CBN 00-9
CBX 00-60
2 October 2000
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Hourglass Studies Including the Position of the Waist and Studies of the Bunch Length Dependence on Beam Current

Abstract

This CBN/CBX updates and expands on the results of our previous CBN 00-6/CBX 00-22. We have uncovered a couple of errors in our previous analysis. We were mistaken about how longitudinally asymmetric beam bunches would affect the luminous region, and we were not using the proper efficiency to correct our observed longitudinal distribution of the luminous region. We struggled to understand why our longitudinal distribution, even after applying the proper efficiency correction, exhibits a large asymmetry, we look at other possible effects such as dependence on $\cos\theta$, the efficiency correction itself, time, and all of the other analysis cuts. Finally we considered a physical effect that could cause an asymmetry, the position of the beta function waist not coinciding with the bunch-bunch collision point. After including this in our fit we get an asymmetry consistent with zero, and as we expect, the other parameters change negligibly when the asymmetry is fixed to zero. We report our updated result and compare it with our previous result. Finally we study the dependence of the bunch length on the beam current in a data set that is concurrent with streak camera based measurements and compare the two results.

1 Corrections

We begin with a definition. We always talk of the asymmetry of a single bunch, not the combined asymmetry of the luminous region. Our mistaken calculation indicated that the two were related by the square root of two, with the bunch asymmetry being larger. Thus to translate any asymmetry we talk about to the asymmetry of the longitudinal distribution of the luminous region multiply by the square root of two. Even though this is wrong it is consistent with our previous work. Since our expectation is, and as shown below we find, that this asymmetry is consistent with zero, it does not matter a great deal.

It is not true that an asymmetry in the longitudinal shape of bunches, as observed in streak camera measurements at CESR [1], lead to an asymmetric longitudinal distribution of the luminous region. Properly taking into account the time integration of the overlap between the two colliding bunches reveals that the size of the asymmetry in the bunches, smaller than 10% as observed in the streak camera measurements, has a negligible impact on the longitudinal distribution of the luminous region. Figure 1 shows the time integrated longitudinal overlap of two 200 unit long Gaussian bunches that have a 10% asymmetry with their heads being shorter

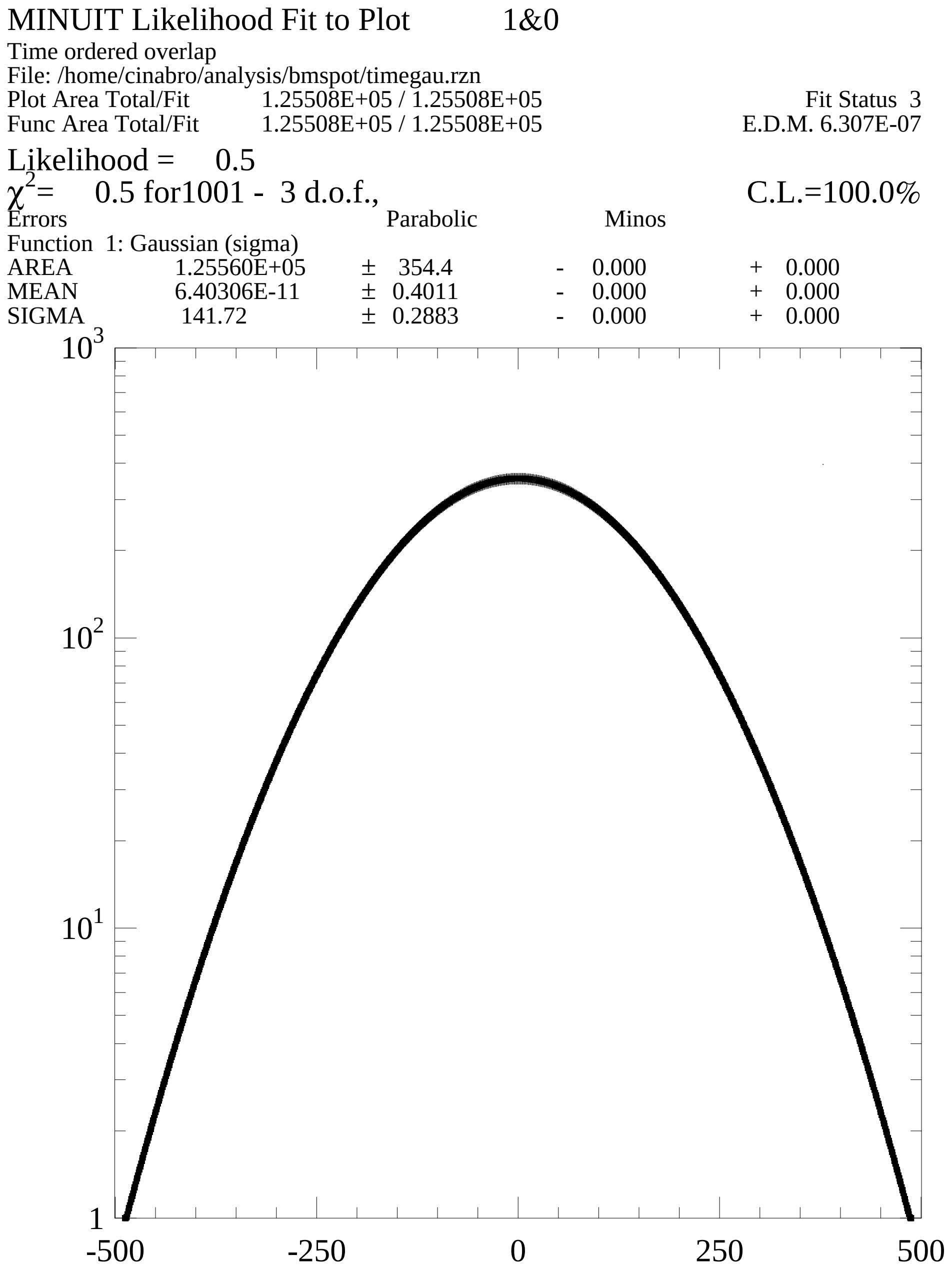

Figure 1: The time-integrated longitudinal overlap of two 200 unit length bunches. The bunches have an asymmetry of 10% with their heads being shorter than their tails.

