# Twist-3 Spin Asymmetries in Electron-Nucleon Scattering

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# Outline

- Background information
  - Transverse momentum dependent PDFs/FFs
  - Twist-3 collinear PDFs/FFs

- Numerical predictions for various spin asymmetries
  - $\vec{e}\,p^{\uparrow} \to \pi\, X$
  - $e\,p^{\uparrow} \to \pi\, X$
  - $e\,p^{\uparrow} \to e\,\gamma\, X$
  - $e\,p^{\uparrow} \to e\, X$

- Summary and outlook

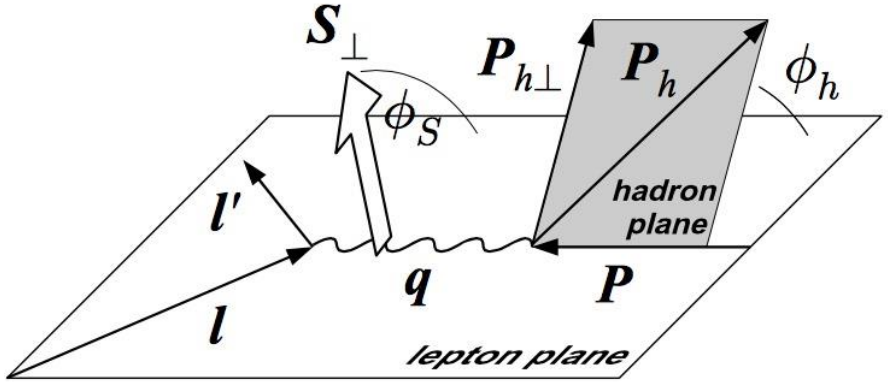
# Background Information

- TMD factorization

$$\frac{d\sigma}{dxdyd\phi_s dzd\phi_h(z^2 dq_T^2)} = W_{UU}(q_T, Q) + |\vec{S}_T| \sin(\phi_h - \phi_S) W_{UT}^{\text{siv}}(q_T, Q) + \dots$$

where $$W_{UU}(q_T, Q) = \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T \cdot \vec{b}_T} \tilde{W}_{UU}(b_T, Q)$$

with $$\tilde{W}_{UU}(b_T, Q) = \sum_j H_j(\mu, Q) \tilde{f}_1^j(x, b_T; \zeta_A, \mu) \tilde{D}_1^{h/j}(z, b_T; \zeta_b, \mu)$$

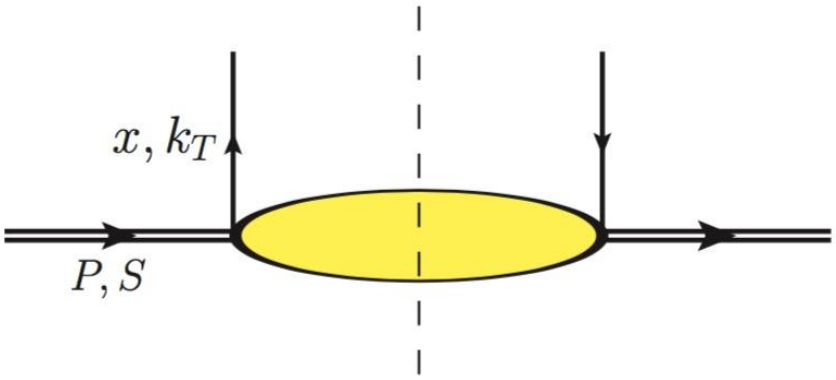



SIDIS ($\Lambda_{QCD} \sim q_T << Q$)

TMD PDFs ($x$, $k_T$)

| q pol. / H pol. | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_{1T}$ $h_{1T}^\perp$ |

## Transverse Momentum Dependent Parton Distribution Function (TMD PDF)



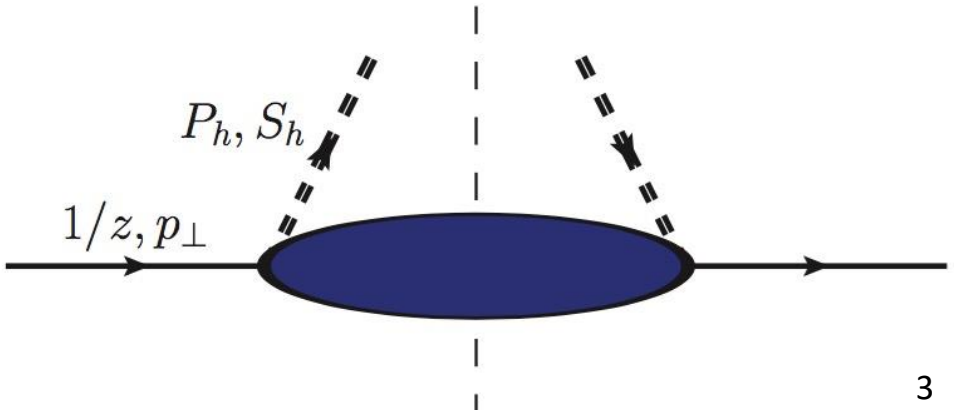
TMD PDFs ($x$, $k_T$)

| q pol. / H pol. | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_{1T}$ $h_{1T}^\perp$ |

TMD FFs ($z, p_\perp$)

| q pol. / H pol. | U | L | T |
|---|---|---|---|
| U | $D_1$ | | $H_1^\perp$ |
| L | | $G_{1L}$ | $H_{1L}^\perp$ |
| T | $D_{1T}^\perp$ | $G_{1T}$ | $H_{1T}$ $H_{1T}^\perp$ |

**Transverse Momentum Dependent Fragmentation Function (TMD FF)**



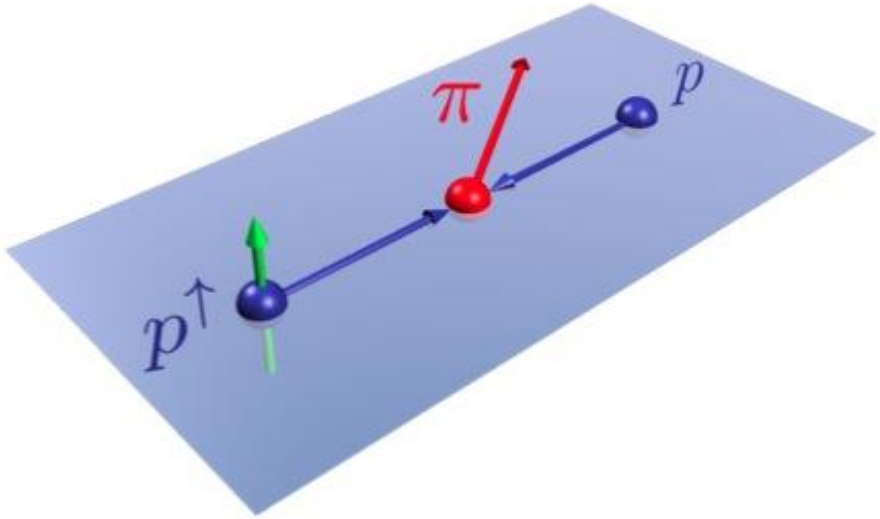
- Collinear twist-3 factorization

$$d\sigma = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} + H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)} + H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{c/C(3)}$$

**A + B -> C + X**

-one hadron T polarized (others U or L)

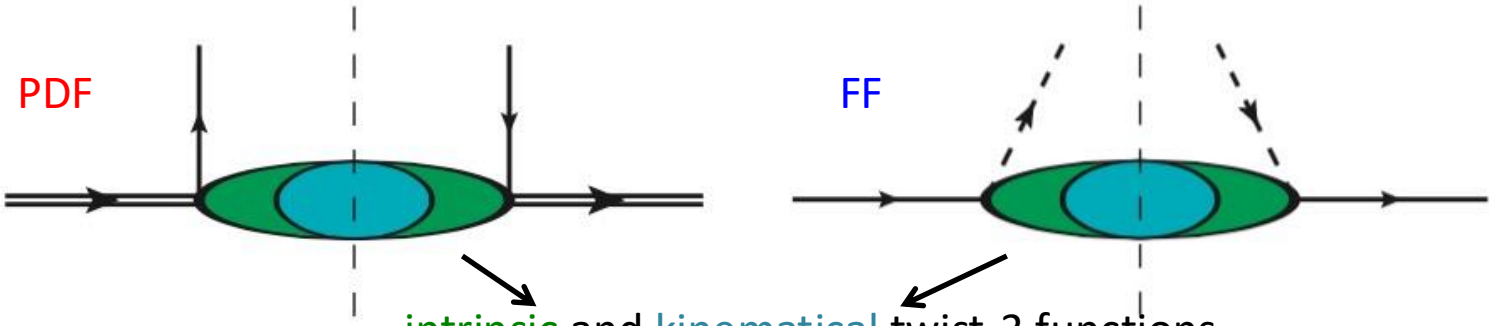
-one large scale ($P_{C,T}$)



