Electron Scattering from Deeply Bound Nucleon on the Light-Front

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Introduction

Why a description of electromagnetic scattering from deeply bound nucleons?

Experiments at quasi-elastic kinematics established signatures that deeply bound nucleons emerge from short range nucleon-nucleon correlations.

Study the structure of nuclei at short distance.

Use of nucleons as the main degrees of freedom

Study high momentum components of the bound nucleon

$$\frac{m_N}{2} \lesssim p_i \simeq m_N \quad \rightarrow \quad Q^2 \sim \text{ a few GeV} \quad \rightarrow \quad p_f \sim \text{ a few GeV}$$

Introduction

Simplest case: Exclusive Electro-Disintegration of Deuteron

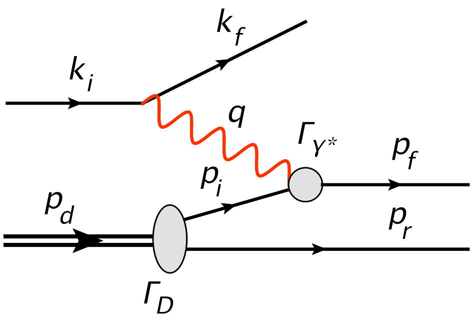
$$e + d \rightarrow e' + N_f + N_r \tag{1}$$

N_f: ejected nucleon

N_r: recoil nucleon

q: virtual photon momentum, $q^2 < 0$

Within the Plane Wave Impulse Approx. (PWIA):



Easy and general enough to extend to bigger nuclei

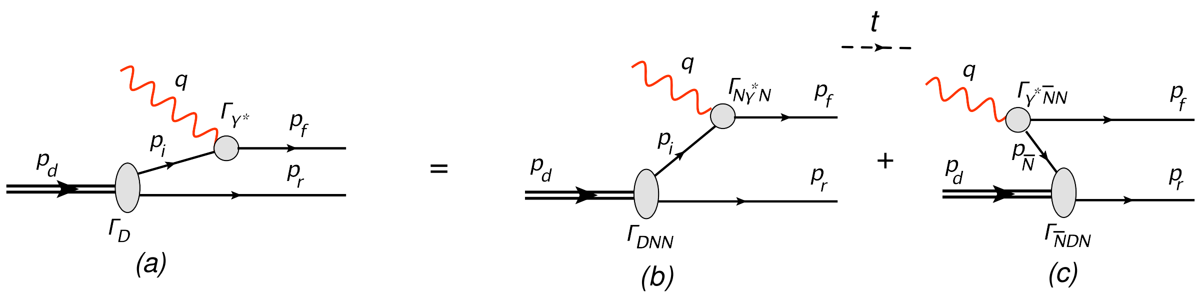
Feynman amplitude:

$$\mathcal{M} = \langle \lambda_f \mid j_e^\nu \mid \lambda_i \rangle \frac{e^2 g_{\nu\mu}}{q^2} \langle s_f, s_r \mid A_o^\mu \mid s_d \rangle, \tag{2}$$

with, $\gamma^* d \to NN$ scattering amplitude:

$$A_o^\mu = \langle s_f, s_r \mid A_o^\mu \mid s_d \rangle = -\bar{u}(p_f, s_f)\Gamma^\mu_{\gamma^*} \frac{\not{p}_i + m_N}{p_i^2 - m_N^2} \; \bar{u}(p_r, s_r)\Gamma_D \; \chi^{s_d} \tag{3}$$

