Generalized Parton Distributions of Composite Light Nuclei

EXCLAIM

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NM STATE

Tensor SIDIS Workshop
Jefferson Lab

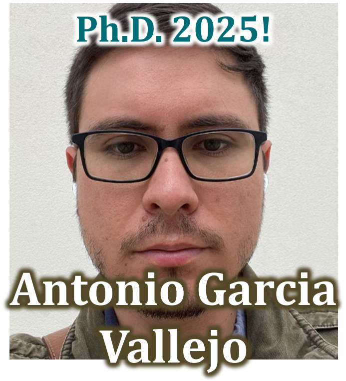
6/4/2026

Important Information

For more details:

[arXiv: 2510.15838]

- To appear in PRD
- Editor's Suggestion



- **Next talk!**

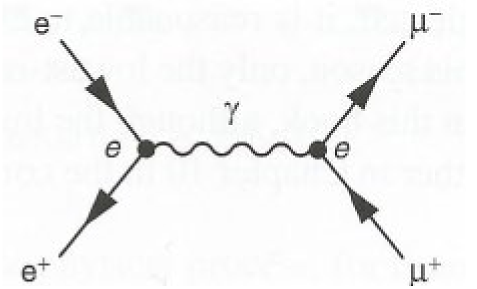
Thurs. 6/4, 11:25am

This work supported by:

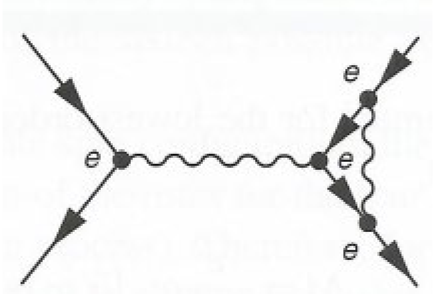
DOE Office of Science, Award #DE-SC0024560

EXCLAIM Collaboration: DOE Office of Science, Award #DE-SC0024644

$$d\sigma = d\sigma^{[0]} + \alpha\, d\sigma^{[1]} + \alpha^2\, d\sigma^{[2]} + \alpha^3 d\sigma^{[3]} + \cdots$$

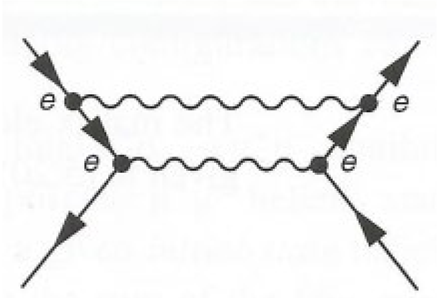


- **Perturbation theory:**
  Taylor expansion in **powers of the coupling** α_s



➢ **Successes:**
  Weak coupling $\alpha_s(Q) \ll 1$ at $Q^2 \gg \Lambda^2_{QCD}$

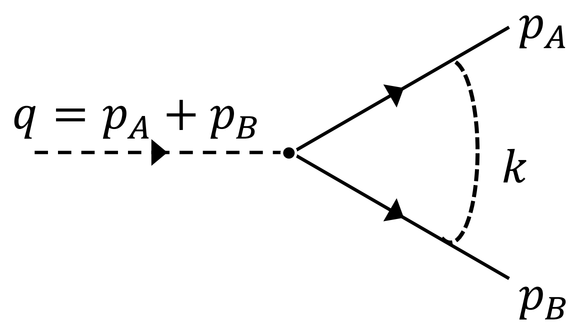
➢ **Limitations:**
  Slow convergence
  Asymptotic series
  Nonperturbative effects



Factorization is a More Powerful Statement

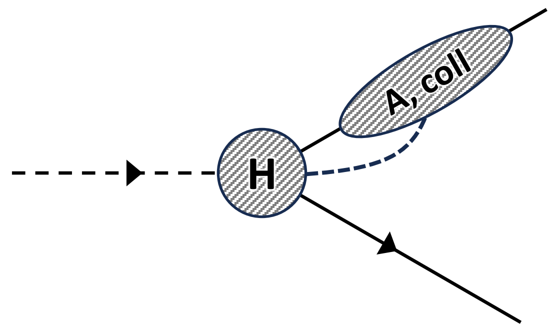
$$I \equiv g^3 \mu^{3(3-d/2)} \int \frac{d^d k}{(2\pi)^d} \frac{1}{(k^2 - m^2)((p_A - k)^2 - m^2)((p_B + k)^2 - m^2)}$$

$$= I_{A,\,coll} + I_{B,coll} + I_{soft} + I_{A,\,soft-coll} + I_{B,\,soft-coll}$$



- **Collinear factorization:**

  Dimensional analysis of $Q^2 \to \infty$ asymptotics



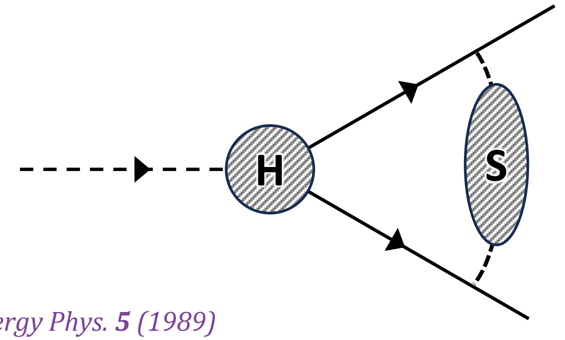
➢ **Superficially:**

Scale all units by Q, then drop other scales $\frac{m^2}{Q^2} \to 0$

➢ **Subtlety:**

Setting $\frac{m^2}{Q^2} \to 0$ can create **IR divergences**.

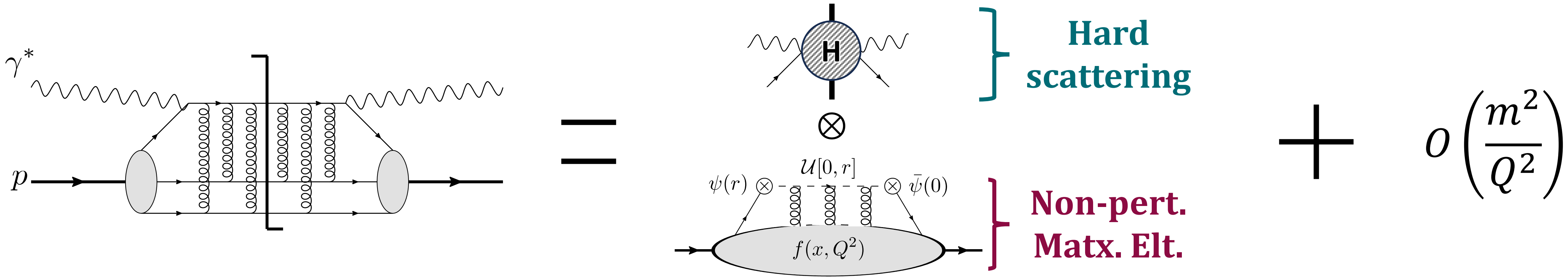
Anomalous power enhancements in momentum space



"Foundations of Perturbative QCD," J. C. Collins, (1989), Cambridge Univ. Press, 2011

*Collins, Soper, Sterman, Adv. Ser. Direct. High Energy Phys. **5** (1989)*

Factorization Theorems, to All Orders in pQCD



- **Factorization theorem:**
  Nonperturbative physics is quarantined into specific, universal matrix elements

- **Kinematic expansion:**
  Hadron structure as seen by an infinitely hard probe $Q^2 \to \infty$ (“**infinite momentum frame**”)

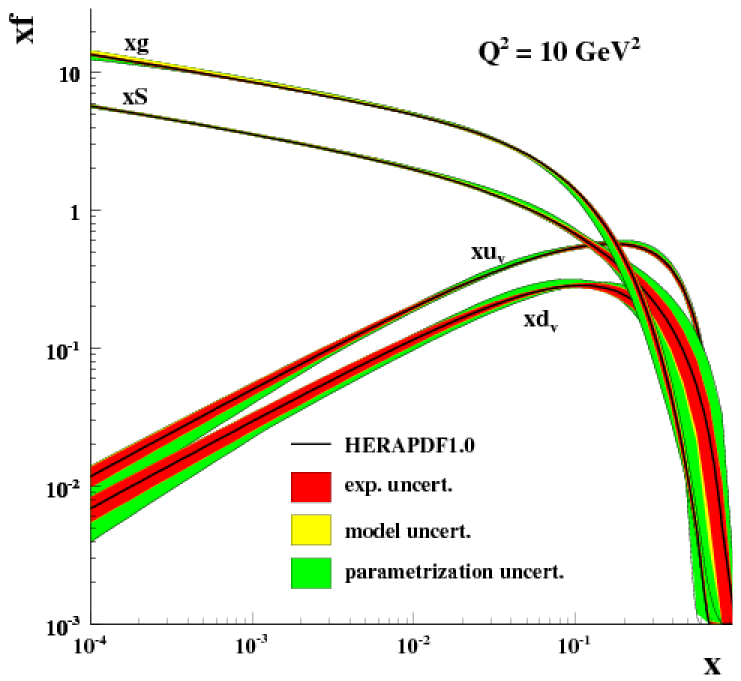
- **Predictive power:**
  The same universal matrix elements appear in multiple reactions

$$\phi_{\alpha\beta}(x) = \int \frac{dr^-}{2\pi} \, e^{ixp^+r^-} \langle p, S| \, \bar{\psi}_\beta(0) \, \mathcal{U}[0, r^-] \, \psi_\alpha(r^-) \, |p, S\rangle$$

- **Collinear Factorization:**
  Inclusive processes with a **single scale** $Q^2 \to \infty$

➢ **Parton Distribution Functions (PDFs):**
  Gauge-invariant operators which correspond to **parton densities** $\frac{dN}{dx}$ in light-front gauge $A^+ = 0$.

