# Nuclear Physics with Electromagnetic Probes
## Lectures 3 & 4

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# Course Outline

- Lecture 1: Beams and detectors
- Lecture 2: Elastic Scattering:
  - Charge and mass distributions
  - Deuteron form factors
- Lectures 3+4:
  - Single nucleon distributions in nuclei
    - Energy
    - Momentum
  - Correlated nucleon pairs.
- Lecture 5: Quarks in Nuclei
  - Nucleon modification in nuclei
  - Hadronization
  - Color transparency

# Comprehensive Theory Overview

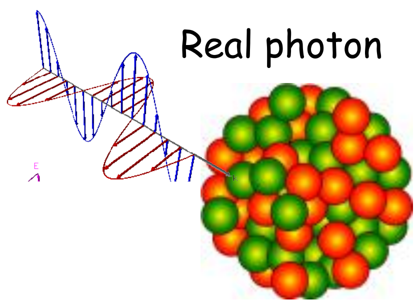

Nuclear Theory, circa 1980

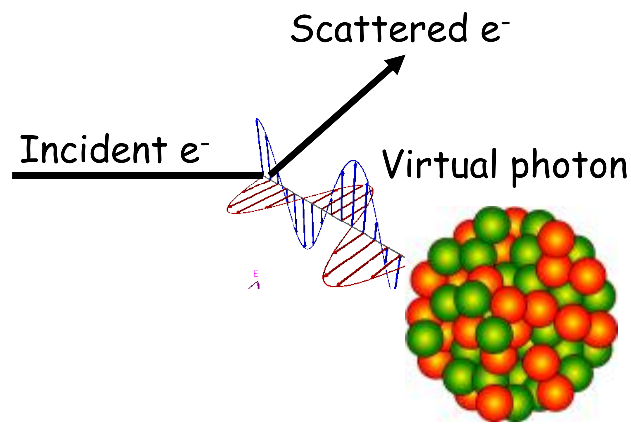

Nuclear Theory - circa 2000

Nuclear Theory - today: 1, 2, 3, … 12, … many

# It's all photons!

- An electron interacts with a nucleus by exchanging a single* virtual photon.



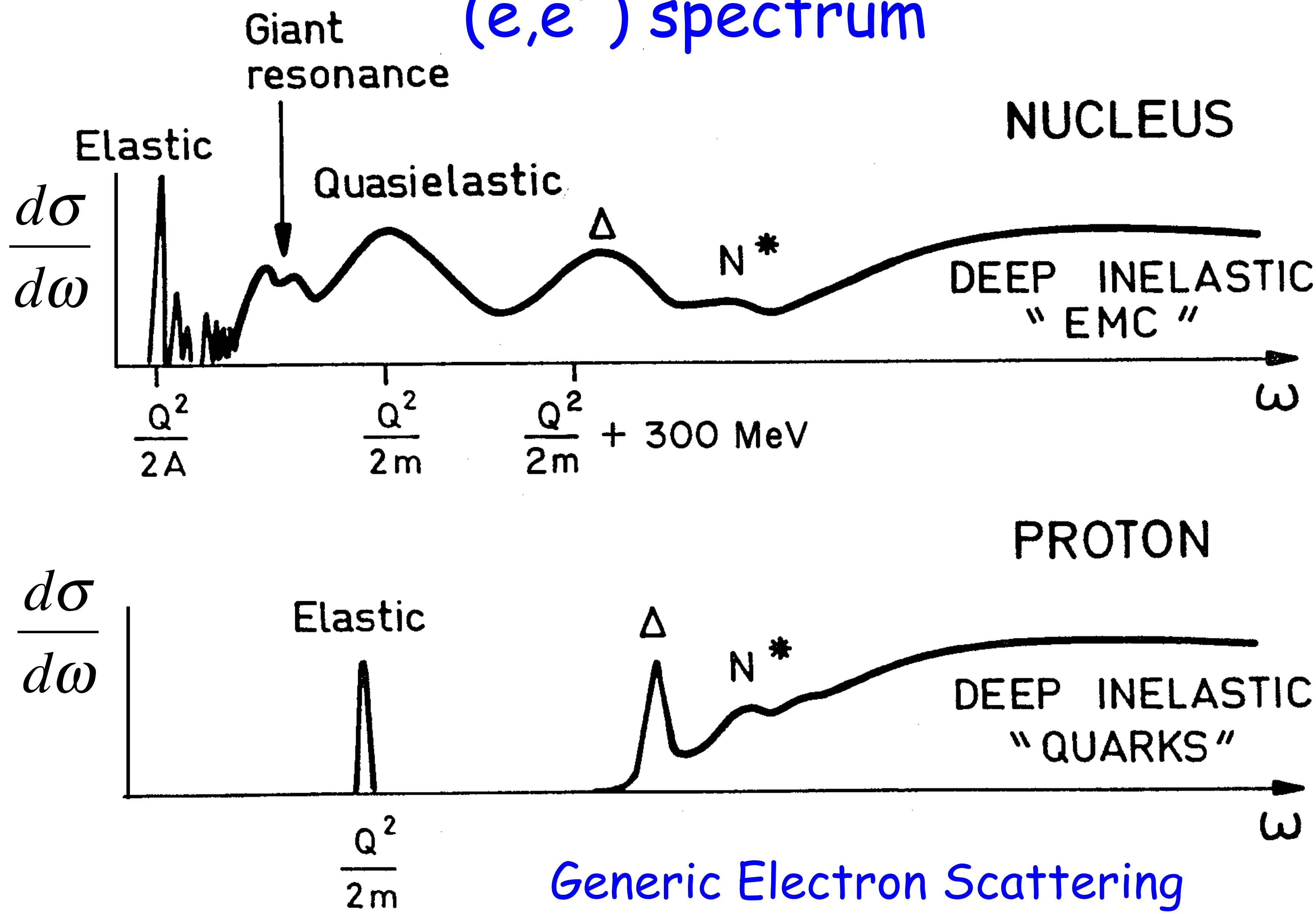

Real photon:
Momentum $q$ = energy $\nu$
Mass = $Q^2 = |\boldsymbol{q}|^2 - \nu^2 = 0$

$$\lambda = \frac{\hbar}{|\vec{q}\,|}$$

Virtual photon:
Momentum $q >$ energy $\nu$
$Q^2 = -q_\mu q^\mu = |\boldsymbol{q}|^2 - \nu^2 > 0$
Virtual photon has mass!

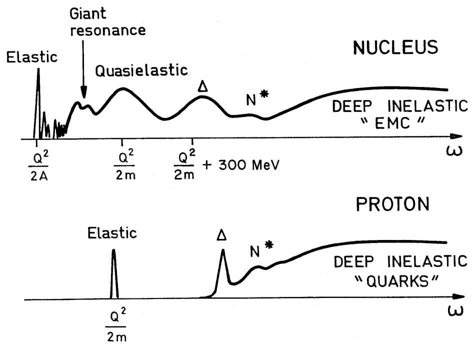
($\nu$ and $\omega$ are both used for energy transfer)

# (e,e’ ) spectrum




Generic Electron Scattering
at fixed momentum transfer

# Experimental goals:




- Elastic scattering
  - structure of the nucleus
    - Form factors, charge distributions, spin dependent FF
- Quasielastic (QE) scattering
  - Shell structure
    - Momentum distributions
    - Occupancies
  - Short Range Correlated nucleon pairs
  - Nuclear transparency and color transparency
- Deep Inelastic Scattering (DIS)
  - The EMC Effect and Nucleon modification in nuclei
  - Quark hadronization in nuclei

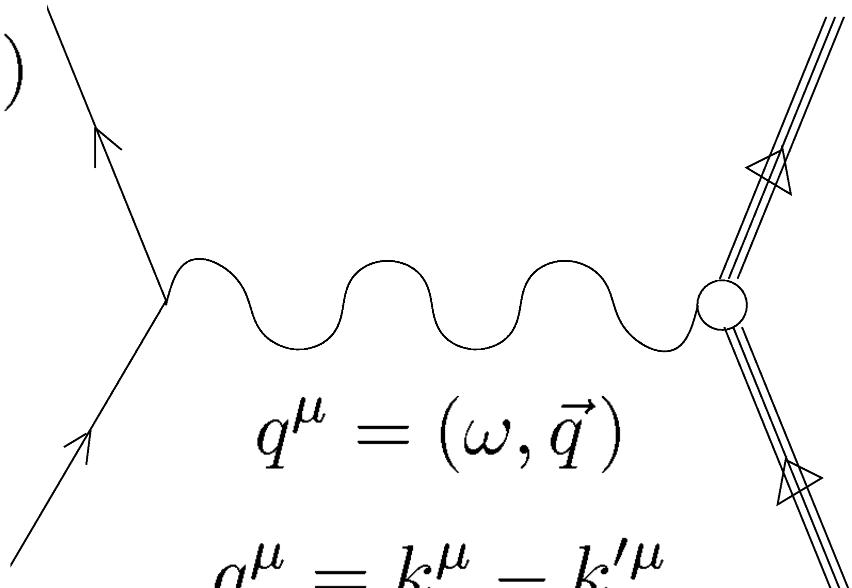
# Inclusive electron scattering (e,e')

$$k'^{\mu} = (E', \vec{k}\,')$$

$$p'^{\mu} = (E_p, \vec{p}_p)$$

(not detected)

Lab frame kinematics



$$q^{\mu} = (\omega, \vec{q}\,)$$

$$k^{\mu} = (E, \vec{k}\,)$$

$$q^{\mu} = k^{\mu} - k'^{\mu}$$

$$p^{\mu} = (M, \vec{0}\,)$$

## Invariants:

$$p^{\mu} p_{\mu} = M^2 \qquad p_{\mu} q^{\mu} = M\omega$$

$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2 \qquad W^2 = (q^{\mu} + p^{\mu})^2 = p'_{\mu} p'^{\mu}$$

# (e,e') Elastic cross section ($p'^2 = M^2$)

Recoil factor — Form factors

$$\frac{d\sigma}{d\Omega} = \sigma_M \frac{E'}{E}\left\{\left[F_1^2(Q^2) + \frac{Q^2}{4M^2}\kappa^2 F_2^2(Q^2)\right] + \frac{Q^2}{2M^2}[F_1(Q^2)+\kappa F_2(Q^2)]^2 \tan^2\frac{\theta}{2}\right\}$$

$$= \sigma_M \frac{E'}{E}\left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau \tan^2\frac{\theta}{2} G_M^2(Q^2)\right]$$

$$= \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^4} R_L(Q^2) + \left(\frac{Q^2}{2\vec{q}^2} + \tan^2\frac{\theta}{2}\right) R_T(Q^2)\right]$$

Mott cross section

$$\sigma_M = \frac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E^2 \sin^4\left(\frac{\theta_e}{2}\right)}$$

**For inelastic scattering:**
$R_L(Q^2) \rightarrow R_L(Q^2,\nu)$

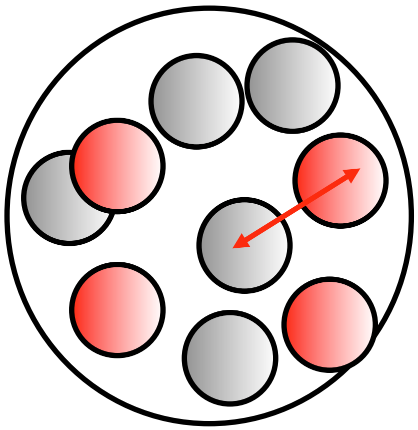
nucleons:
- $F_1, F_2$: Dirac and Pauli form factors
- $G_E, G_M$: Sachs form factors (electric and magnetic)
  - $G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$ $\quad \tau = Q^2/4M^2$
  - $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$ $\quad$ (more standard definition of $F_1$ and $F_2$)

$R_L, R_T$: Longitudinal and transverse response fn

# Notes on form factors

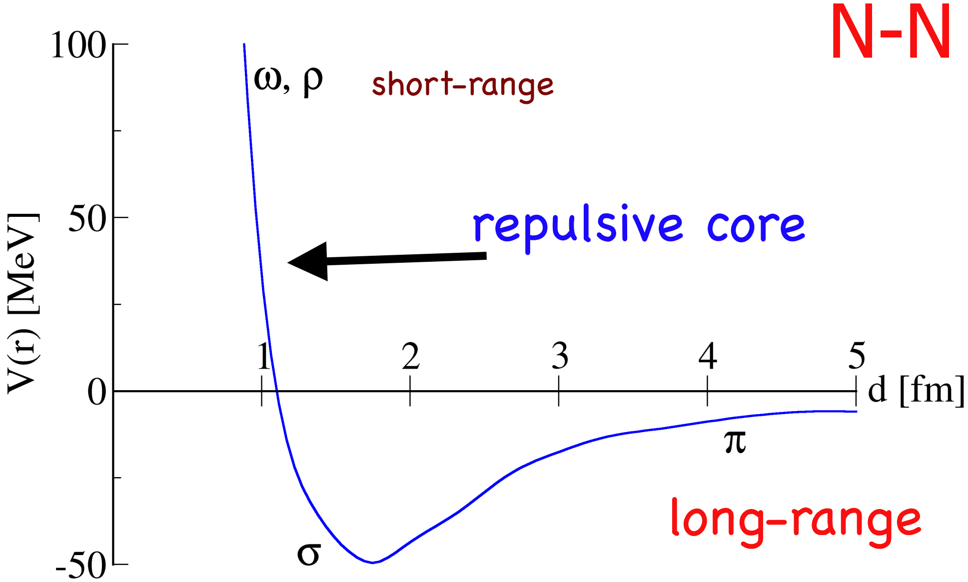
- $G_E$, $G_M$, $F_1$ and $F_2$ refer to nucleons
  - $F_1^p(0) = 1$, $F_2^p(0) = \kappa_p = 1.79$
  - $F_1^n(0) = 0$, $F_2^n(0) = \kappa_n = -1.91$
  - $G_E^p(0) = 1$, $G_M^p(0) = 1 + \kappa_p = 2.79$
  - $G_E^n(0) = 0$, $G_M^n(0) = \kappa_n = -1.91$
- $R_L$ and $R_T$ refer to nuclei

# Structure of the nucleus

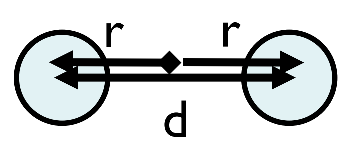


- nucleons are bound
  - energy (*E*) distribution
  - shell structure
- nucleons are not static
  - momentum (*k*) distribution

determined by the N-N potential

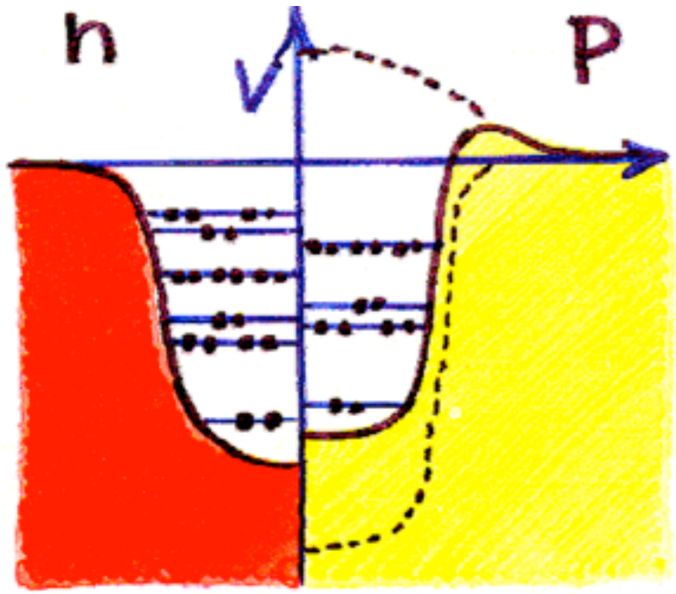



on average:
Net binding energy: ≈ 8 MeV
distance: ≈ 2 fm



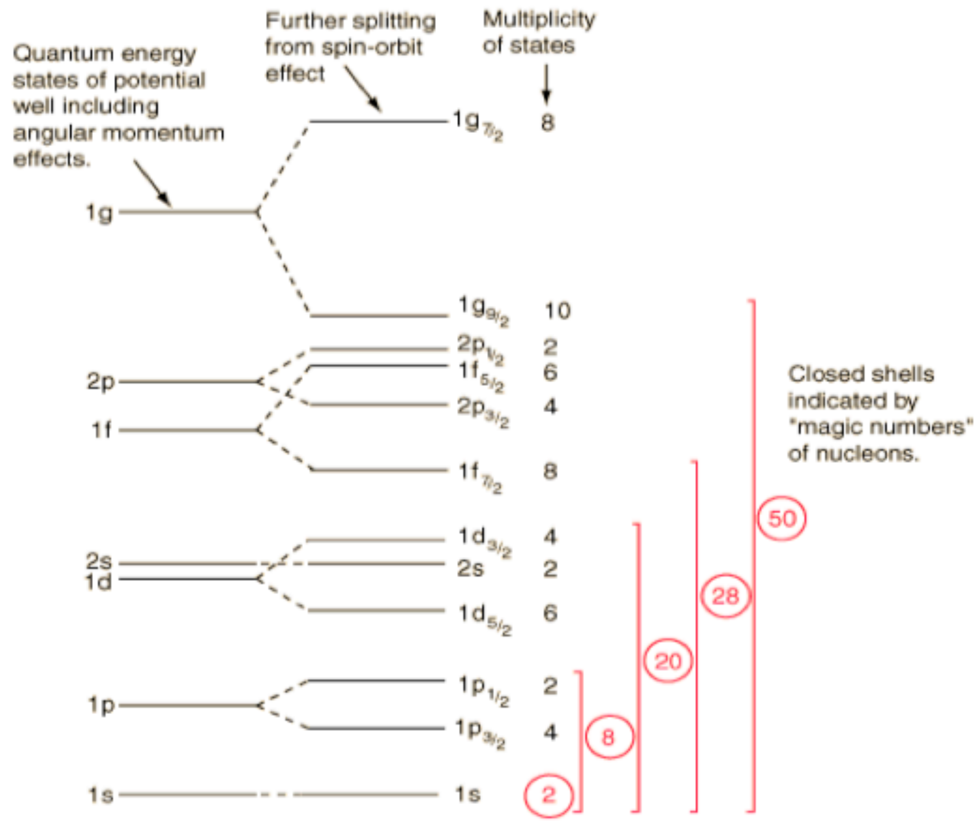

Strong repulsion ⟹ NN correlations

# Shell Structure (Maria Goeppert-Mayer, Jensen, 1949, Nobel Prize 1963)




nuclear density $10^{18}$ kg/m$^3$

With the enormous strong force acting between them and with so many nucleons to collide with, how can nucleons possibly complete whole orbits without interacting?



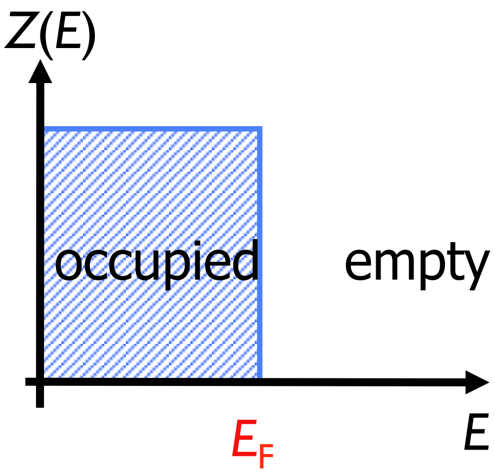

But: there is experimental evidence for shell structure

Pauli Exclusion Principle: ⟶ nucleons can not scatter into occupied levels: Suppression of collisions between nucleons

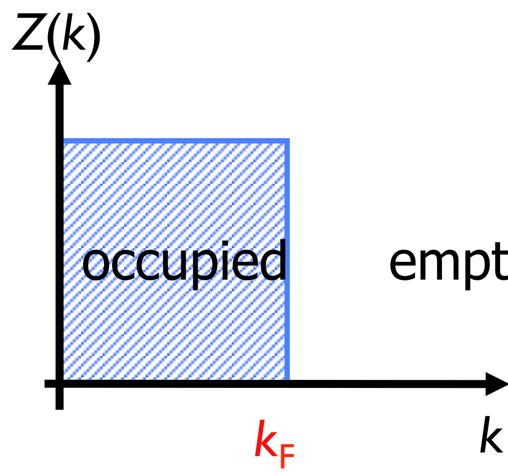
# Independent Particle Shell model (IPSM)

- single particle approximation:
  nucleons move independently from each other
  in an average potential created by the other nucleons (mean field)
  spectral function $S(E,k)$:
  probability of finding a proton with initial momentum $k$ and
  energy $E$ in the nucleus
- factorizes into energy & momentum part

nuclear matter:



