Transverse single spin asymmetry from $g_T(x)$ in SIDIS and DY

Sanjin Benić (University of Zagreb)

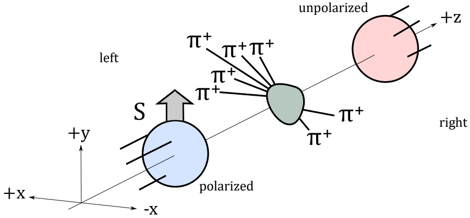
SB, Hatta, Li, Yang Phys. Rev. D 100 (2019) 9, 094027
SB, Hatta, Kaushik, Li Phys. Rev. D 104 (2021) 9, 094027
SB, Hatta, Kaushik, Li, in preparation

REVESTRUCTURE workshop, Zagreb, Croatia, 10-12 July 2023

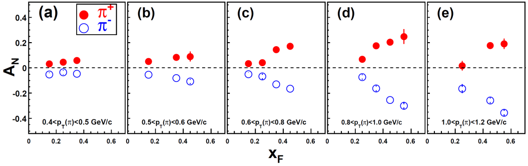
Croatian Science Foundation

Transverse single spin asymmetry

- in $pp^{\uparrow} \to hX$ this is a left-right asymmetry in hadron production



$$A_N \equiv \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} \sim \sin(\phi_h - \phi_S)$$



- u-quark favors left, d-quark favors right

BRAHMS, Phys. Rev. Lett. 101 (2008) 042001

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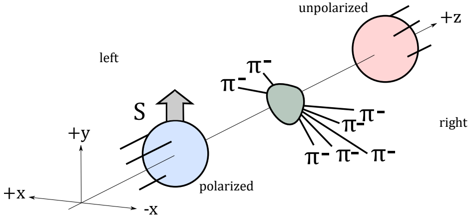

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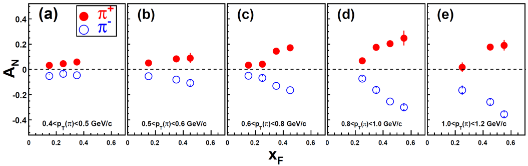

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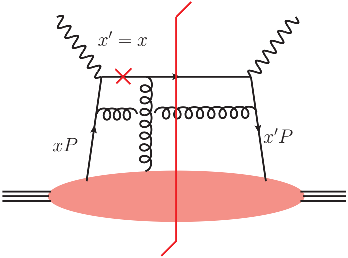
BRAHMS, Phys. Rev. Lett. 101 (2008) 042001

Origin of SSA?

- $A_N \sim \boldsymbol{P} \cdot (\boldsymbol{P}_h \times \boldsymbol{S})$ - naively T-odd
  $\rightarrow$ SSA sensitive to the phase of the amplitude
  $\rightarrow$ interference diagrams (ex. in SIDIS)



- target helicity flip

$$A_N \sim |\mathcal{M}_\uparrow|^2 - |\mathcal{M}_\downarrow|^2 \sim \mathcal{M}_+^* \mathcal{M}_-$$

$\rightarrow$ supplied by the extra gluon attaching to the target

- need twist-3 quantities such as quark-gluon-quark correlations

Efremov, Teryaev, Sov. J. Nucl. Phys. 36, 140 (1982)
Qiu, Sterman, Phys. Rev. D 59, 014004 (1999)

Origin of the phase?

- in collinear framework

ETQS functions: soft gluonic pole, soft fermionic pole, hard pole...

(TMD: closely related to the Sivers function)
Efremov, Teryaev, Sov. J. Nucl. Phys. **36**, 140 (1982)
Qiu, Sterman, Phys. Rev. D **59**, 014004 (1999)

twist-3 fragmentation functions

(TMD: closely related to the Collins function)
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

$\rightarrow$ require new PDFs and/or FFs..

- beyond the collinear framework: Odderon

Kovchegov, Sievert, Phys. Rev. D **86**, 034028 (2012)
Benić, Horvatić, Kaushik, Vivoda, Phys. Rev. D **106** (2022) 11, 114025
Vivoda, Tuesday, July 11, 11:50

SIDIS vs *pp*

- in *pp* both ETQS and twist-3 FFs contribute to A_N
- in SIDIS ETQS and twist-3 FFs contribute to different structure functions

$$F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp(1)}(x) \otimes D_1(z) \qquad \text{(Sivers)}$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1(x) \otimes H_1^{\perp(1)}(z) \qquad \text{(Collins)}$$

$\rightarrow$ opportunity to study ETQS and twist-3 FFs separately

- SIDIS measurements by JLab, HERMES, COMPASS

  $\rightarrow$ low energy, low P_{hT} $\rightarrow$ most of the phenomenological work with TMDs
- polarized *pp* by RHIC (AFTER@LHC)

  $\rightarrow$ high energy, high P_{hT} $\rightarrow$ collinear twist-3 framework
- EIC: a bridge to high P_{hT} SIDIS

Global fits

- how to get large $A_N \leq 10\%$?

