Study of a quasielastic $^{16}O(e,e'p)$ experiment combining a Monte Carlo with a RDWIA code

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ENCUENTRO DE FISICA NUCLEAR
VALENCIA 2006

0) INTRODUCTION:

- Quasielastic A(e,e'p) experiments
- ^{16}O(e,e'p) and ^{208}Pb(e,e'p) experiments at JLAB

1) MOTIVATION for Mceep+RDWIA code

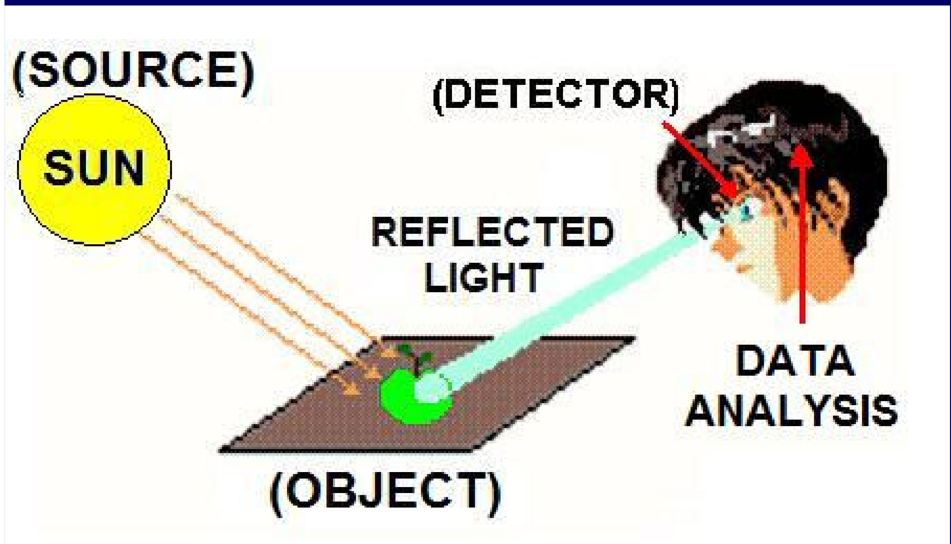
2) METHODS

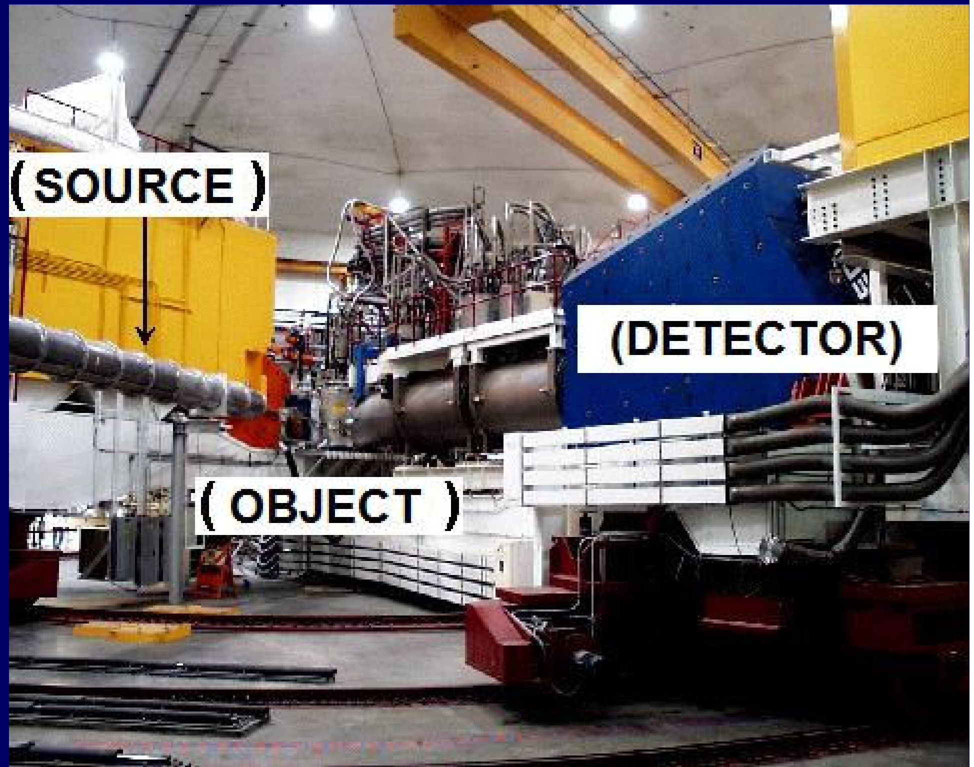
3) RESULTS

4) CONCLUSIONS

Scattering experiments…

Why?





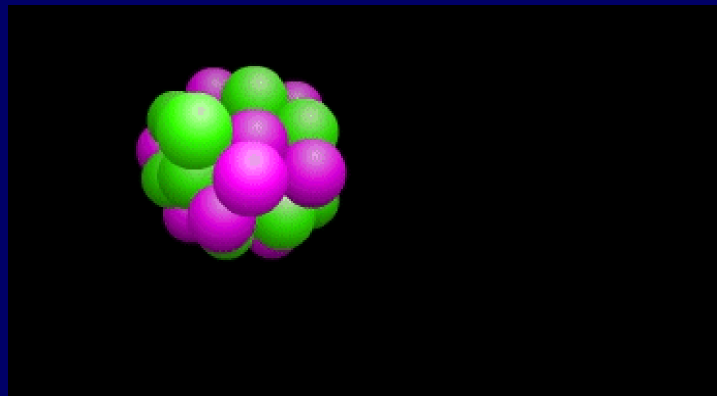
Data analysis…

done by a postgraduate student.

Quasielastic A(e,e'p)B experiments

Electron beams with an Energy of several GeV.

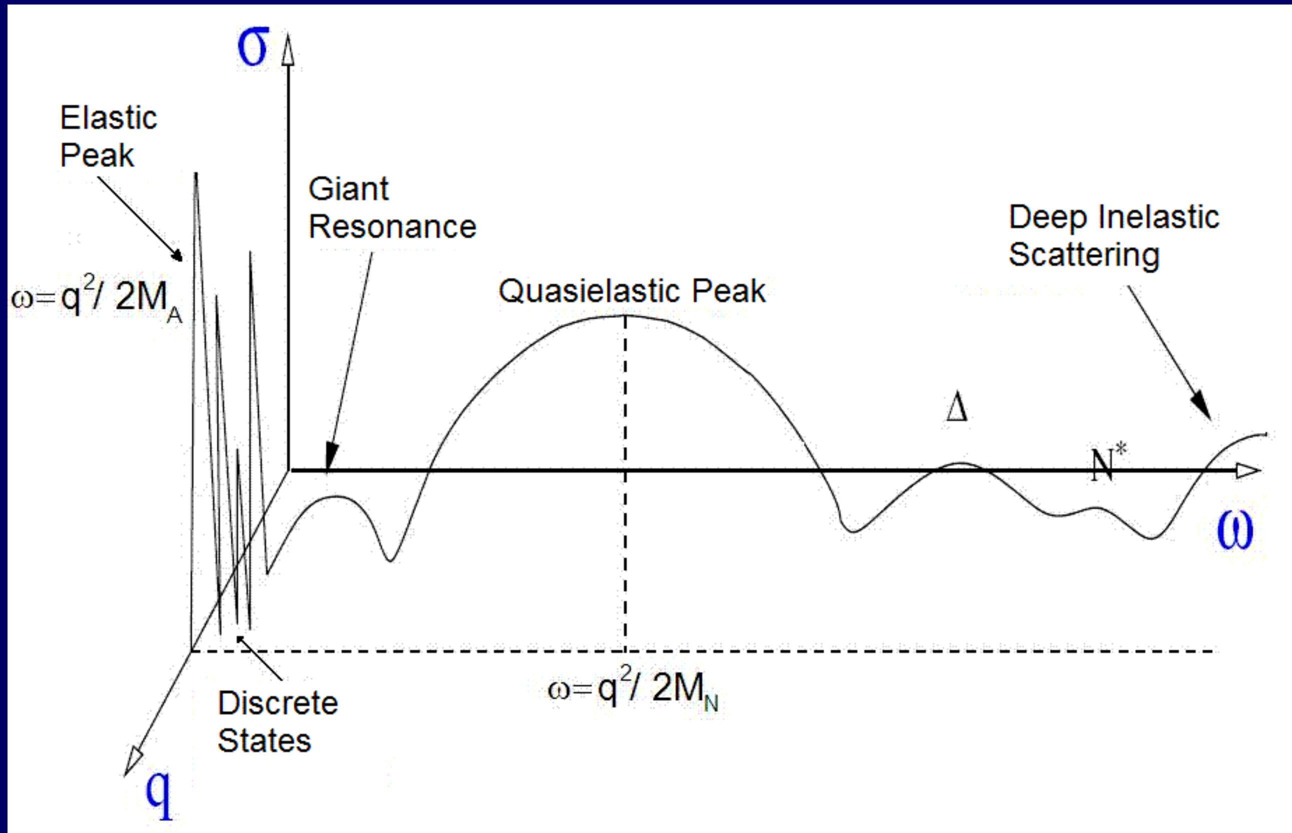
Typical targets are doubly-magic, closed-shell nucleus: ^{16}O, ^{40}Ca, ^{208}Pb. Their bound-nucleon wave functions are well known and relatively easy to calculate.



The calculated cross-section shows the probability of detecting a scattered electron with a given energy and angle in one detector in coincidence with an ejected proton with a given energy and angle in another detector.