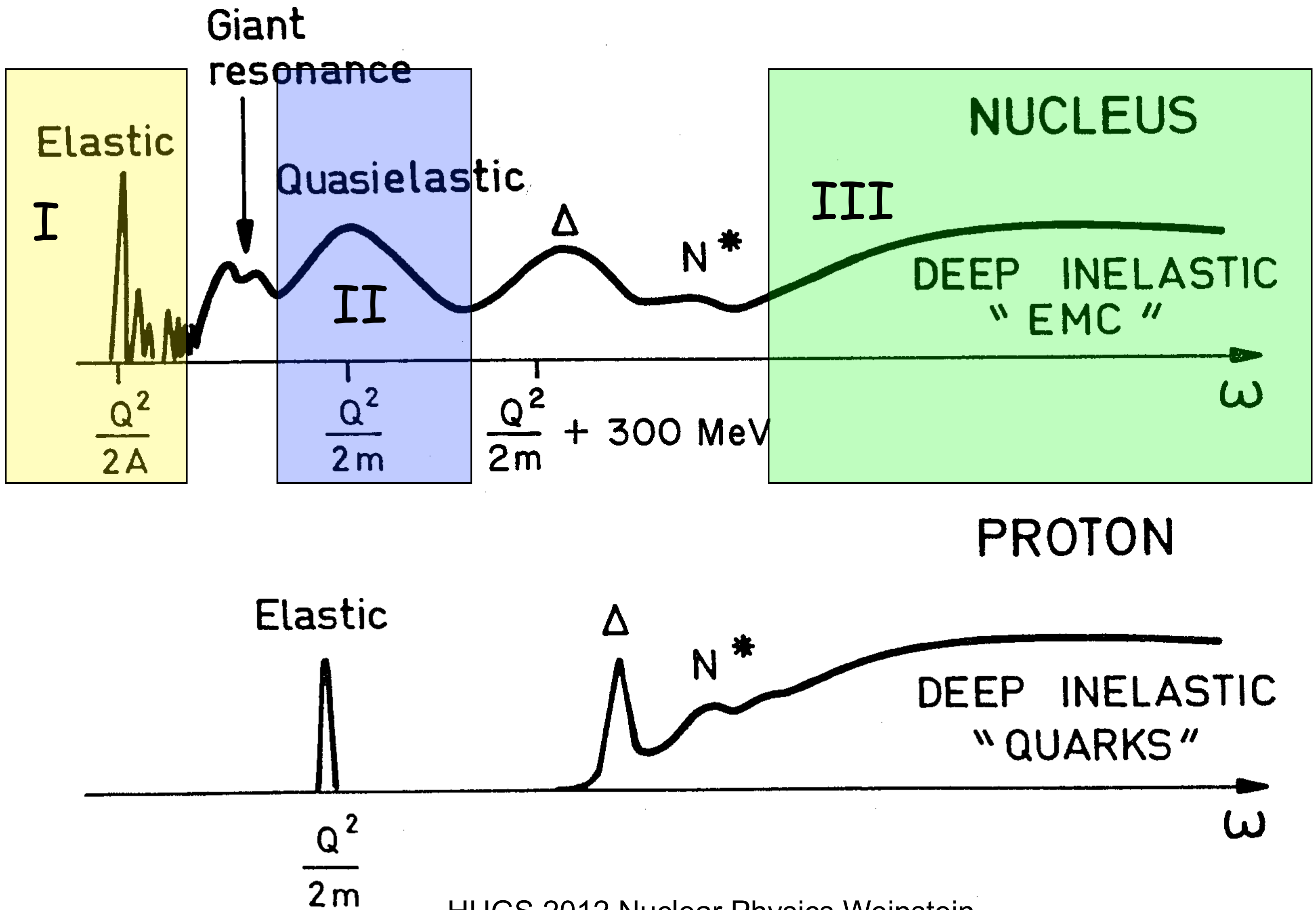

$$E_F = \frac{k_F^2}{2m_p}$$



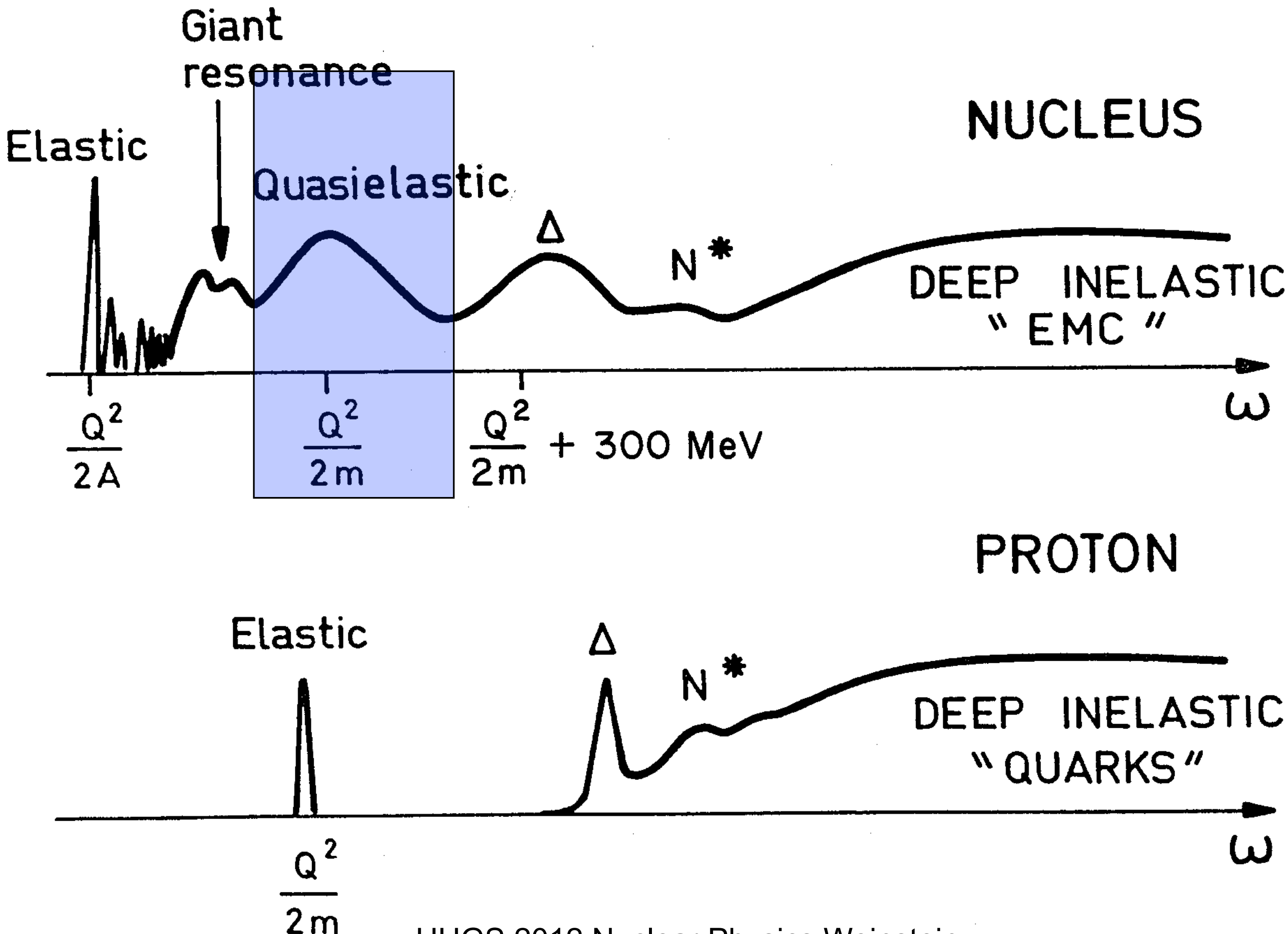

nuclei: $S(\vec{p},E) = \sum_i |\Phi_a(p)|^2 \, \delta(E+\epsilon_a)$

Not 100% accurate, but a good starting point

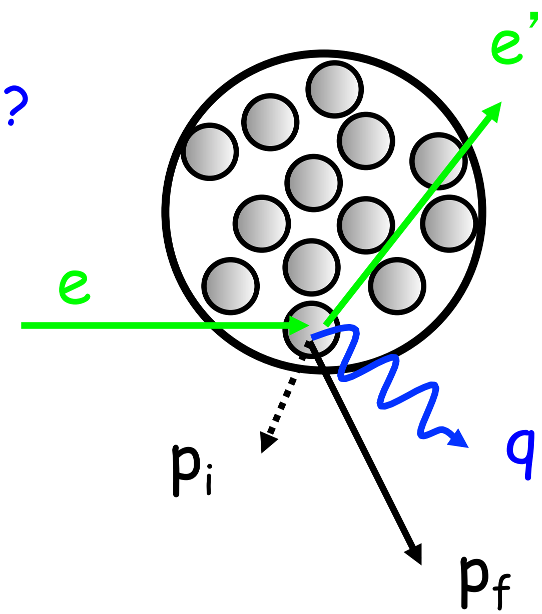
# Electron-nucleus interactions

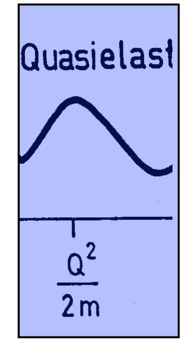


# II. Quasielastic scattering



# Fermi gas model:
## how simple a model can you make ?




Initial nucleon energy: $KE_i = p_i^2 / 2m_p$

Final nucleon energy: $KE_f = p_f^2 / 2m_p = (\vec{q} + \vec{p}_i)^2 / 2m_p$

Energy transfer: $\nu = KE_f - KE_i = \dfrac{\vec{q}^{\,2}}{2m_p} + \dfrac{\vec{q} \cdot \vec{p}_i}{m_p}$

Expect:

- Peak centroid at $\nu = q^2/2m_p + \varepsilon$
- Peak width $2qp_{fermi}/m_p$
- Total peak cross section = $Z\sigma_{ep} + N\sigma_{en}$

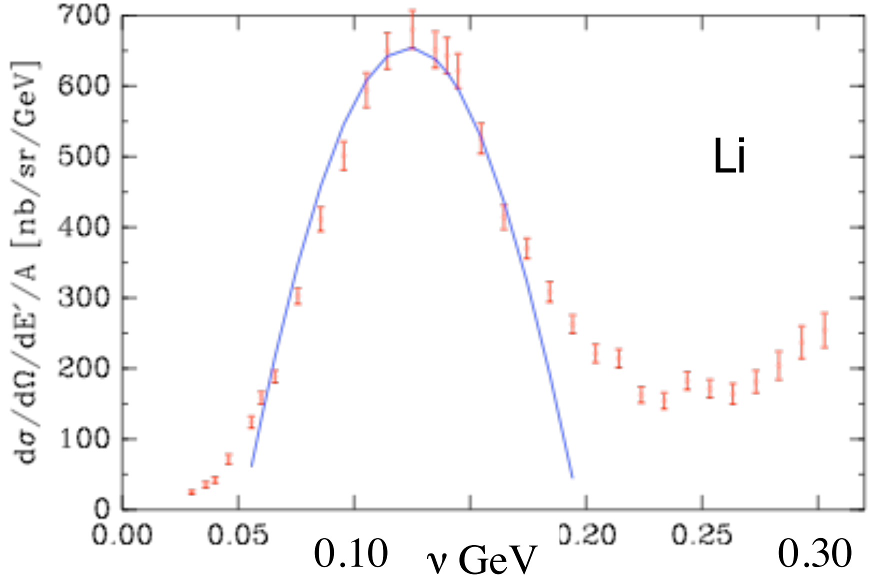
# Early 1970's Quasielastic Data

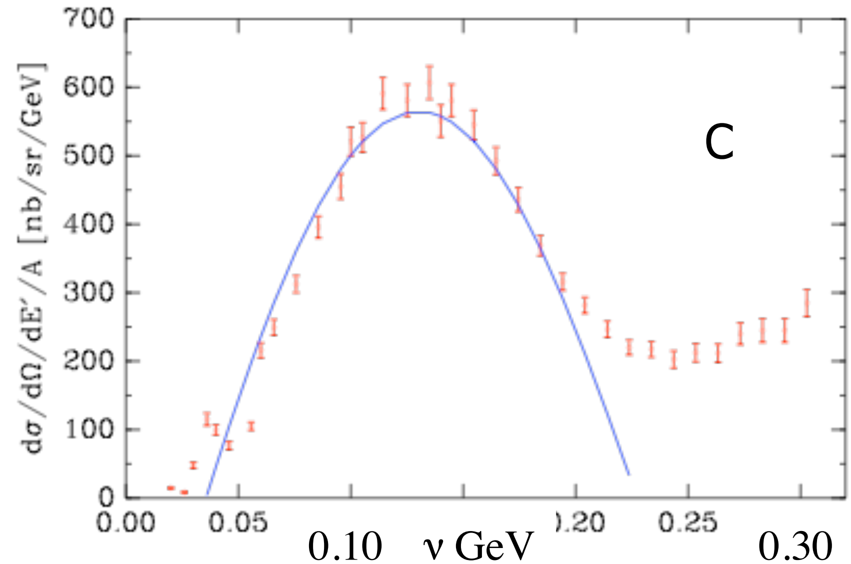
-> getting the bulk features

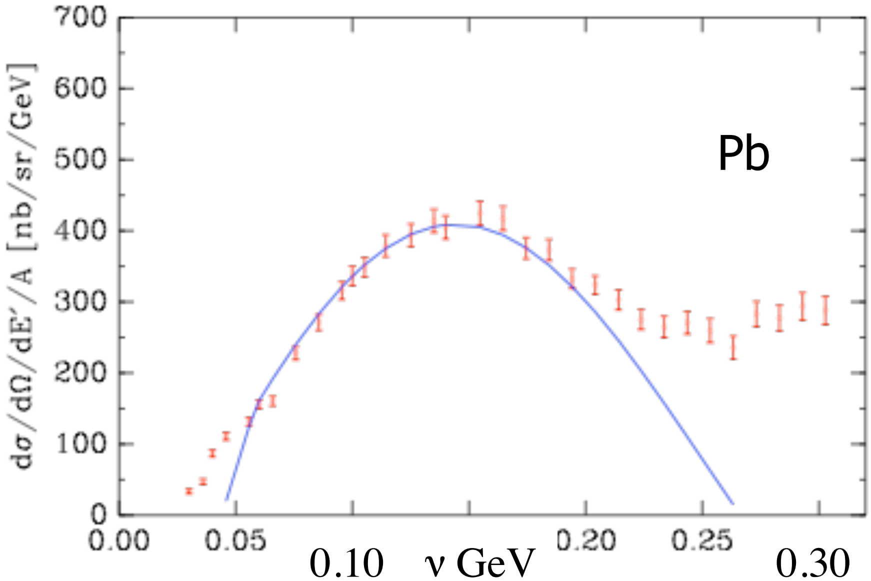
500 MeV, 60 degrees

$\vec{q} \simeq 500 MeV/c$

R.R. Whitney et al., PRC 9, 2230 (1974).



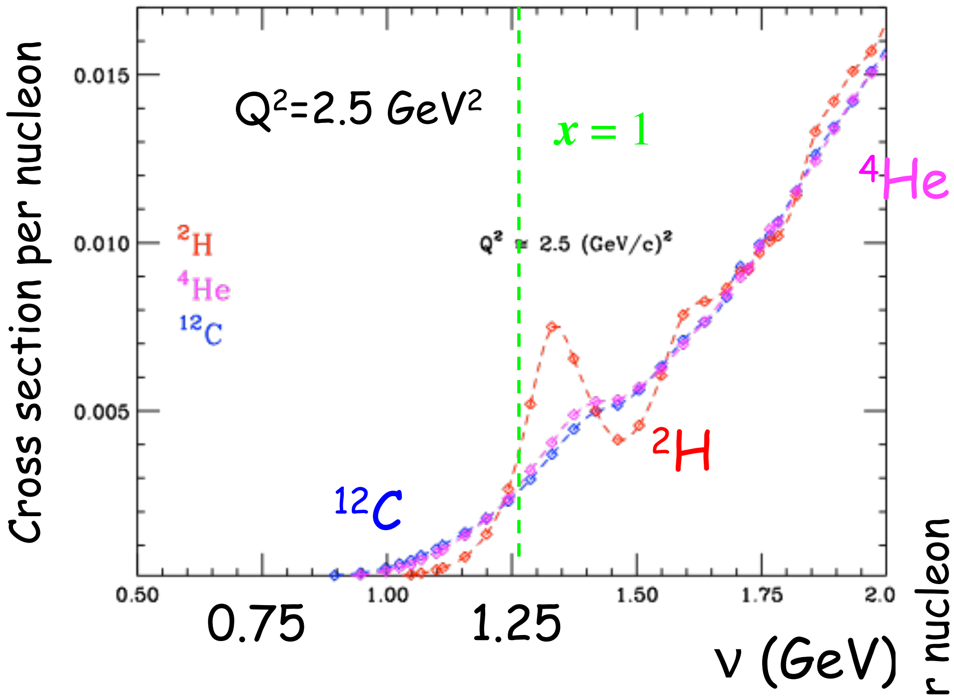




| Nucleus | $k_F$ MeV/c | $\bar{\epsilon}$ MeV |
|---|---|---|
| $^{6}$Li | 169 | 17 |
| $^{12}$C | 221 | 25 |
| $^{24}$Mg | 235 | 32 |
| $^{40}$Ca | 251 | 28 |
| $^{nat}$Ni | 260 | 36 |
| $^{89}$Y | 254 | 39 |
| $^{nat}$Sn | 260 | 42 |
| $^{181}$Ta | 265 | 42 |
| $^{208}$Pb | 265 | 44 |

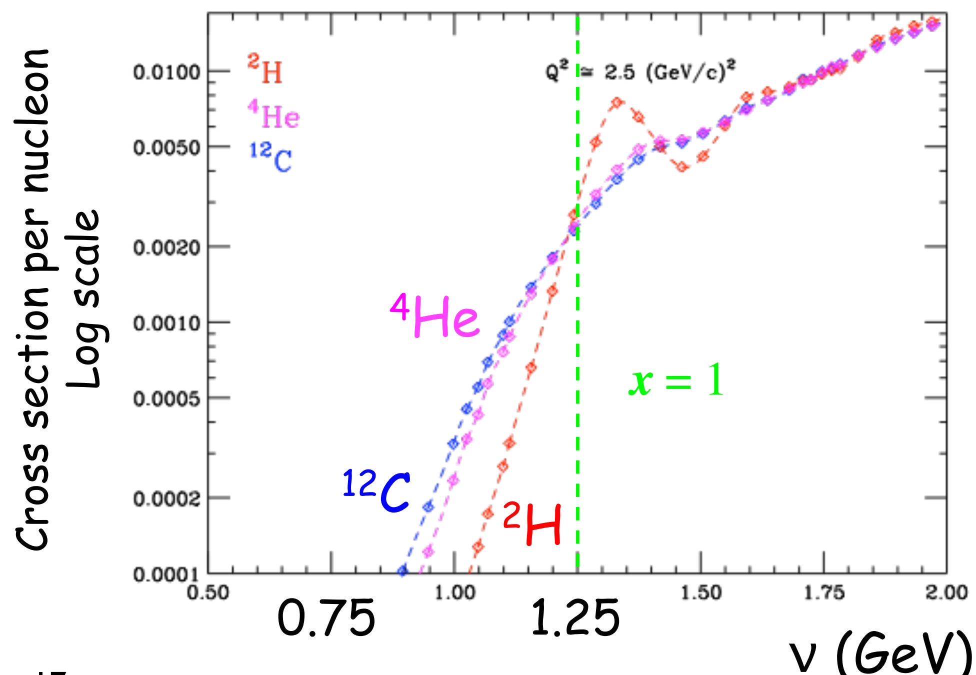
compared to Fermi model:fit parameter $k_F$ and ε

# Nuclear mass (A) dependence




Heavier nucleus
➔higher nucleon momenta
➔broadened peak

(same plot, log scale)

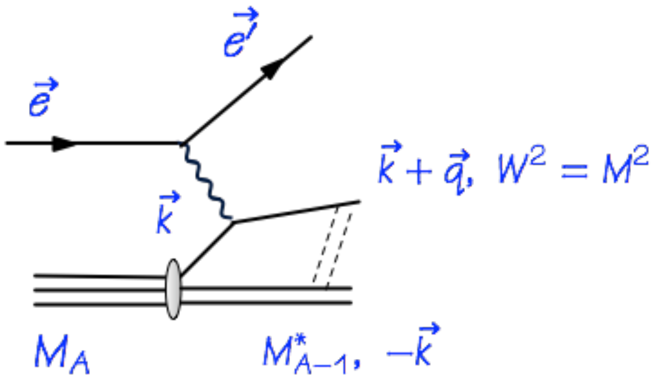



$$x = Q^2 / (2 m_p \nu)$$

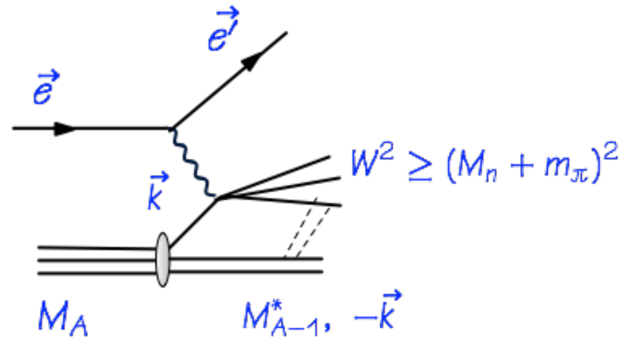
$$x = 1 \rightarrow \nu = Q^2 / (2 m_p)$$

# Inclusive Electron Scattering from Nuclei: Two processes

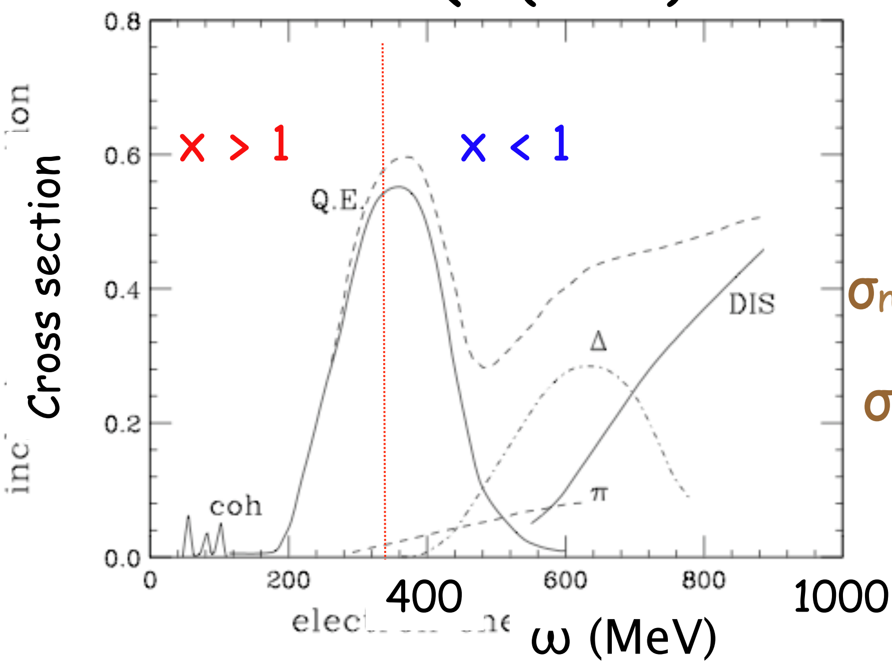
Quasielastic from nucleons




Inelastic from nucleons (including Deep Inelastic Scattering (DIS))




$x = Q^2/(2m\omega)$

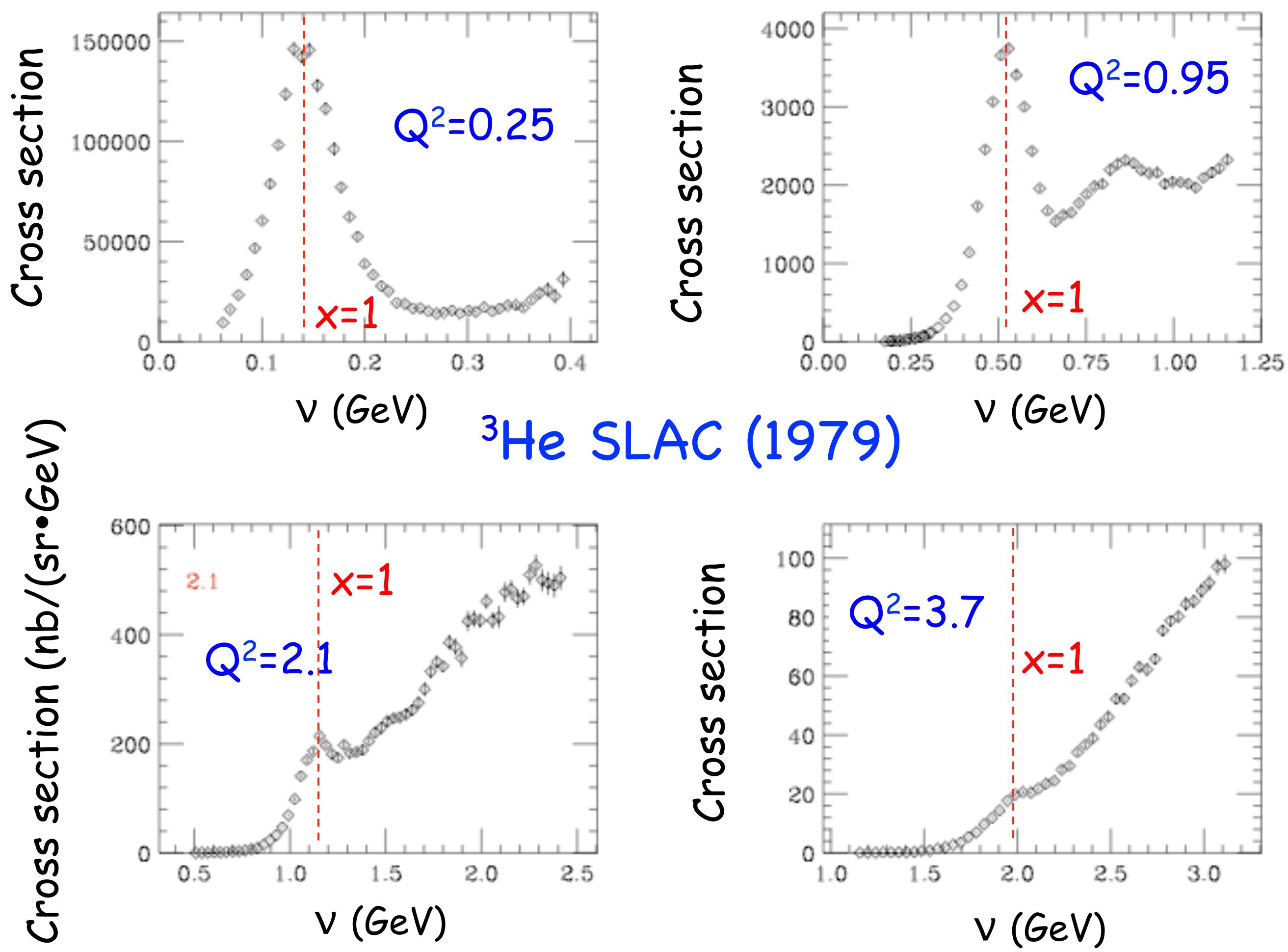



Inclusive final state means cannot separate two processes

Exploit their different $Q^2$ dependencies

$\sigma_{nucleon} \sim$ (nucleon elastic form factor)$^2$

$\sigma_{DIS} \sim \ln(Q^2)$ (at large $Q^2$)




- As $Q^2 \gg 1$ inelastic scattering from the nucleons begins to dominate
- Quasi Elastic scattering is still dominant at low energy loss ($\nu$), even at high $Q^2$

# Scaling

- The dependence of a cross section, in certain kinematic regions, on a single variable.
  - If the data scales, it validates the scaling assumption
  - Scale-breaking indicates new physics
- At moderate $Q^2$ and $x>1$ we expect to see evidence for y-scaling, indicating that the electrons are scattering from quasifree nucleons
  - $y$ = minimum momentum of struck nucleon
- At high $Q^2$ we expect to see evidence for x-scaling, indicating that the electrons are scattering from quarks.
  - $x = Q^2/2m\nu$ = fraction of nucleon momentum carried by struck quark (in infinite momentum frame)

# Classical Scaling

Galileo realized that that if one simply scaled up an animals size its weight would increase significantly faster than its strength, "....you can plainly see the impossibility of increasing the size of structures to vast dimensions...if his height be increased inordinately, he will fall and be crushed under his own weight"


$$\frac{\text{Strength}}{\text{Weight}} \propto \frac{\text{Area}}{\text{Volume}} \propto \frac{L^2}{L^3} \propto \frac{1}{\text{Weight}^{1/3}}$$

Smaller animals appear stronger

Explains why small animals can leap as high as large one ...

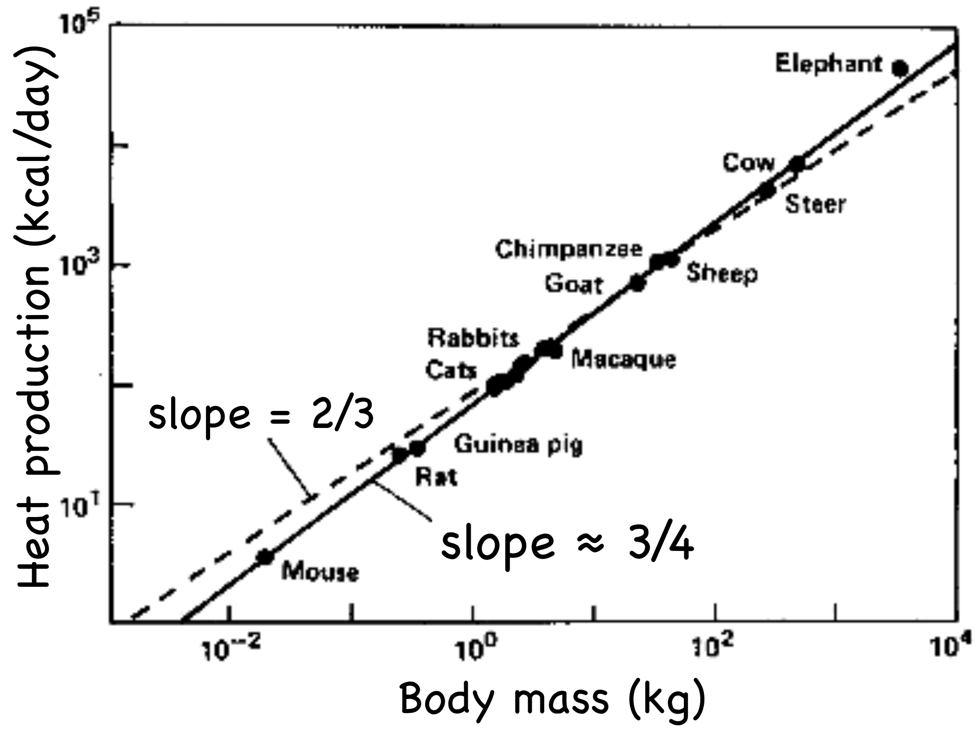
G. West, LANL report

# Metabolism

Metabolic rate B: heat lost by a body in a steady inactive state

Should be dominated by sweating and radiation (proportional to surface area or weight$^{2/3}$)

$B \propto W^{2/3}$

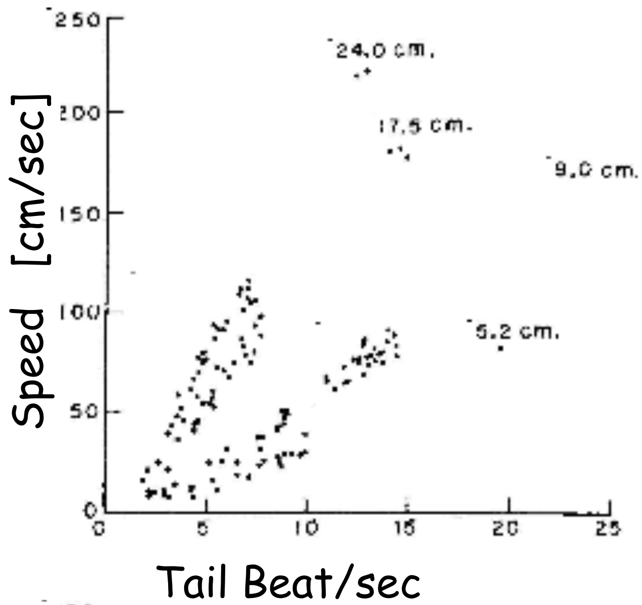


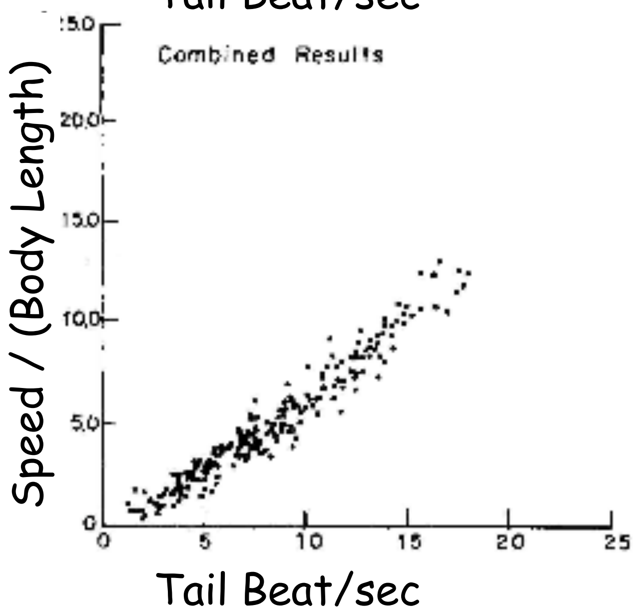

Best fit slope ≈ 3/4
Therefore not just pure geometry
- Different shape animals
- Different insulation (elephants have less fur)

Deviations from the geometrical or kinematic analysis reflects the dynamics of the system.

