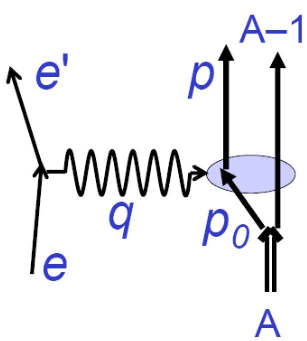
Recent Studies of Correlations in Nuclei using (e,e'p) Reactions

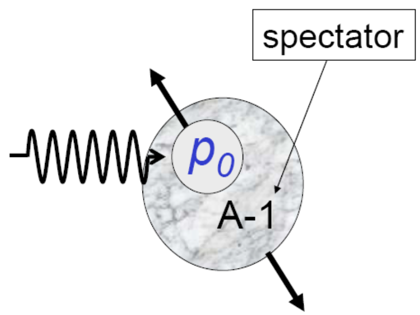
- The A(e,e'p) reactions
- "Our" definition of correlations
- Favorable kinematics for studying correlations
- Recent experimental results
- Limitations of reaction
  - Experimental
  - Theoretical
- Status of the field - other reactions
- Outlook

Shalev Gilad, MIT

Why A(e,e'p)?

Attractiveness of (e,e'p)





$q - p = p_{A-1} = p_m = - p_0$

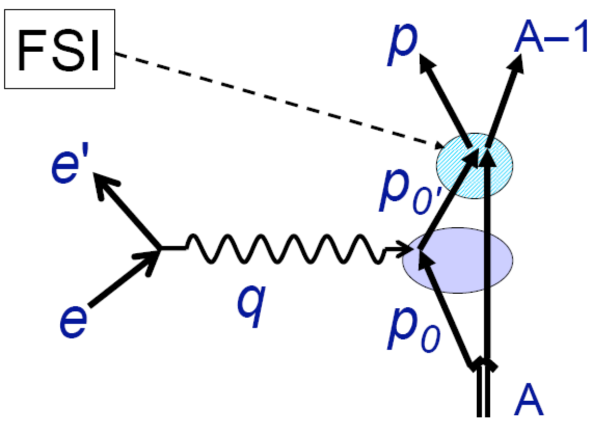
In nonrelativistic PWIA:

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

e-p cross section

nuclear spectral function

Not an observable!!

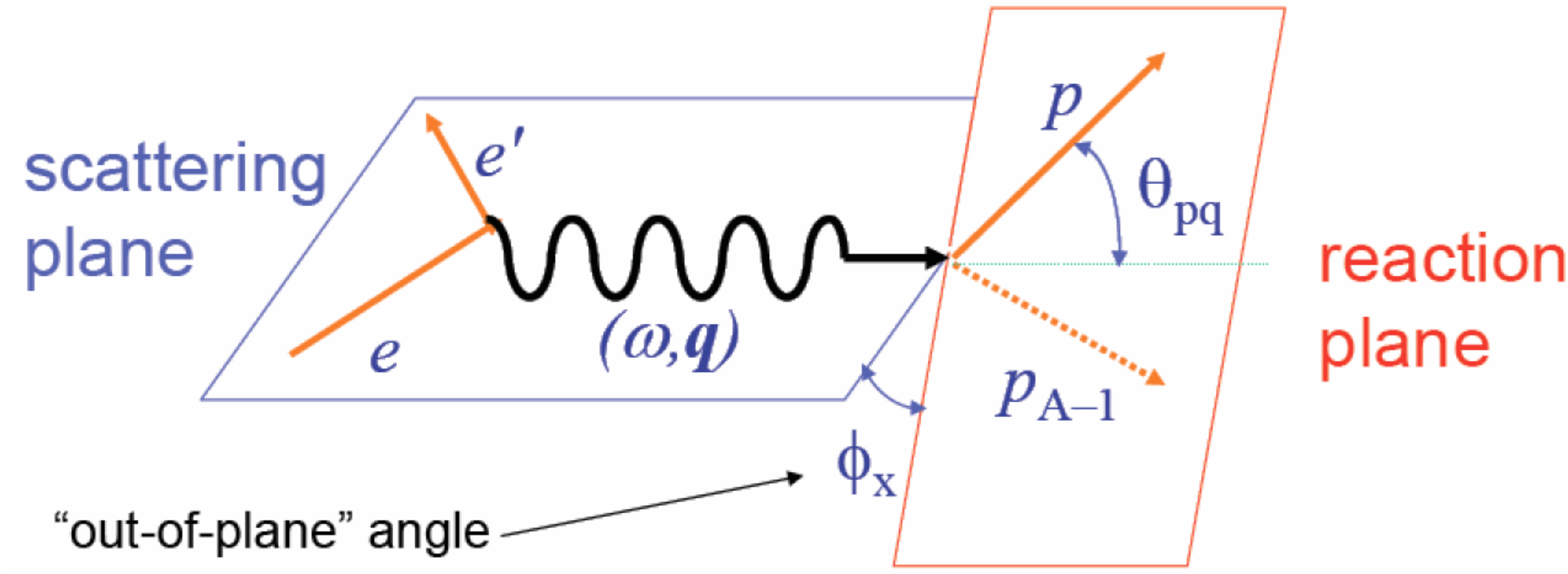


$$\vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0$$

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

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

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

Favorable Kinematics

High p_m

probe small inter-nucleon distances

High Q^2

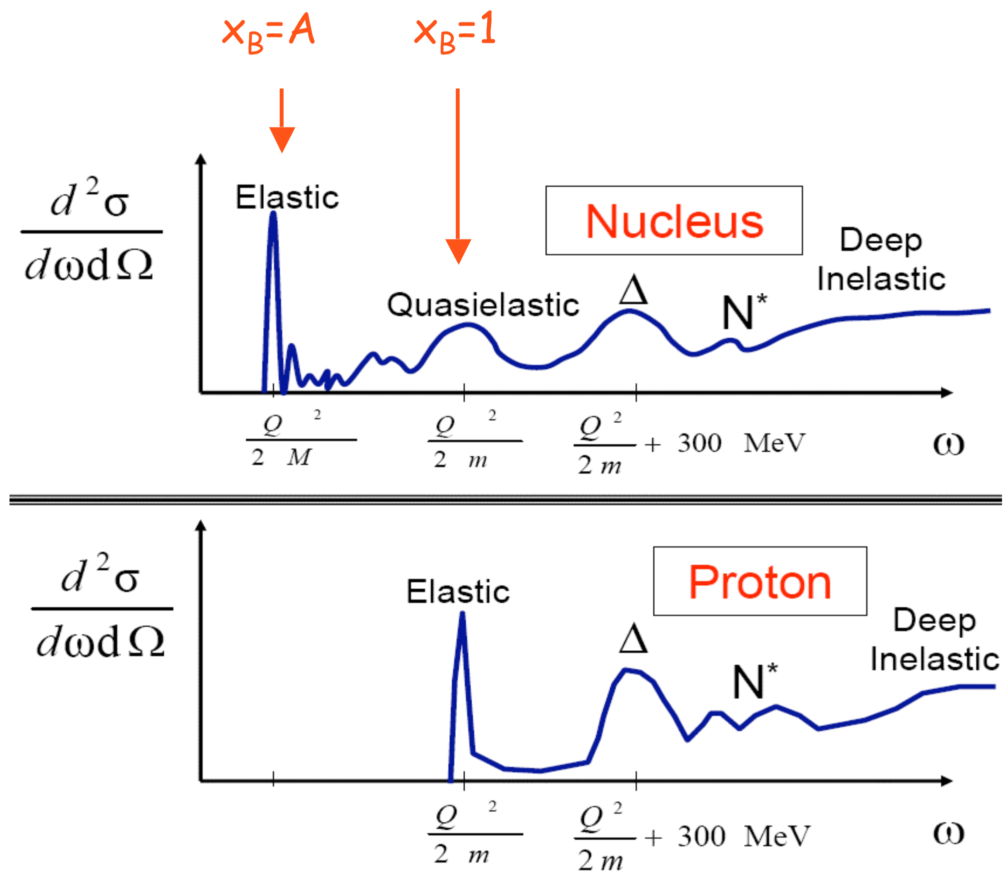
probe small distances
less ambiguity about struck nucleon
can handle FSI using GA or GEA

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

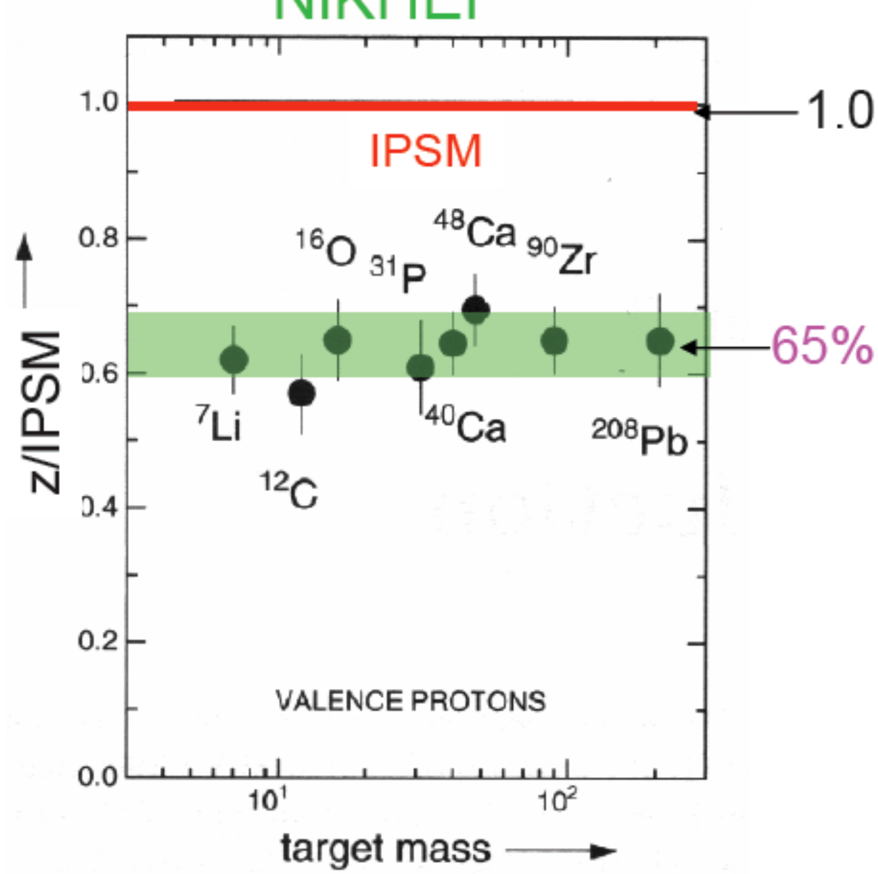
$$Z_{IPSM} = 2j + 1$$

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

single particle state α

- Moderate Q2
- Mainly "Perpendicular", QE kinematics
- Extract "distorted" momentum distributions for moderate pm
- 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

