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The transverse nucleon spin asymmetry in photon SIDIS in the collinear twist-3 formalism

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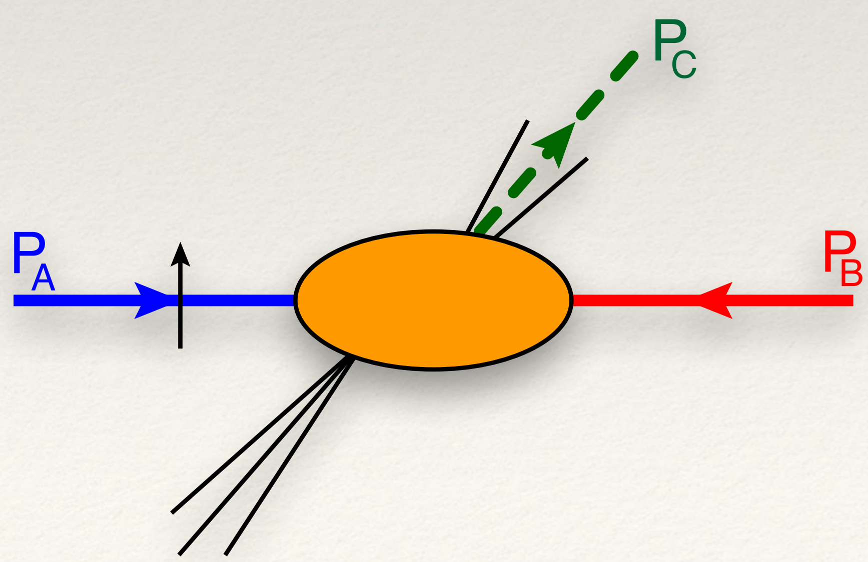
Transverse Spin Effects in Single-Inclusive Hard Processes

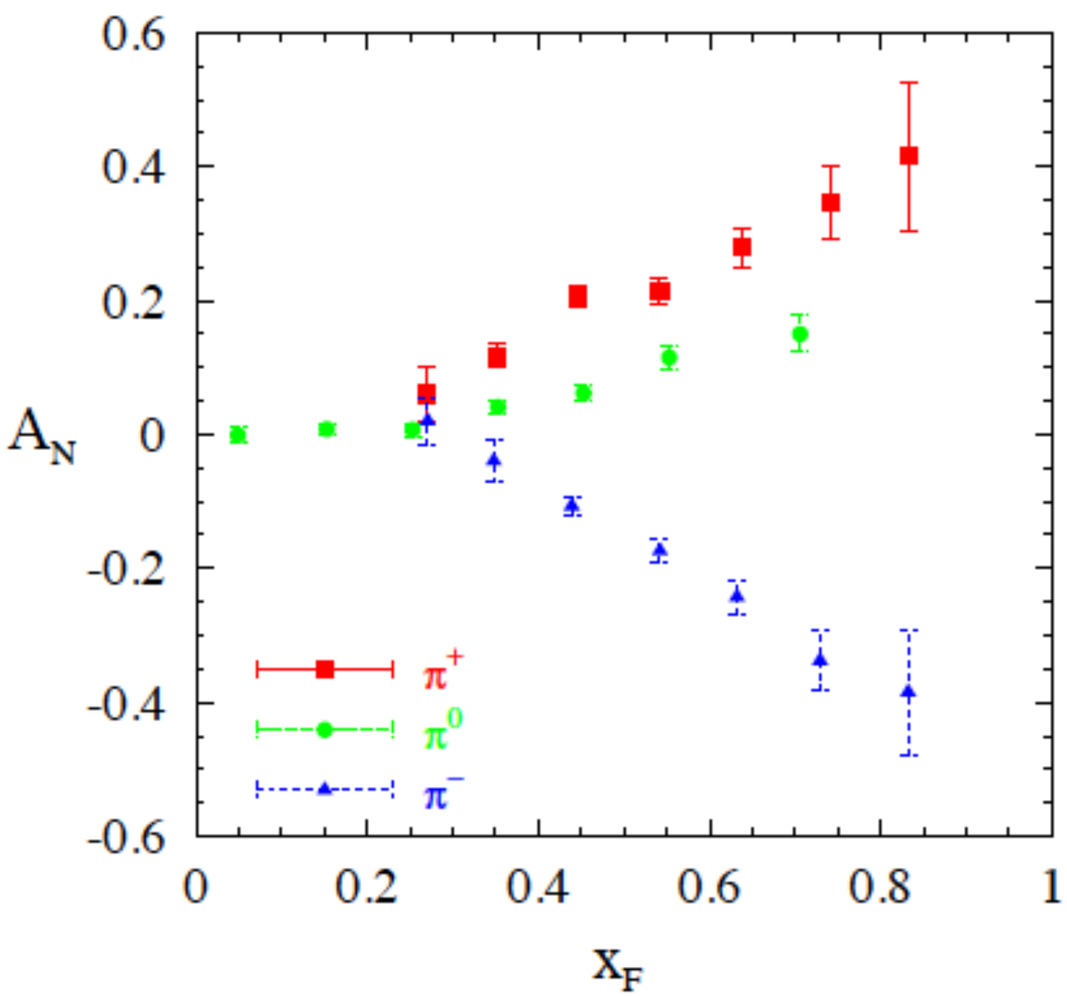
$$P_A^{\uparrow} + P_B \rightarrow P_C + X$$



