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Heavy Quark Production at SLC and LEP

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ABSTRACT

Experiments at SLC and LEP have made preliminary measurements of the relative partial widths of the c and b quarks. Using D^* tagging, DELPHI has found $R_{c\bar{c}} \equiv \Gamma_{c\bar{c}}/\Gamma_{hadr.} = 0.162 \pm 0.032 \pm 0.031$, in good agreement with the Standard Model value of 0.171. ALEPH has used semileptonic decays of charm to obtain $0.148 \pm 0.044^{+0.045}_{-0.038}$. Three experiments have used semileptonic B decays to measurement $R_{b\bar{b}}$: $R_{b\bar{b}} = 0.23 \pm 0.10$ (Mark II), $0.218 \pm 0.010 \pm 0.021$ (L3), and $0.220 \pm 0.016 \pm 0.024$ (ALEPH). All agree well with the expected value of 0.217. The uncertainty in branching ratios of c and b hadrons is the largest systematic error in all of the results. Future LEP measurements of the branching ratios may reduce the errors. $R_{b\bar{b}}$ will also be measured with different, and possibly lower, systematic errors by Mark II using impact parameter tagging.

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1. Introduction

The measurement of the branching fraction of the Z into each family of fermions provides a strict test of the standard model. This paper discusses measurements of heavy quark production at the Z , and is divided into four general sections: strange particle production at SLC; charm quark hadronic fraction using D^* tagging; charm and bottom quark fractions using semileptonic decays; and impact parameter tagging of bottom quark events. The results presented are all preliminary, but where possible, I have given references to preprints.

All analyses discussed are based on hadronic decays of the Z . The specific cuts used by each experiment to select hadronic events depend on the details of each detector, but all have high efficiency and essentially no backgrounds. For this reason I will not describe the hadronic event selection in detail.

2. Strange Particle Production at SLC

2.1. INTRODUCTION

The fragmentation of partons into the hadrons observed in the detector is a low energy — hence, nonperturbative — QCD phenomenon. Thus, hadronization is described by phenomenological models. Measurements of the production rates of K^0 and Λ provide a window on understanding these models. These rates are presumably also sensitive to the branching ratio of the Z to strange quarks, but feed-down from charm and bottom quarks and from gluon jets makes it very difficult to extract a meaningful value.

2.2. EVENT SELECTION

K^0 and Λ 's are identified by the characteristic "V" formed when the neutral particle decays into a pair of charged particles. Because of the long lifetimes, the V is typically displaced by centimeters from the interaction point. Tracks to be considered in the V search must be well-measured ($|\cos\theta| < 0.8$, $p_t > 0.1$ GeV, at least 24 drift chamber hits out of a possible 72) and must have a large distance-of-closest approach (DCA). Specifically, $DCA > 1$ mm, and $p_t \cdot DCA > 2$ mm-GeV. A larger DCA is required at low p_t because multiple scattering broadens the DCA distribution.

A pair of oppositely-charged selected tracks is labeled a V if the distance between the tracks in z , measured at the $r - \phi$ intercept, is less than 4 cm, and if the angle between the momentum and position vector of the V is less than 90° . There are three possible masses for the V — the pair of particles could be $\pi^+\pi^-$, π^-p , or $\bar{p}\pi^+$. The alternative closest to m_{K^0} or m_Λ is chosen. After the tracks are constrained to come from a common vertex and corrections are applied for dE/dx losses, K^0 candidates are selected by $478 < m_V < 518$ MeV, and Λ candidates by $1105 < m_V < 1125$ MeV.

2.3. RESULTS

There are 75 K^0 and 42 Λ candidates in the mass peaks, in $N_{\text{had}}/\epsilon = 548$ hadronic events. The background due to mistracking and random overlap is flat in mass and is extracted from a fit to the wings of the distributions, giving 5 events for the K^0 peak and 6 events for the Λ . The second background is due to the misassignment of K^0 's to the Λ peak and visa-versa. This source necessarily peaks near m_{K^0} and m_Λ and so is not included in the flat background. Monte Carlo calculations indicate that the K^0 peak includes one such event, while the Λ peak includes four.

The selection efficiencies are 0.062 and 0.105 for K^0 and Λ 's respectively. The production rates are therefore $2.0 \pm 0.3 \pm 0.3$ K^0 per hadronic event and $0.58 \pm$

$0.12 \pm 0.09 \Lambda$ per hadronic event. The systematic errors are derived by varying the selection cuts. The K^0 rate as a function of \sqrt{s} is shown in Figure 1.^[1] The observed increase is well described by both the Lund parton shower model with string fragmentation^[2] (solid line) and the Webber-Marchesini parton shower model with cluster fragmentation.^[3]

3. Measurement of $\Gamma_{c\bar{c}}$ using D^* Tagging

3.1. INTRODUCTION

The DELPHI collaboration has measured the Z to $c\bar{c}$ partial width using the process

$$c\bar{c} \rightarrow D^{*+} + X \rightarrow D^0 \pi^+ + X. \quad (3.1)$$

The notable feature of this process is that the residual energy of the $D^{*+} \rightarrow D^0 \pi^+$ decay is only 6 MeV. Thus, the π^+ has low p_t with respect to the jet axis — an average of 65 MeV, versus 300 MeV for typical fragmentation products. This feature is used to tag the D^* , eliminating the need to reconstruct the D^0 .^[4] D^* 's can also be produced in $b\bar{b}$ and gluon jets, but the effect is not as pronounced and cuts are applied to suppress these backgrounds.

3.2. EVENT SELECTION

A total of 37900 hadronic events are used in the analysis. Each event is divided into jets using the Lund cluster finder, and the axis of the jet is determined by its thrust. The jets used in the analysis must have at least three tracks, at least one track with $p > p_{\pi^+}$, $|\cos \theta_j| < 0.8$, and $E_{\text{jet}} > 0.9E_{\text{hemis.}}$. The cuts ensure that the jet is fully contained within the detector and that it is from a primary quark, not a gluon. Candidate tracks are required to have $1.5 < p < 2.5$ GeV and an impact parameter less than 2 cm. The lower cut on momentum rejects soft fragmentation and $b\bar{b}$ events, which tend to give pions from D^* 's with lower momentum and higher p_t . Both cuts help eliminate photon conversions.

