Chapter 9

Detector Requirements

9.1 Detector Systems

The physics signatures described above place rather well-defined requirements on the detector needed at an upgraded Tevatron. We feel that the requirements, though quite stringent, are all technically achievable. The recent discovery of the top quark at the Tevatron has re-emphasized the feasibility of lepton and jet identification, b-tagging, measurement of $\not{E}_T$ and reconstruction of a massive state from its decays into jets, in a hadron collider environment. These techniques will continue to be refined as more Tevatron collider data is accumulated, and this gives us confidence that the detector systems and analysis techniques required represent a reasonable extrapolation of the present state of the art.

9.1.1 Tracking and Vertex-tagging

A magnetic central tracking system is needed in order to measure and trigger on isolated high momentum charged tracks. This will form part of the electron and muon identification and will allow detection of one and three-prong hadronic tau decays.

We expect that the following generic detectors will be needed:

- Silicon vertex detector:
  - Innermost layer is a radiation-hard device;
  - 2-D readouts (some of them should be stereo layers);
  - Self-vertexing capability (with efficiency $\epsilon_{sv} > 99\%$);
  - At least 5 layers;
  - Coverage up to at least $|\eta| = 2$–2.5;
  - Be capable of identifying a displaced vertex from b-decay up to $|\eta| \leq 2$ with an efficiency of 50% and a mistag rate of $\leq 1\%$.
- Outer tracker (e.g. fibers, MSGC's, or straw tubes):

- Tracking efficiency $\epsilon_{track} > 99\%$ for single isolated tracks;
- 3-D tracking;
- Momentum resolution comparable to the current CDF CTC system;
- Tracking up to $|\eta| = 2$–2.5.

It is crucial for a number of analyses (top and light Higgs, for example) to understand whether the 50% b-tagging efficiency and $\leq 1\%$ mistag rate are achievable at the high luminosities envisaged. A detailed Monte Carlo simulation of b-tagging at the upgraded Tevatron is not yet available, but we can make some preliminary observations based on experience with (and/or simulations of) four silicon vertex detector designs:

- The CDF SVX detector as currently operating in Run 1B.
- The DØ Silicon detector under construction for Run 2.
- The ATLAS and CMS silicon detector systems for LHC.

The present performance of the CDF SVX at $\mathcal{L} = 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is a b-tagging efficiency, ϵ_b, of about 60% per jet (within the fiducial region), and a rejection, R, of about 200 against light quark jets. The DØ Silicon detector for Run 2 has been simulated to give $\epsilon_b = 0.5$ or 0.35 for $R = 50$ or 100 respectively, at $\mathcal{L} = 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The CDF and DØ silicon detectors are broadly similar, with 4 or 5 layers of silicon arranged close to the beampipe (the DØ detector covers a larger range of rapidity). The LHC detectors both propose to use many more layers of silicon, covering a larger range of radius from the beam, and to employ finely segmented pixel detectors close to the beam to enhance the tagging capabilities in the high-ocupancy environment. The ATLAS simulations claim a performance of $\epsilon_b = 0.6$ for $R = 200$ at $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and $\epsilon_b = 0.5$ for $R = 50$ at $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The CMS design is somewhat more conservative, and its expected performance is $\epsilon_b = 0.5$ or 0.4 for $R = 50$ or 150 at $\mathcal{L} = 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

As described earlier, the present performance of the CDF SVX is adequate for the Higgs search in the $b\bar{b}$ channel — the challenge is to maintain this performance at much higher luminosity. The LHC designs have chosen to add more silicon layers and to use pixel detectors in order to increase redundancy and reduce occupancy; their performance is also quite adequate for the Higgs search (though at greater cost). An evolution in a similar direction may be expected for the detector(s) at an upgraded Tevatron. We are confident that the necessary b-tagging performance can be obtained, though the design and optimization of the detector will require detailed studies beyond the scope of this report.

