Nucleon Momentum Distributions in Asymmetric Nuclei

A Comparison of ^{3}He(*e*,*e′p*) and ^{3}H(*e*,*e′p*)
PR12-13-012

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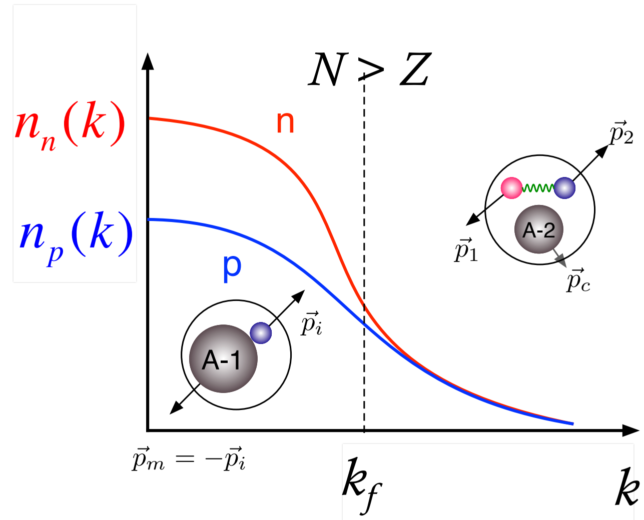
PAC40 – June 2013

Experiment Overview

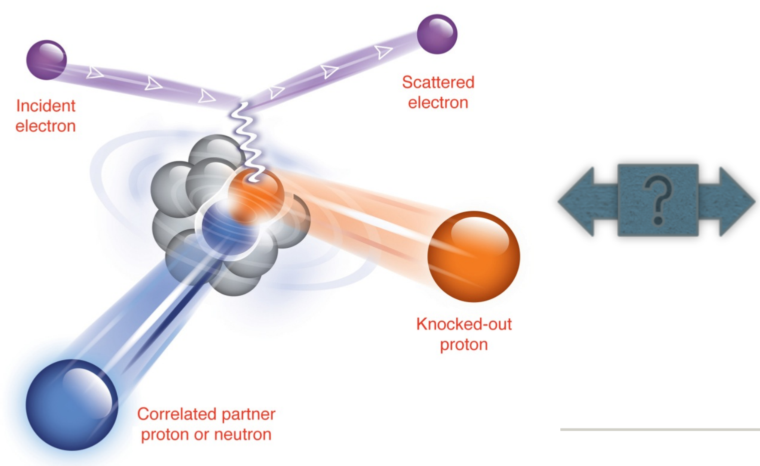
- Measure the quasielastic (*e,e'p*) reaction on ^{3}H, ^{3}He, and ^{2}H
- Compare nucleon momentum distributions in asymmetric nuclei to demonstrate that protons move faster in ^{3}H than in ^{3}He

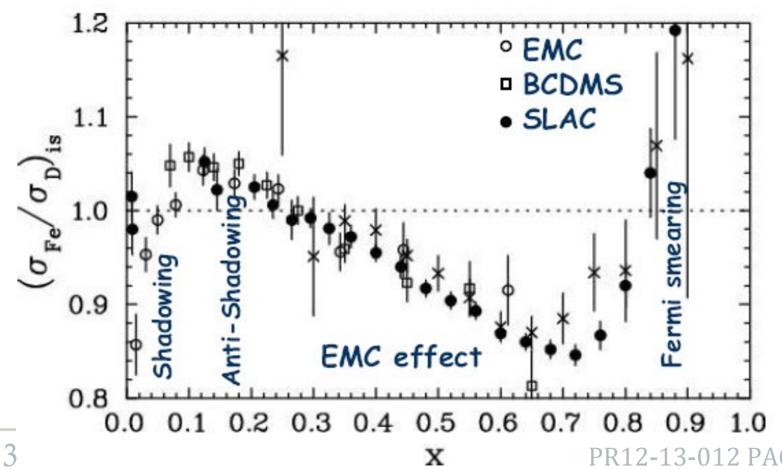


- Simple picture: map the transition as $\sigma(^3\text{He})/\sigma(^3\text{H})$ changes from >2 at small p_{miss} due to proton counting to 1 at large p_{miss} due to *np* pair counting
- Quantitatively compare to precise few-body calculations

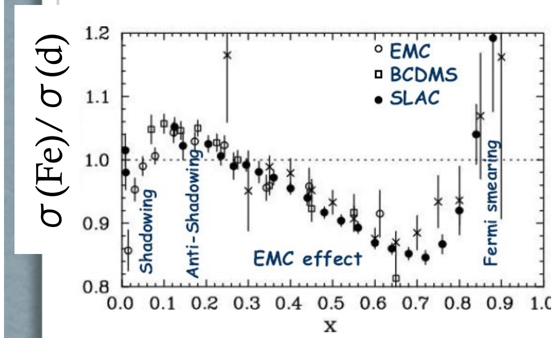
Short Range Correlations in Nuclei

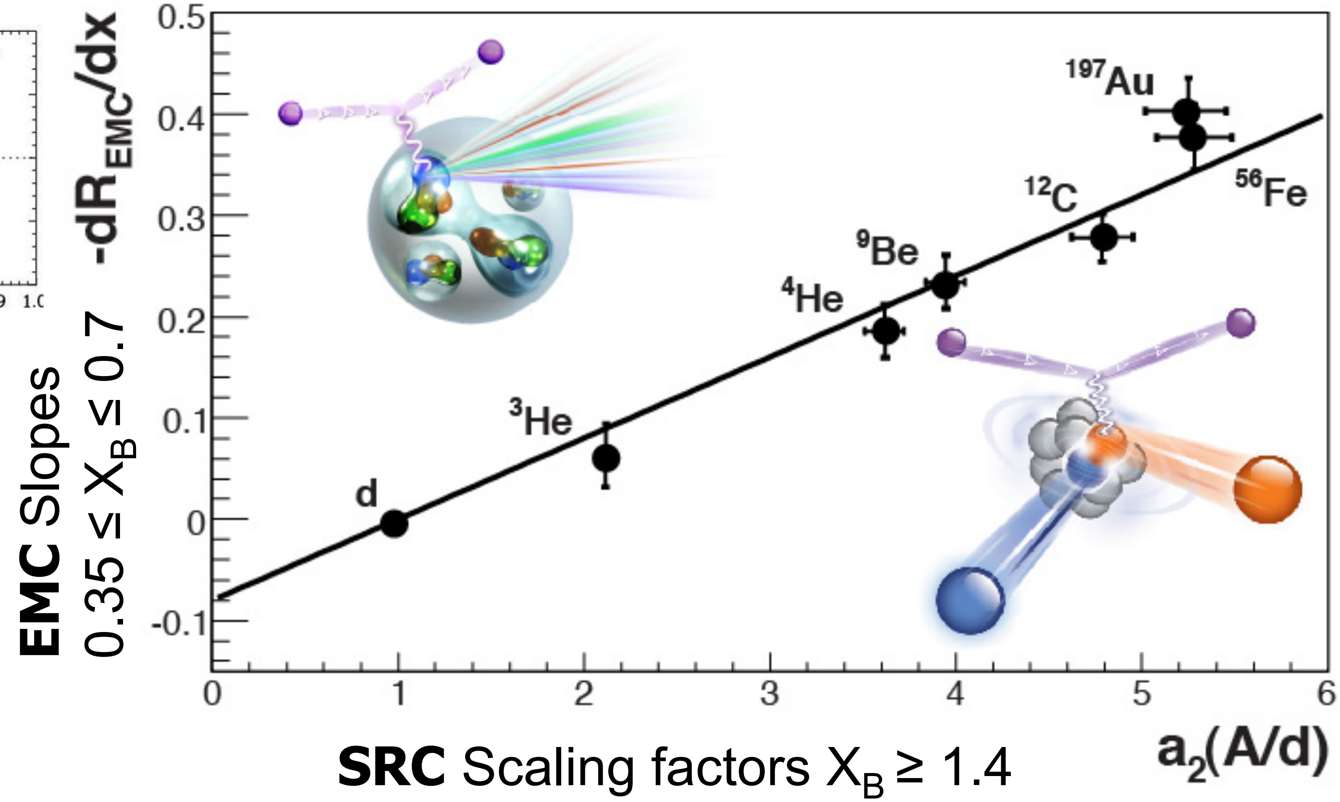
- Almost all nucleons with $p > 275$ MeV/c belong to a short range correlated (SRC) *NN* pair with small cm momentum and large relative momentum.
- 90% of these pairs in ^{12}C are *pn* pairs.
- The proportion of nucleons belonging to SRC *NN* pairs is about 5% in *d* and 10% in ^3He, increasing to 25% in heavy nuclei.
- The strength of the EMC effect in a nucleus is closely correlated with the number of SRC pairs in that nucleus.



