Simulation of the Performance of the DØ Run 2B Silicon Detector

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The DØ Collaboration

Introduction

The Run 2B Silicon Tracker must enable us to fully exploit the physics opportunities of Run 2B. It must have the capability to reconstruct tracks with high efficiency with low fake track rate and an ability to provide good impact parameter resolution for b-tagging. The tracker design and physics performance are described in the technical design report (TDR)[1]. The SMT is conceived as a 6-layer barrel detector. The two inner layers hold axial detectors only, while each of the four outer layers contains a stereo pair of silicon detectors. The full tracker then consists of the new SMT together with the Run 2A Central Fiber Tracker (CFT).

This note summarises studies of the physics performance of the detector, including the effects of inefficiency[2], and of three possible alternative designs with reduced scope[3]. All studies are carried out in the metric of the Standard Model Higgs search.

Datasets and Event Selection

Two representative physics processes have been used: WH production as an example of signal events and Z boson production with decay to light quarks as a way to evaluate light quark mistagging rates. The W-boson was forced to decay leptonically (to muon and neutrino) thus providing a trigger for the WH channel. The Higgs mass was set to 120 GeV/c^2 and forced to decay to $b\bar{b}$. For the high luminosity studies, minimum bias pileup events were generated using a set of parameters tuned to CDF run 1 minimum bias data and were overlaid on the WH and Z events. The number of overlaid pileup events was Poisson distributed with a mean of either 6 or 7.5, which corresponds to a luminosity of 4 or 5×10^{32} $cm^{-2}s^{-1}$. The z position of the primary vertex was Gaussian distributed with a r.m.s. width σ = 15 cm. All processes were generated with PYTHIA version 6.2.

The generated events were passed through a full GEANT simulation, pattern recognition and reconstruction chain. The SMT geometry in GEANT includes the correct gaps between sensors and barrels, correct ganging of silicon sensors at large | z |, and the different stereo angles for different types of silicon modules. Besides the active detectors, the geometry includes passive material in support structures and readout cables

For the track reconstruction the DØ histogramming track finder (HTF) [4] was used. This reconstruction package has been shown to at least match the performance of DØ's production reconstruction package (GTR) on run 2A data (GTR is a Kalman Filter algorithm). The reconstruction of jets in both WH events and Z-decays was performed using the standard DØ Run 2 Cone algorithm on calorimeter cells, with cone size of 0.7. Only jets with energy above 20GeV were used in the analysis. Tracks were assigned to a jet if they were within a cone of 0.5 around the jet axis. The jet flavor was determined by a quark closest to the jet axis in the cone $\Delta R<0.3$. The B-tagging algorithm used in these studies is based on a minimum number of tracks with impact parameter significance greater than some cut [5], typically 3 tracks above 2 standard deviations.

We studied the impact on run 2B physics by considering tracking efficiency, fake track rate, b-tagging efficiency and mistagging rate. We considered both "global tracking" (i.e. for the full CFT + SMT system), and, for the case of SMT-L4, we explored the impact on SMT stand-alone tracking performance. The Standard Model Higgs searches require double b-tagging to reduce the backgrounds to an acceptable level, so the figure of merit is the double b-tagging efficiency ε_{bb} which is directly proportional to the luminosity needed for Higgs discovery or exclusion.

Performance of the TDR design

The TDR contains extensive documentation on the GEANT modelling, digitization, and hit/cluster simulation used. Using single muons, we find the position resolution on a single cluster is 10-12 μm. The mean occupancy is dominated by noise: we assumed an RMS noise of 2.1 ADC counts and a threshold of 6 ADC counts which results in an overall average occupancy of less than 1%. The average occupancy from tracks is 0.2% or less, but the peak occupancy occuring inside jets in WH events is 8% in layer 0 and < 6% elsewhere. The muon momentum resolution is about 2.2% for $1 < p_T < 5$ GeV, with a uniform 100% reconstruction efficiency out to $\eta=1$ and a slight fall off to about 90% at $\eta=2$. The impact parameter resolution is about 10μm for high p_T tracks.

