



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

Prepared for the Fermilab Physics Advisory Council Meeting  
April 2002

*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, and of three possible alternative designs with reduced scope. 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  $120 \text{ GeV}/c^2$  and forced to decay to  $\bar{b}b$ . 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 7.5, which corresponds to a luminosity of  $5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ . 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) [2] 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 [3], 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  $\epsilon_{bb}$  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  $\mu\text{m}$ . 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 occurring 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  $10\mu\text{m}$  for high  $p_T$  tracks.

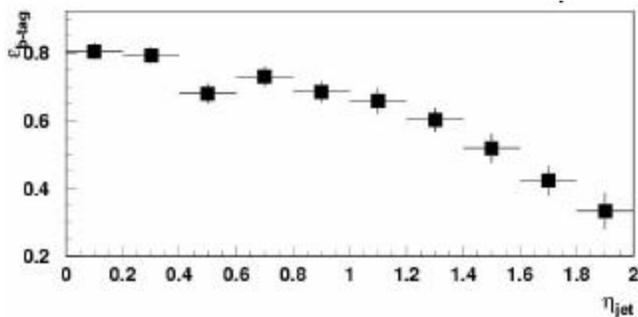


Figure 1 - b-tagging efficiency as a function of the pseudorapidity of the tagged jet.

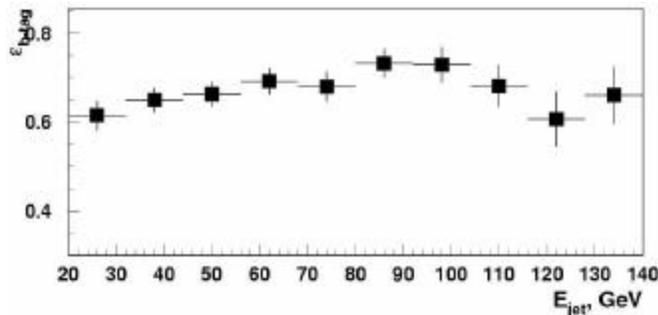


Figure 2 – b-tagging efficiency as a function of the energy of the tagged jet.

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.**

	<i>Run 2A</i>	<i>Run 2B</i>
$P(n_b \geq 1)$	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 [4] 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  $\chi^2/\text{NDF}$  of the fitted track must be less than 3. Only tracks with  $p_T > 0.5\text{GeV}$  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.

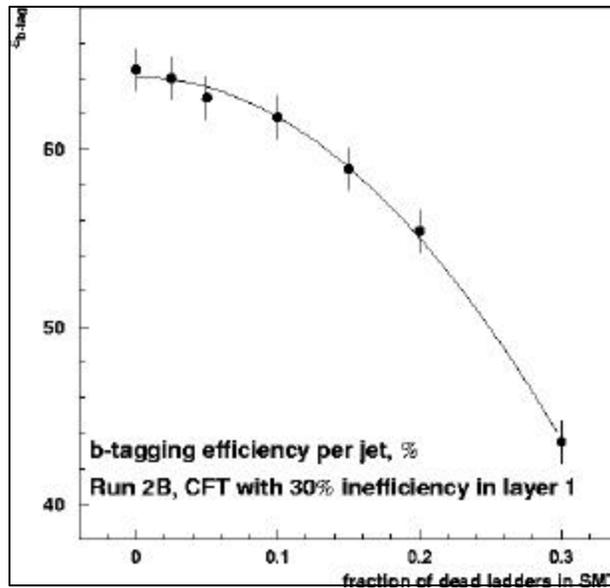


Figure 3 - Degradation of the b-tagging as function of the fraction of dead detectors in SMT.

### ***Additional Ganging***

The collaboration was asked to investigate the effect of ganging in  $|z|$  for all adjacent detectors in layers 2 through 5. The result would be a detector with only two readout segments in  $z$  (north and south) each 60 cm long. Apart from the rather serious handling complications and mechanical problems, ganging of the detectors in long structures will lead to high occupancy, increase in the number of shared clusters and  $z$ -resolution degradation.

Figure 4 shows the effect on occupancy. The plot shows the mean occupancy vs. barrel number for all layers for WH events. Detectors in layers 2 through 5 are ganged together. The occupancy in layer 2 in this case is drastically increased and is 50% higher than in 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  $r$ - $\phi$  view. We find that the proposed 60 cm average readout length of the "ganging" option would result in a doubling 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 six 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 by a large factor (two to three).

