



*The Abdus Salam
International Centre for Theoretical Physics*



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12 - 16 May 2008

Recent Studies of Correlations in Nuclei using $(e,e'p)$ Reactions

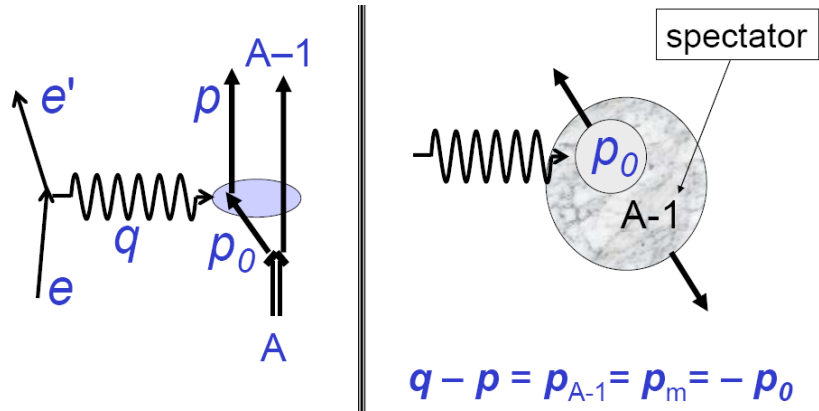
S. Gilad
MIT, USA

Recent Studies of Correlations in Nuclei using $(e,e'p)$ Reactions

- The $A(e,e'p)$ reactions
- "Our" definition of correlations
- Favorable kinematics for studying correlations
- Recent experimental results
- Limitations of reaction
 - Experimental
 - Theoretical
- Status of the field - other reactions
- Outlook

Why $A(e, e'p)$?

Attractiveness of $(e, e'p)$



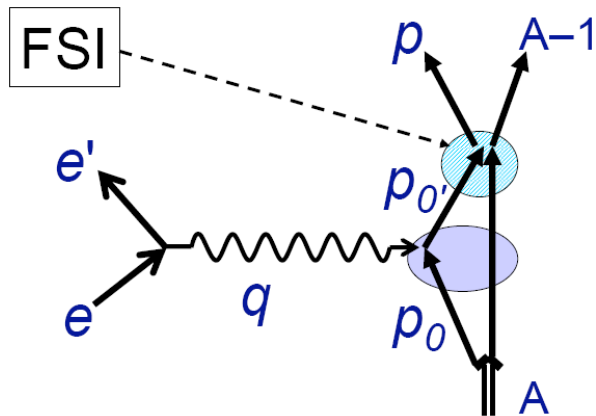
In nonrelativistic PWIA:

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

e-p cross section

nuclear spectral function

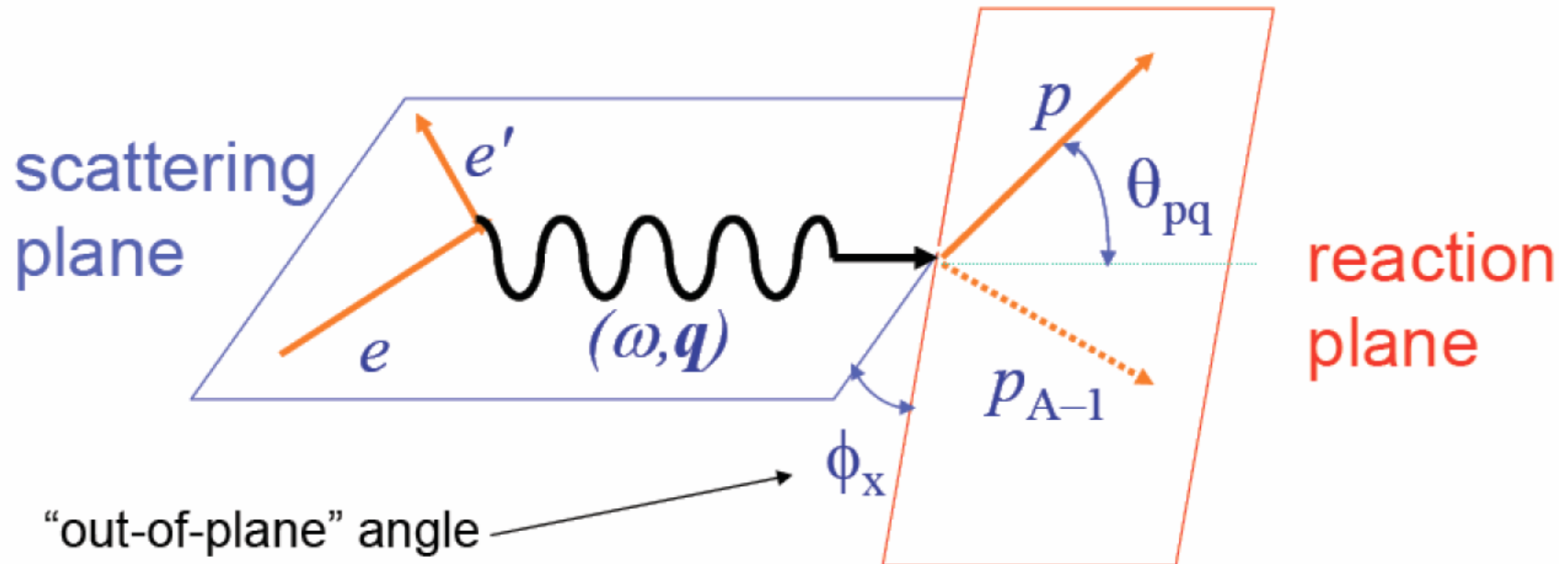
Not an observable!!



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

"Distorted" spectral function

(e,e'p) Kinematics - Facts



Known: e, A

Measure: e', p

Infer: $p_m = q - p = p_{A-1}$
 $E_m = \omega - T_p - T_{A-1}$

A-1 can be **bound** or **unbound**

|| kin.: $p \parallel q$, vary p_m with ω
 electron kin. \neq const.!!

\perp kin.: $p \perp q$, vary p_m with θ_{pq}
FSI!!!

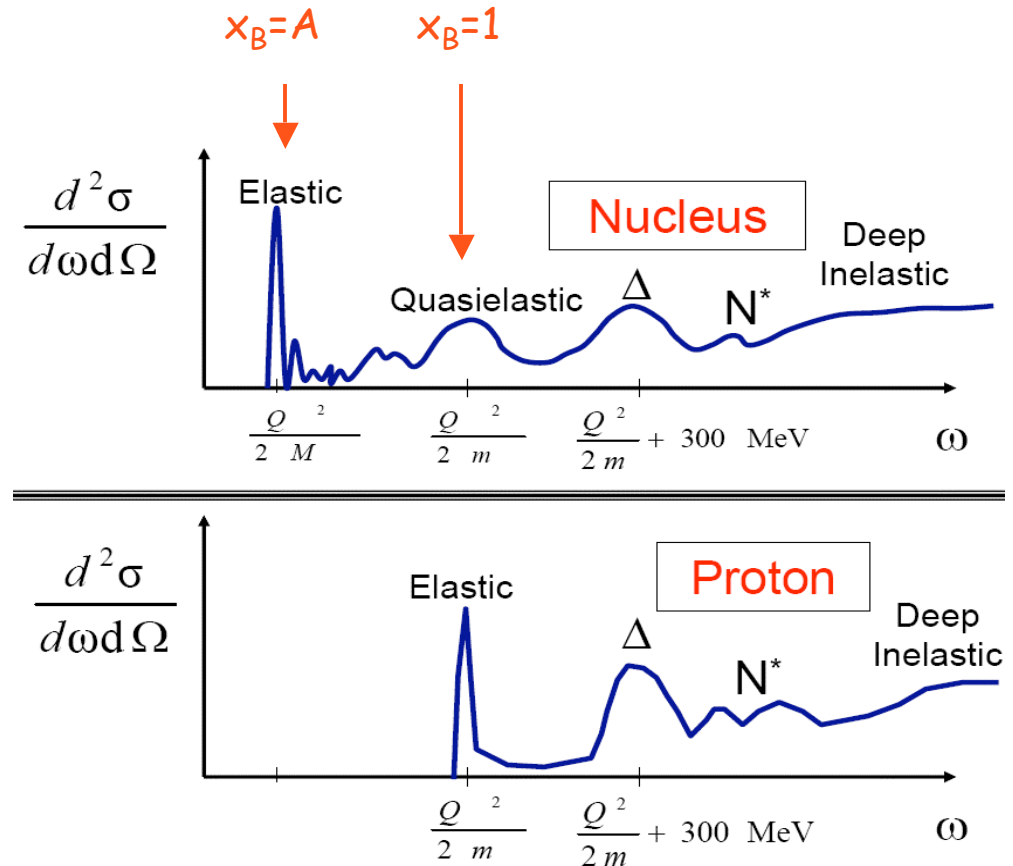
Favorable Kinematics

High p_m
probe small inter-nucleon distances

High Q^2
probe small distances
less ambiguity about struck nucleon
can handle FSI using GA or GEA

High x_B
more than 1 quark share momentum
reduce MEC, Δ contributions

Anti-parallel kinematics
reduce FSI
interaction with more than 1 nucleon



In this experiment, use "semi parallel kinematics"
Triple coincidence (e,e'pN)

Until Early 1990's

Valance states

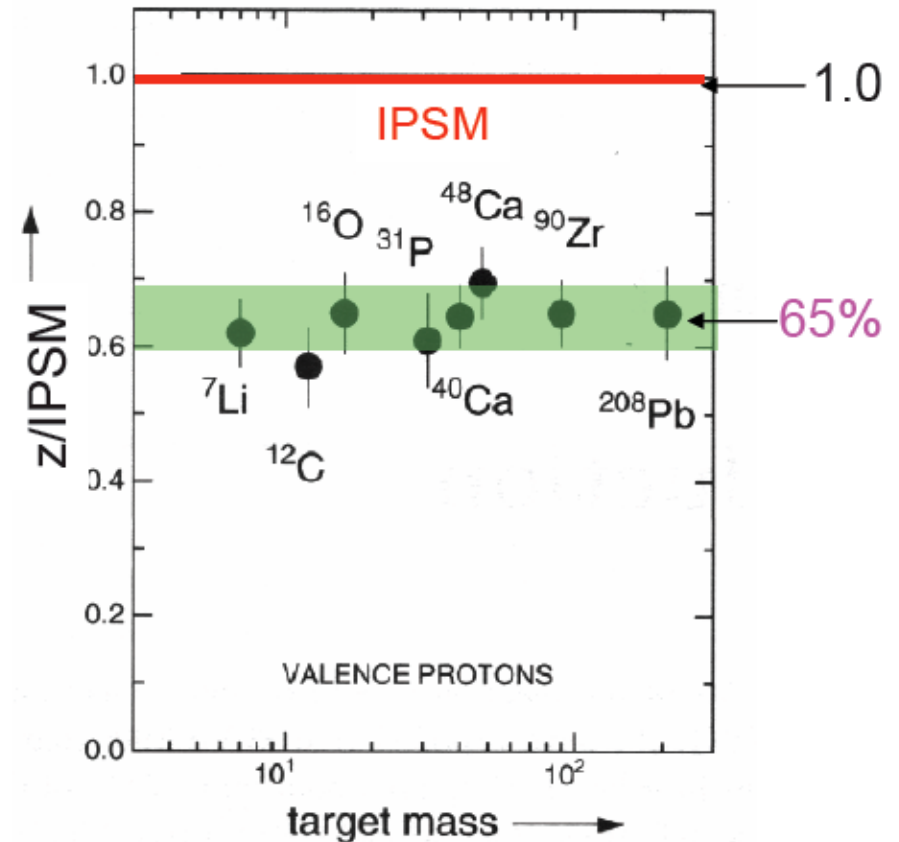
- Moderate Q^2
- Mainly "Perpendicular", QE kinematics
- Extract "distorted" momentum distributions for moderate p_m
- Non relativistic DWIA, Optical Potential for FSI
- Shape of spectra well reproduced
- Occupancy - ~60-70%
- Explain excess at high p_m in terms of complex states, LRC, SRC