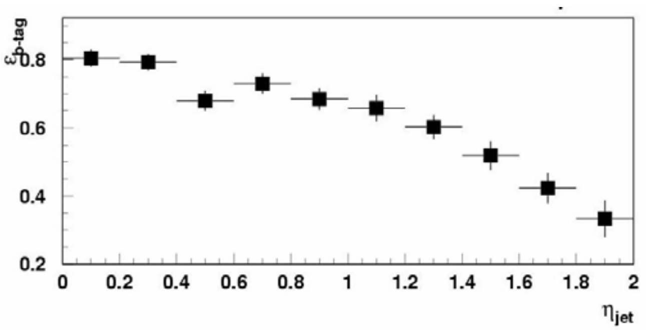

Figure 1 - b-tagging efficiency as a function of the pseudorapidity of the tagged jet.

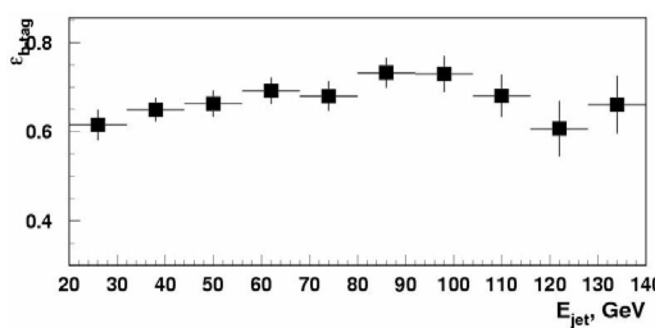

Figure 2 – b-tagging efficiency as a function of the energy of the tagged jet.

The b-tagging performance of the detector is shown in Figures 1 and 2. The mistagging rate is below 1.5% and, within errors, is independent of both the b-jet energy and pseudorapidity.

The probabilities to tag an event with one or two b-jets are shown for the Run 2A detector (estimated from Z-boson decays to bb) and Run 2B (from WH events) in Table 1. The Run 2B simulation includes overlaid minimum bias pileup events.

Table 1 - Probabilities to tag a WH event with one or two b-jets.

	Run 2A	*Run 2B*
$P(n_b \geq 1)$	68 %	76 %
$P(n_b \geq 2)$	21 %	33 %

The proposed tracker meets the requirements of the Higgs search. Comparison with the Run 2 Higgs and Supersymmetry Workshop studies [6] shows that the tagging efficiency per jet obtained here, which rises from about 60% at 20 GeV to 70% at 100 GeV, is well within the range required. Our mistagging rate is higher than what was assumed in these studies but is quite adequate given the need to tag two b-jets per Higgs event. We consider it an achievement that a GEANT simulation of a real detector design with full pattern recognition and reconstruction can match these ambitious performance goals.

Tracking with inefficiencies

The global track reconstruction algorithm exploits both CFT to SMT and SMT to CFT extrapolations. In the CFT to SMT case, a track is required to have at least 7 CFT and 2 SMT hits; and in the case of SMT to CFT extrapolation, the track must have at least 4 SMT hits. An additional requirement on the track reconstruction quality is that the χ^2/NDF of the fitted track must be less than 3. Only tracks with p_T>0.5GeV are used in the analysis.

Inefficiency in the SMT arises from two main sources: discrete readout problems related to whole detector modules, and distributed dead and noisy channels. The first source impacts track reconstruction more severely. This effect has been simulated by dropping all clusters in some fraction of a randomly selected sample of silicon detectors. Possible CFT inefficiency was implemented in the same way in the first layer only where 30% of fibers were assumed to be non-operational. The degradation of b-tagging as function of the fraction of dead silicon detectors in SMT is shown in Figure 3. The detector performance is clearly robust against such inefficiencies at the few % level, but starts to degrade significantly if they exceed 10-15%. In Run 2A the fraction of non-working silicon devices is about 5% for the central barrels.