  (as observed in pp)

- ETQS: opposite sign for A_N

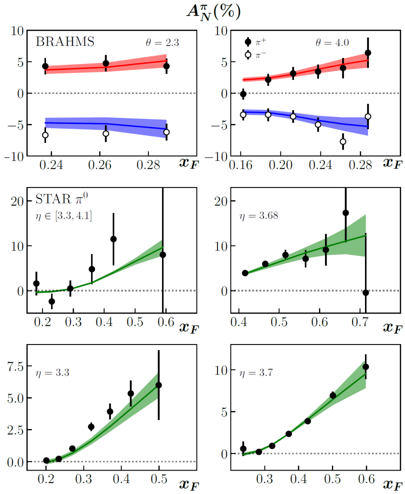
  Kang, Qiu, Vogelsang, Yuan, Phys. Rev. D **83** (2011) 094001

  (“sign mismatch puzzle”)

- current global fits (JAM20/22) favor twist-3 FFs as the main source

  JAM, Phys.Rev.D **106** (2022) 3, 034014

  (ETQS small and negative)



- only soft-gluon pole, how about soft-fermion pole, hard-pole?
- relies on LO cross sections $\rightarrow$ NLO?
- overlaps in kinematics reach for SIDIS and pp? $\rightarrow$ EIC

Revisiting a 40 year old estimate

- the first pQCD estimate of SSA: Kane, Pumplin, Repko (1978) consider the two-loop box diagram

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

G. L. Kane
Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

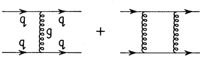
J. Pumplin and W. Repko
Physics Department, Michigan State University, East Lansing, Michigan 48823

(Received 5 July 1978)

Consider $qq \to qq$. In QCD the leading contribution to each helicity amplitude is given by single-gluon exchange, and the next order is the two-gluon-exchange box diagram, plus crossed box, 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 $P = 0$.



(a)

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

$\rightarrow$ believed to be negligible because $m_q \rightarrow 0$

$\rightarrow$ for > 40 years there has been no attempt to go beyond this simple parametric estimate!

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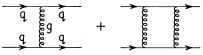

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$$A_N \sim \frac{\alpha_s m_q}{P_{hT}}$$

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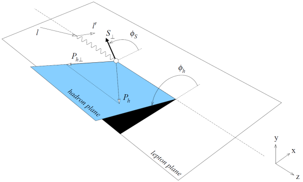
→ for $>$ 40 years there has been no attempt to go beyond this simple parametric estimate!

- our work: explicit computation

SB, Hatta, Li, Yang Phys. Rev. D 100 (2019) 9, 094027
SB, Hatta, Kaushik, Li, Phys. Rev. D 104 (2021) 9, 094027

SIDIS

- semi-inclusive DIS $e(l) + p(P, S_T) \to e(l') + h(P_h) + X$



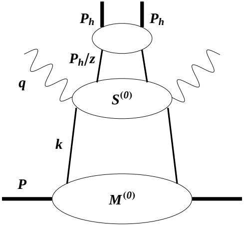
- low P_{hT}: TMDs: Sivers, Collins,... (JLab, HERMES, COMPASS,...)
- high P_{hT}: twist-3 PDFs, FFs,... (EIC)

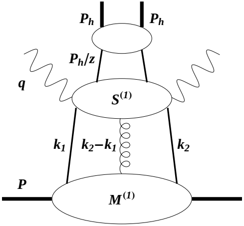
$$x_B = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot l} \qquad z_f = \frac{P\cdot P_h}{P\cdot q}$$

$$\frac{d^5\sigma}{dx_B dy dz_f d\phi_h dP_{hT}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \sin(\phi_h - \phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+ \varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)} + \dots\Big\}$$

Bacchetta, Diehl, Goeke, Metz, Mulders, JHEP 02 (2007) 093

SIDIS: Hadronic tensor





$$M_{ij}^{(0)} \sim \langle PS_T|\bar{\psi}_j \psi_i|PS_T\rangle \qquad M_{ij}^{(1)\sigma} \sim \langle PS_T|\bar{\psi}_j g A^\sigma \psi_i|PS_T\rangle$$