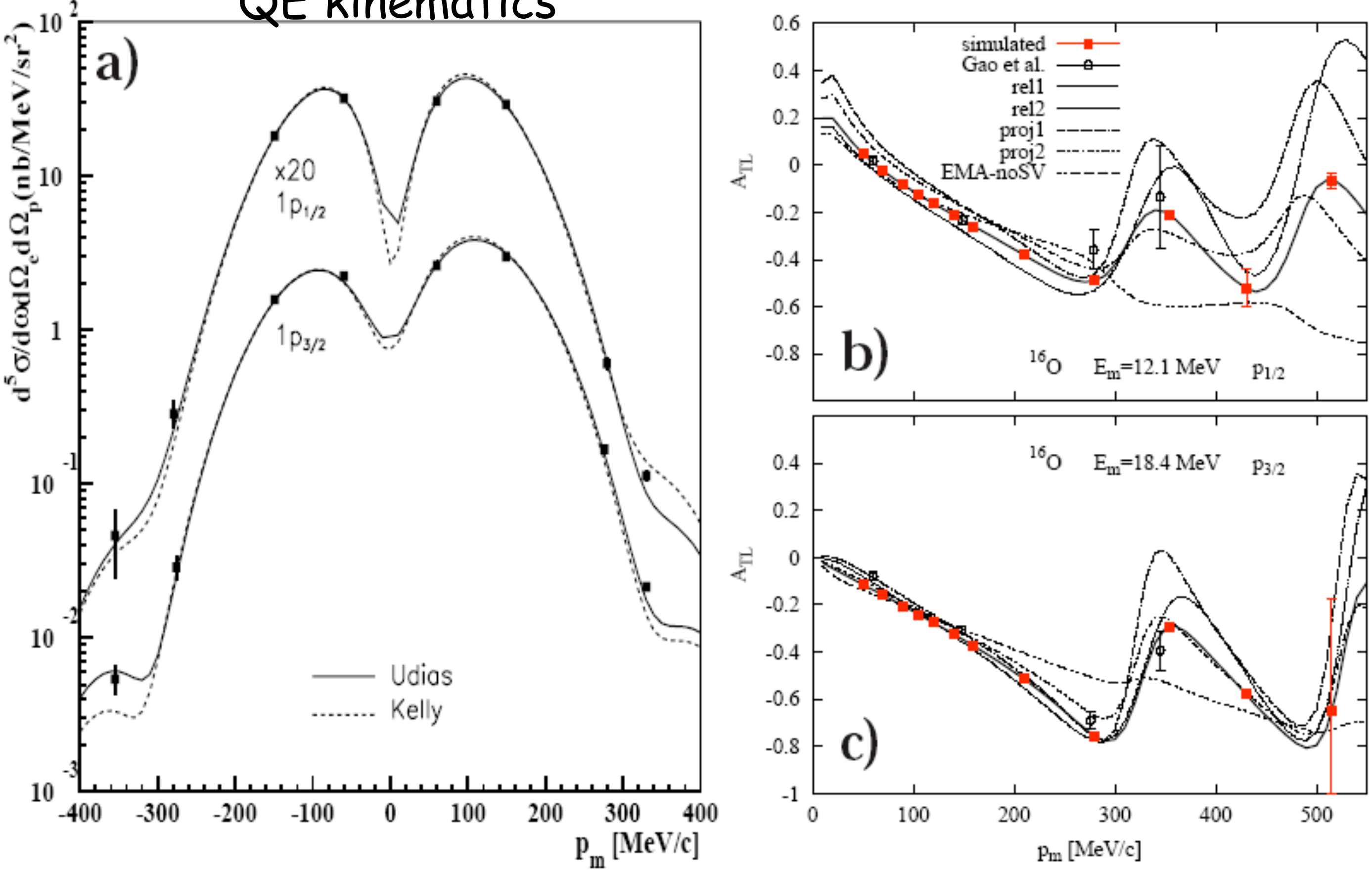
NIKHEF



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

New data to p_m < 750 MeV/c in analysis

QE kinematics



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, ⊥

Analysis:

-RDWIA (Udias *et al.*) un-factorized

-Fully relativistic kinematics and dynamics

-Enhancement of WF at high p_m

-Occupancy ≈ 0.7

OP ↔ GA, GEA

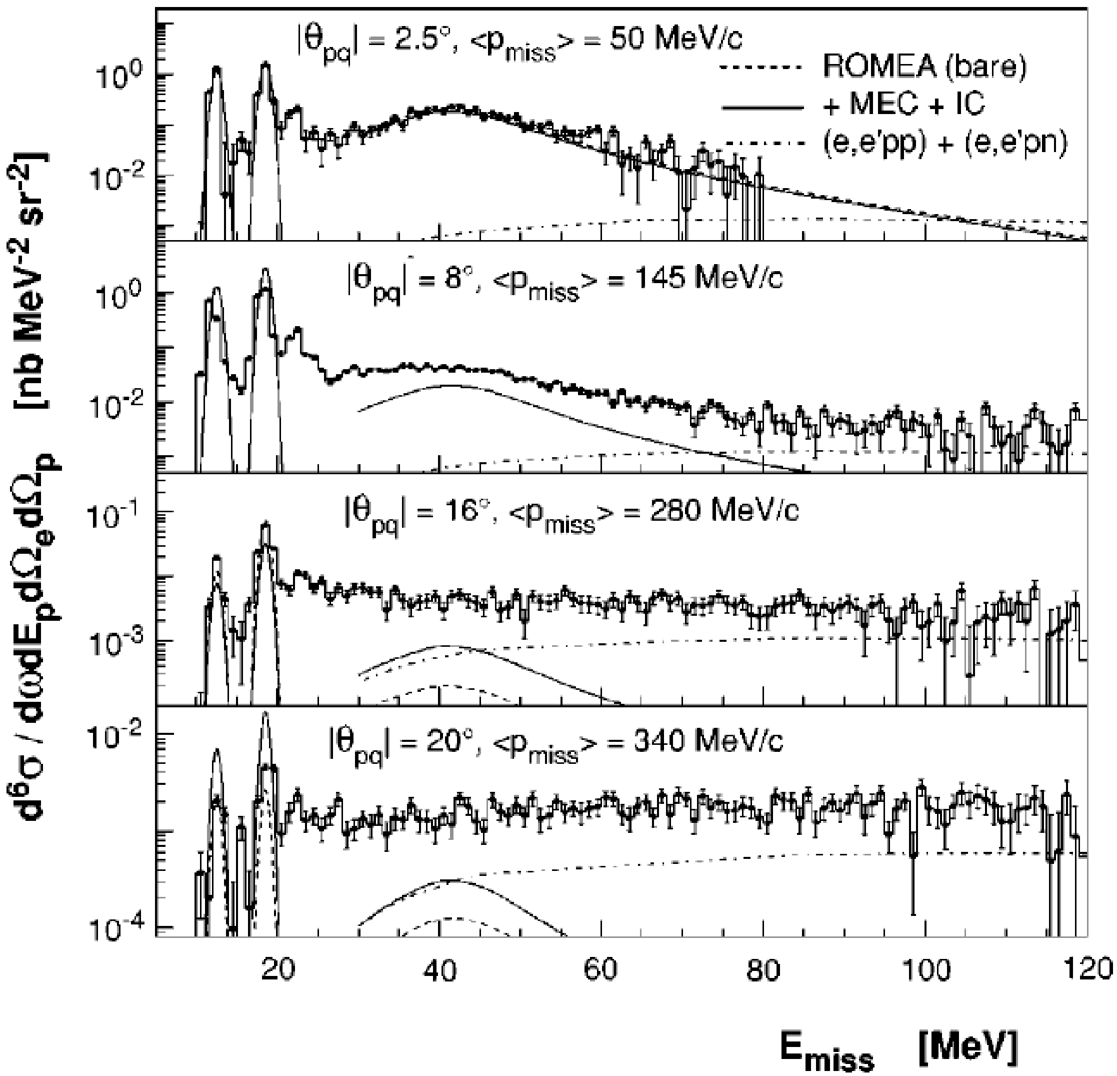
Including (e,e'pN) in Calculating (e,e'p)

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

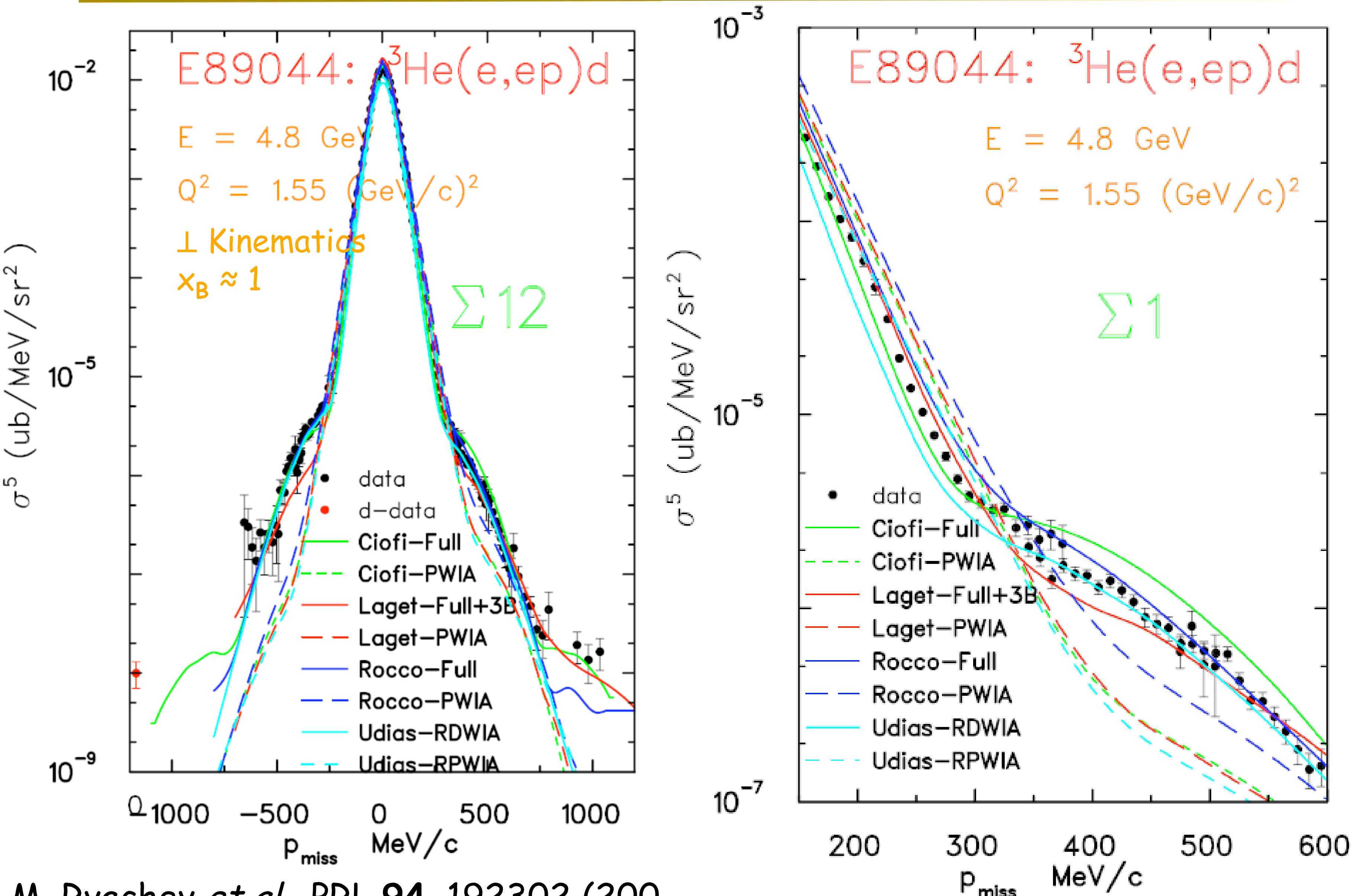
K. Fissum *et al.*, PRC **70**, 034606 (2004)

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

Calculations: J. Ryckebusch *et al.*



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



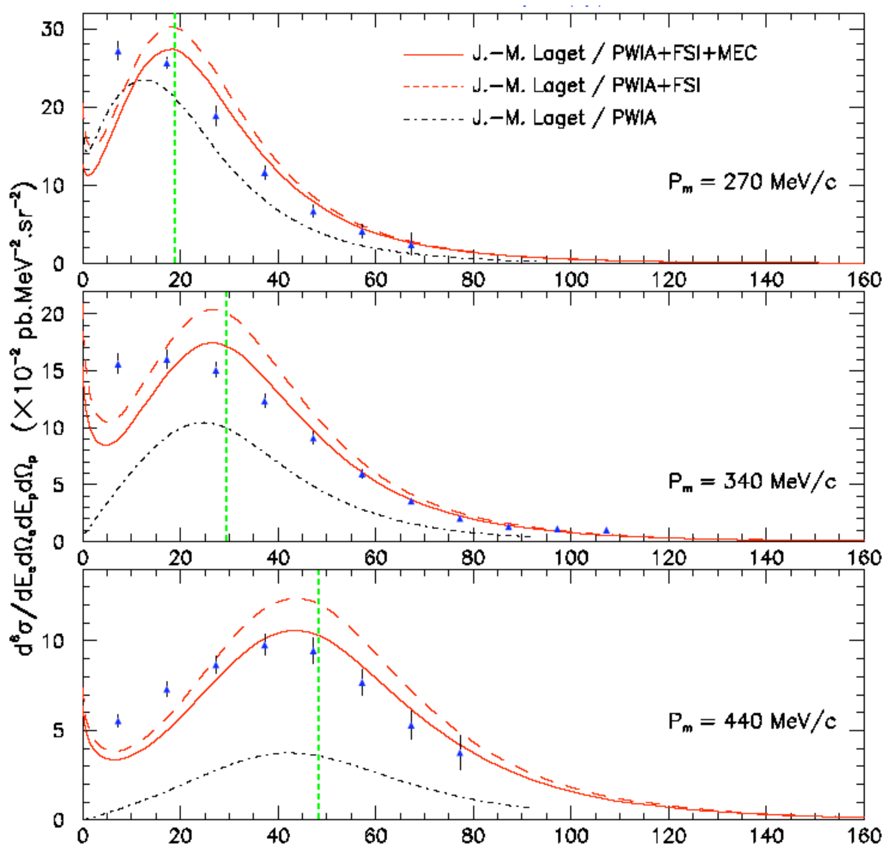
M. Rvachev *et al.*, PRL **94**, 192302 (200_)

^{3}He(e,e'p)pn – 3bbu – Correlations?

