Quasielastic 1p Shell Proton Knockout from ^{16}O at $Q^2 = 0.8$ (GeV/c)^2

J. Gao,[17] B. D. Anderson,[13] K. A. Aniol,[2] L. Auerbach,[29] F. T. Baker,[7] J. Berthot,[1] W. Bertozzi,[17] P. -Y. Bertin,[1] L. Bimbot,[22] W. U. Boeglin,[5] E. J. Brash,[24] V. Breton,[1] H. Breuer,[16] E. Burtin,[26] J. R. Calarco,[18] L. Cardman,[30] G. D. Cates,[23] C. Cavata,[26] C. C. Chang,[16] J. -P. Chen,[30] E. Cisbani,[12] D. S. Dale,[14] A. Deur,[1] B. Diederich,[21] P. Djawotho,[33] B. Doyle,[14] J. -E. Ducret,[26] M. B. Epstein,[2] L. A. Ewell,[16] J. M. Finn,[33] K. G. Fissum,[17] H. Fonvieille,[1] B. Frois,[26] S. Frullani,[12] F. Garibaldi,[12] A. Gasparian,[8,14] S. Gilad,[17] R. Gilman,[25] A. Glamazdin,[15] C. Glashausser,[25] J. Gomez,[30] V. Gorbenko,[15] T. Gorringe,[14] K. Griffieon,[33] F. W. Hersman,[18] R. Holmes,[28] M. Holtrop,[18] N. d'Hose,[26] C. Howell,[4] G. M. Huber,[24] C. E. Hyde-Wright,[21] M. Iodice,[12] C. W. de Jager,[30] S. Jaminion,[1] M. K. Jones,[33] K. Joo,[32] C. Jutier,[1,21] W. Kahl,[28] S. Kato,[34] J. J. Kelly,[16] S. Kerhoas,[26] M. Khandaker,[19] M. Khayat,[13] K. Kino,[31] W. Korsch,[14] L. Kramer,[5] K. S. Kumar,[23] G. Kumbartzki,[25] G. Laveissière,[1] R. De Leo,[10] A. Leone,[11] J. J. LeRose,[30] L. Levchuk,[15] M. Liang,[30] R. A. Lindgren,[32] N. Liyanage,[17] G. J. Lolos,[24] R. W. Lourie,[27] R. Madey,[8,13,30] K. Maeda,[31] S. Malov,[25] D. M. Manley,[13] P. Markowitz,[5] D. J. Margaziotis[2] J. Marroncle,[26] J. Martino,[26] J. S. McCarthy,[32] K. McCormick,[21] J. McIntyre,[25] R. L. J. van der Meer,[24] Z. -E. Meziani,[29] R. Michaels,[30] J. Mougey,[3] S. Nanda,[30] D. Neyret,[26] E. A. J. M. Offermann,[30] Z. Papandreou,[24] C. F. Perdrisat,[33] R. Perrino,[11] G. G. Petratos,[13] S. Platchkov,[26] R. Pomatsalyuk,[15] D. L. Prout,[13] V. A. Punjabi,[19] T. Pussieux,[26] G. Quéméner,[33] R. D. Ransome,[25] O. Ravel,[1] Y. Roblin[1] R. Roché,[6] O. A. Rondon-Aramayo,[32] D. Rowntree,[17] G. Rutledge,[33] P. M. Rutt,[30] A. Saha,[30] T. Saito,[31] A. J. Sarty,[6] A. Serdarevic-Offermann,[24] T. P. Smith,[18] A. Soldi,[20] P. Sorokin,[15] P. Souder,[28] R. Suleiman,[13] J. A. Templon,[7] T. Terasawa,[31] L. Todor,[21] H. Tsubota,[31] H. Ueno,[34] P. E. Ulmer,[21] G. Urciuoli,[12] P. Vernin,[26] S. van Verst,[17] B. Vlahovic,[20] H. Voskanyan,[35] J. W. Watson,[13] L. B. Weinstein,[21] K. Wijesooriya,[33] R. Wilson,[9] B. Wojtsekhowski,[30] D. G. Zainea,[24] V. Zeps,[14] J. Zhao,[17] Z. -L. Zhou,[17]

(The Jefferson Lab Hall A Collaboration)

