Transverse Spin Asymmetries in Deep-Inelastic Processes

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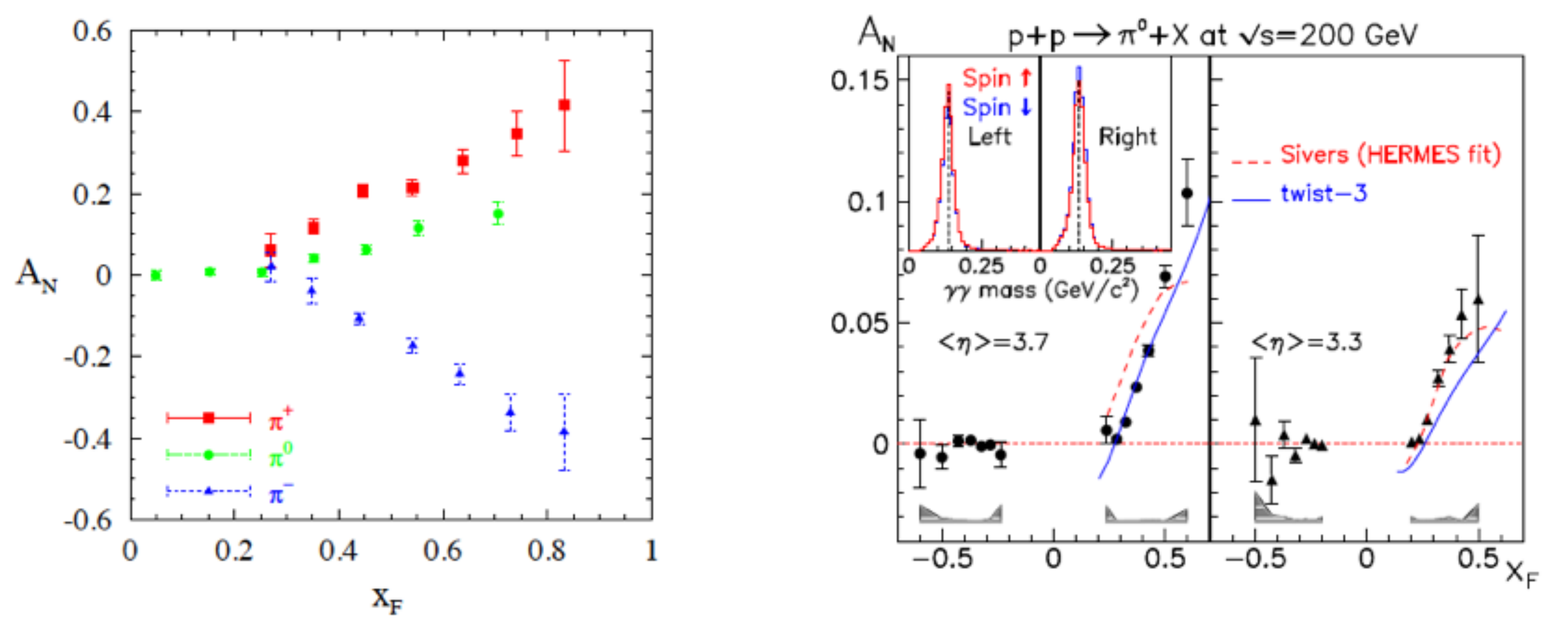
University of Tübingen

"Spin and Orbital Angular Momentum of Quarks and Gluons in the Nucleon", ECT*, Trento, Aug. 28, 2014

Why Transverse Spin Asymmetries?

"Show-off" Transverse SSA $p + p^{\uparrow} \to \pi + X$

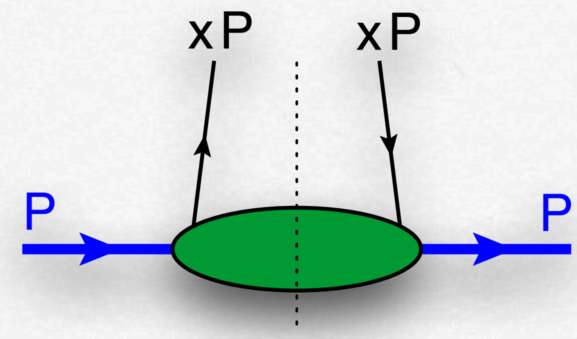


$\sqrt{s} = 20$ GeV [*E704 coll. (1991)*] $\sqrt{s} = 200$ GeV [*STAR coll. (2008)*]

- sizeable effect at large x_F ➔ too large to be left unexplained
- cannot be explained in the naive parton model

➔ Twist-3 Formalism (ETQS)!

Transverse Spin Matrix Elements



1) Transversity distribution

$$h_1^q(x) = \int_{-\infty}^{\infty} \frac{d\lambda}{4\pi}\, \mathrm{e}^{i\lambda x(P\cdot n)}\, \langle P, S_T|\, \bar{q}(0)\, \not{S}_T \not{n} \gamma_5\, [0;\lambda n]\, q(\lambda n)\, |P, S_T\rangle$$

"chiral-odd" structure

→ in combination with other chiral-odd objects (Collins effect)

→ quark mass effects (twist-3)

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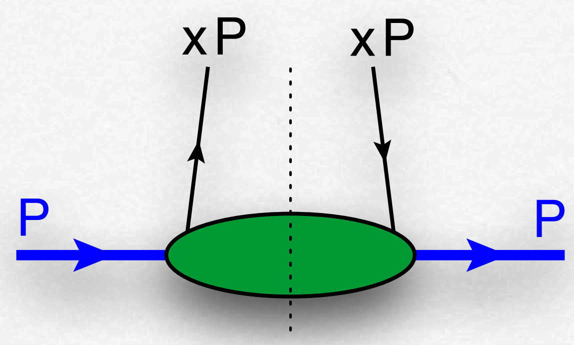

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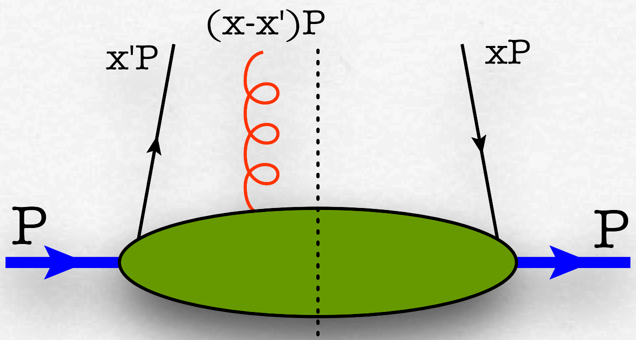
2) 'bad components' → g_T

$$g_T^q(x) = -\frac{(P\cdot n)}{M} \int_{-\infty}^{\infty} \frac{d\lambda}{4\pi}\, \mathrm{e}^{i\lambda x (P\cdot n)}\, \langle P, S_T|\; \bar{q}(0)\; \slashed{S}_T \gamma_5\; [0;\lambda n]\; q(\lambda n)\; |P, S_T\rangle$$

Twist - 3 characteristics hidden in Dirac structure

3) Quark - Gluon - Quark Correlations

(ETQS-matrix elements)



$$\frac{M}{2}\epsilon_T^{\alpha\beta} S_{T\beta}\, G_F^q(x,x') = \int \frac{d\lambda\, d\eta}{2(2\pi)^2}\, e^{i(P\cdot n)(x'\lambda+(x-x')\eta)} \langle P, S_T|\bar{q}(0)\gamma^+\, gF^{+\alpha}(\eta n)\, q(\lambda n)|P, S_T\rangle$$

$$\frac{M}{2} S_T^{\alpha}\, i\tilde{G}_F^q(x,x') = \int \frac{d\lambda\, d\eta}{2(2\pi)^2}\, e^{i(P\cdot n)(x'\lambda+(x-x')\eta)} \langle P, S_T|\bar{q}(0)\gamma^+\gamma_5\, gF^{+\alpha}(\eta n)\, q(\lambda n)|P, S_T\rangle$$

'dynamical twist - 3'

→ 3 - parton correlator: suppression by additional propagator

→ dependence on two parton momenta x, x':

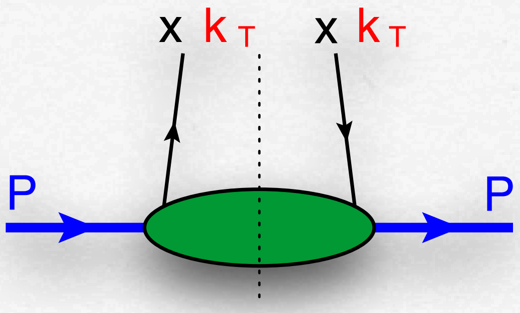
2-dimensional support, richer parton dynamics

→ so far: only "diagonal support" $G_F(x,x)$ constraint by data...

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

$$F^y = [\vec{E} + \vec{v}\times\vec{B}]^y \propto \int dx \int dx'\; G_F(x,x')$$

4) 'Transverse Parton Momenta k_T'



'Sivers function'

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

'wormgear function'

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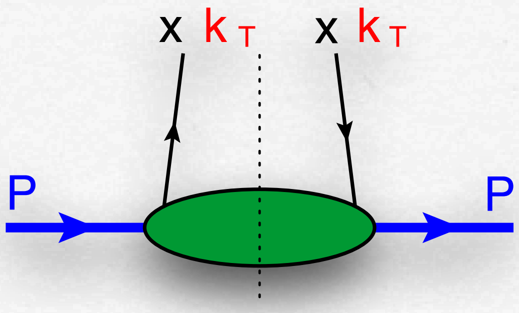

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Relations in collinear factorization

Sivers vs. Gluonic Pole:

$$f_{1T,\mathrm{DIS}}^{\perp(1)}(x) = \frac{\pi}{2} G_F(x,x)$$

'QCD - equation of motion':

$$g_{1T}^{(1)}(x) \;=\; x g_T(x) - \frac{m_q}{M} h_1(x) - \int_0^1 dx' \, \frac{G_F(x,x') + \tilde{G}_F(x,x')}{2(x'-x)}$$

→ eliminate TMD moments in twist - 3 formalism

TMD - factorization: 'Fully evolved' form of Sivers function

[Aybat, Collins, Qiu, Rogers, PRD85,034043]

$$\frac{\partial}{\partial b_T} f_{1T}^{\perp}(x, b_T; \mu, \zeta) \propto \left[\int_x^1 dz\, dz'\, C(z, z', \mu_b)\, G_F(z, z', \mu_b) \right] \mathrm{e}^{(S_{\mathrm{pert}} + S_{\mathrm{non-pert}})(b_T)}$$

→ G_F determines x-dependence of Sivers function

→ C at NLO: full support of G_F needed!