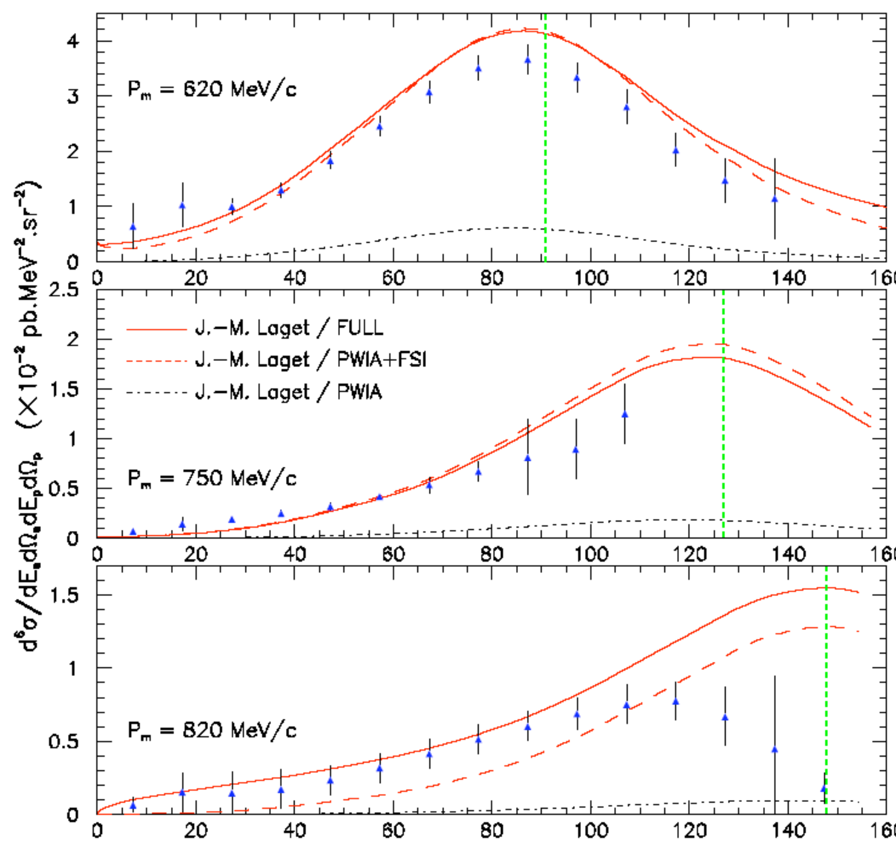
$$E_m = \sqrt{\left(M_{A-2}+\sqrt{M_N^2+p_r^2}\right)^2 - p_r^2} + M_p - M_A$$

Low p_m (still > k_f): correlations?

High p_m dominated by FSI



E_m - E_{th} (MeV)



E_m - E_{th} (MeV)

F. Benmokhtar *et al.*, PRL **94**, 082305 (2005)

Calc. J.M. Laget; similar by C. Ciofi degli Atti

2bbu, 3bbu "Distorted" Spectral Functions

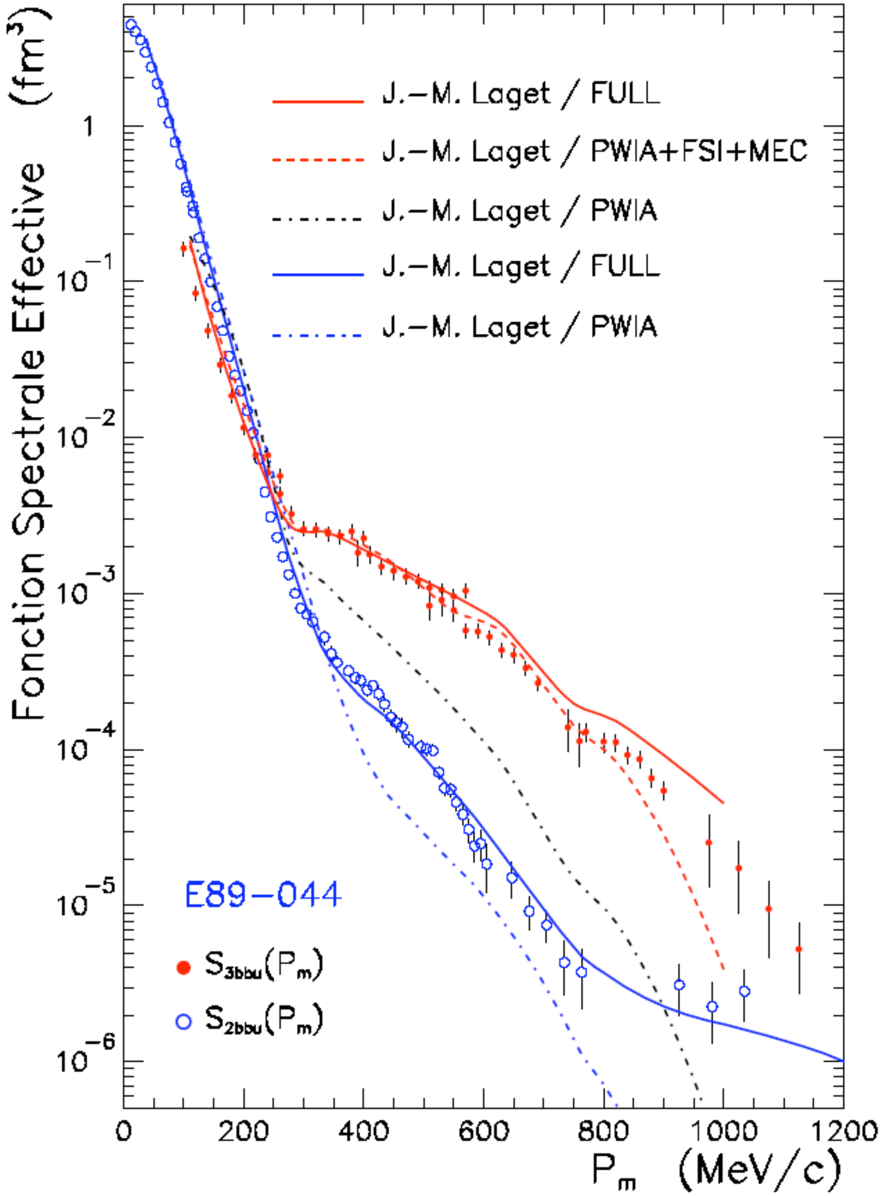
$$\eta(p_m) = \int \left(\frac{d^6\sigma}{dE_e dE_p d\Omega_e d\Omega_p} / K\sigma_{ep} \right) dE_m$$

High Q^2; $x_B \approx 1$
⇒ 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 (?)