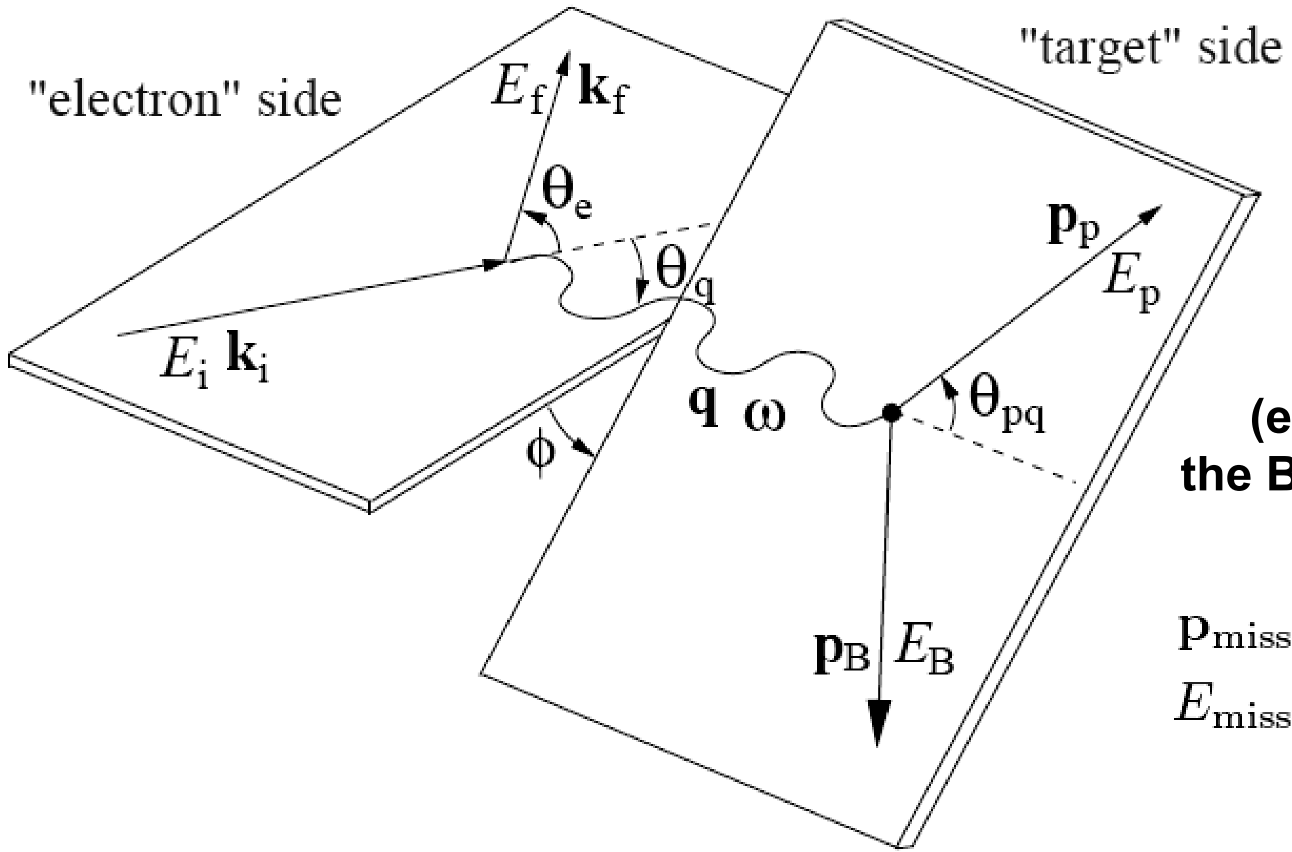
QUASIELASTIC REGION

Cross Section A(e,e'p)B



Depending on the energy ω and the momentum q transferred by the electron to the nuclear system, we find different regions

KINEMATICS



(e,e'p) reaction in the Born Approximation

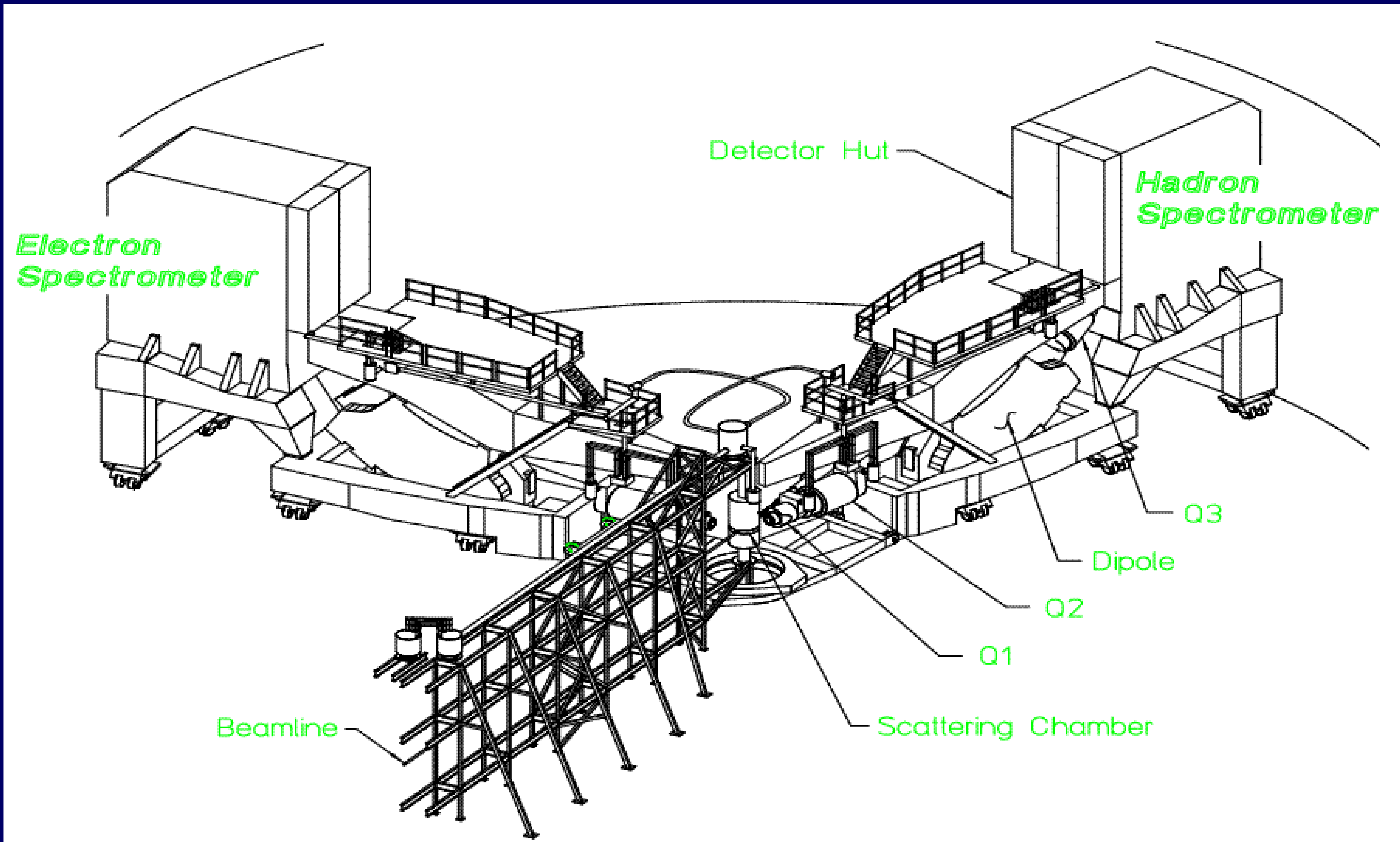
$$\mathbf{p}_{miss} \equiv \mathbf{p}_p - \mathbf{q},$$
$$E_{miss} \equiv \omega - T_p - T_B,$$

Jefferson Lab

Newport News, Virginia (USA)   http://www.jlab.org

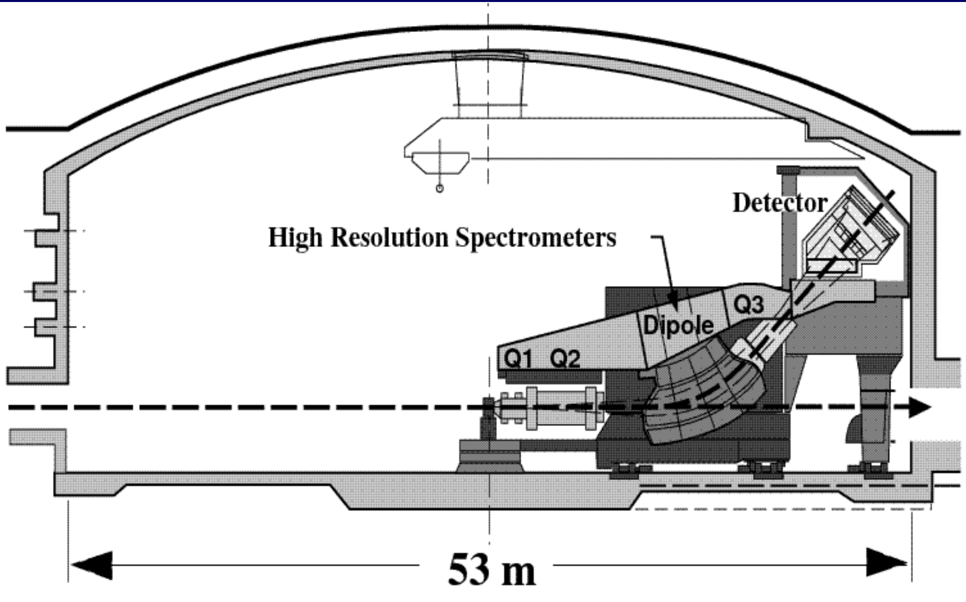
JLAB - HALL A

JLAB - HALL A



Electron Spectrometer
Detector Hut
Hadron Spectrometer
Q3
Dipole
Q2
Q1
Scattering Chamber
Beamline

SPECTROMETERS



Hall A High Resolution Spectrometer.

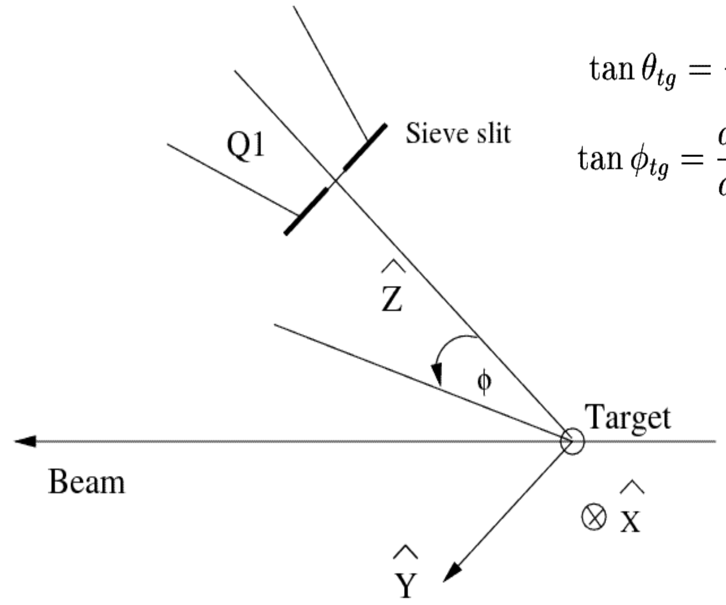
Bending angle	45°
Optical length (m)	23.4
Momentum range (GeV/c)	0.3 to 4
Momentum acceptance (%)	±4.5
Momentum dispersion (cm/%)	11.76
Momentum resolution (FWHM)	$2.5\text{-}4.0\times10^{-4}$
Horizontal angular acceptance (mr)	±25
Transverse angular acceptance (mr)	±50
Horizontal FWHM angular resolution (mr)	1.0
Transverse FWHM angular resolution (mr)	2.0
Transverse position acceptance (cm)	±5cm
Transverse position FWHM resolution (mm)	2.0