than their tails. The distribution is fit to a Gaussian which gives a width of 141.7 units, which agrees with the expectation that the width of the overlap should be reduced by $\sqrt{2}$ from the single bunch width. The distribution also fits beautifully to a Gaussian shape with no hint of asymmetry. Fits for an asymmetry measure it consistent with zero at the 0.1% level. Figure 2 shows the overlap between two 200 unit long bunches with an extreme asymmetry of 50%. The Gaussian fit to that distribution gives a wider width than expected, 147.5 units versus 141.7, and is significantly under the data on the tails of the distribution. A fit for an asymmetry continues to show consistency with zero at the 0.1% level. We conclude that even though the streak camera observation shows that the CESR bunches are longitudinally asymmetric at the $\sim$5% level we should not observe such an asymmetry in the longitudinal distribution of the CLEO luminous region, and the effect of the bunch length asymmetry should be negligible.

This leads to the question of why we observed an asymmetry in the longitudinal distribution of the luminous region in CBN 00-6/CBX 00-22. The observed asymmetry was (-6.18 ± 0.23)%. After checking our results we realized that we were using an efficiency correction, Figure 15 in CBN 00-6/CBX 00-22, that was derived from 4SK simulation data on 4ST data. Recall that this efficiency arises from our use of back-to-back $e^+e^- \rightarrow \mu^+\mu^-$ events with each track required to have 3 SVX hits in either the $r\phi$ or z views and at least 2 SVX hits in the other view. Because of the insensitive region at the center of the SVX detector which is offset from the center of the coordinate system we expect a mainly geometrical effect that causes an asymmetric efficiency and a small enhancement at the longitudinal position of the insensitive region. This is discussed in more detail in our previous CBN/CBX. Silicon experts advised us that the detector did gradually change with time and that we should derive a new efficiency correction from a 4ST simulation. We did so running more than 100,000 $e^+e^- \rightarrow \mu^+\mu^-$ events through CLEOG and PASS2 to obtain the efficiency shown in Figure 3. Unfortunately, using this efficiency on our 4ST data we observed an asymmetry of $\sim$7%. We grew even more puzzled when we used the old 4SK derived efficiency on 4SL data and found an asymmetry of $\sim$-3%. Our investigation into the observed asymmetry in the 4ST data is discussed in detail in the next section.

2 Asymmetry Investigations

We tried to account for an asymmetry in the longitudinal distribution of the luminous region by adding an additional efficiency for tracks as a function of the $\cos\theta_z$. This had a negligible impact on anything, and was dropped as a needless complication.

We divided the 4ST on resonance data set into four bins based on run number, and repeated our procedure in each of the four bins. Table 1 summarizes the results of this study. We see no evidence for a time dependence in the observed asymmetry.

We worried that the efficiency as a function of the measured z position was introducing an artificial asymmetry. Thus we repeated our fit with no efficiency correction and found an asymmetry of (5.11 ± 0.29)%. This is reasonable as the efficiency itself, Figure 3, has an asymmetry of 1.48%, and thus should cause an increase in the raw asymmetry consistent with what we observe. We are still left with the puzzle of why the raw data has an asymmetry of 5% while the simulation predicts that it should have an asymmetry of $\sim$-1.5%.

We also note that in varying the analysis cuts as described in the systematic error section