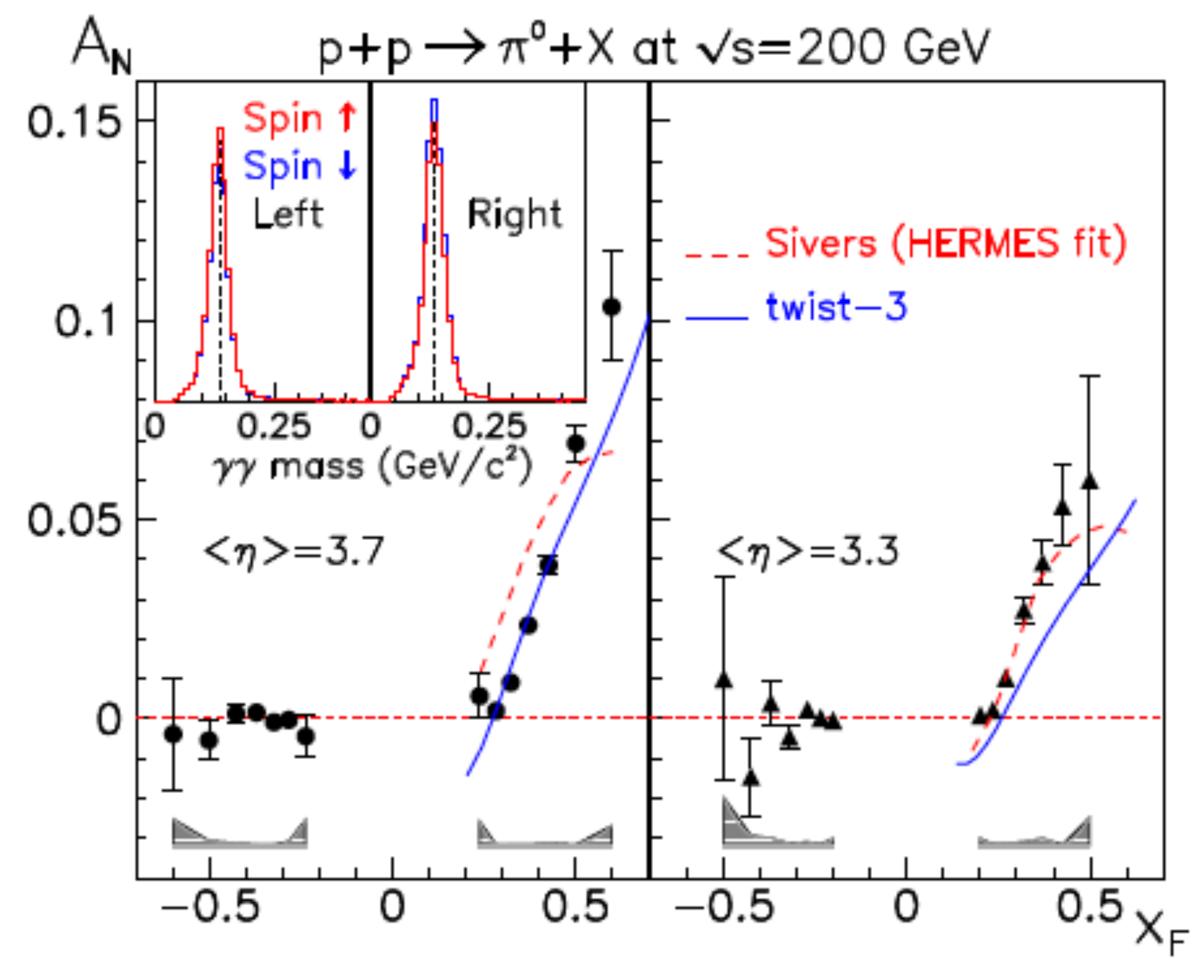
"Show-off" Transverse SSA

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

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



$\sqrt{s} = 20$ 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

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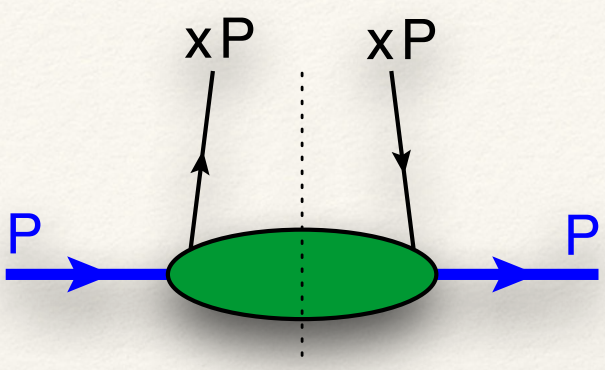
intrinsic twist-3 PDF

