Cross Sections on the $^{12}C(e,e'p)$ Reaction at High Missing Momentum

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INT Workshop INT-13-52W

Nuclear Structure and Dynamics at Short Distances

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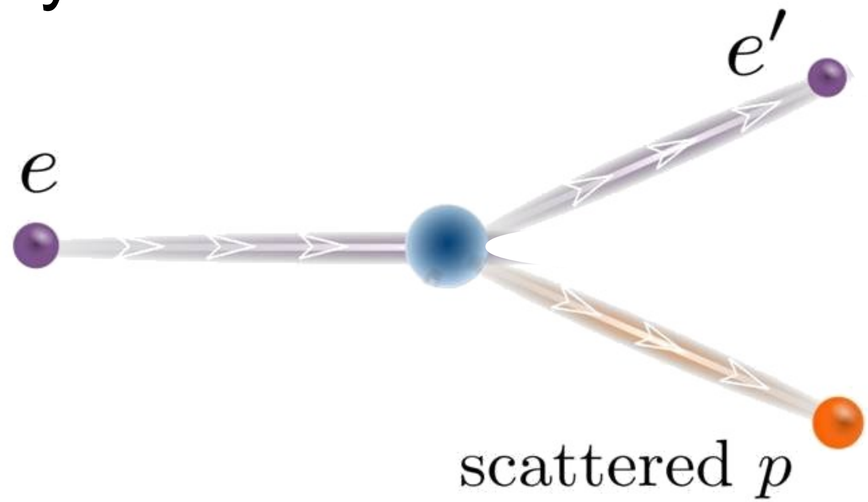
University of Washington

Laboratory for Nuclear Science

Outline

- Introduction: PWIA and Reaction Mechanisms
- Spectroscopic factors and N-N correlations
- Results from Quasi-elastic and $x_B < 1$
- Recent Results and Future Perspectives, $x_B > 1$
- Summary

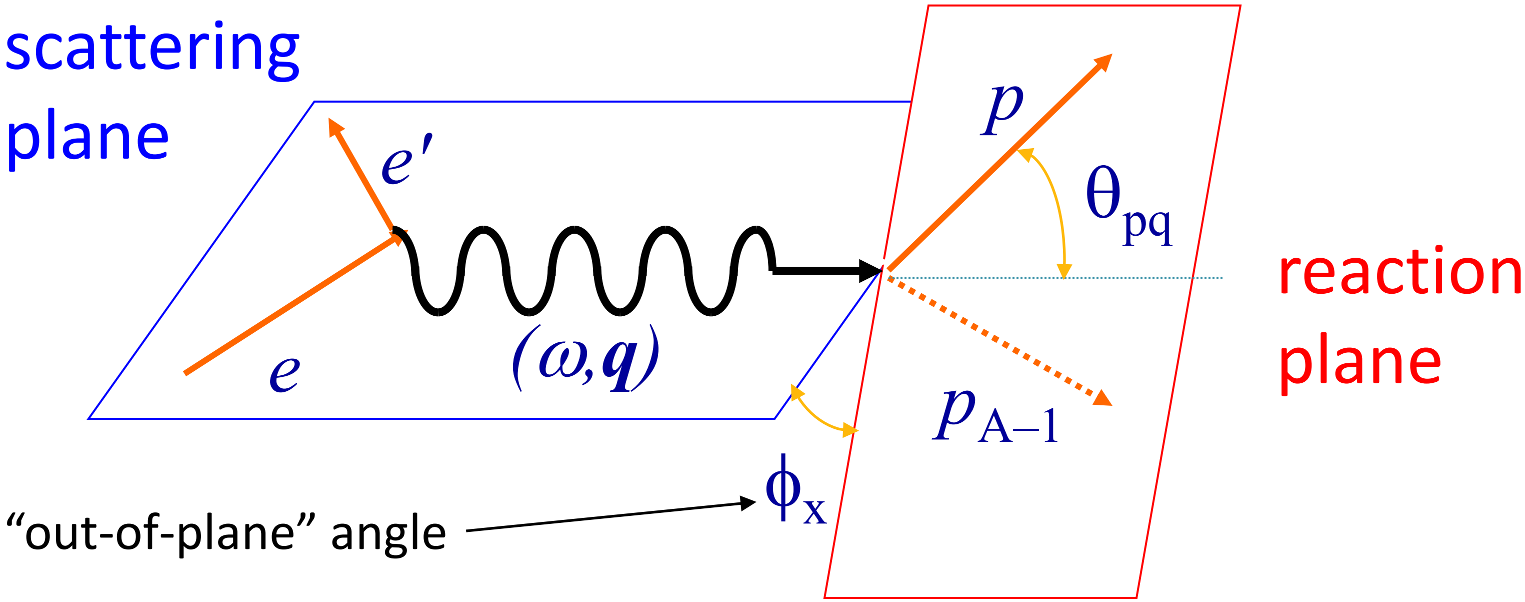


Nucleons in the Nucleus

- Nucleons are comprised of quarks and gluons, but how do they put together from these constituents?
- We can study the constituents and their interactions or the nucleon and it’s interactions.
- If we take a nucleon and place it inside a nucleus, how is the nucleon modified in the nuclear medium?

Electron scattering has proven to be a valuable tool to understand and investigate nucleons inside the nucleus.

A(e,e'p)A-1 Kinematics



Missing momentum: $\boldsymbol{p}_{\mathrm{m}} = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{\mathrm{A-1}} = -\boldsymbol{p}_0$

Difference between transferred and detected momentum

PWIA

Missing energy: $\varepsilon_{\mathrm{m}} = \omega - T_p - T_{\mathrm{A-1}}$

Difference between transferred and detected energy

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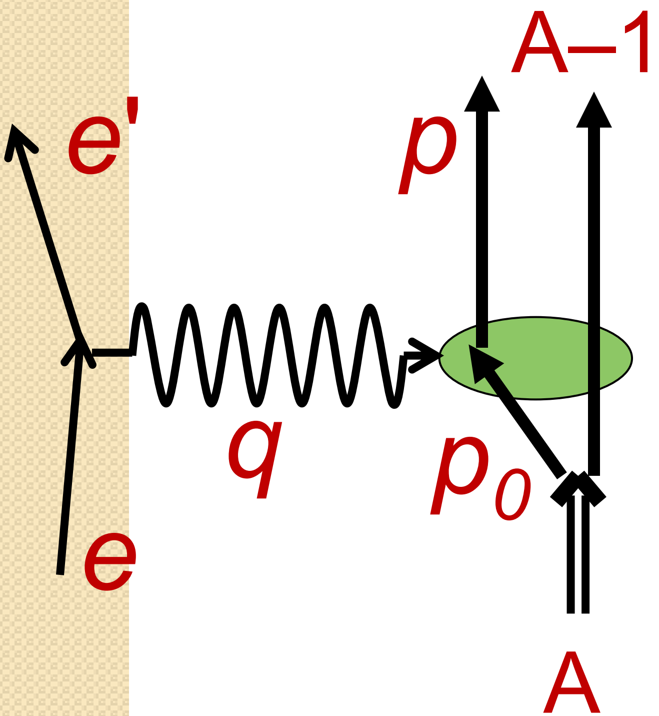
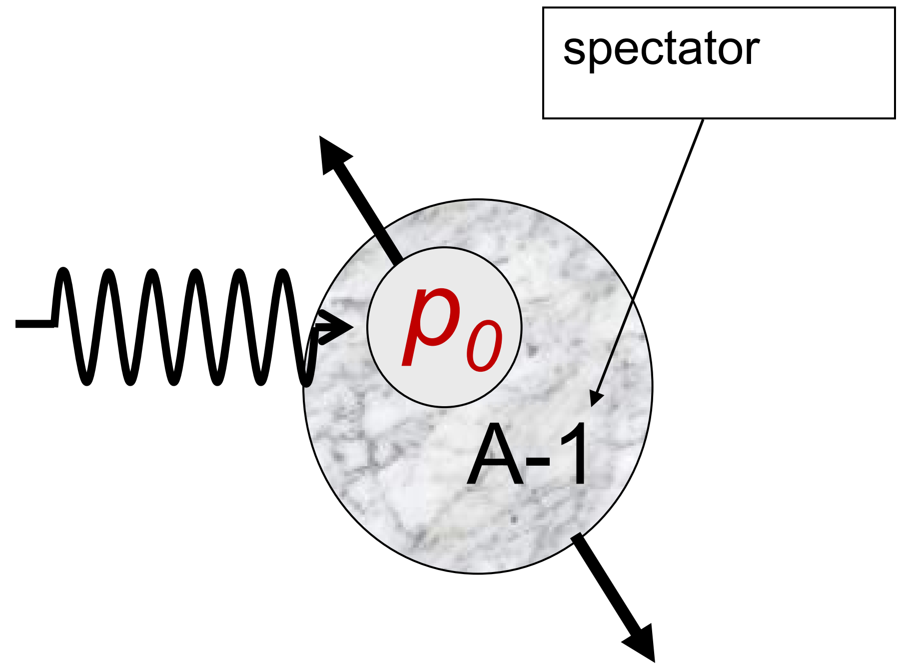
Simple Theory Of Nucleon Knock-out

Plane Wave Impulse Approximation (PWIA)





$$\boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{\text{A-1}} = \boldsymbol{p}_{\text{m}} = - \boldsymbol{p}_{0}$$

Reaction Mechanisms in (e,e'p)