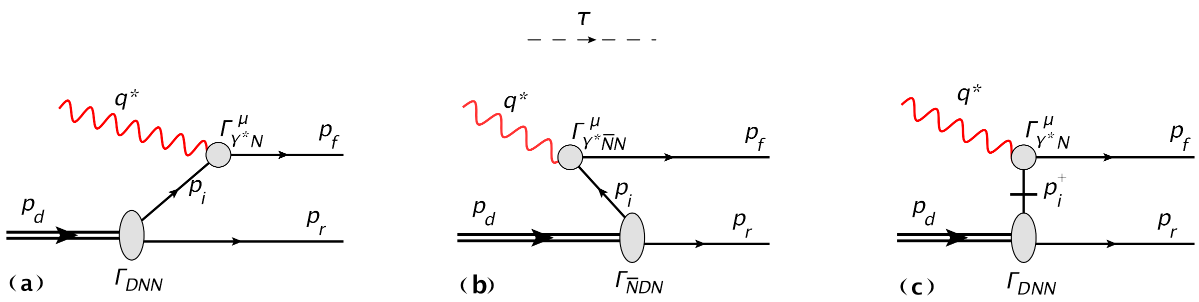
Extracting electro-bound nucleon Cross Sect. $\Longrightarrow$ Time ordered amplitude:



$p_i \gtrsim m_N/2 \; (Q \gtrsim 2m_N) \to$ "Z-graph" can not be ignored

Set Up

Light Front τ-time ordered scattering amplitude:

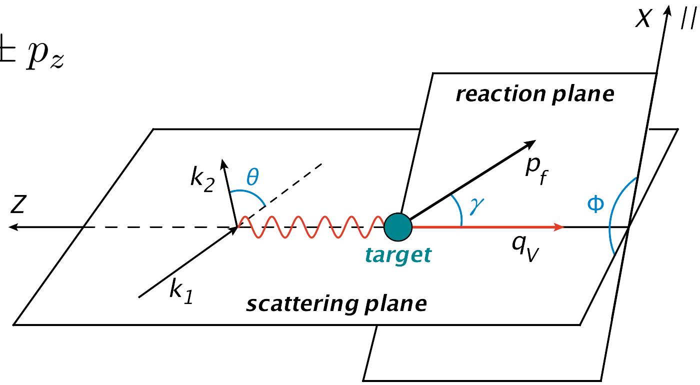


LF coordinates: (x^+, x^-, x, y), $x^\pm = t \pm z$, $x^+ = \tau$

LF momenta: (p^+, p^-, p_x, p_y), $p^\pm = E \pm p_z$

No "Z-Graph" in a collinear-frame

where $\hat{z}$ is opposite to $\mathbf{q}$



Nuclear Amplitude

LFPT diagrammatic rules produces two contributions (Kogut and Soper 1970) (Lepage and Brodsky 1980)

Propagating:

$$A^{\mu}_{prop} = -\bar{u}(p_f, s_f)\Gamma^{\mu}_{\gamma^* N} \frac{1}{p_i^+} \frac{(\not{p}_i + m_N)_{on}}{(p_d^- - p_r^- - p_{i,on}^-)} \bar{u}(p_r, s_r)\Gamma_{DNN}\chi^{s_d} \tag{4}$$

Instantaneous:

$$A^{\mu}_{inst} = -\bar{u}(p_f, s_f)\Gamma^{\mu}_{\gamma^* N} \frac{1}{p_i^+} \left(\frac{1}{2}\gamma^+\right) \bar{u}(p_r, s_r)\Gamma_{DNN}\chi^{s_d} \tag{5}$$

Factorisation of the amplitude:

$$A^{\mu} = A^{\mu}_{prop} + A^{\mu}_{inst} = \sum_{s_i} J^{\mu}_{N}\left(p_f s_f, p_i s_i\right) \frac{\psi_{LF}^{s_i s_r s_d}\left(\alpha, \mathbf{p_T}\right)}{\alpha} \sqrt{2\left(2\pi\right)^3}$$

