JLAB-TN-02-32

Calibration of Spectrometer Central Angles using Hall A HRS in ^{1}H(e,e′p)

Hassan Ibrahim and Paul E. Ulmer

Department of Physics
Old Dominion University
Norfolk, VA 23529-0116

Nilanga Liyanage

Jefferson Laboratory
Newport News, VA 23606

September 4, 2002

Abstract

In conjunction with Hall A experiment E91-011 ($N \rightarrow \Delta$) two sets (referred to here as Set II and Set III) each of five elastic ^{1}H(e,e′p) kinematics were measured during the period May 20–21 and July 8–9, 2000 to determine the absolute angular offsets for each spectrometer. This is a follow-up of a previous scan during the period April 1–2, 2000 (Set I) in order to check whether the spectrometer absolute angular offsets are stable over time. The measurements were taken at two different beam energies of 4530.6 ± 0.9 MeV (for Set II) and 3413.5 MeV (for Set III). For Set II this energy was derived from a measurement using the Hall A Arc system. For Set III, which used a 3-pass beam, no such measurement was performed and the energy was computed from Arc measurements taken for 4- and 5-pass beams and extrapolating to the 3-pass beam. Unfortunately, this leads to a significant inaccuracy which resulted in large uncertainties in the extracted spectrometer angular offsets for this set. Finally, it is possible that the spectrometer absolute angular offsets change with time due to other factors and there were other (more extensive) *ep* scans performed later to study these changes but they have not yet been analyzed.

Contents

1 Overview

The details of the method of extracting the spectrometer angular offsets can be found in Reference [1]. Basically, the beam energy can be expressed as a function of the angles of the outgoing electron and proton in the elastic ^{1}H(e,e'p) reaction. By measuring a set of such elastic kinematics at fixed beam energy, the offsets of each spectrometer central angle may be found through a fitting procedure. Additionally, the beam energy may be determined from the fitting procedure, though this typically leads to substantially larger uncertainties in the extracted angle offsets.

In this paper we describe the application of this method to three sets of elastic scans, the first of which was analyzed previously [1]. As the database for this previous analysis was recently found to be suspect, we present here results for all three sets using the latest databases.

2 Data Set I

2.1 Kinematics

The kinematics are given in Table 1. The beam energy was 3085.8 ± 0.6 MeV (Hall A Arc energy measurement [2]). The electrons were detected in the Left arm and protons in the Right arm for this data set. The kinematic derivatives are given in Table 2.

Run #	θ_n^e (deg)	θ_a^e (deg)	p_e (GeV/c)	θ_n^p (deg)	θ_a^p (deg)	p_p (GeV/c)
3132	12.9744	12.9856	2.845	−63.9619	−63.9678	0.712
3135	19.9623	19.9737	2.585	−52.8125	−52.8183	1.110
3141	32.9616	32.9726	2.022	−38.1156	−38.1208	1.785
3143	49.9587	49.9706	1.422	−26.4202	−26.4230	2.442
3144	80.9628	80.9676	0.818	−15.2196	−15.2219	3.080

Table 1: Set I kinematics. Here, θ_n^e and θ_n^p are the "nominal" electron and proton central angles respectively (*i.e.* before pointing correction) and θ_a^e and θ_a^p are the "actual" electron and proton central angles respectively (*i.e.* after pointing correction).

Run #	$de/d\theta_e$ (MeV/mr)	$de/d\theta_p$ (MeV/mr)
3132	−18.00	10.24
3135	−11.83	8.38
3141	−7.41	8.29
3143	−5.26	10.06
3144	−4.08	15.85

Table 2: Set I derivatives of the beam energy with respect to the electron and proton angles.

2.2 Results

The extracted energies before any offset correction are shown for each kinematic setting in Figure 1. The gaussian fits shown were restricted to data within $\pm 1.5\sigma$ of the mean values. The mean energies and deviations from the Arc value before application of the fitted angular offsets are shown in Table 3. The results after applying the offsets are shown in Table 4 and Figure 2. These values result from a weighted fit, where the spectrometer central angle uncertainties were taken to be 0.08 mr for each arm, leading to a reduced χ^2 of 1.0. If the angular offsets and beam energy are fitted (3-parameter fit), the angular offsets obtained are -0.97 ± 0.13 mr and -0.27 ± 0.21 mr for the electron (Left) arm and hadron (Right)

arm respectively. The fit value of the energy is 3.0902 ± 0.0028 GeV ($+14.3 \pm 10.0 \times 10^{-4}$ deviation compared to the Arc energy measurement). If the energy is constrained to the Arc value and only the angular offsets are fitted (2-parameter fit) we get -0.83 ± 0.10 mr and -0.57 ± 0.09 mr for the electron (Left) arm and hadron (Right) arm angular offsets respectively.

Run #	Mean Energy (GeV)	Deviation from Arc (10^{-4})
3132	3.0751	-34.8
3135	3.0812	-15.1
3141	3.0858	$+0.1$
3143	3.0870	$+3.9$
3144	3.0910	$+17.0$

Table 3: Set I mean energies and deviations from Arc energy **before** application of the absolute angular offsets. The average energy is 3.0840 ± 0.0061 GeV. (The uncertainty quoted here is the standard deviation.)

Run #	3-parameter fit		2-parameter fit	
	Mean Energy (GeV)	Deviation from Arc (10^{-4})	Mean Energy (GeV)	Deviation from Arc (10^{-4})
3132	3.0897	$+12.8$	3.0840	-5.8
3135	3.0904	$+14.8$	3.0861	$+1.0$
3141	3.0907	$+16.0$	3.0871	$+4.3$
3143	3.0894	$+11.5$	3.0855	-0.9
3144	3.0906	$+15.6$	3.0852	-2.0

Table 4: Set I mean energies and deviations from Arc value **after** application of the absolute angular offsets. The average energy is 3.0902 ± 0.0006 GeV for the 3-parameter fit and 3.0856 ± 0.0012 GeV for the 2-parameter fit.