  Differential only in the **longitudinal momentum fraction** ***x***



*H1 and ZEUS Collaborations, JHEP **01** (2010) 109*

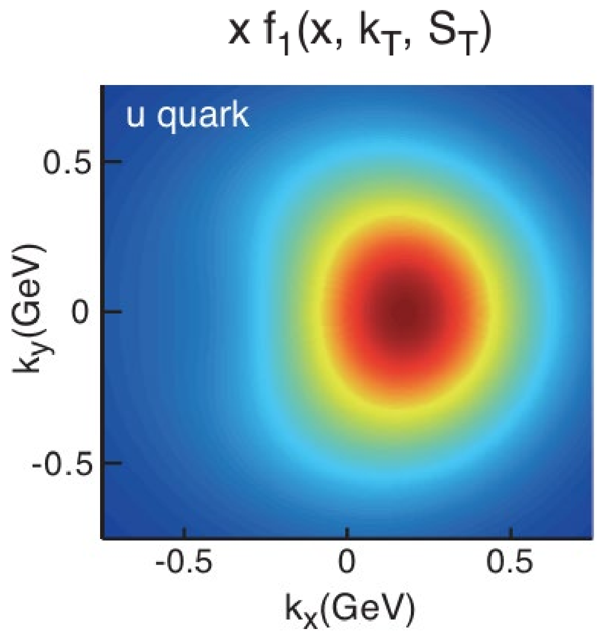
*Collins, Soper, Sterman, Adv. Ser. Direct. High Energy Phys. **5** (1989)*

3D Structure: TMDs

$$\phi_{\alpha\beta}(x, \vec{k}_\perp) = \int \frac{d^2 r_\perp \, dr^-}{(2\pi)^3} \, e^{ixp^+ r^- - i\vec{k}_\perp \cdot \vec{r}_\perp} \langle p, S | \, \bar{\psi}_\beta(0) \, \mathcal{U}[0, r] \, \psi_\alpha(r) \, | p, S \rangle$$

- **Transverse-Momentum-Dependent (TMD) Factorization:**
  Semi-inclusive processes with **two scales**: $Q^2 \to \infty$ and $k_\perp^2 \ll Q^2$

  "Fragile" factorization holds only for select processes, with modified universality



➢ **TMD Parton Distribution Functions (TMDs):**
  Gauge-invariant operators differential in both longitudinal momentum fraction x and **transverse momentum $\vec{k}_\perp$**.

  Not simply parton densities: irreducible physics of **QCD lensing**

Collins, Soper, Sterman, Nucl. Phys. B. ***250*** *(1985)*

"Foundations of Perturbative QCD," J. C. Collins, (1989), Cambridge Univ. Press, 2011

A. Accardi, et al., Eur. Phys. J. A ***52*** *(2016)*

3D Structure: GPDs

$$\phi_{\alpha\beta}(x,\xi,\vec{\Delta}_\perp) = \int \frac{dr^-}{2\pi}\, e^{ixp^+r^-}\, {}_{\text{out}}\langle p', S'|\, \bar{\psi}_\beta(0)\, \mathcal{U}[0,r^-]\, \psi_\alpha(r^-)\, |p,S\rangle_{\text{in}}$$

- **Exclusive Factorization:**

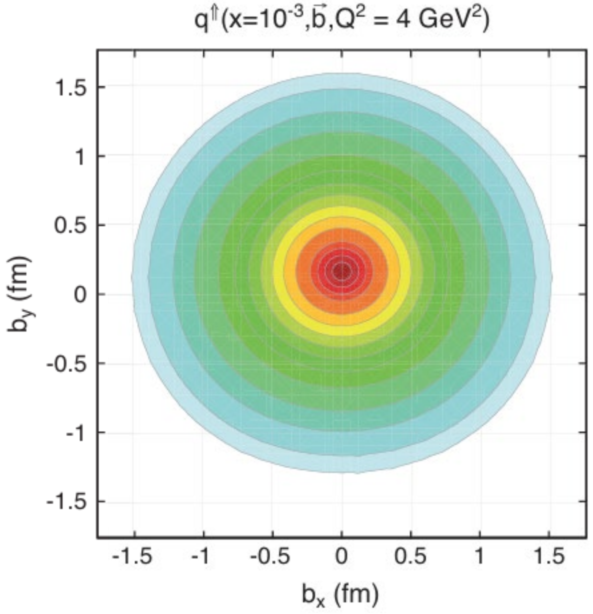
  Exclusive final state provides **two scales**: $Q^2 \to \infty$ and $|t| \ll Q^2$

  Rarer statistics, but greater sensitivity (amplitude level)

- **Generalized Parton Distribution Functions (GPDs):**

  Gauge-invariant operators differential in longitudinal momentum fraction x, longitudinal skewness ξ, and **momentum transfer $\vec{\Delta}_\perp$**.

  Fourier transform $\vec{\Delta}_\perp \to \vec{b}_\perp$ at $\xi = 0$ gives parton densities $\frac{dN}{dx\, d^2 b_\perp}$ in **impact parameter space**.



*Muller et al., Fortschritte der. Physik, **42** (1994)*

*Radyushkin, Phys. Lett. B **380** (1996)*

*Ji, Phys. Rev. D **55** (1997)*

*Collins, Freund, Phys. Rev. D, **59** (1999)*

*A. Accardi, et al., Eur. Phys. J. A **52** (2016)*

$$\phi_{\alpha\beta}(x,\xi,\vec{\Delta}_\perp,\vec{k}_\perp) = \int \frac{d^2r_\perp\, dr^-}{(2\pi)^3}\, e^{ixp^+r^- - \vec{k}_\perp\cdot\vec{r}_\perp}\, {}_{\text{out}}\langle p', S'|\, \bar{\psi}_\beta(-\tfrac{1}{2}r)\, \mathcal{U}[0,r]\, \psi_\alpha(\tfrac{1}{2}r)\, |p, S\rangle_{\text{in}}$$

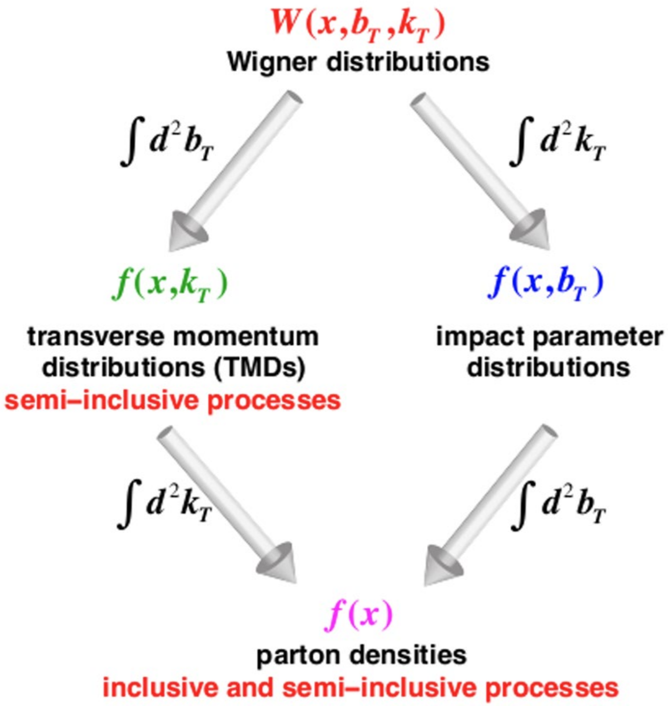
- **Generalized TMD (GTMD) Factorization:**
  Rare processes with both a diffractive component and a momentum imbalance (e.g., diffractive dijets in pA)

➢ **Wigner Functions (GTMDs):**

Gauge-invariant operators differential x, $\vec{k}_\perp$, and $\vec{b}_\perp$

Simultaneously differential in **position and momentum**, without violating the **Uncertainty Principle**

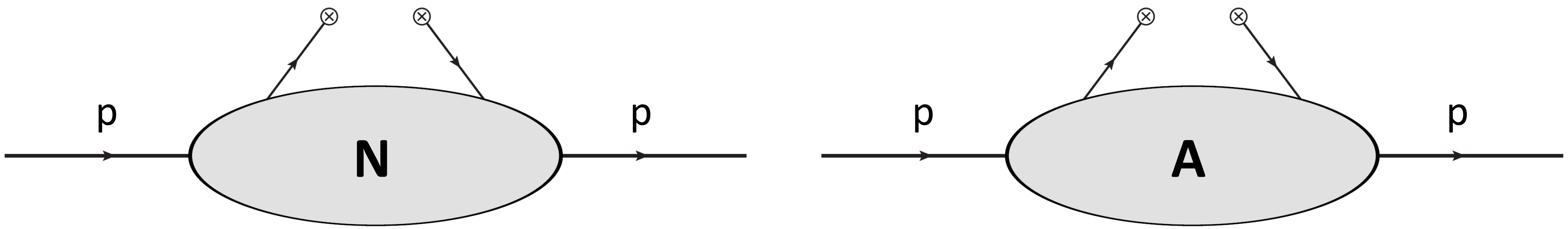
Quantum-mechanical "master functions" with well-defined **TMD, GPD, and classical limits**