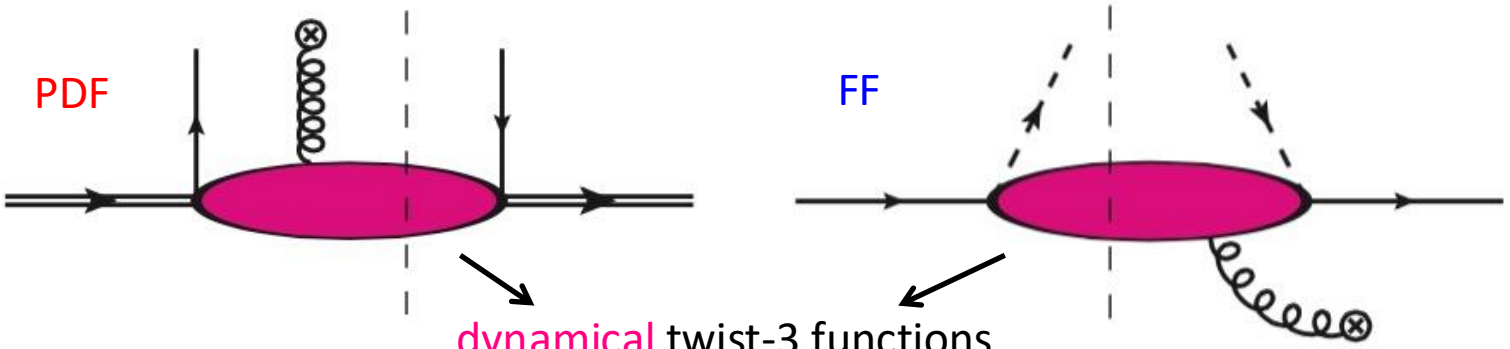
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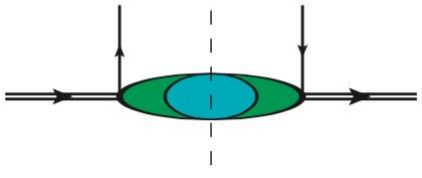
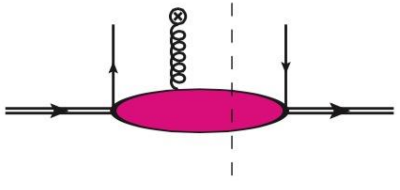
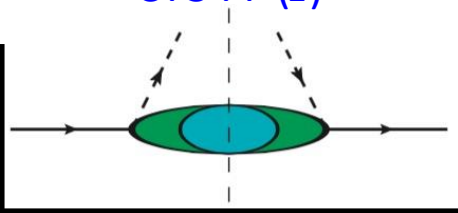
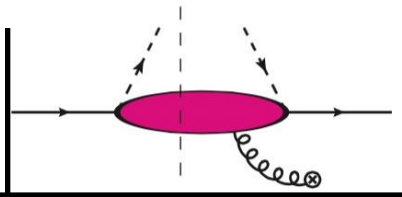
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-one hadron T polarized (others U or L)
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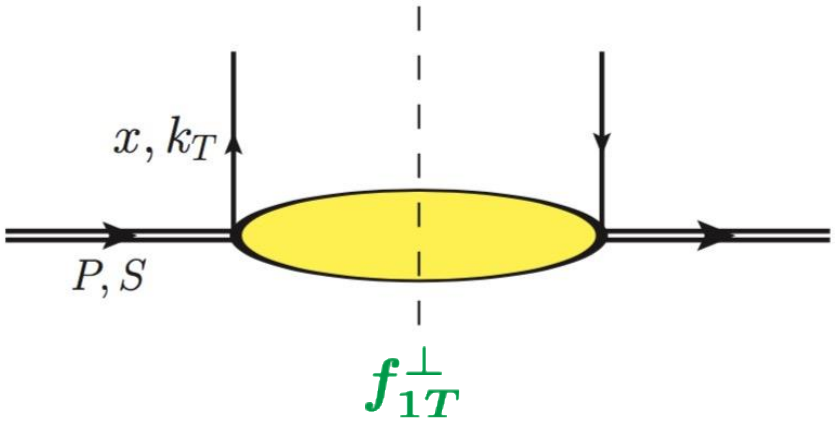

intrinsic and kinematical twist-3 functions



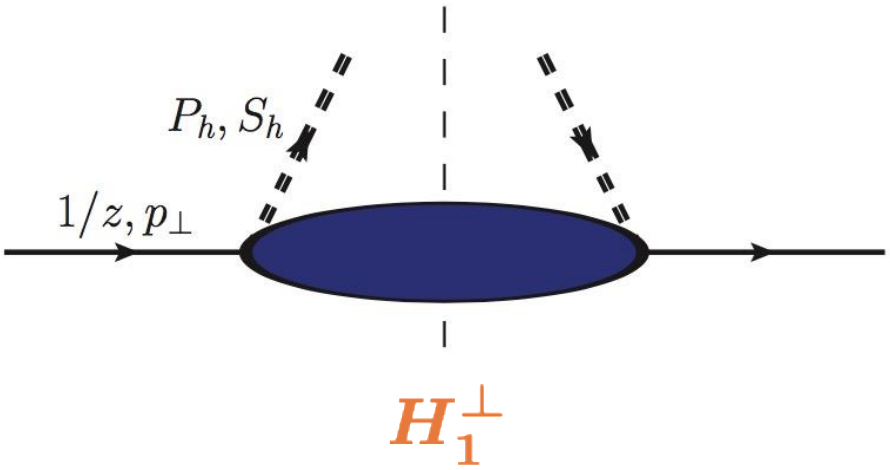

dynamical twist-3 functions

| Hadron Pol. | CT3 PDF ($x$)  | | CT3 PDF ($x$, $x_1$)  | CT3 FF ($z$)  | | CT3 FF ($z$, $z_1$)  |
|---|---|---|---|---|---|---|
| | intrinsic | kinematical | dynamical | intrinsic | kinematical | dynamical |
| **U** | $e$ | $h_1^{\perp(1)}$ | $H_{FU}$ | $E, H$ | $H_1^{\perp(1)}$ | $\hat{H}_{FU}^{\Re,\Im}$ |
| **L** | $h_L$ | $h_{1L}^{\perp(1)}$ | $H_{FL}$ | $H_L, E_L$ | $H_{1L}^{\perp(1)}$ | $\hat{H}_{FL}^{\Re,\Im}$ |
| **T** | $g_T$ | $f_{1T}^{\perp(1)}$, $g_{1T}^{\perp(1)}$ | $F_{FT}, G_{FT}$ | $D_T, G_T$ | $D_{1T}^{\perp(1)}$, $G_{1T}^{\perp(1)}$ | $\hat{D}_{FT}^{\Re,\Im}, \hat{G}_{FT}^{\Re,\Im}$ |

TMD PDF

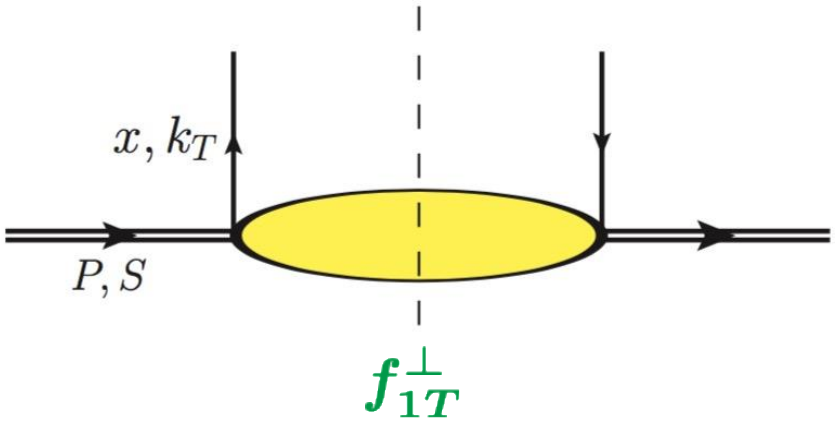



TMD FF



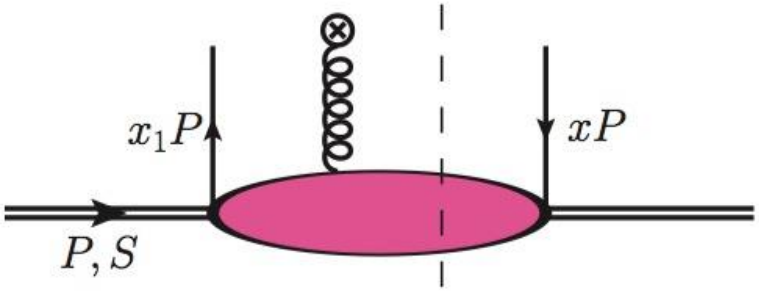

sensitive to intrinsic transverse momentum

TMD PDF



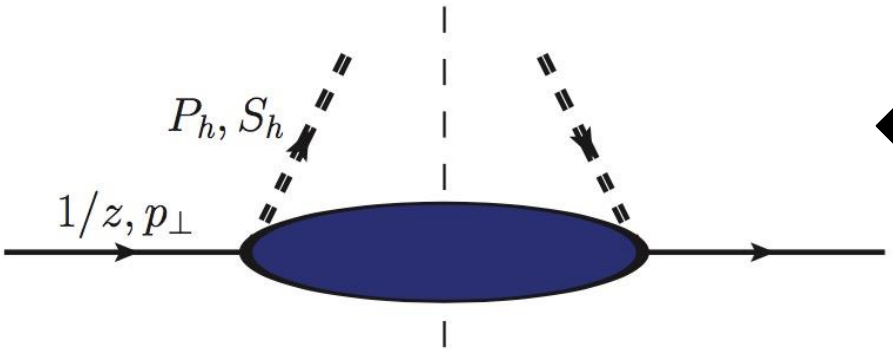

$f_{1T}^{\perp}$

quark-gluon-quark PDF



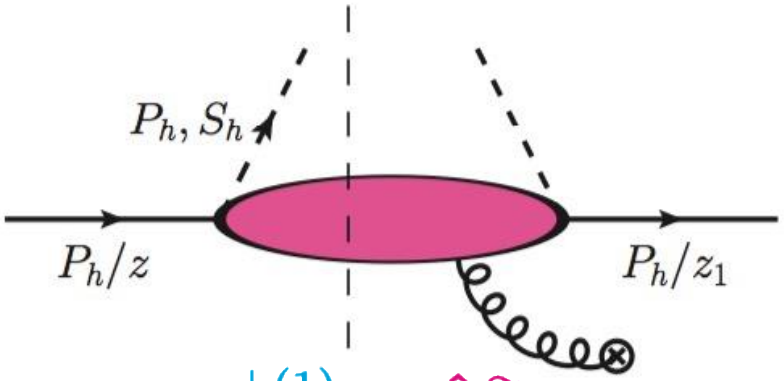

$f_{1T}^{\perp(1)} \sim F_{FT}$

TMD FF




$H_1^{\perp}$

quark-gluon-quark FF




$H_1^{\perp(1)} \sim \hat{H}_{FU}^{\Im}$

sensitive to intrinsic transverse momentum

sensitive to *average* intrinsic transverse momentum

- Example of equation-of-motion and Lorentz invariance relations

EOMR

$$H^q(z) = -2z\, H_1^{\perp(1),q}(z) + 2z \int_z^\infty \frac{dz_1}{z_1^2} \frac{1}{\frac{1}{z} - \frac{1}{z_1}} \hat{H}_{FU}^{q,\Im}(z, z_1)$$

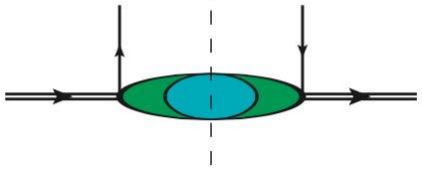
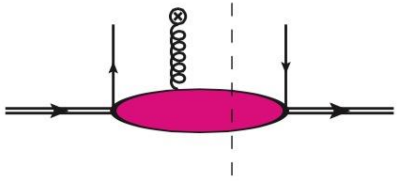
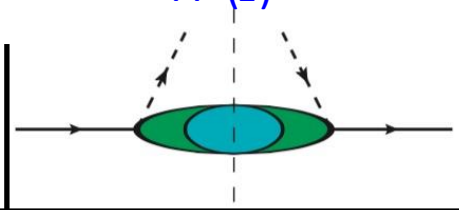
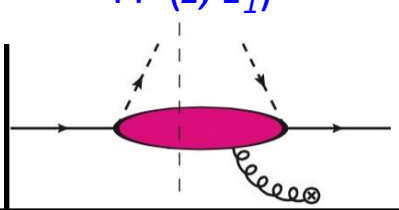
LIR

$$\frac{H^q(z)}{z} = -\left(1 - z\frac{d}{dz}\right) H_1^{\perp(1),q}(z) - \frac{2}{z}\int_z^\infty \frac{dz_1}{z_1^2} \frac{\hat{H}_{FU}^{q,\Im}(z, z_1)}{(1/z - 1/z_1)^2}$$