3.3. EXTRACTING N_{D^*}

The number of D^* 's is extracted by a fit to the p_t spectrum of the tracks passing the cuts above. The Monte Carlo prediction of the signal is fit with a function of the form $S(p_t^2) = N_s^0 e^{-\frac{p_t^2}{B^2}}$, giving $B = 65 \pm 3$ MeV. The specific value found for B depends both on the kinematics of the process and the resolution of the detector. The MC background (tracks from uds quark and c quarks not decaying to D^* 's) is well described by two different forms:

$$\begin{aligned} F_1(p_t^2) &= \frac{a}{1 + bp_t^2 + cp_t^4} \\ F_2(p_t^2) &= a' + b'e^{-\frac{p_t^2}{c'^2}} \end{aligned} \quad (3.2)$$

Figure 2 shows the MC predictions for signal and background. The data, Figure 3, shows a clear signal for tracks in the correct momentum region and no enhancement at low p_t for $3 < p < 4$ GeV. The data is fit with each of the two background forms, with N_s and the three F_i parameters free and $B = 65$ MeV fixed. The number of D^* 's (N_s) is found to be 426 ± 76 using F_1 and 336 ± 68 using F_2 , for an average of 381 ± 76 .

3.4. RESULTS

The $c\bar{c}$ fraction of hadronic events is found from:

$$R_{c\bar{c}} \equiv \frac{\Gamma_{c\bar{c}}}{\Gamma_{\text{hadrons}}} = \frac{N_s}{N_h \epsilon_s}, \quad (3.3)$$

where $N_h = 37900$. The efficiency ϵ_s is the product of three probabilities:

$$\begin{aligned} \epsilon_s &= P_1(c\bar{c} \rightarrow D^{*+} + X \rightarrow D^0 \pi^+ + X) &= 0.031 \pm 0.05 \\ &\cdot P_2(\pi^+ \text{ passes cuts}) &= 0.27 \pm 0.02 \\ &\cdot P_3(\pi^+ \text{ counted by fit}) &= 0.78 \pm 0.05, \end{aligned} \quad (3.4)$$

where the errors are systematic. Thus,

$$R_{c\bar{c}} = 0.162 \pm 0.032 \pm 0.031, \quad (3.5)$$

in good agreement with the Standard Model value of 0.171.

P_1 , which dominates the systematic error, is calculated from CLEO measurements^[5] at $\sqrt{s} = 10.55$ GeV (below the $b\bar{b}$ threshold) and Mark III data.^[6] CLEO has measured $B \cdot \sigma(e^+e^- \rightarrow D^{*+} \rightarrow D^0\pi^+)$ for two final states of the D^0 decay: $D^0 \rightarrow K^-\pi^+$ ($17.0 \pm 1.5 \pm 1.4$ pb) and $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ ($33.0 \pm 3.0 \pm 1.8$ pb). The branching ratios of the D^0 to these two final states have been measured by Mark III running on the $\psi(3770)$ to be $0.042 \pm 0.004 \pm 0.004$ and $0.091 \pm 0.008 \pm 0.008$ respectively. Finally, the total cross section for $e^+e^- \rightarrow c\bar{c}$ at $\sqrt{s} = 10.55$ GeV has been determined by CLEO to be 1232 ± 104 pb. Together, these give $P_1 = 0.31 \pm 0.05$. This calculation assumes that the fragmentation of the c quark does not change between 10.55 and 91 GeV.

As can be seen from the discussion, the error on P_1 has contributions from several sources, so a better value will require a different measurement. For example, with sufficient statistics, DELPHI may be able to determine P_1 by the ratio of events with a single D^* to those with two.

4. Measurements of $R_{c\bar{c}}$ and $R_{b\bar{b}}$ using Inclusive Leptons

4.1. INTRODUCTION

Mark II,^[7] L3^[8] and ALEPH^[9] have used semi-leptonic decays to tag decays of the Z to $b\bar{b}$ and, by ALEPH, $c\bar{c}$. The leptons have high momentum due to the hard fragmentation of heavy quarks and have large transverse momentum with respect to the hadronic jet due to the relatively large quark masses. Thus, hadronic events that contain leptons with high p and p_t tend to be $b\bar{b}$ and, to a lesser extent, $c\bar{c}$ decays. Much of the discussion in this section concerns muon and electron identification, as this is the most difficult part of the analysis.

4.2. EVENT SELECTION

The results presented here are based on 413 hadronic events for Mark II, 38000 for L3 and 25000 for ALEPH. The three experiments use different techniques for dividing the experiment into jets. The most significant difference is that L3 measures the p_t with respect to the jet axis calculated including the lepton, whereas Mark II and ALEPH exclude the lepton when calculating the axis. (Monte Carlo studies indicate higher background rejection in this case). Thus, the p_t distributions cannot be directly compared.

4.3. MUON IDENTIFICATION

I will use ALEPH to illustrate particle identification methods, since L3 does not use electrons. Muons in ALEPH are selected by counting hits in a 3σ wide cone in the 23 layers of the barrel hadron calorimeter. They are required to have at least nine hits, including four in the last ten layers and one in the last three layers. The average plane inefficiency, which is due largely to geometry, is measured using $e^+e^- \rightarrow \mu^+\mu^-$ to be 30%. An additional cut on excess hits within ± 25 cm in the last ten layers reduces hadronic punchthrough. The efficiency for detecting muons in the barrel region with momentum greater than 3 GeV is 0.83 ± 0.03 .

Decays of pions and kaons produce a background of real muons, which is suppressed by requiring that muon candidate tracks have impact parameters less than 5 mm. Monte Carlo calculations are used to predict the remaining background. A second class of backgrounds is hadronic punch-through, in which a hadron — either a primary particle or a shower product — is not stopped in the calorimeter. Monte Carlo calculations predict that 0.3–0.6% of hadrons (depending on momentum and p_t) pass the muon cuts. An uncertainty of $\pm 60\%$ is assumed on this prediction.