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



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

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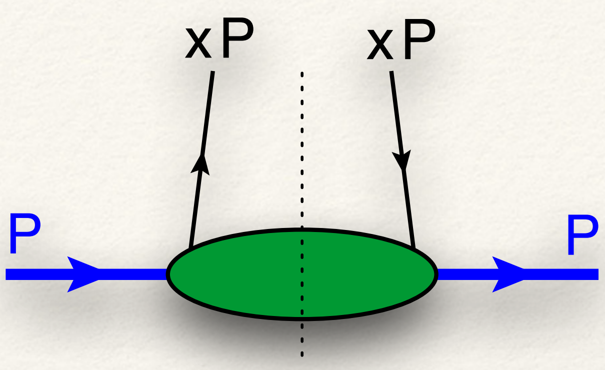

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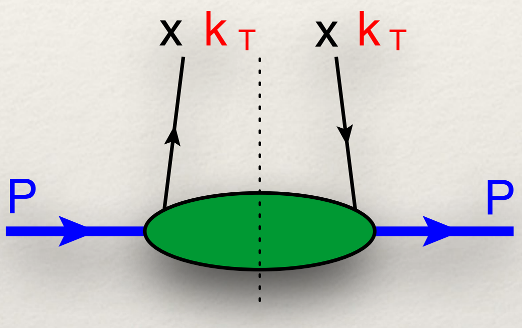
kinematical twist-3 PDFs:

Small transverse quark/gluon momenta k_T:



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

Sivers function

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'transhelicity'

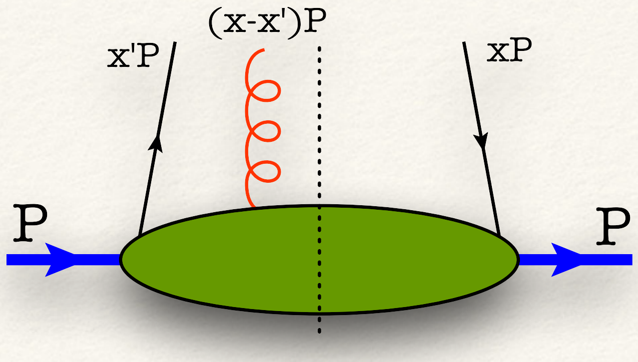
Collinear twist-3 formalism: TMD moments are needed

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

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

→ twist-3 characteristics through small transverse parton momentum k_T

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



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

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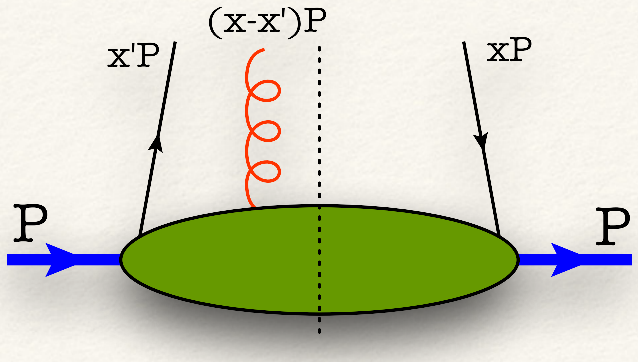

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‘dynamical twist - 3’

→ 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], see talk by M. Burkardt

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

QCD EoM relation & Lorentz-Invariance Relations

[Kanazawa, Koike, Metz, Pitonyak, MS, PRD 2016]

QCD EoM for Twist-3 PDFs

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

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LIR for Twist-3 PDFs

based on translation invariance

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

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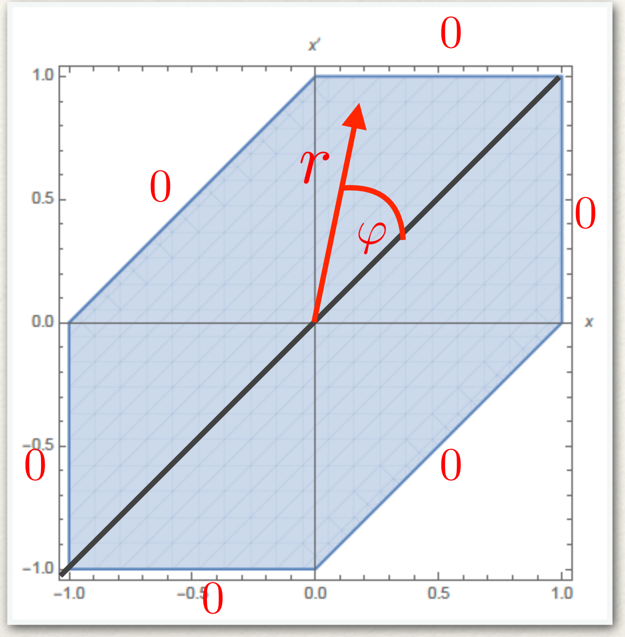
Two equations, three functions → eliminate ‘intrinsic & kinematical twist-3’

