < 1.0$ and $p_T > 0.4 \text{ GeV}/c$, the p_T distribution of PYTHIA or any other generator can be compared. Tracks beyond $|\eta| > 1.0$ have limited acceptance within the CTC. However, such tracks *do* contribute to hits within the CTC. Fortunately, CDF has published charged particle rapidity distributions extending to $\eta \simeq 3.0$, using the VTPC (predecessor to the current VTX). However, only limited p_T information is available from these data, and their use is valid only for studies of the shape.

For $|\eta| < 1$ and $p_T > \sim 0.4 \text{ GeV}/c$, the full p_T distribution exists. However, low p_T tracks for which no measurements at CDF exist do contribute to hits in the inner CTC layers. This results in a normalization uncertainty in any comparison of data with a physics generator.

The dependence of multiplicity with rapidity.

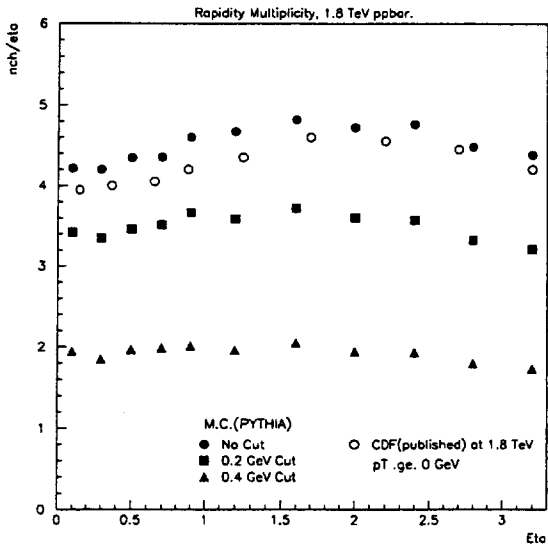
Figure 2 shows the charged track multiplicity of minimum bias events, from the CDF data and the PYTHIA generator. The generated Monte Carlo data use the default parameters for the LHC simulations ².

Figure 2(a) compares the $dN_{ch}/d\eta$ of PYTHIA generator with corrected CDF data [3]. The CTC geometry, however, has an acceptance limit for each superlayer. The η limits for the inner and outer superlayers are $\eta(\text{S.L.1}) = 2.0$, $\eta(\text{S.L.5}) = 1.3$ and $\eta(\text{S.L.9}) = 1.0$ respectively. The η distribution is approximately flat for this acceptance range.

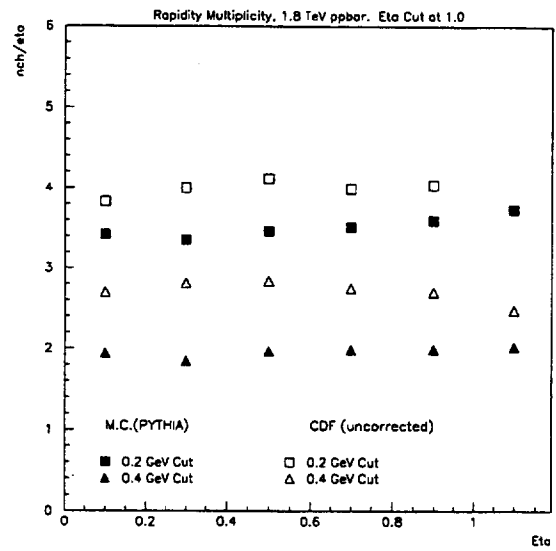
In Figure 2(b), the CDF rapidity distributions are evaluated from the raw CDF data.

The multiplicity distributions are approximately flat in η , thus giving the constant ratio of PYTHIA/CDF in the region of CTC tracking acceptance rapidity range. The corrected and raw CDF data have slightly a higher multiplicity (in the latter case for both p_T cuts). In the latter

²We have performed simulations using both the PYTHIA and GENCL generators, However, full detector simulations have only been made using the PYTHIA generator, following parameter changes to ensure agreement with published data.



