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# The transverse SSA in $\gamma$ SIDIS (within coll. twist-3 formalism)

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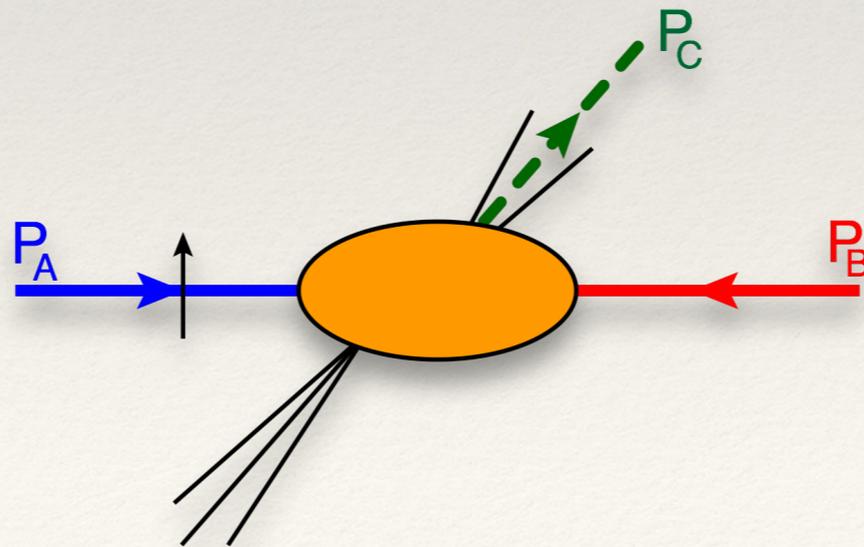
based on W. Albaltan, A. Prokudin, M.S., [arXiv:1910.02883](https://arxiv.org/abs/1910.02883)

Work supported by DOE *TMD collaboration* & NSF



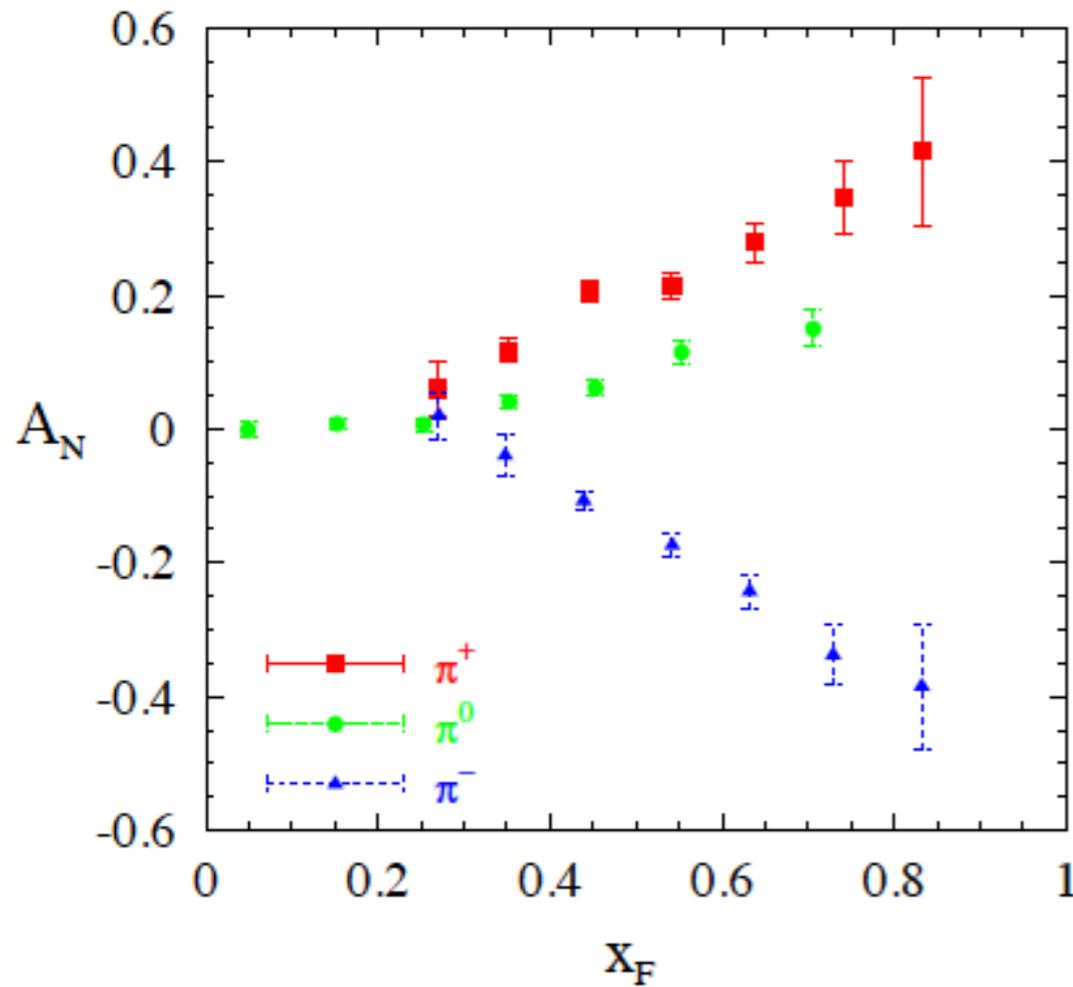
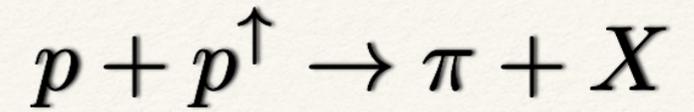
# Transverse Spin Effects in Single-Inclusive Hard Processes