Deviations from naive scaling probe other features of the system

# Scaling: Selecting the relevant variables



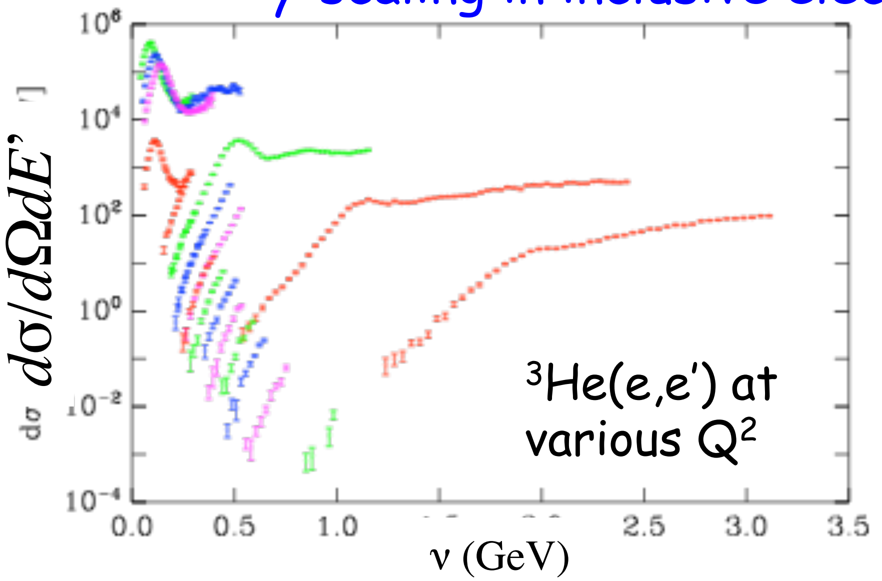



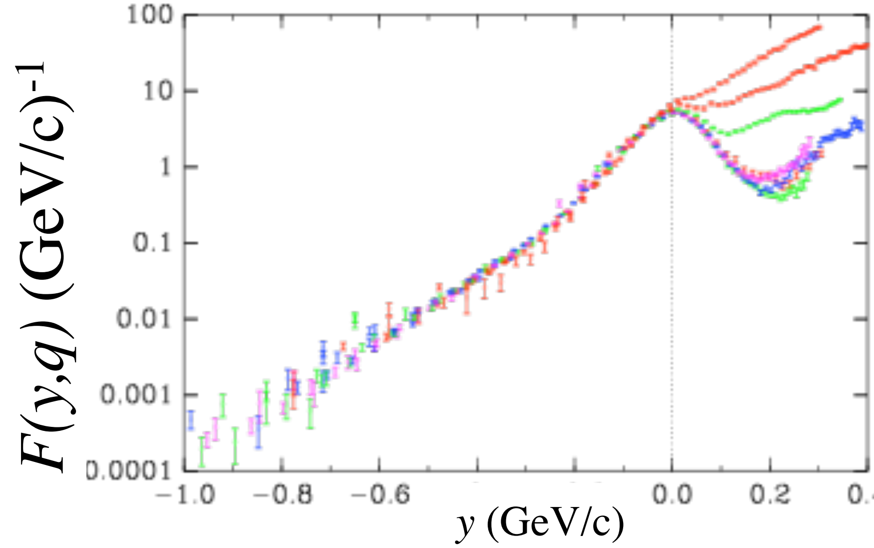

The Dace, a fresh water fish

Scaling and scaling violations reveal information about the dynamics of the system

Knut Schmidt-Nielsen, from Scaling: Why is Animal Size So Important?

# y-scaling in inclusive electron scattering from $^3$He




$$F(y) = \frac{\sigma^{\exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$$

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.

y is the momentum of the struck nucleon parallel to the momentum transfer:
$y \approx -q/2 + m\nu/q$ (nonrelativistically)

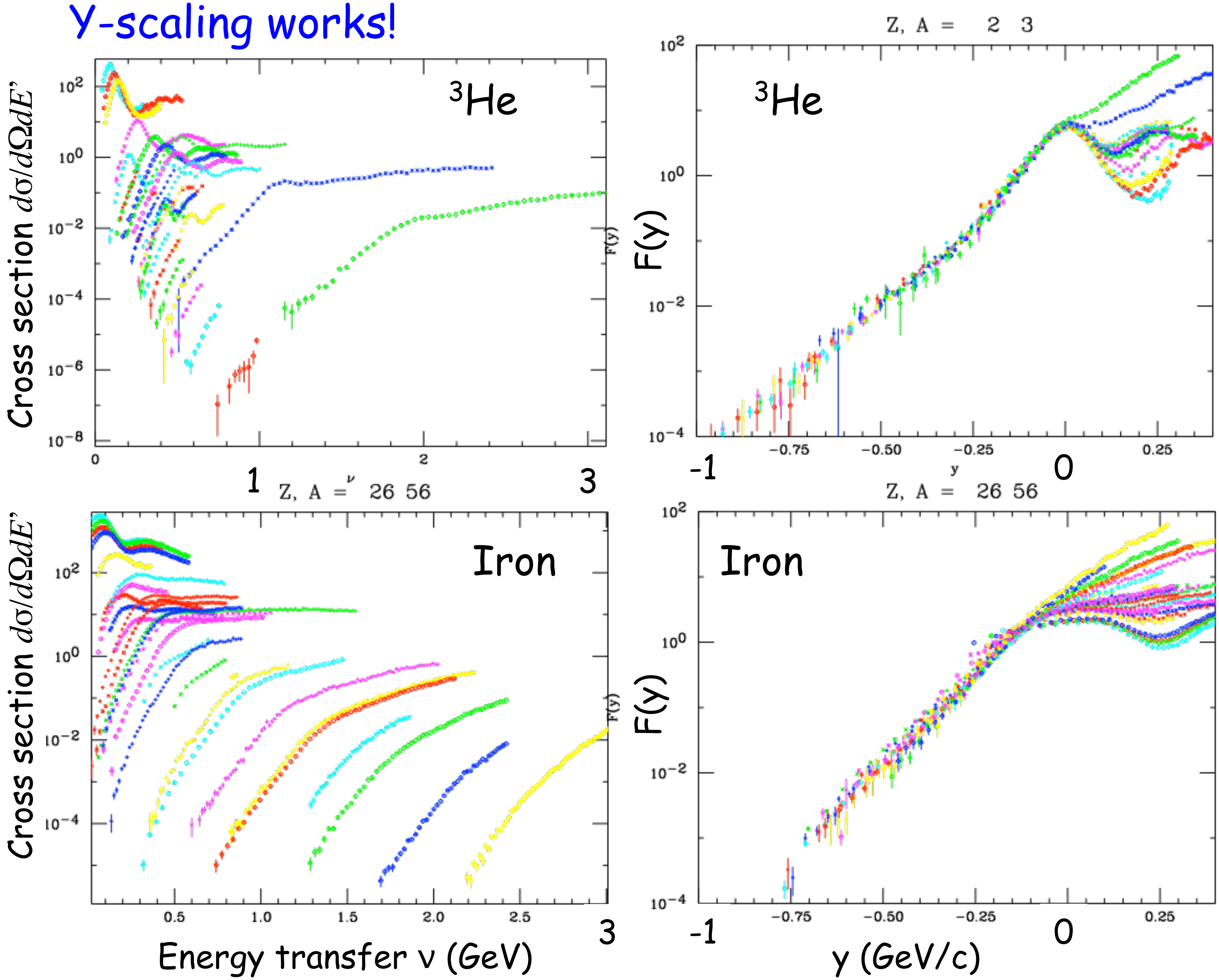
IF the scattering is quasifree, then $F(y)$ is the integral over all perpendicular nucleon momenta (nonrelativistically).

Goal: extract the momentum distribution $n(k)$ from $F(y)$.

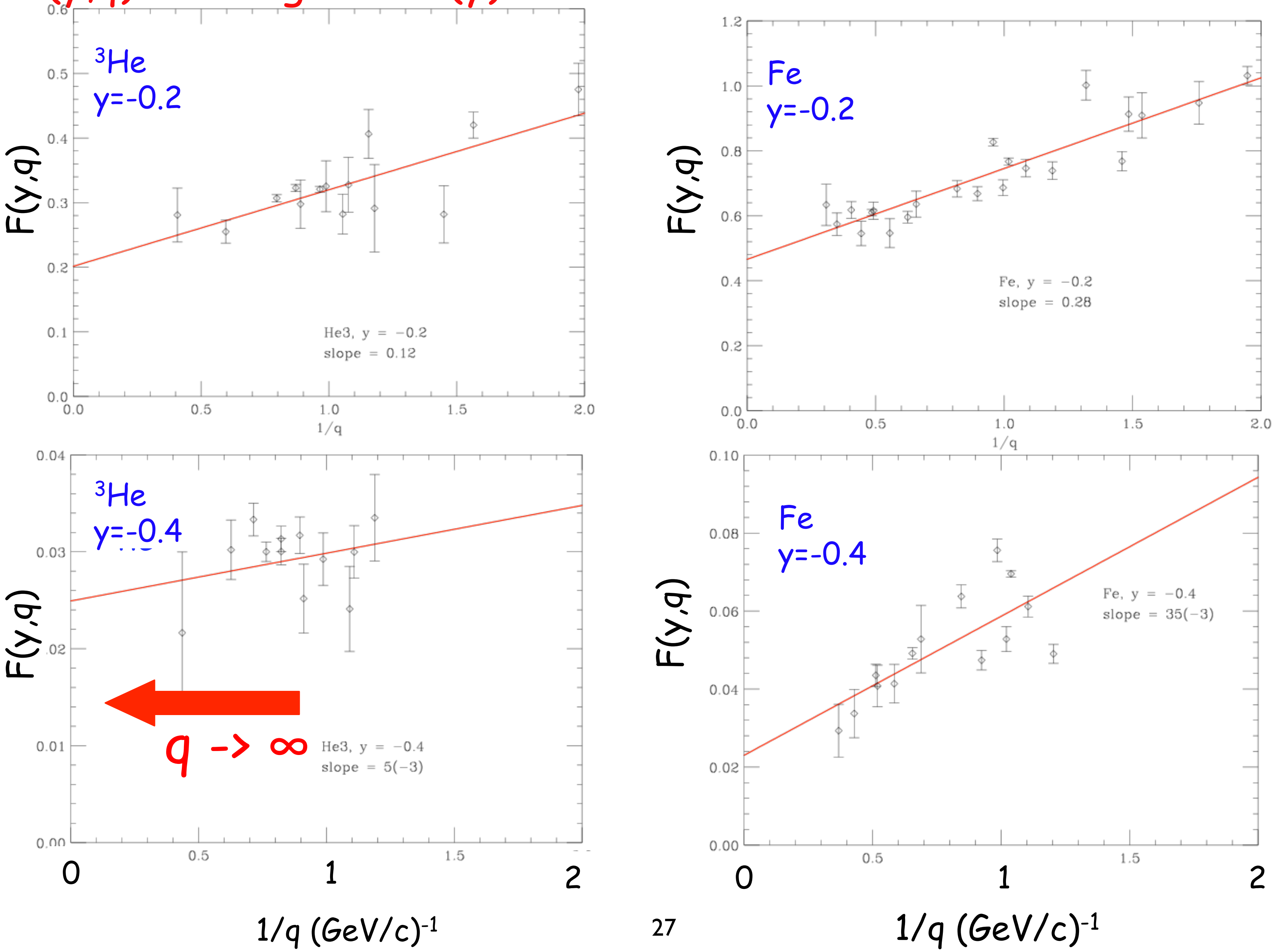
# Assumptions & Potential Scale Breaking Mechanisms

- No Final State Interactions (FSI)
- No internal excitation of (A-1)
- Full strength of Spectral function can be integrated over at finite $q$
- No inelastic processes (choose $y<0$)
- No medium modifications (discussed later)

# Y-scaling works!



# F(y,q) converges to F(y) at moderate momentum transfer





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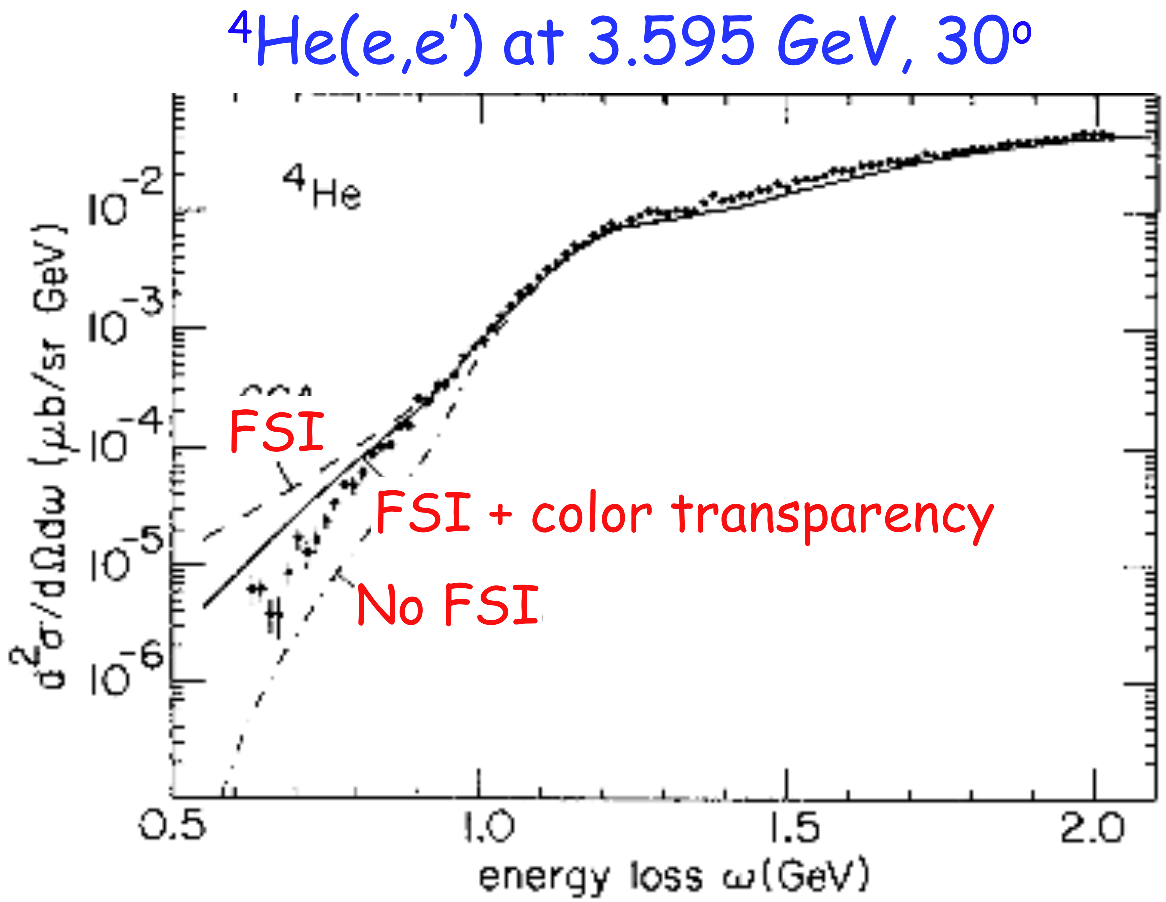
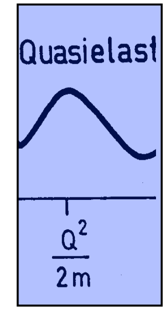
# Final State Interactions (FSI) complicate this simple picture




Benhar et al. PRC 44, 2328
Benhar, Pandharipande, PRC 47, 2218
Benhar et al. PLB 3443, 47

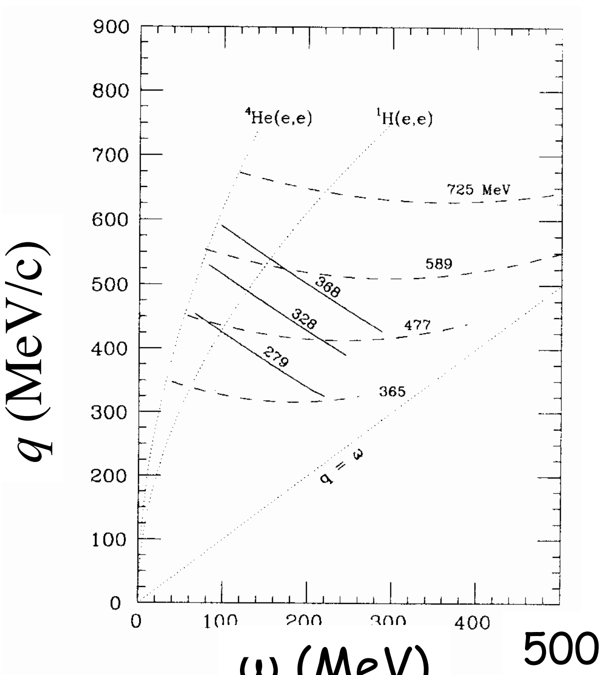
# Now let's separate $R_L$ (longitudinal) and $R_T$ (transverse): $^4$He(e,e')

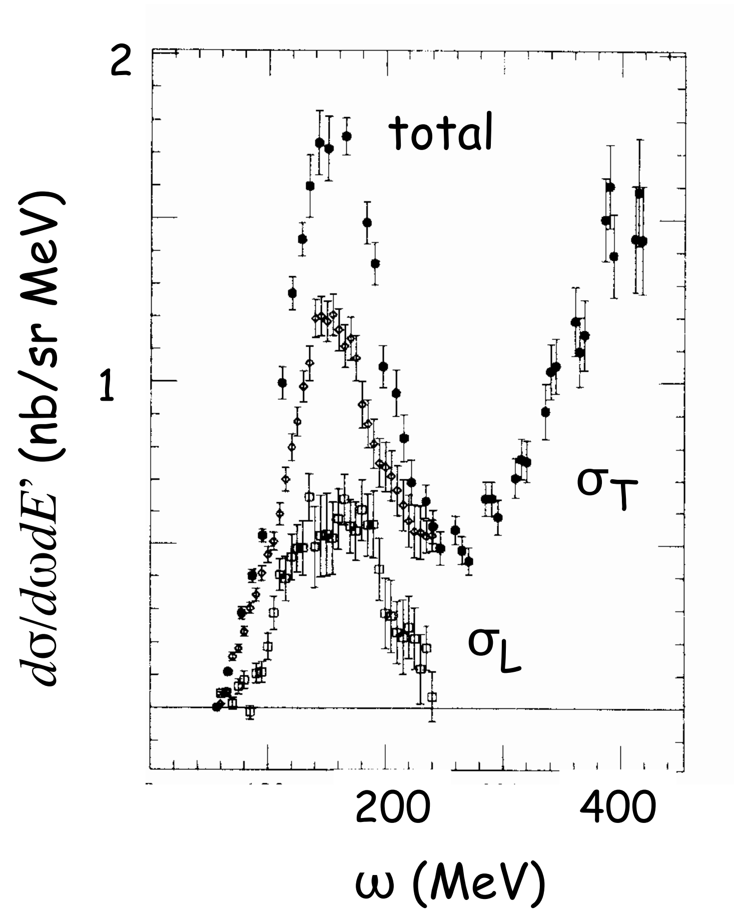



$$\frac{d\sigma}{d\Omega dE} = \sigma_M \frac{E'}{E} \left[ \frac{Q^4}{\vec{q}^4} R_L(Q^2,\omega) + \left( \frac{Q^2}{2\vec{q}^2} + \tan^2\frac{\theta}{2} \right) R_T(Q^2,\omega) \right]$$

Fix $Q^2$ and $\omega$

1. Measure $d\sigma/d\omega dE'$ at large $E_e$ and small $\theta$
2. Measure $d\sigma/d\omega dE'$ at small $E_e$ and large $\theta$
3. Take linear combination to extract $R_L$, $R_T$

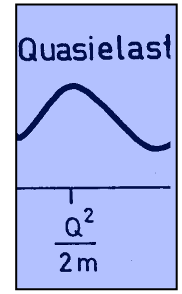


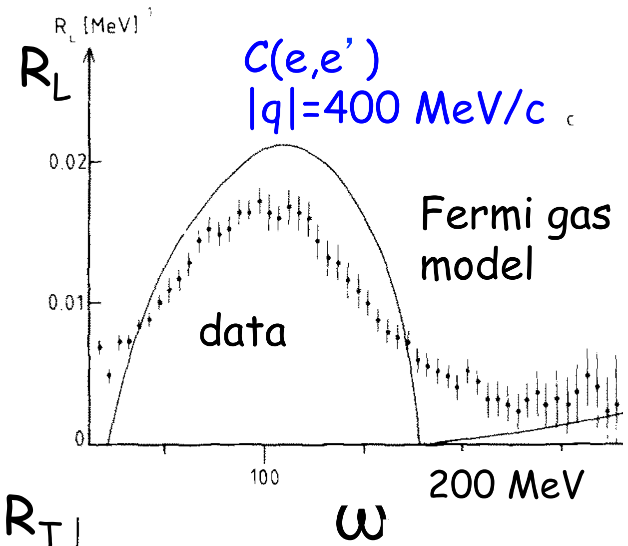




Von Reden et al, PRC 41, 1084 (1990)

# Fermi Gas Model: Too good to be true?

$$\frac{d\sigma}{d\Omega dE} = \sigma_M \frac{E'}{E}\left[\frac{Q^4}{\vec{q}^4}R_L(Q^2,\omega) + \left(\frac{Q^2}{2\vec{q}^2}+\tan^2\frac{\theta}{2}\right)R_T(Q^2,\omega)\right]$$



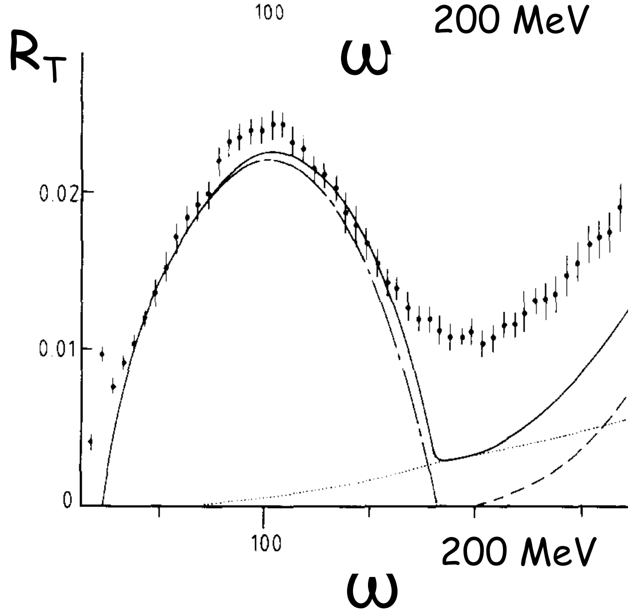

$y$ = minimum initial nucleon momentum

= $m\omega/q$ - $q/2$ (nonrelativistic only!)

$f$ = reduced response function

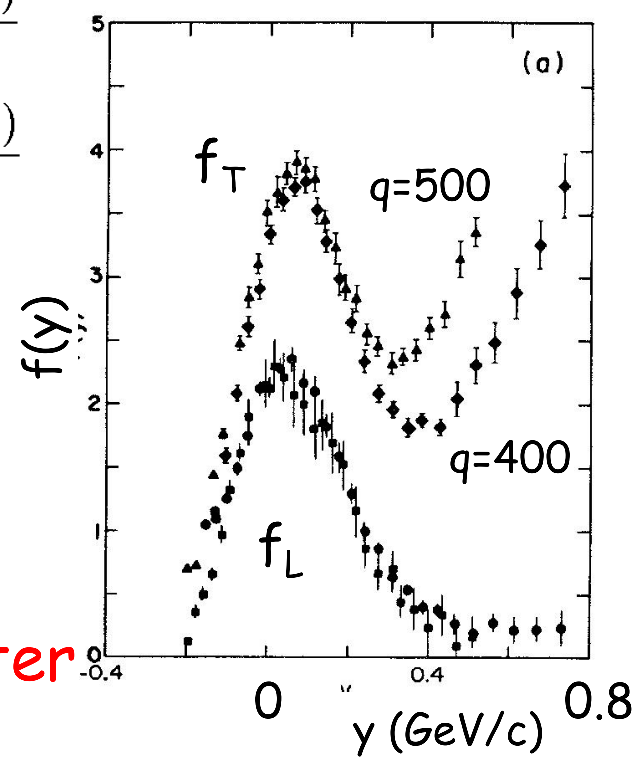
$$f_L(Q^2,\omega) \propto \frac{R_L(Q^2,\omega)}{\tilde{G}_E^2(Q^2)}$$

$$f_T(Q^2,\omega) \propto \frac{R_T(Q^2,\omega)}{\tilde{G}_M^2(Q^2)}$$



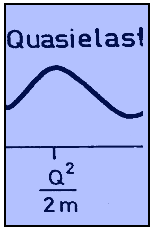

- L scales
- T scales
- T≠L!!

