"Precision Physics with MOLLER", Jefferson Lab,
November 06, 2026

Transverse spin asymmetries in lepton-nucleon collisions within collinear perturbative QCD

Marc Schlegel
Institute for Theoretical Physics
University of Tübingen

The transverse electron SSA in lepton - nucleon collisions



MOLLER

Some basic remarks on (transverse) single-spin asymmetries

1) One of the involved (spin 1/2) particles is transversely polarized.

Transverse: Lab frame vs. Breit frame

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

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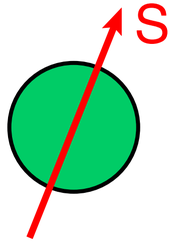
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2) Transverse polarization ⟷ mass of the polarized particle

Spin vector in rest frame



$$P^\mu = (M, 0, 0, 0) = (M, \mathbf{0})$$
$$S^\mu = (0, S_x, S_y, S_z) = (0, \boldsymbol{S})$$
$$P \cdot S = 0 \qquad S \cdot S = -1$$

Example: Dirac particle

$$u_i(P,S)\,\bar{u}_j(P,S) = \tfrac{1}{2}\,(\not{P} + M)\,(1 - \not{S}\gamma_5)$$

chiral odd — chiral even

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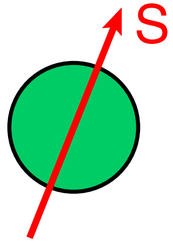
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3) perturbative QCD (collinear factorization) → hard scale: $Q \geq 1\,\mathrm{GeV}$

$$A_N \simeq \frac{M}{Q}$$

power suppression of transverse SSA in inclusive processes expected.

4) Single Spin Asymmetries for inclusive processes [e.m., strong interactions] → Hunt for imaginary parts

$$A_N \simeq i\,\epsilon^{\mu\nu\rho\sigma}\, l_\mu\, l'_\nu\, P_\rho\, S_\sigma = i\,\epsilon^{ll'PS}$$

compensate the imaginary unit i:

Other sources: Loops, non-perturbative phases, γ_5

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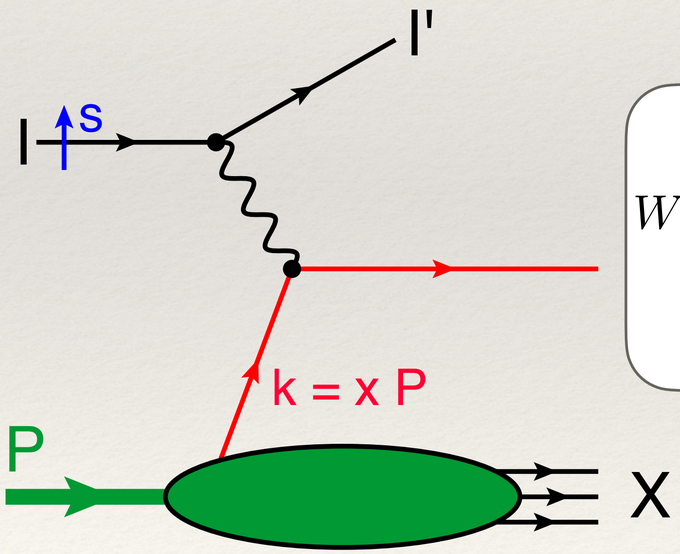
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Deep-Inelastic Scattering (DIS)

Simple Parton model



DIS region

$$Q \geq 1\,\mathrm{GeV}$$

$$W = (P+q)^2 \geq 2 - 4\,\mathrm{GeV}^2$$

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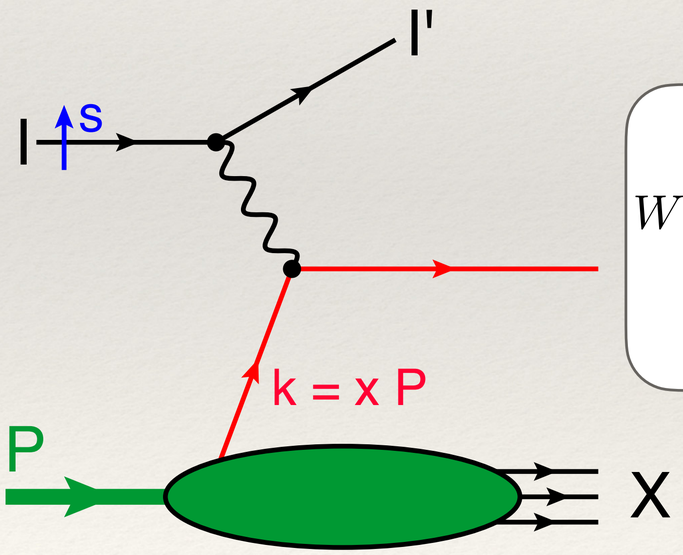
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One-Photon Exchange

$$d\sigma \sim L_{\mu\nu}(l,l',s)\, W^{\mu\nu}(P,q)$$

Leptonic tensor

$$L_{\mu\nu}(l,l',s) = Tr[\gamma^\nu(\not{l}' + m_e)\gamma^\mu(\not{l} + m_e)(1 - \not{s}\gamma_5)]$$

$$\sim l^{\{\mu} l'^{\nu\}} - \tfrac{1}{2}Q^2 g^{\mu\nu} - m_e\, i\,\epsilon^{qs\mu\nu}$$

Unpolarized Hadronic tensor

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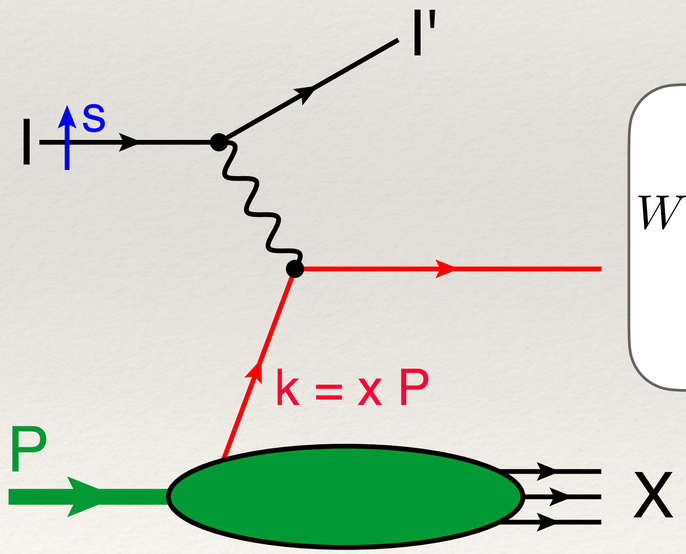
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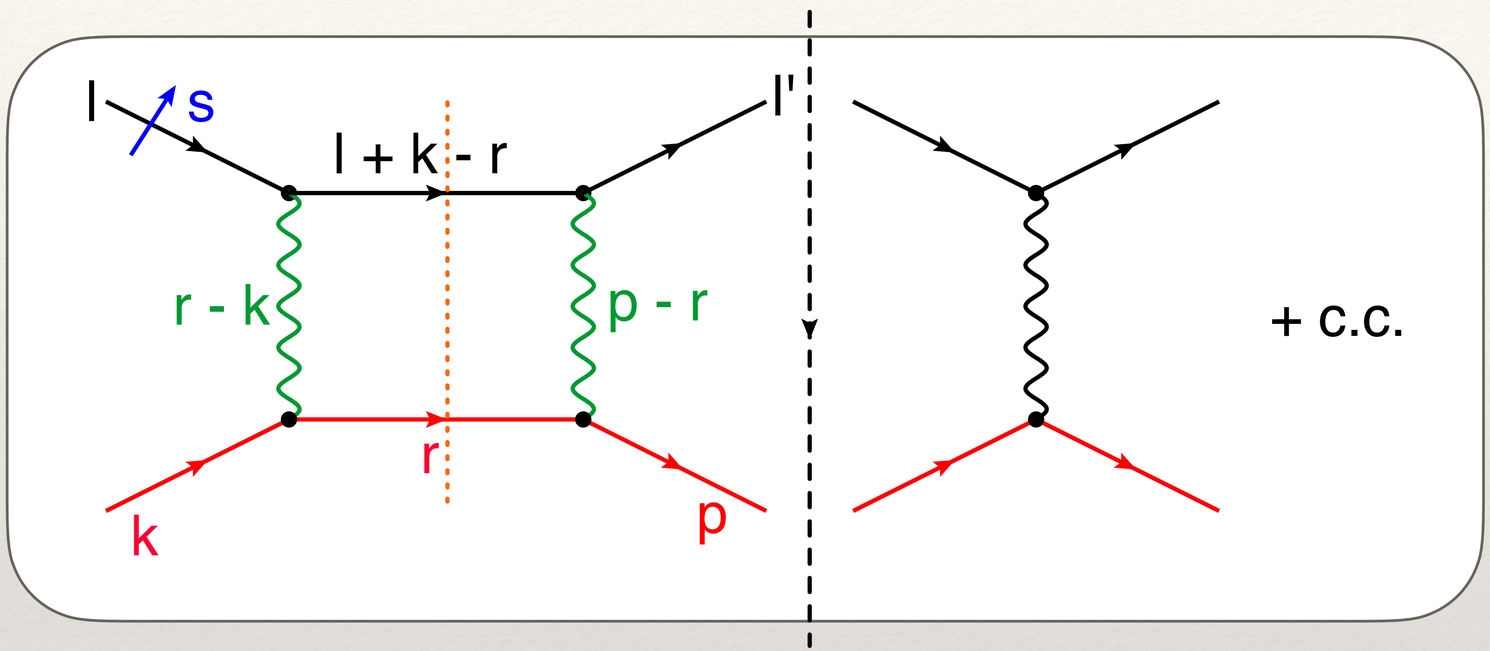
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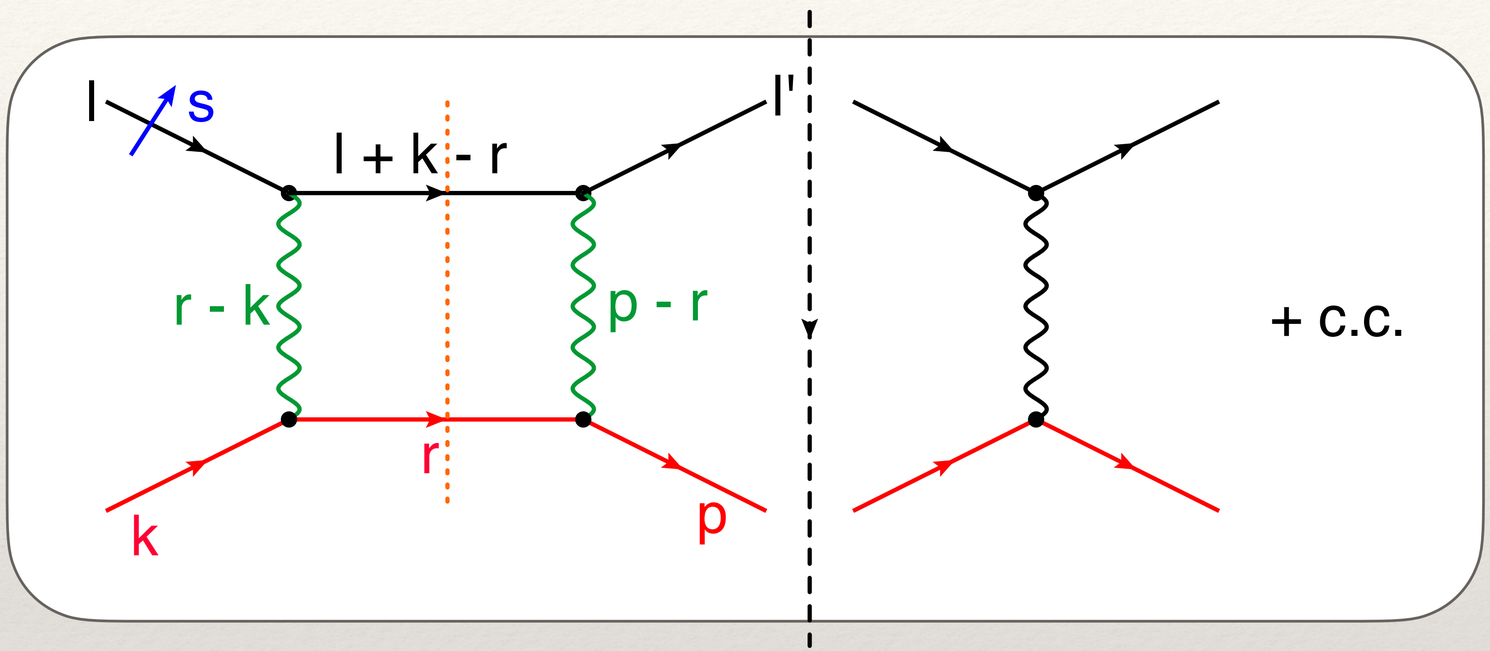