- **Final-State Interactions:**
  Interactions of the extracted proton with the residual nucleus.
- **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.
- **Meson Exchange Currents (MEC)**
- **Intermediate excited nucleonic configurations:**
  e.g. Delta-isobar contributions

$$\vec{p}_m = \vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0$$

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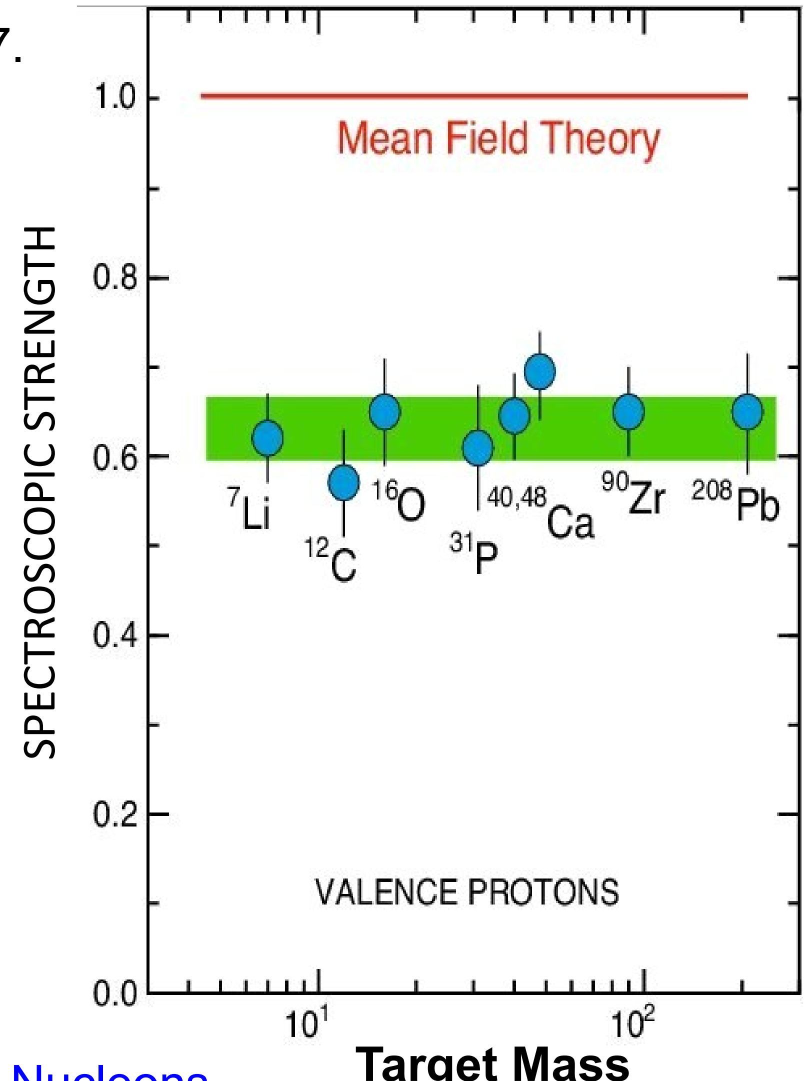
Classic Result from (e,e'p) Measurements

L. Lapikas, Nucl. Phys. A553 (1993) 297.

Independent-Particle Shell-Model is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons

The (e,e'p) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are **60 – 70%** of the mean field prediction.

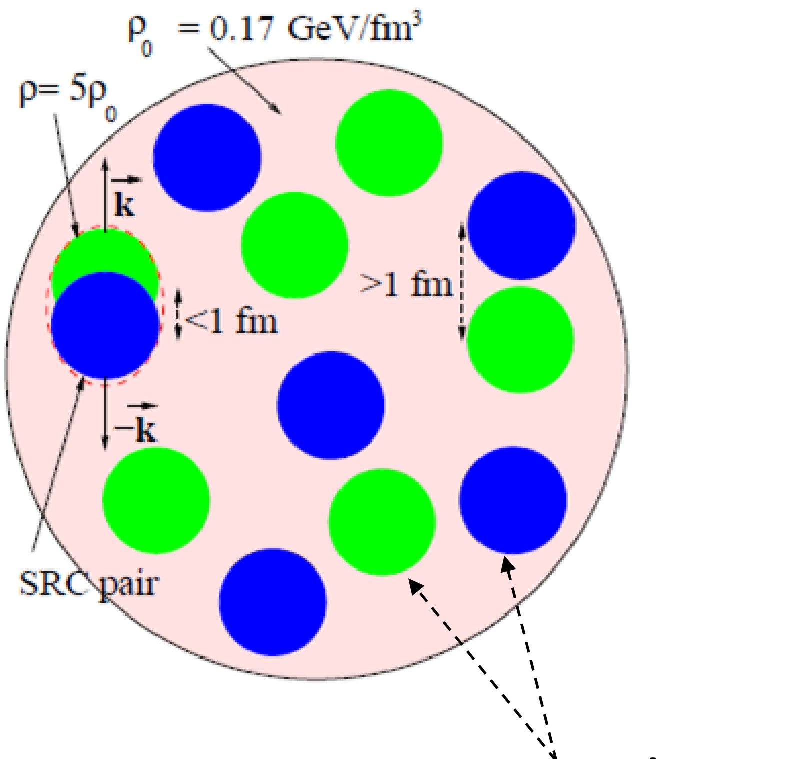


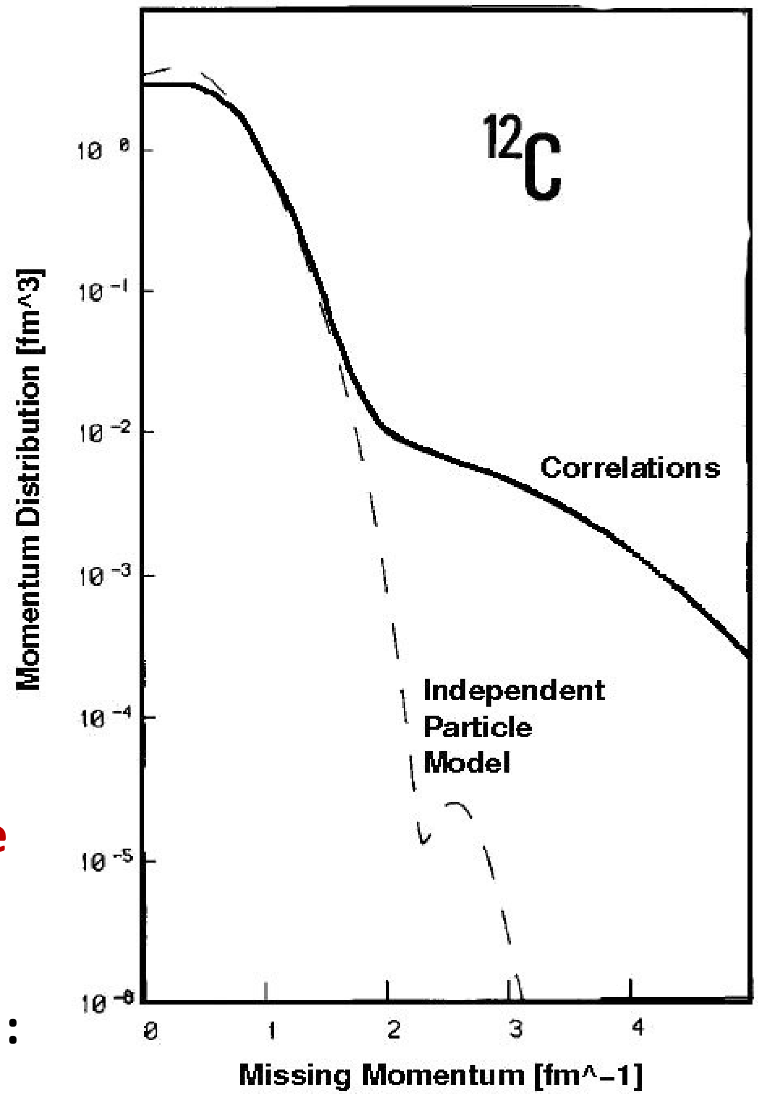
One Solution: Correlations Between Nucleons

Long-range (> 2 fm) and short-range (< 1 fm)

Short-Range Correlations

Benhar et al., Phys. Lett. **B** 177 (1986) 135.





BUT other effects such as Final State re-scattering have masked the signal in the past.

To observe the effects of correlations one must probe beyond the Fermi level :

P_{min}> 275 MeV/c

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2bbu, 3bbu "Distorted" Spectral Functions

Compare $S^D(E_m,p_m)$, $n(p_m)$ to theoretical calculations

$$\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} = K \cdot \sigma_{ep} \cdot S^D(E_m, p_m)$$

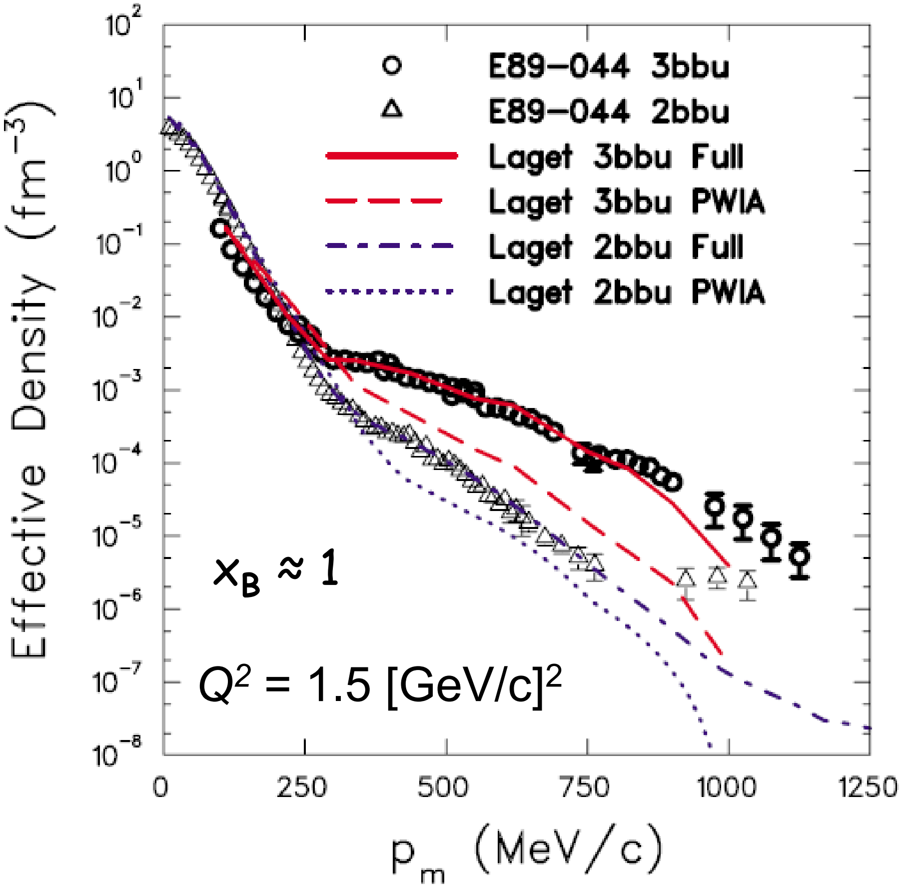
$$\eta(p_m) = \int \left(\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K \cdot \sigma_{ep}\right) dE_m$$

Performed at High Q^2

$\Rightarrow$ Reduced MEC, Δ contributions

At $p_m > p_F$ distorted spectral function is much larger for 3bbu than for 2bbu due to correlations (SRC)