- J. Gao, Ph.D. thesis, MIT,1999

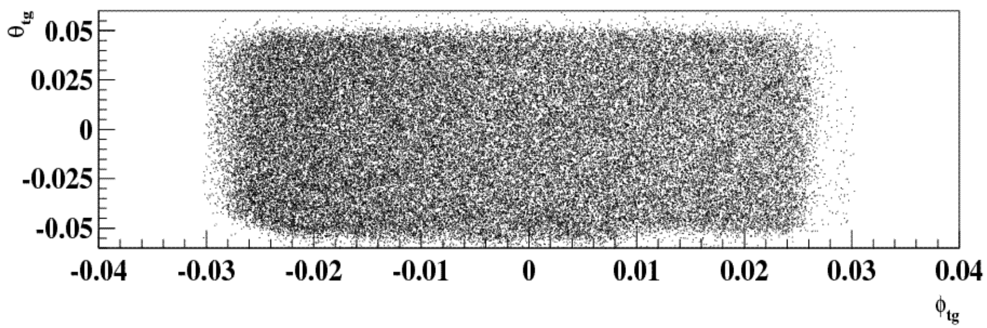
SPECTROMETER ACCEPTANCES

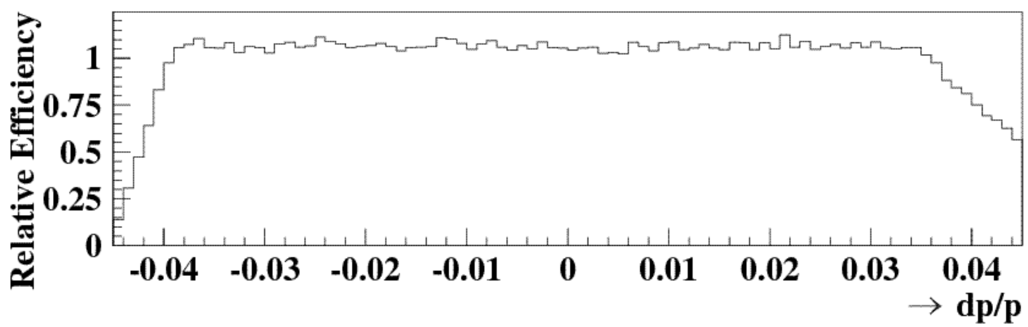
$$\tan\theta_{tg} = \frac{dx}{dz}$$

$$\tan\phi_{tg} = \frac{dy}{dz}$$



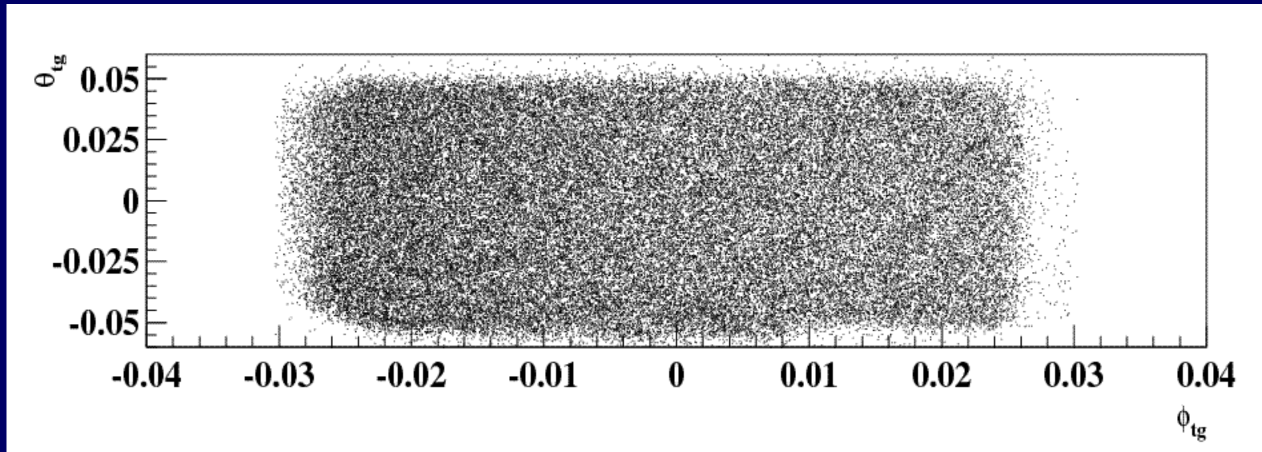
TARGET COORDINATE SYSTEM

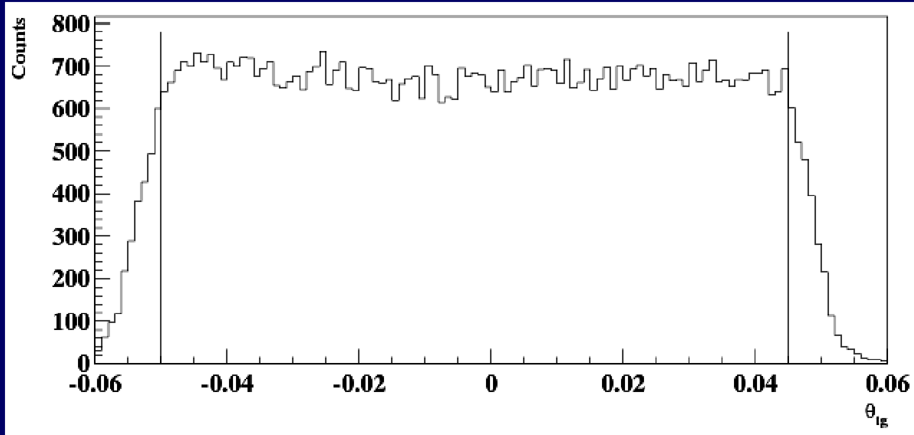


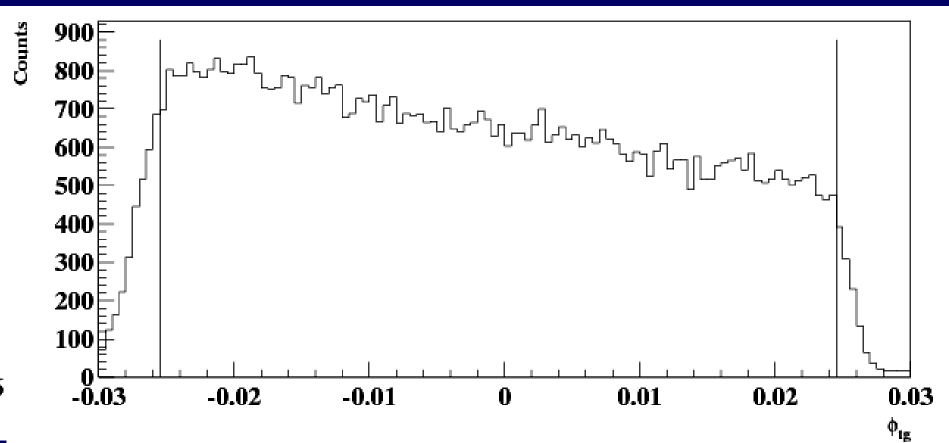


CUTS IN THE ACCEPTANCES

$-0.05 < \theta_{tg} < 0.045,$ $-0.026 < \phi_{tg} < 0.024$	HRSE
$-0.05 < \theta_{tg} < 0.05,$ $-0.022 < \phi_{tg} < 0.022$	HRSH







EXPERIMENTS

- **E89-003** – A Study of the Quasielastic $^{16}O(e,e'p)$ Reaction at High Recoil Momenta (Summer 1997).
- **E00-102** - Testing the Limits of the Single Particle Model in ^{16}O (Autumn 2001).
- **E06-007** - Impulse Approximation Limitations to the (e,e'p) reaction on ^{208}Pb, Identifying Correlations and Relativistic Effects in the Nuclear Medium (Spring 2007).

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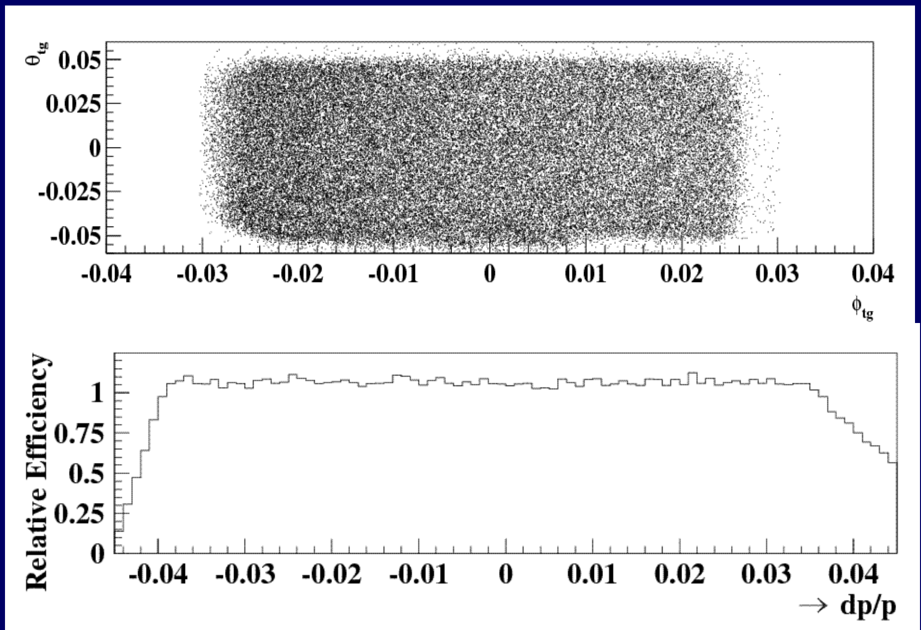
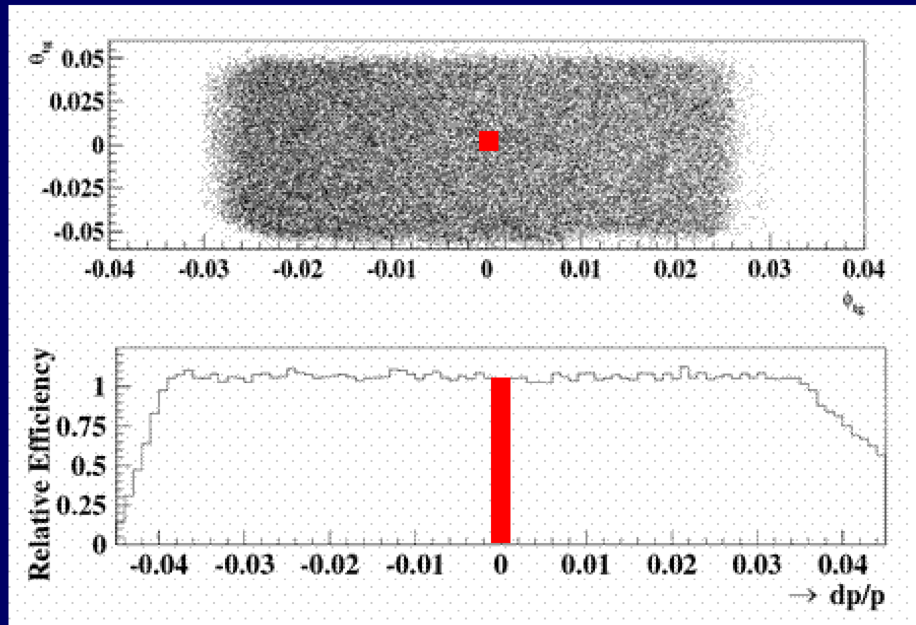
SPECTROMETER ACCEPTANCES