- Box graph only loop diagram with imaginary part
- No separation into leptonic vs. hadronic tensor
- Assume fixed momentum p of outgoing quark.
- Mandelstam variables

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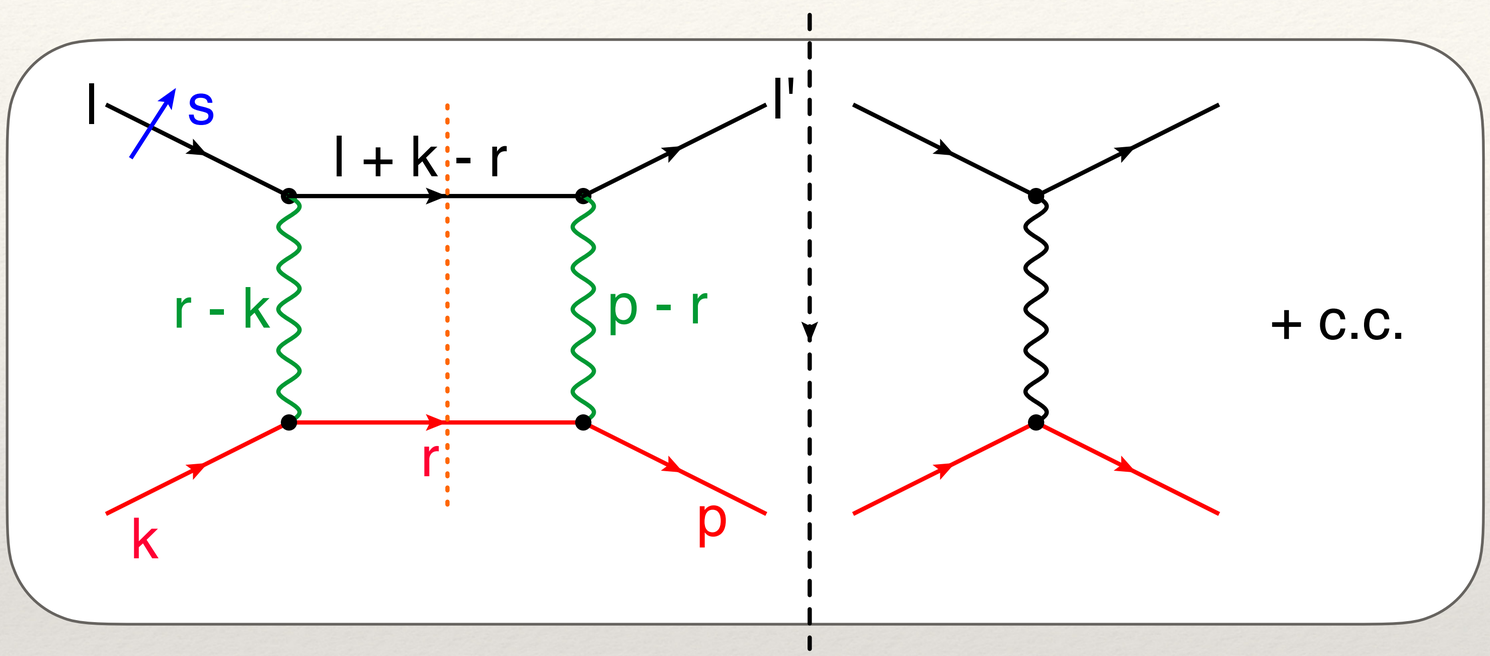
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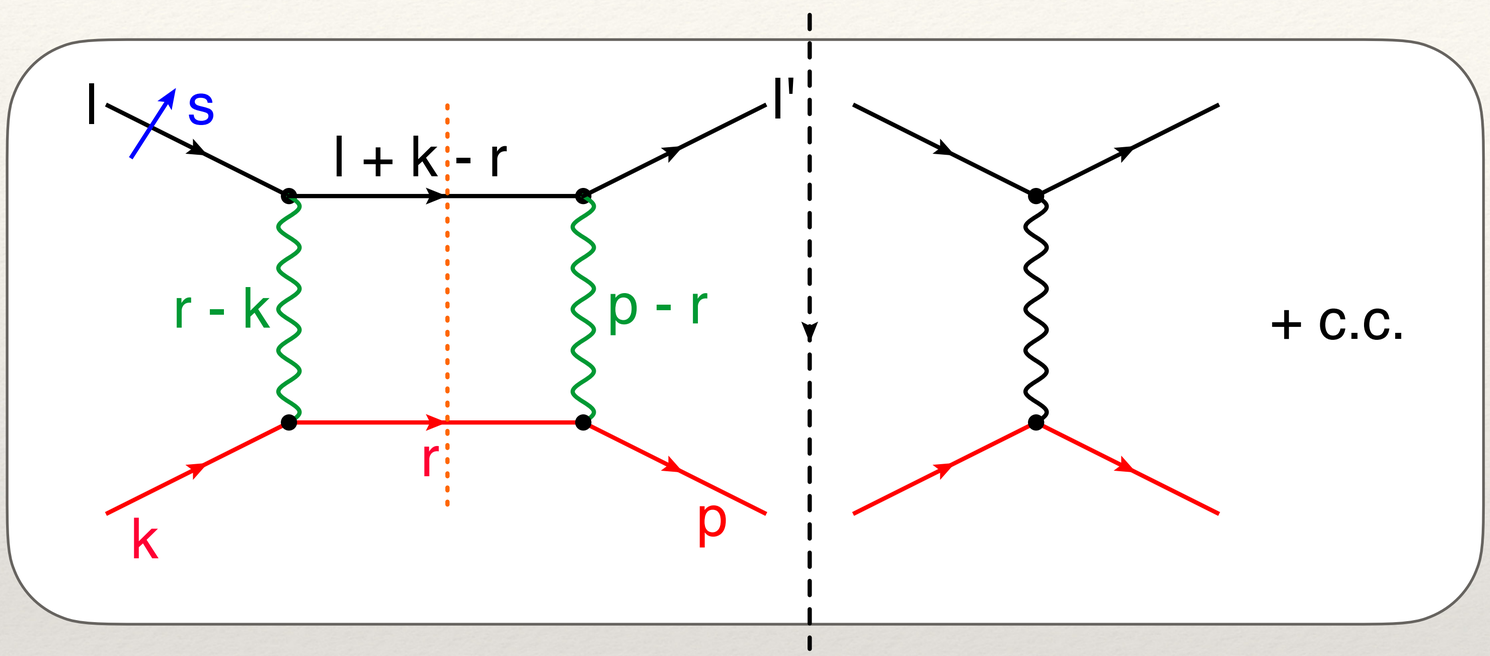
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$$i\,\frac{\alpha^3\, e_q^3}{t}\,\mu^{2\epsilon}\int \frac{d^d r}{(2\pi)^{d-2}}\,\delta^+(r^2)\,\delta^+((l+k-r)^2)\;\frac{Tr[\gamma^\rho(\not{l}+\not{k}-\not{p}+m_e)\,\gamma^\mu(\not{l}+\not{k}-\not{r}+m_e)\gamma^\nu(\not{l}+m_e)(1-\not{s}\gamma_5)]\,Tr[\not{k}\gamma^\rho\not{p}\gamma^\mu\not{r}\gamma^\nu]}{[(r-k)^2+i0]\,[(p-r)^2+i0]}$$

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$$= \ldots = \frac{\alpha^3}{2\pi} \, \frac{m_e \, \epsilon^{klps_T}}{s \, t} \, e_q^3$$

That's it!

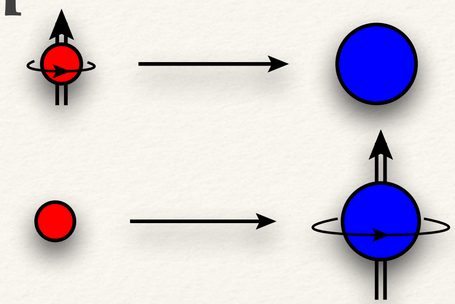
All IR/collinear divergences, Logs etc. cancel!

DIS with transverse electron spin

$A_N = 0$ in 1-γ exchange [Christ, Lee,1966]!