9.1.2 Calorimetry

Electromagnetic calorimetry is required for the identification and measurement of isolated electrons (from $W \to e$ decays) and of soft electrons as b-tagging technique. Ultra-precise energy resolution is not called for (typical EM resolutions of $\sim 15\%/\sqrt{E}$ should be sufficient). The EM calorimeter must cover the pseudorapidity range up to $|\eta| \leq 2.5$ in order to have

adequate Higgs acceptance. The EM calorimeter should provide an isolated electron trigger; in principle one could also attempt to trigger on soft electron b-tags but this has not been assumed in the trigger rate estimates.

Electron and photon identification will be degraded by the extra energy from minimum bias pileup events, which will make isolation cuts less efficient. As described earlier, the supersymmetry study group for this workshop have found that an electron efficiency of 90% may still be obtained in the presence of nine pileup events with a cut of $E_T \leq 4\,\mathrm{GeV}$ in a cone of $R = 0.4$.

The EM calorimeter must be backed with a hadronic section capable of identification and measurement of jets and measurement of missing transverse energy. Again, ultra-precise energy resolution is not called for (typical hadronic resolutions of $\sim 70\%/\sqrt{E}$ should be sufficient) but emphasis should be placed on the performance of the calorimeter for jet-jet invariant mass reconstruction. Studies for the LHC suggest that transverse segmentation of $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$ is desirable in order to reconstruct boosted $W \to jj$ decays but that segmentation finer than this is not called for. The hadron calorimeter should cover at least the range up to $|\eta| \sim 3.5$ in order to be efficient for jets up to $|\eta| = 2.5$ and in order to provide a good measurement of $\not{E}_T$. The hadronic calorimeter must be capable of triggering on jets and on $\not{E}_T$.

Pileup will also degrade the $\not{E}_T$ resolution. The supersymmetry study group have found that ten minimum bias pileup events give an average contribution to $\not{E}_T$ of about 10 GeV but do not yield any extra events with $\not{E}_T \geq 20\,\mathrm{GeV}$.

9.1.3 Muon Detection

A muon detector is required for the identification and measurement of isolated muons (from $W \to \mu$ decays) and of soft muons as a b-tagging technique. The muon system must cover the pseudorapidity range up to $|\eta| \leq 2.5$ in order to have adequate Higgs acceptance. The detector should provide an isolated muon trigger at moderate momenta ($p_T \geq 15 - 20$ GeV/c); one could also attempt to trigger on soft muon b-tags but this has not been assumed in the trigger rate estimates. The most precise measurement of muon momentum will most likely come from the central tracker, so the muon system should concentrate on tagging and triggering fuctions.

It will be noted that these requirements specify a rather general-purpose detector well suited to electroweak and top studies and also capable of some interesting b-physics if sufficient bandwidth is available.

In addition to the physics requirements, the detector systems must operate and be triggerable in the high-rate, high-radiation environment of the upgraded Tevatron collider.

9.2 Lepton Isolation at High Luminosity

Many of the physics topics of interest at the upgraded Tevatron will rely on isolated, high-p_T leptons as a tag for signal events. Examples are W and Z production, top, and mutilepton

signatures for supersymmetry.

Isolation is defined as the sum of all transverse energy, excluding the energy of the lepton, in a cone of radius $\Delta R = 0.4$ surrounding the lepton:

$$\text{ISO} \quad = \quad \sum_{\Delta R < 0.4} E_T - E_T(\ell)$$

Here $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The leptons from W/Z, top and supersymmetry events are expected to be quite well separated from hadronic activity in the event. In contrast, leptons from heavy flavors (b/c quarks) are expected to be non-isolated. Thus, a requirement of small isolation is a powerful tool to reduce backgrounds due to Standard Model jet processes.

The effectiveness of a cut on lepton isolation depends on the level of isotropic energy flow (the underlying event). In Tevatron Run 1A, $\sim \mathcal{O}(1)$ interactions were produced during each bunch crossing. At the large luminosities expected at an upgraded Tevatron (TeV33), as many as $\sim$10 interactions can occur coincident with the physics event of interest. Although these additional interactions are almost always minimum bias events, they create an elevated level of isotropic energy deposition in the calorimeters.