3 Data Set II

3.1 Kinematics

The kinematics are given in Table 5.The beam energy was 4530.6 ± 0.9 MeV (Hall A Arc energy measurement [2]). The electrons were detected in the Left arm and protons in the Right arm for this data set. The kinematic derivatives are given in Table 6.

Run #	θ_n^e (deg)	θ_a^e (deg)	p_e (GeV/c)	θ_n^p (deg)	θ_a^p (deg)	p_p (GeV/c)
1056	18.0647	18.0790	3.660	-47.0869	-47.1008	1.552
1139	19.6888	19.7034	3.533	-44.6092	-44.6200	1.698
1143	24.9659	24.9809	3.122	-37.7262	-37.7406	2.157
1152	30.9658	30.9816	2.683	-31.7391	-31.7476	2.628
1153	35.9667	35.9821	2.358	-27.8311	-27.8366	2.971

Table 5: Set II kinematics. Here, θ_n^e and θ_n^p are the "nominal" electron and proton central angles respectively (*i.e.* before pointing correction) and θ_a^e and θ_a^p are the "actual" electron and proton central angles respectively (*i.e.* after pointing correction).

Set I Energy Distributions

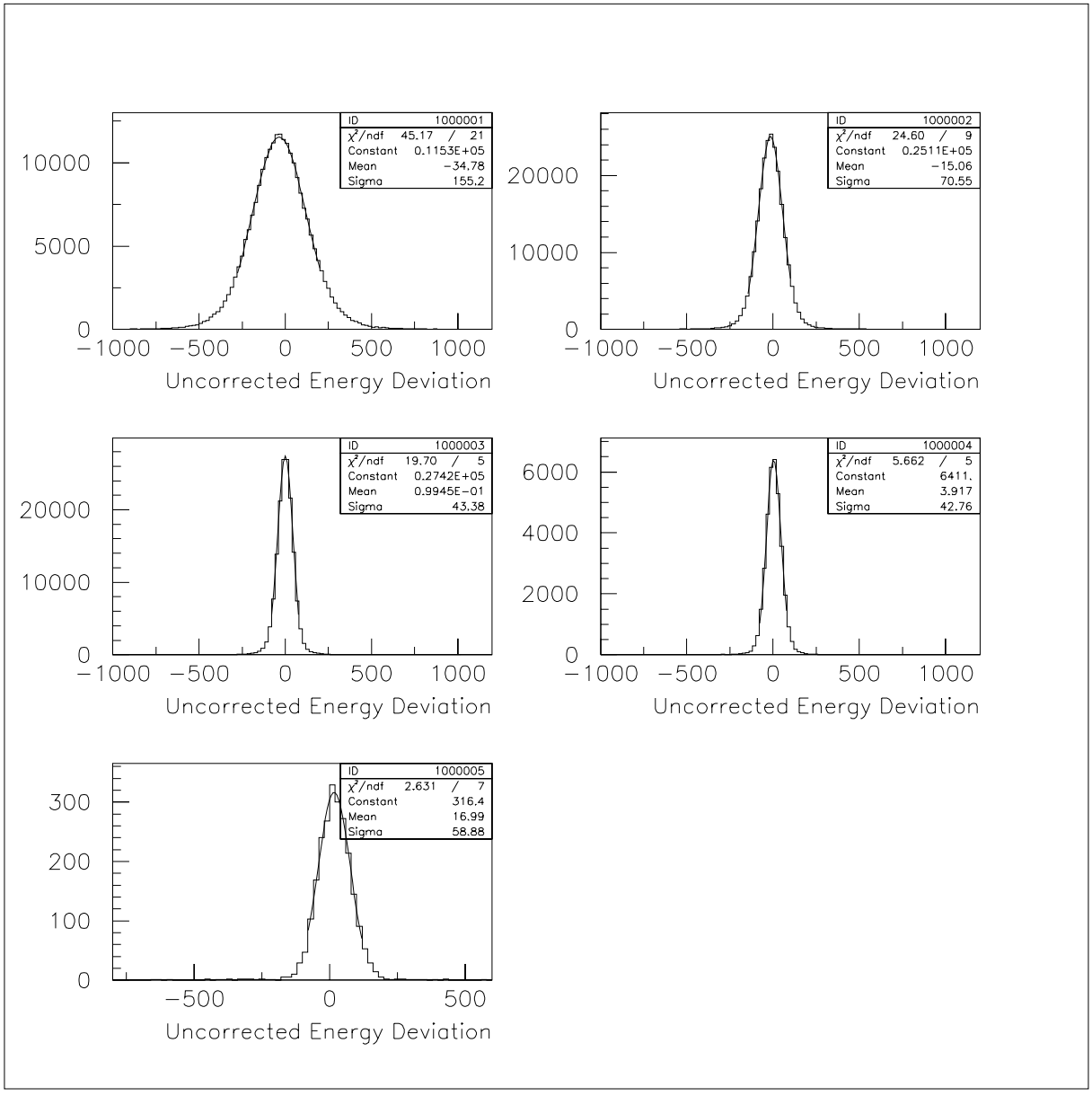

Figure 1: Set I distribution of extracted energy for each kinematic setting along with a gaussian fit over a $\pm 1.5\sigma$ interval. The energy plotted on each horizontal axis is given by $10^4 \times (e_i - e_{arc})/e_{arc}$ where e_{arc} is the Arc energy (3085.8 ± 0.6) and e_i is the energy for each event calculated from the particle angles. The kinematic settings are ordered reading first across from left to right and then down.

