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Observation of Dynamic Beta Effects at CESR with CLEO

Abstract

The dynamic beta effect has been directly observed for the first time anywhere at CESR with hadronic events in the CLEO detector. The vertical width of the luminous region is used to measure the resolution. The horizontal width of the luminous region is seen to grow by 50 microns from the highest bunch currents to the lowest. Unfolding the horizontal width with the resolution and the known horizontal emittance gives a measurement of the horizontal beta as function of bunch current. This is seen to rise by 20% of the expected zero bunch current value from the highest to the lowest bunch currents which agrees with the expectation from beam-beam focusing effects. Also the longitudinal width of the luminous region is used to extract the single bunch length.

1 Introduction

The expected shape of the luminous region at CESR, and at colliders in general, is described in an internal CESR note[1]. The relevant formulas are summarized here. Note that all parameters are assumed to be at the interaction point unless other-wise specified.

There are six parameters that define the shape of a single beam. They are

β_x	The Horizontal Beta
β_y	The Vertical Beta
ϵ_x	The Horizontal Emittance
ϵ_y	The Vertical Emittance
σ_z	The Length of the Bunch
σ_E	The Beam Energy Spread.

The size of the single beam is then given by

$$\sigma_x = \sqrt{\beta_x \epsilon_x} \tag{1}$$
$$\sigma_y = \sqrt{\beta_y \epsilon_y} \tag{2}$$
$$\sigma_z = \sigma_z \tag{3}$$
$$\sigma'_x = \sqrt{\epsilon_x / \beta_x} \tag{4}$$
$$\sigma'_y = \sqrt{\epsilon_y / \beta_y} \tag{5}$$
$$\sigma'_z = \sigma_E / E_{\mathrm{Beam}}, \tag{6}$$

where σ' means the angular spread of the particles in the bunch around the direction of the bunch as a whole.

A detector, such as CLEO, does not see one beam. It sees the luminous region of one beam colliding on the other beam. The luminous region is defined by the following

$$\frac{d\mathcal{L}}{dx} = \mathcal{L}_0 \exp\left(\frac{-x^2}{\sigma_x^2}\right) \tag{7}$$

$$\frac{d\mathcal{L}}{dy} = \mathcal{L}_0 \exp\left(\frac{-y^2}{\sigma_y^2}\right) \tag{8}$$

$$\frac{d\mathcal{L}}{dz} = \mathcal{L}_0 \frac{\exp\left(\frac{-z^2}{\sigma_z^2}\right)}{(1+\frac{z^2}{\beta_x^2})^{1/2}(1+\frac{z^2}{\beta_y^2})^{1/2}}. \tag{9}$$

The complication in the longitudinal direction is called the hourglass effect. The angular spread of events coming from the luminous region is then given by

$$\frac{d\mathcal{L}}{dx'} = \mathcal{L}_0 \exp\left(\frac{-x'^2}{4\sigma_x'^2}\right), \tag{10}$$

and similar expressions for y and z.

Then I can plug in the numbers for the CESR lattice [2] and see how I expect a single beam and the luminous region to look. The average of the on 4S and continuum lattices is used. The two lattices do not differ much. The parameters are shown in Table 1. If I generate the

Table 1: Expectation of the single beam parameters from the CESR lattice.

Quantity	Value
β_x	1.26m
ϵ_x	2.11×10^{-7}m-rad^2
σ_x	516μm
σ'_x	0.41mrad
β_y	1.9cm
ϵ_y	2.12×10^{-9}m-rad^2
σ_y	6.3μm
σ'_y	0.34mrad
σ_z	1.87cm
σ'_z	0.68mrad

expected shape of the luminous region as given by Equations 8 through 10and fit it to Gaussian shapes in x, x', y, y', z, and z' the expectation for the widths of those Gaussians is given in Table 2.

The discussion above assumes that there is no coupling between the vertical and horizontal. This is not correct as the CLEO solenoid introduces such coupling. The only major effect of this is on the vertical height of the beam. These coupling effects cause σ_y to be about 10μm

Table 2: Expectation for the Gaussian shape of the luminous region assuming no horizontal-verrtical coupling from the the CESR lattice.

Quantity	Value
$\sigma_{x\mathcal{L}}$	365μm
$\sigma_{x'\mathcal{L}}$	0.58mrad
$\sigma_{y\mathcal{L}}$	4.5μm
$\sigma_{y'\mathcal{L}}$	0.58mrad
$\sigma_{z\mathcal{L}}$	1.1cm
$\sigma_{z'\mathcal{L}}$	0.96mrad

and thus $\sigma_{y\mathcal{L}}$ to be about 7μm. Thus the shape of the luminous region is a ribbon, much longer than it is wide, and much wider than it is thick.

There is also a dynamic effect caused by the focusing effect of one bunch on the oppositely charged bunch as they collide. This is described in another internal CESR note[3]. The relevant effects from this focusing are to make β_x a strong function and ϵ_x a weak function of the bunch current. Due to the details of the CESR lattice this focusing is small in the vertical direction. Figure 1 shows the dependence of β_x on the bunch current. Note that all the data shown in this note are with 36 bunches. Figure 2 shows the expected dependence of the horizontal emittance on the bunch current.

Operationally I use Equation 1 to extract β_x from the measured Gaussian width of the horizontal primary vertex distribution being sure to remember the missing factor of 2.0 that is missing in Equation 8. When making that extraction as a function of the bunch current I use the ϵ_x as given in Figure 2.

2 Techniques

I have studied the techniques to extract the underlying width of the primary vertex with the CLEO II.V flavor of CLEOG with random trigger noise overlaid. I have indiscriminately used continuum $q\bar{q}$ and $B\bar{B}$ events. At this point due to not having the wafer-to-wafer alignment of the SVX the $B\bar{B}$ events seem to be better match with the data than the continuum. All the simulated distributions shown here are drawn from generic $B\bar{B}$ Monte Carlo.

I have used data events from the 4SJ as processed in the miniPASS2 effort. The data were collected between 7 April and 2 June 1996. The events processed are selected with Bill Ross's HADSEL processor which chooses hadronic events based on trigger bits. Monte Carlo hadronic events are all accepted. I use both the events processed with the SVTF and XDUET packages for linking hits in the SVX to tracks found in the VD and DR. I have not been able to see any significant differences between the two packages. I choose good tracks by requiring them to have KINCD = 0 and over 20 DR plus VD hits. Tracks are also required to have 2 or more hits in the SVX in both the r-ϕ and z views. Events with 2 or more such tracks are accepted. Events with only 2 tracks further are required not to be back-to-back with an archaic requirement that the r-ϕ projection of the acollinearity be greater than 50 milliradians. Data events from the

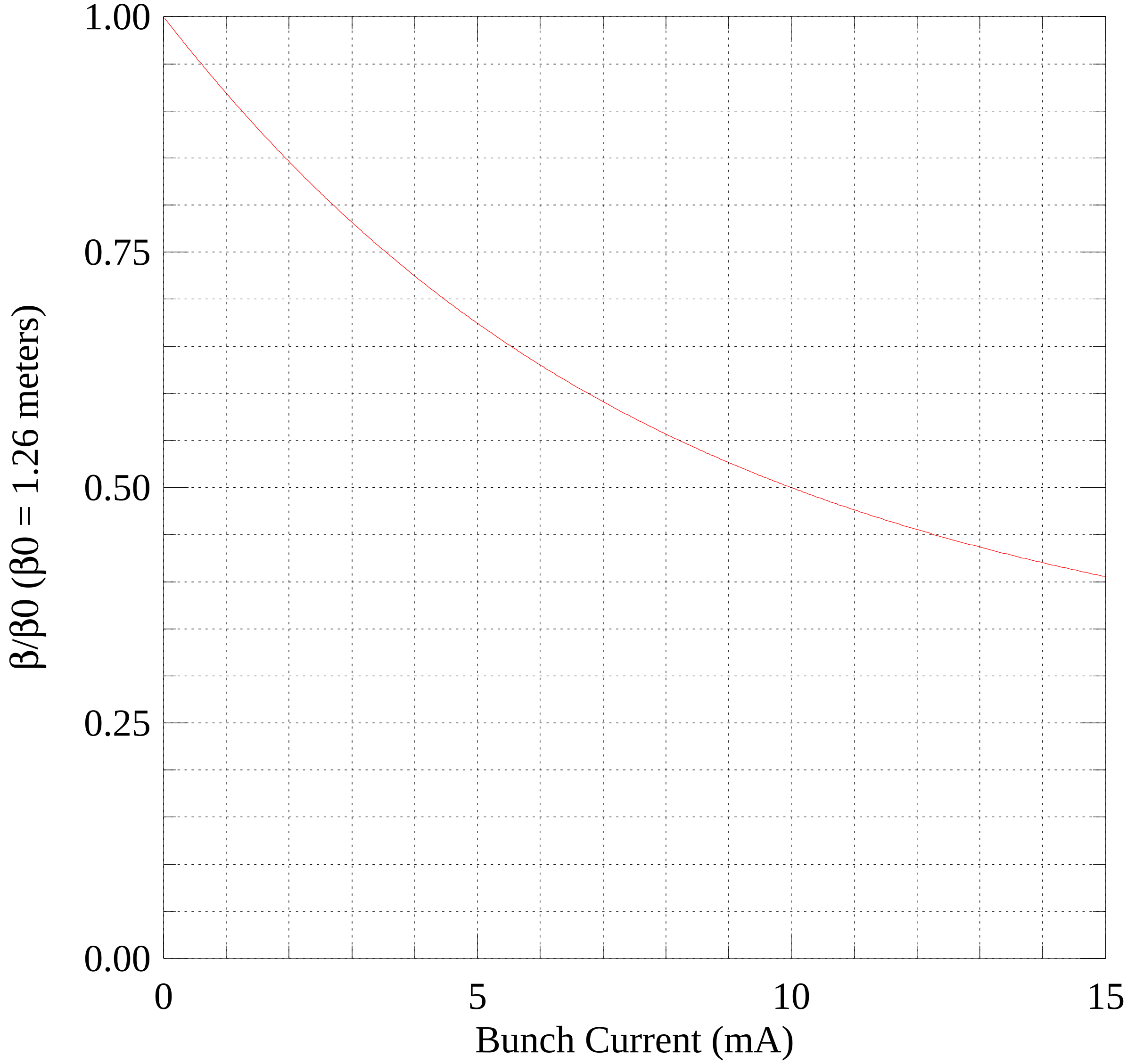

Figure 1: The theoretical dependence of β_x on the bunch current from[3].

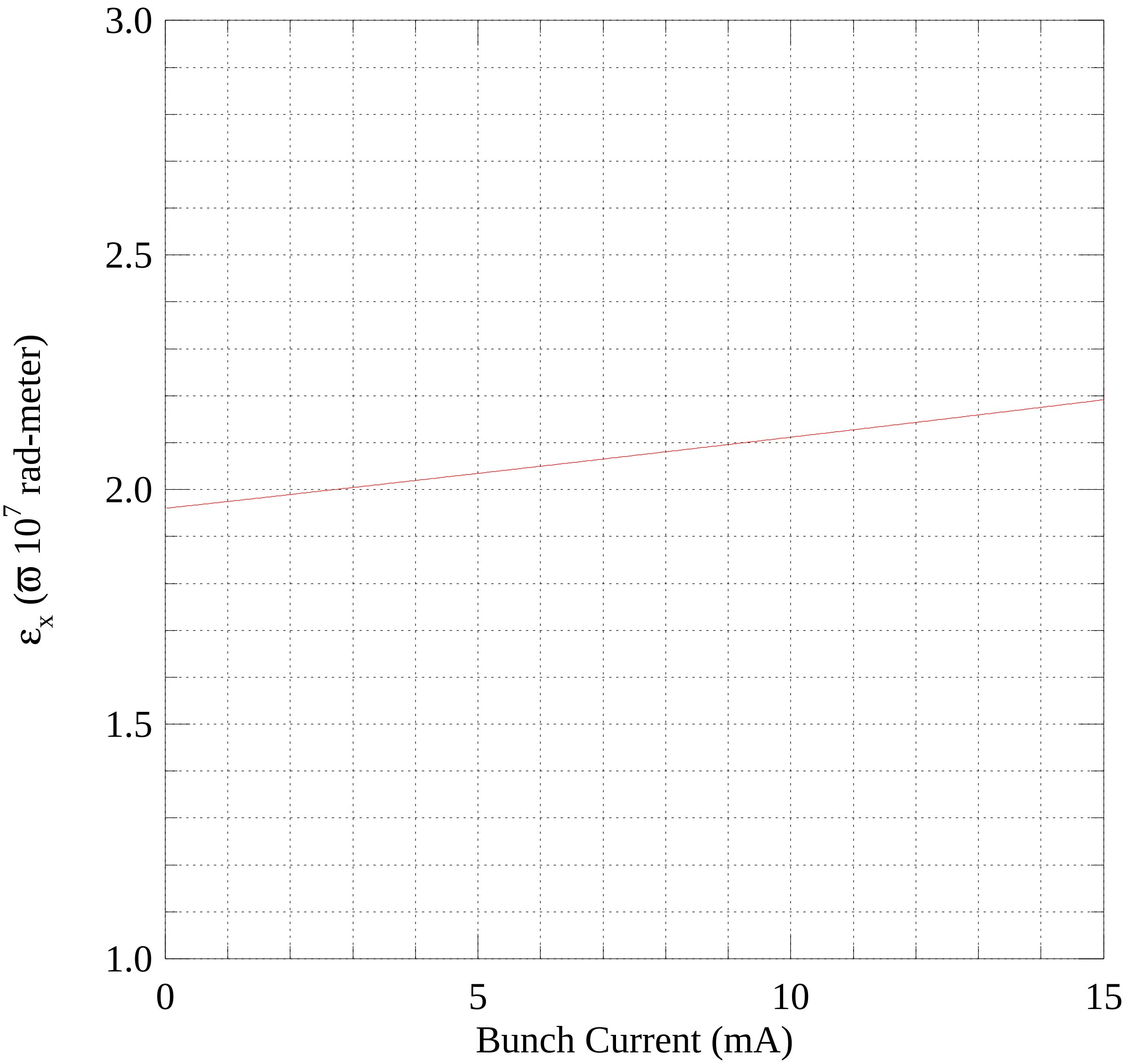

Figure 2: The theoretical dependence of horizontal emittance on the bunch current[3].