- hadronic tensor $W_{\mu\nu} = \int_z \frac{D(z)}{z^2} w_{\mu\nu}$

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

- scattering kernels $S^{(0)}$ and $S^{(1)\sigma}$ connected via Ward identity

$$(k_2 - k_1)^\lambda S_\sigma^{(1)}(k_1, k_2) = S^{(0)}(k_2) - S^{(0)}(k_1)$$

Hadronic tensor

- all-order formula (after collinear expansion)

$$w_{\mu\nu} = \frac{M_N}{2}\int_x g_T(x)\mathrm{Tr}\left[\gamma_5 \not{S}_T S^{(0)}_{\mu\nu}(x)\right]$$
$$+ \frac{M_N}{2}\int_x \mathrm{Tr}\left[\left(g^{(1)}_{1T}(x)\gamma_5 \not{P} S^\alpha_T + f^{(1)}_{1T}(x)\epsilon^{\alpha P n S_T}\not{P}\right)\frac{\partial S^{(0)}_{\mu\nu}(k)}{\partial k^\alpha_T}\bigg|_{k=xP}\right]$$
$$+ \frac{iM_N}{4}\int_{x_1,x_2}\mathrm{Tr}\left[\left(\not{P}\epsilon^{\alpha P n S_T}\frac{G_F(x_1,x_2)}{x_1-x_2} + i\gamma_5 \not{P} S^\alpha_T \frac{\tilde{G}_F(x_1,x_2)}{x_1-x_2}\right)S^{(1)}_{\mu\nu\alpha}(x_1,x_2)\right]$$

Ratcliffe, Nucl. Phys. B 264, 493 (1986)
Xing, Yoshida, Phys. Rev. D 100 (2019) 5, 054024
SB, Hatta, Li, Yang, Phys. Rev. D 100 (2019) 9, 094027

- intrinsic $g_T \sim \langle\bar{\psi}\psi\rangle$
- kinematical $g^{(1)}_{1T} \sim \langle\bar{\psi}\partial^\mu\psi\rangle$ ($\sim$ first moment of worm-gear TMD)
- dynamical $G_F \sim \langle\bar{\psi}F^{\mu\nu}\psi\rangle$
- this work: $g_T(x)$ + relatives

Wandzura-Wilczek approximation

- g_T and $g_{1T}^{(1)}$ have a twist-two piece

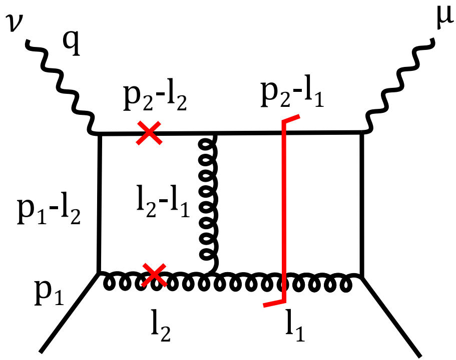
$$g_T(x) = \int_x^1 \frac{dx_1}{x_1} \Delta q(x_1) + \ldots \quad g_{1T}^{(1)} = x \int_x^1 \frac{dx_1}{x_1} \Delta q(x_1) + \ldots .$$

- SSA from twist-two PDFs and twist-two FFs

$$\Delta\sigma \sim \Delta q \otimes H^{(2)} \otimes D_1$$

- Sivers and Collins asymmetry NOT from Sivers and Collins functions
- Δq - twist-two helicity PDF
- D_1 - twist-two unpolarized FF

$S^{(0)}_{\mu\nu}$ at two loops - return of the box

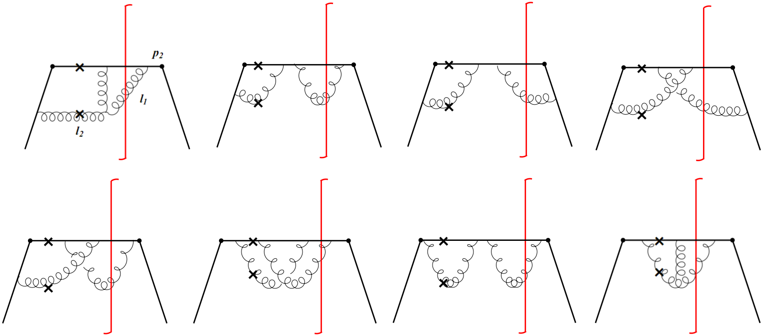


$\rightarrow$ can get a phase

- check all cuts, all diagrams, all channels

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

Two loop analysis



- diagrams in the same gauge invariant set
- total of 12 diagrams (mirrors of first, second and fifth omitted)