[1] *Université Blaise Pascal/IN2P3, F-63177 Aubière, France*
[2] *California State University, Los Angeles, California, 90032*
[3] *Institut des Sciences Nucléaires, F-38026 Grenoble, France*
[4] *Duke University, Durham, North Carolina, 27706*
[5] *Florida International University, Miami, Florida, 33199*
[6] *Florida State University, Tallahassee, Florida, 32306*
[7] *University of Georgia, Athens, Georgia, 30602*
[8] *Hampton University, Hampton, Virginia 23668*
[9] *Harvard University, Cambridge, Massachusetts, 02138*
[10] *INFN, Sezione di Bari and University of Bari, I-70126 Bari, Italy*
[11] *INFN, Sezione di Lecce, I-73100 Lecce, Italy*
[12] *INFN, Sezione Sanitá and Istituto Superiore di Sanitá, Laboratorio di Fisica, I-00161 Rome, Italy*
[13] *Kent State University, Kent, Ohio, 44242*
[14] *University of Kentucky, Lexington, Kentucky, 40506*
[15] *Kharkov Institute of Physics and Technology, Kharkov 310108, Ukraine*
[16] *University of Maryland, College Park, Maryland, 20742*
[17] *Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139*
[18] *University of New Hampshire, Durham, New Hampshire, 03824*
[19] *Norfolk State University, Norfolk, Virginia, 23504*
[20] *North Carolina Central University, Durham, North Carolina, 27707*
[21] *Old Dominion University, Norfolk, Virginia, 23529*
[22] *Institut de Physique Nucléaire, F-91406 Orsay, France*
[23] *Princeton University, Princeton, New Jersey, 08544*
[24] *University of Regina, Regina, Saskatchewan, Canada, S4S 0A2*
[25] *Rutgers, The State University of New Jersey, Piscataway, New Jersey, 08854*
[26] *CEA Saclay, F-91191 Gif-sur-Yvette, France*
[27] *State University of New York at Stony Brook, Stony Brook, New York, 11794*
[28] *Syracuse University, Syracuse, New York, 13244*
[29] *Temple University, Philadelphia, Pennsylvania, 19122*
[30] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia, 23606*
[31] *Tohoku University, Sendai 980, Japan*
[32] *University of Virginia, Charlottesville, Virginia, 22901*
[33] *College of William and Mary, Williamsburg, Virginia, 23187*
[34] *Yamagata University, Yamagata 990, Japan*
[35] *Yerevan Physics Institute, Yerevan 375036, Armenia*

(August 25, 1999)

We have measured cross sections for quasielastic $1p$ shell proton knockout in the ^{16}O(e, e′p) reaction at $\omega = 0.439$ GeV and $Q^2 = 0.8$ (GeV/c)^2 for missing momentum $P_{\rm miss} \leq 355$ MeV/c. This was the first measurement in Jefferson Lab Hall A. We have extracted the response functions R_{L+TT}, R_T, R_{LT}, and the left-right asymmetry A_{LT} for the $1p_{1/2}$ and the $1p_{3/2}$ states. The data are well described by relativistic DWIA calculations. At large $P_{\rm miss}$, structure in A_{LT} indicates the existence of dynamical relativistic effects.

Electron scattering is a powerful probe of the nuclear electromagnetic response [1,2]. Exclusive and semi-exclusive proton knockout reactions, (e, e′p), have been used to study single-nucleon aspects of nuclear structure and to search for non-nucleonic degrees-of-freedom.

^{16}O(e, e′p) $1p$ shell proton knockout experiments have been performed at NIKHEF [3,4], Saclay [5,6], and Mainz [7] at low four-momentum transfers ($Q^2 < 0.4$ (GeV/c)^2) in various kinematics.[1] Leuschner *et al.* [3], Spaltro *et al.* [4], Bernheim *et al.* [5], Chinitz *et al.* [6], and Blomqvist *et al.* [7] have measured the cross section as a function of missing momentum and have fit spectroscopic factors by comparing data to Distorted Wave Impulse Approximation (DWIA) calculations. The published spectroscopic factors were between 0.5 and 0.7 except for those of Blomqvist *et al.* [7], which were significantly lower. Spaltro *et al.* [4] and Chinitz *et al.* [6] also extracted the longitudinal-transverse interference response function[2], R_{LT}, at $Q^2 = 0.2$ (GeV/c)^2 and 0.3 (GeV/c)^2 respectively. Their measurements of proton knockout from the $1p_{1/2}$ state agree but their $1p_{3/2}$ measurements disagree dramatically. DWIA calculations are consistent with the data of Chinitz *et al.* [6]