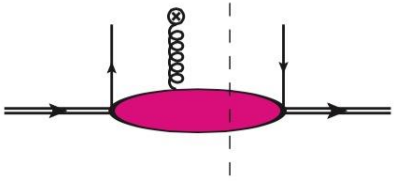
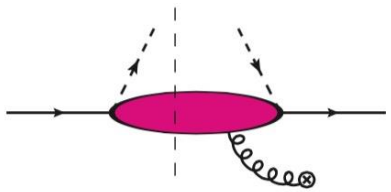
$$H(z) = \int_z^1 dz_1 \int_{z_1}^\infty \frac{dz_2}{z_2^2}\, 2 \left[ \frac{\left(2(\frac{2}{z_1} - \frac{1}{z_2}) + \frac{1}{z_1}\left(\frac{1}{z_1} - \frac{1}{z_2}\right) \delta\left(\frac{1}{z_1} - \frac{1}{z}\right)\right)}{\left(\frac{1}{z_1} - \frac{1}{z_2}\right)^2} \hat{H}_{FU}^{\Im}(z_1, z_2) \right]$$

$$H_1^{\perp(1)}(z) = -\frac{2}{z}\int_z^1 dz_1 \int_{z_1}^\infty \frac{dz_2}{z_2^2} \frac{\left(\frac{2}{z_1} - \frac{1}{z_2}\right)}{\left(\frac{1}{z_1} - \frac{1}{z_2}\right)^2} \hat{H}_{FU}^{\Im}(z_1, z_2)$$

(Kanazawa, Koike, Metz, DP, Schlegel, PRD **93** (2016))

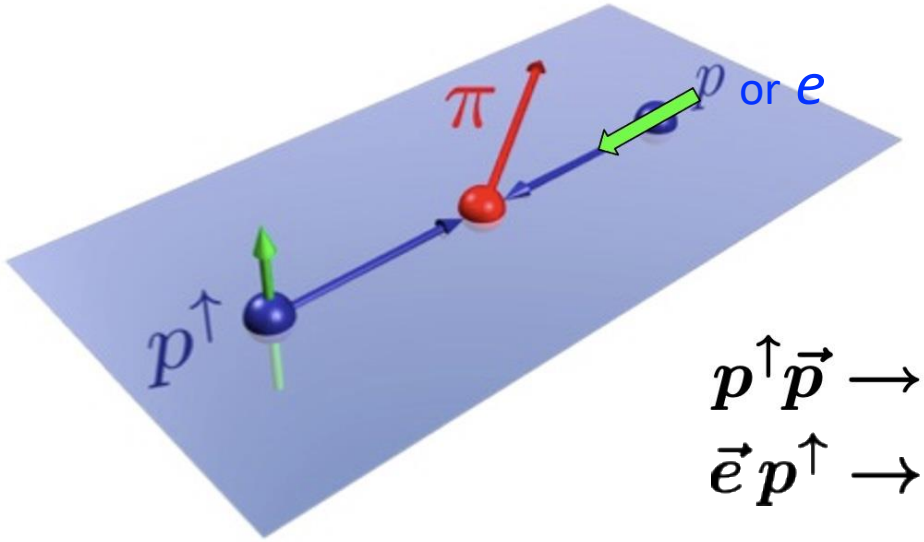
| Hadron Pol. | PDF ($x$)  | PDF ($x$, $x_1$)  | FF ($z$)  | FF ($z$, $z_1$)  |
|---|---|---|---|---|
| | intrinsic \| kinematical | dynamical | intrinsic \| kinematical | dynamical |
| **U** | $e$ \| $h_1^{\perp(1)}$ | $H_{FU}$ | $E, H$ \| $H_1^{\perp(1)}$ | $\hat{H}_{FU}^{\Re,\Im}$ |
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| **T** | $g_T$ \| $f_{1T}^{\perp(1)}$, $g_{1T}^{\perp(1)}$ | $F_{FT}, G_{FT}$ | $D_T, G_T$ \| $D_{1T}^{\perp(1)}$, $G_{1T}^{\perp(1)}$ | $\hat{D}_{FT}^{\Re,\Im}, \hat{G}_{FT}^{\Re,\Im}$ |

(Kanazawa, Koike, Metz, DP, Schlegel, PRD **93** (2016))

| Hadron Pol. | PDF ($x$, $x_1$)  | FF ($z$, $z_1$)  |
|---|---|---|
| | dynamical | dynamical |
| **U** | $H_{FU}$ | $\hat{H}_{FU}^{\Re,\Im}$ |
| **L** | $H_{FL}$ | $\hat{H}_{FL}^{\Re,\Im}$ |
| **T** | $F_{FT}, G_{FT}$ | $\hat{D}_{FT}^{\Re,\Im}, \hat{G}_{FT}^{\Re,\Im}$ |

***ALL*** *twist-3 observables* are driven by *multi-parton correlations*

(Kanazawa, Koike, Metz, DP, Schlegel, PRD **93** (2016))




$$p^\uparrow \vec{p} \to \pi X$$
$$\vec{e}\, p^\uparrow \to \pi X$$

$$A_{LT} \equiv \frac{\frac{1}{4}\Big\{[d\sigma_{LT}(+,\uparrow) - d\sigma_{LT}(-,\uparrow)] - [d\sigma_{LT}(+,\downarrow) - d\sigma_{LT}(-,\downarrow)]\Big\}}{d\sigma_{unp}}$$

(Bauer, DP, Shay, PRD **107** (2023))

$$A_{LT}^{\vec{e}N^{\uparrow}\to\pi X} = \frac{\displaystyle\int_{z_{min}}^{1} \frac{dz}{z^3}\left(\frac{-4P_T}{S+T/z}\right)\frac{1}{x}\sum_a e_a^2\left[\frac{M}{\hat{u}}\,D_1^{\pi/a}(z)\,\mathcal{G}^{a/N}(x,\hat{s},\hat{t},\hat{u}) + \frac{M_\pi}{z\hat{t}}\,h_1^{a/N}(x)\,E^{\pi/a}(z)\left(-\frac{\hat{s}}{\hat{t}}\right)\right]}{\displaystyle\int_{z_{min}}^{1}\frac{dz}{z^2}\,\frac{1}{S+T/z}\,\frac{1}{x}\sum_a e_a^2\,f_1^{a/N}(x)\,D_1^{\pi/a}(z)\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right)}$$

where $\mathcal{G}(x,\hat{s},\hat{t},\hat{u}) = \left(g_{1T}^{(1)}(x) - x\frac{dg_{1T}^{(1)}(x)}{dx}\right)\left(\frac{\hat{s}(\hat{s}-\hat{u})}{2\hat{t}^2}\right) + x\,g_T(x)\left(-\frac{\hat{s}\hat{u}}{\hat{t}^2}\right) + x\,g_1(x)\left(\frac{\hat{u}(\hat{s}-\hat{u})}{2\hat{t}^2}\right)$

$$\sum_h\sum_{S_h} M_h \int_0^1 dz\, E^{h/q}(z) = M_j$$

Connection to dynamical quark mass generation in QCD – $M_j$ is the mass of a "dressed" quark
(Accardi, Signori (2019, 2020))

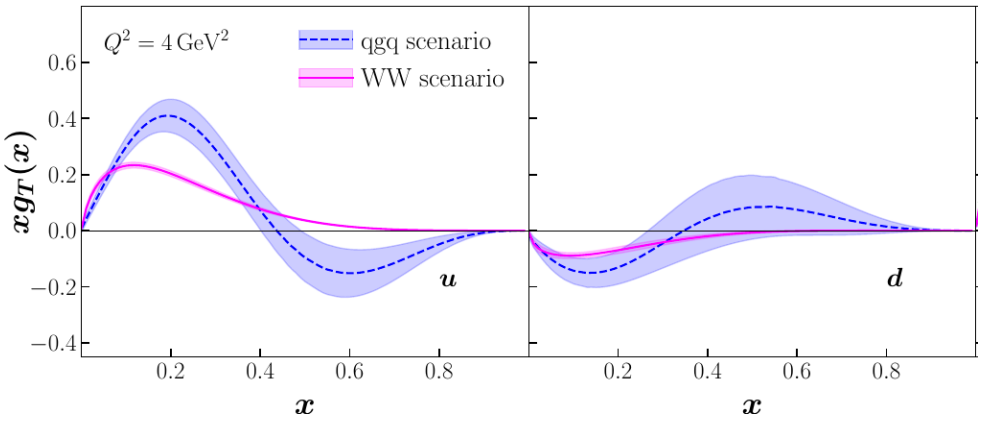
(Bauer, DP, Shay, PRD **107** (2023))

## ➢ Numerical scenarios

Quark-Gluon-Quark (qgq) scenario:

Use direct extraction of $g_{1T}(x,k_T)$ from Bhattacharya, et al. (2021) and the following for $g_T(x)$ (with $G_{FT} = 0$):

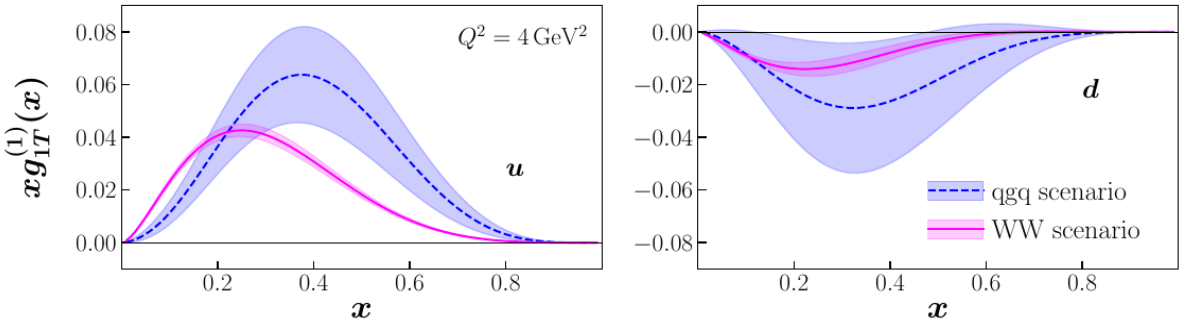
$$g_T^{q/N}(x) = g_1^{q/N}(x) + \frac{dg_{1T}^{(1)q/N}(x)}{dx} - 2\mathcal{P}\int_{-1}^{1} dy\, \frac{G_{FT}^{q/N}(x,y)}{(x-y)^2}$$




WW scenario:

$$g_{1T}^{(1)a/N}(x) \overset{\text{WW}}{\approx} x\int_x^1 dy\, \frac{g_1^{a/N}(y)}{y}$$

$$g_T^{a/N}(x) \overset{\text{WW}}{\approx} \int_x^1 dy\, \frac{g_1^{a/N}(y)}{y}$$