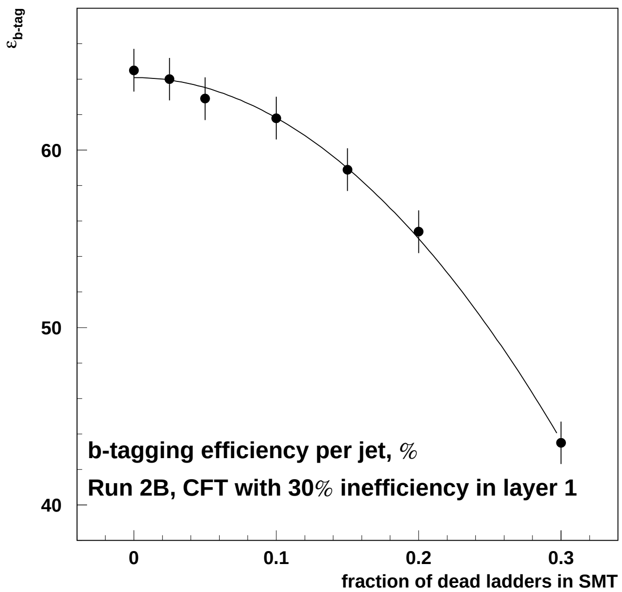

Figure 3 - Degradation of the b-tagging as function of the fraction of dead detectors in SMT.

Evaluation of Alternate Designs of the Silicon Tracker

Time and cost constraints are severe for Run 2B; it is thus appropriate to examine alternate design options with reduced scope relative to the TDR design. We considered options denoted as follows:

- "TDR−L4": removal of silicon layer 4;
- "TDR−L1": removal of silicon layer 1;
- "TDR−Z": removal of silicon detectors in each layer at large |z|.

The TDR-Z option has been considered at the generator level since the dominant effect is one of acceptance. The others were carried out in the full GEANT framework. Some detail differences exist between our latest and most accurate geometry and digitization (used for the TDR-L4 study) and older iterations. It was not possible to repeat all the older studies in the new framework, so some minor inconsistencies may be noted between simulations of the same TDR geometry carried out in different case studies. In all cases, however, our conclusions are based on comparing any given two options within a consistent framework.

TDR-L4 option

SMT Stand-alone tracking

SMT stand-alone tracking is important for tracking in the region $|\eta|>1.2$ where full CFT coverage (8 stereo hits per track) is not available. Forward tracking is of special interest for high-p_T leptons, where both the DØ muon system and electromagnetic calorimeter have much better $|\eta|$ coverage than the CFT system. Associating electrons or muons with SMT track candidates is essential to reduce fake rates and thus allow full exploitation of these systems. The TDR-L4 option allows only three stereo hits per track, which is the bare minimum. Standalone tracking is also important as a tool for silicon detector internal alignment and may need to be relied upon as a fall-back solution for tracking over the full η coverage should the CFT performance degrade unexpectedly at high luminosity because of high occupancies, radiation damage or other unpredictable effects.

We compared the SMT reconstruction efficiency and corresponding fake rate for tracks with at least 4 SMT hits for the TDR SMT and SMT without layer 4 (TDR-L4). The reconstruction efficiency is about 70 % in the central |η| region. The fake track rate is high (3-5%). Most of the fake tracks have only 4 SMT hits, so in order to reduce the fake track rate one should require 5 or more hits per reconstructed track. This reduces the fake rate to approximately 0.5% in both cases. The fake rate obtained by requiring 5/6 hits in the TDR design is therefore dramatically less than that obtained by requiring 4/5 hits in the TDR-L4 option. The 5-hit track reconstruction efficiency in the TDR-L4 design drops by about 10% in the central |η| region and by 22% in the forward |η| region compared to the TDR SMT design. This drop in track reconstruction efficiency leads to an unavoidable drop in b-tagging efficiency, which is shown in Figure 4 as function of jet |η| for the TDR and TDR-L4 options. The b-tagging efficiency per jet in the central region drops by about 20% and and in the forward |η| region (|η|>1.2) by over 40%. For WH signal events, we find that the double b-tagging efficiency ε_{bb} (using only silicon standalone tracking) is 13% for the TDR–L4 design compared to ε_{bb} = 20% for the TDR.

