Deuteron Electro-Disintegration At Very High Missing Momenta

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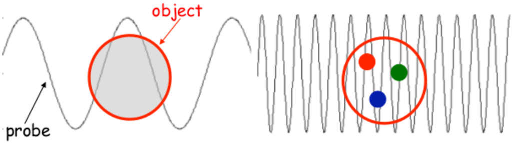
Motivation

- Study Deuteron at short ranges ($\lesssim$ 1fm).

  High momentum transfers (Q^2) $\Longrightarrow$ probe the Deuteron at smaller distances. Smaller internucleon distances enables one to access the high momentum components of nucleons

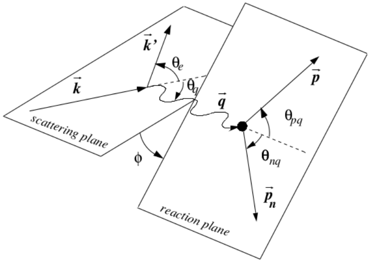
- Extract D(e,e'p)n cross-section beyond 500 MeV/c missing momentum at high Q^2

- Extract momentum distributions(not an observable) from cross sections



Theoretical Framework of D(e,e'p)n

- E.M. Interaction is well understood from Q.E.D.
- One Photon-Exchange (Born) Approximation is valid
- Virtual photon coherently interacts with Deuteron through a variety of processes (MEC, FSI, IC)
- Most direct way to probe internal structure of deuteron



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

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

$$\omega = E - E', \ \mathbf{q} = \mathbf{k} - \mathbf{k}'$$

$$P_D^\mu = (M_D, \mathbf{P_D})$$

$$\mathbf{P_D} = \mathbf{p_{i,p}} + \mathbf{p_{i,n}} = 0$$

$$Q^2 \equiv -q_\mu q^\mu = 4EE' \sin^2\left(\frac{\theta_e}{2}\right)$$

General Unpolarized $(e, e'p)$ Cross-Section

$$\frac{d^6\sigma}{d\omega d\Omega_e dT_p d\Omega_p} = \sigma_{MOTT}\left(v_L R_L + v_T R_T + v_{LT} R_{LT} \cos\phi + v_{TT} R_{TT} \cos 2\phi \right)$$

Mott Cross Section

Electron-scattering off an infinitely massive, spinless point-like object

v_i, v_{ij} - Leptonic Kinematic Factors

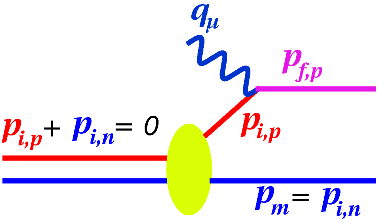
Quantities obtained from the leptonic tensor, $L_{\mu\nu}$, are dependent on electron kinematics ($\mathbf{q}$, ω, θ_e), and describe the longitudinal and transverse polarization of the virtual photon

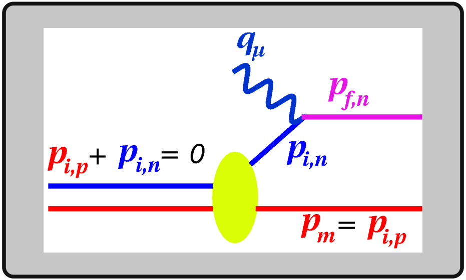
R_i, R_{ij} - Nuclear Response Functions

Consist of combinations of matrix elements from the hadronic tensor, $W^{\mu\nu} \propto \langle \mathbf{p_n}; \mathbf{p_p} | J^\mu | \mathbf{P_D} \rangle^* \langle \mathbf{p_n}; \mathbf{p_p} | J^\nu | \mathbf{P_D} \rangle$

Plane Wave Impulse Approximation (PWIA)

- virtual photon couples to proton
- the other nucleon is a spectator
- final state particles treated as plane waves (free particles)
- direct access to the deuteron momentum distribution (factorization)
- **The PWBA diagram suppressed for $p_m \sim$ few hundred MeV/c, and $p_p \sim$ few GeV/c**