Set I Energy Deviations

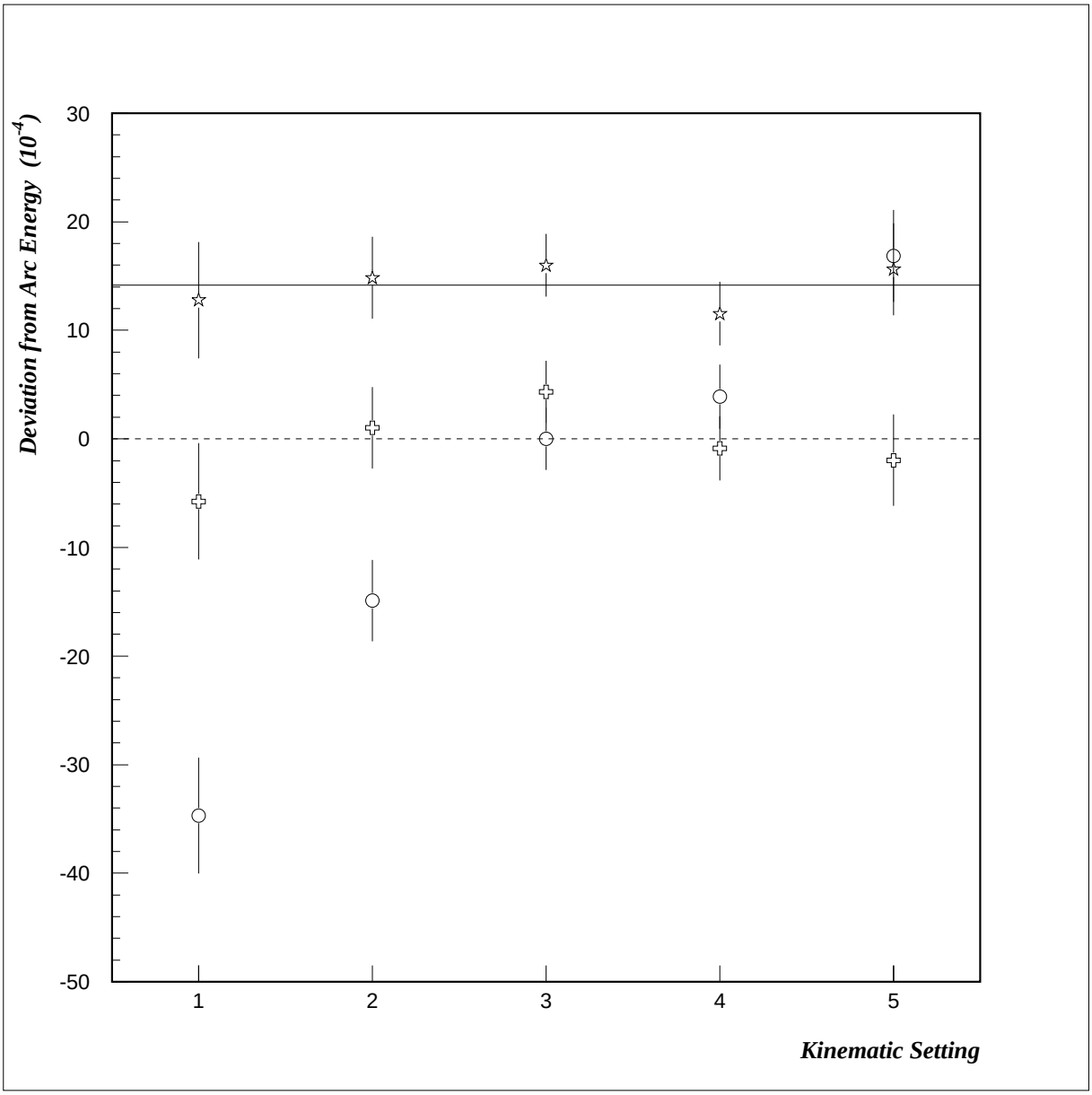

Figure 2: Set I energy deviations from Arc energy before (circles) and after (stars) incorporation of the absolute angular offsets. The crosses show the results if the energy is constrained to the Arc value and only the angular offsets are fitted. The horizontal solid and dashed lines indicate the average of energy deviations for 3- and 2-parameter fits respectively.

Run #	$de/d\theta_e$ (MeV/mr)	$de/d\theta_p$ (MeV/mr)
1056	-17.66	10.96
1139	-16.25	10.93
1143	-12.97	11.28
1152	-10.63	12.19
1153	-9.31	13.21

Table 6: Set II derivatives of the beam energy with respect to the electron and proton angles.

3.2 Results

The extracted energies before any offset correction are shown for each kinematic setting in Figure 3. The gaussian fits shown were restricted to data within $\pm 1.5\sigma$ of the mean values. The mean energies and deviations from the Arc value before application of the fit angular offsets are shown in Table 7. The results after applying the offsets are shown in Table 8 and Figure 4. These values result from a weighted fit, where the spectrometer central angle uncertainties were taken to be 0.08 mr for each arm, leading to a reduced χ^2 of 1.0. If the angular offsets and beam energy are fitted (3-parameter fit), the angular offsets obtained are -0.95 ± 0.50 mr and -0.67 ± 1.68 mr for the electron (Left) arm and hadron (Right) arm respectively. The fit value of the energy is 4.5256 ± 0.0258 GeV ($-11.0 \pm 56.9 \times 10^{-4}$ compared to the Arc energy measurement). If the energy is constrained to the Arc value and only the angular offsets are fitted (2-parameter fit) we get -1.04 ± 0.16 mr and -0.34 ± 0.19 mr for the electron (Left) arm and hadron (Right) arm angular offsets respectively.

Run #	Mean Energy (GeV)	Deviation from Arc (10^{-4})
1056	4.5160	-32.3
1139	4.5174	-29.0
1143	4.5220	-18.9
1152	4.5223	-18.2
1153	4.5262	-9.6

Table 7: Set II mean energies and deviations from Arc energy **before** application of the absolute angular offsets. The average energy is 4.5208 ± 0.0041 GeV. (The uncertainty quoted here is the standard deviation.)