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many competing twist - 3 effect:

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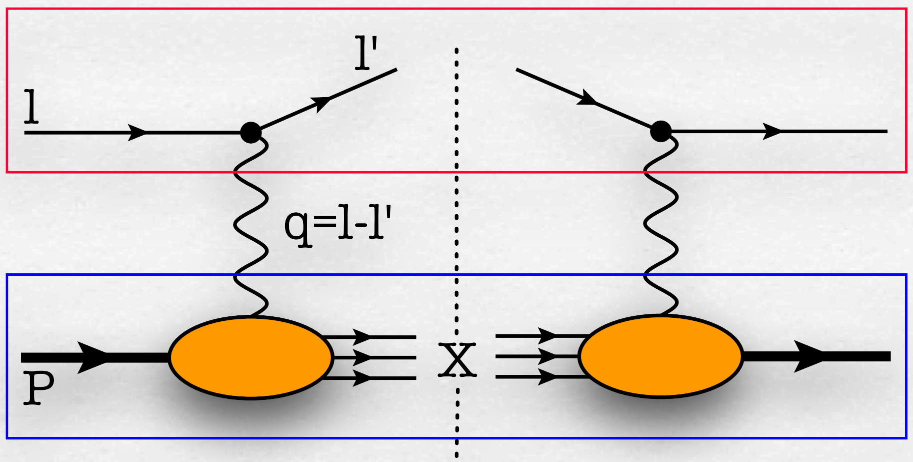
Fragmentation seems to dominate! [Kanazawa, Koike, Metz, Pitonyak, PRD89, 111501(R)]

⇒ Less complicated processes?

Transverse Spin Asymmetries
in
deep-inelastic
lepton-nucleon processes

The archetype: g_2 in DIS ($e^{\rightarrow} + p^{\uparrow} \longrightarrow e + X$)



Structure functions

$$\frac{d\sigma}{dx_B\, dy} \propto (F_1, F_2) + \lambda_e\ S_L g_1 + \lambda_e\ S_T \cos\phi_s (g_1 + g_2)$$

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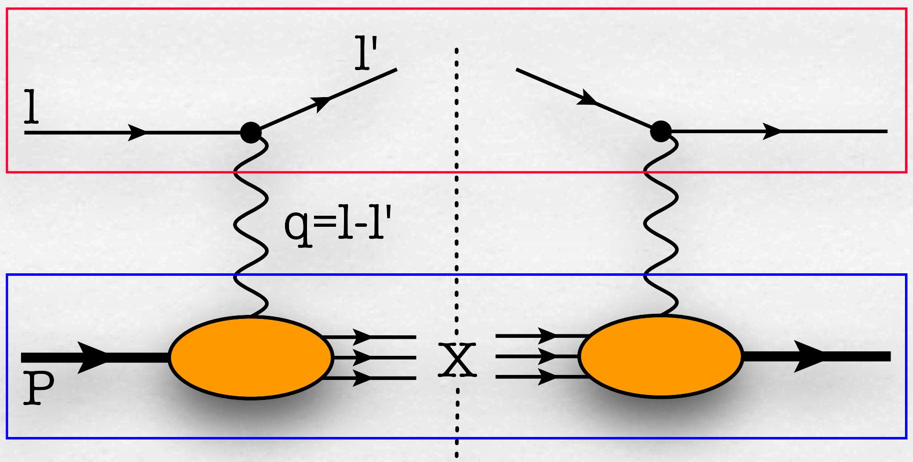

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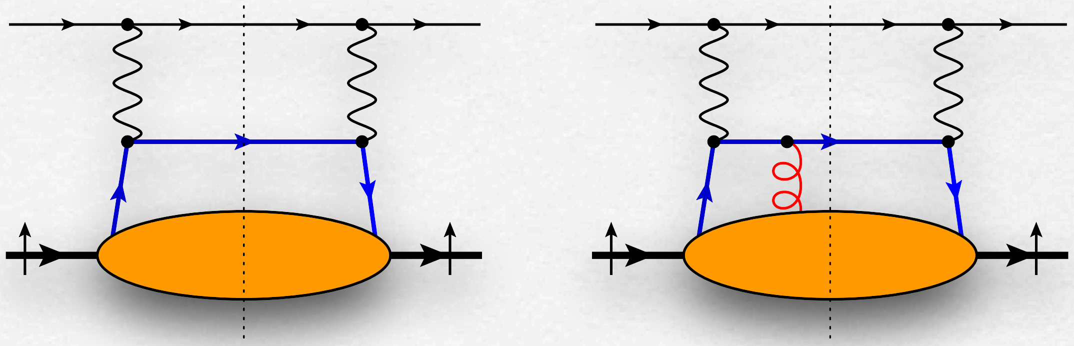
Twist - 3 formalism

Hard part to LO:



Double-Spin Asymmetry:

$$A_{LT} \propto (g_1 + g_2) \quad \propto \quad x g_T(x) + g_{1T}^{(1)}(x) + \frac{m_q}{M} h_1(x) + \int_0^1 dx' \frac{G_F(x,x') + \tilde{G}_F(x',x)}{2(x'-x)}$$

$$(\mathrm{QCD-EOM}) \longrightarrow 2\ x g_T(x)$$

Transverse SSA in DIS

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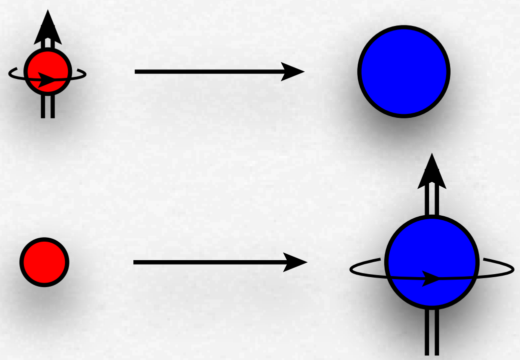
$A_N = 0$ in 1-γ exchange [Christ, Lee,1966]!

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



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

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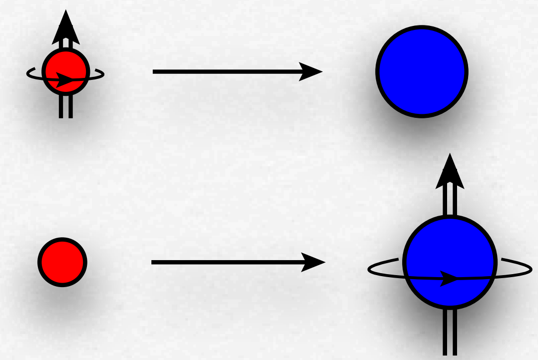

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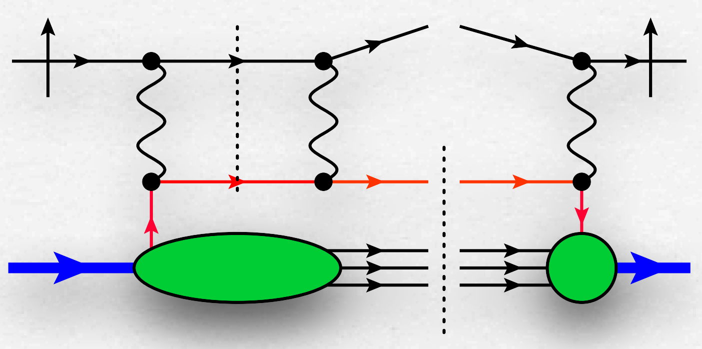
Transverse Single-Beam Spin Asymmetry in DIS

[Metz, M.S., Goeke, PLB 643 (2006) 319]



Transversely polarized lepton → lepton mass effect

$$A_{TU} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \alpha_{\rm em} \frac{m_l}{Q} \sum_q e_q^3 f_1^q(x_B)$$

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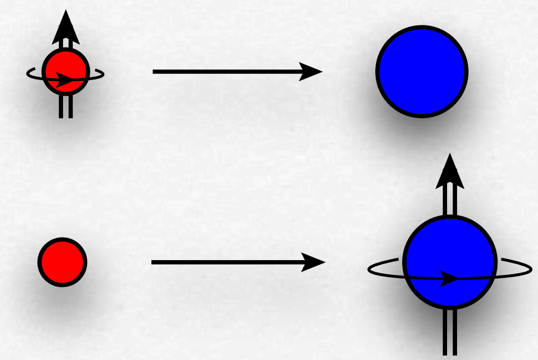

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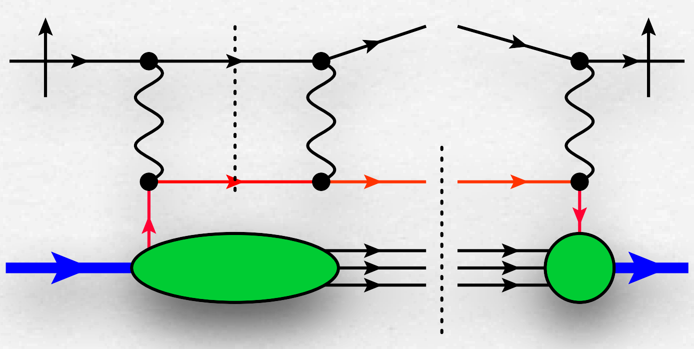

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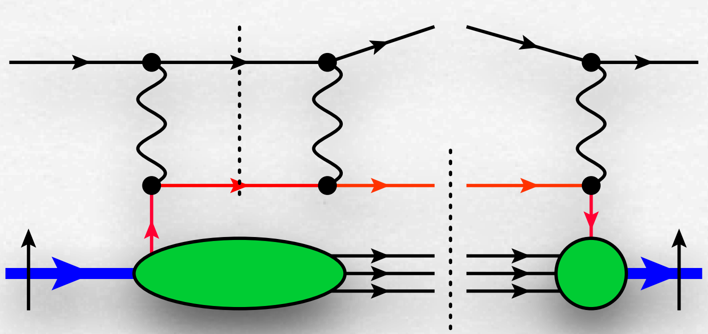
Transverse Target Single Spin Asymmetry in DIS

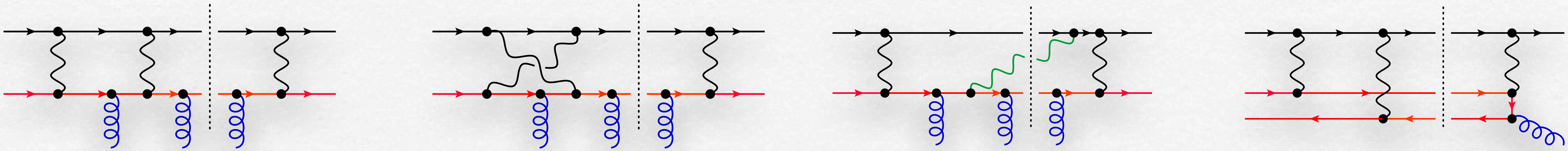
[Metz, M.S., Goeke, PLB 643 (2006) 319]



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

QED NLO soft singularities ⇔ higher twist effects

Inclusion of 'Quark - Gluon Correlations'



→ Sum of all twist-3 Two-Photon effects finite!

