The $g_T(x)$ contribution to single spin asymmetry in SIDIS

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Benić, Hatta, Li, AK Phys. Rev. D 104 (2021) 9, 094027

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HRZZ
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Single-Spin Asymmetries

- Collisions involving transversely polarised hadrons - left-right asymmetry in particle production
- Observed in various *pp* and *ep* processes since the 70s

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

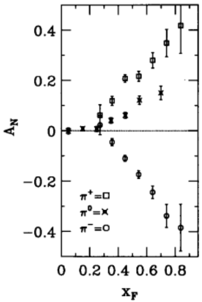
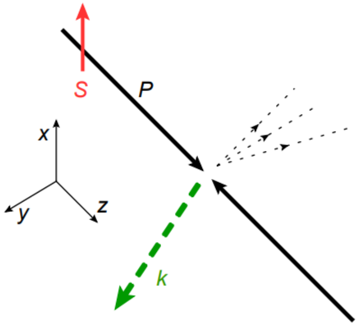


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.



Single-Spin Asymmetries

- QCD is time reversal invariant
- SSAs are T-odd:

$$A_N \propto S \cdot (P \times k)$$

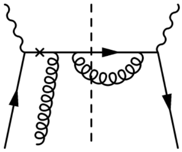
An phase (interference) is required!

- Quest for theoretical description of SSAs is a quest for sources of a complex phase

Theoretical descrption of SSAs

- In a collinear factorization framework, SSAs have been described in terms of three-parton correlation functions, i.e twist-3 parton distribution functions (ETQS) functions and twist-3 fragmentation functions

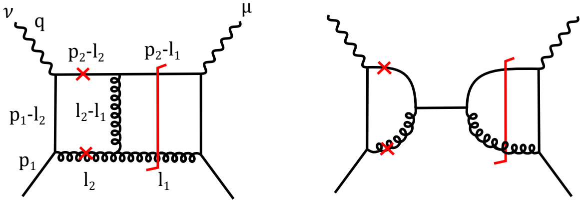
Efremov, Teryaev, Sov. J. Nucl. Phys. 36, 140 (1982)
Qiu, Sterman, Phys. Rev. D 59, 014004 (1999)
Yuan, Zhou Phys. Rev. Lett. 103 (2009) 052001
Kang, Yuan, Zhou Phys. Lett. B 691 (2010) 243
Kanazawa, Koike Phys. Rev. D 88 (2013) 074022



- Eg., above hard part can be convolved with ETQS distribution. Complex phase arises when internal propagator goes on-shell. $1/(k^2 + i\epsilon) = \mathrm{PV}(1/k^2) + i\pi\delta(k^2)$
- Twist-3 distributions not very well known.

Theoretical descrption of SSAs

SSA from $g_T(x)$:



- In an earlier work, my collaborators and D.J. Yang had shown that the twist-3 quark distribution $g_T(x)$ can lead to SSA in SIDIS at the two-loop level

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- Imaginary phase arises from when certain certain internal propagators are cut.
- g_T is a chiral-even transverse-spin dependent contribution to the quark-quark correlator

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS|\bar{\psi}(0)\psi(\lambda n)|PS\rangle = \frac{M_N}{2}\gamma_5 \$_T g_T(x) + \ldots$$

SSAs at two loops

- Schematically,

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto \frac{d\Delta\sigma}{dP_{hT}} \sim g_T(x) \otimes H^{(2)} \otimes D_1(z)$$

- Wandzura-Wilczek relation:

$$g_T(x) = \int_x^1 \frac{dx'}{x'} \Delta q(x') + (\text{genuine twist-3})$$

- In effect,

$$\frac{d\Delta\sigma}{dP_{hT}} \sim g_T(x) \otimes H^{(2)} \otimes D_1(z) \sim \Delta q(x) \otimes H^{(2)} \otimes D_1(z)$$

- SSA completely determined in terms of well understood twist-2 distributions!