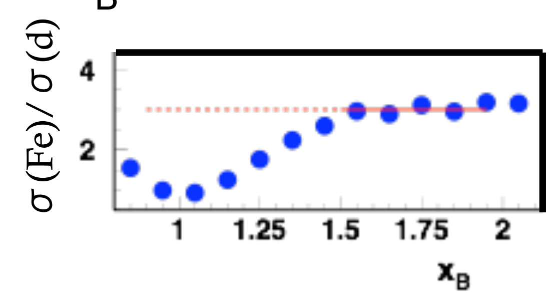


EMC Effect and Short Range Correlations





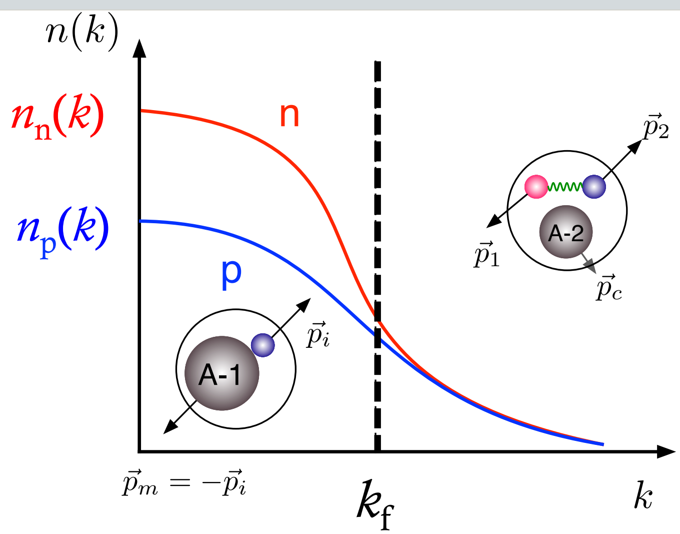
- Both EMC effect and SRC related to high momentum nucleons in nuclei
    - Modification of high momentum nucleons?
- How is this changed in asymmetric nuclei?



Weinstein et al, PRL**106**, 052301 (2011)
Hen et al, PRC**85**, 047301 (2012)

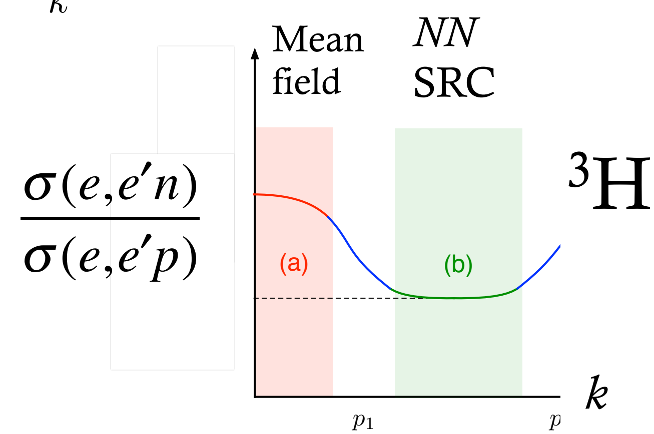
Nucleon momentum distributions in asymmetric nuclei

$p < k_f$
Dominated by independent (mean-field) nucleons



$p > k_f$
Dominated by nucleons belonging to SRC *pn* pairs

- If there are fewer protons than neutrons then the protons should have higher average momentum and kinetic energy
  - If there are fewer boys than girls at a dance, the average boy will dance more than the average girl (assuming boy-girl pair dominance).



Naively expected ratio

Asymmetric nuclei momentum distributions: the broader picture

Light nuclei $A<11$

Ab initio Variational Monte Carlo calculations by Wiringa

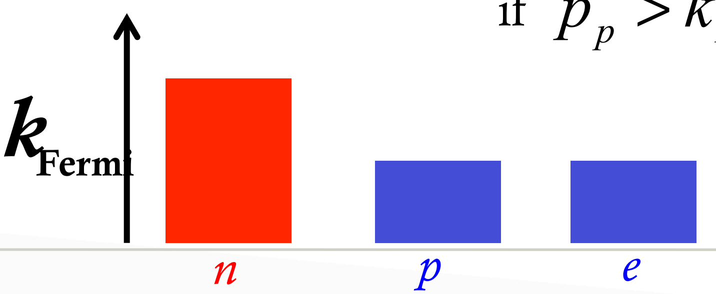
	$\frac{\|N-Z\|}{A}$	$\langle KE \rangle_p$	$\langle KE \rangle_n$	$\langle KE \rangle_{p-n}$
^{8}He	0.50	30.13	18.60	11.53
^{6}He	0.33	27.66	19.06	8.60
^{9}Li	0.33	31.39	24.91	6.48
^{3}He	0.33	14.71	19.35	-4.64
^{3}H	0.33	19.61	14.96	4.65
^{8}Li	0.25	28.95	23.98	4.97
^{10}Be	0.2	30.20	25.95	4.25
^{7}Li	0.14	26.88	24.54	2.34
^{9}Be	0.11	29.82	27.09	2.73
^{11}B	0.09	33.40	31.75	1.65

Qualitative connections:

Heavy nuclei

Possible explanation to the NuTeV anomaly (if *u* quarks move faster than *d* quarks)

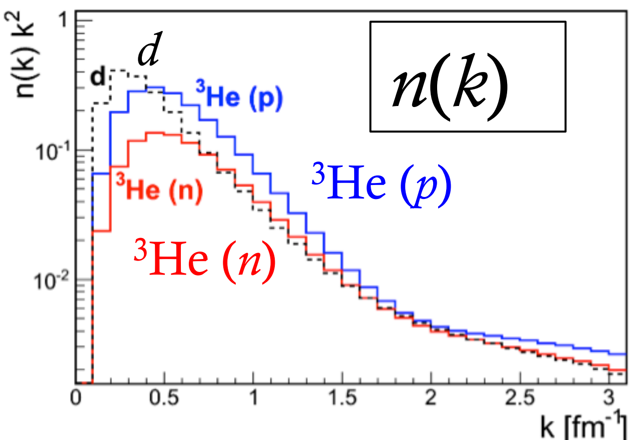
Neutron stars



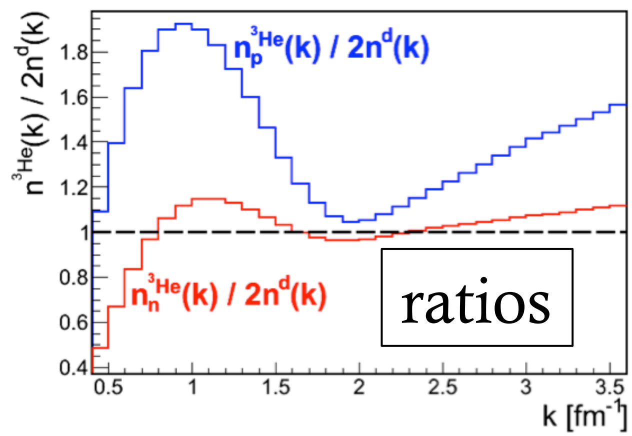
if $p_p > k^{p}_{Fermi}$

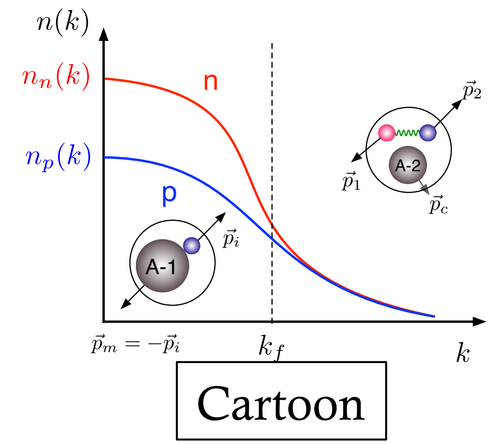
- Changes the cooling rate via the direct URCA process
- Changed momentum distribution changes the spatial distribution