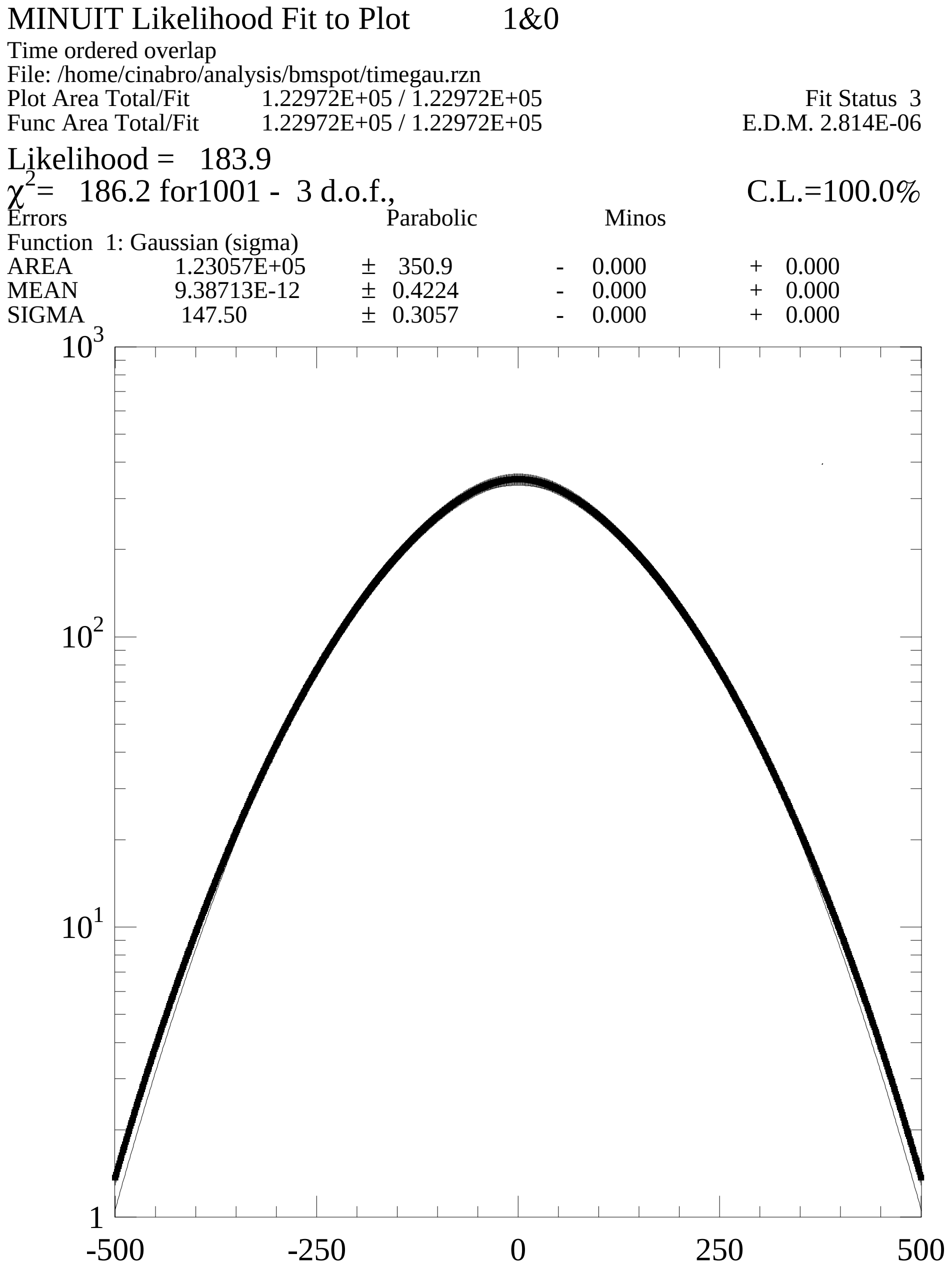

Figure 2: The time-integrated longitudinal overlap of two 200 unit length bunches. The bunches have an asymmetry of 50% with their heads being shorter than their tails. Note that the fit to a Gaussian finds a width bigger than the expected 141.7 units and significantly undershoots the distribution in the tails.

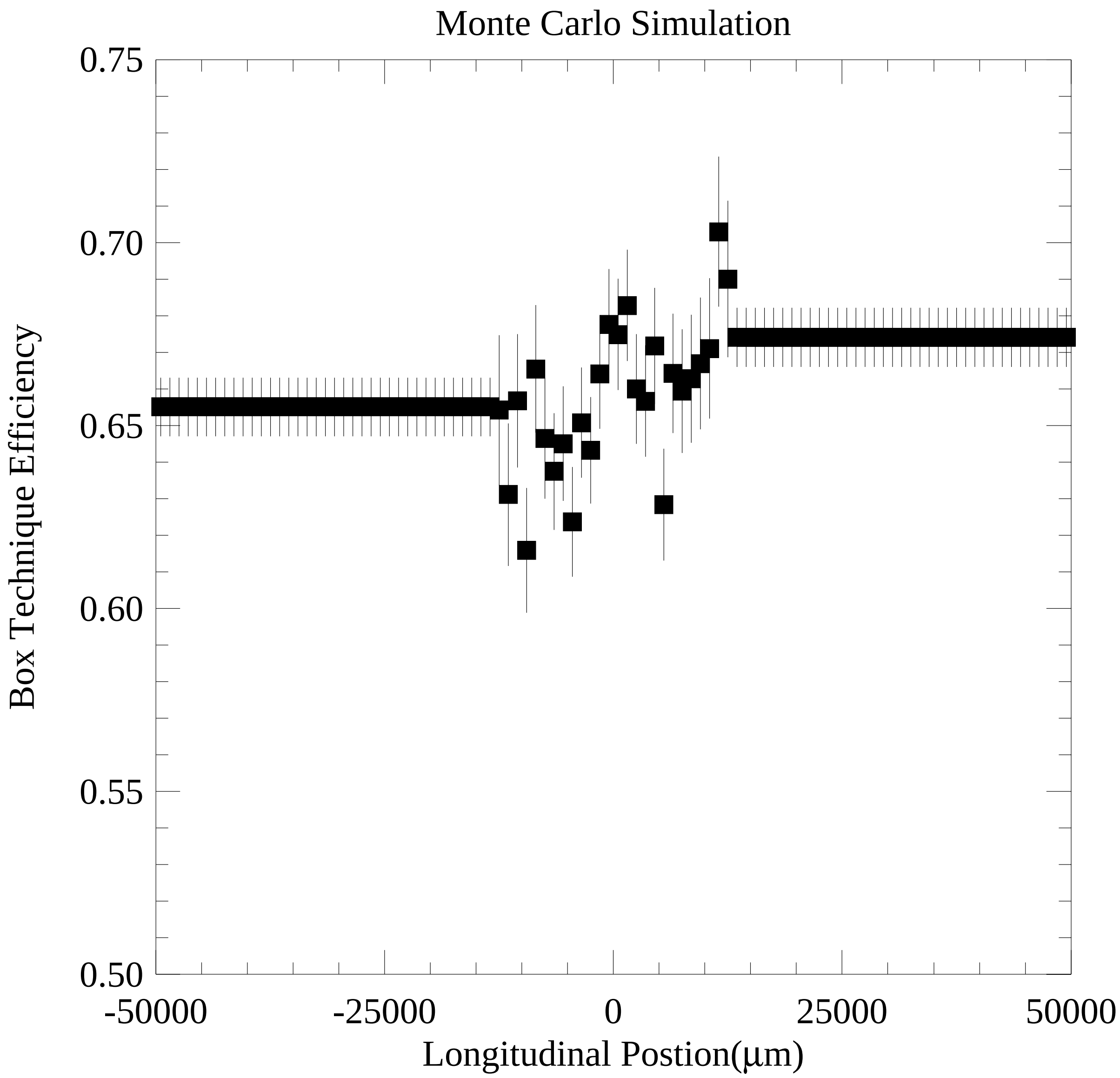

Figure 3: The efficiency from the 4ST simulation of the box technique to select track to measure the longitudinal distribution. This should be compared to Figure 15 of CBN 00-6/CBX 00-22.