EXPERIMENTS:
Spectrometers with significant angular and momentum acceptances

THEORETICAL CALCULATIONS:
Assume central values for the spectrometer acceptances





SPECTROMETER ACCEPTANCES

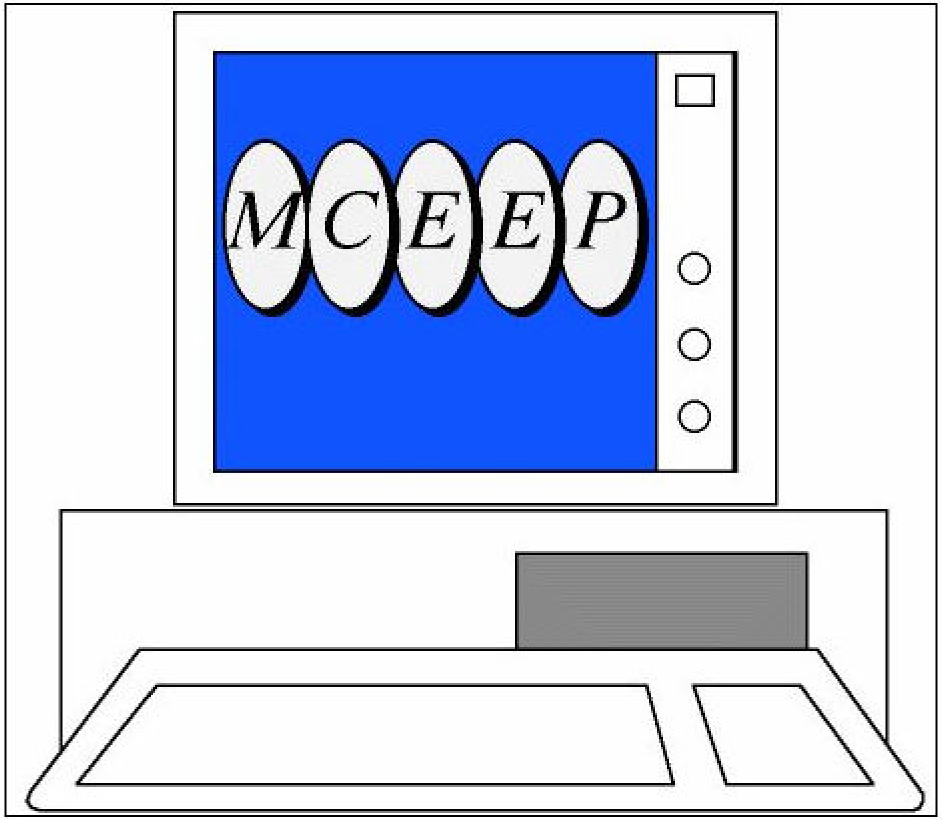
EXPERIMENTS:
Spectrometers with significant angular and momentum acceptances

↔

THEORETICAL CALCULATIONS:
Assume central values for the spectrometer acceptances

In order to correctly compare data to theory, two obvious approaches exist:

- Acceptance effects may be removed from data via stringent cuts (statistics suffer).
- Calculations may be averaged over acceptance (requires very well-understood acceptances, time consuming).



MCEEP: Monte Carlo for (e,e'p) experiments

Version 3.9

June 2006

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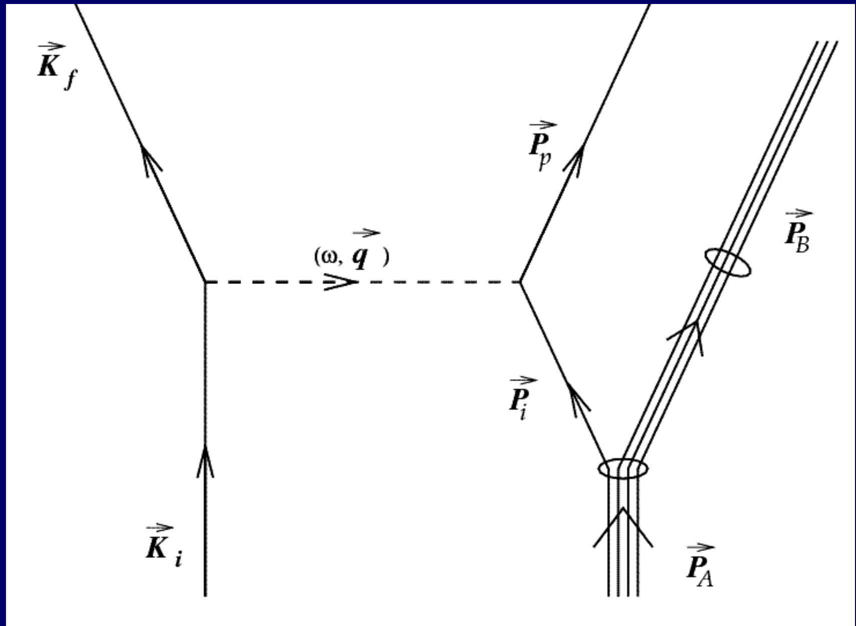
http://hallaweb.jlab.org/software/mceep/mceep.html

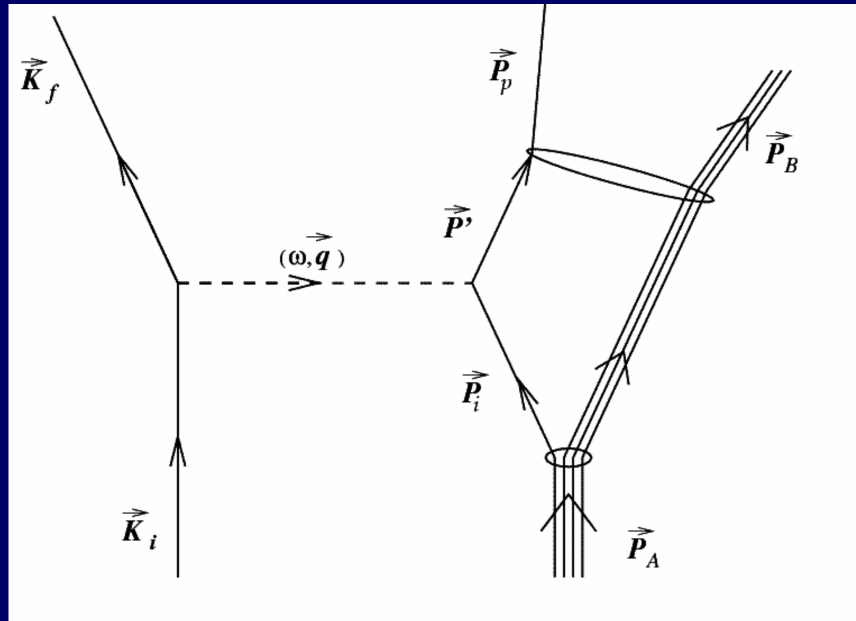
MCEEP

- MCEEP is a simulation open source code written in fortran. It was designed to simulate coincidence (e,e'X) experiments by averaging theoretical models over the experimental acceptances.
- Although it was initially designed with (e,e'p) processes in mind, it is applicable to any single hadron emission experiment.
- MCEEP employs a uniform random sampling method to populate the experimental acceptance.
- It has an important limitation: it uses very simple models of the (e,e'p) reaction to avoid long computational time.

PWIA / DWIA / RDWIA CODES



Plane Wave Impulse Approximation in $(e, e'p)$

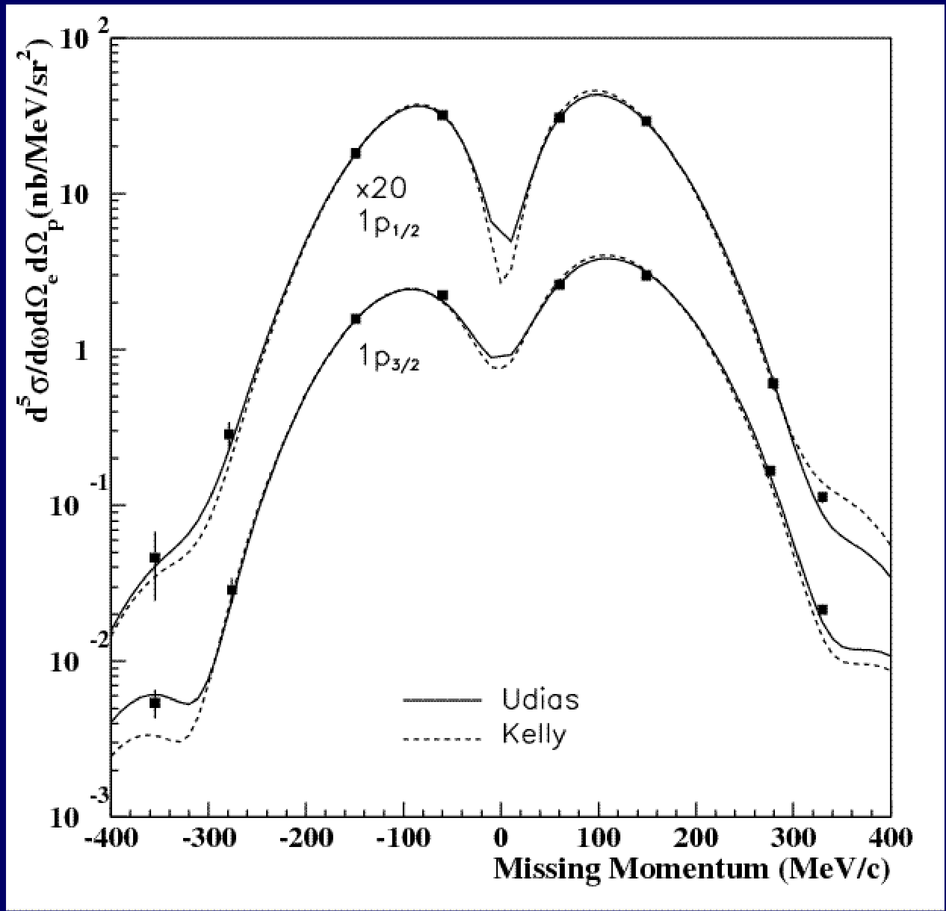


Distorted Wave Impulse Approximation in $(e, e'p)$

RDWBA codes have been shown to give the most accurate results for these kind of processes.

(RDWIA + Coulomb corrections) provides reasonable results.

RDWIA RESULTS



Experimental data from the E89-003 experiment and RDWIA theoretical calculation from Udias et al.

RDWIA code solves the Dirac equation directly in configuration space.