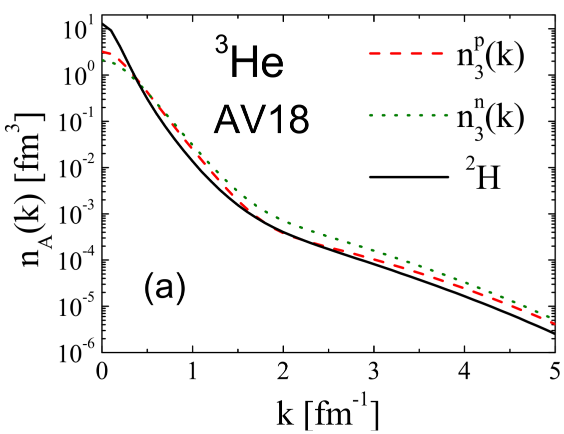
^{3}He ground state momentum density calculations



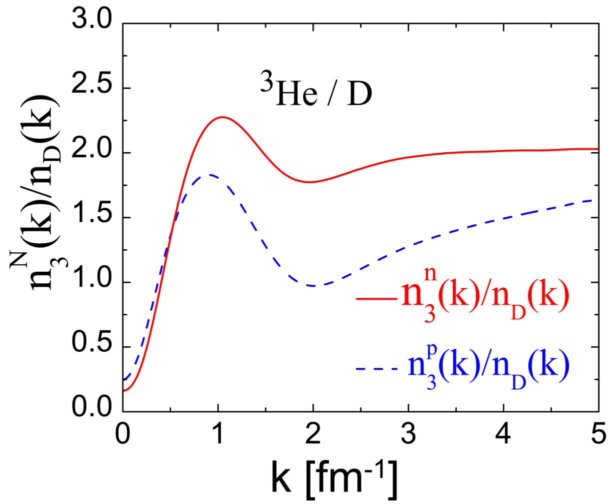
Wiringa, *et al.*

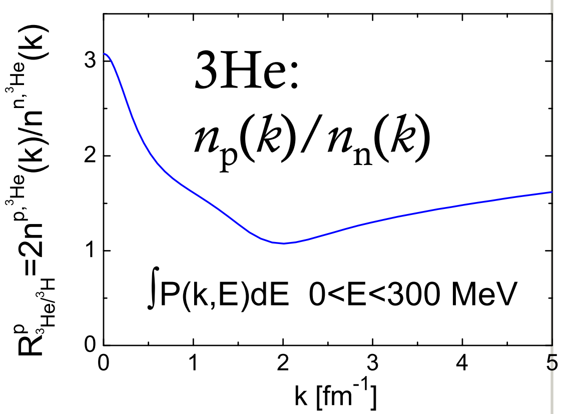




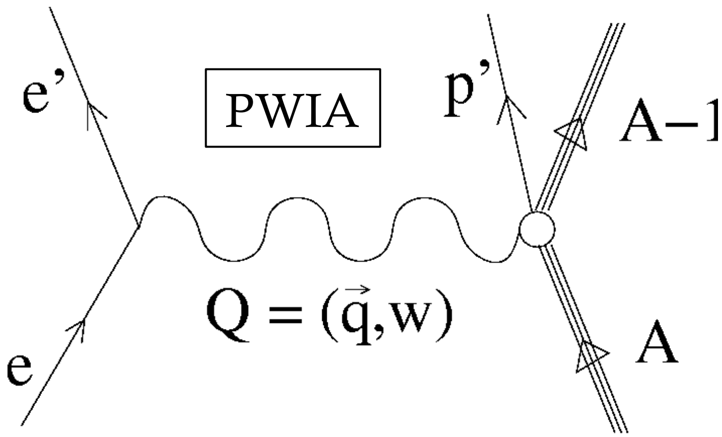


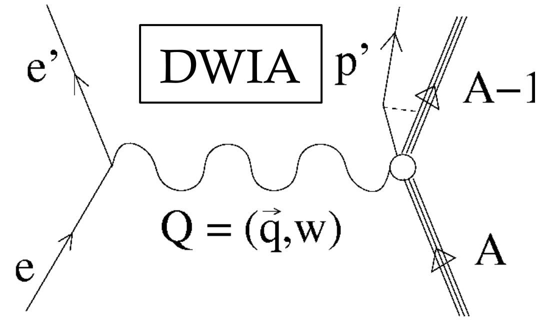
Kaptari, *et al.*





$A(e,e'p)$ kinematics



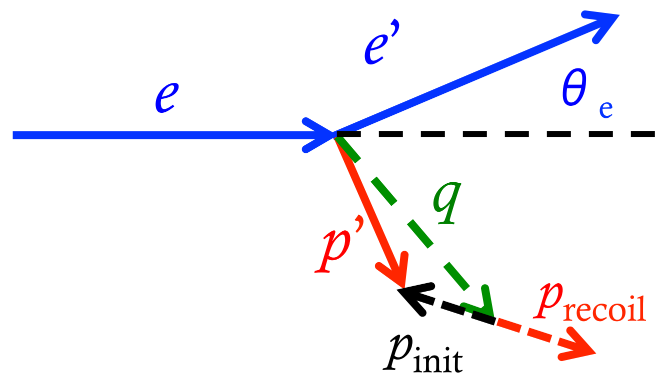


$$E_m = \omega - T_p - T_{A-1}$$

$$= \omega - T_p - \frac{p_m^2}{4m_p}$$

$$\vec{p}_m = \vec{q} - \vec{p}\,' = -\vec{p}_{init}$$

$$\vec{p}_m \approx -\vec{p}_{init}$$



$A(e,e'p)$ Formalism

Spectral function $S(E_m,p_m)$: probability of finding a nucleon in the nucleus with momentum p_m and separation energy E_m

$$\rho(p_m) = \int S(E_m, p_m) dE_m$$

Nuclear momentum distribution

Without FSI, the cross section factorizes:
κ is a known kinematic factor
σ_{ep} is the half-off-shell electron-proton elementary cross section

$$\frac{d^6\sigma}{d\omega d\Omega_e dE_m d\Omega_p} = \kappa\sigma_{ep} S(E_m, p_m)$$

$$\sigma_{red}(E_m, p_m) = \left[\frac{d^6\sigma}{d\omega d\Omega_e dE_m d\Omega_p}\right]^{\text{measured}} / [\kappa\sigma_{ep}]$$