Nucleonic Current

$$J_N^\mu = J_{(prop)}^\mu + J_{(inst)}^\mu \tag{6}$$

where,

$$J_{(prop)}^\mu = \bar{u}(p_f, s_f)\left(\gamma^\mu F_1 + i\sigma^{\mu\nu} q_\nu F_2 \frac{\kappa}{2m_N}\right) u(p_i, s_i) \tag{7}$$

$$J_{(inst)}^\mu = \bar{u}(p_f, s_f)\Gamma_{\gamma * N}^{(inst)\mu} u(p_i, s_i) \tag{8}$$

$$\Gamma_{\gamma^* N}^{(inst)\mu} = \left(\gamma^\mu F_1 + i\sigma^{\mu\nu} q_\nu F_2 \frac{\kappa}{2m_N}\right)\frac{\Delta \not{p}_i}{2m_N} - F_1 \frac{q^\mu}{q^2} \not{q} \left(\mathbf{1} + \frac{\Delta \not{p}_i}{2m_N}\right) \tag{9}$$

dynamic off-shell factor: $\Delta p_i^\mu = p_d^\mu - p_r^\mu - p_{i,on}^\mu = p_i^\mu - p_{i,on}^\mu$

$$2\Delta \not{p}_i = \gamma^+ \left(p_i^- - p_{i,on}^-\right)$$

$J_{(prop)}^\mu$ not an on-shell current, $\quad q^\mu \neq p_f^\mu - p_{i,on}^\mu$

Structure Functions

Electro Nucleon Cross Section in terms of Structure Functions

$$\sigma_{eN} = \frac{1}{2p_d p_i}\,\sigma_{Mott}\,\frac{k_i}{E_f}\left(\eta_L V_L^N + \eta_{TL} V_{TL}^N \cos\phi + \eta_T V_T^N + \eta_{TT} V_{TT}^N \cos(2\phi)\right)$$

Nucleonic EM tensor in LF components

$$\begin{aligned}
V_L^N &= \frac{q_V^4}{4}\left(H_N^{++}\frac{1}{q^+q^+} + \frac{2}{Q^2}H_N^{+-} + \frac{q^+q^+}{Q^4}H_N^{--}\right)\\
V_{TL}^N &= \frac{q_V}{Q^2}\left(H_N^{+\parallel}q^- - H_N^{-\parallel}q^+\right)\\
V_T^N &= H_N^{\parallel\parallel} + H_N^{\perp\perp}\\
V_{TT}^N &= H_N^{\parallel\parallel} - H_N^{\perp\perp}
\end{aligned}$$

Structure Functions

$$
\begin{aligned}
V^N_{L\ prop} &= \mathbf{q}^2\Big[F_1^2\tau^{-1}\Big(1+\frac{p_\mathbf{T}^2}{m_N^2}+\tau\eta_i(\eta_i+\eta_q)\Big)-F_1F_2\kappa\Big(2+\eta_q\Big)+F_2^2\kappa^2\Big(\frac{p_\mathbf{T}^2}{m_N^2}+\tau(1+\eta_q)\Big)\Big]\\
V^N_{L\ inst} &= \mathbf{q}^2\Big[F_1^2\eta_i\Big(\tau\eta_i(1+\eta_q)-2-\eta_q\Big)+F_1F_2\kappa\Big(\tau\eta_i\ (2-2\eta_i-\eta_q)+\eta_q\Big)\\
&\quad +F_2^2\kappa^2\tau\Big(\tau\eta_i(\eta_i+\eta_q)-\eta_q\Big)\Big]\\
V^N_{TL\ prop} &= 2\ |\mathbf{q}|\ p_\mathbf{T}\ \Big(F_1^2+F_2^2\kappa^2\tau\Big)\ \Big[2+4\frac{\alpha_N}{\alpha_q}+2\eta_i+\eta_q\Big]\\
V^N_{TL\ inst} &= 2|\mathbf{q}|p_\mathbf{T}\ \Big(F_1^2+F_2^2\kappa^2\tau\Big)\ (1-\tau\eta_i)\,\eta_q\\
V^N_{T\ prop} &= 4m_N^2\Big[F_1^2\Big(\frac{p_\mathbf{T}^2}{m_N^2}+2\tau(1+\eta_q)\Big)+2F_1F_2\kappa\tau\ (2+\eta_q)+F_2^2\kappa^2\tau\Big(2+\frac{p_\mathbf{T}^2}{m_N^2}+2\tau\eta_i(\eta_i+\eta_q)\Big)\Big]\\
V^N_{T\ inst} &= 2Q^2\Big[F_1^2\Big(\tau\eta_i(\eta_i+\eta_q)-\eta_q\Big)+F_1F_2\kappa\Big(\tau\eta_i\ (2\eta_i+\eta_q-2)-\eta_q\Big)\\
&\quad +F_2^2\kappa^2\tau\eta_i\Big(\tau\eta_i(1+\eta_q)-2-\eta_q\Big)\Big]\\
V^N_{TT\ prop} &= 4p_\mathbf{T}^2\ \Big(F_1^2+F_2^2\kappa^2\tau\Big)\\
V^N_{TT\ inst} &= 0
\end{aligned}
$$