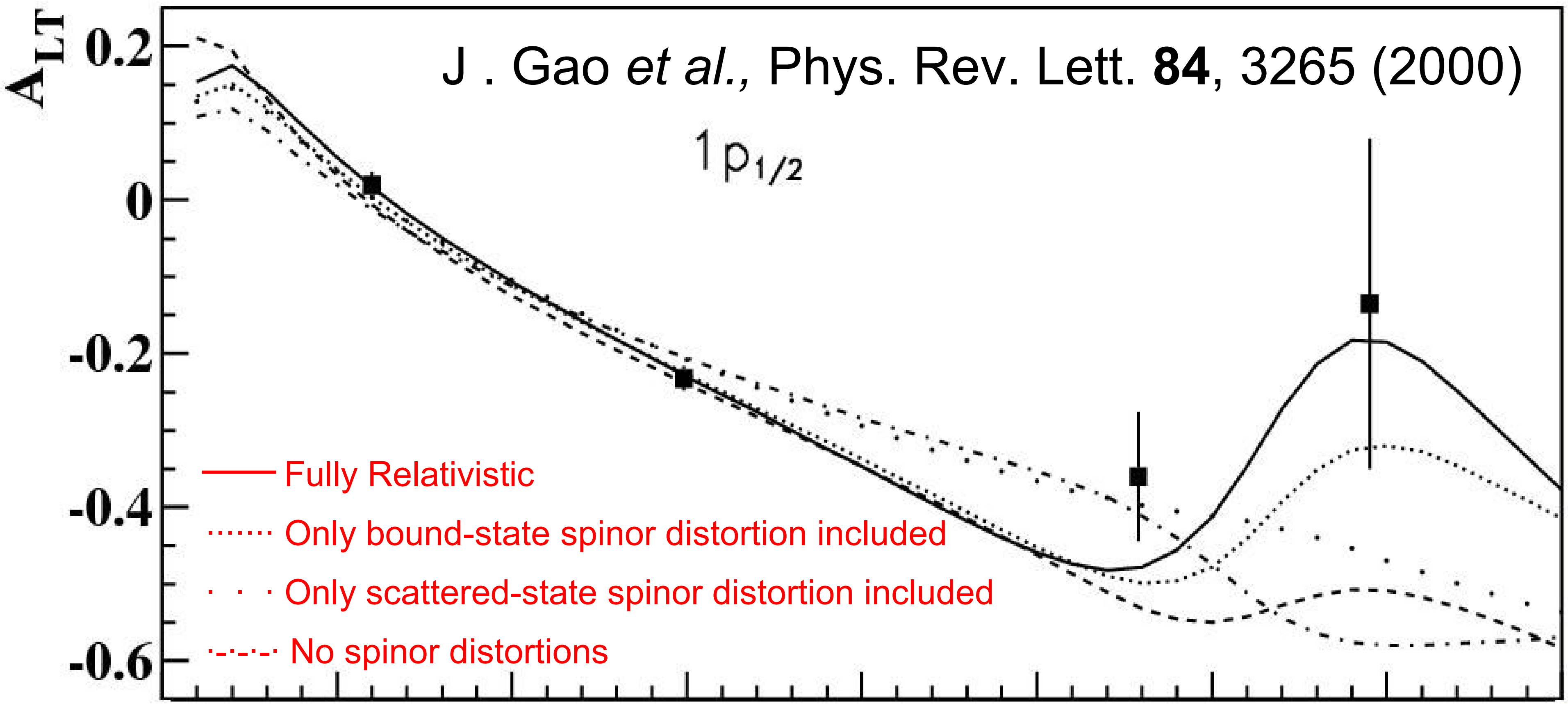
At high Q^2, quasielastic (e,e'p) is dominated by single-body interactions. Therefore RDWIA calculations should be more accurate than at low Q^2.

An excellent agreement between them can be observed. But no tools existed at the time to average the calculations over the extremes in acceptance.

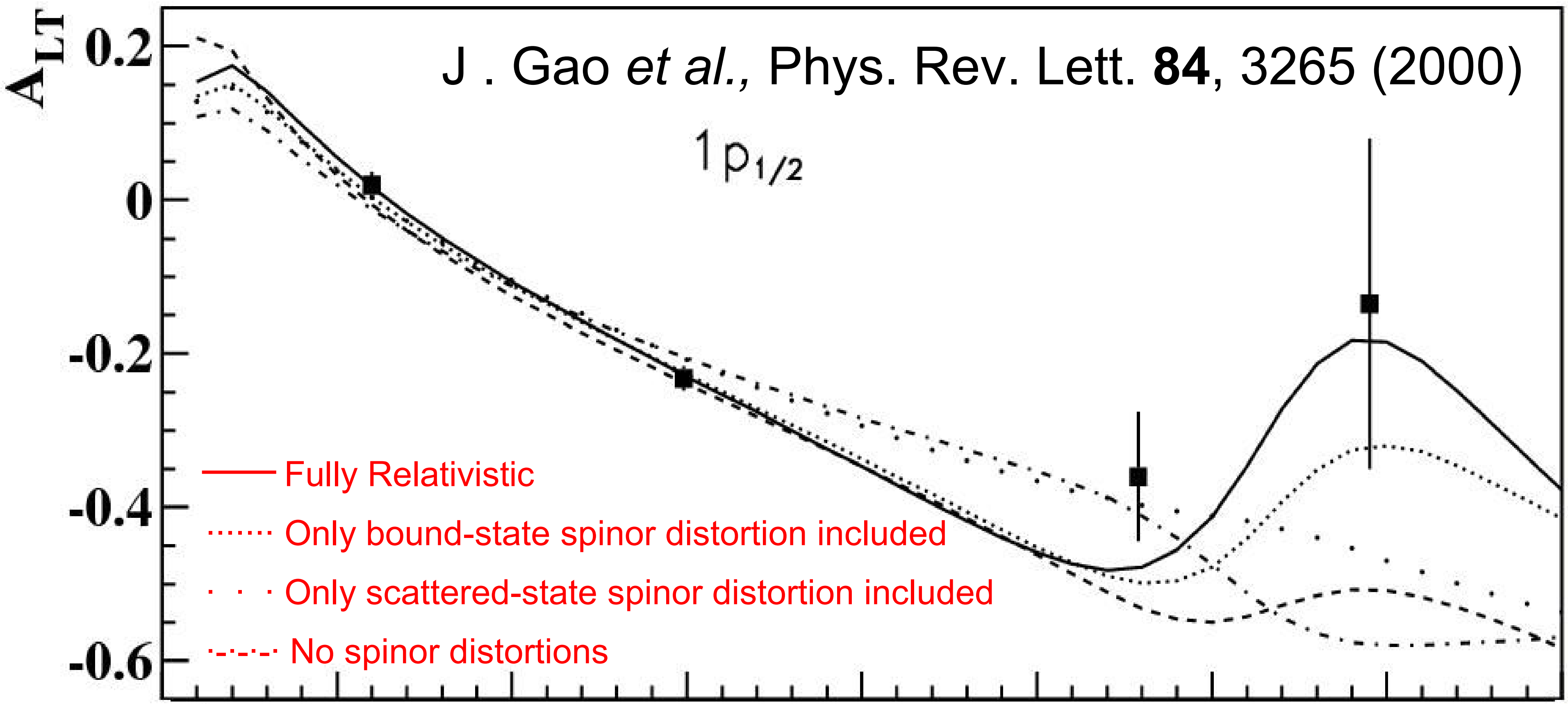
Dynamical Relativistic Effects: ATL and RTL measurements

- In our RDWIA code, the nucleon current is computed with a fully relativistic operator. The wave functions are four-component spinor solutions of the Dirac equation with scalar and vector potentials.
- As a result, their lower components are dynamically enhanced with respect to a solution of Dirac equation without potentials (a free spinor).
- This dynamical effect of spinor distortions affects the ALT and RLT observables.

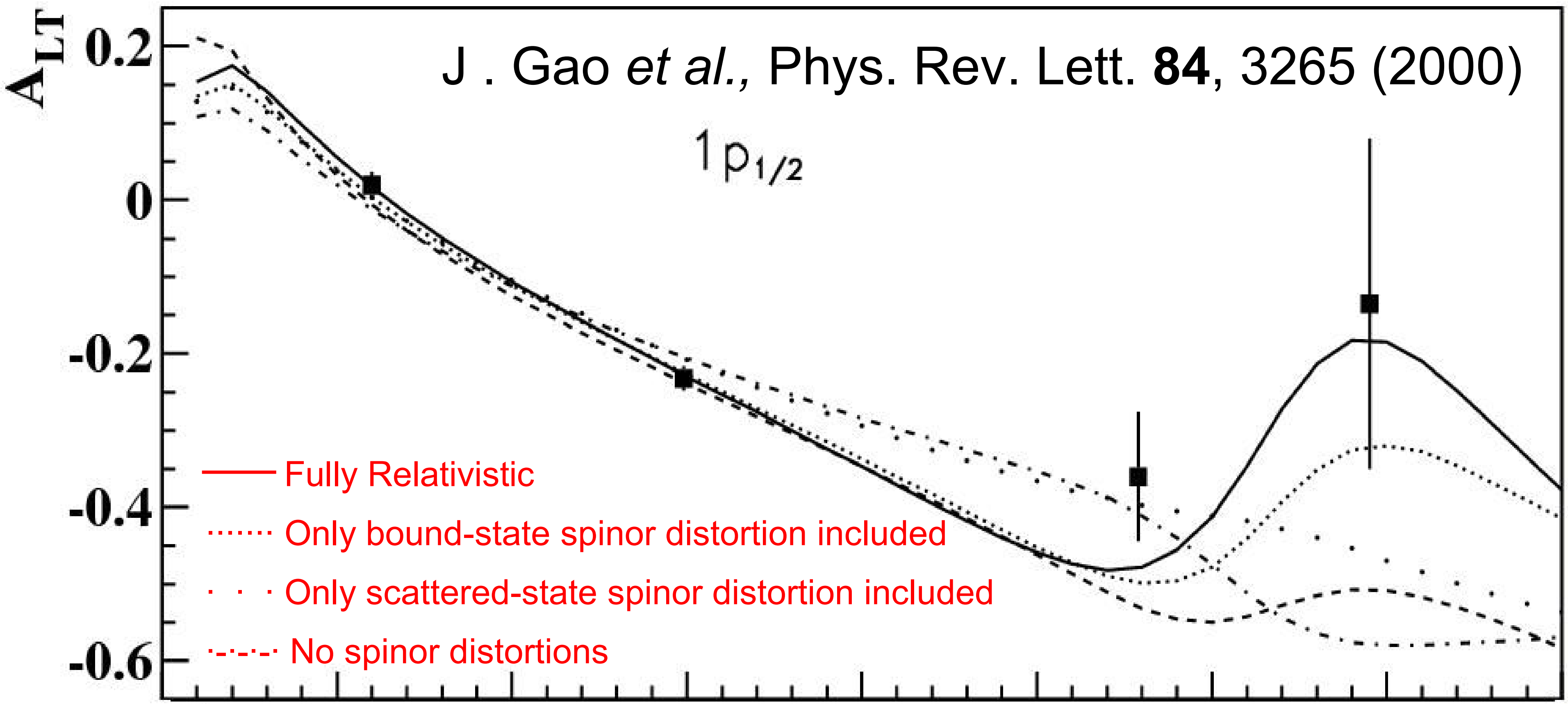
- To illustrate this point, we show calculations in which this enhancement of the lower components is removed from the relativistic wave functions.



- All other ingredients are kept the same, in particular the relativistic structure of the current operator and the upper components of the Dirac spinors.

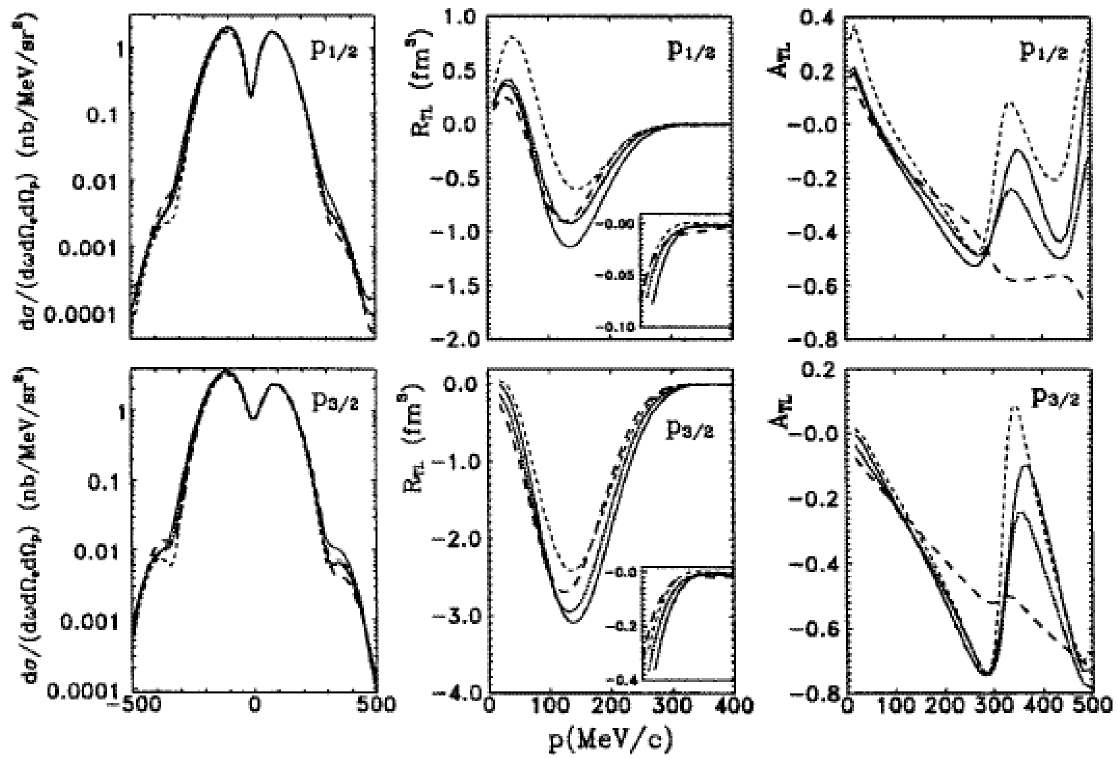


- Thus, the differences between the four curves demonstrate only the effect of spinor distortions.



