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Mechanisms for transverse single-spin asymmetries

Marc Schlegel
Department of Physics
New Mexico State University

Transverse SSA

A + B$^{\uparrow}$ → C + D + ... + X

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

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TMD factorization

SIDIS, DY, e^+e^-

Limitation:

small transverse final state momentum

$q_T << Q$

imaginary part needed

→ T-odd TMDs (e.g. Sivers function)

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No kinematical limitation

Quark-Gluon-Quark correlations

imaginary part from hard part

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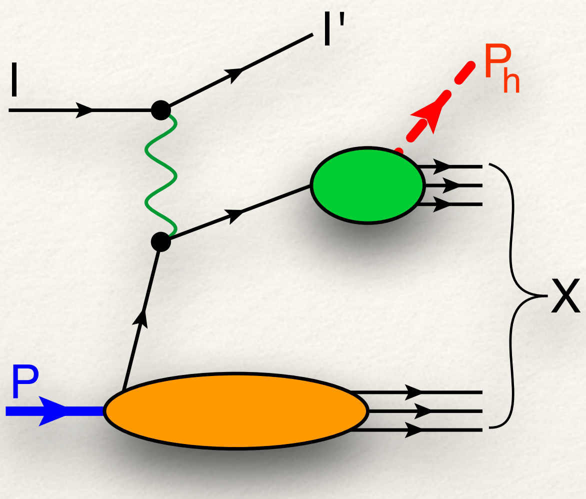
related

- Transverse SSA also possible for final state polarization → Λ - production
- Double spin asymmetries A_{LT} equally important!

TMD factorization: SIDIS $eN^{\uparrow} \to e\pi X$



$$\frac{d\sigma^{\rm SIDIS}}{d^2 P_{h\perp}}$$

SIDIS Spin Structure Functions:

[Bacchetta, Diehl, Goeke, Metz, Mulders, MS, JHEP (2007)]

$$\frac{d\sigma^{\rm SIDIS}}{d^2 P_{h\perp}} \propto \left[F_{UU,T} + S_T \sin(\phi_h - \phi_s)\ F_{UT}^{\rm Siv} + 16 \text{ S.F.}\right]$$

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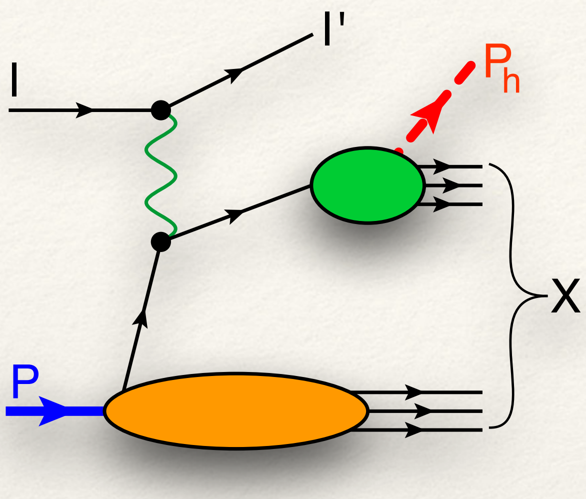

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P_{hT} small → sensitive to partonic transverse momentum k_T

→ Transverse Momentum Dependent (TMD) distributions

$$f(x, k_T^2)$$

$$F \propto |H|^2 \int d^2 k_T \int d^2 p_T\, \delta^{(2)}(k_T - p_T - P_{h\perp}/z)\, f(x, k_T^2)\, D(z, p_T^2) \equiv |H|^2 \left[f \otimes D\right]$$

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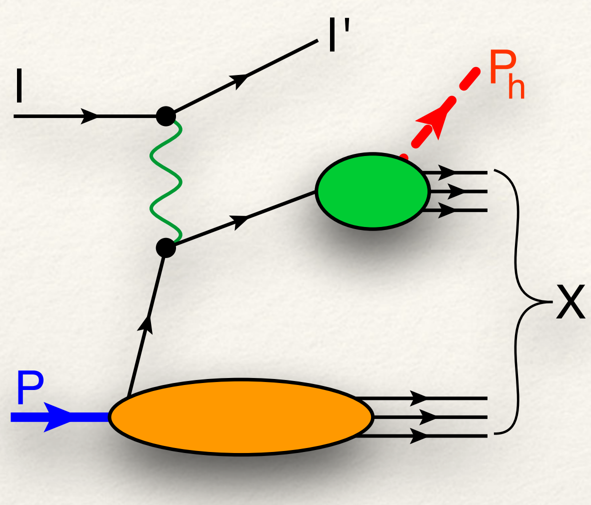

