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# Performance Study of the eXtremely Fast Tracker in High Luminosity.

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## 1 Introduction

The eXtremely Fast Tracker (XFT) has been operating since the beginning of Run 2a. The device identifies tracks in CDF's Central Outer Tracker (COT) and these tracks are used at Level 1 and Level 2 of the online trigger. The performance of the XFT has been quite good. The $P_T$ and $\phi$ resolutions measured in the data are better than the design specifications. The one area of concern is the rate of fake or false tracks identified by the XFT. These are due in part to the higher than expected hit density in the COT - possibly a result of the amount of material associated with the new silicon vertex detector. In addition, the wire hit efficiency of the COT is lower than expected. This forces the XFT Segment Finder to require only 10 out of 12 possible wires per superlayer (rather than the intended 11 out of 12 wires), in order to ensure adequate track finding efficiency.

Although the fake rate is at an acceptable level currently, there is a concern that when we go to the higher luminosities of Run2a and especially Run 2b, that the performance of the XFT will degrade. This note documents a study of the XFT performance at high instantaneous luminosities. For the XFT, the relevant quantity as the luminosity grows is the number of interactions per crossing. Figure 1 shows the number of interactions per crossing as a function of instantaneous luminosity and bunch separation. The XFT was designed to work at a peak luminosity of $2\times10^{32}$ $cm^{-2}s^{-1}$ at 132 $ns$ bunch spacing. This corresponds to $\sim$2 interactions per crossing. Notice that operating at an instantaneous luminosity of $5\times10^{32}$ $cm^{-2}s^{-1}$ and 396 $ns$ bunch spacing leads to $\sim$ 15 interactions per crossing. We examine the scaling of the fake rate and the degradation of the $P_T$ and $\phi$ resolution as a function of the number of interactions per crossing.

We also investigate a number of ways in which the performance of the XFT may be improved. The possibilities include:

- Adding stereo information to the XFT, by identifying segments in the outermost layer of the COT[1]. This involves building new hardware.
- Raising the momentum threshold used to identify track segments within the axial superlayers. This involves changing the XFT firmware, and is relatively straightforward.
- Raising the requirement on the number of wires needed to identify a segment, with each axial superlayer. Again, this involves changing the XFT firmware, and is relatively straightforward.

We examine the impact of each of these changes and how they might help mitigate some of the increase in fakes, as well as the degradation of other performance measures, with higher luminosities.

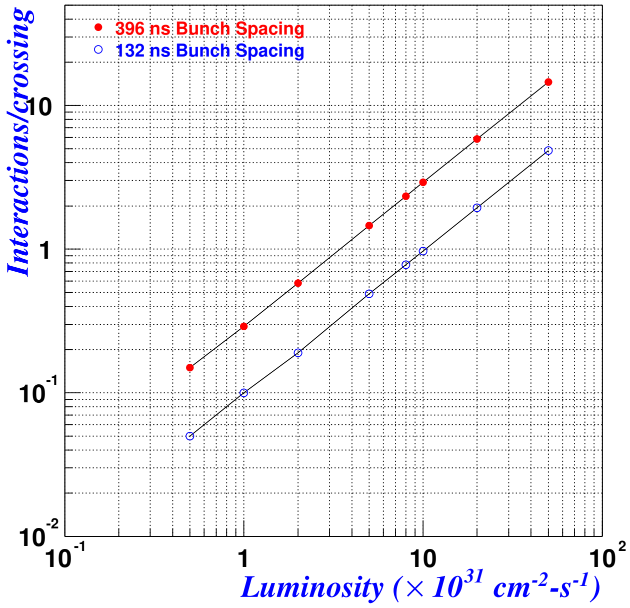


Figure 1: The mean number of interactions per crossing as a function of instantaneous luminosity. The values are shown for two choices of bunch separation, 396 ns and 132 ns.

## 2 Monte Carlo and Data Samples

One of the major difficulties with understanding the performance of any trigger system at high luminosity is obtaining a data set that can be used for the study. Currently, this is especially hard since the Tevatron has not delivered beam over a large range of luminosity. The maximum instantaneous luminosity of Run 2 to date has been $\sim 2 \times 10^{31}$ cm$^{-2}$ $s^{-1}$. The expected highest luminosity of Run 2a is $2{\times}10^{32}$ cm$^{-2}$ $s^{-1}$ (a mean of 6 interactions per crossing) and for Run 2b is $5{\times}10^{32}$ cm$^{-2}$ $s^{-1}$ (a mean of 5 interactions per crossing). These are a factor of 10 and 50, respectively, from our current peak.

In order to attempt to model the performance of the XFT at high luminosity we have relied on samples created in two ways. First, we generated Monte Carlo samples with additional "min-bias" interactions overlaid. The additional interactions are based on the "mbr package" in the CDF simulation. Second, we have used the high $P_T$ electron data sample collected (so far) in Run 2a and overlapped additional data events taken from a minimum bias trigger.

### 2.1 Monte Carlo Samples

For the Monte Carlo sets we generated events for three distinct processes:

- Inclusive W Production where the W is forced to decay to an $e\nu$ or $\mu\nu$ final state.
- $t\bar{t}$ production where one of the W's from a top quark is forced to decay to either an $e\nu$ or $\mu\nu$ final state and the other W is allowed to decay to all its kinematically available modes.
- A single particle ($\mu^+$) with $P_T > 0.5$ and with a steeply falling $P_T$ spectrum.

For each of these processes we generated 5 data sets, each with a different number of interactions per crossing. The five samples have 0, 2, 5, 10, and 15 interactions per crossing. These values represent the means of Poisson distributions so the Monte Carlo sets have a range of overlapped additional interactions as we would expect in the data. The generation and simulation of the sets was performed with CDF Offline version 4.4.0int2.

### 2.2 Data Samples

In order to not rely entirely on the Monte Carlo we examined data from Run 2a. We chose to look at the high $P_T$ electron sample. The sample was chosen to contain an electron with $P_T > 20$ GeV/c and moderately tight ID requirements. The sample contained ~1500 events. A subset of the full $W$ electron sample containing a few hundred events was also used.

In addition, we selected events from a minimum bias trigger. Based on scanning and on distributions of hits in the COT, we noticed that some of the minimum bias events contained only noisy areas in the tracking chamber. We eliminated these events by requiring a minimum of 96 hits in the COT. The minimum bias events that passed this selection criteria were then merged into the high $P_T$ electron events. The merging was performed at the raw hit level (COTD_StoreableBank) using a modified version of the EventMerge package in the CDF offline. The hit merging was performed in such a way that multiple hits on a wire could be merged into a single wide hit, as we would expect in the data. As with the Monte Carlo, we created data sets with 0, 2, 5, 10, and 15 additional interactions per crossing. Once again these values represent the means of a Poisson distribution.

