CPHI 2020, CERN, February 05, 2020

The transverse SSA in gSIDIS

(within coll. twist-3 formalism)

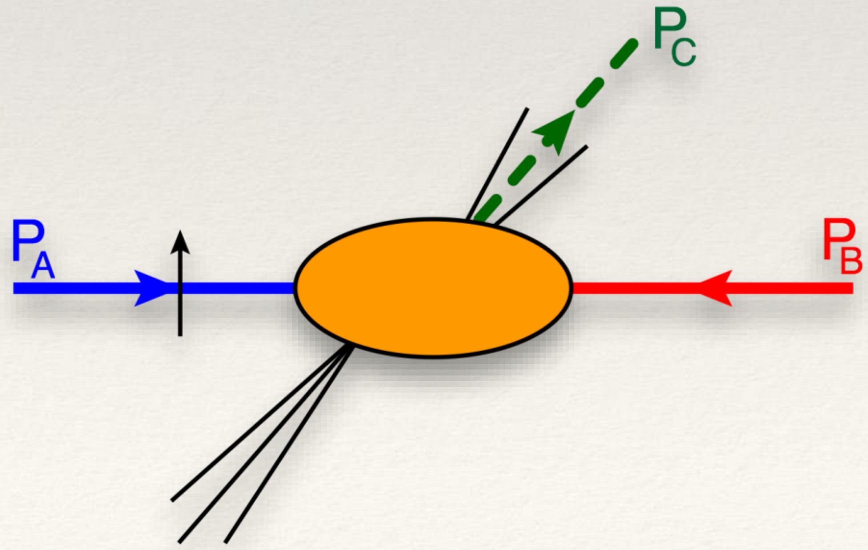
Marc Schlegel
Department of Physics
New Mexico State University