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Sivers effect

$$A_{UT}^{\rm Siv} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

Sivers function

(Naive) definition of the Sivers function

$$f_1^q(x, k_T^2) \propto \int \frac{d\lambda\, d^2 z_T}{(2\pi)^3}\, \mathrm{e}^{i\lambda x + i k_T \cdot z_T} \langle P|\bar{q}(0)\, \not{n} \mathcal{W}\, q(\lambda n + z_T)\,|P\rangle$$

Unpolarized TMD

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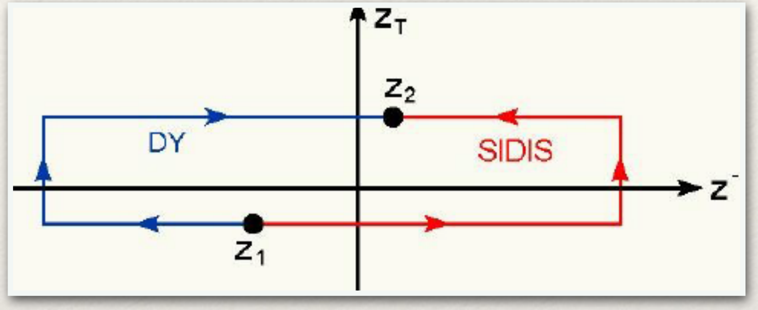
Physics of the Wilson line

$$\mathcal{W}[a;b] = \mathcal{P}\mathrm{e}^{-ig\int_a^b ds\cdot A(s)}$$



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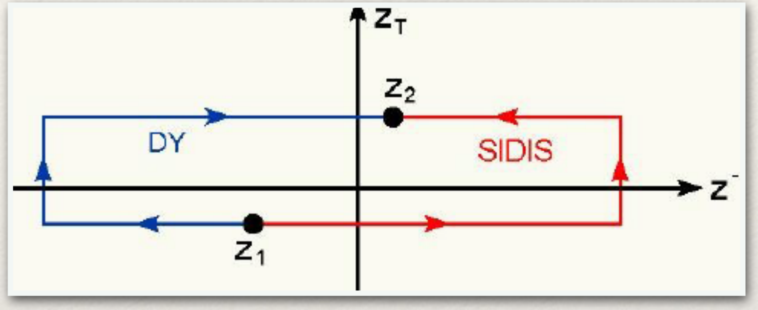
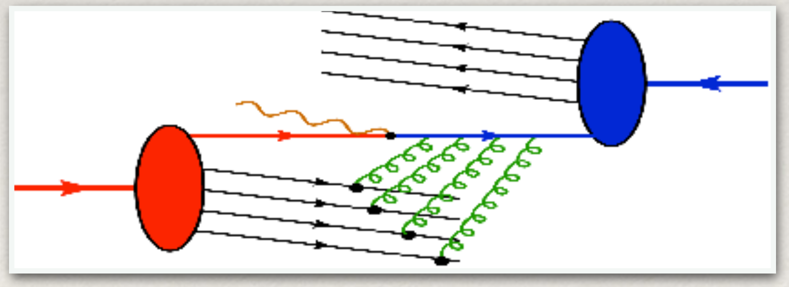
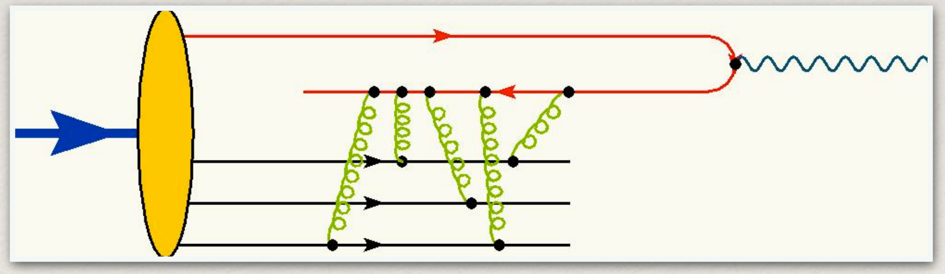


Initial State Interactions: Drell-Yan



Final State Interactions: SIDIS



$\mathcal{PT}$ - Transformation on the quark correlator → ISI ⇔ FSI

→ sign switch of Sivers function "time-reversal (T)-odd"