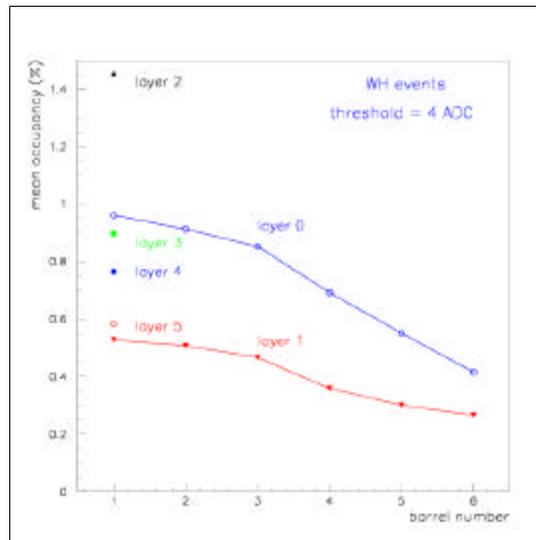


Figure 4 – occupancy by z segment number, if layers 2-5 are ganged in z to form 60cm long readout segments. Note the very high resulting occupancy in layer 2.

## 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.

### 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  $D\phi$  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  $\eta$  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  $|\eta|$  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  $|\eta|$  region and by 22% in the forward  $|\eta|$  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 5 as function of jet  $|\eta|$  for the TDR and TDR-L4 options. The b-tagging efficiency per jet in the central region drops by about 20% and in the forward  $|\eta|$  region ( $|\eta|>1.2$ ) by over 40%. For WH signal events, we find that the double b-tagging efficiency  $\epsilon_{bb}$  (using only silicon standalone tracking) is 13% for the TDR-L4 design compared to  $\epsilon_{bb} = 20\%$  for the TDR.

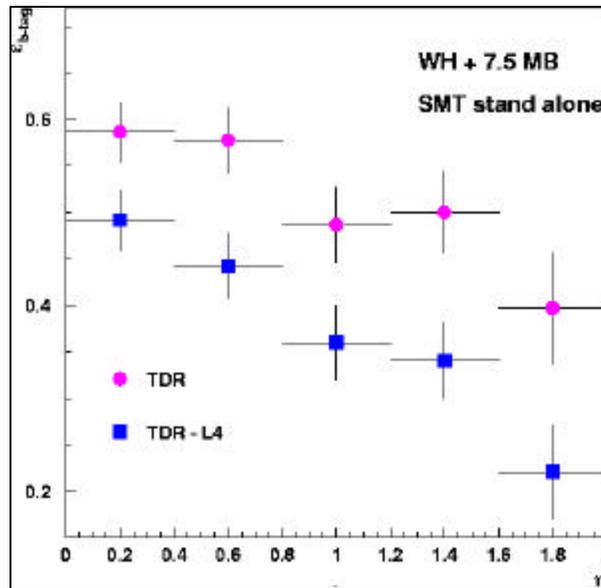


Figure 5 - B-tagging in stand-alone SMT for the TDR version of SMT and for the TDR-L4 geometry.

## 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). Nonetheless, 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 hits, as shown in Fig. 6.