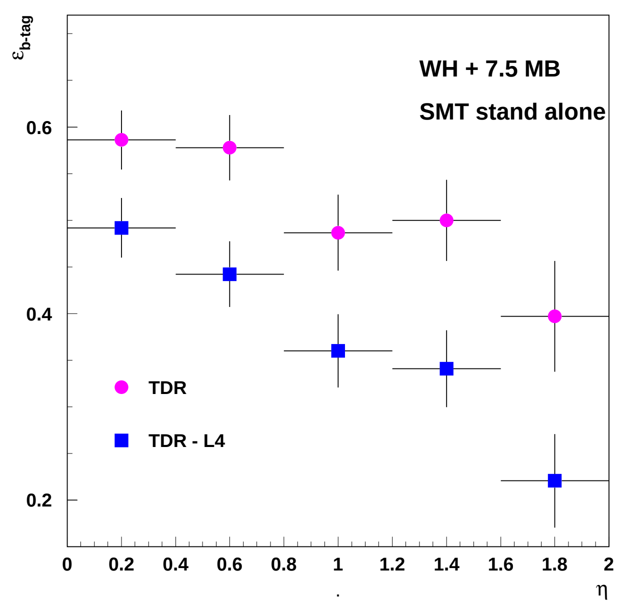

Figure 4 - B-tagging in stand-alone SMT for the TDR version of SMT and for the TDR-L4 geometry.

Global tracking

The effect of removing L4 should be less on global tracking than for SMT stand-alone tracking, since L4 is then only one intermediate stereo measurement out of a possible 12 (plus two axial measurements). It is however a loss of one of only four precision space points. We find that in the TDR design, global tracks with only 4 silicon hits tend to be of poor quality and have a much higher fake rate than tracks with 5 more more hits, as shown in Fig. 5. (note that this is consistent with CDF's Run 1 experience [7])

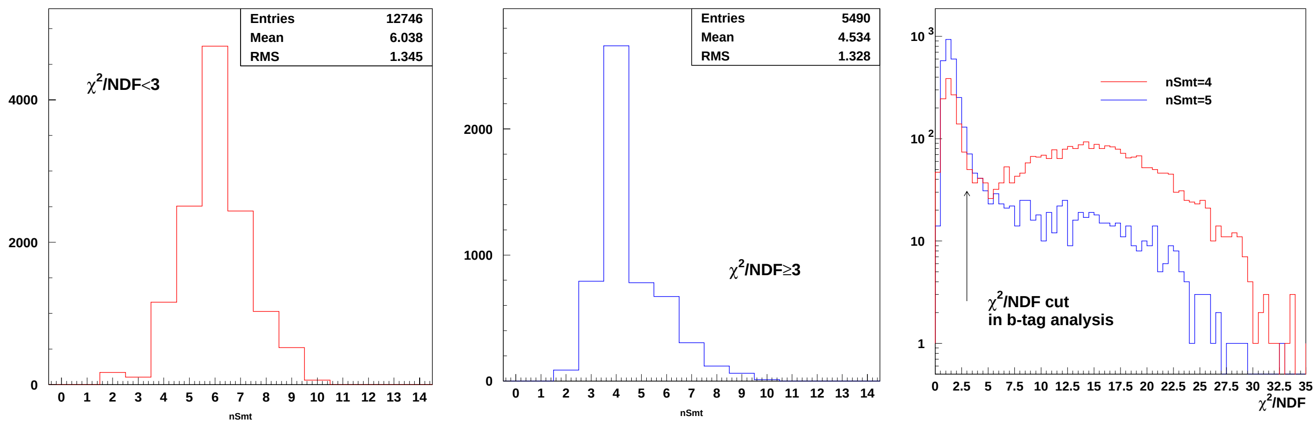

Figure 5 - Number of SMT hits per reconstructed global tracks in |η|<1 for low-χ^2 tracks (left) and high-χ^2 tracks (center); distribution of χ^2 per degree of freedom for samples with 4 and 5 SMT hits respectively (right).

While the isolated track reconstruction efficency in TDR and TDR-L4 options is very similar, the loss of this layer has an impact in the crowded environment inside a jet. In Figure 6, the tracking efficiency is shown for tracks inside jets (defined as tracks within R=0.5 of the jet axis) as function of jet pseudorapidity in WH events at high luminosity. The fake track rate for both options is less than 0.1%.