In the absence of Final State Interactions [FSI] this becomes:

$$S(E_m, p_m) = \sigma_{red}(E_m, p_m)$$

Previous ^{3}H(*e,e'p*) measurements

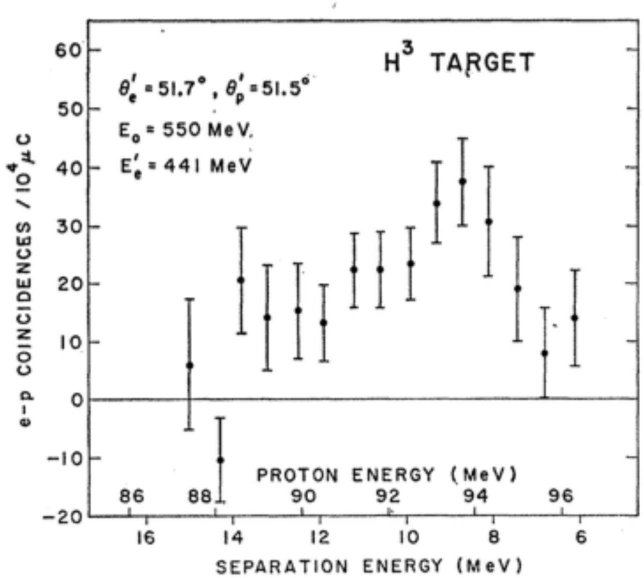


FIG. 2. The energy spectrum of protons at 51.5° in coincidence with 441-MeV electrons at 51.7° from H³ $(e,e'p)$.

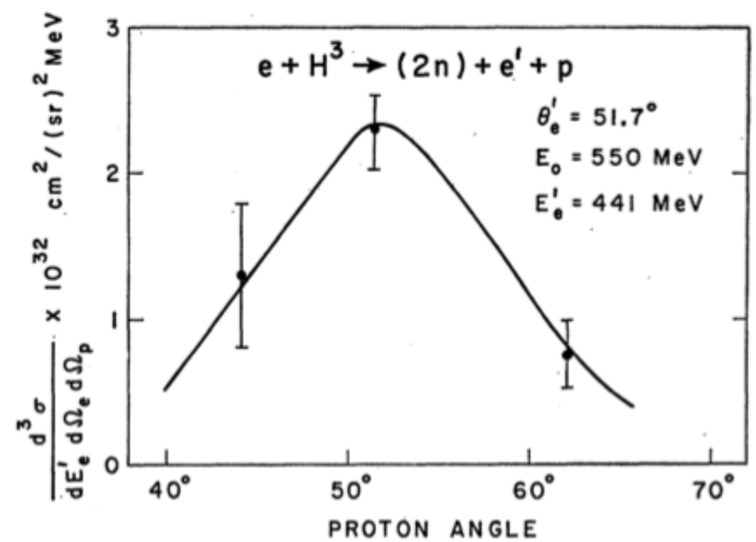
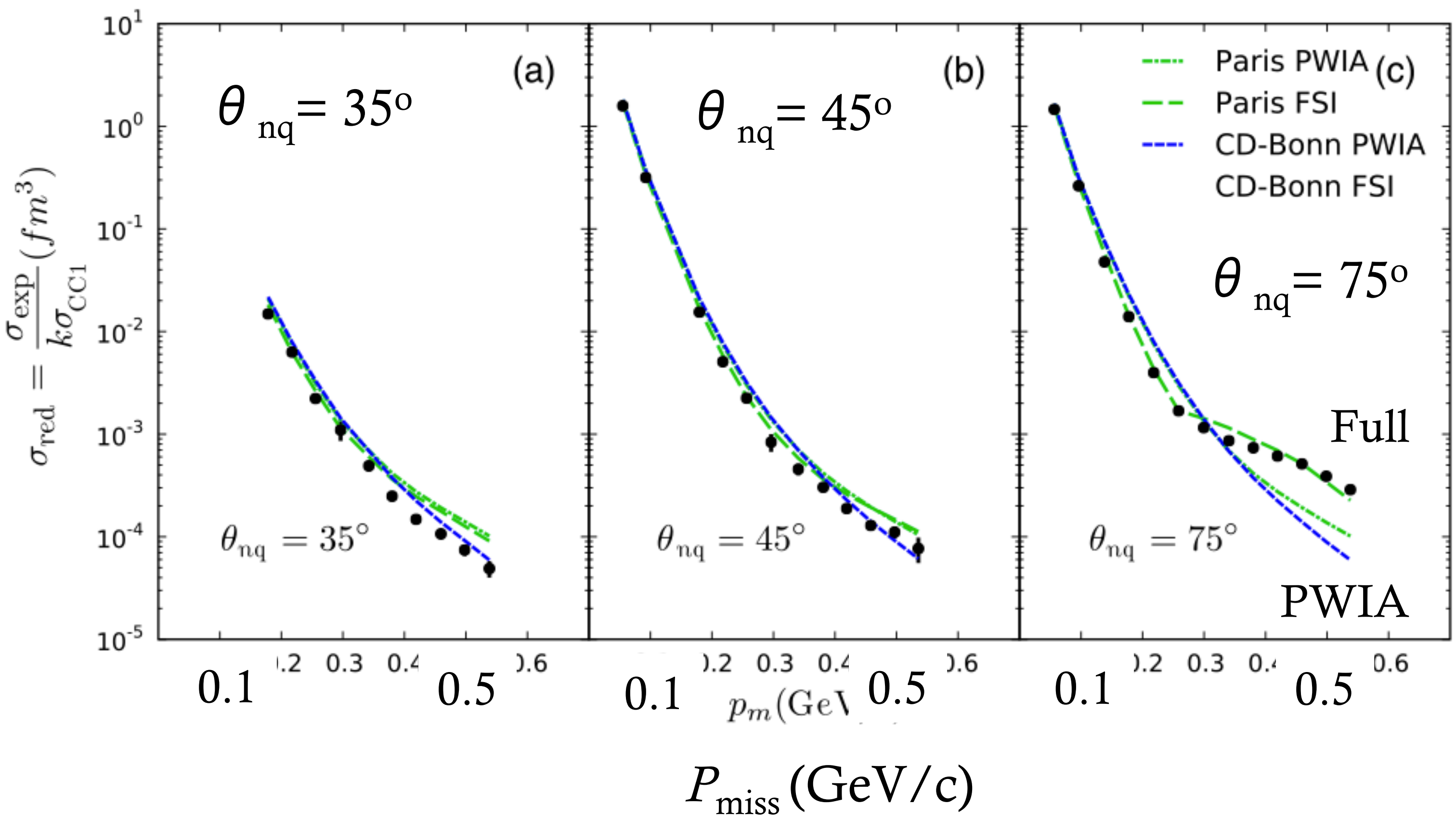


FIG. 4. The coincidence cross section of reaction (C) as a function of proton angle. The curve is explained in Sec. VI of the text.

A. Johansson (by himself!), PR136 (1964) 1030B.

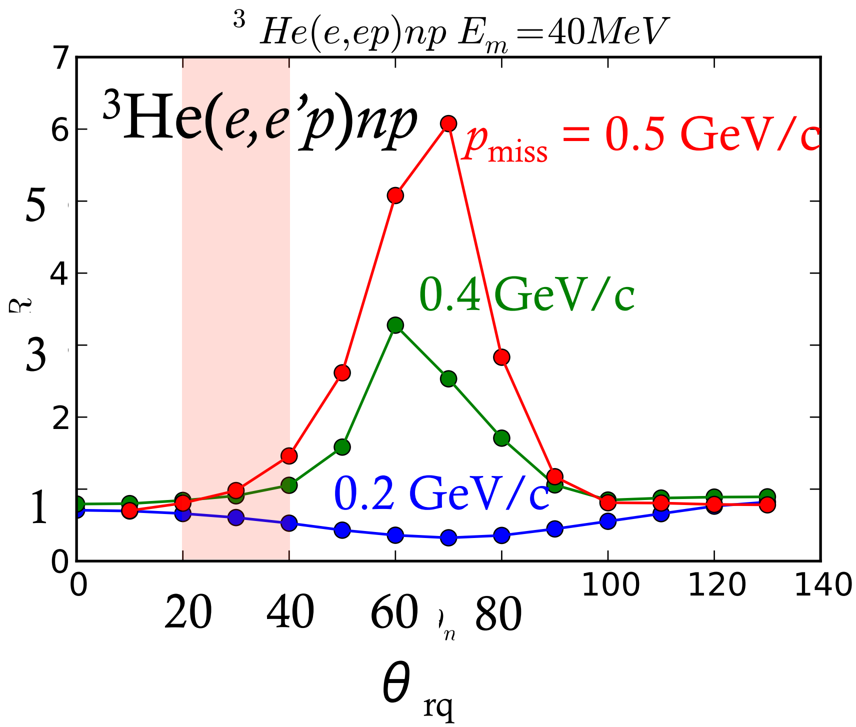
Minimizing *d*(*e,e'p*) Final State Interactions (FSI): choosing kinematics