## 3 Data versus Monte Carlo

To check that our Monte Carlo simulation of the XFT is reasonable, we compare a sample of 300 Monte Carlo W events with a sample of 300 W $\rightarrow e\nu$ events obtained in the data. The data events are from the (so far) low luminosity of Run 2a, such that the expected mean number of additional overlaid interactions is approximately zero.

The two Monte Carlo samples have an average number of additional "min-bias" interactions of 0 and 2 respectively. We will call these WMC_mbr0 and WMC_mbr2. A plot comparing the $P_T$ spectra of the data and Monte Carlo samples is shown in Figure 2. At high $P_T$ (where the W electron tracks would contribute) the distributions look similar. At low $P_T$, shown for less than 10 GeV/c in Figure 3, it can be seen that the WMC_mbr0 sample models the data quite well.

For the XFT, a critical feature has to do with the occupancy in the COT, and one way of measuring this is to look at the number of segments (or pixels) found by the XFT Finder stage. This is shown as a function of axial superlayer in Figure 4. In this case, it can be seen that the two Monte Carlos bound the data, although neither models the data all that well. This is a little surprising since the WMC_mbr0 sample models the low $P_T$ behavior so well.

The basic performance measures for the XFT boil down to 3 basic areas:

- $P_T$ resolution:
  The $P_T$ resolution is defined as:
  $$P_T = \frac{P_t^{xft} - P_t^{offline}}{{P_t^{offline}}^2}$$
  This is shown in Figure 5. In each case, the resolutions are fit to a narrow and wide Gaussian. The narrow Gaussian comprises the bulk of the distributions in each case. The observed widths of this narrow Gaussian are:
  - W Data: $(1.57 \pm 0.12)\%$ per GeV/c
  - WMC_mbr0: $(1.36 \pm 0.09)\%$ per GeV/c
  - WMC_mbr2: $(1.57 \pm 0.08)\%$ per GeV/c

- $\phi_0$ resolution:
  To obtain the $\phi_0$ for the XFT tracks, they are extrapolated from their reported position (the 3rd outermost axial layer) to the beam spot using the XFT $P_T$. The $\phi_0$ resolution is then just the difference between this and the $\phi_0$ of the matched offline track. The result is shown in Figure 6.In each case, the resolutions are fit to a narrow and wide Gaussian. The narrow Gaussian comprises the bulk of the distributions in each case. The observed widths of this narrow Gaussian are:
  - W Data: $(6.8 \pm 1.2)mR$
  - WMC_mbr0: $(4.3 \pm 0.2)mR$
  - WMC_mbr2: $(4.3 \pm 0.2)mR$
- Fake Track rate:
  We will define the fake rate as the number of unmatched 4 layer XFT tracks observed in the sample, independent of reported $P_T$. For the 3 samples, the numbers are:
  - W Data: We observe 10 fake tracks in 170 events.
  - WMC_mbr0: We observe 2 fake tracks in 170 events.
  - WMC_mbr2: We observe 21 fake tracks in 170 events.

The $P_T$ resolution comparison, the fake rate, and the number of found segments versus superlayer all seem to indicate that the activity in the COT is "busier" than one would predict using the Monte Carlo. This activity appears to be at the level of approximately one additional interaction. Note that this is a very crude approximation, and the lack of agreement between data and Monte Carlo (that is - the data looks worse) should serve as a caution when interpreting results where many more additional interactions are added to events. It is possible that the true performance under such circumstances will be worse than predicted here.

# 4 Fake Rates

One of the most important measures of the performance of the XFT is the rate at which fake (or false) tracks are found. These false tracks often arise from reconstructing hits from multiple low momentum particles that cross in such a way to give the appearance of a higher momentum particle (see Figure 7). These false tracks impact the trigger in several ways:

- Combining a fake track with an electromagnetic cluster from generic jets can cause the electron trigger to be satisfied erroneously. Similarly, the fake track could match to noise or background hits in the muon chambers causing the muon trigger to be satisfied erroneously. Both of these lead to higher trigger rates and the consumption of trigger bandwidth by undesired events.
- The presence of fake tracks implies that more tracks are presented to the trigger. This has an impact on the Level 2 track based triggers. For example, the Silicon Vertex trigger (SVT) must attempt to attach silicon hits to these tracks. At best this slows down the processing of events in the SVT and at worst random hits are attached the fake track. Since there is no reason to expect these hits to project back to the interaction point, these SVT fit tracks will potentially raise the trigger rate for SVT.
- There is also the possibility for a reduction in the efficiency of finding true low momentum tracks. The design of the XFT reports tracks in 288 $\phi$ slices ($1.25°$). However, at maximum only 1 track per slice can be reported to the trigger. The highest momentum track is chosen. If that high momentum track is a fake, it would be reported instead of any *true* low momentum track that existed in the same $\phi$ slice. Although a track will still be reported for this $\phi$ slice, it may not extrapolate to the appropriate position in the other detectors.

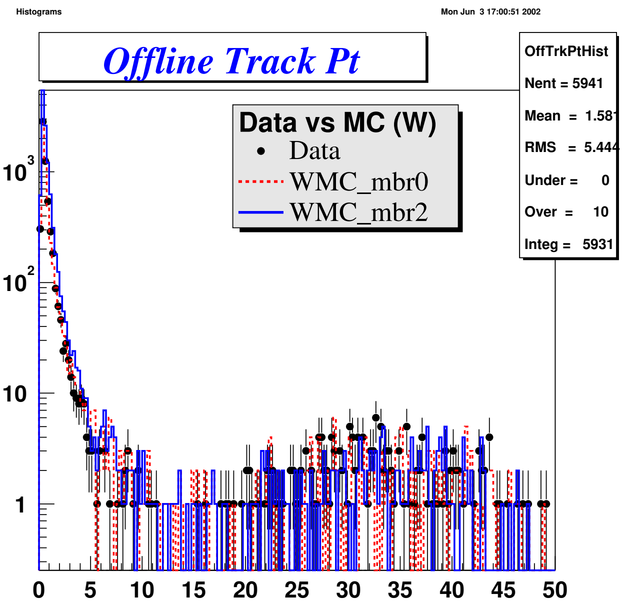


Figure 2: Comparison of the $P_T$ distribution for tracks in W events observed in the data (points with errors) to Monte Carlo W events with 0 additional interactions overlaid (dashed) and a Poisson mean of 2 additional interactions overlaid (solid).