$$P_A^\uparrow + P_B \rightarrow P_C + X$$

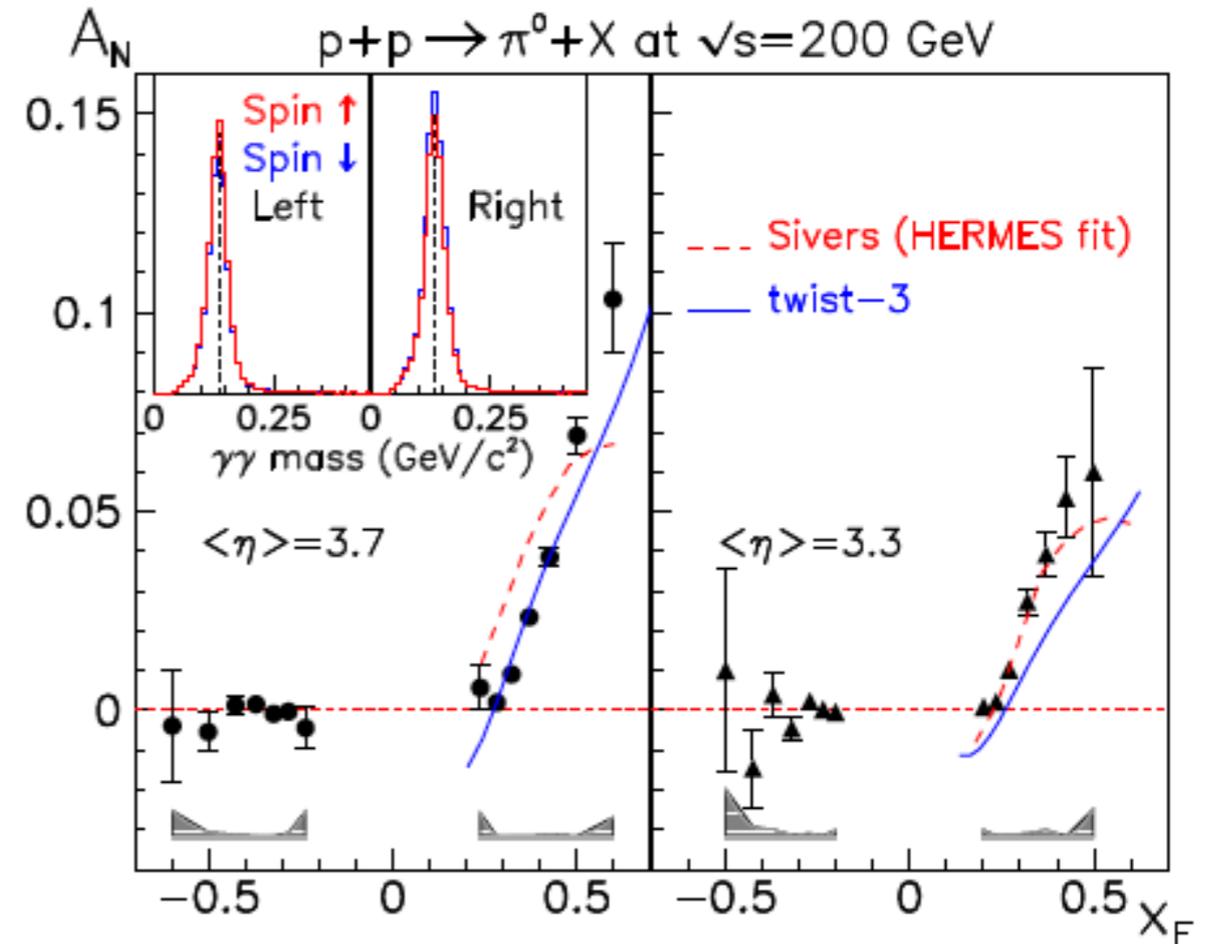


# Transverse SSA

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



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



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

large effects

cannot be explained in the standard parton model  
(using transversity)

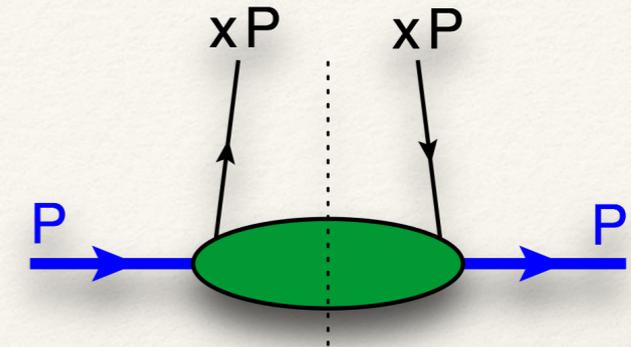
→ collinear Twist-3 Formalism  
(Efremov, Teryaev, Qiu, Sterman)

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

## intrinsic twist-3 PDF

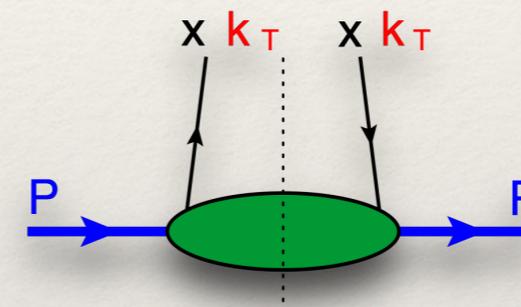
$$g_T^q(x) = -\frac{1}{M} \int \frac{d\lambda}{4\pi} e^{i\lambda x} \langle P, S_T | \bar{q}(0) \not{S}_T \gamma_5 q(\lambda n) | P, S_T \rangle$$

- 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  $k_T$ :



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

Sivers function

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

'transhelicity'

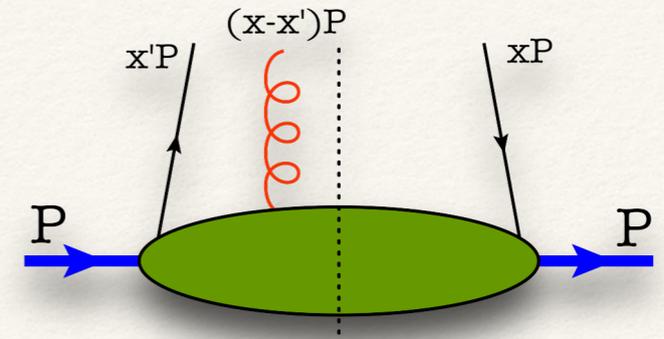
Collinear twist-3 formalism: TMD moments are needed

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

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

→ twist-3 characteristics through small transverse parton momentum  $k_T$

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



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

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

‘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”  $\pi F_{FT}(x, x) = f_{1T}^{\perp(1)}(x)$  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’