Boeglin et al., PRL **107** (2011) 262501

Minimizing ^{3}He(*e,e'p*) FSI: choosing kinematics

Ratio of FSI to PWIA calculations



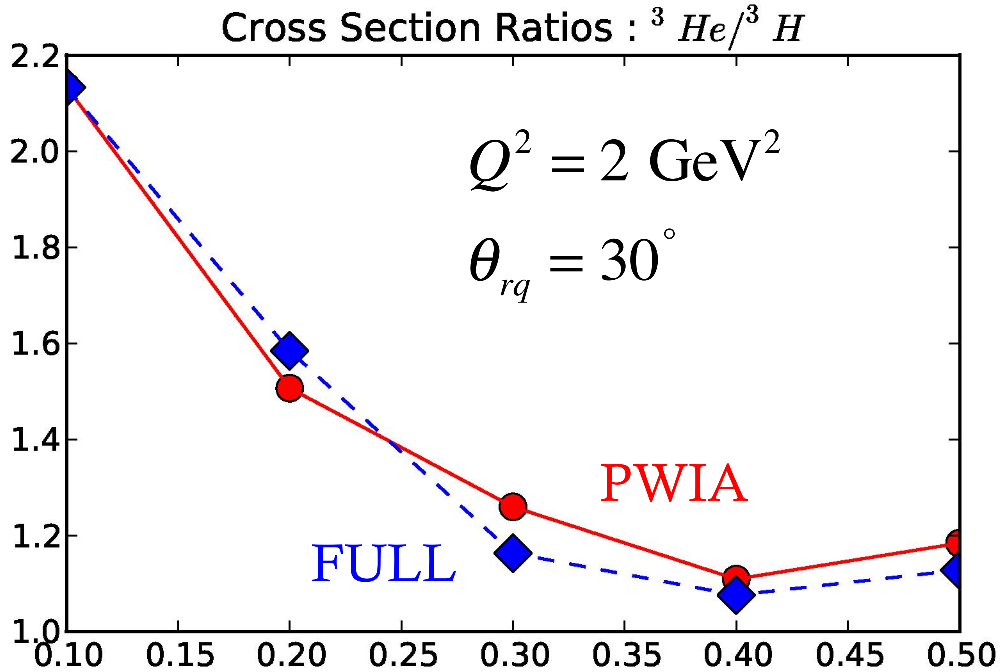
The angle between the recoil momentum and *q*

Conclusions: (from both *d* and ^{3}He(*e,e'p*): Measure at $\theta_{rq} \approx 30^o$

M. Sargsian

Minimizing FSI: taking ratios

$$\frac{\sigma(^3\mathrm{He}(e,e'p))}{\sigma(^3\mathrm{H}(e,e'p))}$$



P_m (GeV/c)

These are the kinematics of this proposal

Sargsian

- Minimize FSI by choosing $\theta_{rq} < 40^o$
- Cancel the residual effects of FSI by calculating ratios

$$\frac{\sigma(^3\mathrm{He}(e,e'p))}{\sigma(^3\mathrm{H}(e,e'p))} \approx \frac{S_{3\mathrm{He}}(E_m,p_m)}{S_{3\mathrm{H}}(E_m,p_m)}$$

The experiment

- $Q^2 \approx 2\ GeV^2$
  - Reduces non-nucleonic currents (MEC, IC)
  - Proton energies high enough for eikonal FSI calculations
- $x = Q^2/2m\omega > 1$ to minimize non-nucleonic currents
- $\theta_{rq} < 40^o$ to minimize FSI
- $E_{beam} = 4.4$ GeV
  - Maximum beam energy for HRSe
  - Maximizes the cross section
- $0 < p_{miss} < 500$ MeV/c
  - Covers the region from mean field to SRC
- HRS^2 with standard electron and proton detection packages

Kinematics

- E_{beam} = 4.4 GeV
- Q^2 = 2.0 GeV^2
- I_{beam} = 25 μA
- $\mathcal{L}(^3H)$ = 8×10^{36} nucleons cm^{-2} s^{-1}

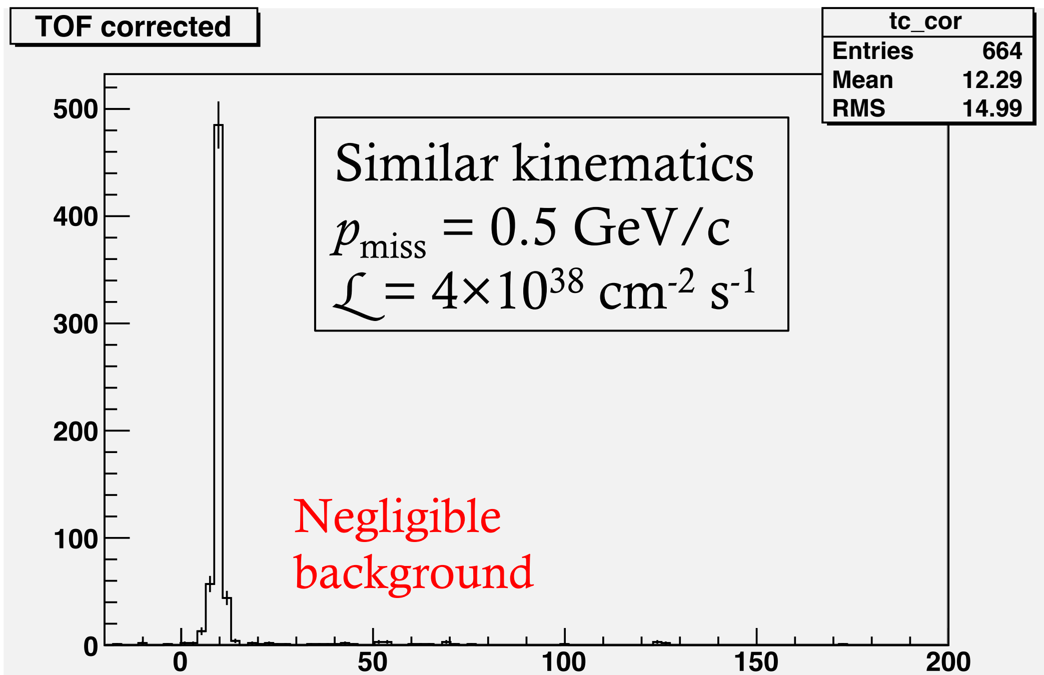
<p_m> (MeV/c)	x	E_e (GeV)	θ_e	p_p	θ_p	Time $d/^3H/^3He$ (days)
100	1.15	3.47	20.9°	1.61	48.7°	0.3/0.3/0.3
300	1.41	3.64	20.4°	1.35	58.6°	5/3/3
450	1.52	3.70	20.2°	1.23	64.9°	0/10/10

Hall A has done many (*e,e'p*) measurements at similar kinematics and much higher luminosities