Meissner, Metz, Goeke, Phys. Rev. D, ***80*** *(2009)*

A. Accardi, et al., Eur. Phys. J. A ***52*** *(2016)*

Partonic Structure of Nuclei



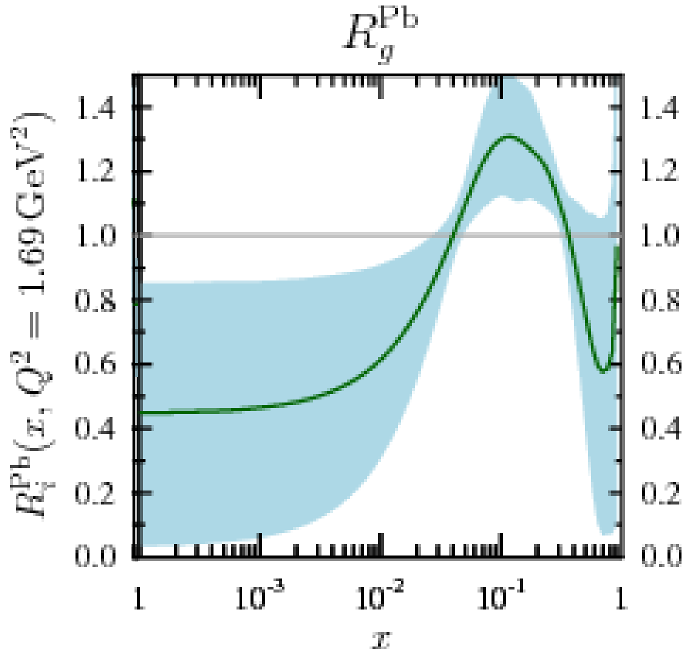
- **Factorization works the same way for nuclei:**
  Same factorization formula and matrix elements

  Dependence on target species through mass number *A*

➢ **Nuclear Modification Factor for PDFs:**
  Compares the ratio of nuclear PDF to nucleon PDF

  Modification of partonic structure of a nucleon due to nuclear environment

  Reveals fascinating nuclear modification associated with the **EMC effect**.



*Helenius et al., JHEP **07** (2012)*

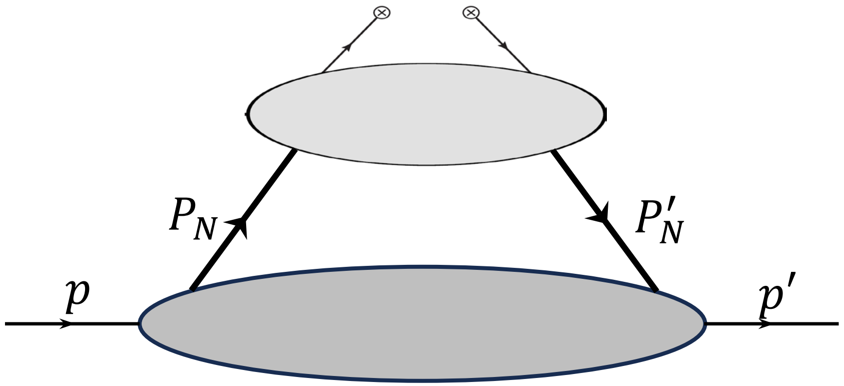
Impulse Approximation: The One-Body Sector

$$\langle A'|\bar{\psi}_\beta\,\psi_\alpha|A\rangle = (\Psi^*_{N'}\Psi_N) \otimes \langle N'|\bar{\psi}_\beta\,\psi_\alpha|N\rangle + \text{correlations}$$

- **A composite system can be decomposed into its constituents:**

  Nuclear state is expressed as **many-body wave function** of its constituents (**spectral function**)

  Only a single active constituent is treated dynamically (**mean-field approximation**), but **systematically improvable**



- **Multiple variations on implementation**

  Instant-form wave functions (nonrelativistic)

  Light-front wave functions (relativistic)

  [**Virtual Nucleon Approximation**]

Geesaman, Saito, Thomas., Ann.Rev.Nucl.Part.Sci. ***45*** *(1995)*

Ericson, Kumano. Phys. Rev. ***C 67*** *(2003)*

Hirai, Kumano, Saito, Watanabe. Phys. Rev. ***C 83*** *(2011)*

Cosyn, Dong, Kumano, Sargsian. Phys. Rev. ***D 95*** *(2017)*

Composite Structure Mixing

- **Orbital motion of constituents mixes 3D partonic structure:**

  A static nucleus simply smears the partonic structure of the nucleon

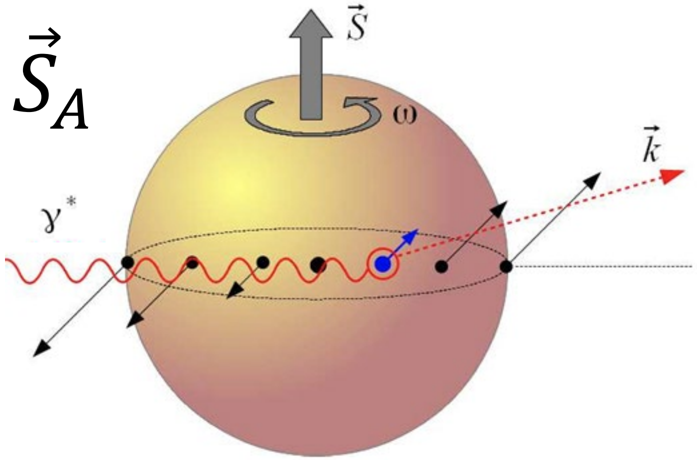
  Nontrivial **orbital motion of the nucleons mixes 3D structure** for, e.g., the Sivers TMD and Boer-Mulders TMD

  QCD lensing effects are essential to some mixing channels

- **An overdetermined problem:**

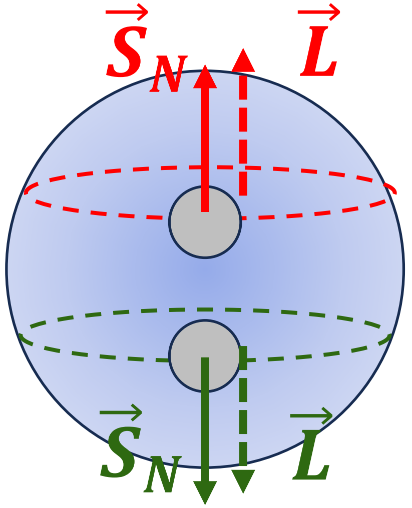
  A small number of nuclear correlations (e.g., $\vec{L} \cdot \vec{S}$) are responsible for **several mixing channels**

$\vec{L} \cdot \vec{S}_A$



*Kovchegov, MS, Phys. Rev. D, **89** (2014)*

$\vec{L} \cdot \vec{S}_N$



*Kovchegov, MS, Nucl. Phys. B, **903** (2016)*

An Application: ^{4}He and ALERT

- **Jlab experiment with CLAS12 + ALERT:**
  Spectator-tagged DVCS and ϕ production

  Will access the **quark and gluon GPDs of ^4He**
  and study the relation to the EMC effect

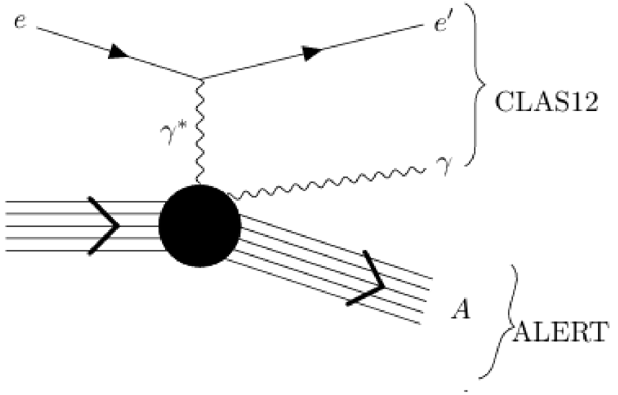
  ^4He is a simple spin-0 composite nucleus

  Recently completed data collection with ongoing analysis;
  leadership of **NMSU colleague M. Paolone**.