Dynamical Relativistic Effects: ATL and RTL measurements

VOLUME 83, NUMBER 26 PHYSICAL REVIEW LETTERS 27 DECEMBER 1999



- J. M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999).

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MCEEP + RDWIA

- In an extended-acceptance experiment, each event can correspond to somewhat different kinematics.
- Evaluating the cross section with the RDWIA code for each event simulated with Mceep requires too much time.
- Our approach has been to pre-calculate a structure-function grid (or “hypercube”) which spans the experimental phase space, and then interpolate on this hypercube on an event-by-event basis, extracting the cross section.

HYPERCUBE

- The cross section of each simulated event can be expressed as a function of the variables $(E_{miss}, p_{miss}, q, \omega)$.

- If we consider only those cases where the ejected protons belongs to a given shell (like $1p_{1/2}$) → Only 3 variables: (p_{miss}, q, ω).

- Using our RDWIA code we can obtain the Response Functions $(R_L, R_T, R_{LT}, R_{TT})$, which contain information about the nuclear charge and current densities, as a function of (p_{miss}, q, ω).

CROSS SECTION

$$\frac{d^5\sigma}{d\Omega_e d\Omega_p d\omega} = K\ \sigma_{\text{Mott}}[v_L R_L + v_T R_T + v_{TL} R_{TL} \cos(\phi) + v_{TT} R_{TT} \cos(2\phi)],$$

$$K = R\,\frac{p_p E_p}{(2\pi)^3} \quad \text{(phase space factor)},$$

$$R = \left| 1 + \frac{E_p}{E_{\text{recoil}}} \frac{\boldsymbol{p_p} \cdot \boldsymbol{p_{\text{miss}}}}{\boldsymbol{p_p} \cdot \boldsymbol{p_p}} \right|^{-1} \quad \text{(recoil factor)},$$

$$\sigma_{\text{Mott}} = \left[\frac{\alpha \cos(\theta_e/2)}{2E_{\text{beam}} \sin^2(\theta_e/2)} \right]^2,$$

$$v_L = \left[\frac{Q^2}{\boldsymbol{q}^2} \right]^2,$$

$$v_T = \frac{1}{2} \left[\frac{Q^2}{\boldsymbol{q}^2} \right] + \tan^2(\theta_e/2),$$

$$v_{TL} = \left[\frac{Q^2}{\boldsymbol{q}^2} \right] \sqrt{\frac{Q^2}{\boldsymbol{q}^2} + \tan^2(\theta_e/2)},$$

$$v_{TT} = \frac{1}{2} \left[\frac{Q^2}{\boldsymbol{q}^2} \right],$$

Cross section as a function of kinematical variables and the Response Functions RL,RT,RTL,RTT.

MCEEP
INPUT AND OUTPUT

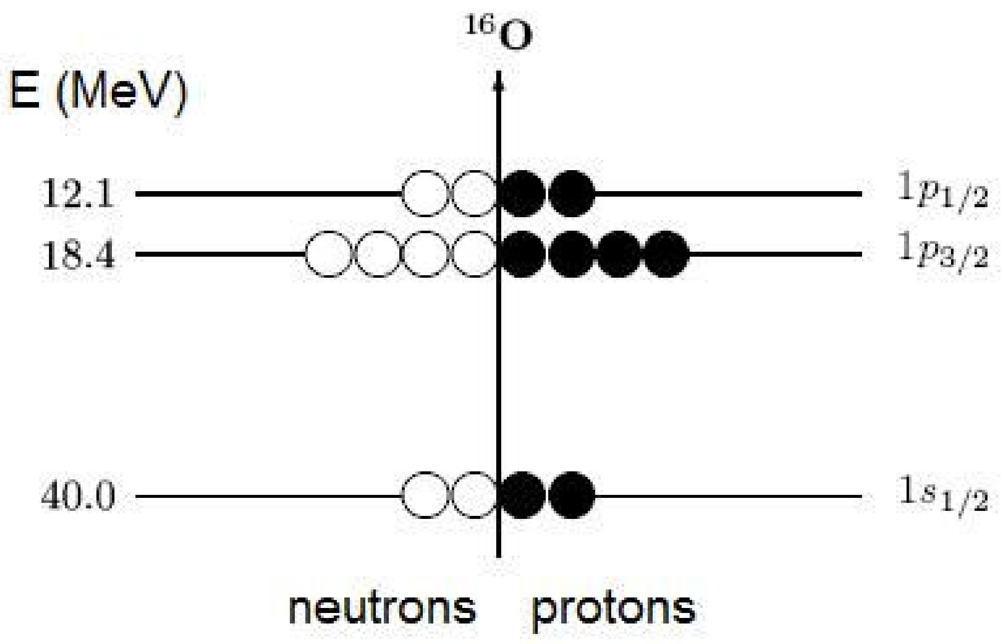
- INPUT FILES →
  - File with kinematics and options
  - File with the 3-Dimensional grid of response functions.
- OUTPUT FILE → hbook files

  Using PAW (Physics Analysis Workstation: http://**cern**.ch/**paw**/) we can work with these hbook files and create histograms of the cross section and the different kinematical variables)

RUNPLAN

- 1) Creation of the Hypercube with RDWIA code:
  - Determination of the phase space range.
  - Determination of a proper step in each variable.
  - Computational calculation (less than 1h.)
- 2) Adding new Subroutines in Mceep:
  - Reading the response-function hypercube.
  - Interpolation and evaluation of the cross section.
- 3) Using an experiment already analyzed [E89-003] to check the accuracy of the method.

E89-003 experiment: ^{16}O NUCLEUS

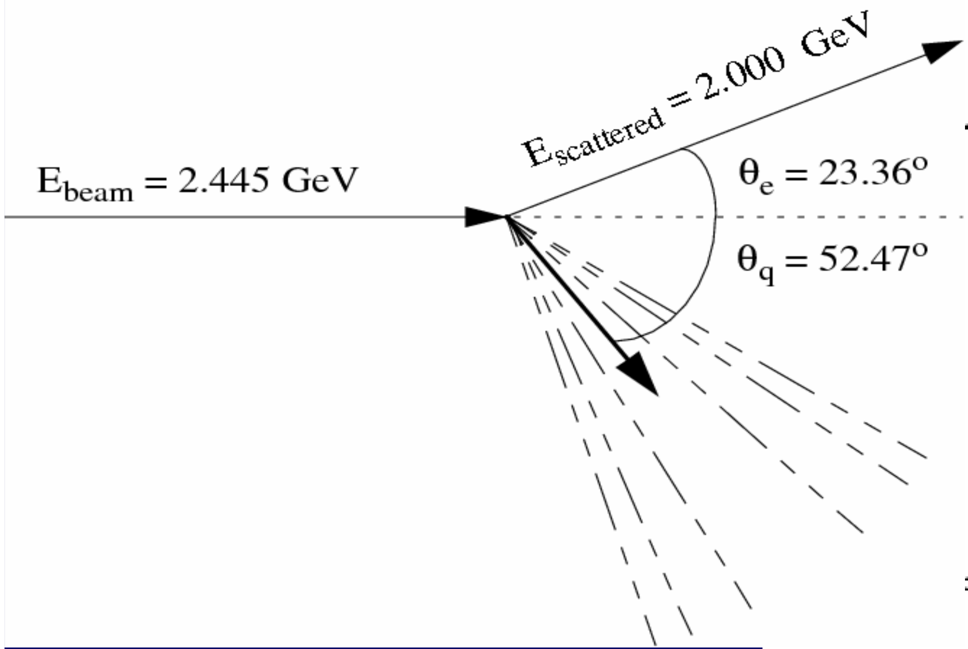


Idealized proton and neutron levels in ^{16}O

Objectives

- Cross section at high Pmiss
- Response Functions
- Asymmetry ATL
- Dynamical Relativistic effects

E89-003 KINEMATICS



E_{beam} (MeV)	θ_e (°)	θ_{pq} (°)	P_{miss} (MeV/c)
2445	23.38	-20	350
2445	23.38	-16	275
2445	23.38	-8	140
2445	23.38	0	0
2445	23.38	8	140
2445	23.38	16	275
2445	23.38	20	350

Kinematics settings for E89-003:
$\omega = 439$ MeV, $Q^2 = 0.8$ (GeV/c)^2, and $T_p = 427$ MeV.

Kinematics simulated for the E89-003 experiment to check the accuracy of our method (Mceep+RDWIA)