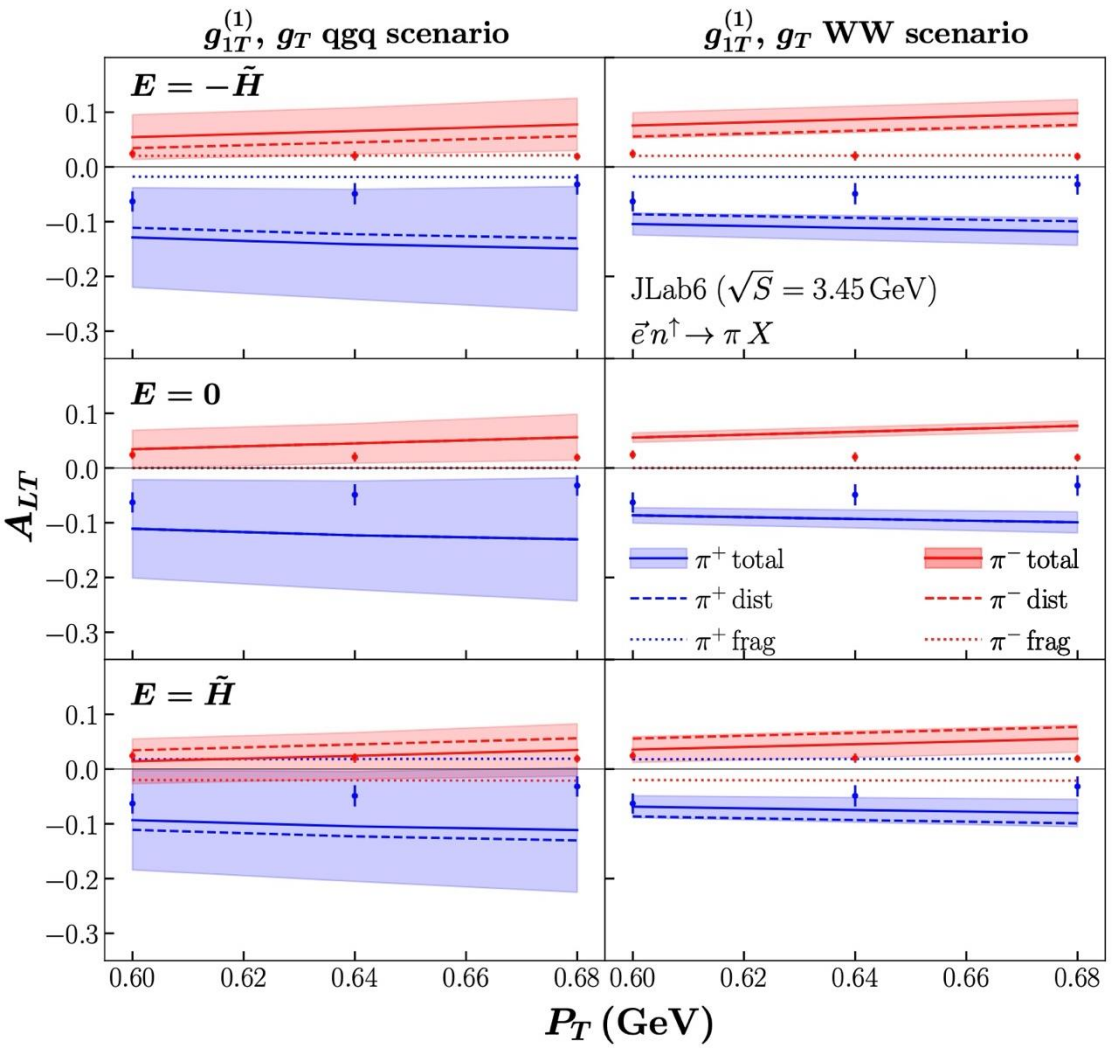

Also, $E = \tilde{H}, E = 0, E = -\tilde{H}$ for each

$$\tilde{H}^{h/q}(z) = 2z\int_z^\infty \frac{dz_1}{z_1^2}\,\frac{\hat{H}_{FU}^{\Im,h/q}(z,z_1)}{\frac{1}{z}-\frac{1}{z_1}} \qquad \sum_h\sum_{S_h} M_h \int_0^1 dz\, \tilde{H}^{h/q}(z) = 0$$

(Bauer, DP, Shay, PRD **107** (2023))

- Measurements of $A_{LT}$ for the electron-neutron case from Jefferson Lab (JLab Hall A (2015))
- We are able to describe the data reasonably well with all scenarios
- Distribution term plays a dominant role over the fragmentation term

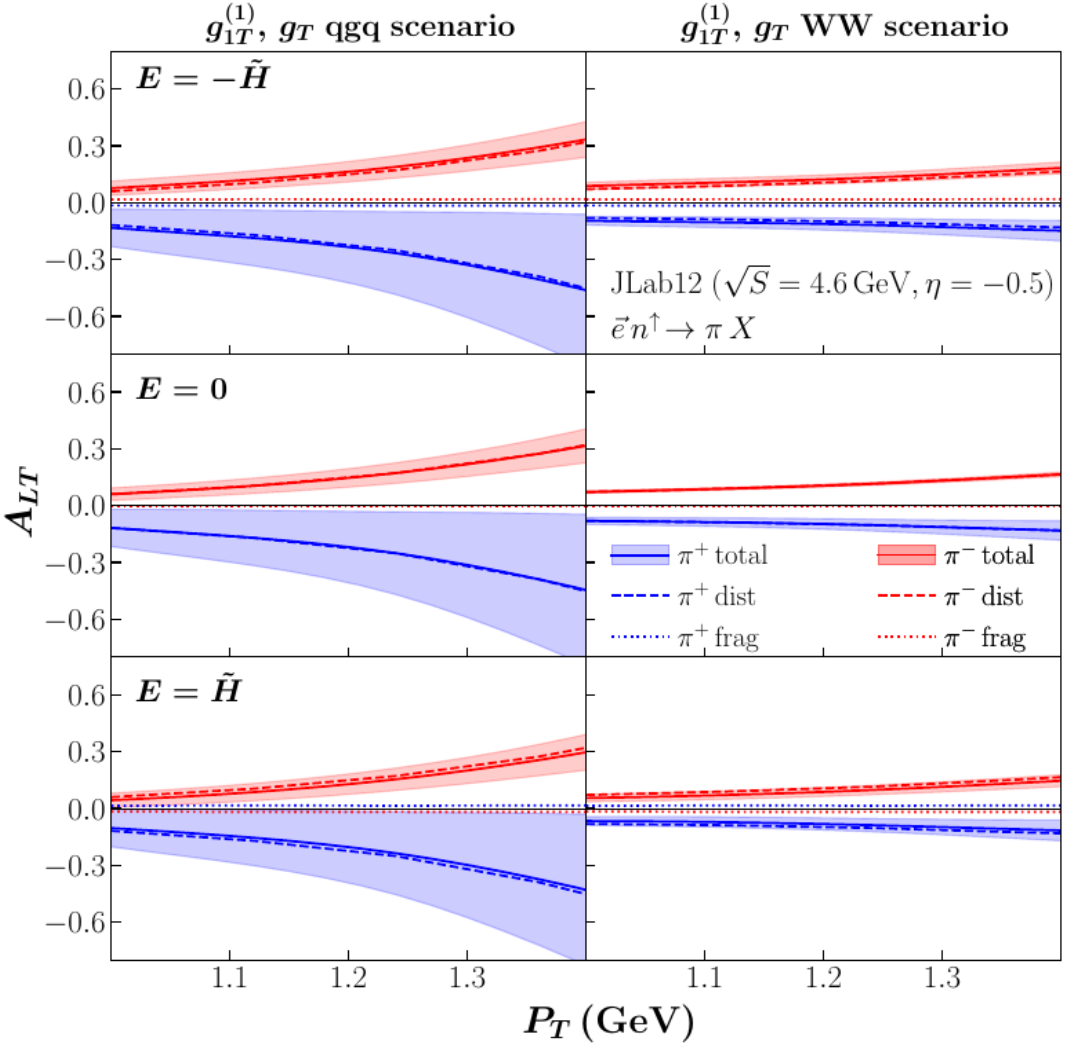
JLab6




(Bauer, DP, Shay, PRD **107** (2023))

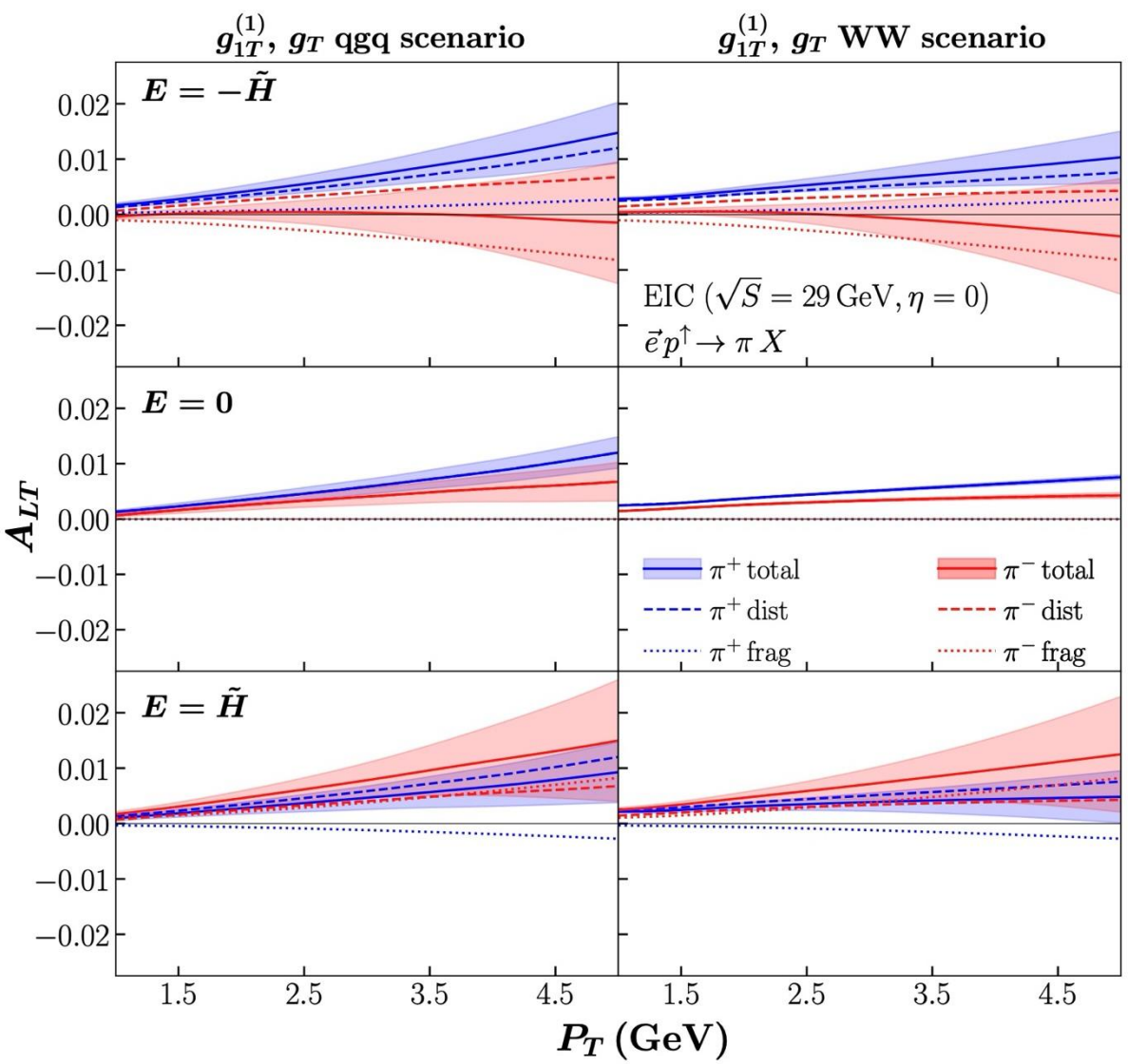
- Asymmetries of 15-30% are predicted which grow more substantial with increasing $P_T$
- $A_{LT}$ is dominated by the distribution term
- One may use JLab12 data to test the WW approximation and extract information about dynamical quark-gluon-quark correlations in the nucleon