(a) Rapidity multiplicity measured by CDF at 1.8 TeV [3], compared with the PYTHIA generator.



(b) Comparison of the rapidity distribution with Pt cuts from CDF data for charged tracks, with the PYTHIA generator (default parameters).

Figure 2: Comparison of the rapidity distributions.

case, the ratio between the CDF data and PYTHIA is not the same for two different p_T cuts. The PYTHIA generator produces more particles with lower p_T than CDF data, in the region between $0.2 \text{ GeV}/c \geq p_T \geq 0.4 \text{ GeV}/c$. This may result from inefficient track reconstruction at low p_T ; it prevents a good knowledge of the p_T spectrum at low p_T .

p_T spectrum

Charged particles with p_T less than $0.3 \text{ GeV}/c$ spiral inside the solenoid. The minimum primary track momentum for hits contributing to superlayer #1 is $\simeq 0.1 \text{ GeV}/c$; exactly the region of little or no p_T measurements.

The tuning of the Monte Carlo generator has been made using the p_T spectrum, as already noted, using published CDF data. The invariant cross section is fitted with the functional form [4],

$$E \frac{d^3\sigma}{d^3p} = \frac{Ap_0^n}{(p_T + p_0)^n}, \quad (1)$$

and the fit parameters and their statistical errors are

$$\begin{aligned} A &= 0.45 \pm 0.01 && [10^{-24} \text{cm}^2 / (\text{GeV}^2 / c^3)], \\ p_0 &= 1.29 \pm 0.02 && (\text{GeV}/c), \\ n &= 8.28 \pm 0.02. && \text{fitted for } \sqrt{s} = 1.8 \text{ TeV} \quad (\text{CDF}) \end{aligned}$$

The normalization of the inclusive cross section assumes a BBC cross-section of 51.2 mb as determined by the most recent CDF measurements, and the spectrum of [3] has consequently been scaled up from the cross-section value of $43 \pm 6 \text{ mb}$ used there.

The tuning of the PYTHIA has been made by adjusting some parameters which are related to multiple parton interactions, pile-up events, and underlying physics assumptions³.

The multiple interaction structure is adjusted by MSTP(82). The hadronic collisions are characterized by a varying impact parameter including the core distribution within the hadrons. By varying this parameter, the overlap between the two colliding hadrons can be adjusted which corresponds to the probability for parton-parton multiple interactions. The core distributions are given by PARP(83) and PARP(84). Parameter PARP(82) regulates the continuous turn-off scale p_{T_0} of the p_T spectrum for multiple interactions, instead of an abrupt $p_{T_{min}}$ cut-off. Adjusting these parameters shifts the peak of the p_T distributions, and also effects the overall multiplicity.

Parameter PARJ(21) corresponds to the width σ in the Gaussian p_x and p_y transverse momentum distributions for primary hadrons. It mainly affects the high energy p_T particle distributions.

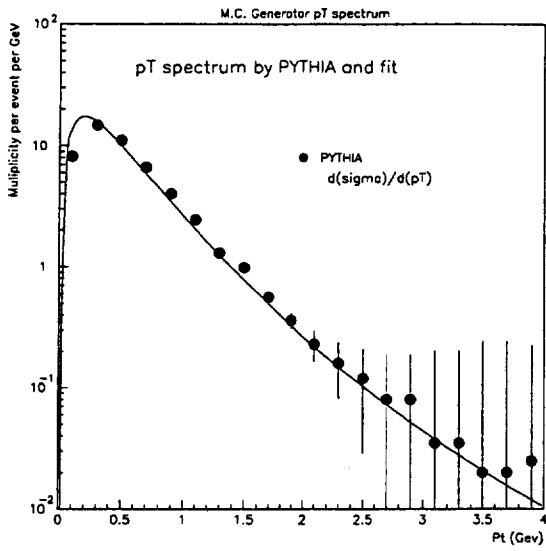
Finally, MSTP(33) and PARP(32) introduces the factor K in hard cross sections for parton-parton interactions.