[MS, PRD 87, 034006 (2013)]

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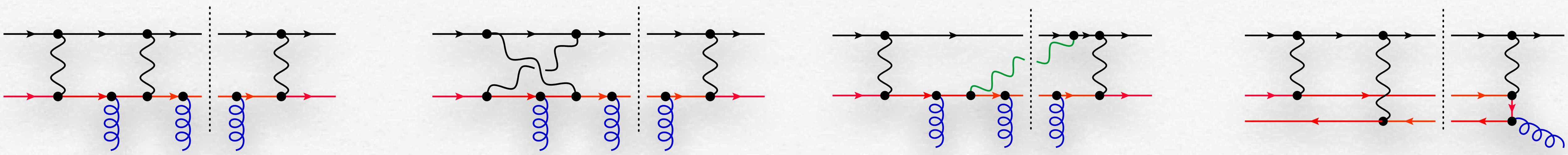

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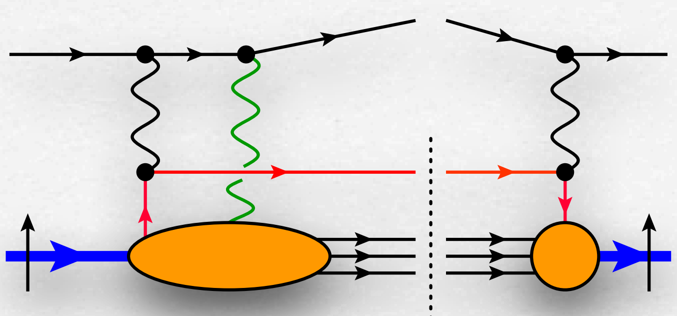
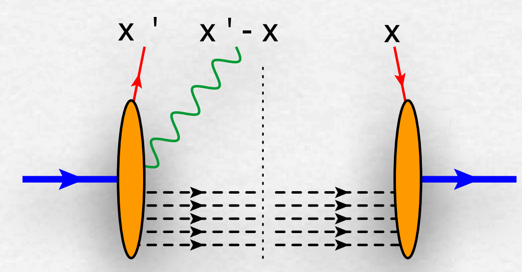
<u>Complementary effect:</u> Soft photon from nucleon wave function

[Metz, Pitonyak, Schäfer, MS, Vogelsang, Zhou, PRD86, 094039 (2012)]



Contributions from Quark - Photon - Quark Correlations

$$G_F^{\gamma}(x,x') \sim \langle \bar{q} \; F_{\text{em}} \; q \rangle$$



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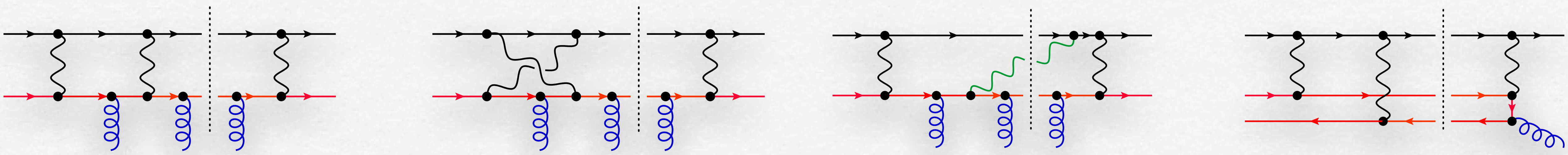

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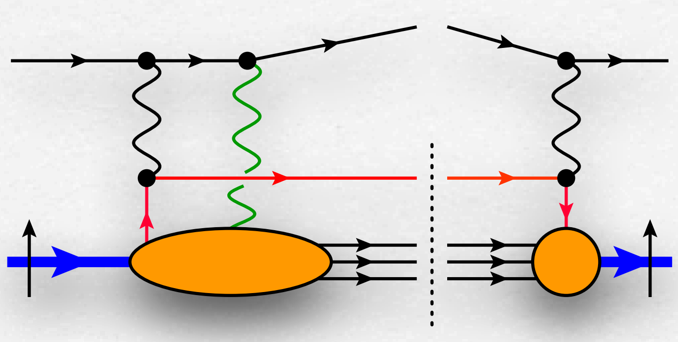

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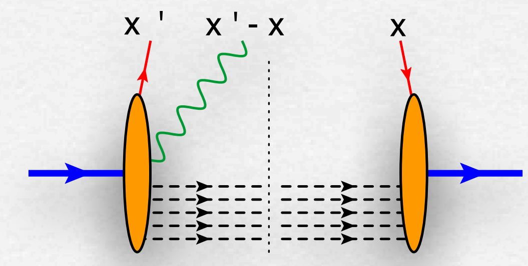


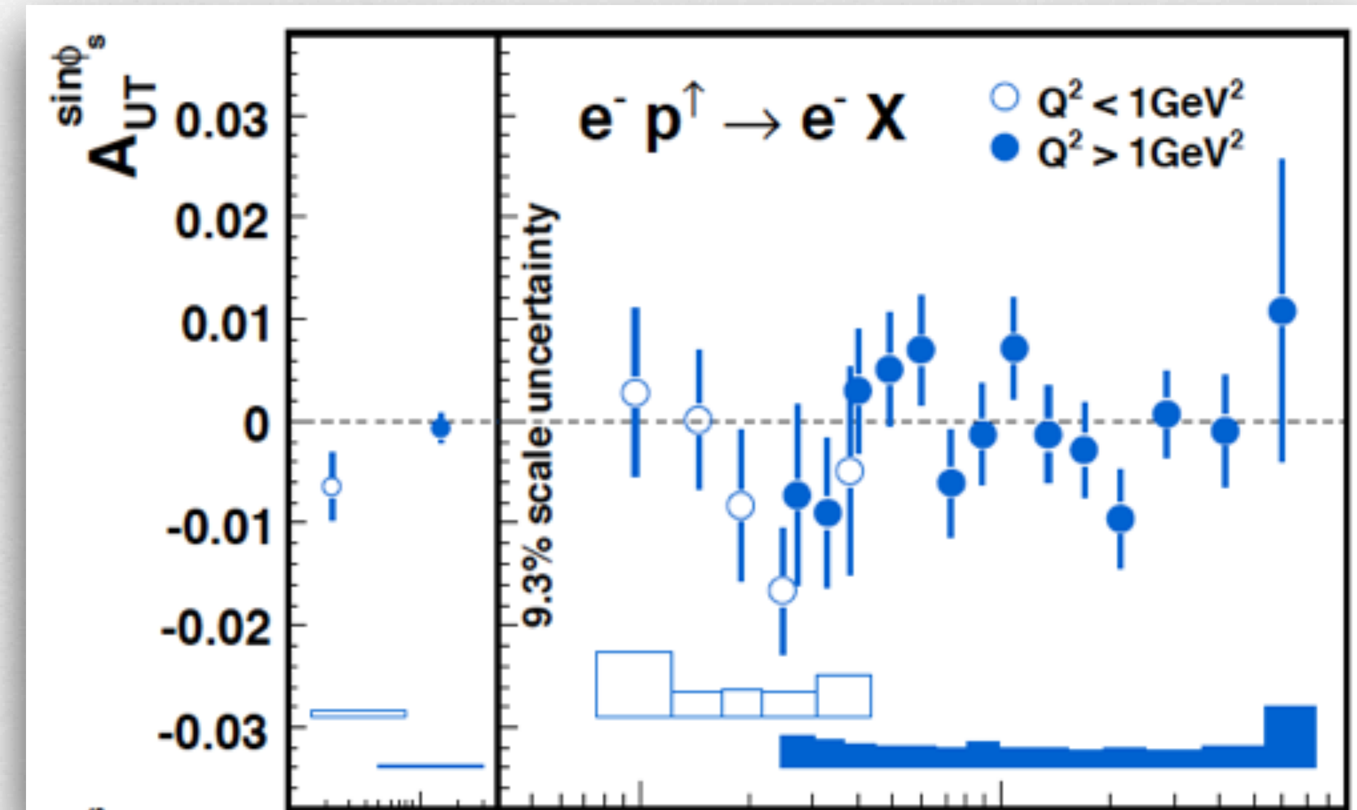
Final result [MS, PRD 87, 034006 (2013)]

$$A_{UT} \quad \propto \quad \alpha_{\mathrm{em}} \frac{M}{Q} \Big[\int_0^1 dx \; \Big(\hat{\sigma}_+ (\tfrac{x_B}{x}, y) G_F(x_B, x) + \hat{\sigma}_- (\tfrac{x_B}{x}, y) \tilde{G}_F(x_B, x) \Big)$$
$$+ f(y) \; (1 - x_B \tfrac{d}{dx_B}) G_F^{\gamma}(x_B, x_B) + g(y) \tfrac{m_q}{M} h_1(x_B) \Big]$$