Calculations reproduce both 2bbu and 3bbu – confidence

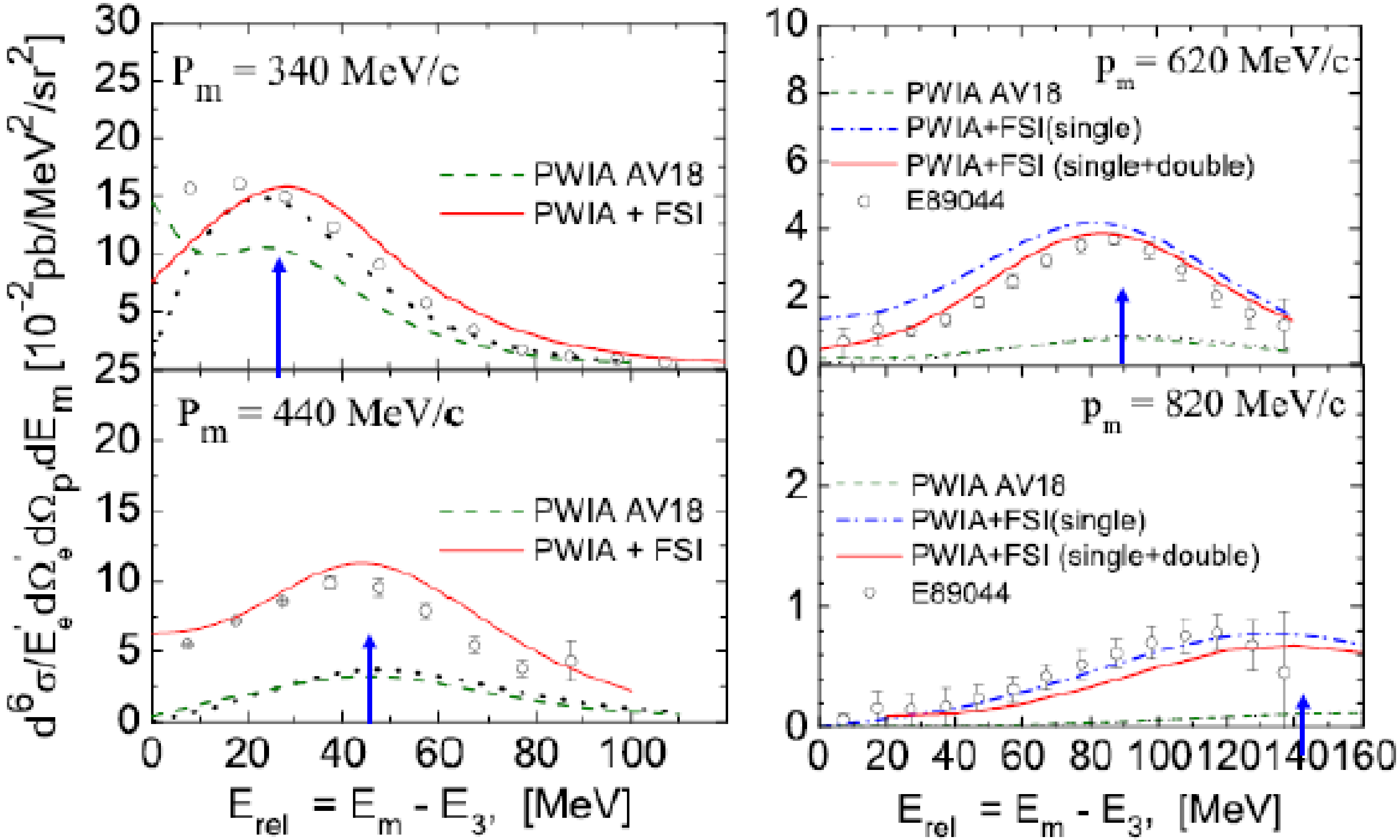


F. Benmokhtar *et al.*, Phys. Rev. Lett. **95** (2004) 082305.

^{3}He(e,e'p)np: 3bbu (High E_m) and High p_m

Pair SRC: large p_{rel}, small p_{CM} ➔ $E_m - E_{th} \gg \frac{p_m}{2M_N}$

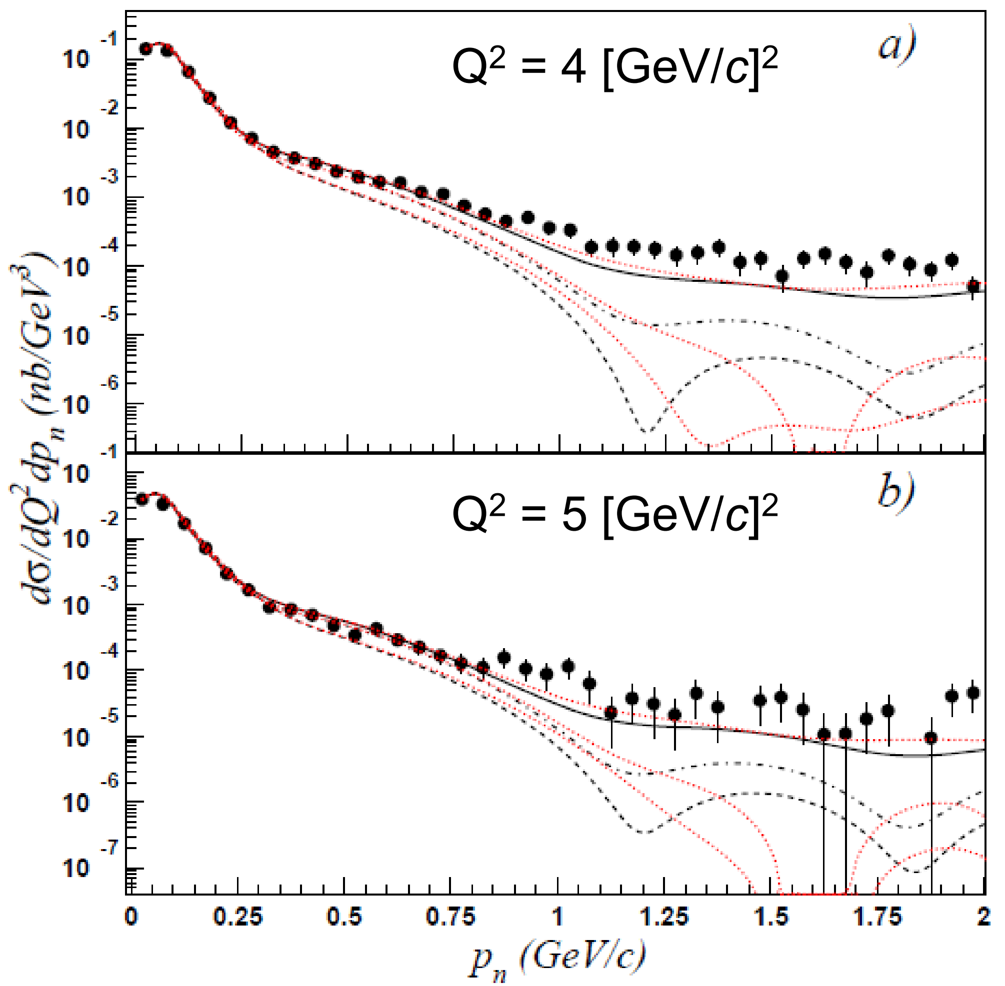
Low p_m (still > k_f): correlations High p_m dominated by FSI



Data: F. Benmokhtar *et al.*, PRL **94**, 082305 (2005)
Calculations: *C. Ciofi degli Atti et al.*

Hall B (CLAS) D(e,e'p)n, x_B< 1 Data

See W. Boeglin's talk from Feb. 19th



Black Paris Potential
Red AV-18 Potential

From Lowest To Highest
PWIA
PWIA+FSI
PWIA+FSI+MEC+NΔ

K. Sh. Egiyan *et al.,* Phys. Rev. Lett. **98** (2007) 262502.

Recent Experimental Results

- Carbon:
  - $x_B > 1$, $Q^2 = 2$ GeV^2
  - Bound data, $p_m = 200 - 425$ MeV/c
  - Continuum data, $p_m = 200 - 600$ MeV/c
- Helium-4:
  - $x_B > 1$, $Q^2 = 2$ GeV^2
  - Bound data, $p_m = 150 - 500$ MeV/c
  - Continuum data, $p_m = 150 - 800$ MeV/c

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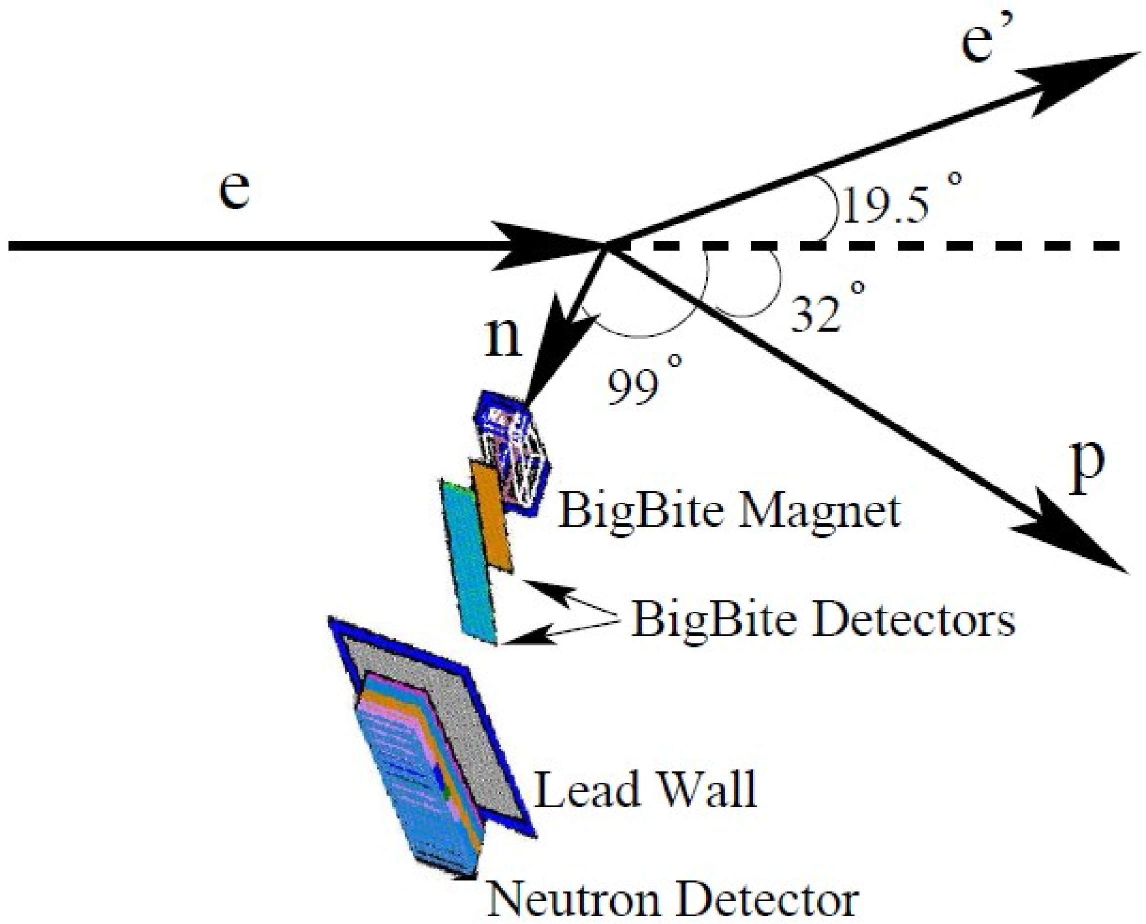
Kinematics



e
e'
19.5 °
32 °
n
99 °
p
BigBite Magnet
BigBite Detectors
Lead Wall
Neutron Detector