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$$

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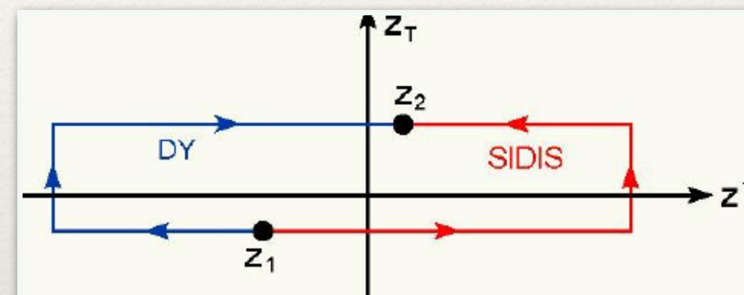

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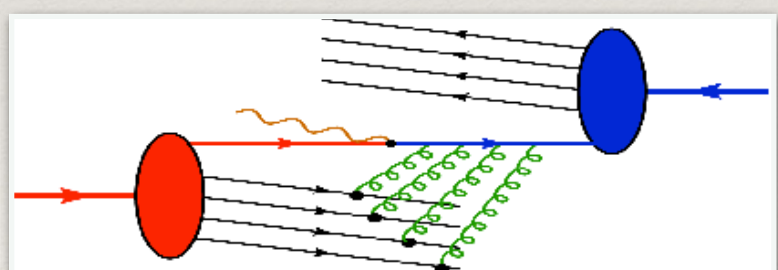

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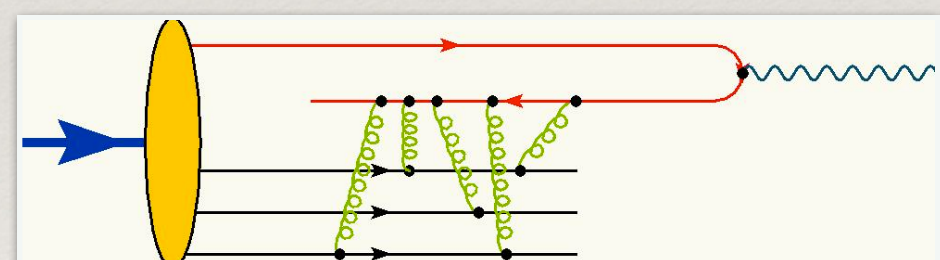

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→ sign switch of Sivers function “time-reversal (T)-odd” $f_{1T}^{\perp}\big|_{DIS} = -f_{1T}^{\perp}\big|_{DY}$

→ important theoretical prediction to test TMD factorization, experimental leads that point in this direction RHIC, COMPASS → talk by M. Radici

Proper TMD definition & Soft function

[Collins; Ji, Yuan; Aybat, Rogers; Echevarria, Idilbi, Scimemi; recent works by Bacchetta et al, Scimemi, Vladimirov et al]

Inclusion of Soft Function $\Longrightarrow$

$$S(b_T) = \frac{1}{N_c} \mathrm{Tr}_c \langle 0 | \mathcal{W}_n^\dagger(-b_T/2)\, \mathcal{W}_{\bar{n}}(-b_T/2)\, \mathcal{W}_{\bar{n}}^\dagger(b_T/2)\, \mathcal{W}_n(b_T/2)\, |0\rangle$$

$$f(x, b_T) \to \frac{f(x, b_T)}{\sqrt{S(b_T)}}$$

Modification needed in order to have:

1) Renormalizable Matrix Element
2) Finite matching coefficients at small b_T

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Evolved unpolarized quark TMD

$$f_1^q(x, \vec{b}_T^2; \mu; \xi) = \sum_{q'} \left(\tilde{C}_{qq'} \otimes q(x)\right)\Big|_{\mu \propto 1/b_*} \mathrm{e}^{S_{\mathrm{pert}}(b_*)}\Big|_{\mu \propto 1/b_*} \mathrm{e}^{g_q(x, b_T) + \frac{1}{2} g_K(b_T) \ln \frac{\xi}{\xi_0}}$$