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

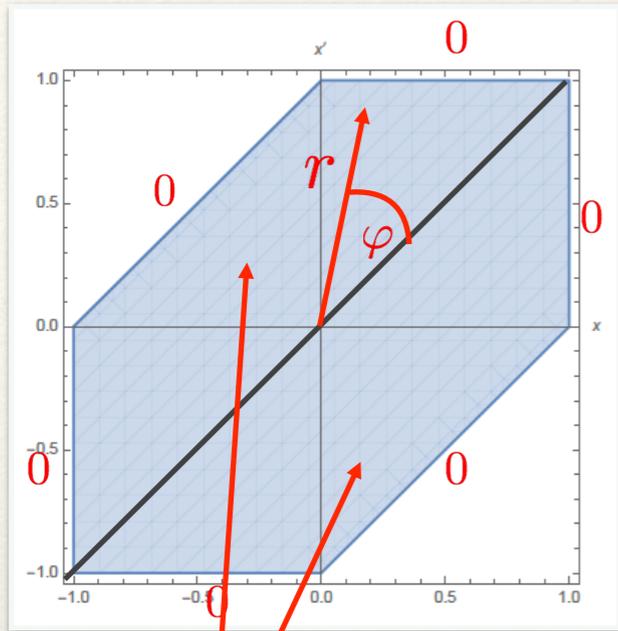
EoM & LIR relation crucial for gauge invariance, invariance of LC vector n

# Support properties

$$-1 \leq x, x' \leq 1$$

$$|x - x'| \leq 1$$

and continuous



'terra incognita'

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

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

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

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

Fixes  $a_0, a_1$

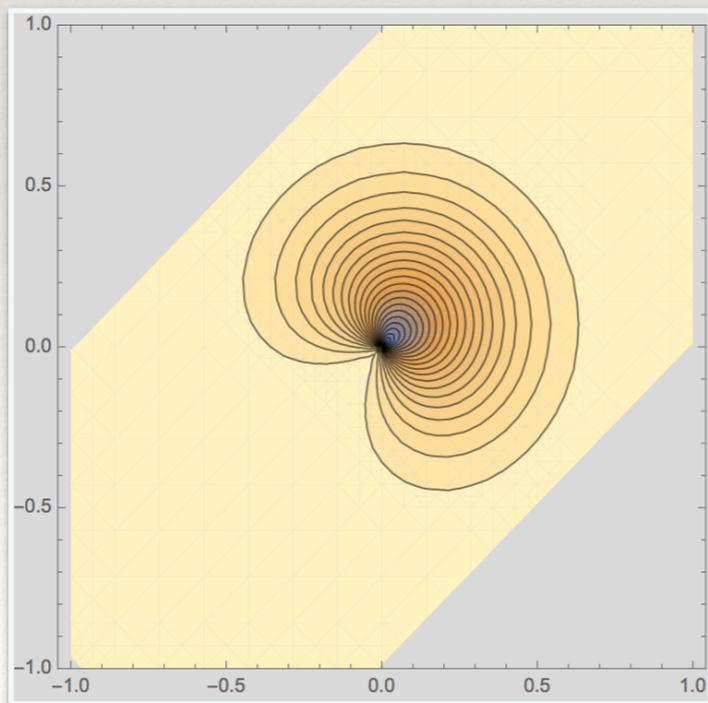
'Gluon poles' 'known' from SIDIS experiments