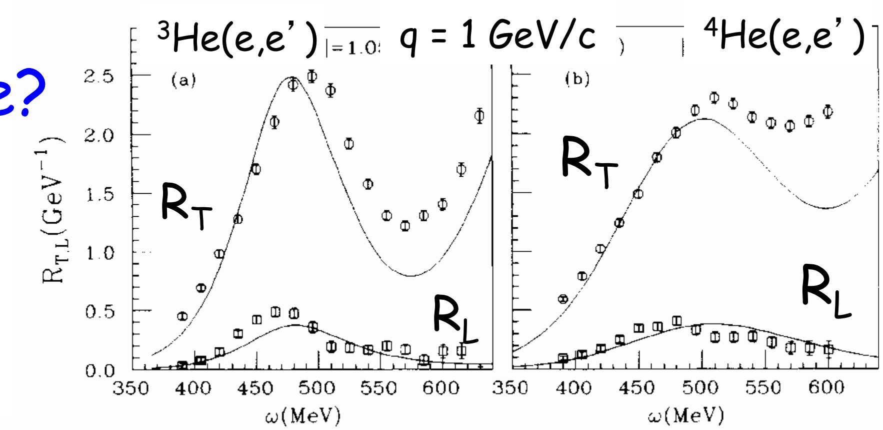
To be explained later

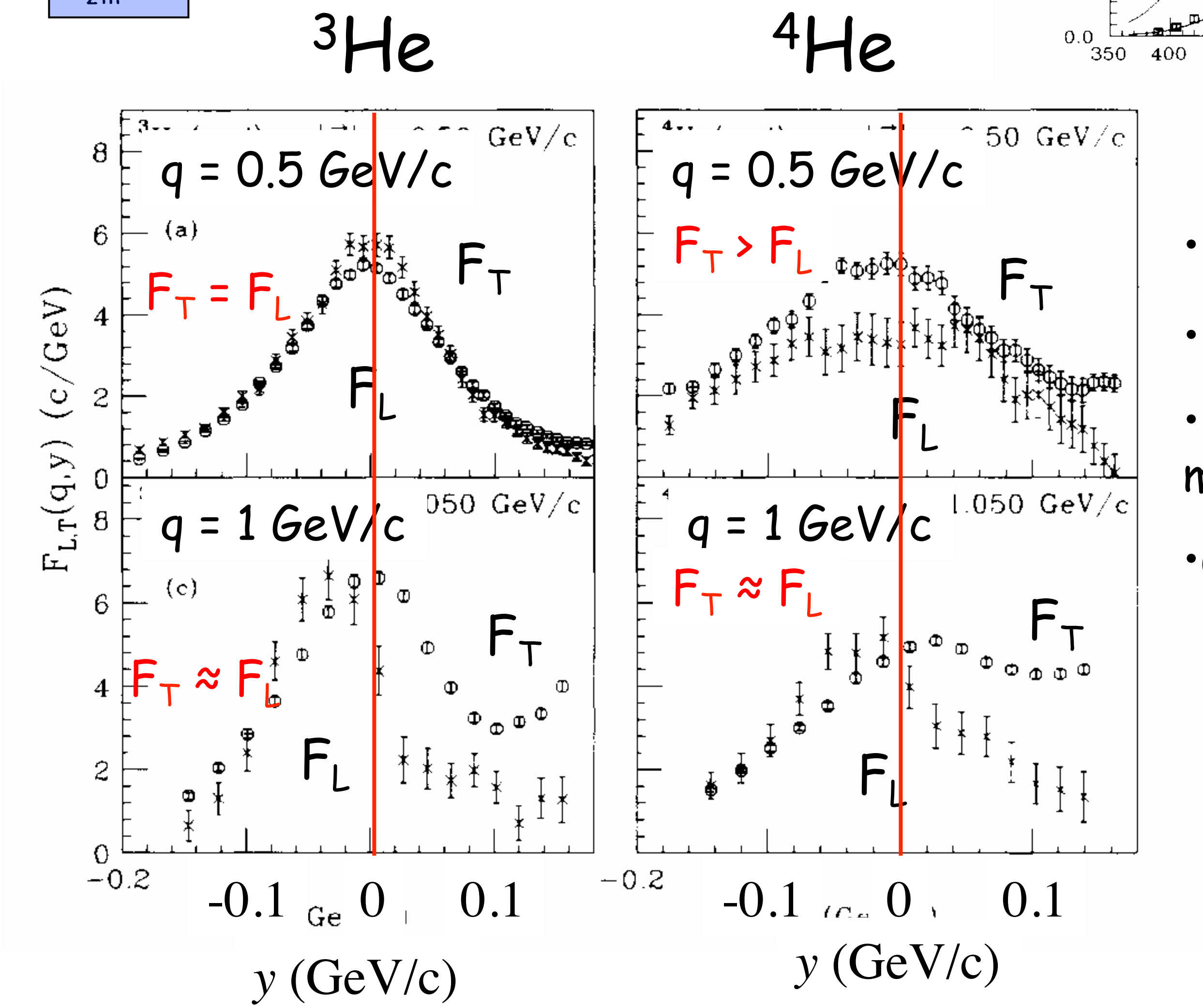



P. Barreau et al, NPA 402, 515 (1983)
Finn et al, PRC 29, 2230 (1984)

# What causes the T/L difference?




- $^3$He: $F_T = F_L$ (at y < 0)
- $^4$He and C: $F_T > F_L$
- Extra transverse reaction mechanism in dense nuclei!
- Gets smaller at higher q

What is it?
To be continued …

Meziani et al, PRL 69 41 (1992)

# (e,e′) summary

- Go to low ω side of QE peak ($y<0$ or $x>1$)
- Scaling ⟹ knockout is quasifree
- Measure momentum distribution of nucleons in nuclei
- But there are some complications

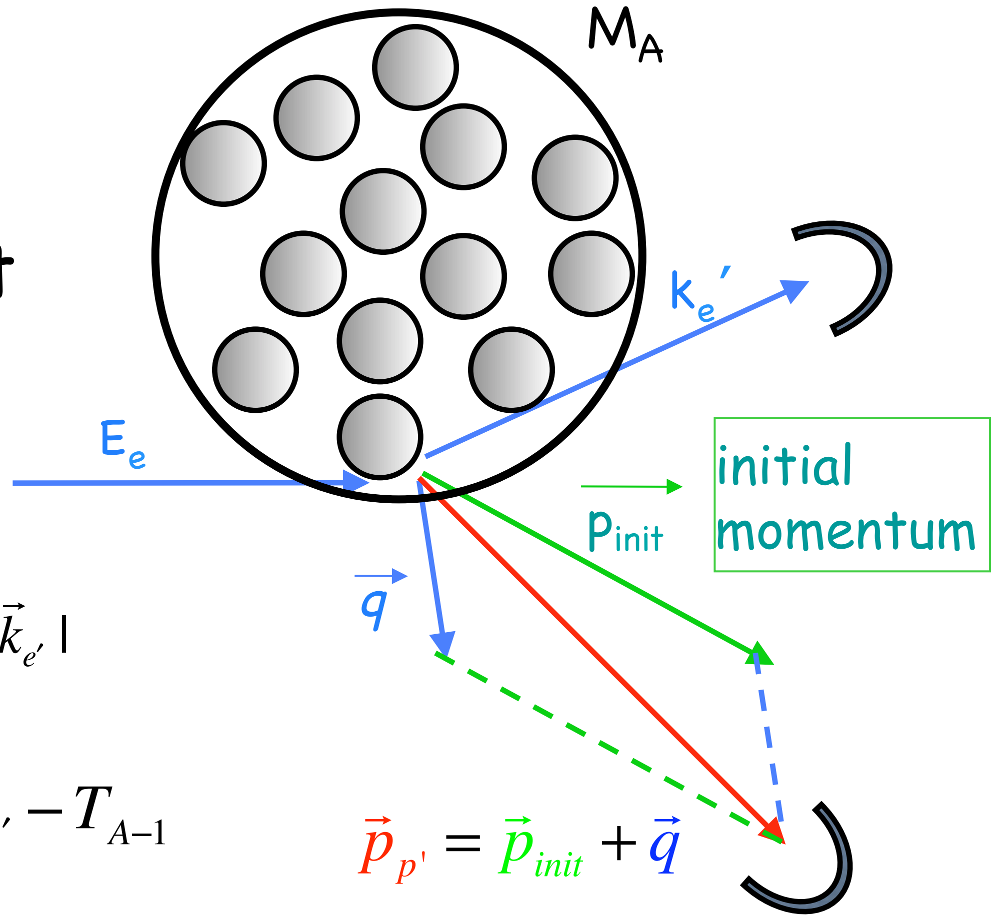
# Get more information:

# Detect the knocked out nucleon (e,e'p)

## coincidence experiment

measure: momentum, angles

electron energy: $E_e$
proton: $\vec{p}_{p'}$
scattered electron: $\vec{k}_{e'}$ $\quad E_{e'} = |\vec{k}_{e'}|$




reconstructed quantites:

missing energy: $E_m = \nu - T_{p'} - T_{A-1}$

missing momentum: $\vec{p}_m = \vec{q} - \vec{p}_{p'}$

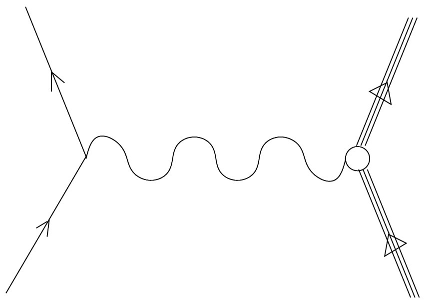
in Plane Wave Impulse Approximation (PWIA):
direct relation between measured quantities and theory:

$$|E| = E_m \qquad \vec{p}_{init} = -\vec{p}_m$$

# Formalism (repeat from previous lecture)

- Inclusive scattering:
  - measure scattering angle $\theta_e$ and energy $E'_e$ ($\nu = E_e - E'_e$) and the cross section $d\sigma/d\Omega d\nu$
- One photon exchange:

$$\mathcal{M}_n = \frac{e^2}{q^2}\bar{u}(k')\gamma_\mu u(k) < n|J_\mu(0)|p, S >$$



$$d\sigma = \frac{1}{4M\vec{k}}\sum_n |\mathcal{M}_n|^2(2\pi)^4\delta^4(p+q-p')\frac{d^3k'}{(2\pi)^3 2E'}$$

$$= \frac{|\vec{k}'|}{ME}\frac{\alpha^2}{Q^4}L^{\mu\nu}H_{\mu\nu}d\omega d\Omega$$

$L^{\mu\nu}$ and $H_{\mu\nu}$ are the lepton and hadron tensors

# Formalism Extension to (e,e'p)

Lepton tensor known (QED):

$$L_{\mu\nu} = \sum_{s'} (\bar{u}(k',s')\gamma_\mu u(k,s))^* (\bar{u}(k',s')\gamma_\nu u(k,s))$$
$$= 2(k_\mu k'_\nu + k_\nu k'_\mu) + q^2 g_{\mu\nu} + 2im_l \epsilon_{\mu\nu\alpha\beta} q^\alpha s_l^\beta$$

Spin dependent

Unchanged

Hadron tensor unknown:

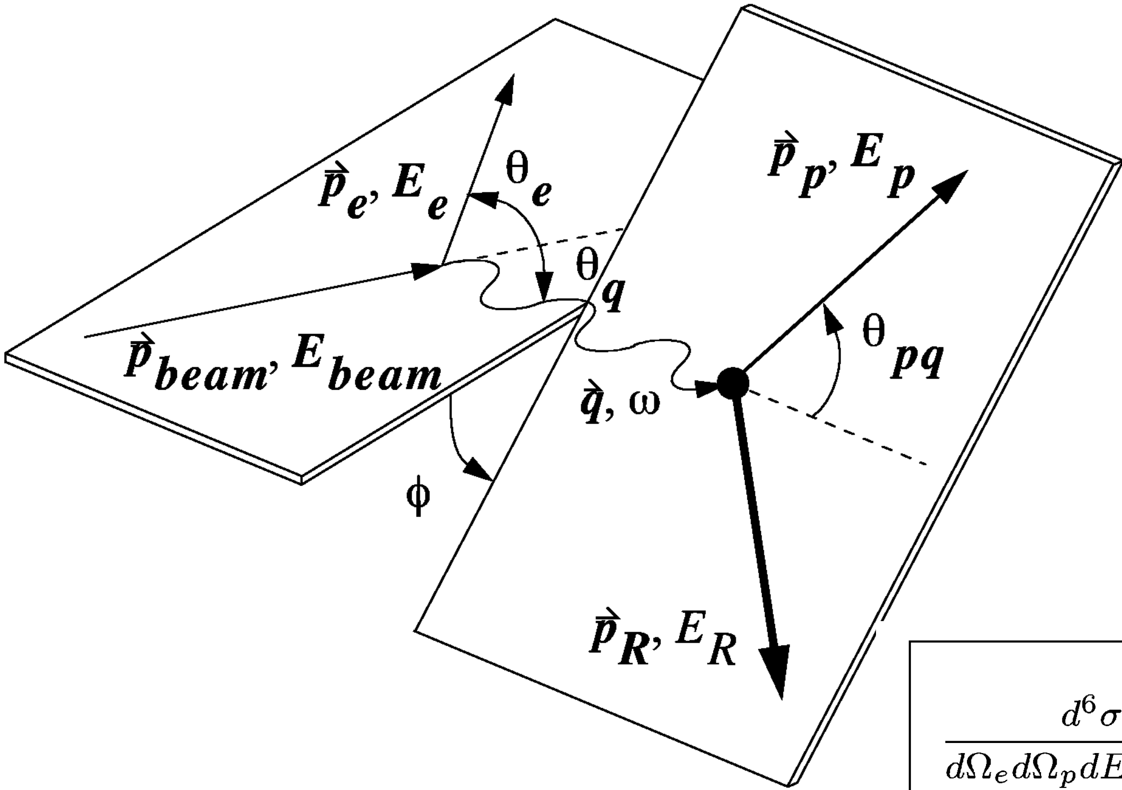
$$H_{\mu\nu} = \frac{1}{4\pi}\sum_n < p,S|\hat{J}_\mu(0)|n >< n|\hat{J}_\nu(0)|p,S > (2\pi)^4 \delta^4(p+q-p')$$
$$= \frac{1}{4\pi}\int d^4\xi \exp(iq\cdot\xi) < p,S|[\hat{J}_\mu(\xi),\hat{J}_\nu(0)]\,|p,S >$$

Nuclear current operators

Now we have another 4-vector (p') to make our Lorentz scalars and tensors from.

Available independent four vectors for (e,e'p):

- target momentum $p_\mu$
- photon momentum $q_\mu$
- proton momentum $p'_\mu$ (new for (e,e'p))




$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_{\text{miss}} d\omega} = K\sigma_{\text{Mott}} \left[ v_L \mathbf{R_L} + v_T \mathbf{R_T} + v_{LT} \mathbf{R_{LT}} \cos(\phi) + v_{TT} \mathbf{R_{TT}} \cos(2\phi) \right]$$

where

$$K = \text{(phase space)}$$
$$\sigma_{\text{Mott}} = \text{(relativistic Rutherford scattering)}$$
$$v = v\ (q, \omega)\ \text{(electron kinematics)}$$

## And then there were four (response functions, that is)

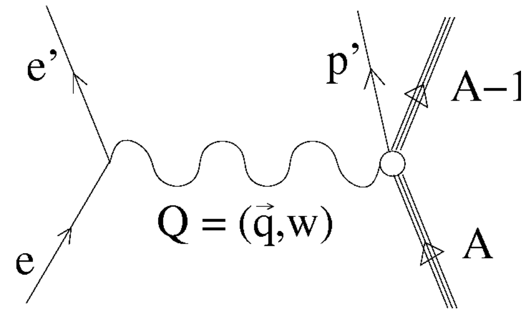
Each R now depends on more variables

$R = R(q, \omega, p_{miss}, E_{miss})$

(When you include electron and proton spin, there are 18. Yikes!)

(And if you scatter from a polarized spin-1 target, there are 41. Double Yikes!!)

# (e,e'p) Plane Wave Impulse Approximation (PWIA)



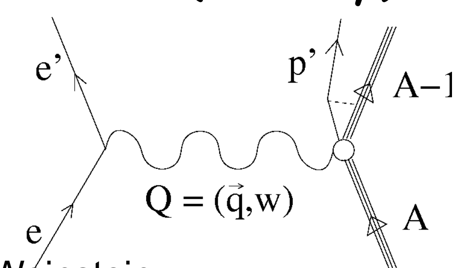

1. Only one nucleon absorbs the virtual photon
2. That nucleon does not interact further
3. That nucleon is detected

Cross section factorizes:

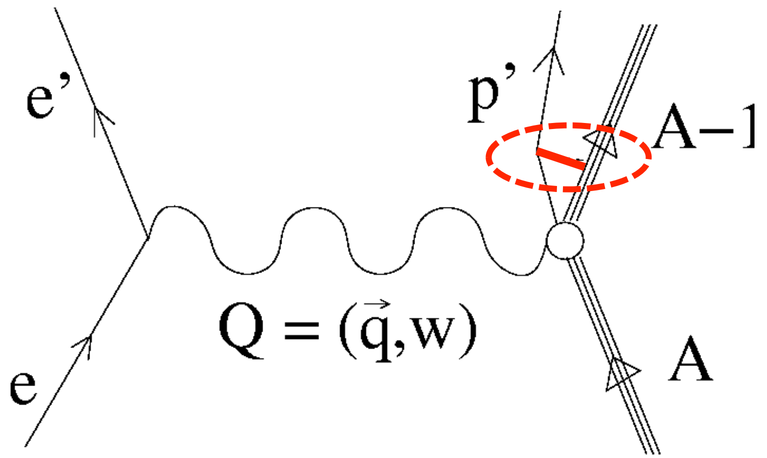
$$\frac{d\sigma^{fi}}{dE_1 d\Omega_1 dE_2 d\Omega_2} = KS(\vec{k},E)\frac{d\sigma^{free}}{d\Omega}$$

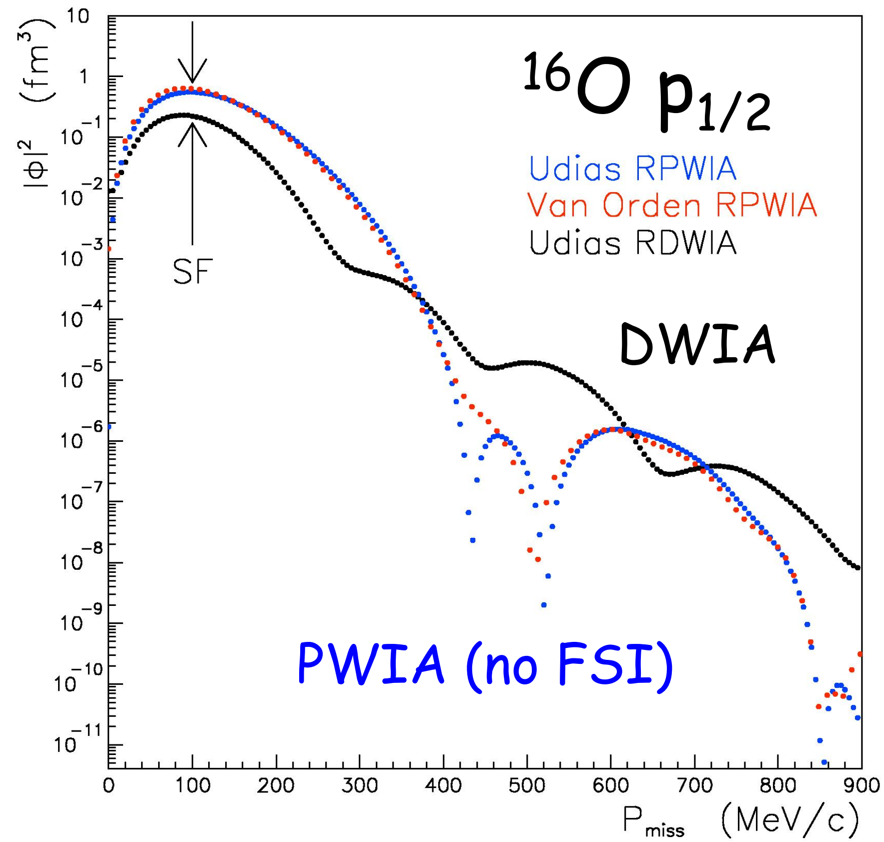
Single nucleon pickup reactions [eg: (p,d), (d,$^3$He) …] are also sensitive to S(p,E) but only sensitive to surface nucleons due to strong absorption in the nucleus

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



# (e,e'p) Distorted Wave Impulse Approximation (DWIA)



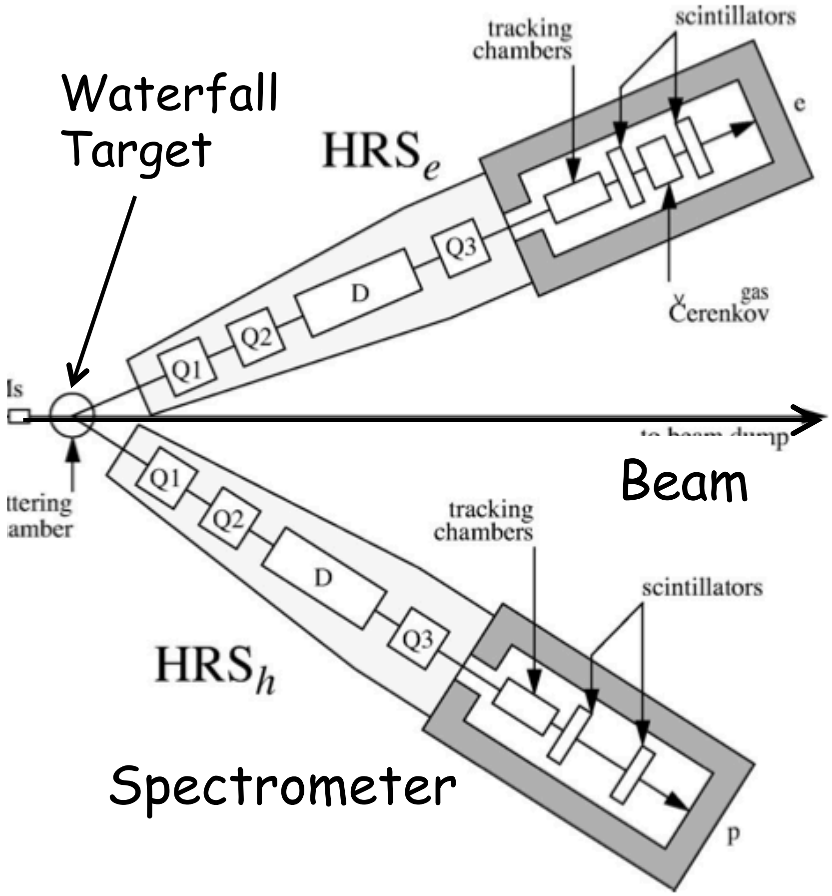



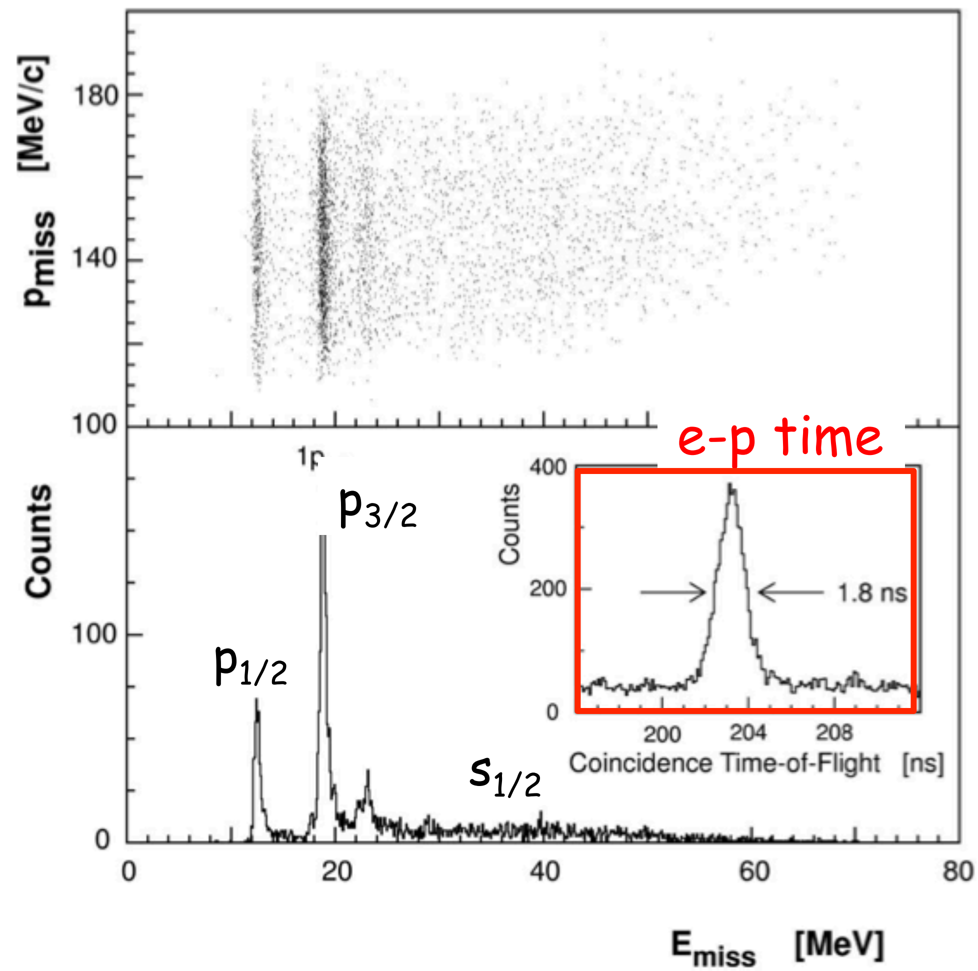

A. Pickelsimer and J.W. Van Orden, Phys. Rev. C. **40**, 290 (1989)
J. M. Udías et al., Phys. Rev. C. **64**, 024614 (2001)

