The DØ Silicon Track Trigger Beam Spot Correction

John Hobbs, Wendy Taylor

*SUNY – Stony Brook*

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Abstract

The initial track parameters derived by the DØ Silicon Track Trigger fitting code assume the Tevatron beams are coincident with the central axis of the silicon microstrip tracker. If this assumption is incorrect, either because the beam is displaced from the axis or because it is tilted with respect to the axis, the tracks resulting from the fits will have apparently large impact parameters, giving significantly degraded trigger rejection. If the beam position is known, an *a posteriori* correction can be applied to the track parameters to recover rejection. This note describes the correction and presents performance using simulated data.

The ideal Tevatron beams are coincident with the center axis (z-axis) of the silicon microvertex detector (SMT). In this situation there is no bias in the track $r\phi$ impact parameter, $b$, or angle $\phi_0$ reconstructed by the Silicon Track Trigger (STT) because the STT fitting-coordinate origin is coincident with the SMT centerline. If the beam is either offset from the $z$-axis or tilted with respect to the $z$-axis, the reconstructed tracks appear to come from a location other than the SMT centerline, and thus to have a large and $\phi$-dependent impact parameter. The Tevatron beam position is guaranteed to be within 1 mm of the nominal position, and the tilt angle will be less than 400 $\mu$rad. This angle is equivalent to an offset of roughly 150 $\mu$m at either end of the SMT. Both effects are large compared to the intrinsic STT impact parameter resolution of better than 50 $\mu$m. If not corrected, such offsets and tilts would introduce an unacceptable bias in the reconstructed STT track parameters.

If the beam position and tilt are known, and if the $z$-coordinate of a reconstructed track is known, $b$ and $\phi_0$ can be recalculated with respect to the known (true) beam position using a simple coordinate transformation. The transformation moves the origin of the track-parameter coordinate system from the SMT centerline to the beam position, and $b$ and $\phi_0$ can be recalculated without requiring the track to be refit. This transformation can completely correct for beam offsets and with sufficient precision for the $z$ position of the track at the beam, it can also completely correct for beam tilt. The practical difficulty in this prescription arises because the STT has no direct, precise information about the $z$ position of the track. Thus, although beam offsets can be corrected with effectively unlimited precision, corrections for beam tilt must be approximate. Despite this approximation, the correction will essentially restore the STT performance for the maximum tilt expected from the Tevatron.

This note briefly describes the mathematics of the coordinate transformation and the equations for correcting $b$ and $\phi_0$. It then contains a description of two possible ways to

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1The impact parameter is the shortest distance between the track and the assumed (average) production point in the $r\phi$ plane, and $\phi_0$ is the angle of the tangent to the track at this point, also measured in the plane transverse to the beam.

2A tilt can be viewed as a $z$-dependent offset.
Figure 1: A cartoon of a track trajectory (thick curved line) and the coordinates defining the nominal beam position (unprimed) and the true beam position (primed). The curvature of the track is greatly exaggerated; for any real STT tracks, the actual curvature is invisible on this scale. The initial STT fit gives $b$ and $\phi_0$. The correction described in this paper converts to $b'$ and $\phi'_0$.

approximate the $z$ position of the track at the production point and compares the effect of the two methods. As a result of the comparisons, it is concluded that a barrel–based correction is sufficient. It is assumed that readers are familiar with the DØ SMT detector[1], DØ coordinate systems[2] and the coordinates used by the STT to define trajectories[3].

1 Correction Mathematics

Figure 1 shows a hypothetical particle trajectory and the origins of two different coordinate systems, $S$ and $S'$. The $S$ system represents the coordinates used in the STT track fitting, the nominal coordinates for a beam centered in the SMT. The $S'$ system represents a coordinate system centered on the true Tevatron beam spot. If the $r\phi$ track parameters in the nominal coordinate system are denoted $(b, \phi_0)$, the parameters in the true beam system $(b', \phi'_0)$ are given by[4]

$$b' = \frac{1}{2\kappa} - \sqrt{A^2 + r_b^2 + 2Ar_b \sin(\phi_b - \phi_0)}$$

$$\phi'_0 = \phi_0 - \arctan \left( \frac{r_b \cos(\phi_b - \phi_0)}{r_b \sin(\phi_b - \phi_0) + A} \right)$$

If $r_b$ is the vector from the $S$ origin to the $S'$ origin, $r_b$ is its magnitude, $\phi_b$ its azimuthal angle and $A \equiv 1/(2\kappa)(1 - 2\kappa b)$. The curvature $\kappa$ is unchanged by the transformation.