$$Z_{\text{IPSM}} = 2j + 1$$

$$Z_{\alpha} = 4 \pi \int_{k_F} dE dk k^2 S(E, k)$$

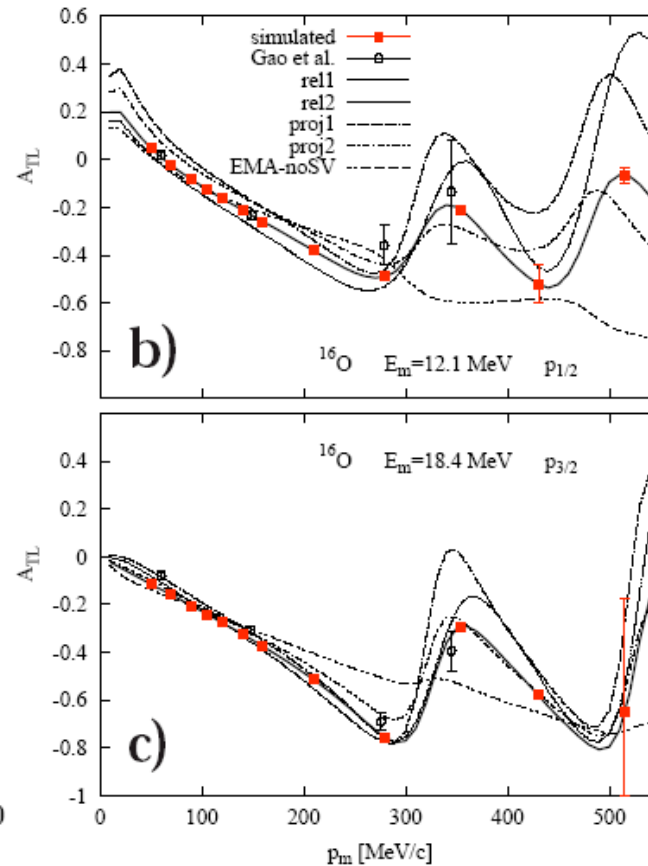
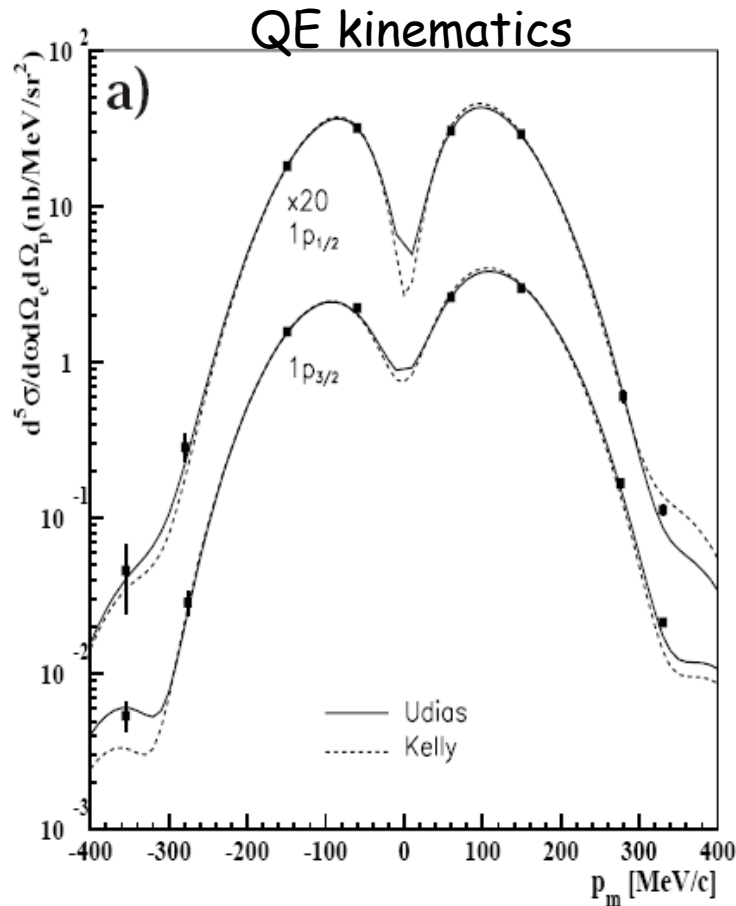
single particle state α

NIKHEF



Recent but "Classic": $^{16}\text{O}(e,e'p)^{15}\text{N}$

New data to $p_m < 750 \text{ MeV}/c$ in analysis



J. Gao et al., PRL **84**, No. 15, 3265 (2000)

Experiment:

- High-energy, intense, high-quality beams
- Small x-sections
- High $Q^2=0.8$
- Const. Electron kinematics, \perp

Analysis:

- RDWIA (Udias *et al.*) un-factorized
- Fully relativistic kinematics and dynamics
- Enhancement of WF at high p_m
- Occupancy ≈ 0.7
- OP \leftrightarrow GA, GEA

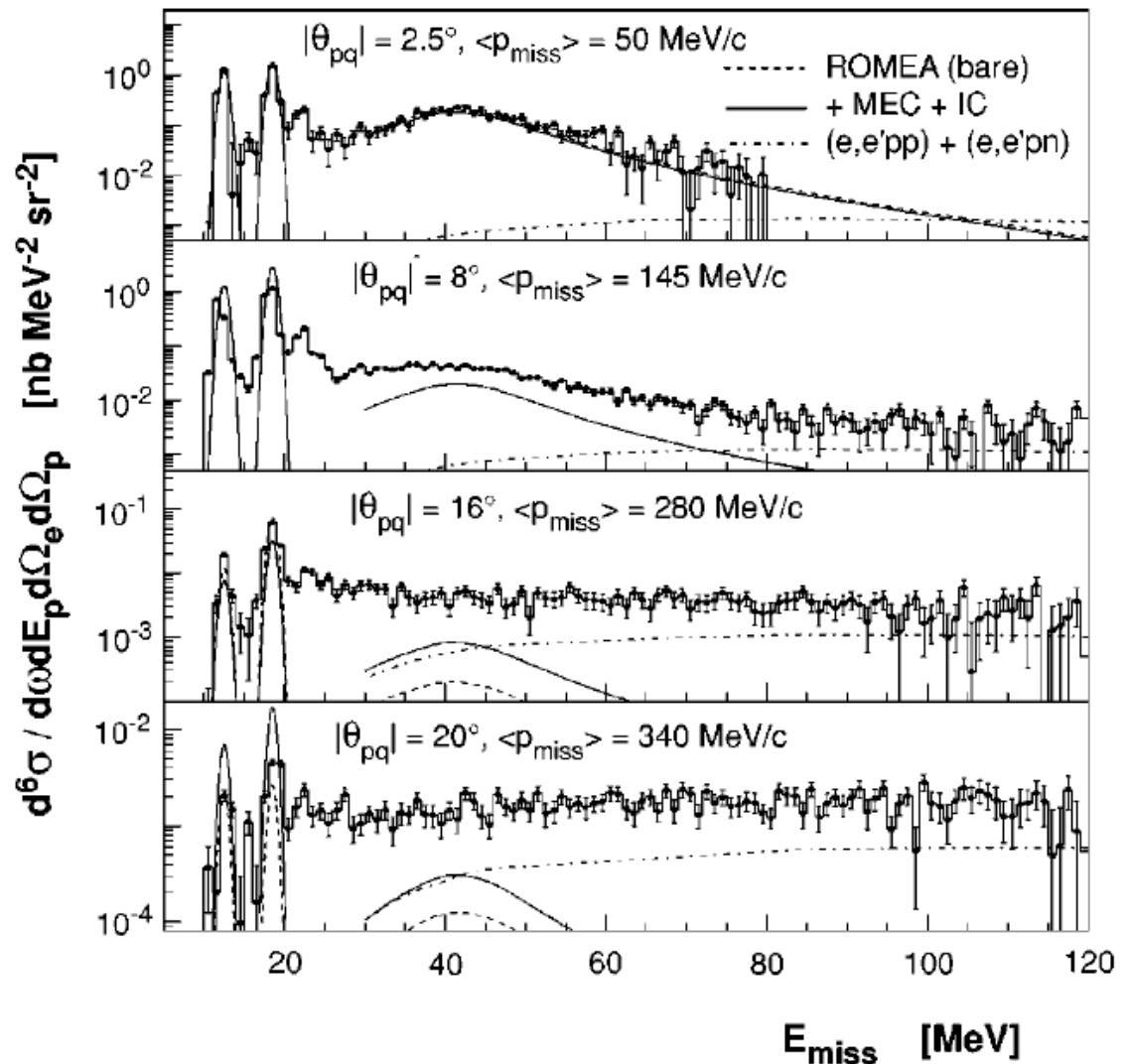
Including $(e,e'pN)$ in Calculating $(e,e'p)$

$^{16}\text{O}(e,e'p)$; $Q^2=0.8 \text{ (GeV/c)}^2$

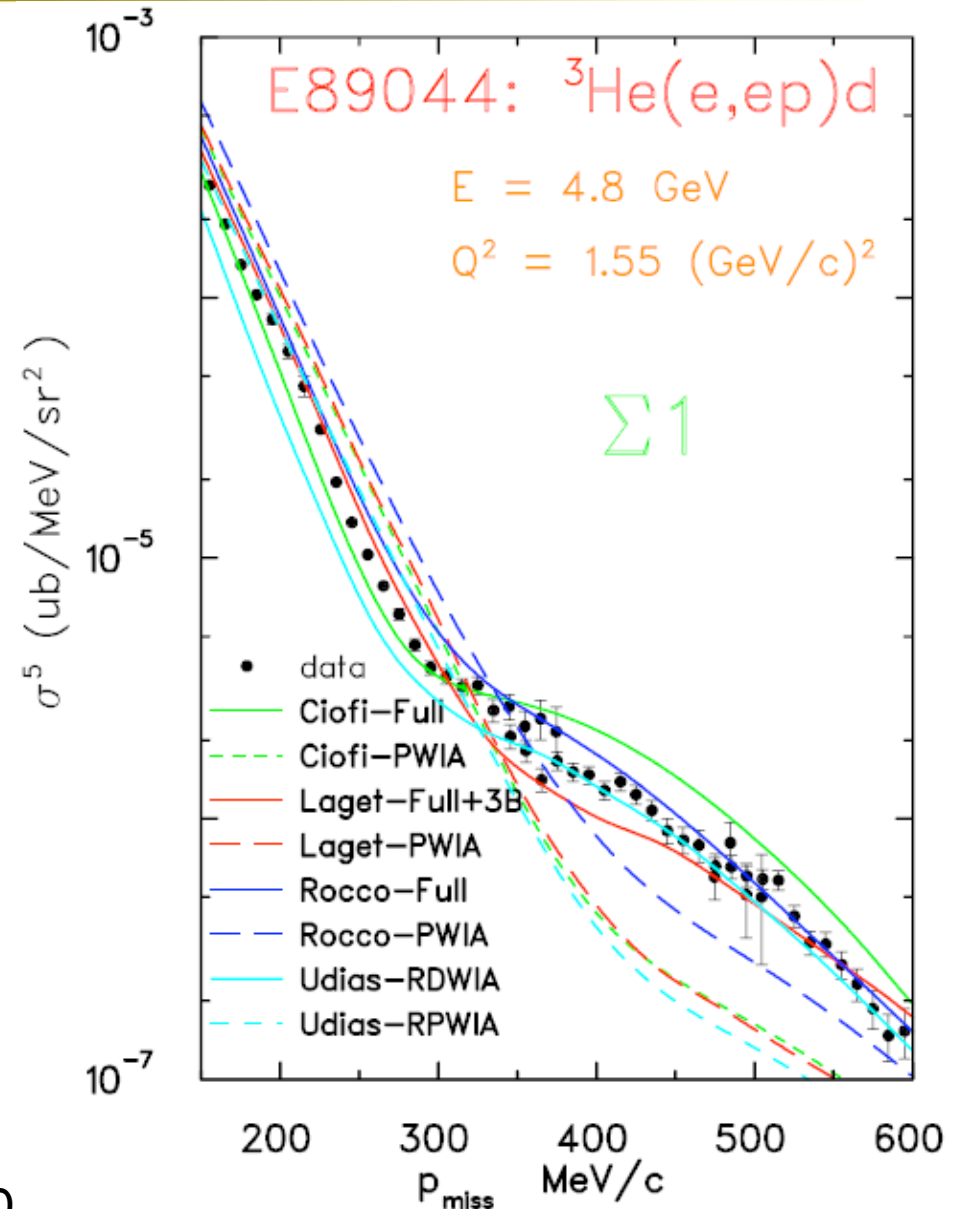
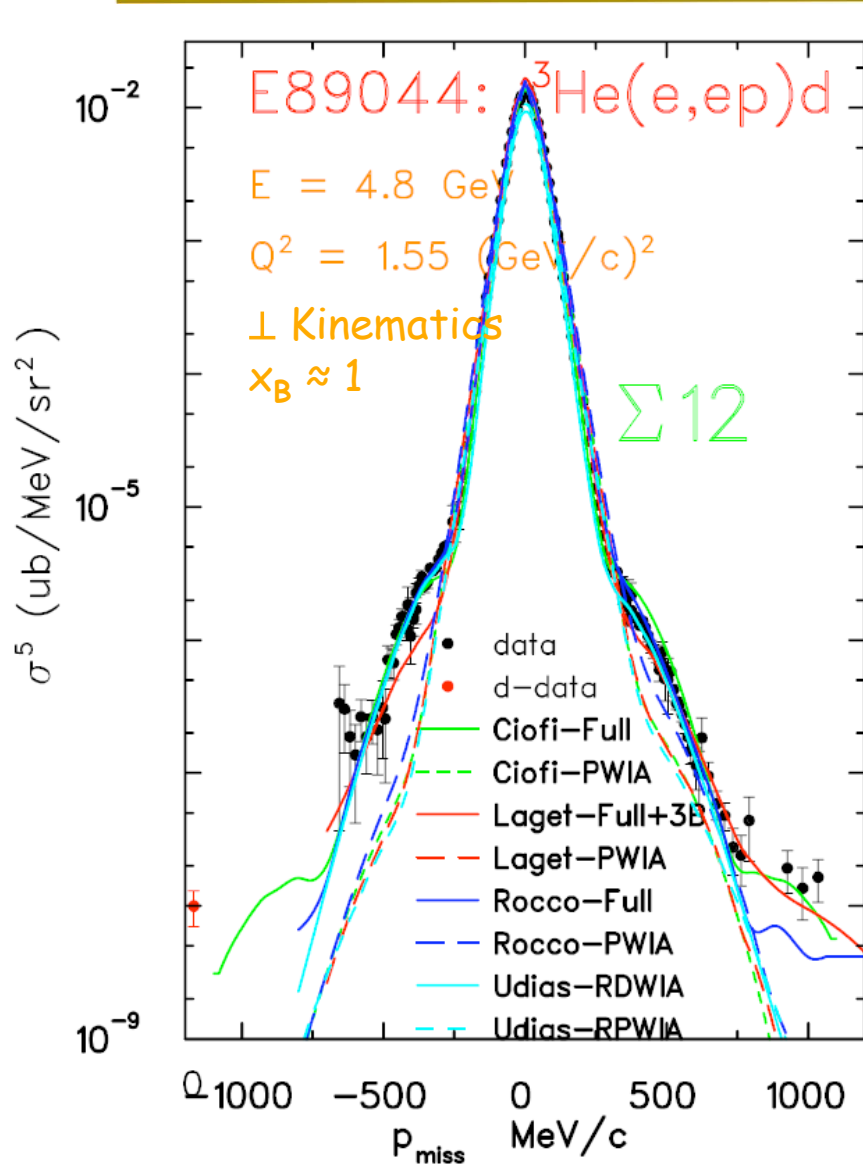
K. Fissum *et al.*, PRC 70,
034606 (2004)