- Low momentum ($p < 0.5$ GeV/c): use optical potential
- High momentum ($p > 1$ GeV/c): use Glauber approximation

Distortions (FSI) make it harder to measure the nucleon initial momentum distributions, especially at high momenta

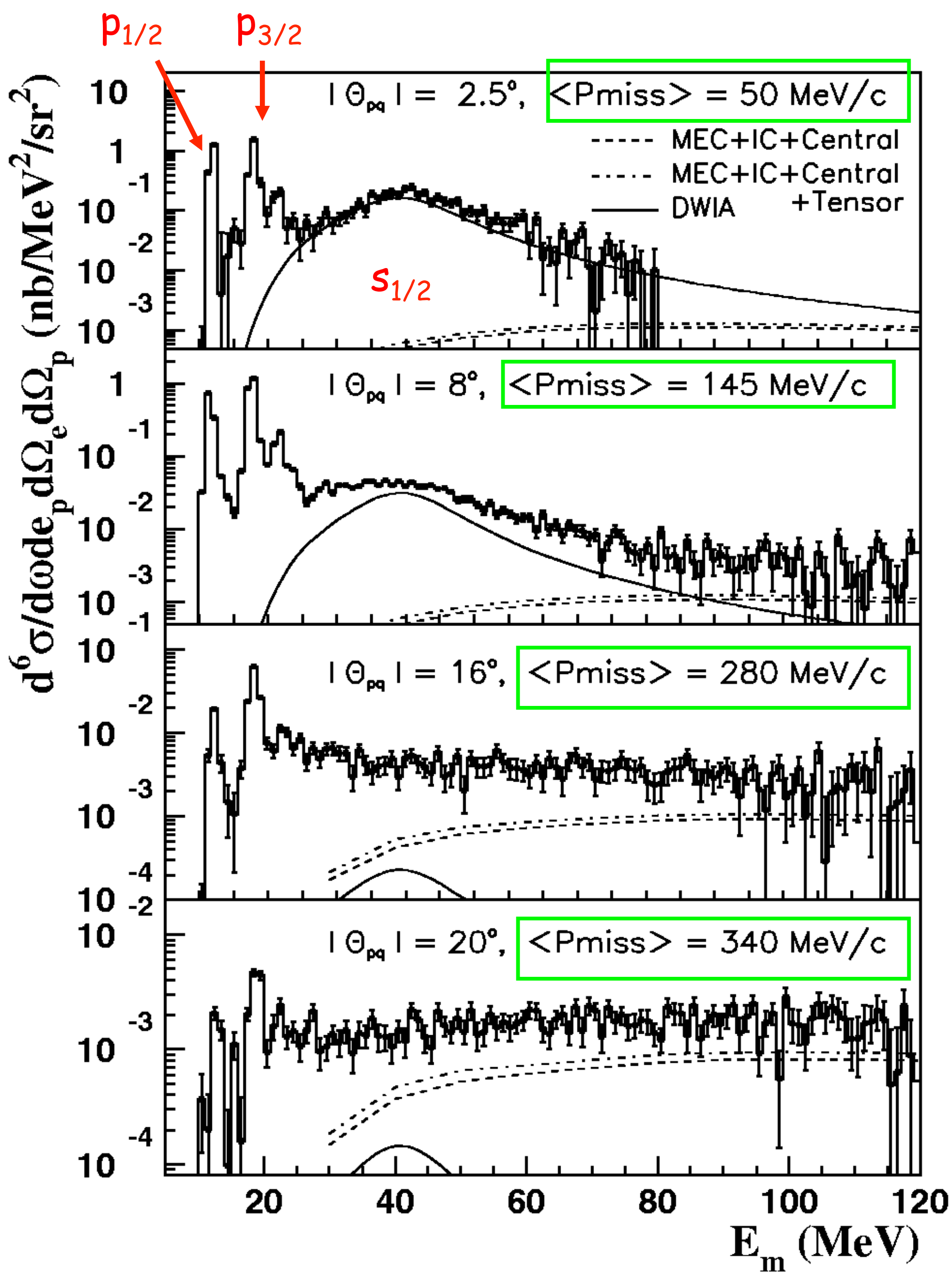
# Measuring O(e,e'p) in Hall A

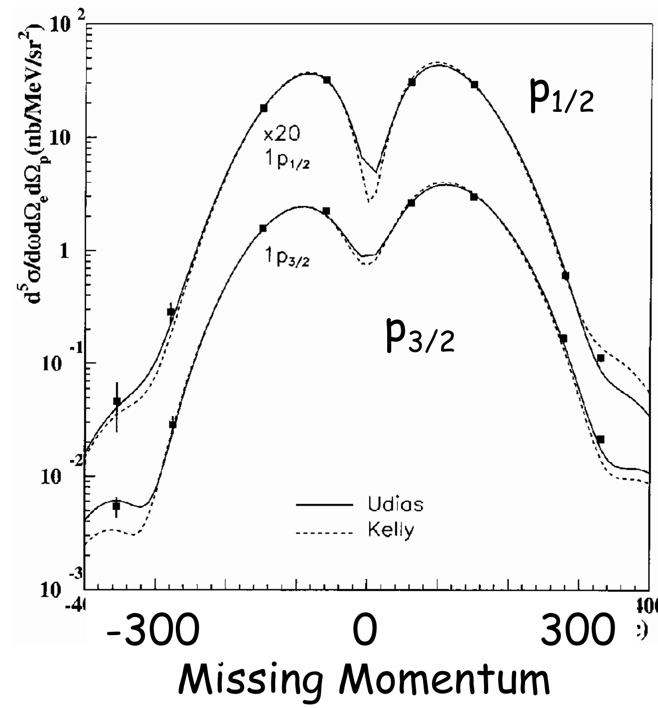



Fissum et al, PRC 70, (2004) 034606

# O(e,e'p) and shell structure



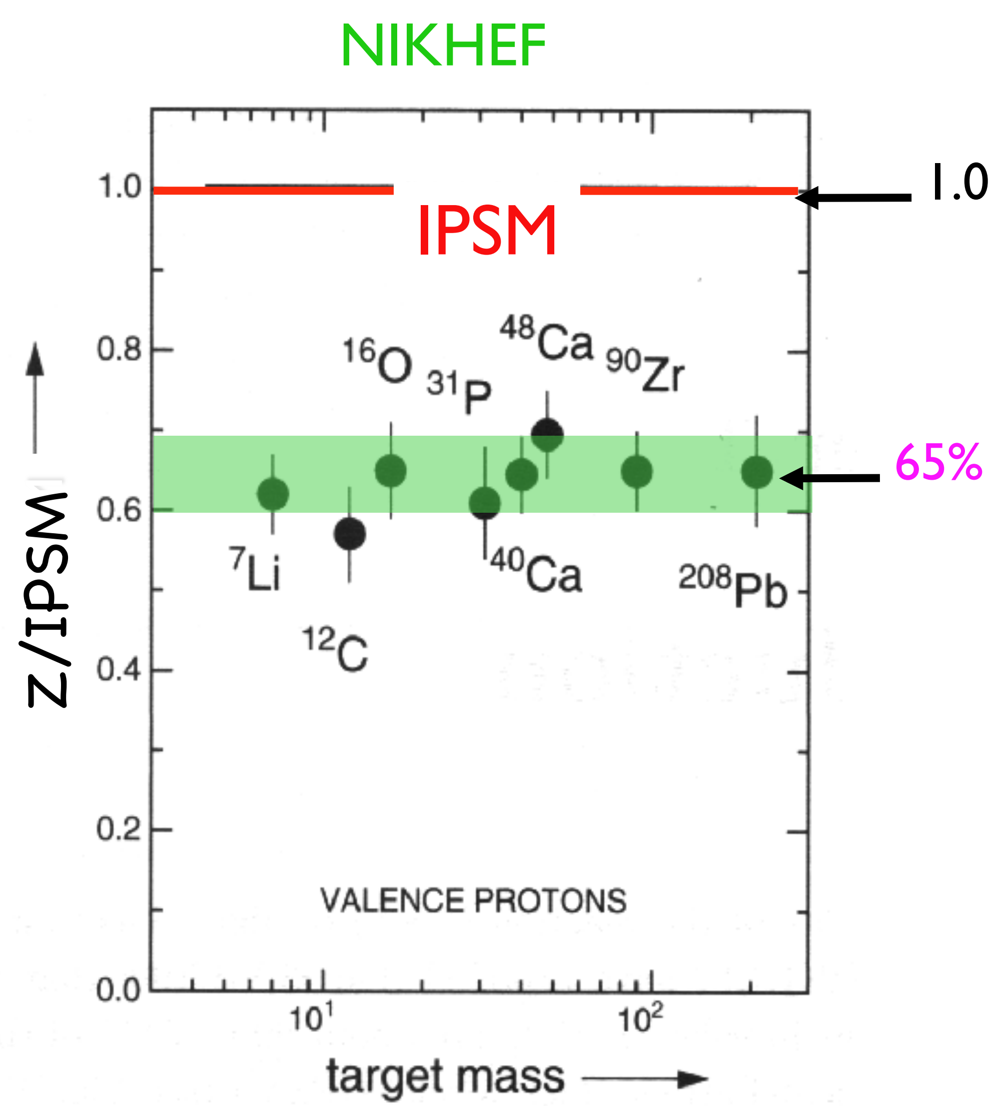




$1p_{1/2}$, $1p_{3/2}$ and $1s_{1/2}$ shells visible

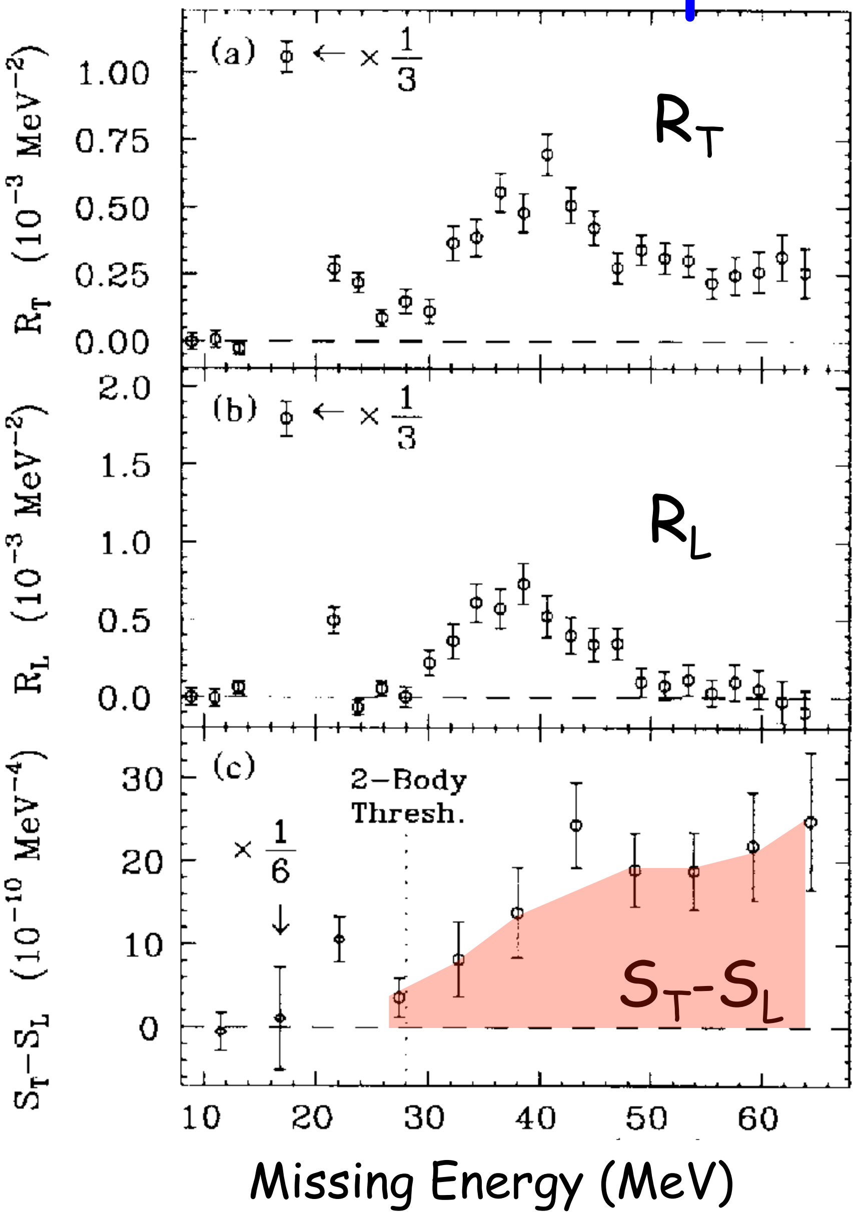
Momentum distribution as expected for $l = 0, 1$

Fissum et al, PRC 70, 034606 (2003)

# But we do not see enough protons!



# Now separate $R_L$ and $R_T$




$^{12}C(e,e'p)$
$q = 0.4$ GeV and $x = 1$

($S_T$ and $S_L$ are just scaled versions of $R_T$ and $R_L$.)

There is extra transverse strength starting at the two-nucleon knockout threshold

Ulmer et al, PRL 59, 2259 (1987); Dutta et al, PRC 61, 061602 (2000)

# (e,e'p) summary

- Measure shell structure directly
- Measure nucleon momentum distributions
- Extra transverse strength seen in (e,e') due to:
    - Two nucleon knockout via
    - Meson exchange currents and correlations
- But:
    - Not enough nucleons seen!

# Short Range Correlations (SRCs)

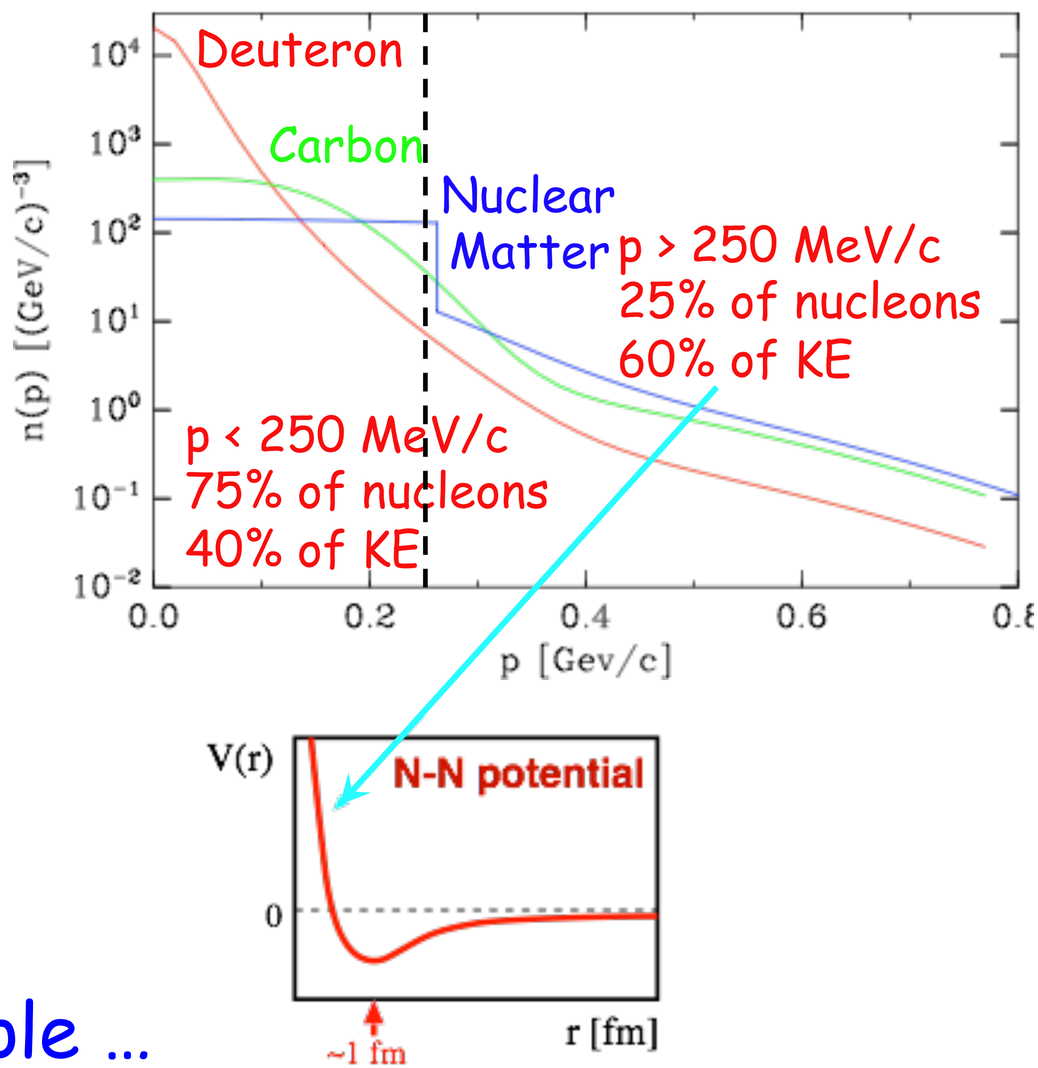
Mean field contributions: $p < p_{Fermi} \approx 250$ MeV/c
Well understood, Spectroscopic Factors ≈ 0.65

High momentum tails: $p > p_{Fermi}$
Calculable for few-body nuclei, nuclear matter.
Dominated by two-nucleon short range correlations

Poorly understood part of nuclear structure

NN potential models not applicable at p > 350 MeV/c

Uncertainty in SR interaction leads to uncertainty at $p > p_{Fermi}$, even for simplest systems




## Nucleons are like people …

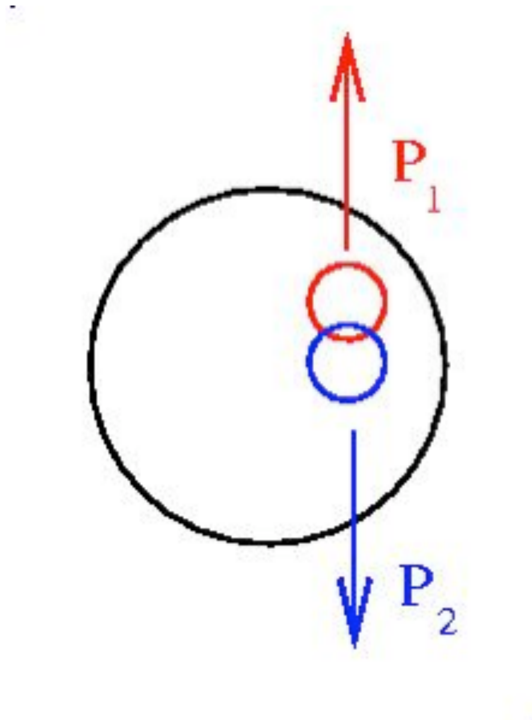
# What are Correlations?

Average Two Nucleon Properties in the Nuclear Ground State

Not Two-Body Currents

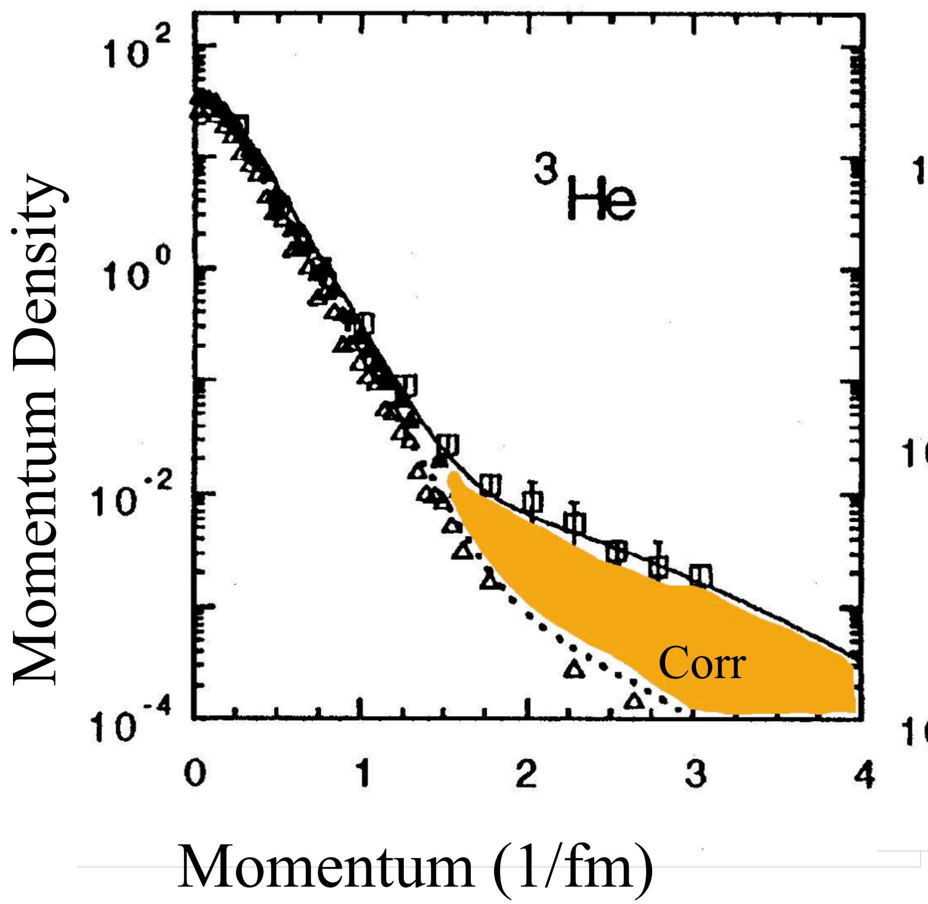
## An Experimentalist's Definition:

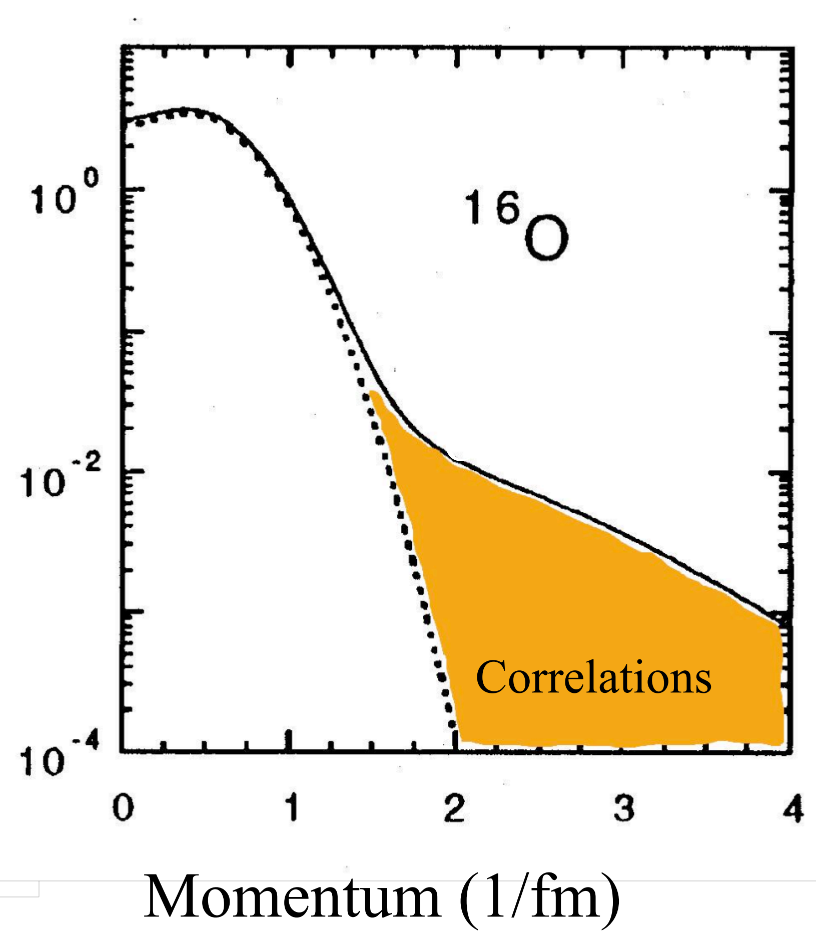
- A high momentum nucleon whose momentum is balanced by **one** other nucleon
  - NN Pair with
    - Large Relative Momentum
    - Small Total Momentum
- Whatever a theorist says it is