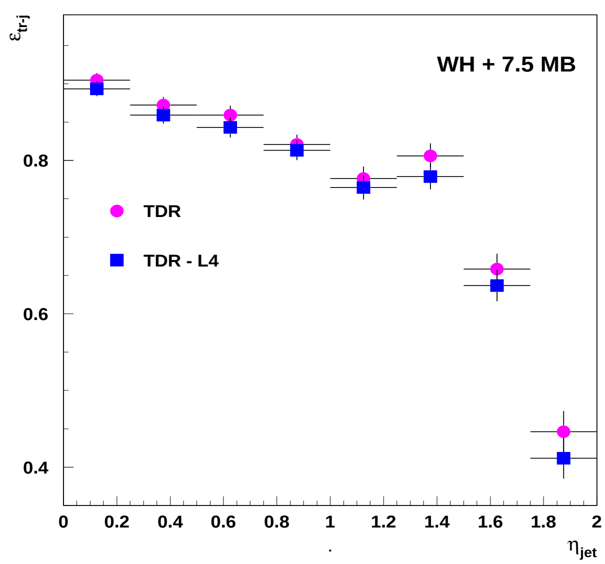

Figure 6 - Track reconstruction efficiency in jets in TDR and TDR-L4 designs.

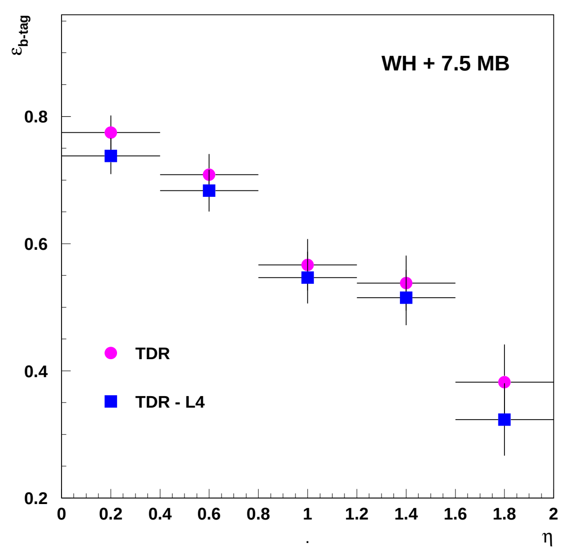

Figure 7 - Comparison of b-tagging efficiency in TDR and TDR-L4 designs.

This difference in tracking in jets results directly in a degradation of the b-tagging efficiencies $\varepsilon_{b\text{-}tag}$ for these two options. The TDR and TDR-L4 designs are compared in Figure 7. The mistagging rates are indistinguishable and are 1-2%. The overall b-tagging efficiencies per jet are (65 ± 1)% and (62 ± 1)% in the TDR and TDR-L4 geometries, respectively. The probability to select a WH event with at least two tagged b-jets is ε_{bb}=29% in the TDR design and ε_{bb}=26% in the TDR-L4 design. Thus, removal of layer 4 leads to a 10% degradation in the double b-tagging performance. In addition, we find a roughly 2% loss in efficiency for the charged lepton from W decay, giving 12% overall.

TDR-L1 option

A full GEANT simulation has been performed for the evaluation of TDR-L1 design assuming that L0 is functioning perfectly. Comparison of TDR to TDR-L1 track reconstruction efficiencies in jets is shown in Figure 8.

The tracking efficiency in jets is not affected in the central |η| region, but at large |η|, TDR-L1 shows a significant loss of efficiency. The b-tagging efficiency suffers a corresponding loss in the forward region, but more importantly we find the mistagging rate roughly doubles in the TDR-L1 geometry. To make a comparison in terms of is ε_{bb}, we therefore required a stricter track quality in the TDR-L1 geometry to equalize the mistagging rate. (We did this two ways: using a tighter track χ^2 cut, or requiring a greater number of hits on each track. The plots show the latter). The b-tagging efficiency after applying this cut is compared to the TDR b-tagging efficiency in Figure 9. We find that the TDR-L1 option has a 24% lower double b-tagging efficiency ε_{bb} than the TDR design, for the same mistag rate.