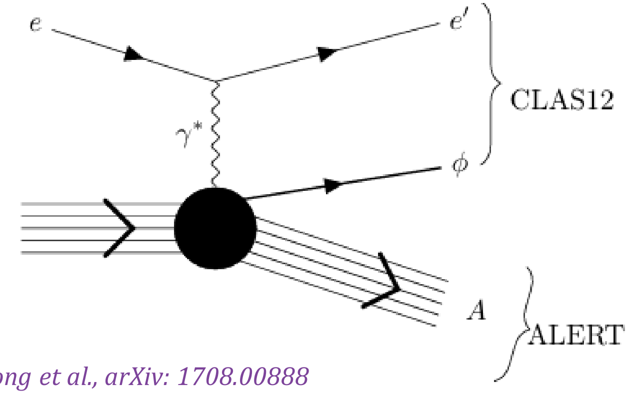
- **This work:**
  Application of a **light-front impulse approximation**
  to study the GPDs of ^4He

  Wigner representation to make symmetries manifest.

$$e + A \to e' + \gamma + A'$$



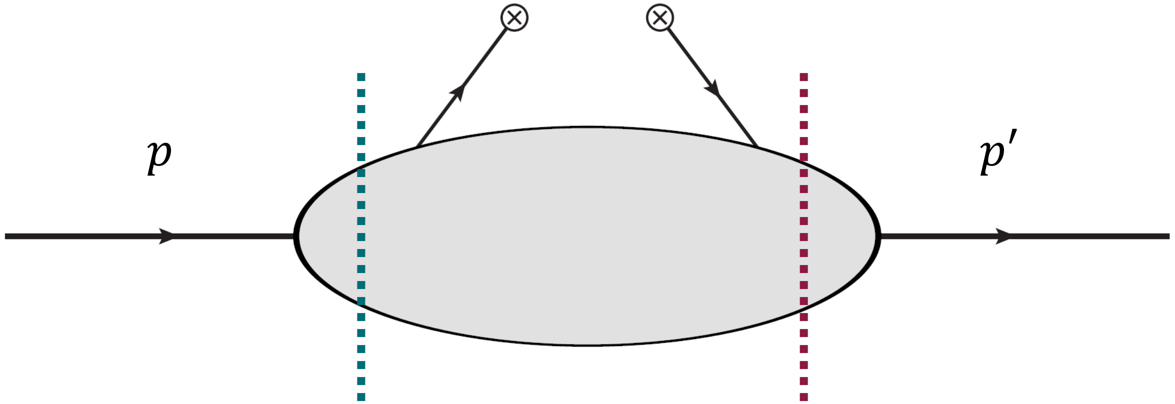
$$e + A \to e' + \phi + A'$$



Armstrong et al., arXiv: 1708.00888

Derivation: Completeness

$$F_{q/\phi}^{[\Gamma]} = \frac{1}{4\pi} \int dr^- e^{ixP^+r^-} (\Gamma)_{JI}$$
$$\times \, {}_{\text{out}}\langle p' | \bar{\psi}_J(-r^-/2) \, \psi_I(r^-/2) | p \rangle_{\text{in}}$$



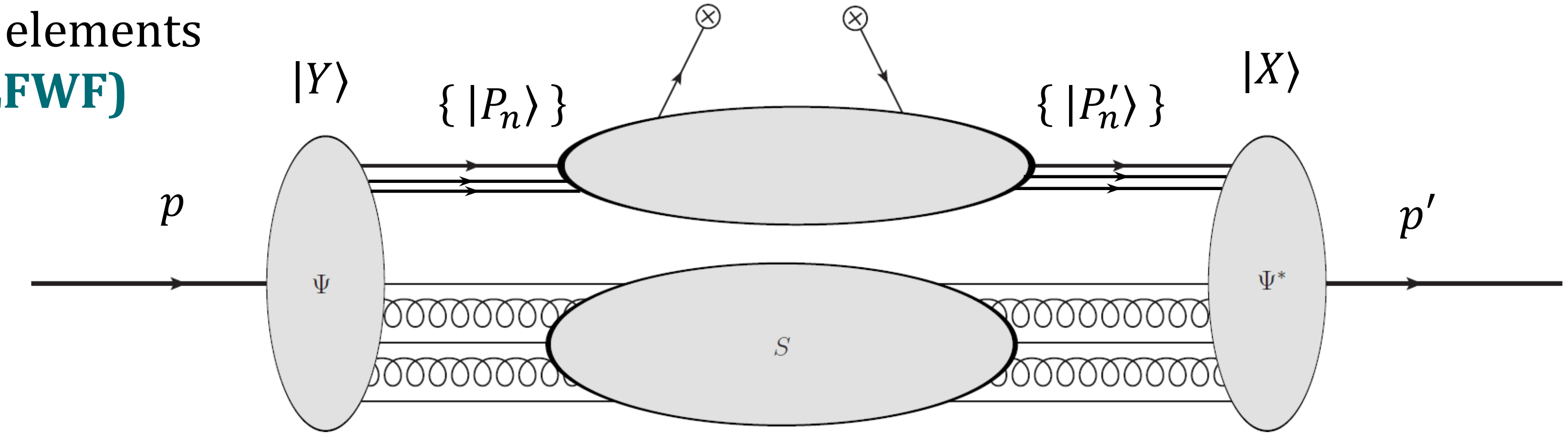
1. Insert **complete sets** of free, on-shell **constituent Fock states**

$$\hat{1} = \sum\!\!\!\!\!\!\int_X |X\rangle\langle X|$$
$$= \sum_n \frac{1}{S_n} \int \frac{d^2p_{1\perp}\, dp_1^+}{(2\pi)^3 2p_1^+} \cdots \frac{d^2p_{n\perp}\, dp_n^+}{(2\pi)^3 2p_n^+} \, |p_1 \cdots p_n\rangle\langle p_1 \cdots p_n|$$

- Expresses in/out states as wave packets of constituents

$${}_{\text{out}}\langle p' | \bar{\psi}_J\left(\frac{-r^-}{2}\right)\psi_I\left(\frac{r^-}{2}\right) | p \rangle_{\text{in}} = \sum\!\!\!\!\!\!\int_{\{X,Y\}} \boxed{{}_{\text{out}}\langle p' | X \rangle_{\text{out}}} \, {}_{\text{out}}\langle X | \bar{\psi}_J(-r^-/2)\psi_I(r^-/2) | Y \rangle_{\text{in}} \, \boxed{{}_{\text{in}}\langle Y | p \rangle_{\text{in}}}$$

2. Relate **in/in** and **out/out** matrix elements to **light-front wave functions (LFWF)**



- LFWF are **boost invariant**
- Integrate out **disconnected spectators**
- Inclusive LFWF remain

$$ {}_{\text{in}}\langle Y|p\rangle_{\text{in}} \equiv (2\pi)^3\, 2p^+\, \delta^2\Big(\sum_i \vec{p}_{Yi\perp} - \vec{p}_\perp\Big)\, \delta\Big(\sum_i p^+_{Yi} - p^+\Big) \times \Psi(\{p^+_{Yi}\}\,;\,\{\vec{p}_{Yi\perp}\}) $$

$$ \Psi\left(\{p^+_{Yi}\}\,;\,\{\vec{p}_{Yi\perp}\}\right) = \Psi\left(\left\{\frac{p^+_{Yi}}{p^+}\right\}\,;\,\{\vec{p}_{Yi\perp}\}\right) $$

Brodsky, Pauli, Pinsky, Phys. Rept. ***301*** *(1998)*

Derivation: Wigner Distribution

3) Re-express the **off-forward product of LFWF** in terms of a **Wigner distribution**

$$\tilde{\Psi}_s(b^-, \vec{b}_\perp) = \int \frac{d^2k_\perp \, dk^+}{(2\pi)^3} e^{-ik^+b^- + i\vec{k}_\perp \cdot \vec{b}_\perp} \frac{\tilde{\Psi}_s(k^+, \vec{k}_\perp)}{\sqrt{2k^+}}$$

- The **Fourier transform** of the LFWF defines a **spacetime position**

$$W_{s's}(p^+, \vec{p}_\perp ; b^-, \vec{b}_\perp) =$$

$$= \int \frac{d^2q_\perp \, dq^+}{(2\pi)^3} e^{-iq^+b^- + i\vec{q}_\perp \cdot \vec{b}_\perp} \frac{\tilde{\Psi}^*_{s'}(p - \frac{1}{2}q)}{\sqrt{2(p - \frac{1}{2}q)^+}} \frac{\tilde{\Psi}_s(p + \frac{1}{2}q)}{\sqrt{2(p + \frac{1}{2}q)^+}}$$