Run #	3-parameter fit		2-parameter fit	
	Mean Energy (GeV)	Deviation from Arc (10^{-4})	Mean Energy (GeV)	Deviation from Arc (10^{-4})
1056	4.5254	-11.6	4.5306	-0.1
1139	4.5255	-11.3	4.5305	-0.2
1143	4.5267	-8.5	4.5316	$+2.2$
1152	4.5242	-14.1	4.5292	-3.2
1153	4.5262	-9.7	4.5313	$+1.6$

Table 8: Set I mean energies and deviations from Arc value **after** application of the absolute angular offsets. The average energy is 4.5208 ± 0.0041 GeV for the 3-parameter fit and 4.5306 ± 0.0010 GeV for the 2-parameter fit.

Set II Energy Distributions

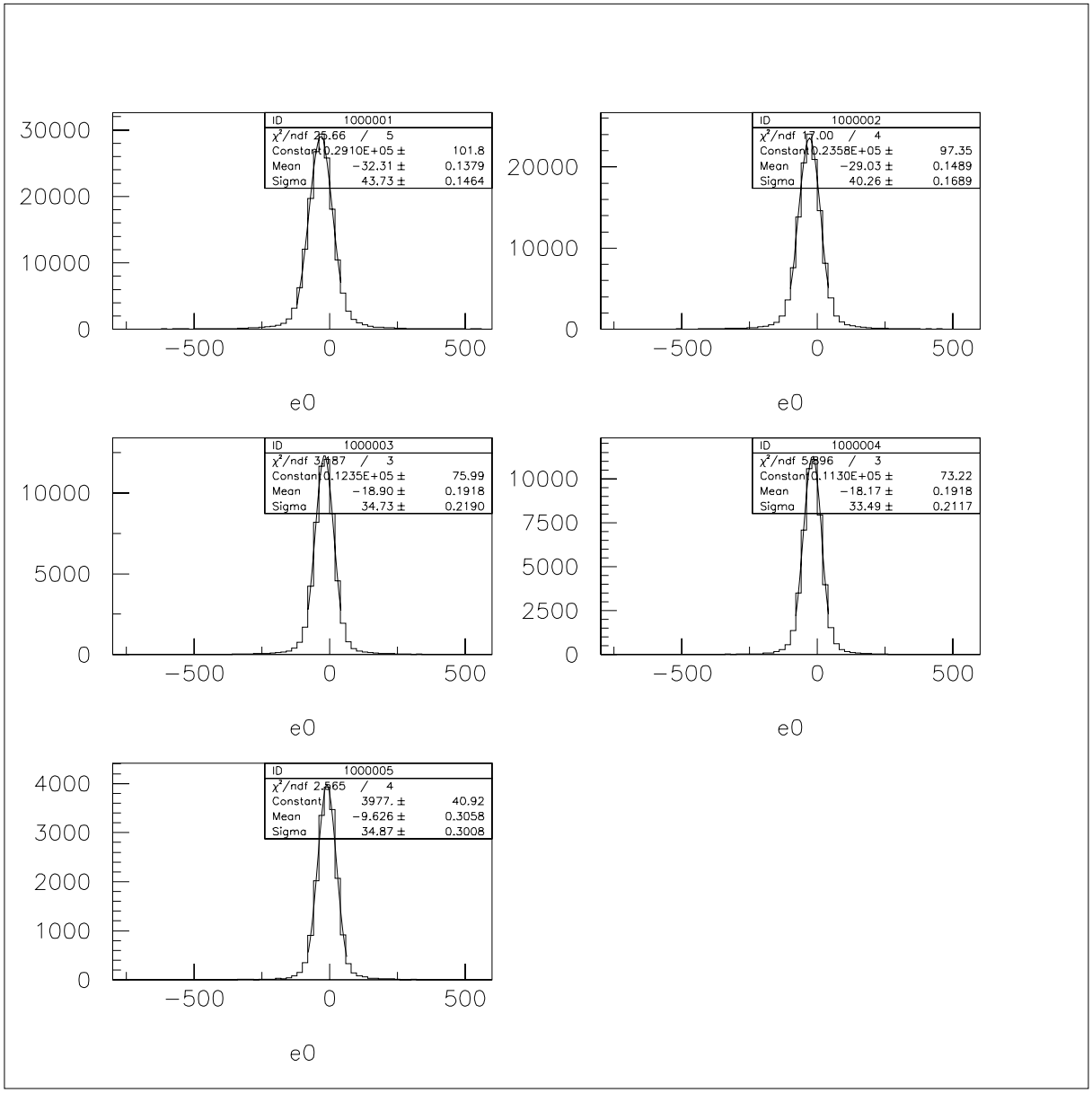

Figure 3: Set II distribution of extracted energy for each kinematic setting along with a gaussian fit over a $\pm 1.5\sigma$ interval. The energy plotted on each horizontal axis is given by $10^4 \times (e_i - e_{arc})/e_{arc}$ where e_{arc} is the Arc energy (4530.6 ± 0.9) and e_i is the energy for each event calculated from the particle angles. The kinematic settings are ordered reading first across from left to right and then down.