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

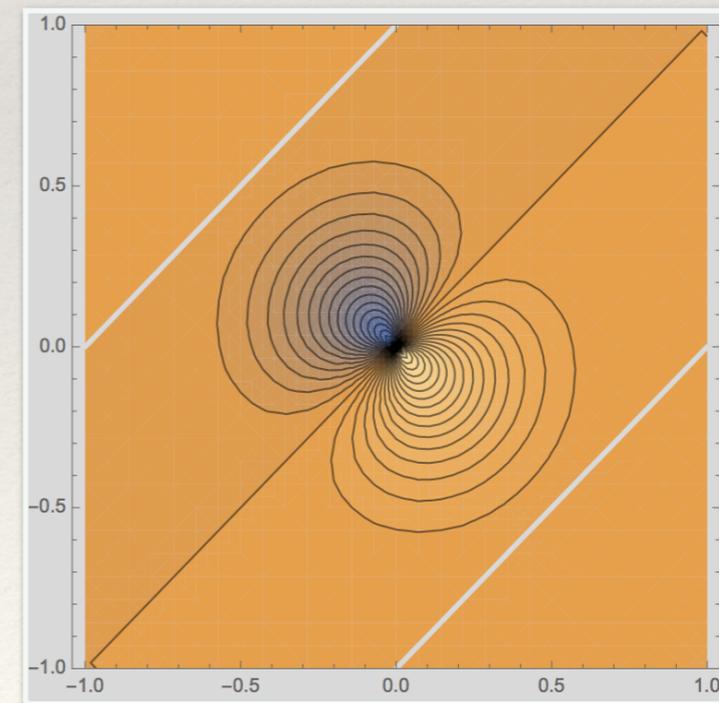
$$G_{FT}(x, x') = \left( \frac{(1-x^2)(1-x'^2)(1-(x-x'))}{(1-xx')^2} \right)^\delta (a_0(r) \sin(\varphi))$$

Model ansätze

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



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

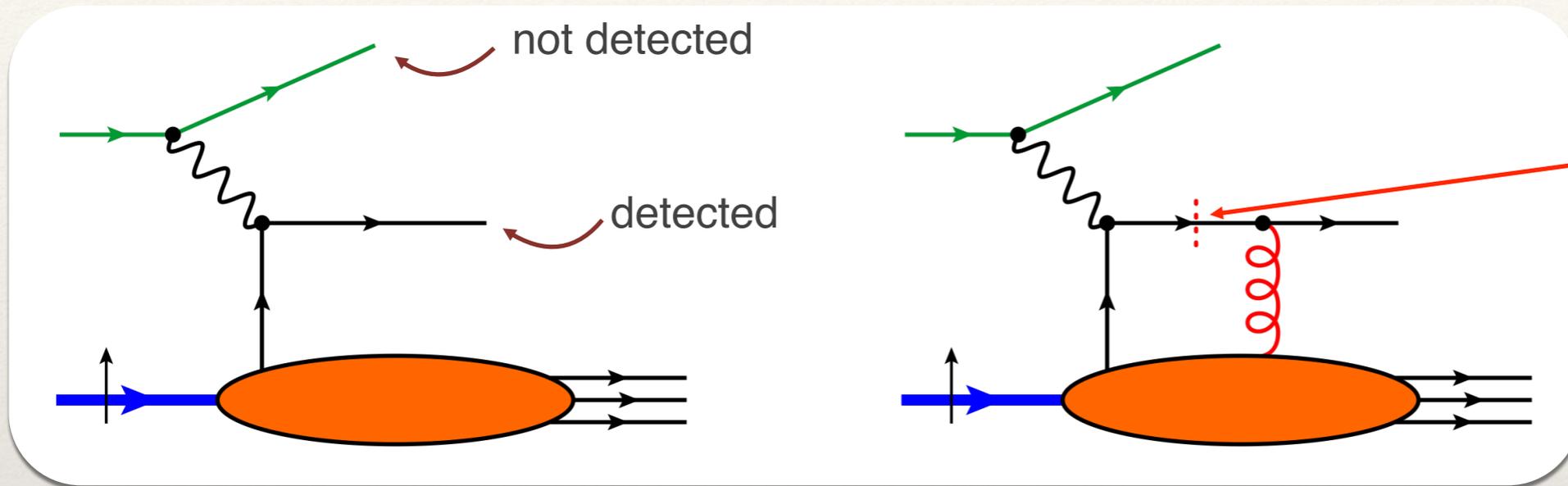


# How do quark-gluon correlations generate an SSA?

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



Kinematical twist-3

Dynamical twist-3

Soft gluon pole

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

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

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: $e(l) + N(P) \rightarrow e(l') + \gamma(P_\gamma) + X$