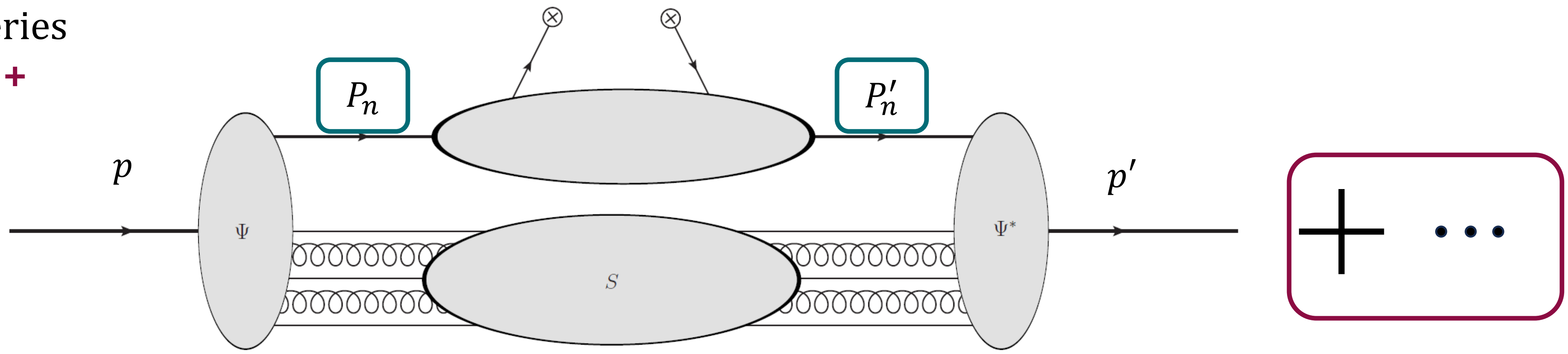
- A Wigner distribution is a **mixed Fourier transform** that fixes the **average momentum and impact parameter**

$$= \int d^2r_\perp \, dr^- e^{+ip^-r^- - i\vec{p}_\perp \cdot \vec{r}_\perp} \tilde{\Psi}^*_{s'}(b - \frac{1}{2}r) \, \tilde{\Psi}_s(b + \frac{1}{2}r)$$

- Fully **quantum**, but **semi-classical correspondence**

$$\frac{\tilde{\Psi}^*_{s'}(k')}{\sqrt{2k'^+}} \frac{\tilde{\Psi}_s(k)}{\sqrt{2k^+}} = \int d^2b_\perp \, db^- \, e^{+i(k-k')^+b^- - i(\vec{k}-\vec{k}')_\perp \cdot \vec{b}_\perp} \times W_{s's}\left(\tfrac{1}{2}(k^+ + k'^+), \tfrac{1}{2}(\vec{k}_\perp + \vec{k}'_\perp) ; b^-, \vec{b}_\perp\right)$$

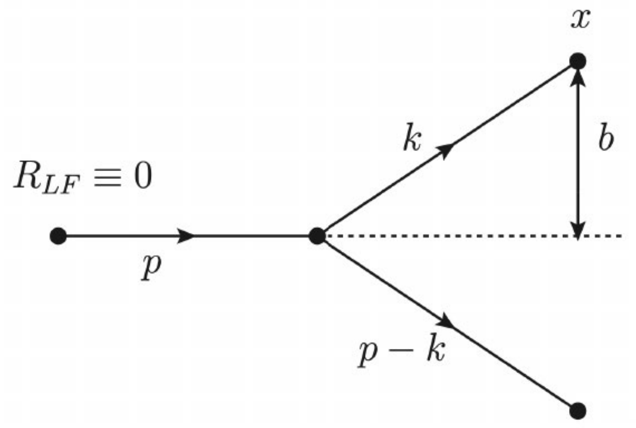
4) Expand in a series of **mean field + correlations**

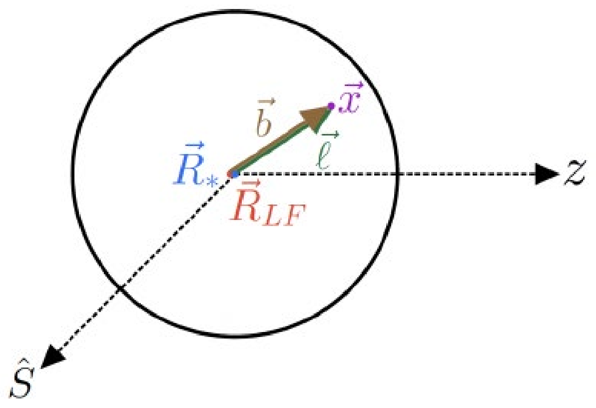


$$
{}_{\text{out}}\langle p'|\,\bar\psi_J\left(\frac{-r^-}{2}\right)\psi_I\left(\frac{r^-}{2}\right)|p\rangle_{\text{in}} = \frac{1}{2}\sum_{ss'}\int d^2P_{1\perp}\,dP_1^+\int d^2b_\perp\,db^-\;e^{-i\Delta^+b^-+i\vec\Delta_\perp\cdot\vec b_\perp}\left(\frac{1}{\sqrt{P_1^+}}\frac{p'^+}{\sqrt{P_1^++\Delta^+}}\frac{p^+}{P^+}\frac{p^+-P_1^+}{P^+}\right)
$$
$$
\times W_{s's}(P_1+\tfrac{1}{2}\Delta,b;P,\Delta)\;\langle(P_1+\Delta)s'|\,\bar\psi_J(-r^-/2)\psi_I(r^-/2)\,|P_1 s\rangle + \text{correlations}.
$$

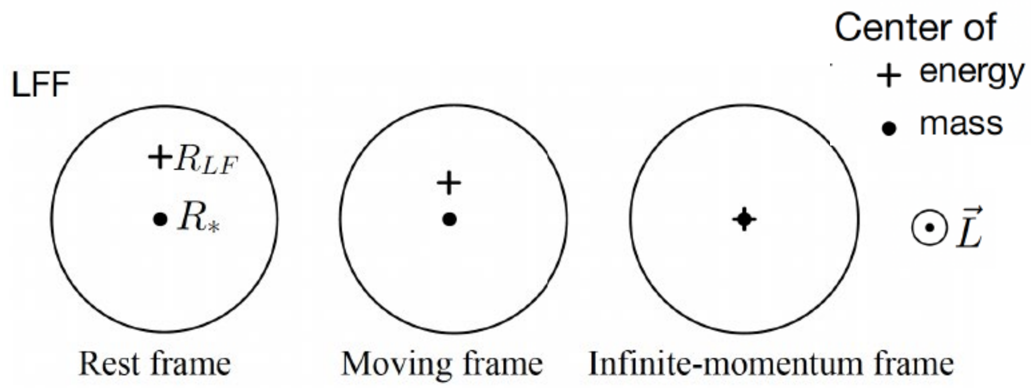
- In a **large nucleus**, dominance of the **mean field** is guaranteed by $A \gg 1$
- In a **small nucleus**, must be considered just the **first term in a series**
  - ➢ Start with the mean field, but **correlations may not be small** (e.g. SRC)

Derivation: Light Front / Rest Frame Dictionary





Infinite-momentum frame



5) Exploit **boost invariance** to **relate IMF Wigner function to RF**

- Since ***W* is boost invariant**, only its arguments change
- Use **boost-invariant products** to map to Rest Frame

❖ **Caveat: relativistic CoM**

$$\alpha_{IMF} = \alpha_{LF} \qquad (P^+ b^-)_{IMF} = (P^+ b^-)_{LF}$$
$$\xi_{IMF} = \xi_{LF}$$

$$(P_{N,z})^{R.F.} \equiv \sqrt{\frac{\Lambda^2}{4(1-\xi^2)}} \left[\alpha - \left(\frac{1-\xi^2}{1-(\xi/\alpha)^2} \right) \frac{\left(\vec{P}_{N\perp} + \frac{1}{2}\vec{\Delta}_\perp\right)^2 - (1-\xi/\alpha)(\vec{P}_{N\perp} \cdot \vec{\Delta}_\perp) + m^2}{\alpha \Lambda^2} \right]$$

$$(\Delta_z)^{R.F.} \equiv -2\xi \sqrt{\frac{\Lambda^2}{1-\xi^2}}$$

$$(b_z)^{R.F.} \equiv -\sqrt{\frac{1-\xi^2}{\Lambda^2}} (b^- P^+) \, .$$

$$\Lambda^2 \equiv \frac{1}{4} \vec{\Delta}_\perp^2 + M^2$$

6) Use a **Pauli matrix basis** to change from spin projection to **spin vector**

$$W(P_N, b, S; P, \Delta) = \boxed{W_{unp} - \vec{W}_{pol} \cdot \vec{S}}$$

- Decomposes polarized quantities with **explicit linear dependence on $\vec{S}$**

$$W_{s's}(P_N, b; P, \Delta) = W_\nu(P_N, b; P, \Delta)\,[\sigma^\nu]_{s's}$$
$$\equiv \boxed{W_{unp}\,[\mathbb{1}]_{s's} - \vec{W}^i_{pol}\,[\vec{\sigma}^i]_{s's}}$$