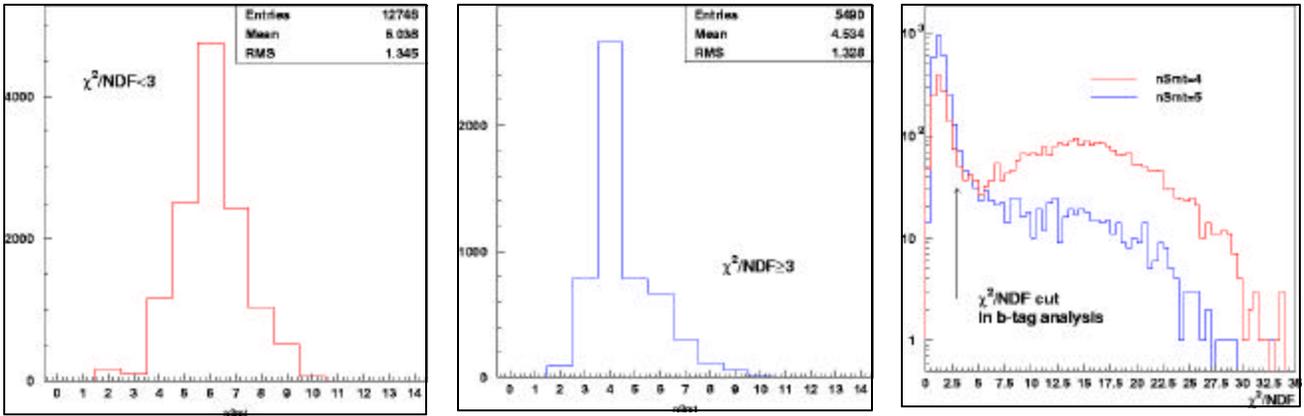


Figure 6 - Number of SMT hits per reconstructed global tracks in  $|\eta| < 1$  for “good” tracks (left) and “bad” tracks (center); distribution of  $\chi^2$  per degree of freedom for these two samples (right).

While the isolated track reconstruction efficiency 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 7, 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%.

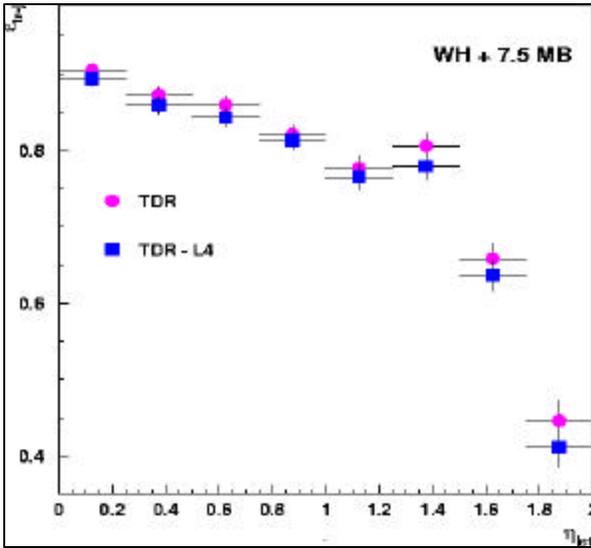


Figure 7 - Track reconstruction efficiency in jets in TDR and TDR-L4 designs.

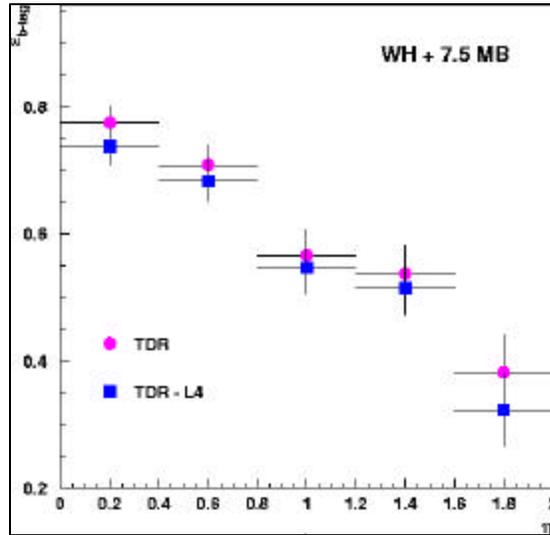


Figure 8 - Comparison of b-tagging efficiency in TDR and TDR-L4 designs.

This difference in tracking in jets results directly in a degradation of the b-tagging efficiencies  $\epsilon_{b\text{-tag}}$  for these two options. The TDR and TDR-L4 designs are compared in Figure 8. The mistagging rates are indistinguishable and are 1-2%. The overall b-tagging efficiencies per jet are  $(65 \pm 1)\%$  and  $(62 \pm 1)\%$  in the TDR and TDR-L4 geometries, respectively. The probability to select a WH event with at least two tagged b-jets is  $\epsilon_{bb}=29\%$

in the TDR design and  $\epsilon_{bb}=26\%$  in the TDR-L4 design. Thus, removal of layer 4 leads to a 10% degradation in the double b-tagging performance.