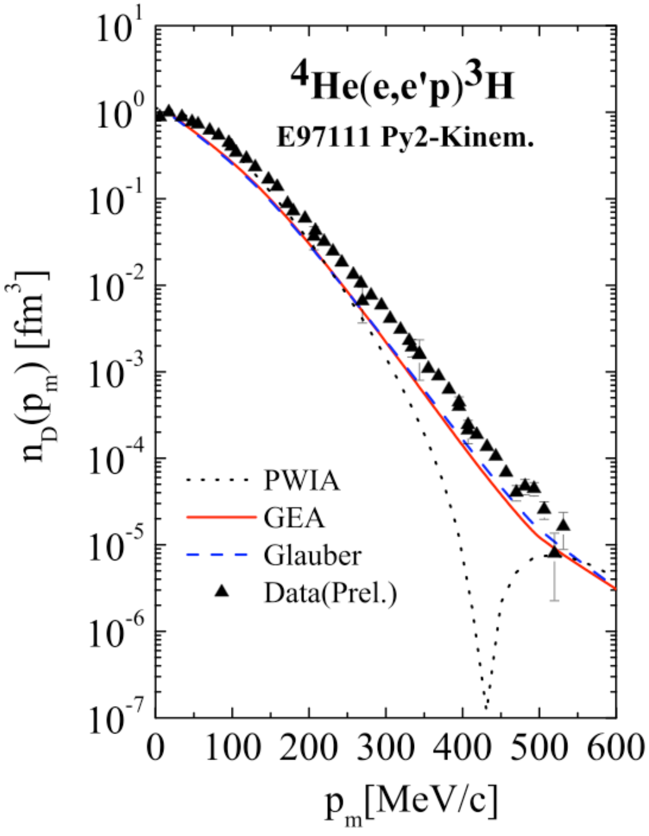


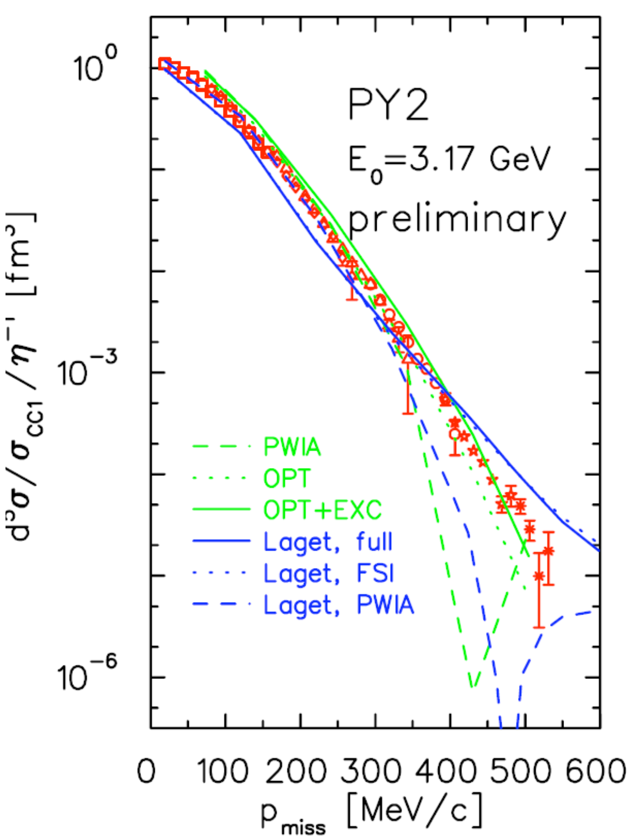
An Attempt to Observe SRC

Predict a minimum in spectral function
at pmiss ≈ 450 MeV/c

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

Calculations:
Schiavilla
Laget
Ciofi



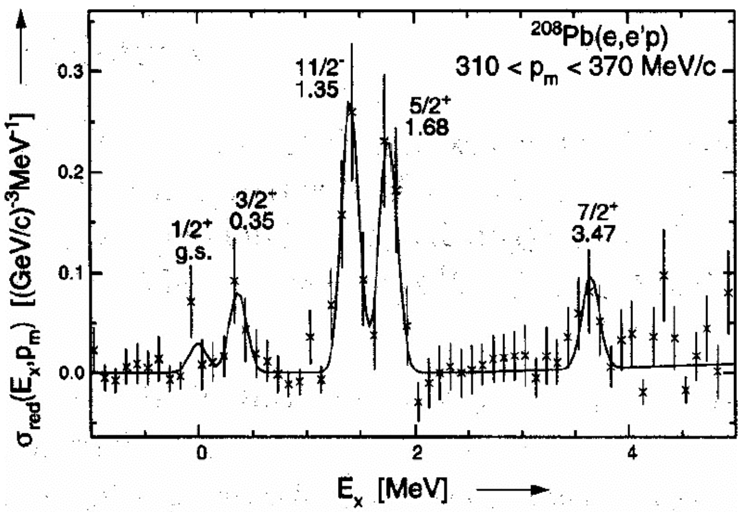


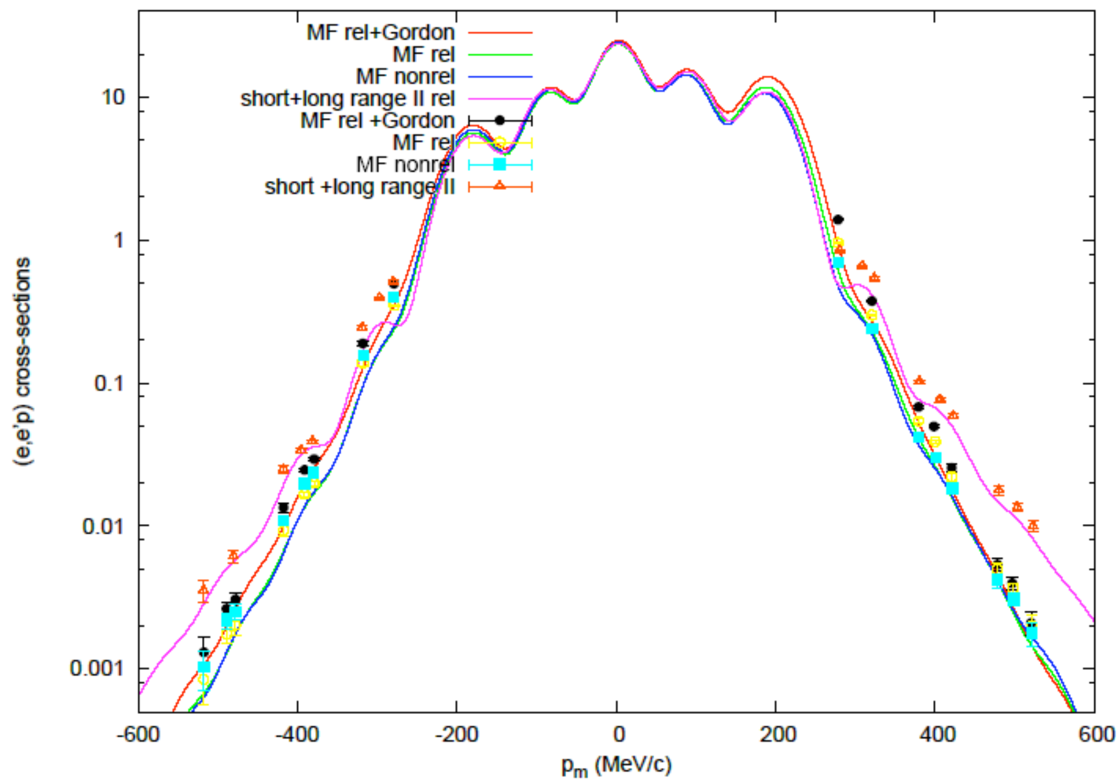
Very New Measurements

^{208}Pb(e,e'p)^{207}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 207Tl

g.s.	3s1/2
0.351	2d3/2
1.348	1h11/2
1.683	2d5/2
3.470	1g7/2

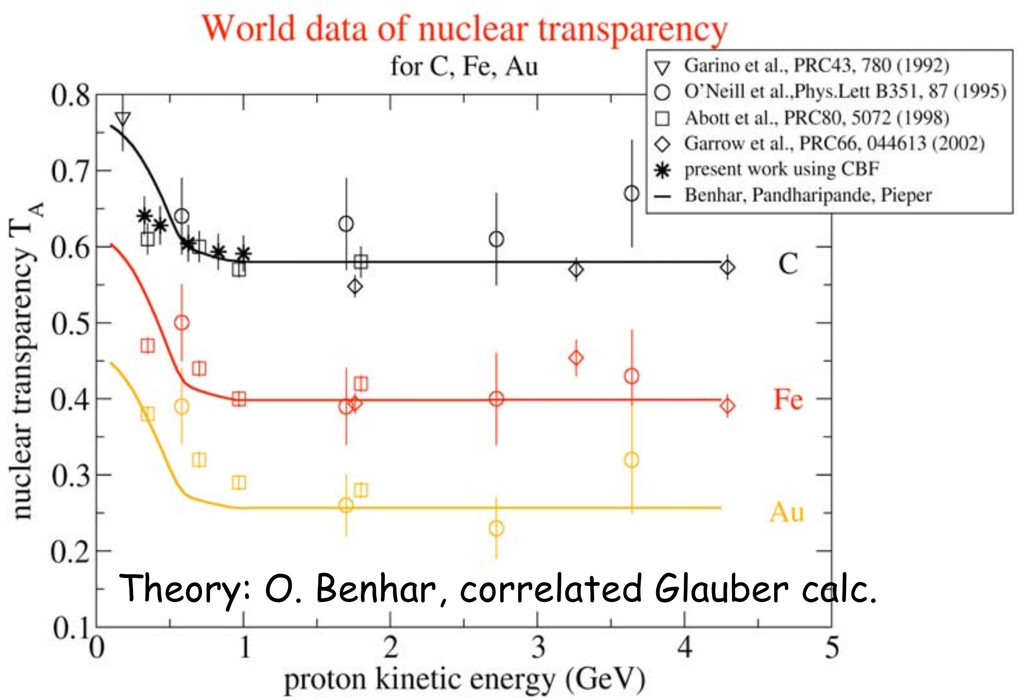
Another Approach to Correlations

Daniela Rohe, nucl-ex/0601003

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

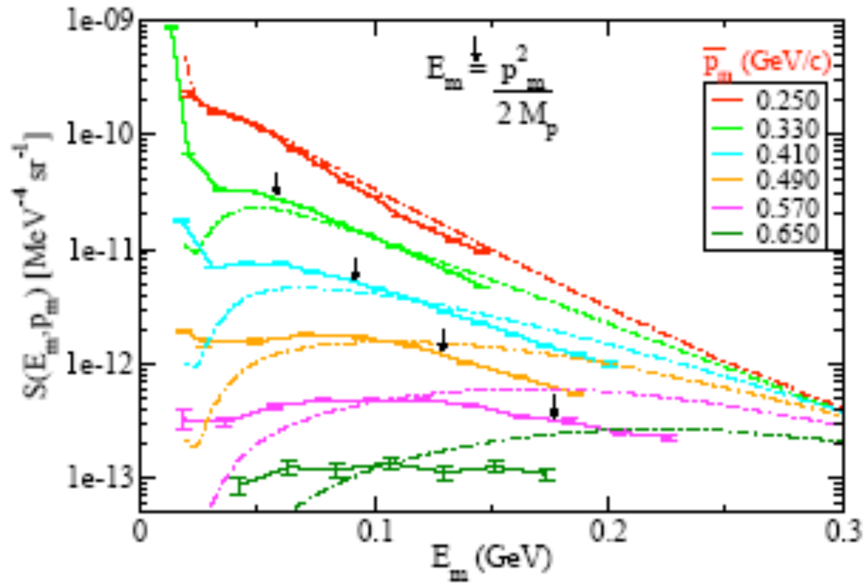
Everything done in || kinematics
- reduce FSI $\vec{q} \geq 1$ GeV/c; $x_B \leq 1$