TMD at large k_T, matching coeff NNLO

perturbative Sudakov factor, N^{3}LO

non-perturbative input

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Evolved Sivers function

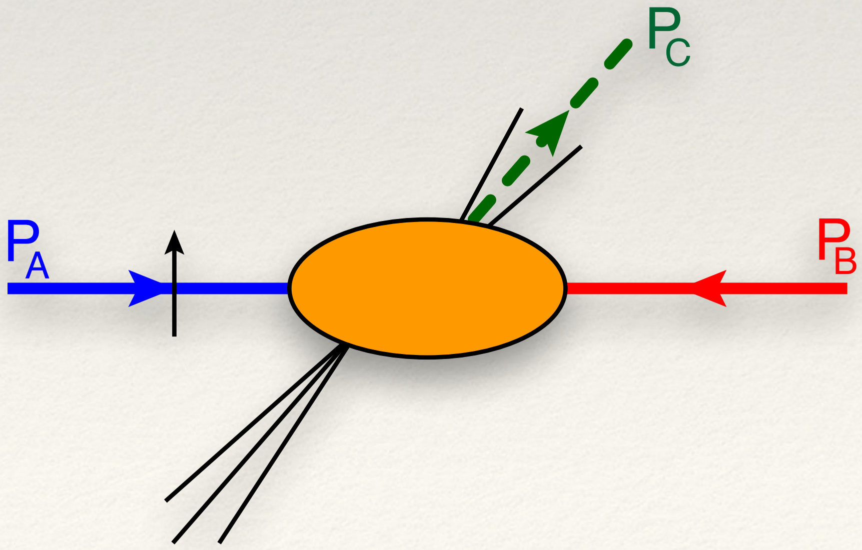
$$f_{1T}^{\perp, q}(x, b_T, ; \mu; \xi) \propto \left[\int dz\, dz'\, C_{1T}^{\perp}(z, z')\, F_{FT}^q(z, z') \right] e^{(S_{\mathrm{pert}} + S_{\mathrm{non-pert}})}$$

matching coeff NLO

quark-gluon-quark correlation function!

Collinear twist-3 in Single-Inclusive Hard Processes

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



Collinear twist-3 formalism: several types of matrix elements

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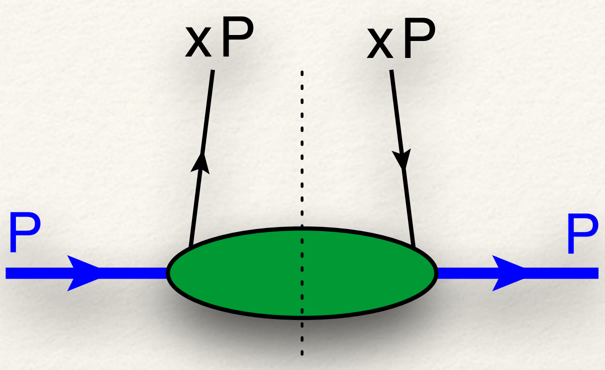
intrinsic twist-3 PDF

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



- sensitive to ‘bad quark field components’,
- twist-3 characteristics hidden in Dirac structure
- generates the g_2 structure function in DIS, relevant for SSA in DIS (2γ)
- No probabilistic interpretation

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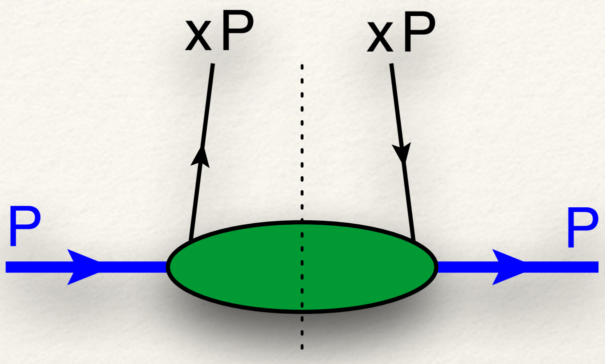

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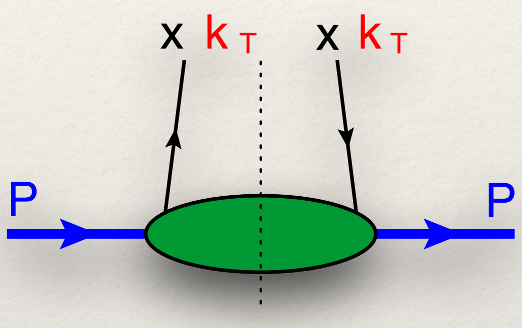

kinematical twist-3 PDFs:

Small transverse quark/gluon momenta k_T:

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

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'transhelicity'

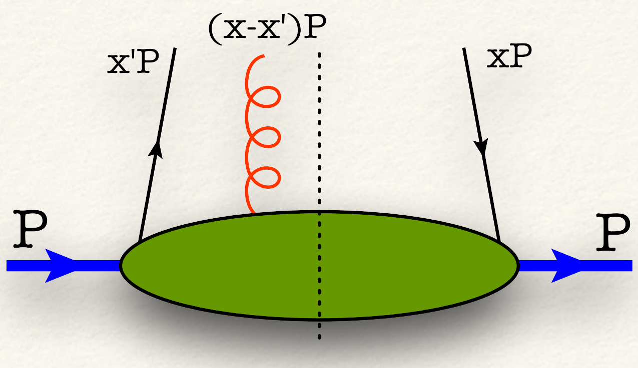
Collinear twist-3 formalism: TMD moments are needed