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

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



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

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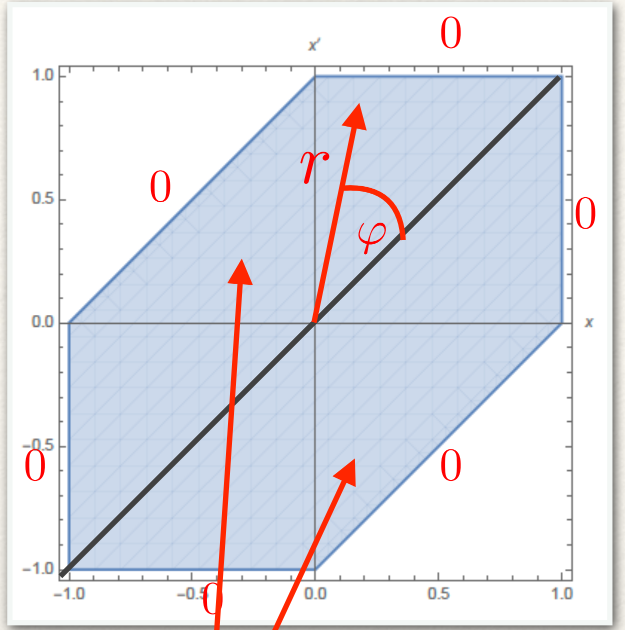

'terra incognita'

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Fixes a_0, a_1

Gluons poles 'known' from SIDIS experiments

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

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Model ansätze

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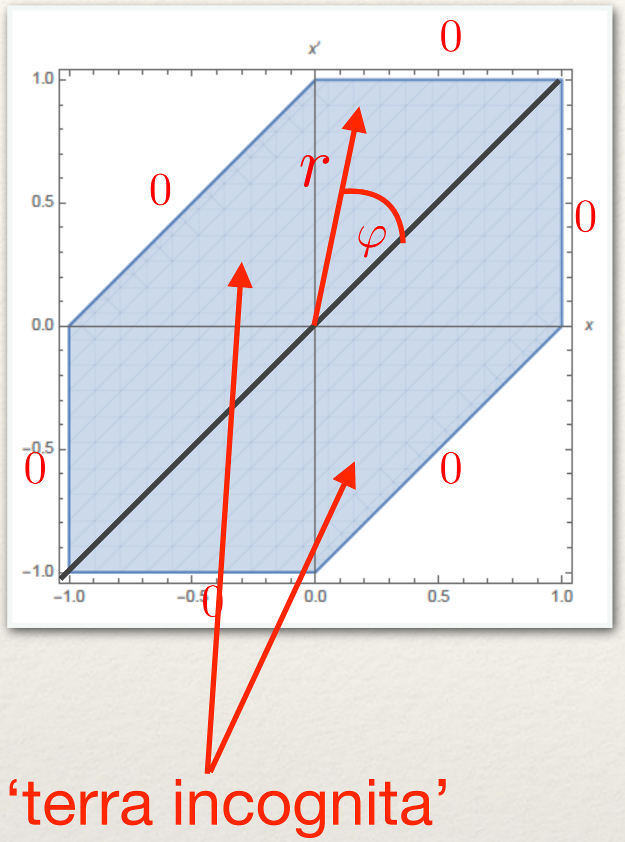

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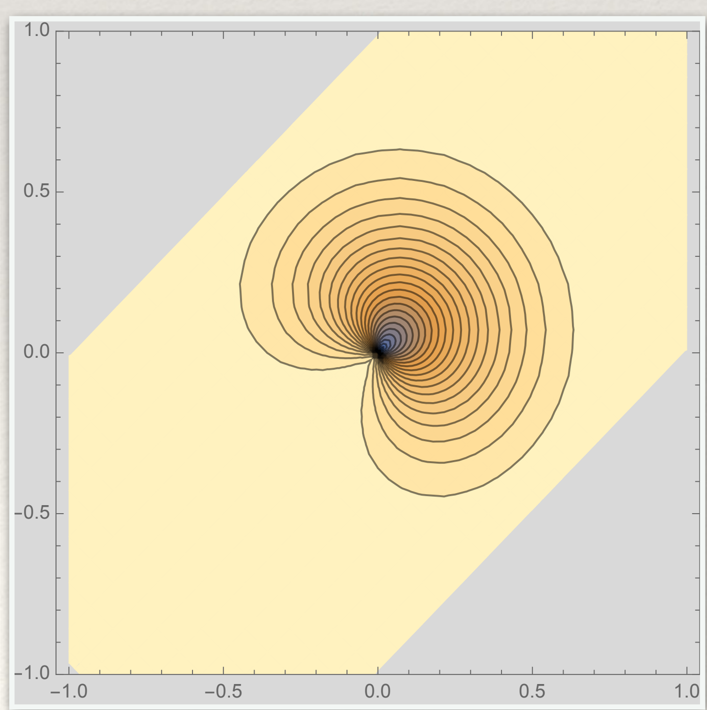