based on W. Albaltan, A. Prokudin, M.S., arXiv:1910.02883

Work supported by DOE *TMD collaboration* & NSF

Transverse Spin Effects in Single-Inclusive Hard Processes

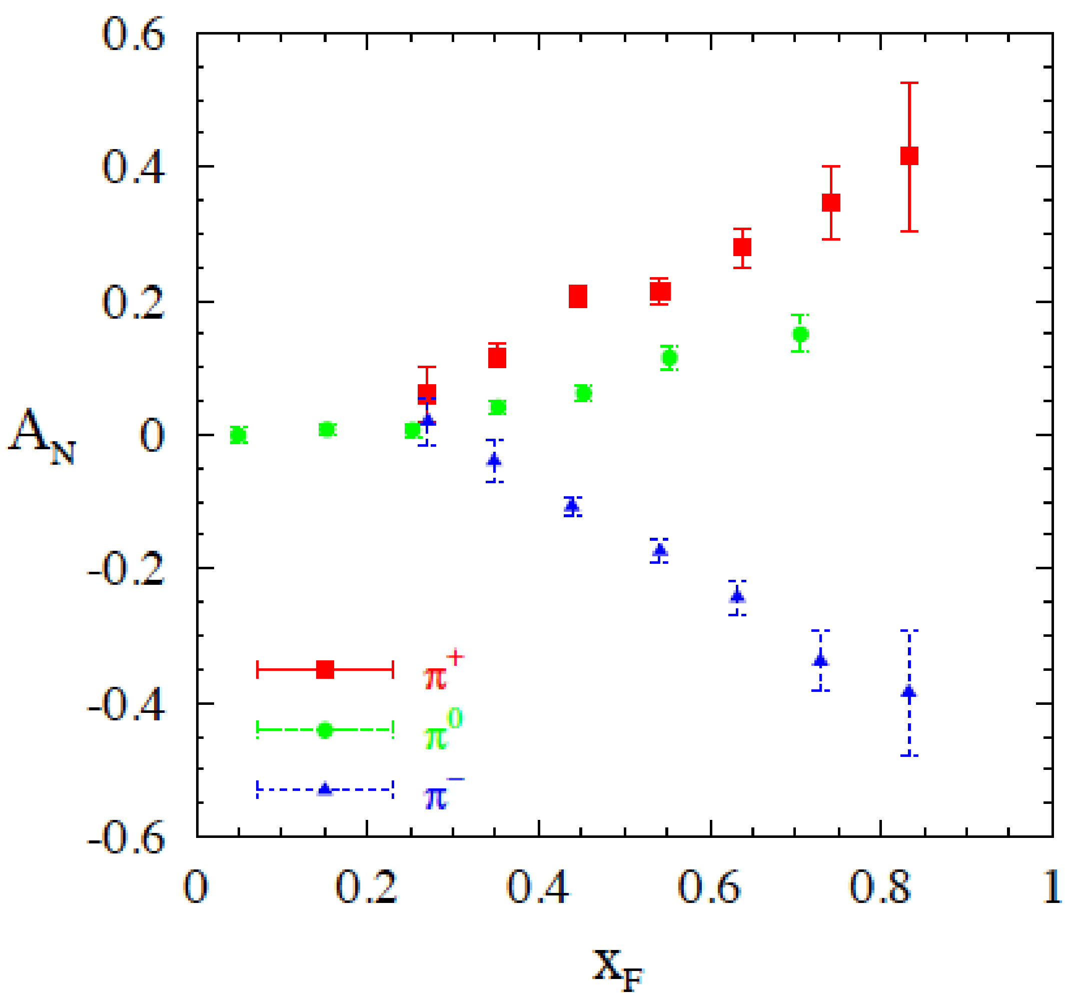
$$P_A^{\uparrow} + P_B \to P_C + X$$



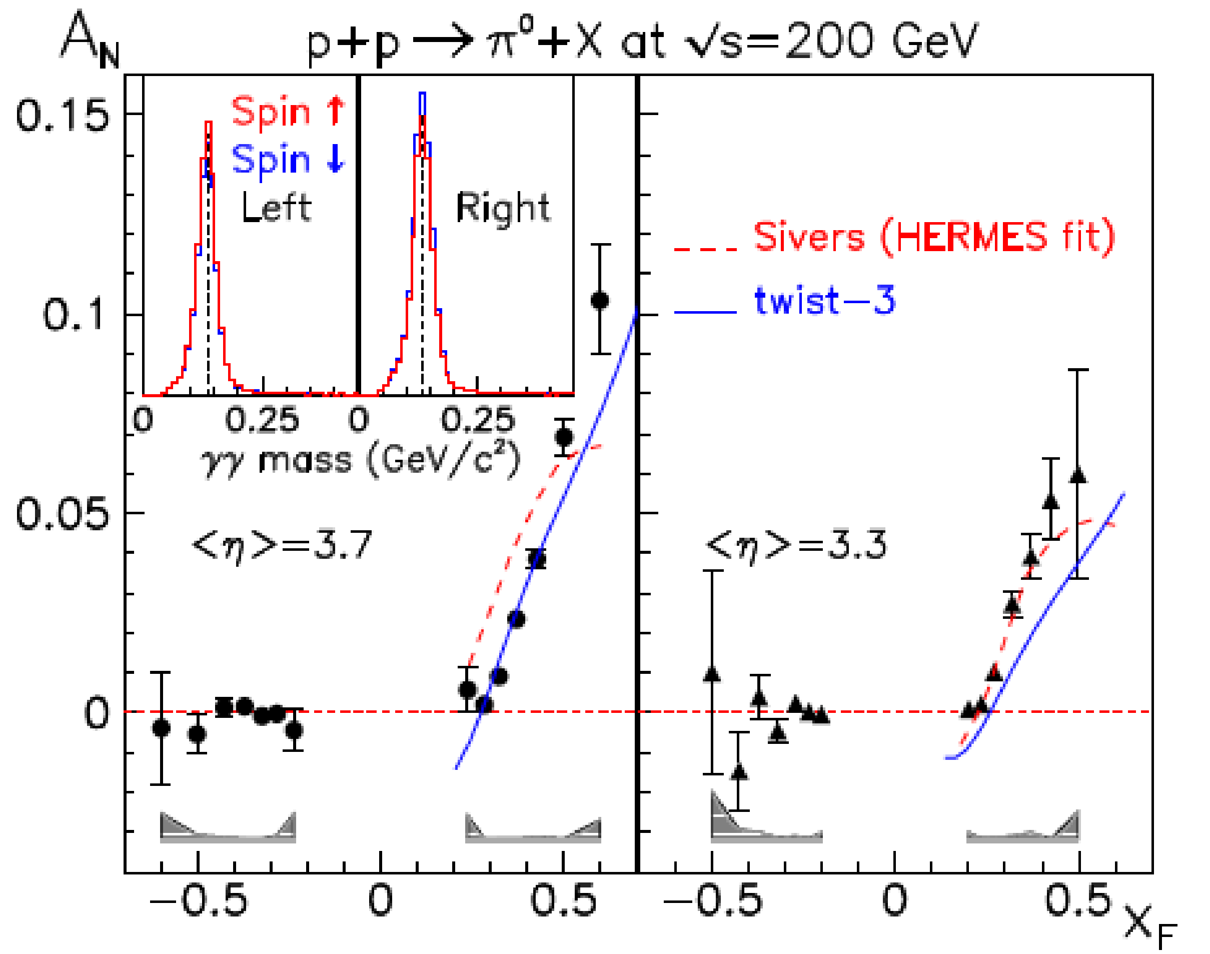
Transverse SSA

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

$$p + p^\uparrow \to \pi + X$$



$\sqrt{s} = 20$ GeV [*E704 coll. (1991)*]



$\sqrt{s} = 200$ GeV [*STAR coll. (2008)*]

large effects

cannot be explained in the standard parton model

(using transversity)