Experimental situation

HERMES [PLB682, 351 (2010)]

polarized proton target



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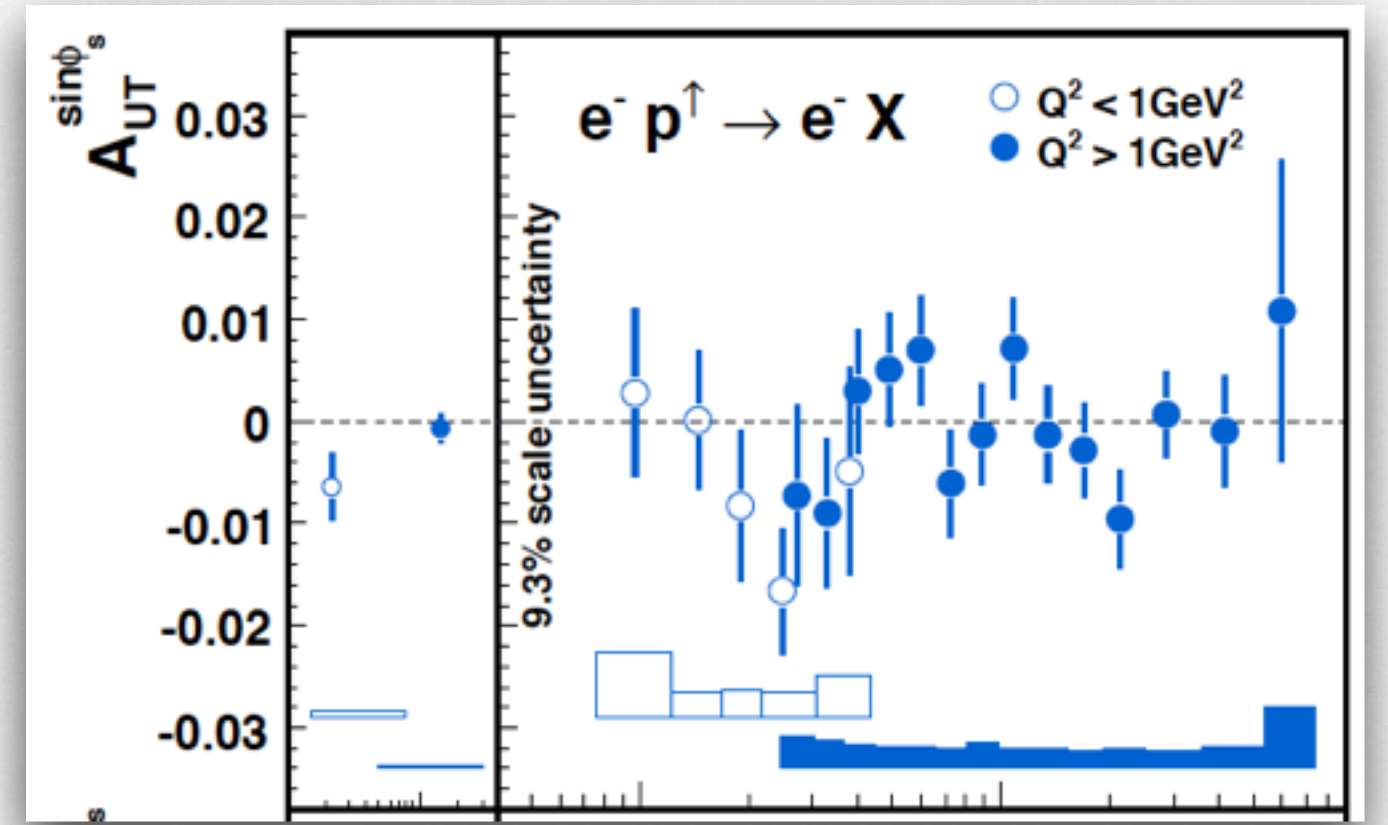
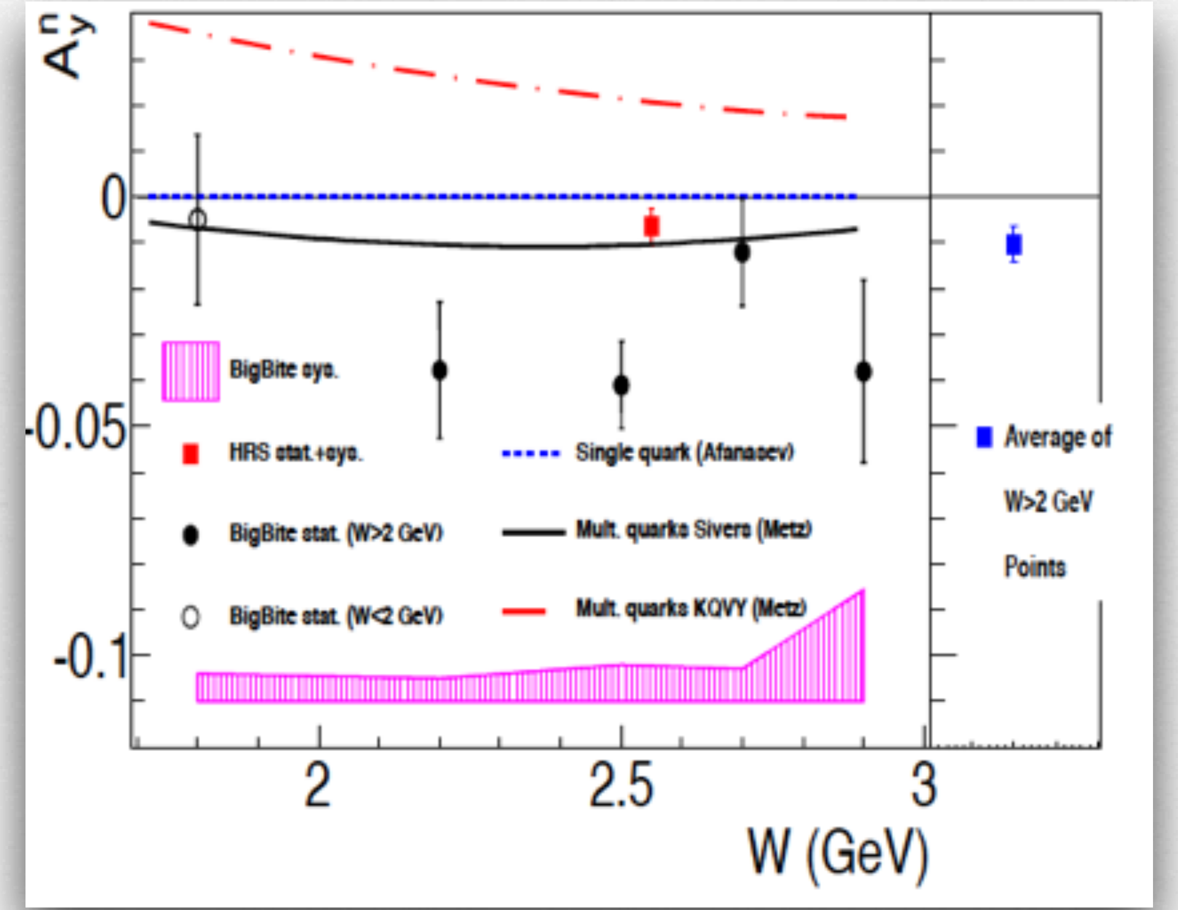


JLab [PRL113, 022502]
polarized He^3 (~neutron) target



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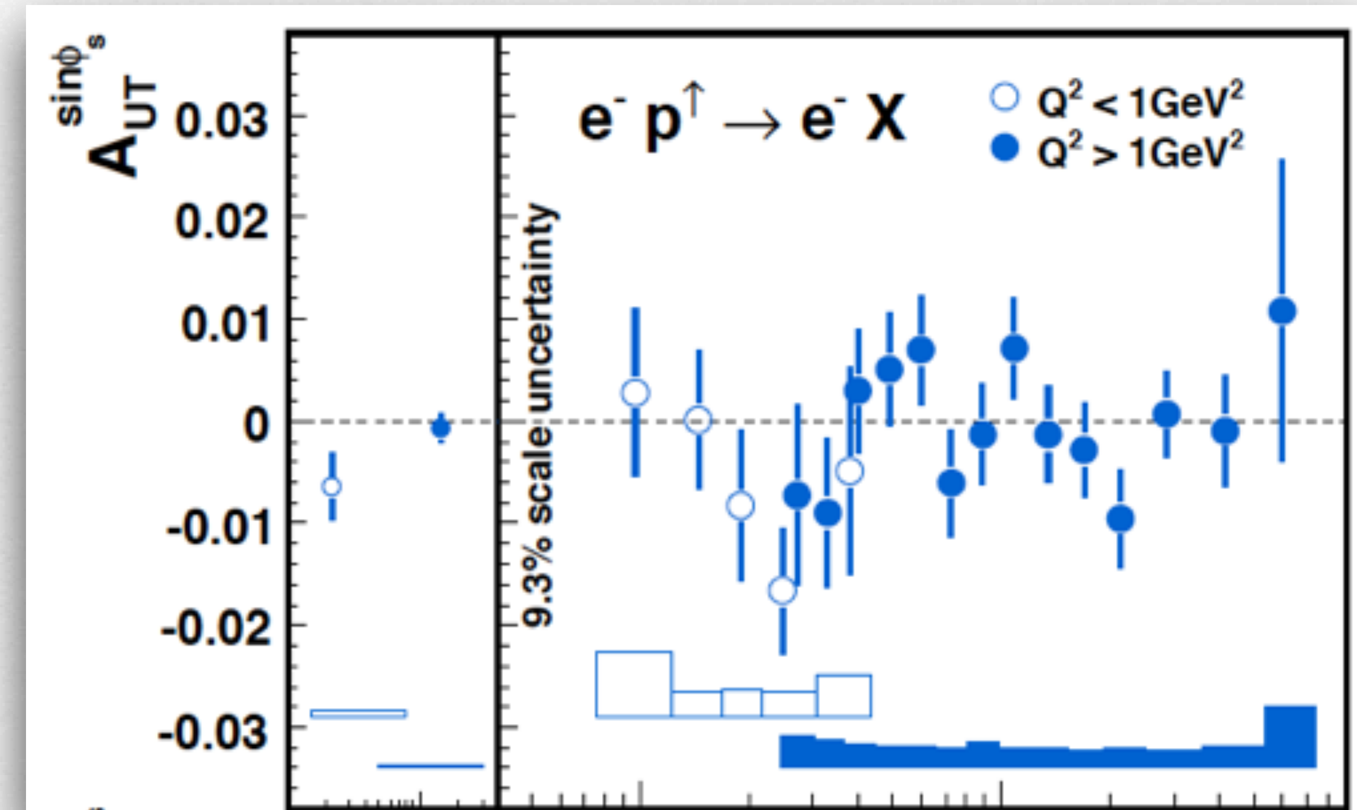