4.4. ELECTRON IDENTIFICATION

Electromagnetic calorimeter (ECAL) data and dE/dx from the TPC are used to identify electrons. Two ECAL quantities are defined, the first a comparison of the calorimeter energy to the TPC momentum measurement: $R_T \equiv (X - \langle X \rangle) / \sigma(X)$, where $X \equiv E/p$ (E = four-tower sum). The other is dependent on the longitudinal energy distribution: $R_L \equiv (A - \langle A \rangle) / \sigma(A)$, where A^{-1} is the mean longitudinal position in the ECAL. The tests were developed using test beam data. The efficiency — measured using photon conversions — is 0.80 ± 0.02 , independent of momentum and p_t . Hadron showers typically start too late ($R_L < 0$) and have X too low ($R_T < 0$), as is clear in Figure 4. Electrons are required to satisfy $R_T > -3.0$ and $-2.4 < R_L < 3.0$.

The orthogonal electron identification by the TPC dE/dx provides a good measurement of backgrounds and improves signal to noise for low momentum. The TPC gives up to 330 wire hits; electron candidates are required to have at least 80 isolated hits. These hits are used to define $R_I \equiv (I - \langle I_e \rangle) / \sigma(I)$, where I is the 60% truncated mean and $\langle I_e \rangle = 1.58$ is the average for electrons. The efficiencies and $\sigma(I)$ are from hadronic data. $\epsilon_I = 0.50-0.90$, depending on p_t . Most of the inefficiency is due to requiring that the 80 hits be isolated. The ECAL and dE/dx cuts are most effective for different regions in momentum (Figure 5).

Background electrons from conversions and Dalitz decays are reduced by cuts on track impact parameter, invariant mass of oppositely charged tracks and number of inner-tracking-chamber hits. The remaining contamination is extracted as a function of momentum and p_t from the observed R_I distributions (Figure 6). The background R_I shape is determined from tracks failing the ECAL cuts, while the signal is a gaussian of unit width. The remaining contamination is 0.04–0.25% of hadronic tracks.

4.5. DETERMINATION OF $R_{b\bar{b}}$

ALEPH uses only the high- p_t sample of leptons — defined as $p > 3$ GeV, $p_t > 2$ GeV — to measure $R_{b\bar{b}}$. The dE/dx cuts are not used in this case. The b purity is high for this sample: 75% for electrons and 71% for muons. The remaining tracks are from c quarks (10% e^- , 9% μ^-), and other backgrounds (15% e^- , 20% μ^-). After a background subtraction, there are 278 ± 19 electrons and 191 ± 17 muons. The $b\bar{b}$ fraction times leptonic branching ratio is measured for e^- and μ^- to be:

$$\begin{aligned} B(b \rightarrow e) \cdot R_{b\bar{b}} &= 0.0217 \pm 0.0019 \pm 0.0010 \\ B(b \rightarrow \mu) \cdot R_{b\bar{b}} &= 0.0238 \pm 0.0028 \pm 0.0012, \end{aligned} \tag{4.1}$$

where the errors are statistical and systematic. From ARGUS and CLEO measurements at the $\Upsilon(4S)$,^[10] $B(b \rightarrow l\nu X) = 0.102 \pm 0.007 \pm 0.007$. Thus, the average of e^- and μ^- gives

$$R_{b\bar{b}} = 0.220 \pm 0.016 \pm 0.024, \tag{4.2}$$

in good agreement with the Standard Model prediction of 0.217.

Mark II, using a similar analysis but with much lower statistics, has found $R_{b\bar{b}} = 0.23 \pm 0.10$.

L3 currently uses only muons in the analysis. The distribution of tracks in p , p_t and missing transverse energy is fit for tracks with $4 < p < 25$ GeV. (The neutrino accompanying the leptonic B decay increases the missing energy for the desired events). L3 finds:

$$R_{b\bar{b}} = 0.218 \pm 0.010 \pm 0.021. \tag{4.3}$$

The semileptonic branching ratio used is $B(b \rightarrow \mu\nu X) = 0.118 \pm 0.011$.

For both LEP experiments, the systematic errors are now dominant and are due largely to the uncertainty in the semileptonic branching ratios. These ratios will be measured at LEP by double tagging when sufficient data (several hundred thousand Z 's) has been recorded.

4.6. DETERMINATION OF $R_{c\bar{c}}$

ALEPH has obtained $R_{c\bar{c}}$ using electrons with $p > 2$ GeV. This measurement requires a careful understanding of the backgrounds, because of the relatively low p_t of the leptons from c quarks (Figure 7). Muons are not used because the low p_t backgrounds are not well understood. dE/dx cuts are applied in this case. A fit is performed to the p and p_t distribution in six bins of fragmentation $x \equiv E_{\text{had}}/E_{\text{beam}}$, for four fit parameters: $R_{b\bar{b}}$, $R_{c\bar{c}}$, $\langle x_b \rangle$ and $\langle x_c \rangle$. The results are:

$$\begin{aligned} R_{b\bar{b}} &= 0.215 \pm 0.017(\text{stat}) \\ R_{c\bar{c}} &= 0.148 \pm 0.044^{+0.045}_{-0.038}. \end{aligned} \tag{4.4}$$

The Standard Model value for $R_{c\bar{c}}$ is 0.171. The largest systematic error is again the uncertainty in the semileptonic branching ratios.

5. Impact Parameter Tagging of $b\bar{b}$ Events using Mark II Vertex Detectors

5.1. INTRODUCTION

A measurement of $R_{b\bar{b}}$ with different, and possibly lower, systematic errors can be made by using the relatively long B lifetime to tag $b\bar{b}$ events. At the Z resonance, the average flight path is 1.6 mm, giving an average impact parameter of 200 μm . Because of the small beampipe radius at SLC — 2.5 cm — the two Mark II vertex detectors have the best resolution and so will be emphasized in this section. Both the drift chamber vertex detector (DCVD) and the silicon strips (SSVD) were installed in December 1989 and have since been check out with cosmic rays and a short data run.