$\Upsilon(4S)$ have a $\sim 79\%$ efficiency to pass this event selection while MC $B\bar{B}$ have an $(87 \pm 2)\%$ efficiency.

All the good tracks are then fed to the VCFIT[4] package in an attempt to find a common vertex. I remove tracks that give a value for their contribution to the vertex χ^2 divided by the number of degrees of freedom in the vertex fit, called FNCHIS, greater than 2.0. The distribution is shown in Figure 3. The agreement between the data and the simulation is not so bad considering that the detector is not yet aligned. This could be a bad thing. This procedure is iterated until no tracks fail the cut or there are fewer that two tracks left to find a vertex.

Finally I require the vertex to have a good probability of χ^2, $P(\chi^2)$. Figure 4 shows the distribution of $P(\chi^2)$. The cut on FNCHIS was chosen to make this distribution flatter for the data. Cutting harder on FNCHIS causes a peak to rise at high values of $P(\chi^2)$. In the simulation a FNCHIS cut of around 1.25 results in a flat $P(\chi^2)$. distribution. I require $P(\chi^2)$ to be larger than 0.1. Variations of this cut that avoid very low values of $P(\chi^2)$ have little effect on the analysis.

With this procedure 52% of data events from the $\Upsilon(4S)$ form a good vertex with an average of 4.5 tracks. For MC $B\bar{B}$ the corresponding numbers are 58% and 4.7 tracks. Figures 5 through 7 show the MC's prediction of the resolution in the horizontal, vertical and longitudinal directions. The distributions are fit to a single Gaussian and a flat function using the maximum likelihood technique. I wasted way too much time with toy Monte Carlo's convincing myself that the maximum likelihood technique produced the correct width for such distributions while χ^2 minimization systematically underestimated the width. I use this procedure for all fitting described in this note. Note that the MC predicts that the resolution is essentially the same in the three directions. I also checked that this remains true in the presence of misalignments by adding an error on the DACD and Z0CD of all the good tracks drawn from a 100μm width Gaussian. With this error the resolution on the primary vertex goes to $\sim 170\mu$m from the $\sim 85\mu$m visible in Figures 5 through 7. Figures 8 through 10 show the MC's prediction for the resolution divided by the errors returned from VCFIT, the pull distributions, for the three direction. The widths of the these are 20-30% larger than the expected 1.0, which is pretty good by historical CLEO standards.

The problem in extracting the underlying width is knowing the resolution in the data. Fortunately the shape of the luminous region offers a way to measure the resolution. The vertical height of the luminous region is less than 10μm. Our expected resolution on the primary vertex with hadronic events is expected to be around 100μm, and in special cases we have managed to get resolutions as small as 40μm. Even in the worst case of the resolution being 40μm on an underlying distribution with a width of 10μm, the simple procedure of taking the resolution as the observed width of the distribution gives a resolution that is only 3% larger than the true resolution. This is the procedure I follow for determining the resolution on the vertical primary vertex. I then use this resolution for the horizontal and longitudinal directions to extract the underlying widths.

One other complication in the data is that the beam is not guaranteed to stay in one spot due to operator tuning or other effects. I deal with this in two ways. One is for each run compute the mean of the primary vertex distribution in each direction, subtract off this mean, and combine runs after making this correction. Second choosing only good runs defined as those with over 1000 events passing all the primary vertex selections. This does two good things. It makes for a very accurate determination of the run-by-run mean thus improves combining runs.

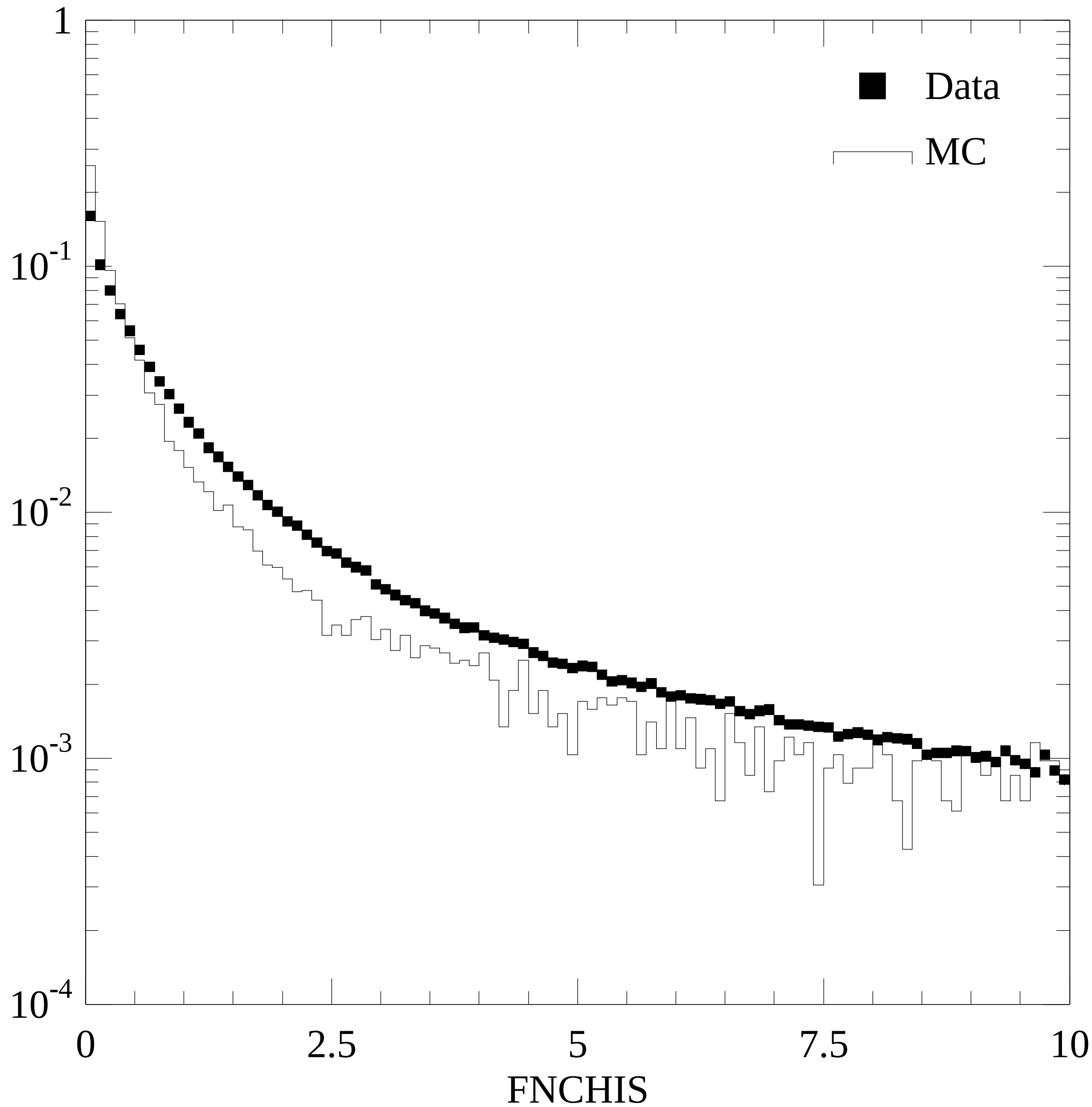

Figure 3: The per track distribution of the tracks contribution to the vertex χ^2 divided by the number of degrees of freedom of the vertex fit. Tracks with values greater than 2.0 are removed from the vertex fit.

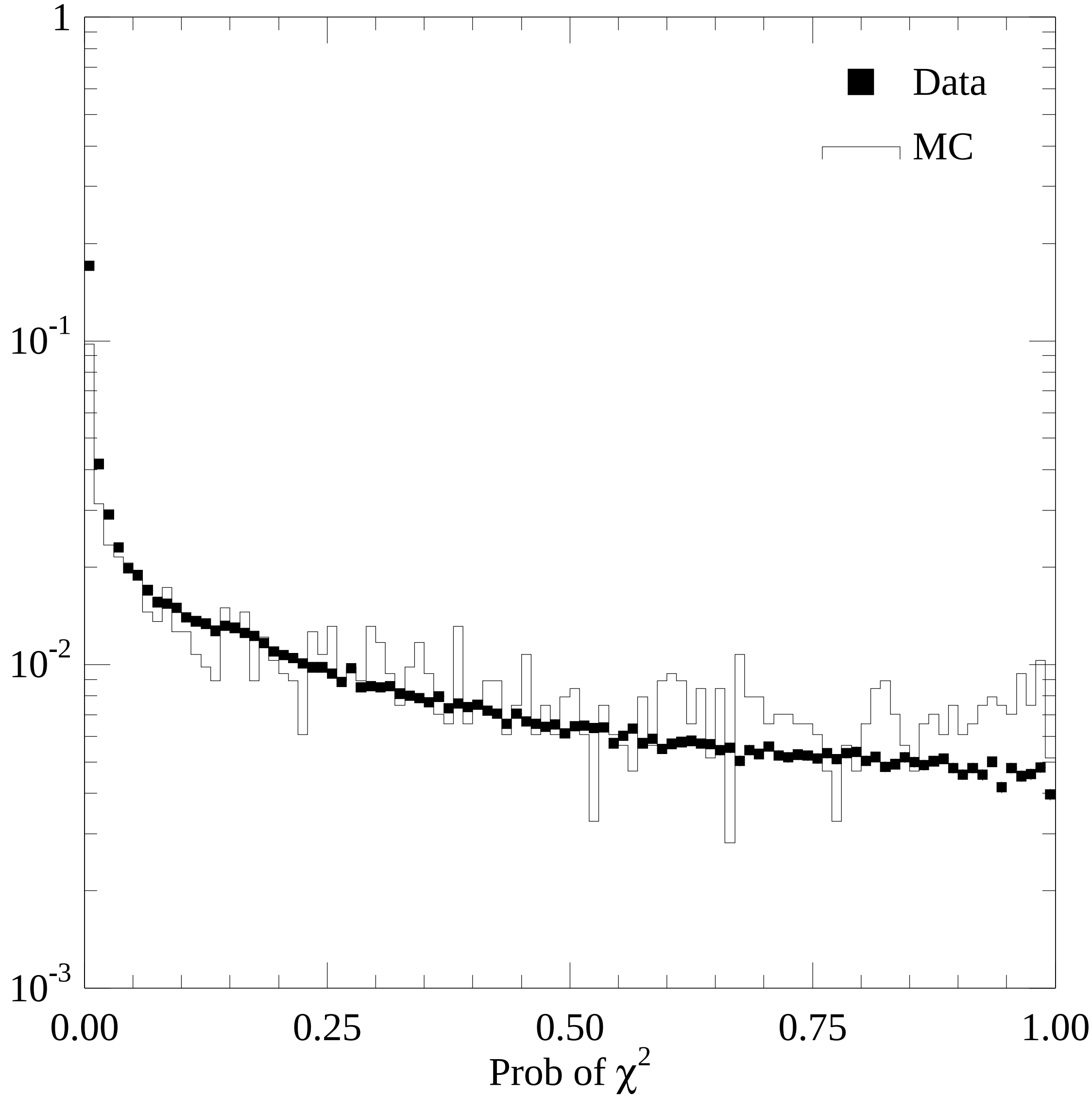

Figure 4: The per vertex distribution of $P(\chi^2)$.