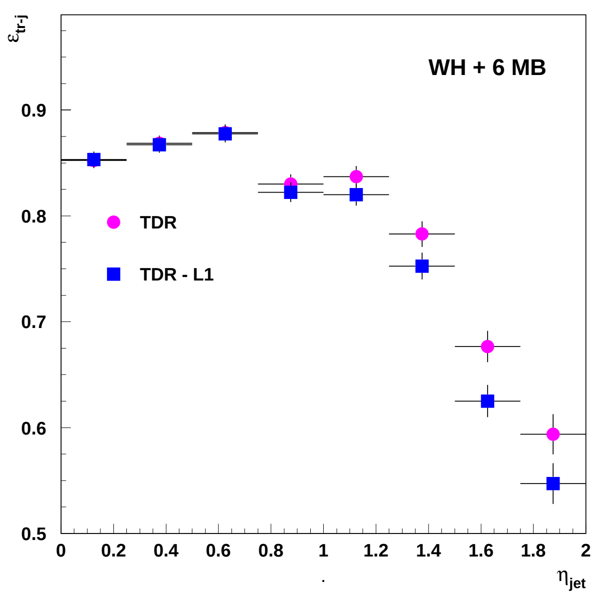

Figure 8 - Reconstruction efficiencies of tracks in jets in TDR and TDR-L1 designs.

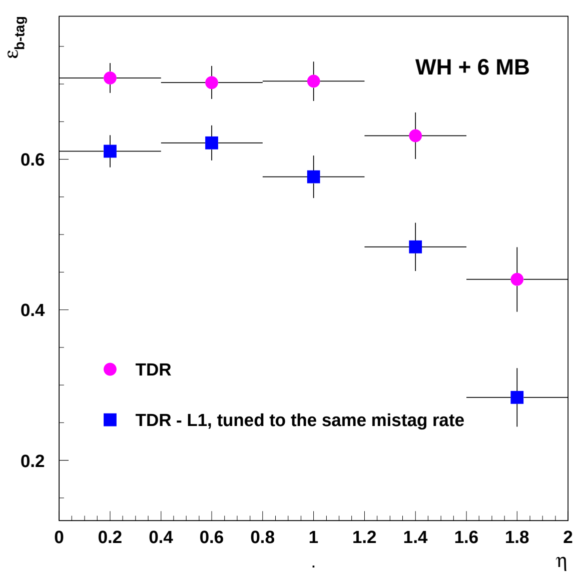

Figure 9 - B-tagging efficiency in TDR and TDR-L1 geometries at the same mis-tagging rate tuned by cut on number of hits.

Removing layer 1 from the SMT is also an undesirable option for several other reasons. Layer 0 is the closest detector to the beamline, and its operation might therefore require considerable effort to understand effects like beam-induced noise and readout problems. In the worst case, L0 may suffer a premature death to inadvertent radiation overexposure. Removal of L1 would make the detector significantly less robust to possible loss of L0 because it would degrade the impact parameter resolution that could be obtained without it.

Removing detectors at large z (TDR-Z option)

The Technical Review committee suggested considering a 6-layer SMT detector with silicon modules at large |z| removed from each layer. Such a reduction in the layers' lengths leads to a reduction of the |η|-acceptance of the detector. Table 2 shows the impact of such an acceptance reduction on Higgs physics using 2000 WH events (with $H\rightarrow b\bar{b}$ and $W\rightarrow l\nu$) . We considered only events where both b-quarks had energies above 20 GeV and the charged lepton had transverse momentum $p_T > 15$ GeV/c. As the table shows, a reduction of the |η|-acceptance from 2.0 to 1.5 leads to a 23% decrease in the number of events where both b-quarks fall within the acceptance. As if this were not bad enough, we would also lose the ability to reconstruct either electrons or muons in the interval $1.5<|\eta|<2.0$. Over this range, we have good calorimetry and muon coverage, but the silicon provides essentially the only tracking. The third column in the table shows the combined effect of requiring that both the lepton and the two b-jets fall within the acceptance. Overall, there is a 27% loss in Higgs events if the |η|-coverage is reduced from 2.0 to 1.5.