More detailed description of these parameters can be found in the PYTHIA manual [6].

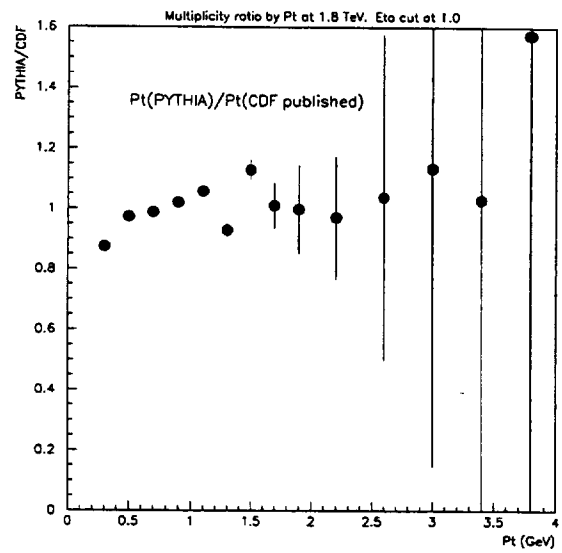
The p_T spectra from the Monte Carlo generators are plotted in Figure 3, with a cut at $|\eta| = 1.0$. The fit was made using the inclusive cross section formula. The over all multiplicity $\langle n_{ch} \rangle$ depends on σ_{tot} of minimum bias events and other fit constants. We multiplied the inclusive cross section formula with an arbitrary constant, K , to obtain an optimal normalization fit. Figure 3(a) shows the p_T spectrum comparison between tuned PYTHIA and fitted CDF data.

Figure 3(b) shows the ratio of PYTHIA and the inclusive cross section from the fitted CDF data, as a function of p_T , after all the above corrections, and including the normalization factor

³The new(default) values of the adjusted parameters are MSTP(33)= 2(3), MSTP(82)= 4(1), PARP(32)= 1.1(2.0), PARP(82)= 1.50(1.55), PARP(84)= 0.50(0.20), and PARJ(21)= 0.50(0.36).



(a) Transverse momentum spectrum from 1.8 TeV $p\bar{p}$ events for charged particles. PYTHIA generator is presented. The curve is from inclusive cross section fitted with experimental data at the CDF, with $|\eta| \geq 1.0$.



(b) The ratio of the multiplicity of p_T bins verse the transverse momentum of charged particles between Pythia generator and the fitted value from the inclusive cross section with the CDF data.

Figure 3: Charged particle p_T multiplicity.

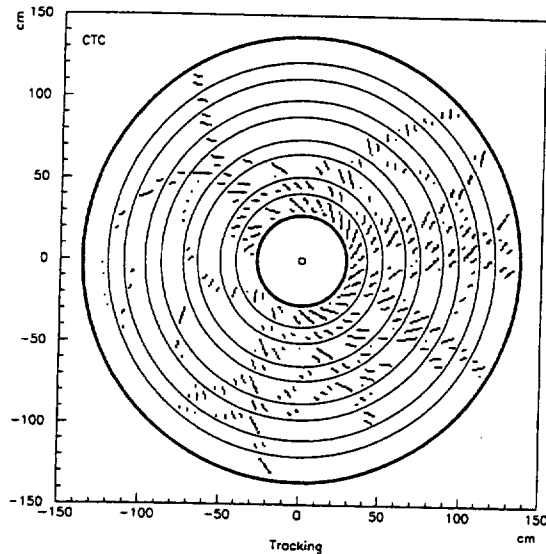


Figure 4: Wire hits from one minimum bias event in CTC.

K. Over several orders of magnitude, including the dominant low p_T region, PYTHIA agrees reasonably well with published data.

The above discussion concerns only the optimization of the physics generator, and is independent of the experimental layout. The result of the GEANT simulation is described in the next section.

