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SPECTROSCOPIC FACTORS AND TRANSVERSE-LONGITUDINAL ASYMMETRY FROM (e,e'p) EXPERIMENTS IN ^{16}O, ^{12}C AND ^{208}Pb

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1) QUASIELASTIC (e,e'p) REACTION

2) SIMULATIONS

3) DESCRIPTION OF THE EXPERIMENTS

4) DATA ANALISIS

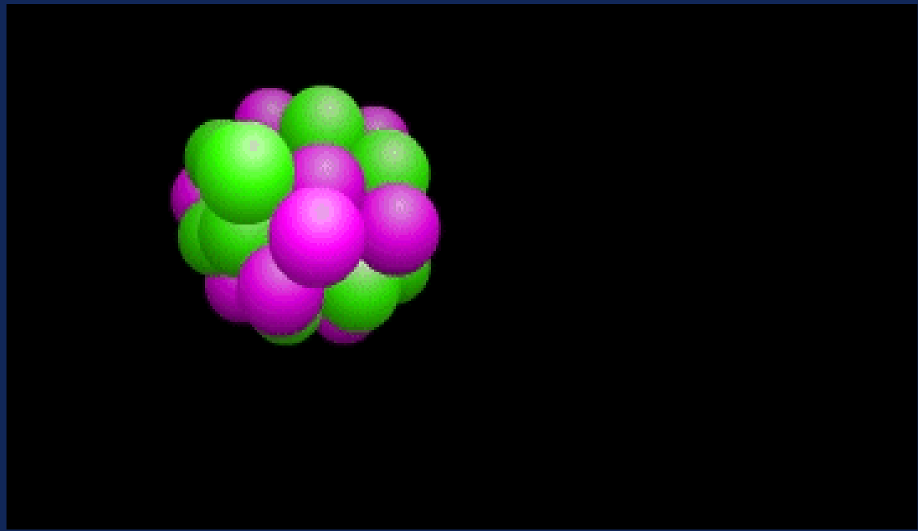
5) RESULTS

6) SUMMARY AND CONCLUSIONS

Quasielastic A(e,e'p)B Experiments

Unpolarized electron beams with an Energy of several GeV.

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



The scattered electron is detected in coincidence with an ejected proton. The three-momentum of these particles are measured and based on this information we obtain the properties of the proton in the nucleus.

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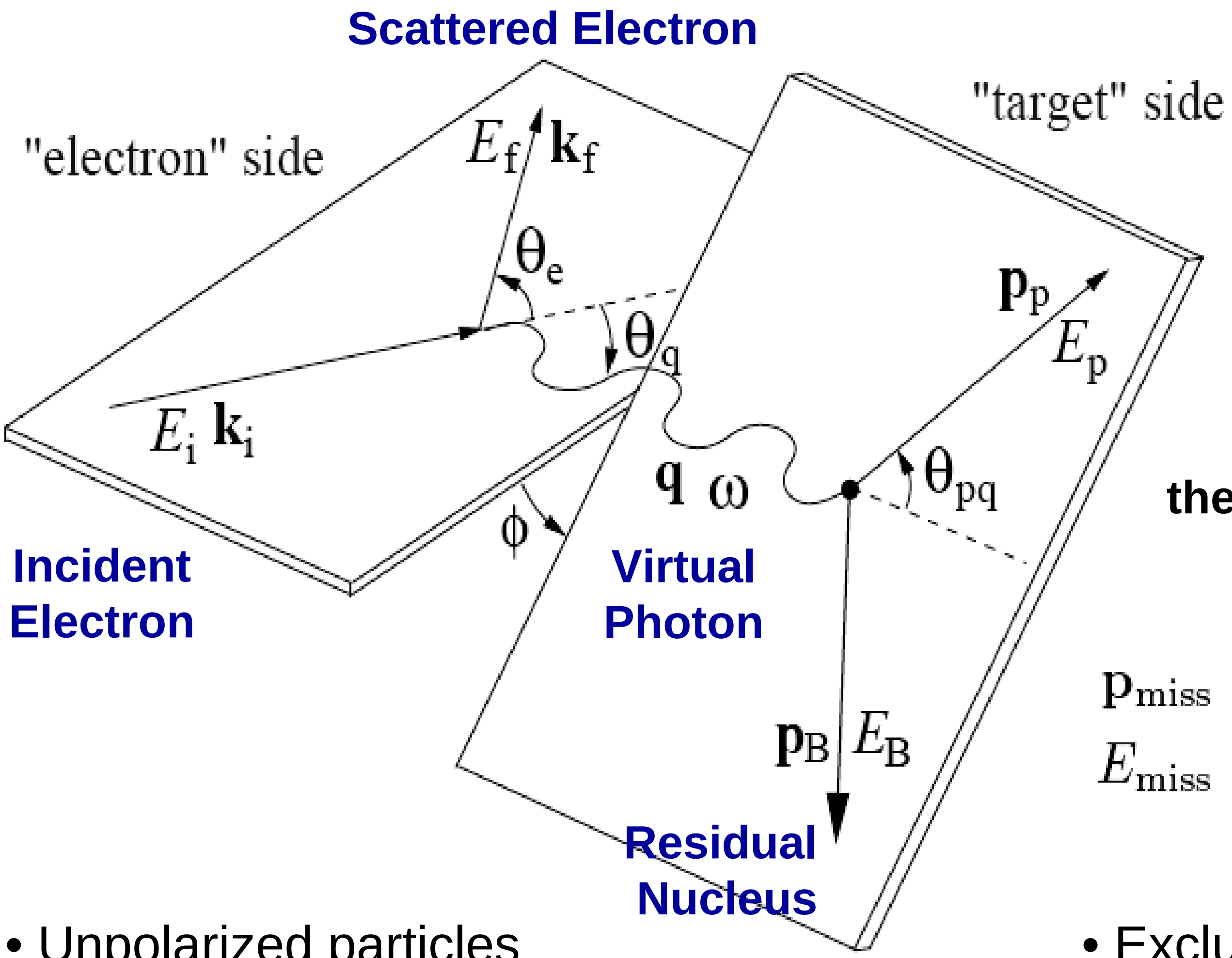
Kinematics



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

$$\mathbf{p}_{\rm miss} \equiv \mathbf{p}_{\rm p} - \mathbf{q},$$
$$E_{\rm miss} \equiv \omega - T_{\rm p} - T_{\rm B},$$

- Unpolarized particles
- Exclusive conditions

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Simple Description of the (e,e'p) Reaction

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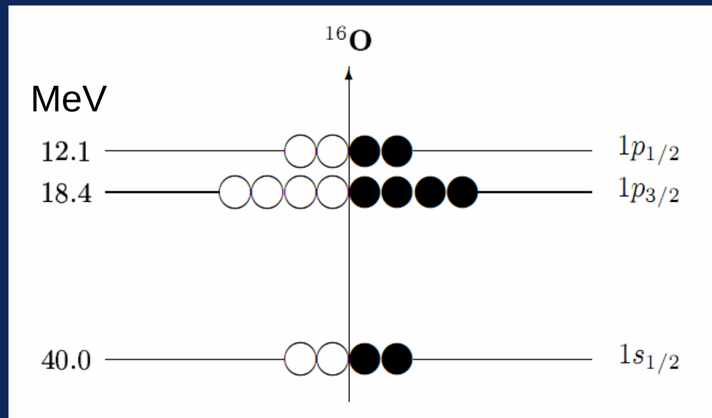
- Single-photon Exchange and Impulse Approximation (IA)
- Mean-Field and Independent Particle Shell Model (IPSM)
- Plane-Waves (PWIA)

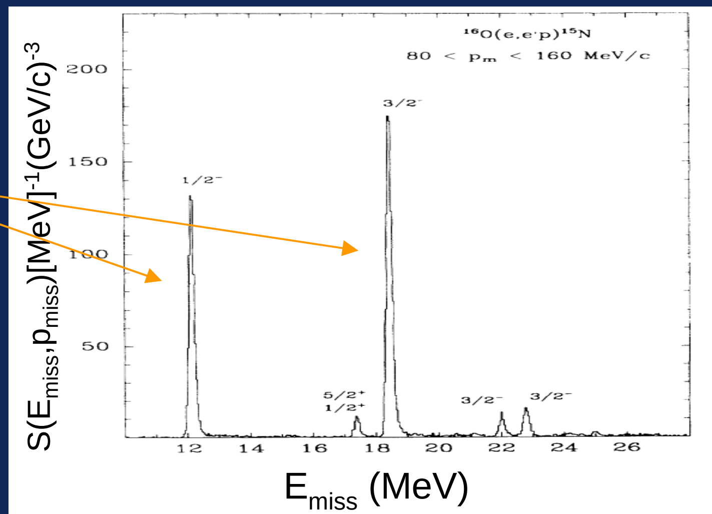
$$\frac{d^6 s}{dE_f dW_e dE_p dW_p} = K \times s_{ep} \times S(E_{miss}, p_{miss})$$

Measured Cross Section | Kin. Factor | electron-proton Cross Section | Spectral Function

$$S(E_{miss},\ p_{miss}) = r(\mathrm{p}_{miss}) \times d(E_a - E_{miss})$$

Probability of finding a proton in the nucleus with binding energy E_{miss} and momentum p_{miss}.





Other Effects in the (e,e'p) Reaction

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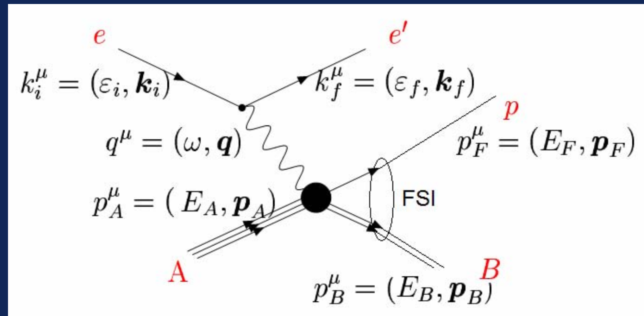
A more accurate description of the (e,e'p) reaction includes:

- Final-State Interactions: Interactions of the extracted proton with the residual nucleus. This is modeled by an optical potential from elastic (p,p) data. Proton is described by Distorted Waves (DWIA).



- Coulomb Distortion and Internal Radiative Corrections: The momentum of the electrons at the reaction point is different to their asymptotic measured values.

- External Effects (From atomic interactions in the target) Energy Loss, External Radiative Corrections, Straggling, Proton Absorption.

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(e,e'p) Observables

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- For a E_{miss} peak (shell)

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} \approx K \cdot R \cdot \sigma_{ep} \cdot \int_{E_{miss}} S(E_{miss}, p_{miss}) = K \cdot R \cdot \sigma_{ep} \cdot \rho(p_{miss})$$

- Reduced cross-section (Distorted Momentum Distribution)

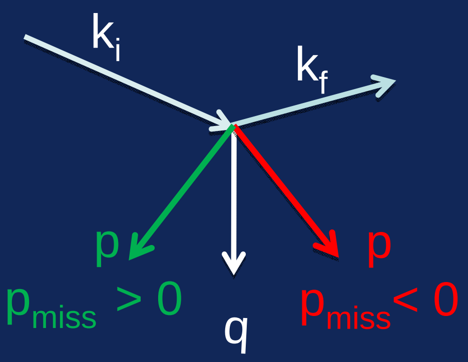
$$\sigma_{red} \equiv \frac{1}{K \cdot R \cdot \sigma_{ep}} \cdot \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p}$$

- Spectroscopic Factors – Scale factor required to fit the simulated reduced cross section with the measured one.

$$spect.fact. = \sigma_{red}(\text{exper.}) / \sigma_{red}(\text{theor.})$$

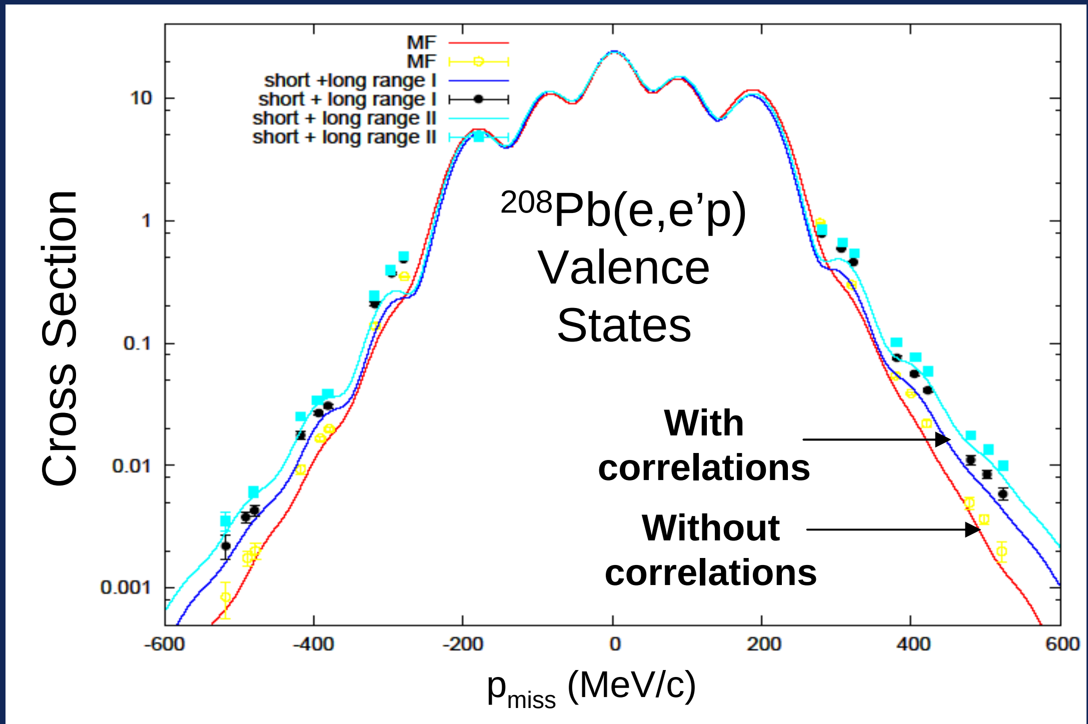
- Transverse-longitudinal assymetry (A_{TL})

$$A_{TL} = \frac{d^5\sigma(\varphi = 0^\circ) - d^5\sigma(\varphi = 180^\circ)}{d^5\sigma(\varphi = 0^\circ) + d^5\sigma(\varphi = 180^\circ)}$$



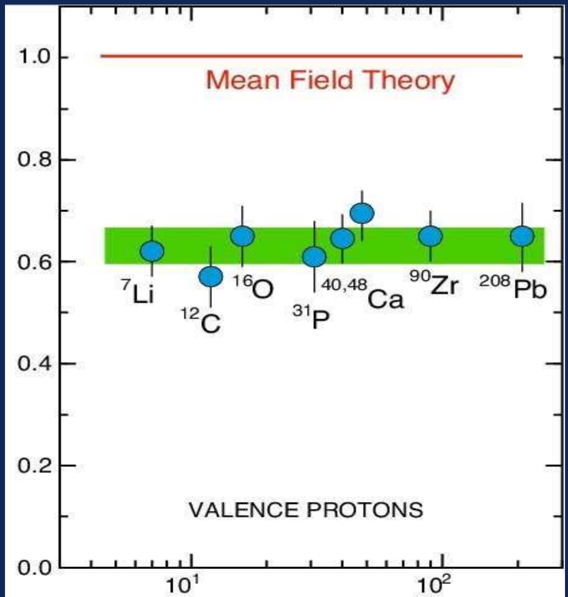
Objectives of these (e,e'p) Experiments (I)

- 1) Momentum Distribution of protons – Measurement of the reduced cross section for different shells in the nucleus in a large p_{miss} range. Search for correlation effects at high p_{miss}.
  - ^{208}Pb is one of the best nucleus to observe these effects.