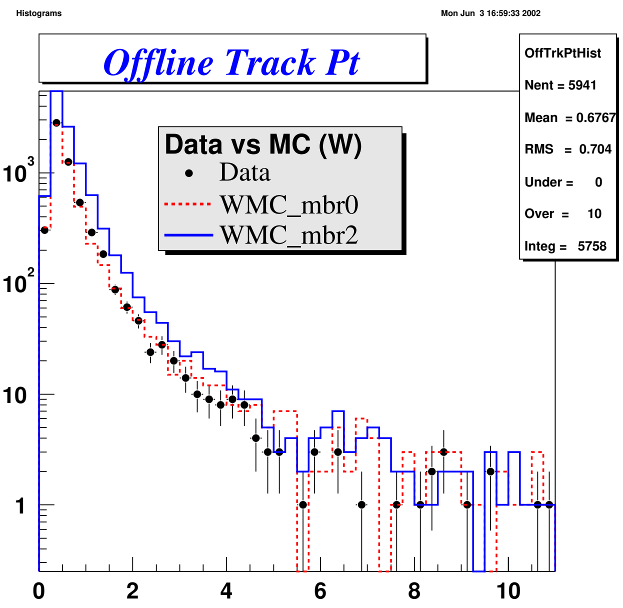


Figure 3: Comparison of the low $P_T$ (less than 10 GeV/c) distribution for tracks in W events observed in the data (points with errors) to Monte Carlo W events with 0 additional interactions overlaid (dashed) and a Poisson mean of 2 additional interactions overlaid (solid).

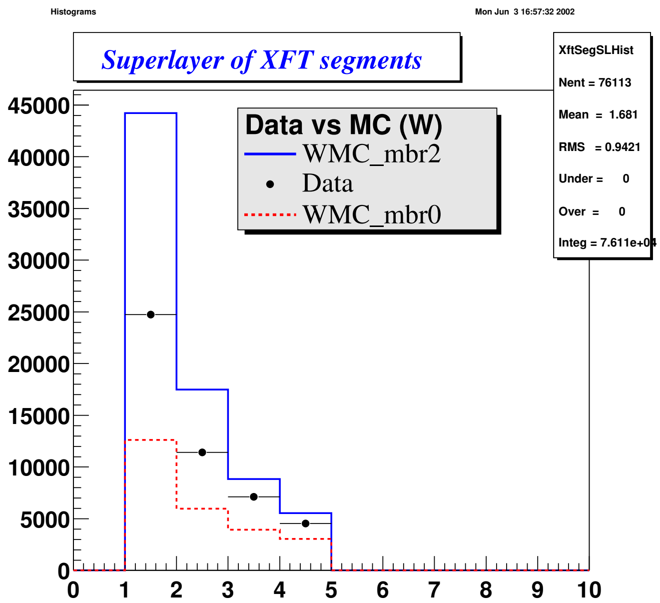


Figure 4: Comparison of the number of found XFT segments in W events observed in the data (points with errors) to Monte Carlo W events with 0 additional interactions overlaid (dashed) and a Poisson mean of 2 additional interactions overlaid (solid).

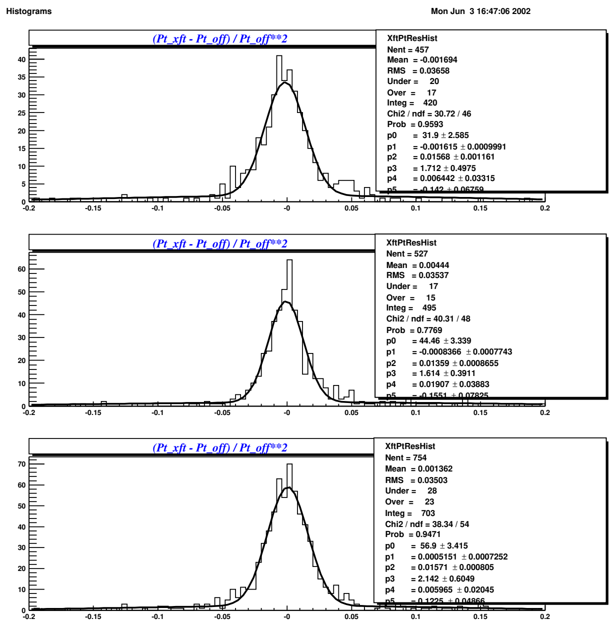


Figure 5: Comparison of the $P_T$ resolution for tracks in W events observed in the data (top) to Monte Carlo W events with 0 additional interactions overlaid (middle) and a Poisson mean of 2 additional interactions overlaid (bottom).

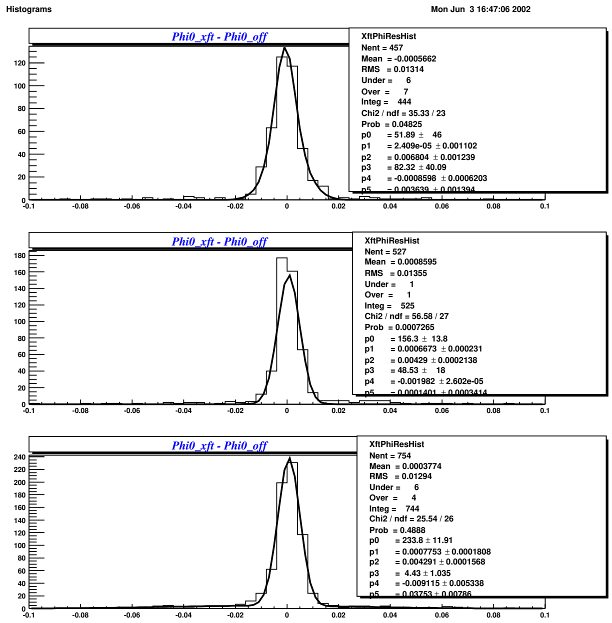


Figure 6: Comparison of the $\phi_0$ resolution for tracks in W events observed in the data (top) to Monte Carlo W events with 0 additional interactions overlaid (middle) and a Poisson mean of 2 additional interactions overlaid (bottom).