Data: N. Liyanage *et al.*,
PRL 86, 5670 (2001)

Calculations: J.
Ryckebusch *et al.*



${}^3\text{He}(e,e'p){}^2\text{H}$ at const. Electron Kinematics



M. Rvachev *et al.*, PRL **94**, 192302 (2005),
 ICTP08, Trieste, Italy

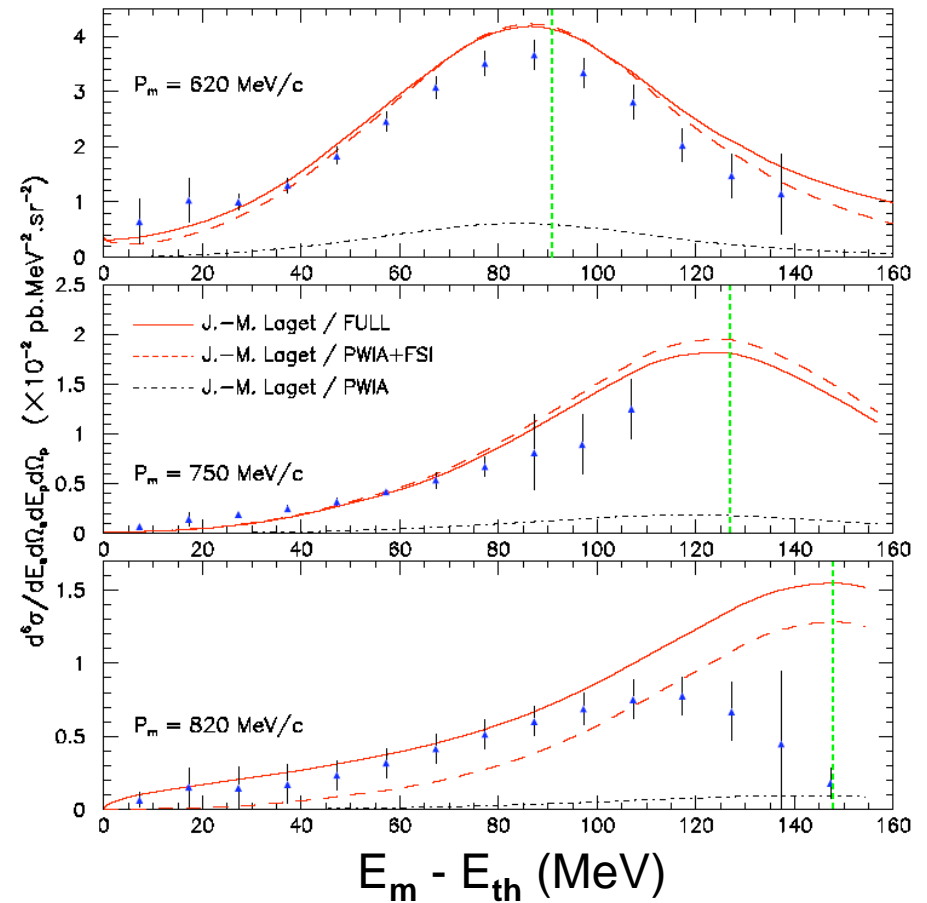
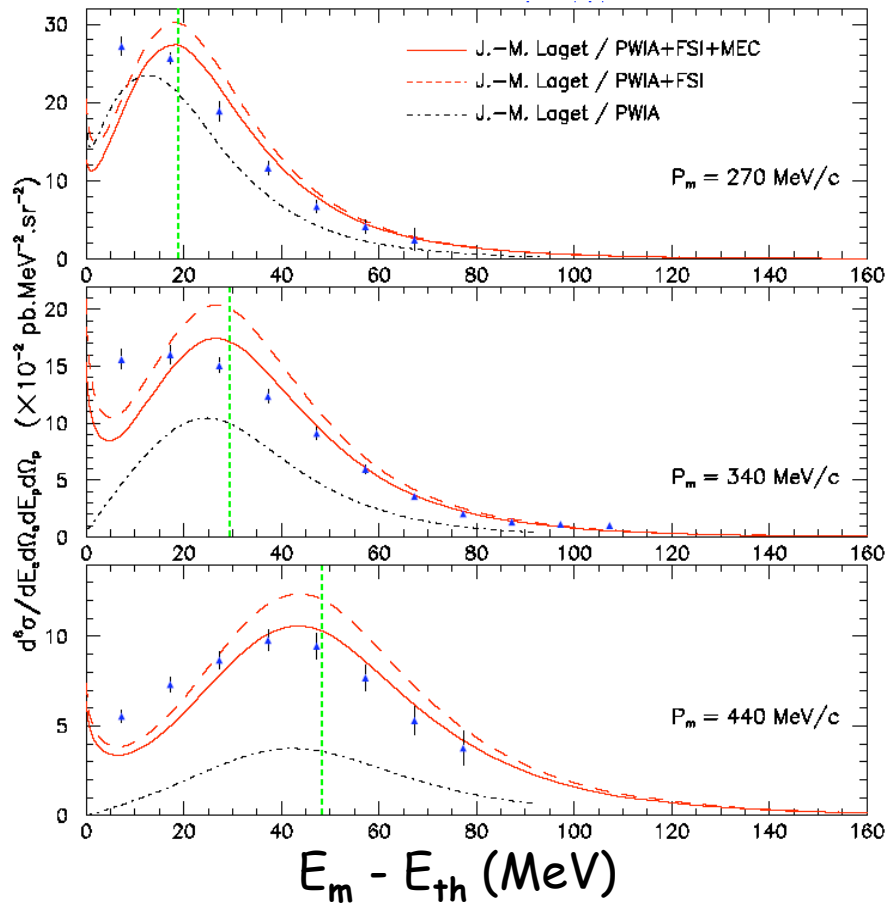
Shalev Gilad, MIT

$^3\text{He}(e,e'p)pn - 3\text{bbu} - \text{Correlations?}$

$$E_m = \sqrt{\left(M_{A-2} + \sqrt{M_N^2 + p_r^2}\right)^2 - p_r^2} + M_p - M_A$$

Low p_m (still $> k_f$): correlations?

High p_m dominated by FSI



F. Benmokhtar *et al.*, PRL **94**, 082305 (2005)
 Calc. J.M. Laget; similar by C. Ciofi degli Atti

2bbu, 3bbu "Distorted" Spectral Functions

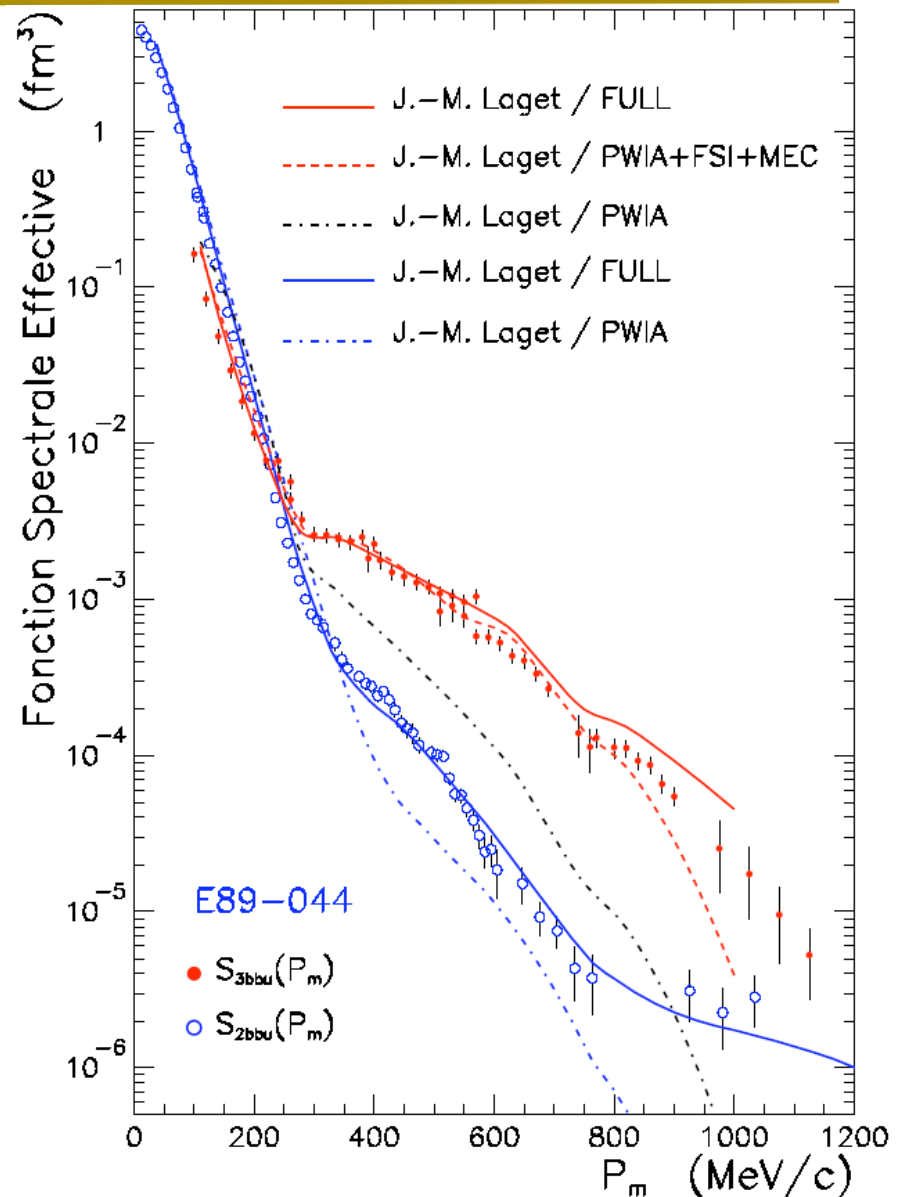
$$\eta(p_m) = \int \left(\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K\sigma_{ep} \right) dE_m$$

High Q^2 ; $x_B \approx 1$
 \Rightarrow Reduced MEC, Δ contributions

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

Calculations reproduce both 2bbu and 3bbu - confidence

Awaiting calculations by Schiavilla (?)