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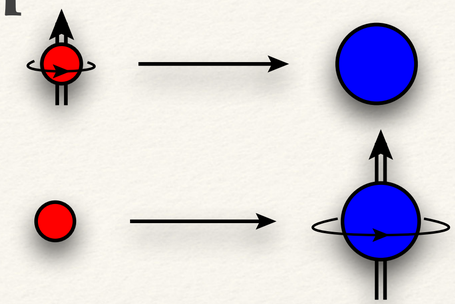


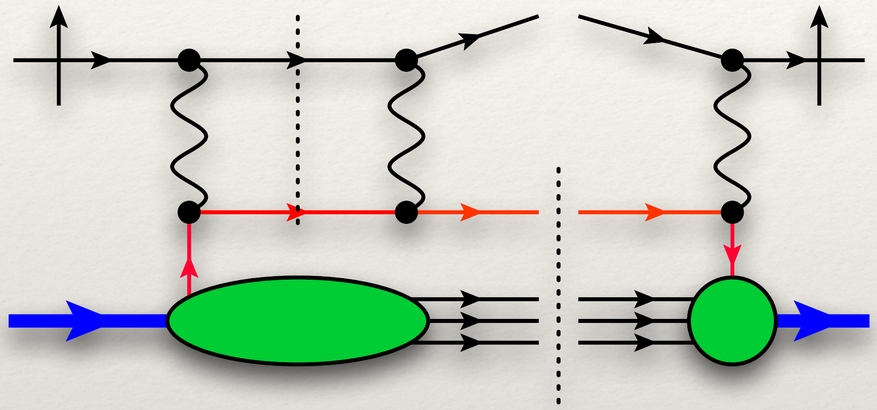
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[Metz, M.S., Goeke, PLB 643 (2006)]

Spin-dependent Lorentz-invariant cross section

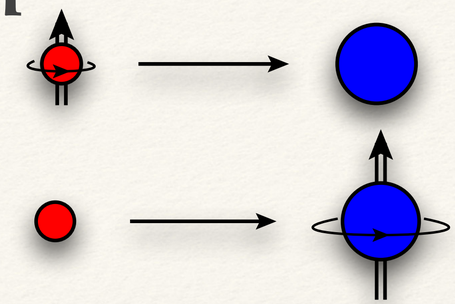
$$k'^0 \frac{d\sigma_{L,\mathrm{pol}}}{d^3\vec{k}'} = \frac{4\alpha_{\mathrm{em}}^3}{Q^8} m x y^2 \varepsilon_{\mu\nu\rho\sigma} S^{\mu} P^{\nu} k^{\rho} k'^{\sigma} \sum_q e_q^3 x f_1^q(x).$$

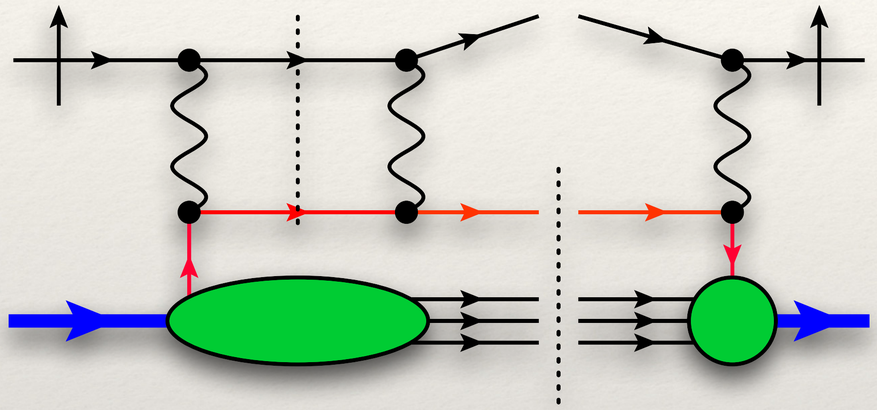
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[M.S., arXiv/0902.0781]

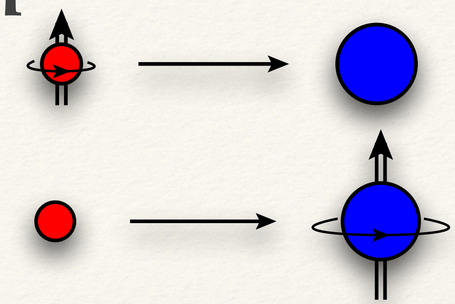
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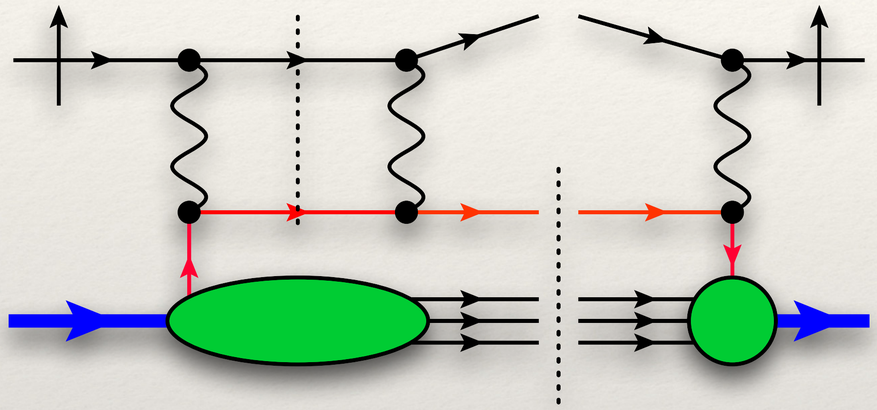
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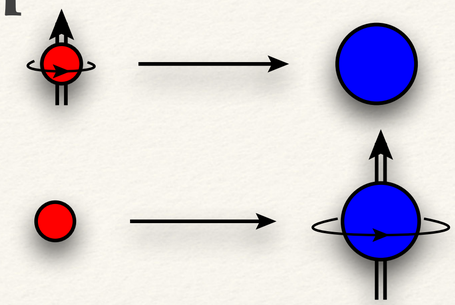
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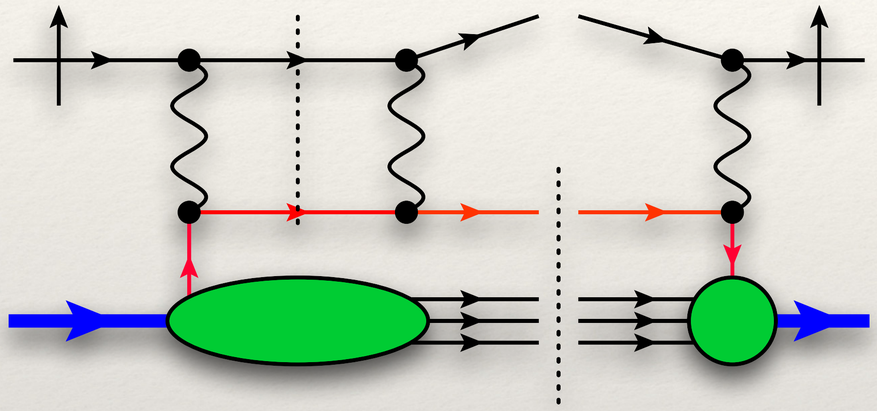
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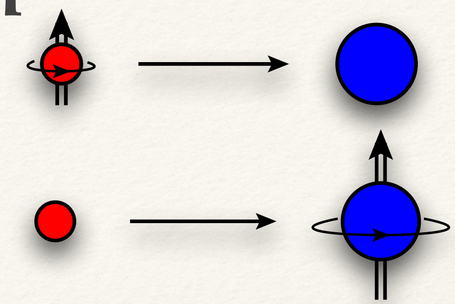
$$0.2 - 0.5 \; < \; 1$$

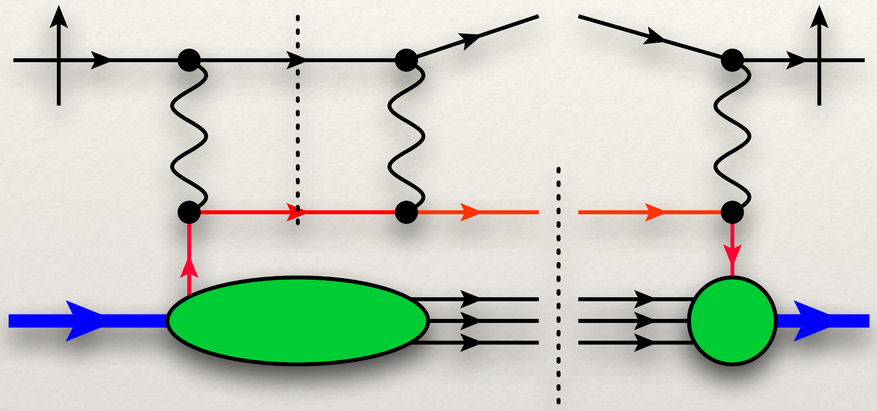
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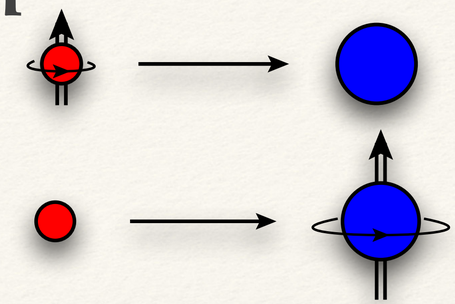
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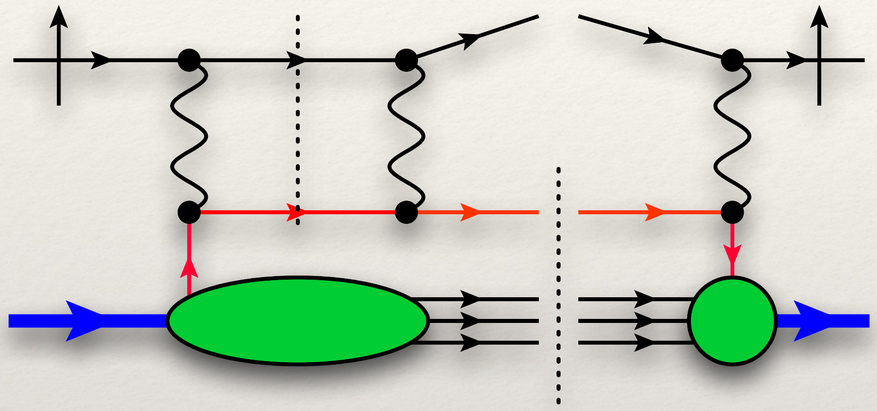
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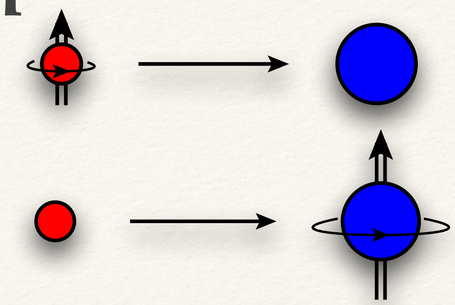
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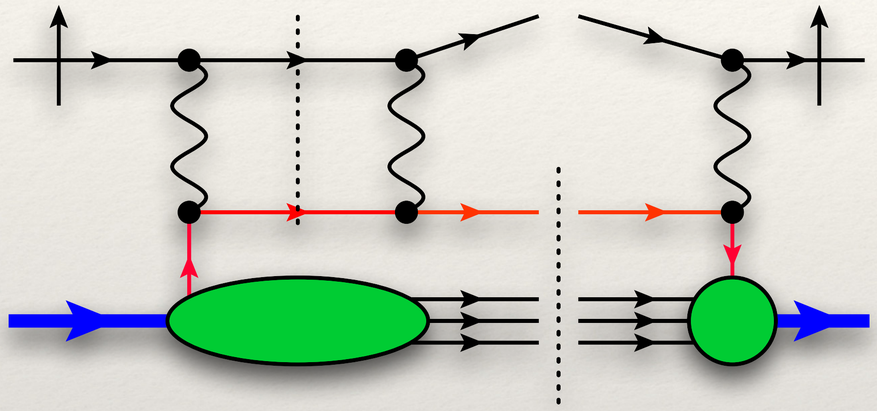
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$$k'^0 \frac{d\sigma_{L,\mathrm{pol}}}{d^3\vec{k}'} = \frac{4\alpha_{\mathrm{em}}^3}{Q^8} m x y^2 \varepsilon_{\mu\nu\rho\sigma} S^\mu P^\nu k^\rho k'^\sigma \sum_q e_q^3 x f_1^q(x).$$