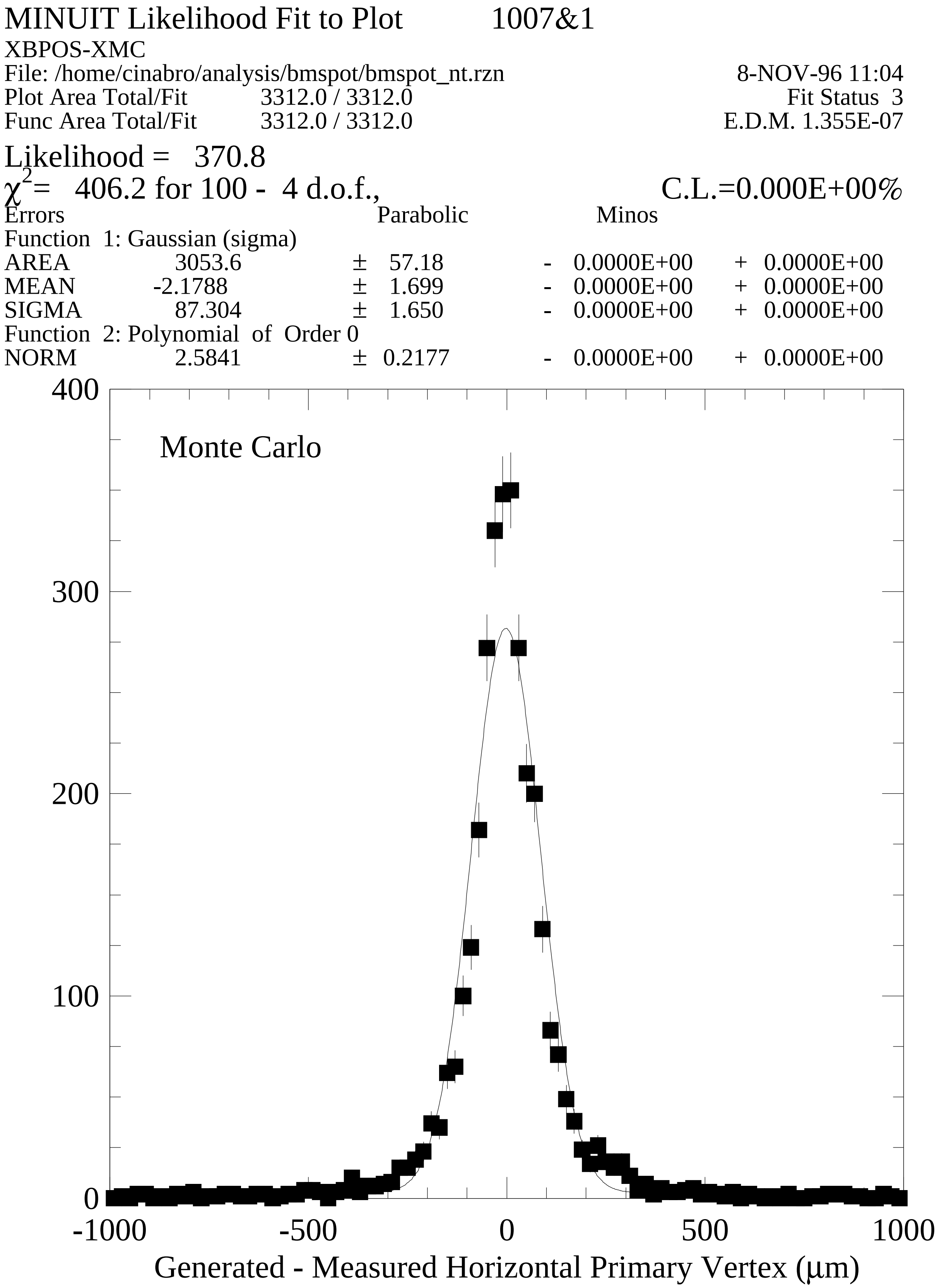

Figure 5: The resolution on the horizontal primary vertex.

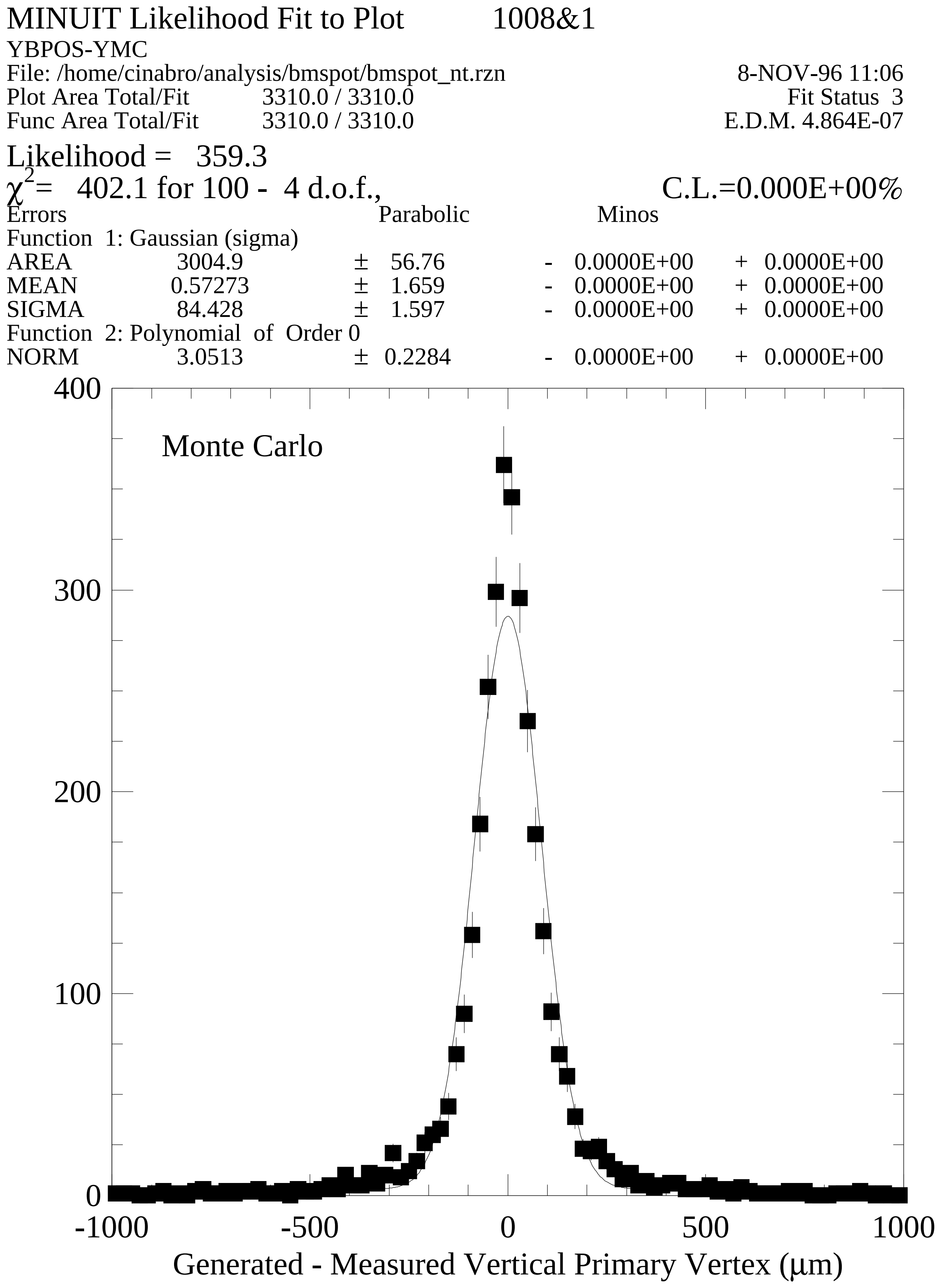

Figure 6: The resolution on the vertical primary vertex.

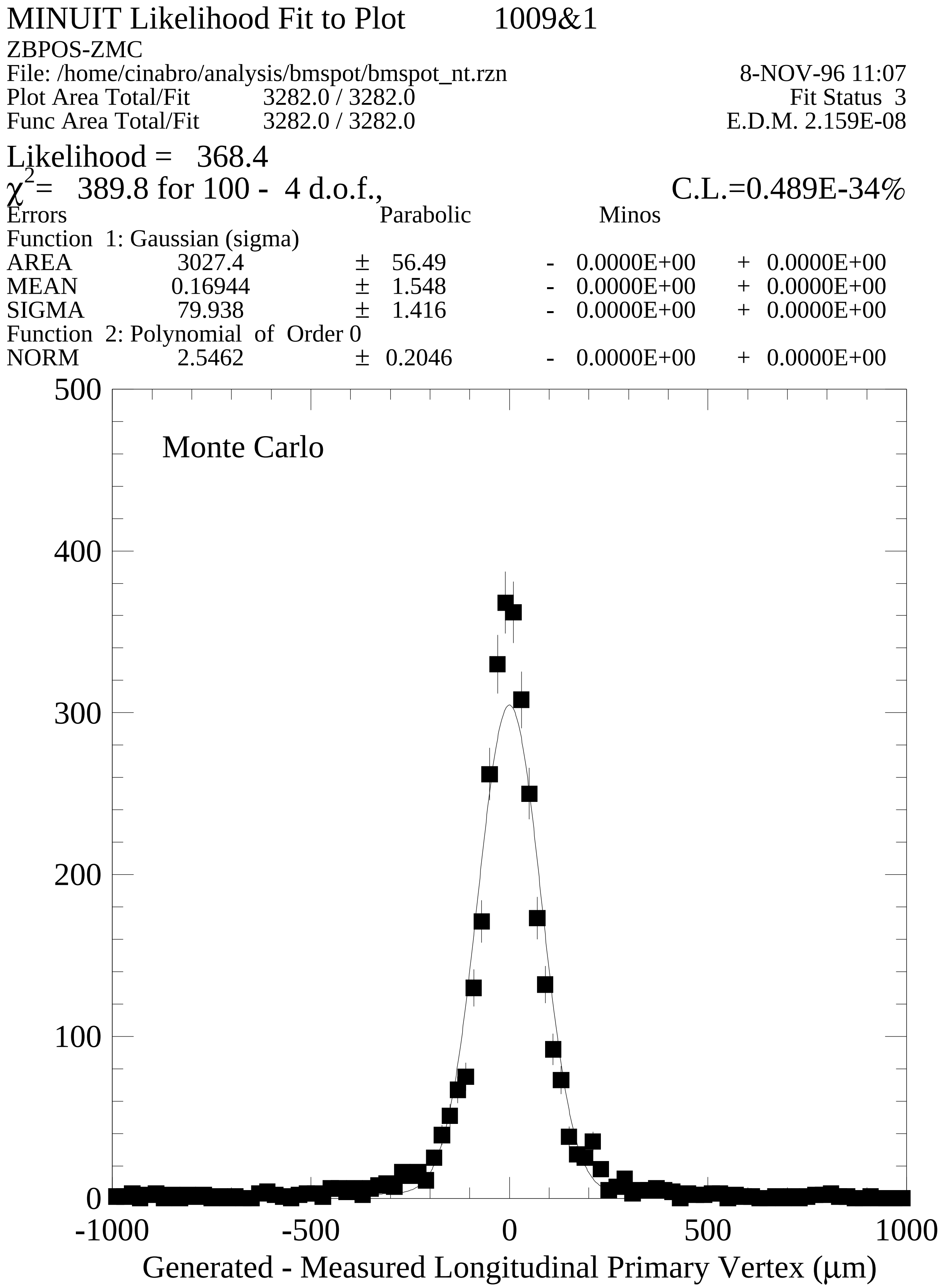

Figure 7: The resolution on the longitudinal primary vertex.