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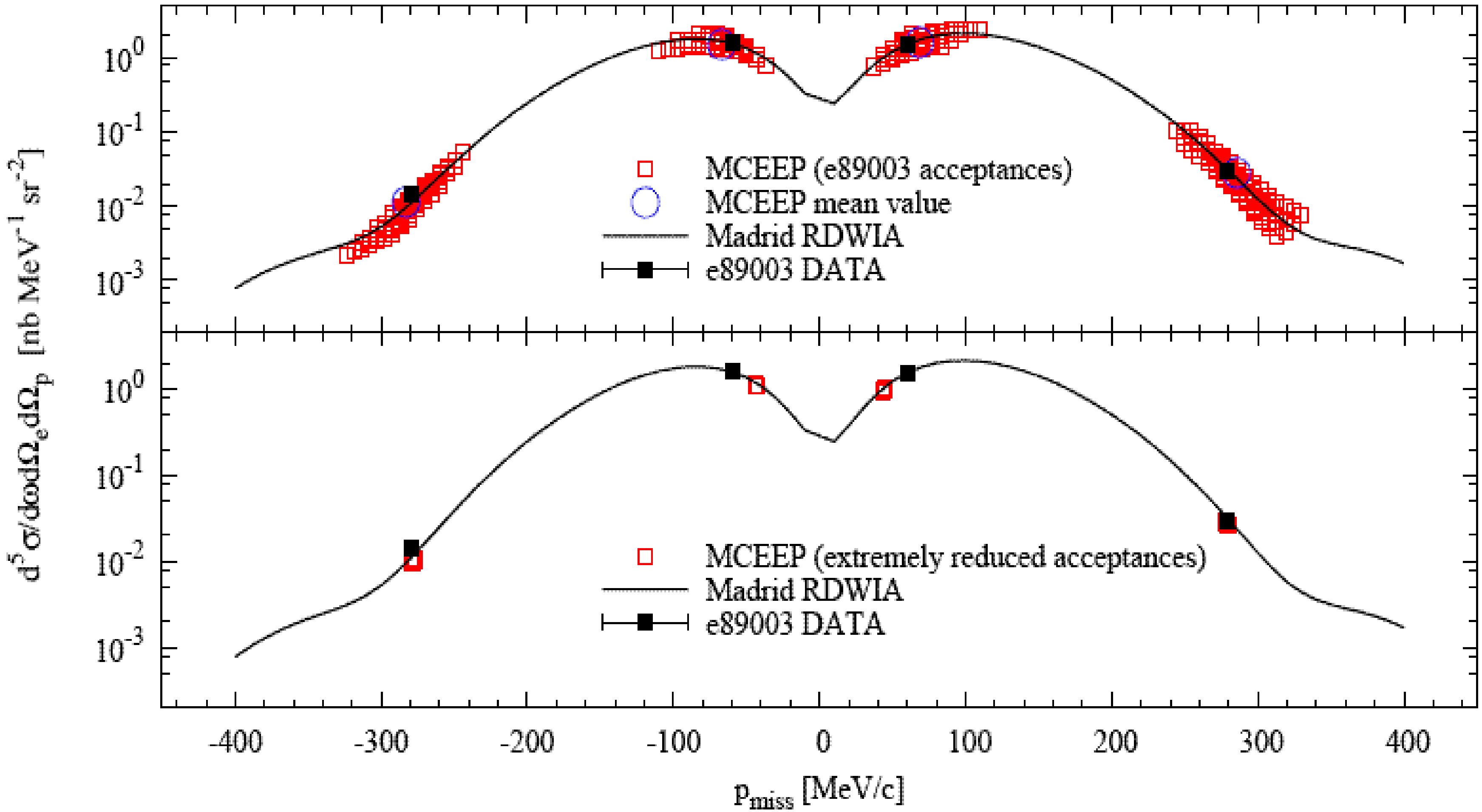
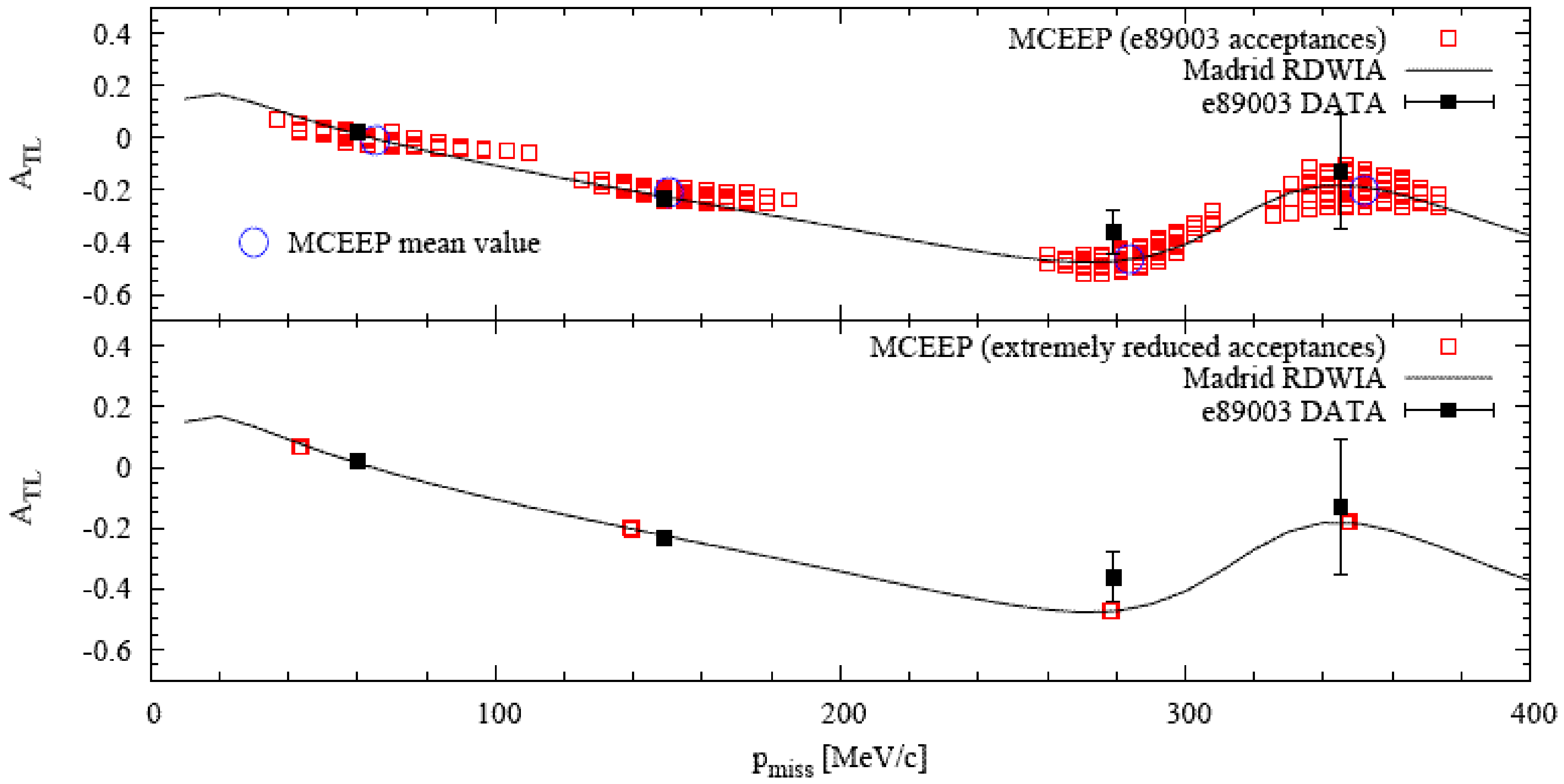
CROSS SECTION



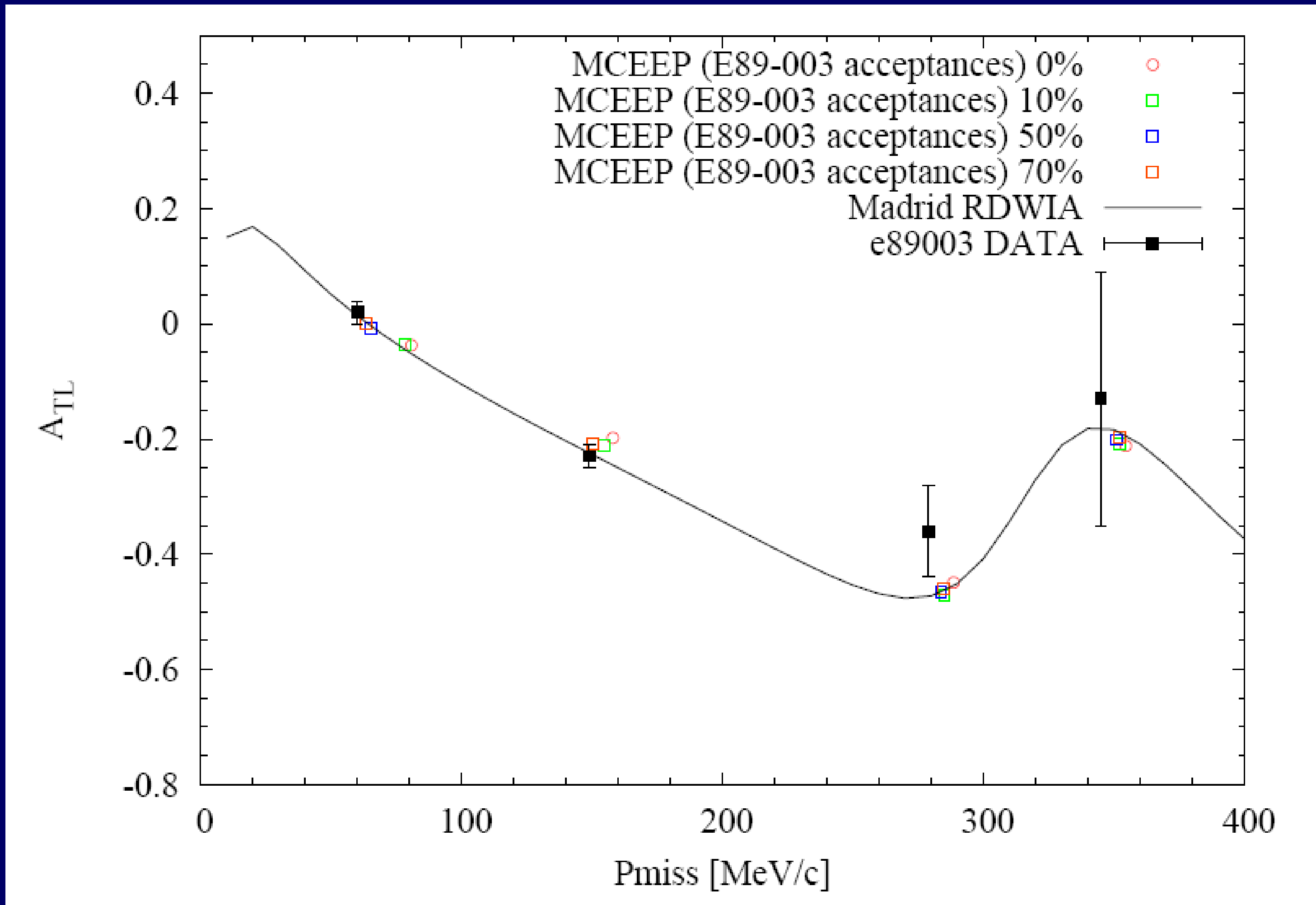
Cross section for spectrometer angles of θ_{pq}= ±2.5 and ±16.0 degrees.