Objectives of these (e,e'p) Experiments (II)

- 2) Spectroscopic Factors - Deviation from the mean field occupation prediction expected for each shell in the Shell Model. It is obtained as the factor required to fit theoretical calculations to measured data.
  - It was argued that there could be a dependence of spectroscopic factors with Q^2.



- In this work this possible dependence was studied in two different nucleus: ^{12}C and ^{208}Pb, obtaining the spectroscopic factor at three different Q^2 values: 0.8, 1.4 and 2.0 $(GeV/c)^2$.

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Objectives of these (e,e’p) Experiments (III)

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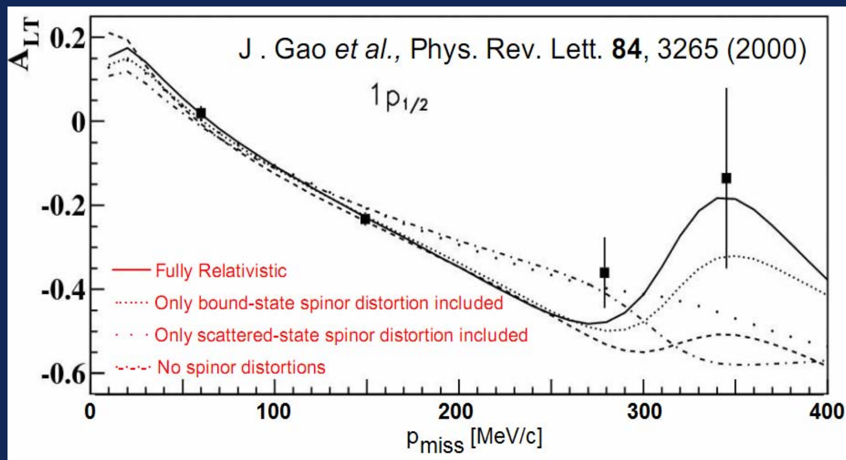
- 3) Dynamical Relativistic Effects – Enhancement of the lower components of the proton spinor inside the nucleus.

- Relativistic DWIA: Nucleon current computed with a fully relativistic operator. The wave functions are four-component spinor solutions of the Dirac equation with scalar and vector potentials and their lower components are dynamically enhanced with respect to a solution of Dirac equation without potentials (a free spinor).

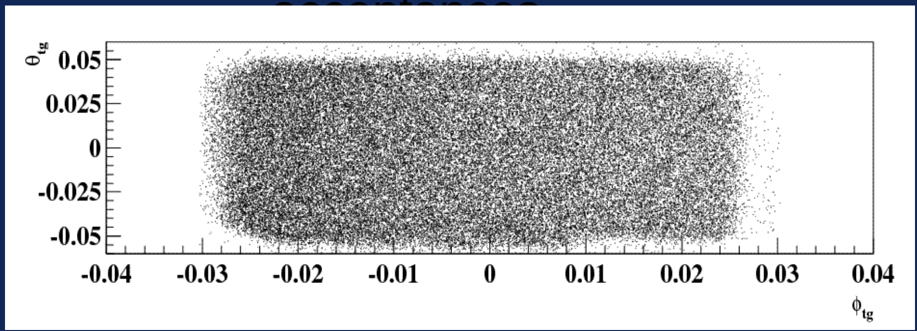
The effect of spinor distortions is visible in A_{TL} observable, specially for the $1p_{1/2}$ shell in ^{16}O, whose (relativistic) lower component is a $1s_{1/2}$ shell

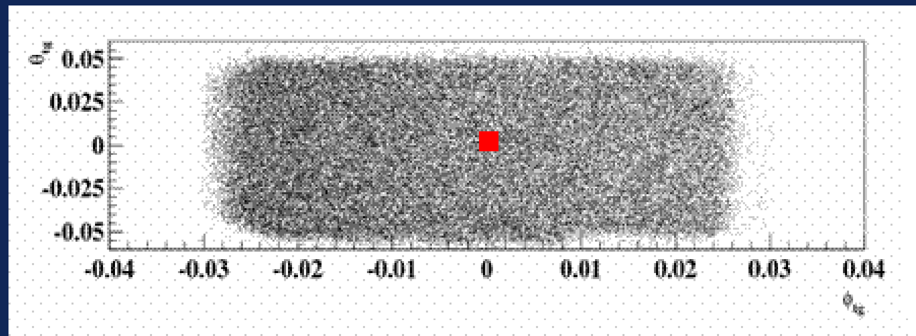


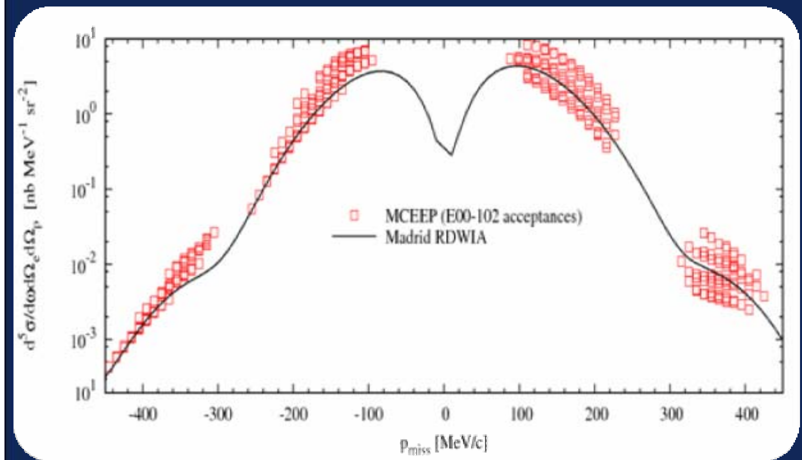
Spectrometer Acceptances

EXPERIMENTS:
Spectrometers with significant angular and momentum

THEORETICAL CALCULATIONS:
Assume central values for the spectrometer acceptances

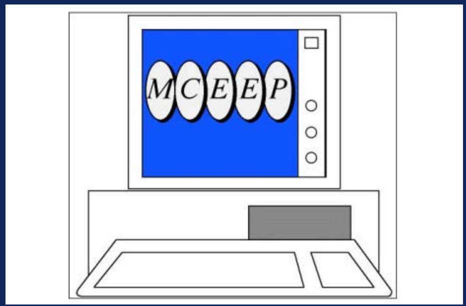






1) Acceptance effects may be removed from data via stringent cuts (statistics suffer).
2) Assuming factorization, acceptances effects can be removed via reduced cross section and significant cuts.
3) Calculations may be averaged over acceptance (requires combination of theory and simulation).

MCEEP



MCEEP V3.9 (June 2006) P. E. Ulmer et al.

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

- MCEEP (Monte Carlo for (e,e'p) experiments) 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.
- 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.

MCEEP + DWIA

- In an extended-acceptance experiment, each event can correspond to somewhat different kinematics. Evaluating the cross section with the DWIA code for each event simulated with MCEEP requires too much time.
- In our approach the Response Functions (R_L,R_T,R_{LT},R_{TT}), which contain the information of the nuclear charge and current densities, are precomputed in a grid (E_{miss},p_{miss},q,ω) which spans the experimental phase space.
- After that, we interpolate within this grid in MCEEP for extracting the cross section on an event-by-event basis.
- Radiation effects are included in MCEEP simulations than thus can be directly compared to data.

$$\frac{d^5\sigma}{d\omega\, d\Omega_e\, d\Omega_p} = R\,\frac{E_p p_p}{(2\pi)^3}\,\sigma_M \left[V_L R_L + V_T R_T + V_{TL} R_{TL} \cos\phi + V_{TT} R_{TT} \cos 2\phi \right]$$

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Experiment E00-102 $^{16}O(e,e'p)$

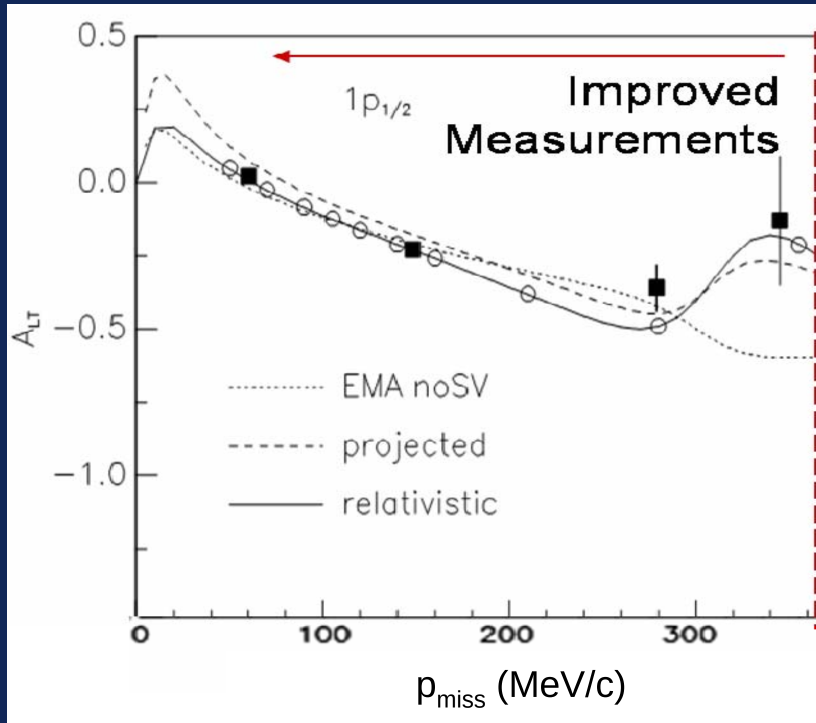
- A continuation of experiment E89-003, which measured $^{16}O(e,e'p)N$ cross section using a waterfall target.
- In this experiment, the cross section was measured in the quasielastic peak (Q^2=0.9 GeV^2, ω=0.5 GeV) with a larger missing momentum range and much higher precision.

Data acquisition

- October-December, 2001

Requirements

- Luminosity from H(e,e)
- Contamination from H(e,e'p) events → Low p_{miss} region not available.



Experiment E06-007
^{12}C(e,e’p) and ^{208}Pb(e,e’p)

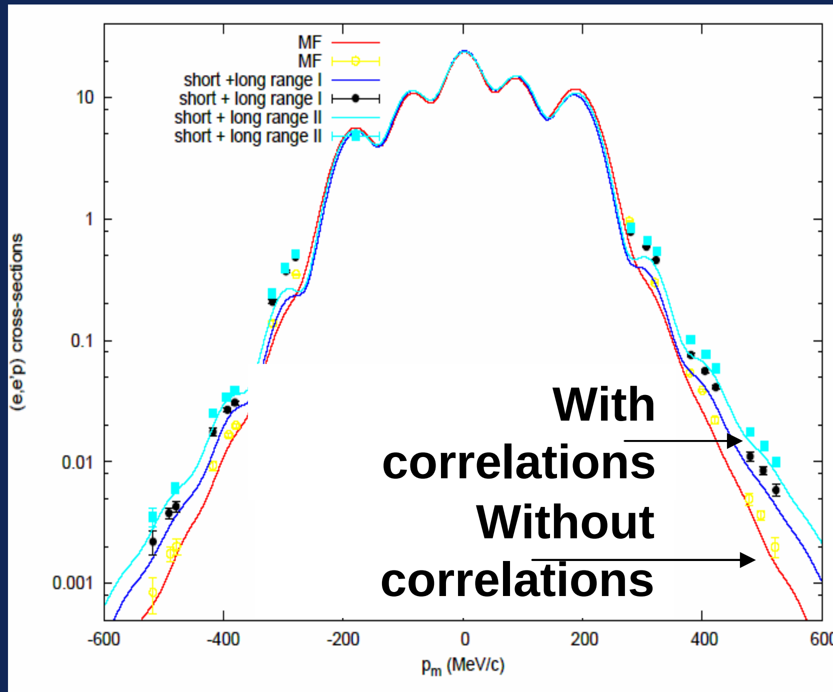
- We measured ^{208}Pb(e,e’p)^{207}Tl cross sections at true quasielastic kinem. ($x_B = 1$, q = 1 GeV/c, ω = 0.433 GeV/c) and at both sides of q.
- This has never been done before for A>16 nucleus.
- Additionally we measured ^{12}C(e,e’p) as a reference.

Data acquisition

- RUN 1 – (March, 3-26, 2007)
- RUN 2 – (January 2008)

Requirements

- Good Energy Resolution
- Rastered Beam & Composed Target (Diamond+Pb+Diamond)



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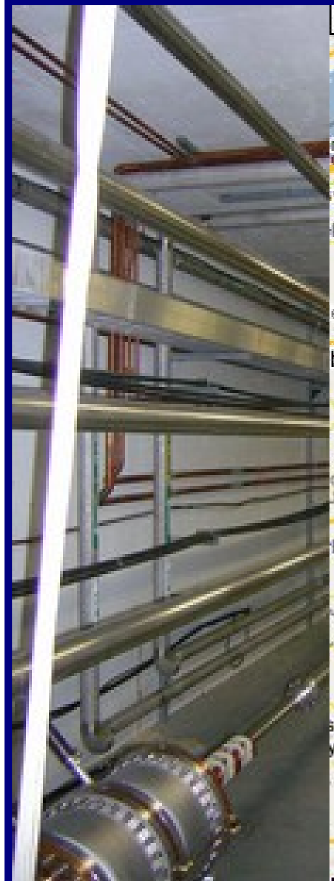
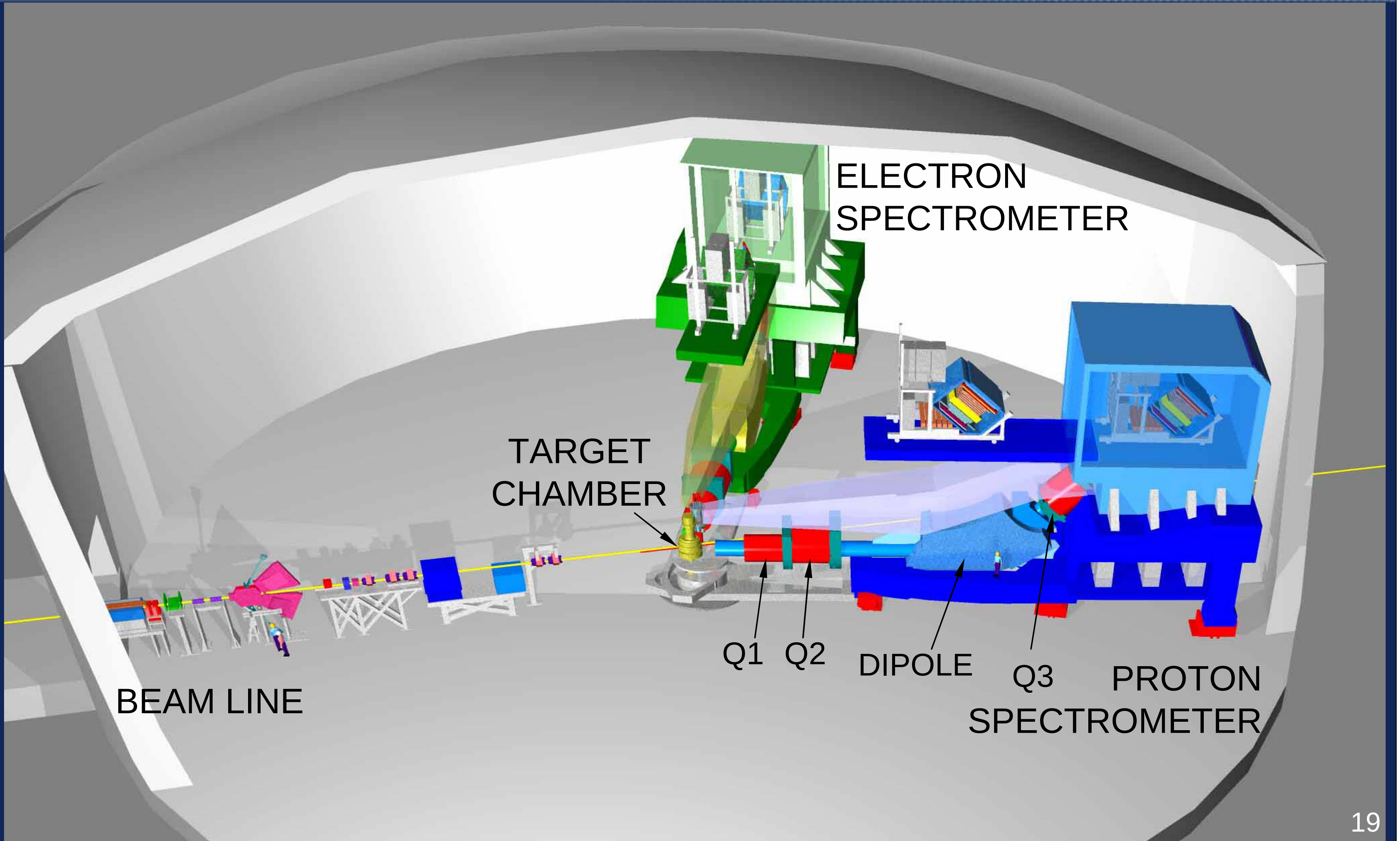
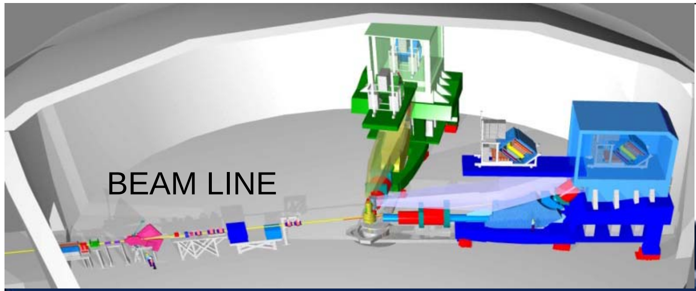