SSA in the Breit frame

[M.S., arXiv/0902.0781]

$$A_{TU}(x_B, y, \phi_s) = \alpha \frac{m_l}{2Q} |\vec{S}_T| \sin(\phi_s) \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2} \frac{\sum_q e_q^3 f_1(x_B)}{\sum_q e_q^2 f_1(x_B)}$$

$1/137 \quad 2.5 \times 10^{-4} \quad 0.2 - 0.5 \quad < 1$

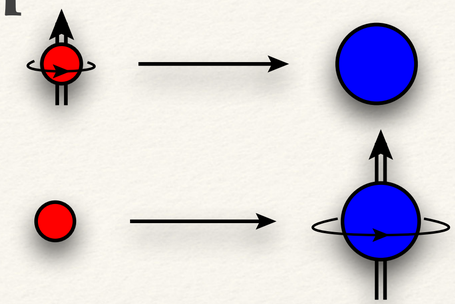
$< 9 \times 10^{-7}$ at $Q = 1\,\mathrm{GeV}$

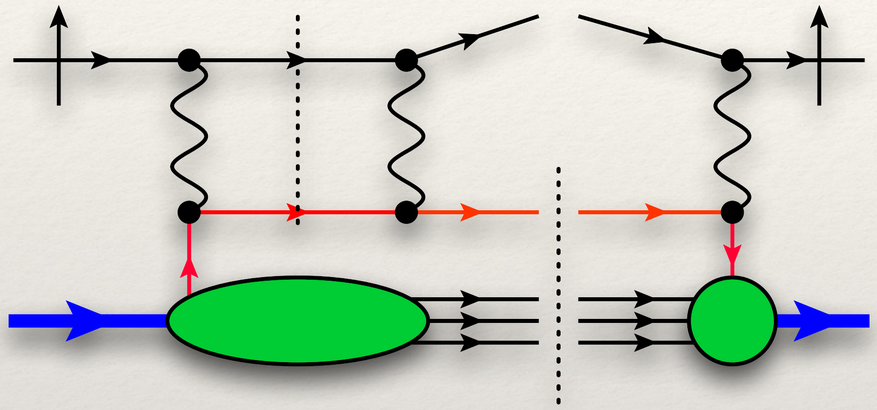
DIS with transverse electron spin

$A_N = 0$ in 1-γ exchange [Christ, Lee,1966]!

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

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





Transverse Single-Beam Spin Asymmetry in DIS

[Metz, M.S., Goeke, PLB 643 (2006)]

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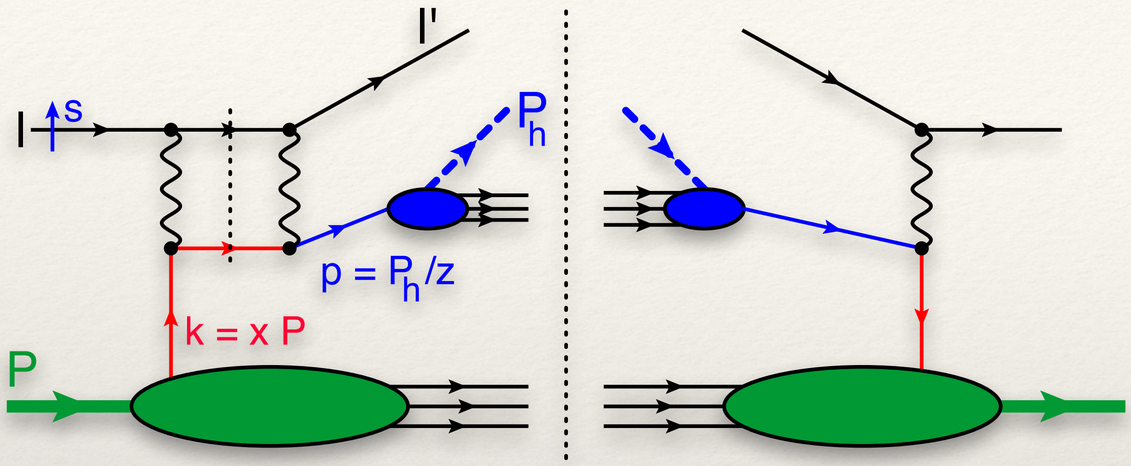
$$< 9 \times 10^{-7} \text{ at } Q = 1\,\mathrm{GeV}$$

Measurable? COMPASS maybe?

From point of view of hadron structure: not too interesting observable…

Hadron Production with transverse electron spin

include fragmentation into detected hadron (pion)



single-inclusive $e^{\uparrow} + N \to \pi + X$

hard scale $P_{h\perp} > 1\,\mathrm{GeV}$

$$\frac{d\sigma_{\mathrm{s.i.}}}{dx_F\, dP_{h\perp}}$$

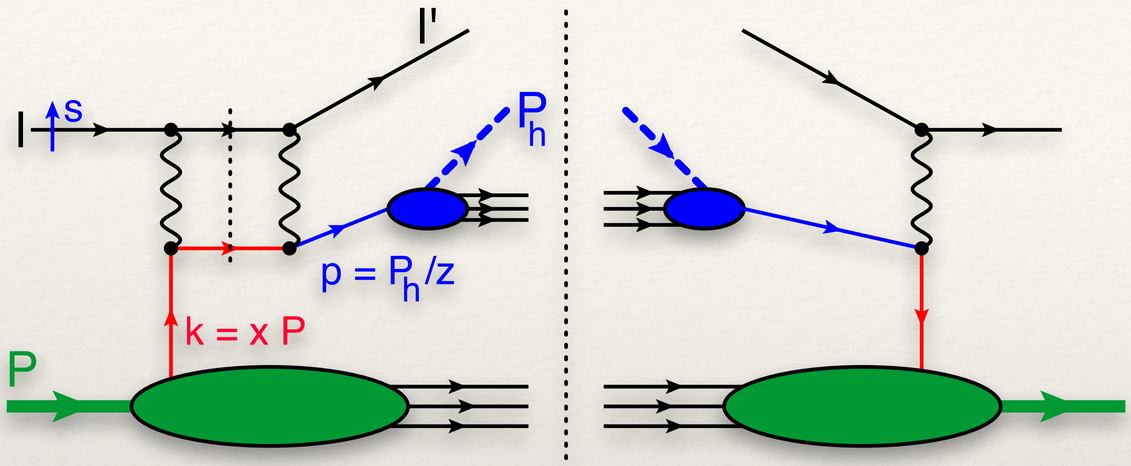
SIDIS $e^{\uparrow} + N \to e + \pi + X$

integrated over transverse momentum

$$\frac{d\sigma_{\mathrm{SIDIS}}}{dx_B\, dy\, dz_h}$$

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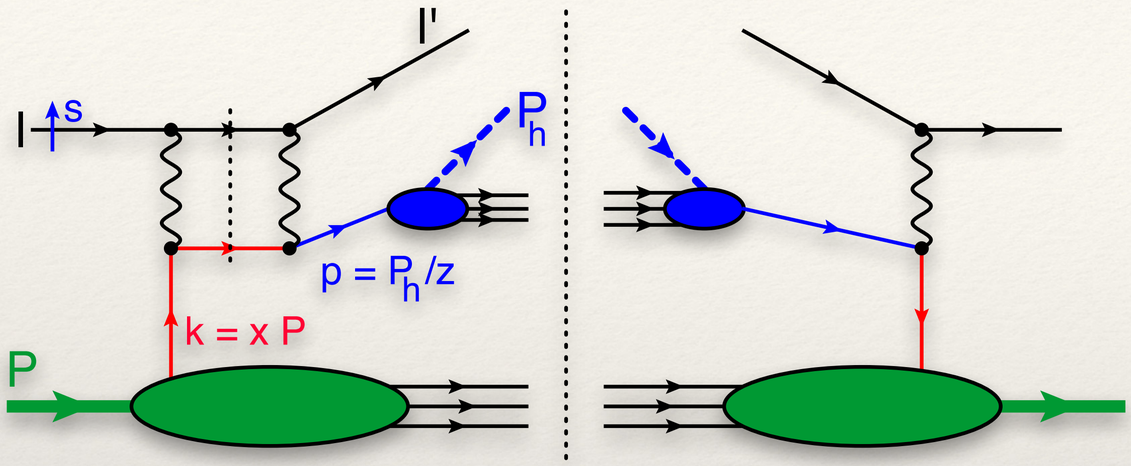
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SIDIS in the Breit frame

$$A_{TU}(x_B, y, z_h, \phi_s) = \alpha_{\mathrm{em}}\, \frac{m_e}{2Q}\, |\boldsymbol{s}_T|\, \sin\phi_s\, \frac{y^2\sqrt{1-y}}{1-y+\frac{1}{2}y^2}\, \frac{\sum_q e_q^3\, [f_1^q(x_B)\, D_1^q(z_h) - f_1^{\bar{q}}(x_B)\, D_1^{\bar{q}}(z_h)]}{\sum_q e_q^2\, [f_1^q(x_B)\, D_1^q(z_h) + f_1^{\bar{q}}(x_B)\, D_1^{\bar{q}}(z_h)]} \quad < 9 \times 10^{-7}\ \mathrm{at}\ Q = 1\,\mathrm{GeV}$$

Hadron Production with transverse electron spin

include fragmentation into detected hadron (pion)



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SIDIS $e^{\uparrow} + N \to e + \pi + X$

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$< 9 \times 10^{-7}$ at $Q = 1\,\mathrm{GeV}$

single-inclusive in the lab frame

$$A_{TU}(x_F, \boldsymbol{P}_{h\perp}, s) = \alpha_{\mathrm{em}}\, \frac{m_e}{\sqrt{s}}\, \epsilon^{lPP_h s_T}\, \frac{\sum_q e_q^3 \int dz\, \Delta_T\hat{\sigma}(z)\, (f_1^q(x)\, D_1^{\pi/q}(z) - \{q \to \bar{q}\})}{\sum_q e_q^2 \int dz\, \hat{\sigma}(z)\, (f_1^q(x)\, D_1^q(z) + \{q \to \bar{q}\})}$$