This is a very low luminosity for an (*e,e'p*) experiment

- ➢ Low rates
- ➢ Very little coincidence background

Previously Measured *d*(*e,e'p*) Backgrounds and Rates



Corrected e-p Time of Flight

From the 6 GeV *d*(*e,e'p*) measurement
W. Boeglin

E_{in} = 4.7 GeV,
θ_{nq} = 40°,
p_{miss} = 0.5 GeV/c
Q^2 = 2.1 (GeV/c)^2,

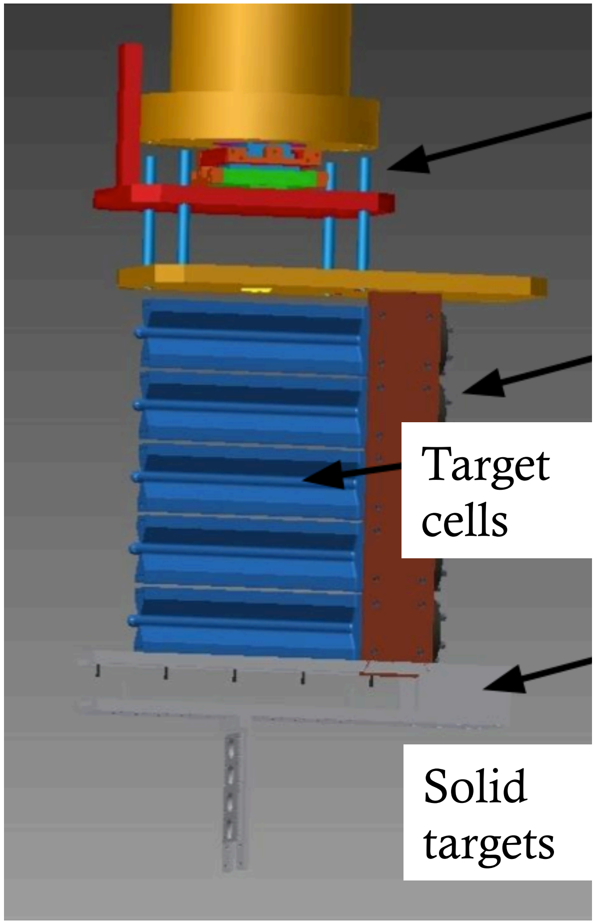
θ_e = 19.3°
θ_p = 66.3°
p_e = 3.97 GeV/c
p_p = 1.23 GeV/c

Proton rates (T1): 1.6 kHz
Electron rates (T3): 4.6 kHz
Coincidence rate (T5): 4.3 Hz

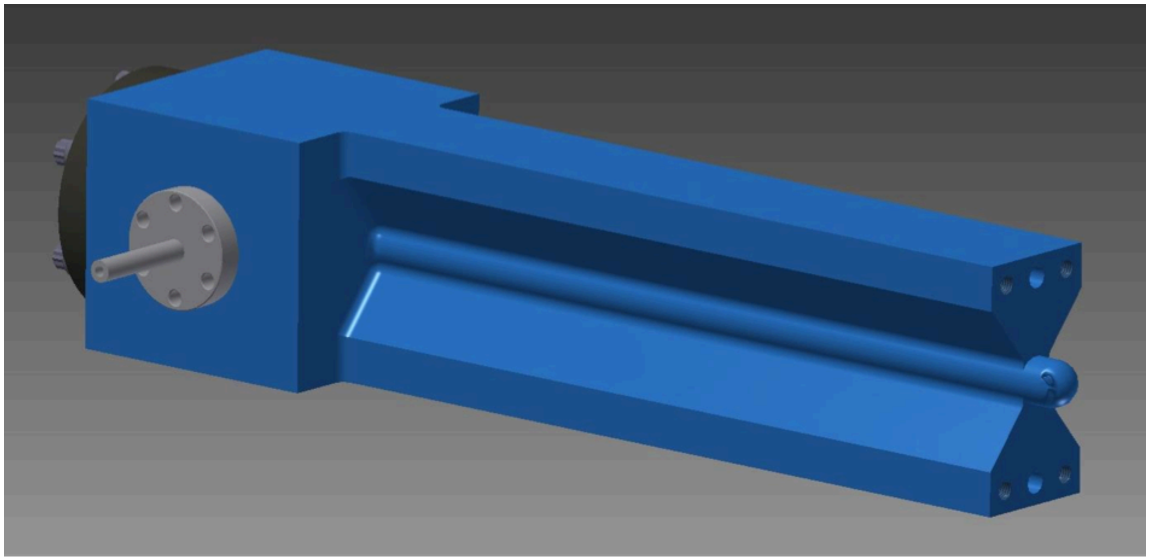
The Marathon Target

- Identical 25-cm sealed-cell gas target cells for H_2, D_2, T_2, ^3He
- $I_{beam} \leq 25\ \mu A$

Cell	Thickness (mg/cm²)	Pressure (psi)	Number density
H_2	55	400	2
D_2	111	400	2
T_2	82	200	1
^3He	82	400	1



The Marathon Target

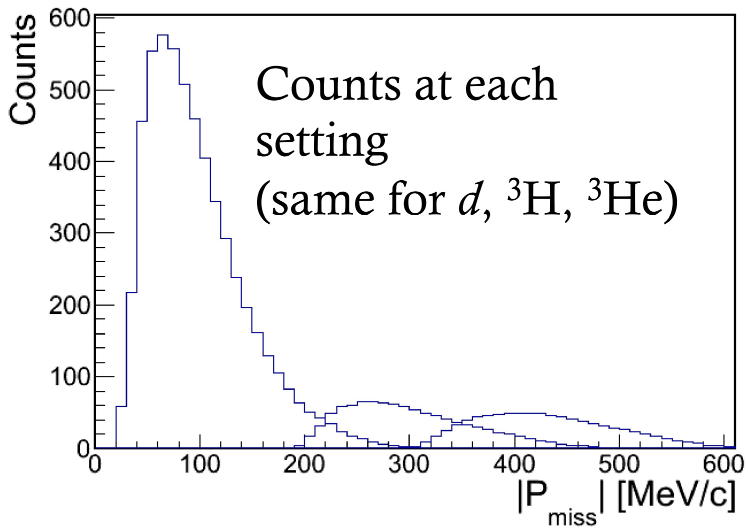


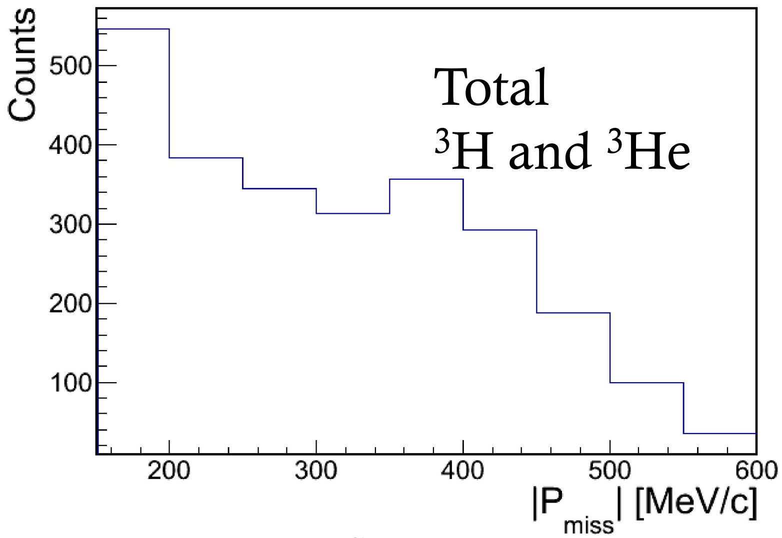
- Open cell design allows a wide range of scattering angles
- Wall thickness 0.018” Al (120 mg/cm^2)
- Entrance and exit windows: 0.010” Al (65 mg/cm^2)
- The proton HRS will not see the cell windows