Newport News, Virginia (USA) **http://www.jlab.org**

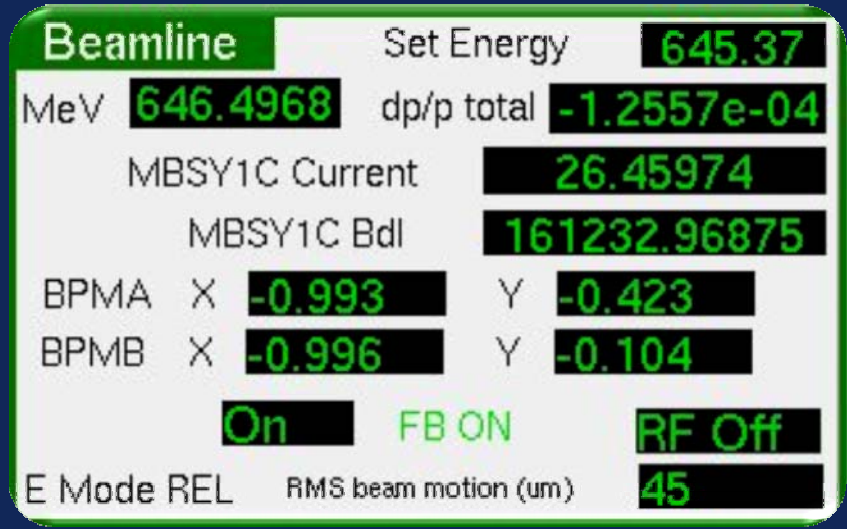
JLAB - Hall A


ELECTRON
SPECTROMETER
TARGET
CHAMBER
BEAM LINE
Q1
Q2
DIPOLE
Q3
PROTON
SPECTROMETER

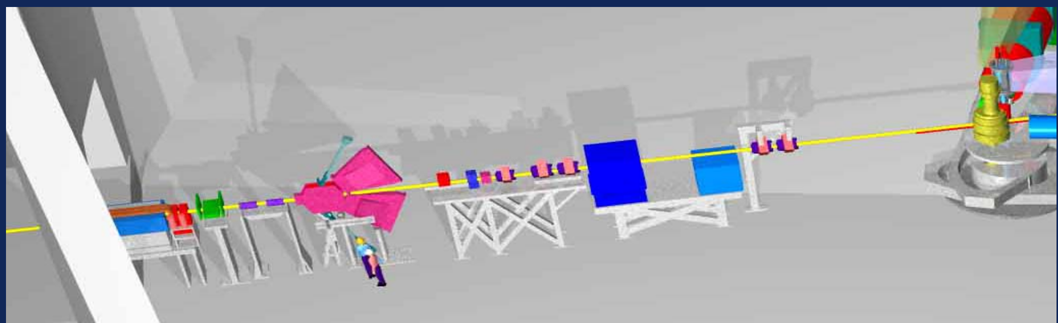


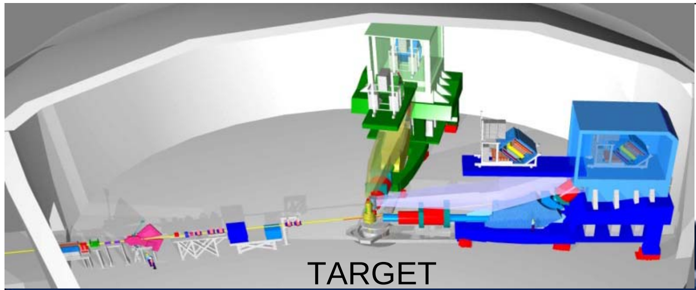
Experimental Setup: 1. - Beamline

- The quality of the beam is crucial for obtaining good and reliable results.
- Beam characteristics are continuously measured.
  - Position - Width
  - Raster - Energy
  - Intensity (Current)



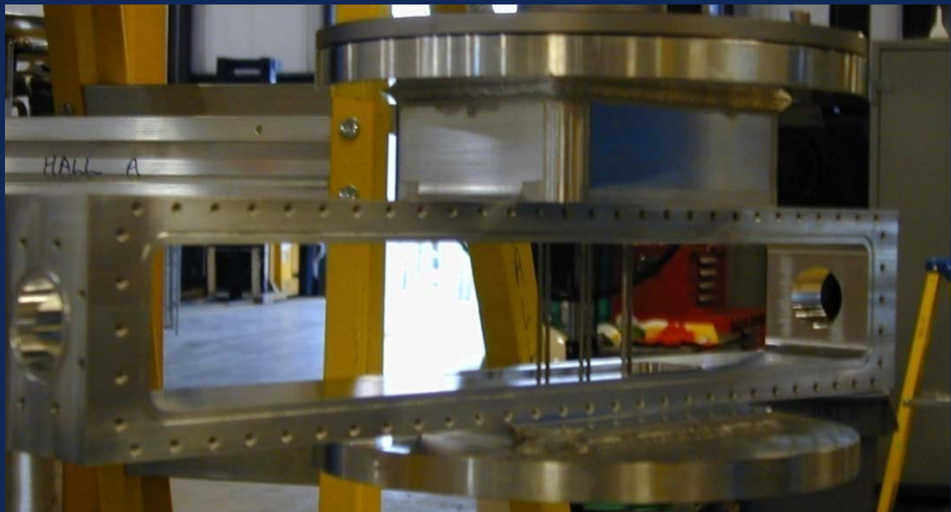
The beamline monitor shows basic beam information during the experiment

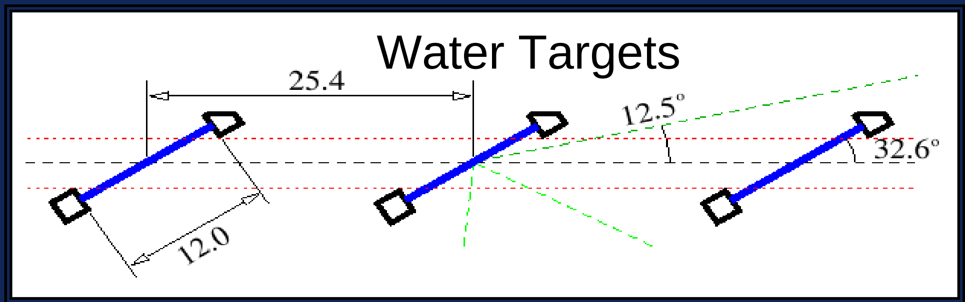




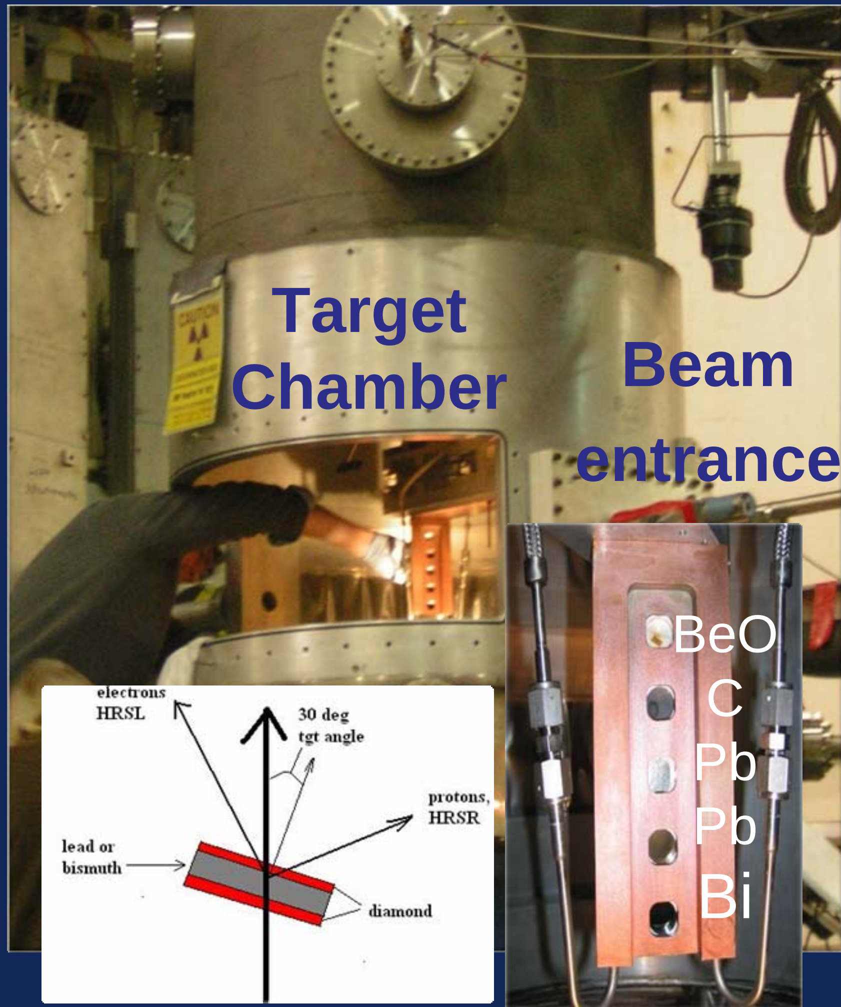
Experimental Setup: 2. - Targets

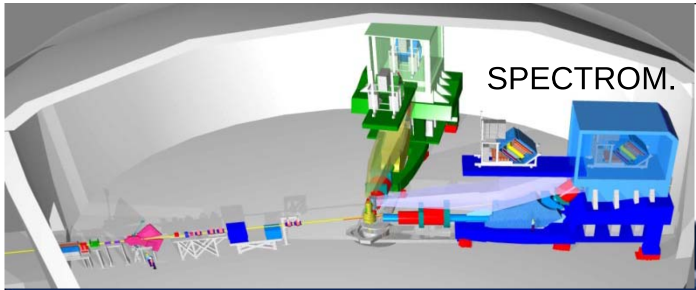
Waterfall Target (^{16}O)