$^{12}C(e,e'p)$ Data

High p_m: 300-600 GeV/c

probe small inter-nucleon distances

High $Q^{2:}$ 2 [GeV/c]^2

probe small distances

less ambiguity about struck nucleon

can handle FSI using GA or GEA

High $x_B \sim 1.2$

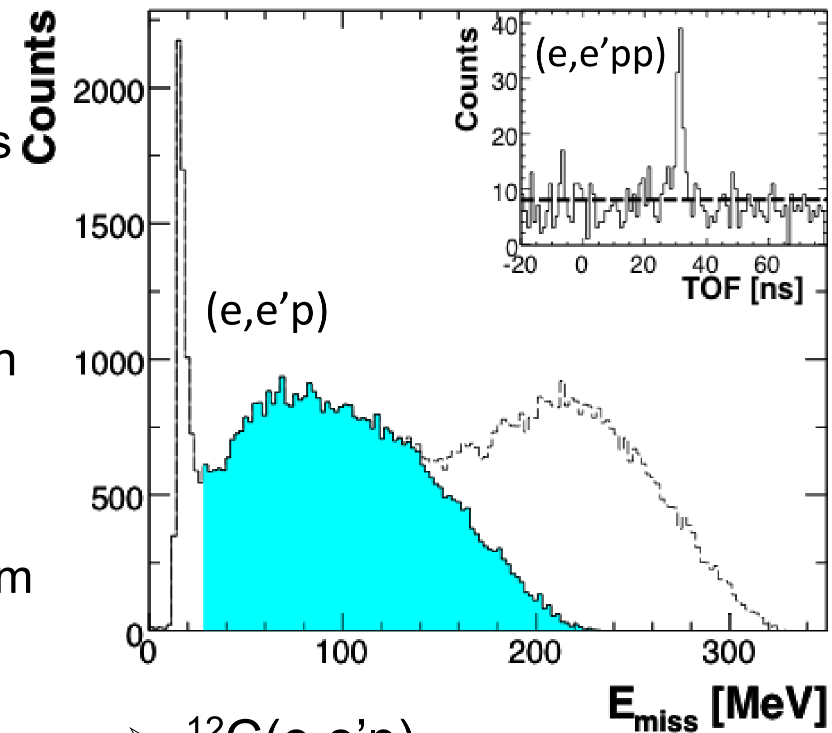
more than 1 quark share momentum

reduce MEC, Δ contributions

Anti-parallel kinematics

reduce FSI

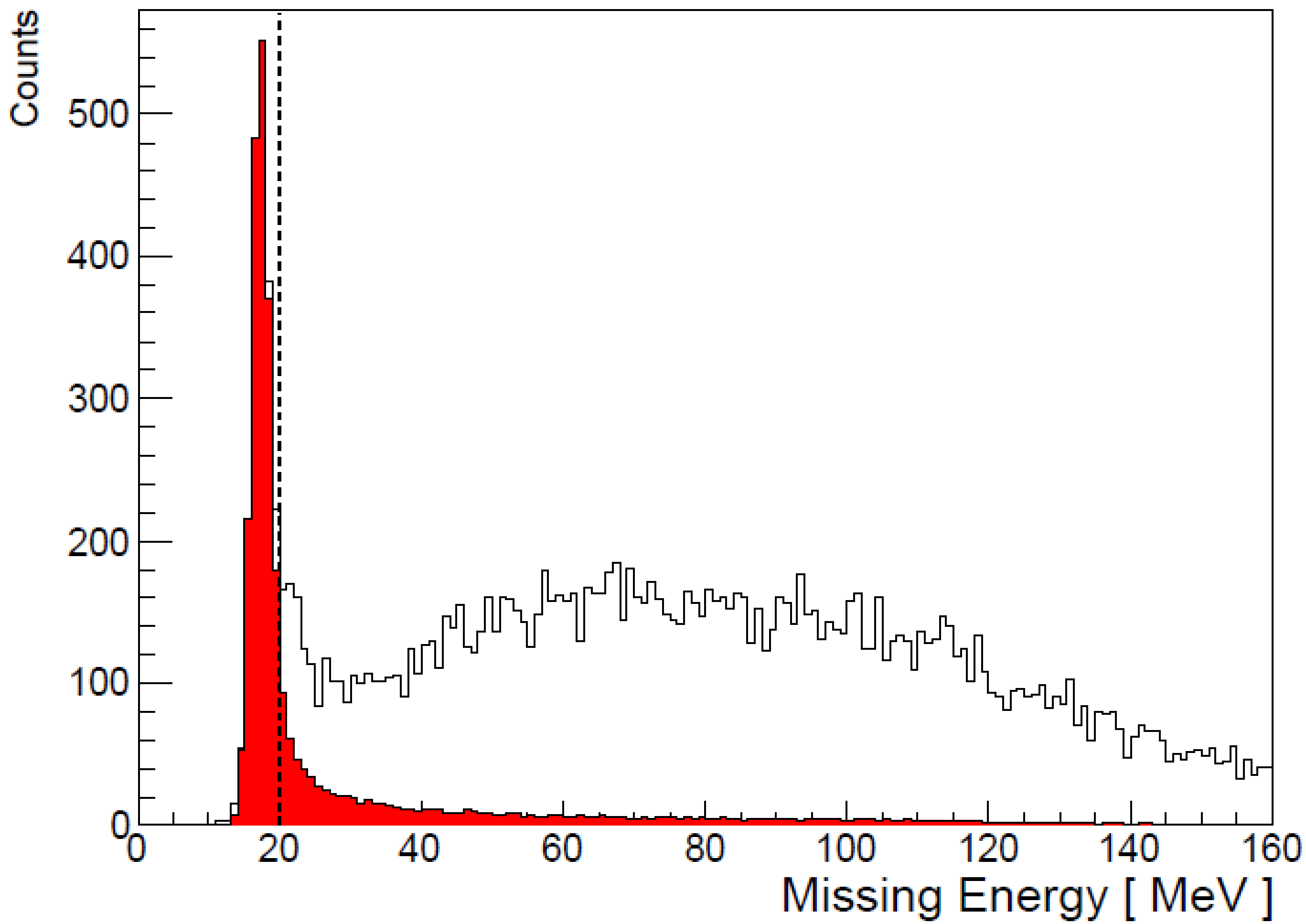
interaction with more than one nucleon



- $^{12}C(e,e'p)$
- Quasi-Elastic shaded in Blue