This paper reports the results of the first experiment in Jefferson Lab Hall A [8,9]. In this experiment we measured the ^{16}O(e, e′p) reaction cross section in quasielastic kinematics ($\omega = Q^2/2m_p$) at $Q^2 = 0.8$ (GeV/c)^2 and $\omega = 0.439$ GeV for $P_{\rm miss} < 355$ MeV/c. We separated A_{LT} and the response functions R_{L+TT}, R_T, and R_{LT} for $1p$ shell proton knockout.

At high Q^2, quasielastic (e, e′p) is expected to be dominated by one-body currents, hence DWIA calculations should be more accurate than at low Q^2. Calculations, as well as data at lower Q^2, show that R_{LT} and A_{LT} are sensitive to dynamical relativistic effects [6,10–13].

The 100% duty factor beam current was typically 70 μA and was incident on a waterfall target with three foils, each about 130 mg/cm^2 thick along the beamline [14]. We used the two Hall A High Resolution Spectrometers (further details can be found in Ref. [15]) to detect the outgoing particles. We studied the spectrometer optical properties and acceptances both before and during the experiment. The angle of the particle was determined to 0.3 mrad and the absolute momentum of a particle was measured to $\frac{\delta p}{p} = 1.5 \times 10^{-3}$ [16–18].

The hydrogen in the H_2O target greatly simplified our normalizations and calibrations. We monitored the luminosity by continuously measuring the elastic H(e,e) cross section. We used H(e,ep) to determine the momentum transfer $|\vec{q}|$ absolutely to an accuracy of 1.5×10^{-3} and to reproduce this momentum transfer at each beam energy to an accuracy of 1.5×10^{-4}.

We measured the cross section at fixed $|\vec{q}| = 992$ MeV/c at three beam energies (virtual photon polarizations) to redundantly separate the response functions and understand our systematic uncertainties (see Table I). The angles $\theta_{pq} = 0°, \pm 2.5°, \pm 8°, \pm 16°$, and $\pm 20°$ correspond to central missing momenta of 53, 60, 148, 280, and 345 MeV/c respectively. Note that at $\theta_{pq} = 0°$, we had to remove events with $P_{\rm miss} < 45$ MeV/c to eliminate contamination from H(e, ep).

For $\theta_{pq} = \pm 8°$, R_{LT} and A_{LT} extracted at $E_{\rm beam} = 2.4$ GeV agree with those extracted at $E_{\rm beam} = 1.6$ GeV within one standard deviation. The overall systematic uncertainty in the response functions is about 5%. This uncertainty is dominated by the uncertainty of the H(e, e) cross section to which the data were normalized [19].

We radiatively corrected the cross section using a modified version of the code RADCOR [20]. The missing energy resolution is 0.9 MeV FWHM. This does not allow us to separate the $(2s_{1/2}, 1d_{5/2})$ doublet from the $1p_{3/2}$ state. The strength of this doublet was estimated using the spectroscopic factors obtained by Leuschner *et al.* [3] to be approximately 5% of the $1p_{3/2}$ for this kinematical region. It was not subtracted from the $1p_{3/2}$ cross section.

The first relativistic calculations for (e, e′p) were performed by Picklesimer and Van Orden [10,11]. We com-

[1] The kinematical quantities are as follows: the scattered electron transfers momentum $\vec{q}$ and energy ω with $Q^2 = \vec{q}^2 - \omega^2$. The ejected proton has mass m_p, momentum $\vec{p}_p$, energy E_p, and kinetic energy T_p. The cross section is typically measured as a function of missing energy $E_{\rm miss} = \omega - T_p - T_{\rm recoil}$ and missing momentum $P_{\rm miss} = |\vec{q} - \vec{p}_p|$. The angle between the ejected proton and virtual photon is θ_{pq} and the out-of-plane angle is ϕ. $\theta_{pq} > 0$ corresponds to $\phi = 180°$ and $\theta_p > \theta_q$. $\theta_{pq} < 0$ corresponds to $\phi = 0°$.