^{208}Pb, ^{209}Bi and ^{12}C foils





DESCRIPTION OF THE EXPERIMENTS

Experimental Setup: 3. - Spectrometers

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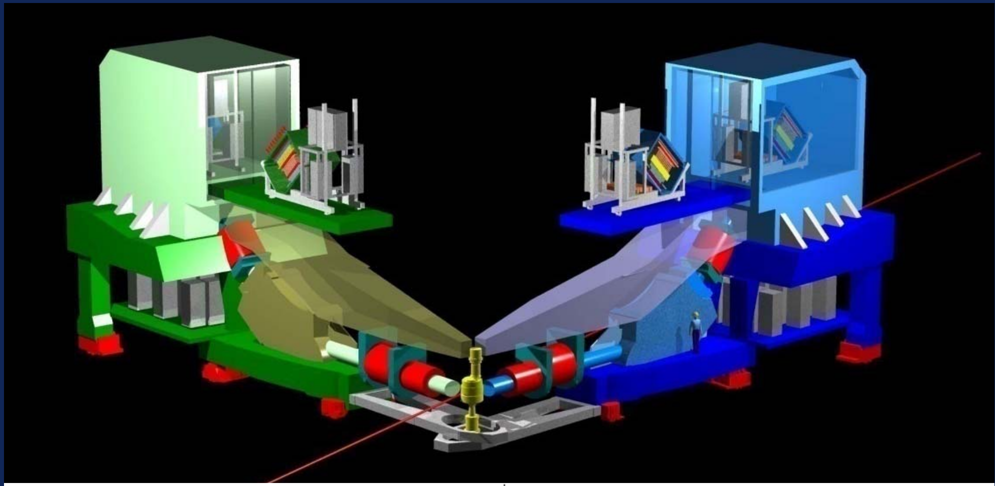
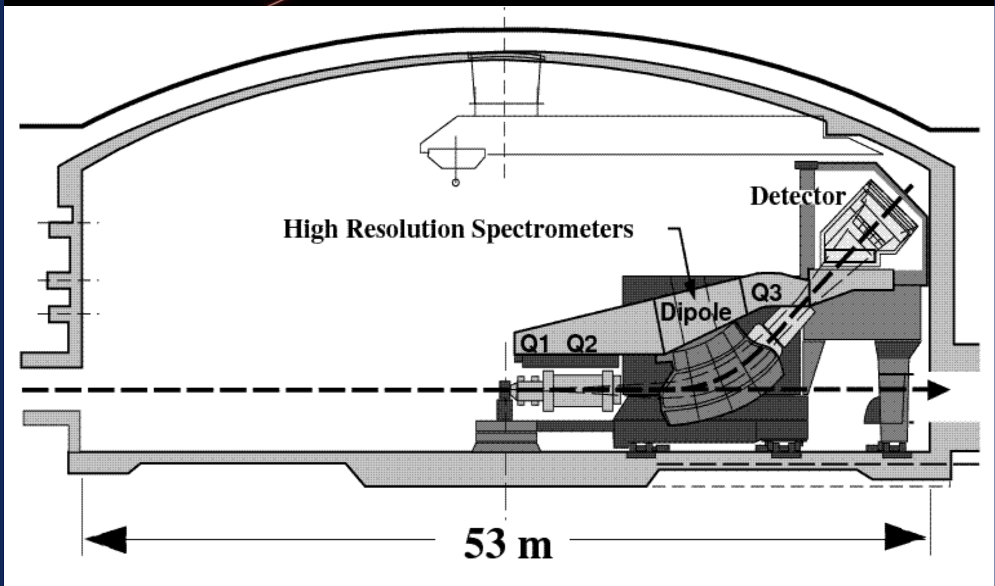
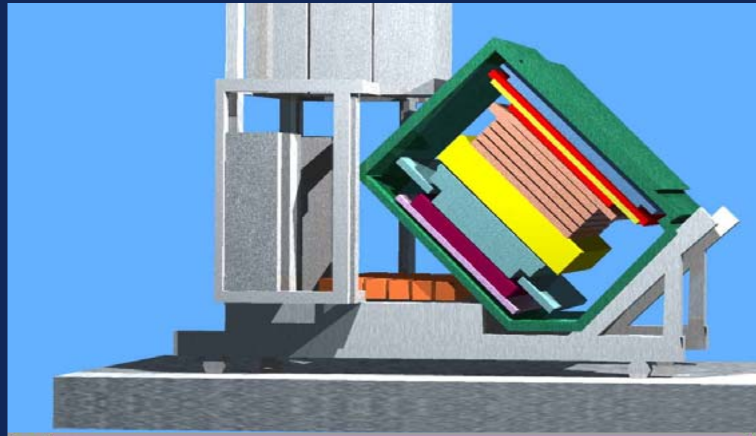
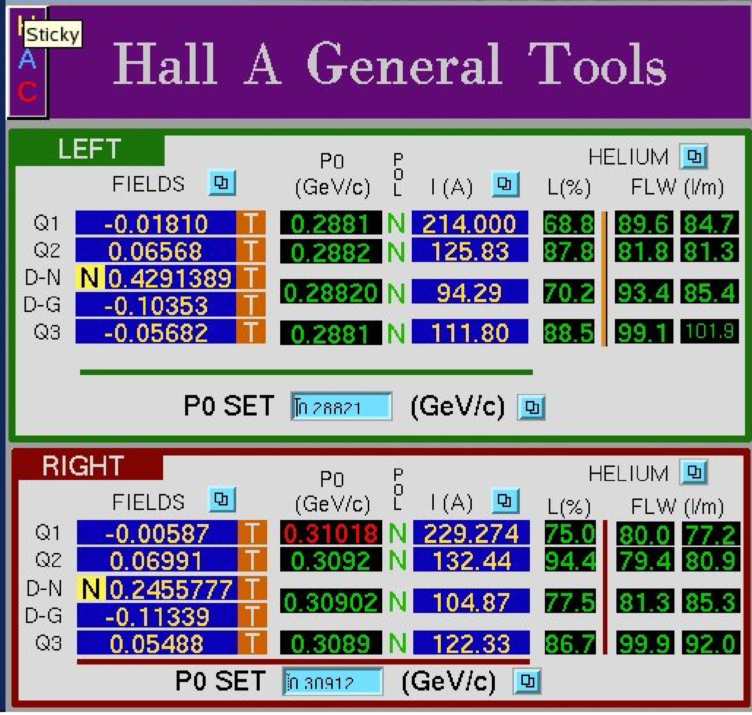


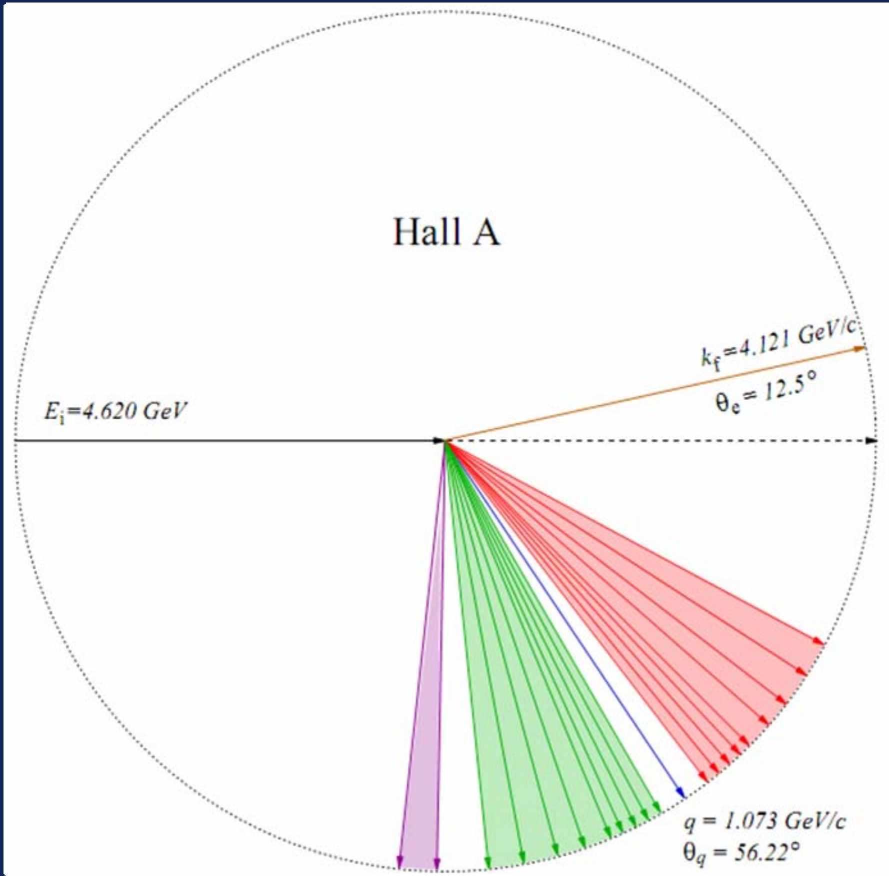


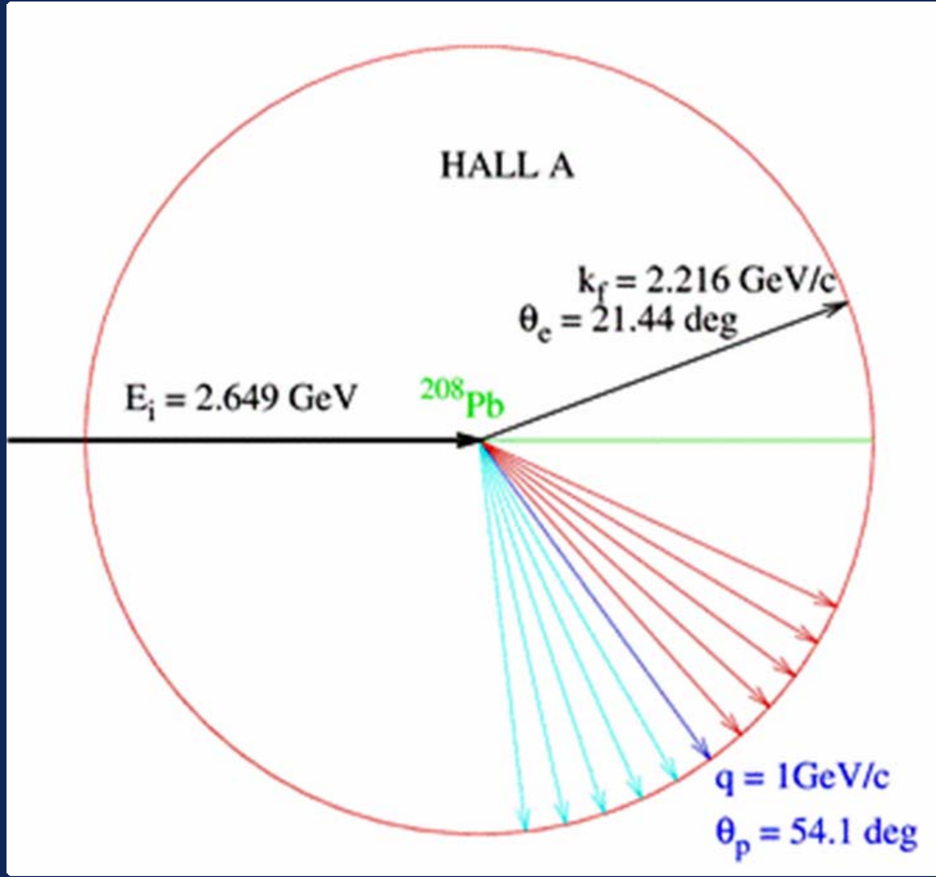
Hall A High Resolution Spectrometer.





Experimental Setup: 4. - Kinematics





$^{16}O(e,e'p)$

$^{208}Pb(e,e'p)$ and $^{12}C(e,e'p)$

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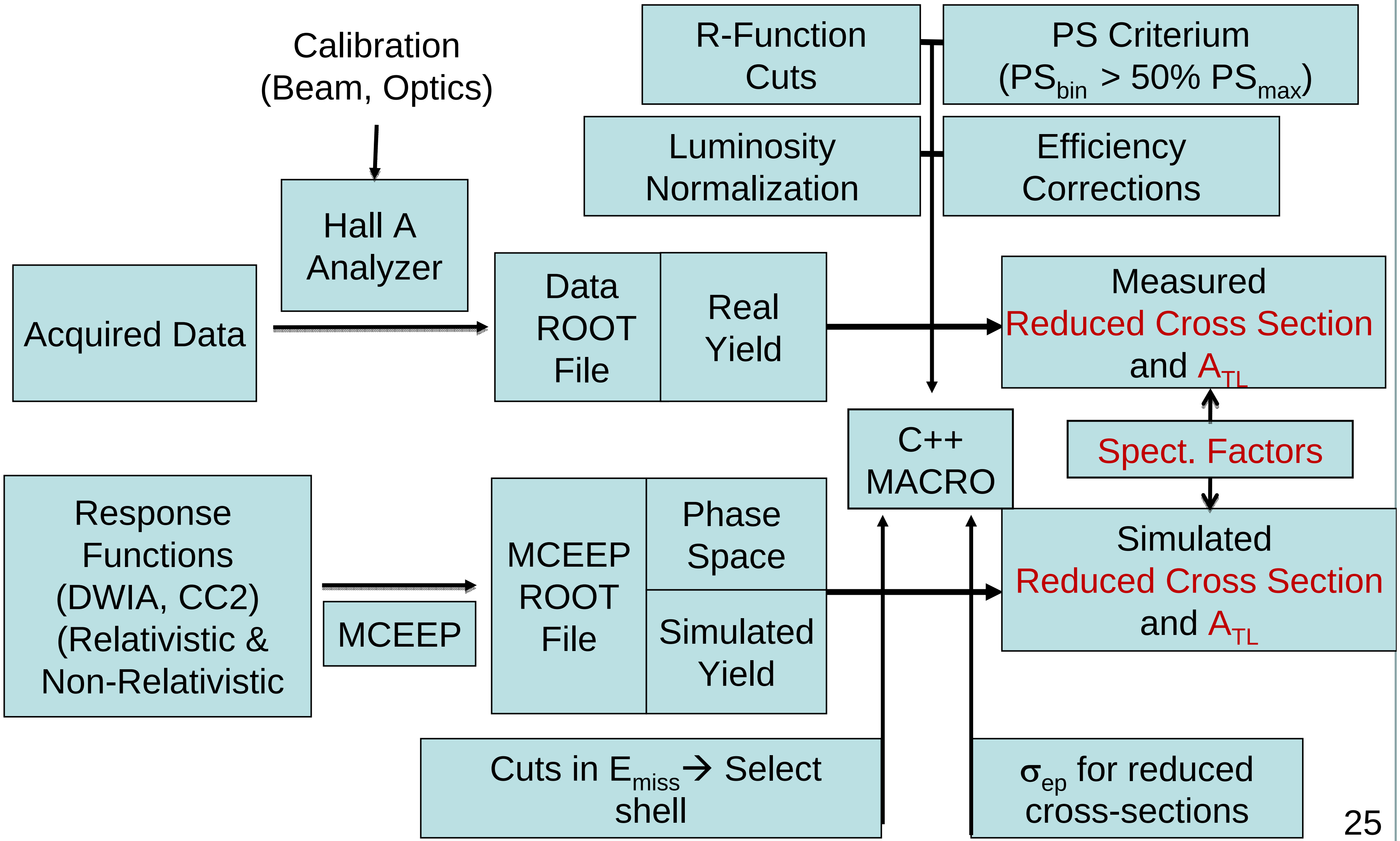
Data Analysis: Steps



Beam Calibration:

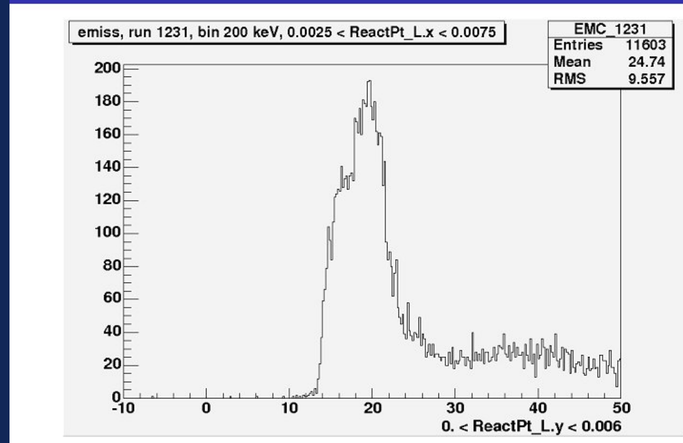
Beam Parameters:

- Energy
- Position: (With and Without Raster, Width)
- Current

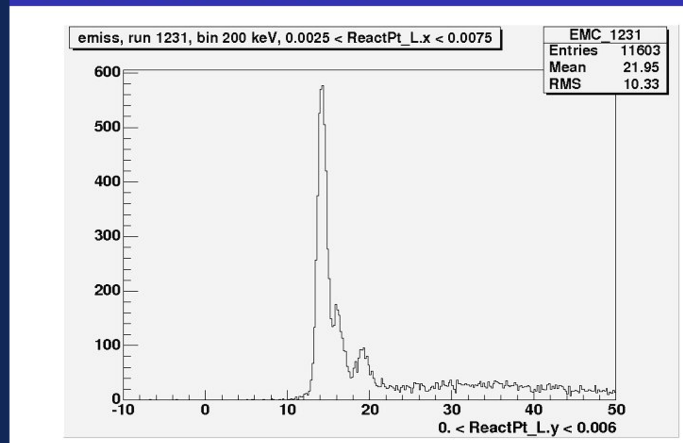
RASTER: To avoid melting the ^{208}Pb target there exists a raster which spread the incident electrons in the whole target.

The position of the beam with raster at each moment was known and it was taken into account in the event reconstruction.