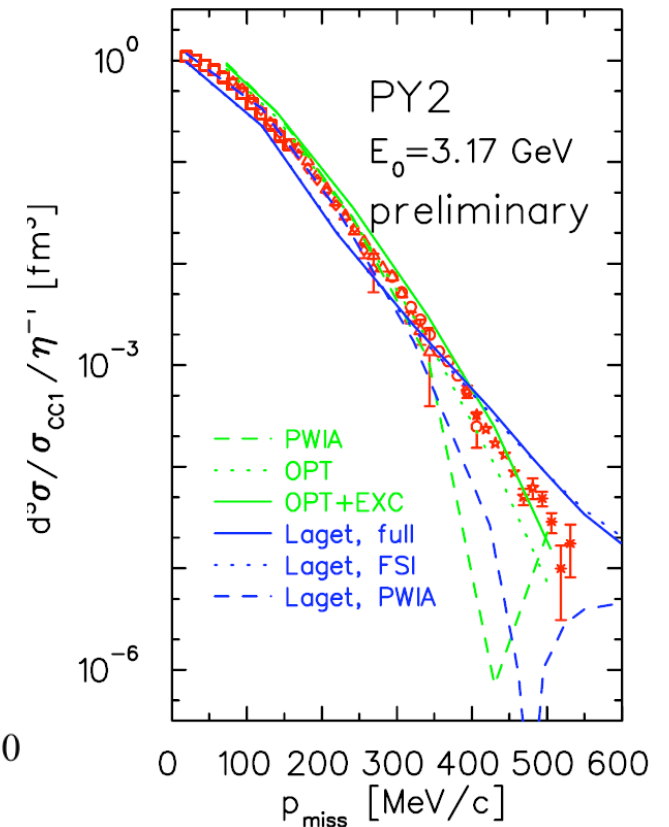
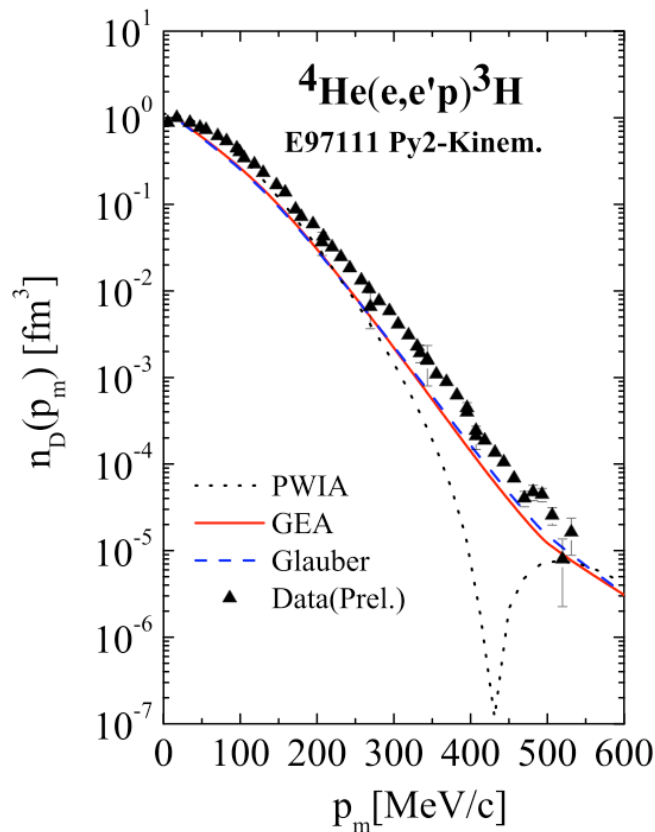


An Attempt to Observe SRC

Predict a minimum in spectral function
at $p_{\text{miss}} \approx 450 \text{ MeV}/c$

Data: || kinematics
Hall-A JLAB
Bodo Reitz *et al.*

Calculations:
Schiavilla
Laget
Ciofi

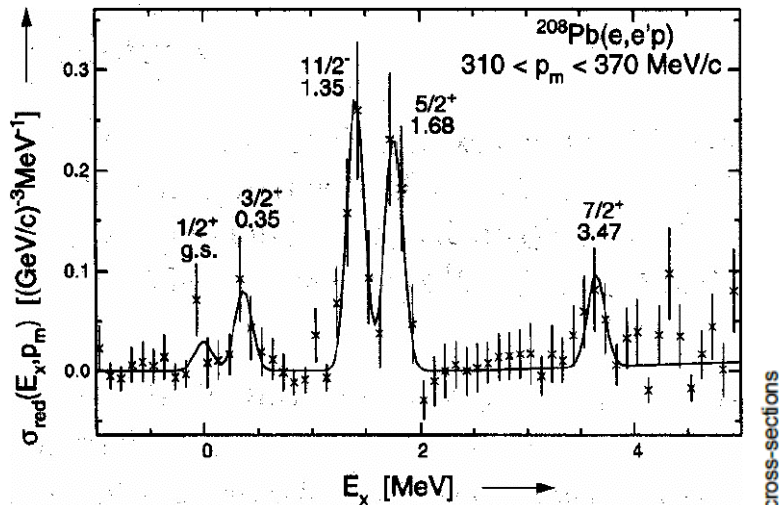


Very New Measurements

$^{208}\text{Pb}(e,e'p)^{207}\text{Tl}$ at the limit of the IPM

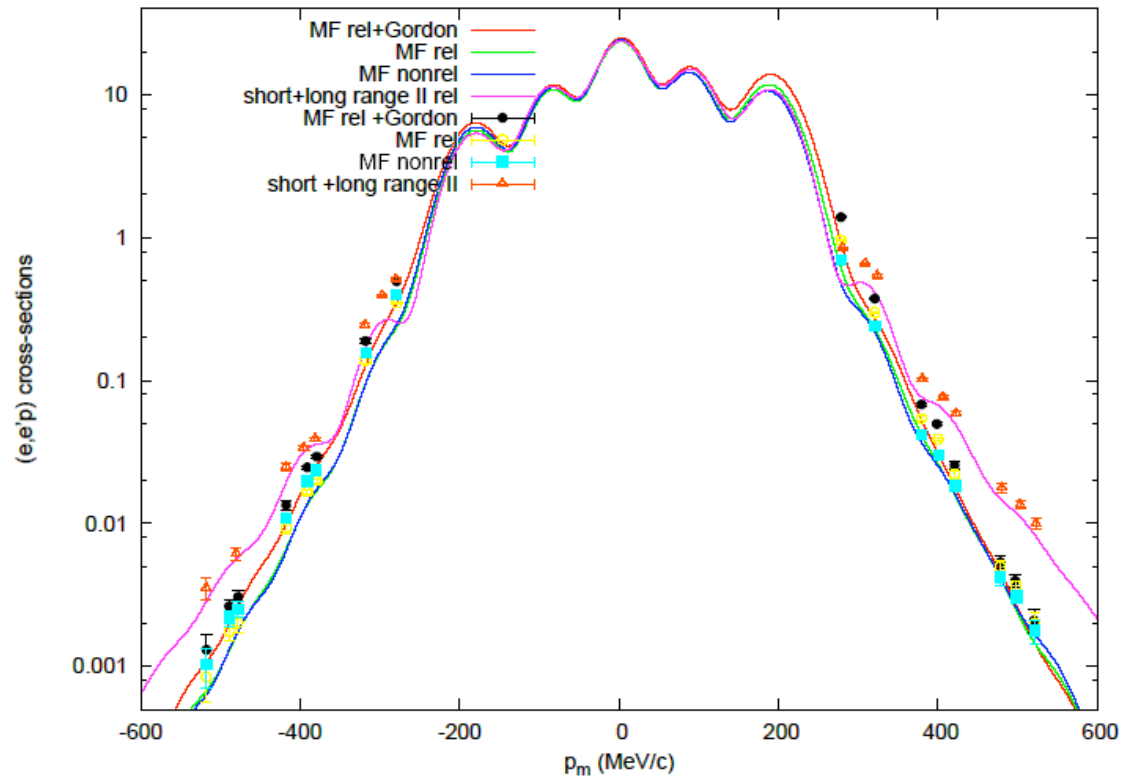
Talk by J. M. Udias

Spectroscopic factors up to $Q^2=2.0$
 Relativistic description of IPM
 Enhancement due to LRC at $|p_m| \geq k_F$



low lying states in ^{207}Tl

g.s.	$3s_{1/2}$
0.351	$2d_{3/2}$
1.348	$1h_{11/2}$
1.683	$2d_{5/2}$
3.470	$1g_{7/2}$



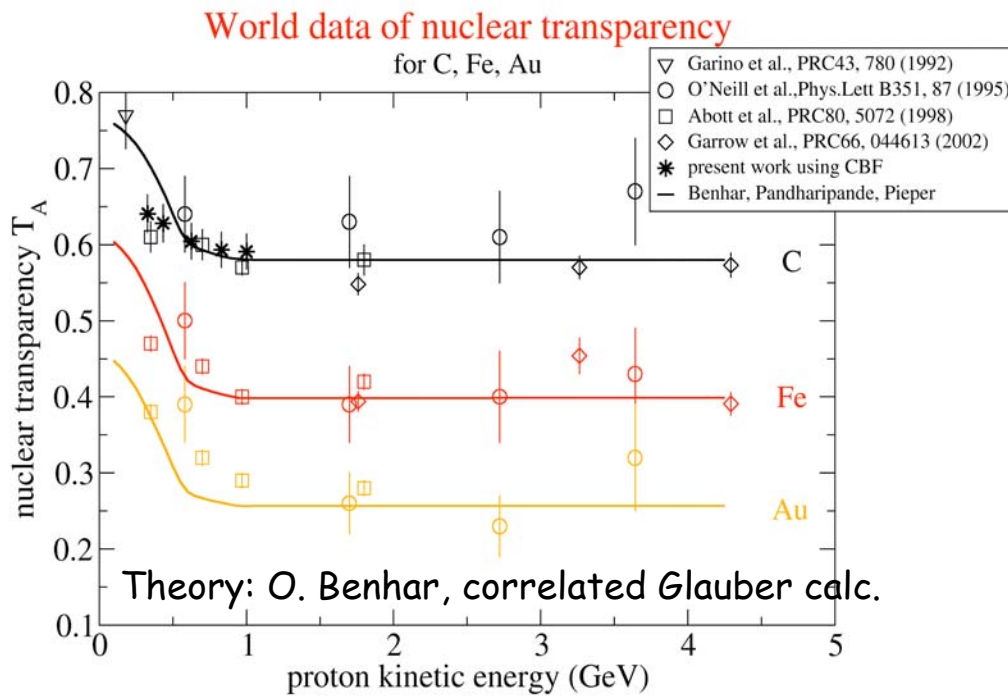
Another Approach to Correlations

Daniela Rohe, nucl-ex/0601003

$$\frac{d\sigma}{d\Omega_e d\Omega_p dE'_e dE'_p} = K \sigma_{ep} S(E_m, p_m) T_A$$

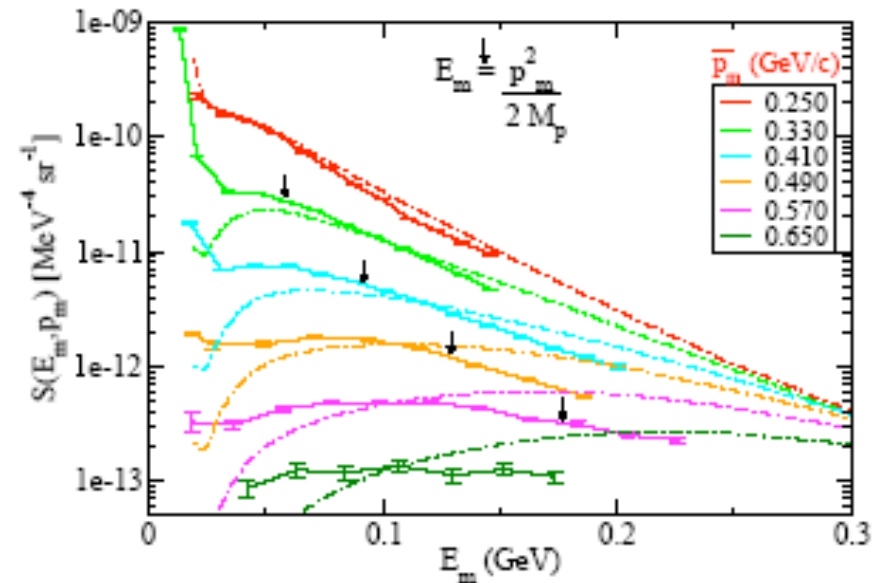
$$T_A(Q^2) = \frac{\int_V d\mathbf{p}_m dE_m N^{exp}(E_m, \mathbf{p}_m)}{\int_V d\mathbf{p}_m dE_m N^{sim}(E_m, \mathbf{p}_m)}$$

Everything done in || kinematics
- reduce FSI $\vec{q} \geq 1 \text{ GeV}/c$; $x_B \leq 1$