A_{TL}

$$A_{TL} = \frac{\sigma(\phi = 0^\circ) - \sigma(\phi = 180^\circ)}{\sigma(\phi = 0^\circ) + \sigma(\phi = 180^\circ)}.$$

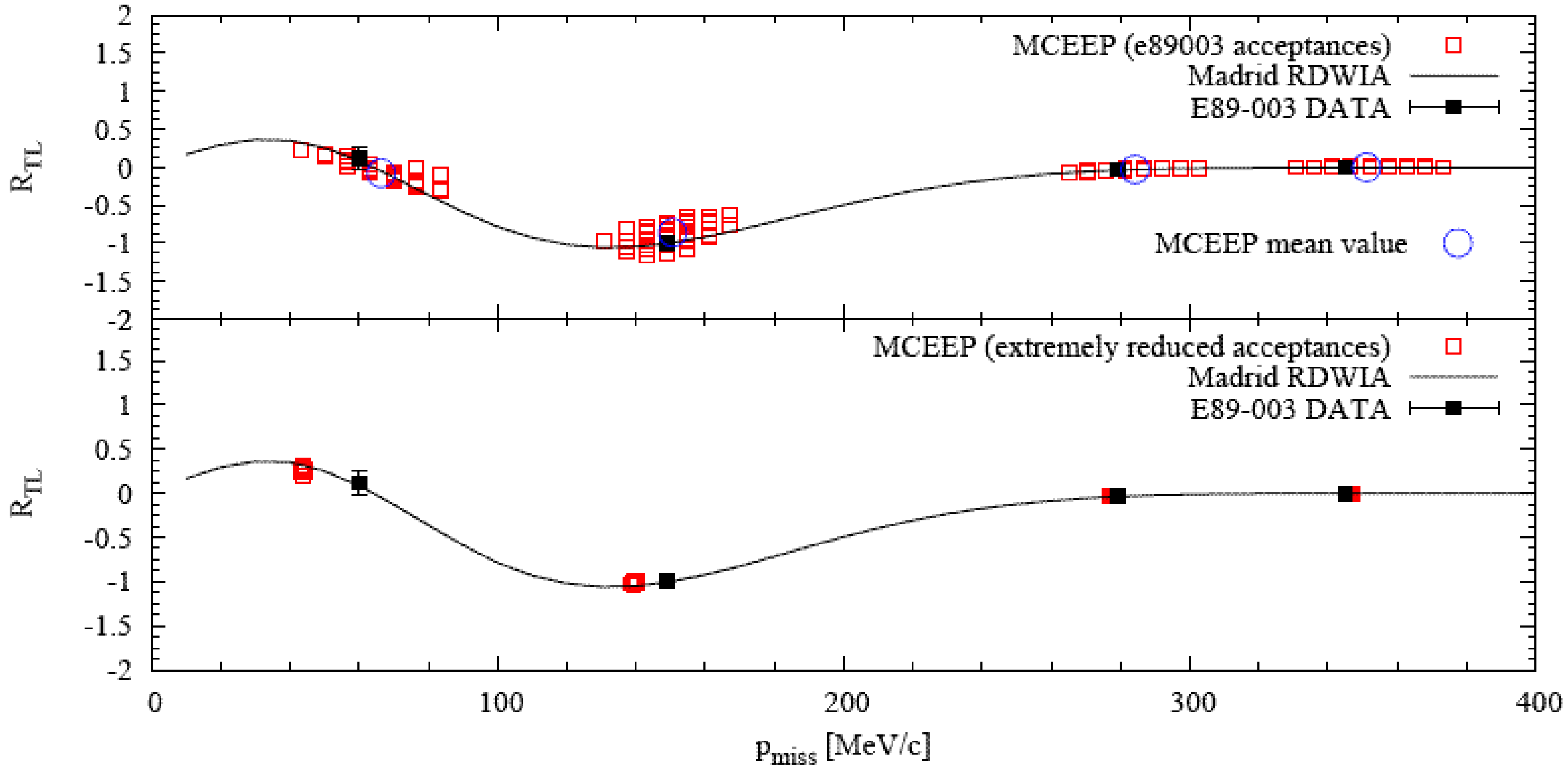


A_{TL} – Dependence on the criteria applied to the data during the analysis

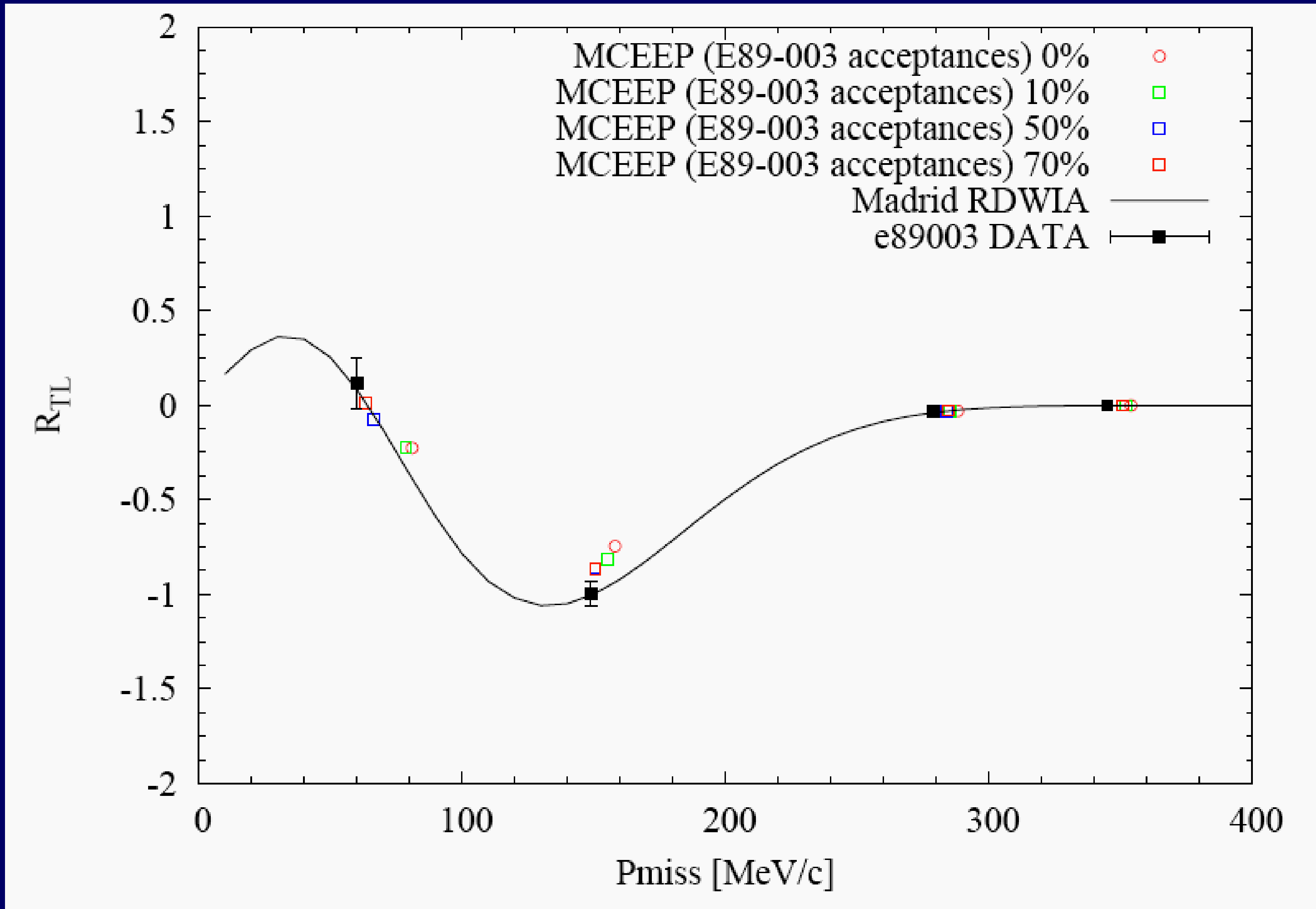


R_{TL}

$$R_{TL} = \frac{1}{2 v_{LT} K \sigma_{\mathrm{Mott}}} \left[\sigma(\phi = 0^\circ) - \sigma(\phi = 180^\circ) \right]$$



R_{TL} – Dependence on the criteria applied to the data during the analysis



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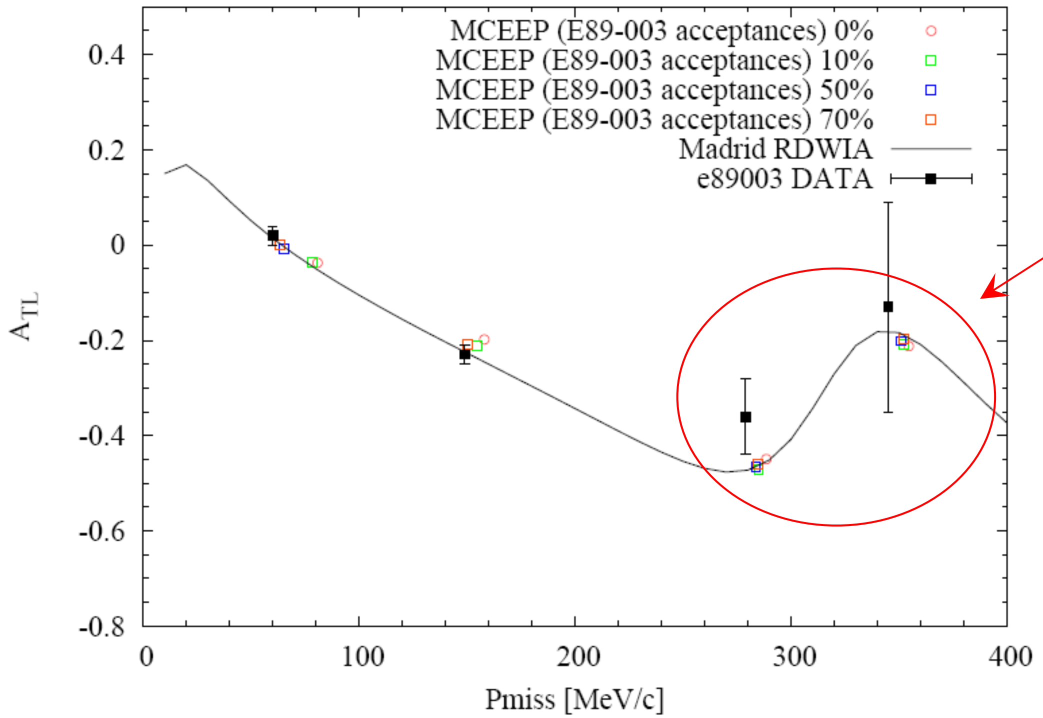

70%	23	0.236	351.0	−0.192
80%	14	0.149	352.7	−0.197
90%	6	0.065	348.5	−0.200

- At high p_{miss} it can be seen that it is not necessary to be very restrictive with the cuts imposed on the data.
- By relaxing this constraint, we anticipate that we can double our available statistics.

Dependence on the criteria applied to the data during the analysis

	$\theta_{pq}=\pm 20.0°$			
$\Delta V/V_{\max}$	bins	events (rel)	$< p_{\text{miss}} >$ (MeV/c)	A_{TL}
0%	241	1.000	354.1	−0.218
10%	114	0.727	352.5	−0.208
20%	86	0.631	351.3	−0.206
30%	67	0.533	352.3	−0.202
40%	53	0.455	351.7	−0.202
50%	43	0.390	351.2	−0.201
60%	29	0.289	351.9	−0.197
70%	23	0.236	351.0	−0.192
80%	14	0.149	352.7	−0.197
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FOLLOWING STEPS

- There are many effects that we still have to include in the simulations of the ^{16}O experiments:
  - The three water foils
  - Radiative effects
  - Contamination of the ^{16}O data by ^{1}H
  - Checking the spectrometer model
- E00-102 experiment is waiting for being analyzed and E06-007 is already scheduled.

CONCLUSIONS

- We have described a method for combining a Monte Carlo simulation software (Mceep) and our RDWIA code for the calculation of (e,e’p) reactions.
- With this procedure we can make use of a fully relativistic code with realistic kinematics and experimental acceptances, without extremely long computational time.
- The results of this approach have been validated against data from an already analyzed ^{16}O(e,e’p) experiment in quasielastic kinematics.
- The method is ready for the analysis of similar experiments [E00-102 and E06-007].

ACKNOWLEDGMENTS

- J.R. Vignote acknowledges S. Strauch his fruitful collaboration during his visit to Jlab and further years.
- Kevin Fissum acknowledges Paul Ulmer support with Mceep.
- J.L.Herraiz acknowledges the other authors his support in countless discussions and specially Kevin Fissum for his kind support in Lund, where most of this work was done.