Uncorrected Carbon Spectra



First order raster corrections

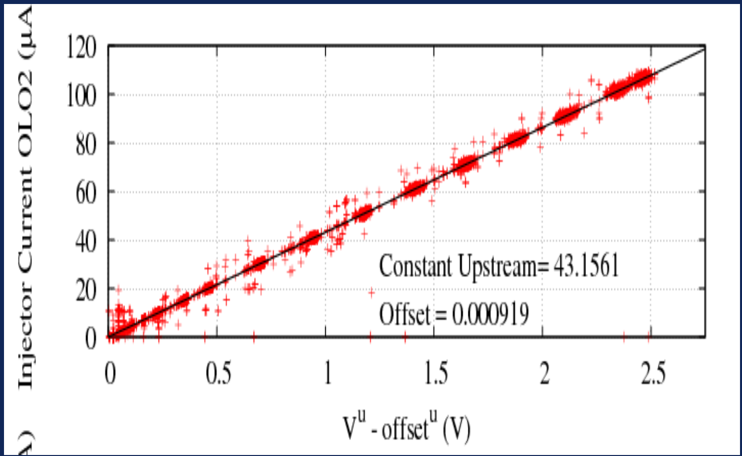


Beam Calibration:

Beam Parameters:

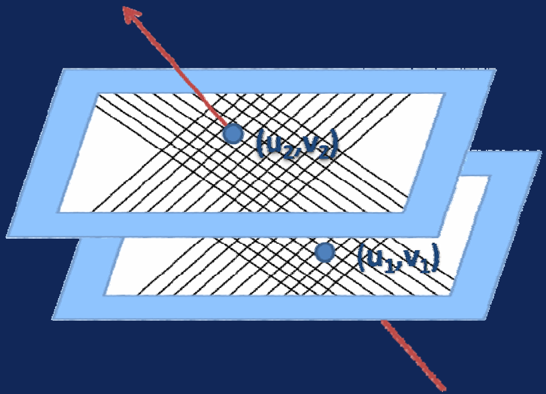
- Energy
- Position: (With and Without Raster, Width)
- Current

CURRENT: The number of incident electrons should be accurately measured. A correct beam charge calibration is crucial for the luminosity.

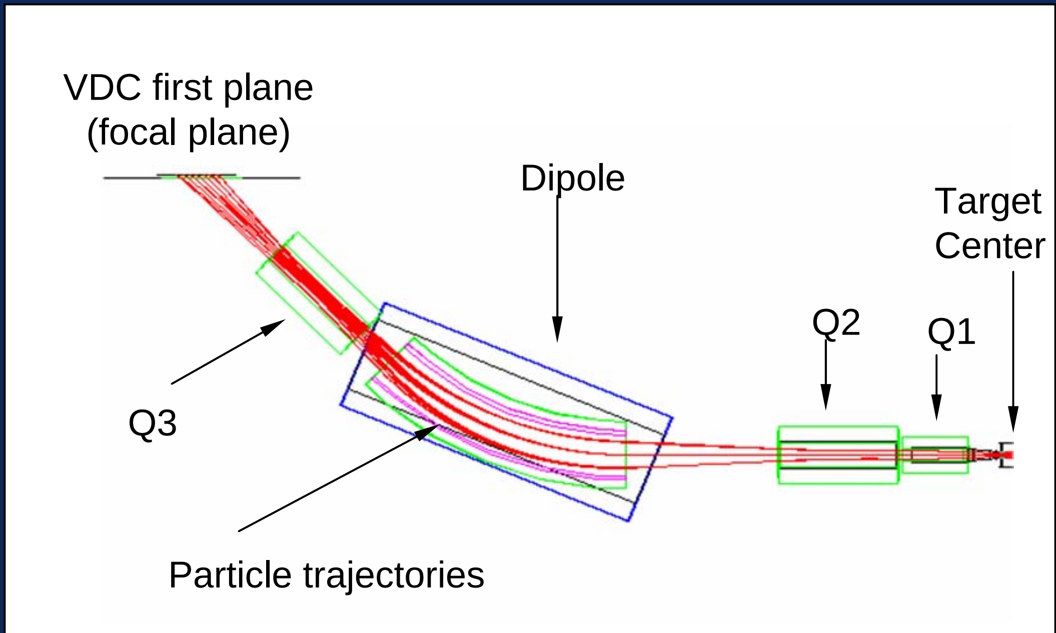


Calibration measurements at different currents allowed were used.

Spectrometer Calibration: Optics Optimization



$$\begin{matrix}(u_1,v_1)\\(u_2,v_2)\end{matrix} \longrightarrow \begin{pmatrix} x_{fp} \\ y_{fp} \\ \theta_{fp} \\ \phi_{fp} \end{pmatrix} \xrightarrow{\ OPTICS\ } \begin{pmatrix} y_{tg} \\ \theta_{tg} \\ \phi_{tg} \\ \delta p_{tg} \end{pmatrix} \xrightarrow[INFORMATION]{+BPM \ +RASTER} \begin{pmatrix} x_{tg} \\ y_{tg} \\ z_{tg} \\ \theta'_{tg} \\ \phi_{tg} \\ \delta p'_{tg} \end{pmatrix}$$



$$y_{tg} = \sum_{ijkl} Y_{ijkl} x^i_{fp} \theta^j_{fp} y^j_{fp} \phi^k_{fp}$$

$$\theta_{tg} = \sum_{ijkl} T_{ijkl} x^i_{fp} \theta^j_{fp} y^j_{fp} \phi^k_{fp}$$

$$\phi_{tg} = \sum_{ijkl} P_{ijkl} x^i_{fp} \theta^j_{fp} y^j_{fp} \phi^k_{fp}$$

$$\delta p_{tg} = \sum_{ijkl} D_{ijkl} x^i_{fp} \theta^j_{fp} y^j_{fp} \phi^k_{fp}$$

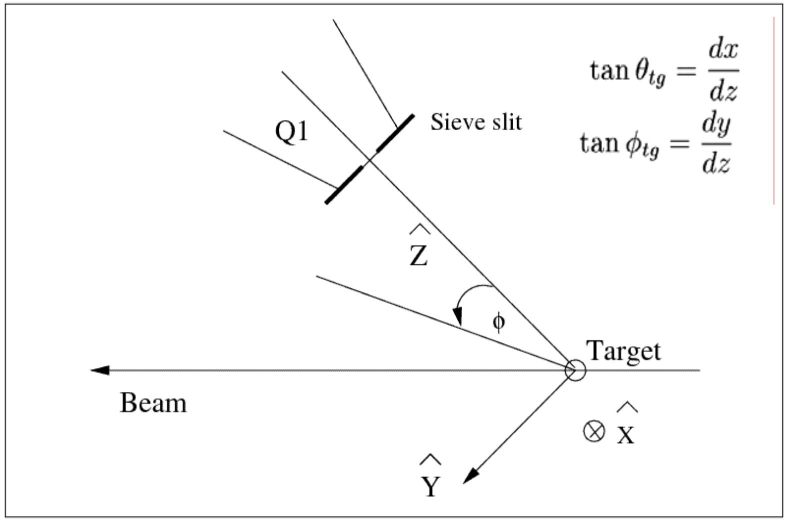
Spectrometer Calibration: Optics Optimization

- Elastic $^{12}C(e,e')$ data used for optics calibration.
- The common optics calibration procedure in Hall A is based on a gradient-based χ^2 minimization (Optimize++):

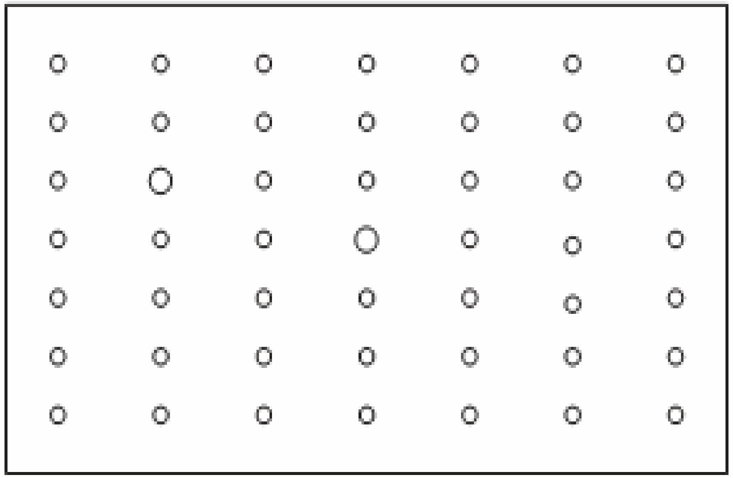
$$\chi^2 = \frac{1}{N}\sum_{i=1}^{N}\frac{\left[\delta p_{tg}(measured) - \delta p_{tg}(teor)\right]^2}{\delta p_{tg}(teor)} \qquad \delta p_{tg}(measured) = \sum_{ijkl} D_{ijkl}\, x^{i}_{fp}\, \theta^{j}_{fp}\, y^{j}_{fp}\, \phi^{k}_{fp}$$

- The optics calibration was improved by developing a code based on a genetic algorithm for the χ^2 minimization.
- This way, all database coefficients could be optimized simultaneously and there were no problems with local minima.

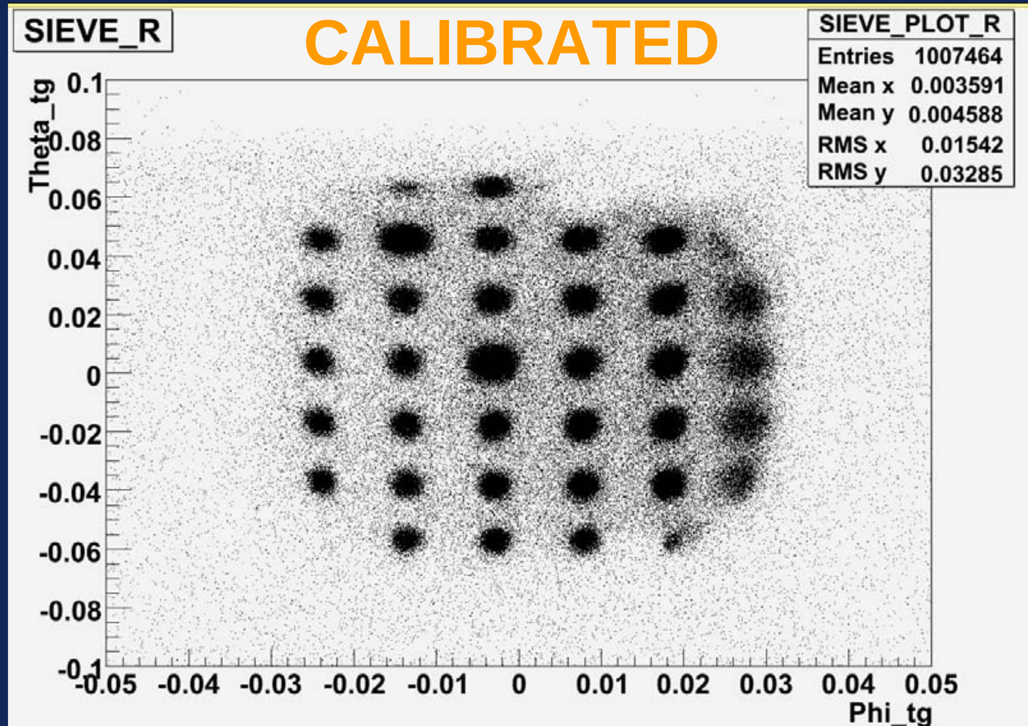
Spectrometer Calibration
Optics Optimization: Angles



SIEVE SLIT



The angles measured by the spectrometers are calibrated using data acquired with a sieve slit plate placed at the detector's entrance.



Spectrometer Calibration: Coincidence Time

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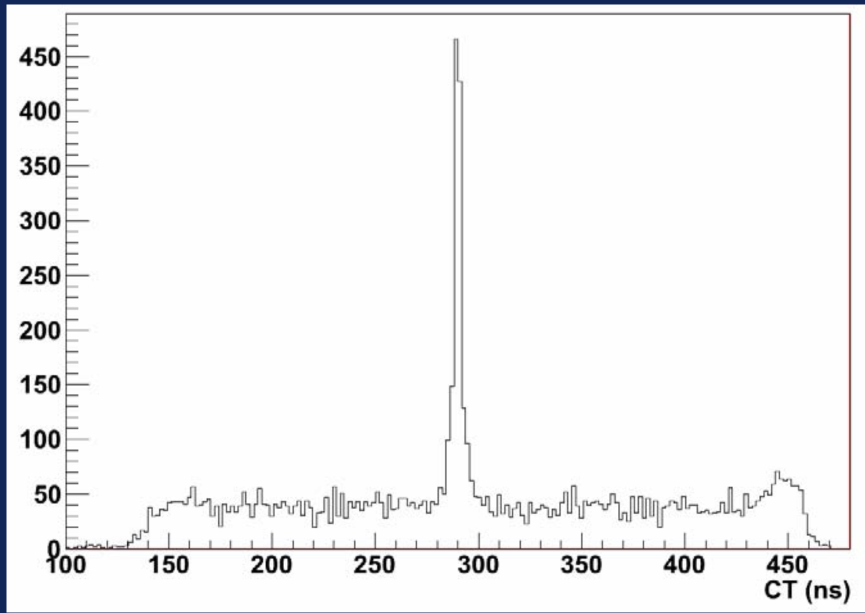
A good coincidence time (CT) resolution is important to remove random coincidences, by applying a narrow cut in the CT peak.

$$t - t_0 = l_0 \cdot \left(\frac{1}{v} - \frac{1}{v_0} \right) + \frac{\Delta l}{v}$$

Particles with different momentum and trajectory within the spectrometers will have a different time-of-flight (TOF). This effect can be corrected and the CT is improved.



Calibrated CT spectrum for the experiment E06-007.
(^{12}C, Kin7, p_{miss}= -300 MeV/c).
Resolution ~ 3 ns

Efficiency corrections

- Deadtime – Good events not recorded due to electronics or computer deadtime.
- Trigger efficiency – Good events not detected by the scintillators. Obtained from redundant measurements.
- Tracking efficiency – Good events not properly reconstructed from the VDC measurements. Obtained from the number of events reconst. with unphysical values.
- Proton absorption – Lost by interactions with material before being detected.