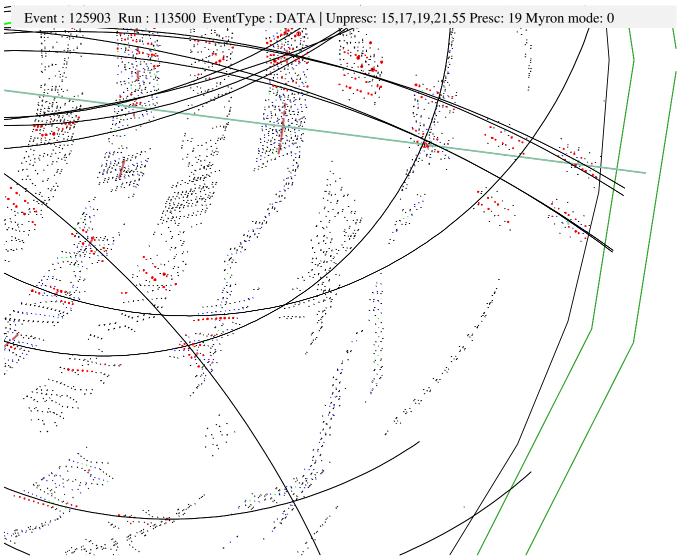


Figure 7: An event showing a fake XFT track. The light shaded track is a high $P_T$ XFT track. The dark tracks are the offline reconstructed tracks. The XFT track is using hits from different physical particles. Recall that the XFT only uses the axial layers of the COT (2,4,6, and 8).

- Finally, fake tracks tend to occur at higher momenta, therefore, they will impact the high $P_T$ lepton triggers.

We have attempted to measure how the rate of fake tracks changes with the addition of multiple interactions. We use the data sets described in Section 2. For each sample we run the XFT trigger simulation. The default Finder Segment Mask and Linker Road set is based on tracks with $P_T > 1.5$ GeV/c and we require 10 out of 12 wires in a superlayer be present for the Finder Segment to be found. This is the current default operating condition in the online system. When we analyze the collision data we use the Linker Road set that is appropriate for the beam spot shift. For the Monte Carlo, the beam spot location is at (x,y)=(0.,0.) and the XFT simulation uses a Linker Road set that is appropriate.

Fakes are identified by examining every found XFT track and comparing it to the list of true tracks in the event. In Monte Carlo this list is defined as the "OBSP" particles (Monte Carlo Generator Level) and in data the true track list is defined as the offline reconstructed tracks. The location of the XFT and true tracks are compared at each of the four axial COT superlayers. To have a layer match, the difference between the XFT and true track must be less than 10 pixels. For the XFT and true track to be fully matched, they must have 3 out of the possible 4 axial layers matched. Although this requirement is loose, we have verified that it gives reasonable results by hand scanning several hundred events. If an XFT does not match to any true track, the XFT track is labeled as a fake track.

The *Figure of Merit* we use is the **mean number of fake tracks per event**. This is determined by counting all the fake XFT tracks in our sample and dividing by the number of events. We calculate this quantity for fakes with $P_T > 8$ GeV/c and for fakes with $P_T > 20$ GeV/c. The results are summarized in Figures 8 and 9 for the minimum bias only Monte Carlo data set and for the $t\bar{t}$ Monte Carlo. The circles are the rates for the default XFT. When there are 15 interactions per crossing, the number of fake tracks per event with $P_T > 20$ GeV/c is ∼5 *in minimum bias events*. This is unacceptably high and the trigger cannot function under these conditions. In these same figures we see the reduction of the fake rate that is achieved by demanding that a segment is present in the outer stereo layer. This reduction is approximately a factor of 10 for the minimum bias only sample and a factor of 5 for the $t\bar{t}$ sample.

We also studied the impact of raising the $P_T$ threshold for the Finder Segment Masks and the Linker Roads. Figures 10 and 11 show the impact of raising this default threshold from 1.5 GeV/c to 4 GeV/c. The reduction of fakes is not as great as the reduction gained from the stereo veto. In addition, raising the threshold to 4 GeV/c would dramatically reduce the efficiency of all the low $P_T$ physics including the SVT triggers which are critical for the Higgs search.

Finally we examine the impact of running with a Finder Segment mask design which demands that 11 out of 12 wires in a superlayer have their hits present in order to create a Finder segment. Figure 12 shows the fake rate comparing the standard 10/12 to the 11/12 case. This requirement reduces the fakes by $\sim \times 10$. The same figure shows the impact of both requiring 11/12 wires for the Finder Segment and requiring the presence of a segment in the outer stereo layer. These two in conjunction provide a $\sim \times 100$ reduction of the fakes. The problem of requiring 11/12 hits for a Finder segment is efficiency. When we originally started running the XFT, the 11/12 requirement was used. However, the single hit efficiency of the COT chamber was not high enough to provide adequate track identification efficiency for the XFT. We have reexamined this issue in the recent data by processing the data offline with a 11/12 design. Figure 13 shows the efficiency of the 11/12 versus the 10/12 cases as a function of $P_T$. This plot implies the efficiency loss is not too large. We are investigating this further with higher statistics data samples.

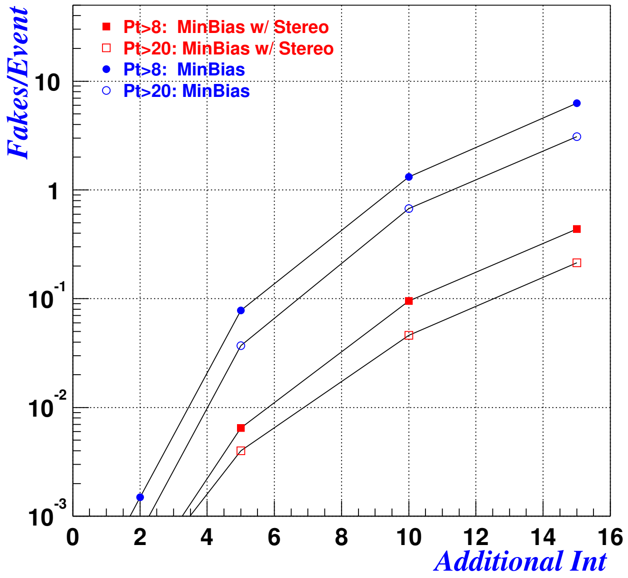


Figure 8: The average number of fake tracks per event in minimum bias events with the standard track set and one that demands the presence of a segment in the outer stereo layer as a veto against fakes.

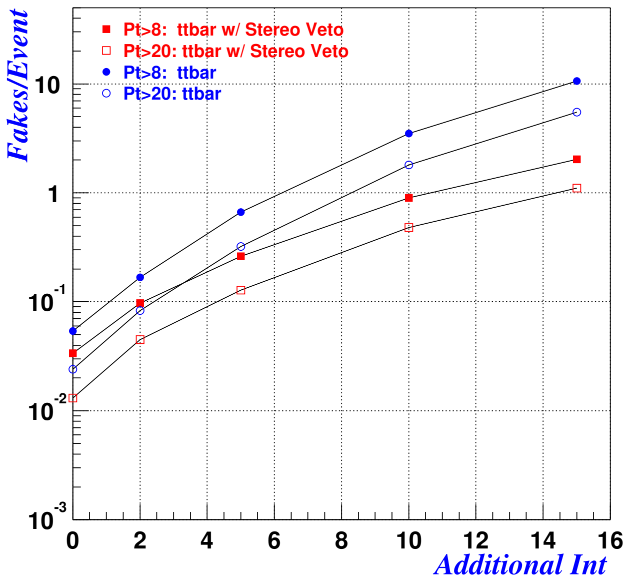


Figure 9: The average number of fake tracks per event in $t\bar{t}$ events with the standard track set and one that demands the presence of a segment in the outer stereo layer as a veto against fakes.