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

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

→ twist-3 characteristics through small transverse parton momentum k_T

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



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

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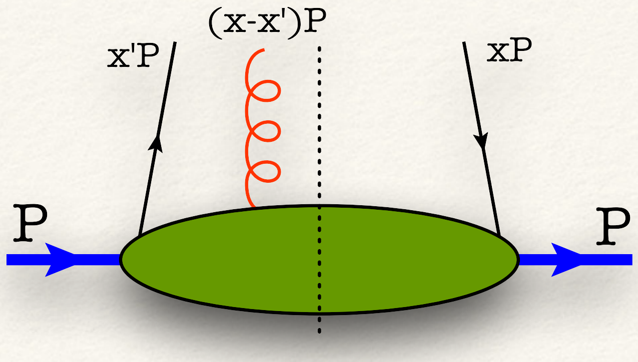

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'dynamical twist - 3'

→ 3 - parton correlator: suppression by additional propagator

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

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

→ 'integrated' $F_{FT}(x,x')$: average transverse color Lorentz force on struck quark
[Burkardt, PRD88, 114502], [Aslan, Burkardt, M.S., 1904.03494]

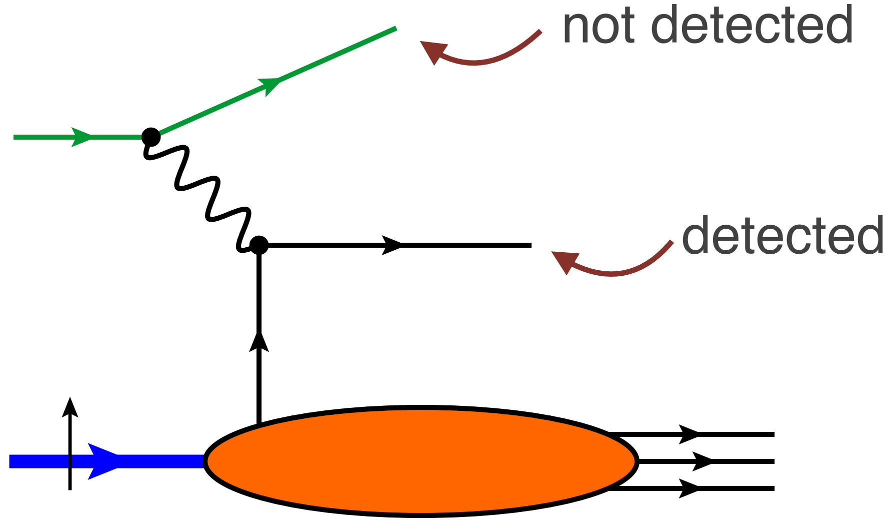
$$F^{n\rho} = [\vec{E} + \vec{n} \times \vec{B}]^\rho \propto \int dx \int dx'\, F_{FT}(x,x') \propto \int dx\, x^2\, g_T(x)$$

How do quark-gluon correlations generate an SSA?

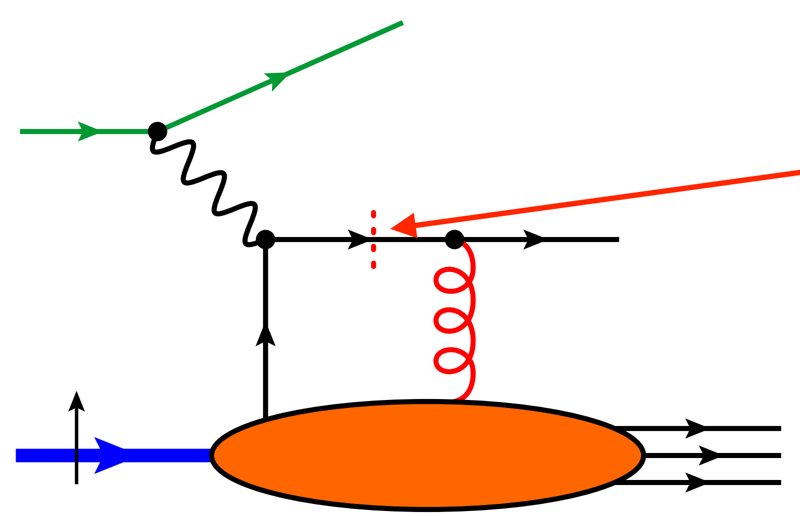
Example: Single-inclusive jet production e $N^{\uparrow}$ → jet X

[Gamberg, Kang, Metz, Pitonyak, Prokudin; Kanazawa, Koike, Metz, Pitonyak, MS]