Measure in IPM region

In correlated region,
extract E_m spectra for
different p_m



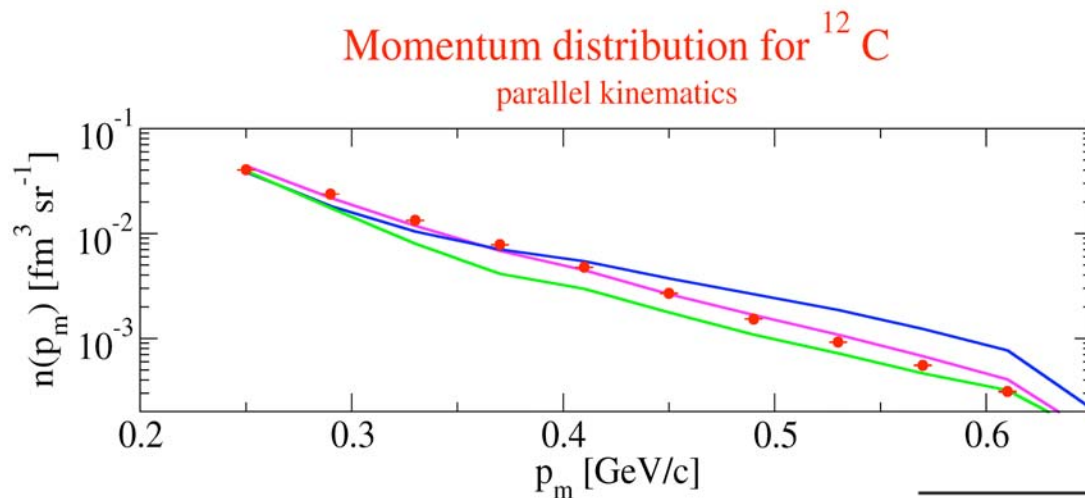
Correlated Strength

$$n_{\text{exp}}(p_m) = \int_{40\text{MeV}}^{<\Delta(p_m)} dE_m S(E_m, p_m)$$

Integrate spectral function over E_m, p_m

Measured correlated strength in terms of the **number of protons**

~ 10% of protons are correlated



CBF theory
 Greens function approach
 selfconsistent, finite temperature G.F.
 data

Experiment	0.61 ± 0.06
Greens function theory [3]	0.46
CBF theory [2]	0.64
SCGF theory [4]	0.61

Thanks to Daniela Rohe

A New Measurement

$^{12}\text{C}(e,e'p)^{11}\text{B}$ gs

Data: Preliminary
P. Monaghan
MIT thesis 2008

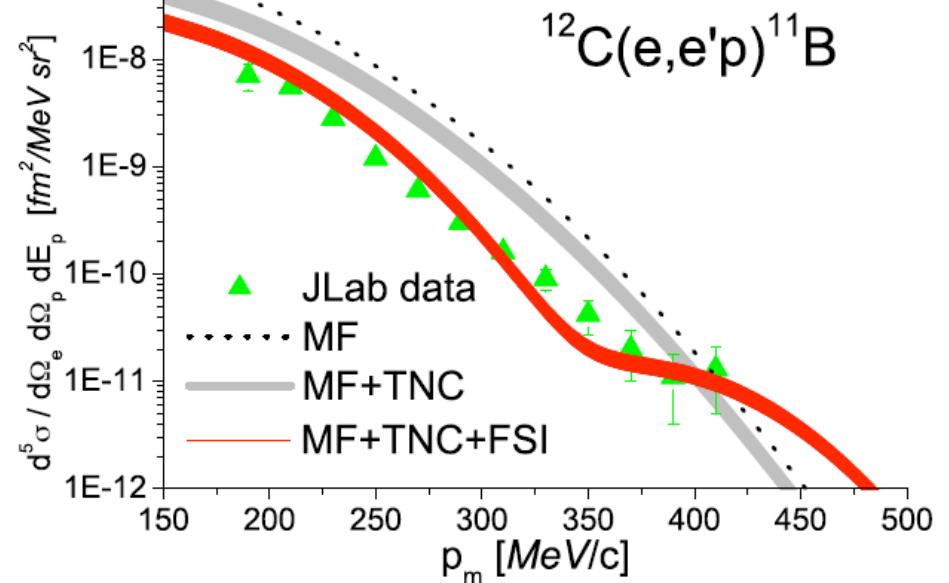
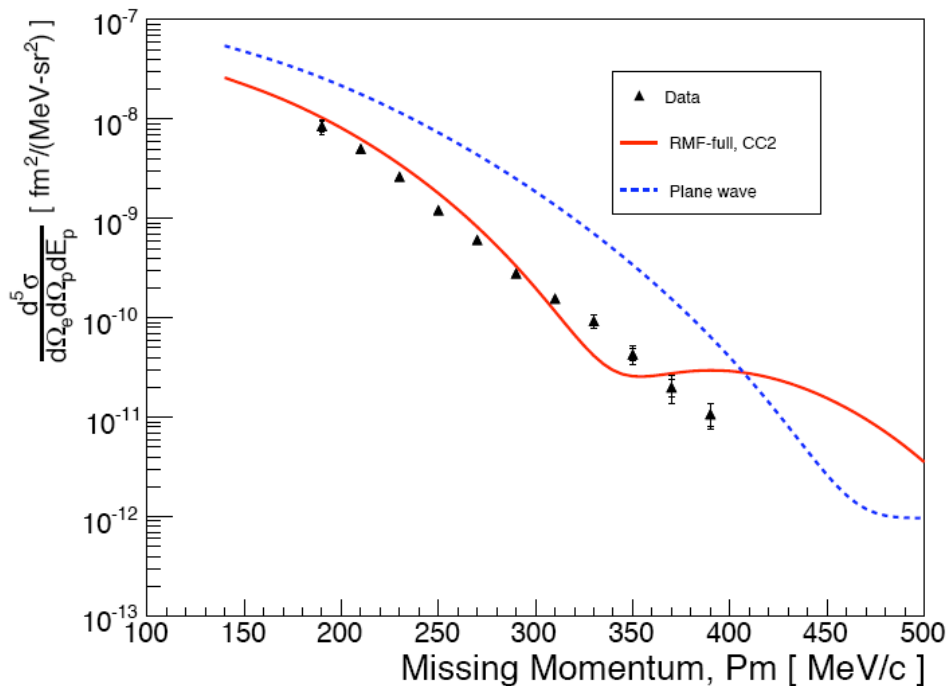
Calculations: J.M Udias

$Q^2 \approx 2 \text{ (GeV/c)}^2$

$x_B \approx 1.2$

"semi anti-parallel" kinematics

Calculations: C. Ciofi degli Atti et al.



$^{12}\text{C}(e,e'p)$ to Continuum

$$Q^2 \approx 2 (\text{GeV}/c)^2$$

$$x_B \approx 1.2$$

P. Monaghan
Ph.D. thesis MIT 2008

E_m for slices of p_m

$$E_m = \sqrt{\left(M_{A-2} + \sqrt{M_N^2 + p_r^2}\right)^2 - p_r^2} + M_p - M_A$$

$$P_r = 0.8 p_m$$

$$P_r = 0.8 p_m \text{ and } A-2=(A-2)+25 \text{ MeV}$$

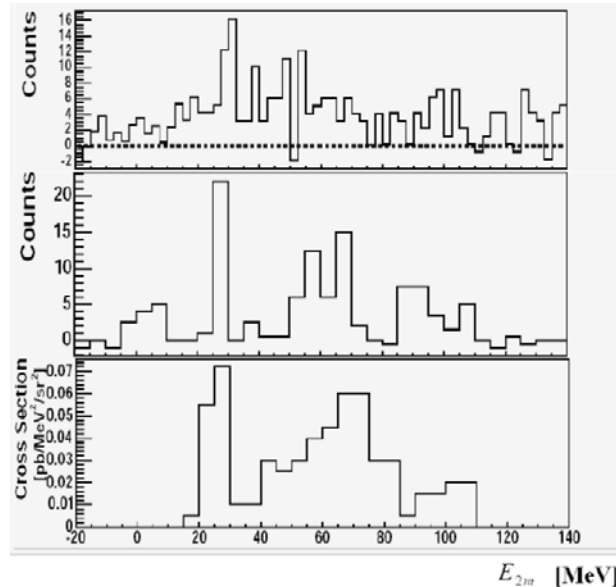


$^{12}\text{C}(e,e'pp)$
R. Shneur
Ph.D. thesis TAU 2007

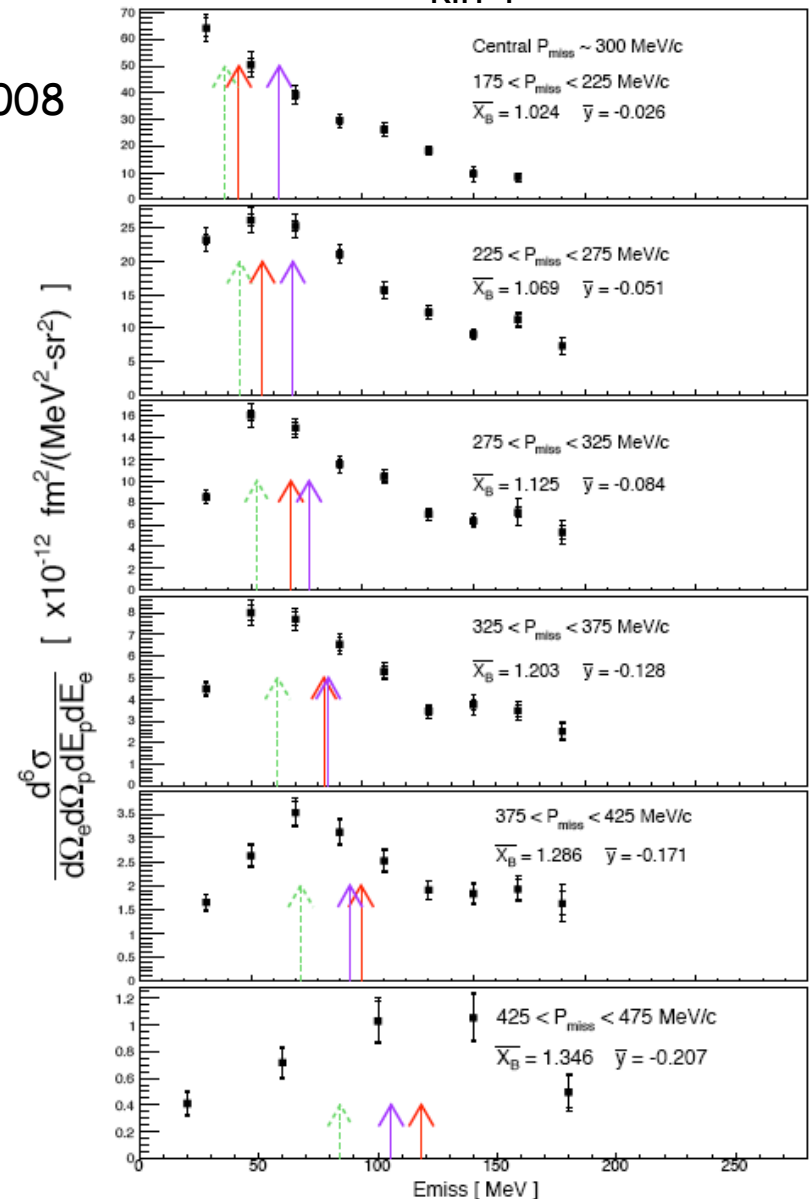
$^{12}\text{C}(e,e'pp)$
Kester et al.
PRL **74**, 1712 (1995)