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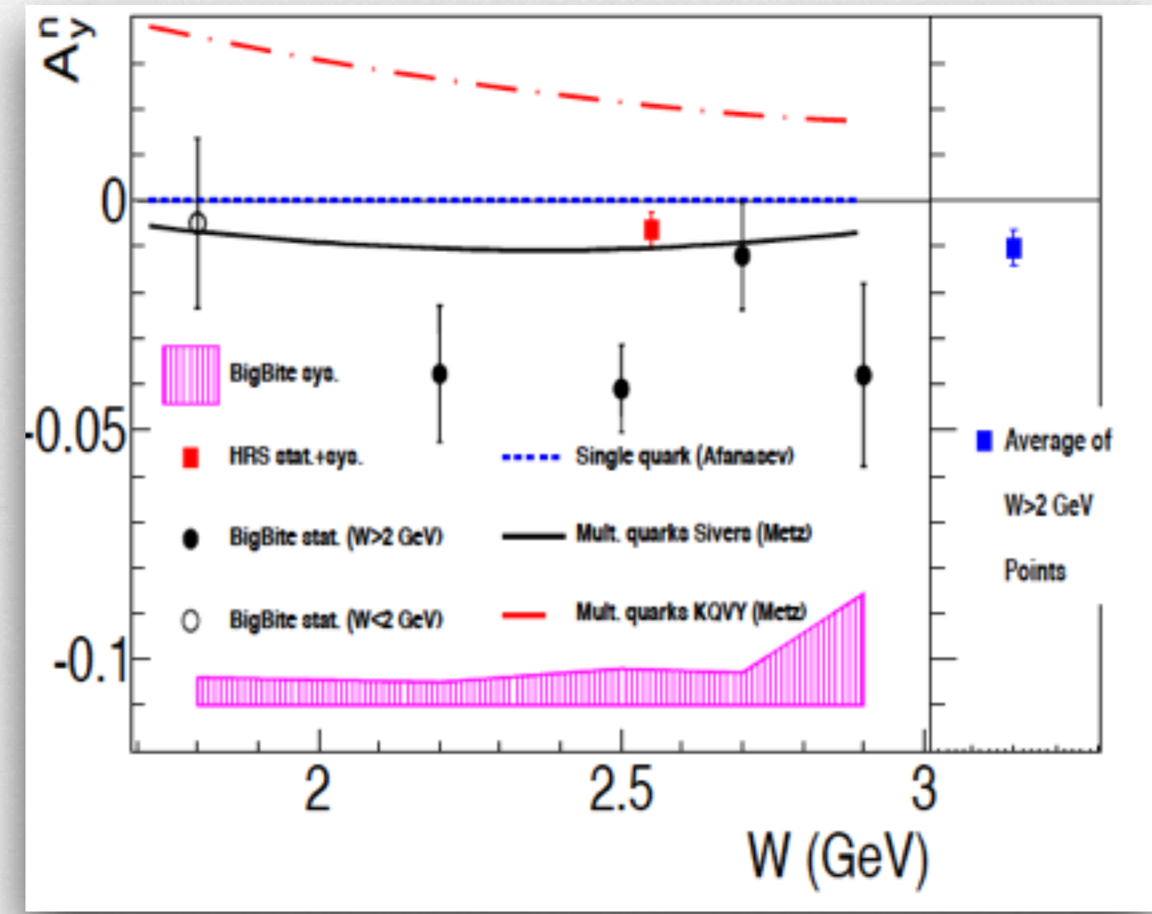


Models → quark-photon-quark correlations seem to dominate for He^3

Measurements to be continued at JLab12 for He^3 and proton target

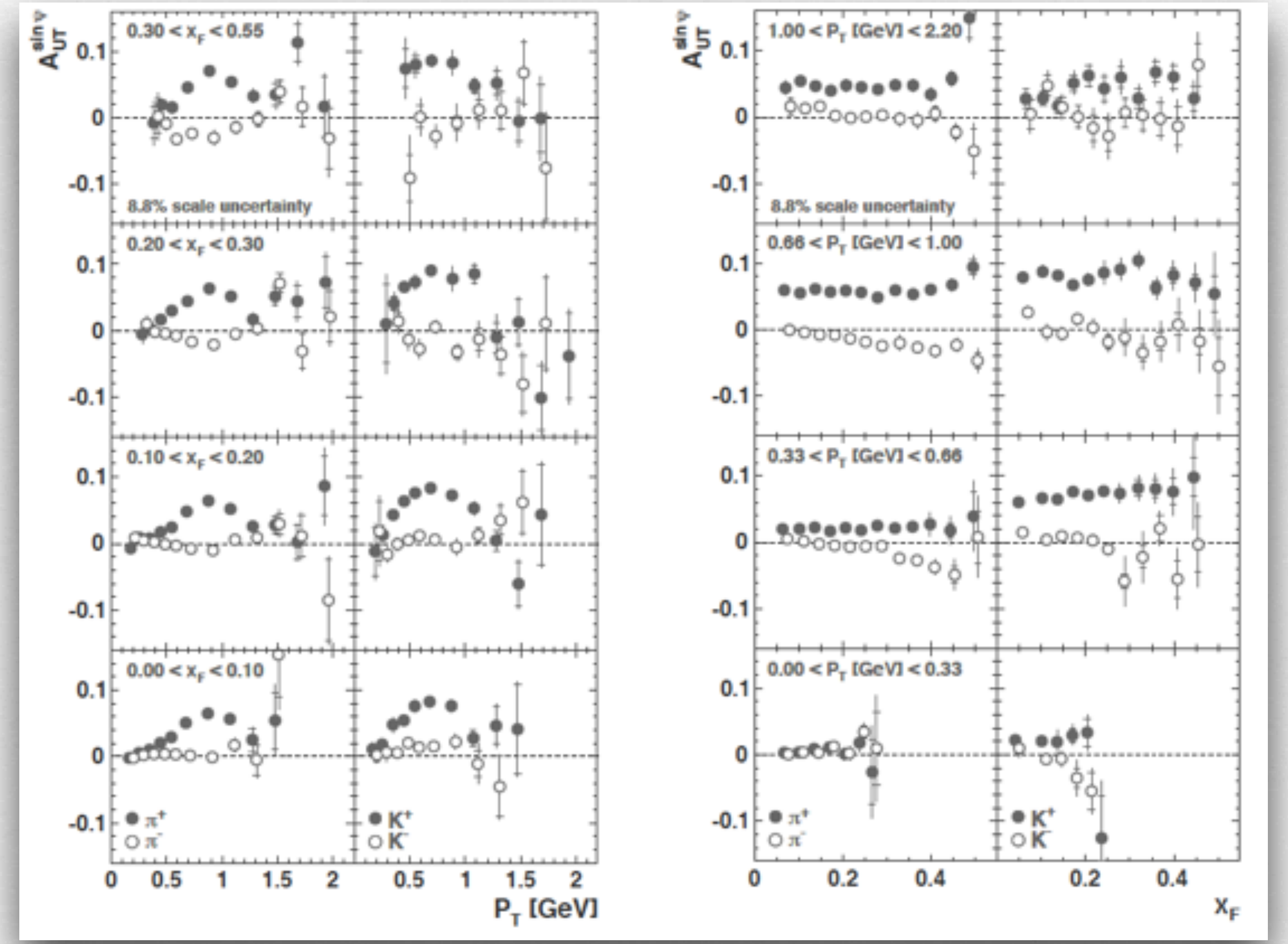
Hadron production in lepton - hadron collisions

$$(e + p^{\uparrow} \longrightarrow h + X)$$

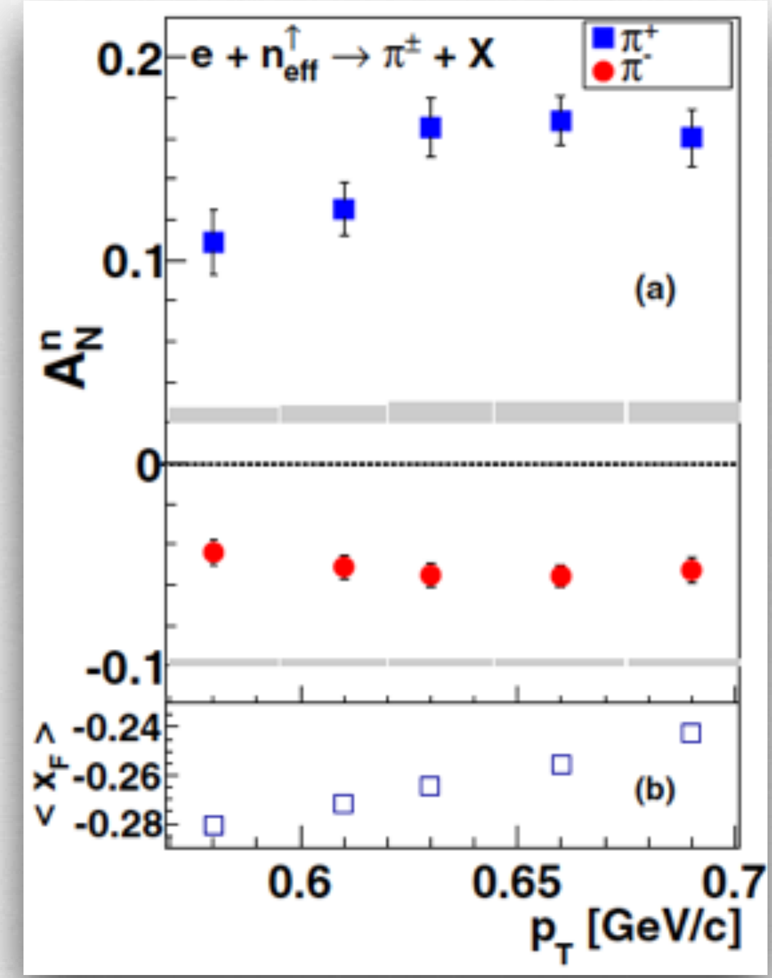
$$P_T \gg \Lambda_{QCD}$$

amazingly accurate data from HERMES, JLab...