Simple LO diagrams



Kinematical twist-3



Dynamical twist-3

Soft gluon pole

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

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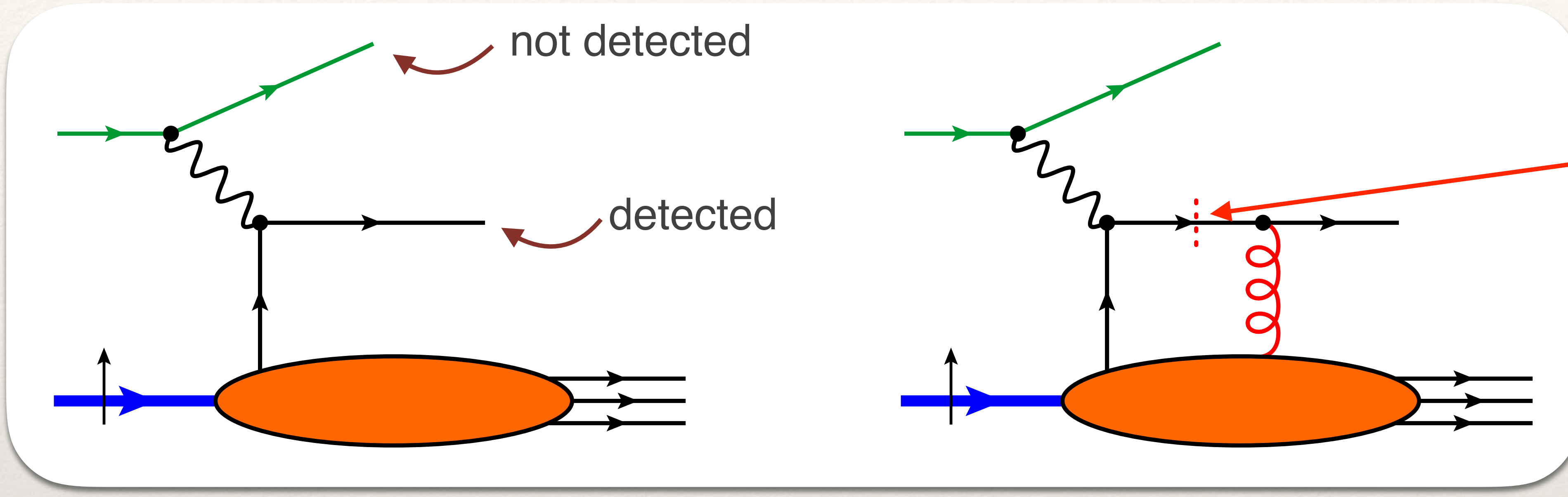

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Kinematical twist-3

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

Photon SIDIS: $e + p \longrightarrow e + \gamma + X$

[Albaltan, Prokudin, M.S., in preparation]

Photon SIDIS: e + p ⟶ e + γ + X

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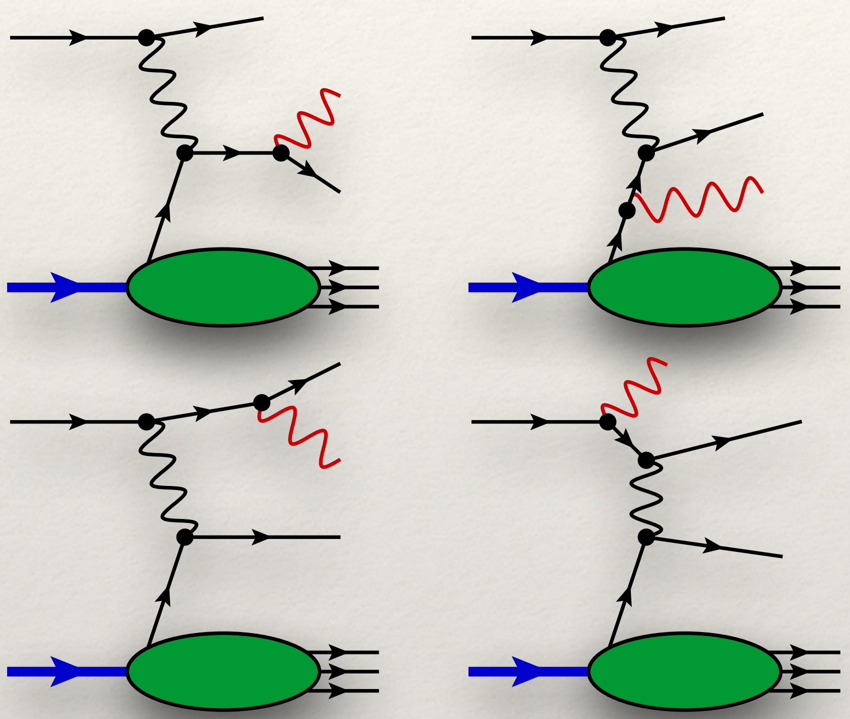
unpolarized cross section in the parton model