with,

$\eta=\frac{1}{Q^2}\left(4\frac{(m_N^2+\mathbf{p_T}^2)}{\alpha(2-\alpha)}-m_d^2\right)$, a universal parameter controlling off-shell effects

and, $\tau=Q^2/(4m_N^2)$, $\eta_i=\eta\ \alpha_N/2$, $\eta_q=\eta\ \alpha_q/2$

Results

Different off-shell Scattering Cross Sections lead to significantly different results (specially for deeply bound nucleons).

Comparison with the widely used de Forest off-shell extrapolations:

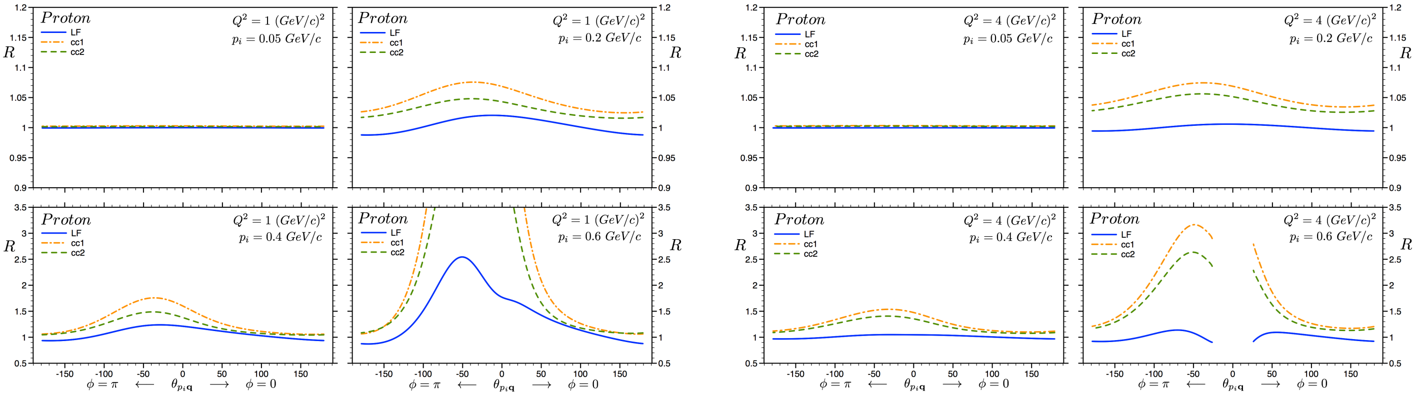


Figure 1: Angular distribution. $R = \frac{\sigma_{eN}}{\sigma_{eN}^{free}}$

Results

Comparison with the widely used de Forest off-shell extrapolations:

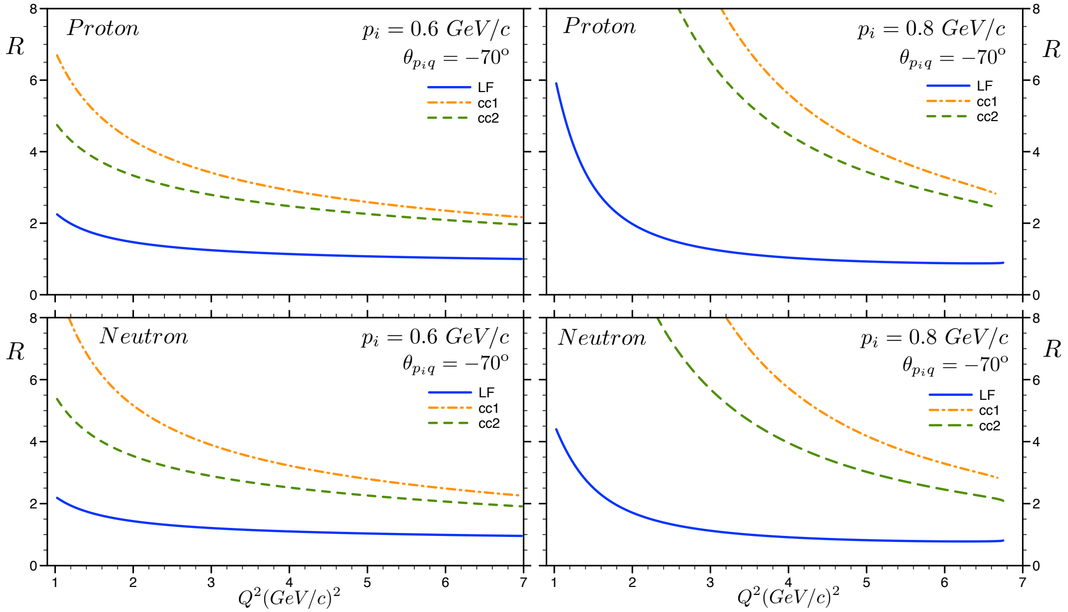


Figure 2: Q^2 distribution. $R = \frac{\sigma_{eN}}{\sigma_{eN}^{free}}$

Increasing the photon's virtuality reduces the off-shell effects.

Results

Kinematics for E01-020 (Boeglin et al., arXiv:1410.6770)