This work

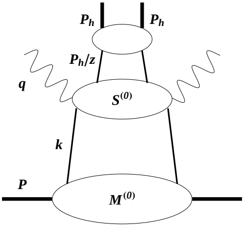
In this work we,

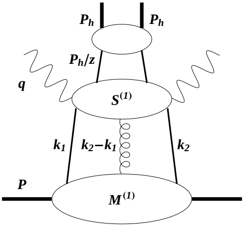
1. extend the analysis to include gluon-initiated contribution from the twist-3 distribution $\mathcal{G}_{3T}$, which is the gluonic counterpart of g_T.
   - In analogy with the quark case,

$$\frac{d\Delta\sigma}{dP_{hT}} \sim \mathcal{G}_{3T}(x) \otimes H_g^{(2)} \otimes D_1(z) \sim \Delta G(x) \otimes H_g^{(2)} \otimes D_1(z)$$

2. present numerical estimates for asymmetry in SIDIS through these mechanisms at COMPASS and EIC.

Why g_T at two loops?





- g_T appears in the hadronic tensor through the collinear expansion of the two-parton correlator $M^{(0)}$.

$$M^{(0)} \sim \not{p} f(x) + M_N \not{p}\gamma_5 (S\cdot n)\Delta q(x) + M_N \not{S}_T \gamma_5 g_T(x) + ...$$

- g_T appears in correlator with γ_5. Traces involving γ_5 produce a factor of $i \implies g_T$ recieves no contributions from hard part $S^{(0)}$ at the Born level

Eguchi, Koike, Tanaka Nucl. Phys. B 763, 198, (2007)

- Can receive non-zero contributions beyond Born level.

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Gluon initiated contribution $\mathcal{G}_{3T}$

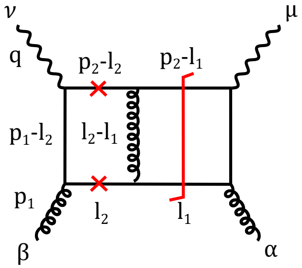
Two-gluon correlator in a polarised proton,

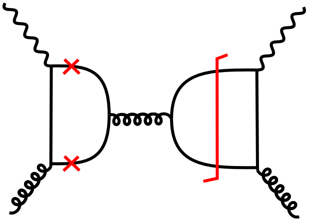
$$M^{(0)\alpha\beta} \sim \langle PS_T | F^{n\alpha}\ W\ F^{n\beta} | PS_T \rangle \quad \sim \quad xG(x) g_T^{\alpha\beta} + iM_N x \Delta G(x)(S\cdot n)\epsilon^{nr\alpha\beta} + iM_N x \mathcal{G}_{3T}(x) \epsilon^{n\alpha\beta S_\perp}$$

Ji, Phys. Lett. B 289, 137 (1992)
Hatta, Tanaka, Yoshida, JHEP 02, 003 (2013)

- $\mathcal{G}_{3T}$ - transverse spin dependent contribution to the two-gluon correlator.
- WW approximation

$$\mathcal{G}_{3T}(x) \quad = \quad \frac{1}{2}\int_x^1 \frac{dx'}{x'}\Delta G(x') + \text{(genuine twist three)}$$



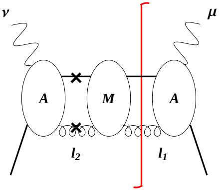


Calculation of hard part

Asymmetry can be written schematically as,

$$A_{UT}^{\sin(\alpha\phi_h+\beta\phi_S)} \sim \frac{\alpha_s^2\ (xg_T(x) \text{ or } x\mathcal{G}_{3T}(x)) \otimes H^{(2)} \otimes D_1(z)}{\alpha_s\ q(x) \otimes H^{(1)} \otimes D_1(z)} \sim \alpha_s \frac{x\Delta q \text{ or } x\Delta G}{q(x)}$$

All contributions to $H^{(2)}$ have a generic 'AMA' structure:



- Each blob represents 2-2 scattering
- Phase arises from cutting internal lines, i.e., regions of loop momentum l_2 where the two lines go on-shell.
- Potential divergence when l_2 gluon is collinear to proton cancels out between $S_{\mu\nu}^{(0)}$ and $\frac{dS_{\mu\nu}^{(0)}}{dk_T^\alpha}$

Calculation of hard part

$$\frac{d^6\Delta\sigma}{dx_B\, dQ^2\, dz_f\, dq_T^2\, d\phi\, d\chi} = \frac{\alpha_{\rm em}^2 \alpha_S^2 M_N}{16\pi^2 x_B^2 S_{ep}^2 Q^2} \sum_k \mathcal{A}_k \mathcal{S}_k \int \frac{dx}{x} \int \frac{dz}{z}$$
$$\times\, \delta\left(\frac{q_T^2}{Q^2} - \left(1 - \frac{1}{\hat{x}}\right)\left(1 - \frac{1}{\hat{z}}\right)\right)$$
$$\times \sum_f e_f^2 \left[D_f(z) x^2 \frac{\partial g_{Tf}(x)}{\partial x} \Delta\hat{\sigma}_{Dk}^{qq} + D_f(z) x g_{Tf}(x) \Delta\hat{\sigma}_k^{qq} + (\text{qg channel}) + (\text{gq channel})\right]$$

$$\Delta\hat{\sigma}_{D8}^{qq} = \frac{(N_c^2-1)\,\hat{x}\hat{z}}{2N_c^2 Q(1-\hat{z})^2}\left[(1-\hat{z})\left(1-\hat{x}+\hat{z}-3\hat{x}\hat{z}+N_c^2(1-\hat{x}-\hat{z}+3\hat{x}\hat{z})\right)+2(1-2\hat{x})\,\hat{z}\log(\hat{z})\right],$$

$$\Delta\hat{\sigma}_{D9}^{qq} = \frac{(N_c^2-1)(1-\hat{x})\,\hat{x}\hat{z}}{2N_c^2 q_T(1-\hat{z})^2}\left[(1-\hat{z})\left(3N_c^2(1-\hat{z})+3\hat{z}-1\right)-2(1-2\hat{z})\log(\hat{z})\right],$$

$$\Delta\hat{\sigma}_{1}^{qq} = \frac{N_c^2-1}{2N_c^2 q_T(1-\hat{z})\,\hat{z}}\Big[(1-\hat{z})\big(\hat{z}\hat{x}(\hat{x}(3+10\hat{z})-3(1+\hat{z}))-1\big)$$
$$+N_c^2\hat{z}\left(\hat{x}^2(3+2\hat{z}(5\hat{z}-6))-1-3\hat{x}(1-\hat{z})^2\right)+6\hat{x}(2\hat{x}-1)\,\hat{z}^2\log(\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{2}^{qq} = \frac{(N_c^2-1)\,\hat{x}}{{N_c}^2 q_T(1-\hat{z})}\left[(1-\hat{z})\left((1+N_c^2)(-1+\hat{x})+\left(N_c^2-1\right)(1-3\hat{x})\,\hat{z}\right)+2(2\hat{x}-1)\,\hat{z}\log(\hat{z})\right],$$