If the beam is tilted, then the distance between the origins of the $S$ and $S'$ systems is a linear function of $z$. 

2
If the actual beam is offset from the nominal axis, but remains parallel to it, the above correction can be trivially applied using the measured beam position. If the beam is tilted with respect to the nominal axis, the distance $r_b$ (in the $xy$ plane) from the nominal beam position to the actual beam position depends on $z$ as $r_b = \frac{dr}{dz} \times z$. To apply the correction, the $z$ value of the track at the point closest to the beam must be known. Unfortunately, the STT does not determine precision $z$ information for tracks because of processing time constraints, and an approximation must be used. Two possible approximations are discussed in section 3.

### 2 Simulated data samples

All data used for analyses in this note are from simulated samples. The samples are summarized in Table 1. The data were passed through the standard DØ detector simulation chain including dØgstar and dØsim. The QCD samples are a simple concatenation of samples with hard scatter $p_T$’s satisfying $p_T > 5, 10, 20, 40, 80$ and 160 GeV. STT tracks used in this study (hereafter called good STT tracks) were required to satisfy

$$\chi^2/\text{dof} \leq \sqrt{4^2 + (20/p_T)^2}.$$  

with $p_T$ in GeV. The $p_T$ dependence arises because the fits do not include multiple scattering effects.

### 3 Determination of a track $z$ position.

In order to apply the correction of eqn. 1 for tilted beams, the $z$ position of a track must be used. Although the STT does not have precision $z$ information, SMT clusters have a hardware address which can be used to determine which SMT barrel, layer and ladder the cluster is from. The SMT ladders are roughly 12 cm long in $z$, and coupled with the barrel, layer and ladder information, this can be used to constrain the production $z$ position.

Figure 2 shows an illustration of five possible STT tracks viewed in the $rz$ plane. Each track is assigned a barrel number and a layer crossing number based on topology of the clusters used in the fit. The track barrel number is defined as the barrel number of the lowest radius (innermost layer) cluster used in the fit. The crossing number is defined as the layer of the highest radius (outermost layer) cluster in the same barrel as the innermost cluster.
cluster. Crossing numbers are positive if the final barrel has a higher number than the initial, and negative if the final barrel has a lower number than the initial. If all clusters used in a track fit are in the same barrel, the crossing number is zero. The assignments corresponding to the cartoon tracks in Fig. 2 are given in table 2.

Two approaches to constrain the production $z$ position using the topology are considered. In the first approach (barrel–only), the track barrel number alone is used to constrain the $z$ value. In the second approach (barrel+crossing), the track barrel number and track crossing number are used. As described in the following paragraphs, both approaches turn out to have similar precision, resulting in $z$–position resolutions of approximately 5 cm.

The correlations between track barrel number and production $z$ position or track barrel and crossing numbers and production $z$ position are determined in simulated events and then applied to simulated or collider data to correct for tilted beams. Figures 3 and 4 show the difference $\delta z$ between a track’s $z$ production point and the $z$ value at the center of the barrel of the smallest radius SMT cluster used in the fit. The results are shown for the barrel–only and barrel+crossing methods using simulated $p\bar{p} \rightarrow ZH \rightarrow \nu\bar{\nu}b\bar{b}$ events. Figure 3 shows the difference as a function of barrel number. Figure 4 shows the $z$ difference as a function of
The previous figures were derived for simulated $ZH$ events. Both of the methods considered for defining the track production $z$ might have a physics–dependent bias. This is particularly true if the $|\eta|$ distributions differ significantly for different physics processes or if the center of the beam is not at $z = 0$. Figure 5 shows the mean of the $\delta z$ distributions as a function of barrel number and crossing number for three simulated physics processes: (1) the $ZH$ sample used above, (2) a sample of exclusive decays $B_s \to D_s + e + X$ and (3) a QCD sample in which the $q^2$ of the partonic hard scatter is at least 5 GeV. The spread between the mean $\delta z$ values (for a given initial barrel) is less than 1 cm when plotted as a function of initial barrel number. The spread is larger, up to 2 cm when plotted as a function of layer crossing number. Both of these spreads are considerably smaller than the typical widths of the $\delta z$ distributions shown in Fig. 3 and Fig. 4.