# Why are Correlations Interesting?

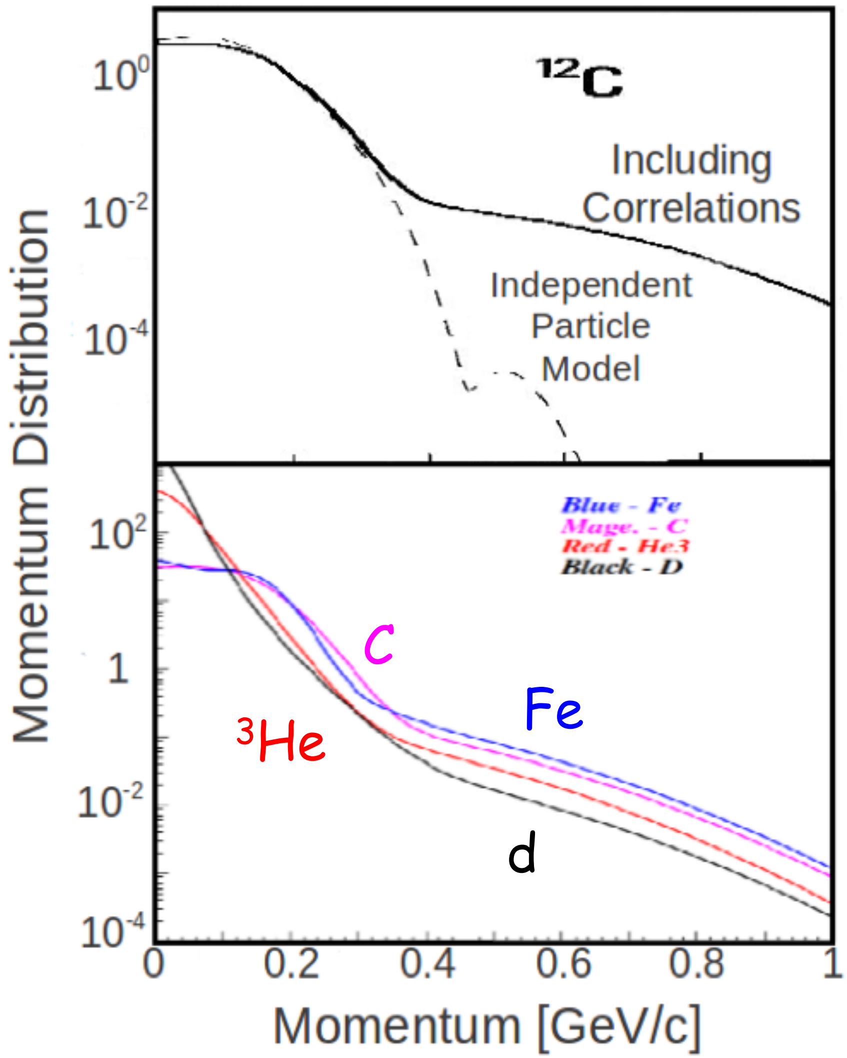
Responsible for high momentum part of Nuclear WF




Ciofi degli Atti, PRC 53 (1996) 1689

# Correlations should be universal



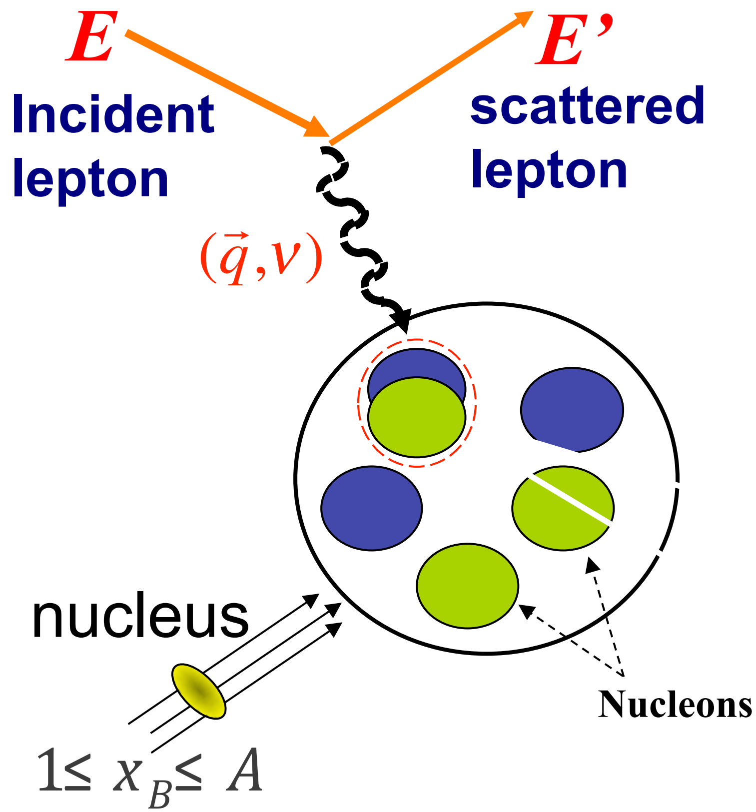

Many-body calculations predict that the high momentum distribution for all nuclei has the same shape:

$n_A(k)/n_d(k) = a_2(A/d)$

O. Benhar, Phys Lett B **177** (1986) 135
C. Ciofi degli Atti, Phys Rev C **53** (1996) 1689.

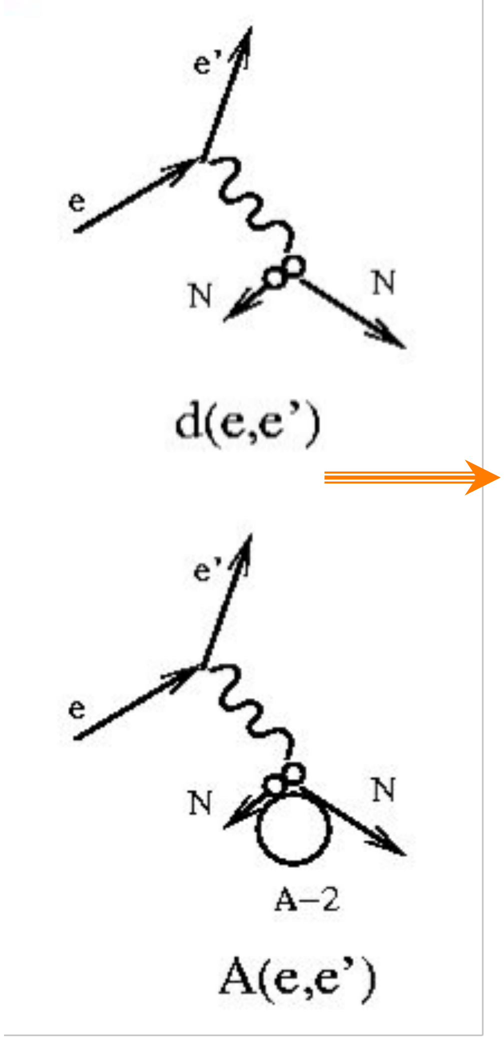
# Inclusive Electron Scattering at $x_B$>1

- At fixed $Q^2$, $x_B$ determines a minimum initial momentum for the scattered nucleon (remember y-scaling?)
- If the momentum distributions of two nuclei have the same shape, then the ratios of their cross sections should be flat

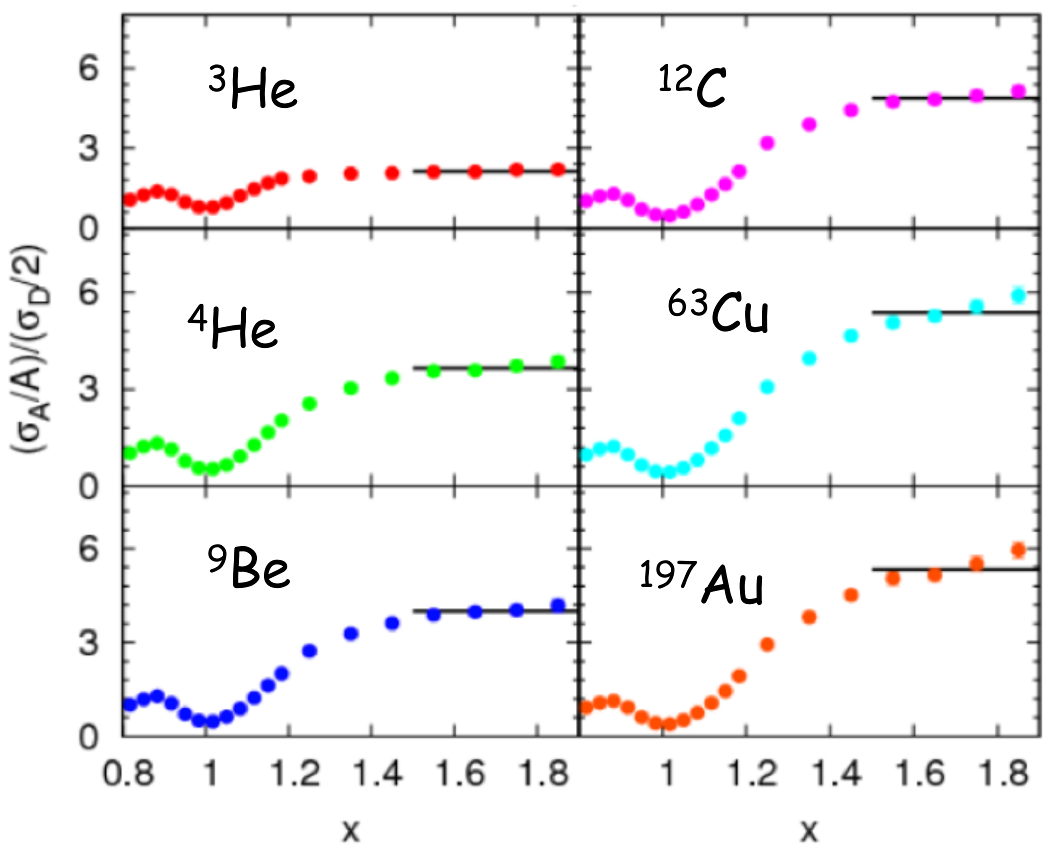



**momentum scaling ↔ $x_B$ scaling**

# Correlations are Universal




Ratio to deuterium: $(2/A)\ \sigma_A/\sigma_d$



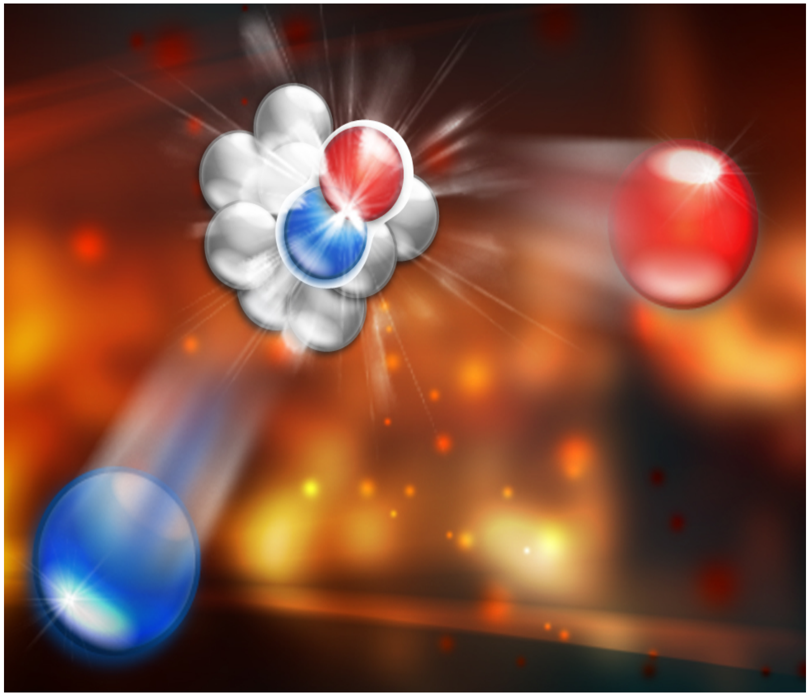

$a_{2N}$ ≈20%
$a_{3N}$ ≈1%

Scaling (flat ratios) indicates a common momentum distribution.
1 < x < 1.5: dominated by different mean field n(k)
1.5 < x < 2: dominated by 2N SRC n(k)

Day et al, PRL **59**, 427 (1987)
Frankfurt et al, PRC **48** 2451 (1993)
Egiyan et al., PRL **96**, 082501 (2006)
Fomin et al., PRL **108**, 092502 (2012)

# Short Range Correlations (SRC)

- 2N-SRC are pairs of nucleons that:
  - Are close together (overlap) in the nucleus.
  - Have high relative momentum and low center-of-mass (cm) momentum, where high and low is compared to the Fermi momentum of the nucleons (≈250 MeV/c in heavy nuclei)



# Exclusive SRC Studies

## *A(e,e'pN): detect electron + two nucleons*

- Pros: Measure the both nucleons to characterize the 2N-SRC pairs

- Cons:
  - <u>Interpretation difficulties:</u>
    - Competing processes,
    - Final State Interactions (FSI)
    - Transparency.
  - <u>Experimental difficulties:</u>
    - Large backgrounds,
    - Low rates,
    - Large installation,
    - Dedicated detectors

Who knew nuclear physics could be so complicated

# Exclusive SRC Studies

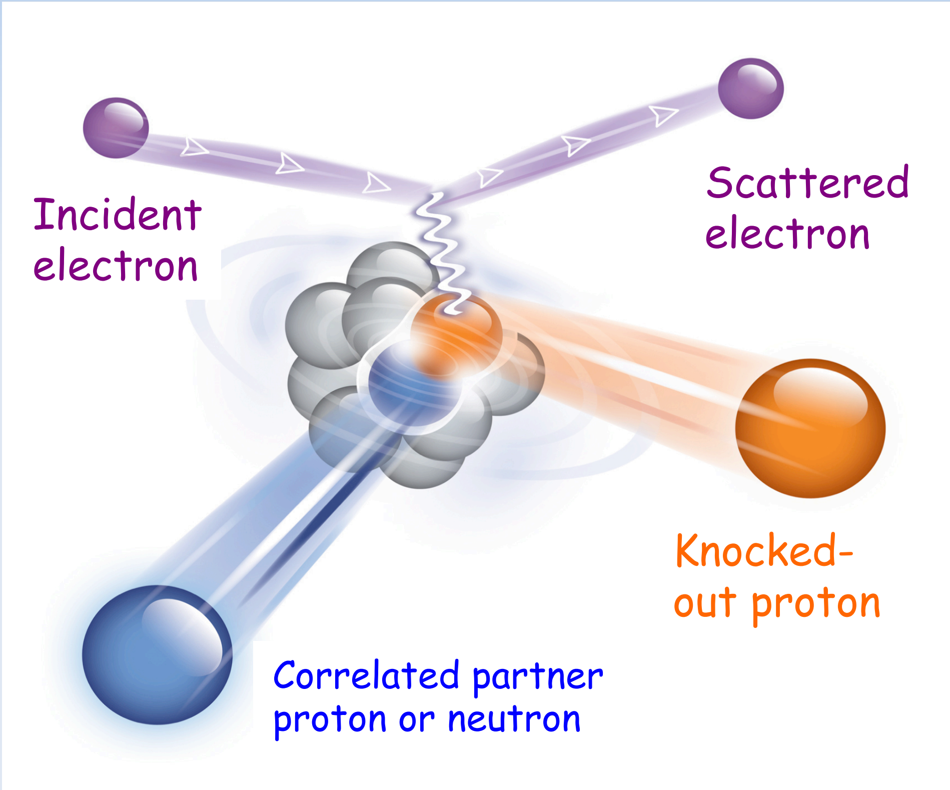
*A(e,e'pN): detect electron + two nucleons*

<u>Measurement Concept:</u>

1. Hit a high momentum proton hard ($Q^2 > 1$ GeV$^2$)

2. Reconstruct the initial (missing) momentum of the struck nucleon

3. Look for a recoil nucleon with momentum that balanced that of the struck proton

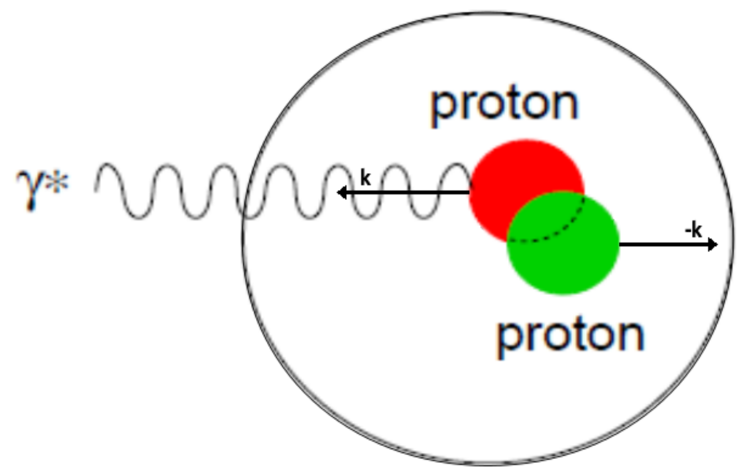



$$\vec{p}_{miss} = \vec{q} - \vec{p}_p = -\vec{p}_{initial}$$

# JLab Hall-A E01-015 (2004)

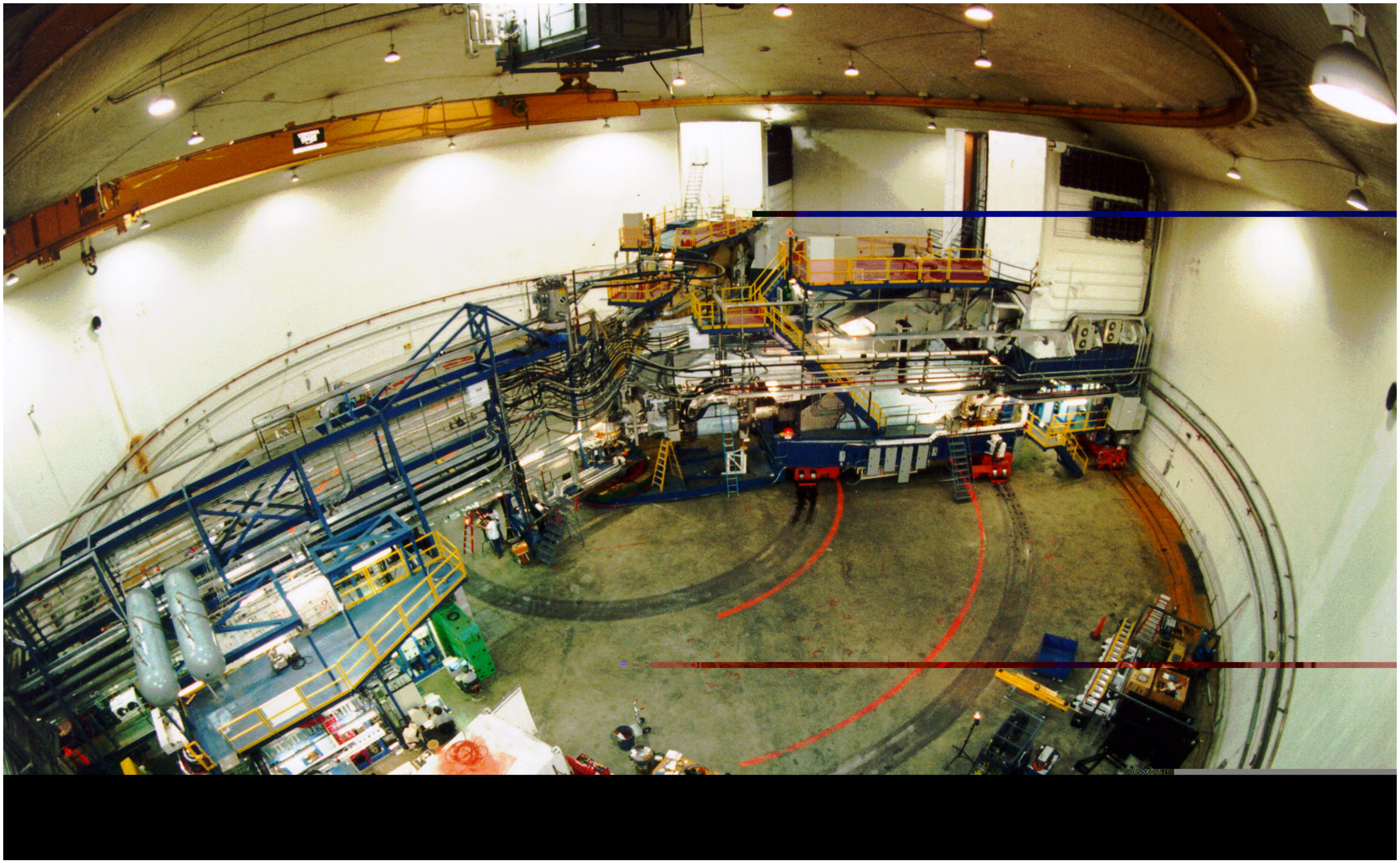
- Goal: Study both **pn** and **pp** SRC in $^{12}C$ over an (e,e'p) missing momentum range of 300-600 MeV/c

- Kinematics:
  - High $Q^2$ to minimize Meson Exchange Currents (MEC)
  - $x > 1$ to suppress Delta production