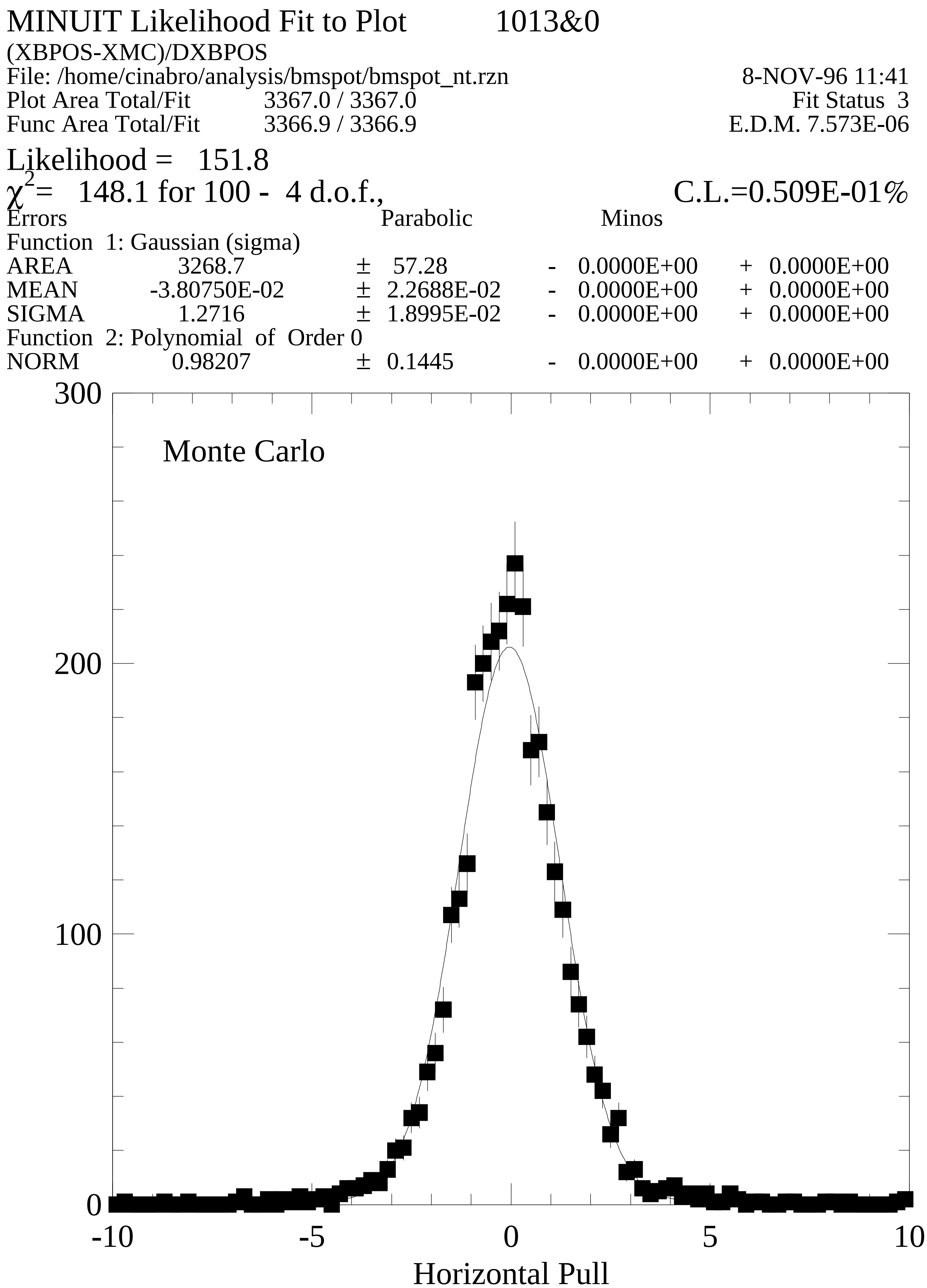

Figure 8: The measured minus generated over error distribution for the horizontal primary vertex.

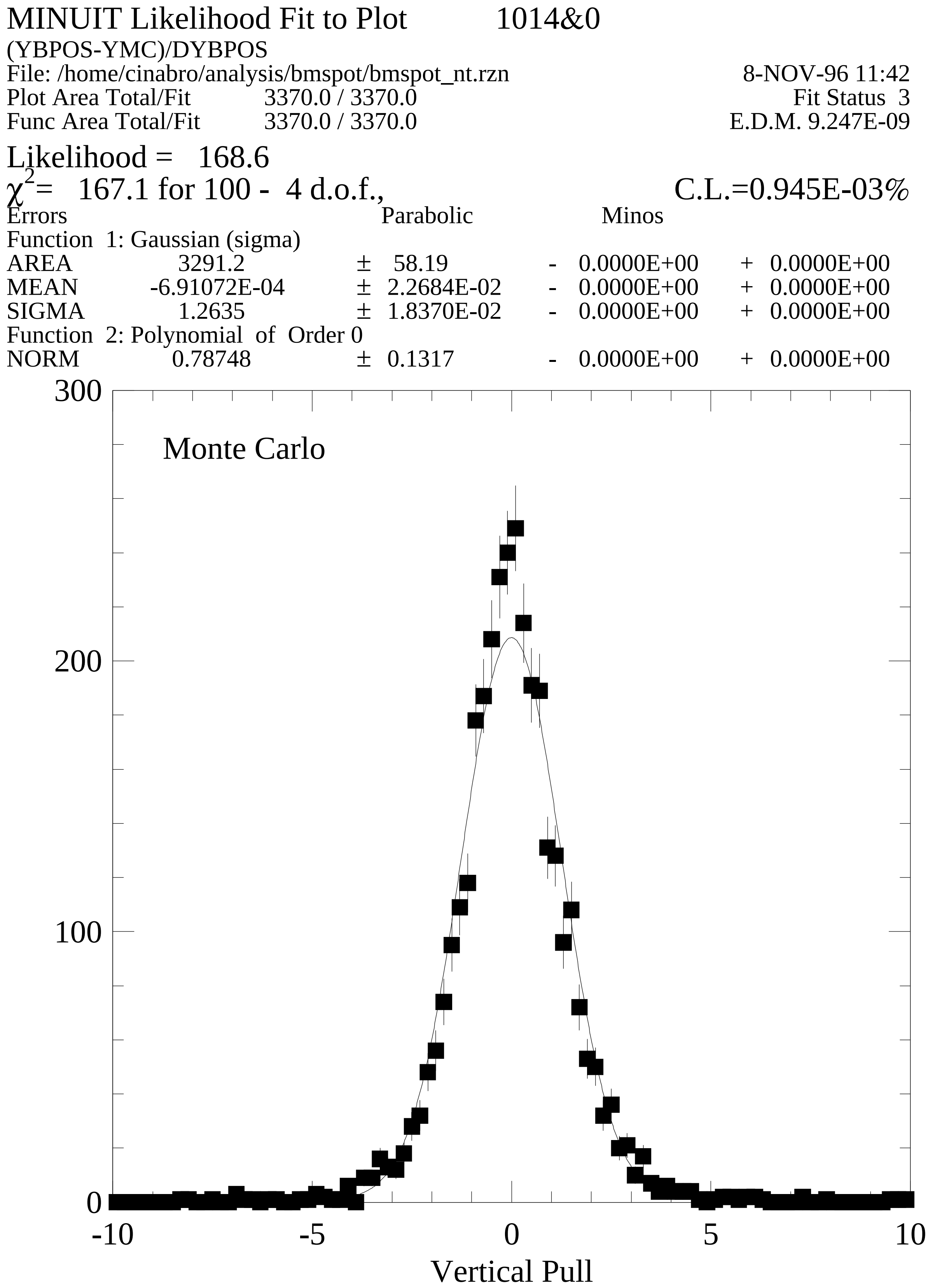

Figure 9: The measured minus generated over error distribution for the vertical primary vertex.

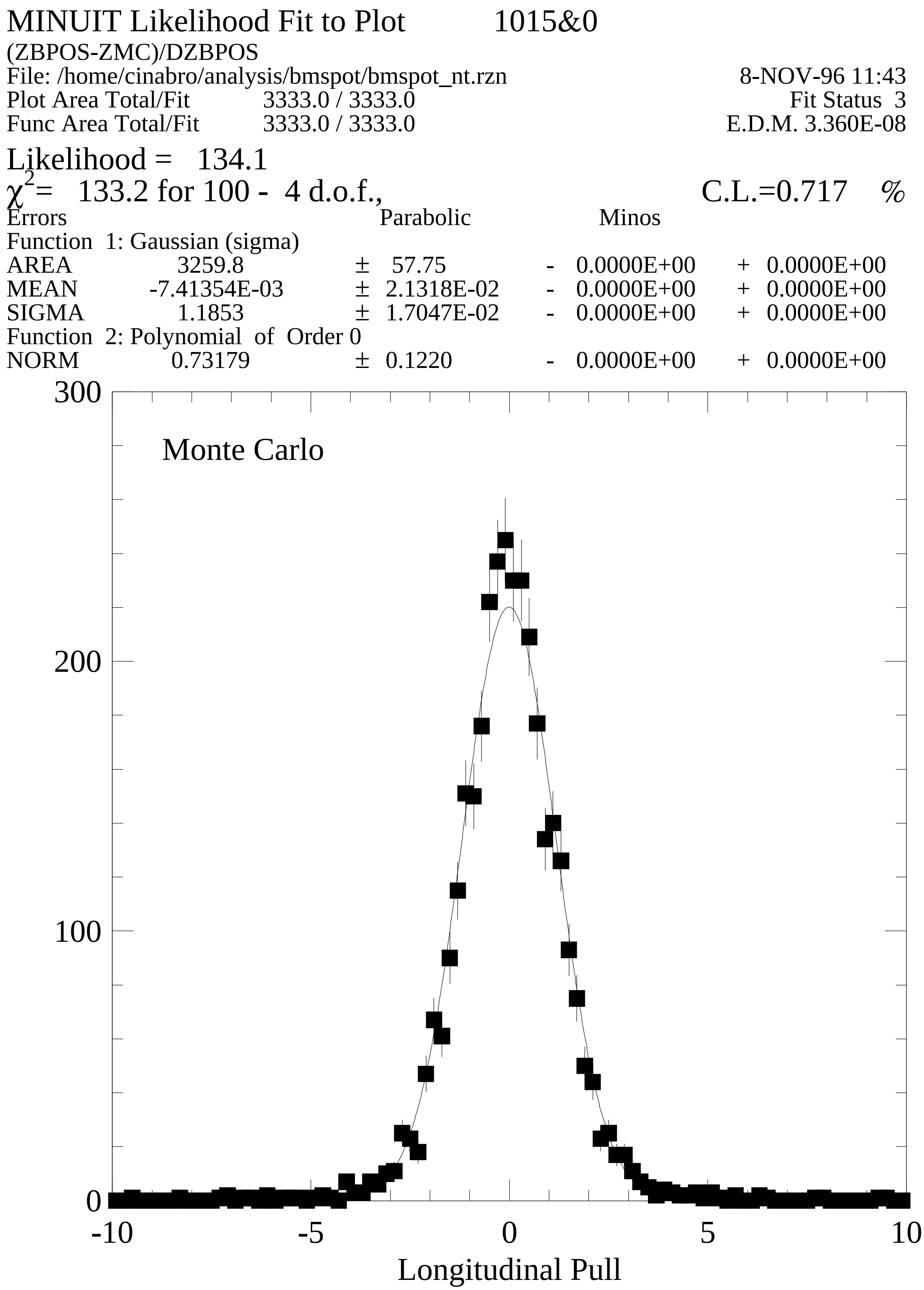

Figure 10: The measured minus generated over error distribution for the longitudinal primary vertex.

This also tends to avoid runs when operators were aggressively tuning or something else was going wrong. Without this requirement it is very difficult to see the decline in the horizontal beam size at the higher beam currents. To estimate how large the effect of the moving beam I have compared the mean of vertexes from the first and second half of the run after. I find a shift of -10μm horizontally, -1.5μm vertically, and -90μm longitudinally. All of these are quite small compared to the widths of the distributions.

3 Results

After making these selections there are 168569 data events that give a primary vertex. Figure 11 shows the distribution of bunch currents for the vertexes selected. The average is 6.4mA. Figures 12 through 14 shows the distributions of the primary vertex found. Much can be learned from these distributions. The width of the vertical distribution, $(165.50 \pm 0.44)\mu$m, indicates that there are misalignments on the level of 100μm as discussed above. If we take this vertical width as the resolution on the horizontal distribution we extract an underlying horizontal width of the luminous region of $\sigma_{x\mathcal{L}} = (295.13 \pm 0.94)\mu$m which is much smaller that expected zero bunch current value of 365μm that appears in Table 2. Using a horizontal emittance of $\epsilon_x = 2.11 \times 10^{-7}$m-rad^2 I extract a horizontal beta of $\beta_x = 0.826$m using equation 1. This is much smaller than the expected value of 1.26m in Table 1, and this beta over the beta at zero beam current, β_x/β_{x0} is 0.656 which agrees remarkable well with what is expected from Figure 1 for a bunch current of 6.4mA. In the longitudinal direction the width of (1.1023 ± 0.0023)cm agrees with the expectation of Table 2. Figure 15 shows the result of fitting the primary vertex longitudinal distribution to the hourglass shape given by equation 9. The fit gives a bunch length (1.814 ± 0.010)cm, while we expect 1.87cm. I also get an indirect measure of the vertical beta, $\beta_y = (1.520 \pm 0.041)$cm which agrees well with the expectation of 1.9cm. More work on understanding the shapes of the distributions and the resolutions would be needed to assign any sort of realistic error on this measure of β_y.

To be convinced that I have observed the dynamic beta effect I slice the data in 14 bins of beam(bunch) current from 180(5.0) to 320(8.9)mA, and repeat the procedure described above for each bin. Figures 16 and 17 shows the mean from the Gaussian fits versus the bunch current in the horizontal and vertical directions, and Figures 18 and 19 show the Gaussian widths. The scatter in the means indicates that the beam position is stable at the level of 10μm in the r-ϕ plane. This agrees with the differences observed from the first to the second half of run. When extracting β_x I will include a systematic error of 10μm on the resolution measured from the vertical distribution.

I have two choices for the resolution as a function of bunch current. I can use one resolution of $(166 \pm 10)\mu$m from the fit to the full vertical distribution of Figure 13. The results of this unfolding are shown in Figure 20. Here I have shown a range for the theory prediction based on the range of horizontal tunes (0.537 to 0.544) observed during the fills in which this data were gathered. An alternative choice for the resolution is to use the results visible in Figure 19 which clearly show the width of the vertical primary vertex distribution changing with bunch current. Figure 21 shows the results of the unfolding with the resolution changing as a function of bunch current. This second approach agrees better with the theory. No matter the dynamic beta effect is clearly observed and agrees very well with the theoretical expectation.