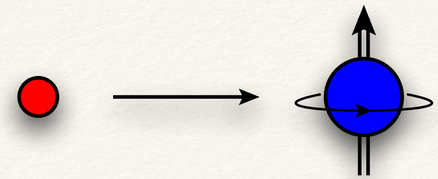
similar size, expect < 10^{-6}

The transverse nucleon SSA in lepton - nucleon collisions

→ JLab, EIC

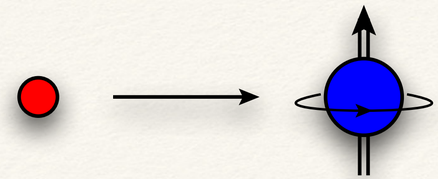
DIS with transverse nucleon spin

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



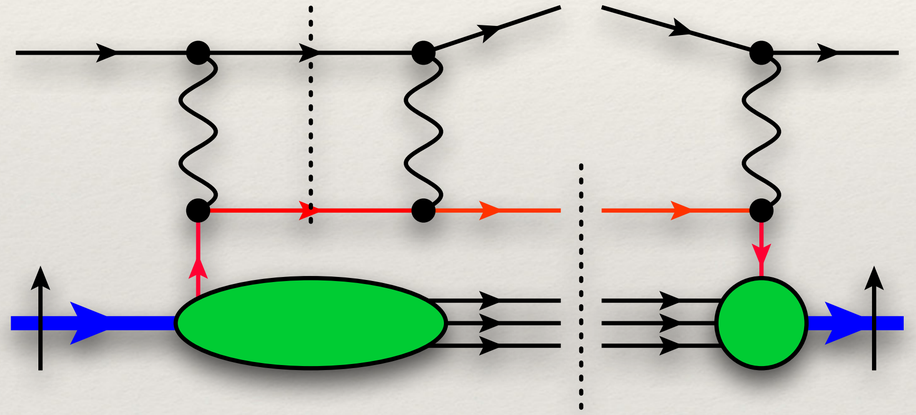
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Transverse Target Single Spin Asymmetry in DIS

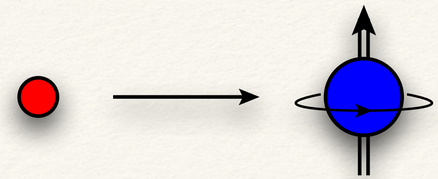
[Metz, M.S., Goeke, PLB (2006)]



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

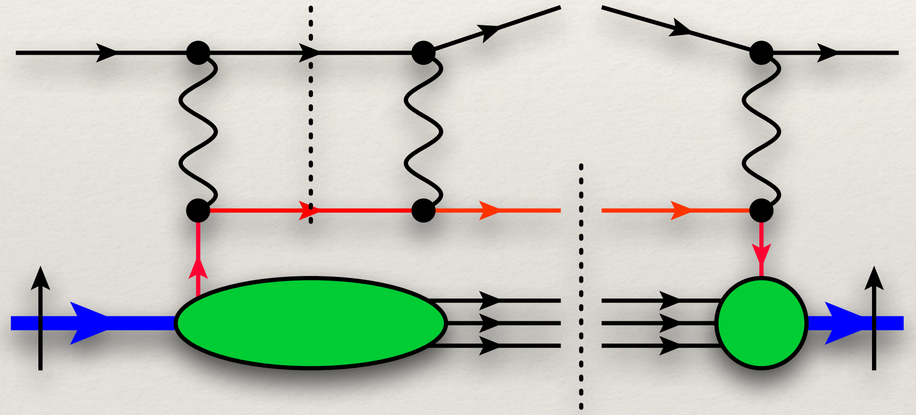
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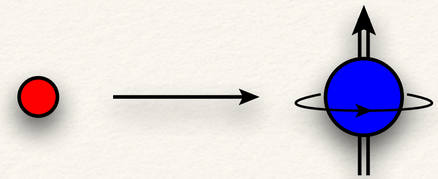


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$1/137$

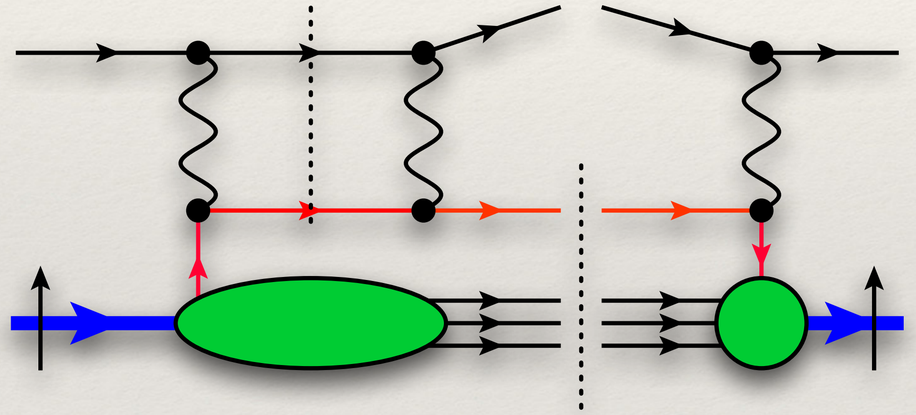
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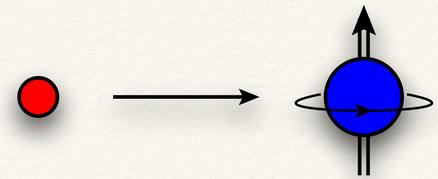


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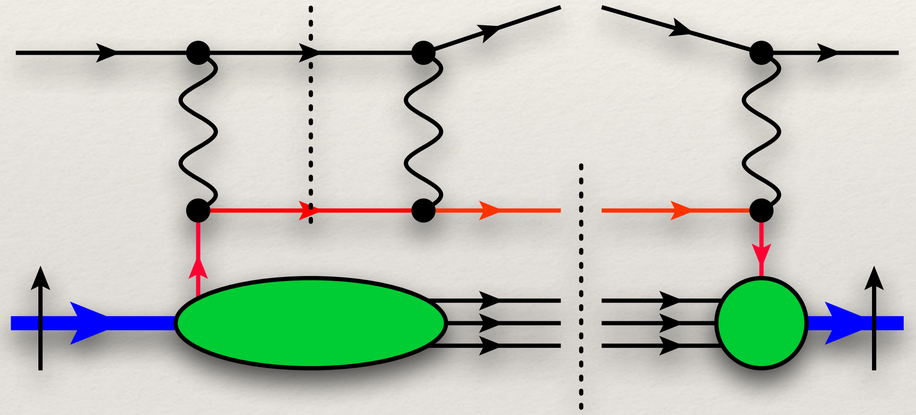
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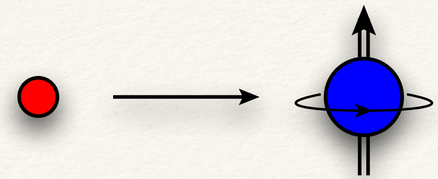


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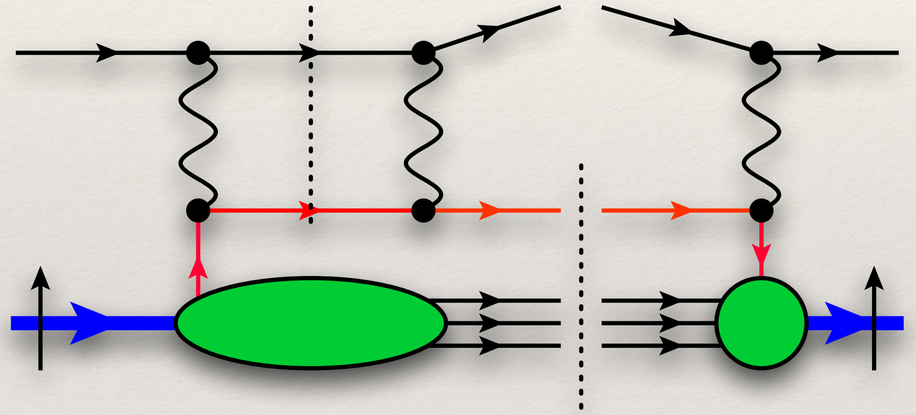
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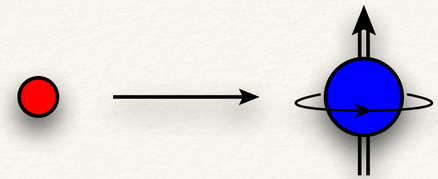
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soft divergence (!)

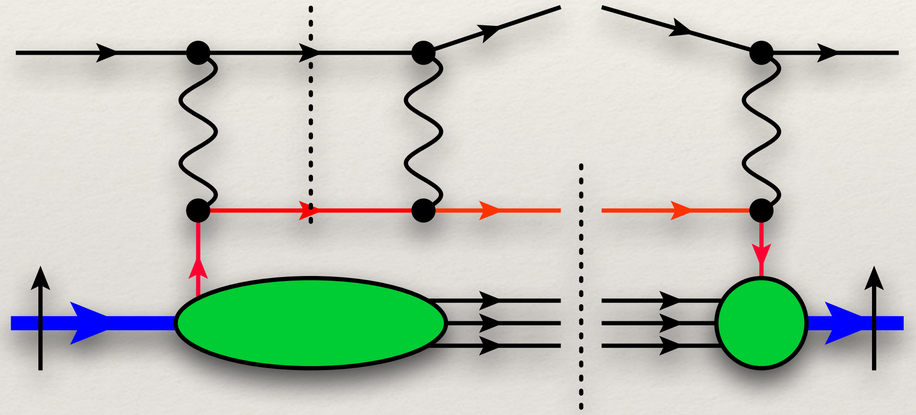
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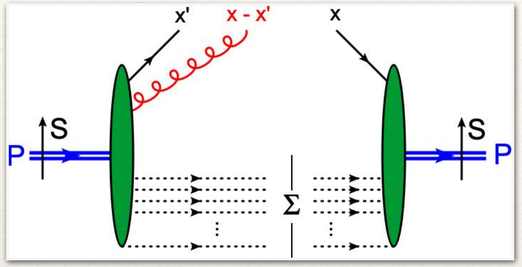
What is missing?