Set II Energy Deviations

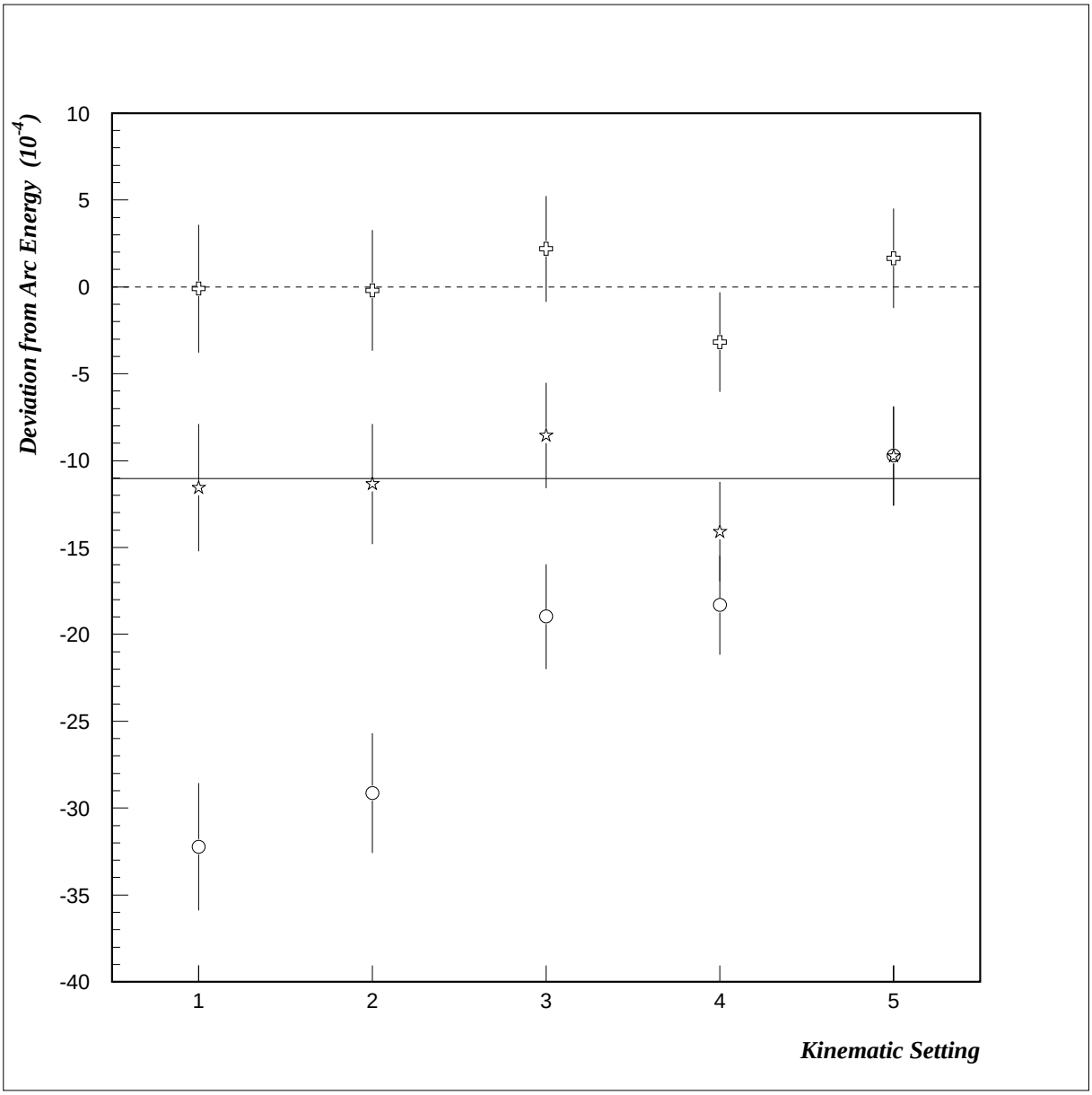

Figure 4: Set II energy deviations from Arc energy before (circles) and after (stars) incorporation of the absolute angular offsets. The crosses show the results if the energy is constrained to the Arc value and only the angular offsets are fitted. The horizontal solid and dashed lines indicate the average of energy deviations for 3- and 2-parameter fits respectively.

4 Data Set III

4.1 Kinematics

The kinematics are given in Table 9.The beam energy was 3413.5 MeV (obtained by extrapolating Hall A Arc energy measurements for different energy passes [2]). The electrons were detected in the Right arm and protons in the Left arm for this data set (reversed compared to Set I and Set II). The kinematic derivatives are given in Table 10.

Run #	θ_n^e (deg)	θ_a^e (deg)	p_e (GeV/c)	θ_n^p (deg)	θ_a^p (deg)	p_p (GeV/c)
2733	−16.0059	−16.0131	2.994	56.8465	56.8657	0.986
2735	−19.9967	−20.0058	2.802	50.6683	50.6863	1.239
2755	−34.6213	−34.6323	2.076	34.6101	34.6281	2.077
2758	−40.0003	−40.0145	2.239	30.6246	30.6416	1.845
2761	−50.0213	−50.0335	1.485	24.7699	24.7860	2.713

Table 9: Set III kinematics. The beam energy was 3.4315 GeV. Here, θ_n^e and θ_n^p are the "nominal" electron and proton central angles respectively (*i.e.* before pointing correction) and θ_a^e and θ_a^p are the "actual" electron and proton central angles respectively (*i.e.* after pointing correction).

Run #	$de/d\theta_e$ (MeV/mr)	$de/d\theta_p$ (MeV/mr)
2733	15.85	−9.53
2735	12.79	−8.92
2755	7.69	−9.35
2758	6.80	−9.99
2761	5.70	−11.51

Table 10: Set III derivatives of the beam energy with respect to the electron and proton angles.

4.2 Results

The extracted energies before any offset correction are shown for each kinematic setting in Figure 5. The gaussian fits shown were restricted to data within $\pm 1.5\sigma$ of the mean values. The mean energies and deviations from the extrapolated Arc value before application of the fit angular offsets are shown in Table 11. The results after applying the offsets are shown in Table 12 and Figure 6. These values result from a weighted fit, where the spectrometer central angle uncertainties were taken to be 0.08 mr for each arm, leading to a reduced χ^2 of 1.0. If the angular offsets and beam energy are fitted (3-parameter fit), the angular offsets obtained are $+0.23 \pm 0.18$ mr and -2.21 ± 0.69 mr for the electron (Right) arm and hadron (Left) arm respectively. The fit value of the energy is 3.4322 ± 0.0079 GeV ($+54.8 \pm 23.1 \times 10^{-4}$ compared to the energy extrapolated from the Arc measurements). If the energy is constrained to the extrapolated Arc value and only the angular offsets are fitted (2-parameter fit) we get -0.08 ± 0.14 mr and -0.60 ± 0.32 mr for the electron (Right) arm and hadron (Left) arm angular offsets respectively. Here, an Arc energy uncertainity of 10^{-3} was assumed.