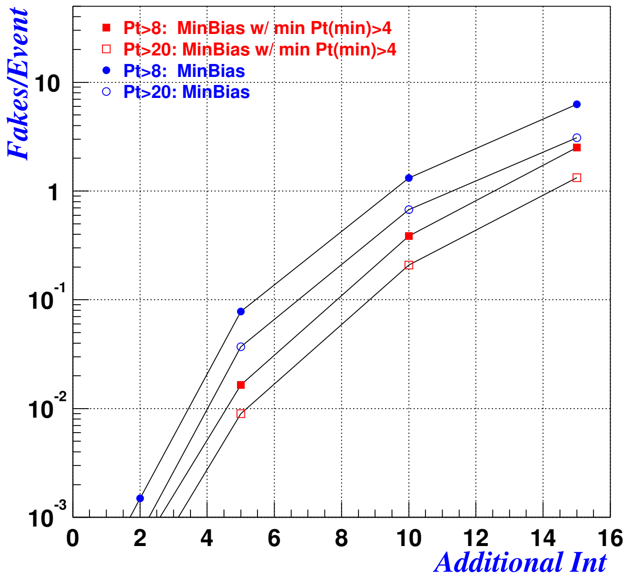


Figure 10: The average number of fake tracks per event in minimum bias events for the standard track set with a $P_T$ threshold at 1.5 GeV/c and track set with the $P_T$ threshold at 4.0 GeV/c.

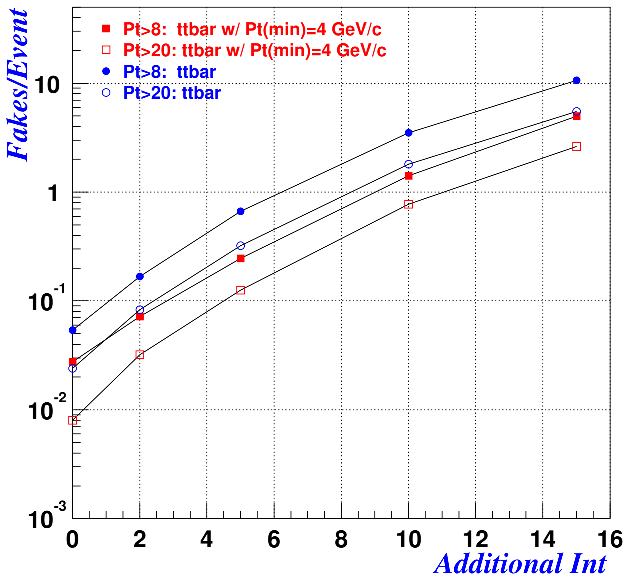


Figure 11: The average number of fake tracks per event in $t\bar{t}$ events for the standard track set with a $P_T$ threshold at 1.5 GeV/c and track set with the $P_T$ threshold at 4.0 GeV/c.

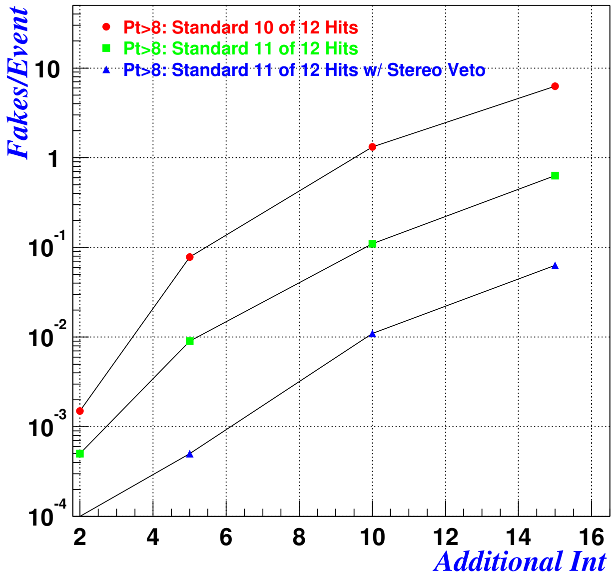


Figure 12: The average number of fake tracks per event in minimum bias events for the standard track set with a $P_T$ threshold at 1.5 GeV/c. Four cases described in the text are considered.

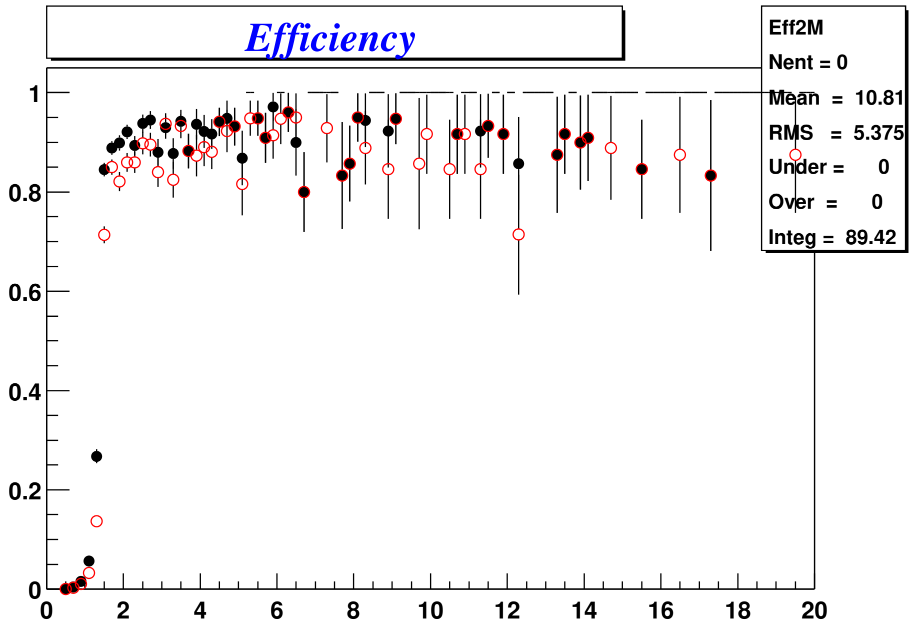


Figure 13: The XFT track finding efficiency versus $P_T$ in the data. The open circles are for the case where we demand 11 out of 12 wires for a Finder Segment and the closed circles where we demand 10 out of 12 wires (current default). There are no overlapped minimum bias events in this sample.