Because the physics–dependent spreads are small compared with the intrinsic spread of the track $z$ values, the physics–dependence is ignored in the remaining analysis. In the absence of more compelling arguments, the slightly smaller spread (for a fixed $z$) indicates a preference for the barrel–based $z$ determination. The $z$–coordinate values for the barrel corrections used here are assumed to be the center of the barrels. This approximation ignores the slight change for the barrels furthest from the center. The barrel crossing corrections must deal with larger physics bias. In order to simplify the corrections in this study, the $z$–coordinate value for the barrel+crossing correction is taken as the integer value (in cm) which best matches the value in Fig. 3. The values are summarized in Table 3.

4 Performance

The performance is studied in two ways. The first is to measure beam tilt using the STT tracks and compare this with known input tilt, and the second is to correct the tracks for the known beam tilt effects and then compare the impact–parameter significance and $\phi$
Figure 3: The difference $\delta z$ in particle production $z$ and the $z$ at the center of the first SMT barrel (innermost SMT layer) in which a particle leaves a cluster used in fitting. Each plot represents a different barrel. Barrel #1 is the barrel with the most negative $z$ values; barrel #6, the most positive. The data are from the simulated $ZH$ sample.
Figure 4: The difference $\delta z$ in particle production $z$ and the $z$ at the center of the first SMT barrel (innermost SMT layer) in which a particle leaves a cluster used in fitting. Each plot represents a different barrel boundary crossing situation. The uppermost plot is for a trajectory which crosses no barrel boundaries. The second row is for the case in which a particle crosses barrel boundaries in the positive $z$ direction. The third row is for crossing in a negative $z$ direction. For the lower rows the lefthand plot is for crossings between layers 1 and 2, the center is for crossings between layers 2 and 3, and the righthand is for crossing between layers 3 and 4. A considerable shift from the center of the barrel is seen for tracks crossing between layers 3 and 4. The data are from the simulated $ZH$ sample.
Figure 5: The mean values of the $\delta z$ distributions for various physics samples. The upper plot shows the mean values plotted as a function of track barrel number. The lower plot shows the means plotted as a function of crossing number. (See text for barrel number and crossing number definitions. The true values must be integers. Two points for each allowed value have been artifically shifted a small amount in the abscissa for clarity.)
dependence before and after the corrections. Both the barrel–only and the barrel+crossing based corrections are tried. These studies are carried out using two different Monte Carlo samples. The first is the sample of $Z \rightarrow \mu\mu$ events generated with known beam tilt (See Table 1). The $B_s$ sample with no beam tilt was used as a cross-check to insure a null result in the absence of tilt.

For a beam with an offset $\vec{r}_b$ with respect to the nominal beam, the mean of the impact parameter distribution has a track $\phi_0$ dependence given by

$$< b > = \vec{r}_b \cdot \sin(\phi_0 - \phi_b), \quad 0 \leq \phi_b \leq 2\pi, \quad \text{and} \quad 0 < r_b < \infty$$

in which $r_b = |\vec{r}_b|$ and $\phi_b$ is the azimuthal angle of $\vec{r}_b$. For a tilted beam with slope $m_z \equiv dr_b/dz$, $r_b = m_z|z|$. This form can, in principle, be fitted to the $< b >$ vs. $\phi_0$ distributions as a function of (STT approximated) track $z$. However, in this form there is a discontinuity in $\phi_b$ as $z$ changes sign.5 Thus, the function used to fit the mean impact parameter vs. $\phi_0$ is actually

$$< b > = r_b \cdot \sin(\phi_0 - \phi_b), \quad 0 \leq \phi_b \leq \pi, \quad \text{and} \quad -\infty \leq r_b \leq \infty. \quad (3)$$

This form provides continuity in both $r_b$ and $\phi_b$ as the sign of $z$ changes.