- Resonance Even at x_B>1

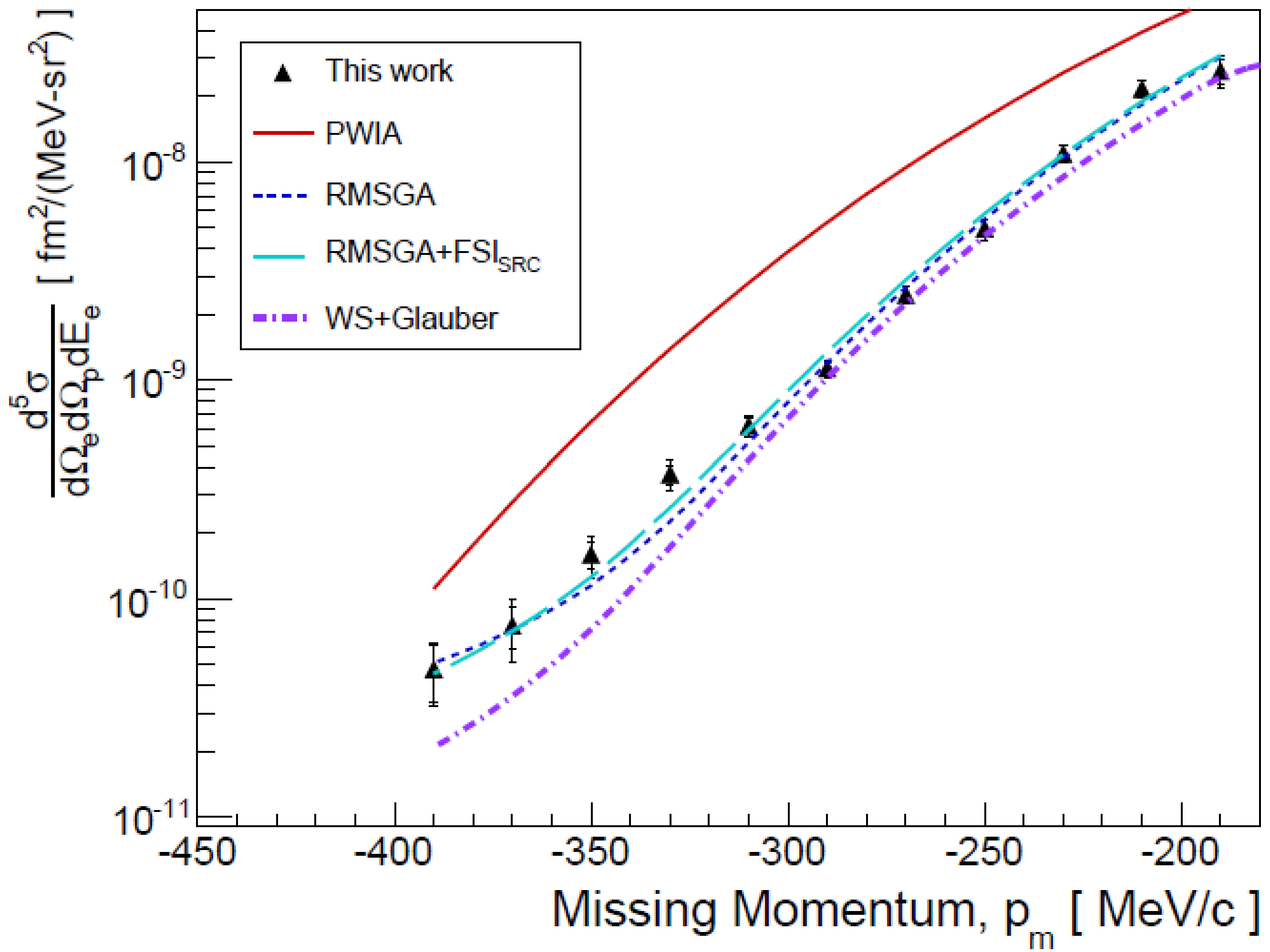
$^{12}C(e,e'p)^{11}B$ Cross Sections

Results from P. Monaghan; arXiv:1301.7027



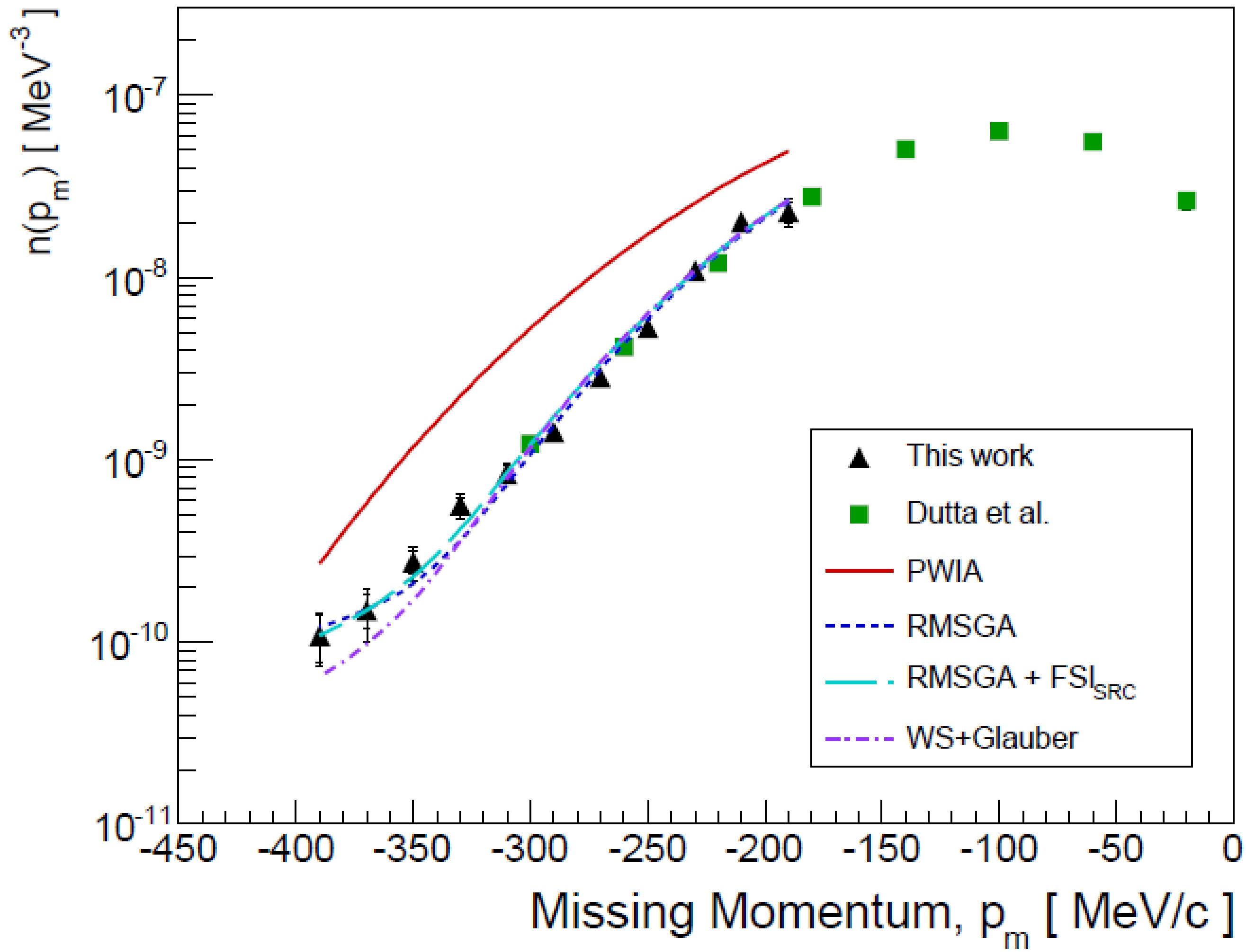
$^{12}C(e,e'p)^{11}B$ Cross Sections

Results from P. Monaghan; arXiv:1301.7027



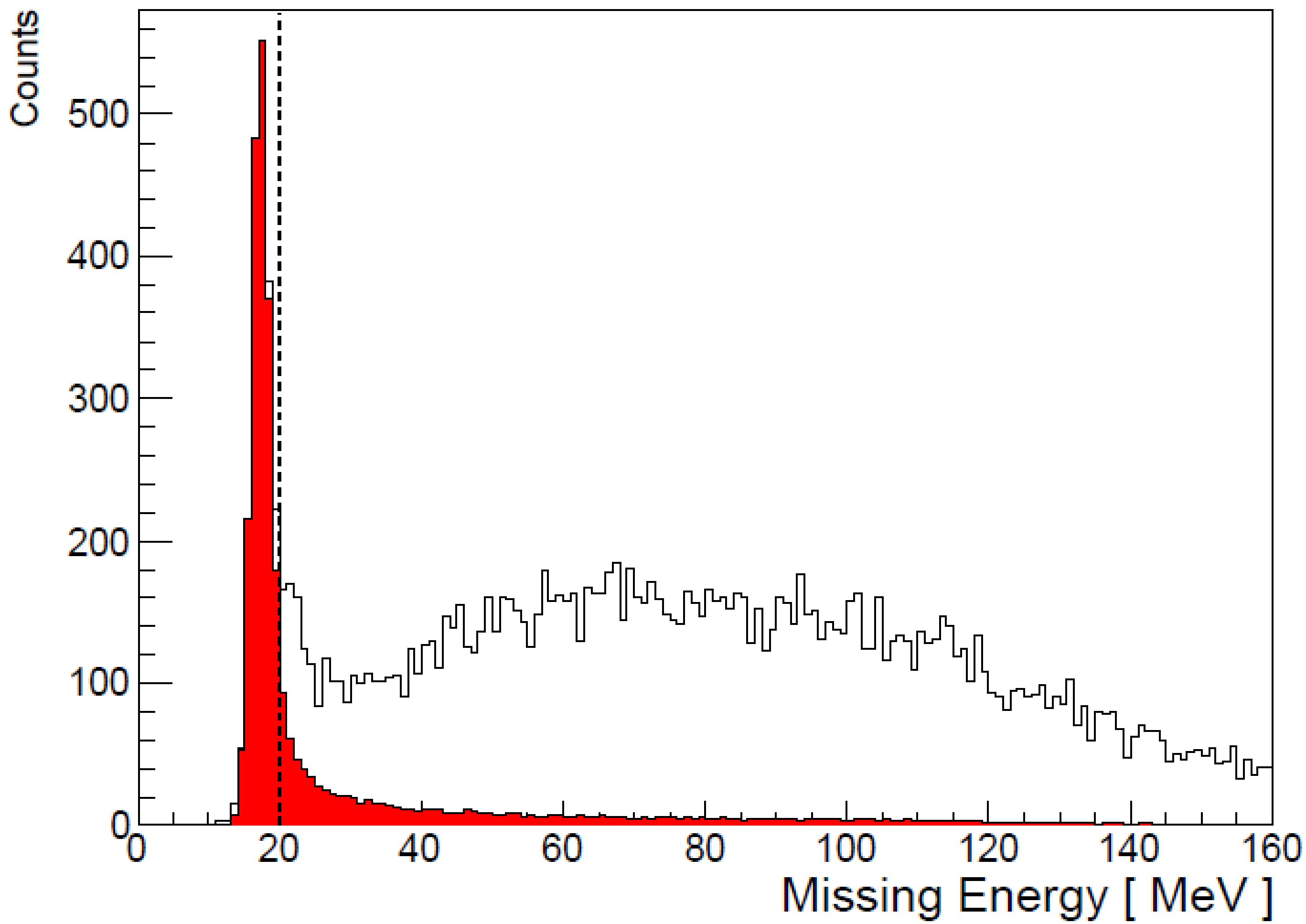
Distorted Momentum Distribution

$$n_{distorted}(P_m) = \left\langle \frac{d^5\sigma}{d\Omega_e d\Omega_p dE_e} \right\rangle_{exp} / \langle K\sigma_{cc2} \rangle_{unit}$$