$$\Delta\hat{\sigma}_{3}^{qq} = \frac{(N_c^2-1)\,\hat{x}}{4N_c^2 Q(1-\hat{x})(1-\hat{z})^2}\Big[(1-\hat{z})\Big\{(1-\hat{x})\left(5\hat{x}+N_c^2(2-11\hat{x})\right)\hat{z}-\left(1+N_c^2\right)(1-\hat{x})^2$$
$$-\left(N_c^2-1\right)(1+\hat{x}(14\hat{x}-13))\,\hat{z}^2\Big\}-2\hat{z}(1-\hat{z}-\hat{x}(5-4\hat{x}-8(1-\hat{x})\hat{z}))\log(\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{4}^{qq} = \frac{(N_c^2-1)\,\hat{x}}{2N_c^2 q_T(1-\hat{z})^2}\Big[(1-\hat{z})\Big\{3(1-\hat{z})^2+\hat{x}(-3+(5-4\hat{z})\hat{z})$$
$$-N_c^2(1-\hat{z})(2-3\hat{z}+\hat{x}(-2+4\hat{z}))\Big\}-2\left(\hat{x}-(1-\hat{z})^2-2\hat{x}(1-\hat{z})\hat{z}\right)\log(\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{8}^{qq} = \frac{(N_c^2-1)\hat{x}}{4N_c^2 Q(1-\hat{x})(1-\hat{z})^2}\Big[\left(1+N_c^2\right)(1-\hat{x})^2+(1-\hat{x})\left(5-10\hat{x}+N_c^2(6\hat{x}-5)\right)\hat{z}$$
$$-\left(9+\hat{x}(15\hat{x}-26)-N_c^2(7+9(\hat{x}-2)\hat{x})\right)\hat{z}^2$$
$$-\left(N_c^2-1\right)(3+\hat{x}(4\hat{x}-9))\,\hat{z}^3-2\hat{z}(\hat{x}(7-4\hat{x}-2\hat{z})+\hat{z}-3)\log(\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{D8}^{qg} = \frac{(N_c^2-1)\,\hat{x}}{2N_c^2 Q\hat{z}}\left[\hat{z}\left(-2+\hat{z}-N_c^2\hat{z}+\hat{x}\left(4-3\hat{z}+N_c^2(-2+3\hat{z})\right)\right)-2(1-2\hat{x})(1-\hat{z})\log(1-\hat{z})\right],$$

$$\Delta\hat{\sigma}_{D9}^{qg} = \frac{(N_c^2-1)(1-\hat{x})\,\hat{x}(1-\hat{z})}{2{N_c}^2 q_T\hat{z}^2}\left[\hat{z}\left(2+3\left(N_c^2-1\right)\hat{z}\right)+(2-4\hat{z})\log(1-\hat{z})\right],$$

$$\Delta\hat{\sigma}_{1}^{qg} = \frac{N_c^2-1}{2N_c^2 q_T\hat{z}^2}\Big[\hat{z}\left(1+\hat{x}^2\left(-13+23\hat{z}-10\hat{z}^2\right)+3\hat{x}\left(2-3\hat{z}+\hat{z}^2\right)\right)$$
$$-N_c^2(1-\hat{z})\left(-1-3\hat{x}\hat{z}^2+\hat{x}^2\left(1-8\hat{z}+10\hat{z}^2\right)\right)-6\hat{x}(-1+2\hat{x})(1-\hat{z})^2\log(1-\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{2}^{qg} = \frac{(N_c^2-1)\,\hat{x}(1-\hat{z})}{N_c^2 q_T\hat{z}^2}\left[\hat{z}\Big(2-\hat{z}+N_c^2\hat{z}-\hat{x}\left(4-3\hat{z}+{N_c}^2(-2+3\hat{z})\right)\Big)+2(1-2\hat{x})(1-\hat{z})\log(1-\hat{z})\right],$$