JLab12

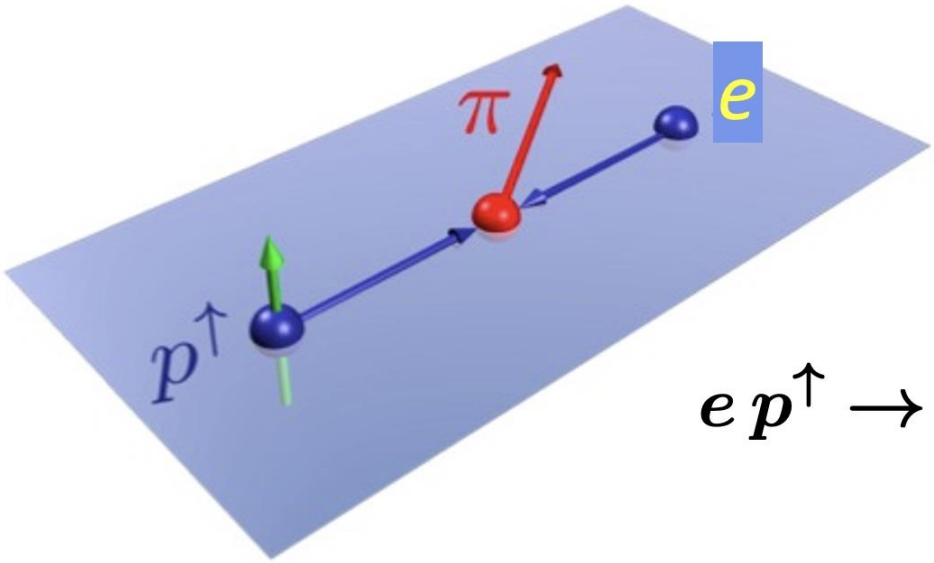



(Bauer, DP, Shay, PRD **107** (2023))

- Predictions at midrapidity show $A_{LT}$ ~0.5-1.5%
- A clearly negative signal for $\pi^-$ production would be caused by $E(z)$ – might be possible to extract this function and learn about dynamical quark mass generation




(Bauer, DP, Shay, PRD **107** (2023))




$$e\,p^\uparrow \to \pi\,X$$

$$A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\sigma_{UT}}{d\sigma_{UU}}$$

(Fitzgibbons, Malda, Marsh, DP, Smith, PLB **852** (2024))

$$d\sigma_{UT} = \frac{-8\alpha_{\rm em}^2 P_{hT}}{S}\int_{z_{min}}^{1}\frac{dz}{z^3}\left(\frac{1}{S+T/z}\right)\frac{1}{x}\sum_q e_q^2\left[\frac{M}{\hat{u}}\,D_1^{\pi/q}(z)\,\mathcal{F}^{q/p} + \frac{M_\pi}{\hat{t}}\,h_1^{q/p}(x)\,\mathcal{H}^{\pi/q}\right]$$

$$\mathcal{F}^{q/p}(z, x_F, P_{hT}, \sqrt{S}) = \left(f_{1T}^{\perp(1)q/p}(x) - x\frac{df_{1T}^{\perp(1)q/p}(x)}{dx}\right)\left(\frac{\hat{s}(\hat{s}^2+\hat{u}^2)}{2\hat{t}^3}\right),$$

$$\mathcal{H}^{\pi/q}(z, x_F, P_{hT}, \sqrt{S}) = \left(H_1^{\perp(1)\pi/q}(z) - z\frac{dH_1^{\perp(1)\pi/q}(z)}{dz}\right)\left(\frac{\hat{s}\hat{u}}{\hat{t}^2}\right) + \frac{1}{z}\left(-2zH_1^{\perp(1)\pi/q}(z) + \tilde{H}^{\pi/q}(z)\right)\left(\frac{\hat{s}(\hat{u}-\hat{s})}{\hat{t}^2}\right)$$

(Gamberg, et al. (2014); Kanazawa, et al. (2016))

$$d\sigma_{UU} = \left(\frac{-U}{S^2}\right)\sum_{i,f}\int_{\frac{U}{T+U}}^{1+\frac{T}{S}}\frac{dv}{v(1-v)}\int_{\frac{1-v}{v}\frac{U}{T}}^{1}\frac{dw}{w^2}$$

$$\times\ H^{if}(v,w)\left[\hat{\sigma}^{i\to f}_{\mathrm{LO}}(v)+\frac{\alpha_s(\mu)}{\pi}\hat{\sigma}^{i\to f}_{\mathrm{NLO}}(v,w,\mu)\right.$$

$$\left.+\ f^{\gamma/\ell}_{\mathrm{ren}}\left(\frac{1-v}{1-vw},\mu\right)\frac{\alpha_s(\mu)}{\pi}\hat{\sigma}^{\gamma i\to f}_{\mathrm{LO}}(v,w)\right]$$

$$H^{if}(v,w) \equiv \left.\frac{f^{i/N}(x,\mu)}{x}\frac{D^{h/f}(z,\mu)}{z^2}\right|_{x=\frac{1-v}{vw}\frac{U}{T},\, z=\frac{-T}{(1-v)S}}$$

**NLO Term**

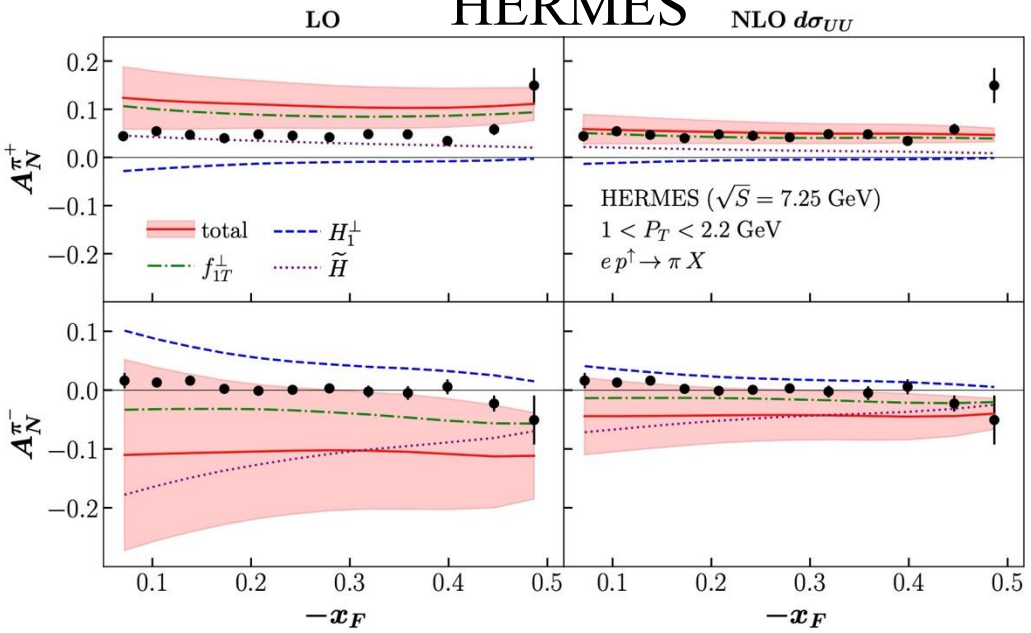
**LO Term**

**Weizsacker-Williams term**

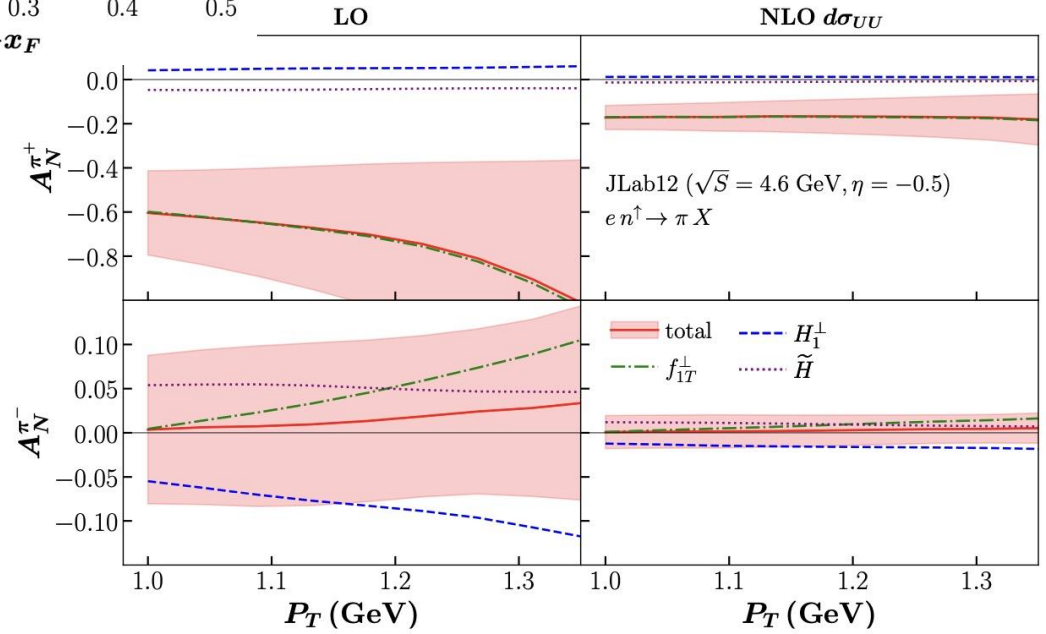
(Hinderer, Schlegel, Vogelsang (2015))