1) QUASIELASTIC (e,e'p) REACTION

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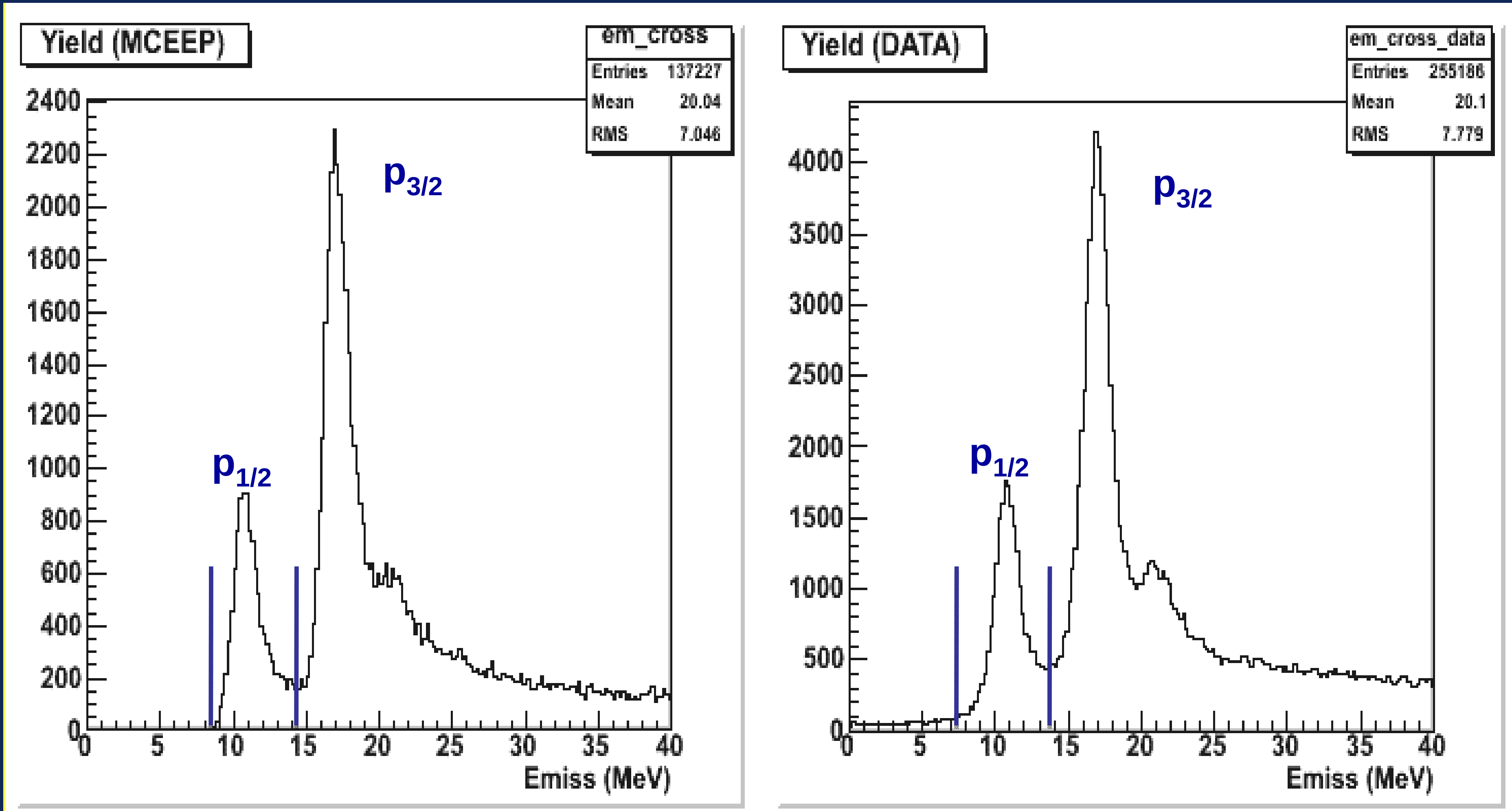
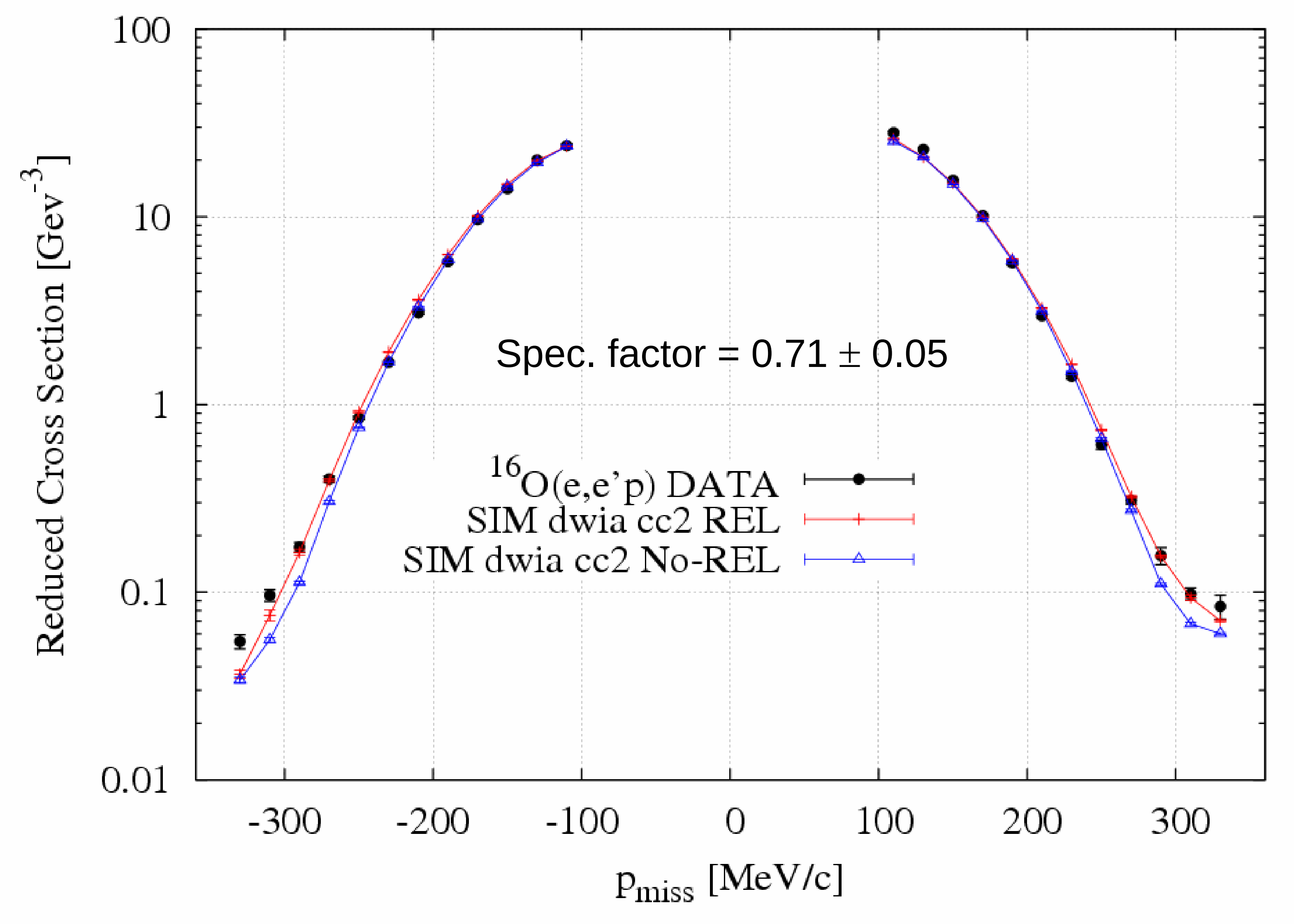
$^{16}O(e,e'p)\ E_{miss}$

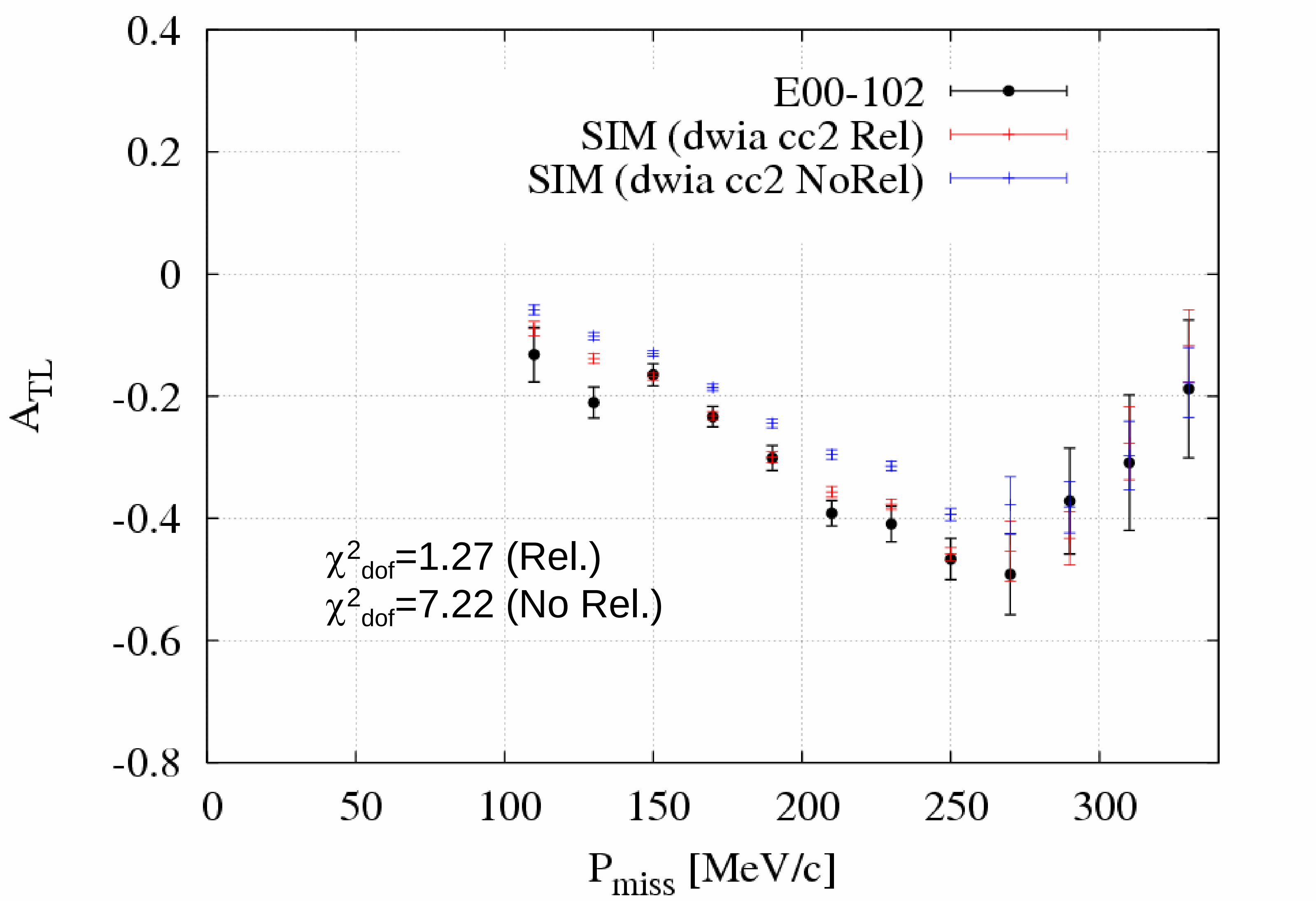
p_{miss} = 100-200 MeV/c



$^{16}O(e,e'p)$ – $1p_{1/2}$ SHELL Reduced Cross Section

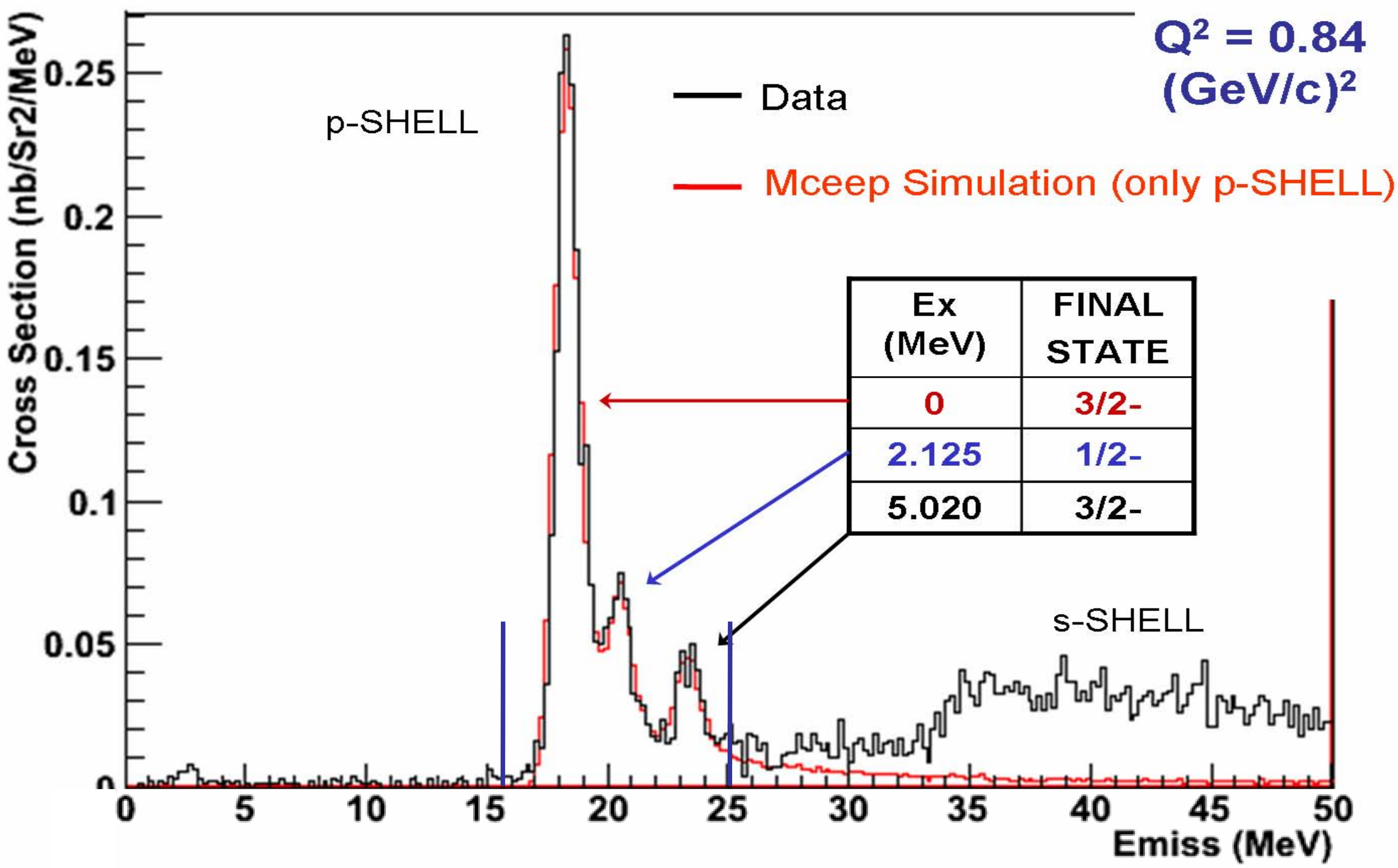


$^{16}O(e,e'p)$ – $1p_{1/2}$ SHELL A_{TL}



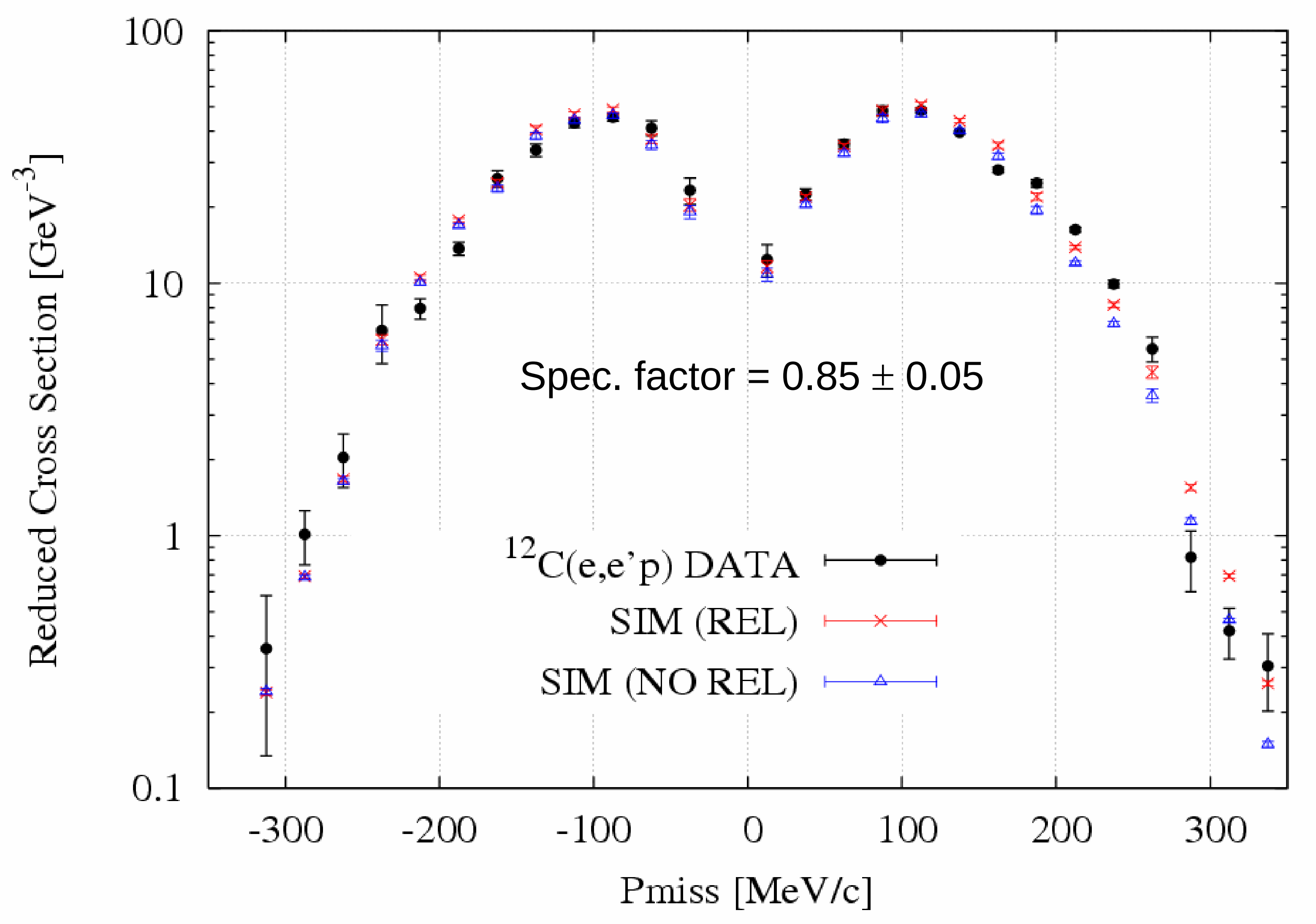
$^{12}C(e,e'p)\ E_{miss}$

(^{12}C)