HERMES [PLB728, 183]



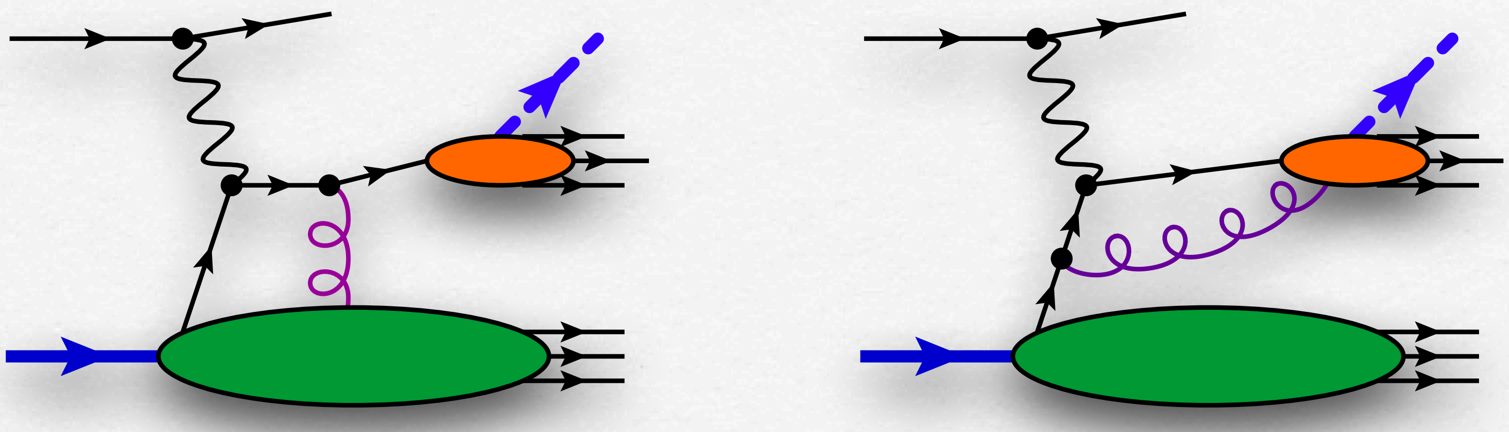
JLab [PRC89, 042201(R)]



$p_T < 1$ GeV $\Rightarrow$ pQCD?

LO calculation:

[Gamberg, Kang, Metz, Pitonyak, Prokudin, arXiv:1407.5078]



outgoing lepton momentum integrated out:

twist - 3 ETQS matrix elements & twist - 3 fragmentation

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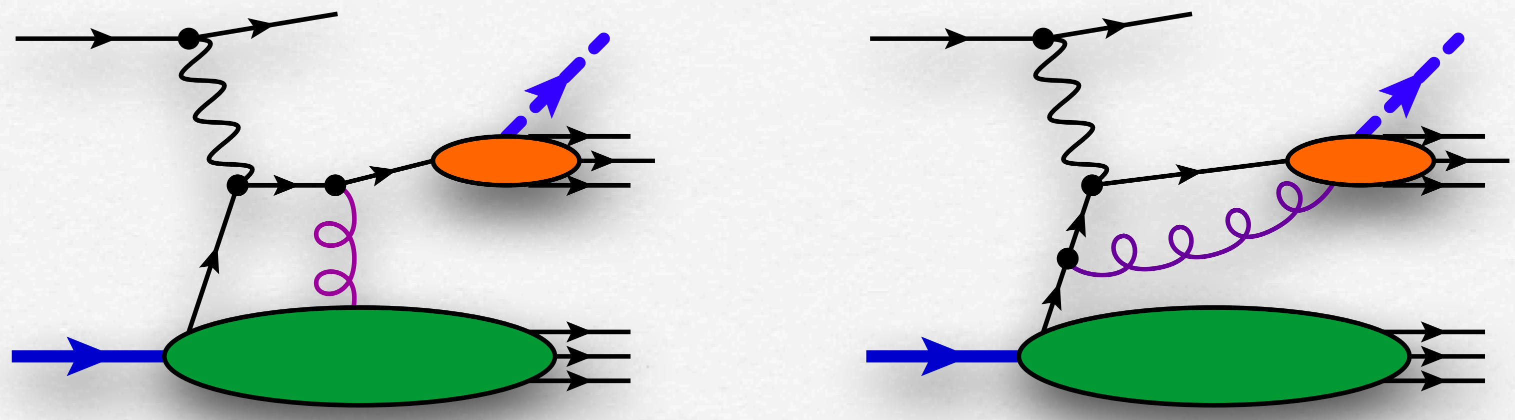

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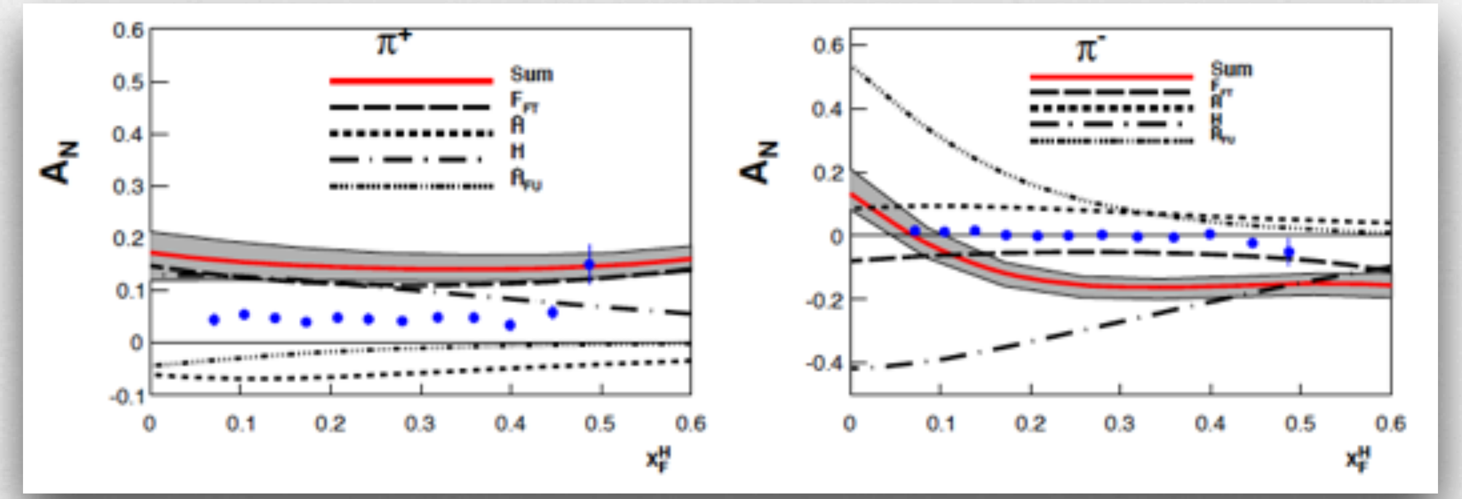


LO input typically overshoots the data

→ NLO?

→ refit?

⇒ opportunity for EIC

opportunity for EIC: $e + p^\uparrow \longrightarrow \text{jet} + X$

Photon Semi-inclusive DIS

or

'inclusive DVCS'

$$(e + p \longrightarrow e + \gamma + X)$$

Photon semi-inclusive DIS: $e + p \longrightarrow e + \gamma + X$

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

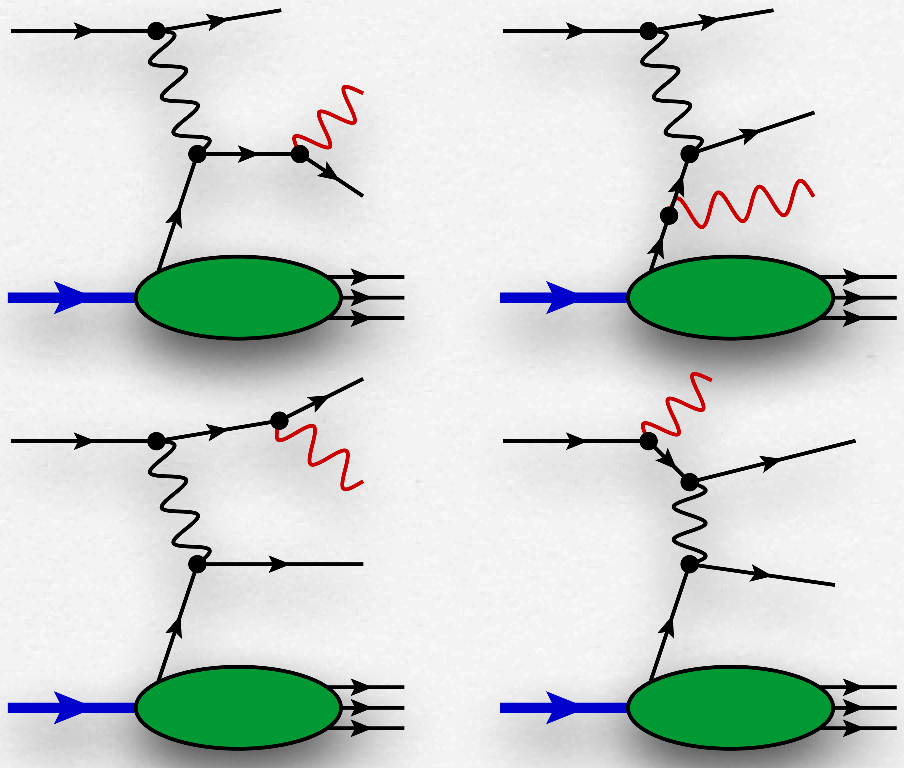
Circumvent Christ - Lee theorem: real photon emission