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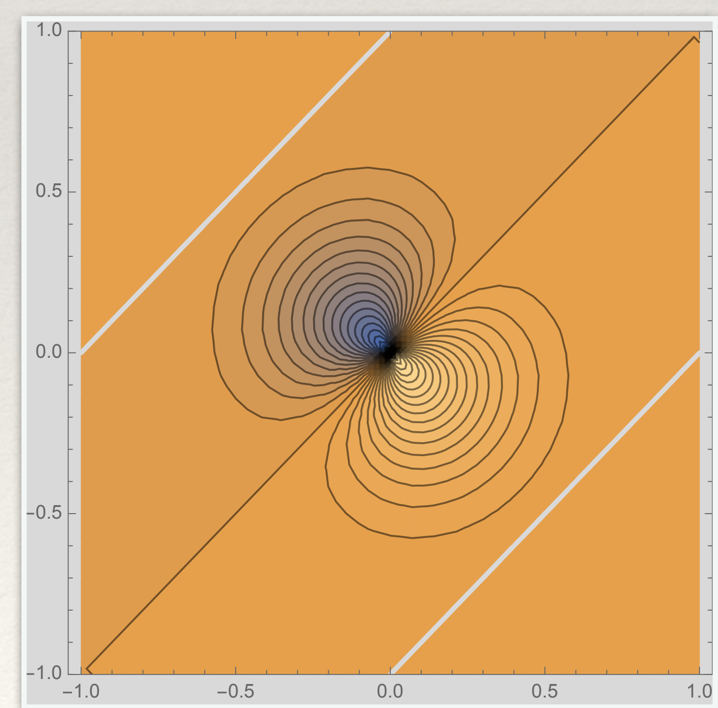

Transverse Spin Asymmetries
in
Photon SIDIS

Transverse SSA in DIS

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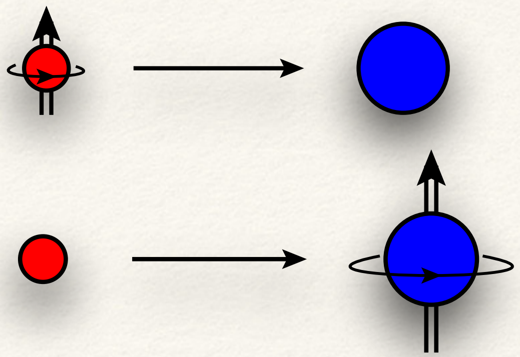
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$



$\Longrightarrow$ New effects for a Two-Photon Exchange!

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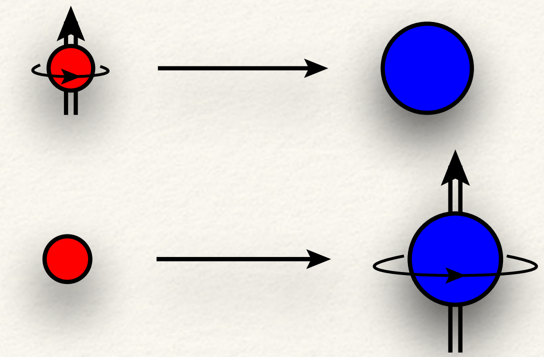
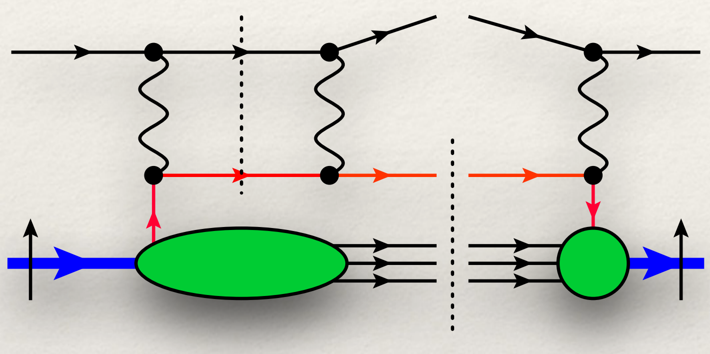


Transverse Target Single Spin Asymmetry in DIS

[Metz, M.S., Goeke, PLB 2006]



$$A_{UT} \propto \alpha_{\rm em} \frac{M}{Q} \left(\frac{a}{\varepsilon} + b\right) \sum_q e_q^3 \, x_B \, g_T^q(x_B)$$

QED NLO soft singularities ⇔ higher twist effects

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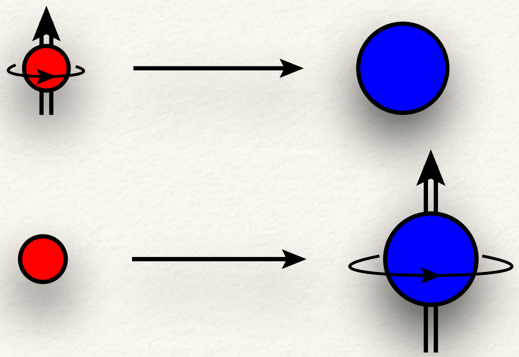