Table 2 - Number of b-quarks and muons within various acceptance cuts for WH events.

η cut	Probability for muon to be within η cut	Probability for two b-jets to be within η cut	Probability for two b-jets and lepton to be within η cut
$\|\eta\|<2.0$	93 %	74%	67%
$\|\eta\|<1.5$	86 %	57%	49%

We conclude that any reduction in |η| coverage caused by removing detectors at large |z| would lead to a very significant increase in the luminosity needed to achieve the same Higgs mass sensitivity as the full TDR design. It is also useful to note that removing silicon modules at large |z| reduces the number of silicon sensors without any reduction in the number of readout channels, unlike the options TDR-L1 and TDR-L4.

Alternate Designs with Inefficiencies Included

We repeated the studies above, assuming 5% dead silicon ladders in the SMT and 30% dead fibers in the first layer of CFT. The tracking efficiency drops by about 5% in all three cases (TDR, TDR-L1, TDR-L4), as shown in Fig. 10. The overall b-tagging efficiency is reduced in all options, and the reduction is more serious especially for the TDR-L1 option.

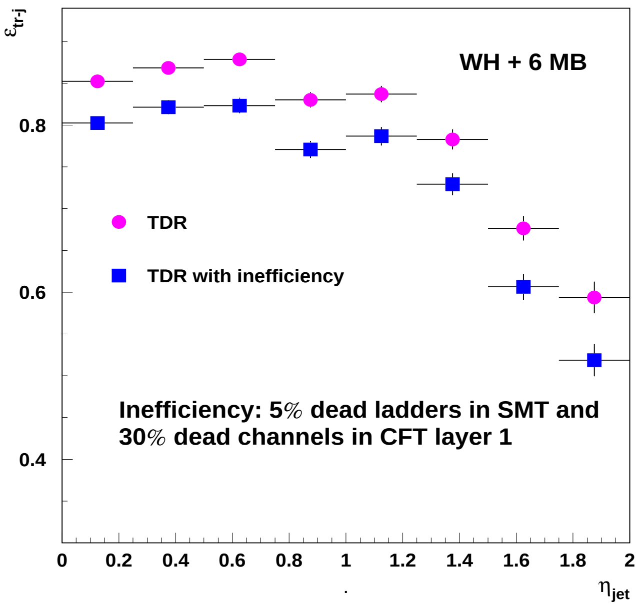

Figure 10 - Comparison of track reconstruction efficiencies in ideal TDR and TDR with inefficiencies.

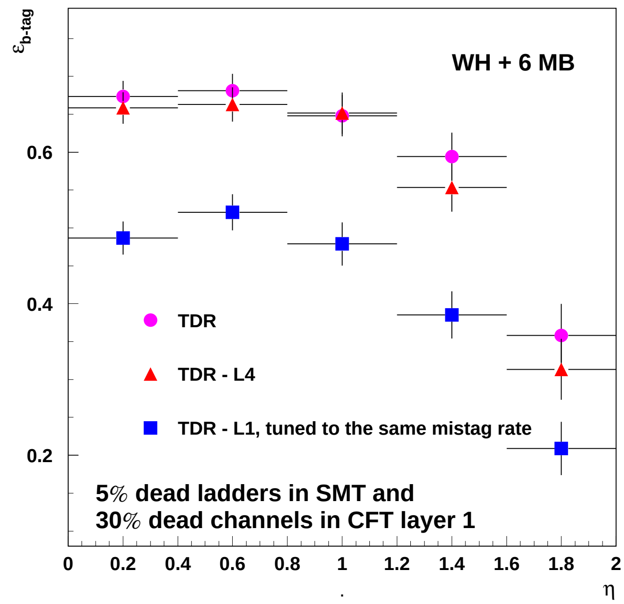

Figure 11 – b-tagging efficiency for all three geometries with inefficiencies included.