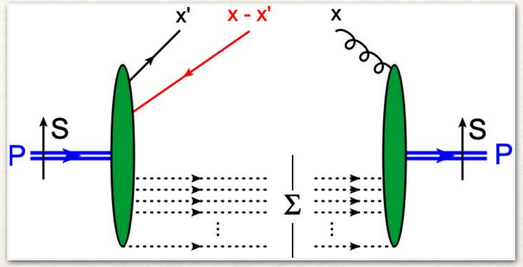
QED NLO soft singularities ⇔ higher twist effects

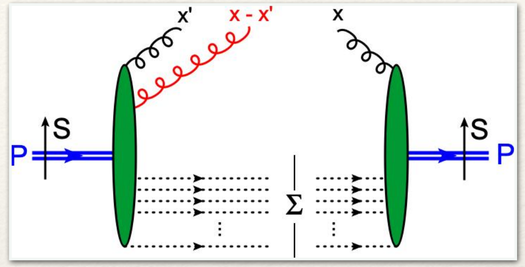
Quark - Gluon - Quark correlations

Quantum interference effect of non-valence-type nucleon LF wave functions

[e.g., Braun, Lautenschlager, Manashov, PRD 2011]



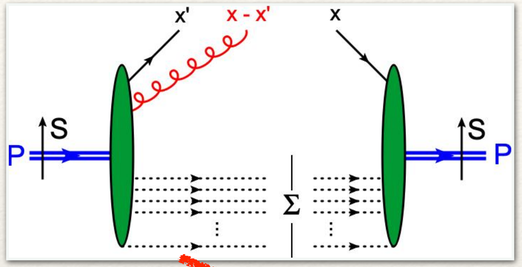


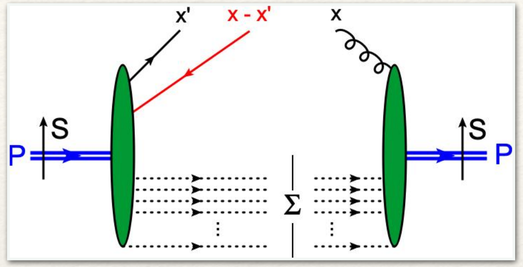


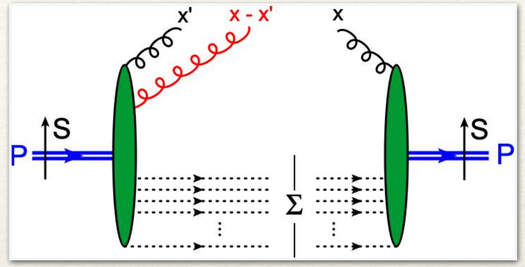
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(Chiral-even) Quark - Gluon - Quark correlation functions

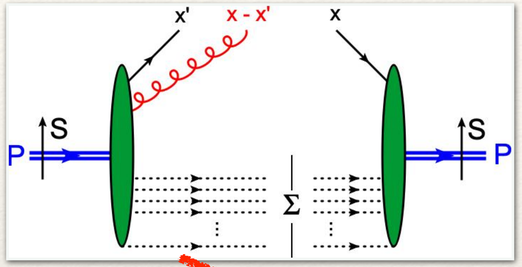
$$2M\, i\epsilon^{Pn\rho S} F_{FT}^{q}(x,x') = \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} \mathrm{e}^{i\lambda x'} \mathrm{e}^{i\mu(x-x')} \langle P, S_T | \, \bar{q}(0) \not{n}\, igF^{n\rho}(\mu n)\, q(\lambda n) \, | P, S_T \rangle$$

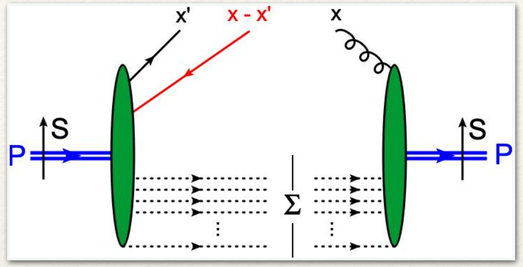
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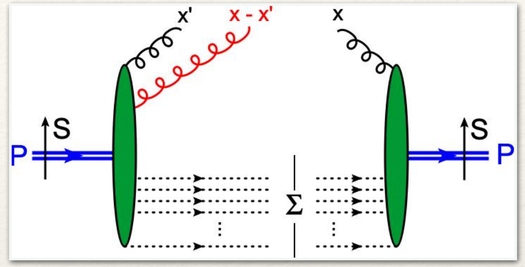
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Why relevant?

→ collinear pQCD: they generate transverse SSA

→ dynamical information: color Lorentz force [M. Burkardt]

→ TMD physics: large transverse momentum behavior of Sivers, Boer-Mulder, worm gear function & their evolution

→ first NLO extractions from data available [Vladimirov, Portela, Rodini, 2026]

back to DIS with transverse nucleon spin…

need to include many more contributions from Quark-Gluon/Photon-Quark Correlations:

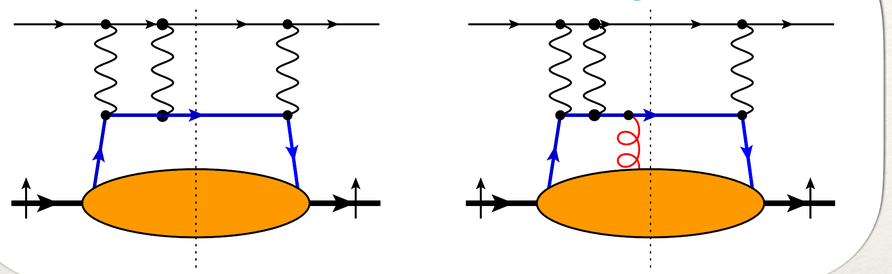
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Two Photon Exchange

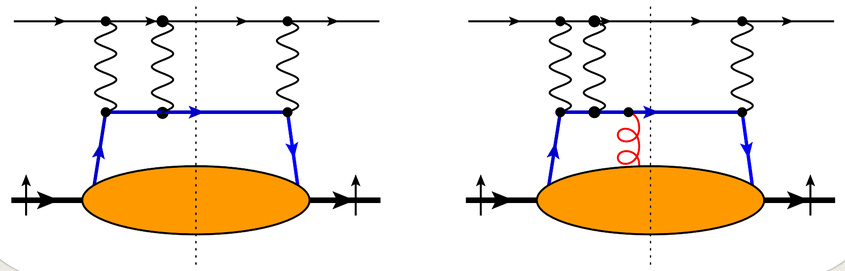


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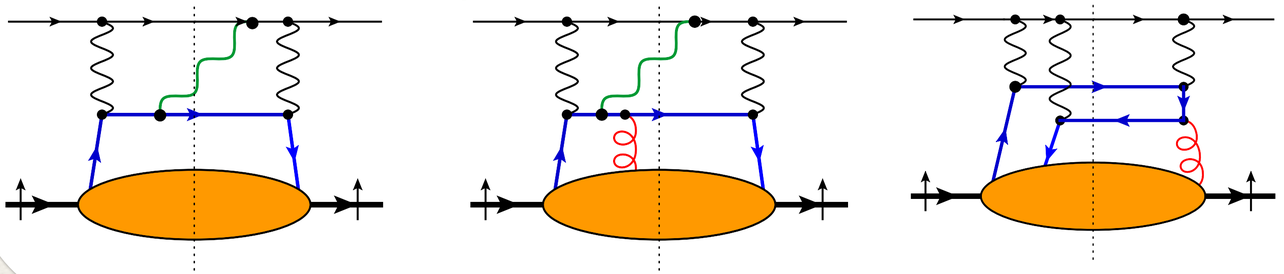
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Two Photon Exchange



real photon emission:

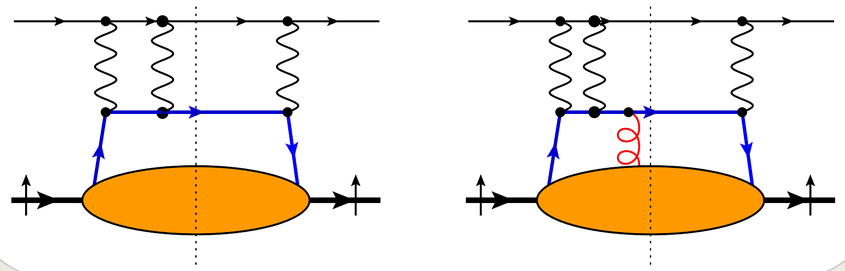


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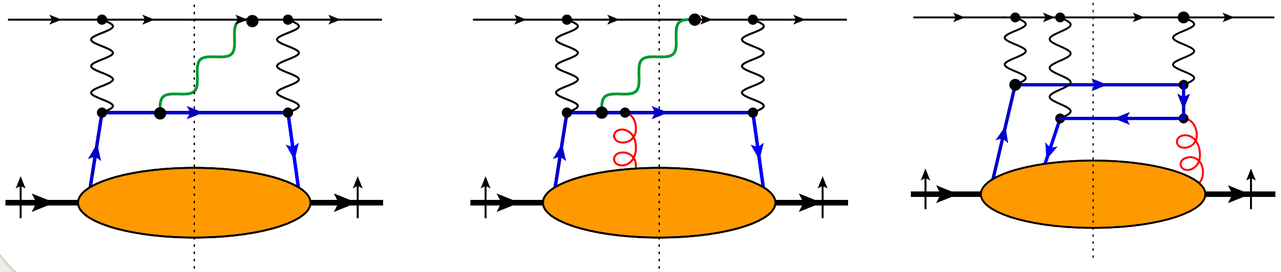
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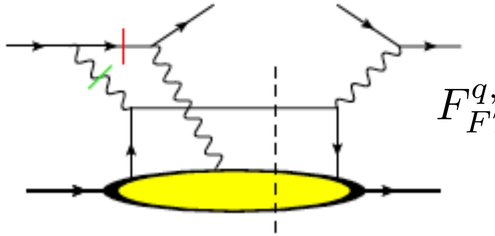
Two Photon Exchange



real photon emission:



"Quark-Photon Correlations"



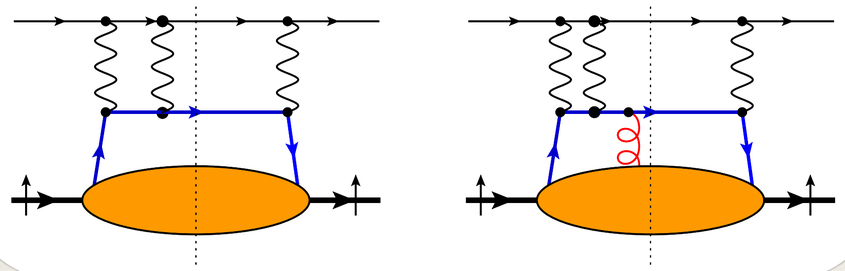
$$F_{FT}^{q,\gamma}(x,x') \sim \langle \bar{q}\, F_{\rm em}\, q \rangle$$

back to DIS with transverse nucleon spin…

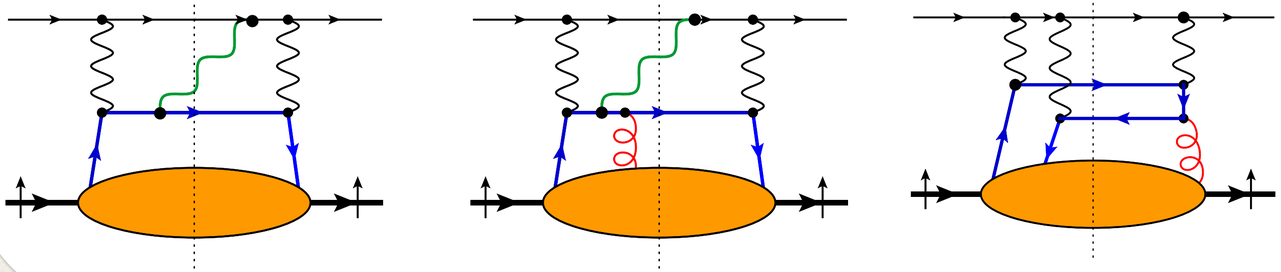
need to include many more contributions from Quark-Gluon/Photon-Quark Correlations:

[M.S., PRD 2013; Metz, Pitonyak, Schäfer, M.S., Vogelsang, Zhou, PRD 2012]

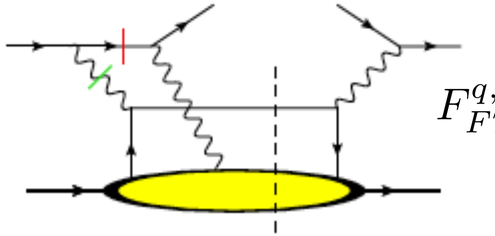
Two Photon Exchange



real photon emission:



"Quark-Photon Correlations"



$$F_{FT}^{q,\gamma}(x,x') \sim \langle \bar{q}\, F_{\rm em}\, q \rangle$$

"Quark-mass term"

[Afanasev, Weiss, Strikman, PRD77,014028]

Assume non-zero quark mass

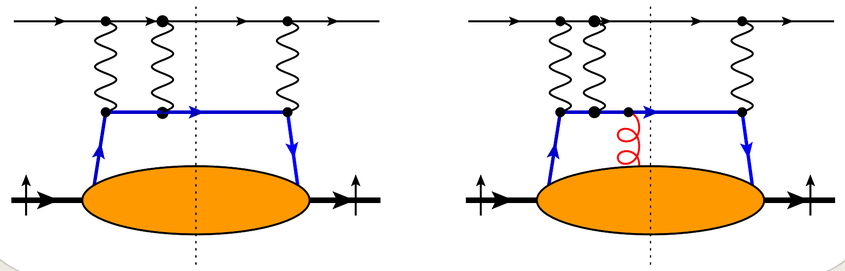
$$A_N \sim \sum_q e_q^3 \, \frac{m_q}{M} \, h_1^q(x_B)$$

back to DIS with transverse nucleon spin…

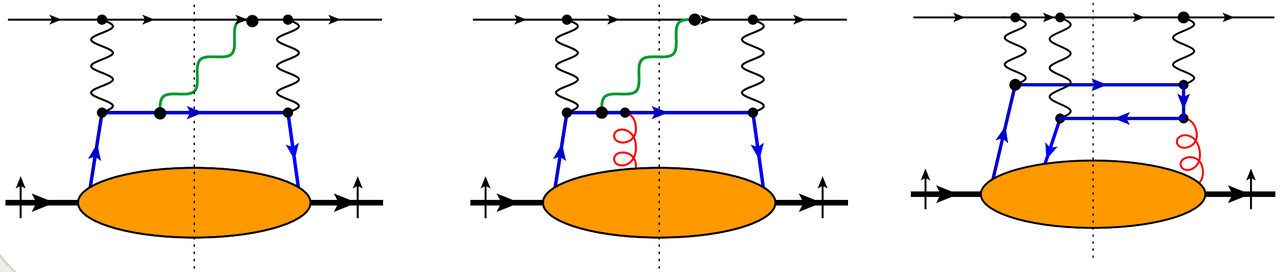
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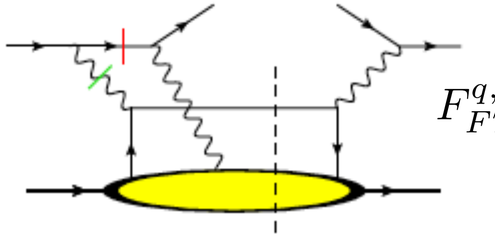
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Assume non-zero quark mass

$$A_N \sim \sum_q e_q^3 \, \frac{m_q}{M} \, h_1^q(x_B)$$

$$A_N(x_B,y,Q^2) \simeq \alpha_{\rm em}\,\frac{M}{Q}\,\sin\phi_S \left[\sum_q e_q^3 \int dx'\, \left(\hat{\sigma}_1(x_B,y,x')\, F_{FT}(x_B,x') + \hat{\sigma}_5(x_B,y,x')\, G_{FT}(x_B,x')\right)\right.$$
$$\left. + \sum_q \left(e_q^2\, \hat{\sigma}_\gamma(y)\,(1 - x_B \tfrac{d}{dx_B})\, F_{FT}^{\gamma,q}(x_B,x_B) + e_q^3\, \tfrac{m_q}{M}\, \hat{\sigma}_h(y)\, h_1^q(x_B)\right)\right]$$

Soft divergences cancel!

Used for phenomenology in

[M.S., arXiv:1303.0978 & Proc. QCD Evol 2013]

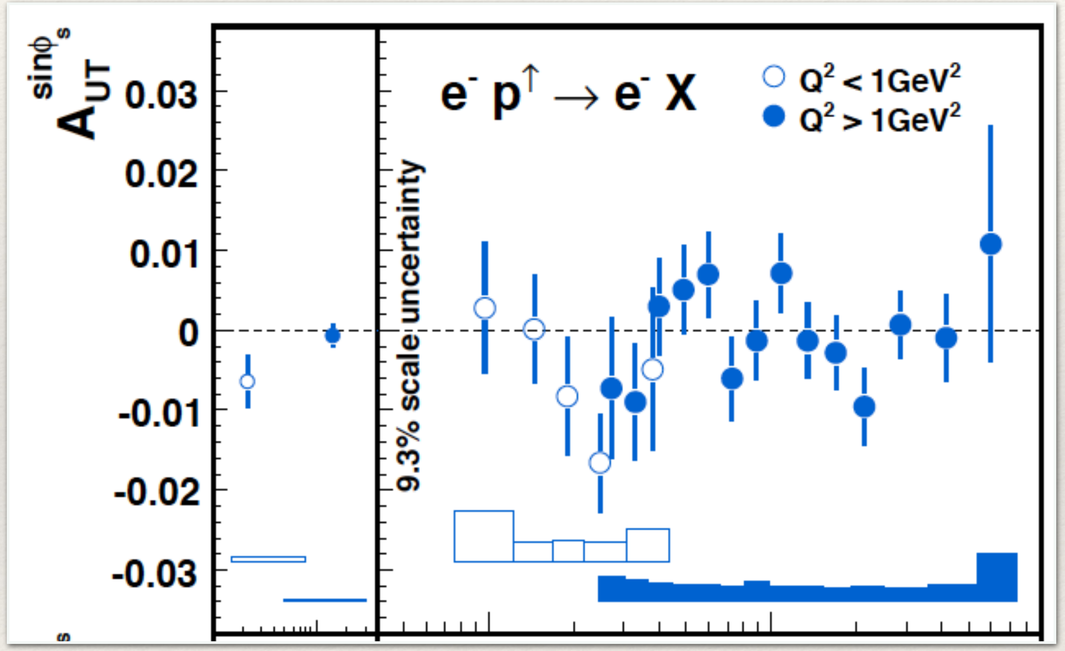
$$A_N^p \sim 5 \times 10^{-4}$$
$$A_N^n \sim 5 - 10 \times 10^{-3}$$

Has the transverse nucleon SSA ever been measured?

HERMES

[PLB682, 351(2010)]

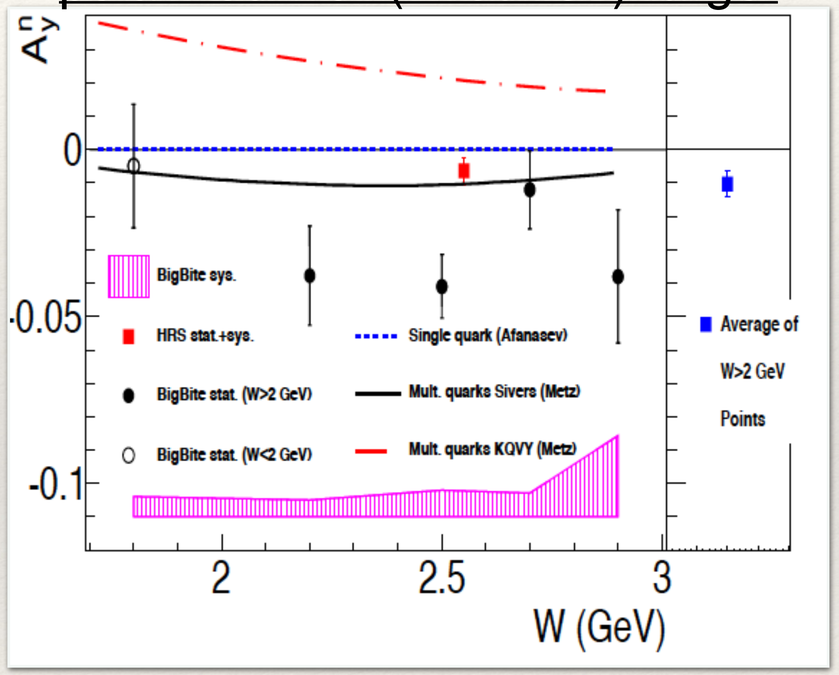
polarized proton target



JLab 6 GeV

[PRL113, 022502(2014)]

polarized He^3 (~neutron) target



Measurements planned at JLab12 (SoLID) for He^3 (= neutron) & NH_3 (= proton) target

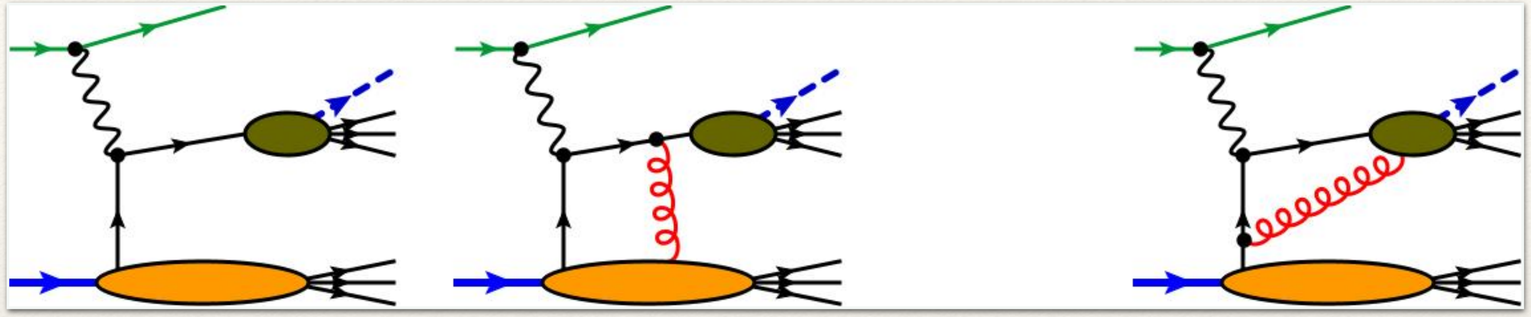
→ opportunity for an EIC(?)

Single-inclusive hadron production e $N^{\uparrow}$ → π X

[Rein, M.S., Tollkuehn, Vogelsang, PRL & PRD 2025; Scantamburlo, M.S., work in progress]

Final state electron *not* detected, transverse momentum of π large

Leading order:
No TPE needed!