We introduced the next-to-leading order (NLO) term as well as the Weizsacker-Williams term to improve the accuracy of the $d\sigma_{UU}$ (unpolarized) cross section in the denominator of $A_N$

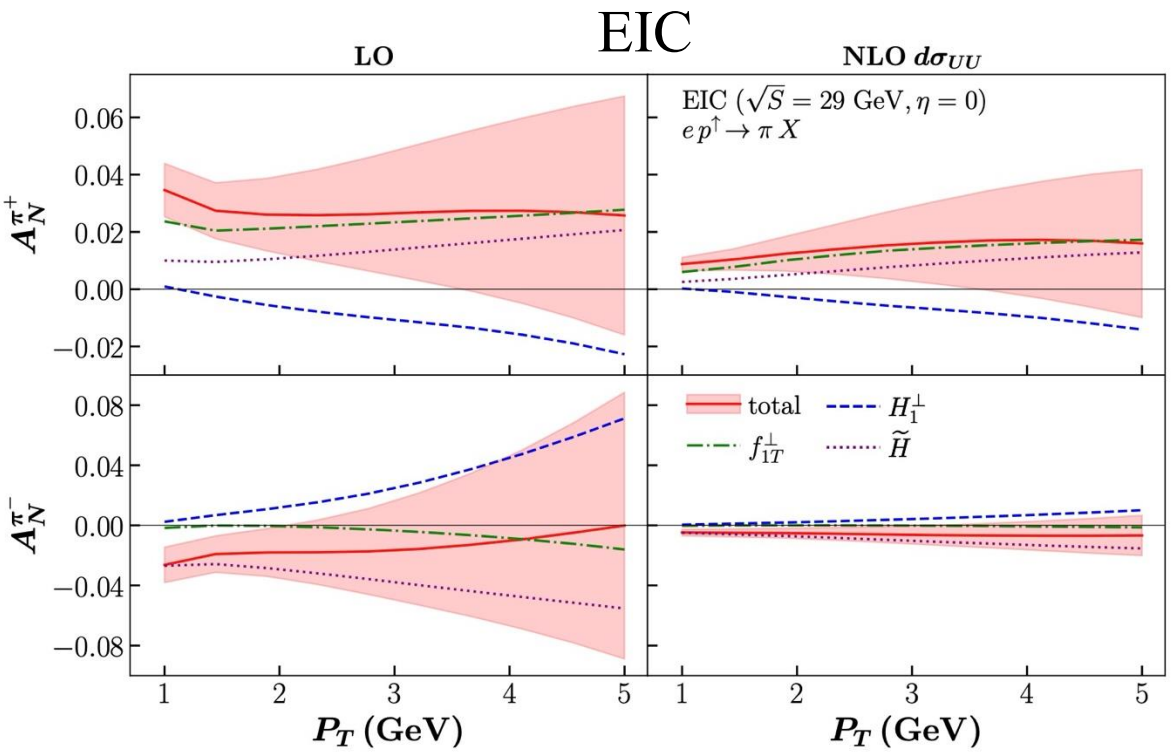
HERMES




JLab12



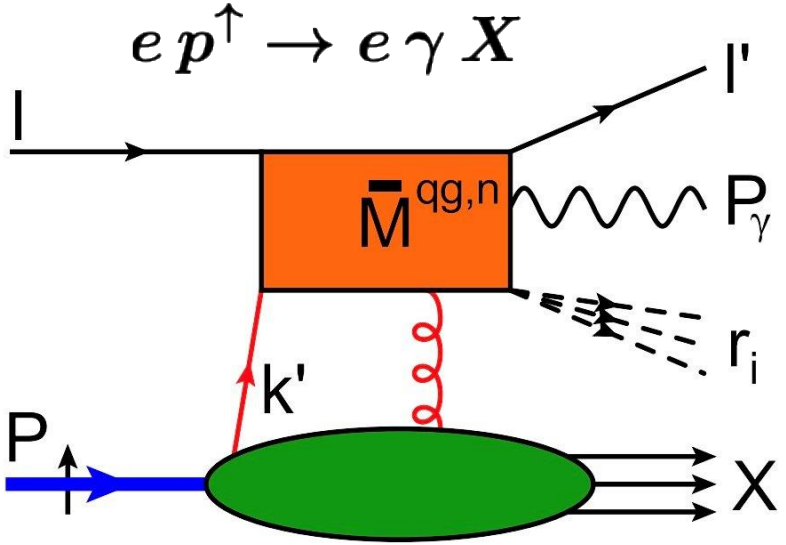

(Fitzgibbons, Malda, Marsh, DP, Smith, PLB **852** (2024))

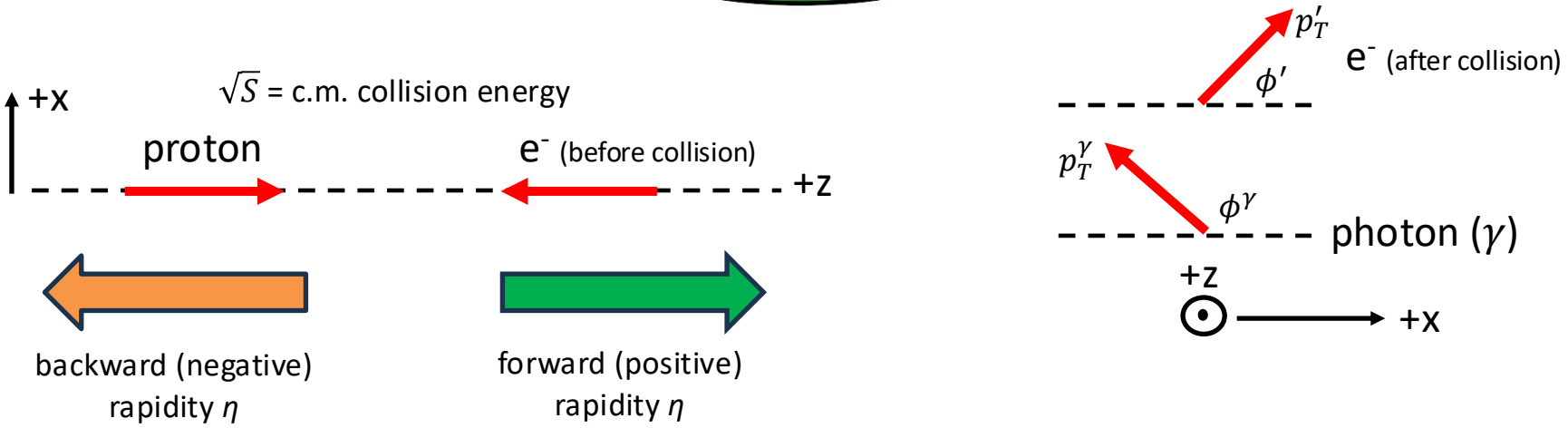



- There is a delicate interplay between different terms that enter the asymmetry, and kinematic regions where the input PDFs and FFs are unconstrained cause large uncertainties, sometimes generating very large asymmetries.

- Therefore, this observable can be a fruitful testing ground and any new data at these various kinematics can greatly enhance our understanding of the Sivers-like and Collins-like quark-gluon-quark functions that underly TSSAs.

(Fitzgibbons, Malda, Marsh, DP, Smith, PLB **852** (2024))

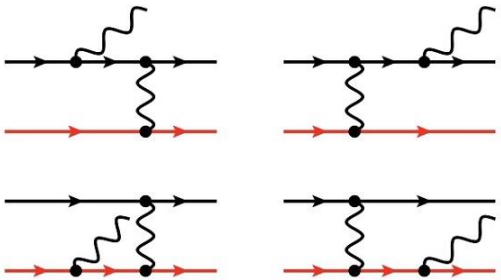



$$A_{UT} \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

(Harris, Marsh, DP, Prokudin, Putnam, Rein, Schlegel PLB **869** (2025))

$$\frac{d\sigma_{UU}}{dp'_T d\eta' d\phi' dp_T^\gamma d\eta^\gamma d\phi^\gamma} = \frac{\alpha_{em}^3}{4\pi^2 s Q^4} p'_T p_T^\gamma \sum_{n=\mathrm{BH,C,I}} \hat{\sigma}_{UU}^n \, f_1^n(x_B, \mu_n)$$



BH = Bethe-Heitler – square of diagrams where photon is radiated off the lepton
C = Compton – square of diagrams where photon is radiated off the quark
I = Interference – diagrams where the photon is radiated off the lepton and quark

$$f^{\mathrm{BH}} \equiv \sum_{q=u,d,s} e_q^2 \left(f^q + f^{\bar{q}}\right), \quad f^{\mathrm{C}} \equiv \sum_{q=u,d,s} e_q^4 \left(f^q + f^{\bar{q}}\right), \quad f^{\mathrm{I}} \equiv \sum_{q=u,d,s} e_q^3 \left(f^q - f^{\bar{q}}\right)$$

Relevant kinematic variables: $s = (P+l)^2$, $Q^2 = -(l - l' - P_\gamma)^2$, $\tilde{Q}^2 = -(l - l')^2$, $x_B = \frac{Q^2}{2P \cdot q}$, $\tilde{x}_B = \frac{\tilde{Q}^2}{2P \cdot \tilde{q}}$

Partonic description is valid if $Q^2 \gg M^2$, $\tilde{Q}^2 \gg M^2$, $Q^2 - \tilde{Q}^2 \gg M^2$ (Brodsky, Gunion, Jaffe (1972))

Scale choices in the PDFs: $\mu_{\mathrm{BH}} = Q$, $\mu_{\mathrm{C}} = \tilde{Q}$, $\mu_{\mathrm{I}} = \sqrt{Q\tilde{Q}}$

Albaltan, Prokudin, Schlegel (2020)

$$\frac{d\sigma_{UT}}{dp_T' d\eta' d\phi' dp_T^\gamma d\eta^\gamma d\phi^\gamma} = \frac{\alpha_{em}^3 M}{4\pi s Q^8} p_T' p_T^\gamma \left[\epsilon^{Pll'S}\, \sigma_{UT}^{\phi'} + \epsilon^{PlP_\gamma S}\, \sigma_{UT}^{\phi_\gamma}\right]$$

where $\sigma_{UT}^{\phi'(\phi_\gamma)} = \sum_{n=\mathrm{C,I}} \Big[\hat{\sigma}_{\mathrm{HP},+}^{n,\phi'(\phi_\gamma)} F_+^n(x_B, \tilde{x}_B, \mu_n) + \hat{\sigma}_{\mathrm{HP},-}^{n,\phi'(\phi_\gamma)} F_-^n(x_B, \tilde{x}_B, \mu_n)$

$+ \hat{\sigma}_{\mathrm{SFP},+}^{n,\phi'(\phi_\gamma)} F_+^n(x_B, 0, \mu_n) + \hat{\sigma}_{\mathrm{SFP},-}^{n,\phi'(\phi_\gamma)} F_-^n(x_B, 0, \mu_n)\Big]$