5.2. MARK II VERTEX DETECTORS

The DCVD^[11] is a high precision drift chamber with 38 layers covering $5 < r < 17$ cm. Individual wires are placed in planes with errors of less than $3 \mu\text{m}$, while the planes of wires are located with $20 \mu\text{m}$ accuracy. The gas is $\text{CO}_2(92)/\text{ethane}(8)$ at 2 atmospheres. The drift velocity depends linearly on temperature, pressure and the applied high voltage, so all are controlled to within 5 parts in 10^4 . The resulting single-layer resolution depends on drift distance, averaging $50 \mu\text{m}$ (Figure 8a). The impact parameter resolution has been measured with cosmic rays to be $30 \mu\text{m}$, slightly larger than the expected $23 \mu\text{m}$ (Figure 8b). It is expected to decrease with further study, but is already more than sufficient to tag B events.

The SSVD^[12] consists of three layers of silicon strips at radii of 29, 33 and 37 mm, covering $|\cos \theta| < 0.78$. The modules are arranged in ϕ so that 50% of tracks go through two layers and 50% go through three. The SSVD was internally aligned to within $5 \mu\text{m}$ before installation, and the data recorded so far give single layer resolutions consistent with the expected value of $6 \mu\text{m}$. The resolution is less than the strip pitch of $25\text{--}33 \mu\text{m}$ because each track deposits energy in an average of four strips. The impact parameter resolution for the SSVD is $\sigma_b^2 = (40/p)^2 + 5^2 \mu\text{m}^2$ (p in GeV). The first term is due to multiple scattering, while the second is the intrinsic resolution. An additional contribution is the uncertainty in the position of the interaction point.

5.3. B TAGGING WITH THE MARK II VERTEX DETECTORS

Events from $Z \rightarrow b\bar{b}$ can be selected by requiring in at least one hemisphere that there be at least three tracks with impact parameters $> 3\sigma_b$, and that the invariant mass of the high-impact-parameter tracks be greater than 2 GeV. The mass cut suppresses charm events. These cuts tag $b\bar{b}$ events with an efficiency of 30–35% and give a purity of 77%. For a sample of 3000 Z 's — the expected number from the ongoing run — Mark II will be able to measure $R_{b\bar{b}}$ with a statistical error of approximately 7% and a systematic error of 5–10%.

6. Conclusions

Measurements of heavy quark production at SLC and LEP agree with the predictions from the Standard Model that $R_{c\bar{c}} = 0.171$ and $R_{b\bar{b}} = 0.217$. Using D^* tagging, DELPHI has found $R_{c\bar{c}} = 0.162 \pm 0.032 \pm 0.031$, while ALEPH has used semileptonic decays of charm to obtain $0.148 \pm 0.044^{+0.045}_{-0.038}$. Mark II, L3 and ALEPH have used semileptonic decays to measure $R_{b\bar{b}}$:

$$\begin{aligned}
 R_{b\bar{b}} &= 0.23 \pm 0.10 && \text{Mark II} \\
 &= 0.218 \pm 0.010 \pm 0.021 && \text{L3} \\
 &= 0.220 \pm 0.016 \pm 0.024 && \text{ALEPH.}
 \end{aligned}
 \tag{6.1}$$

The dominant systematic errors are due to uncertainty in the branching ratios of the D and B . These branching ratios will eventually be measured at LEP. $R_{b\bar{b}}$ will also be measured with different, and possibly lower, systematic errors by Mark II using impact parameter tagging.

FIGURE CAPTIONS

- 1) Number of K^0 's per hadronic event as a function of \sqrt{s} . Both the Lund string fragmentation (solid line) and Webber-Marchesini cluster fragmentation (dashed line) models describe the data well.
- 2) Monte Carlo predictions for the p_t^2 distribution of tracks with respect to the jet axis, $1.5 < p < 2.5$ GeV, for (a) $c\bar{c}$ events and (b) other quarks. The cross hatched histogram in (a) is for π^+ 's from $D^{*+} \rightarrow D^0 \pi^+$ decays. The solid line is the fit for $S(p_t^2) + F_2(p_t^2)$, the dashed line is F_2 only.
- 3) p_t^2 distribution of charged tracks in the DELPHI data for (a) $1.5 < p < 2.5$ GeV and (b) $3.0 < p < 4.0$ GeV. The solid line is the fit for $S(p_t^2) + F_2(p_t^2)$, the dashed line is F_2 only.
- 4) Electromagnetic calorimeter electron-ID quantities for tracks with $p > 2$ GeV (ALEPH). Electrons have $\langle R_L \rangle = \langle R_T \rangle = 0$, while hadrons tend to have $R_L < 0$ and $R_T < 0$.

- 5) Electron identification as a function of track momenta (ALEPH). (a) ECAL quantity R_T , after the cut on R_L has been applied. (b) dE/dx cut R_i , after both R_T and R_L cuts are applied.
- 6) The distribution of R_i for tracks with $3 < p < 7$ GeV that pass the ECAL electron ID cuts. The solid line is a fit to the data. The background shape (dashed line) is found from tracks failing the ECAL cuts. The signal is a gaussian of unit width.
- 7) p_t with respect to jet axis of tracks passing the ECAL and dE/dx cuts, together with Monte Carlo predictions of the distribution for each component of the data. The solid line is a fit to the data.
- 8) (a) Single layer resolution of the Mark II DCVD and (b) two track miss distance for high momentum cosmic rays. The impact parameter resolution is $30 \mu\text{m}$.