# JLab Hall-A

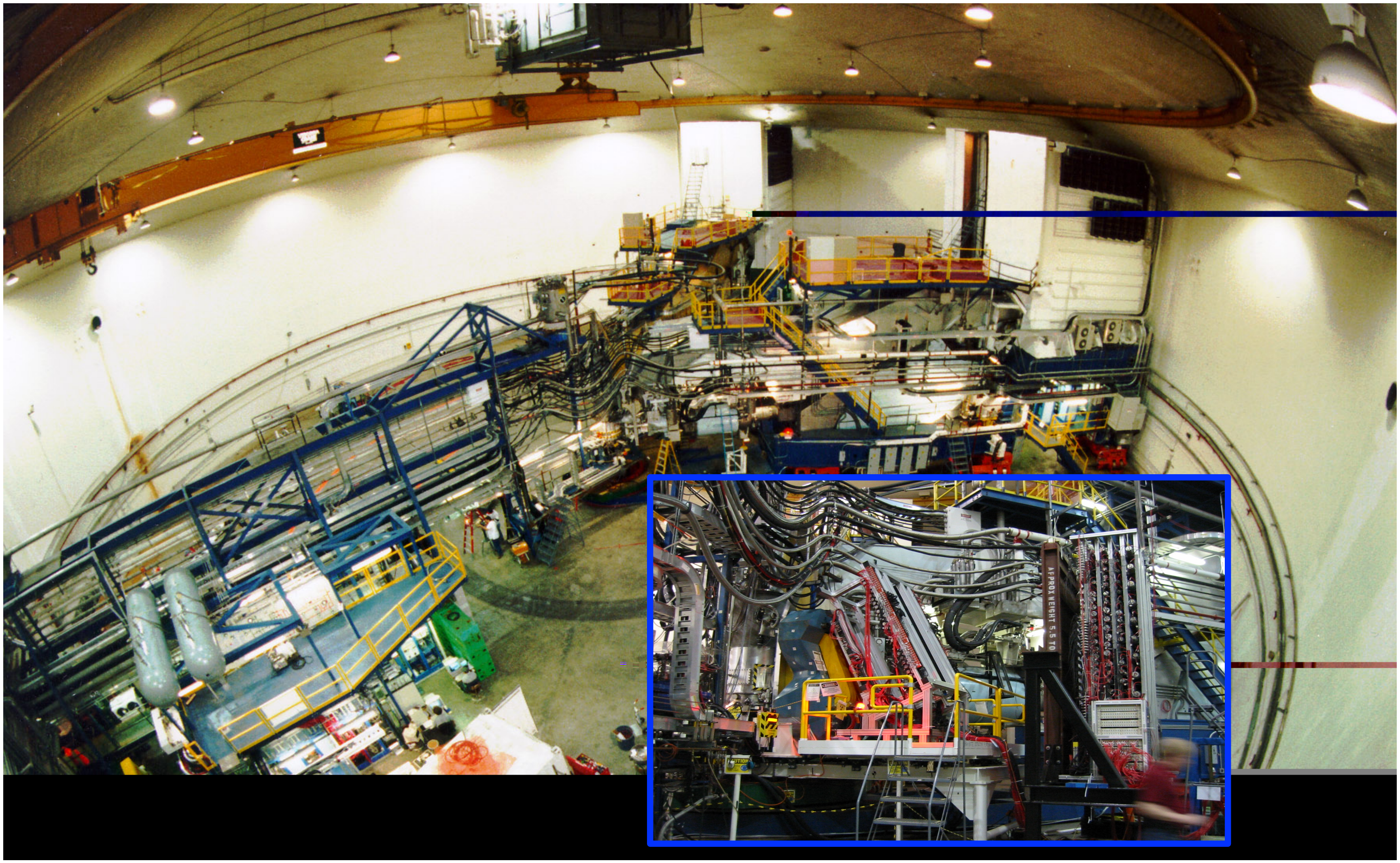
## Physicists Tend To Fill Empty Space©



©D. Higinbotham

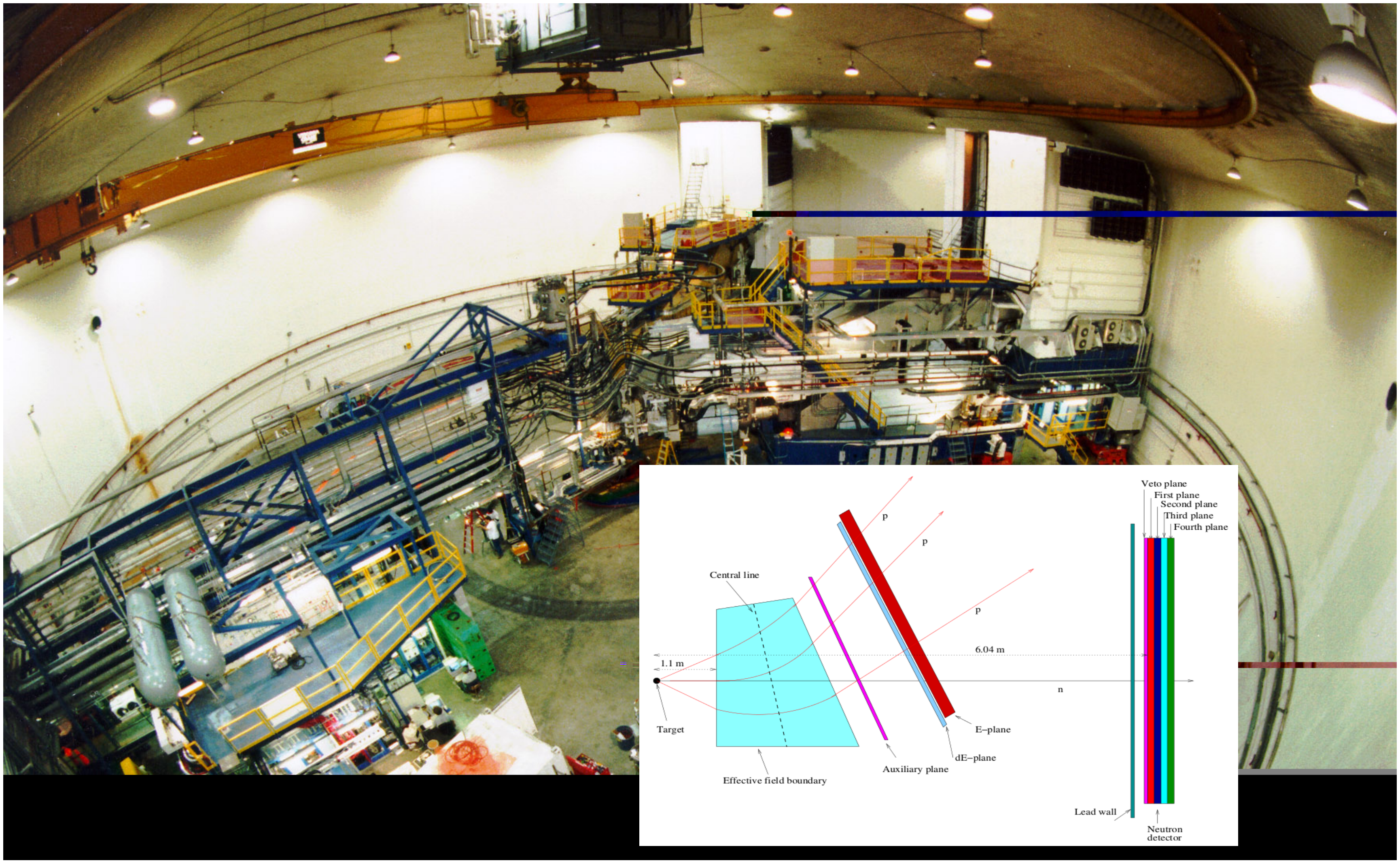
# JLab Hall-A E01-015

## Physicists Tend To Fill Empty Space©



# JLab Hall-A E01-015

## Physicists Tend To Fill Empty Space©

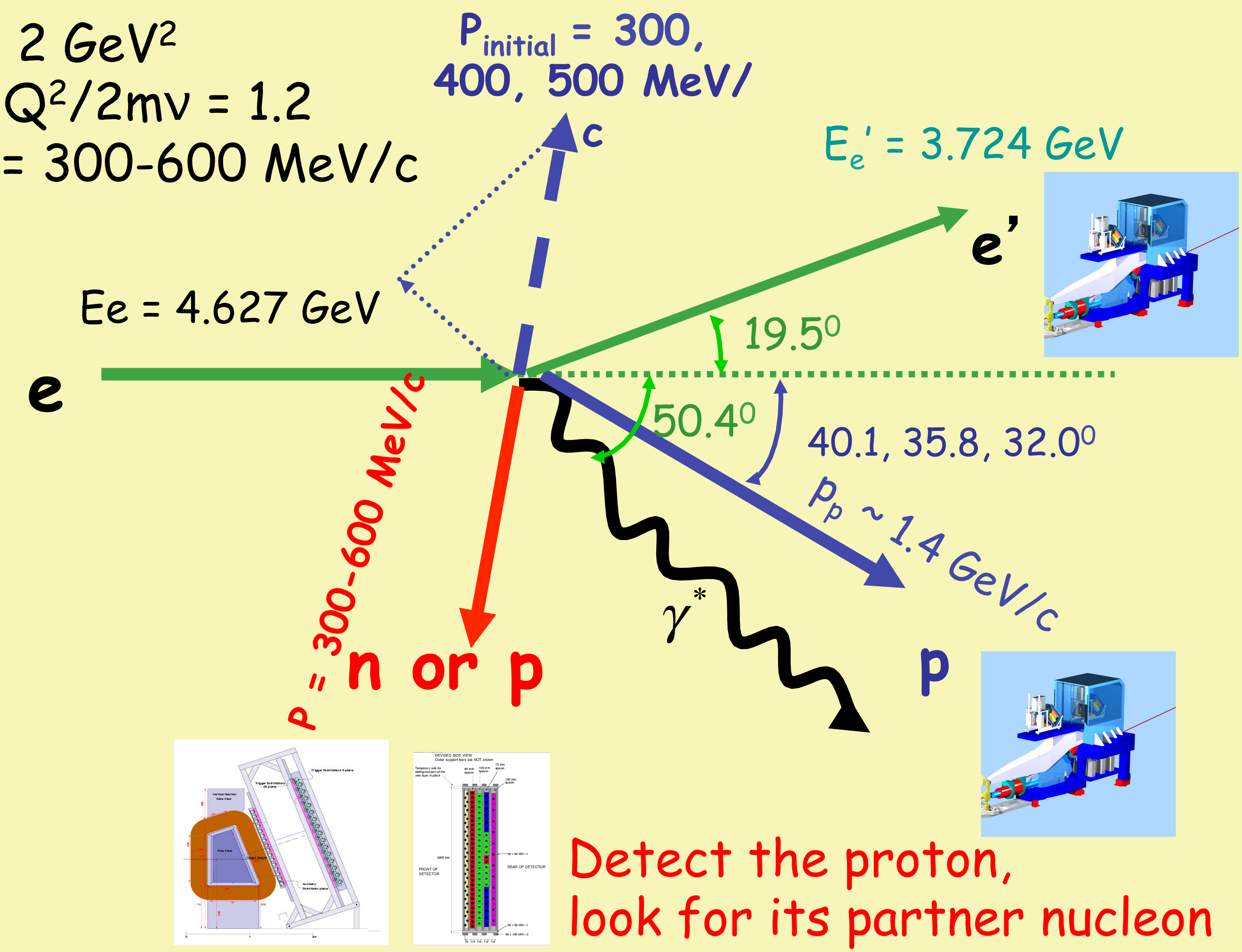


# Now detect yet another nucleon
# JLab Hall A C(e,e'pN) - selected kinematics

$Q^2 = 2\ GeV^2$

$x_B = Q^2/2m\nu = 1.2$

$P_{miss} = 300\text{-}600\ MeV/c$




Detect the proton,
look for its partner nucleon

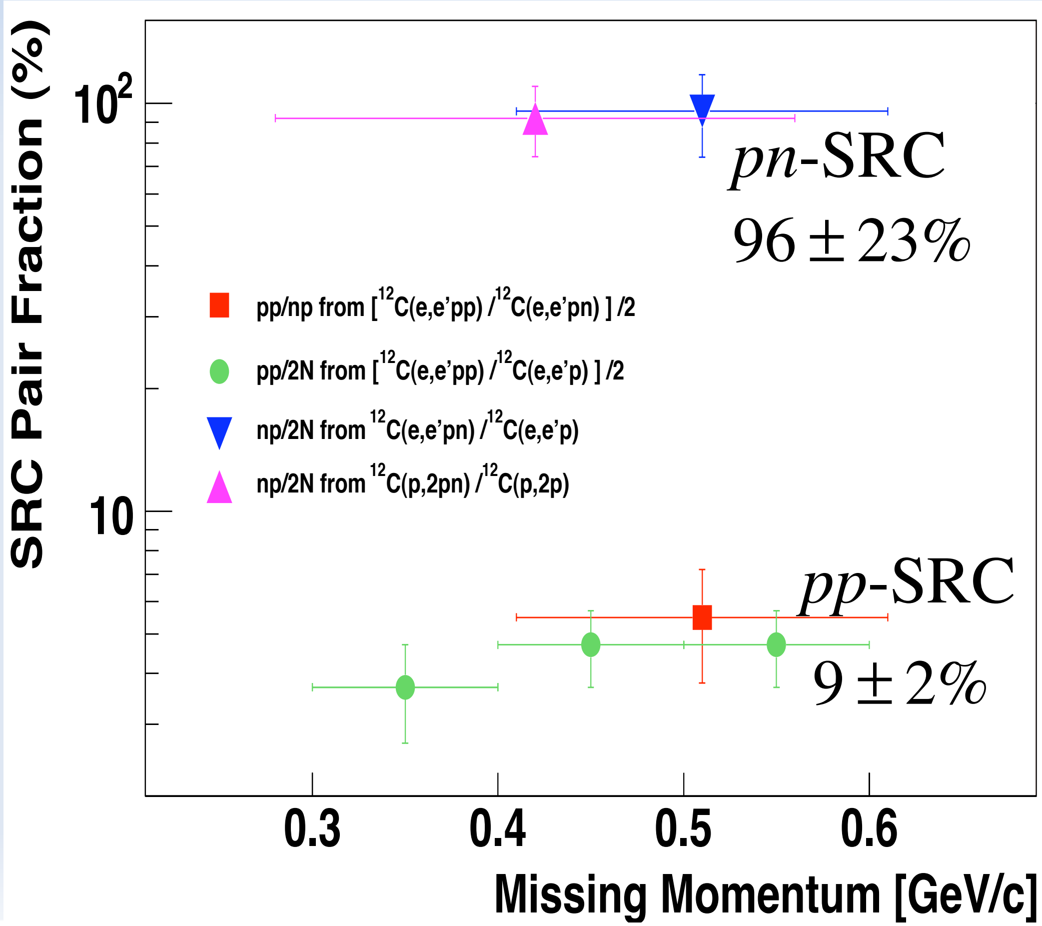
# JLab Hall-A E01-015

## *[pn and pp SRC Probabilities and the pp/np ratio]*

- The (e,e'pN)/(e,e'p) ratio gives the probability for a high momentum proton to be part of a pN-SRC pair.

- **All** high $p_{initial}$ protons have a correlated partner

- np pairs dominate
  - Importance of tensor force at $0.3<p_{initial}<0.6$ GeV/c




R. Subedi et al., **Science 320**, 1476 (2008)

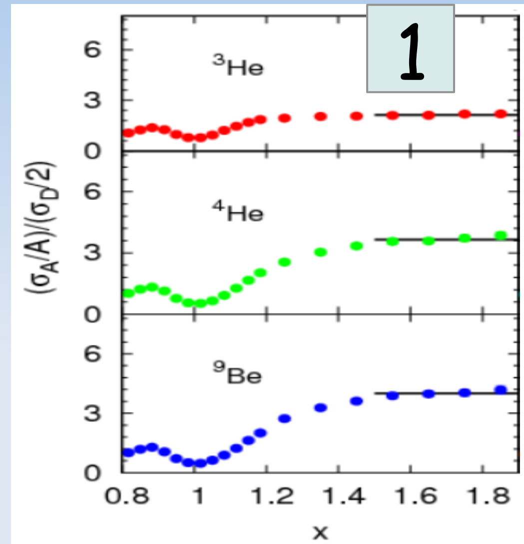
# 2N-SRC from inclusive and exclusive measurements

1 The probability for a nucleon to have p≥300 MeV/c in medium nuclei is 20-25%

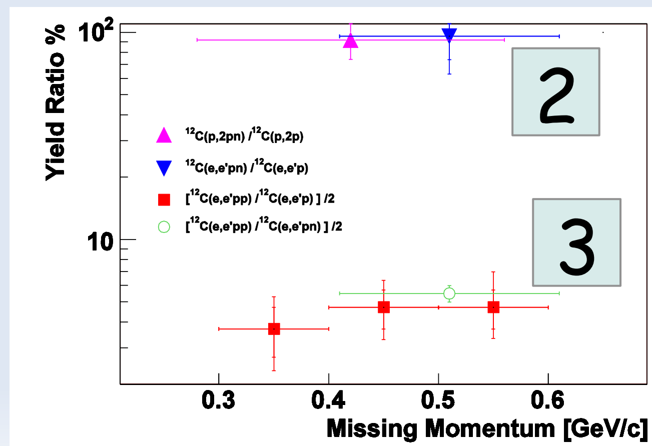
2 More than ~90% of all nucleons with p≥300 MeV/c belong to 2N-SRC.

3 2N-SRC dominated by np pairs

- → **Tensor interaction**

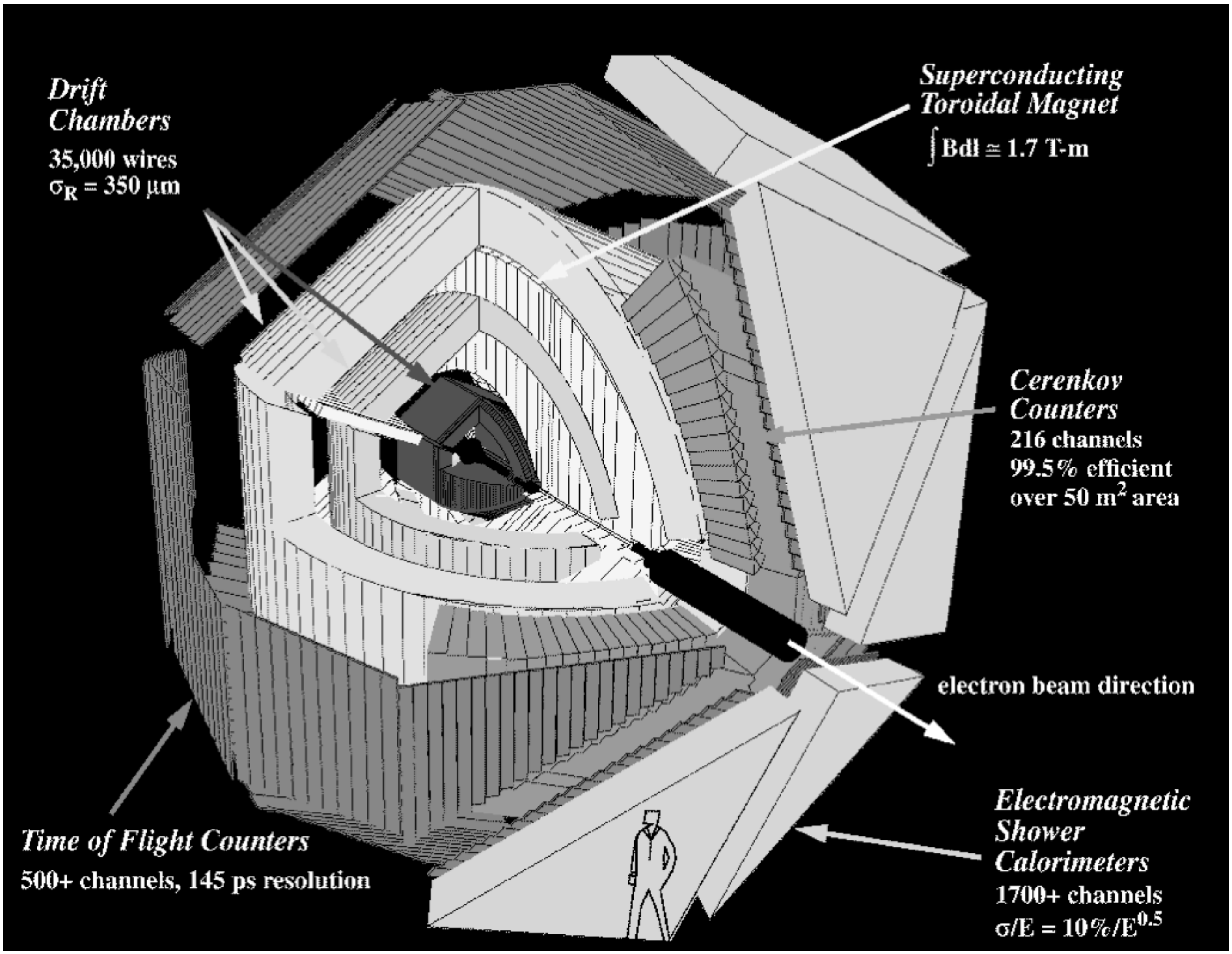



1
2 → ~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.



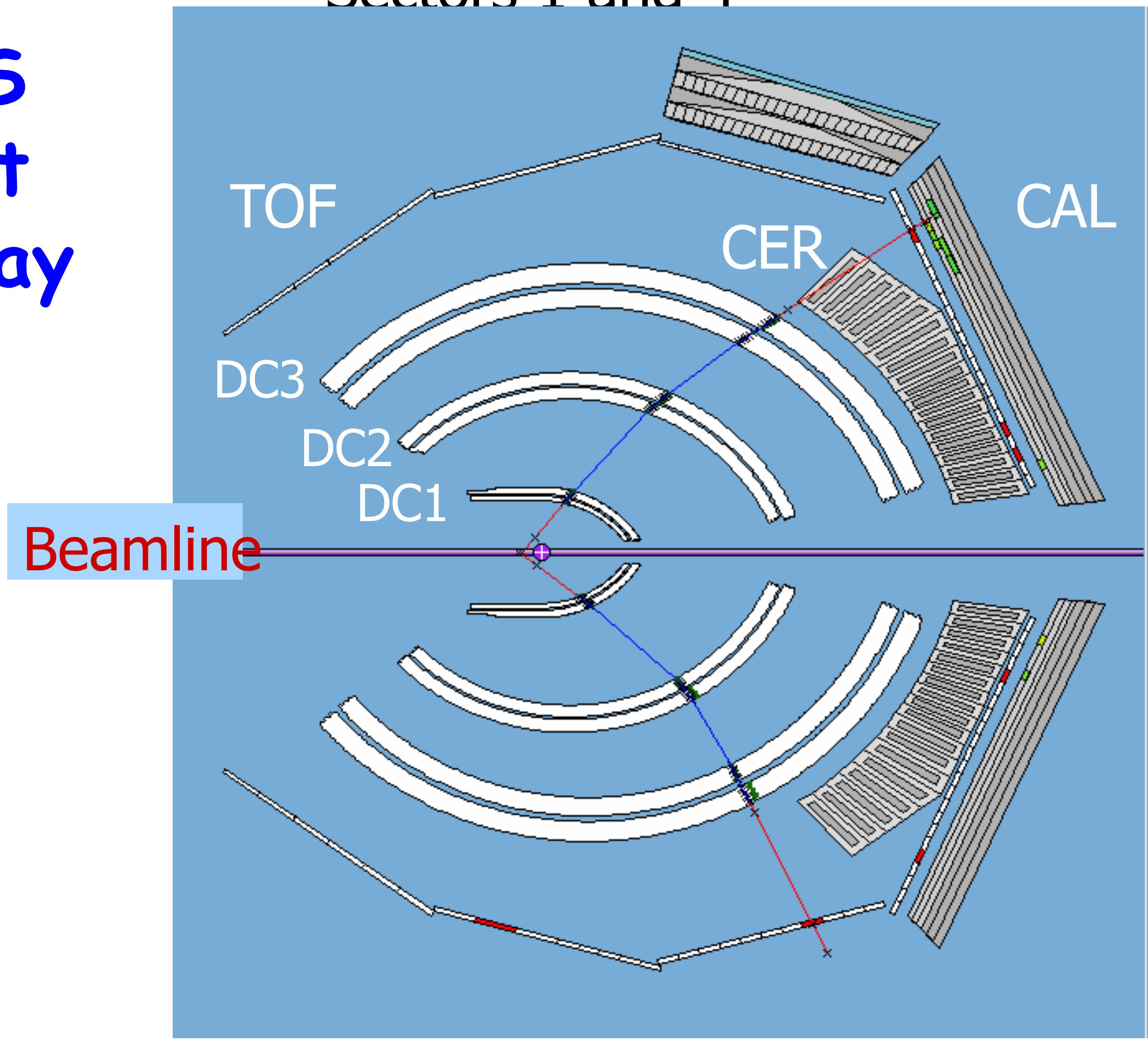
# $^3He(e,eX)$ in JLab CLAS

- 2.2 and 4.7 GeV electrons
- Inclusive trigger
- Almost 4π detector

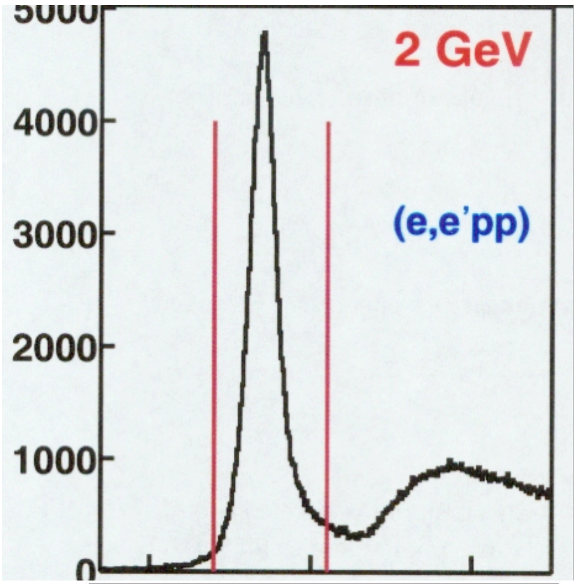


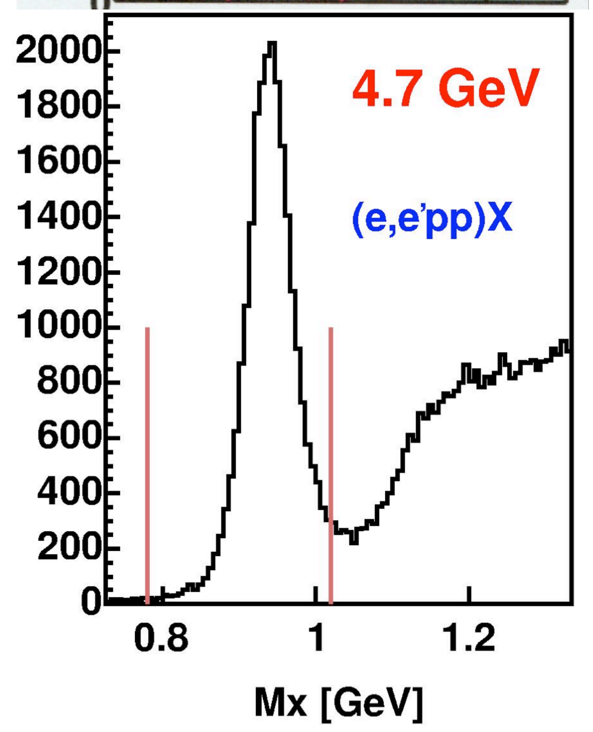
# CLAS Event Display

Sectors 1 and 4



# CLAS in Maintenance Position

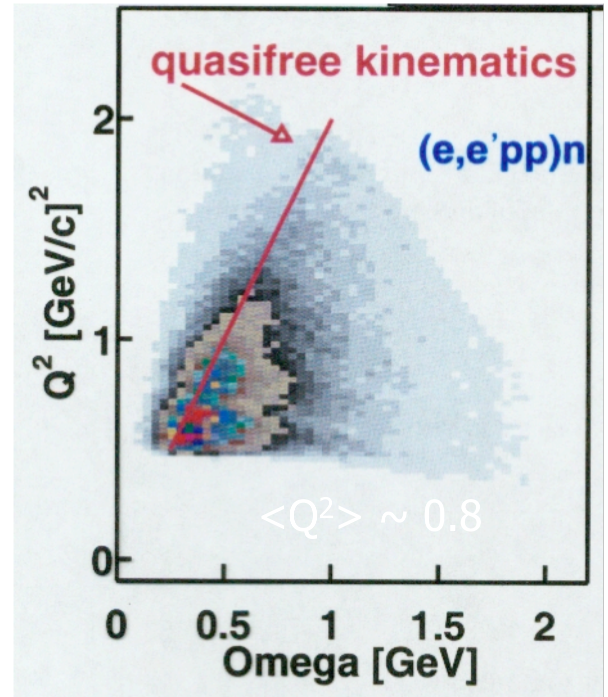


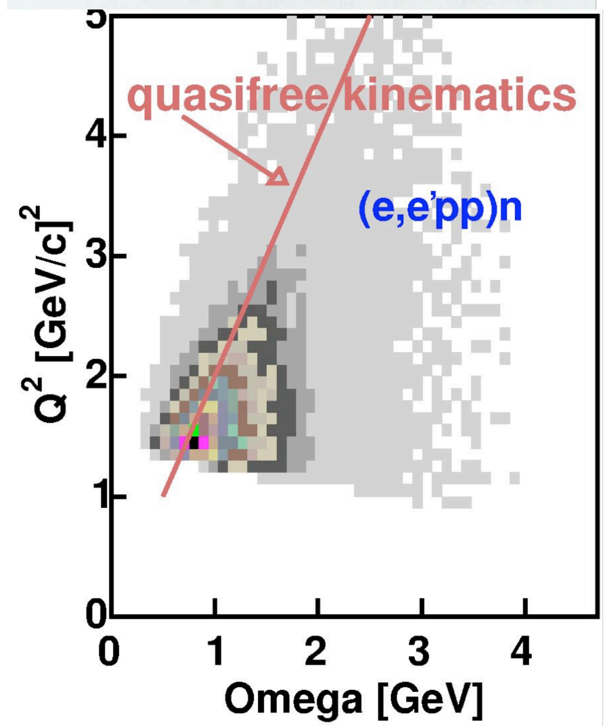




# CLAS
# $^3He(e,e'pp)$

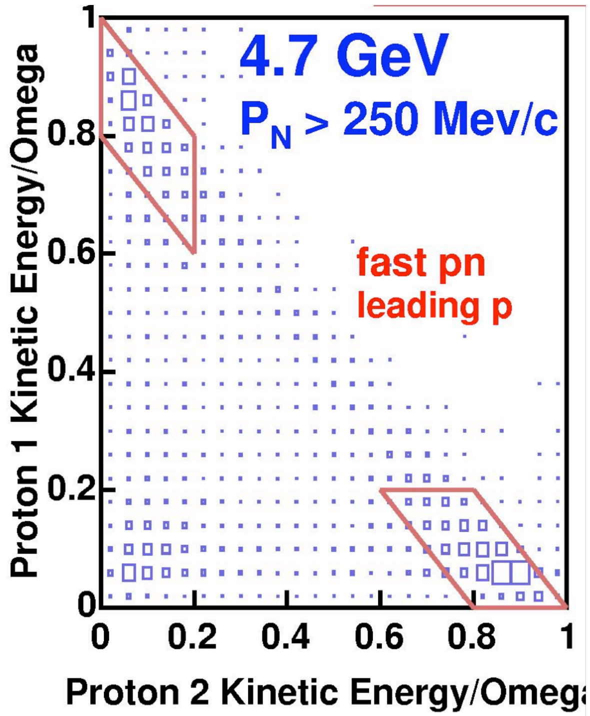
Detect 2 protons, reconstruct the neutron