5 Summary and Conclusions

The results for both the 2- and 3-parameter fits of Set I, II and III are shown in Tables 13 and 14 and Figures 7 and 8 ($\delta\theta_L$ and $\delta\theta_R$ are the Left arm and Right arm angular offsets which must be added to the raw spectrometer central angles to obtain the correct absolute angles). The results of Set I show

Set III Energy Distributions

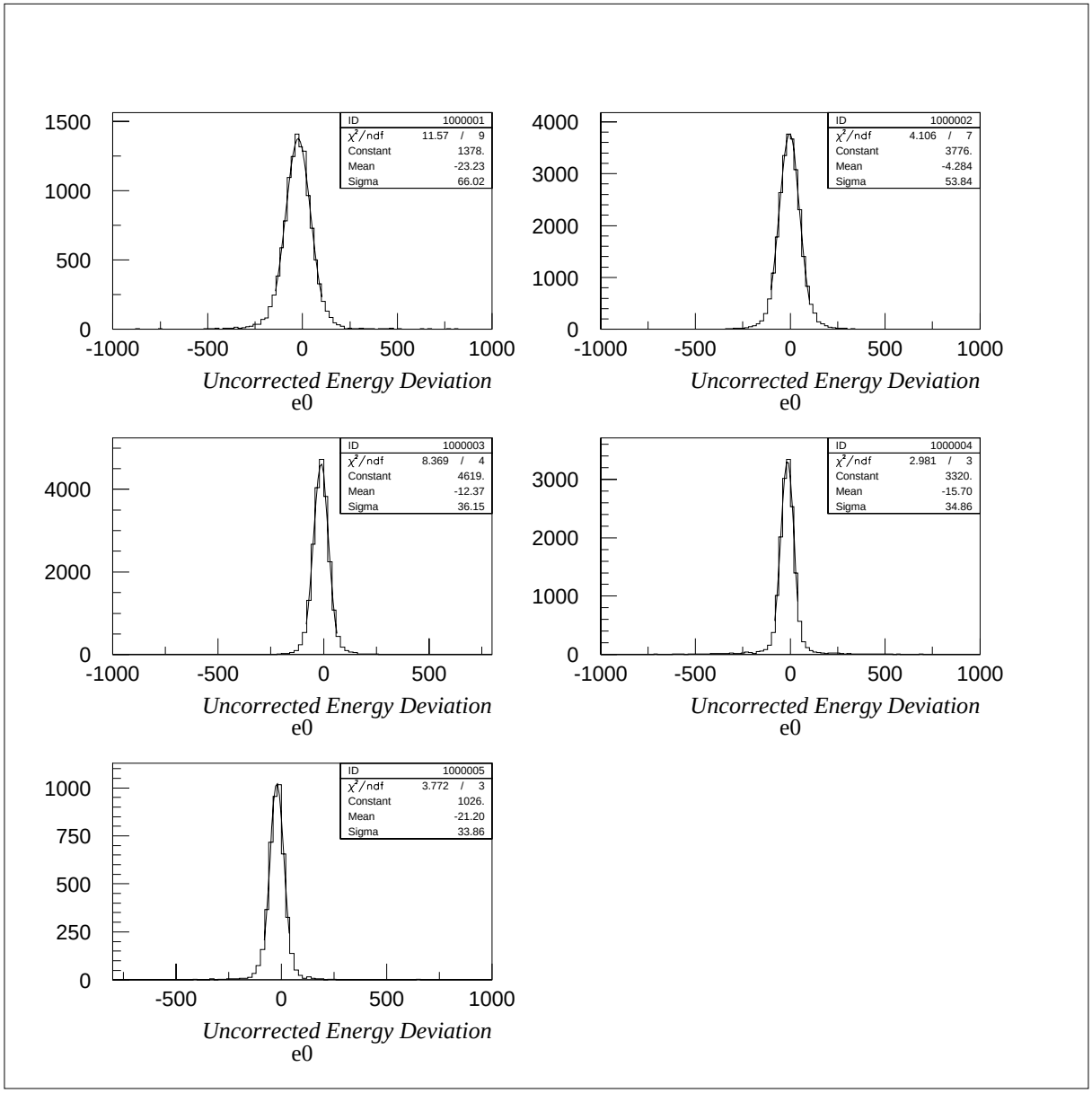

Figure 5: Set III distribution of extracted energy for each kinematic setting along with a gaussian fit over a $\pm 1.5\sigma$ interval. The energy plotted on each horizontal axis is given by $10^4 \times (e_i - e_{arc})/e_{arc}$ where e_{arc} is the extrapolated Arc energy (3413.5 MeV) and e_i is the energy for each event calculated from the particle angles. The kinematic settings are ordered reading first across from left to right and then down.