$^{12}C(e,e'p)$ Continuum Results

Results from P. Monaghan's thesis



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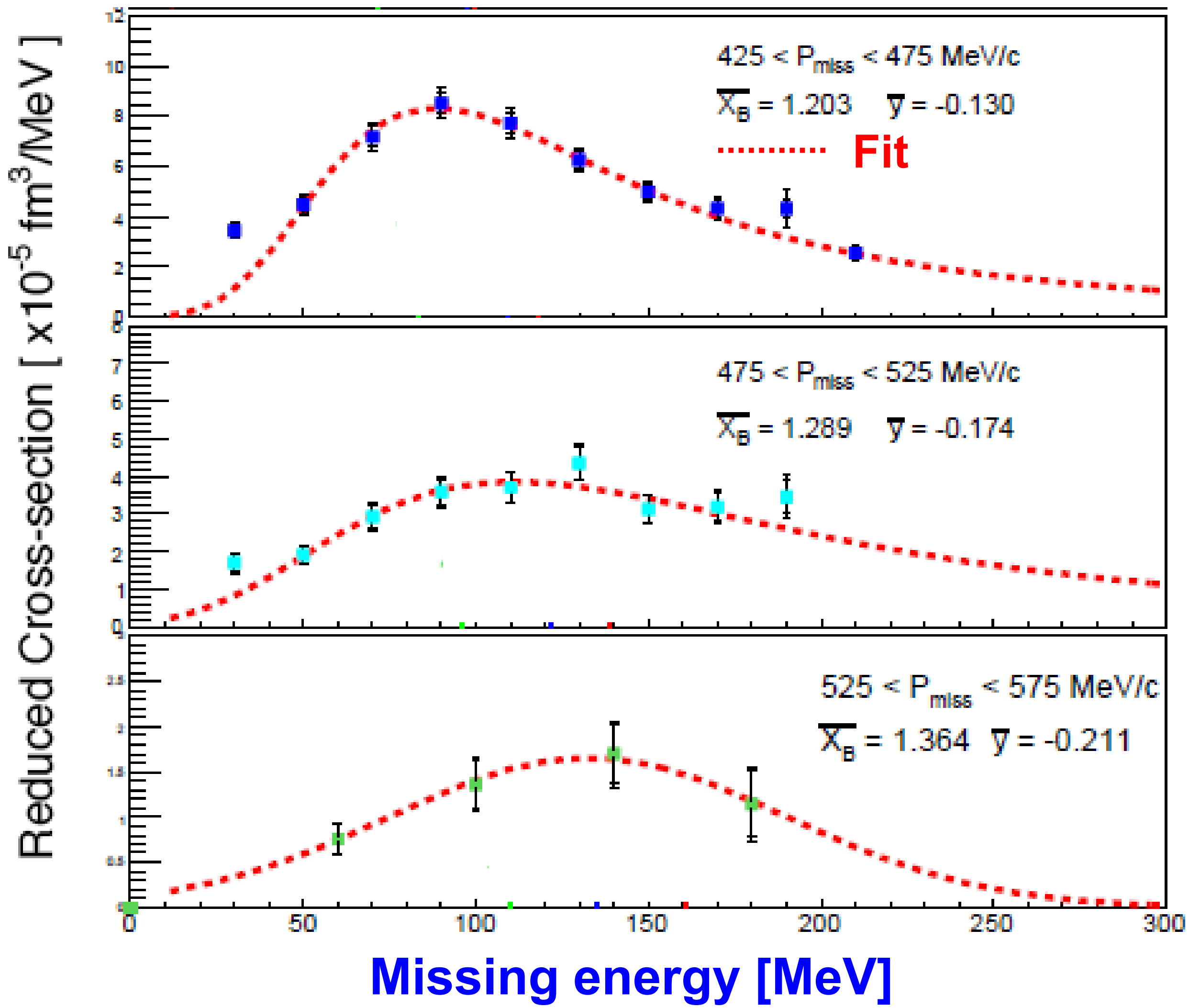
Extracted Spectral Functions

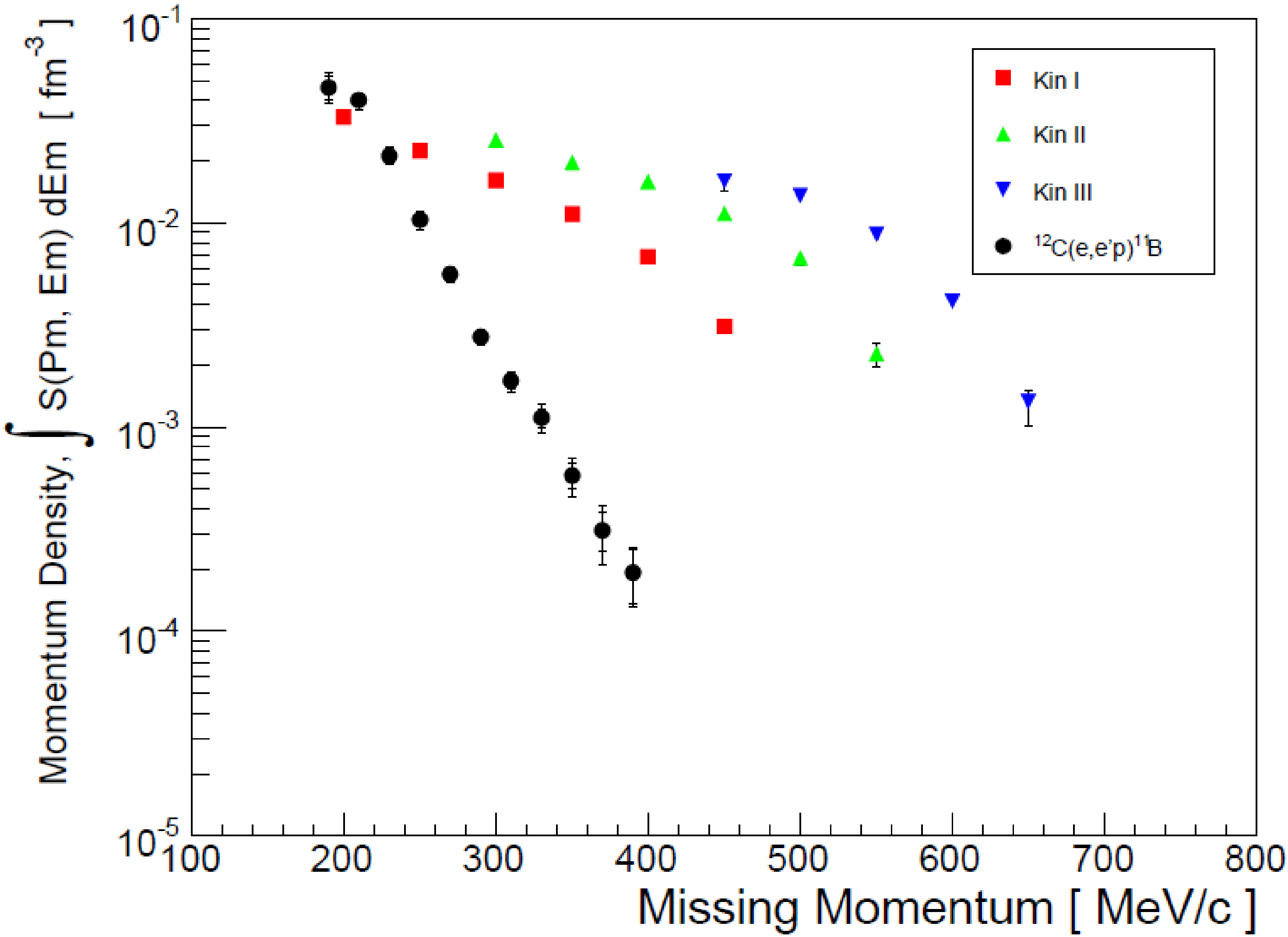
Kinematics 1 and 3 with lower and higher p_m range are also available



Kinematic 2

Distorted Momentum Density

$$\eta(p_{miss}) = \int_{E_{min}}^{E_{max}} \left\langle \frac{d^6\sigma}{d\Omega_e d\Omega_p dE_e dE_p} \right\rangle_{exp} / \langle K\sigma_{cc2}\rangle_{unit} \, dE_{miss}$$



E07-006: ^{4}He(e,e'pN)pn SRC

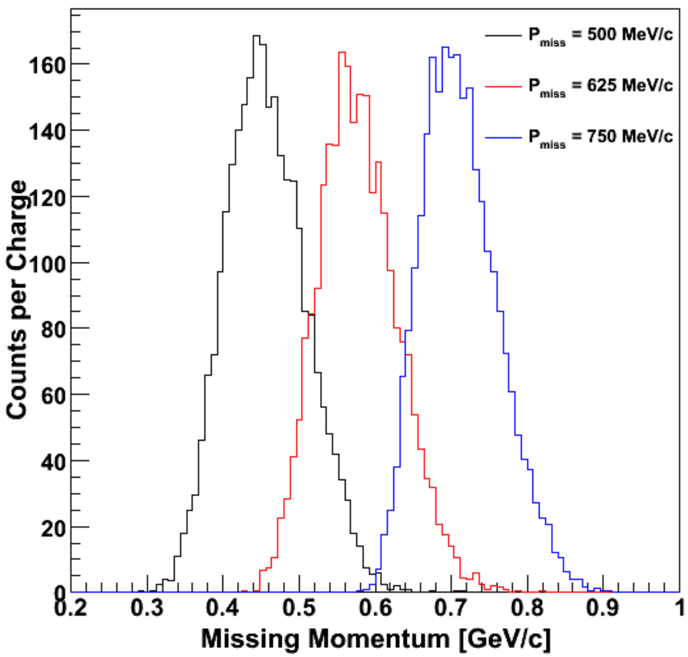
- ^{4}He Target
- P_m: 400 – 800 MeV/c
- Pushing Limits of NN Potential
  - Long range attraction
  - Short range repulsion

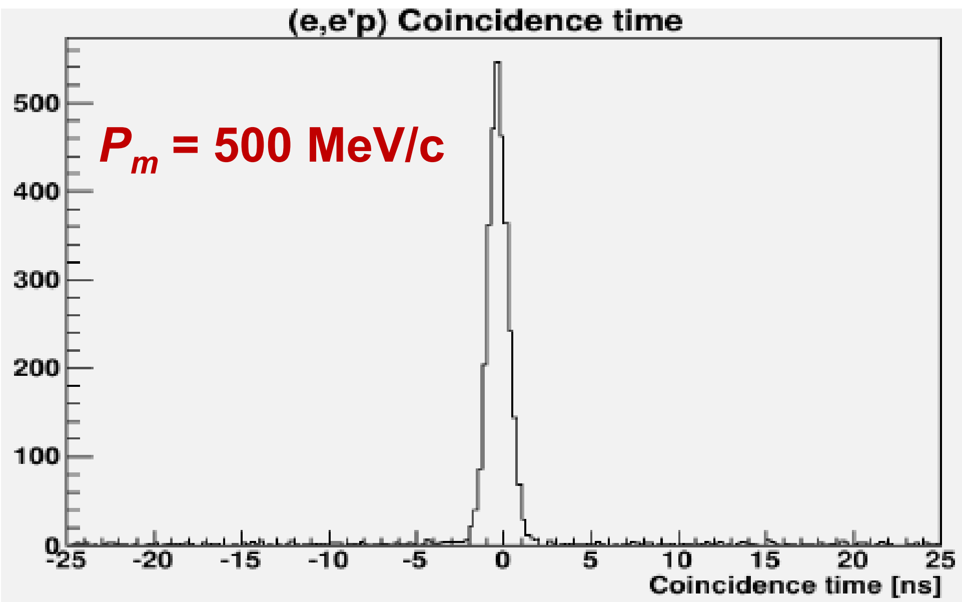
E01-015	E07-006
x_B >1, Q^2 = 2 $[Gev/c]^2$	x_B >1, Q^2 = 2 $[Gev/c]^2$
300 – 600 MeV/c	400 – 800 MeV/c
Tensor Force	Tensor to Repulsive core
Target – ^{12}C	Target – ^{4}He (Less FSI)
BigBite and HAND	BigBite with MWDCs Upgraded HAND (new lead wall)