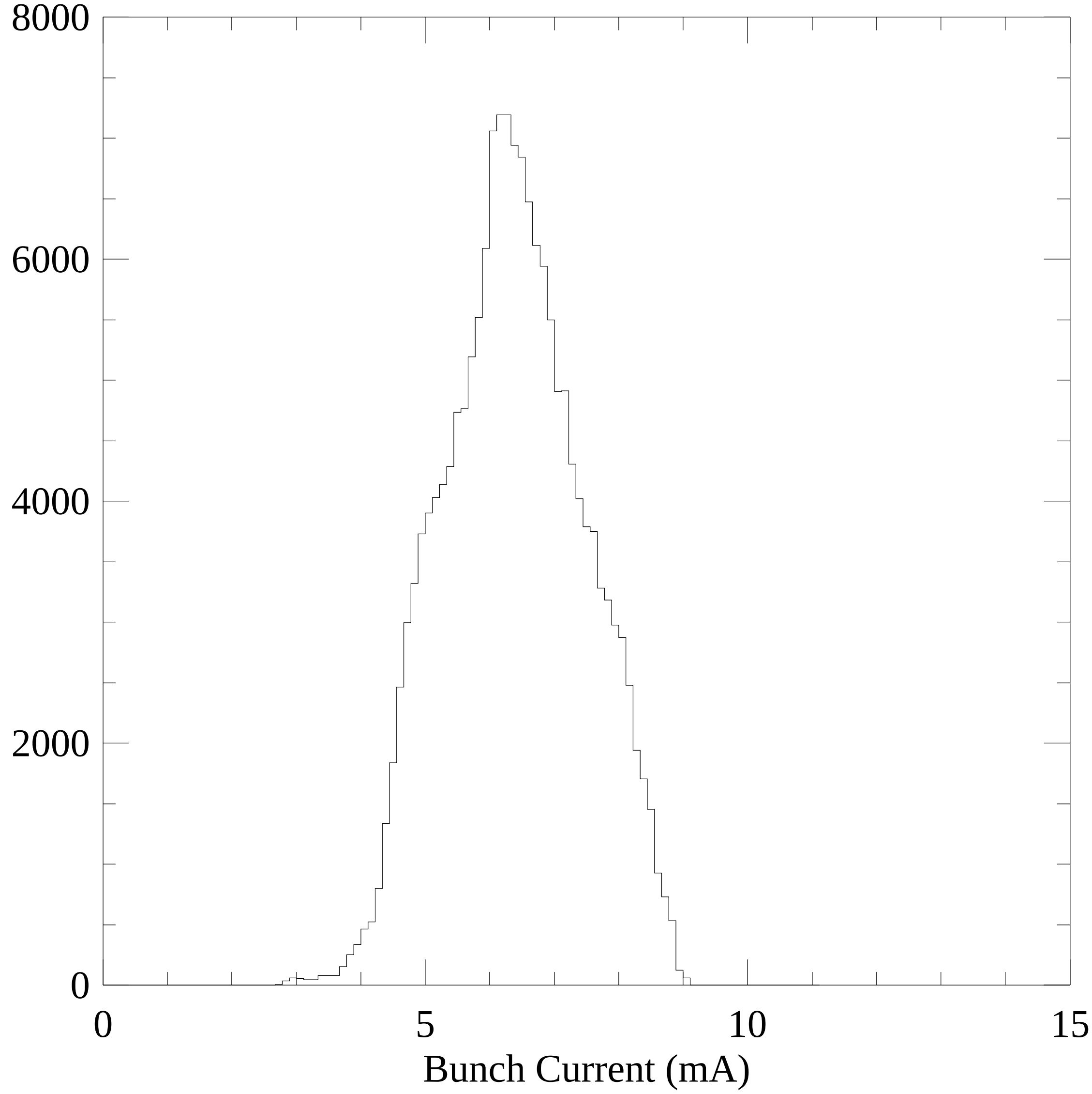

Figure 11: The bunch current for the selected primary vertexes.

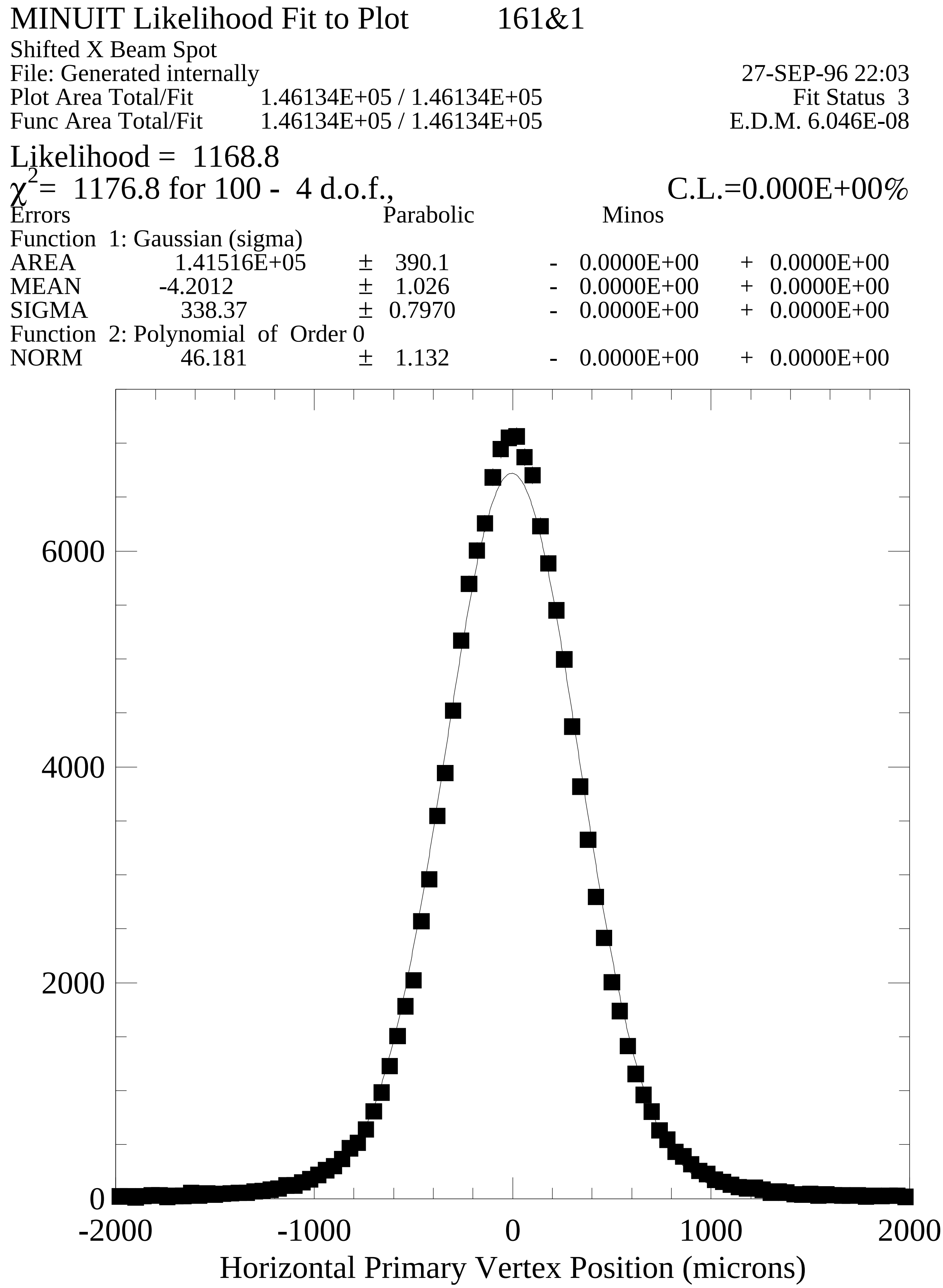

Figure 12: The horizontal primary vertex distribution.

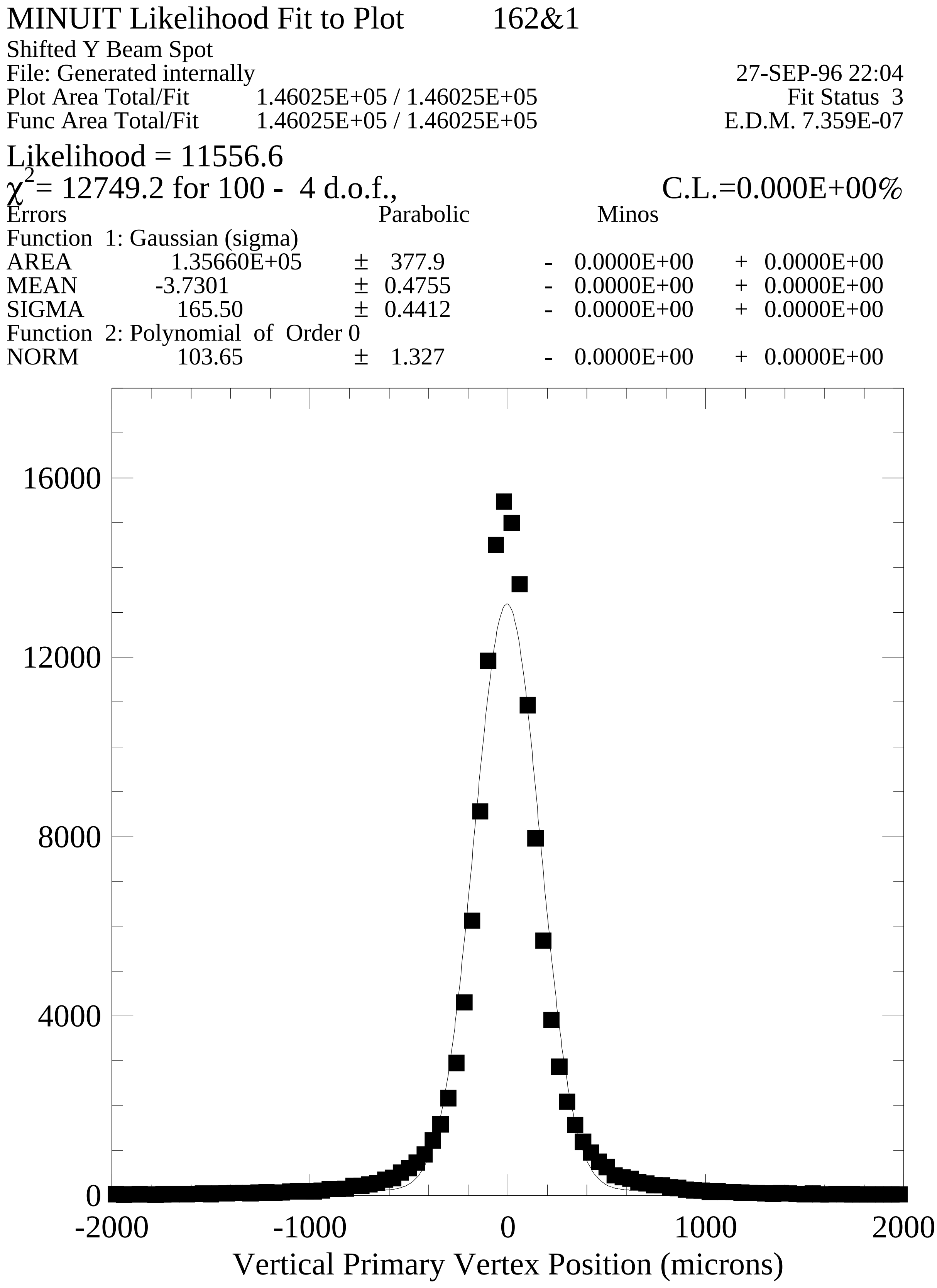

Figure 13: The vertical primary vertex distribution.