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

SSA at two loops - gluonic channel

- a gluonic analog of $g_T(x)$

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS | F^{n\alpha}(0)[0,\lambda n] F^{n\beta}(\lambda n) | PS \rangle = -\frac{1}{2} x G(x) g_T^{\alpha\beta}$$
$$+ \frac{i}{2} x \Delta G(x) \epsilon^{nP\alpha\beta}(n \cdot S) + i M_N x \mathcal{G}_{3T}(x) \epsilon^{n\alpha\beta S_T} + \dots$$

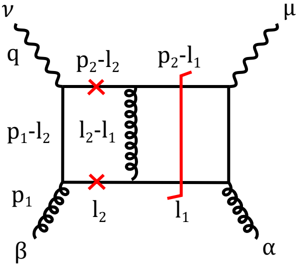
Ji Phys. Lett. B **289** (1992) 137-142
Hatta, Tanaka, Yoshida JHEP **02** (2013) 003

- by a completely analogous computation

$$w_{\mu\nu} = i M_N \int \frac{dx}{x} \mathcal{G}_{3T}(x) \epsilon^{n\alpha\beta S_\perp} S^{(0)\alpha'\beta'}_{\mu\nu}(p_1) \omega_{\alpha'\alpha} \omega_{\beta'\beta}$$
$$- i M_N \int \frac{dx}{x^2} \tilde{g}(x) \left(g_\perp^{\beta\lambda} \epsilon^{\alpha P n S_\perp} - g_\perp^{\alpha\lambda} \epsilon^{\beta P n S_\perp} \right) \left(\frac{\partial S^{(0)}_{\mu\nu\alpha\beta}(k)}{\partial k^\lambda} \right)_{k=p_1} + \dots$$

Hatta, Kanazawa, Yoshida Phys. Rev. D **88** (2013) 1 014037
SB, Hatta, Kaushik, Li, Phys. Rev. D 104 (2021) 9, 094027

SSA at two loops - gluonic channel



- WW approx

$$\mathcal{G}_{3T}(x) = \frac{1}{2}\int_x^1 \frac{dx_1}{x_1}\Delta G(x_1) + \ldots$$

$$\tilde{g}(x) = \frac{x^2}{2}\int_x^1 \frac{dx_1}{x_1}\Delta G(x_1) + \ldots$$

- SSA from twist-two PDFs and FFs

$$\Delta\sigma = \Delta G \otimes H^{(2)} \otimes D_1$$

- ΔG - twist-two gluon helicity
- can contribute to open-charm, J/ψ,...
  $\rightarrow$ a background in extracting the gluon Sivers function

SB, Hatta, Kaushik, Li, Phys. Rev. D 104 (2021) 9, 094027

Revisit hard coefficients

- hadronic tensor in the WW approx ($g_T = g_{1T}^{(1)}/x$)

$$w_{\mu\nu} = \frac{M_N}{2} \int dx g_T(x) \left(S_T^\lambda \frac{\partial}{\partial k_T^\lambda} \mathrm{Tr}\left[\gamma_5 \not{k} S_{\mu\nu}^{(0)}(k) \right] \right)_{k=p_1}$$

$\rightarrow$ 5 structure functions

$\sin(\phi_h - \phi_S)$

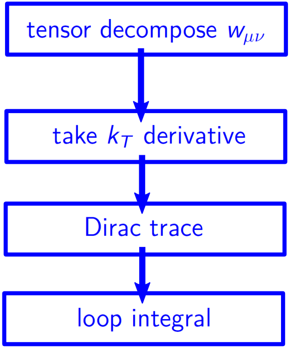
$\sin(\phi_h + \phi_S)$

$\sin(\phi_S)$

$\sin(2\phi_h - \phi_S)$

$\sin(3\phi_h - \phi_S)$

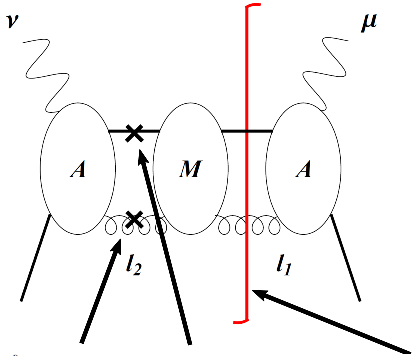
workflow



SB, Hatta, Kaushik, Li, Phys. Rev. D 104 (2021) 9, 094027

Revisit hard coefficients

- complication: δ-functions



$$S^{(0)\mu\nu}(k) \propto \int_{l_2} \delta\left(l_2^2\right) \delta\left((k+q-l_2)^2\right) \delta\left((k+q-p_q)^2\right)$$
$$\times A^{\alpha\mu} M_{\alpha\beta} A^{\nu\beta}$$