$$\Delta\hat{\sigma}_{3}^{qg} = -\frac{(N_c^2-1)\,\hat{x}}{4{N_c}^2 Q(1-\hat{x})\,\hat{z}^2}\Big[\hat{z}\Big\{(-1+\hat{z})\left(2+\left(N_c^2-1\right)\hat{z}\right)+\hat{x}\left(10-24\hat{z}+13\hat{z}^2+N_c^2\left(-4+16\hat{z}-13\hat{z}^2\right)\right)$$
$$+\hat{x}^2\left(-8+23\hat{z}-14\hat{z}^2+N_c^2\left(4-17\hat{z}+14\hat{z}^2\right)\right)\Big\}$$
$$+2(1-\hat{z})\left(-1+\hat{x}(5-8\hat{z})+\hat{z}+\hat{x}^2(-4+8\hat{z})\right)\log(1-\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{4}^{qg} = -\frac{(N_c^2-1)\,\hat{x}(1-\hat{z})}{2{N_c}^2 q_T\hat{z}^3}\Big[\hat{z}\left(2+\left(4N_c^2-3\right)\hat{z}-3\left(N_c^2-1\right)\hat{z}^2+\hat{x}\left(-2+\left(3-2{N_c}^2\right)\hat{z}+4\left(N_c^2-1\right)\hat{z}^2\right)\right)$$
$$+2\left((1-\hat{z})^2-\hat{x}\left(1-2\hat{z}+2\hat{z}^2\right)\right)\log(1-\hat{z})\Big],$$

$$\Delta\hat{\sigma}_{8}^{qg} = \frac{(N_c^2-1)\,\hat{x}}{4N_c^2 Q(1-\hat{x})\,\hat{z}^2}\Big[\hat{z}\Big\{6-\left(1+{N_c}^2\right)\hat{z}+3\left(N_c^2-1\right)\hat{z}^2+\hat{x}\left(-22+8\hat{z}+9\hat{z}^2+{N_c}^2\left(4-9\hat{z}^2\right)\right)$$
$$+\hat{x}^2\left(16-9\hat{z}-4\hat{z}^2+N_c^2\left(-4+3\hat{z}+4\hat{z}^2\right)\right)\Big\}+2(1-\hat{z})\left(3+8\hat{x}^2+\hat{z}-\hat{x}(11+2\hat{z})\right)\log(1-\hat{z})\Big],$$

Numerical results

$$A_{UT}^{\sin(\alpha\phi_h+\beta\phi_S)} = \frac{2\int_0^{2\pi} d\phi_h d\phi_S \sin(\alpha\phi_h+\beta\phi_S)\left[d\sigma(\phi_h,\phi_S) - d\sigma(\phi_h,\phi_S+\pi)\right]}{\int_0^{2\pi} d\phi_h d\phi_S \left[d\sigma(\phi_h,\phi_S) + d\sigma(\phi_h,\phi_S+\pi)\right]} ,$$

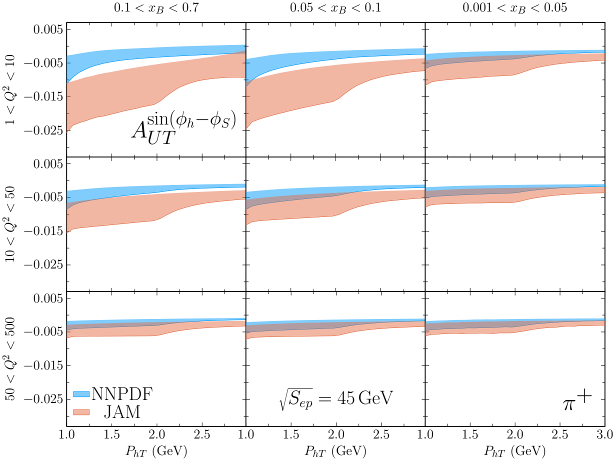
- Five independent moments including Sivers $A_{UT}^{\sin(\phi_h-\phi_S)}$ and Collins $A_{UT}^{\sin(\phi_h+\phi_S)}$
- Sivers and Collins asymmetry NOT from Sivers and Collins functions.
- $g_T(x)$ and $\mathcal{G}_{3T}$ from helicity distributions using the WW approximation.

$$g_T(x) = \int_x^1 \frac{dx'}{x'}\Delta q(x'), \qquad \mathcal{G}_{3T}(x) = \int_x^1 \frac{dx'}{x'}\Delta G(x')$$

- We used the latest fits of helicity distributions from NNPDF and JAM.
  Nocera, Ball, Forte, Ridolfi, and Rojo, Nucl. Phys. B 887, 276 (2014)
  Ethier, Sato, and Melnitchouk, Phys. Rev. Lett. 119, 132001 (2017)