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



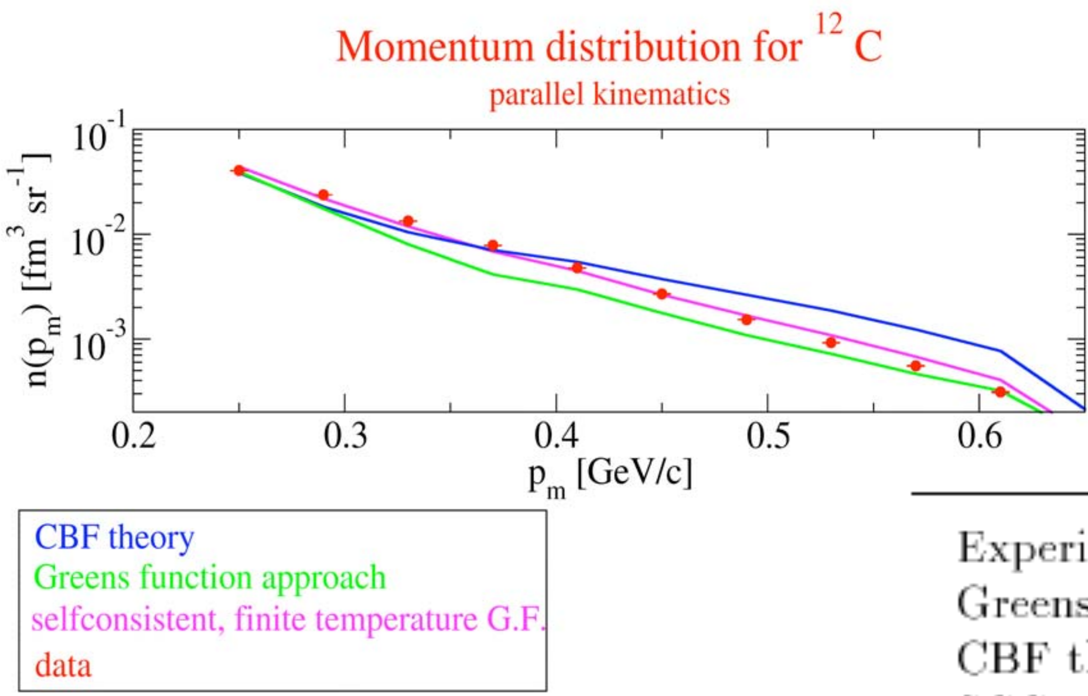
Measure in IPM region

In correlated region, extract E_m spectra for different p_m



Correlated Strength

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



Integrate spectral function over E_m, p_m

Measured correlated strength in terms of the number of protons

~ 10% of protons are correlated

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

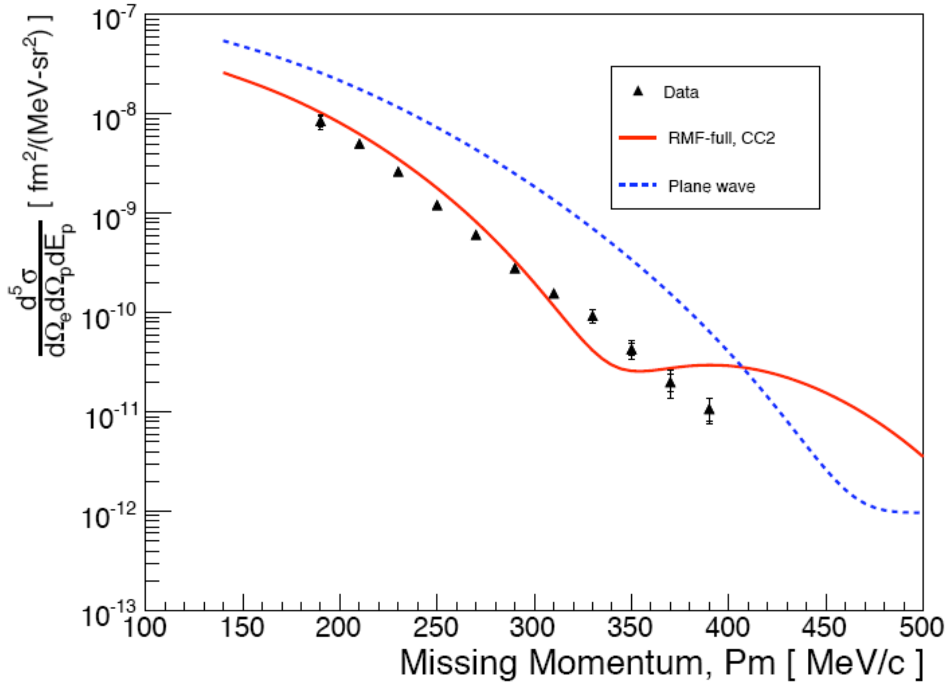
$^{12}C(e,e'p)^{11}B$ gs

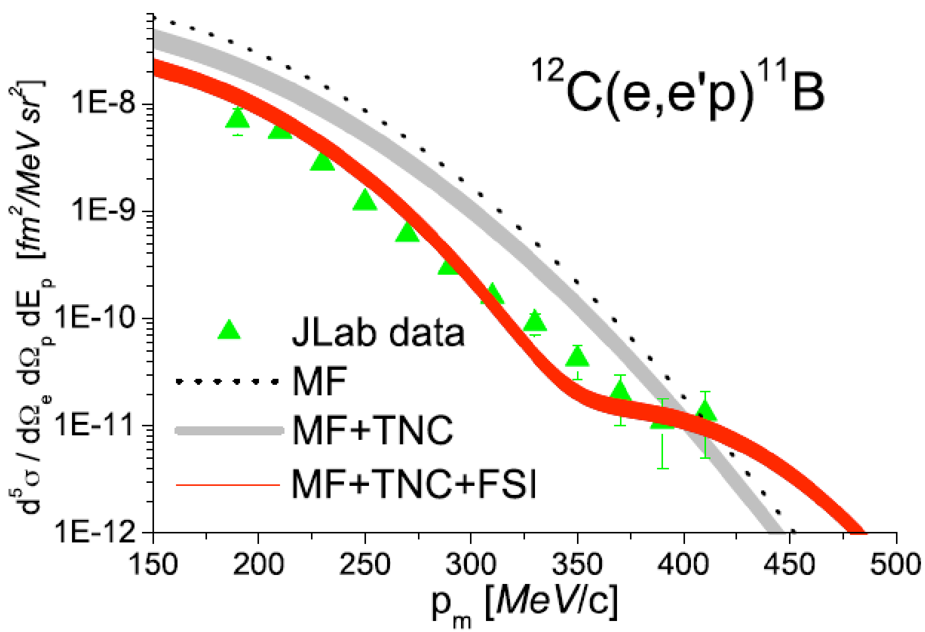
Data: Preliminary
P. Monaghan
MIT thesis 2008

$Q^2 \approx 2\ (GeV/c)^2$
$x_B \approx 1.2$
"semi anti-parallel" kinematics

Calculations: J.M Udias

Calculations: C. Ciofi degli Atti et al.





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

$Q^2 \approx 2\ (GeV/c)^2$
$x_B \approx 1.2$

P. Monaghan
Ph.D. thesis MIT 2008

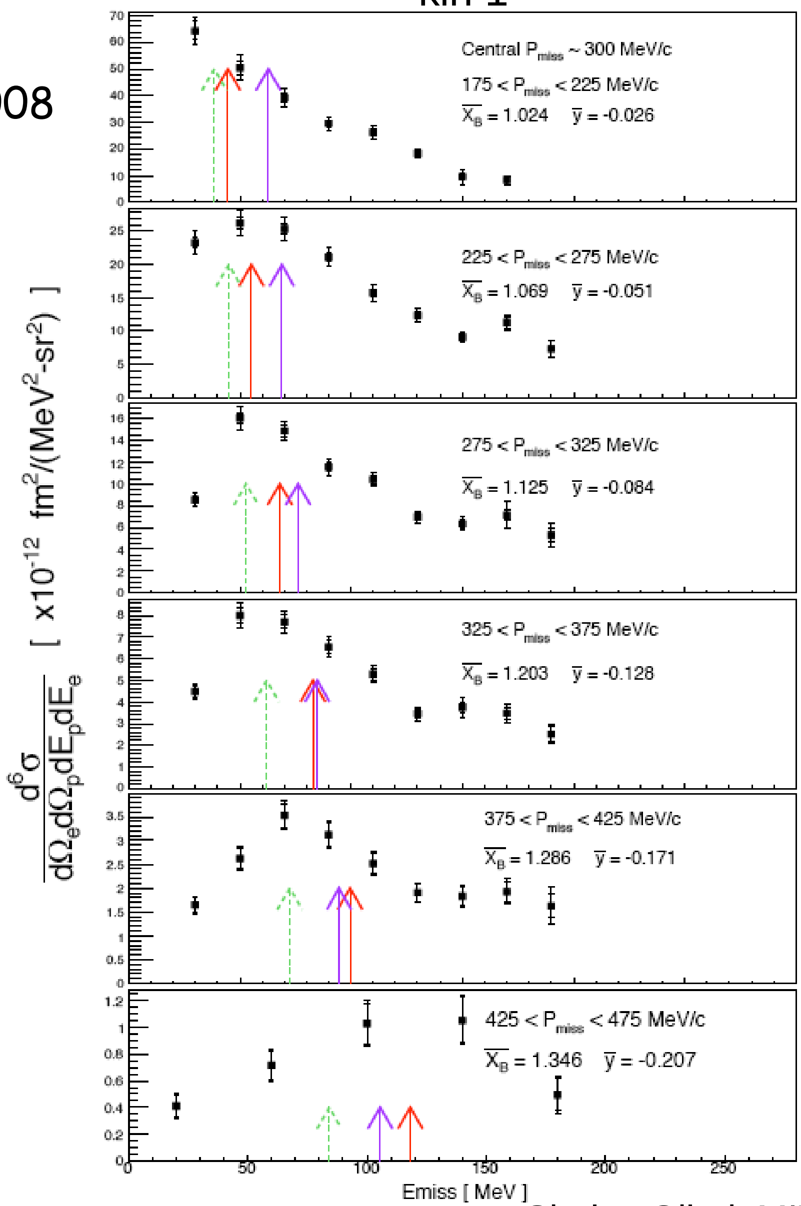
E_m for slices of p_m

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

$P_r = 0.8\ p_m$

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

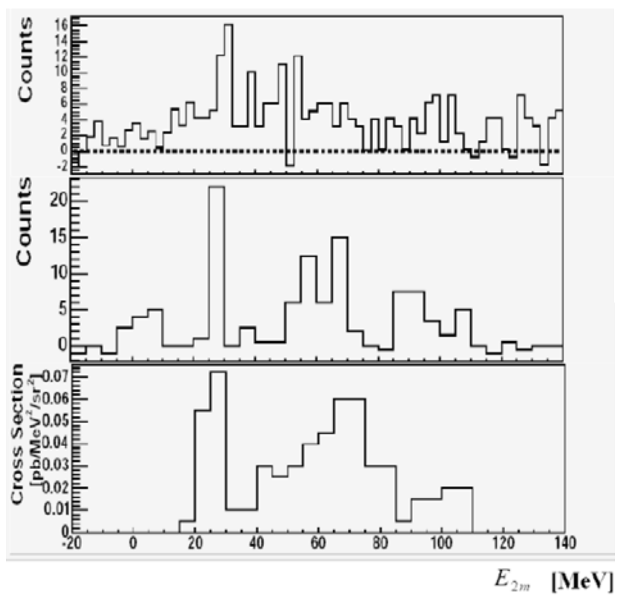
"kin 1"



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

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

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



ICTP08, Triete, Italy

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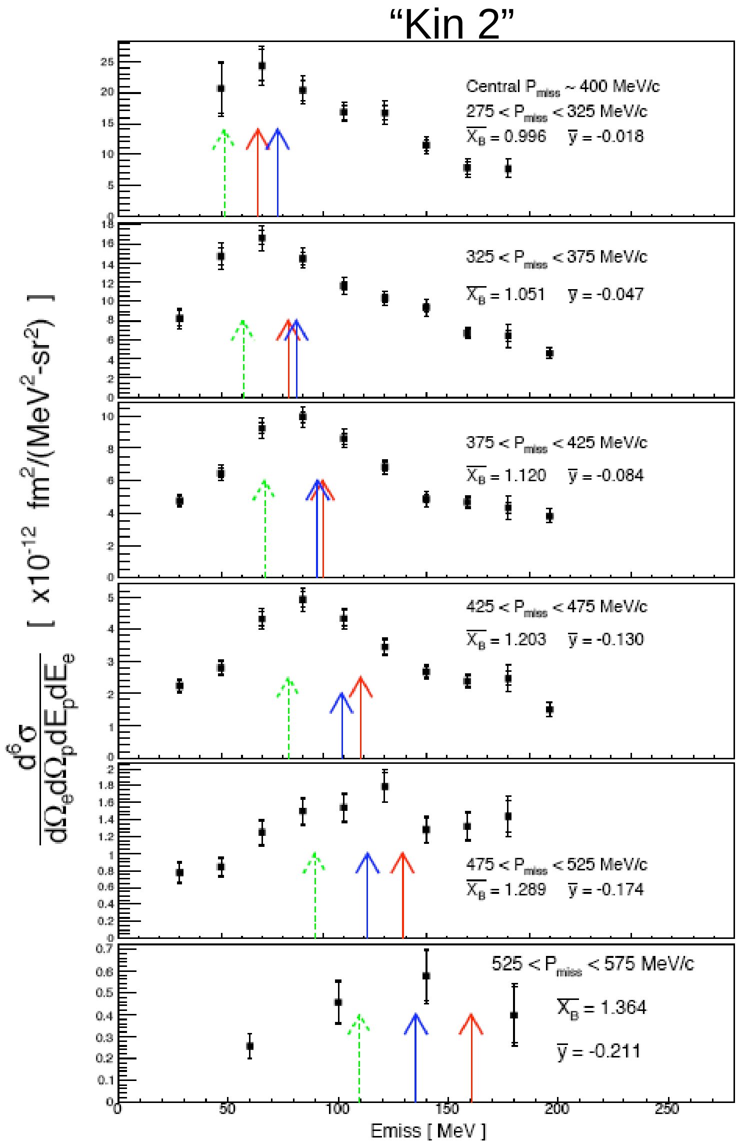
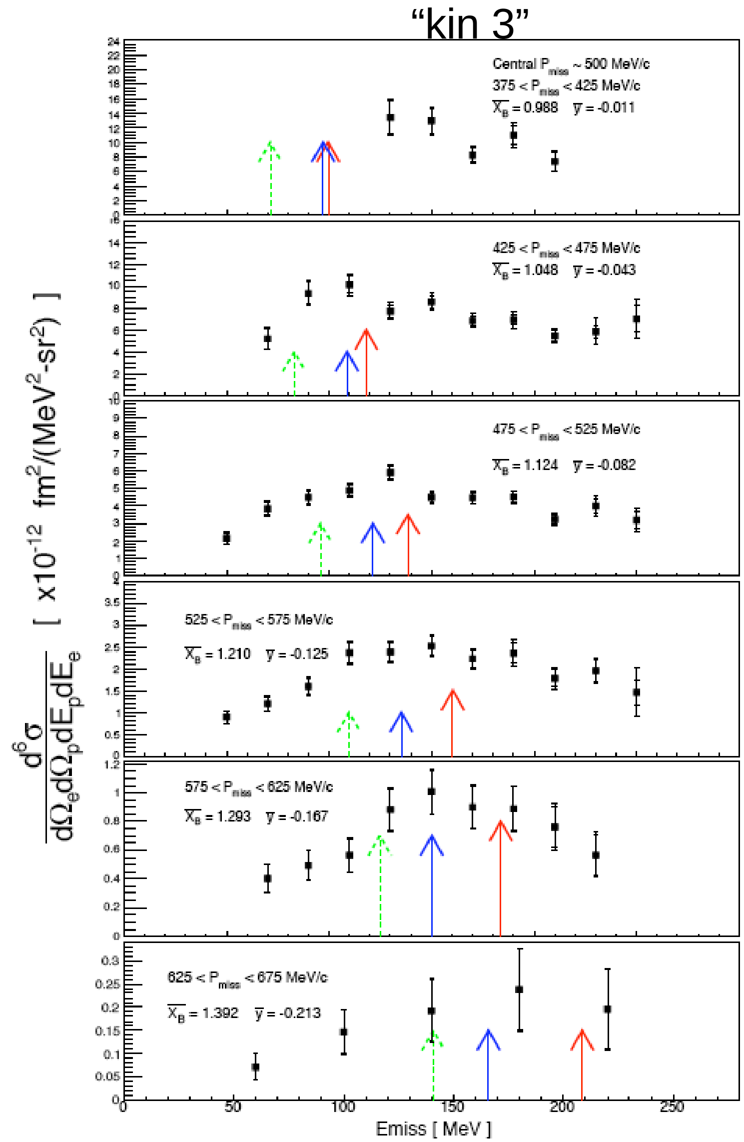
Additional $E_m(p_m)$