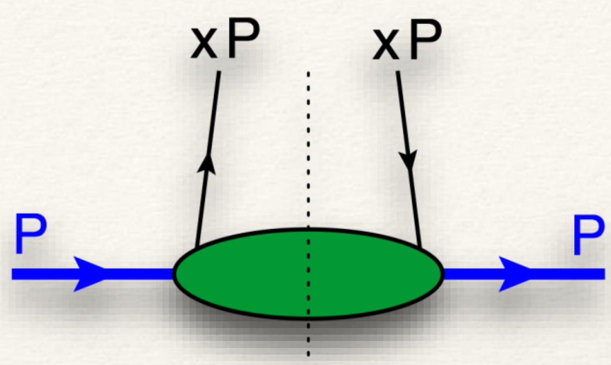
→ collinear Twist-3 Formalism

(Efremov, Teryaev, Qiu, Sterman)

Collinear twist-3 formalism: several types of matrix elements compete

intrinsic twist-3 PDF

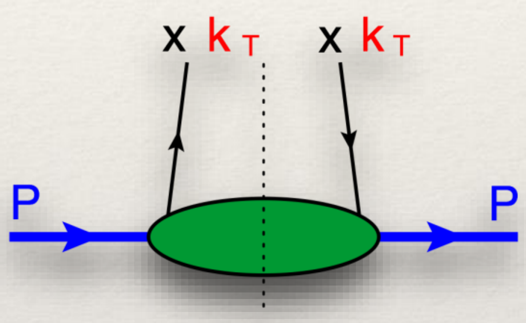
$$g_T^q(x) = -\frac{1}{M}\int \frac{d\lambda}{4\pi}\, \mathrm{e}^{i\lambda x}\langle P, S_T|\, \bar q(0)\, \not{S}_T\gamma_5\, q(\lambda n)\,|P, S_T\rangle$$



- sensitive to 'bad quark field components',
- twist-3 characteristics hidden in Dirac structure
- generates the g_2 structure function in DIS
- No probabilistic interpretation

kinematical twist-3 PDFs:

Small transverse quark/gluon momenta k_T:



$$(k_T\times S_T)\, f_{1T}^{\perp,q}(x, k_T^2) \propto \int \frac{d\lambda\, d^2 z_T}{(2\pi)^3}\, \mathrm{e}^{i\lambda x + i k_T\cdot z_T}\langle P, S_T|\bar q(0)\, \not{n}\mathcal{W}\, q(\lambda n + z_T)\,|P, S_T\rangle$$

Sivers function

$$(k_T\cdot S_T)\, g_{1T}^q(x, k_T^2) \propto \int \frac{d\lambda\, d^2 z_T}{(2\pi)^3}\, \mathrm{e}^{i\lambda x + i k_T\cdot z_T}\langle P, S_T|\bar q(0)\, \not{n}\gamma_5\mathcal{W}\, q(\lambda n + z_T)\,|P, S_T\rangle$$

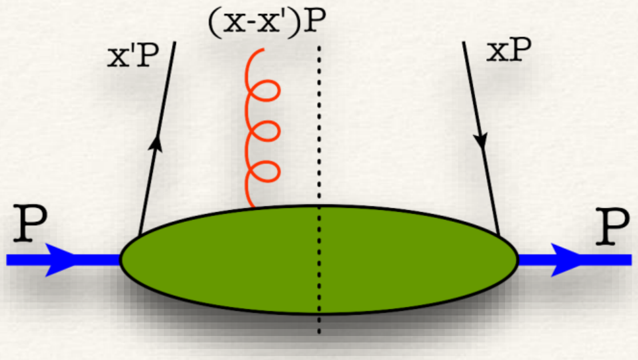
'transhelicity'

Collinear twist-3 formalism: TMD moments are needed

$$f_{1T}^{\perp,(1)}(x) = \int d^2k_T\, \frac{k_T^2}{2M^2}\, f_{1T}^{\perp}(x, k_T^2)$$

$$g_{1T}^{(1)}(x) = \int d^2k_T\, \frac{k_T^2}{2M^2}\, g_{1T}(x, k_T^2)$$

$\longrightarrow$ twist-3 characteristics through small transverse parton momentum k_T



Dynamical twist-3: Quark - Gluon - Quark Correlations
(ETQS-matrix elements)

$$2M\, i\epsilon^{Pn\rho S} F^q_{FT}(x,x') = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} \mathrm{e}^{i\lambda x'} \mathrm{e}^{i\mu(x-x')} \langle P, S_T |\, \bar{q}(0)\, \not{n}\, igF^{n\rho}(\mu n)\, q(\lambda n)\, | P, S_T \rangle$$

$$2M\, S^\rho_T G^q_{FT}(x,x') = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} \mathrm{e}^{i\lambda x'} \mathrm{e}^{i\mu(x-x')} \langle P, S_T |\, \bar{q}(0)\, \not{n}\gamma_5\, igF^{n\rho}(\mu n)\, q(\lambda n)\, | P, S_T \rangle$$

'dynamical twist - 3'

→ 3 - parton correlator: suppression by additional propagator

→ Quark-Gluon-Quark correlation functions
drive x-dependence of evolved TMDs like Sivers function, transhelicity, etc. beyond LO