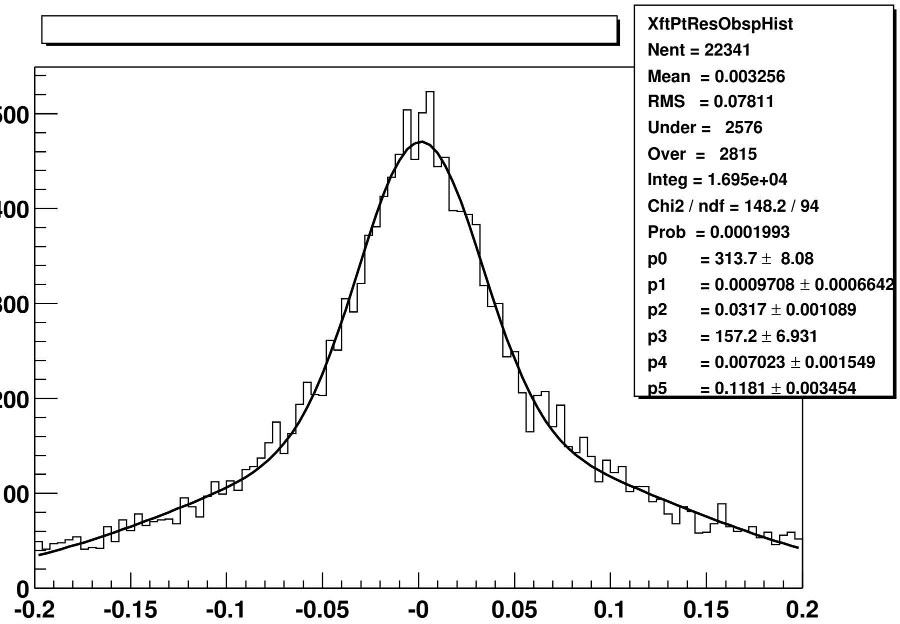


Figure 14: The $P_T$ resolution for tracks in minimum bias events (Monte Carlo) for the case where there is a mean of 15 interactions per crossing.

# 5 Resolution

Two other measures of the performance of the XFT are the $P_T$ and azimuthal $\phi$ resolution. Good $P_T$ resolution is desired to maintain sharp $P_T$ thresholds. Good $\phi$ resolution is important when the track is extrapolated back into the silicon system for the Silicon Vertex Trigger.

## 5.1 Momentum Resolution

The momentum resolution is measured for XFT tracks that match to true tracks. For each sample the resolution distribution was fit to the sum of two Gaussians. Figure 14 shows the fit for the case of only minimum bias Monte Carlo with 15 interactions per crossing. From this fit the $\sigma$ of the narrow and wide Gaussians are extracted. In addition, a weighted sum of the two $\sigma$'s is also determined. This procedure is repeated for all the samples. Figures 15, 16, 17, and 18 show how the values of the fit (and therefore the resolution) evolve with multiple interactions. All samples show a degradation of the momentum resolution as the number of interactions per crossing increases. The degradation becomes more severe above $\sim$5 interactions per crossing. It is also interesting to note that the Run 2a data curves more or less model the behavior predicted by the Monte Carlo.

Stereo information has no impact on the $P_T$ resolution and therefore is not included in any of the curves in this section. However, the requirement of 11/12 wires for a Finder Segment could have an impact. Figure 19 shows how the resolution, as measured by the weighted mean of the two Gaussians, changes when we demand 11/12 wire for a Finder Segment. It provides a modest improvement in the momentum resolution.

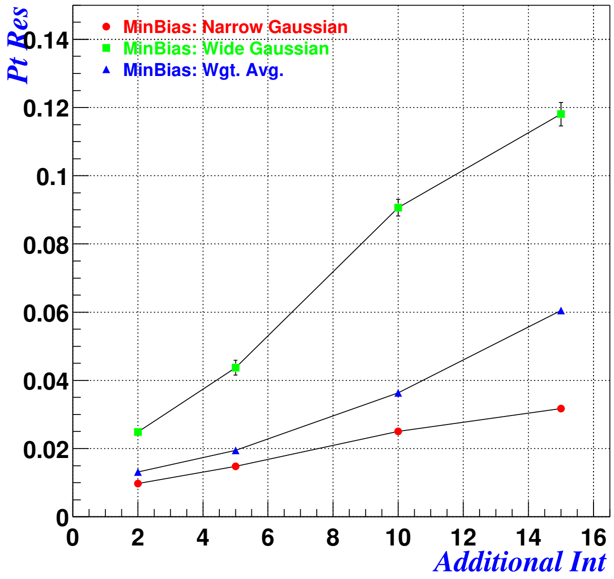


Figure 15: The $P_T$ resolution for tracks in minimum bias events (Monte Carlo) as a function of the mean number of additional interactions per crossing. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

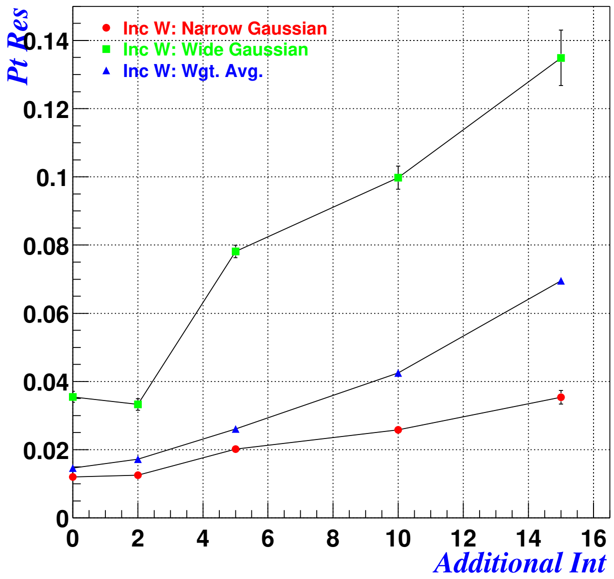


Figure 16: The $P_T$ resolution for tracks in inclusive $W \to e\nu$ events (Monte Carlo) as a function of the mean number of additional interactions per crossing. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