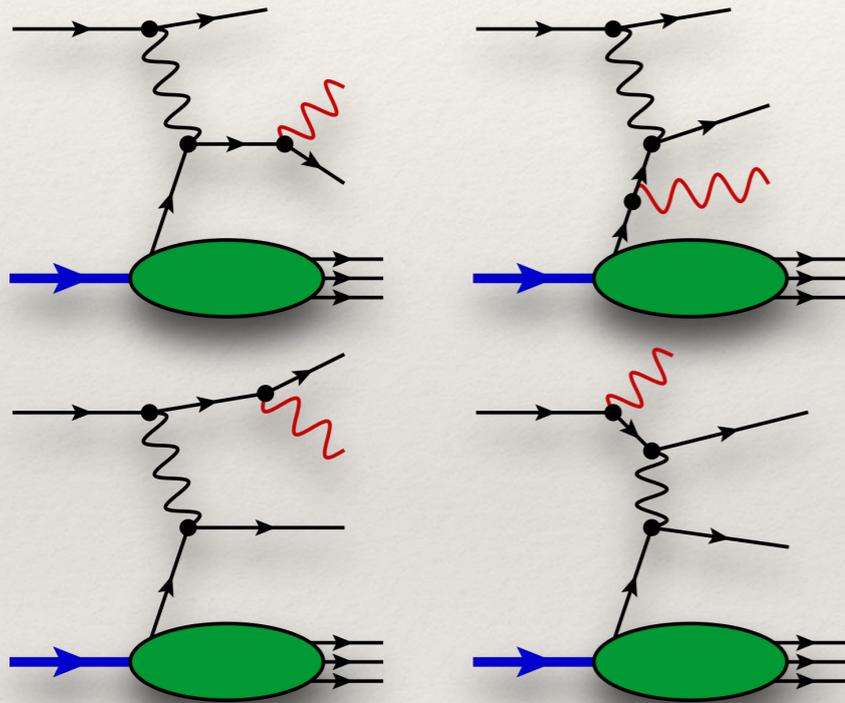
[Albaltan, Prokudin, M.S., arXiv:1910.02883]

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:

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

$$f_{\text{BH}}(x_B) = \sum_{q=u,d,\dots} e_q^2 (f_1^q + f_1^{\bar{q}})(x_B) \quad f_{\text{C}}(x_B) = \sum_{q=u,d,\dots} e_q^4 (f_1^q + f_1^{\bar{q}})(x_B)$$

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

- two scales:

$$Q^2 = -(l - l' - P_\gamma)^2$$

$$\tilde{Q}^2 = -(l - l')^2$$

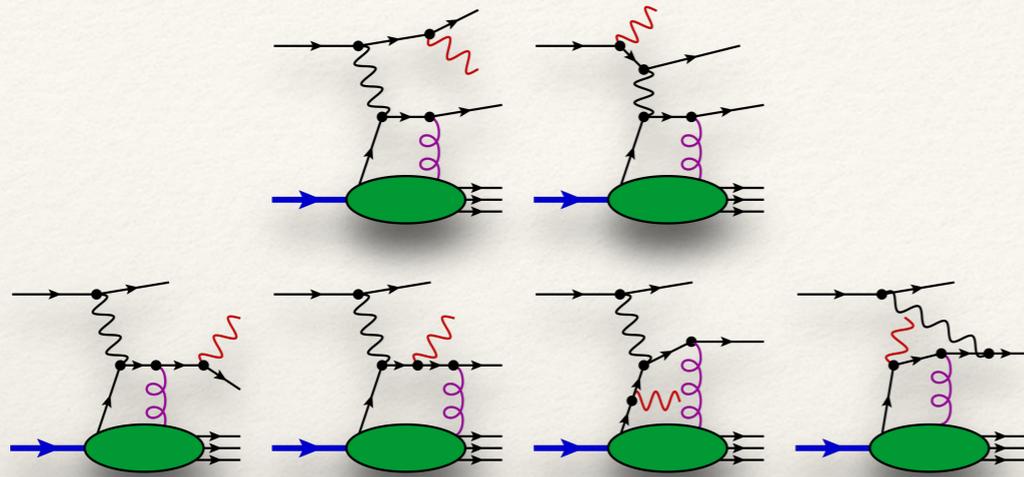
- two scaling 'Bjorken-x':

