

Light-front nuclear structure from chiral effective field theory

The deuteron and its peripheral pion density

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Central question for the EIC era

Problem

Hard nuclear reactions probe correlations at fixed

$$x^+ = x^0 + x^3,$$

not at ordinary equal time. A deuteron wave function used in DIS, tagged DIS, DVCS, or coherent diffraction should therefore be organized on the same hypersurface as the light-ray operator.

Aim

Construct low-energy nuclear dynamics at fixed light-front time, while preserving the scale separation and counterterm logic of chiral EFT.

Output of this talk

- LF variables and deuteron vertex
- LO chiral NN interaction on the LF
- Pion plus-momentum density in the deuteron
- Destructive two-body exchange effect

Scale separation: deuteron binding versus chiral dynamics

$$\gamma \ll M_\pi \ll \Lambda_\chi \sim 1 \text{ GeV}$$

$$\gamma \equiv \sqrt{m_N \epsilon_d} = 45.7 \text{ MeV},$$

$$\epsilon_d = 2.2246 \text{ MeV}$$

- Binding controls the large pn separation.
- Pions resolve distances $b = O(M_\pi^{-1})$.
- Contacts absorb unresolved short-distance dynamics.

The observable target is the universal long-distance tail, not the short-distance core.

LF scaling of the pion cloud

Soft peripheral pion:

$$k_{\pi T} = O(M_\pi), \quad y = O(M_\pi/m_N).$$

This is exactly the domain where the pion is a resolved EFT degree of freedom and the nucleon core is not resolved.

Light-front two-nucleon kinematics

For the deuteron, define

$$\alpha_p = 2 \frac{p_p^+}{P_d^+}, \quad \alpha_n = 2 - \alpha_p, \quad p_{pT} = -p_{nT} \equiv p_T.$$

The invariant mass of the on-shell pn configuration is

$$M_{pn}^2 = \frac{4(m_N^2 + p_T^2)}{\alpha_p(2 - \alpha_p)}.$$

Rotationally symmetric Terentev variable

$$k_T = p_T, \quad k_z = (\alpha_p - 1)E_k, \quad E_k = \sqrt{m_N^2 + \mathbf{k}^2},$$

$$\alpha_p = 1 + \frac{k_z}{E_k}, \quad \frac{d\alpha_p d^2 p_T}{\alpha_p(2 - \alpha_p)} = \frac{d^3 k}{E_k}.$$

At $|\mathbf{k}| \ll m_N$, the LF wave function reduces smoothly to the familiar nonrelativistic pn wave function.

LO chiral NN interaction at fixed LF time

Covariant χ EFT NN amplitude \rightarrow LF time-ordered irreducible kernel V \rightarrow Bound-state

Leading-order potential

$$V^{(0)} = V_{1\pi} + V_{\text{ct}}^{(0)}.$$

$$V_{1\pi}(\mathbf{q}) = -\frac{g_A^2}{4F_\pi^2} \frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{q})(\boldsymbol{\sigma}_2 \cdot \mathbf{q})}{\mathbf{q}^2 + M_\pi^2} (\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2).$$

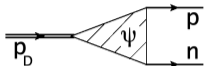
In the deuteron channel, $l = 0$ and $\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 = -3$.

Contacts and power counting

$$V_{\text{ct}}^{(0)} = C_S + C_T \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2.$$

- WPC: iterate OPE + LO contacts.
- MWPC: promote counterterms where singular OPE demands RG stability.
- Long-distance pion tail is independent of the UV prescription.

LF wave function, deuteron vertex



Deuteron to pn transition vertex.

$$\psi_{s_p s_n}^\lambda = - \sum_{s'_n} \bar{u}(p, s_p) \Gamma^\mu \gamma_5 \epsilon_{s_n s'_n} u(n, s'_n) \epsilon_\mu^\lambda$$

Choice of independent momenta

$$P_{NN} = p + n, \quad p_{\text{rel}} = \frac{p - n}{2}, \quad \Delta = P_{NN} - p_d,$$

$$\Delta^\mu = (0, 0_T, \Delta^-), \quad \Delta^- = \frac{M_{NN}^2 - M_d^2}{P_d^+}.$$