$^{12}\text{C}(e,e'd)$ $x_B = 2$
S. Penn
Ph.D. thesis MIT 1985

ICTP08, Trieste, Italy

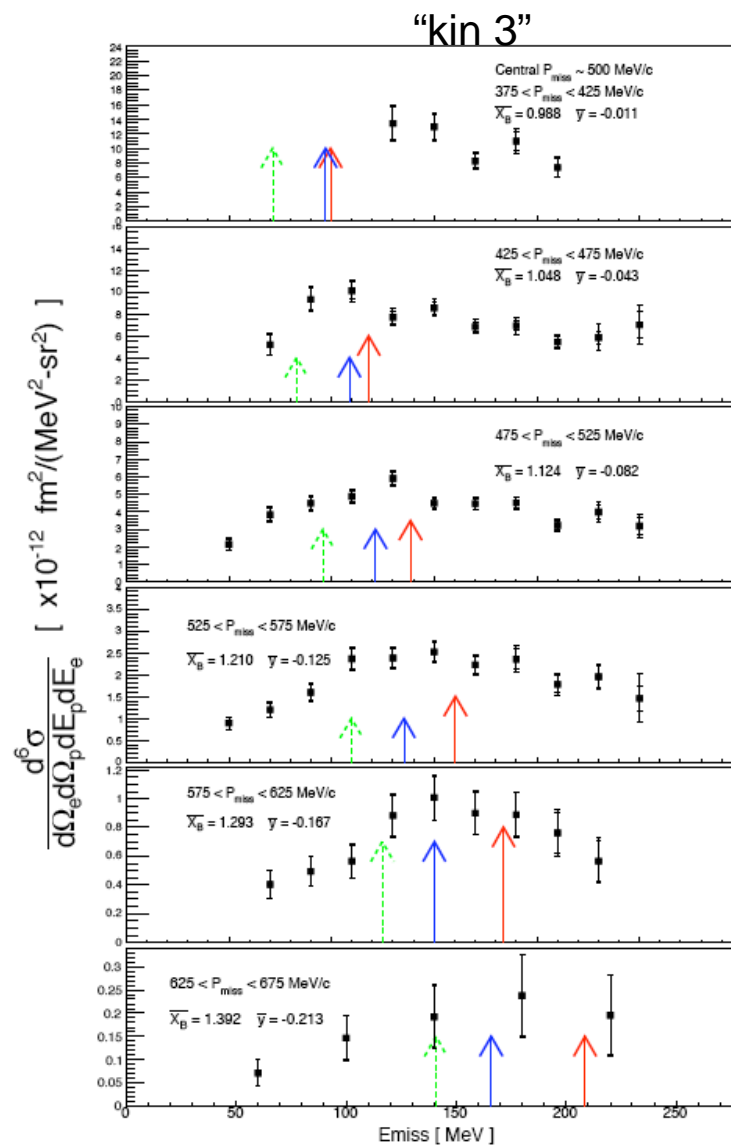
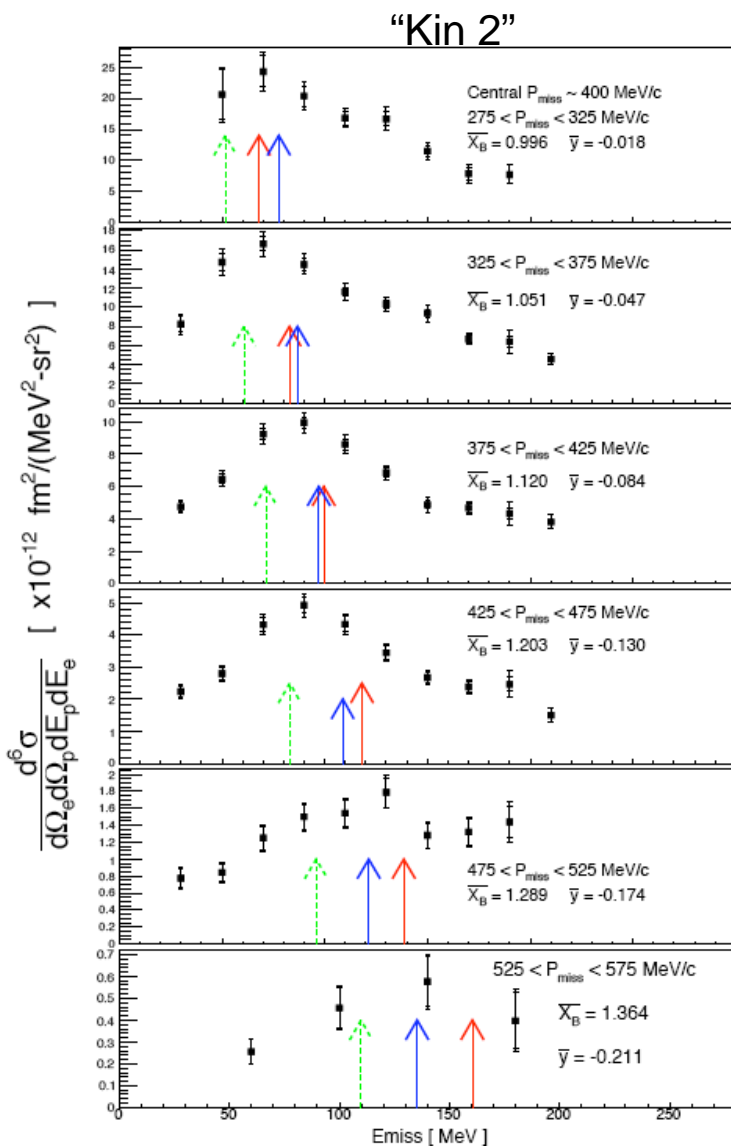


“kin 1”



Shalev Gilad, MIT

Additional $E_m(p_m)$



Note: $x_B(\text{kin 1}) > x_B(\text{kin 2}) > x_B(\text{kin 3})$ for same p_m

"Reduced x-sections"

Remember

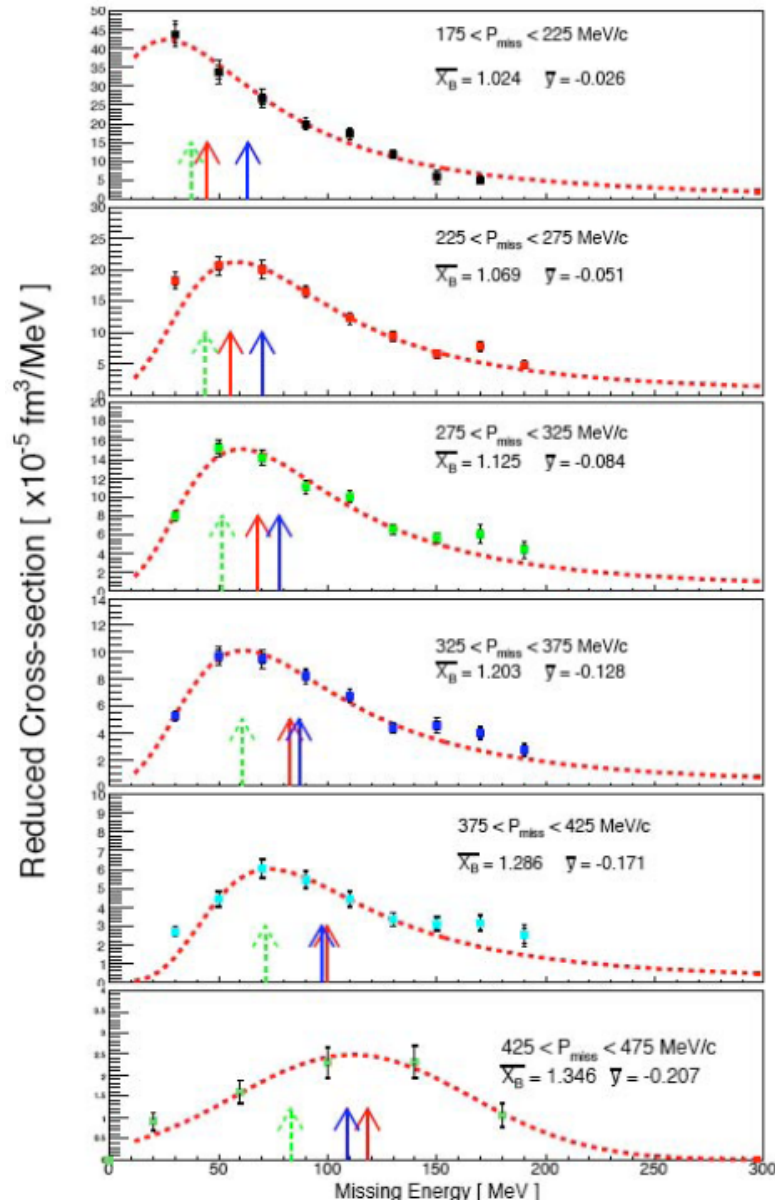
$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \sigma_{ep} S^D(p_m, \epsilon_m, p)$$

"Distorted" spectral function

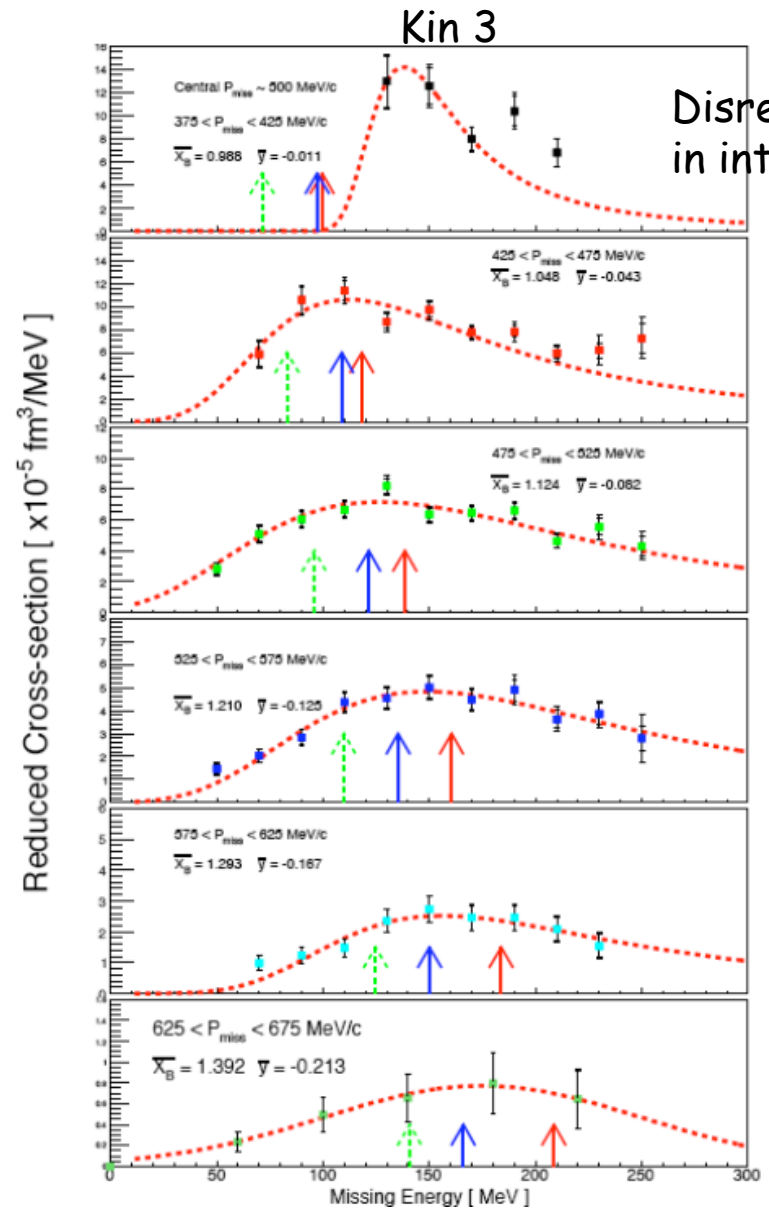
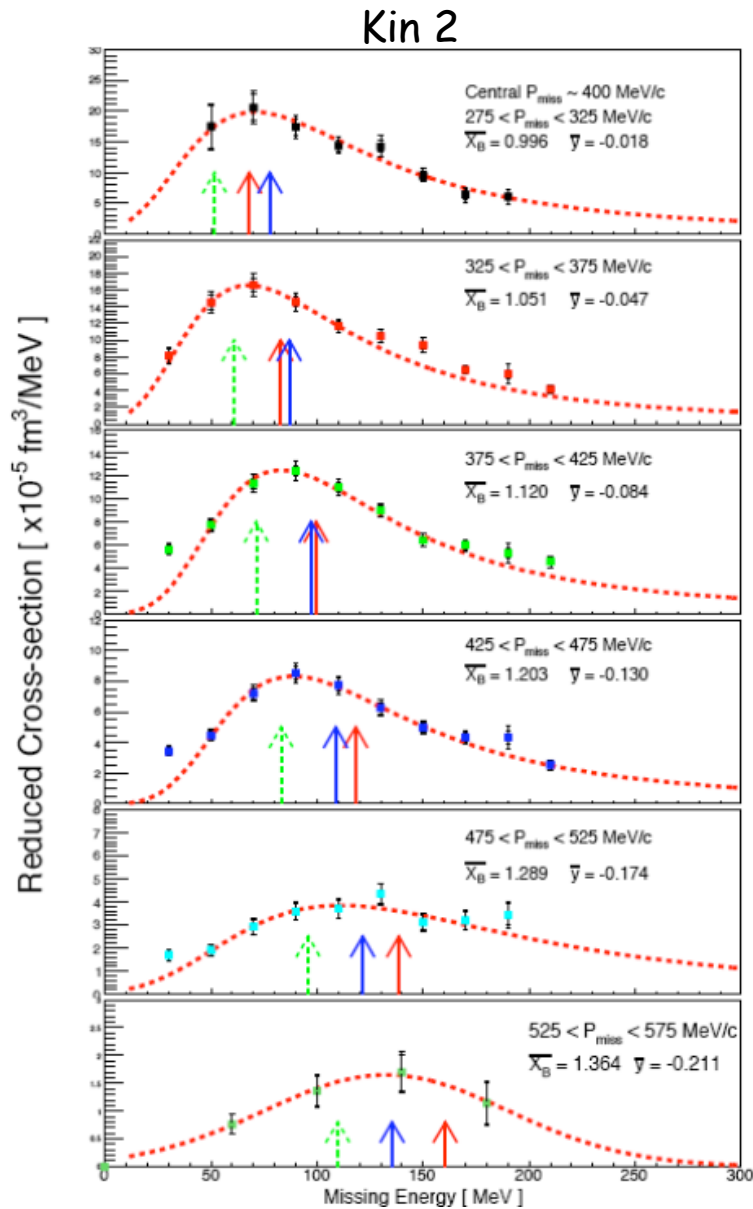
Reduces x-sections \equiv
"Distorted" spectral function

Take out σ_{ep} (=CC2) and
electron kinematics out
of x-sections

Fits to Landau distributions
to eliminate remains of π -
production events



More Reduced x-sections



Disregard
in integral

Compare Reduced x-sections

Remember again:

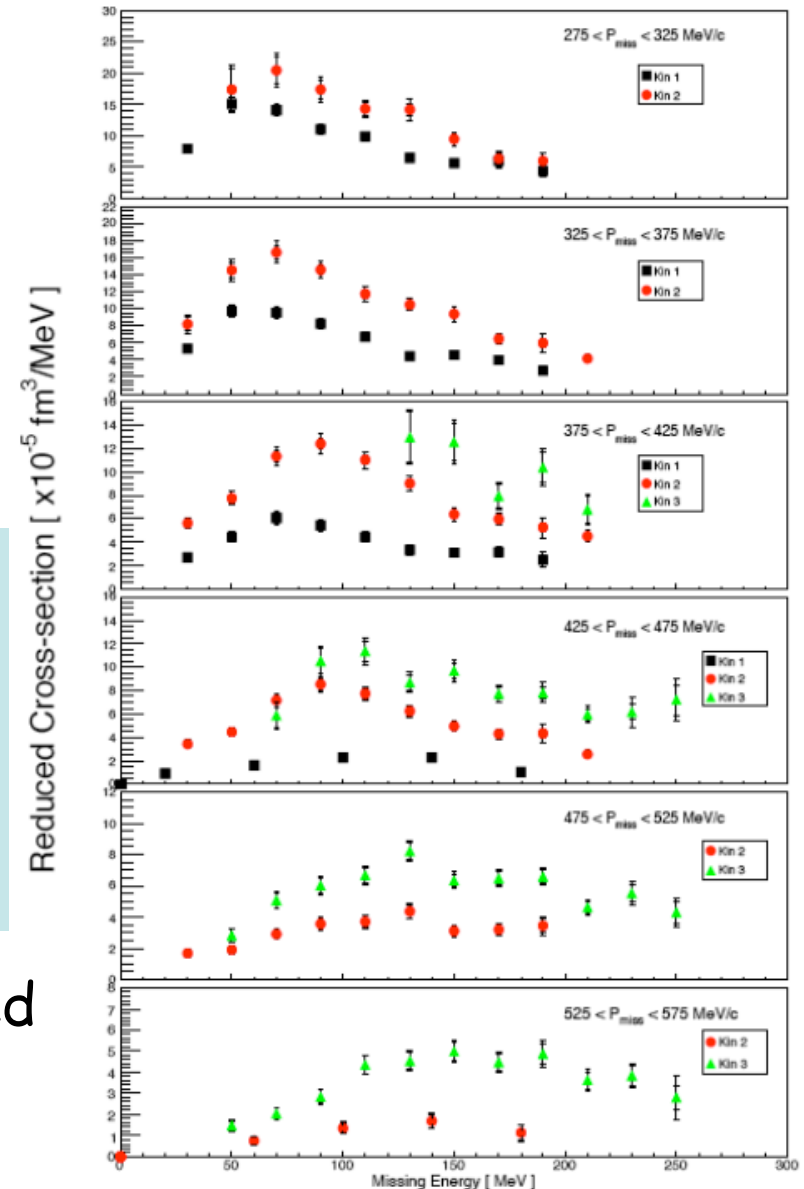
Reduces x-sections \equiv
 "Distorted" spectral function

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

"Distorted" spectral function

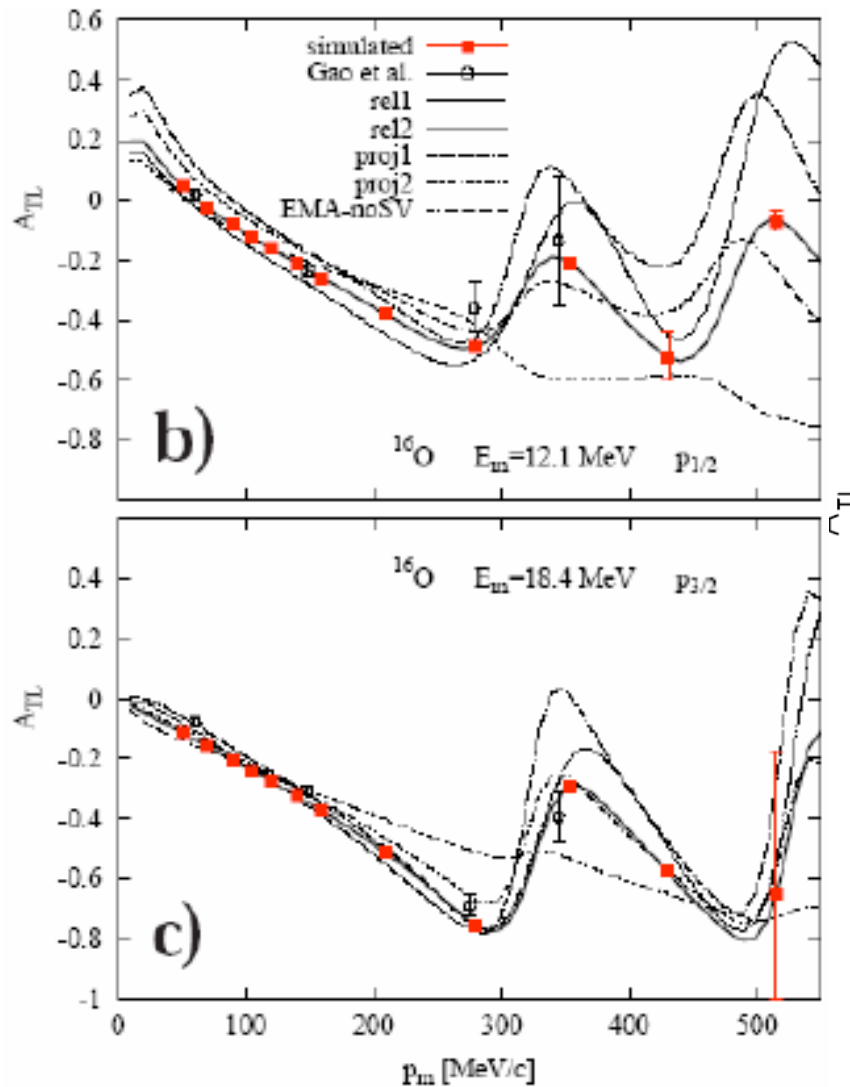
Factorization is badly broken!
 Or
 Poor knowledge of σ_{ep} at $x_B > 1$
 Or
 Both

- can we do $A(e,e'p)$ un-factorized calculations to continuum?
- How to test σ_{ep} for $x_B > 1$

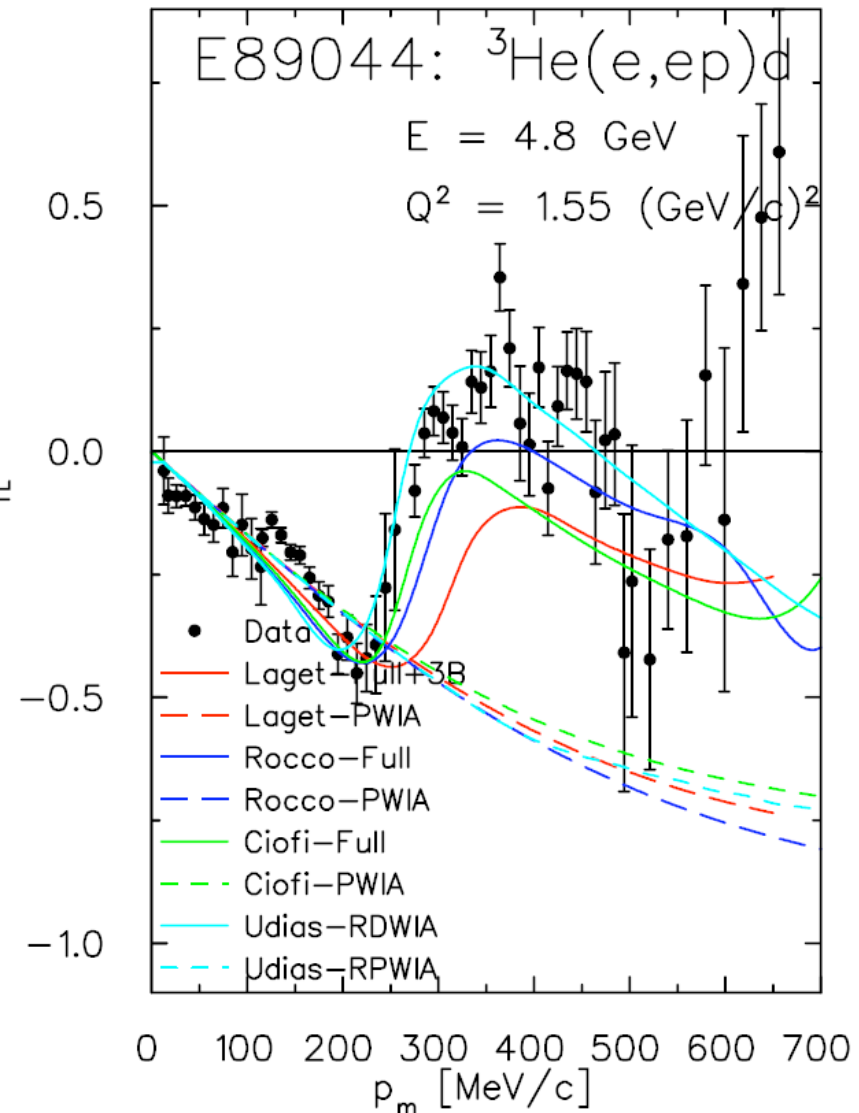


Broken Factorization

$^{16}\text{O}(e,e'p)^{15}\text{N}$ - rel. dynamics

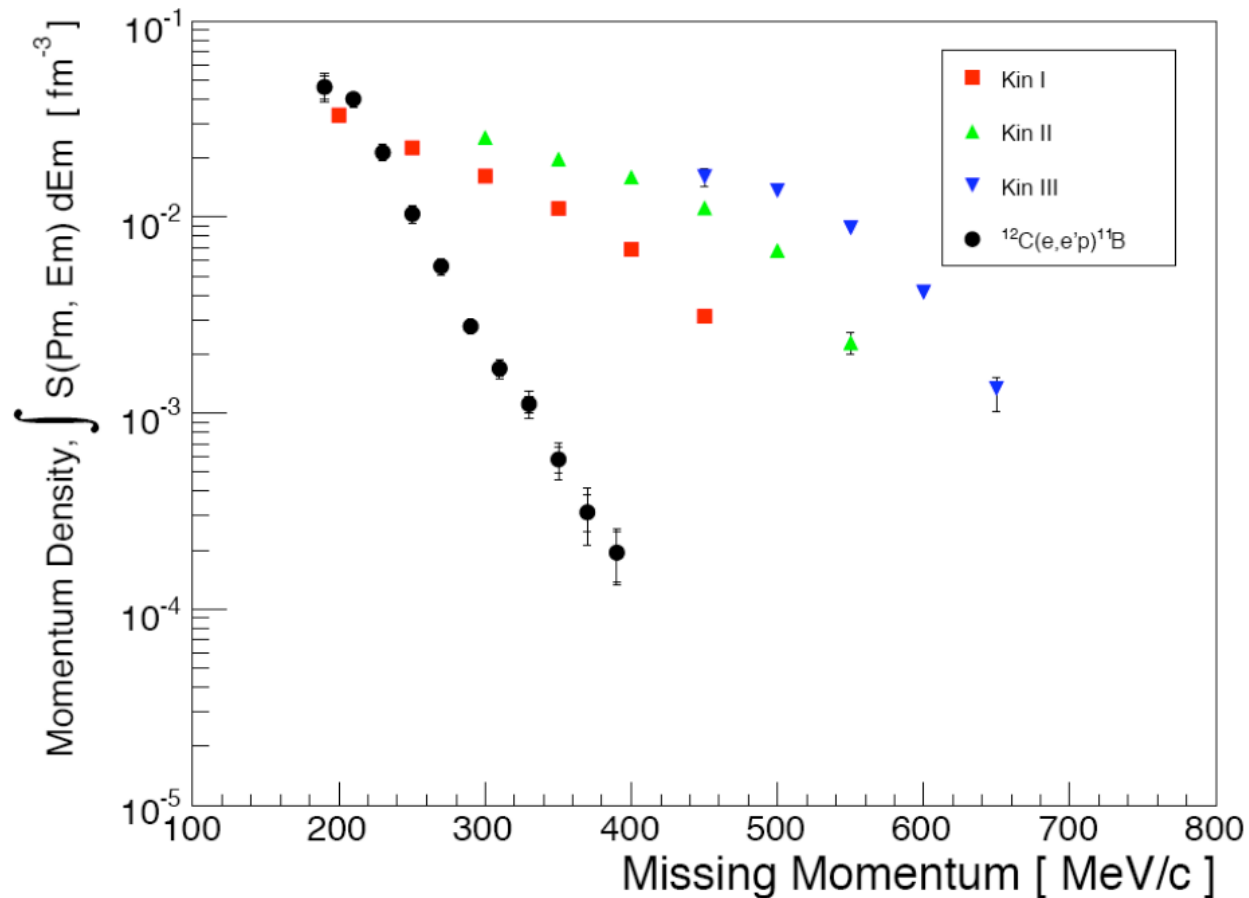


$^3\text{He}(e,e'p)^2\text{H}$ - FSI



"Distorted Spectral Function"