Note: x_B(kin 1) > x_B(kin 2) > x_B(kin 3) for same p_m

"Reduced x-sections"

Remember

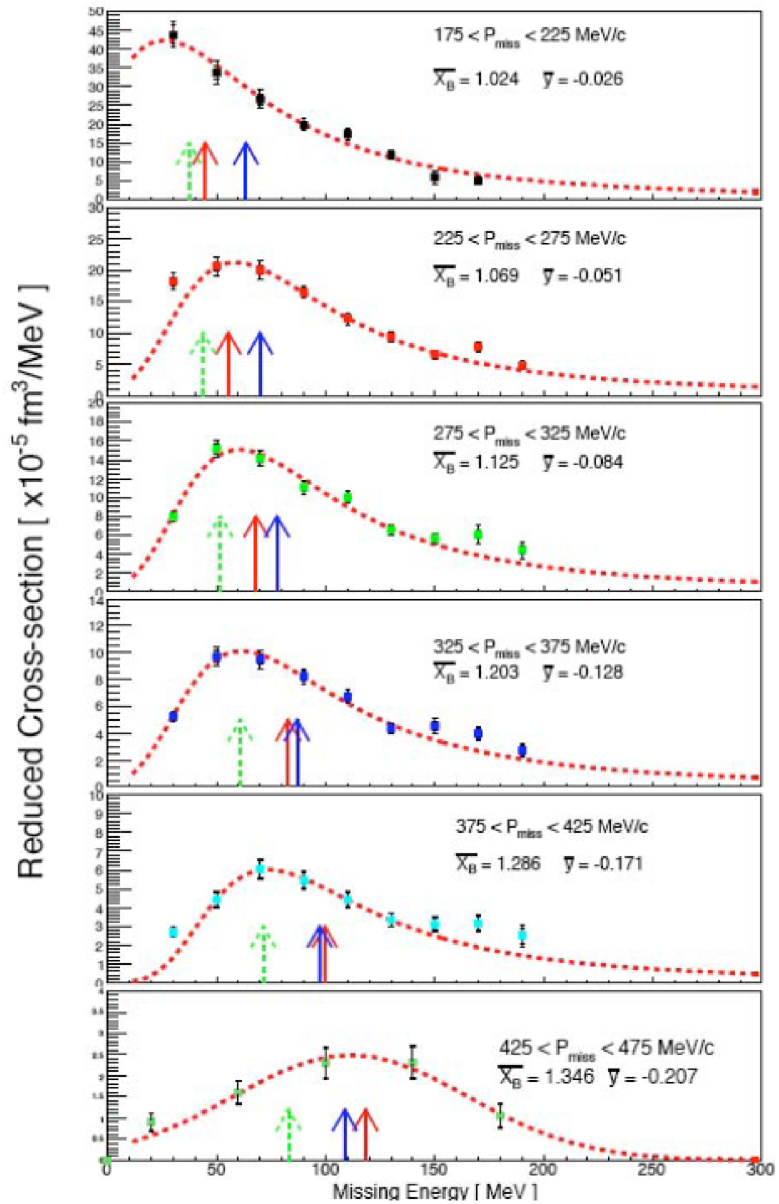
$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K\,\sigma_{ep}\,\boxed{S^D(p_m,\varepsilon_m,p)}$$

"Distorted" spectral function

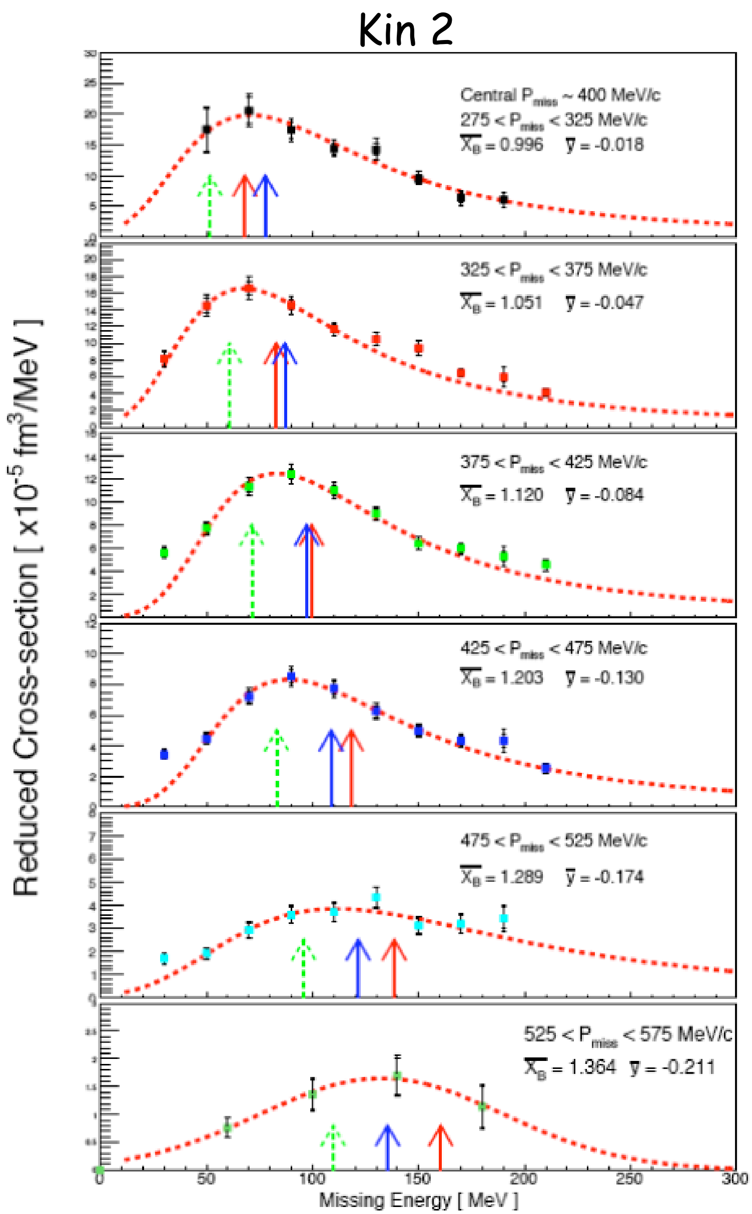
Reduces x-sections ≡
"Distorted" spectral function

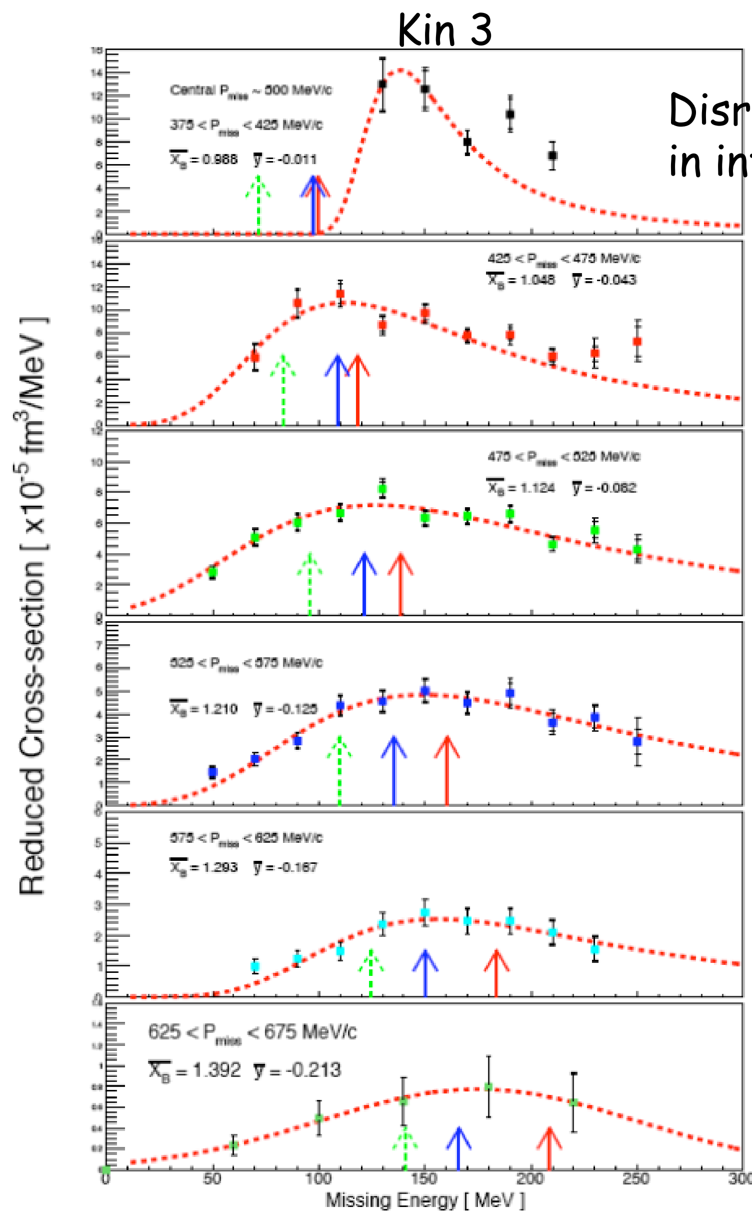
Take out σ_{ep} (=CC2) and electron kinematics out of x-sections