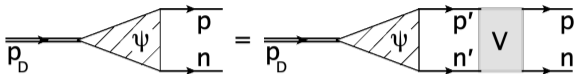
Γ^μ : six independent covariant structures, at leading order in k/m_N only the usual 3S_1 and 3D_1 structures remain.

$$\psi_{s_p, s_n}^\lambda = N \phi_{s_p}^\dagger \left[f_0(k) \sigma \cdot s_d^\lambda - f_2(k) / \sqrt{2} \left((\sigma \cdot \hat{k})(\hat{k} \cdot s_d^\lambda) - \sigma \cdot s_d^\lambda \right) \right] \epsilon_{s_n s'_n} \phi_{s'_n}$$

Interpretation

- f_0 : 3S_1 component; controls long-distance deuteron tail.
- f_2 : 3D_1 component; generated by the tensor force.
- The Terentev variable makes the leading rotational structure explicit on the LF.

Bound-state equation



LF bound-state equation generated by OPE.

Invariant-mass equation

$$[M_{NN}^2(k) - M_d^2] \Psi^\lambda(k) = \int \frac{d^3 k'}{(2\pi)^3 E_{k'}} V(k, k') \Psi^\lambda(k')$$

For small momenta,

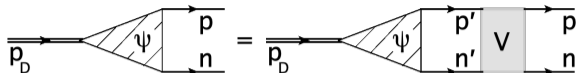
$$M_{NN}^2 - M_d^2 = 4m_N \left(\frac{k^2}{m_N} + \epsilon_d + O(Q^4/m_N^3) \right),$$

so the Schrödinger equation is recovered after the conventional rescaling.

Why LF helps high-energy scattering

Nucleons in the LF wave function are on mass shell. Binding and interactions enter through finite invariant-mass denominators, not through an energy off-shellness growing with the external beam energy.

Coupled partial-wave bound-state equation



LF bound-state equation generated by OPE.

$$\begin{pmatrix} f_0(k)/\sqrt{2} \\ f_2(k)/2 \end{pmatrix} = \frac{1}{4E_k^2 - M_d^2} \int_0^\infty k'^2 dk' \begin{pmatrix} V_{00} & V_{02} \\ V_{20} & V_{22} \end{pmatrix} \begin{pmatrix} f_0(k')/\sqrt{2} \\ f_2(k')/2 \end{pmatrix}$$

The OPE projections involve Legendre functions $Q_L(z)$,

$$V_{00}(k, k') = g_\pi \left[-Q_0(z) + \frac{1}{3} \delta(k, k') \right],$$

$$V_{02}(k, k') = V_{20}(k, k') = 4g_\pi \left[\frac{1}{2} Q_0(z) - \frac{3}{2} Q_1(z) + z Q_1(z) \right],$$

$$V_{22}(k, k') = g_\pi \left[-2Q_2(z) + 3z Q_1(z) - \frac{3}{2} Q_0(z) \right],$$

$$\text{with, } z = \frac{k^2 + k'^2 + M_\pi^2}{2kk'}$$

...

Contact terms enter the S-wave channel and are fixed by low-energy NN data or deuteron observables.

Pion plus-momentum density as a light-ray matrix element

For the unpolarized deuteron, define the pion plus-momentum distribution

$$f_{\pi/d}(\alpha_\pi) = (P_d n) \alpha_\pi \int \frac{d\lambda}{2\pi} e^{i\lambda\alpha_\pi(P_d \cdot n)} \langle d | \pi^a(-\lambda n/2) \pi^a(\lambda n/2) | d \rangle.$$

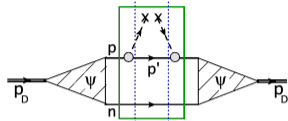
Here $\alpha_\pi = 2p_\pi^+ / P_d^+$. The relevant pion momenta are soft:

$$p_{\pi T}^2 = O(M_\pi^2), \quad \alpha_\pi = O(M_\pi / m_N).$$

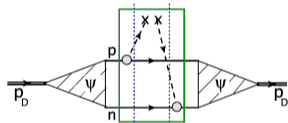
Peripheral simplification

- At $b \gtrsim M_\pi^{-1}$ the pion field is dilute, $\pi(b) \sim e^{-M_\pi b}$.
- The two-pion term gives the leading large-distance part of any chirally invariant light-ray operator; nonlinear completions affect only shorter distances.
- This is the nuclear analogue of peripheral chiral dynamics in the single nucleon.