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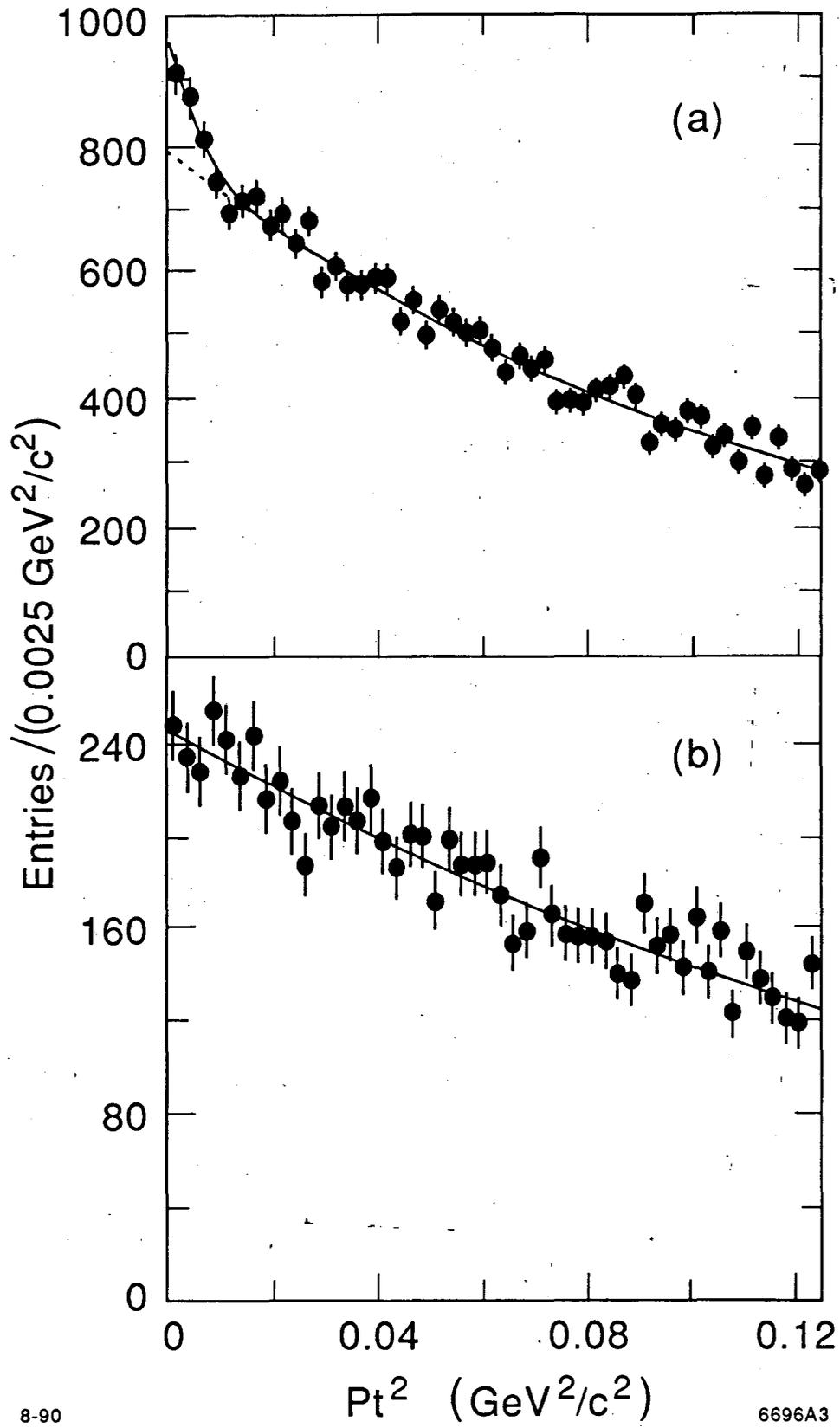