Table 1: The observed asymmetry in the longitudinal distribution of the luminous region for various run ranges in the 4ST on resonance running period. The errors are only statistical.

Run Range	Observed Asymmetry (%)
96544-96950	8.07 ± 0.51
96951-97300	6.44 ± 0.43
97301-97700	6.39 ± 0.46
98000-98159	7.35 ± 0.54
96544-98159	7.01 ± 0.18

of CBN 00-6/CBX 00-22 the asymmetry was not largely affected by them. The biggest effect is seen when the data only at large longitudinal positions are considered. The observed asymmetry is reduced by 1.5% in this case.

At this point we were prepared to take the difference of fits with the asymmetry fixed at zero and floating as a measure of a systematic error caused by some unknown deficiency in our efficiency correction. Fortunately our inability to make sense of the asymmetry observed in the 4SL data used for the bunch length dependence on beam current study discussed below made us stop and think.

3 The Waist Effect

In the ideal situation the longitudinal center of the bunch collision point would coincide with the longitudinal position of the minimum in the beta function. In CESR the former is determined by the point between the west and east RF cavities and the latter is determined by the point between the two final focus REQ's. Typically these two points have been made to coincide with an accuracy of a few millimeters. The CESR folks call this exercise adjusting "the waist" of the beam, and they even have a knob that the operator can adjust to tune this by a few millimeters. Up until now we have been assuming that these points coincided exactly.

Recall the formula for the measured vertical width of the luminous region as a function of the longitudinal position near the interaction point,

$$\sigma_y(z) = \sqrt{\left[\frac{\epsilon_y}{2}\left(\beta_y^* + \frac{(z - z_{0\mathrm{beta}})^2}{\beta_y^*}\right)\right] + \mathrm{yres}^2}, \tag{1}$$

where z is the longitudinal position, ϵ_y is the vertical emittance, β_y^* is the minimum value of the vertical beta function, $z_{0\mathrm{beta}}$ is the longitudinal position of the minimum of the beta function, and yres is the resolution. Also recall the formula for the longitudinal distribution of the luminous region,

$$\frac{d\mathcal{L}}{dz} = \mathcal{L}_0 \frac{\exp\left(\frac{-(z - z_{0\mathrm{bunch}})^2}{\sigma_z^2}\right)}{\left(1 + \left(\frac{z - z_{0\mathrm{beta}}}{\beta_x^*}\right)^2\right)^{1/2}\left(1 + \left(\frac{z - z_{0\mathrm{beta}}}{\beta_y^*}\right)^2\right)^{1/2}}, \tag{2}$$

where β_x^* is the minimum value of the horizontal beta function, $z_{0\text{bunch}}$ is the longitudinal position of the center of the bunch-bunch collision, and σ_z is the bunch length. We also include a flat background to account for non-beam related events. If $z_{0\text{bunch}}$ is not equal to $z_{0\text{beta}}$ then the longitudinal distribution will be asymmetric. In principle there could be different $z_{0\text{beta}}$'s for the horizontal and vertical, but the longitudinal distribution of the CESR/CLEO luminous region is not sensitive to the horizontal beta as has been discussed in CBN 00-6/CBX 00-22. We only consider the case of $z_{0\text{beta}}$ being the same for horizontal and vertical.

We will now reconsider our data allowing $z_{0\text{bunch}}$ and $z_{0\text{beta}}$ to float freely in our simultaneous fit to the measured vertical width of the luminous region versus the longitudinal position and the longitudinal distribution of the luminous region. As a cross check we will include an asymmetry in σ_z as described in CBN 00-6/CBX 00-22. In our standard fit we will fix this asymmetry to zero as we expect, and then we will allow it to float. When allowed to float we expect that it should return with a value consistent with zero. The results of these fits are discussed in the next section.

Note that the zero of the longitudinal distribution is determined for each CLEO run, usually corresponding to one CESR fill, by a Gaussian fit to the longitudinal distribution of the luminous region found with hadronic events and discussed in our earlier work on dynamic beta effects.[2] Thus by construction the longitudinal distribution of the luminous region should peak at zero. It is worth noting that the distribution of the position of this peak measured in the CLEO coordinate system, with the zero being the center of the drift chamber, over the 4ST data set is not constant. It varies in a range of ± 250 μm centered on zero with the majority of the data at $+150 \pm 50$ μm. This variation is caused by a combination of the statistical error on the measurement, based on order of 2000 hadronic events/CLEO run measuring a ~ 10000 μm wide peak, and the CESR induced variations caused by operator tuning. These facts indicate that the extraction of any absolute longitudinal position information from the data should have an error of a few hundred microns due to this variation.

4 Updated Results

Figure 4 shows our standard fit with the asymmetry fixed at zero. Table 2 shows the results of the fit with the statistical errors and Table 3 shows the correlations among the fit parameters from this fit. There is a large change in β_y and σ_z in this fit from the results in CBN 00-6/CBX 00-22. This is mostly driven by using the correct efficiency rather than allowing different values for $z_{0\text{beta}}$ and $z_{0\text{bunch}}$. The fit does find a significant difference for $z_{0\text{beta}} - z_{0\text{bunch}} = -3740 \pm 130$ μm, which agrees with the CESR expectation of a few millimeters. The two are strongly anti correlated and $z_{0\text{beta}}$ does have non-negligible correlations with β_y and σ_z. All the other large correlations are reduced from our previous result.