Additional Ganging

The collaboration was asked to investigate the effect of ganging in |z| for all adjacent detectors in layers 2 through 5. We have simulated a detector with two readout segments in each z half (north and south). In layers 2 and 3, there would be a 20cm ganged sensor, followed by a hybrid, followed by a 30cm ganged sensor; in layers 4 and 5, there would be two 30cm ganged sensors with a hybrid between. Apart from the rather serious handling complications and mechanical problems with such 60cm long structures, ganging of the detectors will lead to higher occupancy, an increase in the number of shared clusters and z-resolution degradation, as well as reduced signal-to-noise ratio.

Figure 12 shows the effect on occupancy for this ganging. The plot shows the mean occupancy vs. barrel number for all layers for WH events. The occupancy in layer 2 in this case is drastically increased almost to the level of layer 0. We have also investigated the effect on shared clusters. In such long detectors, there is a significant probability that two tracks separated in *z* will produce clusters that overlap in the r-ϕ view. We find that the proposed "ganging" option would result in a 60% increase in the number of shared clusters over the TDR design. Clearly, this increases the difficulty of pattern recognition and worsens the track measurements. Finally, ganging of three 10 cm sensors in one module will require a decrease of stereo angle compared with the current design due to mechanical constraints. This obviously will lead to a corresponding worsening of z resolution.

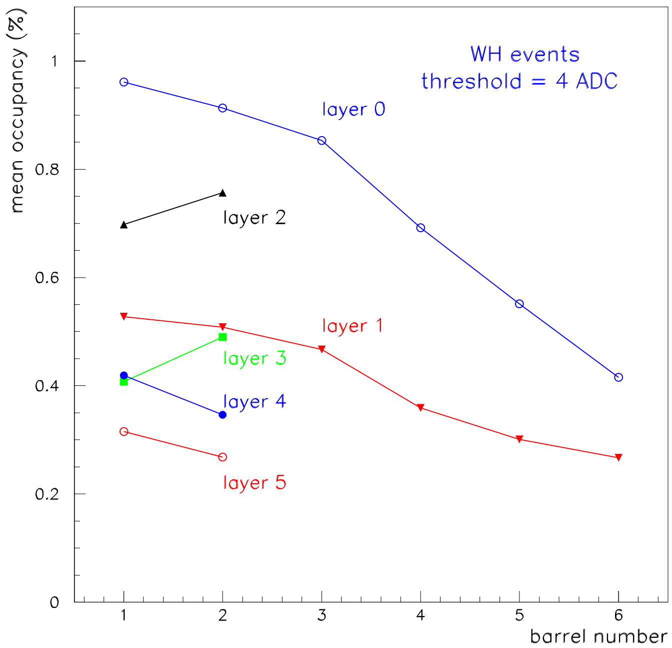

Figure 12 – occupancy by z segment number, if layers 2-5 are ganged in z to form longer readout segments. Note the high resulting occupancy in layer 2.

Conclusions

- The silicon detector as proposed is adequate to address the Higgs physics goals of run 2B.
- It is robust against a few % inefficiency from loss of strips/ladders.
- A detailed comparison of the TDR design to three alternative geometries TDR−L4 (removal of layer 4), TDR−L1 (removal of layer 1) and TDR−Z (removal of sensors at large |z|) has been performed. Results are summarized in terms of luminosity loss in Table 3. Compared with $15 fb^{-1}$, a 20% loss in luminosity would require roughly a year's extra running time to recoup, or would translate into a 5 GeV reduction in Higgs mass reach (for WH production with m_H in the range 115−135 GeV).

Table 3 – effect of descoping options expressed in terms of luminosity loss.

Alternative Design		Effective luminosity loss relative to TDR design	Comment
TDR–L1		– 24% (no inefficiencies) – 44% (with inefficiencies)	Tuned to same mistagging rate as TDR No backup for loss of L0
TDR–L4	Global tracking	– 12% (no inefficiencies) – 12% (with inefficiencies)	With similar mis-tagging rate to TDR
	SMT stand-alone	– 38%	Serious degradation of silicon stand-alone tracking.
TDR–Z		– 27%	Large loss of electron and muon acceptance as well as b-jets

References

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