The good STT tracks in an event are used to determine $< b >$ vs. $\phi_0$ as a function of barrel number. These distributions are then fit to the form in eqn. 3. These fits are shown for the $B_s$ and $Z \rightarrow \mu\mu$ (uncorrected and corrected) in the upper panels of Fig. 6 through Fig. 9. In Fig. 6 one sees that $r_b$ is consistent with zero as expected, indicating no tilt, and in Fig. 7 that the beam tilt in the $Z \rightarrow \mu\mu$ sample is clear. The upper panels of the remaining two of these four figures show the $< b >$ vs. $\phi_0$ distributions after either the barrel–only or the barrel+crossing corrections have been applied. As expected, the beam tilt correction has significantly reduced the effect of the beam tilt.

Once the parameters $r_b$ and $\phi_0$ in eqn. 3 have been determined by fits to the observed $< b >$ vs. $\phi_0$ distributions for each barrel, fits of the forms

$$r = m_z z + b_o \quad (4)$$

$$\phi_b = c \quad (5)$$

can be performed to determine the the beam tilt, $m_z$, the offset at the origin $b_o$ and the constant value of $\phi_b$. The lower left–hand panel of Figs. 6 through 9 shows the plot of the fitted $r_b$ vs. $z$. Overlaid on these are the results of the fit $r = m_z z + b$. The fit results are summarized in Table 4. One sees that the slopes (before corrections) are as expected, and that while the correction significantly reduces the slope, it is not completely eliminated.6 The fits to $r_b$ versus $z$ confirm the basic premise of the tilt correction, that the beam slope can be determined from the relatively low $z$–precision STT fits.

The final tests use the known slope and angle of the tilt sample and compare the impact parameter significance $S_b$ and the fraction of tracks $f_2$ having $|S_b| > 2$ plotted as a function of $\phi_0$. If a beam correction works properly, these should both be significantly reduced after applying a correction. The distributions of $S_b$ and $f_2$ vs. $\phi_0$ are shown in the righthand two panels of the bottom row of Figs. 6 through 9. These results are also summarized in

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5This arises if the beam is e.g. in the first quadrant for positive $z$ and thus the third quadrant for negative $z$ and if $r_b$ is forced to be positive, then $\phi_b \rightarrow \phi_b + \pi$ and $+z \rightarrow -z$.

6It is not completely clear why the slope differs from zero. However, the $r_b$ sign convention chosen here forces an opposite sign of $r_b$ for positive and negative $z$ tracks. This is likely the cause, and will be further investigated.
Table 4: The performance parameters for the untilted $B_S$ sample and for the tilted $Z \rightarrow \mu\mu$ sample without any correction, with the barrel–only correction and with the barrel+crossing correction.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Correction</th>
<th>$dr/dz$, fitted</th>
<th>Fit P($\chi^2$)</th>
<th>$S_B$, FWHM/$\sqrt{2}$</th>
<th>$f_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_S$</td>
<td>none</td>
<td>$-0.04 \pm 0.05$</td>
<td>0.12</td>
<td>1.1</td>
<td>$0.194 \pm 0.003$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>none</td>
<td>$4.38 \pm 0.07$</td>
<td>0.69</td>
<td>2.0</td>
<td>$0.133 \pm 0.003$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>barrel</td>
<td>$0.12 \pm 0.07$</td>
<td>0.61</td>
<td>1.7</td>
<td>$0.085 \pm 0.003$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>barrel+crossing</td>
<td>$0.13 \pm 0.06$</td>
<td>0.73</td>
<td>1.7</td>
<td>$0.085 \pm 0.003$</td>
</tr>
</tbody>
</table>

One sees clearly the significant improvement resulting from either the barrel–only or the barrel+crossing correction. Neither the $S_b$ distribution nor the $f_2$ vs. $\phi_0$ plot shows a significant preference for either of the two correction methods over the other. In both methods, the impact parameter significance and pass fraction have the same values after correction. Given this, the simpler barrel–only correction will be used.

In principle, the barrel+crossing correction should give superior performance. However, the $\delta z$ offset is significant compared with the RMS only for those tracks which cross barrels between the outer two layers. Only 15% of the tracks are in this category.