→ so far: only "diagonal support" p $F_{FT}(x,x) = f_{1T}^{\perp(1)}(x)$ constraint by SIDIS data

→ 'integrated' $F_{FT}(x,x')$: average transverse color Lorentz force on struck quark
[Burkardt, PRD88, 114502]

$$F^{n\rho} = [\vec{E} + \vec{n} \times \vec{B}]^\rho \propto \int dx \int dx'\, F_{FT}(x,x') \propto \int dx\, x^2\, g_T(x)$$

QCD EoM relation & Lorentz-Invariance Relations

[Kanazawa, Koike, Metz, Pitonyak, M.S., PRD 2016]

QCD EoM for Twist-3 PDFs

$$g_{1T}^{(1)}(x) = x\, g_T(x) - \frac{m_q}{M}\, h_1(x) + \int_{-1}^{1} dx' \, \frac{F_{FT}(x,x') - G_{FT}(x,x')}{x - x'}$$

$$\pi F_{FT}^{q}(x,x) = f_{1T}^{\perp(1),q}(x)$$

LIR for Twist-3 PDFs

based on translation invariance

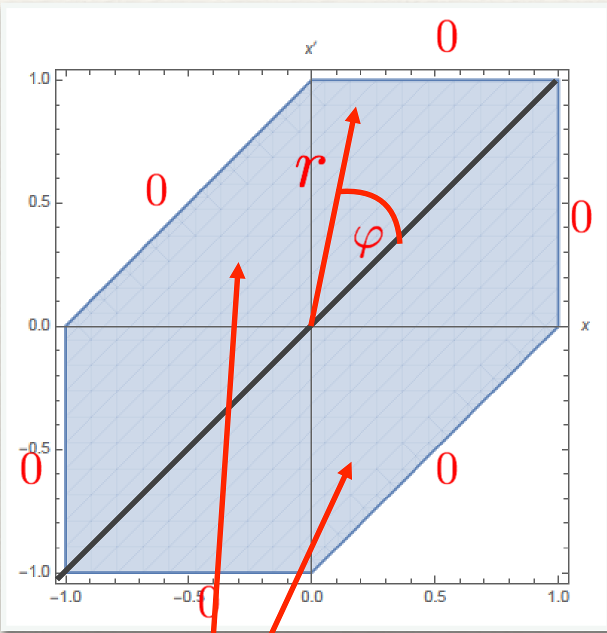
$$g_T(x) = g_1(x) + \frac{d}{dx} g_{1T}^{(1)}(x) - 2 \int_{-1}^{1} dx' \, \frac{G_{FT}(x,x')}{(x-x')^2}$$

Two equations, three functions → eliminate ‘intrinsic & kinematical twist-3’

$$g_T(x) = \int_x^1 \frac{dy}{y}\, g_1(y) + \frac{m_q}{M} \left(\frac{1}{x}\, h_1(x) - \int_x^1 \frac{dy}{y^2}\, h_1(y) \right) + \int_x^1 \frac{dy}{y^2} \int_{-1}^{1} dz \left[\frac{(1-y\delta(y-x))\, F_{FT}(y,z)}{y-z} - \frac{(3y-z-y(y-z)\delta(y-x))\, G_{FT}(y,z)}{(y-z)^2} \right]$$

EoM & LIR relation crucial for gauge invariance, invariance of LC vector n

Support properties $-1 \le x, x' \le 1$ $|x - x'| \le 1$ and continuous



‘terra incognita’

$$F_{FT}(x,x') = +F_{FT}(x',x) \Longrightarrow \sum_n a_n(r)\,\cos(n\varphi)$$

$$G_{FT}(x,x') = -G_{FT}(x',x) \Longrightarrow \sum_n b_n(r)\,\sin(n\varphi)$$

$$\pi F^q_{FT}(x,x) = f_{1T}^{\perp(1),q}(x)$$

$$\pi F^q_{FT}(-x,-x) = f_{1T}^{\perp(1),\bar{q}}(x)$$

Fixes a_0, a_1

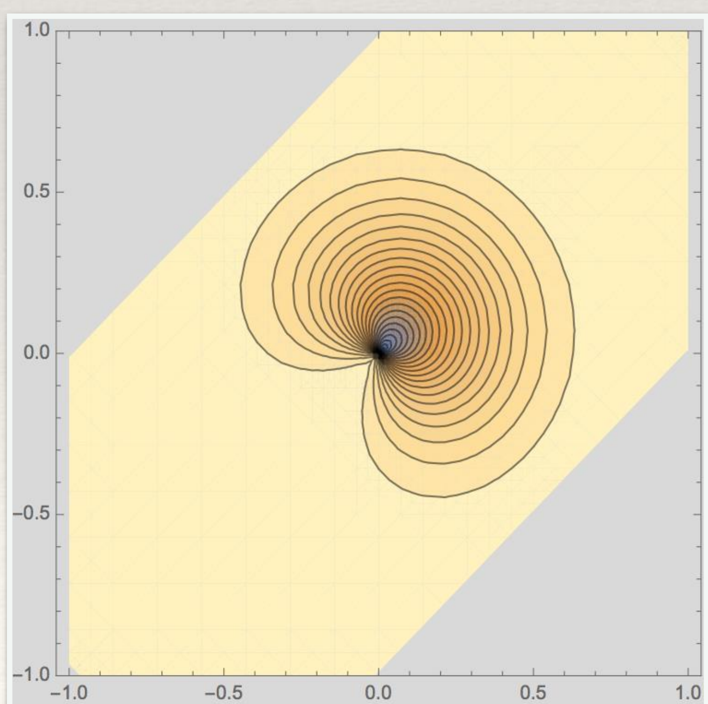
'Gluon poles' ‘known’ from SIDIS experiments