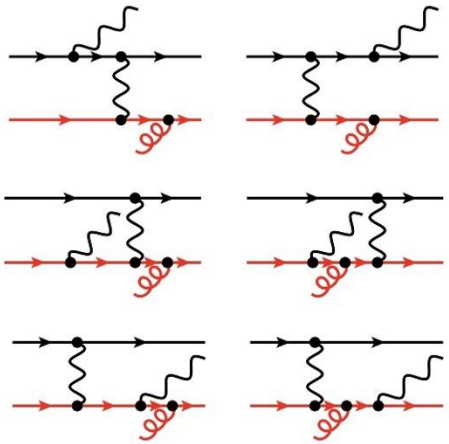
Note: SGP terms (where $x = x'$) cancel, as does the BH part

$\epsilon^{Pll'S} \propto \sin(\phi_S - \phi')$

$\epsilon^{PlP_\gamma S} \propto \sin(\phi_S - \phi^\gamma)$

(fix $\phi_S = \pi/2$)

$F_\pm^n(x, x') \equiv F_{FT}^n(x, x') \pm G_{FT}^n(x, x')$



$F_{FT}$ and $G_{FT}$ are quark-gluon-quark correlators that can be probed point-by-point on the full support $x$, $x'$, which is an unprecedented feature of this observable

Albaltan, Prokudin, Schlegel (2020)

$$F^q_{FT}(x,x') = \left\{ \frac{1}{2\pi} f_{1T}^{\perp(1),q+\bar{q}}(r/\sqrt{2}) \left[ 1 + \sum_{n=1}^{3} [a^q_{2n}(\cos(2n\phi) - 1)] \right] \right.$$
$$\left. + \frac{1}{2\pi} f_{1T}^{\perp(1),q-\bar{q}}(r/\sqrt{2}) \left[ \cos(\phi) + \sum_{n=1}^{3} [a^q_{2n+1}(\cos((2n+1)\phi) - \cos(\phi))] \right] \right\} e(x,x')$$

$$G^q_{FT}(x,x') = \left\{ -\frac{1}{\pi} f_{1T}^{\perp(1),q+\bar{q}}(r/\sqrt{2}) \sum_{n=1}^{6} [b^q_n \sin(n\phi)] \right\} e(x,x')$$

where $$e(x,x') = \left( \frac{2}{1+e^{-50(1-x^2)^3}} - 1 \right) \left( \frac{2}{1+e^{-50(1-(x')^2)^3}} - 1 \right)$$
$$\times \left( \frac{2}{1+e^{-50(1-(x-x')^2)^3}} - 1 \right) \theta(1-|x|)\theta(1-|x'|)\theta(1-|x-x'|)$$

$$r = \sqrt{x^2 + x'^2}$$

$$\phi = \begin{cases} -\frac{\pi}{4} + \arctan(x'/x) \text{ if } x' \geq |x| \geq 0 \\ \frac{3\pi}{4} + \arctan(x'/x) \text{ if } -x \geq |x'| \geq 0 \\ \frac{3\pi}{4} + \arctan(x'/x) \text{ if } -x' \geq |x| \geq 0 \\ \frac{7\pi}{4} + \arctan(x'/x) \text{ if } x \geq |x'| \geq 0 \end{cases}$$

(Harris, Marsh, DP, Prokudin, Putnam, Rein, Schlegel PLB **869** (2025))

$$\boldsymbol{a^q} = (a_2^q, a_4^q, a_6^q; a_3^q, a_5^q, a_7^q) \qquad \boldsymbol{b^q} = (b_1^q, b_2^q, b_3^q, b_4^q, b_5^q, b_6^q)$$

There is no experimental data to constrain these parameters, but lattice QCD has calculated the $d_2$ matrix element for u and d quarks:

$$d_2^q = -\int_{-1}^{1} dx \int_{-1}^{1} dx'\, F_{FT}^q(x,x')$$

$$d_2^u = 0.026(4)(13)$$
$$d_2^d = -0.0086(26)(146)$$

} Lattice QCD results at $\mu$ = 2 GeV from RQCD Collaboration (2022)

These values can be used to constrain $a_2$ once values are chosen for $a_{4,6,3,5,7}$ :

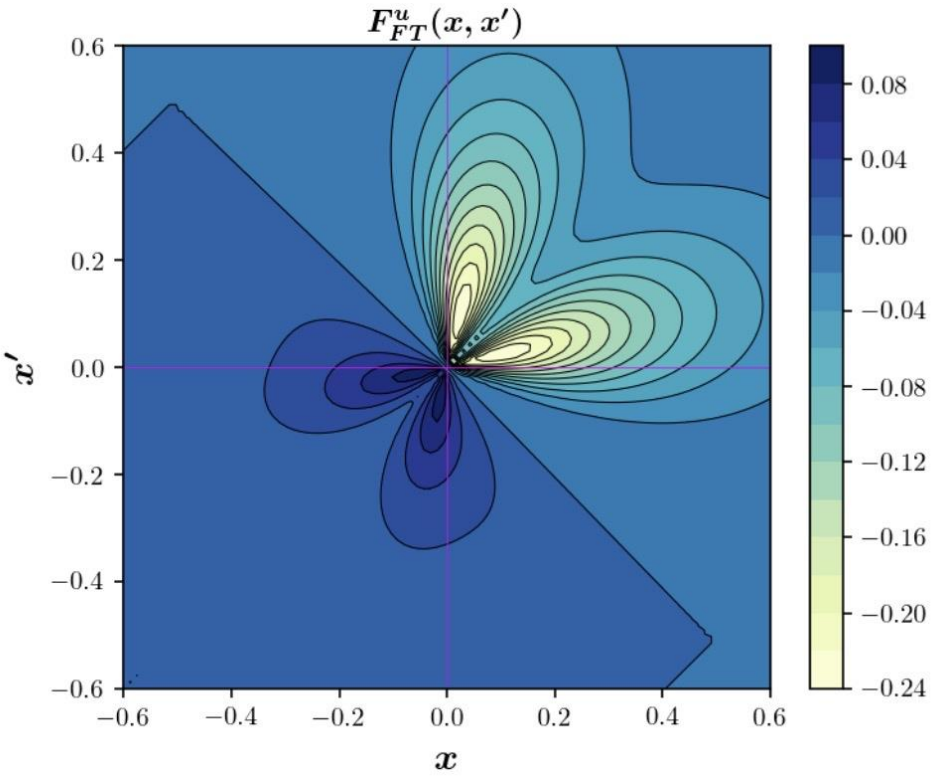
$$a_2^q = (d_2^q - (A_0^q + A_4^q a_4^q + A_6^q a_6^q + A_3^q a_3^q + A_5^q a_5^q + A_7^q a_7^q))/A_2^q$$

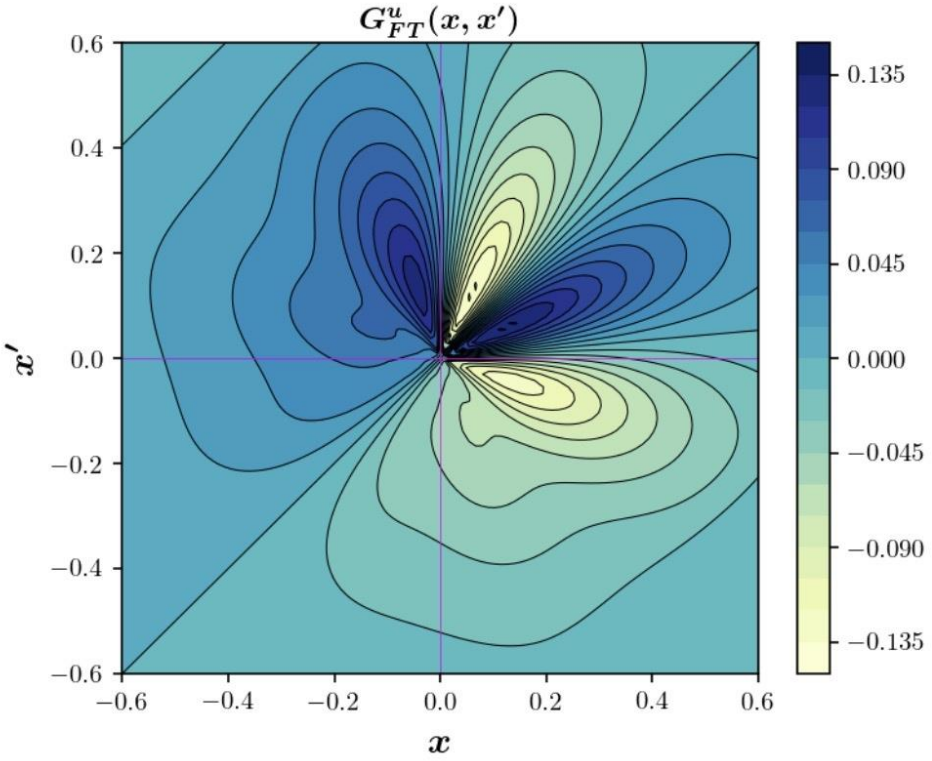
where $A_0^q \equiv -\int_{-1}^{1} dx \int_{-1}^{1} dx'\, F_{FT}^q(x,x')\Big|_{\boldsymbol{a^q}=0}$, $\quad A_i^q \equiv -A_0^q - \int_{-1}^{1} dx \int_{-1}^{1} dx'\, F_{FT}^q(x,x')\Big|_{a_i^q=1, a_{j\neq i}^q=0}$

Note that we also fix $b_1 = -a_2$.