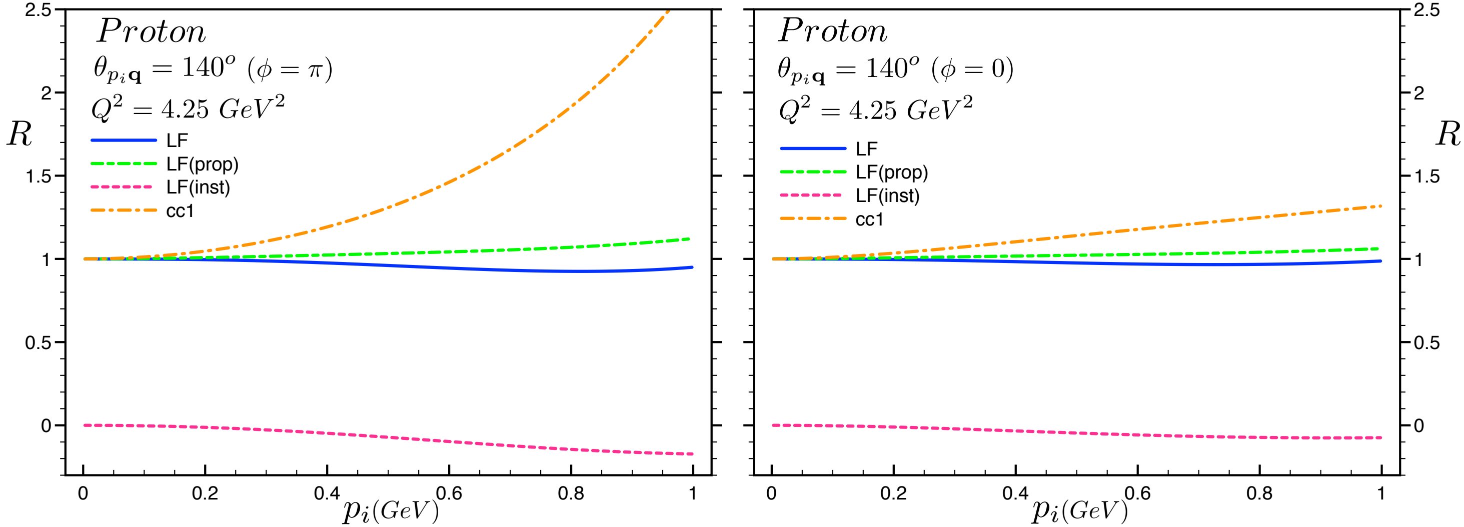


Figure 3: p_i distribution. $R = \frac{\sigma_{eN}}{\sigma_{eN}^{free}}$

Results

For wide range of kinematics, $\eta < 0.1 \implies$ off-shellness $\lesssim 5\%$

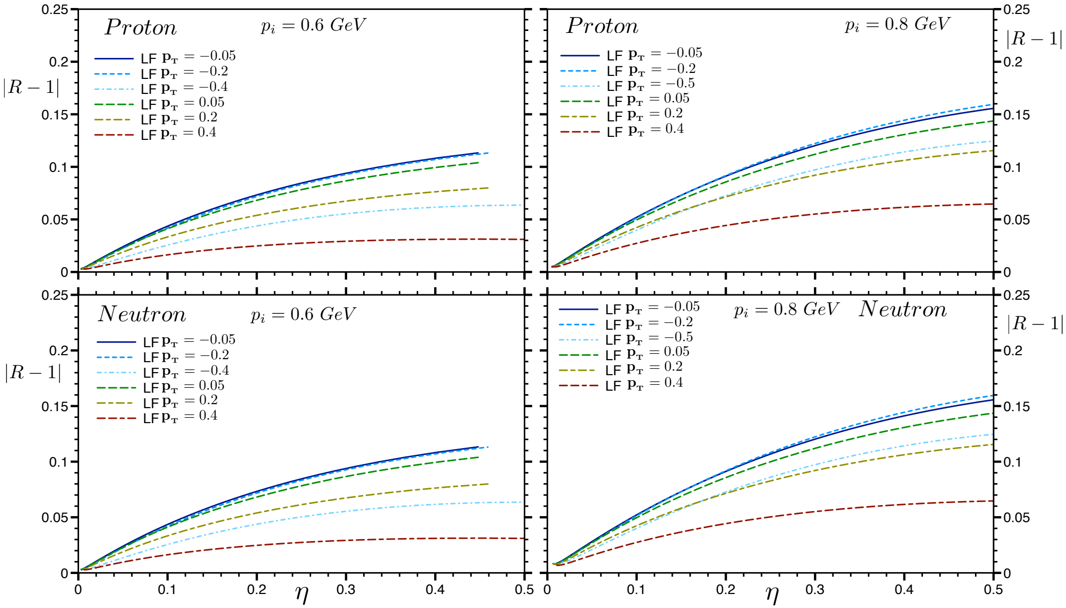


Figure 4: $\eta = \frac{1}{Q^2}\left(4\frac{(m_N^2 + \mathbf{p_T}^2)}{\alpha(2-\alpha)} - m_d^2\right)$

Effective method for controlling the uncertainties in the reaction mechanism.

Summary

Electron–bound-nucleon cross section calculation based on Light Front Perturbation Theory.

Identification of parameter (η) that universally characterizes the off-shell extend of the electromagnetic current.

η can be used by experimentalists to suppress or isolate the off shell effects for dedicated studies.

Results are more general than just PWIA:
The EM current is applicable to FSI within eikonal approximation.

End

Thank You