Photon semi-inclusive DIS: e + p ⟶ e + γ + X

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

Circumvent Christ - Lee theorem: real photon emission

unpolarized cross section in the parton model



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

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

- Different 'Bjorken-x': $\bar{x} = -\frac{\bar{S}+\bar{T}+\bar{U}}{S+T+U}$

Photon semi-inclusive DIS: $e + p \longrightarrow e + \gamma + X$

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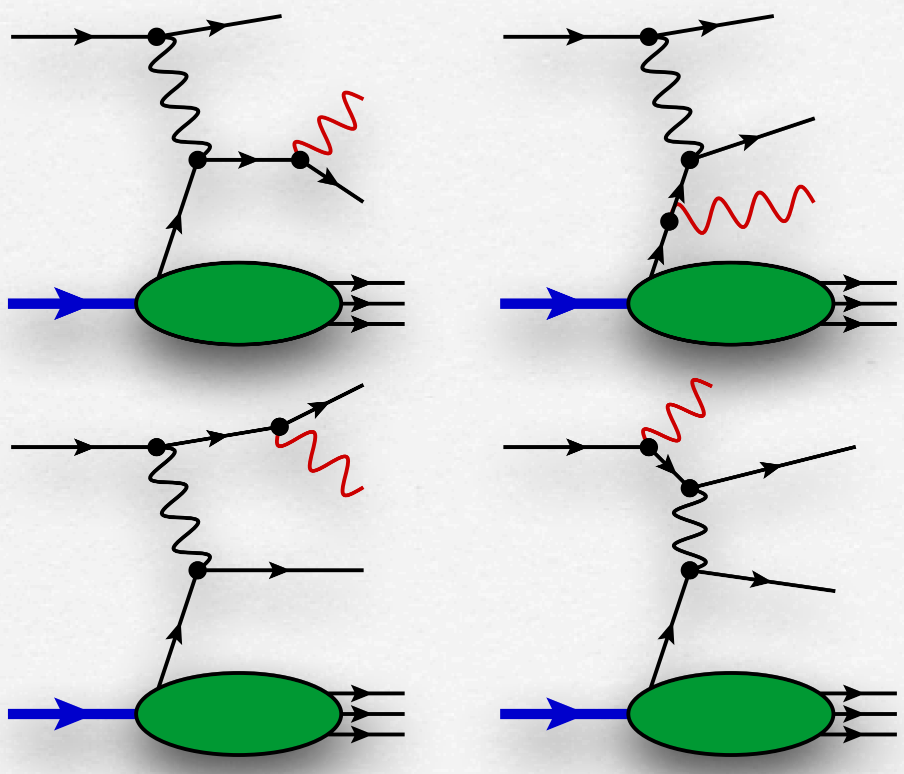

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- Different 'Bjorken-x': $\bar{x} = -\frac{\bar{S}+\bar{T}+\bar{U}}{S+T+U}$

rare process, cross section = $O(\alpha^3)$ → too rare?

LO numerical estimate

- Assume collider mode, $S^{1/2} = 100$ GeV (EIC)
- e - p - c.m. frame & midrapidity "back-to-back" lepton-photon pairs

$\Longrightarrow$ assume cuts $-1 \leq \eta_{\gamma/e} \leq 1$, $E_{\gamma/e} \leq S^{1/2}/2$, $\pi/2 \leq \Delta\phi \leq 3\pi/2$

$\Longrightarrow$ no "soft" propagators in LO hard part

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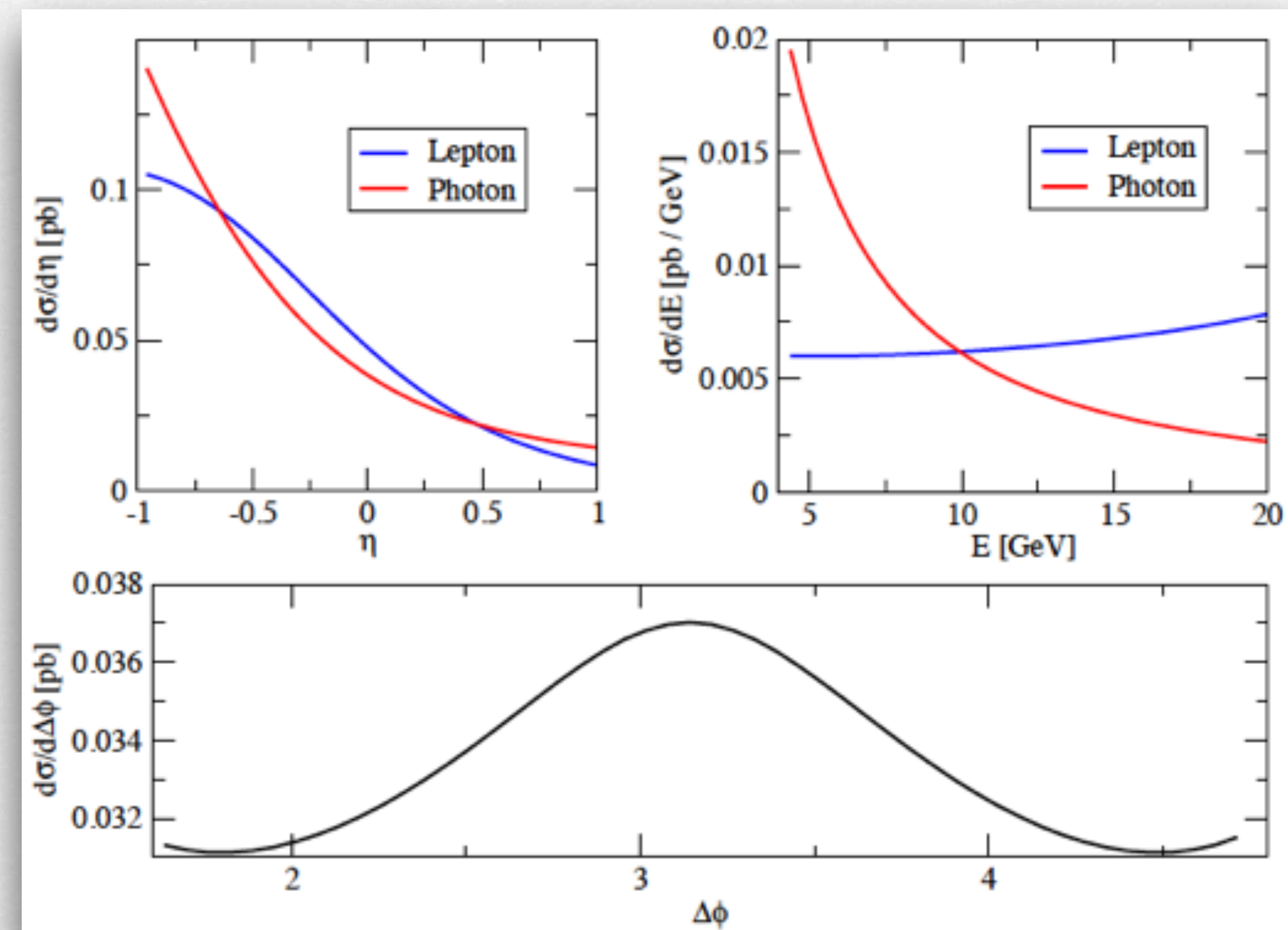


total cross section

$\sigma^{\gamma SIDIS} \simeq 100$ fb

($\sigma^{DIS} \simeq 100$ pb)

differential cross section

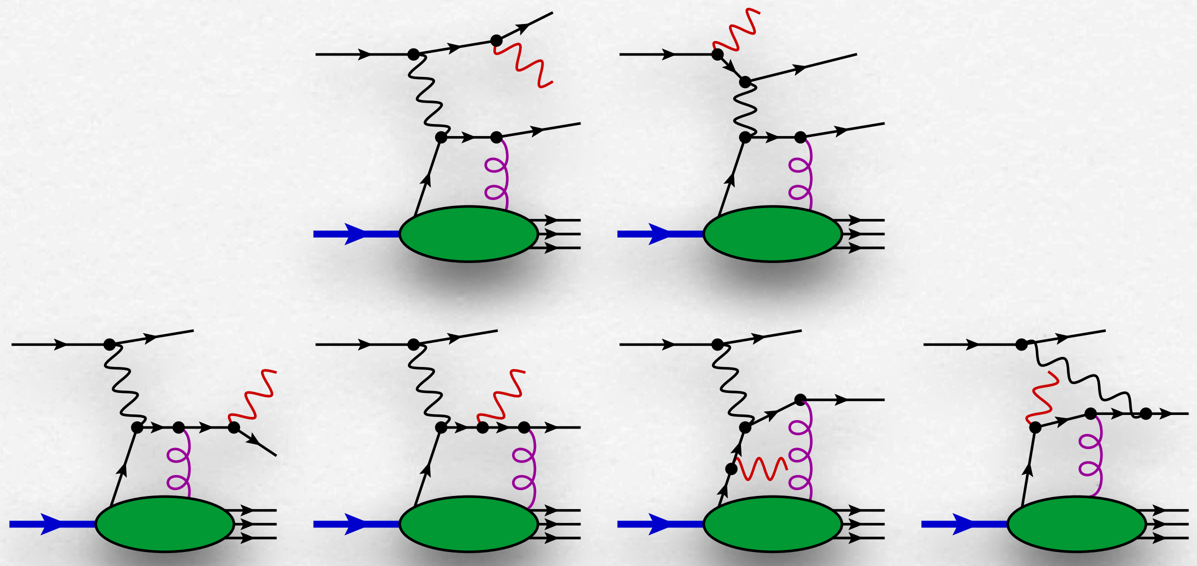
$d\sigma^{\gamma SIDIS} \simeq O(10$ fb)

⇒ Needs large luminosity

(JLab or EIC)