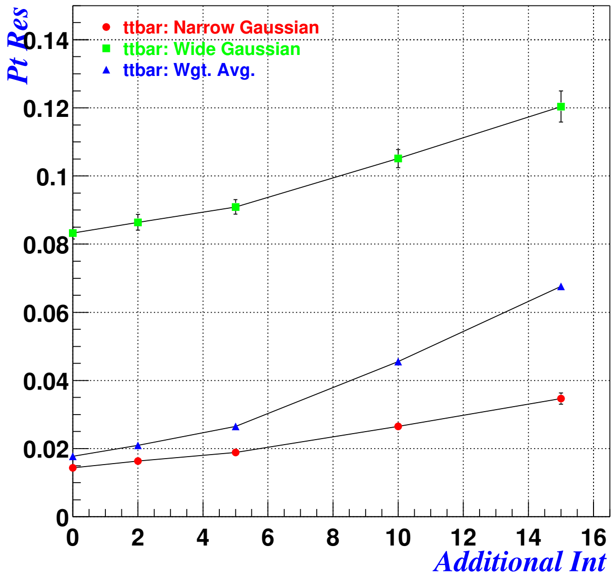


Figure 17: The $P_T$ resolution for tracks in $t\bar{t}$ events (Monte Carlo) as a function of the mean number of additional interactions per crossing. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

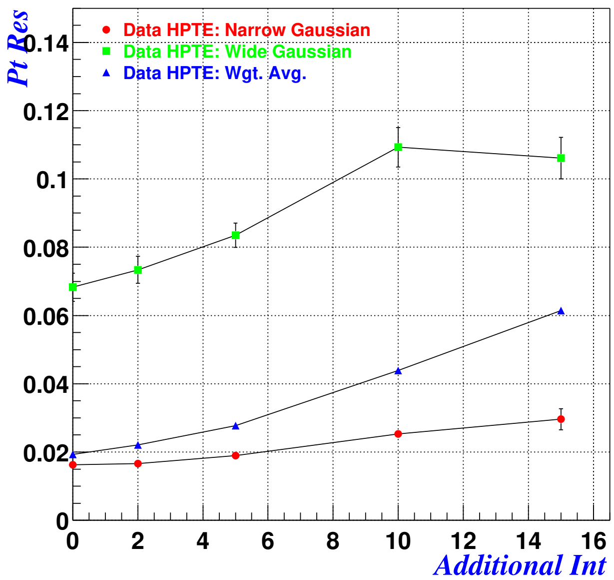


Figure 18: The $P_T$ resolution for tracks in data events with an electron with $P_T > 20$ GeV/c as a function of the mean number of additional interactions per crossing. The additional interactions are modeled by merging in minimum bias events from the data. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

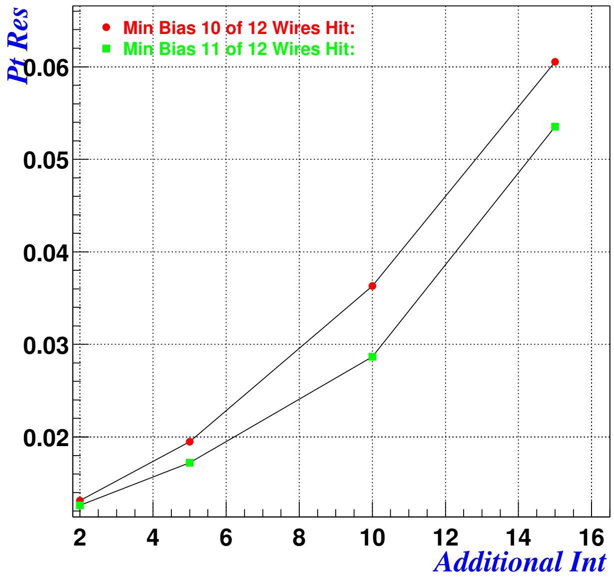


Figure 19: The $P_T$ resolution for tracks in minimum bias only Monte Carlo as a function of the mean number of additional interactions per crossing. The two curves show the cases of 10 out of 12 wires required for a Finder Segment and 11 out of 12 wires required for a Finder Segment.

### 5.2 Azimuthal $\phi$ Resolution

The $\phi$ resolution has been measured in the same fashion as the $P_T$ resolution. Figures 20, 21, 22, and 23 show the $\sigma$'s from the narrow and wide Gaussians of the fit. Also shown is the weighted mean. Interestingly, the width of the narrow and wide Gaussians does not change much with the increasing number of interactions per crossing. However, the relative population of the narrow and wide Gaussians does evolve as indicated by the weighted mean. The design specification for the silicon vertex trigger required the $\phi$ resolution of the XFT be better than 8-10 mR. From the plots this is exceeded by the time we get to 5-8 interactions per crossing. As with the $P_T$ resolution, the addition of stereo information has no impact on the $\phi$ resolution. However, the requirement of 11/12 wires for the Finder Segment could have an impact. Figure 24 shows a comparison of the $\phi$ resolution for the case of 10/12 wires versus requiring 11/12 wires. In this case there is again only a modest improvement in the resolution.

## 6 Conclusion

From the studies presented above we draw several conclusions

- Comparisons between Monte Carlo and data indicate that the Monte Carlo does not properly reproduce the activity in the COT. The number of XFT segments in the axial superlayers is larger than the Monte Carlo would predict, given the expected number of additional interactions in the current data. In addition, the $P_T$ and $\phi_0$ resolutions are slightly worse than we would expect. However, the number of tracks and the $P_T$ spectrum are reasonably well modeled by the Monte Carlo.

- The performance of the XFT above $\approx 6$ interactions per crossing degrades rapidly. The addition

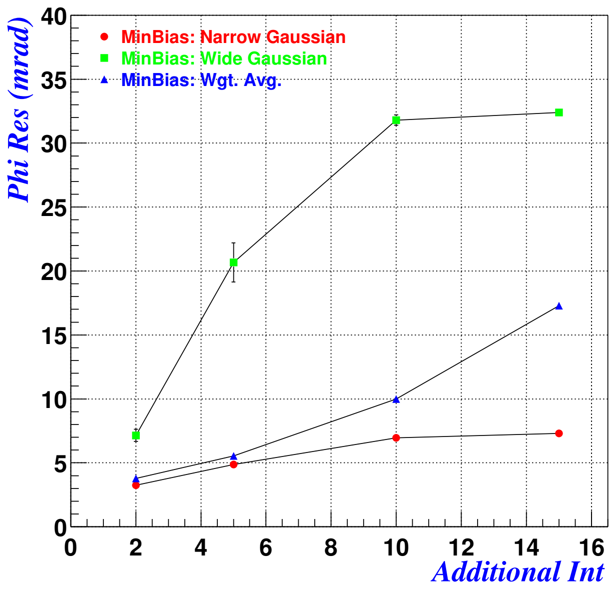


Figure 20: The $\phi$ resolution for tracks in minimum bias events (Monte Carlo) as a function of the mean number of additional interactions per crossing. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