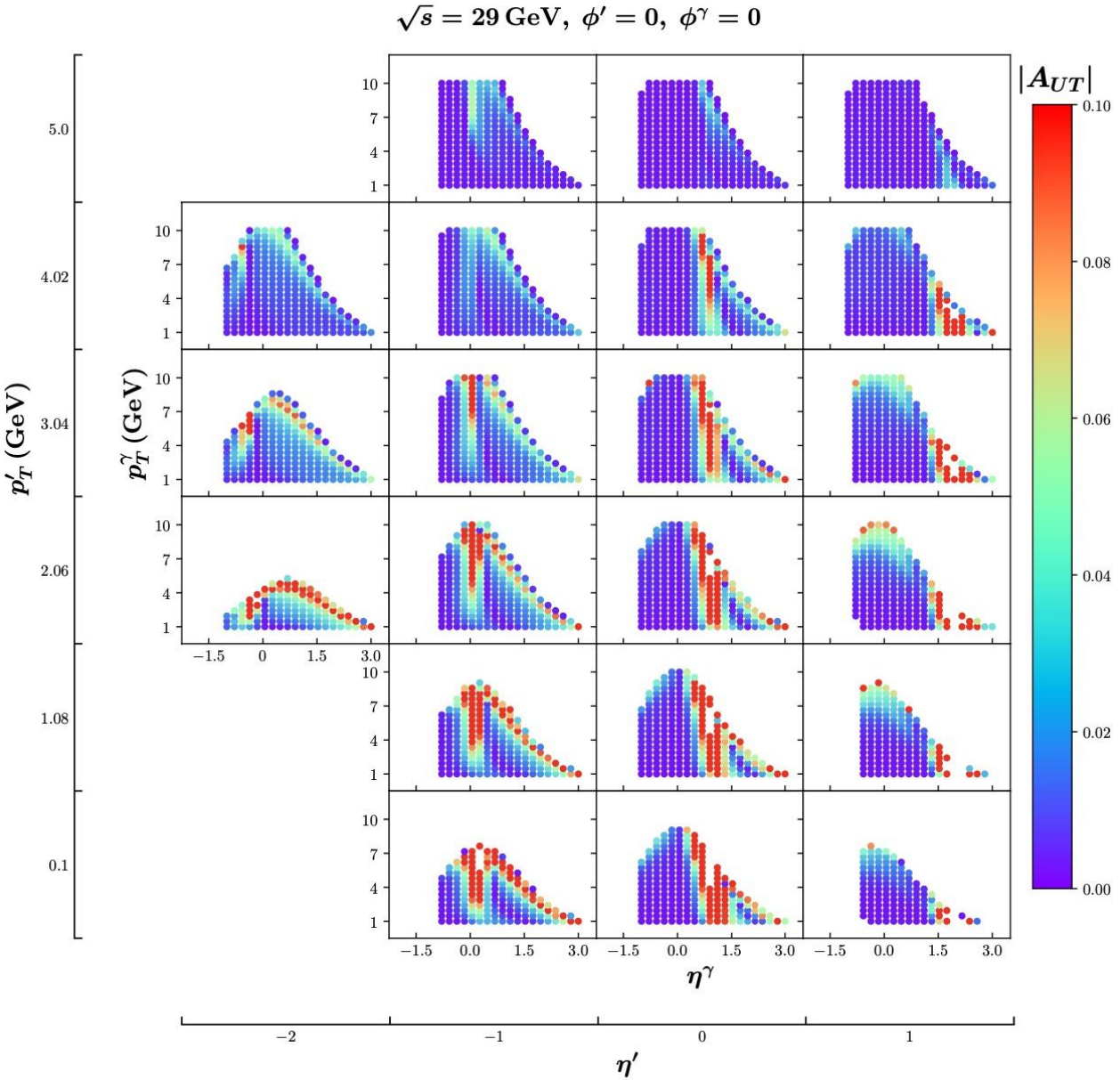
(Harris, Marsh, DP, Prokudin, Putnam, Rein, Schlegel PLB **869** (2025))

$$\boldsymbol{a^u} = (1.1585, -\tfrac{2}{3}, -\tfrac{2}{3}; -\tfrac{1}{3}, -1, -\tfrac{1}{3}), \quad \boldsymbol{a^d} = (-0.6658, \tfrac{2}{3}, \tfrac{2}{3}; \tfrac{1}{3}, 1, \tfrac{1}{3})$$




(Harris, Marsh, DP, Prokudin, Putnam, Rein, Schlegel PLB **869** (2025))



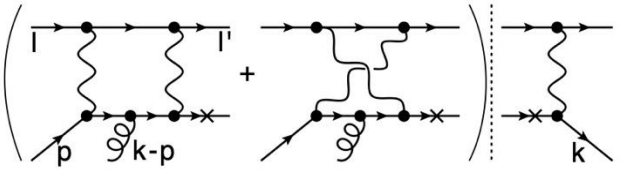

(Harris, Marsh, DP, Prokudin, Putnam, Rein, Schlegel PLB **869** (2025))

- At the low-energy Electron-Ion Collider configuration ($\sqrt{S} = 29$ GeV), the asymmetry has the largest values (~10% or more) when the following kinematic criteria are satisfied:
  - ✓ outgoing electron is at mid or backward rapidity
  - ✓ photon is at mid to forward rapidity
  - ✓ smaller electron transverse momentum
  - ✓ higher photon transverse momentum
  - ✓ electron and photon are produced at azimuthal angles of 0 or $\pi$

$$e\,p^{\uparrow} \to e\,X$$

$$d\sigma_{UT}^{DIS} = -|S_T|\sin(\phi_S)\frac{4\alpha_{EM}^3}{yQ^4}\frac{M}{Q}\frac{x_B y}{\sqrt{1-y}}$$

qgq terms

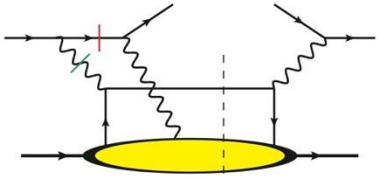



$$\times \sum_q \left[ e_q^3 \int_0^1 dx \left( \hat{C}_+ F_{FT}^q(x_B, x) + \hat{C}_- G_{FT}^q(x_B, x) \right) \right.$$

qvq term

$$\left. + (1-y)\frac{e_q^3 m_q}{M} h_1^q(x_B) + \frac{2-y}{2y} e_q^2 (1 - x_B \frac{d}{dx_B}) F_{FT}^{\gamma,q}(x_B, x_B) \right]$$

quark-mass term

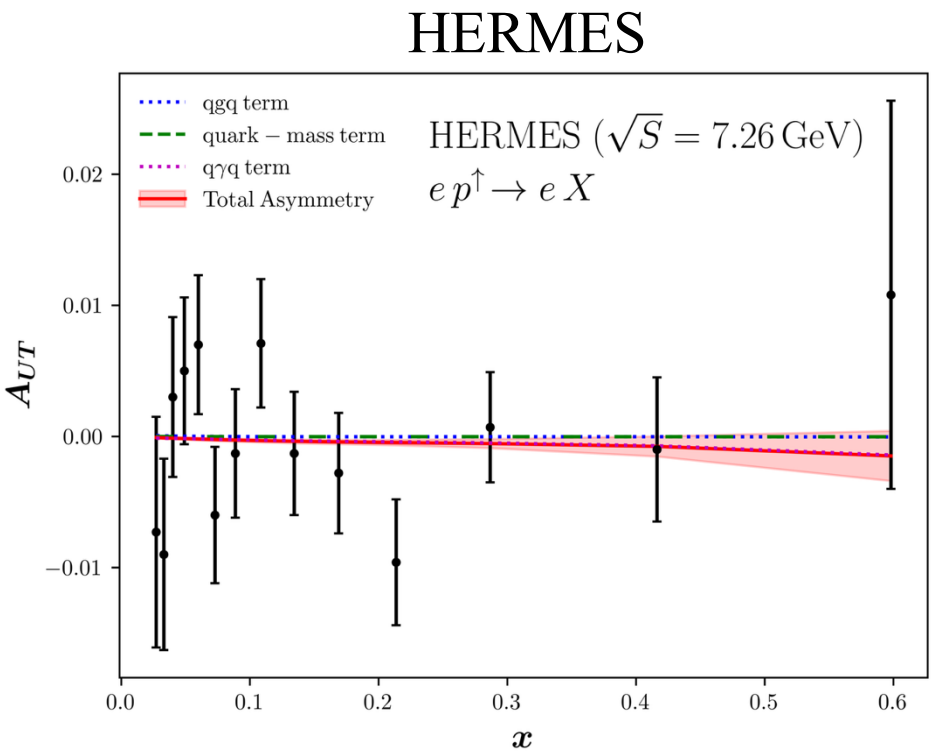


A. Metz, et al. (2012); M. Schlegel (2013)

$$F_{FT}^{\gamma,u/p}(x,x) = \frac{\alpha_{em}}{3\pi C_F \alpha_s} f_{1T}^{\perp(1),u/p}(x)\,, \quad F_{FT}^{\gamma,d/p}(x,x) = \frac{4\alpha_{em}}{3\pi C_F \alpha_s} f_{1T}^{\perp(1),d/p}(x)$$

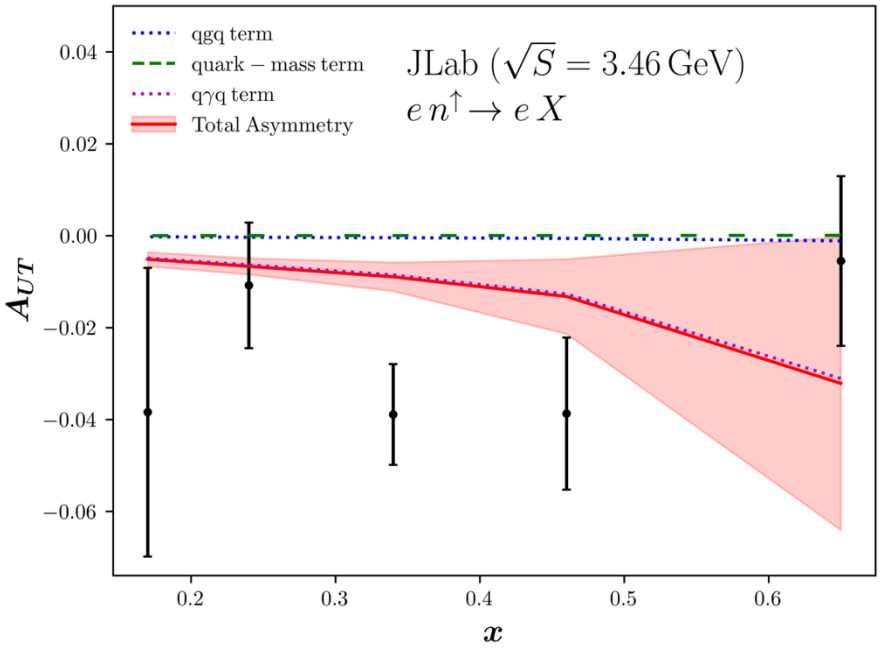
$$F_{FT}^{\gamma,u/n}(x,x) = -\frac{2\alpha_{em}}{3\pi C_F \alpha_s} f_{1T}^{\perp(1),u/n}(x)\,, \quad F_{FT}^{\gamma,d/n}(x,x) = \frac{\alpha_{em}}{3\pi C_F \alpha_s} f_{1T}^{\perp(1),d/n}(x)$$

- Predicted asymmetry consistent with HERMES (2010) measurement of a zero $A_{UT}$
- Theoretical calculation does go negative somewhat near higher momentum fractions
- Still within range of errors of the measurement
- Quark-photon-quark term seems to be main cause of the asymmetry



- The theoretical result when compared to JLab Hall A (2015) slightly undershoot the data at intermediate *x*
- Overall, it is in line with the magnitude and sign of the asymmetry

JLab6



# Summary and Outlook

- Twist-3 spin asymmetries in electron-nucleon collisions are a fruitful avenue to probe quark-gluon-quark correlations in hadrons
- We've made numerical predictions for a variety of such observables using reasonable models for twist-3 PDFs/FFs
- Both at current and future facilities, there are encouraging prospects to measure sizeable asymmetries for various spin configurations and final states