$\rightarrow$ multiple partial integrations

SB, Hatta, Kaushik, Li, Phys. Rev. D 104 (2021) 9, 094027

Revisit hard coefficients

- tensor decompose the trace instead!

  $\rightarrow$ no spin S_T^λ $\rightarrow$ only 2 structure functions!

$$\mathrm{Tr}\left[\gamma_5 \not{k} S^{(0)\mu\nu}(k)\right] = \delta\left(\tilde{s} + \tilde{t} + \hat{u} - Q^2\right) \times \left(T_1^{\mu\nu} S_1^{(0)}(\tilde{s}, \tilde{t}, \hat{u}, Q^2) + T_2^{\mu\nu} S_2^{(0)}(\tilde{s}, \tilde{t}, \hat{u}, Q^2)\right)$$

$$T_1^{\mu\nu} = \left(k^\mu + \frac{k\cdot q}{Q^2} q^\mu\right)\epsilon^{\nu k q p_q} + \left(k^\nu + \frac{k\cdot q}{Q^2} q^\nu\right)\epsilon^{\mu k q p_q}$$

$$T_2^{\mu\nu} = \left(p_q^\mu + \frac{p_q\cdot q}{Q^2} q^\mu\right)\epsilon^{\nu k q p_q} + \left(p_q^\nu + \frac{p_q\cdot q}{Q^2} q^\nu\right)\epsilon^{\mu k q p_q}$$

- similar to longitudinal spin asymmetry

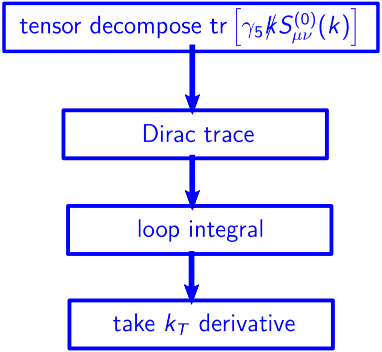
SB, Hatta, Kaushik, Li, in preparation
Abele, Aicher, Piacenza, Schäfer, Vogelsang, Phys. Rev. D 106 (2022) 1, 014020

Revisit hard coefficients

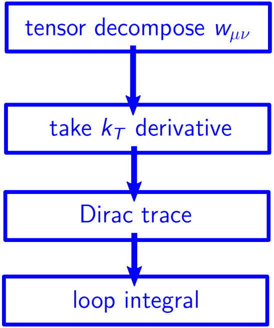
- hadronic tensor in the WW approx ($g_T = g_{1T}^{(1)}/x$)

$$w_{\mu\nu} = \frac{M_N}{2}\int dx g_T(x)\left(S_T^\lambda \frac{\partial}{\partial k_T^\lambda}\mathrm{Tr}\left[\gamma_5 \not{k} S_{\mu\nu}^{(0)}(k)\right]\right)_{k=p_1}$$

new workflow



old workflow



SB, Hatta, Kaushik, Li, in preparation

Revisit hard coefficients

- no contribution in the $Q^2 \to 0$ limit: $e^2 L_{\mu\nu}/q^4 \to -g_{\mu\nu}$

$$g_{\mu\nu} T^{\mu\nu}_{1,2} \to 0$$

- no contribution to A_N in $pp^\uparrow \to hX$ (similar logic)

  $\to$ valid to all-orders!

- unfortunately, our original computation from '21 does not pass the $Q^2 \to 0$ check

  $\to$ some hard coefficients change

  SB, Hatta, Kaushik, Li, in preparation

- computation of $S^{(0)}_{1,2}$ consistent with Vogelsang et al.