Transverse SSA in photon SIDIS

Include ‘bad components’, ‘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: $G_F(x,x)$
2) Soft Fermion Poles: $G_F(x,0)$
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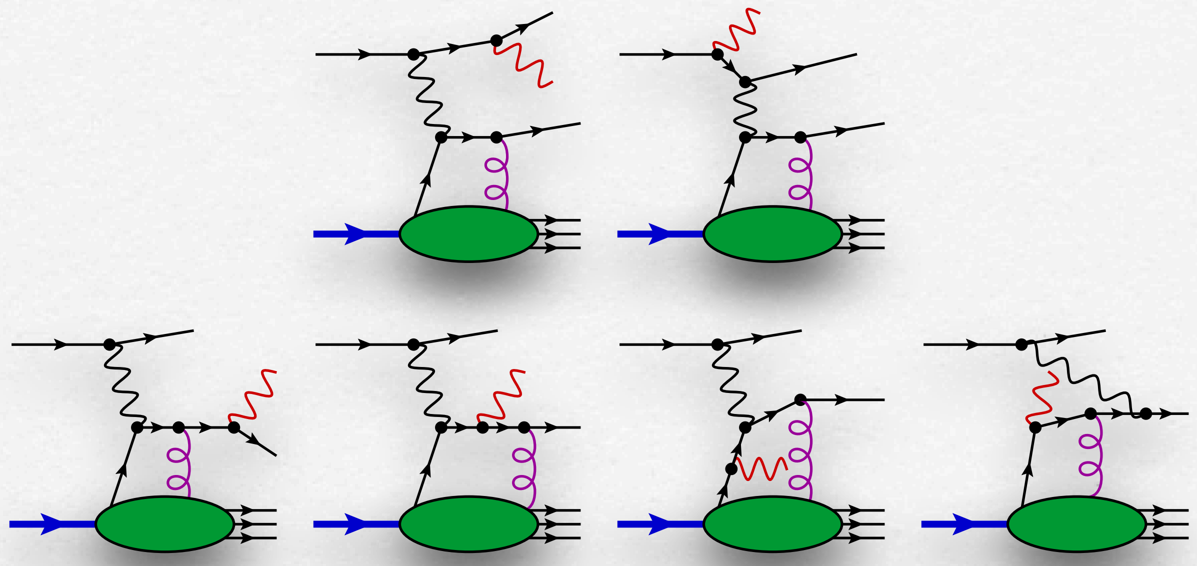

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LO Result:

$$\bar{x} = -\frac{\bar{S}+\bar{T}+\bar{U}}{S+T+U} \quad ; \quad \tilde{x} = -\frac{\bar{T}}{S+T}$$

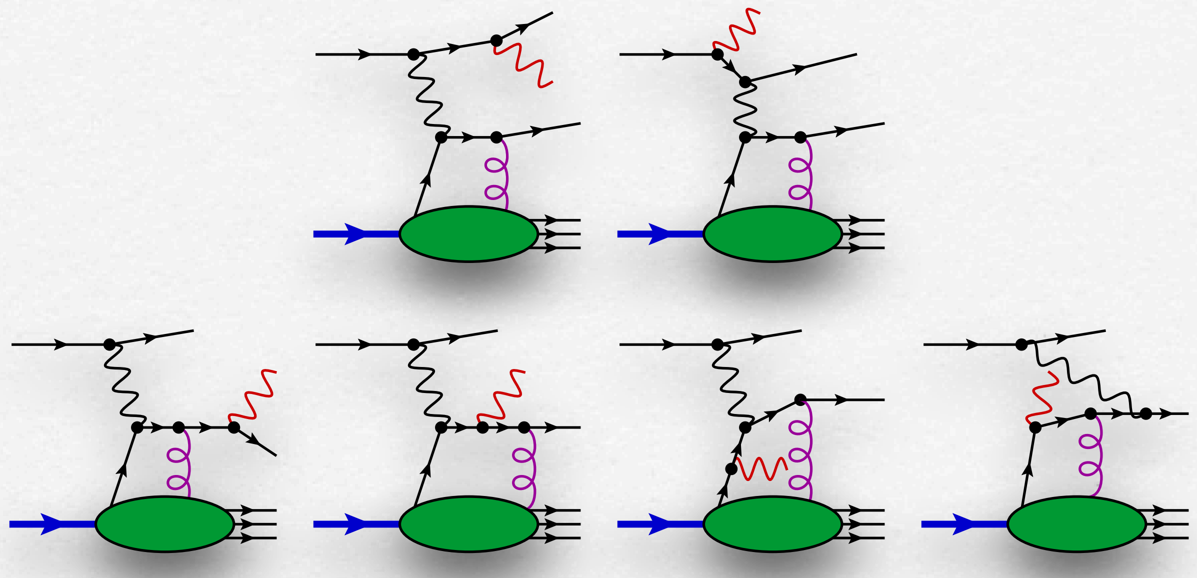
$$E_\gamma E_e \frac{d\sigma_{UT}}{d^3\vec{P}_\gamma \; d^3\vec{P}_e} = \sum_q \Big[\hat{C}_{1,\mathrm{SGP}} \; G_F(\bar{x},\bar{x}) + \hat{C}_{2,\mathrm{SGP}} \; \frac{\mathrm{d}}{\mathrm{d}\bar{x}} G_F(\bar{x},\bar{x}) + \hat{C}_{+,\mathrm{SFP}} \; G_F(\bar{x},0) + \hat{C}_{-,\mathrm{SFP}} \; \tilde{G}_F(\bar{x},0) + \hat{C}_{+,\mathrm{HFP}} \; G_F(\bar{x},\tilde{x}) + \hat{C}_{-,\mathrm{HFP}} \; \tilde{G}_F(\bar{x},\tilde{x}) \Big]$$

Soft Gluon Poles vanish ($C_{1/2,\,SGP}=0$)!

Coefficients e_q^2 $C^2 = 0$ (Christ - Lee theorem)!

Transverse SSA in photon SIDIS

Include 'bad components', 'kinematical' & 'dynamical' twist - 3 contributions



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$$\bar{x} = -\frac{\tilde{S}+\tilde{T}+\tilde{U}}{S+T+U} \quad ; \quad \tilde{x} = -\frac{\tilde{T}}{S+T}$$

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Soft Gluon Poles vanish ($C_{1/2,\,SGP}=0$)!

Coefficients $e_q^2 \, C^2 = 0$ (Christ - Lee theorem)!

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

Summary

- Twist - 3 matrix elements essential for the understanding of transverse SSA.
- ETQS - matrix element $G_F(x,x)$: extractions from semi-inclusive data
- Most promising process to fine-tune $G_F(x,x)$: $e + p^{\uparrow} \longrightarrow h/jet + X$!
- Direct information at LO on "non-diagonal" from photon SIDIS.

Wandzura - Wilczek (WW) relation

$$(g_1 + g_2)(x_B, Q^2) = \int_{x_B}^{1} \frac{dy}{y} g_1(y, Q^2) + \Delta(x_B, Q^2)$$

- derivation from Operator Product Expansion
- Breaking term of the WW approximation: Δ - term
- Common assumption: $\Delta = 0$ (small!)
- $\Delta \Longleftrightarrow$ Quark - Gluon Correlation functions $G_F(x, x'), \; \tilde{G}_F(x, x')$

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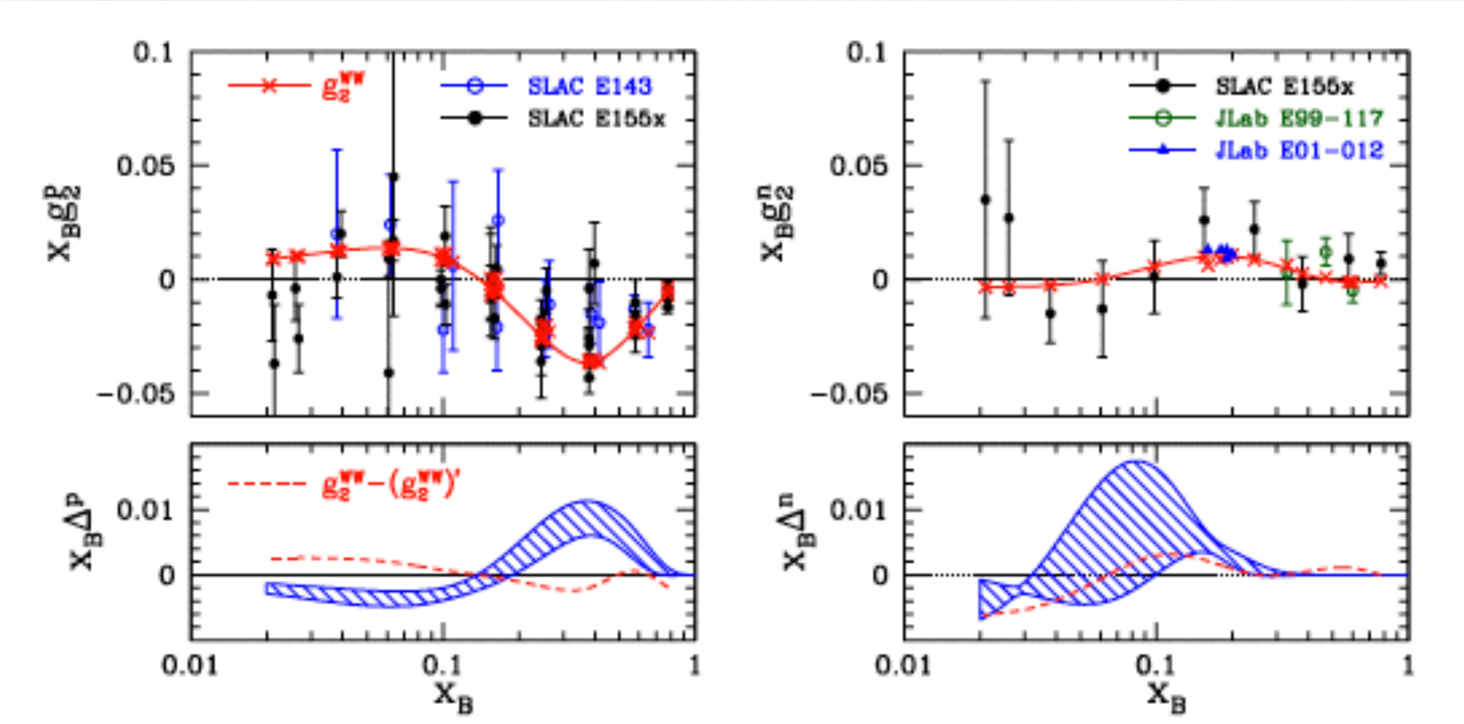

Quantitative analysis

[Accardi, Bacchetta, Melnitchouk, MS, JHEP0911(2009)093]

Fit to JLab & SLAC (p,n) data

$$\Delta(x_B) = \alpha(1 - x_B)^{\beta}((2 + \beta)x_B - 1)$$

Effect about 15% - 40% of g_2^{WW}!

Quark - Gluon - Quark Correlations not necessarily small!