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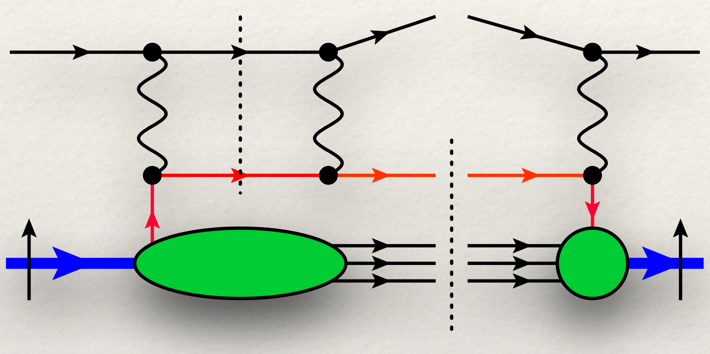

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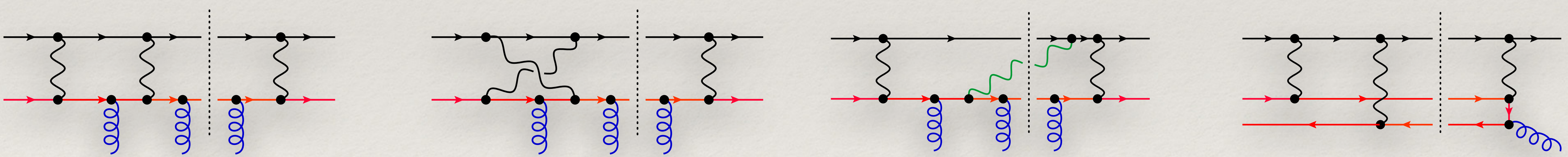
Inclusion of 'Quark - Gluon Correlations'



→ Sum of all twist-3 Two-Photon effects finite with QCD EoM! [MS, PRD 2013]

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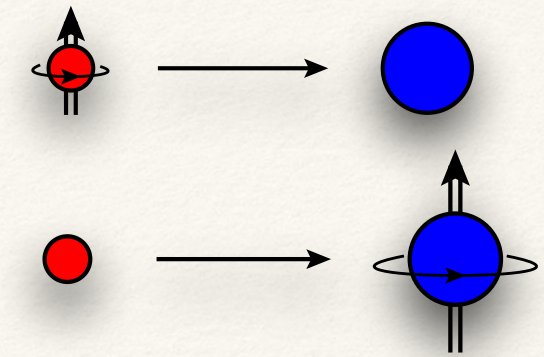

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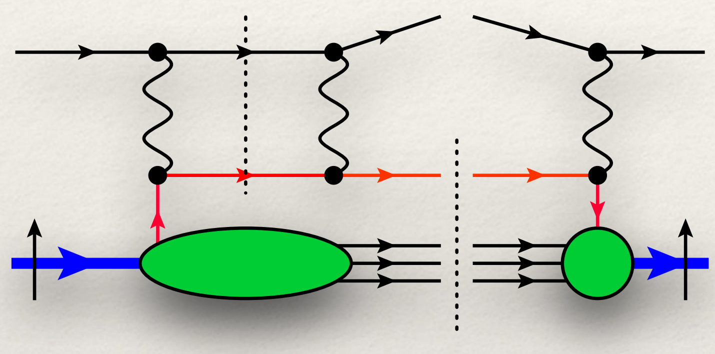

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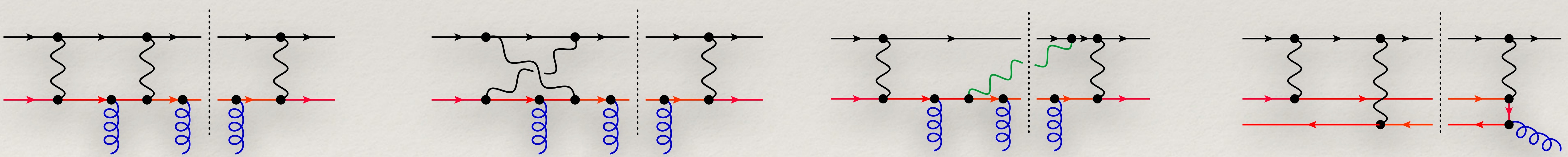

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Result: [MS; Metz, Pitonyak, Schäfer, Schlegel, Vogelsang, PRD 2012, 2013]

$$A_{UT} \propto \alpha_{\rm em} \frac{M}{Q} \left[\int dx' \, \left(\hat{\sigma}_+ \, F_{FT}(x_B, x') + \hat{\sigma}_- \, G_{FT}(x_B, x')\right) + \hat{\sigma}^{\gamma} \, F_{FT}^{\gamma}(x_B, x_B) \right]$$