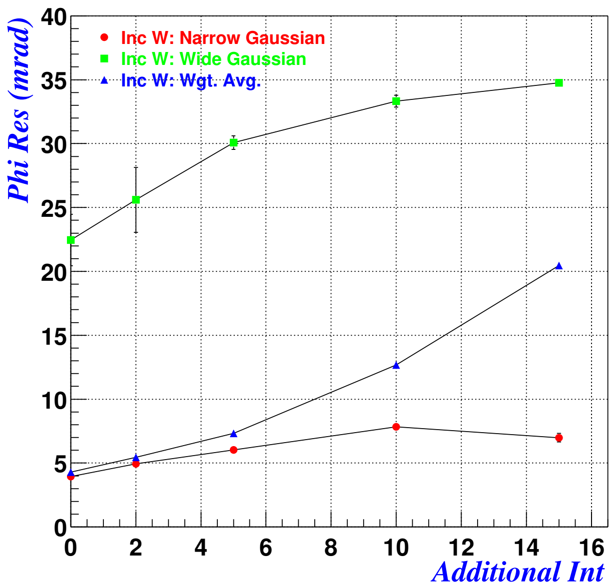


Figure 21: The $\phi$ resolution for tracks in inclusive $\mathrm{W} \to e\nu$ events (Monte Carlo) as a function of the mean number of additional interactions per crossing. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

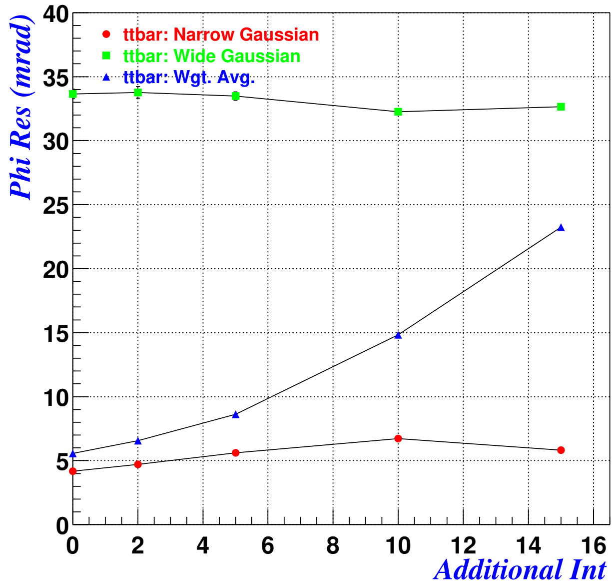


Figure 22: The $\phi$ resolution for tracks in $t\bar{t}$ events (Monte Carlo) as a function of the mean number of additional interactions per crossing. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

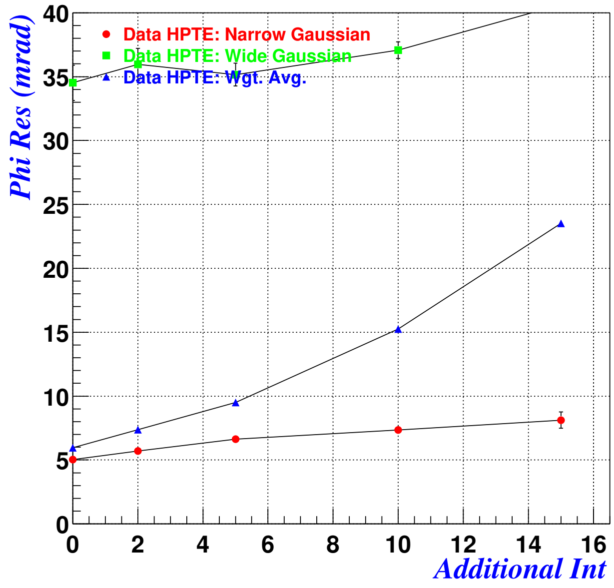


Figure 23: The $\phi$ resolution for tracks in data events with an electron with $P_T > 20$ GeV/c as a function of the mean number of additional interactions per crossing. The additional interactions are modeled by merging in minimum bias events from the data. The resolution is fit to the sum of two Gaussian distributions ("wide" and "narrow"). The middle line is the weighted average of the two distributions.

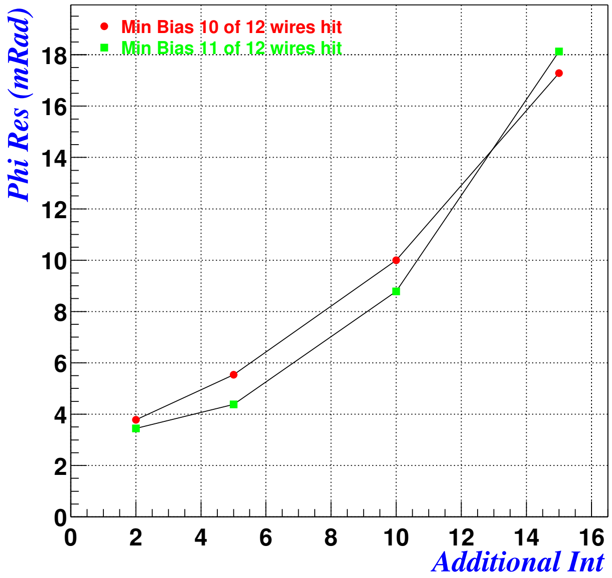


Figure 24: The $\phi$ resolution for tracks in minimum bias only Monte Carlo as a function of the mean number of additional interactions per crossing. The two curves show the cases of 10 out of 12 wires required for a Finder Segment and 11 out of 12 wires required for a Finder Segment. (Note: The cross over of the resolution at large number of interactions is not physical and must be attributed to a statitical fluctation of the measurements at N=15)

of stereo information, although helpful, is not large enough to recover the loss in performance. Also, the addition of stereo information does nothing to mitigate the degradation of the $P_T$ and $\phi$ resolutions. Operation at such large number of interaction per crossing or higher would likely require a complete redesign of the XFT system.

- At $\approx$ 5 interactions per crossing the $P_T$ and $\phi$ resolutions of the XFT are marginal. More experience with data taken at higher luminosities will help us extrapolate to this region with more confidence. The fake rate grows quickly as additional interactions per crossing are added. These fakes can be reduced in several ways. First, if we can operate the XFT Segment Finder requiring 11 out of 12 wires hit, the Monte Carlo indicates that we can reduce the fake rate almost an order of magnitude. Second, the addition of a segment in the outer stereo layer of the COT could reduce the fake rate by roughly an additional order of magnitude.

# References

[1] John Hoftiezer, et. al., CDF/4300, "XFT3D: A Proposal for Adding Stereo Segment Finding and 3D XFT tracking in the Trigger ".
Also see the Run IIb TDR:
*http://www-cdf.fnal.gov/internal/run2b.html.*