Deuteron Momentum Distribution

$$\sigma_{exp} \equiv \frac{d^6\sigma}{d\omega d\Omega_e dT_p d\Omega_p} = K \cdot \boxed{\sigma_{ep}} \cdot \boxed{S(E_m, p_m)}$$

$$\boxed{S(p_m)} \approx \sigma_{red} \equiv \frac{\sigma_{exp}}{K\sigma_{ep}}$$

ep off-shell cross section

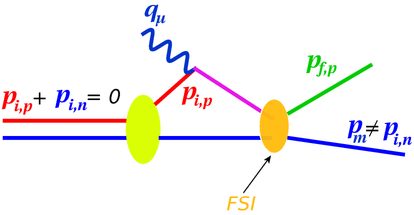
electron scatters off a bound proton within the nucleus; usually, de Forest σ_{cc1} or σ_{cc2} is prescribed

Spectral Function, $S(p_m)$

the momentum distribution inside the deuteron is interpreted as the probability density of finding a bound proton with momentum p_i

Final State Interactions (FSI)

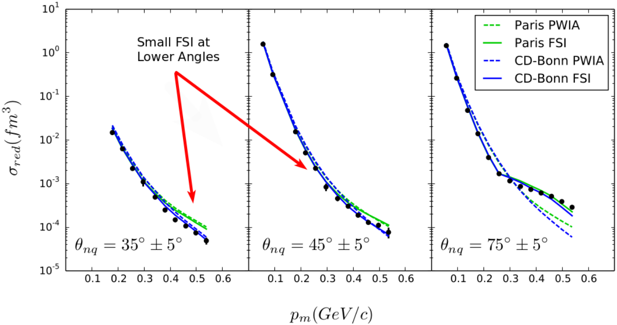
- in final state, the nucleons are at short enough distances ($\sim$ 2 fm) and continue to interact
- neutron re-scatters with a final momentum different than inside the deuteron
- generalized eikonal approximation: potentially infinite NN interactions are represented by an effective NN interaction amplitude obtained from NN scattering experiments



Experimental Support for D(e,e'p)n at Hall C

Previous D(e,e'p)n data from Hall A at Q^2=3.25 GeV^2

W.U.Boeglin *et. al* Phys.Rev.Let 89, 6 (2002)

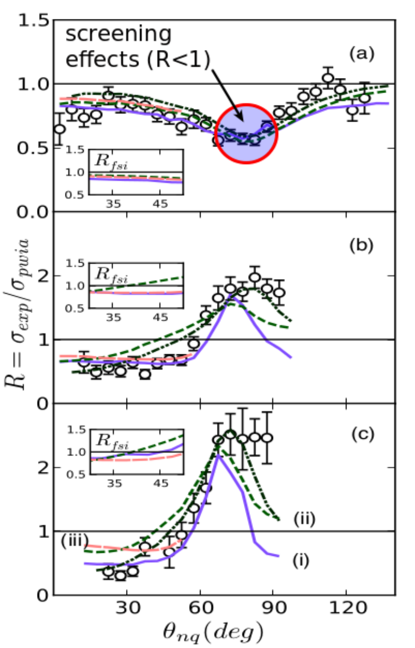


- New Hall C will focus at θ_{nq} ~40° and p_m ≥500 MeV/c at Q^2=4.25 GeV^2
- greater sensitivity of deuteron momentum distribution to different NN potential models (e.g. CD-Bonn, Paris, etc.)

○ Data (JLAB HallA)
-.-.-.- JML (FSI+MEC+IC)
- - - - - JML (FSI)
—— MS using CD-Bonn potential
- - - - - JVO

$Q^2 = 3.5\ (\mathrm{GeV/c})^2$
(a)p_m=0.2 GeV/c
(b)p_m=0.4 GeV/c
(c)p_m=0.5 GeV/c