[2] The cross section for (e, e′p) can be written as $\frac{d^6\sigma}{d\Omega_e\, d\omega\, d\Omega_p\, dE_{\rm miss}} = \frac{E_p p_p}{(2\pi)^3}\sigma_{\rm Mott}(V_L R_L + V_T R_T + V_{LT} R_{LT}\cos\phi + V_{TT} R_{TT}\cos 2\phi)$ where the kinematic factors $\{V_i\}$ are known and the response functions $\{R_i\}$ contain information about the nuclear charge and current densities. One can extract response functions by measuring the cross section at fixed Q^2, ω, and θ_{pq} while varying the electron scattering angle (which changes V_T) and ϕ. One can also extract the left-right asymmetry by measuring the cross section at $\phi = 0, 180°$: $A_{LT} = \frac{\sigma(\phi=0°) - \sigma(\phi=180°)}{\sigma(\phi=0°) + \sigma(\phi=180°)}$.

pared our data to more recent calculations by Udias *et al.* [12,21–23] and by Kelly [13]. Both calculations use Coulomb gauge, the NLSH bound state wavefunction [24], the EDAIO optical potential of Cooper *et al.* [25] for ^{16}O, the cc2 vertex function [26] (the use of cc1 yielded slightly worse agreement with the data), and include the effects of electron distortion. The results for the $1p_{3/2}$ state from both calculations include an incoherent contribution from the positive parity contaminants as parametrized by Leuschner *et al.* [3] Udias *et al.* solved the Dirac equation in configuration space, while Kelly solved a relativized Schrödinger equation and used the effective momentum approximation (EMA) to incorporate spinor distortion into an effective current operator based on Hedayati-Poor *et al.* [27] The primary difference between these two calculations is that Kelly used an EMA approximation for the lower components of the Dirac spinors while Udias *et al.* solved the Dirac equation directly.

Figure 1 shows the cross section as a function of missing momentum at $E_{\rm beam} = 2.4$ GeV. The calculations of Udias *et al.* and of Kelly are in excellent agreement with the data. This agreement is attributed to the use of good (NLSH [24]) bound-state wave functions, which yield better binding energies and rms radii than other bound-state wave functions. The spectroscopic factors are 0.73 and 0.72 for the $1p_{1/2}$ state and 0.71 and 0.67 for the $1p_{3/2}$ state for the calculations of Udias *et al.* and Kelly, respectively.

We extracted A_{LT} from the measured cross sections (see Figure 2). Note the large change in slope of A_{LT} at $P_{\rm miss} \approx 300$ MeV/c. The change in slope is reproduced, at least qualitatively, by both calculations, although only when they include modification of the lower components of the Dirac spinors. As can be seen in Udias' calculations in Figure 2, modification of the bound state spinors is more important than modification of the ejectile spinors, although both are needed. Kelly also sees an effect due to distortion of the bound state spinors, but due to approximations, his calculations are not as accurate for $P_{\rm miss} > 300$ MeV/c [13].

We also extracted the response functions R_{L+TT}, R_{LT}, and R_T. Since we measured the cross sections in perpendicular kinematics, we could not isolate the longitudinal response function R_L. Instead, we extracted the combination $R_{L+TT} = R_L + \frac{V_{TT}}{V_L} R_{TT}$. Kelly calculates that R_{TT} is small ($< 10\%$) for these kinematics. Figure 3 shows the response functions and calculations. The calculations agree with the data.

In summary, we have measured ^{16}O(e, e′p) $1p$ shell proton knockout in a previously inaccessible region of momentum transfer. These measurements included cross sections, the left-right asymmetry A_{LT}, and the response functions R_{L+TT}, R_{LT}, and R_T for missing momentum up to approximately 350 MeV/c. Our cross sections, asymmetries, and response functions are in very good agreement with modern relativistic DWIA calculations. We see structure in A_{LT} at higher missing momentum which appears due to dynamic enhancement of the lower components of Dirac spinors.

We acknowledge the outstanding support of the staff of the Accelerator and Physics Divisions of Jefferson Laboratory that made this experiment successful. We thank Drs. T.W. Donnelly, J.M. Udias, and J.W. Van Orden for providing their theoretical calculations and for valuable discussions. We also thank Dr. J.M. Udias for providing us with the NLSH bound-state wave functions. This work was supported in part by DOE and NSF.