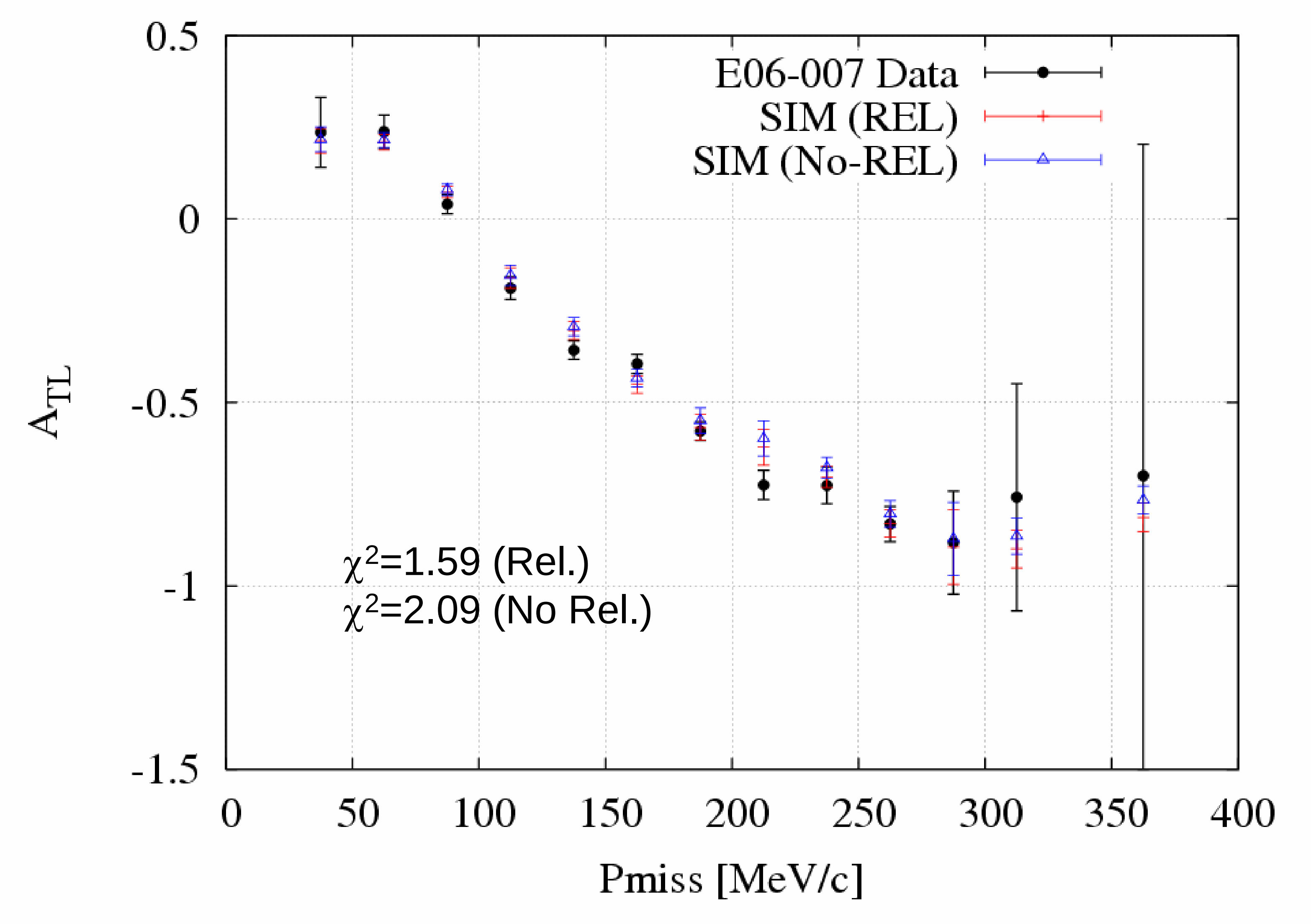


Ex (MeV)	FINAL STATE
0	3/2-
2.125	1/2-
5.020	3/2-

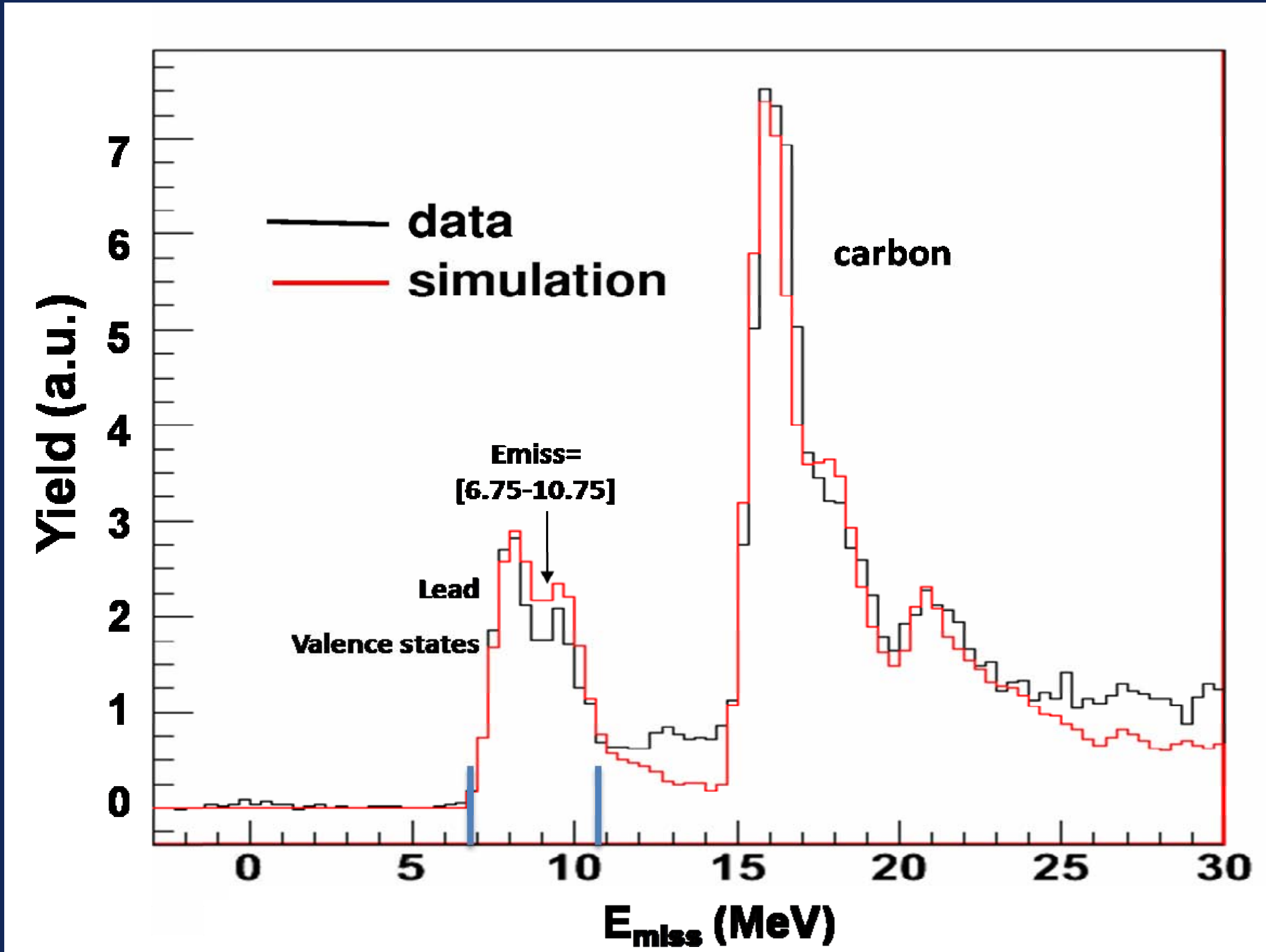
$^{12}C(e,e'p)$ – $1p_{3/2}$ shell Reduced Cross Section



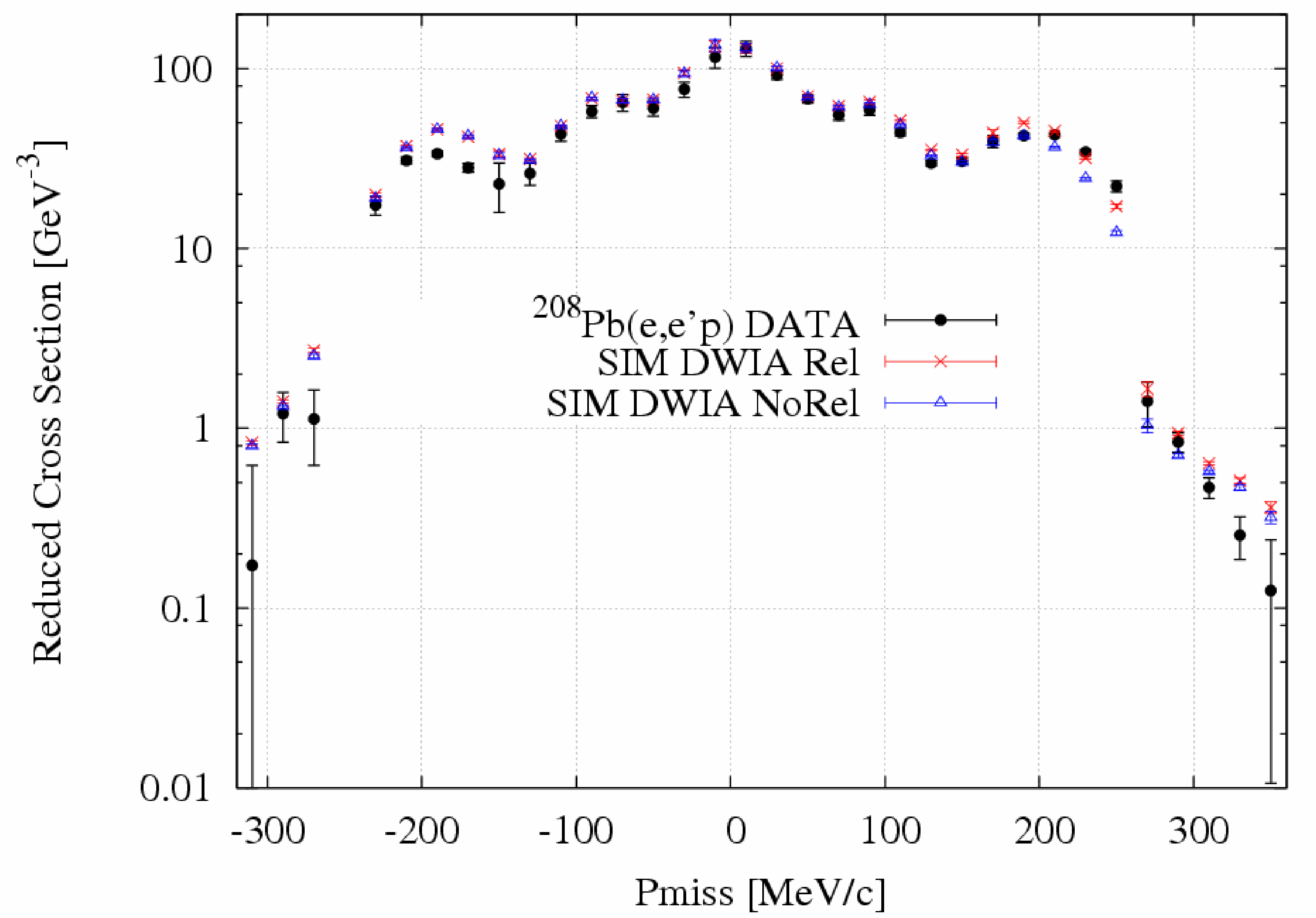
$^{12}C(e,e'p)$ - $1p_{3/2}$ shell A_{TL}