In order to simulate multiple interactions, calorimeter energy is summed in random cones of radius $\Delta R = 0.4$. A random direction in $\eta - \phi$ space is then generated, with the cone centered in the pseudo-rapidity region $|\eta| < 1.0$ (this is approximately the η range of the CDF central calorimeter). We also generate Poisson-distributed random numbers $\mathrm{N_{cones}}$, with mean μ_{P}. Using one random cone per minimum bias event, the $\mathrm{E_T}$ in $\mathrm{N_{cones}}$ + 1 random cones was then added, simulating the effect of adding a Poisson averaged μ_{P} additional interactions to the primary physics event of interest.

For this study, a sample of minimum bias (MB) events ($< \mathcal{L} > = 3.6 \times 10^{30}$ cm^{-2}sec^{-1}) from the CDF Run 1A data was used. Minimum bias events at CDF are collected via a special trigger line, which periodically accepts any event that merely exhibits a beam-beam counter coincidence - no additional trigger requirements are imposed.

Table 9.1 lists the preliminary results of this study. The high efficiency obtained for 0 additional MB (cone) events (*i.e.*, $\sim$Tevatron Run 1A conditions) is in agreement with previous studies. When 9 additional MB (cone) events are present, the efficiency drops by 9% for ISO $<$ 4 GeV, or 46% for ISO $<$ 2 GeV.

The results shown in the table are conservative estimates since the average number of interactions in one MB trigger is greater than one. Table 9.2 shows the distribution of number of interactions after removing 0-interaction events from a Poisson distribution. Therefore, one MB trigger in the sample will contain 1.34 interactions on average. In order to simulate 9 additional MB events, we should add 6.7 random cones from MB trigger data. The inefficiencies for ISO $<$ 2, 3 and 4 GeV are 68%, 86%, and 94% respectively for 6.7 random cones.

For the CDF supersymmetry to trileptons analysis in Run 1A, a cut of ISO $<$ 2 GeV was used, yielding

$$\epsilon_\ell(\text{Run 1A}) \quad = \quad 96\%,$$

(obtained from the Z sample). This should be compared to ϵ_ℓ(ISO$<$2 GeV) for $\mu_{\mathrm{P}} = 1$ in Table 9.1: 97%. The 2-GeV cut is optimized to provide the best signal/background ratio

Table 9.1: Efficiencies of isolation cuts for a single lepton. A minimum bias data sample (Tape CCE788) was used.

# additional cones (μ_P)	ϵ_ℓ [%]		
	ISO<2.0 GeV	ISO<3.0 GeV	ISO<4.0 GeV
0	99.2 ± 1.0	99.9 ± 1.0	100. ± 1.0
1	97.3 ± 1.3	99.4 ± 1.4	99.8 ± 1.4
3	90.6 ± 1.8	97.2 ± 1.9	98.9 ± 1.9
6	72.3 ± 2.2	88.8 ± 2.4	95.5 ± 2.5
9	54.3 ± 2.2	78.6 ± 2.7	90.6 ± 2.9

Table 9.2: Fraction of number of interactions after removing N(int) = 0 at $\mathcal{L} = 3.6 \times 10^{30}$ cm^{-2}sec^{-1}).

	N(int)			
	1	2	3	4
Fraction	72%	23%	4%	1%

for single interaction luminosities. Naively, we expect the same rejection power of the b-decay lepton with a 3-GeV cut. Detailed MC study is under way. Therefore, for TeV33, we expect a single electron efficiency of 86% with no loss of background rejection. The resultant trilepton efficiency of 64% will be acceptable.

9.3 Missing E_T at High Luminosity

A study of the effect of pile-up of minimum bias events on the $\not\!\!E_T$ was done using a simulation of the DØ detector. This study was only concerned with the effects of pile-up on the calorimeter measurement; it was assumed that the hard scatter vertex was found correctly by the tracking. The effect of the vertex position resolution is likely to be the dominant effect in the $\not\!\!E_T$ resolution, but due to the lack of any model for an upgraded tracker (realistic or not), it is not possible to study this effect at this time. One should also note that in the present study no serious attempt to model upgrade calorimeter electronics or accelerator parameters was made. Instead a model of the current DØ experiment and accelerator was implemented. The simulation program used for this study also takes into account the effects of ten minimum bias events in the previous and post buckets.