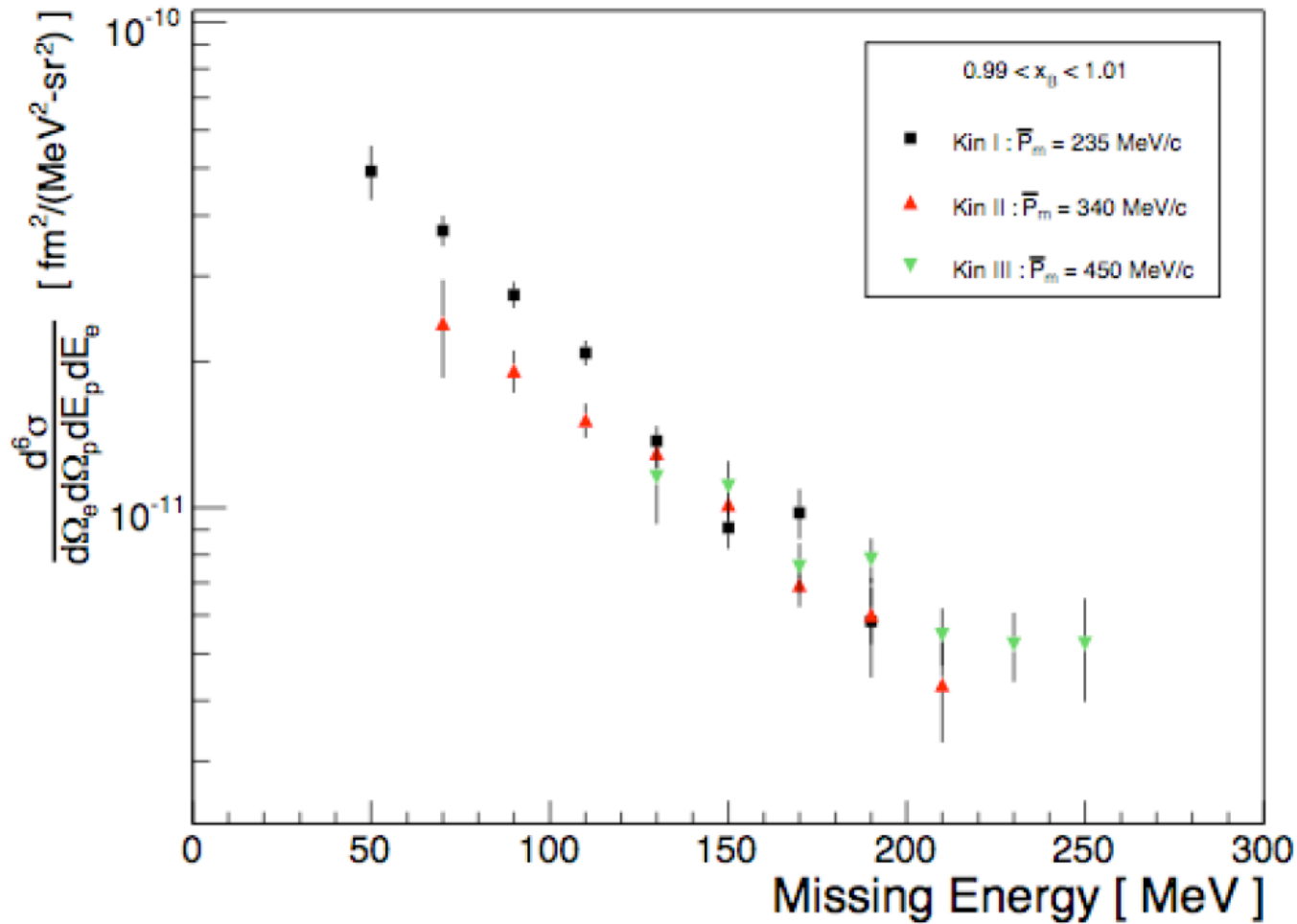
Integrate fitted curves to get "distorted momentum density"



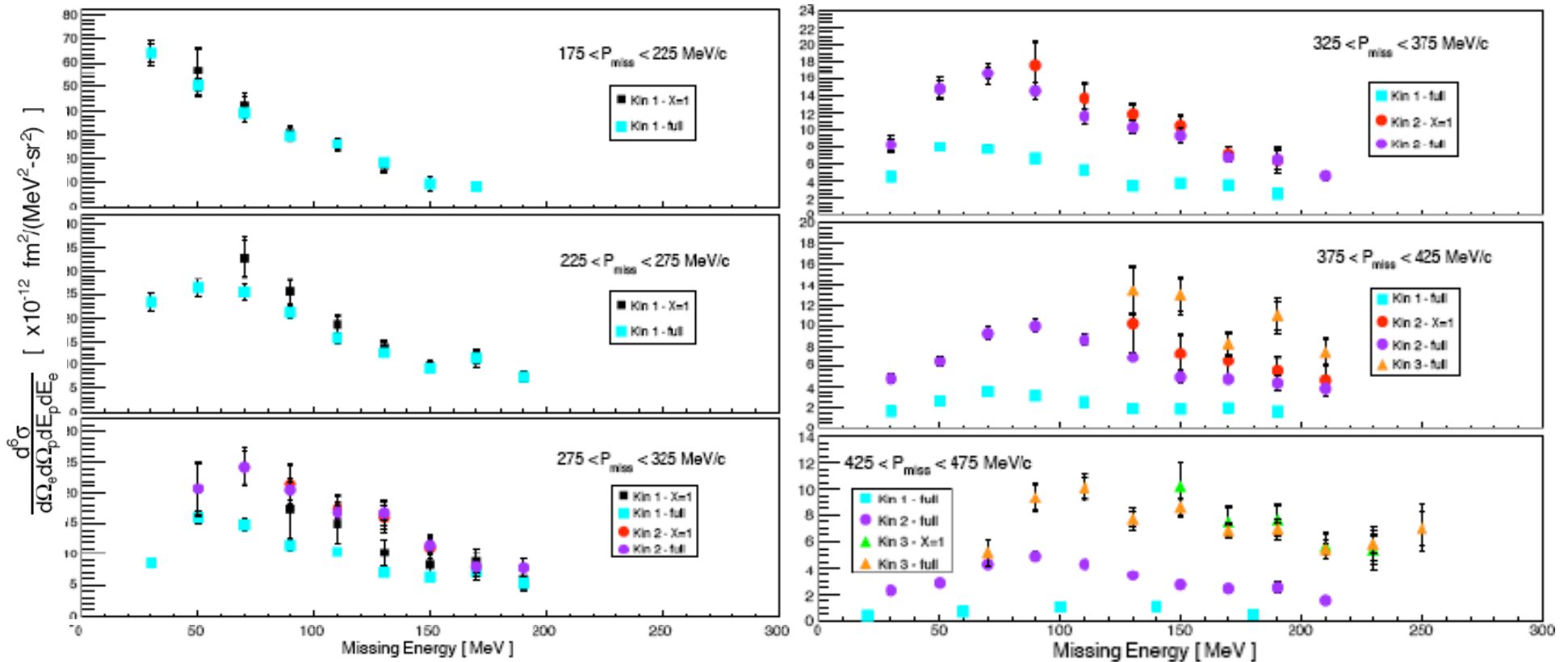
"distorted spectral function is not very meaningful!!"

$^{12}\text{C}(e,e'p)$ to continuum at $x_B = 1$

This means \perp kinematics!



$x_B=1$ vs. $x_B > 1$ x-sections



Better agreement at lower p_m
 Better agreement at Lower x_B
 Do we have proper understanding of the off-shell σ_{ep} at $x_B > 1$???!

Ghost from the Past

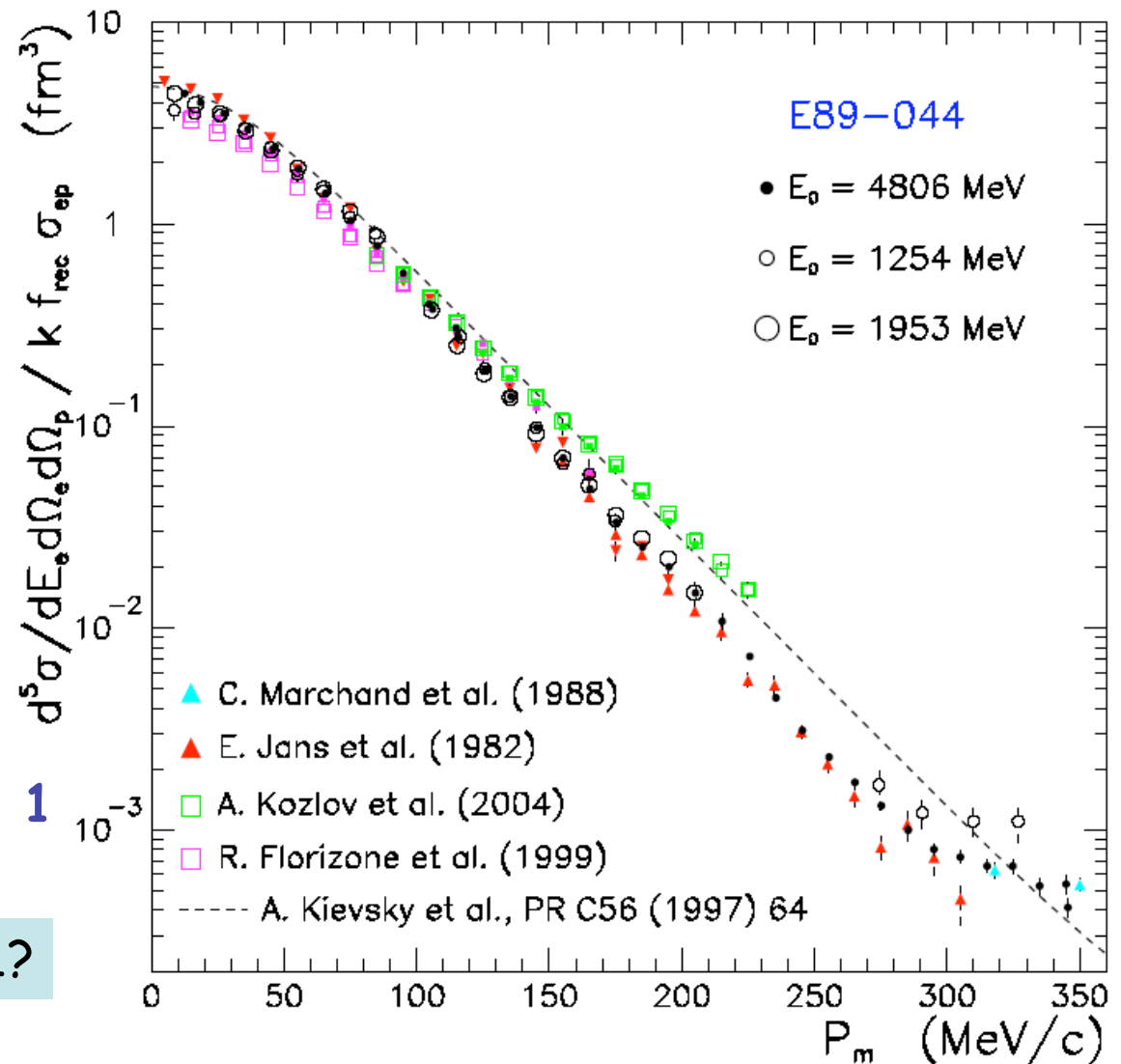
${}^3\text{He}(e,e'p){}^2\text{H}$

Different laboratories
 Different times
 $Q^2 \approx 0.2 - 1.5 \text{ (GeV/c)}^2$
 || and \perp kinematics
 All for $x_B = 1$

Except!!!!

Kozlov: || kinematics; $x_B > 1$

A problem with σ_{ep} at $x_B > 1$?



Summary

- New data for $^{12}\text{C}(e,e'p)$ at kinematics favorable to correlations
 - High p_m
 - High Q^2
 - $x_B > 1$
 - "semi anti-parallel"
- $^{12}\text{C}(e,e'p)^{11}\text{B}$ gs
 - x-sections as a function of p_m
 - "effective momentum distribution"
- $^{12}\text{C}(e,e'p)$ to continuum
 - E_m spectra for different p_m slices
 - re-define relationship between E_m and p_m to take into account recoil and excitation of A-2
 - Reduced x-sections of $E_m(p_m)$

Summary (cont.)

- Extracted “distorted spectral function” is not very meaningful
- Compared data at $x_B = 1$ to $x_B > 1$
 - Better agreement at lower p_m and lower x_B
- Challenges to theorists
 - Do we understand Ω_{ep} at $x_B > 1$?
 - Need un-factorized $A(e, e' p)$ calculations for understanding