$$F_{FT}(x,x') = \left(\frac{(1-x^2)(1-x'^2)(1-(x-x'))}{(1-xx')^2}\right)^\delta (a_0(r) + a_1(r)\,\cos(\varphi))$$

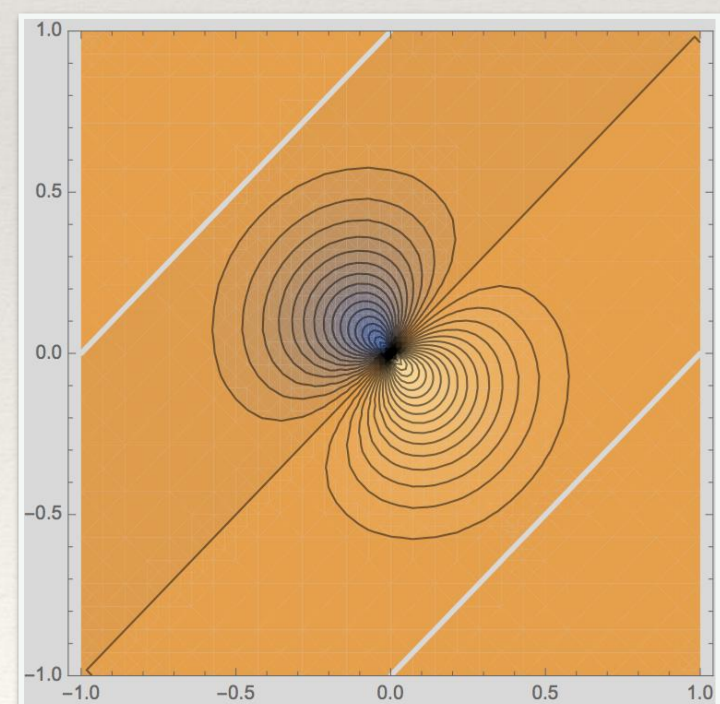
$$G_{FT}(x,x') = \left(\frac{(1-x^2)(1-x'^2)(1-(x-x'))}{(1-xx')^2}\right)^\delta (a_0(r)\,\sin(\varphi))$$

Model ansätze

$F_{FT}(x,x')$



$G_{FT}(x,x')$

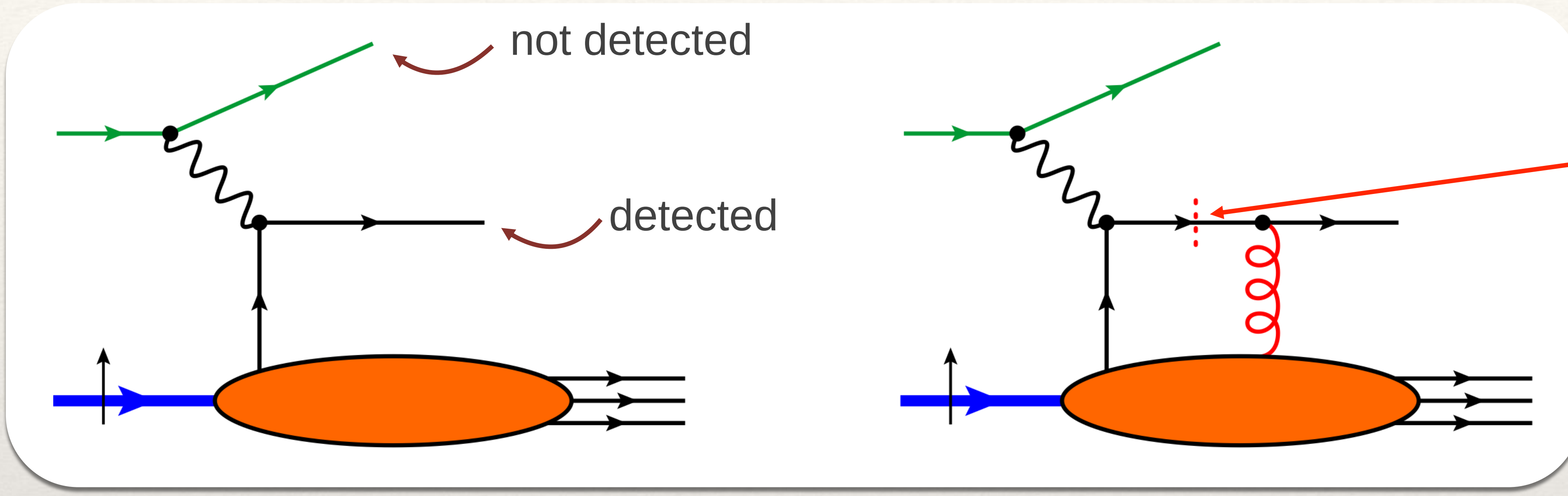


How do quark-gluon correlations generate an SSA?