As a benchmark for a physics process with a $\not\!\!E_T$ signal, a sample of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to eee + X$ (supersymmetry) events was used as the hard scattering event. The events were generated using ISAJET [14] with the following parameter cards:

Figure 9.1: Missing E_T distribution for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to eee + X$ events with a full D$\emptyset$ detector simulation: (a) no pile-up and (b) 10 MB events.

MSSM1 $M_{\tilde{g}} = 265$, $M_{\tilde{q}} = 1000$, $M_{\tilde{l}_R} = 200$, $M_{\tilde{l}_L} = 200$, $M_{\tilde{\nu}} = 1000$;

MSSM2 $M_{\tilde{t}_L} = 1000$, $M_{\tilde{t}_R} = 1000$, $A_t = -100$, $M_{\tilde{b}_R} = 1000$, $A_b = 1000$;

MSSM3 $\tan\beta = 2.0$, $\mu = -500$, $M_A = 500$.

Ten random minimum bias, Monte Carlo generated, events were added to each chargino-neutralino event in addition to the measured calorimeter uranium and electronic noise on a cell by cell basis. These combined events were then reconstructed with a standard version of the D$\emptyset$ reconstruction program. The correct vertex was always found.

The calculated $\not{E}_T$ before and after the addition of pile-up for a sample of 100 events is shown in Fig. 9.1. As can be seen, the addition of the ten minimum bias events makes little difference to the calorimetric measurement of $\not{E}_T$. Less than 0.5 GeV change in the average $\not{E}_T$ and slightly more than 1 GeV increase in the spread of the $\not{E}_T$ is observed. We also find

$$\epsilon_{\not{E}_T}\,(\text{pile-up}) \;=\; \epsilon_{\not{E}_T}\,(\text{no pile-up}) \quad (\not{E}_T > 20\ \text{GeV}).$$

Figure 9.1 represents the effect of adding the $\not{E}_T$ from a random set of minimum bias events vectorially to the $\not{E}_T$ of a signal event. As a cross-check, if the signal event is subtracted, then one finds that the average $\not{E}_T$ from the minimum bias is about 10 GeV with a spread of about 6 GeV. These numbers closely matched results derived from a study of adding ten minimum bias events together using a toy calorimeter model.

In conclusion, it appears that from the standpoint of the calorimetric measurement of $\not{E}_T$, pile-up should not be a problem in degrading the $\not{E}_T$ measurement. One should also note that the signal sample used in this study has a relatively flat $\not{E}_T$ distribution. The effect of adding ten minimum bias events to a background sample with a steeply falling $\not{E}_T$ spectrum is likely to be different. The effect on signal efficiency for a given $\not{E}_T$ cut will probably be less than the effect on the rejection power of the $\not{E}_T$ cut on some backgrounds.

9.4 Trigger and Data Acquisition

In order to obtain some semi-realistic estimates of trigger rates at an upgraded Tevatron detector, we have assumed a three-level trigger system. The first level is assumed to be analogue hardware (e.g. a calorimeter tower above threshold); the second level programmable digital hardware (e.g. isolation or track-matching using a DSP chip); and the third level a software trigger running on general purpose cpu's with access to full event information.

The following primitives should be available to the trigger:

- **Isolated Electrons** based on the EM calorimeter up to $|\eta| \leq 2.5$. In principle one could also attempt to trigger on soft electron b-tags but this has not been assumed in the rate estimates.

- **Isolated Muons** using the muon system up to $|\eta| \leq 2.5$. Again, soft muon b-tags could also be added to the trigger but this has not been assumed in the rate estimates.
- **Charged Tracks**. An isolated high momentum charged track trigger will be needed to trigger on one and three-prong hadronic tau decays.
- **Jets** based on EM+hadronic calorimeter up to $|\eta| \leq 2.5$. At trigger level 2 or 3 a jet-jet invariant mass requirement could be used but this has not been assumed in the rate estimates.
- **Missing** E_T based on the sum of towers in the EM+hadronic calorimeters. At trigger levels 2 or 3 this estimate can be refined by inclusion of muons, use of fitted vertex z-position, etc.
- **Displaced Vertex**. A silicon vertex tracking trigger capable of a displaced vertex b-tag up to $|\eta| \leq 2$ at trigger level 2 or 3 may be useful but has not been assumed in the rate estimates.