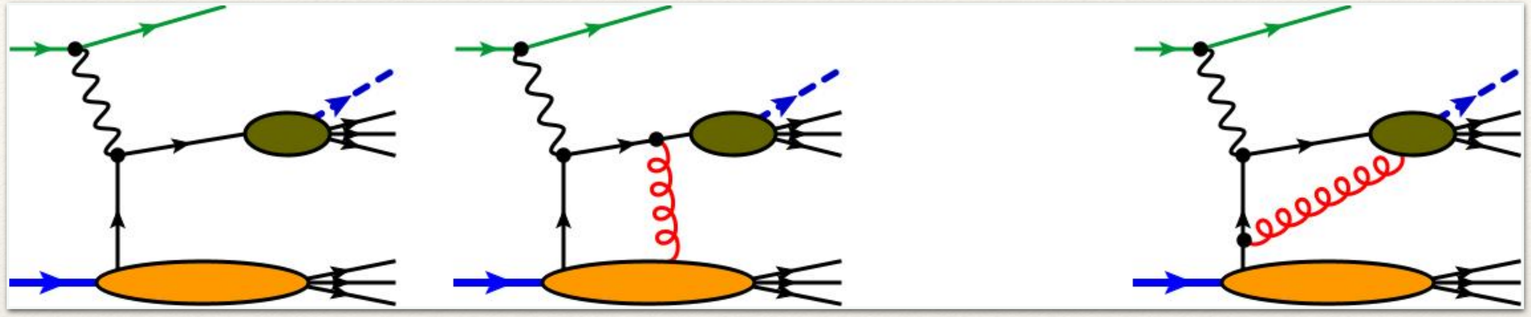


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$$A_N \propto \frac{M}{\sqrt{s}}\,\epsilon^{lPP_hS}\sum_q e_q^2 \int dz\,(1 - x\,\tfrac{d}{dx})F_{FT}^q(x,x)\,D_1^{\pi/q}(z)$$

$$+\sum_q e_q^2 \int dz\,h_1^q(x) \int dz_1 \int dz_2\,\Im[\hat{H}_{FU}^{\pi/q}](z_1,z_2)\,f(z_1,z_2)$$

“Sivers” effect

transversity pdf

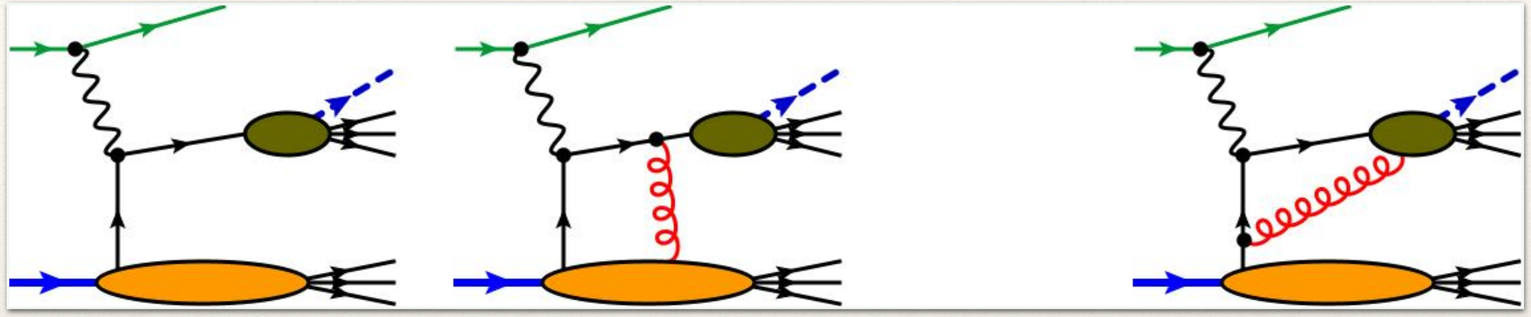
chiral-odd qgq FF

Single-inclusive hadron production e $N^{\uparrow} \to \pi$ X

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transversity pdf

chiral-odd qgq FF

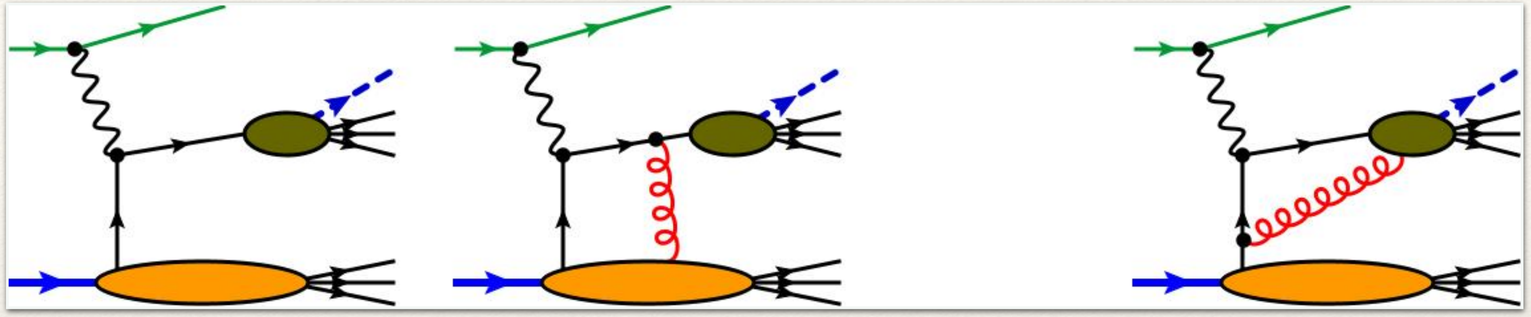
- NLO corrections in pQCD available for qgq-correlations in the nucleon (QCD factorization valid at NLO!)
- NLO corrections for qgq-fragmentation: work in progress
- NLO can be large and make a difference on the extraction of qgq-functions
- Data exist from HERMES (2010) & JLab (2014)

SSA in SIDIS: e $N^{\uparrow}$ → e π X

[Scantamburlo, M.S., PRD 2026; and in preparation]

Final state electron *is* detected, but transverse momentum of π integrated out.

Leading order:
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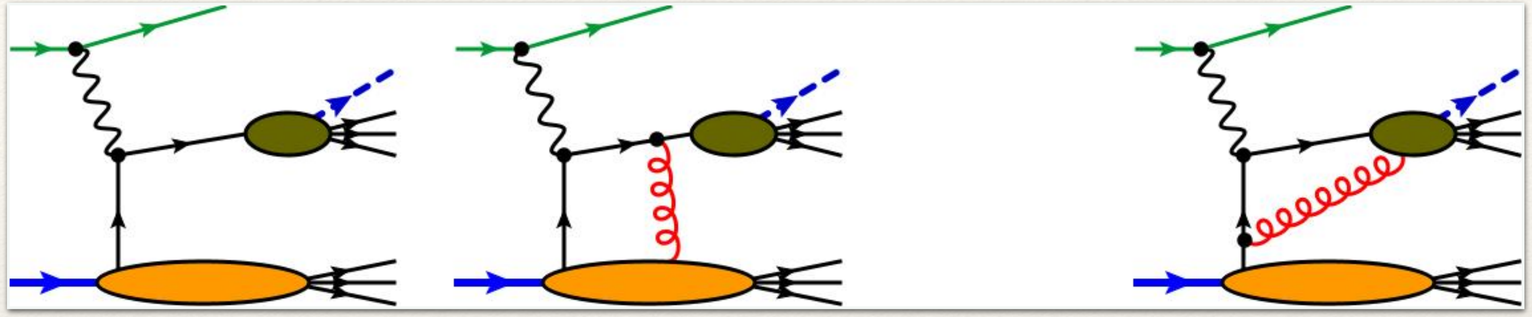


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SIDIS structure functions:

weighting factor needed

"Sivers" effect:

$$\int d^2\boldsymbol{P}_{\pi\perp}\, \boldsymbol{P}_{\pi\perp}\, F_{UT,T}^{\sin(\phi_\pi-\phi_S)}(x_B, z_h, \boldsymbol{P}_{\pi\perp}^2, Q) \propto \frac{M}{Q}\sum_q e_q^2\, F_{FT}^q(x_B, x_B)\, D_1^{\pi/q}(z_h)$$

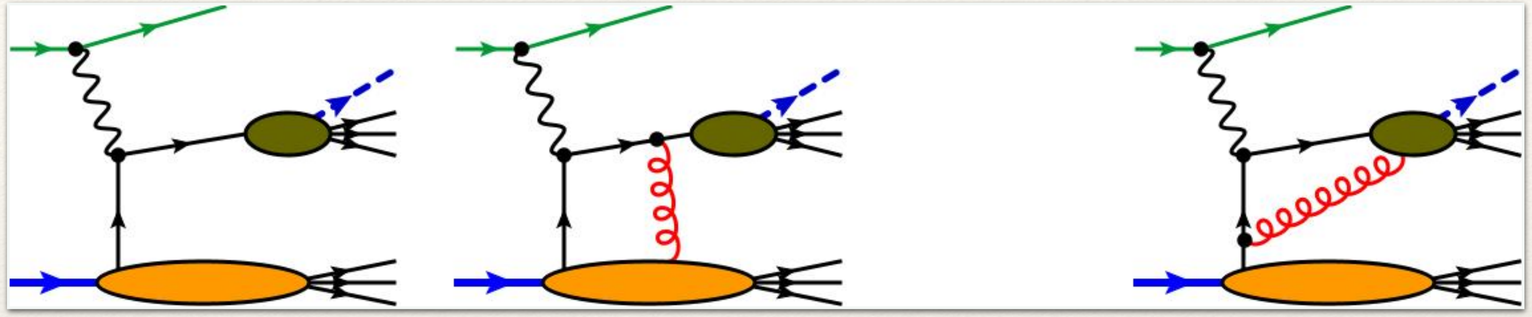
NLO available since 2013 [Kang et al, 2013,15; Yoshida 2016; Chen, Ma, Zhang 2018]

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NLO available since 2013 [Kang et al, 2013,15; Yoshida 2016; Chen, Ma, Zhang 2018]

"unweighted" S.F.:

$$\int d^2\boldsymbol{P}_{\pi\perp}\,F_{UT}^{\sin(\phi_S)}(x_B,z_h,\boldsymbol{P}_{\pi\perp}^2,Q)\propto\frac{M_h}{Q}\sum_q e_q^2\,h_1^q(x_B)\,\frac{\tilde{H}^{\pi/q}(z_h)}{z_h}$$

- NLO for qgq-fragmentation available, soon for qgq-correlations in the nucleon
- NLO correction can make a difference for extractions
- HERMES data exist (JHEP 2020), opportunity for JLab, EIC

Summary/Take-away messages

- Transverse beam spin SSA :
  inclusive DIS, SIDIS, single-inclusive hadron production in pQCD due to TPE

$$A_N \propto \alpha_{\rm em} \frac{m_e}{Q} \epsilon^{ll' P s_T} ... \simeq 10^{-7} - 10^{-6}$$

- SSA in inclusive DIS at an EIC → γ/Z-Interference may be relevant
  [Boughezal, de Florian, Petriello, Vogelsang, PRD 107, 075028 (2023)]
- Transverse target spin SSA :
  inclusive DIS: TPE necessary, chance to study multi-parton correlations

$$A_N \propto \alpha_{\rm em} \frac{M}{Q} \epsilon^{ll' P s_T} ... \simeq 10^{-4} - 10^{-2}$$

More data from JLab needed.

- Transverse target SSA in SIDIS, single-inclusive hadron production:
  One-photon exchange enough, NLO (partially) known,
  good observables to study multi-parton correlations