[1] S. Frullani and J. Mougey, Adv. Nucl. Phys. **14**, 1 (1984).
[2] J.J. Kelly, Adv. Nucl. Phys. **23**, 75 (1996).
[3] M. Leuschner *et al.*, Phys. Rev. **C49**, 955 (1994).
[4] C.M. Spaltro *et al.*, Phys. Rev. **C48**, 2385 (1993).
[5] M. Bernheim *et al.*, Nucl. Phys. **A375**, 381 (1982).
[6] L. Chinitz *et al.*, Phys. Rev. Lett. **67**, 568 (1991).
[7] K.I. Blomqvist *et al.*, Phys. Lett. **B344**, 85 (1995).
[8] A. Saha, W. Bertozzi, R.W. Lourie, and L.B. Weinstein, Jefferson Laboratory Proposal 89-003, 1989.
[9] K.G. Fissum *et al.*, MIT-LNS Internal Report #02, 1997; www.cebaf.gov/~fissum/e89003.html.
[10] A. Picklesimer, J.W. Van Orden, and S.J. Wallace, Phys. Rev. **C32**, 1312 (1985).
[11] A. Picklesimer and J.W. Van Orden, Phys. Rev. **C40**, 290 (1989).
[12] J.M. Udias *et al.*, LANL Preprint Library, nucl-th/9905030.
[13] J.J. Kelly, LANL Preprint Library, nucl-th/9905024.
[14] F. Garibaldi *et al.*, Nucl. Inst. and Meth. **A314**, 1 (1992).
[15] J. Gao, Ph.D. thesis, MIT, 1999 (unpublished).
[16] J. Gao *et al.*, MIT-LNS Internal Report #04, 1998.
[17] N. Liyanage *et al.*, MIT-LNS Internal Report #05, 1998.
[18] M. Liang, 'Survey Summary Report', Jefferson Lab Technical Notes JLAB-TN-99029.
[19] G.G. Simon *et al.*, Nucl. Phys. **A333**, 381 (1980).
[20] E. Quint, Ph.D. thesis, NIKHEF 1988 (unpublished); R. Florizone, Ph.D. thesis, MIT 1999 (unpublished).
[21] J.M. Udias *et al.*, Phys. Rev. **C48**, 2731 (1993).
[22] J.M. Udias *et al.*, Phys. Rev. **C51**, 3246 (1995).
[23] J.M. Udias, private communication.
[24] M.M. Sharma, M.A. Nagarajan, and P. Ring, Phys. Lett. **B312** 377 (1993).
[25] E.D. Cooper, S. Hama, B.C. Clark, and R.L. Mercer, Phys. Rev. **C47**, 297 (1993).
[26] T. De Forest, Nucl. Phys. **A392**, 232 (1983).
[27] M. Hedayati-Poor, J.I. Johansson, and H.S. Sherif, Phys. Rev. **C51**, 2044 (1995).

Beam Energy (GeV)	θ_e (degree)	θ_{pq} (degree)
0.843	100.7	0, 8, 16
1.643	37.2	0, 8
2.442	23.4	0, ±2.5, ±8, ±16, ±20