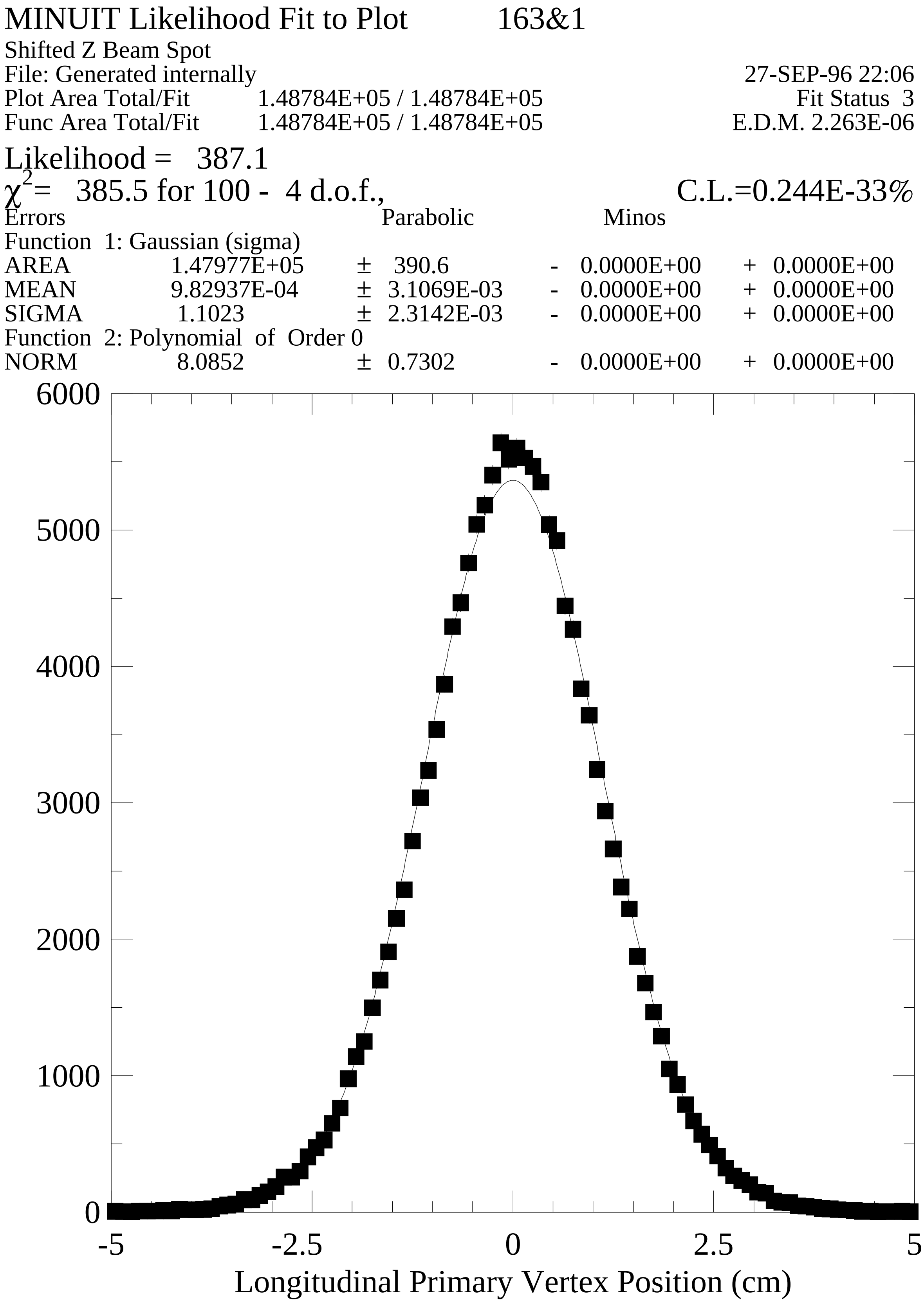

Figure 14: The longitudinal primary vertex distribution.

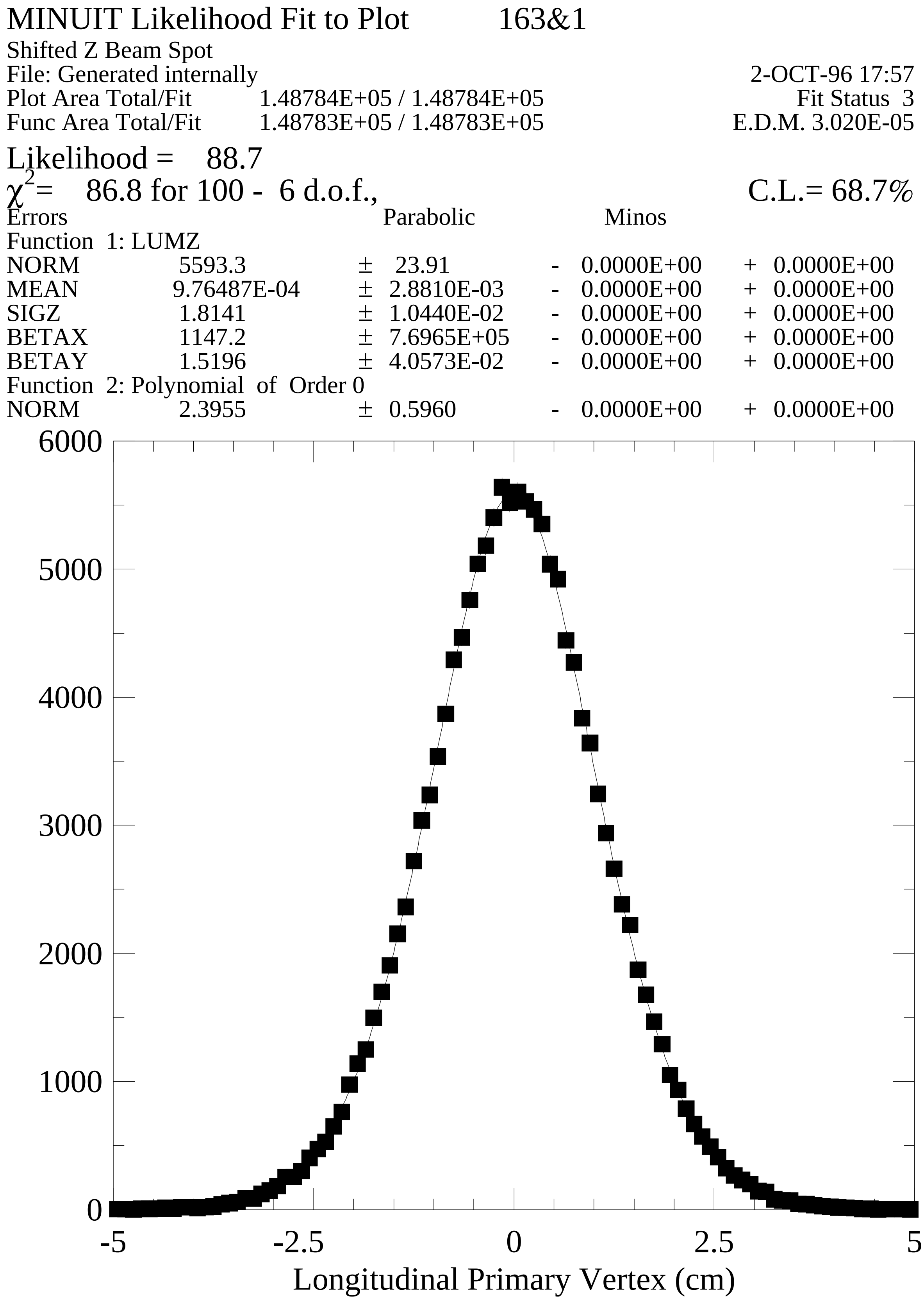

Figure 15: The longitudinal primary vertex distribution with a fit to the expected hourglass shape.

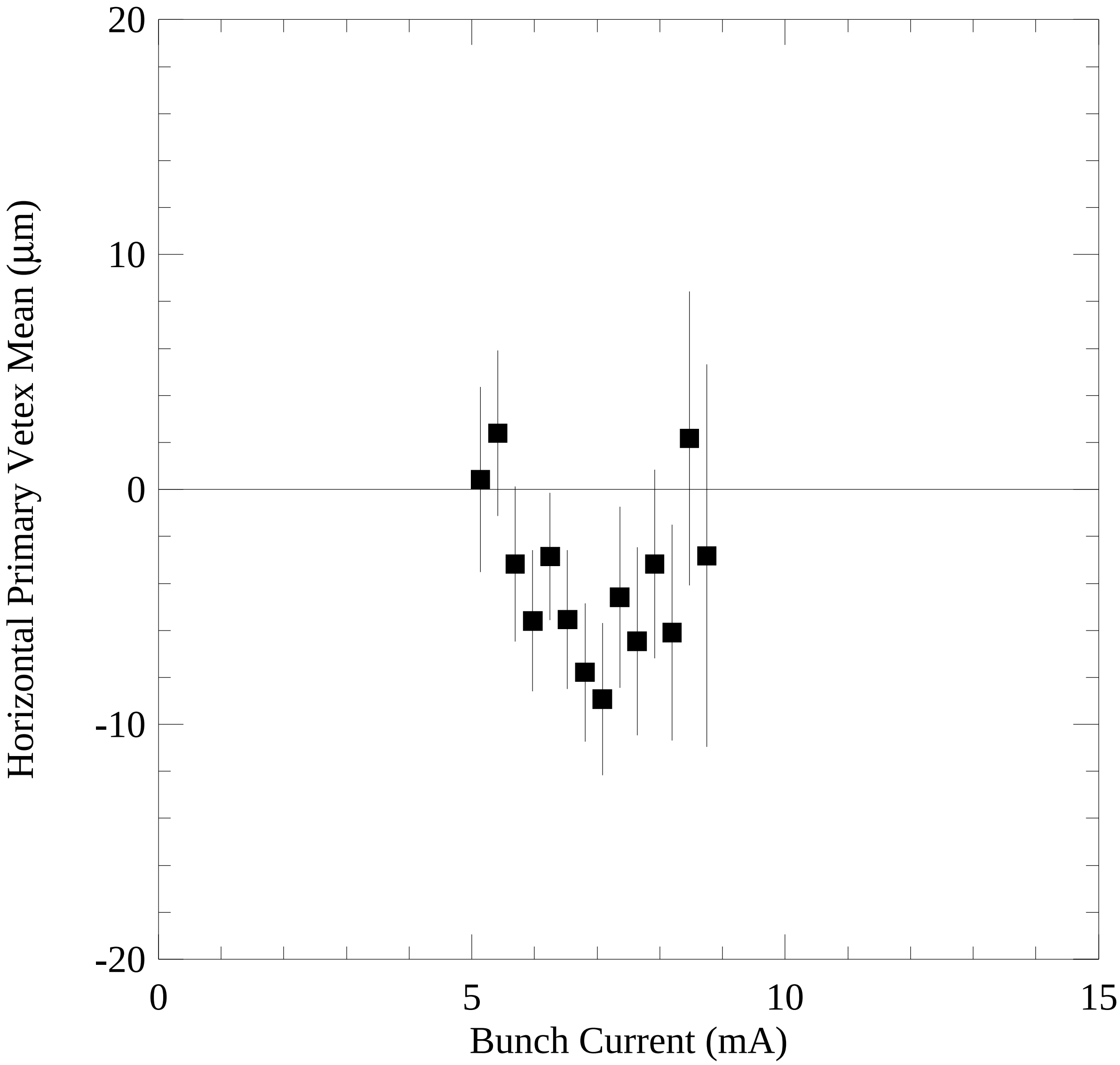

Figure 16: The mean of the fits to the horizontal primary vertex distribution versus the bunch current.

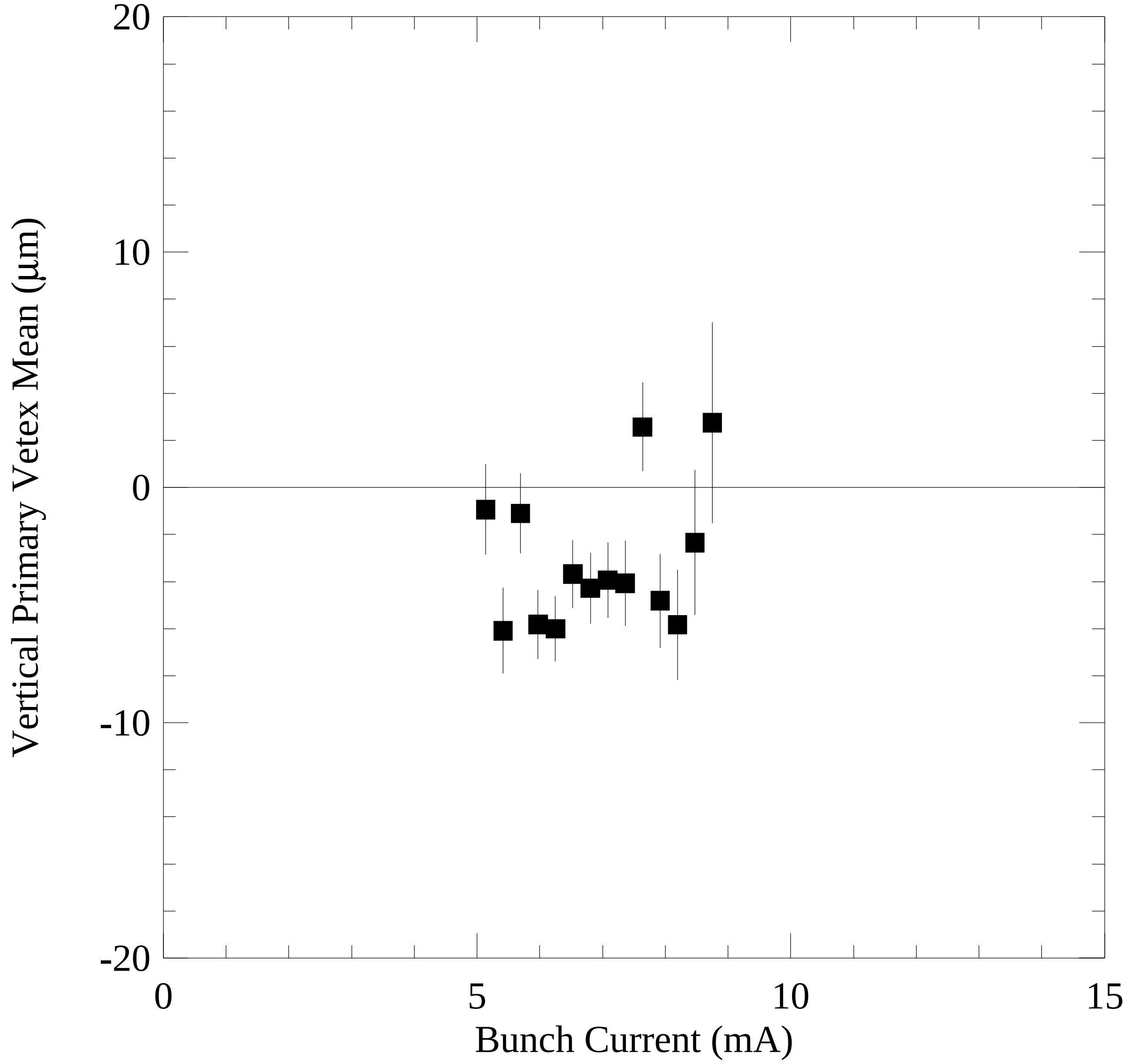

Figure 17: The mean of the fits to the vertical vertex distribution versus the bunch current.