W.U. Boeglin et. al
PRL 107(2011) 262501

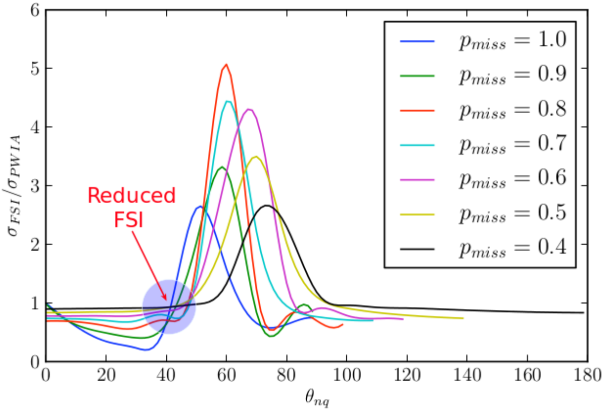


GEA: Theoretical Prediction

D(e,e'p)n Kinematics

$E_e = 11$ GeV
$Q^2 = 4.25$ (GeV/c)^2
$x_{B_j} = 1.35$
$p_m = 0.5 - 1.0$ GeV/c
$\theta_{nq} = 35° - 40°$

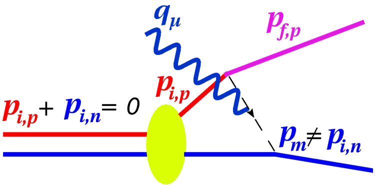
W.U. Boeglin *et. al*
Int.J.Mod.Phys. E24 (2015) no.03, 1530003



Theoretical Calculation by: M. Sargsian

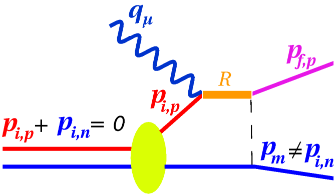
Meson Exchange Currents (MEC)

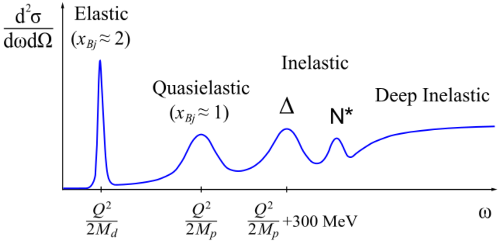
- virtual photon couples with exchange meson between nucleons
- virtual meson may become real after photon absorption
- meson exchange propagator is proportional to $(1 + \frac{Q^2}{m^2_{meson}})^{-1}$
  $\implies$ MEC suppressed for $Q^2 \gg m^2_{meson}$



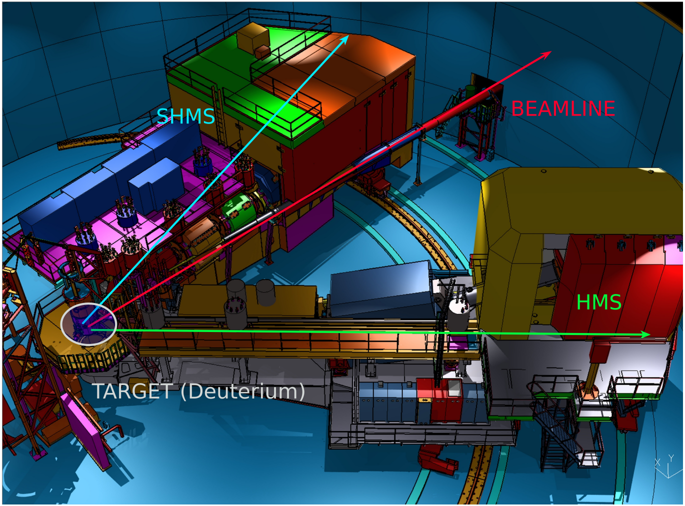
Isobar Configuration Currents (IC)

- virtual photon excites nucleon into resonance
- resonance de-excites through meson exchange with spectator nucleon
- for high Q^2, and $x_{Bj} > 1$ ($x_{Bj} \equiv \frac{Q^2}{2M_p\omega}$) one is able to probe the lower ω region of the quasi-elastic peak to suppress Δ or N^* resonance production