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

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

Idea: Circumvent Christ - Lee theorem: hard, isolated real photon emission

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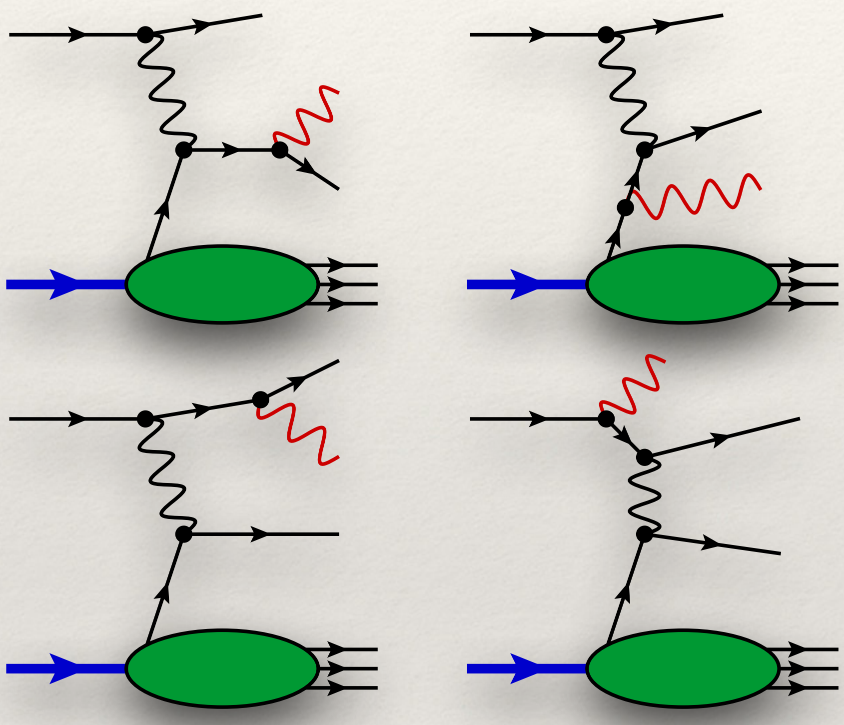
unpolarized cross section in the parton model
[Brodsky, Gunion, Jaffe, PRD 1972]



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

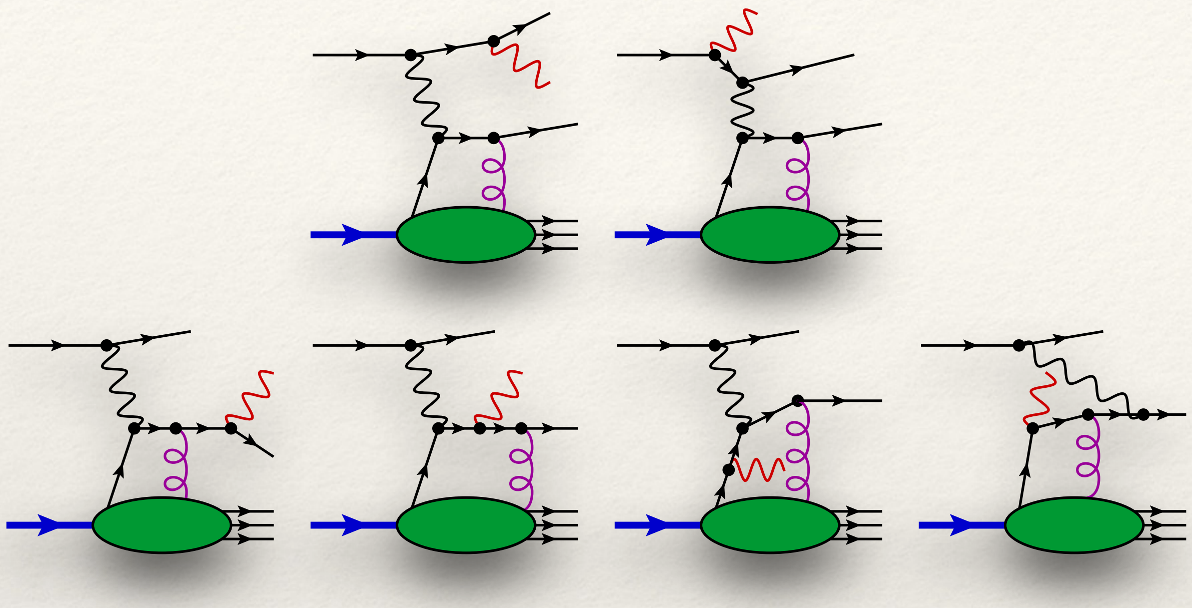
$$E_\gamma E_e \frac{d\sigma_{UU}}{d^3\vec{P}_\gamma\; d^3\vec{P}_e} = \sum_q \left[e_q^2\; \hat{\sigma}_2 + e_q^3\; \hat{\sigma}_3 + e_q^4\; \hat{\sigma}_4 \right]\; f_1^q(\bar{x})$$

