Two-Photon Exchange effects in inclusive DIS

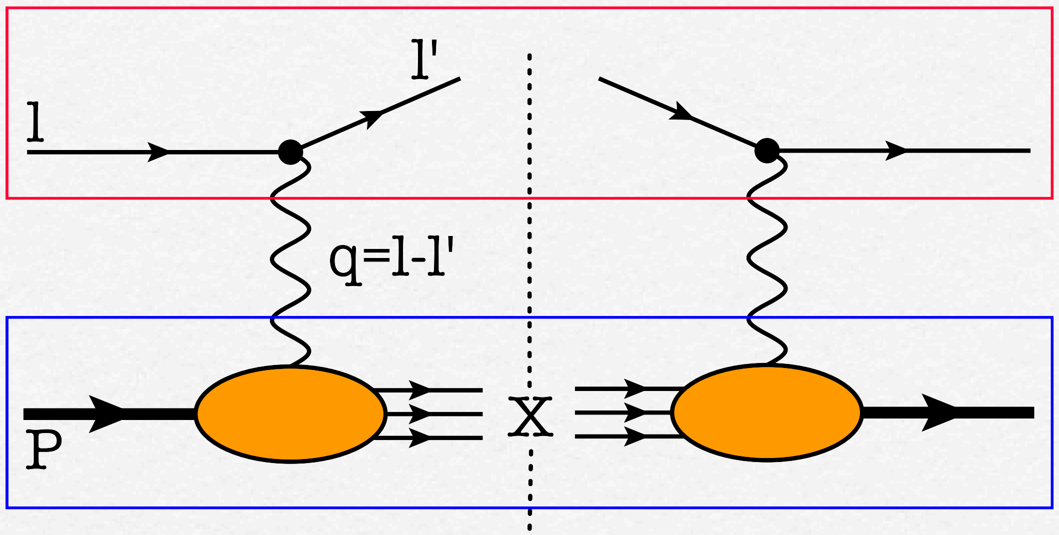
Marc Schlegel

University of Tübingen

based on:
M.S., PRD87 (2013) 034006;
Metz, Pitonyak, Schäfer, M.S., Vogelsang, Zhou, PRD86 (2012) 094039

Jefferson Lab Theory Center seminar,
Aug 5, 2013

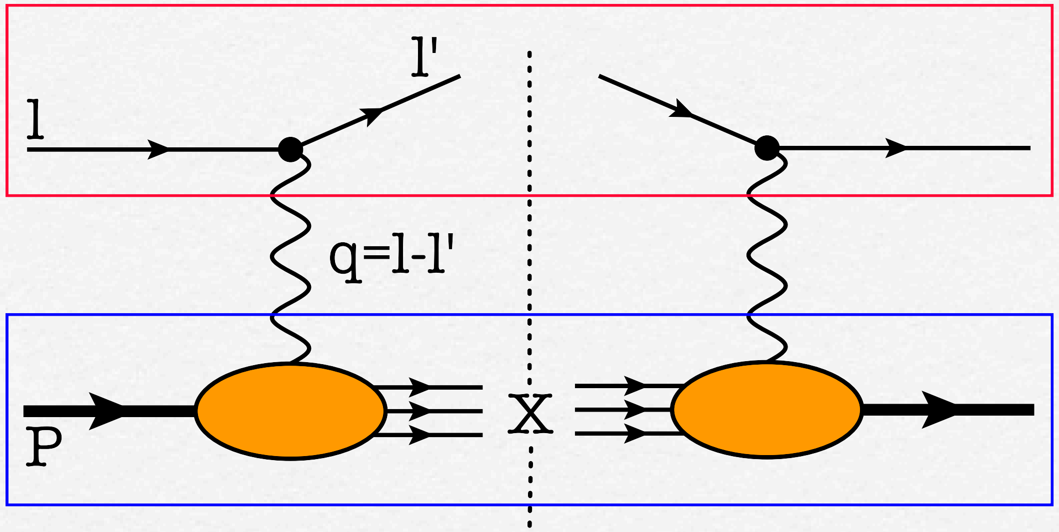
Deep-inelastic scattering (One-Photon Exchange)



Decomposition:

Leptonic - Hadronic Tensor

$$\boxed{d\sigma \propto L_{\mu\nu} W^{\mu\nu}}$$



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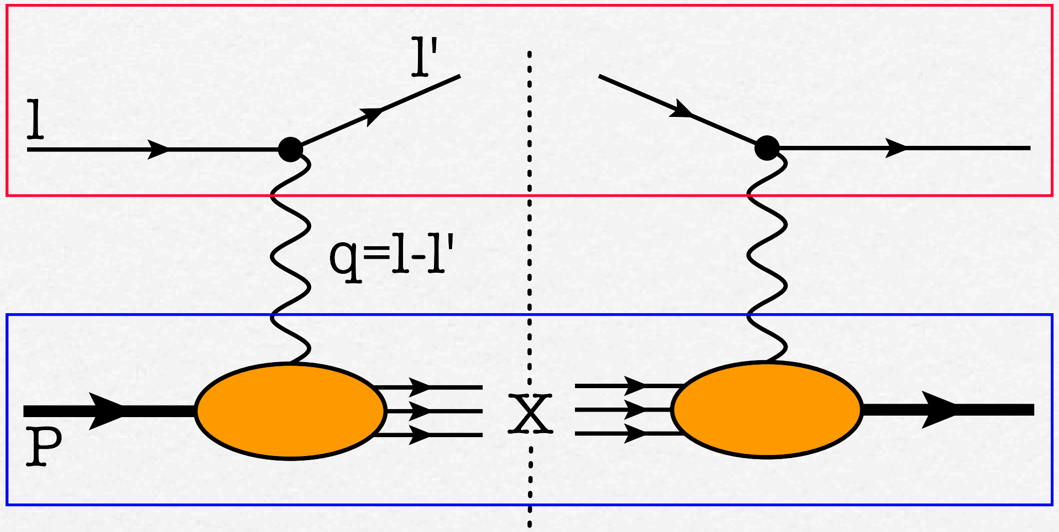
Leptonic Tensor: $L_{\mu\nu} \propto (l_\mu l'_\nu + l_\nu l'_\mu - \frac{Q^2}{2} g_{\mu\nu}) - i\lambda_e \varepsilon_{\mu\nu l l'}$

Hadronic Tensor ➛ Parameterization / Structure Functions

$$W^{\mu\nu} \propto \int d^4x\, \mathrm{e}^{iq\cdot x} \langle P, S | [J^\mu(x), J^\nu(0)] | P, S\rangle \longrightarrow (F_1,\ F_2) + \varepsilon^{\mu\nu\rho S}(g_1, g_2)$$



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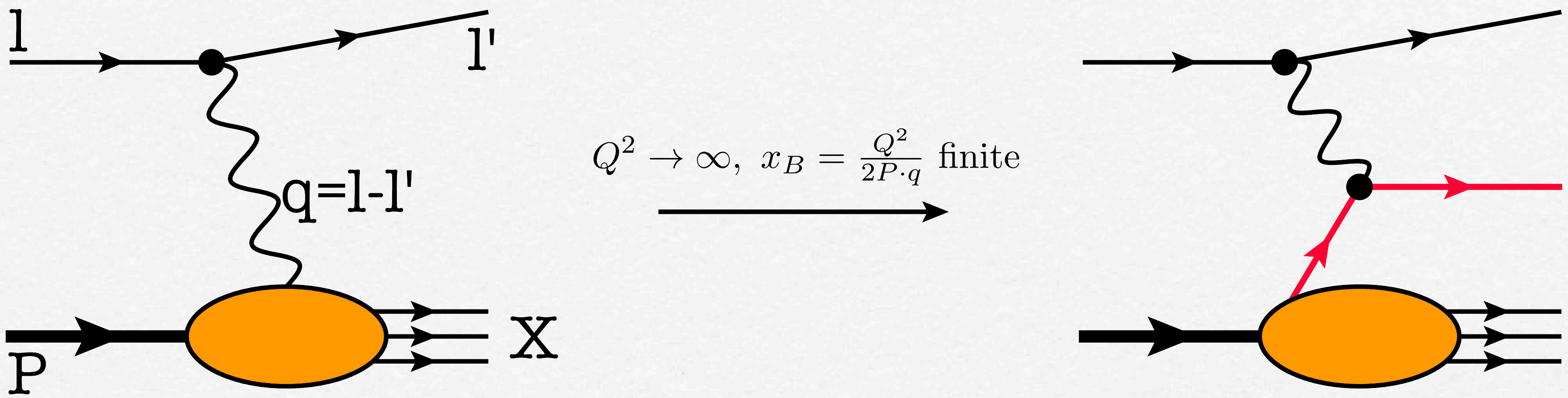
Observables for One-Photon Exchange

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

→ no single transverse spin observable [Christ-Lee, 1966]

Parton Model in the Bjorken-limit



Parton Model (leading twist, LO)

Unpolarized Cross Section:

$$2x_B F_1(x_B,Q) = F_2(x_B,Q^2) = x_B \sum_q e_q^2\, q(x_B,Q) = x_B \sum_q e_q^2 \int \frac{d\lambda}{4\pi}\, \mathrm{e}^{ix_B\lambda(P\cdot n)} \langle P|\bar{q}(0)\gamma^+ q(\lambda n)|P\rangle$$

Double longitudinal Polarization:

$$g_1(x_B,Q) = \tfrac{1}{2} \sum_q e_q^2\, \Delta q(x_B,Q) = \tfrac{1}{2} \sum_q e_q^2 \int \frac{d\lambda}{2\pi}\, \mathrm{e}^{ix_B\lambda(P\cdot n)} \langle P,S_L|\bar{q}(0)\gamma^+\gamma_5 q(\lambda n)|P,S_L\rangle$$

Transverse Polarization: "Subleading Twist"

$g_1+g_2 \rightarrow \sigma_{LT}$: suppressed by factor $M/Q \rightarrow$ many effects...