Figure 3

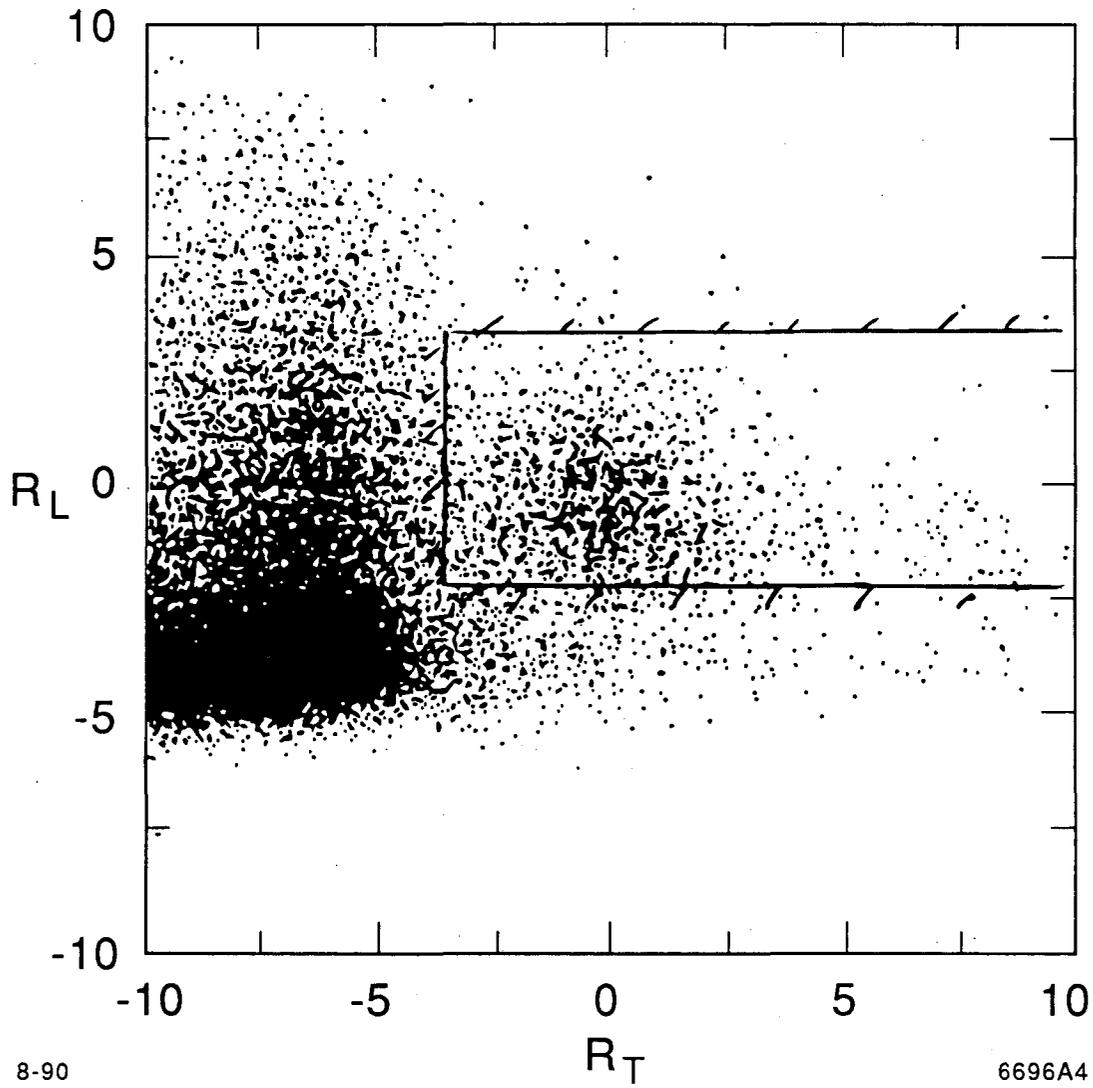


Figure 4

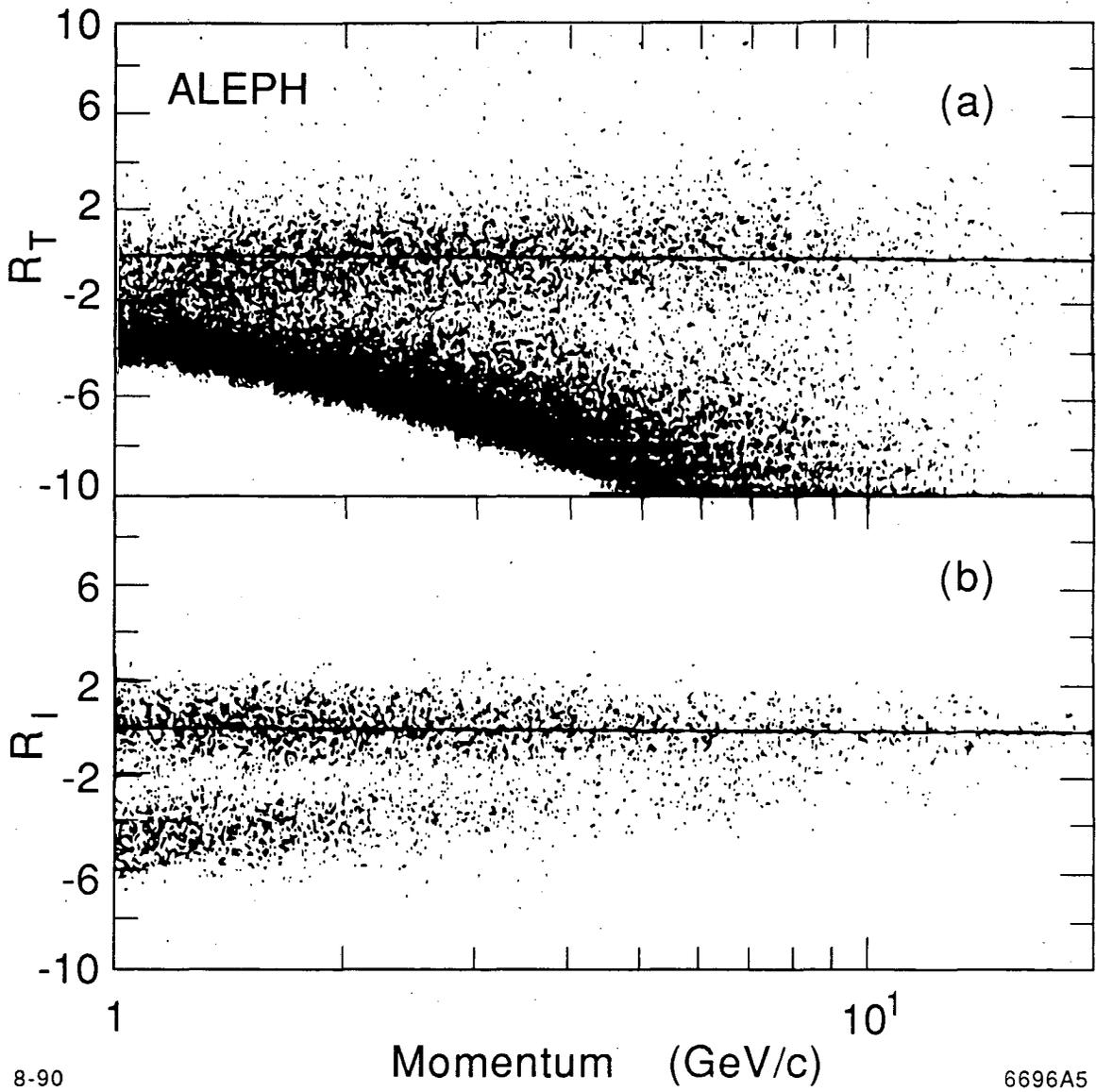


Figure 5