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



More Reduced x-sections





Disregard in integral

ICTP08, Triete, Italy

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Compare Reduced x-sections

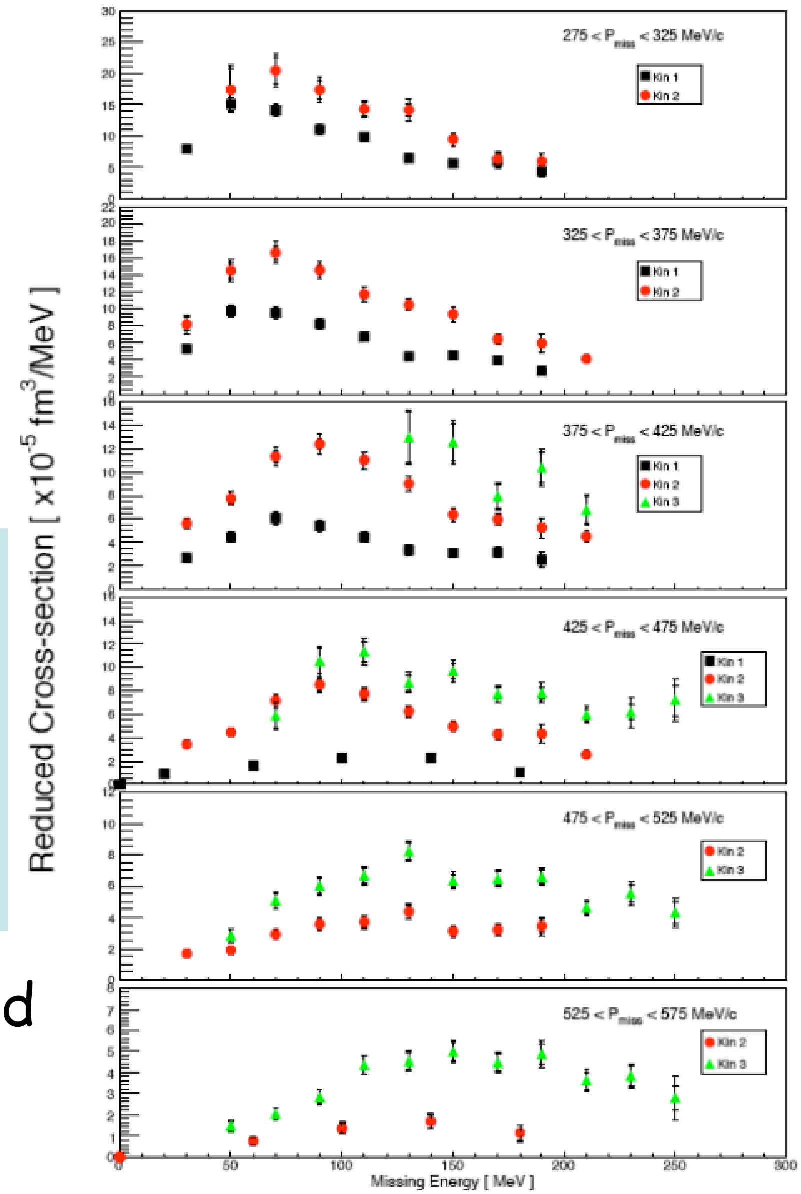
Remember again:

Reduces x-sections ≡
"Distorted" spectral function

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

"Distorted" spectral function

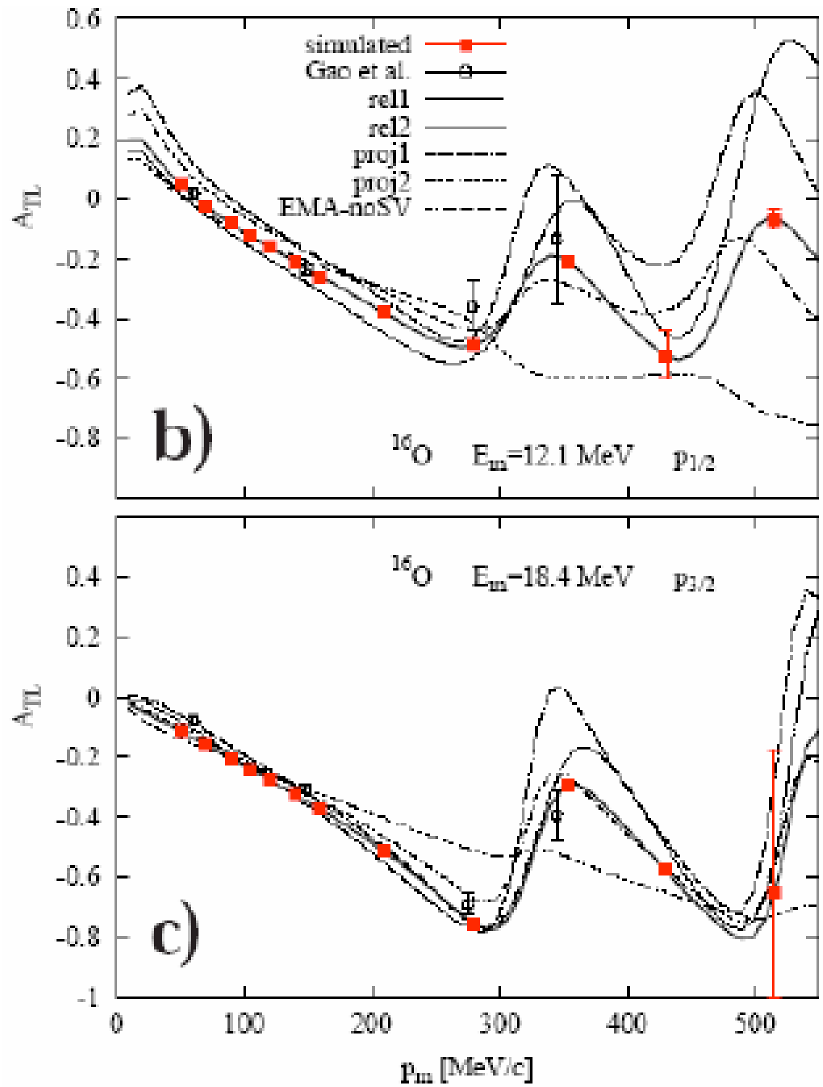
Factorization is badly broken!
Or
Poor knowledge of σ_{ep} at $x_B > 1$
Or
Both



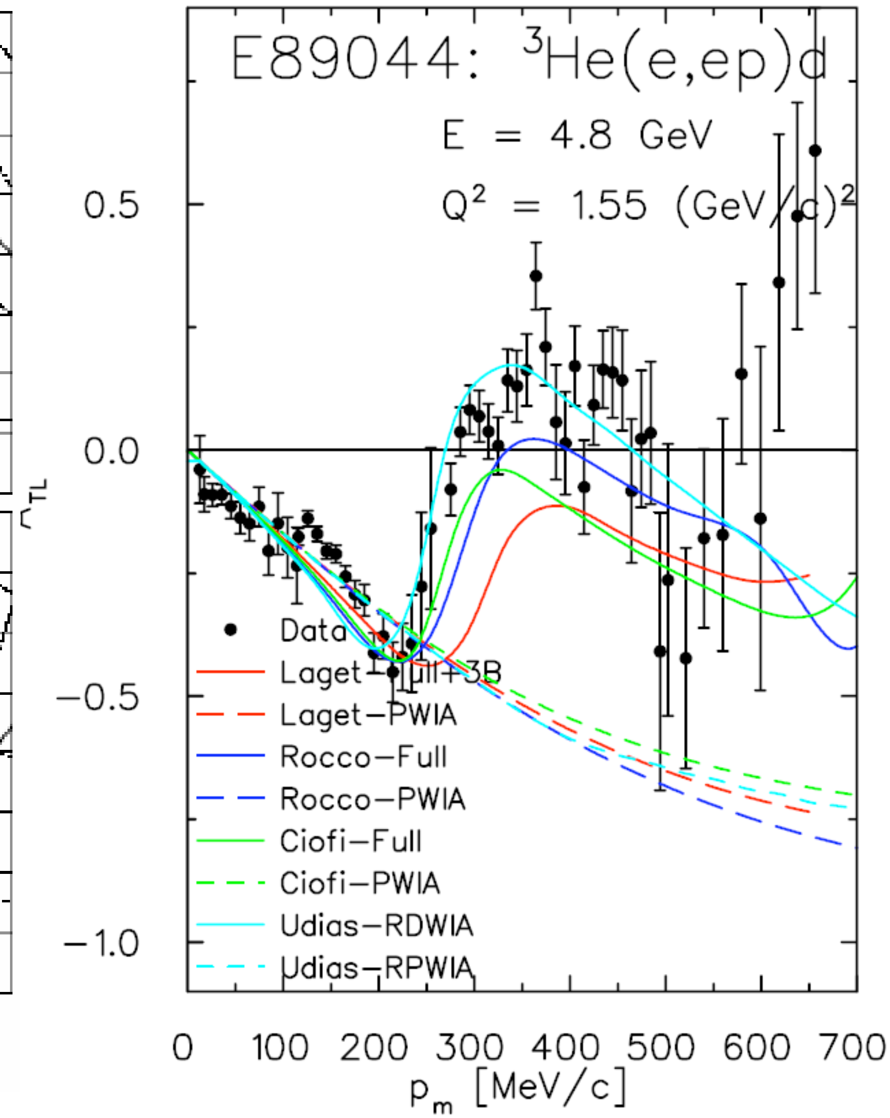
- can we do A(e,e′p) un-factorized calculations to continuum?
- How to test σ_{ep} for $x_B > 1$

Broken Factorization

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



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



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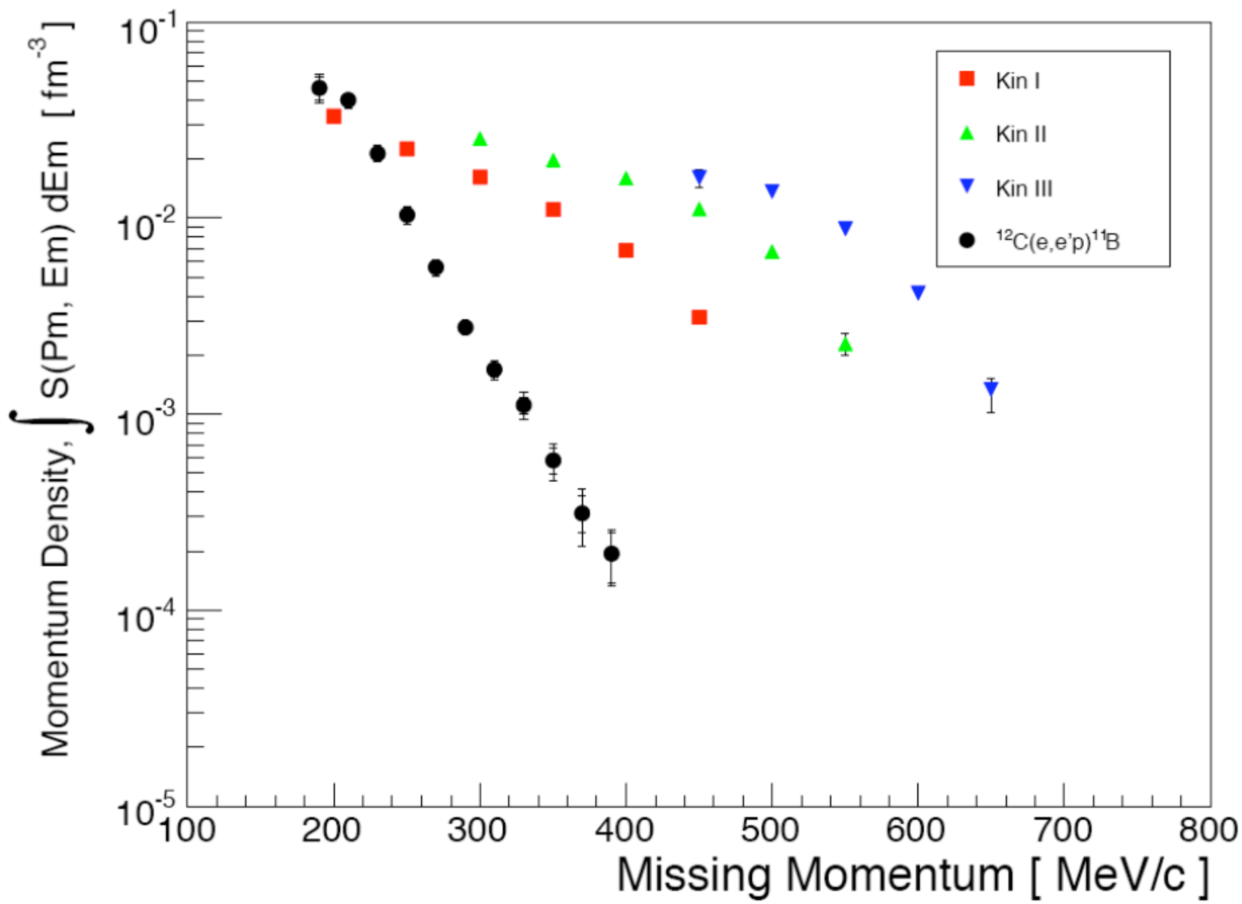
"Distorted Spectral Function"