Figure 5, Tables 4, and 5 show the same things but with the asymmetry in the bunch length allowed to float. Note that the asymmetry is consistent with zero and that the other parameters of the fit change negligibly. This gives us confidence that the bunch length asymmetry we were observing was caused by a displacement of $z_{0\text{beta}}$ from $z_{0\text{bunch}}$. We do not include an additional systematic error due to an asymmetry in the longitudinal distribution of the luminous region. When we allow the asymmetry to float we see changes in the key parameters that are small compared to the systematic errors we are already including due to the efficiency correction and

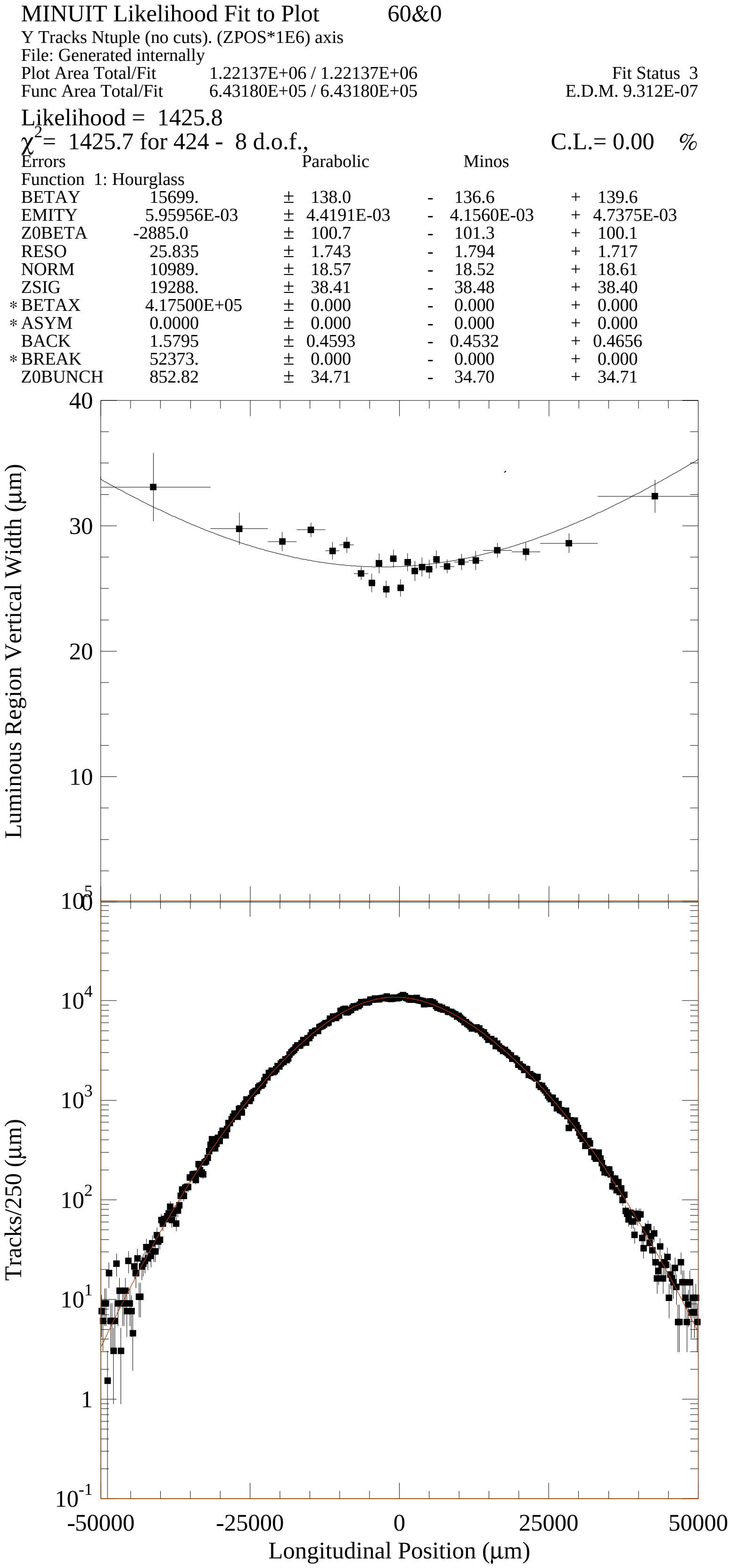

Figure 4: The simultaneous fit to the data distributions for the vertical width of the luminous region as function of longitudinal position and the longitudinal distribution. The asymmetry in the bunch length is fixed at zero.

Table 2: The results of the simultaneous fit to the data distributions for the vertical width of the luminous region as function of longitudinal position and the longitudinal distribution with the asymmetry fixed at zero.

Parameter	Fitted Value (μm)
β_y^*	15699 ± 138
ϵ_y	$0.0060 + 0.0047 - 0.0042$
σ_z	19288 ± 38
resolution	25.8 ± 1.7
$z_{0\mathrm{beta}}$	-2885 ± 101
$z_{0\mathrm{bunch}}$	852.8 ± 34.7

Table 3: The correlation coefficients for the standard fit of Table 2 and Figure 4.

	Correlation Coefficient					
Parameter	β_y^*	ϵ_y	σ_z	yres	$z_{0\mathrm{beta}}$	$z_{0\mathrm{bunch}}$
β_y^*	1.000	0.010	-0.875	-0.008	-0.280	-0.068
ϵ_y		1.000	-0.008	-0.754	0.003	-0.006
σ_z			1.000	0.007	0.417	-0.090
yres				1.000	-0.001	0.004
$z_{0\mathrm{beta}}$					1.000	-0.853
$z_{0\mathrm{bunch}}$						1.000

Table 4: The results of the simultaneous fit to the data distributions for the vertical width of the luminous region as function of longitudinal position and the longitudinal distribution with the asymmetry allowed to float.