4 Monte Carlo Detector Simulation

The PYTHIA and GENCL generator programs can be used to generate minimum bias events. We use PYTHIA as the input for the GEANT Detector Simulation. We generate minimum bias events at the energy of $\sqrt{s} = 1.8$ TeV, following the corrections discussed in the previous section. Figure 4 shows an event from one minimum bias event, using Monte Carlo simulations⁴. A hit in this simulation is recorded when a charged particle traverses a sensitive volume of the detector and deposits a minimal ionizing energy. The hit is registered at the center of that volume where the anode wire is located.

Double hits occur when two ionizing particles traverse the same sensitive volume. An algorithm was used to record multiple hits within a single drift volume when the difference of the absolute distance of contributing tracks from the sensitive wire is greater than the resolution of the CTC detector, typically 2 to 4 mm⁵. The merging algorithm takes account of the screening effect from low momentum tracks.

The simulation program has an energy cut, below which GEANT abandons the tracking. By default, an 100 KeV cut is applied by GEANT for tracking. We have varied this energy threshold

⁴In this hit display, all hits are displayed at the center of the sensitive volume, or at the position of the sensitive wire. The drift distance of hits, or right and left ambiguity are ignored.

⁵In this simulation, the double hit resolution was set to 2.5 mm for super layer #1 to 3, 3.5 mm for super layer #4 to 9.

from 10 KeV to 500 KeV. The variation of the threshold in this range does not significantly affect the hit profiles.

Consequently, the default cut was applied by GEANT for the tracking and tracking was processed up to 100 ns after the bunch crossing.

The simulation produces one minimum bias interaction per event. However this is not the case with the CDF data. The mean number of interactions at each crossing at the CDF can be computed from the machine luminosity and the minimum bias cross section. The data used were taken from CDF runs with luminosity $\sim 4.5 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, yielding on average 0.77 interactions at each bunch crossing. Using the Poisson distribution, one can compute the average number of interaction per trigger, N . This value N is taken into account in the simulation by randomly superimposing PYTHIA events according to a Poisson distribution. In our case N is calculated to be 1.42.

There are several other effects which have been taking into account in the simulation. One is afterpulsing (real or otherwise) of the front-end electronics. This effect is estimated to be approximately 20% in S.L. 1-3 and 12 – 15% in S.L. 4-9. The difference of the level is due to a change of the preamplifier for external layers.

A second small effect degrading the agreement is that of the hit detection efficiency, estimated to be 96% in S.L. 1-3 and 99% in S.L. 4-9.

With the corrected PYTHIA generator, the hit profile from the CTC simulation is presented in the next section.

5 Hit Profile Comparison

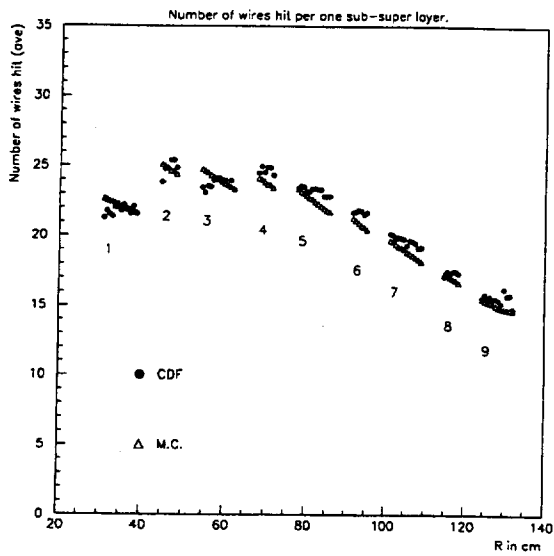
The CTC detector has been simulated using the generator and tracking as described in sections 3 and 4. The hit profile can then be compared with CDF data.

Figure 5 compares the number of wires hit in each layer (*a*) and the number of total hits in a each layer (*b*). These figures show saturation due to occupancy for the inner layers. Within a superlayer, the data show a reduced hit wire count for inner layers. (see Figure 5 (*a*)). This is in disagreement with the simulation and further study is needed to reach a full understanding. However, the comparison of the number of wires by superlayers agrees quite well between the data and the simulation.