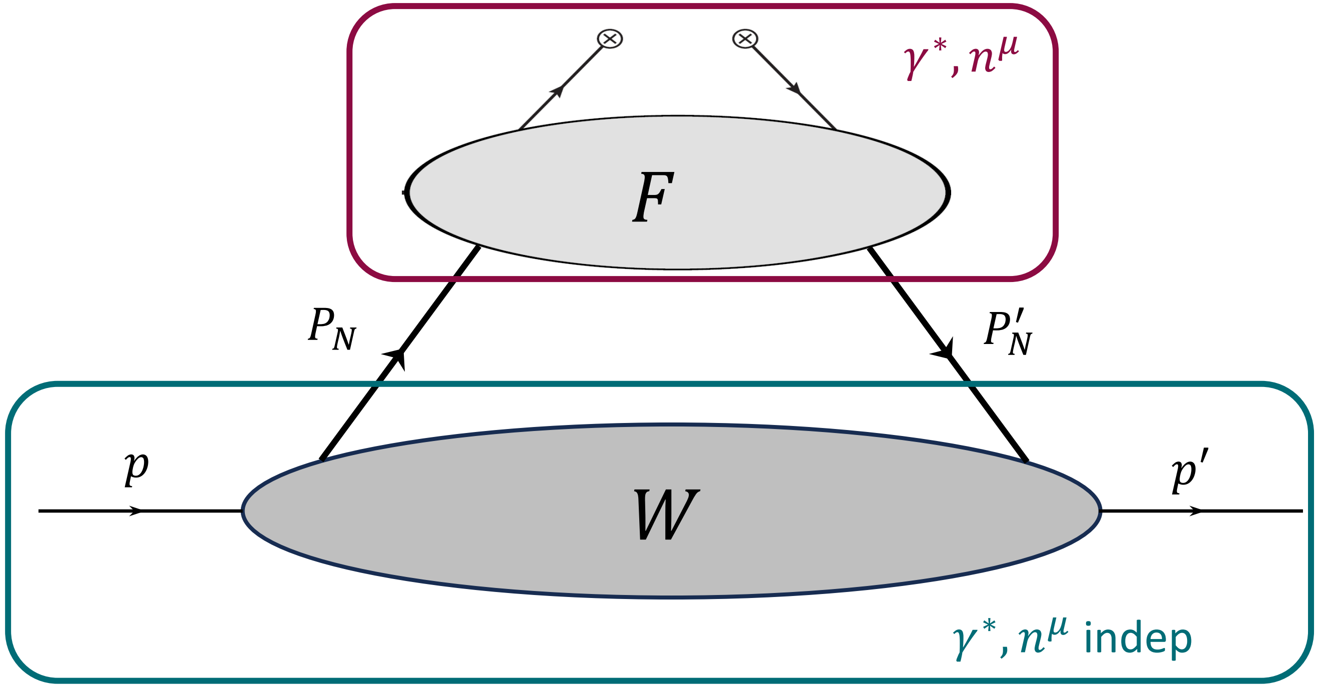
- Decomposes the nuclear GPD as a **sum over unpolarized, longitudinally-, and transversely-polarized channels**

$$F^{[\Gamma]}_{q/N}(x'; P_N, \Delta; s', s) = F^{[\Gamma]}_{q,\mu}(x'; P_N, \Delta; s', s)\,[\sigma^\mu]_{ss'}$$
$$\equiv \boxed{F^{[\Gamma]}_{q,unp}\,[\mathbb{1}]_{ss'} - \vec{F}^{[\Gamma],j}_{q,pol}\,[\vec{\sigma}^j]_{ss'}}$$

$$F^{[\Gamma]}_{q/\phi} = (1-\xi^2)\int \frac{db^-\, dP_N^+}{\sqrt{1-\xi_N^2}}\left(\frac{1-\alpha}{\alpha}\right)\int d^2b_\perp d^2P_{N\perp}\, e^{-i[b^-\Delta^+ - \vec{b}_\perp\cdot\vec{\Delta}_\perp]}\boxed{\left[W_{unp}F^{[\Gamma]}_{q,unp} + \vec{W}_{pol}\cdot\vec{F}^{[\Gamma]}_{q,pol}\right]}$$

Derivation: Symmetry Constraints

7) Impose **symmetry constraints** on the **Wigner function**



- The GPD is a property of the **high-energy cross section**
  - ➢ **2D rotational symmetry** about the collision axis n^μ

- LFWF / Wigner distribution are properties of the **target only**
  - ➢ **3D rotational symmetry** in the RF
  - ➢ Unbroken ***T*, *P* symmetry**

$$W_{unp}(\vec{\Delta}, \vec{P}_N, \vec{b}) \equiv W_{unp}\big(\vec{b}^2, \vec{\Delta}^2, \vec{P}_N^2, (\vec{\Delta}\cdot\vec{P}_N), (\vec{b}\cdot\vec{\Delta}), (\vec{b}\cdot\vec{P}_N), \vec{\Delta}\cdot(\vec{b}\times\vec{P}_N)\big)$$

$$\vec{W}^i_{pol} = (\vec{b}\times\vec{P}_N)^i\,\omega_1 + (\vec{b}\times\vec{\Delta})^i\,\omega_2 = \omega_1\,\vec{L}^i_{P_N} + \omega_2\,(\Delta\vec{L}^i)$$

- Only $(\vec{L}\cdot\vec{S})$ and $(\Delta\vec{L}\cdot\vec{S})$ correlations survive

8) Combine with constituent GPDs to obtain nucleon / nucleus "master formula"

$$F_{q/N}^{[\gamma^+]}(p', s'; p, s) = \frac{1}{2P^+}\bar{u}(p', s')\left[H^q \gamma^+ + E^q \frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}\right]u(p, s)$$

$$F_{q/\phi}^{[\gamma^+]}(x,\xi,t) = (1-\xi^2)\int \frac{db^- \, dP_N^+}{\sqrt{1-\xi_N^2}}\left(\frac{1-\alpha}{\alpha}\right)\int d^2b_\perp d^2P_{N\perp}\, e^{-i[b^-\Delta^+ - \vec{b}_\perp\cdot\vec{\Delta}_\perp]}$$

Unp

$$\times\Bigg\{\omega_0\sqrt{1-\xi_N^2}\left[H_q(x',\xi_N,t) - \frac{\xi_N^2}{1-\xi_N^2}E_q(x',\xi_N,t)\right]$$

$(\vec{L}\cdot\vec{S})$

$$+\frac{i\omega_1}{2m\sqrt{1-\xi_N^2}}\left\{(b_z)^{R.F.}\left[(\vec{\Delta}_\perp\cdot\vec{P}_{N\perp}) + 2\xi_N\vec{P}_{N\perp}^2\right] - (P_{N,z})^{R.F.}\left[(\vec{\Delta}_\perp\cdot\vec{b}_\perp) + 2\xi_N(\vec{P}_{N\perp}\cdot\vec{b}_\perp)\right]\right\}E_q(x',\xi_N,t)$$

$(\overrightarrow{\Delta L}\cdot\vec{S})$

$$+\frac{i\omega_2}{2m\sqrt{1-\xi_N^2}}\left\{(b_z)^{R.F.}\left[\vec{\Delta}_\perp^2 + 2\xi_N(\vec{P}_{N\perp}\cdot\vec{\Delta}_\perp)\right] - (\Delta_z)^{R.F.}\left[(\vec{\Delta}_\perp\cdot\vec{b}_\perp) + 2\xi_N(\vec{P}_{N\perp}\cdot\vec{b}_\perp)\right]\right\}E_q(x',\xi_N,t)\Bigg\}.$$

Illustration: A Simple Model for ^{4}He

- **Static, isotropic nucleus**

$$\omega_0(\vec{P}_N, \vec{b}) \overset{R.F.}{=} A_0\, \theta(R - |\vec{b}|)\, \theta(P_N^{max} - |\vec{P}_N|)$$