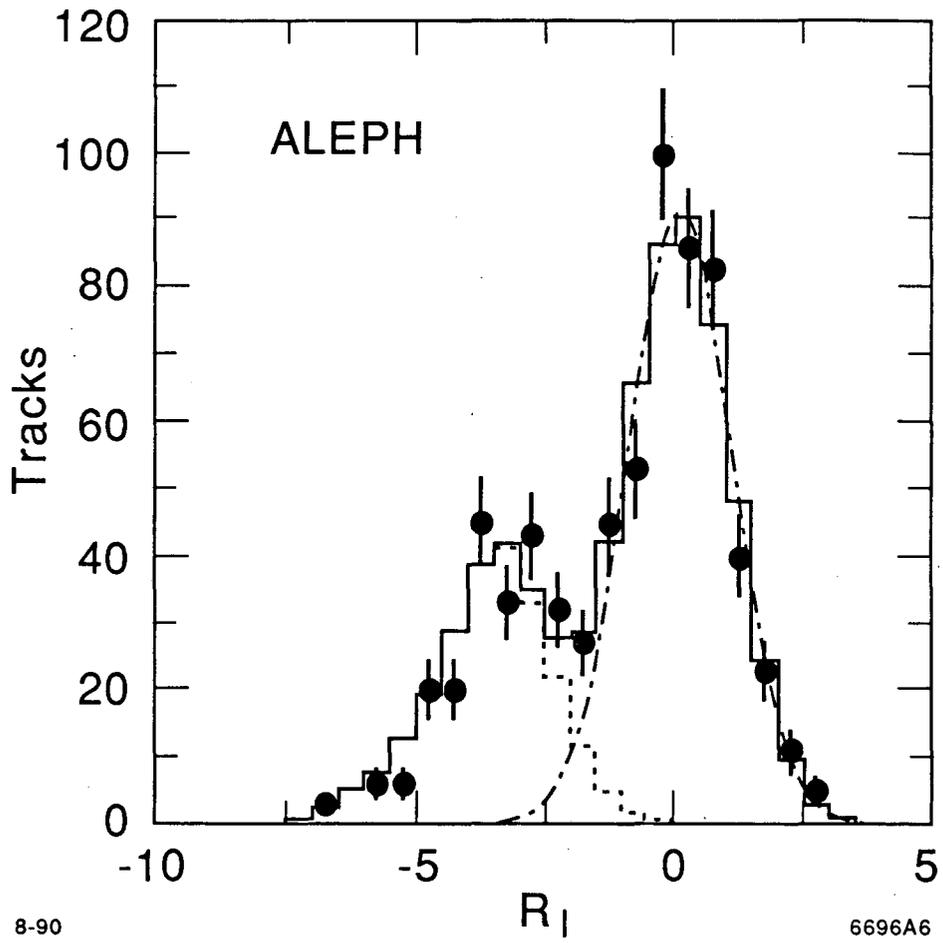


Figure 6

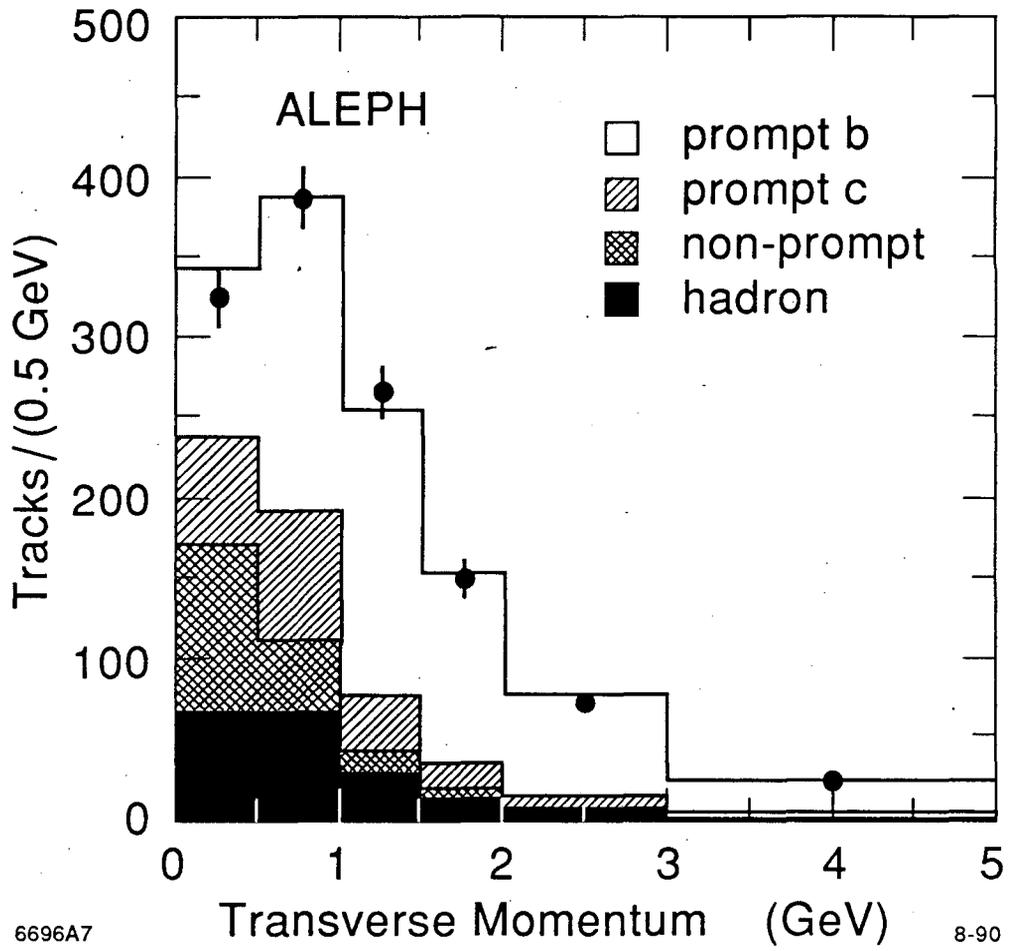
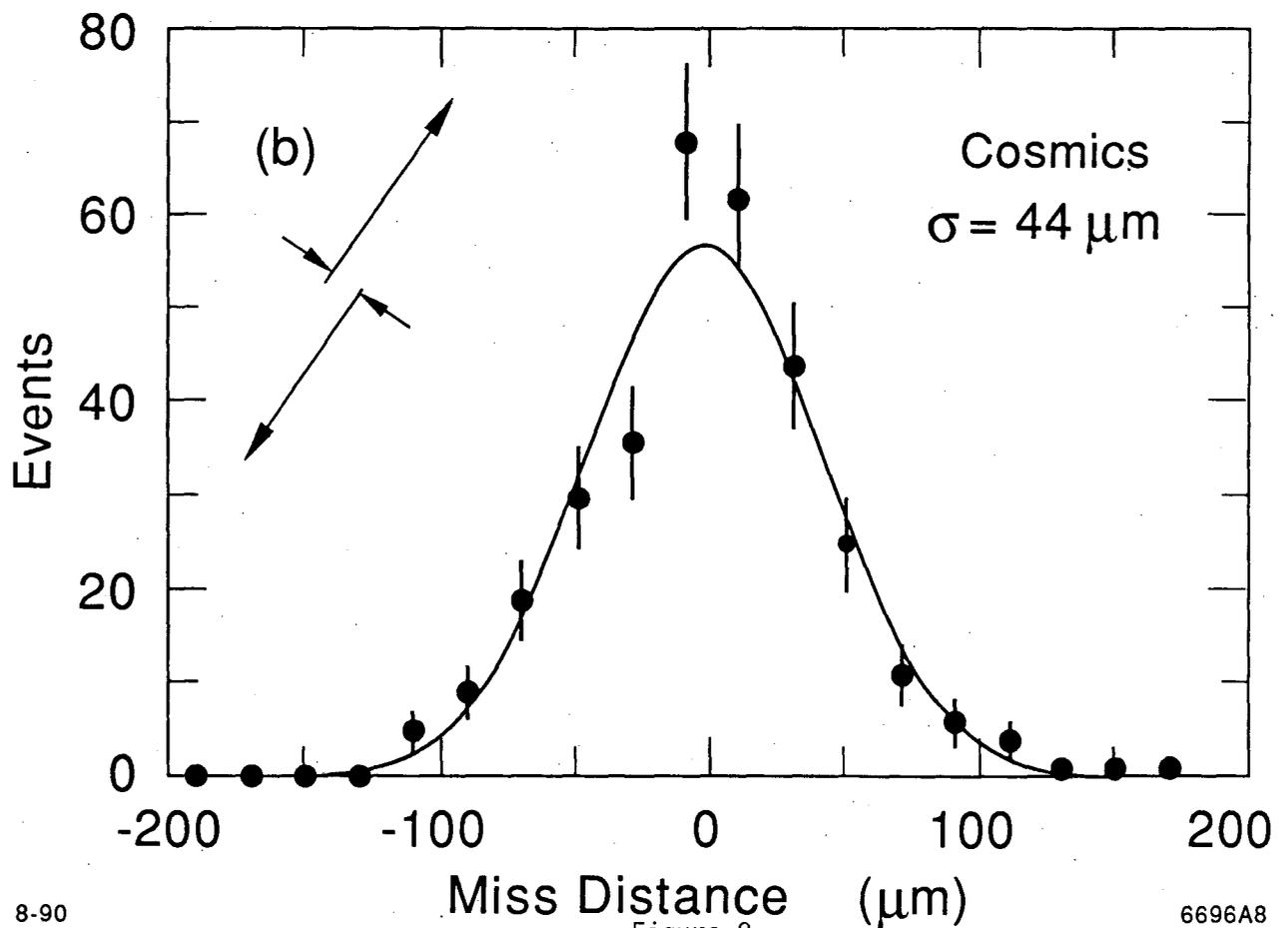