TABLE I. Experimental Kinematics

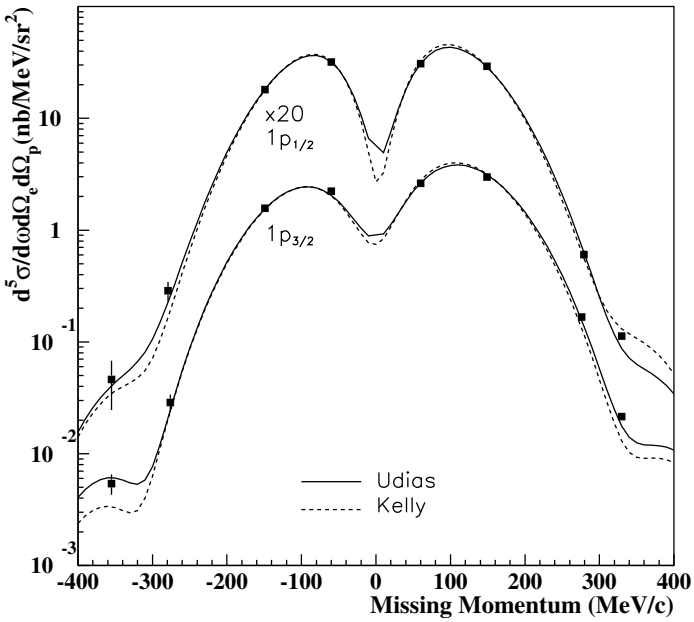

FIG. 1. Measured cross sections and DWIA calculations at $E_{\rm beam} = 2.4$ GeV. The solid line is the Udias [12,23] calculation, and the dashed line is the Kelly [13]. The $1p_{1/2}$ state cross section and calculations have been multiplied by a factor of 20.

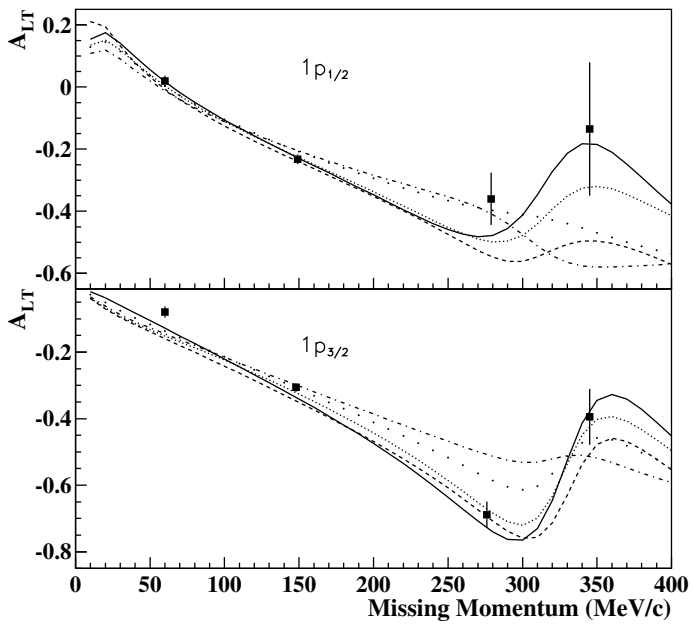

FIG. 2. Measured left-right asymmetry A_{LT} and DWIA calculations at $E_{\rm beam} = 2.4$ GeV. The solid line is the Udias [12,23] fully relativistic calculation, the close dotted line is the Udias [12,23] calculation with the bound state spinor distortion included, the dot-dashed line is the Udias [12,23] calculation with the scattered state spinor distortion included, and the wide dotted line is the Udias [12,23] calculation without spinor distortion included, and the dashed line is the Kelly [13].

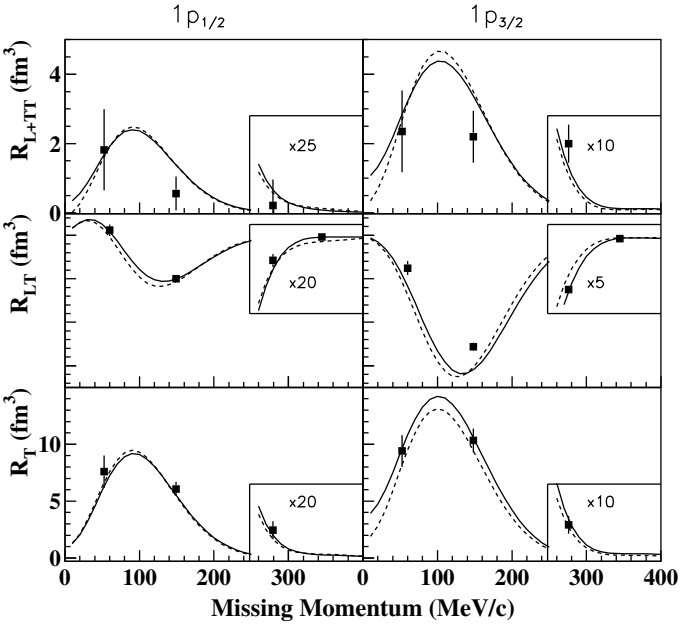

FIG. 3. Measured R_{L+TT}, R_{LT}, and R_T and DWIA calculations. The solid line is the Udias [12,23] calculation, and the dashed line is the Kelly [13]. The data beyond 250 MeV/c missing momentum are expanded for clarity.