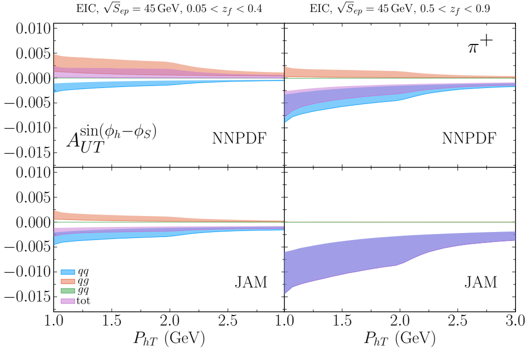
$$A_{UT}^{\sin(\alpha\phi_h+\beta\phi_S)} \sim \frac{\alpha_s^2\ (xg_T(x) \text{ or } x\mathcal{G}_{3T}(x)) \otimes H^{(2)} \otimes D_1(z)}{\alpha_s\ q(x) \otimes H^{(1)} \otimes D_1(z)} \sim \alpha_s \frac{x\Delta q \text{ or } x\Delta G}{q(x)}$$

Sivers asymmetry at EIC



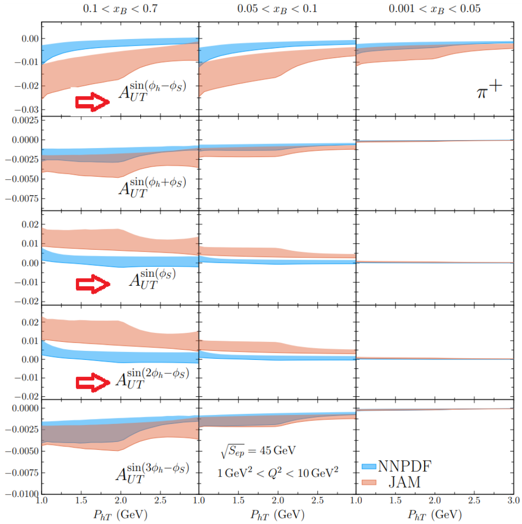
- Sivers asymmetry up to 2% with JAM at moderate-to-large x and low Q^2.
- Decreases at low-x.

Channel breakdown



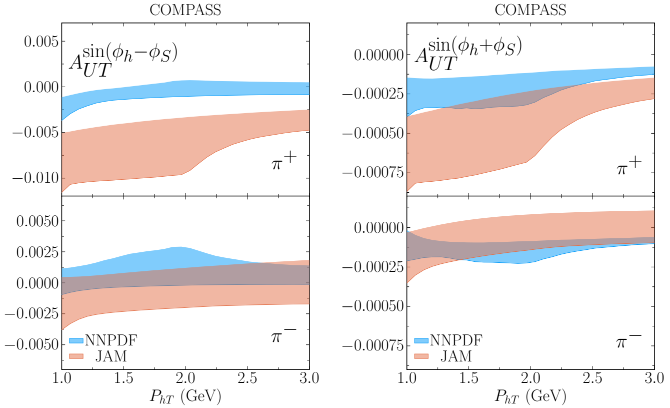
- cancellation between qq and qg channels
- qg channel kinematically suppressed at large z_f — sign change in asymmetry with NNPDF
- JAM has smaller $g \to \pi^+$ FF $\implies$ less cancellations
- Negligible contribution from gluon-initiated (gq) channel (x^2 suppression).

All A_{UT} moments at EIC



- $\sin(\phi_h - \phi_S)$ (Sivers), $\sin(\phi_S)$ and $\sin(2\phi_h - \phi_S)$ moments are at percent level. Collins negligible.