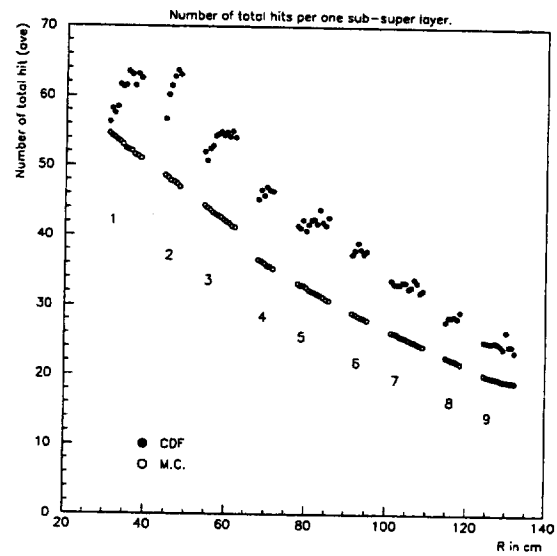
A comparison of the total number of hits is shown in Figure 5 (*b*). The simulation has a smaller number of hits than the data, the deficit ranging from less than 15% in inner layers to 25% in outer layers. The total number of hits is roughly inversely proportional to the radius, as expected.

The ratio of the hit profile by superlayer is shown in Figure 6(*a*). The level of the agreement is best in the inner layers, as shown already by the hit profiles. Table 2 shows the ratio of M.C./CDF, for the number of hit wires and number of hits for all superlayers. Figure 6(*b*) shows the average number of hits registered per wire per event for each of the 9 superlayers. The simulation and the CDF data are in the best agreement for inner layers.

Figure 7 shows the percentage of merged hits in each superlayer. In the innermost superlayer, 30% of the hits are merged according to the simulation. The low p_T charged particles, with $p_T \sim 0.1 \text{ GeV}/c$ spiral inside the solenoid, at the radius of the inner superlayers. These spiral tracks which go through a cell *sideways* wipe out the ability to register another hit for the whole width of a cell, not just the resolution of the wire chambers.

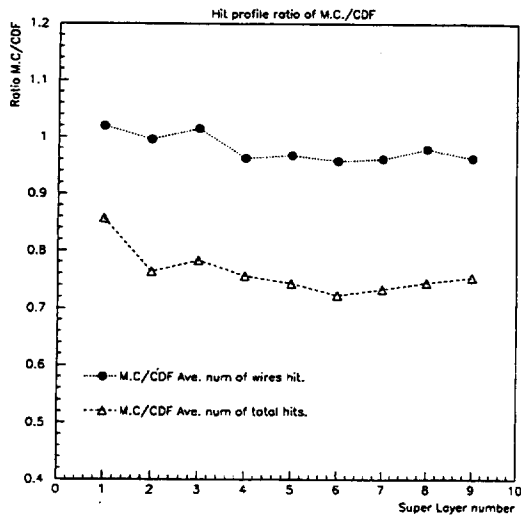


(a) Number of wires hit in the individual layers of a superlayer. The numbers 1 through 9 are the super-layer numbers.

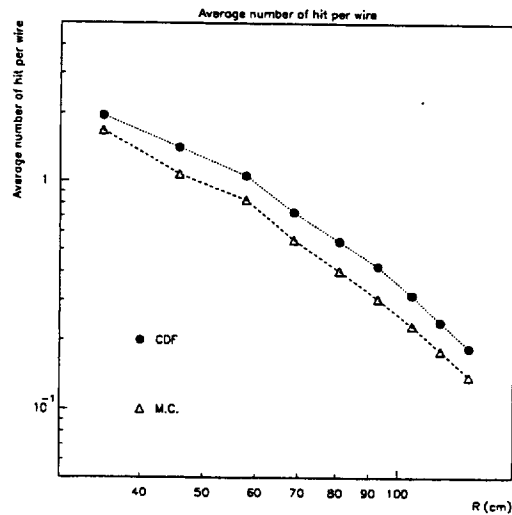


(b) Number of total hits in individual layers of a superlayer.