Huge electron acceptance

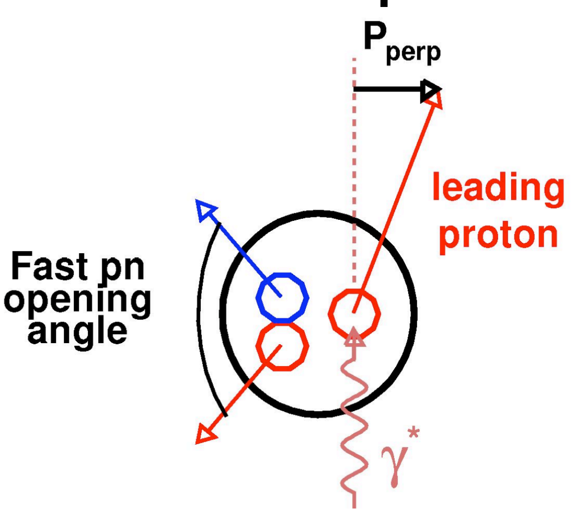


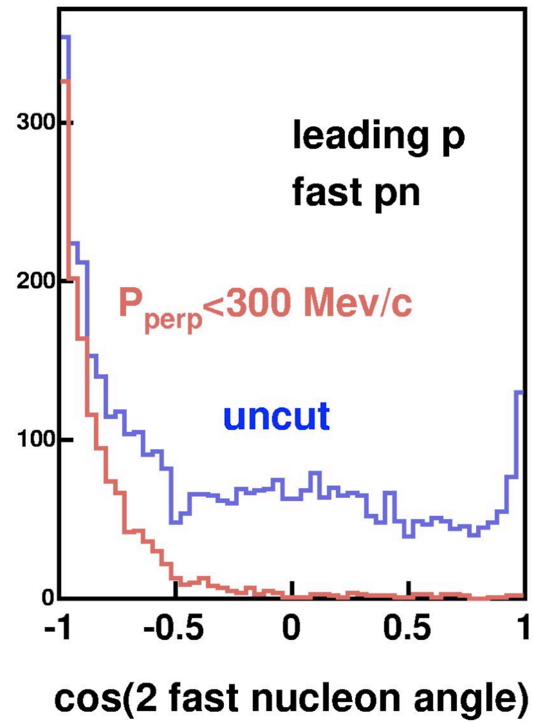



# $^3He(e,e'pp)n$ nucleon energy balance: p > 250 MeV/c

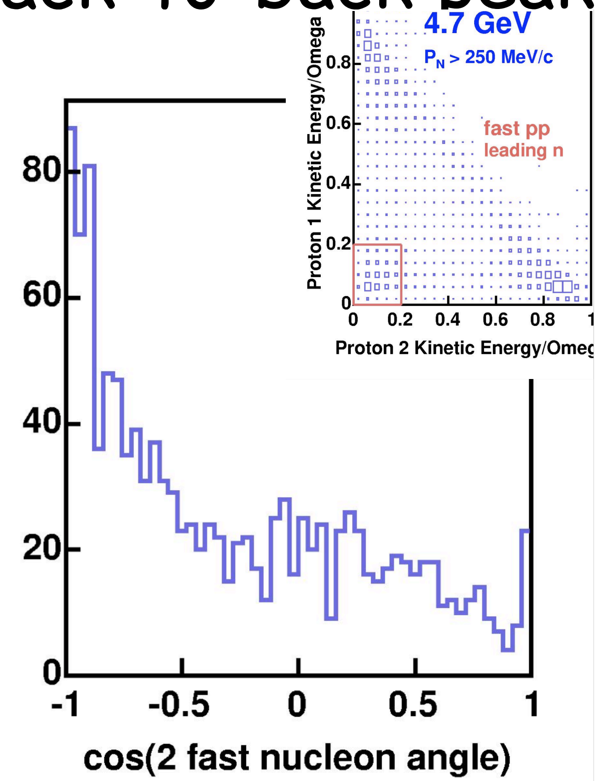



Select peaks in Dalitz plot



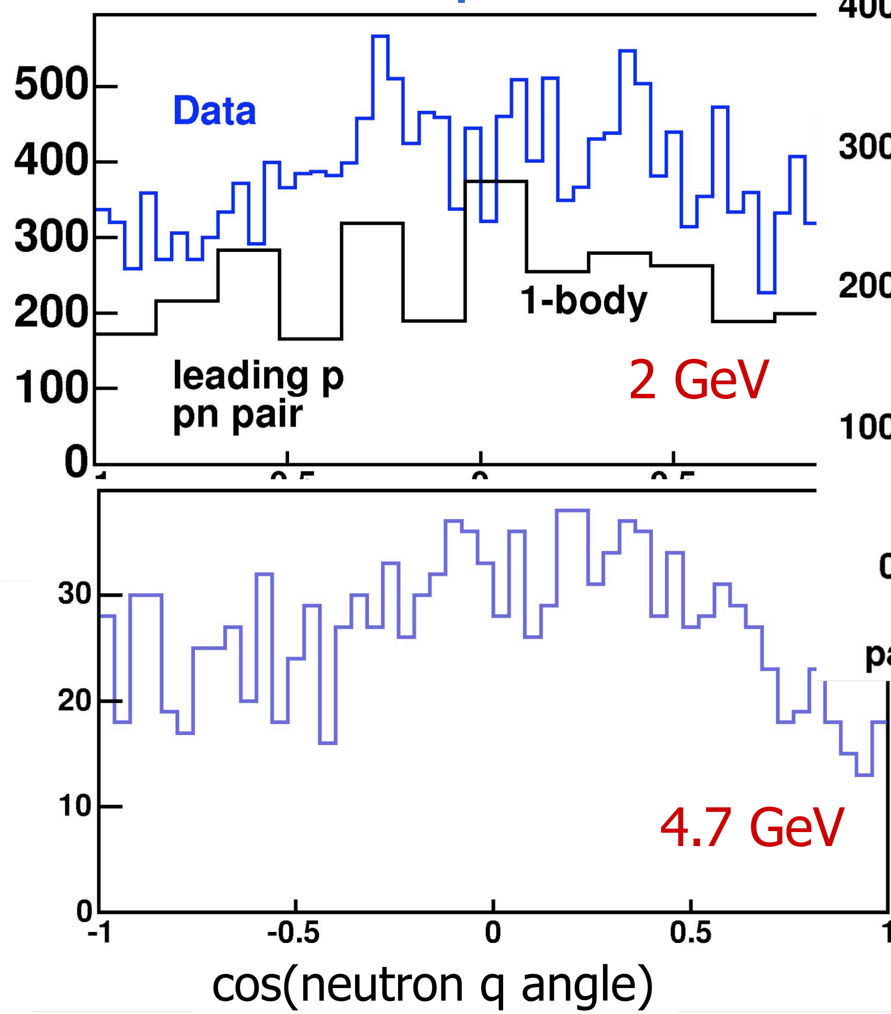



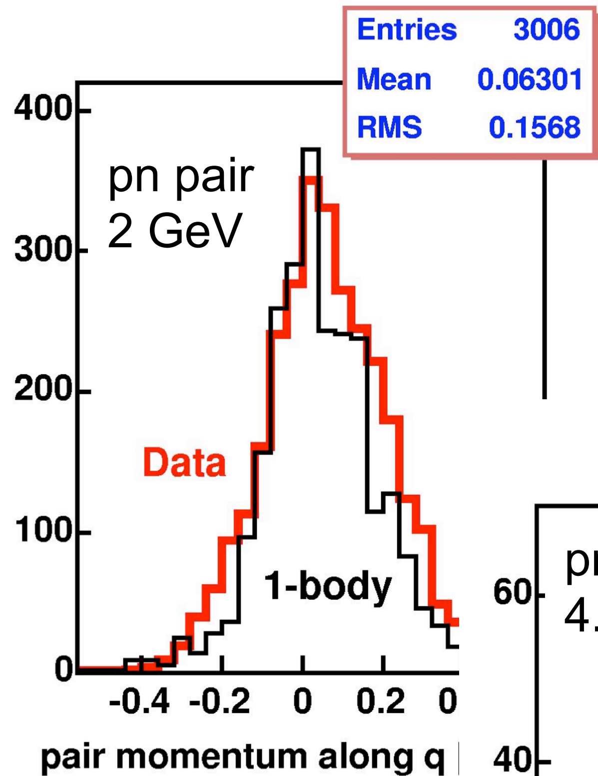

Pair has back-to-back peak



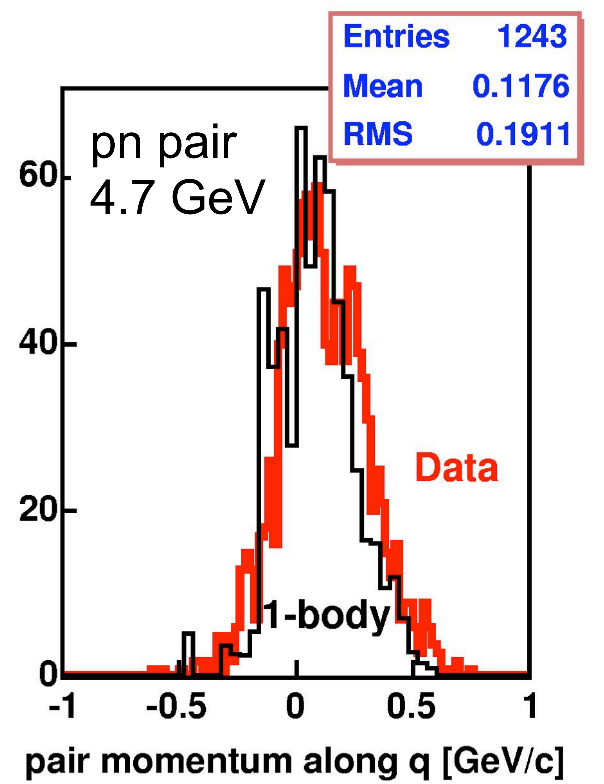
# I don't want to get involved: spectator correlated pairs

Isotropic!




Small forward momentum (described by theory)



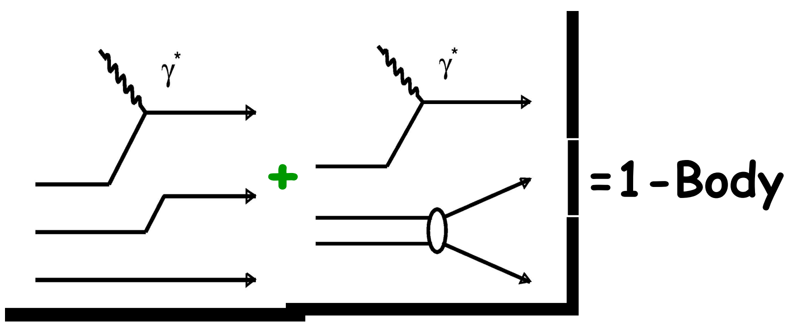
# Measured momentum distributions:

2.2 GeV ($Q^2 \approx 0.8$ GeV$^2$)
4.7 GeV ($Q^2 \approx 1.5$ GeV$^2$)

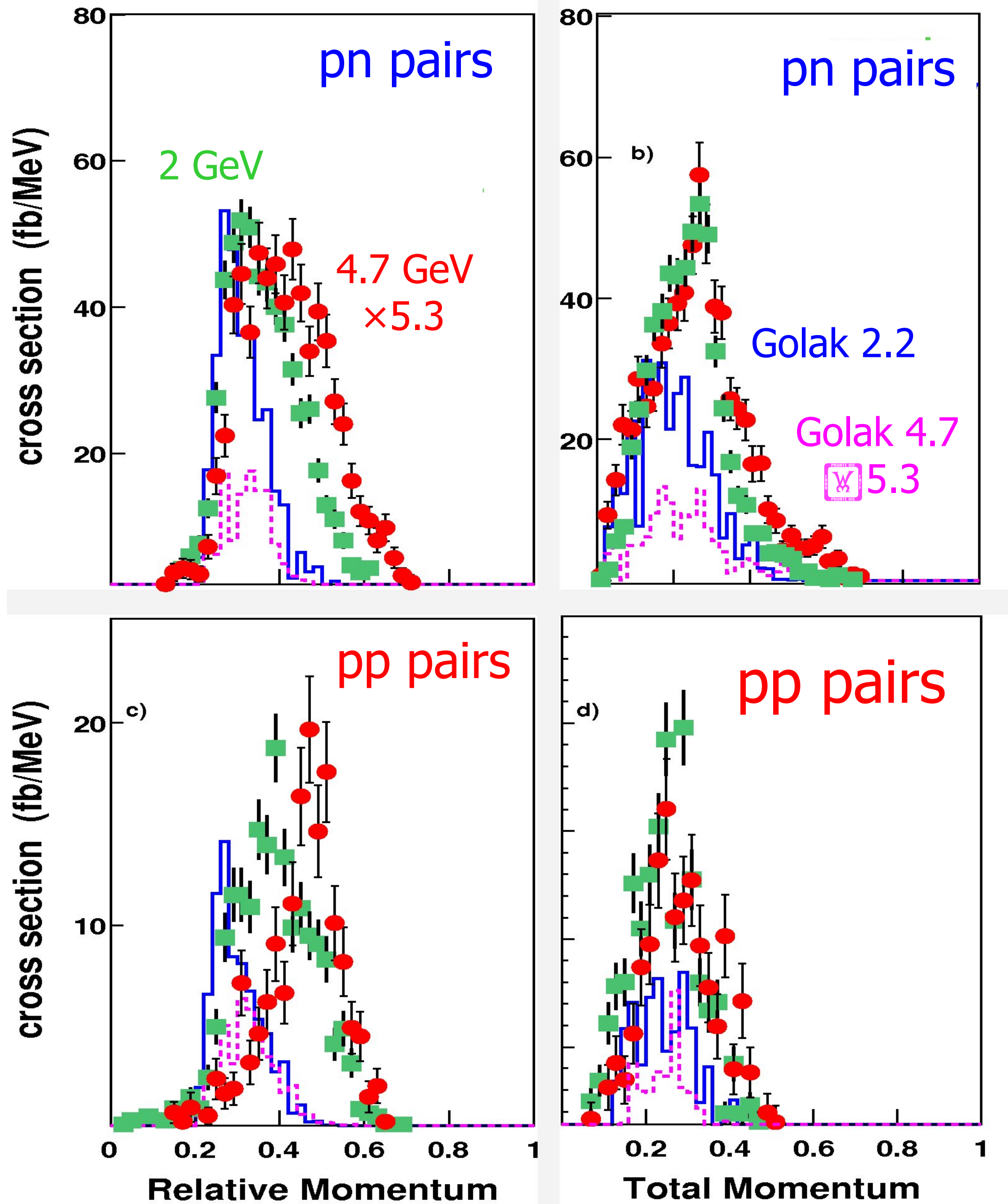
(4.7 GeV scaled by 5.3)

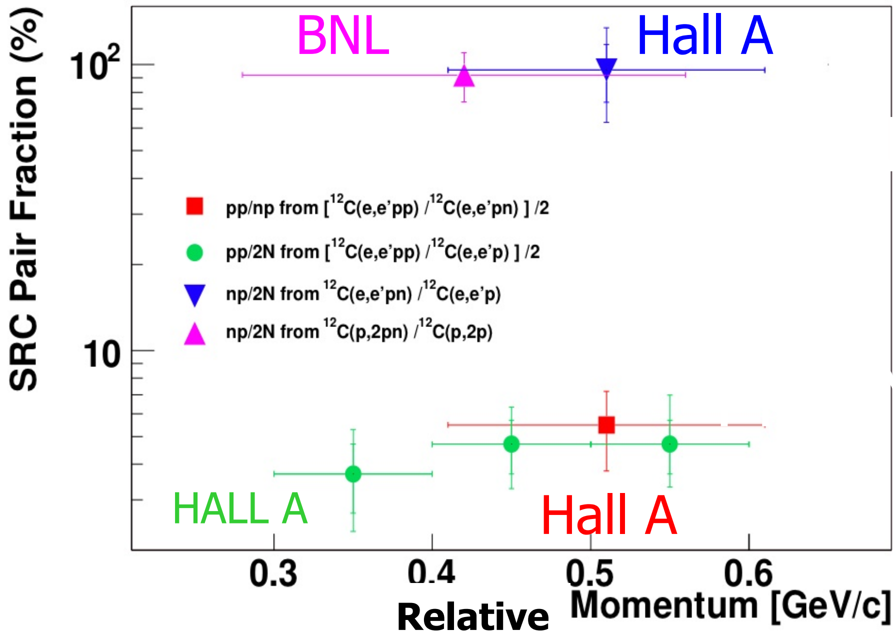
Similar momentum dist
- Relative
- Total

pn:pp ratio ~ 4



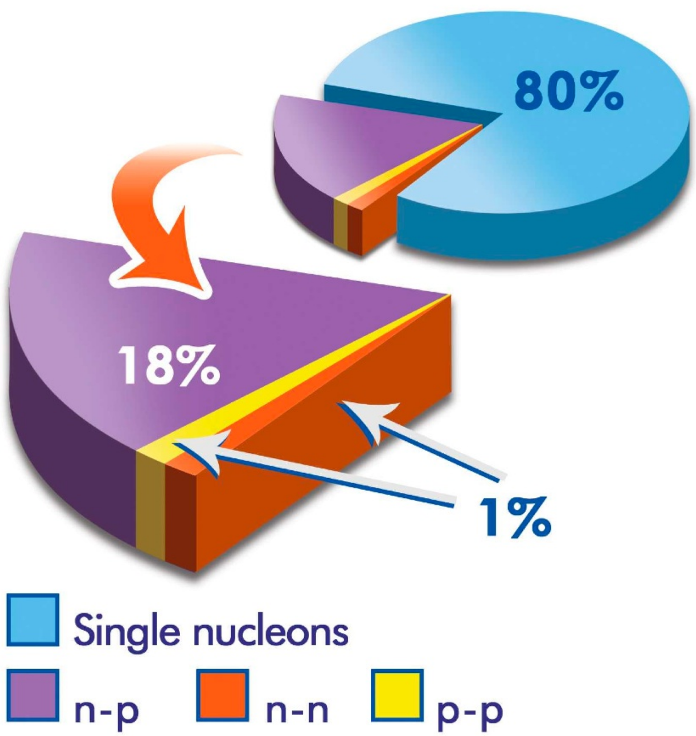

Theory (Golak)
- Describes 2 GeV OK
  - $P_{rel}$ too low
- Too low at 4.7 GeV






# pp to pn comparison

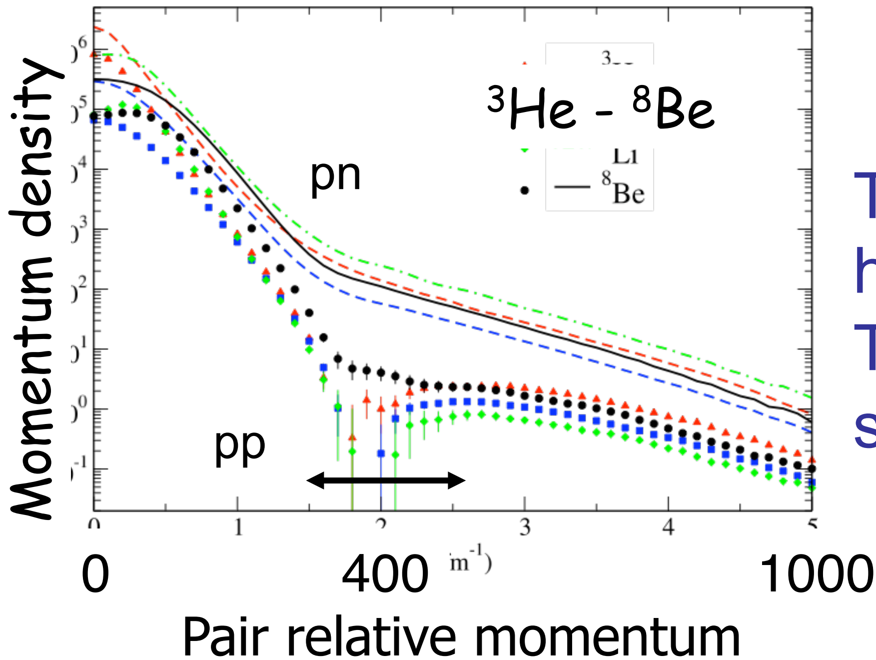
Subedi et al, Science (2008)




| $E_{beam}$ | $<Q^2>$ | *pn* to *pp* ratio |
|---|---|---|
| Hall A / BNL | 2 / ?? | 18 |
| CLAS | 0.8—1.5 | 3 — 4.5 |

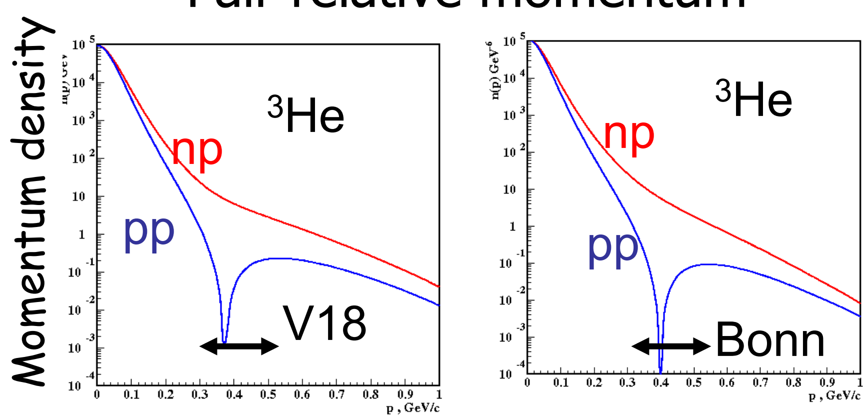
Contradiction???

# Why is pp/np so small at 300 < $p_{rel}$ < 500 MeV/c?




The s-wave momentum distribution has a minimum

The *np* minimum is filled in by strong tensor correlations




Pair relative momentum

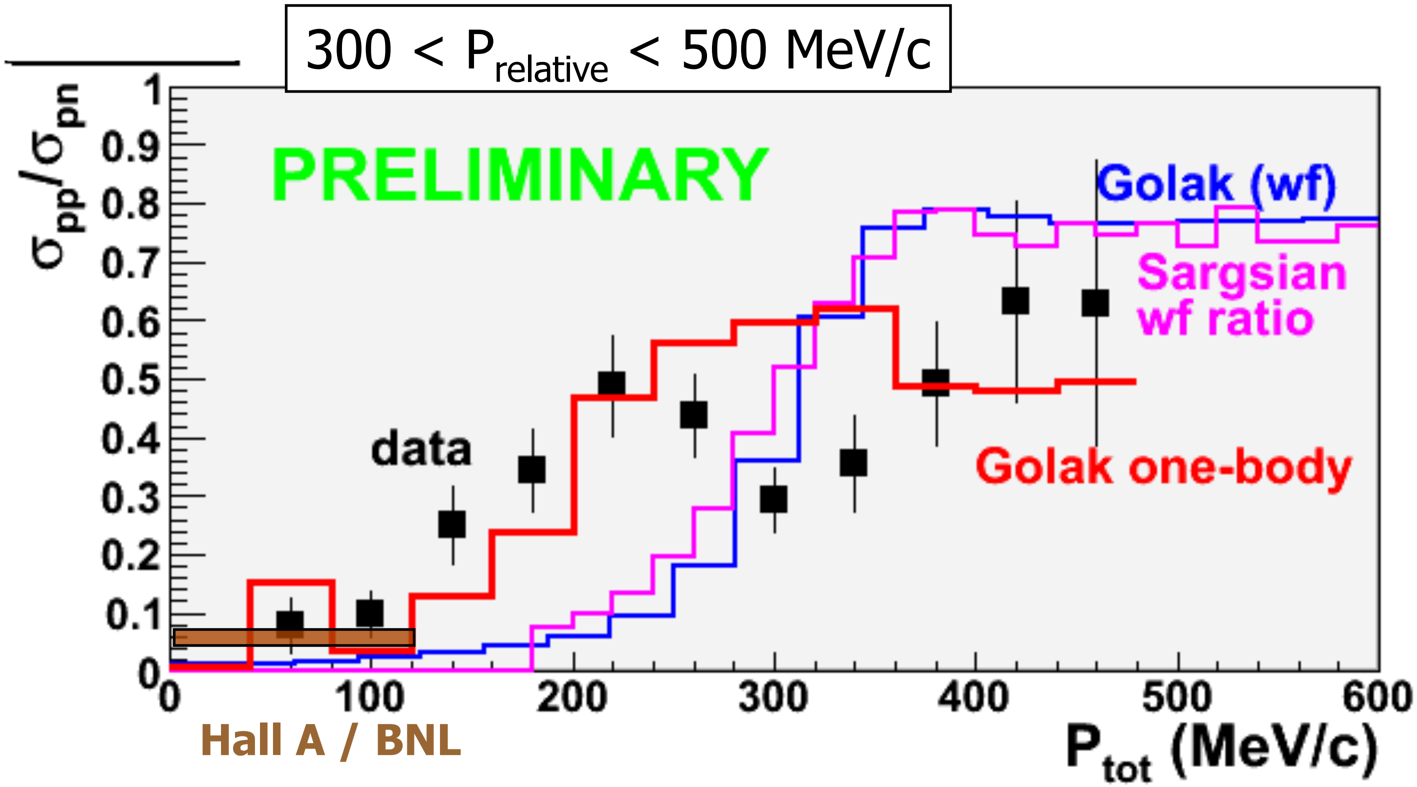
Ciofi degli Atti, Alvioli;

Schiavilla, Wiringa, Pieper, Carlson

Sargsian, Abrahamyan, Strikman, Frankfurt

# pp to pn resolution:

*pp*/*pn* ratio increases with pair total momentum $P_{tot}$




Tensor Correlations!

Small $P_{tot}$ ➔ *pp* pair in *s*-wave (no tensor)
➔ wave fn minimum at $p_{rel}$=400 MeV/c

Hall A: small $P_{tot}$ ➔ less *pp*
Hall B: large $P_{tot}$ ➔ more *pp*

# Correlations and Neutron Stars

'Classical' neutron star: fermi gases of *e*, *p* and *n*
Low temperature ➔ almost filled fermi spheres
➔ limited ability of p -> n decays (Urca process)

Correlations ➔ high momentum tail and holes in the fermi spheres

## Why does this matter?

Cooling should be dominated by the Urca process:

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$p + e^- \rightarrow n + \nu_e$$

Correlations-caused holes in the proton fermi sphere should enhance this process by large factors and speed neutron star cooling.

## Quasielastic summary: (e,e'), (e,e'p) and (e,e'pN)

- (e,e') scaling shows the electron is (mostly) scattering from single nucleons
- (e,e') ratios measure the probability of short range correlations (SRC) in nuclei
- (e,e'p) measures E and p distributions of single nucleons
- (e,e'pN) measures E and p distributions of nucleon pairs

The nucleus:

60-70% single particle – E + p dists measured
20±5% SRC - starting to measure
10-20% LRC