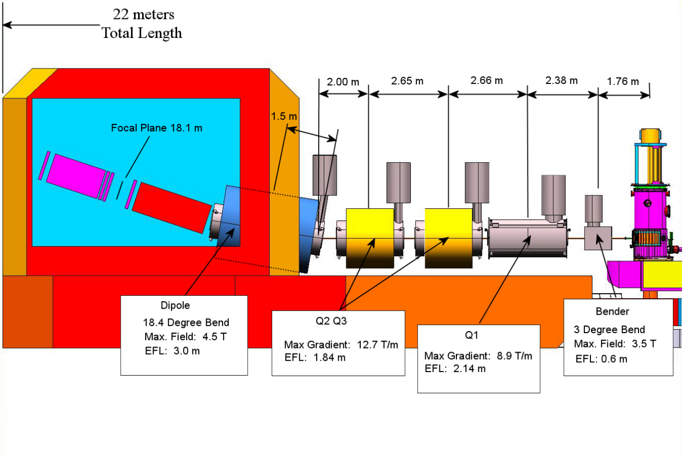




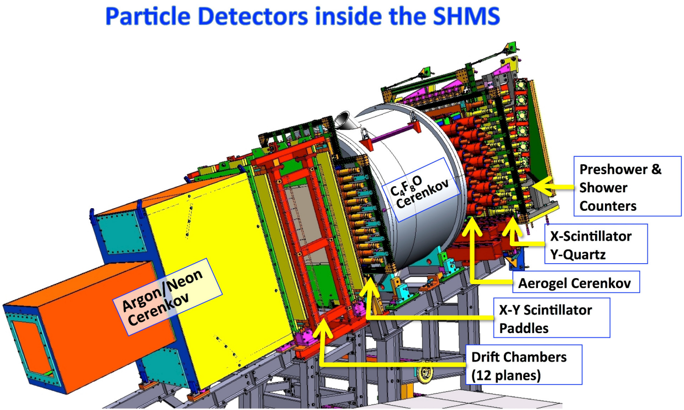
Hall C Overview



SHMS Carriage: Side View



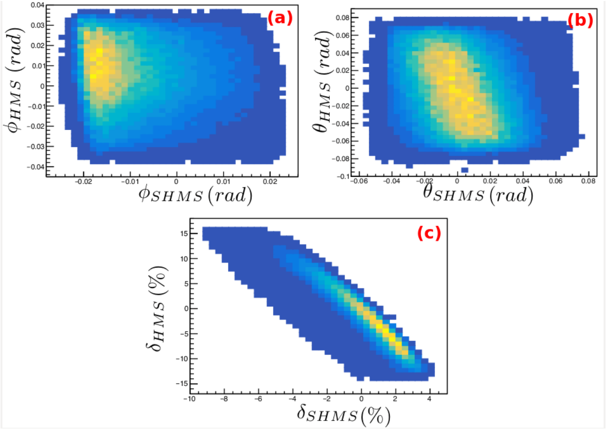
SHMS Detector Stack



E12-10-003: D(e,e'p)n Commissioning at Hall C

Spectrometer Acceptance Requirements During D(e,e'p)n Commissioning

- D(e,e'p)n will **NOT** require SHMS full acceptance
- SIMC kinematic setting, p_m =500 MeV/c

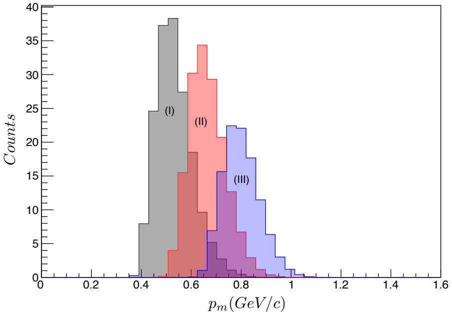


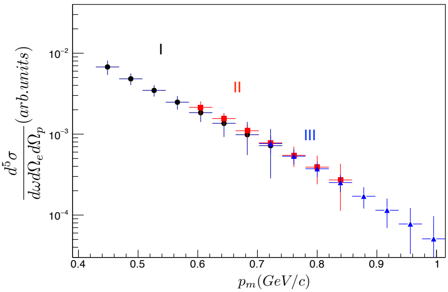
D(e,e'p)n Kinematics and Simulation Results