Figure 5: Comparison of the number of hits per event for 84 layers of the CTC.



(a) Ratio, M.C./CDF, of the hit profile by superlayer.



(b) Average number of hits per wire per event for each 9 superlayers.

Figure 6: M.C. and CDF comparison of the number of hits per wire.

Super layer Number	Average # of wires hit		Average # of total hits		Average # of hits per wire per event
	*FIGURE 5 a) M.C./CDF data	= ratio	*FIGURE 5 b) M.C./CDF data	= ratio	*FIGURE 6 b) M.C./CDF data
S.L.1	248/243	1.02	598/699	.86	1.66/1.94
S.L.2	139/140	1.00	270/353	.76	1.07/1.40
S.L.3	270/266	1.02	477/609	.78	.83/1.06
S.L.4	134/139	.96	199/263	.76	.55/.73
S.L.5	252/261	.97	350/471	.74	.41/.55
S.L.6	116/121	.96	154/213	.72	.31/.42
S.L.7	209/218	.96	268/365	.73	.23/.32
S.L.8	93/95	.98	116/156	.75	.18/.24
S.L.9	163/169	.96	200/266	.75	.14/.18

Table 2: Hit count comparison between CDF data and M.C.

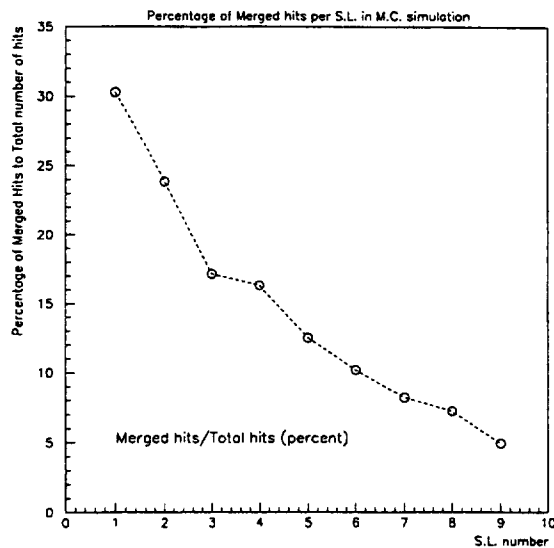


Figure 7: Percentage of merged hits plotted by superlayers in GEANT simulation.

6 Conclusion

We have simulated the CDF Tracking Detector with ATLAS detector simulation program, and compared the hit profiles of the CTC detector. The p_T spectrum and multiplicity distributions of the PYTHIA and GENCL generators are studied and PYTHIA has been used as the generator for the detector simulations. The GEANT program has been studied for its efficiency, the thresholds for the hits, and the energy cuts, and it is shown that small variations do not make a significant difference to the simulation results. The efficiency of the detector, the double hit algorithm, and some other factors are taken into account for the Monte Carlo detector simulation.

From the comparison, we conclude that the simulation and the CDF data agree reasonably well. However, the simulation registers fewer hits than the actual CDF data, between 15% for the innermost superlayer, and 25% for the outer superlayers. From the simulation, 30% of the possible hits are merged in the inner superlayers; less than 5% of hits are merged for the outer superlayers.

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List of Publication

With the UA1 collaboration

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- [2] F. Bedeshi *et al.*, Nuclear instruments and methods in physics research, **A268** (1988) 50.
- [3] F. Abe *et al.*, Physical Review D, **Vol. 41** (1990) 2230.,
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- [6] T. Sjöstrand, PYTHIA Manual and Physics, **CERN-TH.7112** (1993) 221, 225.
- [7] D. Bernard *et al.*, Physical Review Letters, **B 186** (1987) 227.