### 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 9.

The tracking efficiency in jets is not affected in the central  $|\eta|$  region, but at large  $|\eta|$ , 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  $\epsilon_{bb}$ , we therefore required a stricter track quality in the TDR-L1 geometry (a tighter  $\chi^2$  cut). The b-tagging efficiency after applying this cut is compared to the TDR b-tagging efficiency in Figure 10.

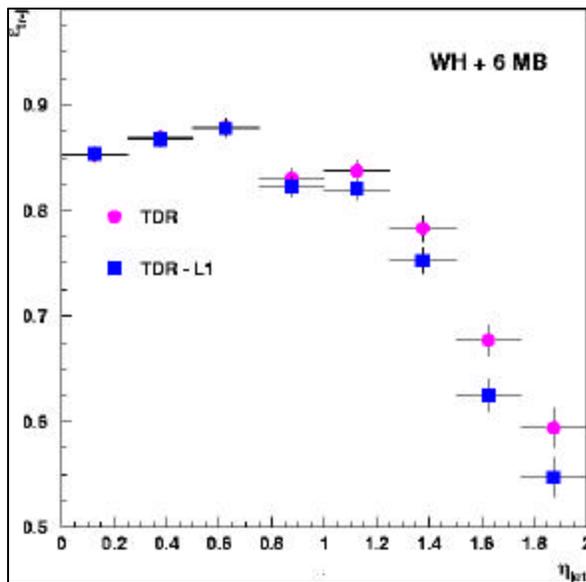


Figure 9 - Reconstruction efficiencies of tracks in jets in TDR and TDR-L1 designs.

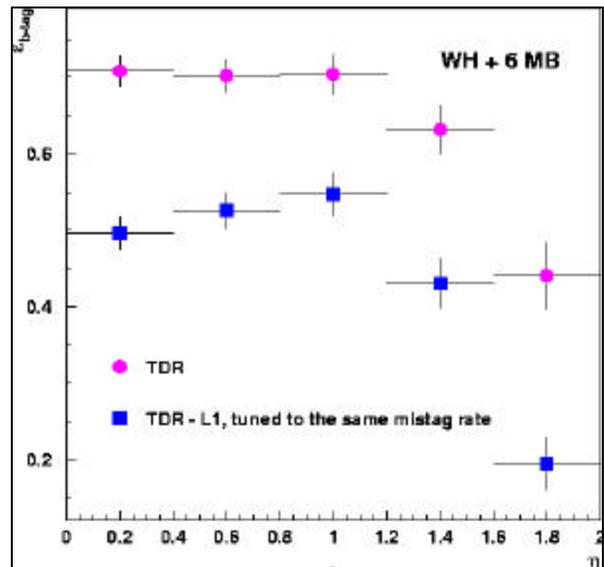


Figure 10 - B-tagging efficiency in TDR and TDR-L1 geometries at the same mis-tagging rate tuned by cut on track quality.

Removing layer 1 from the SMT is also an undesirable option for several 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  $|\eta|$ -acceptance of the detector. Table 1 shows the impact of such an acceptance reduction on Higgs physics using 2000 WH events. The table shows the total number of b-jets above 20 GeV and the probability to have at least one or both b-quarks in the acceptance after different cuts.

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

$\eta$ cut	Number of jets with $E > 20\text{GeV}$	Probability for at least one jet in $\eta$ cut	Probability for at least two jets in $\eta$ cut
No $ \eta $ -cut	3744		
$ \eta  < 2.0$	3453 (85%)	98 %	74 %
$ \eta  < 1.5$	3040 (75%)	94 %	57%

One can easily see from this table that a reduction of the  $|\eta|$ -acceptance from 2.0 to 1.5 leads to an 11.8% relative decrease in the number of b-quarks with energy  $E_b > 20\text{GeV}$ . For the double b-tagging the relative drop of the available b-quarks is 23%. As if this were not bad enough, we would 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. Thus any reduction in  $|\eta|$  coverage caused by removing detectors at large  $|z|$  would lead to a very significant increase of 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. 11. The overall b-tagging efficiency is reduced by a few percent in all options, but the relative losses in going from TDR to TDR-L1 or TDR-L4 options are not significantly affected.