Beam:
Energy:10.6 GeV
Current:70μA
Target:
LD_2 (10 cm)

electron arm (SHMS) ***fixed*** **at:**
p_{cen} =8.92 GeV/c
θ_e=12.17° Q^2=4.25 $(GeV/c)^2$
x_{Bj}=1.35 θ_{nq} ~40°

vary **proton arm (HMS) to:**
p_m = 0.5, 0.65, 0.8 GeV/c
HMS: 2.12$\leq p_{cen} \leq$2.3 GeV/c
Angles: 59.6° $\geq \theta_p \geq$53.1°





SIMC Results — Statistical Uncertainties

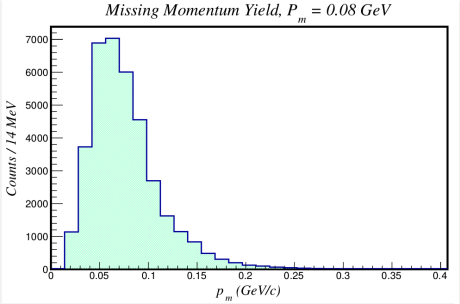
SIMC Results	Statistical Uncertainties
I. p_m=0.5 GeV/c, beam time 8 hours	16.1%
II. p_m=0.65 GeV/c, beam time 18 hours	17.0%
III. p_m=0.8 GeV/c, beam time 36 hours	20.9%

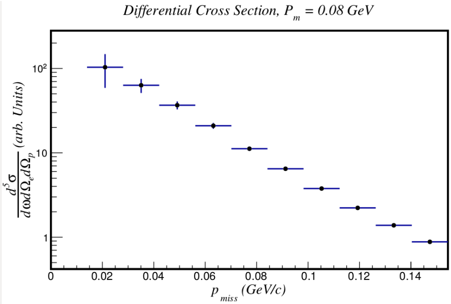
Calibration Run Setting

Beam:
Energy:10.6 GeV
Current:70μA
Target:
LD_2 (10 cm)

electron arm (SHMS) ***fixed*** **at:**
SHMS p_{cen} = 8.44 GeV/c
$\theta_e = 12.51^\circ$ $Q^2 = 4.25$ (GeV/c)^2
$x_{Bj} = 1.05$ $\theta_{nq} \sim 59^\circ$

proton arm (HMS) to ***measure*****:**
p_m = 0.08 GeV/c
HMS p_{cen} = 2.94 GeV/c
Angle: 39.14°





SIMC Results	Statistical Uncertainties
p_m=0.08 GeV/c, beam time 1 hour	1.29%

Uncertainty in Kinematic Variables

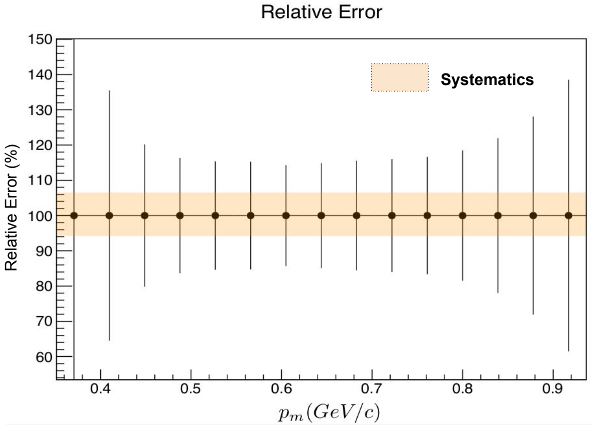
- Study sensitivity of cross-section due to small variations in kinematic variables

Kinematic Variable	**Symbol**	**Conservative Kinematic Uncertainty**	**Optimum Kinematic Uncertainty**
Beam Energy, E_B	$\Delta E_B/E_B$	1×10^{-3}	5×10^{-4}
Electron Final Momentum, $\mathbf{k_f}$	$\Delta k_f/k_f$	1×10^{-3}	5×10^{-4}
Proton Final Momentum, $\mathbf{p_f}$	$\Delta p_f/p_f$	1×10^{-3}	5×10^{-4}
Electron Scatt. Angle, θ_e	$\Delta\theta_e$	$\pm$1mrad	$\pm$0.2mrad
Proton Scatt. Angle, θ_p	$\Delta\theta_p$	$\pm$1mrad	$\pm$0.2mrad