9.4.1 Available Bandwidth

A survey of current and proposed experiments gives the following trigger bandwidths at each level. The last line of the table shows the rates that we have assumed as limits on what is feasible; they are consistent with being audacious but technically achievable on the timescale of an upgraded Tevatron.

Experiment	*L1* $\rightarrow$ *L2* (kHz)	*L2* $\rightarrow$ *L3* (KHz)	*L3* $\rightarrow$ *host* (Hz)
DØ (Run 1b)	0.25	0.25	4
DØ (Run 2)	10	1	10
DØ (Run 3 EOI)	50	5	200
CDF (Run 1b)	?	?	100?
CDF (Run 2)	?	?	?
CDF (Run 3 EOI)	?	1	?
SDC	10–100	0.1–1	100
GEM	10–100	0.3–3	100
ATLAS	few $\times 10$	few $\times 10$?	few$\times 100$
CMS	few $\times 10$	few $\times 10$?	< 100
Assumed	50 kHz	10–20 kHz	100–200 Hz

9.4.2 A Toy Trigger Menu

Rates have been estimated for an illustrative mix of triggers:

- *top*: single and dilepton top triggers based on the current DØ menu.
- $W/Z \rightarrow e, \mu$: unprescaled single lepton plus $\not{E}_T$ trigger for W's and uprescaled dilepton trigger for Z's.

- $\not{E}_T$ +jets: for supersymmetry and $ZH \to \nu\nu b\bar{b}$. The $\not{E}_T$ threshold would be about 40 GeV for a pure $\not{E}_T$ trigger, and could be lowered to about 25 GeV if two jets were also required.

- $(W/Z)H \to qq\tau\tau$: charged track tau trigger for Higgs.

The rate estimates use measured (Run 1b) DØ calorimeter trigger cross sections, estimates for DØ charged track and muon trigger cross sections for Run 2, and measured rejection factors at level 2 and 3. The rates include allowance for the overlap between the electron and muon triggers for top, W/Z and $\tau \to \ell\nu\bar{\nu}$.

Mode	$L1 \to L2$	$L2 \to L3$	$L3 \to host$
Top	7.2 kHz	4.0 kHz	50 Hz
$W/Z \to \ell$	8.0 kHz	3.4 kHz	28 Hz
met + jets	1.3 kHz	1.3 kHz	30 Hz
$(W/Z)H \to q\bar{q}\tau^+\tau^-$	15 kHz	5.8 kHz	37 Hz
Total	23.5 kHz	11.1 kHz	145 Hz
(Limit)	50 kHz	5–10 kHz	100–200 Hz

The immediate conclusion is that the situation does not look too bad. The rates at all levels are consistent with the limits assumed. Some more rejection at level 2 may be desirable, but there are a number of tools available that have not been assumed to be used so far — triggering for top on soft lepton tags or displaced vertex b-tags at level 2 or 3, for example.

Two points must be emphasized. Firstly this is, of course, only a very first look at trigger rates. Many factors such as multiple interactions at higher luminosity may dramatically increase the rates over what is quoted here. Secondly the bandwidths listed, while achievable, represent a large increase over the capabilities of the present DØ and CDF data acquisition systems and will be expensive and technically challenging to implement.

9.5 Offline Processing

If the rate of events out of Level 3 is 200 Hz, this cannot be spooled to tape (unless the event size is tiny or a large number of drives is used). It is more reasonable to imagine a 'near-line' processing farm where the reconstruction is performed in quasi-real-time. The present DØ and CDF reconstruction programs requires of the order of 15–20 seconds per event on a $\sim$ 30 MIPS machine, i.e. 500 MIPS-sec. If we assume the same reconstruction time per event then a reconstruction facility of 10^5 MIPS will be required to keep pace with the events being written. This could be thought of as a farm of two hundred workstations, each with 500 MIPS of cpu(s), which is quite conceivable on the timescale required.