  Abele, Aicher, Piacenza, Schäfer, Vogelsang, Phys. Rev. D 106 (2022) 1, 014020

- also consistent with NLO e^+e^- via crossing

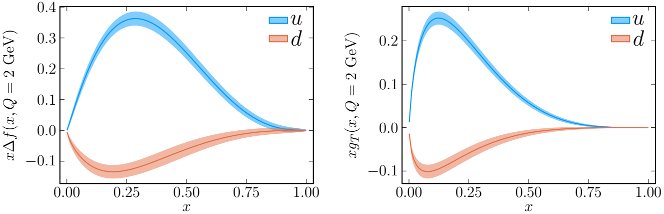
  Körner, Melić, Merebashvili, Phys.Rev.D 62 (2000) 096011

Numerical setup

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

- numerator: $O(\alpha_s^2)$ g_T contribution
- denominator: $O(\alpha_s)$ unpolarized cross section
  Meng, Olness, Soper Nucl. Phys. **B371**, 79, (1992)
  $\rightarrow$ A_{UT}'s sensitive to scale variations

- $g_T(x)$ and $\mathcal{G}_{3T}(x)$ computed from the WW relation to helicity PDFs
- recent global fits for helicity PDFs from JAM



Either, Sato, Melnitchouk, Phys. Rev. Lett. 119 (2017) 13, 132001

Results @ EIC

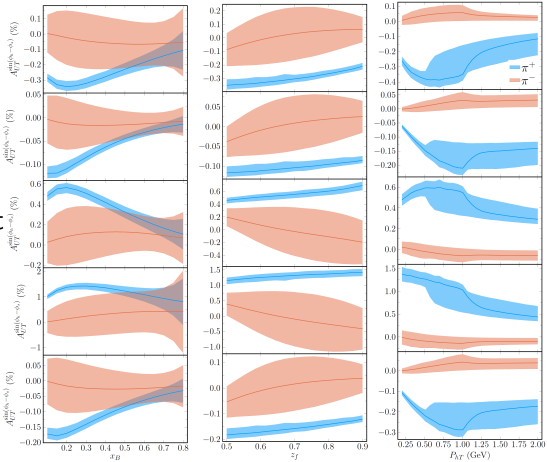
Sivers per mille

Collins per mille

$\sin\phi_S$ half percent

$\sin(2\phi_h - \phi_S)$ percent level

Pretzelosity per mille

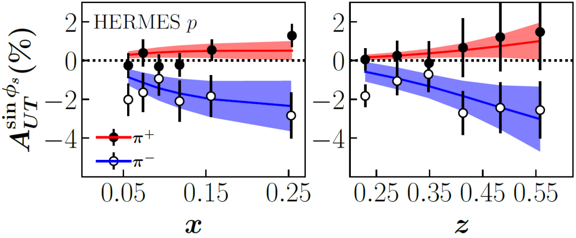


- change from '21 result: Sivers drops from a few percent to per-mille level

SB, Hatta, Kaushik, Li, in preparation

$A_{UT}^{\sin\phi_S}$ from HERMES

- recently HERMES released comprehensive 3D data sets for all harmonics
- a non-zero $A_{UT}^{\sin\phi_S}$ identified for the first time



HERMES, JHEP 12, 010 (2020)
JAM, Phys.Rev.D **106** (2022) 3, 034014

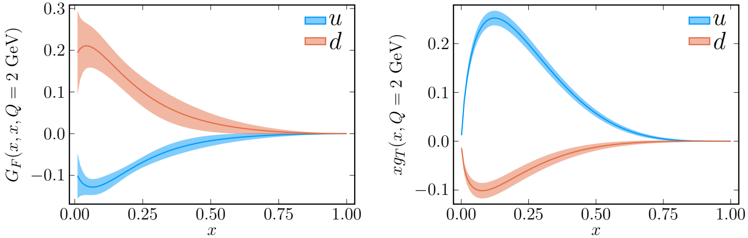
- JAM22: $A_{UT}^{\sin\phi_S} \propto h_1(x) \otimes \tilde{H}(z)$ $\tilde{H}(z)$ = dynamical twist-3

(JAM20: WW approx $\tilde{H}(z) = 0$)
JAM, Phys. Rev. D **102**, 054002 (2020)

Other sources for $A_{UT}^{\sin\phi_S}$?