[Brodsky, Gunion, Jaffe, PRD 1972; see also works by Metz et al, Pisano, Mukherjee, Vogelsang, …]



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

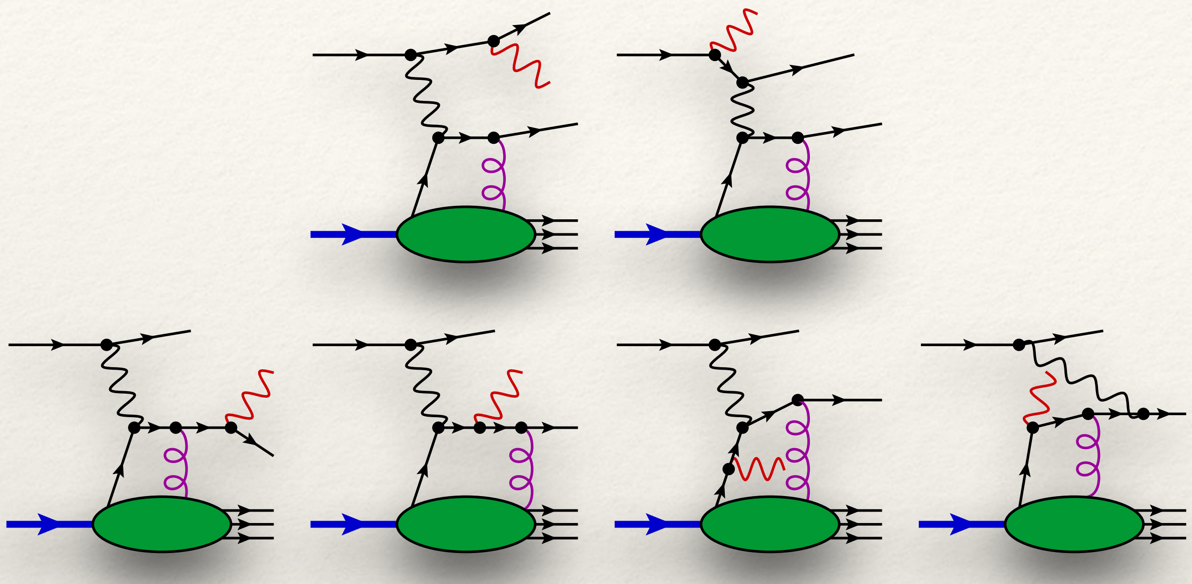
$$E_\gamma E_e \frac{d\sigma_{UU}}{d^3\vec{P}_\gamma \; d^3\vec{P}_e} = \sum_q \left[e_q^2 \; \hat{\sigma}_2 + e_q^3 \; \hat{\sigma}_3 + e_q^4 \; \hat{\sigma}_4 \right] \; f_1^q(\bar{x})$$

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

BGJ - criterion for parton model dominance: $Q^2, \, \tilde{Q}^2 \, , \, |Q^2 - \tilde{Q}^2| \gg M^2$

Transverse SSA in photon SIDIS

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



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: $F_{FT}(x_B,\tilde{x}_B)$

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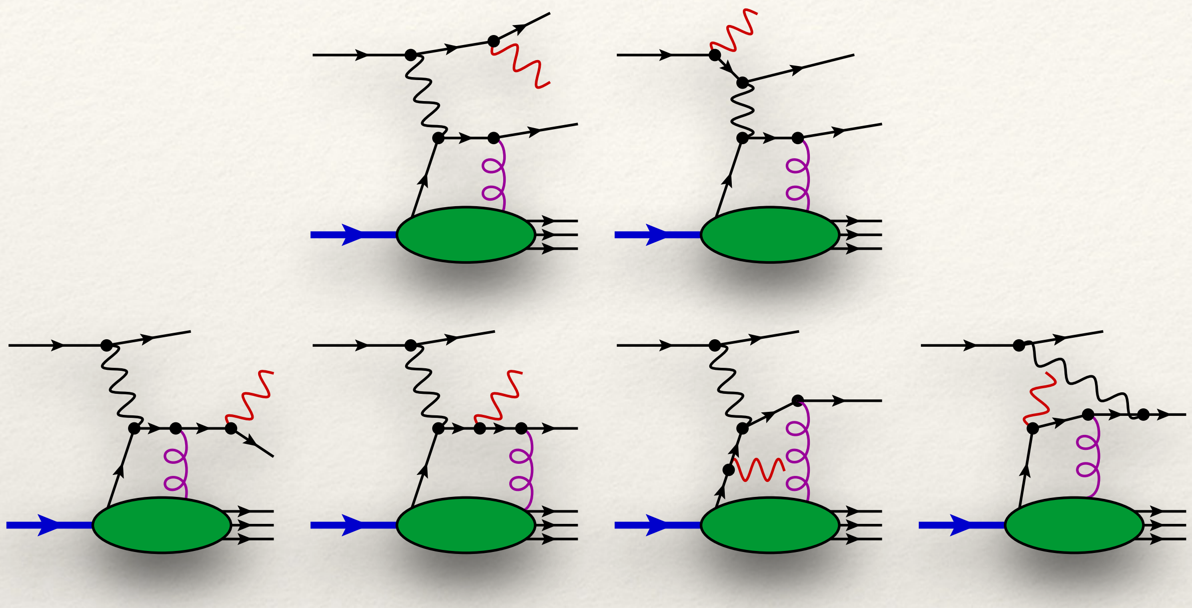