In addition to the results described here, the same studies were performed on samples of simulated single muon events with an ideal beam and $ZH$ events having a beam tilted with an angle of 70 $\mu$rad. The conclusions from these, less sensitive tests are consistent with those presented here.

5 Conclusions

A simple algorithm has been given for correcting STT fitted track parameters for beam offsets in the plane transverse to the nominal beam axis and for beam tilts with respect to the nominal beam axis. For beam offsets, the correction has essentially unlimited precision. The main difficulty in applying such an algorithm to tilted beams arises because the STT does not have precision $z$ position information. However, an approximation to the initial $z$ position of the track derived from the barrel of the lowest radius SMT cluster on the track gives sufficient precision to correct for the tilts expected from the Tevatron. A second, more complex, algorithm in which the track $z$ was approximated using both the initial barrel information and barrel boundary crossing information was tried. It did not give significantly better performance, so the simpler barrel–only correction will be used.

6 Acknowledgements

We thank Lars Sonnenschein for providing the tilted–beam $Z \rightarrow \mu^+\mu^-$ sample and the single muon samples used in this study, and Huishi Dong for generating the $ZH$ sample. We also thank Michiel Sanders and other members of the DØ STT group for useful discussions.
Figure 6: Results from testing the beam tilt prescription on a sample with an ideal beam. The plots are for the $B_S$ sample from table 1. The upper six panels show the average impact parameter $<b>$ as a function of STT track $\phi_0$ as a function of track barrel. The lowest row shows the $dr_b/dz$ fit described in the text (lefthand panel), the impact parameter significance $S_b$ distribution and the fraction $f_2$ of tracks with $|S_b| > 2$ as a function of $\phi_0$. As expected the $<b>$ vs. $\phi_0$ plots show no $\phi_0$ dependence: the probability of fitting a constant value is slightly higher than the probability of a sine wave fit. The fitted value $dr_b/dz$ determined from the sine wave amplitudes is also consistent with zero.
Figure 7: Results from testing the beam tilt calculations on the tilted–beam sample from table 1 prior to applying the correction. The upper six panels show the average impact parameter $<b>$ as a function of STT track $\phi_0$ as a function of track barrel. The lowest row shows the $dr_b/dz$ fit described in the text (lefthand panel), the impact parameter significance $S_b$ distribution and the fraction $f_2$ of tracks with $|S_b| > 2$ as a function of $\phi_0$ (righthand panel). The fit value for the slope $dr_b/dz = 4.38 \pm 0.07 \mu m/cm$, roughly consistent with the expected value of 4.24$\mu m/cm$. 
Figure 8: Results from testing the beam tilt prescription on the tilt sample from table 1 after applying the barrel-only correction. The upper six panels show the average impact parameter $< b >$ as a function of STT track $\phi_0$ as a function of track barrel. The lowest row shows the $dr_b/dz$ fit described in the text (lefthand panel), the impact parameter significance $S_b$ distribution and the fraction $f_2$ of tracks with $|S_b| > 2$ as a function of $\phi_0$ (righthand panel). The fit value for the slope $dr_b/dz = 0.12 \pm 0.07 \, \mu m/cm$, significantly reduced as a result of the correction. The impact parameter significance distribution and the fraction of tracks with $|S_b| > 2$ are also significantly improved with respect to the uncorrected results in Fig. 7. In particular the $\phi_0$ dependence of $f_2$ is significantly reduced.
Figure 9: Results from testing the beam tilt prescription on the tilt sample from table 1 after applying the barrel+crossing correction. The upper six panels show the average impact parameter $<b>$ as a function of STT track $\phi_0$ as a function of track barrel. The lowest row shows the $dr_b/dz$ fit described in the text (lefthand panel), the impact parameter significance $S_b$ distribution and the fraction $f_2$ of tracks with $|S_b| > 2$ as a function of $\phi_0$ (righthand panel). The fit value for the slope $dr_b/dz = 0.13 \pm 0.06 \mu m/cm$, significantly reduced as a result of the correction. The impact parameter significance distribution and the fraction of tracks with $|S_b| > 2$ are also significantly improved with respect to the uncorrected results in Fig. 7. These results are essentially indistinguishable from those from the barrel–only correction.
References