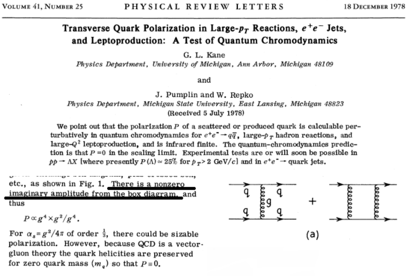
Sivers and Collins at COMPASS



- Sivers at percent level for π^+ with JAM. Collins negligible.
- Only available datapoint from COMPASS at $P_{hT} \approx 1.5$ shows positive Sivers asymmetry ($\sim 2.5\%$) but with large errors.

Adolph et al., Phys. Lett. B744, 250 (2015)

Comparison with the KPR estimate



VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

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(Received 5 July 1978)

We point out that the polarization P of a scattered or produced quark is calculable perturbatively in quantum chromodynamics for $e^+e^- \to q\bar{q}$, large-p_T hadron reactions, and large-Q^2 leptoproduction, and is infrared finite. The quantum-chromodynamics prediction is that $P=0$ in the scaling limit. Experimental tests are or will soon be possible in $pp \to \Lambda X$ [where presently $P(\Lambda) \simeq 25\%$ for $p_T > 2$ GeV/c] and in $e^+e^- \to$ quark jets.

etc., as shown in Fig. 1. There is a nonzero imaginary amplitude from the box diagram, and thus

$P \propto g^4 \times g^2/g^4.$

For $\alpha_s = g^2/4\pi$ of order $\frac{1}{3}$, there could be sizable polarization. However, because QCD is a vector-gluon theory the quark helicities are preserved for zero quark mass (m_q) so that $P \equiv 0$.

- Kane, Pumplin and Repko (1978) presented the first parametric estimate of SSA in pQCD as

$$A_N \sim \alpha_s \frac{m_q}{P_{hT}}$$

- expected to vanish since $m_q \to 0$
- but in this mechanism,

$$A_N \sim \alpha_s \frac{x M_N}{P_{hT}}$$

Conclusions

Presented numerical results for g_T contribution to SSA at two loops.

- Asymmetry can be calculated entirely in terms of well-known twist-2 distributions.
- Upto 2% Sivers asymmetry at EIC at low-Q^2 with $P_{hT} > 1$.
- Asymmetry suppressed at small-x.
- Two-loop mechanism needs to be accounted for when constraining other mechanisms (ETQS, twist-3 fragmentation etc.).

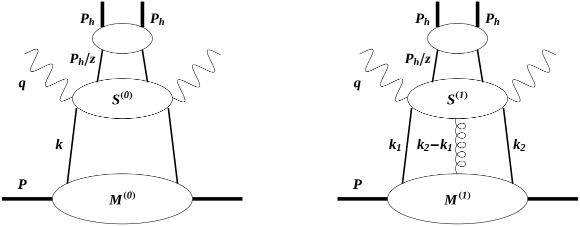
Work in progress...

- Calculating similar contributions for SSA in pp
- Open-charm in SIDIS - isolates the $\mathcal{G}_{3T}$ contribution.

Appendix

g_T contribution to SSA

Hadronic tensor in SIDIS



- $W^{\mu\nu} = \int_z \frac{dz}{z^2} D(z) w^{\mu\nu}$,

$$w_{\mu\nu} = \int_k M^{(0)}(k) S^{(0)}_{\mu\nu}(k) + \int_{k_1}\int_{k_2} M^{(1)}_{\sigma}(k_1,k_2) S^{(1)\sigma}_{\mu\nu}(k_1,k_2)$$

- Need to include twist-3 distributions $\Longrightarrow$ consider hadronic tensor upto three parton correlator.
- $M^{(0)}_{ij} \sim \langle PS_T|\bar{\psi}_j \psi_i|PS_T\rangle$
- $M^{(1)\sigma}_{ij} \sim \langle PS_T|\bar{\psi}_j g A^{\sigma} \psi_i|PS_T\rangle$

g_T contribution to SSA

- Hard part - expand in collinear limit: $k^\mu = xP^\mu + k_T^\mu$

$$S_{\mu\nu}^{(0)}(k) = S_{\mu\nu}^{(0)}(xP) + k_T^\alpha \frac{dS_{\mu\nu}^{(0)}}{dk_T^\alpha}(xP)$$