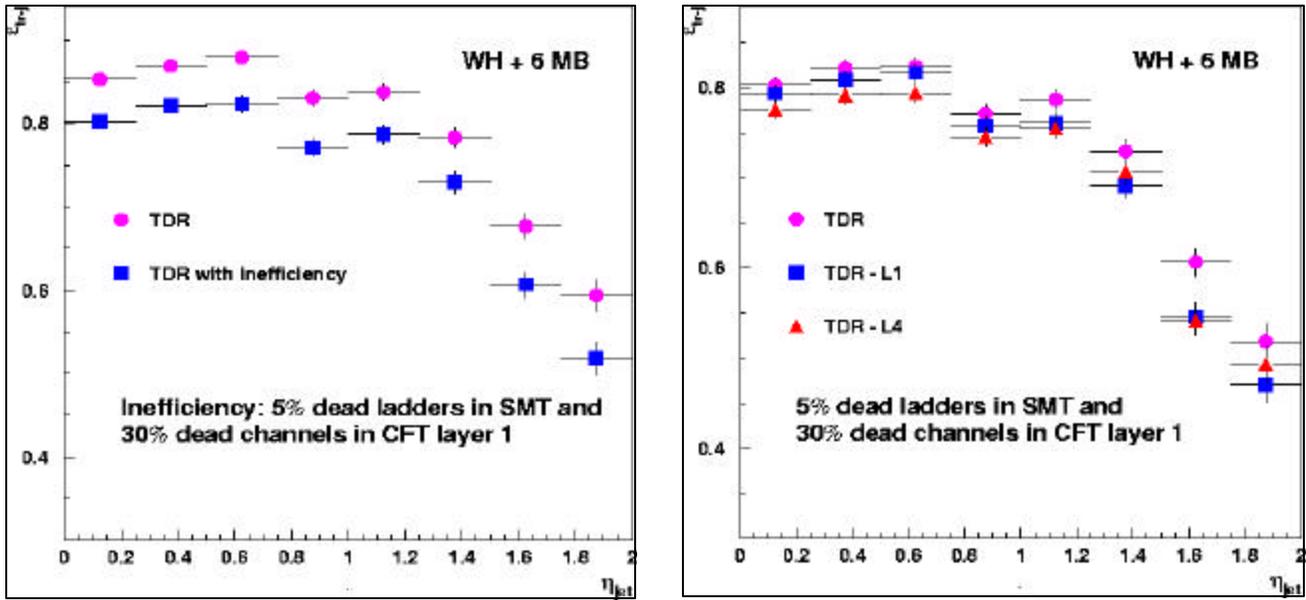


Figure 11 - Comparison of track reconstruction efficiencies in ideal TDR and TDR with inefficiencies (left); and for all three geometries with inefficiencies included (right)

## 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  $15\text{fb}^{-1}$ , 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%	Tuned to same mistagging rate	No backup for loss of L0
TDR–L4	Global tracking	– 10%	Similar mis-tagging rate	
	SMT stand-alone	– 38%	Serious degradation of silicon stand-alone tracking.	
TDR–Z		– 23%	Plus additional loss of electron and muon acceptance	

## References

This note is based on extensive simulation studies carried out by T. Bolton, R. Demina, A. Khanov, F. Rizatdinova, (Kansas State University), E. Chabalina (U. of Illinois at Chicago), and A. Nomerotski (Fermilab).

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[http://d0server1.fnal.gov/Projects/run2b/Silicon/TDR/D0\\_Run2b\\_Silicon\\_TDR\\_11Oct01\\_v3.pdf](http://d0server1.fnal.gov/Projects/run2b/Silicon/TDR/D0_Run2b_Silicon_TDR_11Oct01_v3.pdf)  
  
D0 Note 3951, Expanded Run 2B Silicon Simulation Studies for the December 2001 TDR, F. Rizatdinova, E. Chabalina, A. Khanov, T. Bolton, R. Demina, R. Lipton, L. Stutte, 3/7/02.
2. D0 Note 3845, Histogramming Track Finding Algorithm Performance Study, R. Demina, A. Khanov, 3/25/01
3. D0 Note 3855, Histogramming Track Finder: the impact parameter b-tagging performance, Regina Demina, Alexander Khanov, 4/17/01
4. Report of the Higgs Working Group of the Tevatron Run 2 SUSY/Higgs Workshop, M. Carena et al, hep/ph-0010338. See Fig. 23.