$^{208}Pb(e,e'p)\ E_{miss}$

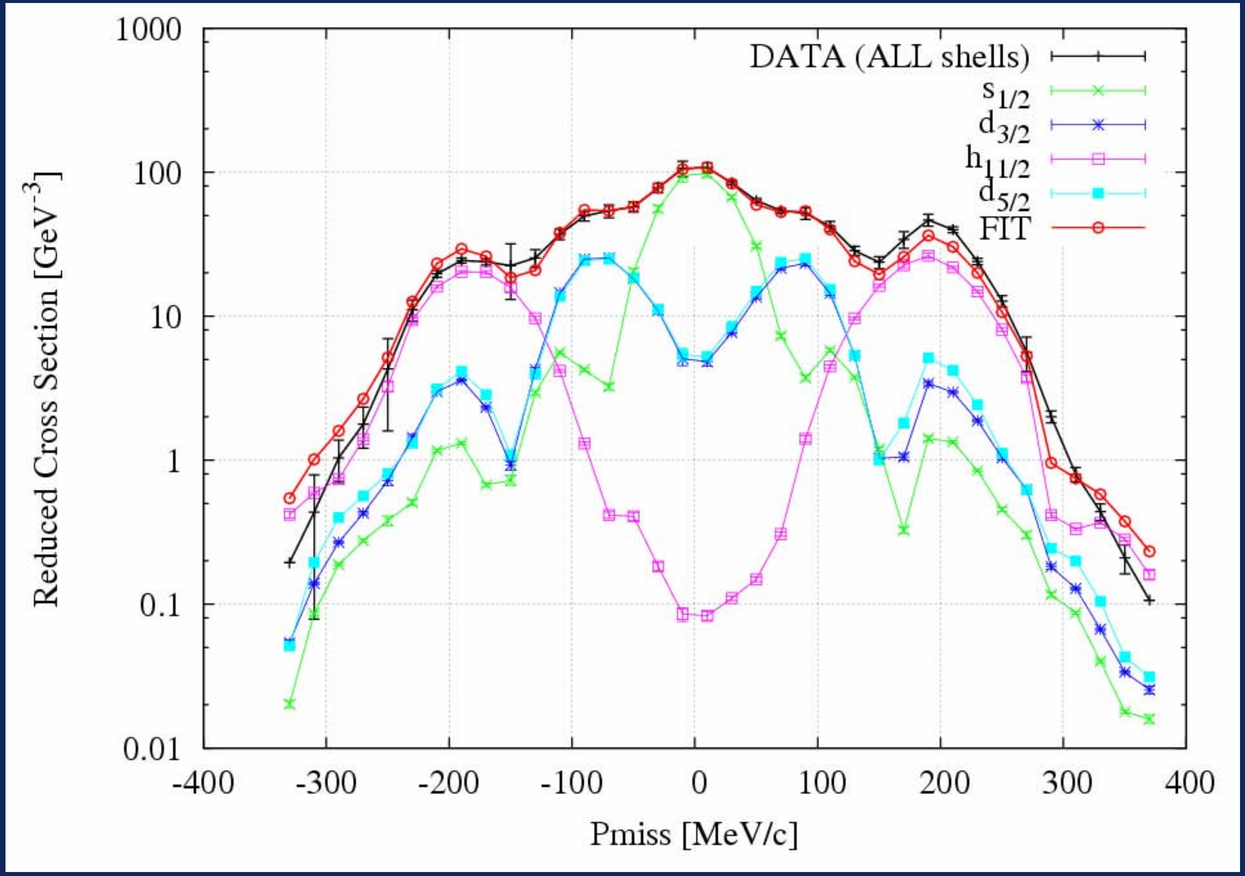


$^{208}Pb(e,e'p)$ – Valence States Reduced Cross Section



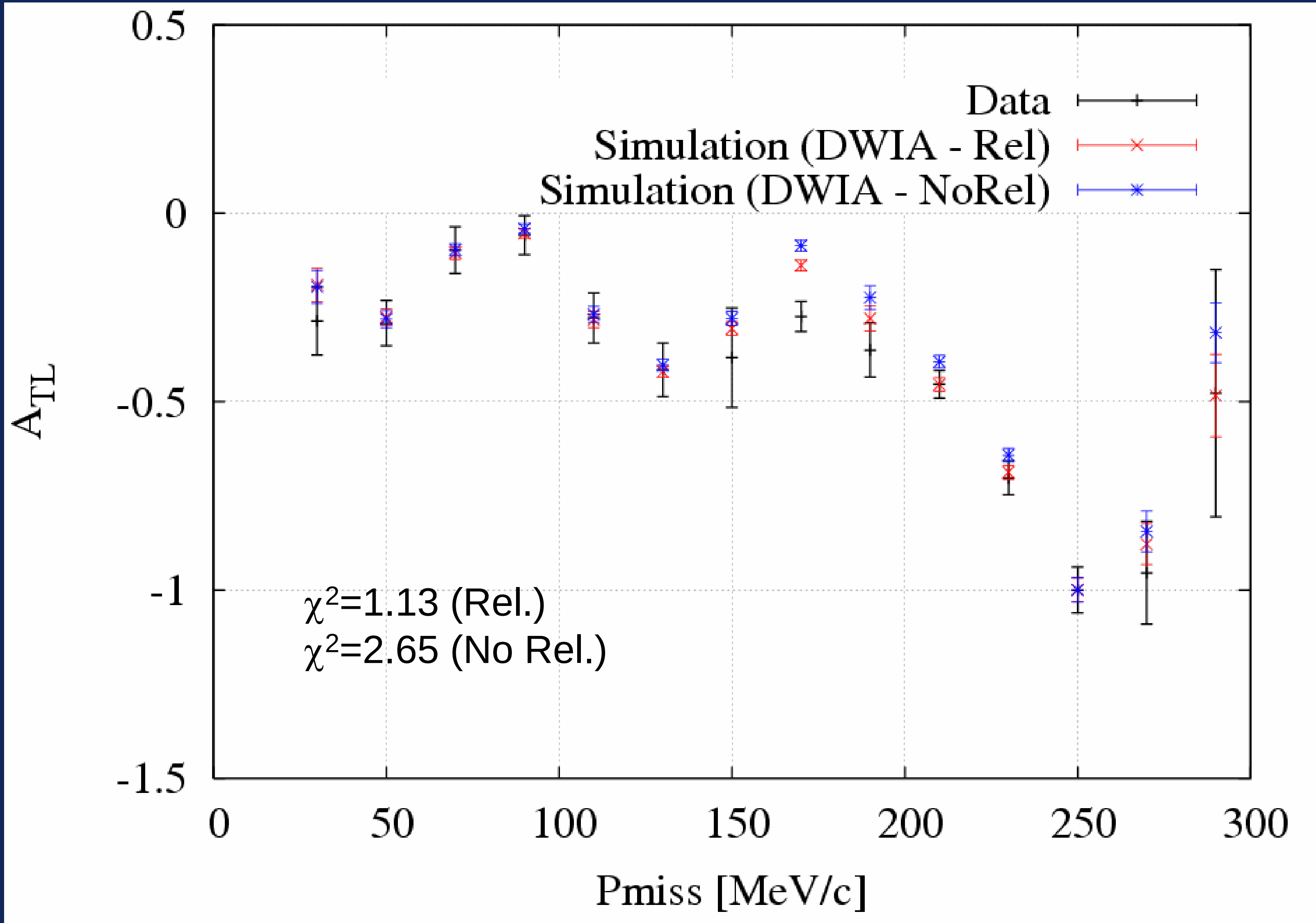
^{208}Pb(e,e'p) – Valence States Reduced Cross Section

Spectroscopic Factors	
$3s_{1/2}$	0.52 ± 0.06
$2d_{3/2}$	0.59 ± 0.06
$1h_{11/2}$	0.65 ± 0.06
$2d_{5/2}$	0.52 ± 0.06



Experimental ^{208}Pb(e,e'p) reduced cross section (for the aggregate of valence states) together with the results from relativistic DWIA for the contributions from individual shells.

$^{208}Pb(e,e'p)$ - Valence States A_{TL}

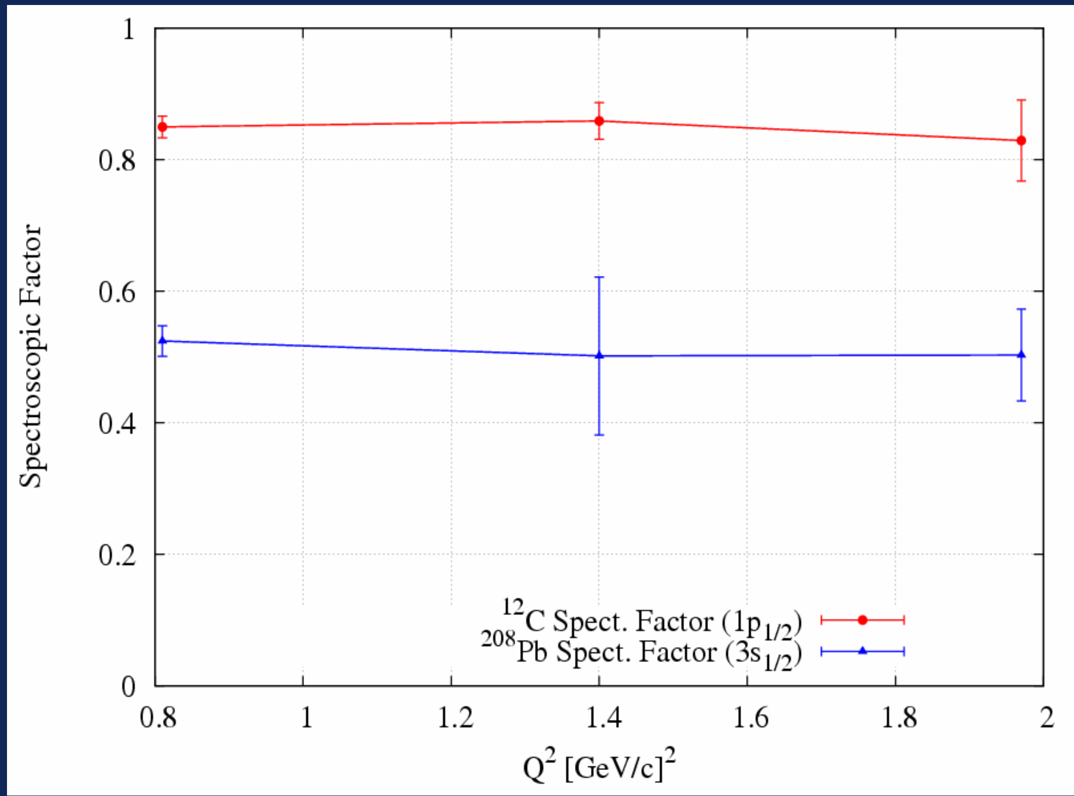


Spectroscopic Factors

Nucleus	Shell	Spect. Factor
^{16}O	$1p_{1/2}$	0.71 (5)
^{12}C	$1p_{3/2}$	0.85 (5)
^{208}Pb	$3s_{1/2}$	0.52 (6)
	$2d_{3/2}$	0.59 (6)
	$1h_{11/2}$	0.65 (6)
	$2d_{5/2}$	0.52 (6)

Spectroscopic Factors for several shells in ^{16}O measured at $Q^2=0.9$ $(GeV/c)^2$ and in ^{12}C and ^{208}Pb measured at $Q^2=0.8$ $(GeV/c)^2$.

$-100 < p_{miss} < 100$ MeV/c



No dependence of the spectroscopic factors with Q^2 has been found

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Summary

☑ Two (e,e'p) experiments performed at JLab with ^{16}O,^{12}C and ^{208}Pb targets have been analyzed.

☑ These experiments studied the (e,e'p) reaction in perpendicular quasielastic kinematics with $Q^2 \sim 1$.

☑ In this work, results in the p_{miss} range [-350,350] MeV/c are shown.

☑ Results of the $p_{1/2}$ shell of ^{16}O have been obtained with good statistical accuracy.

☑ ^{208}Pb(e,e'p) data have been obtained for the valence states over more complete kinematics than previous experiments. First measurements of the A_{TL} asymmetry are shown.

☑ ^{12}C(e,e'p) data was also measured. Results from the knockout of protons from the $p_{3/2}$ shell have been obtained.

Conclusions

☑ The DWIA calculations show good agreement in general with the experimental cross sections.

☑ Spectroscopic factors of 0.6 to 0.85 have been obtained in the shells analyzed in all nuclei.

☑ Carbon and Lead results show that there is no significant dependence of spectroscopic factors with Q^2 in the 0.8-2 $(GeV/c)^2$ range.

☑ Simulations obtained from just relativistic mean field calculations (without long-range correlations included) seem to compare fairly well with data at both low and high missing momentum.

☑ A_{TL} data, which are sensitive to dynamical relativistic effects, clearly favors the results that include relativistic dynamics.

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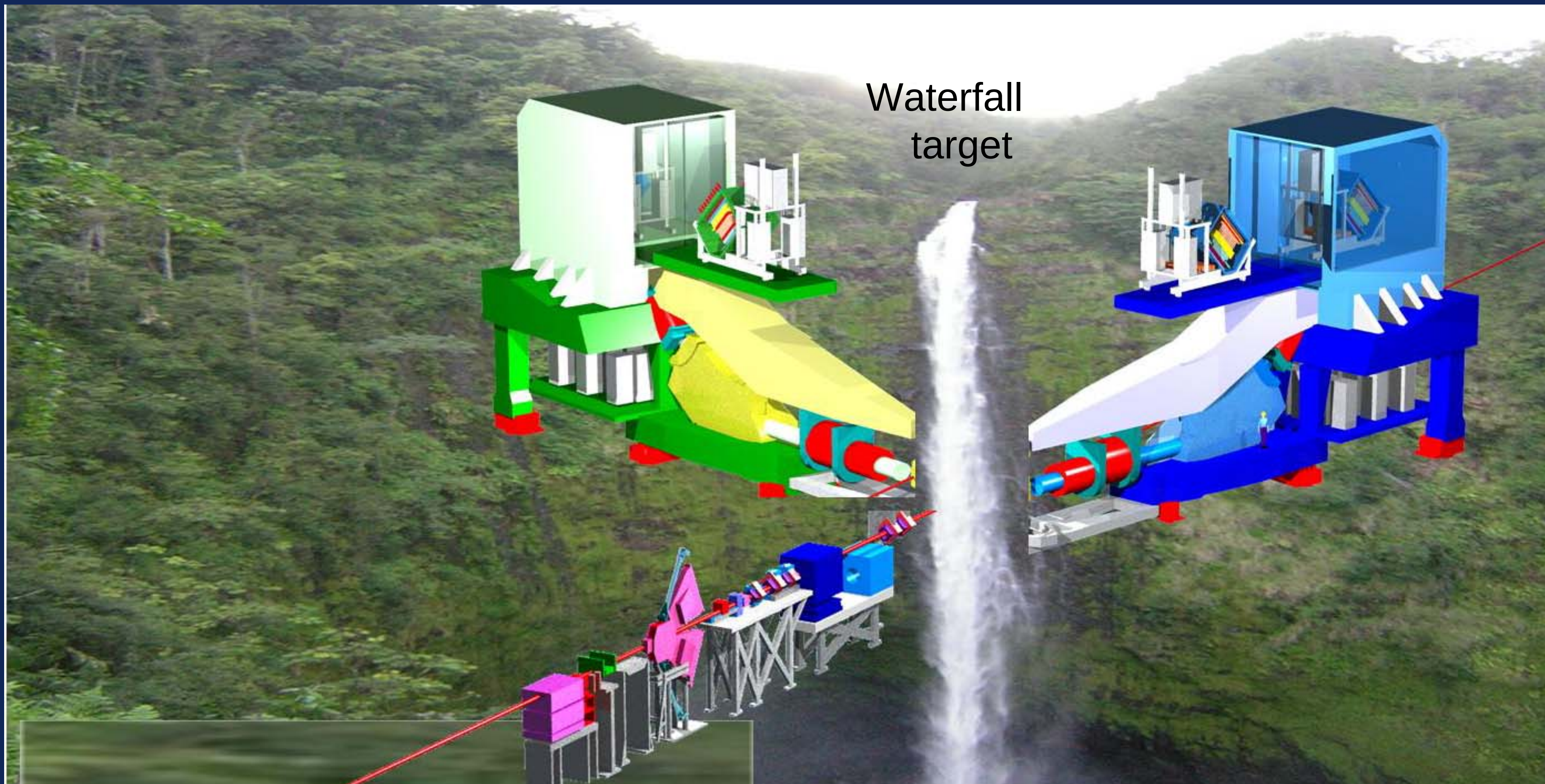
THANKS FOR YOUR ATTENTION!



Data Analysis: Cross-Section

- Measured data are corrected by efficiencies, dead-time, and random coincidences.
- All these events are histogrammed into the relevant variables ($E_{miss}, p_{miss}, q, \omega, \phi$) and cross section is obtained as:

$$\frac{d^6\sigma}{d\omega d\Omega_e dT_p d\Omega_p}[E_{miss}, p_{miss}, q, \omega, \phi] = \frac{Coincidences[E_{miss}, p_{miss}, q, \omega, \phi]}{Luminosity \times PhaseSpace[E_{miss}, p_{miss}, q, \omega, \phi]}$$

- The phase-space volume of each bin is obtained with a simulation with uniform distribution over the acceptances.

$$PhaseSpace\left[E_{miss}, p_{miss}, q, \omega, \phi\right] = \Delta\omega \Delta\Omega_e \Delta T_p \Delta\Omega_p \times \frac{n\left[E_{miss}, p_{miss}, q, \omega, \phi\right]}{N}$$