See Igor Korover's talk this afternoon

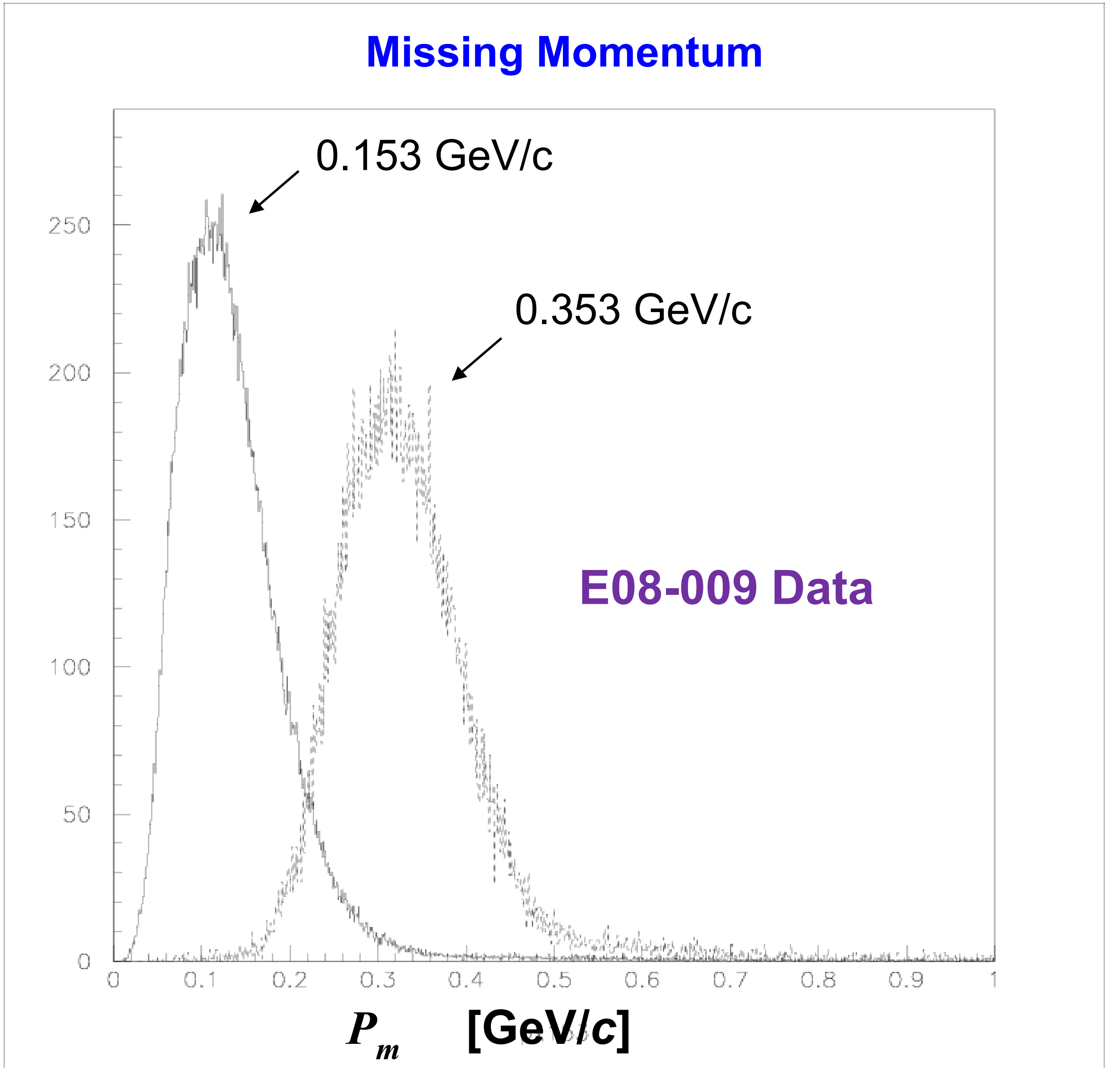
^{4}He(e,e'p) Preliminary Results

P_{miss} [MeV/c]	Charge [C]	^{4}He(e,e'p) Counts
500	2.0	3000
625	2.5	1900
755	3.9	2000



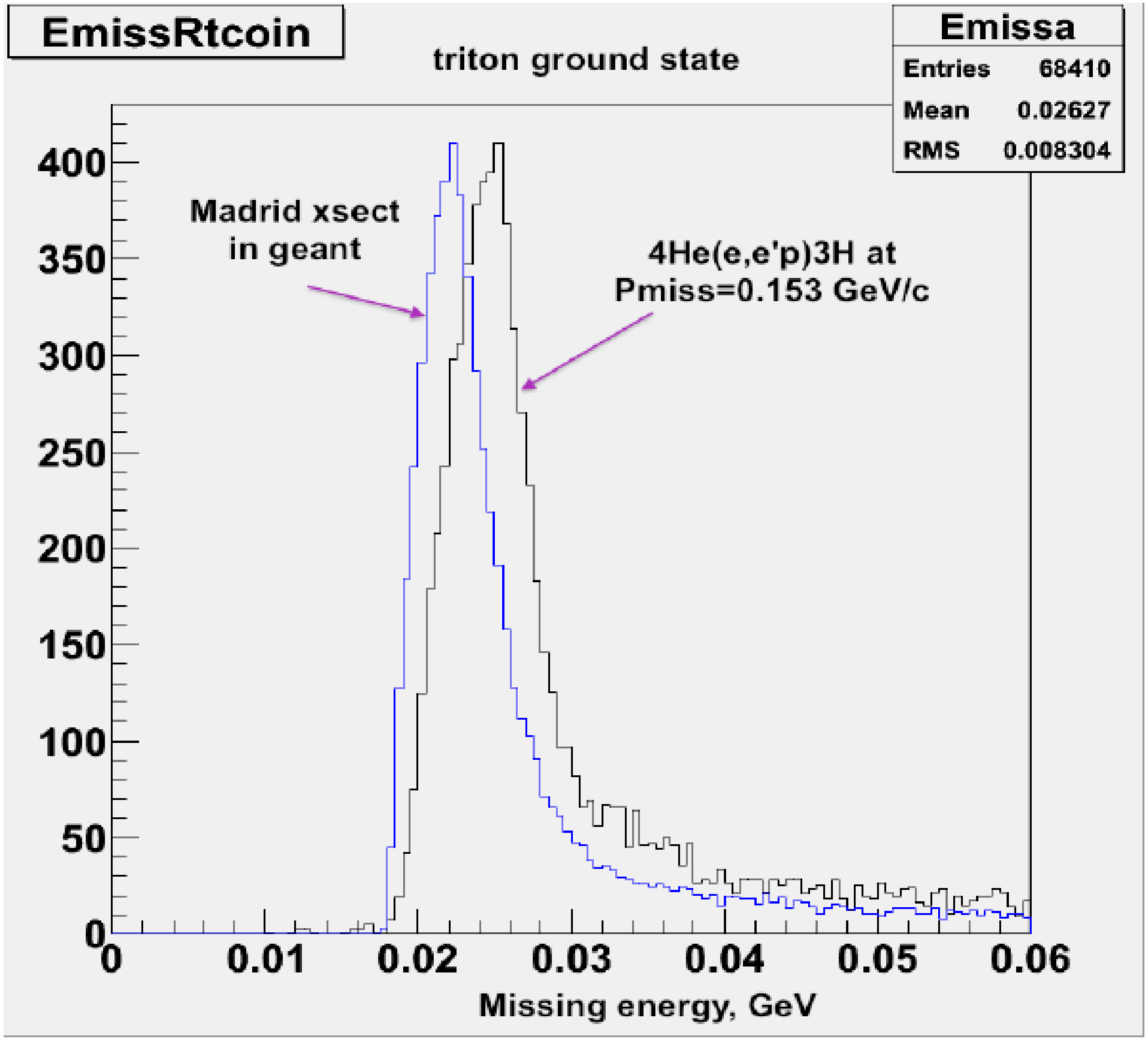


Low P_m Results



^{4}He(e,e'p)^{3}H Preliminary Results

Results from S. Iqbal



Madrid theory: Single particle model using relativistic QM wave functions

No energy loss corrections

Summary

- Quenching of spectroscopic strength might be an indication of N-N correlations.
- Reaction dynamics unfortunately complicate the picture and make isolating N-N SRC difficult.
- Recent data for ^{12}C(e,e'p) and ^{4}He(e,e'p) at kinematics favorable to correlations:
  - High P_{m}, High Q^2, $x_B > 1$, "semi anti-parallel"
  - Analysis of carbon bound state data is complete and shows good agreement with theory: **arXiv:1301.7027**
  - Publication on continuum results expected soon
  - Helium-4 is data being analyzed
- Theoretical calculations and input are desired

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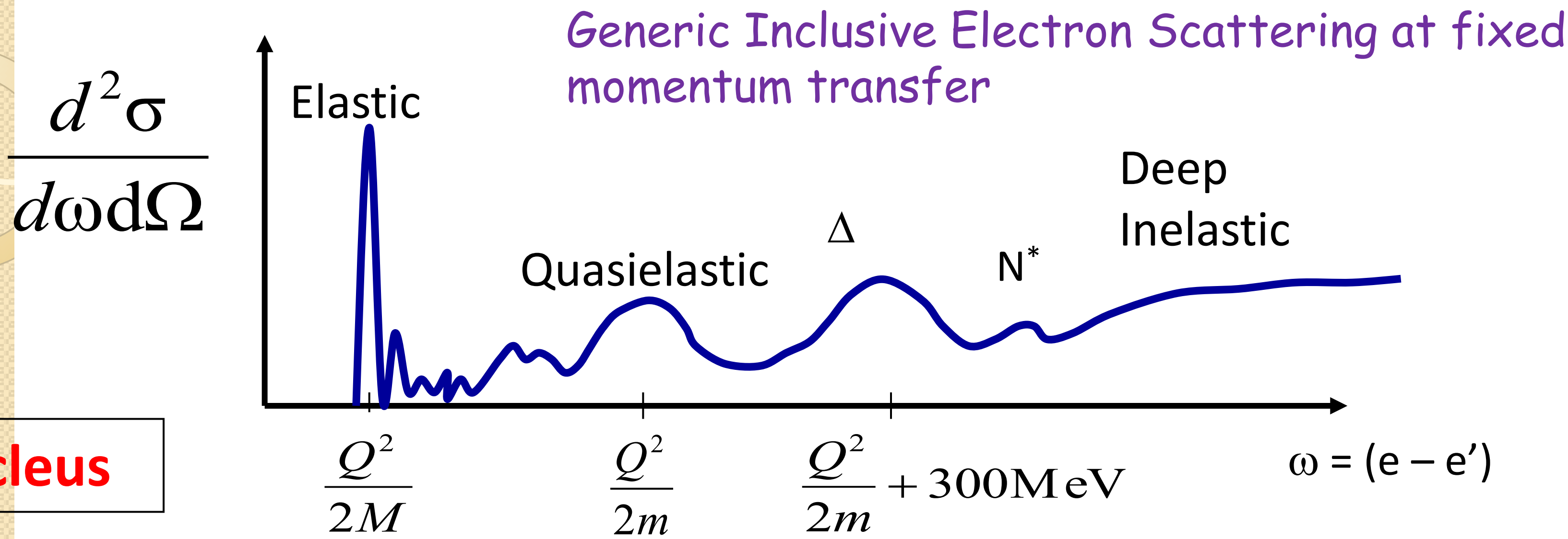
Acknowledgements