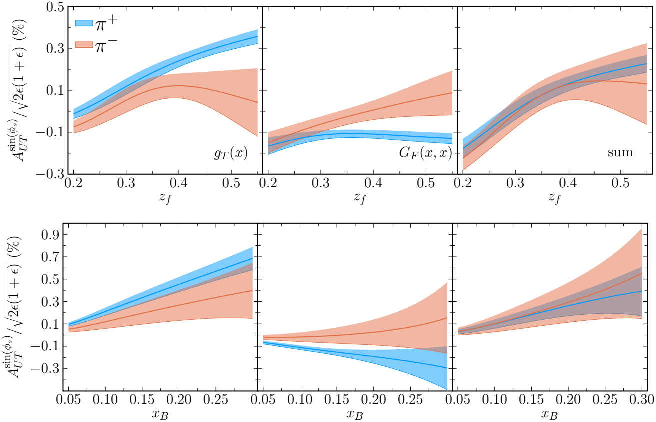
- contribution from ETQS:
$$A_{UT}^{\sin\phi_S} \propto G_F(x,x) \otimes H^{(1)} \otimes D_1(z) + x\frac{dG_F(x,x)}{dx} \otimes H_D^{(1)} \otimes D_1(z)$$

- contribution from g_T:
$$A_{UT}^{\sin\phi_S} \propto x g_T(x) \otimes H^{(2)} \otimes D_1(z) + x^2\frac{dg_T(x)}{dx} \otimes H_D^{(2)} \otimes D_1(z)$$



Koike, Tanaka, Phys. Lett. B 646, 232 (2007)
JAM, Phys.Rev.D **106** (2022) 3, 034014
Benić, Hatta, Kaushik, Li, in preparation

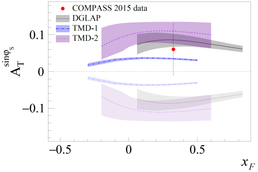
Preliminary result @ HERMES

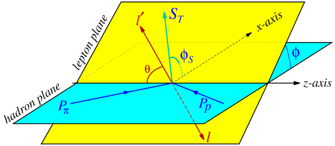


- $g_T(x)$ contribution not really suppressed even though it is higher order $\rightarrow$ P_{hT} too low?
- underlines the need for a full NLO computation..

Koike, Tanaka, Phys. Lett. B 646, 232 (2007)
JAM, Phys.Rev.D **106** (2022) 3, 034014
Benić, Hatta, Kaushik, Li, in preparation

Drell-Yan lepton pair production





- SIDIS → DY: sign-change of the Sivers function!
- DY program at COMPASS with π^- beams: $\pi^- p^\uparrow \to \mu^+\mu^- + X$

COMPASS, Phys. Rev. Lett. 119 (2017) 11, 112002
Bastami, Gamberg, Parsamyan, Pasquini, Prokudin, Schweitzer, JHEP 02 (2021) 166

$$\frac{d^4\sigma}{d^4 d\Omega} = \frac{\alpha^2}{2sq^2}\Big[(1+\cos^2\theta)F_{UU,1} + (1-\cos^2\theta)F_{UU,2}$$

$$+ \sin(2\theta)\cos\phi F_{UU}^{\cos\phi} + \sin^2\theta\cos(2\phi)F_{UU}^{\cos(2\phi)}$$

$$+ \sin\phi_S\left((1+\cos^2\theta)F_{UT,1}^{\sin\phi_S} + (1-\cos^2\theta)F_{UT,2}^{\sin\phi_S}\right)$$

$$+ \sin(2\theta)\sin(\phi-\phi_S)F_{UT}^{\sin(\phi-\phi_S)} + \sin(2\theta)\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)}$$

$$+ \sin^2\theta\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)} + \sin^2\theta\sin(2\phi+\phi_S)F_{UT}^{\sin(2\phi+\phi_S)} + \ldots\Big]$$

Collins, Soper, Phys. Rev. D 16, 2219 (1977)
Boer, Vogelsang, Phys. Rev. D 74 (2006) 014004
Arnold, Metz, Schlegel, Phys.Rev.D 79 (2009) 034005

Hadronic tensor in DY

- no twist-3 FF contribution in DY
- global fits: ETQS is small
  $\rightarrow$ g_T might play a more important role!

- hadronic tensor in DY (e. g. qg channel)

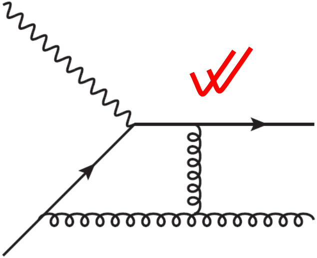
$$W_{\alpha\beta} = \frac{M_N}{2}\frac{1}{(2\pi)^4}\int dx g_T(x)\int \frac{dx'}{x'}\frac{G(x')}{2(N_c^2-1)}S_T^{\lambda}\frac{\partial}{\partial k_T^{\lambda}}\mathrm{Tr}\left[\gamma_5 \not{k} S^{(0)}_{\alpha\beta}(k)\right]$$