Parameter	Fitted Value (μm)
β_y^*	15770 ± 190
ϵ_y	$0.0060 + 0.0048 - 0.0042$
σ_z	19284 ± 39
resolution	25.8 ± 1.8
$z_{0\mathrm{beta}}$	-2740 ± 290
$z_{0\mathrm{bunch}}$	740.4 ± 211.1
Asym	$(0.43 \pm 0.80)\%$

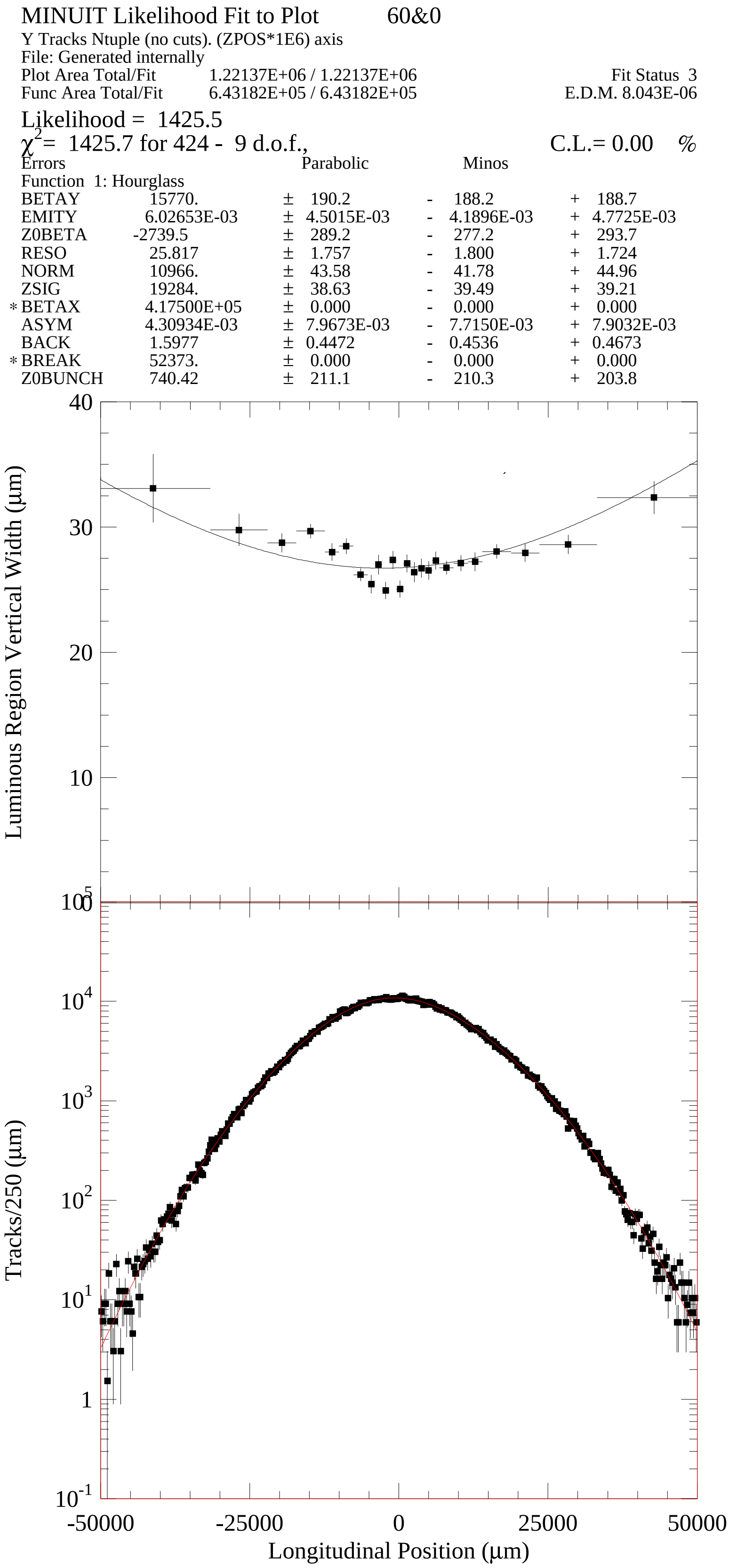

Figure 5: The simultaneous fit to the data distributions for the vertical width of the luminous region as function of longitudinal position and the longitudinal distribution. The asymmetry in the bunch length is allowed to float.

Table 5: The correlation coefficients for the asymmetry floating fit of Table 4 and Figure 5.

Parameter	Correlation Coefficient						
	β_y^*	ϵ_y	σ_z	yres	$z_{0\mathrm{beta}}$	$z_{0\mathrm{bunch}}$	A
β_y^*	1.000	0.034	-0.784	-0.024	0.577	-0.681	0.681
ϵ_y		1.000	-0.031	-0.758	0.024	-0.029	0.030
σ_z			1.000	0.026	-0.096	0.219	-0.232
yres				1.000	-0.011	0.016	-0.018
$z_{0\mathrm{beta}}$					1.000	-0.976	0.941
$z_{0\mathrm{bunch}}$						1.000	-0.987
A							1.000

Table 6: Summary of systematic effects. All values are in μm.

Source	β_y^*	ϵ_y	σ_z
Fit Procedure	± 198	± 0.0010	± 94
$\lvert\cos\theta_y\rvert$ cut variation	± 0	± 0.0012	± 0
$\lvert\cos\theta_z\rvert$ cut variation	± 240	± 0.0005	± 150
Track Selection	± 220	± 0.0010	± 75
Efficiency and MC Stats	± 250	± 0.0002	± 60
Quadrature Sum	± 456	± 0.0019	± 201

the measured asymmetry is consistent with zero, Also note that the quality of the fit changes only negligibly between the two fits. Fits without allowing anything to account for the observed asymmetry have much poorer quality.