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

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: $F_{FT}(x_B,0)$
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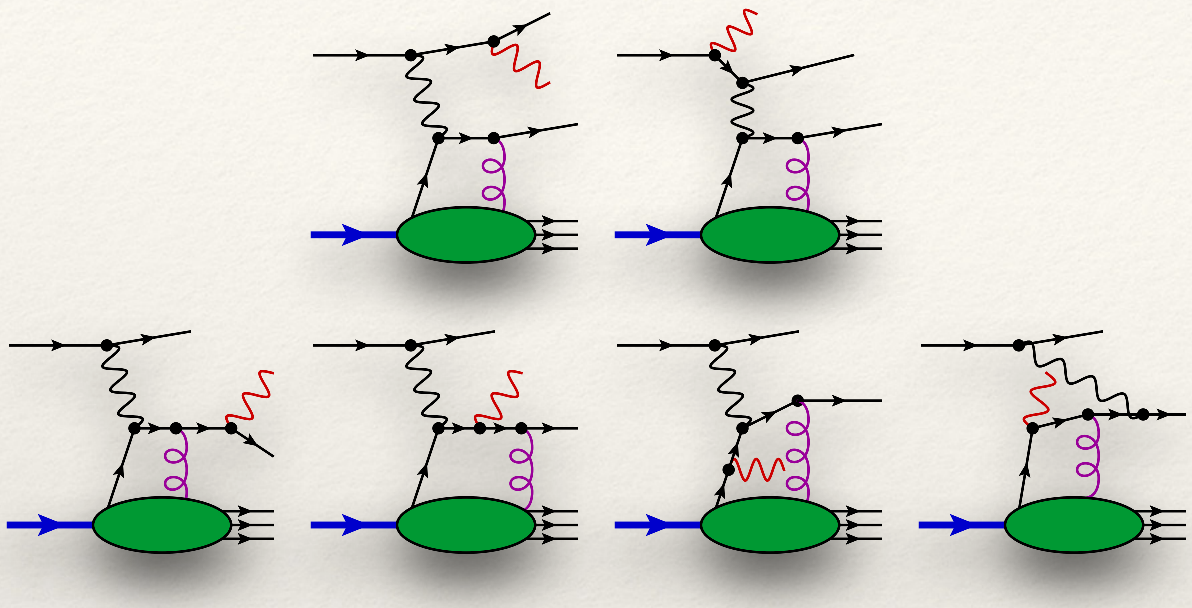

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Soft Gluon Poles vanish !

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

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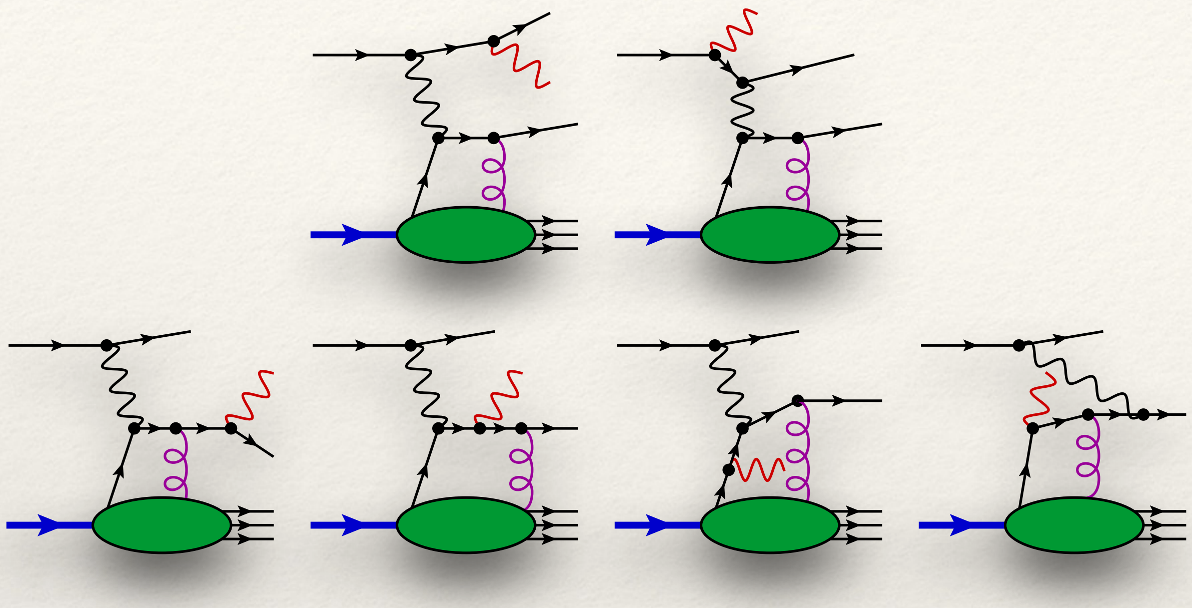

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⇒ unique process to directly study “off-diagonal” support of twist - 3 Quark - Gluon Correlation functions!

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Comparison to DIS cross section at EIC: suppression by α = 1/137

Event rate smaller

→ (1/200 - 1/1000) x DIS ‘total’ (binned) cross section at EIC

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

Comparison to DIS cross section at EIC: suppression by $\alpha = 1/137$

Event rate smaller

→ (1/200 - 1/1000) x DIS 'total' (binned) cross section at EIC

Size of SSA

→ unknown, any estimate would be pure speculation

→ Probably small, no BH contribution, (partial) cancellation of Compton & interference contribution (charge signs)

→ but too small?

Any experimental information would help…

Summary

- Transverse Spin Polarization: Long history, measured in ep/pp-collisions, theoretical treatment more complicated
- 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.