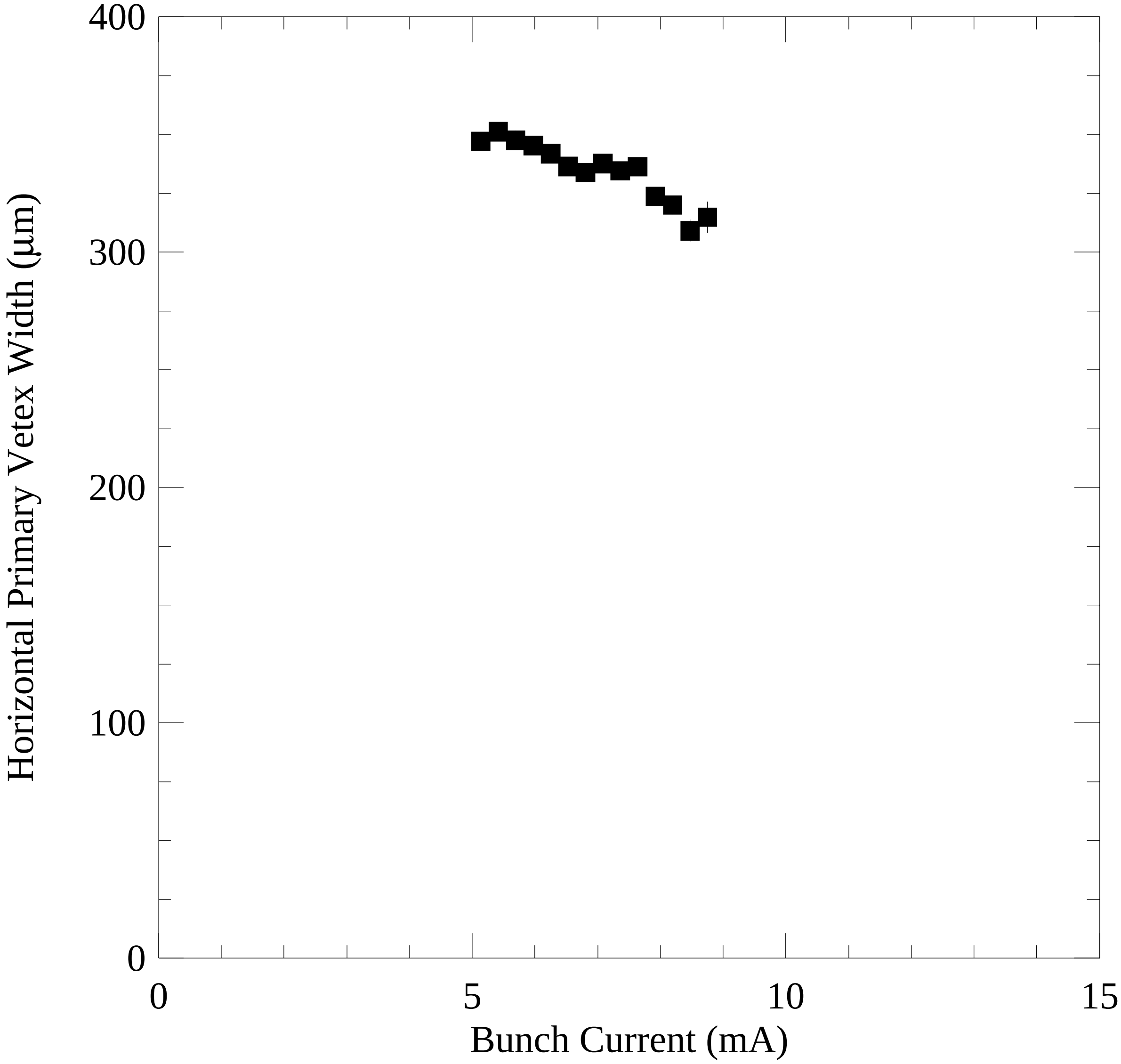

Figure 18: The width of the fits to the horizontal primary vertex distribution versus the bunch current.

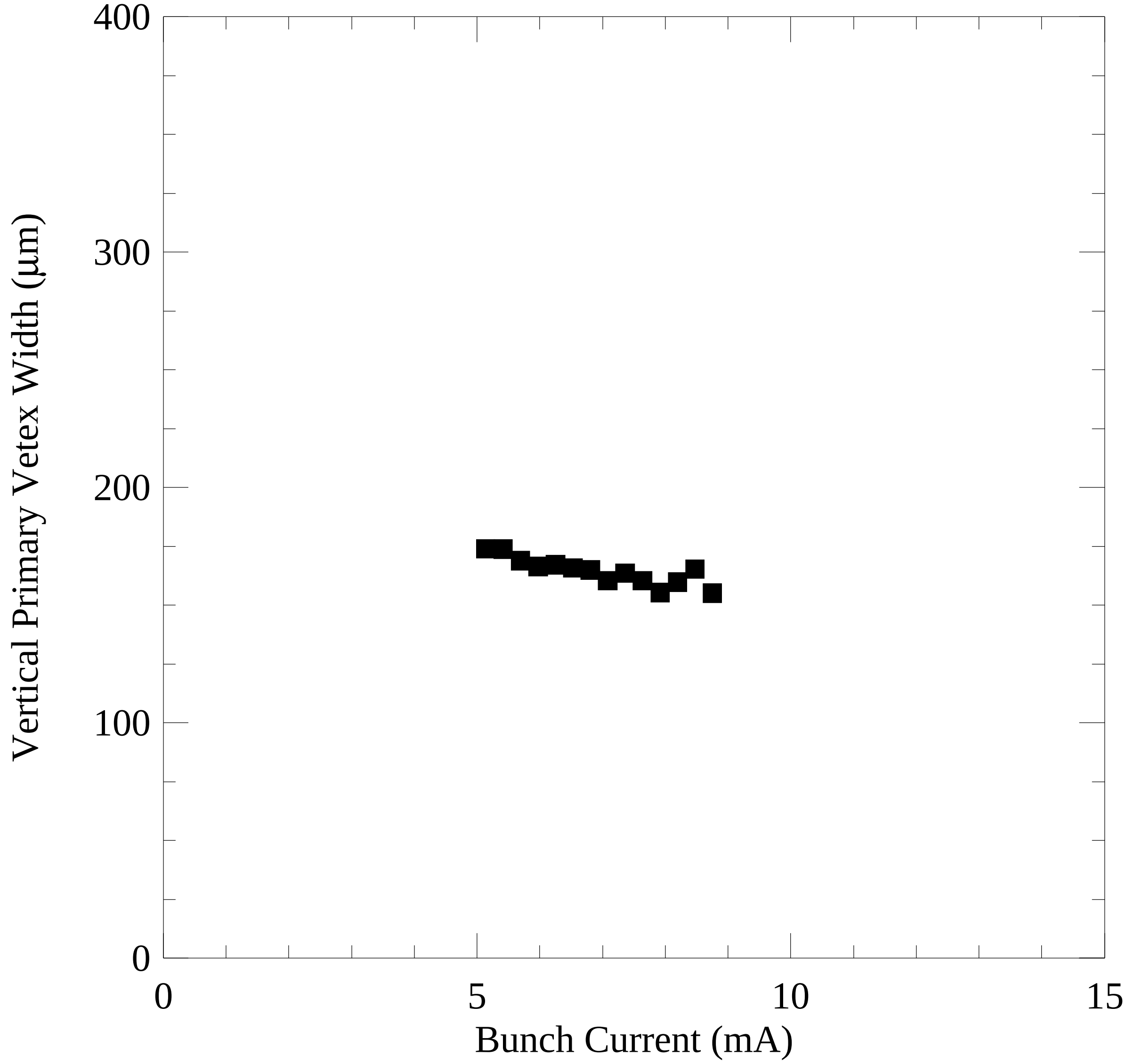

Figure 19: The width of the fits to the vertical vertex distribution versus the bunch current.

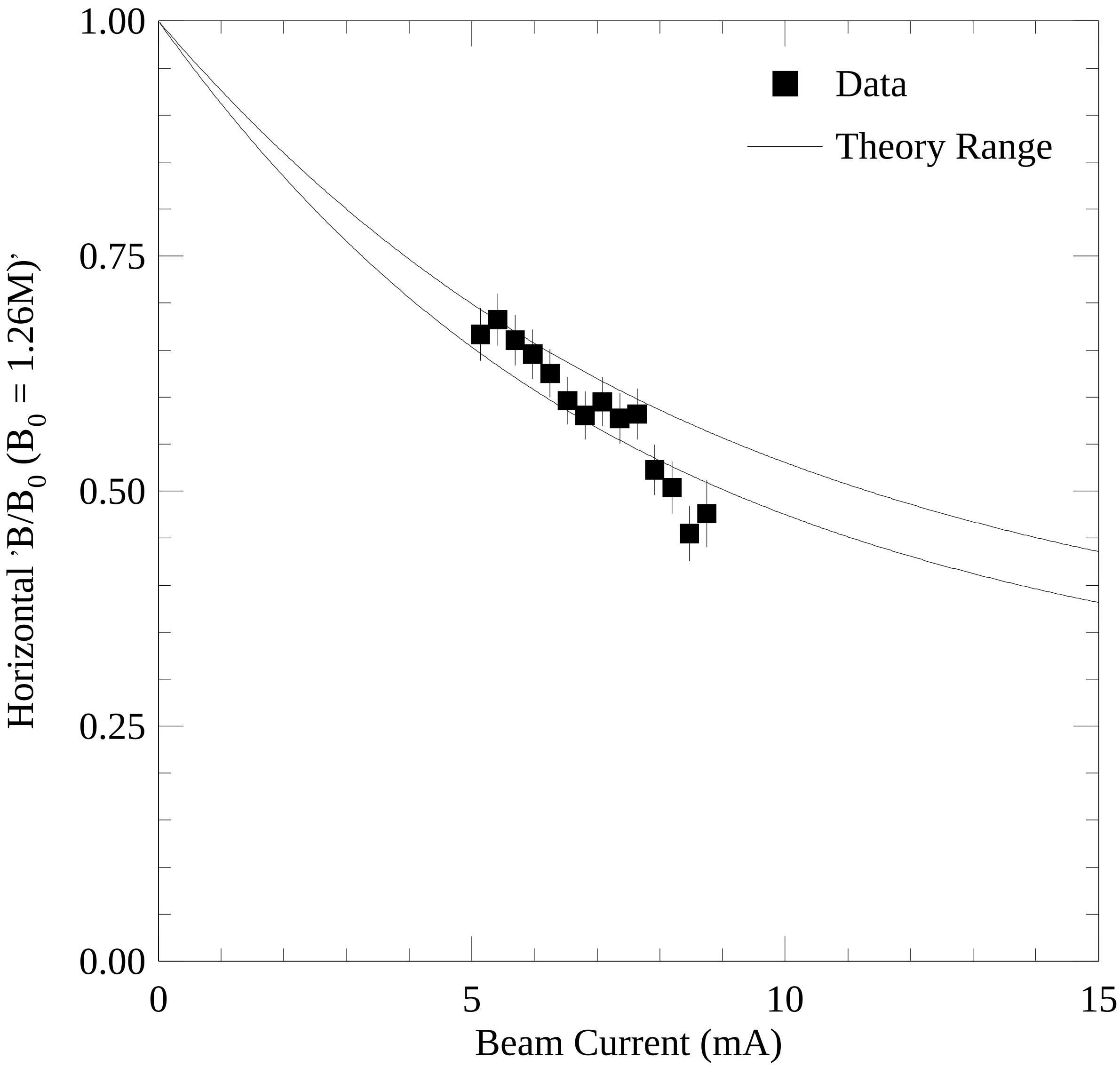

Figure 20: The horizontal beta as function of bunch current with a fixed resolution.