For completeness we include Table 6 which is taken from CBN 00-6/CBX 00-22 and give our new results with their statistical and systematic errors:

$$\beta_y^* = (15700 \pm 140 \pm 460)\ \mu\text{m}, \tag{3}$$
$$\epsilon_y = (0.0060 \pm 0.0045 \pm 0.0019)\ \mu\text{m}, \tag{4}$$
$$\sigma_z = (19290 \pm 40 \pm 200)\ \mu\text{m}. \tag{5}$$

We note that if we compute the expected β_y^* taking into account dynamic beta effects we expect

$$\beta_y^* = \frac{\beta_{y0}^*}{\sqrt{1 + 4\pi\xi_0 \cot\mu_0 - 4\pi\xi_0^2}} \tag{6}$$

where β_{y0}^* is the nominal value at zero beam current, 17900 μm, ξ_0 is the beam-beam tune shift which we take to be 0.045 reflecting the very good performance of CESR during this time, and μ_0 is the vertical tune, $10.60 \times 2\pi$. This yields an expected $\beta_{y0}^* = 13300\ \mu$m. That our measured value falls somewhere between the zero beam current value and "best performance" value should not be a surprise since our value is an average over a long time and many beam conditions. The other measured parameters agree well with the expectations from CESR. These are discussed in more detail in CBN 00-6/CBX 00-22.

As another cross check of this we also looked at the longitudinal distribution of the luminous region as given by the 4ST hadronic events using the methods of the dynamic beta analysis.[2] This measurement is more difficult due to the non-negligible resolution, larger than 100 μm, the much higher amount of background, and the possibility of an efficiency that depends on the longitudinal position. Nevertheless we fit the distribution with the functional form given by Equation 2, fixing β_x and β_y to the values given above, and a flat function to take into account the non-beam related background. Focusing on $z_{0\text{beta}}$ and $z_{0\text{bunch}}$ we find $z_{0\text{beta}} = -1878 \pm 36$ μm and $z_{0\text{bunch}} = 705 \pm 14$ μm where the errors are only statistical. If we allow an asymmetry we find a substantial one of $-4.1 \pm 0.2\%$ and an increase in magnitude by about 1000 μm but no change in sign for both $z_{0\text{beta}}$ and $z_{0\text{bunch}}$. This indicates that a non-negligible efficiency correction is needed to this method. Going one step further we note that if we convoluted our functional form with a 100 μm width Gaussian to represent the resolution the results changed negligibly. These results confirm our observation in both magnitude, order of millimeter difference between $z_{0\text{beta}}$ and $z_{0\text{bunch}}$, and sign. We do not go on to try to model the efficiency for both signal and background events in this method which would be difficult and time consuming.

5 Bunch Length Dependence on Beam Current

We promised to study the effect of the beam current on the bunch length in CBN 00-6/CBX 00-22. We did this in the 4SL, from mid-November 1996 to mid-March 1997, data set as this data was taken at the same time the streak camera measurements of [1] were done. We also had 4SK derived efficiency corrections that would be good enough to model the 4SL data. The procedures that we follow are exactly as described in CBN 00-6/CBX 00-22 and as modified by previous sections. When we do this, we do not have enough data to get good measures of the vertical width as a function of longitudinal position as the 4SL data set is much smaller than the 4ST. Thus we have a preliminary look at the entire data set using all beam currents. The main goal with this exercise is to check the procedures we developed in the previous section on an independent data set. Thus we check to see if we observe a significant difference between $z_{0\text{beta}}$ and $z_{0\text{bunch}}$ and if we have unexpected asymmetry. This fit finds $z_{0\text{beta}} = (1390 \pm 140)$ μm and $z_{0\text{bunch}} = (-867 \pm 42)$ μm. The difference is again of the expected size, but with the opposite sign as observed in the 4ST. CESR expectations on this difference are not clear due to many moves of the RF cavities and the effect of tuning. When we let the bunch length asymmetry float we observe an asymmetry of $(0.06 \pm 0.13)\%$, consistent with zero as expected. Thus we confirm that a difference between $z_{0\text{beta}}$ and $z_{0\text{bunch}}$ accounts for an asymmetry in the longitudinal distribution of the luminous region, and our procedures used in the 4ST data are not flawed. We also measure $\beta_y^* = (15970 \pm 200)$ μm and $\epsilon_y = (0.0025 \pm 0.0052)$ μm. These are consistent with the 4ST results, but with larger errors.

To extract the bunch length as a function of beam current we bin the data by the beam current. We drop the fit to the vertical width as a function of the longitudinal position as there is not enough statistics to make useful measurements of the vertical width when it is binned by beam current. That is we are fitting the longitudinal distribution of the luminous region to Equation 2 as a function of beam current. In these fits we fix β_x^* to 417500 μm, there is little

Table 7: Our measurement of the bunch length as a function of beam current in the 4SL data set. The error is a combined statistical and systematic.

Beam Current (mA)	Bunch Length (mm)
92	16.99 ± 0.27
100	17.41 ± 0.21
108	17.45 ± 0.21
117	17.39 ± 0.20
125	17.44 ± 0.20
133	17.39 ± 0.21
142	17.50 ± 0.21
150	17.45 ± 0.21
158	17.27 ± 0.22

dependence on this parameter, and $z_{0\mathrm{beta}}$, $z_{0\mathrm{bunch}}$, β_y^* to the values found in the fit to the entire data set as discussed above. We only let the normalization, bunch length, and background float.

The results are shown in Figure 6 and Table 7. The Figure also shows the line found in [1] in colliding beam conditions averaging the electron and positron beam parameters. The other line is a fit to our observation and it has parameters of 0.0026 ± 0.0035 mm/mA for the slope and 17.04 ± 0.45 mm for the offset. These should be compared with 0.0238 and 15.83 respectively for the streak camera line. That measurement has an error of about 1 mm also shown on the plot. We do not see a significant dependence of the bunch length on the beam current and our numbers are systematically lower than the streak camera measurement although with the errors the difference is not significant.