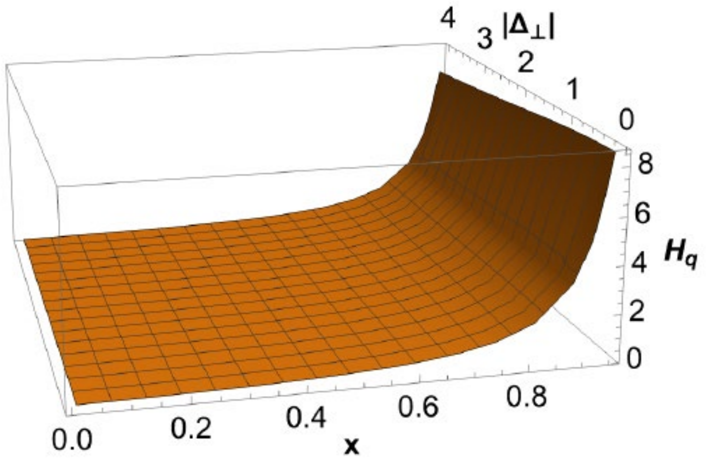
- **Ballpark ^{4}He parameters**

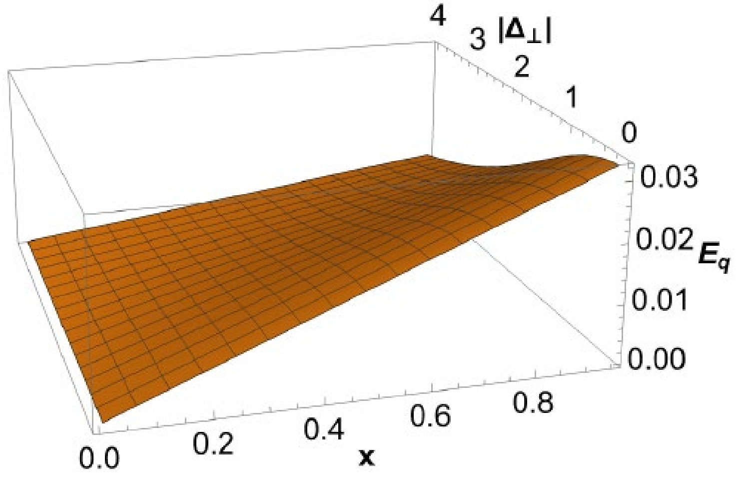
$R = 1.7$ fm $\quad m = 1.0$ GeV

$P_N^{max} = 0.12$ GeV $\quad M = 4.0$ GeV

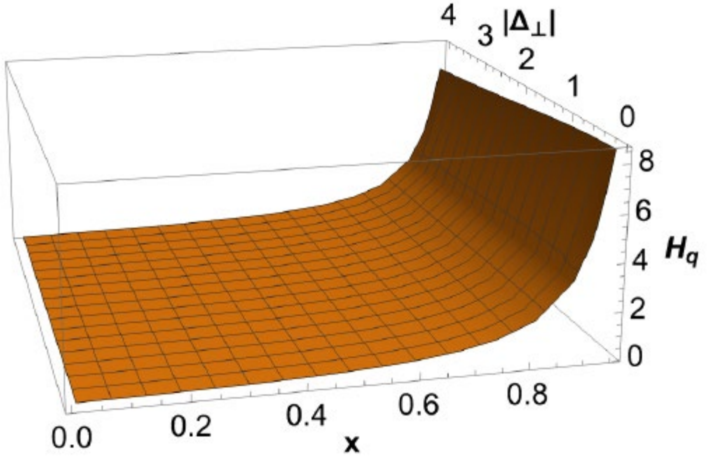
- **Quark Target Model GPDs at $\xi = 0$**

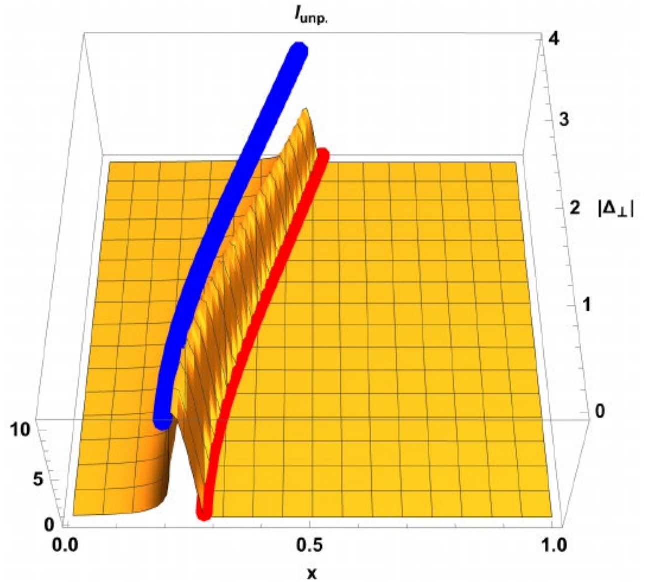
Meissner, Metz, Goeke, Phys. Rev. D ***76*** *(2007)*





$$F_{q/\phi}^{[\gamma^+],unp} = A_0[\pi R^3][\pi(P_N^{max})^3] \times \Phi_{unp}(|\vec{\Delta}_\perp|) \times \mathcal{I}_{unp}(x,|\vec{\Delta}_\perp|)$$





$$\Phi_{unp}(|\vec{\Delta}_\perp|) = \frac{4\Lambda}{|\vec{\Delta}_\perp|^3 R^3}\left[\sin(|\vec{\Delta}_\perp| R) - |\vec{\Delta}_\perp| R\cos(|\vec{\Delta}_\perp| R)\right]$$

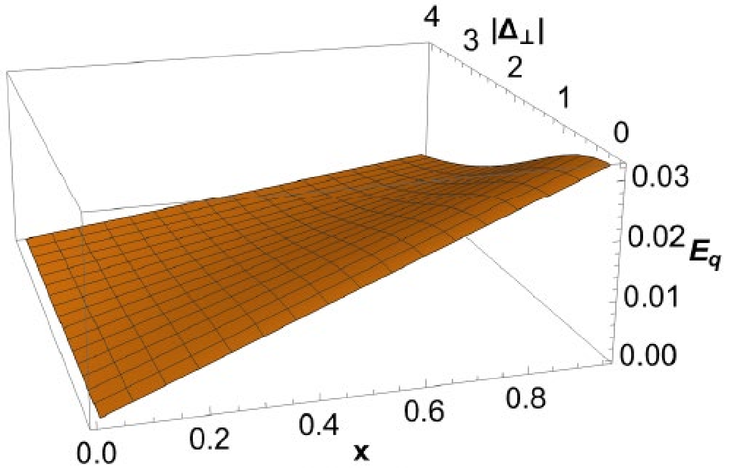
$$\mathcal{I}_{unp}(x,|\vec{\Delta}_\perp|) \equiv \frac{2}{(P_N^{max})^3}\int_0^{P_N^{max}} dP_{N\perp}\, P_{N\perp}\int_{\alpha_{min}}^{\alpha_{max}} d\alpha\left(\frac{1-\alpha}{\alpha}\right) H_q\left(\frac{x}{\alpha}, 0, -\vec{\Delta}_\perp^2\right)$$

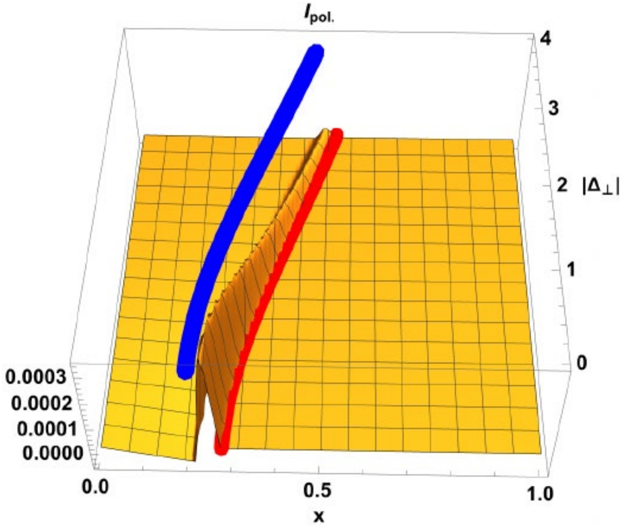
- Nuclear GPD is a **product of 2 factors** (reflects **factorized form of *W***)
  - **Fourier Transform of spatial profile**: R → Δ dependence
  - **Longitudinal downshift and smearing**: $P_z \to x$ dependence

$$\Delta \mathbf{x} = 2\sqrt{\frac{P_N^{max\,2} + \lambda^2}{\Lambda^2}}$$

Signatures of Nuclear Effects: Intermediate Polarization

$$F_{q/\phi}^{[\gamma^+],pol} = A_0[\pi R^3][\pi(P_N^{max})^3] \times \Phi_{pol}(|\vec{\Delta}_\perp|) \times \mathcal{I}_{pol}(x, |\vec{\Delta}_\perp|)$$





$$\Phi_{pol}(|\vec{\Delta}_\perp|) = \frac{4\Lambda}{|\vec{\Delta}_\perp|^3 R^3}\left[3R|\vec{\Delta}_\perp|\cos(R|\vec{\Delta}_\perp|) + (R^2|\vec{\Delta}_\perp|^2 - 3)\sin(R|\vec{\Delta}_\perp|)\right]$$

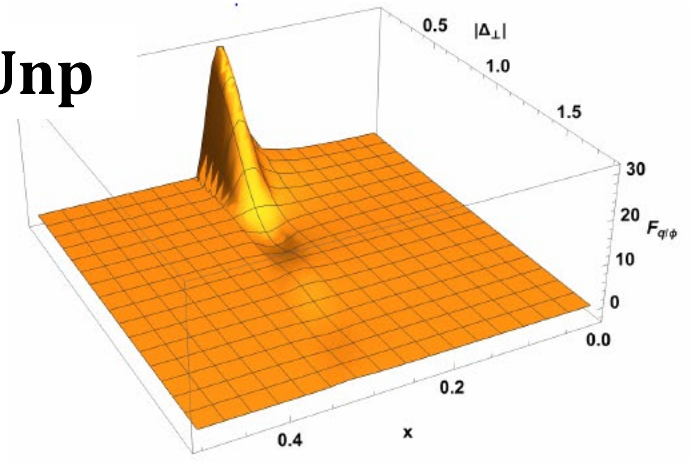
$$\mathcal{I}_{pol}(x, |\vec{\Delta}_\perp|) \equiv \frac{2}{P_N^{max\,3}} \int_0^{P_N^{max}} dP_{N\perp}\, P_{N\perp} \int_{\alpha_{min}}^{\alpha_{max}} d\alpha \left(\frac{1-\alpha}{\alpha}\right) E_q\left(\frac{x}{\alpha}, 0, -\vec{\Delta}_\perp^2\right) \times \left\{\beta_1 \frac{\Lambda}{4m\alpha}\left[\alpha^2 - \frac{\vec{P}_{N\perp}^2 + \lambda^2}{\Lambda^2}\right]\right\}$$

- If $(\vec{L} \cdot \vec{S})$ correlation is present, it couples to GPD E to generate mixing
  - **Different spatial Fourier transform**
  - **Longitudinal downshift and smearing**