Set III Energy Deviations

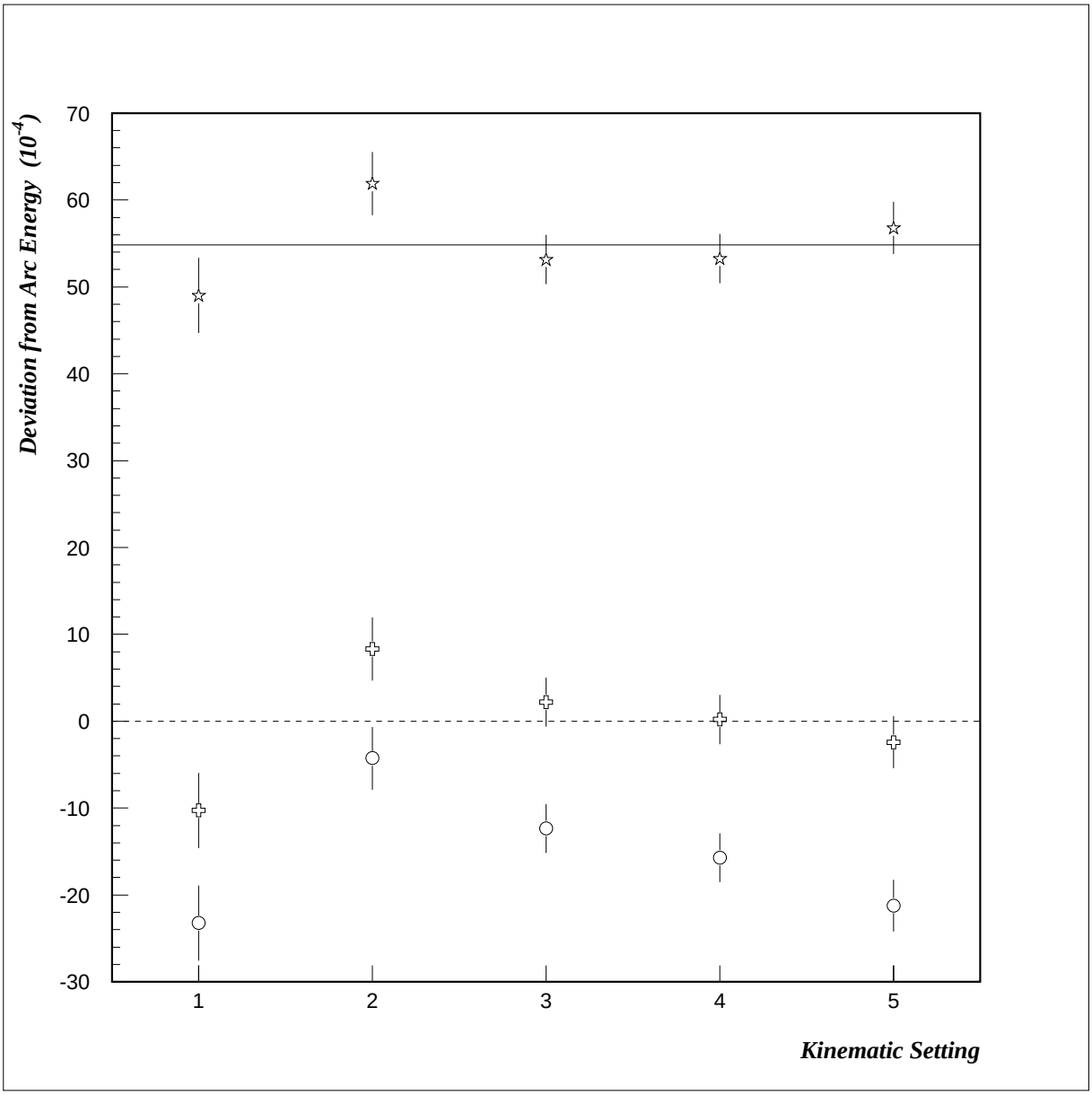

Figure 6: Set III energy deviations from Arc energy before (circles) and after (stars) incorporation of the absolute angular offsets. The crosses show the results if the energy is constrained to the Arc value and only the angular offsets are fitted. The horizontal solid and dashed lines indicate the average of energy deviations for 3- and 2-parameter fits respectively.

Run #	Mean Energy (GeV)	Deviation from Arc (10^{-4})
2733	3.4056	-23.2
2735	3.4121	-4.3
2755	3.4093	-12.4
2758	3.4082	-15.7
2761	3.4063	-21.2

Table 11: Set III mean energies and deviations from extrapolated Arc value **before** application of the absolute angular offsets. The average energy is 3.4083 ± 0.0026 GeV. (The uncertainty quoted here is the standard deviation.)

Run #	3-parameter fit		2-parameter fit	
	Mean Energy (GeV)	Deviation from Arc (10^{-4})	Mean Energy (GeV)	Deviation from Arc (10^{-4})
2733	3.4302	$+49.0$	3.4100	-10.3
2735	3.4346	$+61.9$	3.4163	$+8.3$
2755	3.4317	$+53.1$	3.4143	$+2.2$
2758	3.4317	$+53.3$	3.4136	$+0.2$
2761	3.4329	$+56.8$	3.4127	-2.4

Table 12: Set I mean energies and deviations from Arc value **after** application of the absolute angular offsets. The average energy is 3.4322 ± 0.0017 GeV for the 3-parameter fit and 3.4134 ± 0.0023 GeV for the 2-parameter fit.

substantial deviations from the results of [1], due to improvements in the database. The results of Set I and Set II for both the 2- and 3-parameter fits are reasonably consistent with one another. For Set III, the 3-parameter fit results in a beam energy which is 2.4 σ different than the value obtained from extrapolating the Arc measurements. This discrepancy, and the lack of a direct measurement of the energy, makes the 2-parameter fit for Set III somewhat suspect. The 3-parameter fit for Set III yields values of the angular offsets which differ by 1.7 and 1.2 σ for the Left and Right arms respectively from the weighted average determined by all three sets (this weighted average yields an offset which is nearly zero for the Right arm). The Right arm deviation is significantly larger if one, instead, compares the 3-parameter fit value for Set III to the, better determined, 2-parameter fits for Set I and Set II. If we completely disregard Set III, for lack of a direct energy measurement, then, based on weighted averages of the Set I and Set II 2-parameter fits, the angular offsets for the Left arm and Right arm are -0.89 ± 0.08 mr and -0.53 ± 0.08 mr respectively. More *ep* scans were performed later to calibrate the spectrometer central angles. These scans have not yet been analyzed but will add to our knowledge of the stability of the angular offsets over time.

Data Set	e (GeV)	$\frac{e}{e_{arc}} - 1$ (10^{-4})	$\delta\theta_L$ (mr)	$\delta\theta_R$ (mr)
I	3.0902 ± 0.0028	$+14.3 \pm 10.0$	-0.97 ± 0.13	-0.27 ± 0.21
II	4.5256 ± 0.0258	-11.0 ± 56.9	-0.95 ± 0.50	-0.67 ± 1.68
III	3.4322 ± 0.0079	$+54.8 \pm 23.1$	-2.21 ± 0.69	$+0.23 \pm 0.18$
Weighted Average			-1.01 ± 0.12	$+0.01 \pm 0.14$

Table 13: Summary of fit results for 3-parameter fit (angular offsets and beam energy fitted).