Example: Single-inclusive jet production $e\,N^{\uparrow} \rightarrow \text{jet}\,X$

[Gamberg, Kang, Metz, Pitonyak, Prokudin (2014); Kanazawa, Koike, Metz, Pitonyak, M.S. (2016)]

Simple LO diagrams



Soft gluon pole

$$\frac{1}{x - x' + i\epsilon} = \frac{\mathcal{P}}{x - x'} - i\pi\delta(x - x')$$

Kinematical twist-3

Dynamical twist-3

$$A_N \propto \left(1 - x\frac{d}{dx}\right) F_{FT}^{q}(x, x)$$

SSA generated by soft-gluon pole only

Feasible at a future EIC, NLO corrections might be large

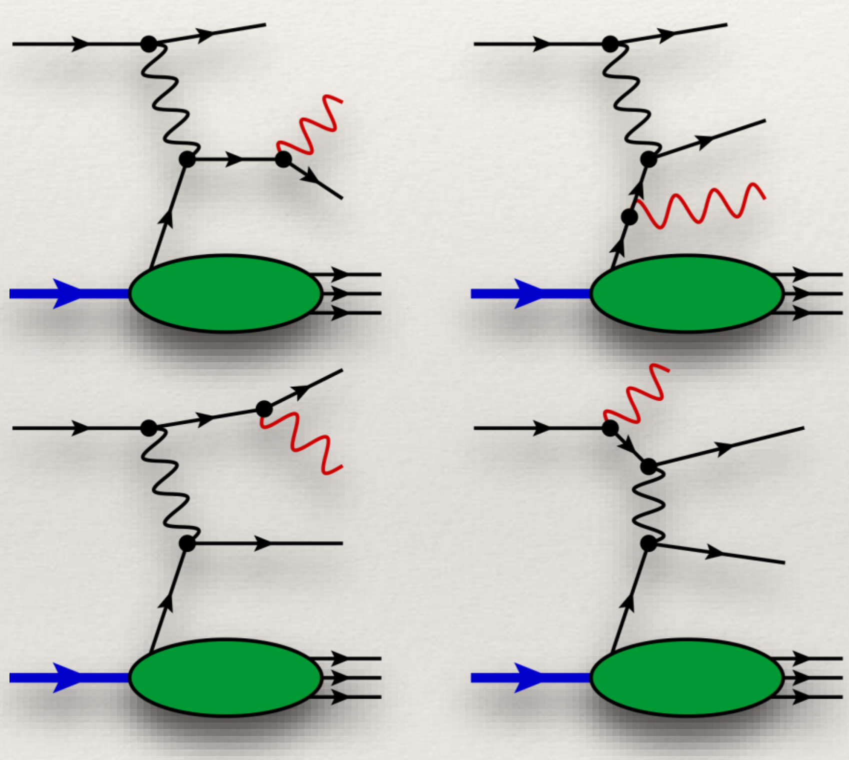
Transverse Spin Asymmetries in Photon SIDIS

Photon SIDIS: e(l) + N(P) $\longrightarrow$ e(l') + g(P_g)+ X

[Albaltan, Prokudin, M.S., arXiv:1910.02883]

TSSA in DIS: need two-photon exchange [Christ-Lee, 1970s]
Idea: Circumvent Christ - Lee theorem: isolated high-p_T real photon emission

unpolarized cross section in the parton model
[Brodsky, Gunion, Jaffe, PRD 1972; see also works by Metz et al; Pisano, Mukherjee; de Rujula, Vogelsang; …]



- avoid/reduce photon fragmentation: isolated photons
- collinear factorization:
  information on final quark is integrated out
- LO result:

$$E_\gamma E_e \frac{d\sigma}{d^3\vec{P}_\gamma\, d^3\vec{l'}} = \hat{\sigma}_{\rm BH}\, f_{\rm BH}(x_B) + \hat{\sigma}_{\rm C}\, f_{\rm C}(x_B) + \hat{\sigma}_{\rm I}\, f_{\rm I}(x_B)$$

$$f_{\rm BH}(x_B) = \sum_{q=u,d,\ldots} e_q^2 (f_1^q + f_1^{\bar{q}})(x_B) \qquad f_{\rm C}(x_B) = \sum_{q=u,d,\ldots} e_q^4 (f_1^q + f_1^{\bar{q}})(x_B)$$