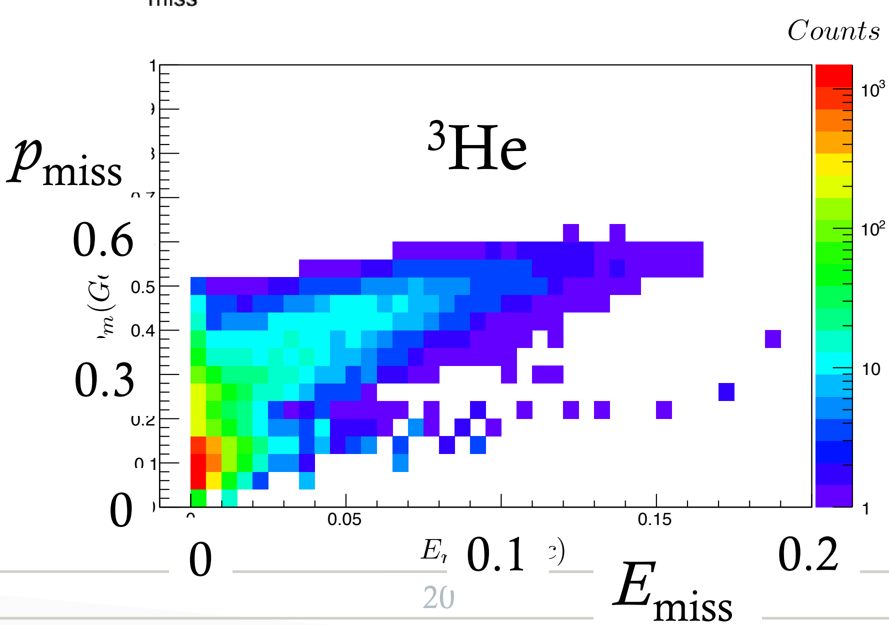
Count Rate Estimates

- MCEEP
  - Automatically includes all spectrometer acceptances
  - *R*-function cuts
- Deuteron PWIA cross section including electron radiation
  - $I_{beam} = 25\ \mu A$
  - $t = 111$ mg/cm^2 deuterium
- Used deuterium count rates for D_2, T_2 and ^3He
  - Ratio of number densities D_2:T_2:^3He = 2:1:1
  - Ratio of high p_{miss} cross sections: 1:2:2
- Factor of 1.5 to account for
  - More restrictive acceptance cuts
  - Known spectrometer tracking inefficiencies (about 15% each)