$$x_B = \frac{Q^2}{2P \cdot (l - l' - P_\gamma)}$$

$$\tilde{x}_B = \frac{\tilde{Q}^2}{2P \cdot (l - l')}$$

# 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

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

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

## 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

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

$$C_{l,\gamma} = \sum_{i=BH,C,I} \left[ \begin{array}{l} \Delta\hat{c}_{1;l,\gamma}^i g_1^i(x_B) + \Delta\hat{c}_{2;l,\gamma}^i \int_{x_B}^1 \frac{dx}{x} g_1^i(x) \quad \text{WW - contribution} \\ \text{dyn. tw3} \quad + \int_{x_B}^1 dx \int_{-(1-x)}^1 dx' (\Delta\hat{c}_{F;l,\gamma}^i(x,x') F_{FT}^i(x,x') + \Delta\hat{c}_{G;l,\gamma}^i(x,x') G_{FT}^i(x,x')) \end{array} \right]$$

- 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)?

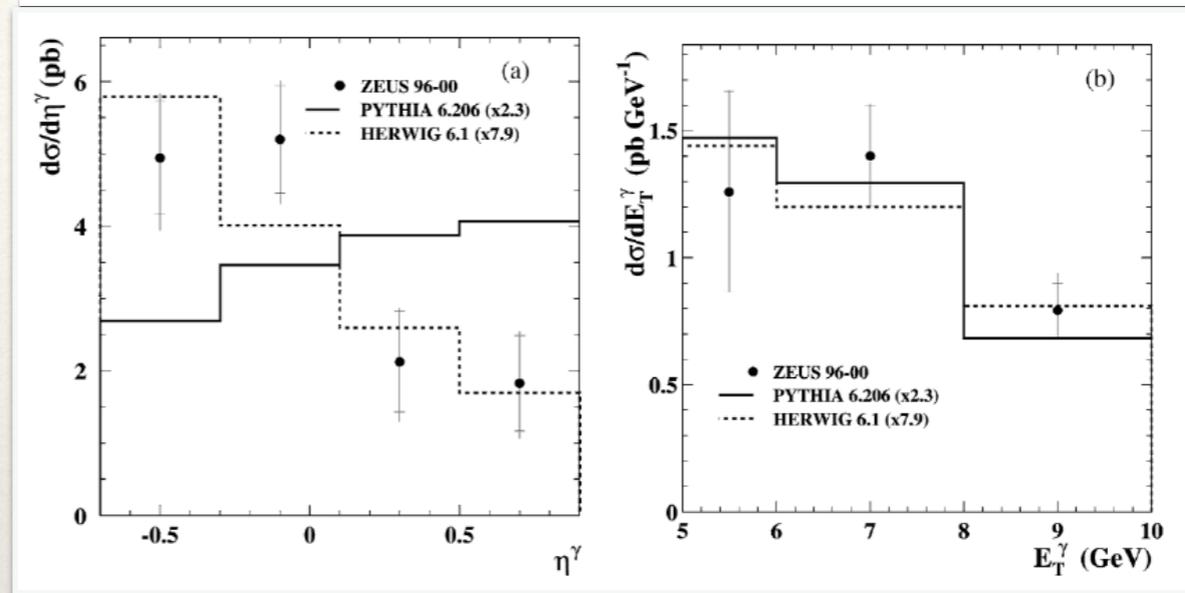
Previous HERA measurements at ZEUS (2004), H1 (2006)

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

**Bins:**

$$\begin{aligned} \tilde{Q}^2 &> 35 \text{ GeV}^2 \\ E_e &> 10 \text{ GeV} \\ 139.8^\circ &< \theta_e < 171.8^\circ \\ 5 \text{ GeV} &< E_T^\gamma < 10 \text{ GeV} \\ -0.7 &< \eta^\gamma < 0.9 \\ &+ \text{photon isolation cuts} \end{aligned}$$

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



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...

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# Summary

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- ❖ 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 ?)
  - input would help our understanding of quark-gluon correlation
  - valuable for evolution of qgq functions and TMDs.