- Soft part

$$M^{(0)} \sim \not{p} f(x) + M_N \not{p}\gamma_5 (S\cdot n)\Delta q(x) + M_N \not{S}_T \gamma_5 g_T(x)$$
$$+\text{transversity and higher twist terms...}$$

- g_T appears in correlator with γ_5. Traces involving γ_5 produce a factor of i.
- Hence g_T recieves no contributions from $S^{(0)}$ at the Born level.

  Eguchi, Koike, Tanaka Nucl. Phys. B 763, 198, (2007)

- Can receive non-zero contributions beyond Born level.

  Benić, Hatta, Li, Yang Phys. Rev. D 100 (2019) 9, 094027

g_T contribution to SSA

All order and gauge invariant result:

$$\begin{aligned} w_{\mu\nu} &= \frac{M_N}{2}\int dx g_T(x)\mathrm{Tr}\left[\gamma_5 \not{S}_T S^{(0)}_{\mu\nu}(xP)\right] \\ &- \frac{M_N}{4}\int dx \tilde{g}(x)\mathrm{Tr}\left[\gamma_5 \not{P} S_T^\alpha \left.\frac{\partial S^{(0)}_{\mu\nu}(k)}{\partial k_T^\alpha}\right|_{k=xP}\right] \\ &+ \frac{iM_N}{4}\int dx_1 dx_2 \mathrm{Tr}\left[\left(\not{P}\epsilon^{\alpha P n S_T}\frac{G_F(x_1,x_2)}{x_1-x_2} + i\gamma_5 \not{P} S_T^\alpha \frac{\tilde{G}_F(x_1,x_2)}{x_1-x_2}\right) S^{(1)}_{\mu\nu\alpha}(x_1P, x_2P)\right] \end{aligned}$$

- $\tilde{g}(x)$ is another "kinematic" twist-3 distribution - first moment of worm-gear TMD g_{1T} (talk by Shohini Bhattacharya)

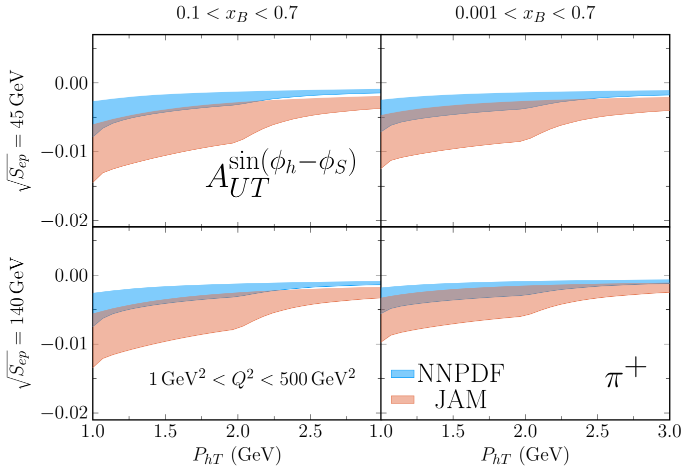
$$g_T(x) + \frac{\tilde{g}(x)}{2x} = \int dx' \frac{G_F(x,x') + \tilde{G}_F(x,x')}{x-x'}$$

Eguchi, Koike, Tanaka, Nucl. Phys. B 763, 198 (2007)

Neglecting explicit twist-3 contributions (WW approximation),

$$w_{\mu\nu} \approx \frac{M_N}{2}\int dx g_T(x) S_T^\alpha \left(\frac{\partial}{\partial k_T^\alpha}\mathrm{Tr}[\gamma_5 \not{k} S^{(0)}_{\mu\nu}(k)]\right)_{k=xP}$$

Energy dependence



- Percent level Sivers contribution (JAM) at highest EIC energy.