One-body and two-body pion densities



Incoherent nucleon pion cloud.



Coherent exchange pion.

Decomposition

$$D_{\pi/d}(r_T, \alpha_\pi) = D_{\pi/d}^N(r_T, \alpha_\pi) + D_{\pi/d}^{NN}(r_T, \alpha_\pi) + O(Q/\Lambda_\chi)$$

Physical signs

- $D_{\pi/d}^N > 0$: convolution of the deuteron LF density with the pion cloud of an on-shell nucleon.
- $D_{\pi/d}^{NN} < 0$: pion exchanged between the two nucleons; subtracts double counting of the binding pion field.

One-body convolution: $D_{\pi/d}^N(r_T, \alpha_\pi) \propto \sum_{N=p,n} \int \frac{d\alpha_N}{\alpha_N(2-\alpha_N)} |\Psi_d(r_T, \alpha_N)|^2 f_{\pi/N}\left(\frac{\alpha_\pi}{\alpha_N}\right)$

Two-body exchange: $D_{\pi/d}^{NN}(r_T, \alpha_\pi) \propto - \int d\alpha_p d\alpha'_p \frac{\Psi_d^*(r_T, \alpha'_p) \Psi_d(r_T, \alpha_p)}{\alpha_p \alpha'_p (2-\alpha_p)(2-\alpha'_p)} f_{\pi/NN}(r_T, \alpha_p - \alpha'_p)$

Numerical implementation: two-pole S-wave test

Exploratory estimates use

$$\Phi_d(k) = \frac{1}{\sqrt{c}} \left(\frac{1}{k^2 + a^2} - \frac{1}{k^2 + b^2} \right), \quad c = \frac{\pi}{2} \frac{(a-b)^2}{ab(a+b)}.$$

$$a = \sqrt{m_N \epsilon_d} = 0.0458 \text{ GeV}, \quad b = 0.2719 \text{ GeV}.$$

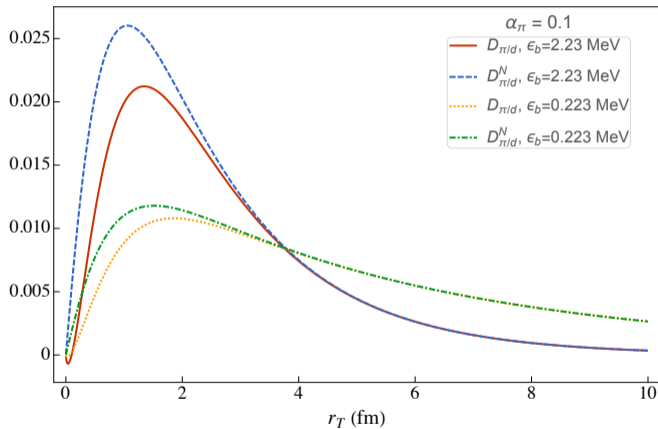
What it captures

- Correct weak-binding S-wave tail.
- Sensitivity to extended pn configurations.
- Qualitative size and sign of exchange contribution.

What it omits

- D wave and short-range correlations.
- Regulator variation and EFT truncation error.
- Consistent higher-order light-ray operators.

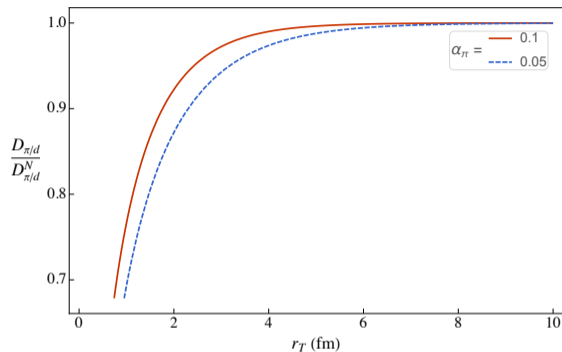
Result I: destructive exchange contribution