- ✓ Peter Monaghan (Hampton)
- ✓ Shalev Gilad (MIT)
- ✓ Douglas Higinbotham (JLab)
- ✓ Konrad Aniol (California State)
- ✓ Sophia Iqbal (California State)

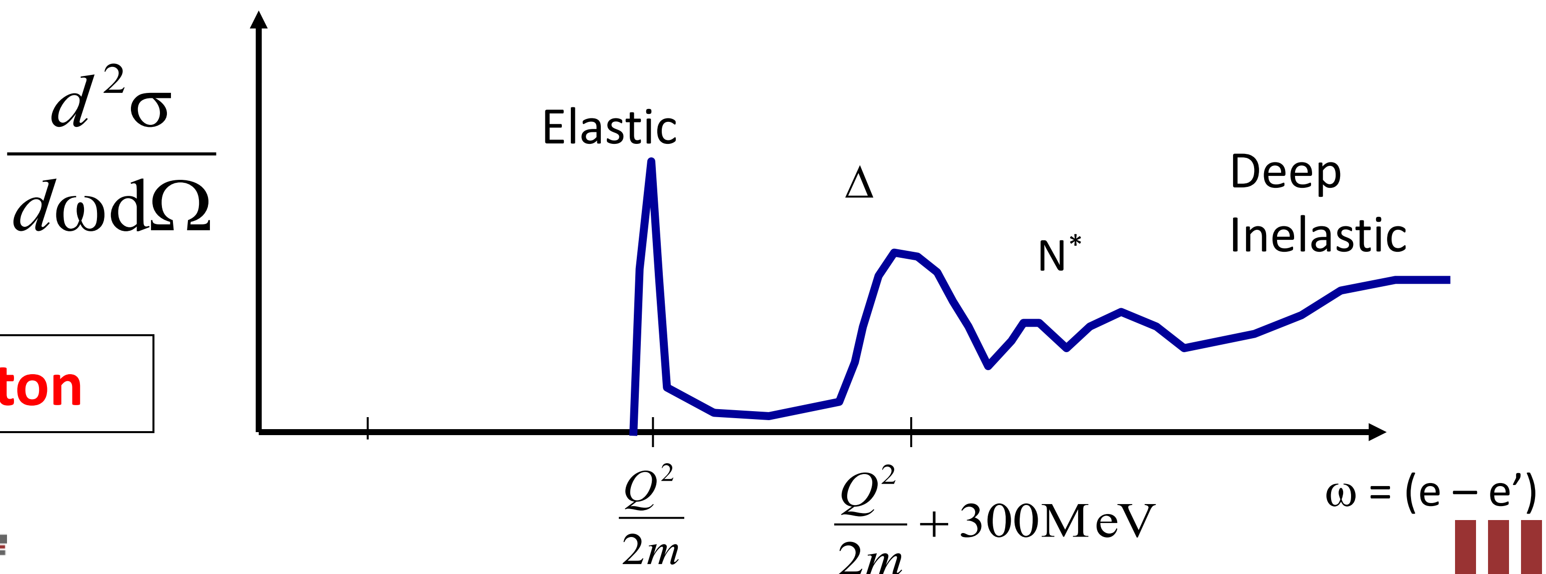

Thank You!

Electron Scattering (e,e’) at Fixed Q^2

Nucleus



Proton



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Spectral Function

In nonrelativistic PWIA:

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S(p_m, \varepsilon_m)$$

e-p cross section

nuclear spectral function

For bound state of recoil system:

proton momentum distribution

$$\rightarrow \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = K' \sigma_{ep} \left|\Phi(p_m)\right|^2$$

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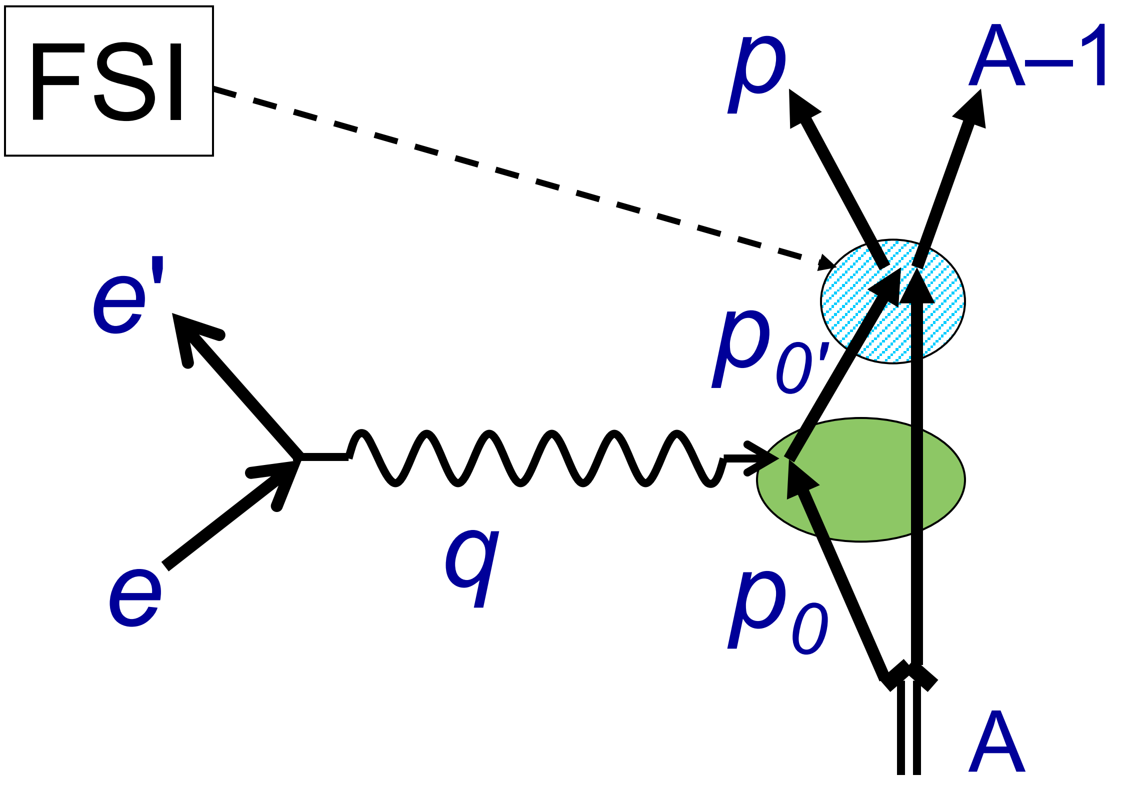
Reaction Mechanisms

Example: Final State Interactions (FSI)



$$\vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0$$

Improve Theory

Distorted Wave Impulse Approximation (DWIA)

This is modeled by an optical potential from elastic (p,p) data. Proton is described by Distorted Waves.

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dp d\omega} = K \sigma_{ep} \boxed{S^D(p_m, \varepsilon_m, p)}$$

"Distorted" spectral function

DWIA: If the struck nucleon re-interacts with the rest of the nucleus, then the cross section still factorizes (mostly) but we measure a distorted spectral function.

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Madrid Theory

Relativistic wave functions from solutions of the Dirac equation with both scalar and vector mean field potentials used for the initial and final states.

The optical potential is a folding potential with effective NN interactions phenomenologically fitted to elastic proton scattering on light nuclei at energies of interest for this experiment. For more details see:

Relativistic Description of $^{3}He(e,e'p)^{2}H$

Reference: Few-Body Systems 50, 359-362(2011)

Alvarez-Rodriguez R, Udias JM, Vignote JR, Garrido E, Sarriguren P, Moya de Guerra E, Pace E, Kievsky A, Salme G

The calculation for ^{4}He followed similar lines for the final state interactions/optical potential, while the bound state of ^{4}He is a simple mean field solution.

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Brief Theoretical Review

- **Relativistic Approaches**:
  - Relativistic Distorted Wave Impulse Approximation (RDWIA):
    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).

    Groups: A. Picklesimer, J.W. Van Orden and S. J. Wallace
    The Madrid Group (J. Udías *et al.)*
    J. J. Kelly (Effective Momentum Approximation)
    A. Meucci *et al.*

Far from a complete list of approaches and contributors !

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Theoretical Review II

- **Relativistic Approaches**:
  - Relativistic Multiple Scattering Glauber Approximation (RMSGA):
    Also uses the EA but instead evaluates multiple scattering by the nucleon-nucleon interaction directly rather than through a mean field. Bound-state wave functions are solutions to Dirac equation with scalar and vector potentials fitted to ground state nuclear properties.

    Group: Ghent (J. Rychkebusch *et al*.)

  - Relativistic Optical-Model Eikonal Approximation (ROMEA):
    Employs an Eikonal Approximation (EA) that should be equivalent to RDWIA for large Q^2, but a partial-wave expansion is avoided. Difference compared to RDWIA is the use of EA to compute the scattering wave functions.

    Group: M. Radici *et al.*

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Theoretical Review III

- **C. Ciofi degli Atti and H. Morita:**
  - Mean field calculation using the Woods-Saxon form for the wave function.
  - FSI modeled using Glauber approach to describe rescattering of the struck proton. Glauber approximation assumed A-1 spectator nucleons are stationary during any rescattering of the struck nucleon.

- **J. M. Laget**:
  - Microscopic calculation of continuum cross section including a PWIA calculation with correlations but no FSI, and successive implementation of various interaction effects.
  - Both single and double NN scattering as well as meson exchange and Δ formation are included.
  - Nucleon and meson propagators are relativistic and no Glauber approximations have been made. For FSI used a global parameterization of the NN scattering amplitudes from experiments