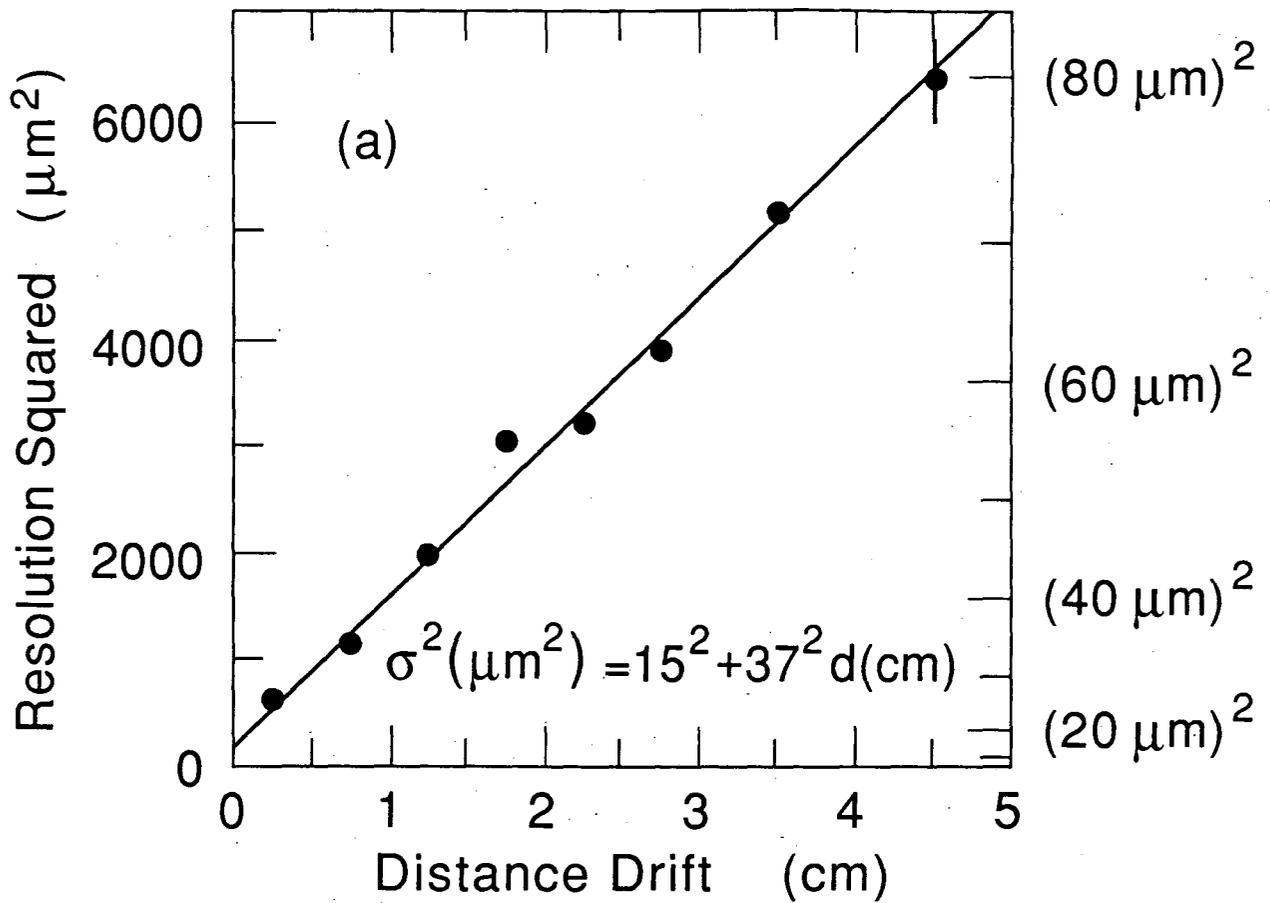


Figure 7



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