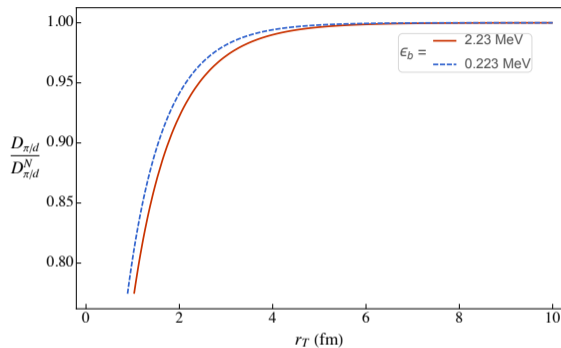
Robust pattern

- One-body density is positive.
- Full LO-OPE density is smaller.
- Suppression appears at $r_T \sim 1 - 3$ fm, where pion range and deuteron size overlap.
- Reducing the binding produces a more dilute pn system and weakens the nuclear interaction effect.

Result II: ratios expose the nuclear effect



Dependence on pion plus momentum fraction.



Dependence on binding energy.

Interpretation

The ratio $D_{\pi/d}/D_{\pi/d}^N$ is less sensitive to normalization and shows directly that the physical deuteron does not equal two independent nucleon pion clouds at finite transverse distance.

Tagged DIS

$$e + d \rightarrow e' + N_{\text{spec}} + X.$$

The measured spectator fixes the LF deuteron configuration and allows extrapolation toward the nucleon pole, where binding effects are minimized.

Pionic contribution to nuclear PDFs

$$\delta f_{i/d}(x) \sim \int \frac{d\alpha_\pi}{\alpha_\pi} f_{\pi/d}(\alpha_\pi) f_{i/\pi}\left(\frac{x}{\alpha_\pi}\right).$$

Non-forward extensions

- Deuteron GPDs
- Spatial tomography at fixed x^+ .

Next steps

- Solve the LF bound-state equation with regulated chiral potentials.
- Construct pion, quark, and gluon light-ray operators consistently to the same order.
- Match to tagged DIS spectral functions and final-state interactions.
- Extend from $A = 2$ to light nuclei.

Conclusions

- 1 LF nuclear wave functions are the natural low-energy input for high-energy nuclear scattering.
- 2 Chiral EFT can be formulated at fixed LF time with OPE plus contact terms and controlled long-distance operators.
- 3 The deuteron LF wave function matches onto the standard ${}^3S_1 - {}^3D_1$ representation through rotationally symmetric variables.
- 4 The peripheral pion density contains a positive one-body term and a negative coherent two-body exchange term.
- 5 The physical deuteron pion density is suppressed relative to two independent nucleon pion clouds at finite transverse distance.

Questions

Backup: LF normalization conventions

Single-nucleon states:

$$\langle p', \sigma' | p, \sigma \rangle = 2p^+ (2\pi)^3 \delta(p'^+ - p^+) \delta^{(2)}(p'_T - p_T) \delta_{\sigma' \sigma}.$$

Deuteron NN component:

$$\langle p_p \sigma_p, p_n \sigma_n | d(P_d, \lambda) \rangle = 2P_d^+ (2\pi)^3 \delta(P_d^+ - p_p^+ - p_n^+) \delta^{(2)}(P_{dT} - p_{pT} - p_{nT}) (2\pi)^{3/2} \Psi_{\sigma_p \sigma_n}^\lambda(\alpha_p, p_T).$$

$$\sum_{\sigma_p \sigma_n} \int \frac{d\alpha_p d^2 p_T}{\alpha_p (2 - \alpha_p) (2\pi)^3} |\Psi_{\sigma_p \sigma_n}^\lambda|^2 = 1.$$







Backup: peripheral domain and universality

The large-distance result is meaningful in the window

$$r_T \gtrsim M_\pi^{-1} \sim 1.4 \text{ fm}, \quad \rho_N \lesssim M_\pi,$$

where the pion field is dilute and the EFT expansion is controlled. At smaller distances the pion density depends on the UV completion of the light-ray operator and on contact operators; this region should not be interpreted as a parameter-free chiral prediction.

Selected references

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