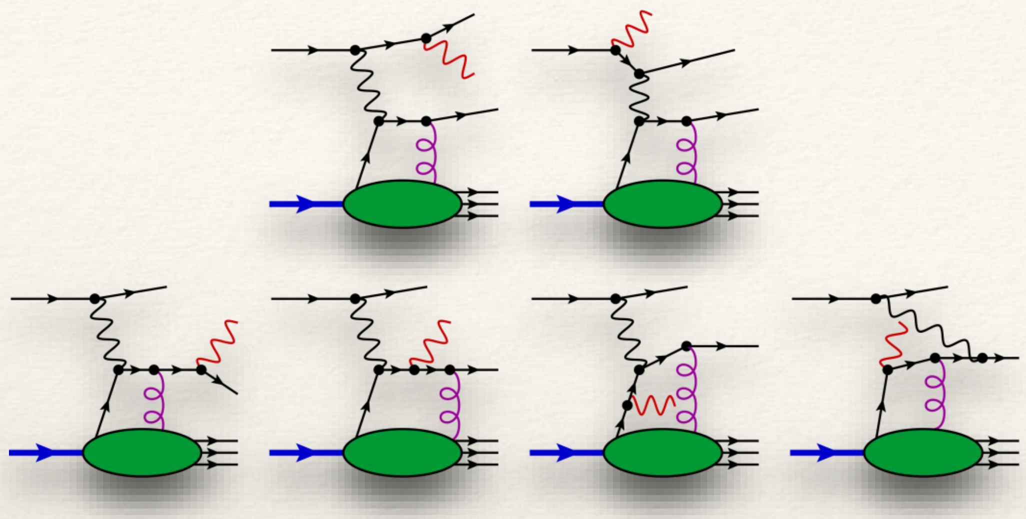
$$f_{\rm I}(x_B) = \sum_{q=u,d,\ldots} e_q^3 (f_1^q - f_1^{\bar{q}})(x_B)$$

- two scales: $Q^2 = -(l - l' - P_\gamma)^2$ $\qquad \tilde{Q}^2 = -(l - l')^2$

- two scaling 'Bjorken-x': $x_B = \dfrac{Q^2}{2P\cdot(l - l' - P_\gamma)}$ $\qquad \tilde{x}_B = \dfrac{\tilde{Q}^2}{2P\cdot(l - l')}$

Transverse SSA in photon SIDIS

Include *intrinsic*, *kinematical* & *dynamical* twist - 3 contributions



Bethe-Heitler contribution vanishes
(Christ - Lee theorem)!

At tree-level (LO):

No contribution from g_T and $g_{1T}^{(1)}$
(no imaginary part)

Quark - Gluon correlations:

1) Soft Gluon Poles: $F_{FT}(x_B,x_B)$
2) Soft Fermion Poles: $F_{FT}(x_B,0)$
3) Hard Poles: $F_{FT}(x_B,\tilde{x}_B)$

Soft Gluon Poles vanish !

eN c.m. frame: 4 azimuthal dependences

$$A_{UT}(\phi_s) = \sin(\phi_s - \phi_l)\, A_l + \sin(\phi_s - \phi_\gamma)\, A_\gamma + \sin(\phi_l - \phi_\gamma)\, \cos(\phi_s - \phi_l) B_l + \sin(\phi_l - \phi_\gamma)\, \cos(\phi_s - \phi_\gamma) B_\gamma$$

LO result

$$B_{l,\gamma} = \sum_{i=C,I} \left[\hat{b}^i_{l,\gamma;\mathrm{HP,G}}\, G^i_{FT}(x_B,\tilde{x}_B) + \hat{b}^i_{l,\gamma;\mathrm{SFP,G}}\, G^i_{FT}(x_B,0) \right]$$

$$A_{l,\gamma} = \sum_{i=C,I} \left[\hat{a}^i_{l,\gamma;\mathrm{HP,F}}\, F^i_{FT}(x_B,\tilde{x}_B) + \hat{a}^i_{l,\gamma;\mathrm{SFP,F}}\, F^i_{FT}(x_B,0) + \hat{a}^i_{l,\gamma;\mathrm{HP,G}}\, G^i_{FT}(x_B,\tilde{x}_B) + \hat{a}^i_{l,\gamma;\mathrm{SFP,G}}\, G^i_{FT}(x_B,0) \right]$$

Double Spin Asymmetry A_{LT}: Longitudinally pol. lepton on transversely pol. Nucleon