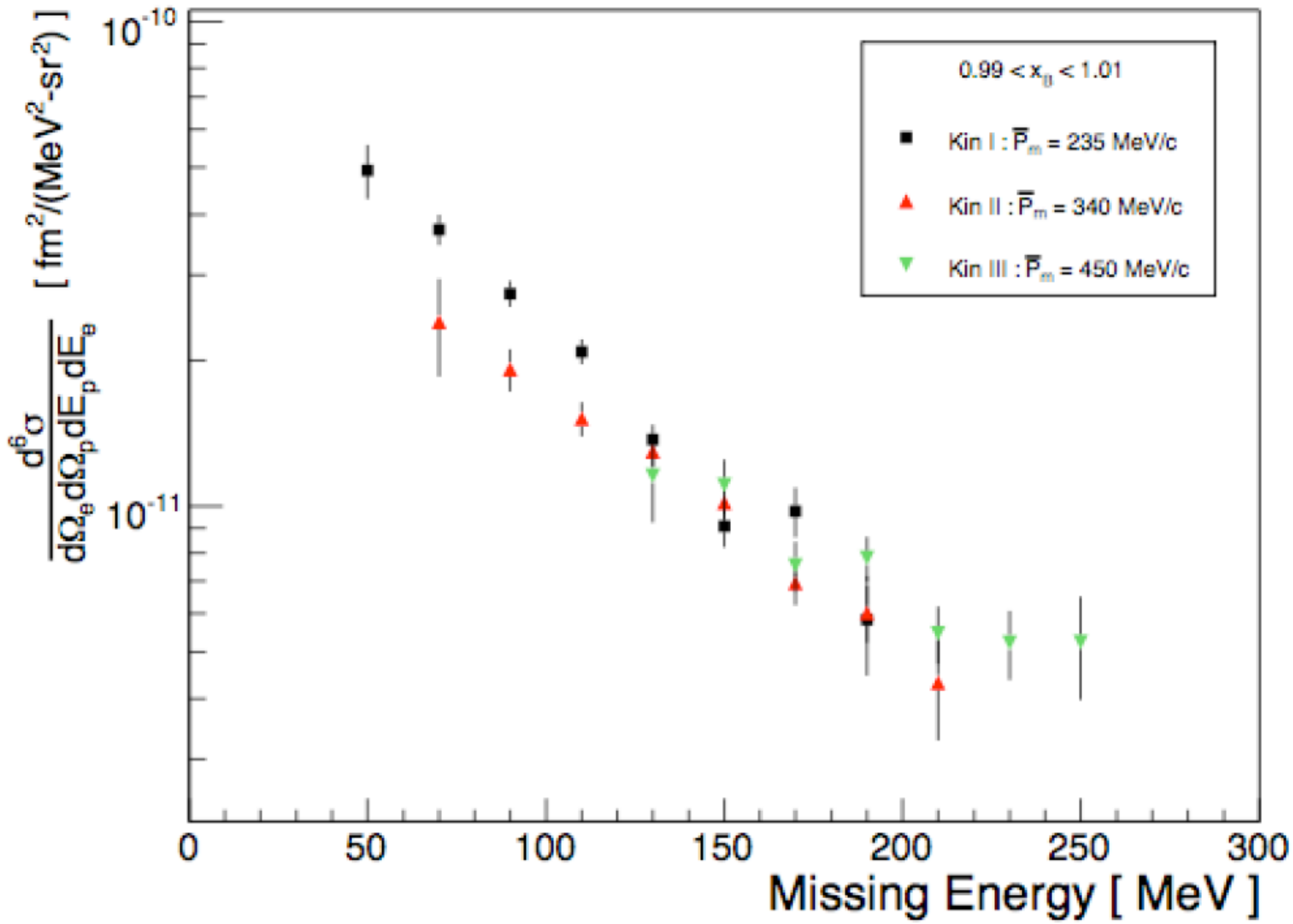
Integrate fitted curves to get "distorted momentum density"



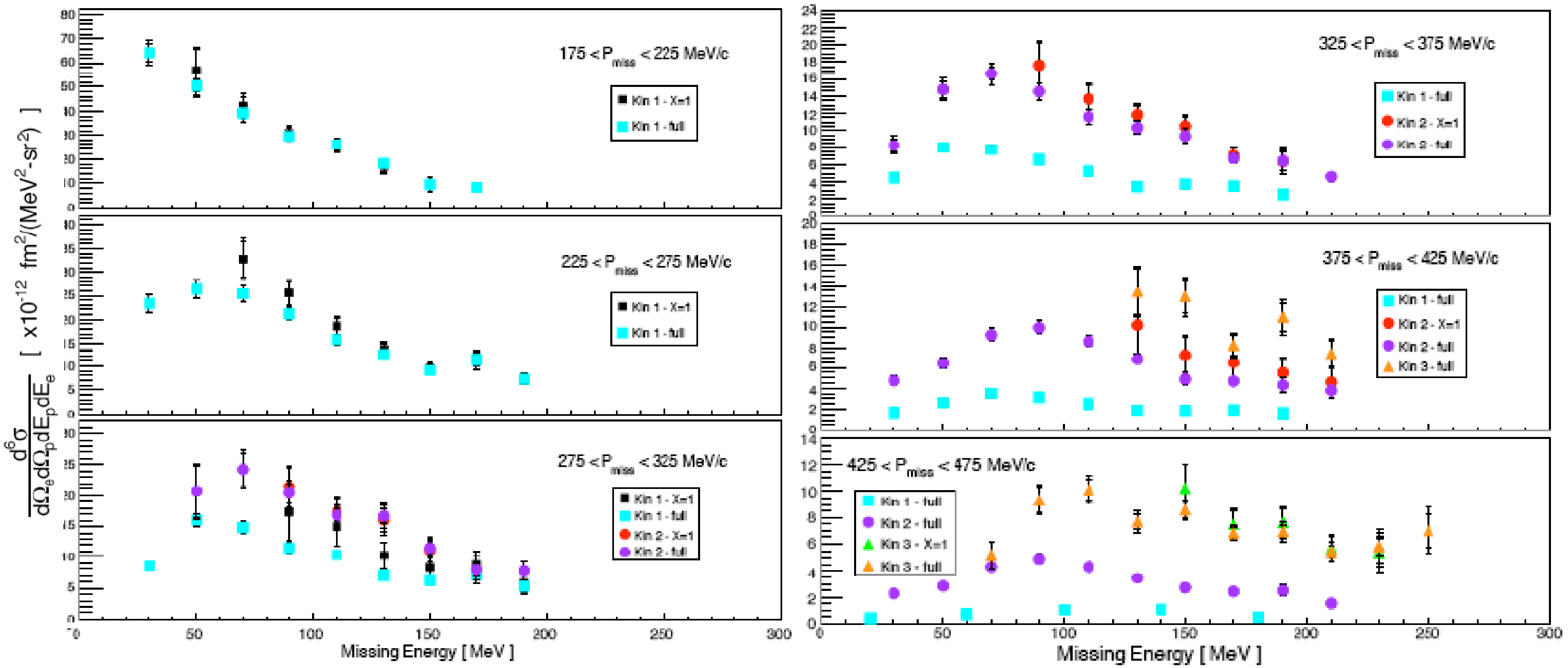
"distorted spectral function is not very meaningful!!

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

This means ⊥ 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 ???!

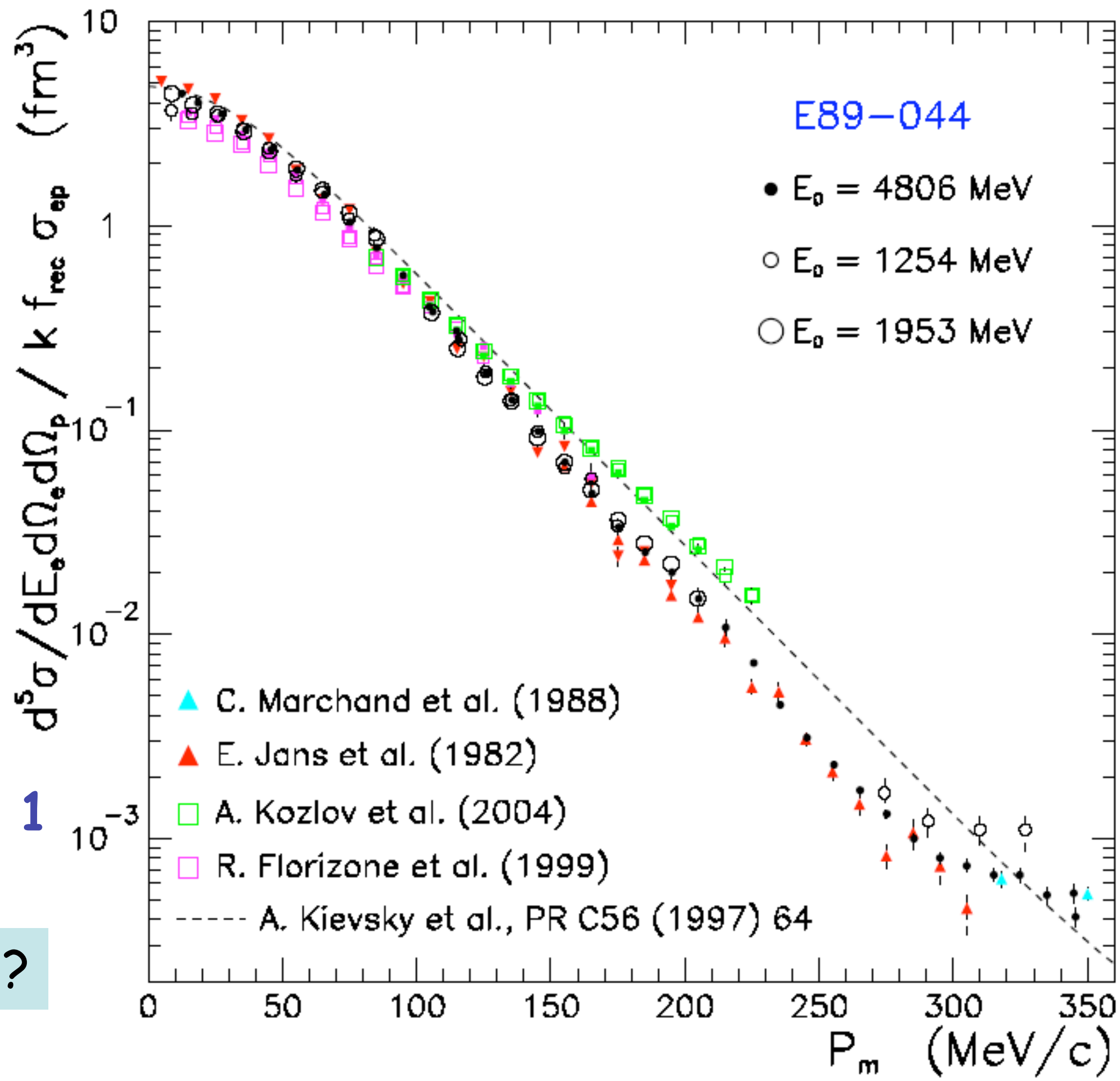
Ghost from the Past

$^3He(e,e'p)^2H$

Different laboratories
Different times
$Q^2 \approx 0.2 - 1.5\ (GeV/c)^2$
|| and ⊥ 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 $^{12}C(e,e'p)$ at kinematics favorable to correlations
  - High p_m
  - High Q^2
  - $x_B > 1$
  - "semi anti-parallel"
- $^{12}C(e,e'p)^{11}B$ gs
  - x-sections as a function of p_m
  - "effective momentum distribution"
- $^{12}C(e,e'p)$ to continuum
  - E_m spectra for different p_m slices
  - re-definde 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
- Callenges to theorists
  - Do we understand Ω_{ep} at x_B >1?
  - Need un-factorized A(e,e'p) calculations for understanding