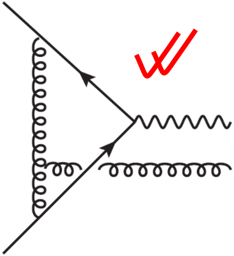
  $\rightarrow$ 5 structure functions
- similar trick to SIDIS $\rightarrow$ trace contains only 2 tensorial structures
- integrating over the lepton angles the result vanishes ($L^{\alpha\beta} \rightarrow g^{\alpha\beta}$)
  $\rightarrow$ no contribution to direct photon A_N

SB, Hatta, Kaushik, Li, in preparation

From SIDIS to DY

- which diagrams contribute?
- naive crossing of the phase?





- diagram that contributes in SIDIS and in DY
- additional cut on the $q\bar{q}$ lines in DY case

Pire, Ralston, Phys. Rev. D 28, 260 (1983)
Körner, Melić, Merebashvili, Phys.Rev.D 62 (2000) 096011
SB, Hatta, Kaushik, Li, in preparation

From SIDIS to DY

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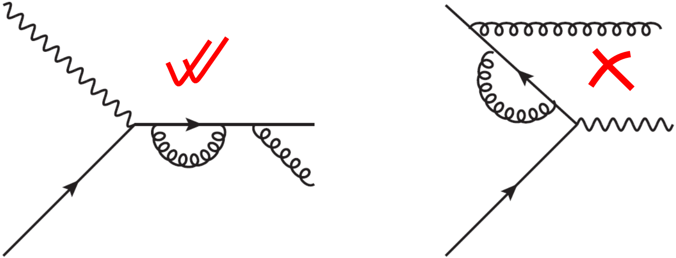

- diagram that contributes in SIDIS (time-like q^*) but not in DY (space-like q^*)

Pire, Ralston, Phys. Rev. D 28, 260 (1983)
Körner, Melić, Merebashvili, Phys.Rev.D 62 (2000) 096011
SB, Hatta, Kaushik, Li, in preparation

From SIDIS to DY

- which diagrams contribute?
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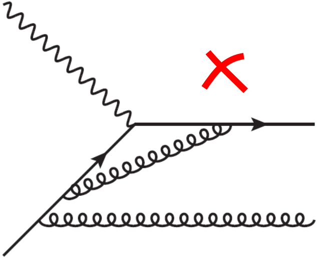

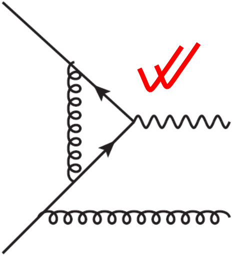

- does not contribute to SIDIS (space-like γ^*) but contributes to DY (time-like γ^*)

Pire, Ralston, Phys. Rev. D 28, 260 (1983)
Körner, Melić, Merebashvili, Phys.Rev.D 62 (2000) 096011
SB, Hatta, Kaushik, Li, in preparation

From SIDIS to DY

PHYSICAL REVIEW D VOLUME 28, NUMBER 1 1 JULY 1983

Single-spin asymmetries in the Drell-Yan process

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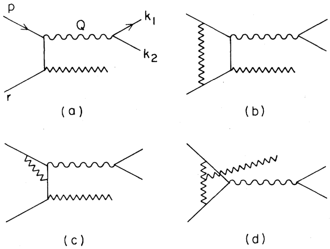

FIG. 1. (a) The lowest-order graph for $q\bar{q} \to \gamma^* g$. (b) The graphs contributing in Feynman gauge to the imaginary part of $W^{\mu\nu}$ at order $\alpha_s{}^2$ (crossed graphs have been omitted).

Pire, Ralston, Phys. Rev. D 28, 260 (1983)

- total of 5 amplitude diagrams
- first identified by Pire and Ralston in ’83
- single longitudinal spin asymmetry in DY

Conclusions and outlook

- new contribution to SSA from $g_T(x) \sim \int_x^1 dx_1 \Delta f(x_1)/x_1$ in SIDIS at two loops

$$A_{UT} \sim \frac{\alpha_s M_N}{P_{hT}} \frac{x\Delta f(x)}{f(x)}$$

- involves only (known) twist-2 PDFs and FFs (after WW approx)
- SIDIS: percent asymmetry for sub-leading moments
- permille contributions to Sivers, Collins, pretzelosity
- interestingly, there is no contribution to A_N in $pp^{\uparrow}$ from this mechanism
- DY: computation ongoing..