Systematic Uncertainty Estimates on D(e,e'p)n Cross Section

p_{miss} (GeV/c)	Total Error in dσ/dΩ (%)	δE_B (%)	δk_f (%)	$\delta\theta_e$ (%)	$\delta\theta_p$ (%)
0.69	7.4	1.1	0.6	7.0	2.2
0.72	7.6	1.2	0.7	7.1	2.3
0.76	7.8	1.2	0.8	7.2	2.5
0.80	8.1	1.3	0.9	7.5	2.7
0.84	8.5	1.3	1.0	7.8	2.9
0.88	9.0	1.4	1.1	8.2	3.1
0.91	9.5	1.5	1.2	8.6	3.4
0.95	10.2	1.6	1.3	9.2	3.7
0.99	11.2	1.8	1.4	10.0	4.1

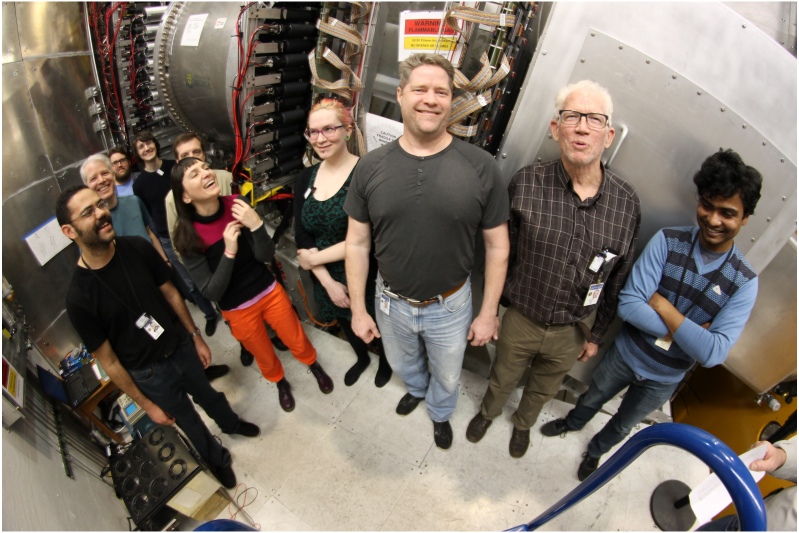
Relative Systematic and Statistical Errors on the D(e,e'p)n Cross Section



Conclusion and Future Outlook

- First meaningful data at very high missing momenta obtainable during commissioning period
- Systematic errors on the cross section are consistently smaller than statistical errors for the range of missing momentum studied
- Requirements on initial spectrometer performance are realistic
- 3 days of beam time required
- Good opportunity to obtain new early physics results

SHMS Detector Stack Photo



Acknowledgments

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BACKUP SLIDES

Cuts Applied to Extract Yield

Kinematic Cuts:

-10 MeV $\leq E_{miss} \leq$ 25 MeV

$35° \leq \theta_{nq} \leq 45°$

$1.30 \leq x_{Bj} \leq 1.40$

$3.1 \leq Q^2 \leq 5.2$

Solid Angle Cuts:

e-arm: $|\frac{dx}{dz}|_{tgt} = |\theta|_{tgt} \leq 0.05$ rad

(SHMS) $|\frac{dy}{dz}|_{tgt} = |\phi|_{tgt} \leq 0.025$ rad

p-arm: $|\frac{dx}{dz}|_{tgt} = |\theta|_{tgt} \leq 0.08$ rad

(HMS) $|\frac{dy}{dz}|_{tgt} = |\phi|_{tgt} \leq 0.035$ rad

Momentum Acceptance Cuts:

e-arm: $-8 \leq \delta_e \leq 4$

(SHMS)

p-arm: $-15 \leq \delta_p \leq 15$

(HMS)

where $\delta \equiv \frac{p - p_{cen}}{p_{cen}}$