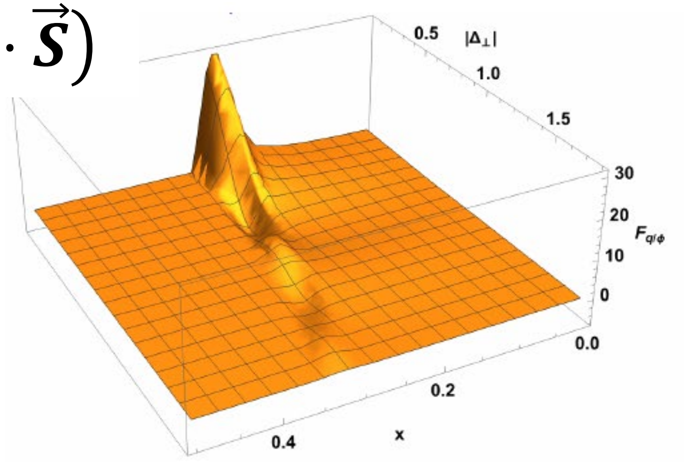
QTM: $E \propto m \ll H$

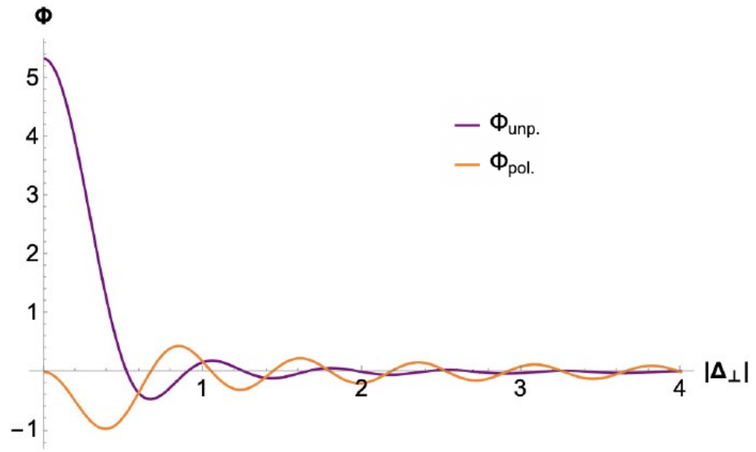
Unpolarized vs. Polarized Channels

Unp



$(\vec{L} \cdot \vec{S})$





- Artificially scale up $E \sim H$ and compare shapes:
  - ➢ **Qualitatively similar:** Fourier Transform, downshift, smearing
  - ➢ Spin-orbit correlations **change the Δ dependence** and **shift the nodes**

- First steps toward theory guidance and interpretation for ALERT

- **This Work:**

  Further theoretical developments on **light-front impulse approximation** in **Wigner representation**

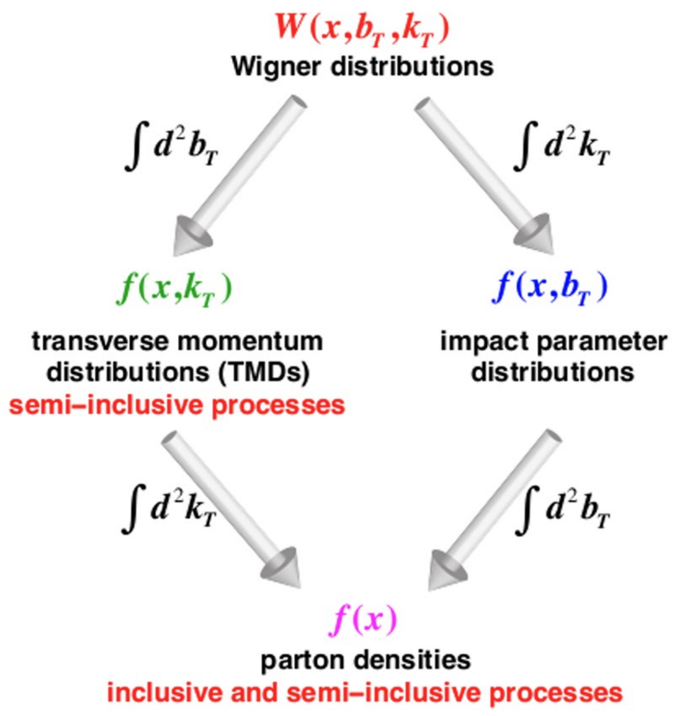
  General formalism applies to **full family of matrix elements**

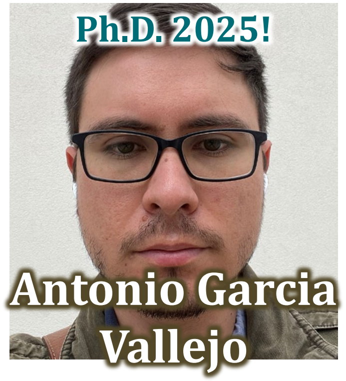
  First application to GPDs, revealing **novel $\overrightarrow{\Delta L} \cdot \vec{S}$ mixing channels** in exclusive processes

  Illustrative **toy phenomenology for ^{4}He**

- **Next Steps:**

  Application to a **TMDs of a composite spin-1 target** for SIDIS on tensor-polarized deuterium





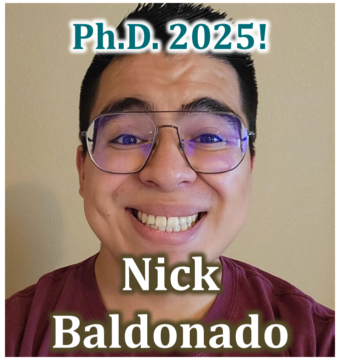
❖ **Next talk!**

Thurs. 6/4, 11:25am

The Sievert Group(s) at NMSU

Hot QCD

Cold QCD



This Work

Physics Education Research

Backup Slides

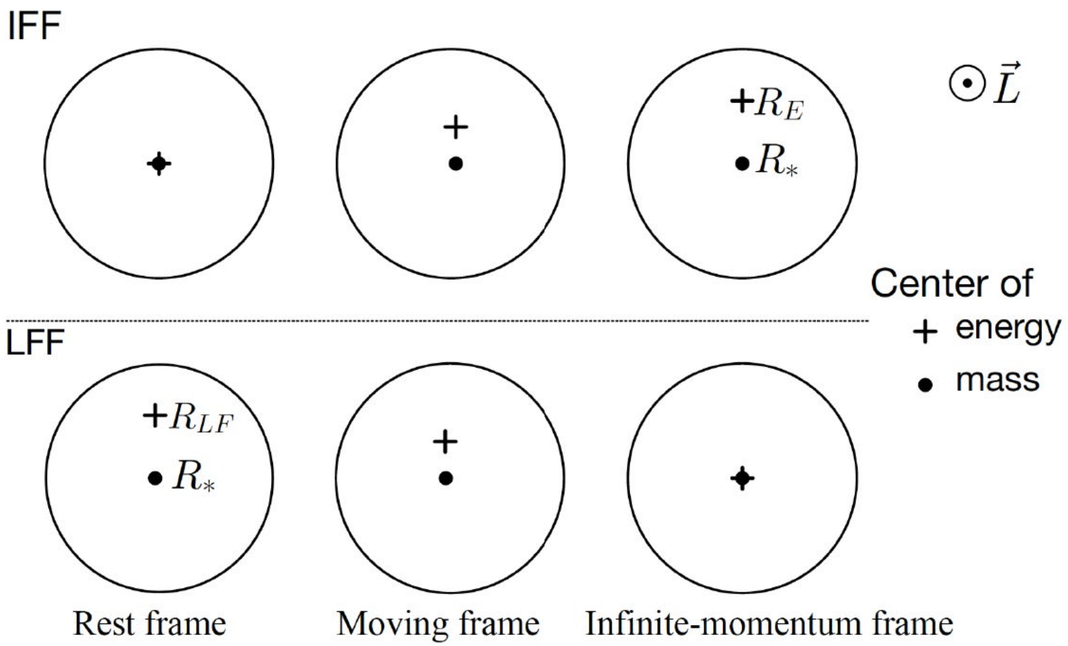
$$R_E^\mu \equiv \frac{1}{p^0} \int d^3x \, x^\mu T^{00}(x)$$

$$R_*^\mu \equiv R_E^\mu \text{ if } \vec{p} = 0$$
(rest frame)

$$R_{LF}^\mu \equiv \frac{1}{p^+} \int d^2x_\perp dx^- \, x^\mu T^{++}(x)$$

$$\vec{R}_E - \vec{R}_* = \frac{\vec{p} \times \vec{W}}{p^0 m^2}$$

$$R_{LF}^\mu - R_*^\mu = -\frac{\varepsilon^{\mu\alpha\beta+} W_\alpha p_\beta}{m^2 p^+}$$



- Text

$$b^\mu \equiv x^\mu - R^\mu_{LF} ,$$
$$\ell^\mu \equiv x^\mu - R^\mu_* ,$$
$$b^\mu = \ell^\mu - (R^\mu_{LF} - R^\mu_*)$$

$$P^+ b^- \stackrel{IMF}{=} P^+ \ell^- = -\sqrt{\frac{\Lambda^2}{1-\xi^2}}\,(\ell_z)^{RF}$$