Data Set	$e \equiv e_{arc}$ (GeV)	$\delta\theta_L$ (mr)	$\delta\theta_R$ (mr)
I	3.0858 ± 0.0006	-0.83 ± 0.10	-0.57 ± 0.09
II	4.5306 ± 0.0009	-1.04 ± 0.16	-0.34 ± 0.19
III	3.4135 ± 0.0034	-0.60 ± 0.32	-0.08 ± 0.14
Weighted Average		-0.87 ± 0.08	-0.41 ± 0.07

Table 14: Summary of fit results for 2-parameter fit (only angular offsets fitted; beam energy fixed). Here, the uncertainties for the angular offsets include the quoted uncertainties in the arc energy measurements folded in quadrature with the uncertainties arising from our assumed random errors in the spectrometer angles of 0.08 mr.

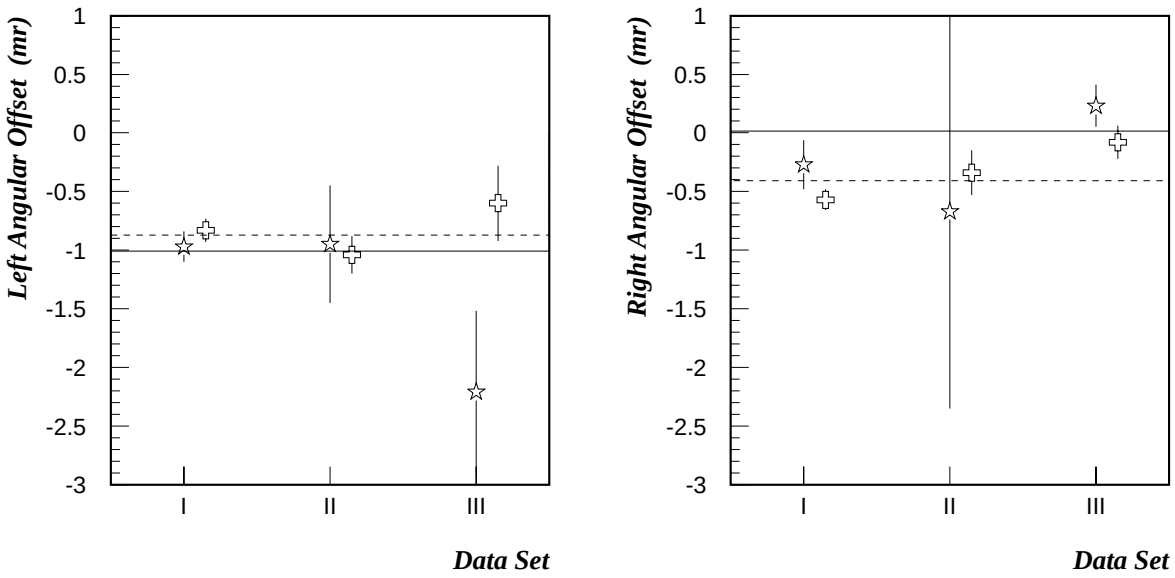

Figure 7: Left arm and Right arm angular offsets for the 3-parameter fit (stars) and 2-parameter fit (crosses). The horizontal lines indicate the weighted averages for the 3-parameter fit (solid) and 2-parameter fit (dashed).

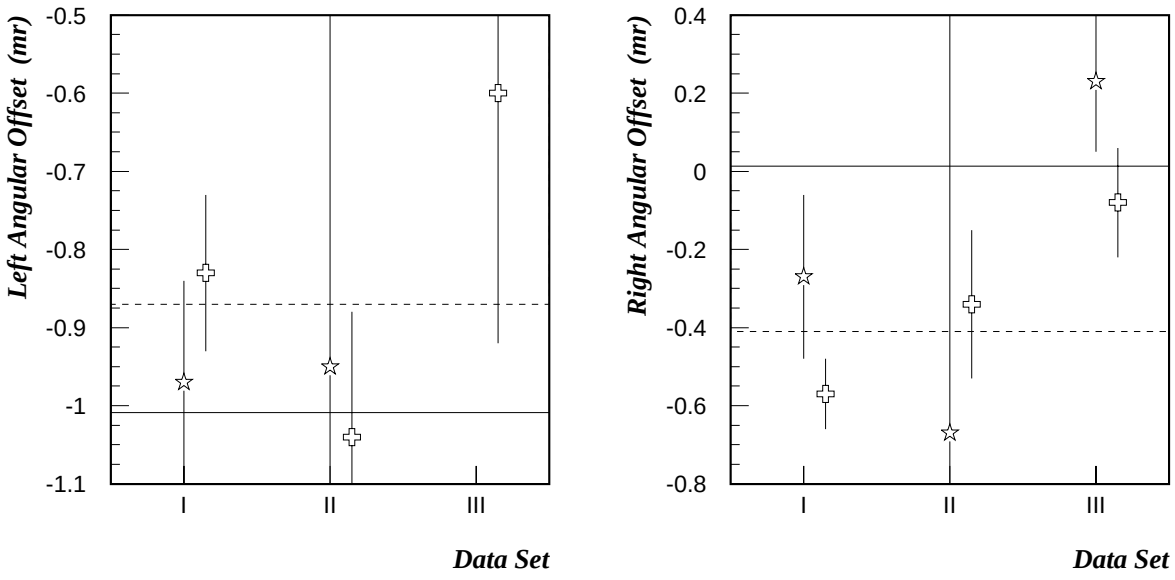

Figure 8: A blow-up of Figure 7. Note that in the left panel one of the six data points is outside the ordinate's range here and so is not plotted.

References

[1] P. E. Ulmer, H. Ibrahim and N. Liyanage, *Calibration of Beam Energy and Spectrometer Central Angles using Hall A HRS in* ^{1}*H(e,e'p)*, JLab Technical Note # 00-024 (2000).

[2] Hall A Absolute Beam Energy Measurements, http://www.jlab.org/~brittin/beam_energy_table.html