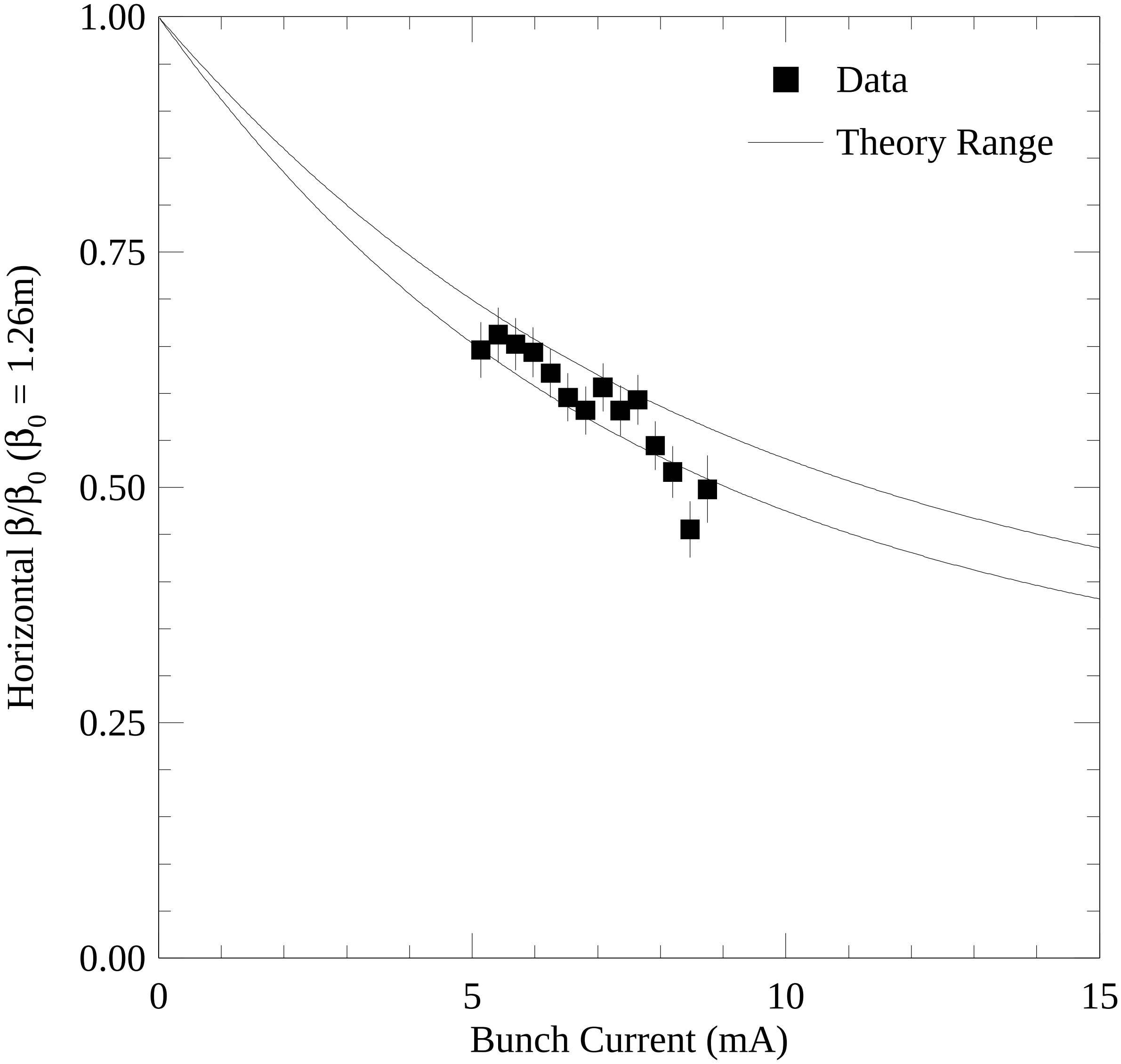

Figure 21: The horizontal beta as function of bunch current with a variable resolution.

As a final cross check I have also looked at the longitudinal distribution of the primary vertex as a function of the bunch current. This should not change with the bunch current. Figure 22 shows the mean from the Gaussian fits versus the bunch current in the longitudinal direction. All the means are consistent with zero, but I add a systematic error of 0.02cm on the resolution of the width of the longitudinal primary vertex distribution when extracting the bunch length. Figure 23 shows the extraction of the bunch length versus the beam current. For this extraction I fixed the horizontal beta to the values found in Figure 21 and the vertical beta to 1.9cm. While the points are consistent with each other there is a clear trend for the bunch length to get smaller with rising beam current. This may be an indication of the vertical beta's dependence on the bunch current, but as I said above more work would have to be made to understand the extraction of the vertical beta from the longitudinal primary vertex distribution to firmly conclude this.

4 Conclusion

The study of the primary vertex distribution with CLEO has led to an unambiguous observation of the dynamic beta effect at CESR. This effect has only been observed indirectly[5] via the luminosity before. This is the first direct observation of the effect. Many future accelerators are depending on this effect to achieve their very high luminosity goals[6], and are likely to find this observation of great interest. This also represents a demonstration that the SVX is capable of observing significant physics effects even at this very early stage of its career.

References

[1] Stephen Milton, CBN 89-1.

[2] Private communications from Mike Billing, Stu Peck, Dave Rubin, and David Sagan.

[3] David Sagan, CBN 94-06, and specific numbers for the current CESR lattice were given in private communication by Dave Sagan.

[4] W. T. Ford, CSN 94/329.

[5] S. Milton, PSI-PR-90-05 and references therein, and P. Raimondi, F. J. Decker and P. Chen SLAC-PUB-95-6882.

[6] For example the NLC expects a “pinch enhancement” of 1.4-1.5. See the Zeroth Order Design Report... SLAC-474.

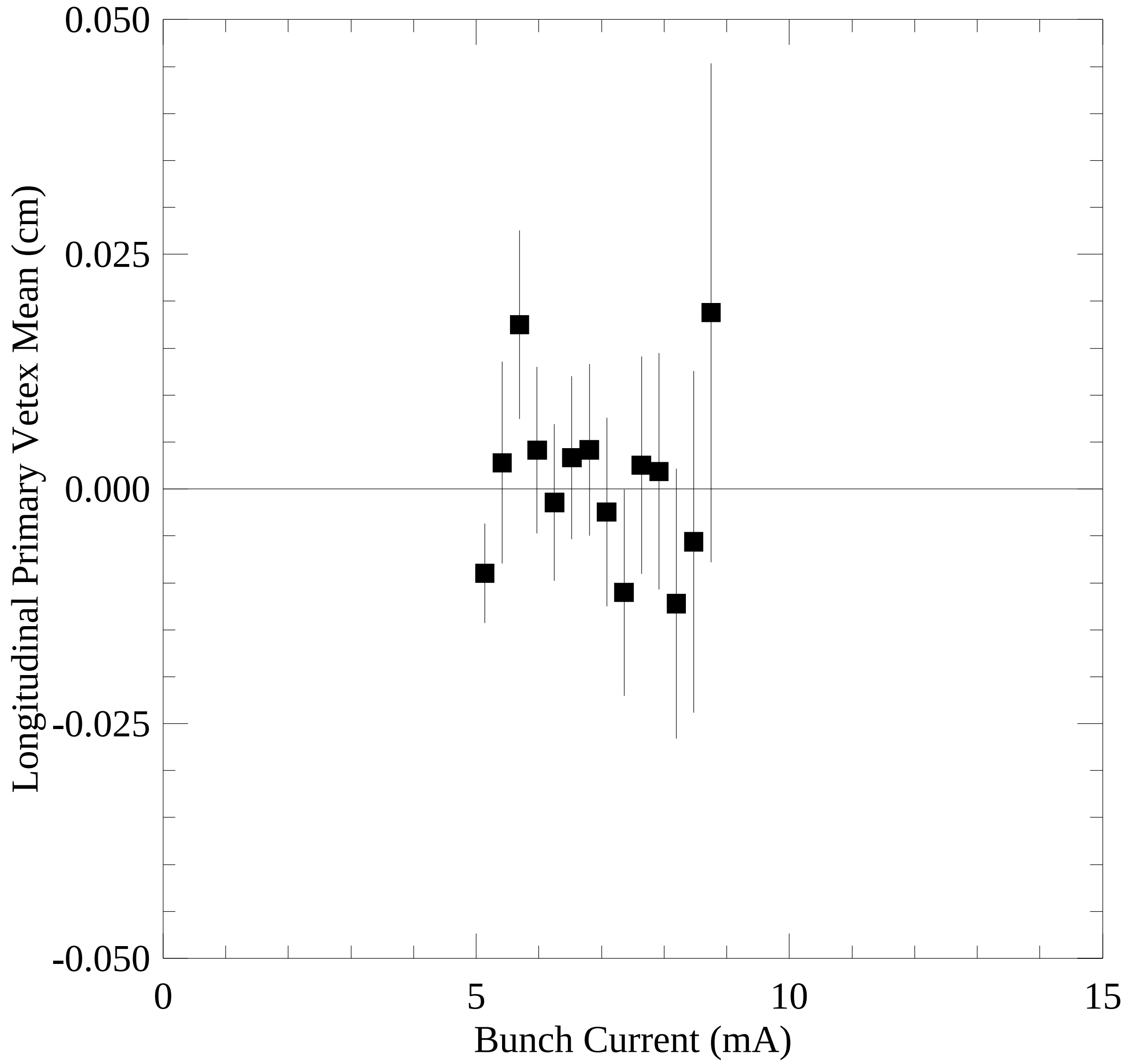

Figure 22: The mean of the fits to the longitudinal primary vertex distribution versus the bunch current.

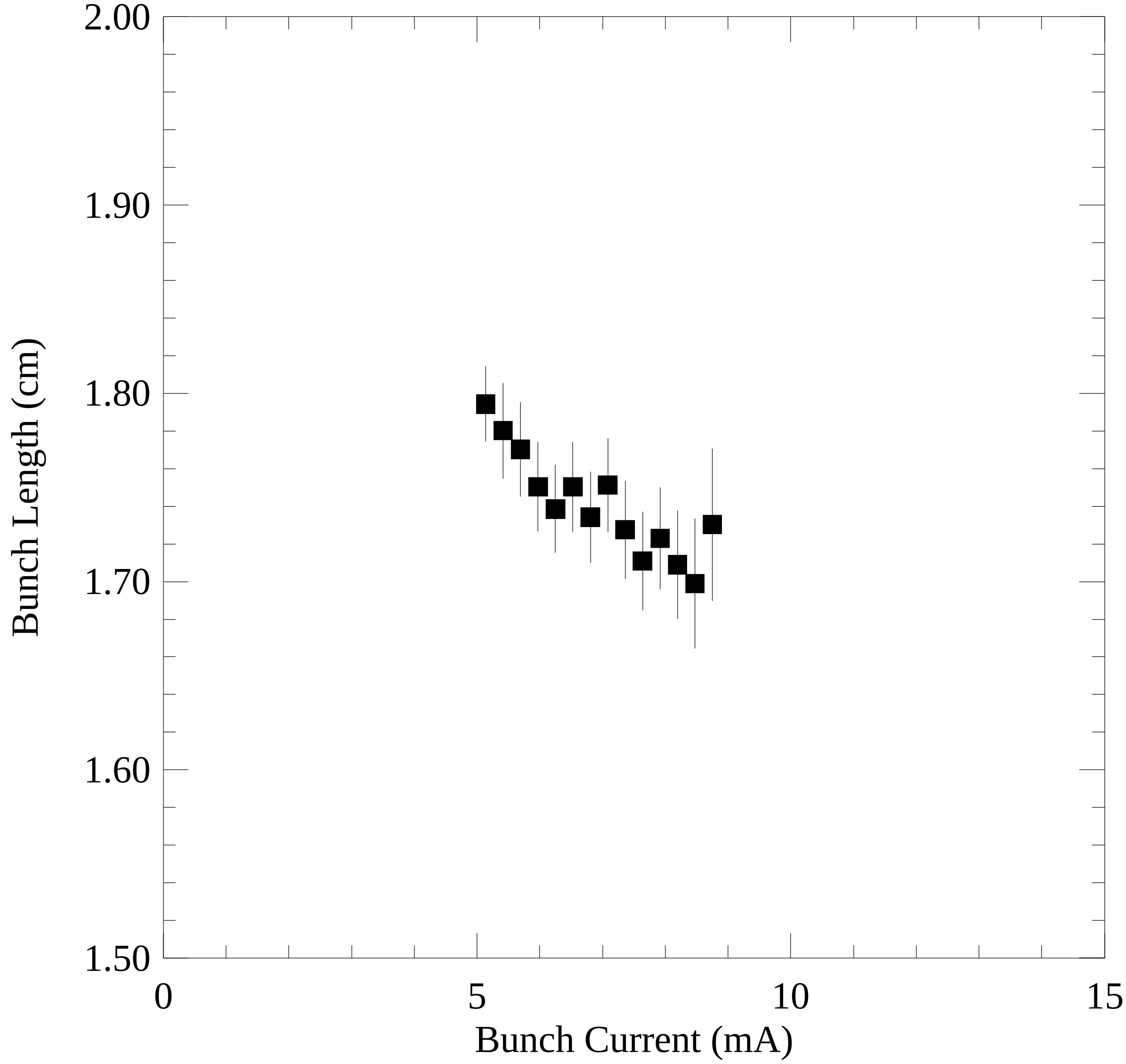

Figure 23: The extracted bunch length versus the bunch current.