- Same diagrams, but real parts of propagators
- Remove intrinsic and kinematical twist-3 by EoM and LIR relations

$$A_{LT}(\phi_s) = \cos(\phi_s - \phi_l)\, C_l + \cos(\phi_s - \phi_\gamma)\, C_\gamma$$

$$C_{l,\gamma} = \sum_{i=BH,C,I} \Big[\Delta\hat{c}^i_{1;l,\gamma}\, g^i_1(x_B) + \Delta\hat{c}^i_{2;l,\gamma} \int_{x_B}^1 \frac{dx}{x} g^i_1(x) \qquad \text{WW - contribution}$$

$$\text{dyn. tw3} \qquad + \int_{x_B}^1 dx \int_{-(1-x)}^1 dx' \left(\Delta\hat{c}^i_{F;l,\gamma}(x,x')\, F^i_{FT}(x,x') + \Delta\hat{c}^i_{G;l,\gamma}(x,x')\, G^i_{FT}(x,x') + \right) \Big]$$

- All three types of contributions (BH,I,C) appear
- Complication: Double integrals, probably dominating WW - contribution

⇒ SSA uniquely simple observable to directly study “off-diagonal” support of twist - 3 Quark - Gluon Correlation functions!

Is the transverse nucleon SSA feasible in an experiment (EIC, COMPASS, JLab)?

Previous HERA measurements at ZEUS (2004), H1 (2006)

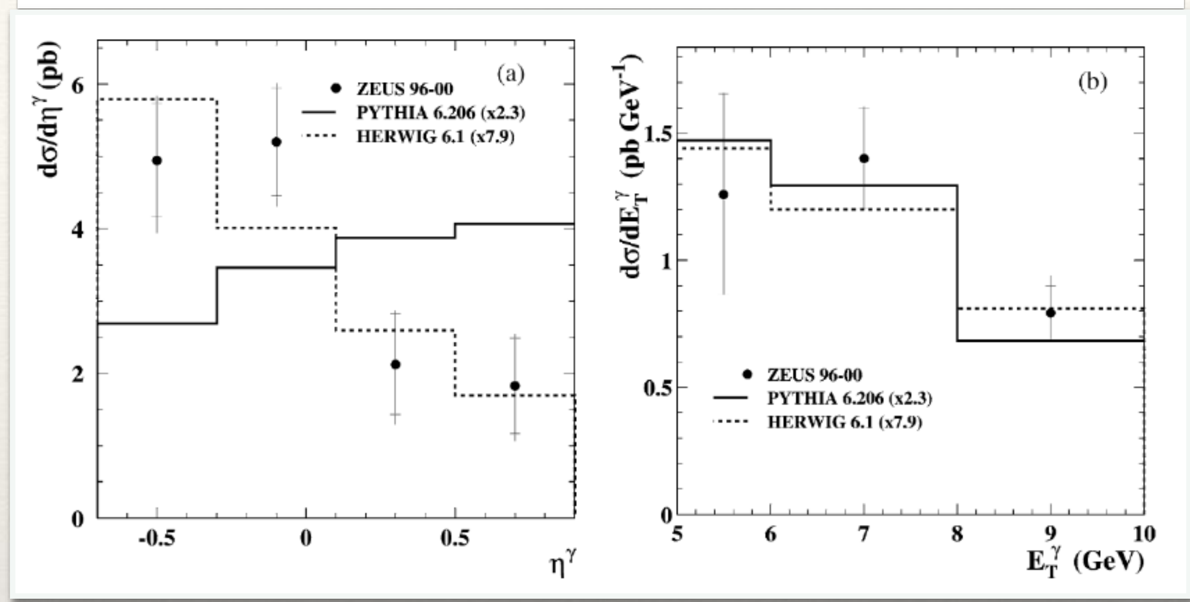
ZEUS [PLB 595, 86-100 (2004)]:

$$\sigma(ep \to e\gamma X) = 5.64 \pm 0.58\ (\text{stat.})^{+0.47}_{-0.72}\ (\text{syst.})\ \text{pb.}$$

Bins:

$$\tilde{Q}^2 > 35\,\text{GeV}^2$$
$$E_e > 10\,\text{GeV}$$
$$139.8^\circ < \theta_e < 171.8^\circ$$
$$5\,\text{GeV} < E_T^\gamma < 10\,\text{GeV}$$
$$-0.7 < \eta^\gamma < 0.9$$

+ photon isolation cuts



H1 [hep-ph/0607093]: Similar, but slightly different bins

Numbers well reproduced by LO QCD by A. Gehrmann-de Ridder et al. [PRL 2006, EPJC 2006]

Promise of EIC

Whatever HERA could do, EIC can do better!

(due to larger luminosity)

Size of SSA

→ unknown, any estimate would be pure speculation, probably small

Any experimental information would help…

Summary

- Transverse Spin Polarization: Long history, measured in ep/pp-collisions, theoretical treatment more complicated than unpol. CS
- We can learn about the parton dynamics in the nucleon, e.g., transverse forces, non-perturbative QCD EoM and LIR are crucial
- Photon SIDIS: May be able to scan the support of dynamical twist-3 functions point-by-point at LO.
- Experimental opportunity at EIC (COMPASS, JLab ?)
  $\longrightarrow$ input would help our understanding of quark-gluon correlation
  $\longrightarrow$ valuable for evolution of qgq functions and TMDs.