It is difficult to draw quantitative conclusions as the streak camera measurement was made during one fill at a specific RF voltage while our measurement is the average over many fills with changing conditions. Also note that the 4SL bunch length is about 17.3 mm while the 4ST is 19.3 mm. The RF conditions of the two data sets is very different, with only one superconducting RF cavity during the 4SL and two during the 4ST.

6 Conclusion

We corrected an error that we were led to by our misunderstanding of the effect asymmetric bunches would have on the longitudinal distribution of the luminous region. Bunches with a head-tail asymmetry do not cause an asymmetry in the luminous region. We now use the appropriate efficiency for the 4ST data set we have been considering. The longitudinal asymmetry we are observing is accounted for by the longitudinal position of the minimum of the beta function not coinciding with the center of the bunch-bunch collision. We make new measurements of the CESR beam parameters taking into account the possibility of such a difference that supersede those of our previous work in CBN 00-6/CBX 00-22. We clearly see a difference between these positions in both the 4ST and 4SL data sets.

We investigated the dependence of the bunch length on the beam current in the 4SL data

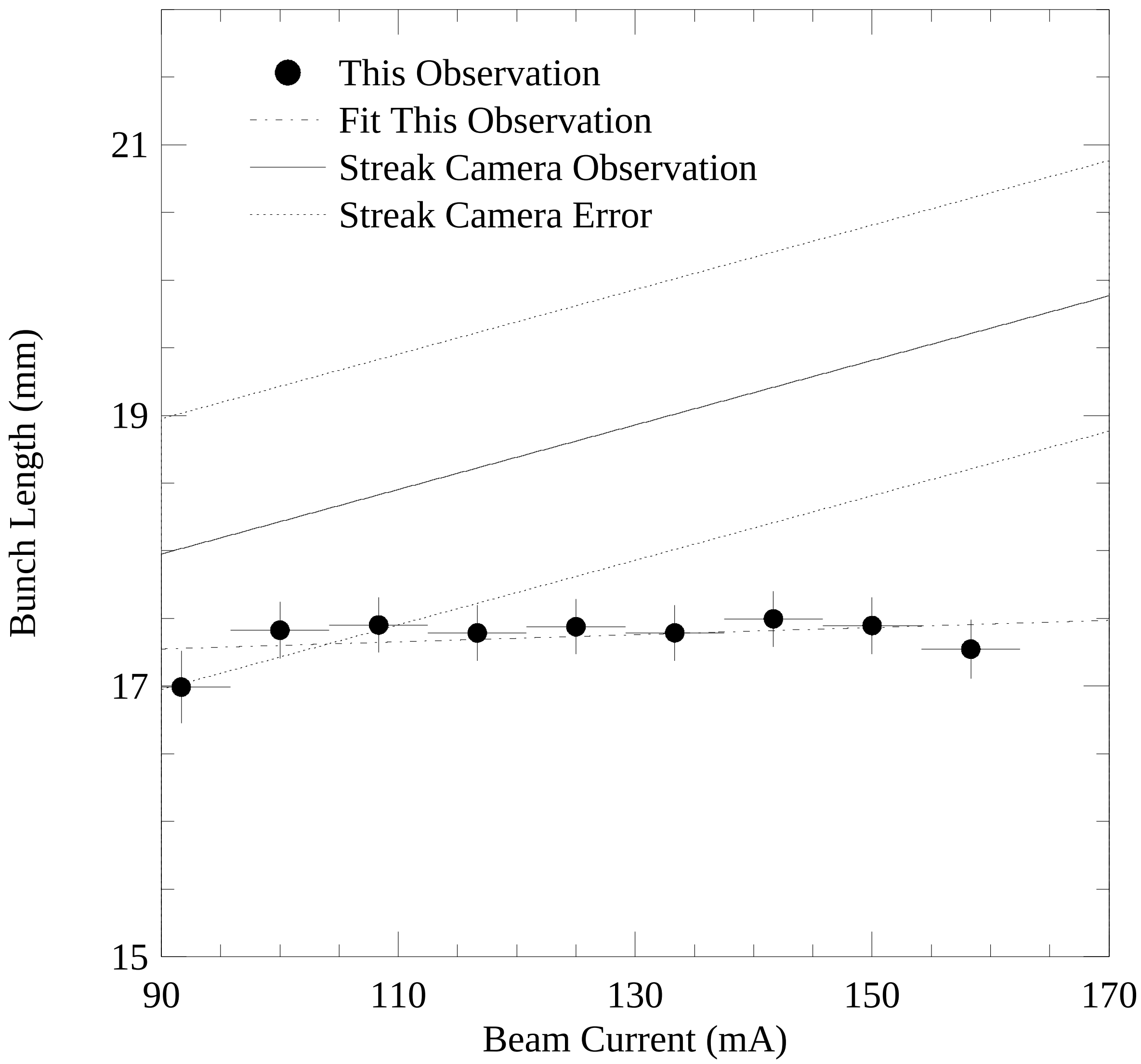

Figure 6: This measurement of the bunch length as a function of beam current in the 4SL data set. The solid and dotted lines show the results of the streak camera observation and the dash-dot line shows a fit to our data.

set. In contrast to the results of the streak camera measurements in [1] we do not see a strong dependence. We also note that we see a a significantly shorter bunch length in the 4SL than in the 4ST.

References

[1] CBN 99-9 and CBN 99-10, R. Holtzapple, *et al* and R. Holtzapple, *et al*, Phys. Rev. ST Accel. Beams **3**, 034401.

[2] CBX 96-94/CBN 96-17 and CBX 97-39/CBN 97-14, D. Cinabro.