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LO Result:

$$E_\gamma E' \frac{d\sigma_{UT}}{d^3\vec{P}_\gamma d^3\vec{P}_e} = \sum_q \left[\hat{\sigma}_{+,\mathrm{HP}}\, F^q_{FT}(x_B, \tilde{x}_B) + \hat{\sigma}_{+,\mathrm{SFP}}\, F^q_{FT}(x_B, 0) + \hat{\sigma}_{-,\mathrm{HP}}\, G^q_{FT}(x_B, \tilde{x}_B) + \hat{\sigma}_{-,\mathrm{SFP}}\, G^q_{FT}(x_B, 0) \right]$$

Soft Gluon Poles vanish !

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

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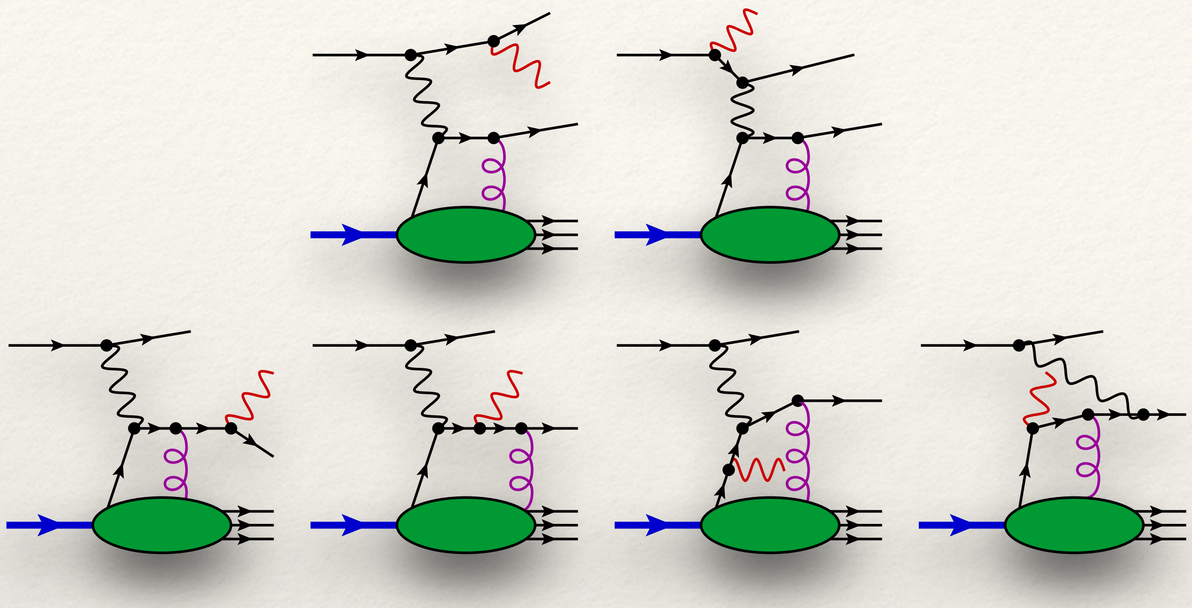

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⇒ unique process to directly study “off-diagonal” support of twist - 3 Quark - Gluon Correlation functions!

Summary

- Transverse Spin Polarization: Long history, measured in ep/pp-collisions, theoretical treatment more complicated
- TMD formalism: Sivers effect in SIDIS and DY: sign change
- Evolved Sivers function through Quark-Gluon correlations
- 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.