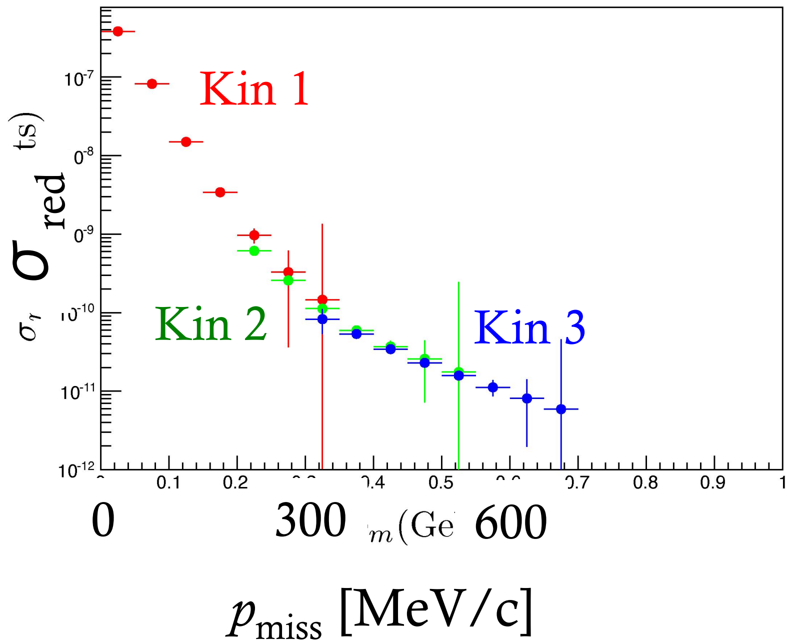
Count Rate Estimates

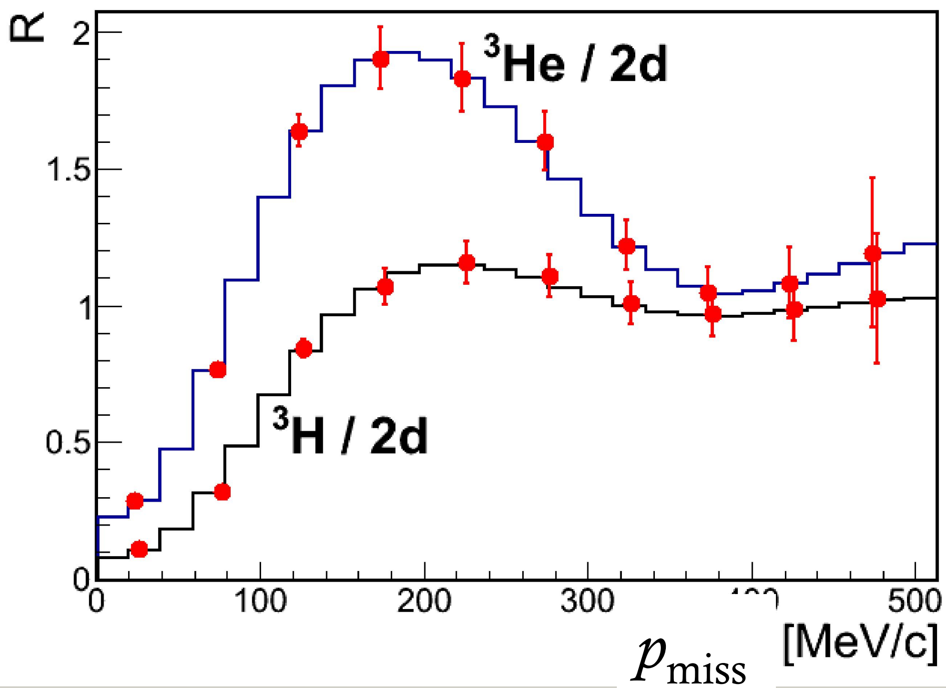




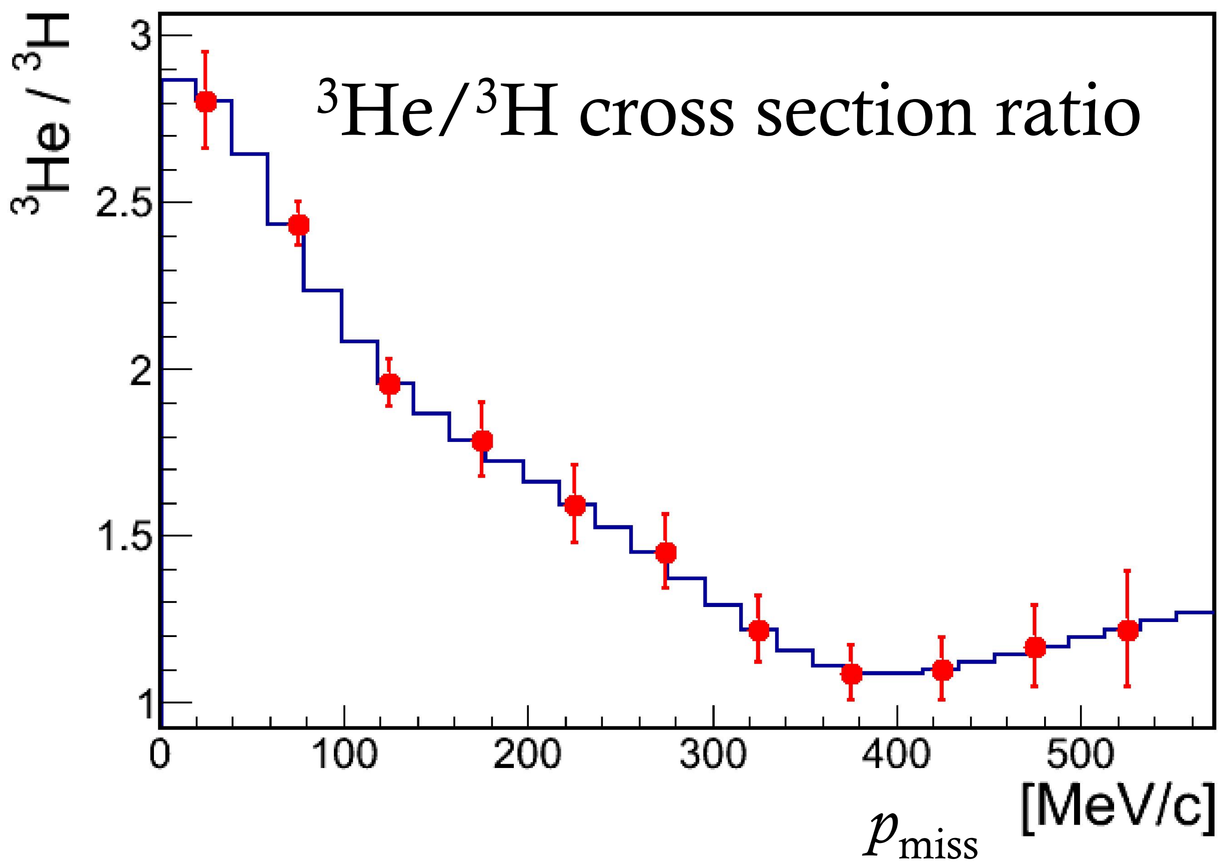


Expected Results





Expected Results



Summary

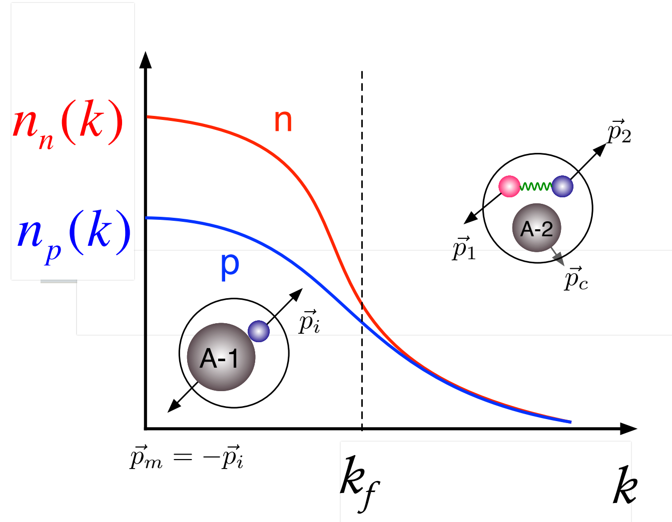
- Goal: understand nucleon momentum distributions in asymmetric nuclei

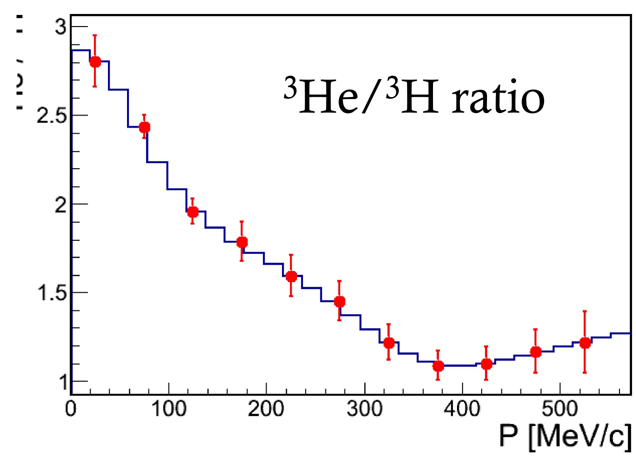
- Measure *d*, ^{3}H, and ^{3}He(*e,e'p*)
  - 33 days of beam time at 4.4 GeV
  - Q^2 = 2 GeV^2 and $x > 1$ to minimize MEC, IC
  - $\theta_{rq} < 40^o$ to maximize sensitivity to nucleon momentum distributions
  - ^{3}He/^{3}H ratio cancels residual FSI

- Measure the mean-field to SRC transition in the ^{3}He/^{3}H ratio from >2 at low p_{miss} to 1 at high p_{miss}

- Measure absolute cross sections and ratios to deuterium to constrain detailed calculations

- Unique opportunity to measure ^{3}H(*e,e'p*)

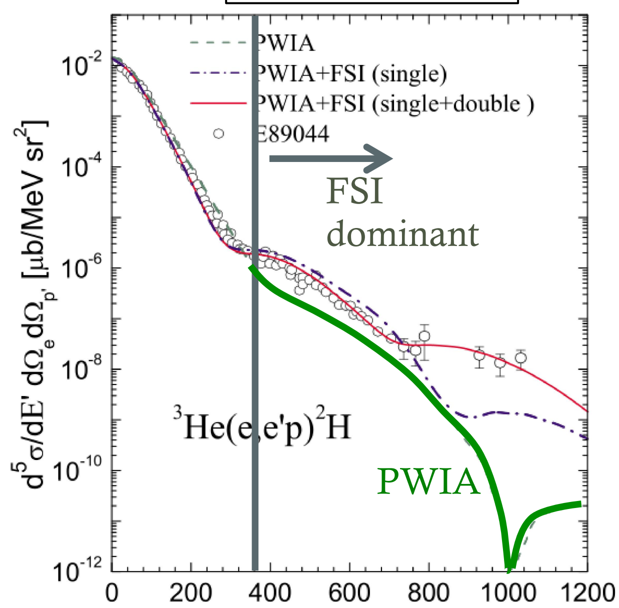




Back up

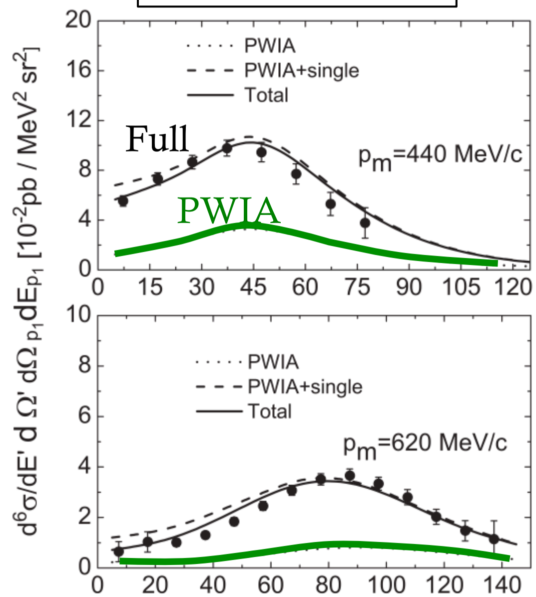
Previous Hall A ^{3}He($e,e'p$) measurements

^{3}He($e,e'p$)d



p_m [MeV/c]

^{3}He($e,e'p$)np



E_m [MeV]

p_m = 440 MeV/c

p_m = 620 MeV/c

Data:
Rvachev *et al.*, PRL94 192302
Benmokhtar *et al.*, PRL94 082305
Calculations:
Ciofi degli Atti and Kaptari, PRL95 052502
Alvioli *et al.*, PRC81 021001
Laget, PLB609 49 (not shown)

Dominated by FSI at large missing momentum
Well described by calculation