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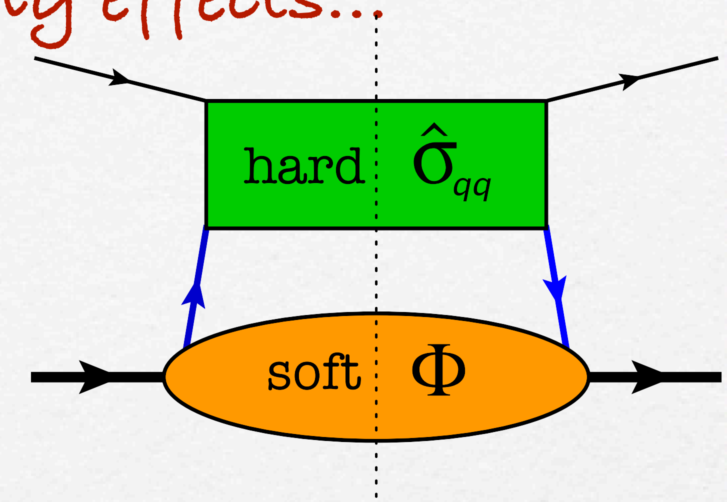

Quark Correlations

$$\boxed{\hat{\sigma}_{qq} \otimes \Phi = \int dx\ \hat{\sigma}_{qq}(x)\ \Phi(x)}$$

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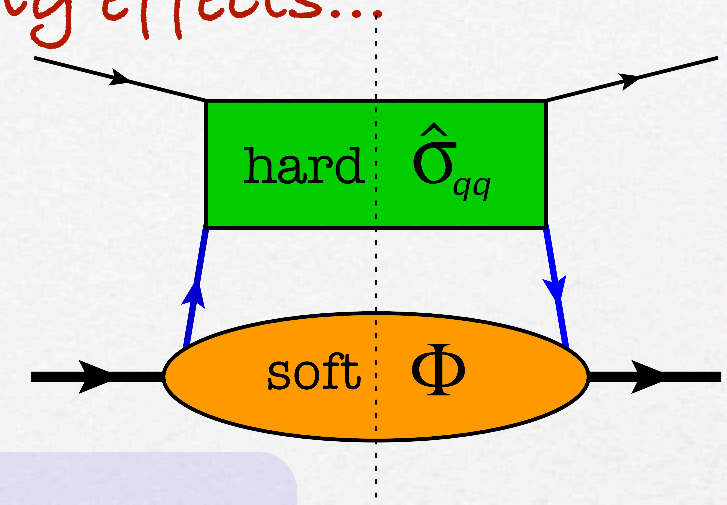

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“bad components” $\hat{\sigma}^{\perp} \otimes g_T(x)$

$$\boxed{S_T^{\rho}\ g_T^q(x) = \frac{P^+}{M} \int \frac{d\lambda}{4\pi}\ e^{ix_B\lambda(P\cdot n)} \langle P, S_T | \bar{q}(0) \gamma_{\perp}^{\rho} \gamma_5 q(\lambda n) | P, S_T \rangle}$$

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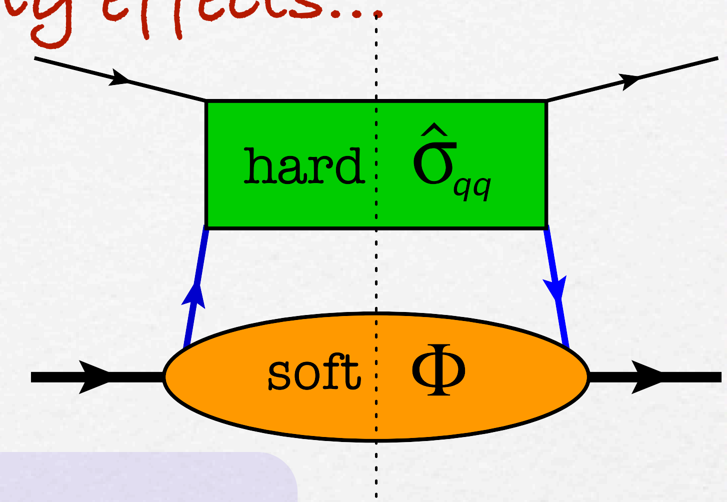

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"kinematical twist-3" (k_T-effects)

$$\hat{\sigma}_{qq}^{\partial} = \hat{\sigma}_{qq} + k_T^{\rho} \frac{\partial}{\partial k_T^{\rho}} \hat{\sigma}_{qq} + \ldots \Big|_{k_T=0}$$

$$\Phi_{\partial}(x) = \int d^2k_T \; k_T \; \Phi(x, k_T)$$

→ $g_{1T}^{(1)}(x)$ "T-even"

→ $f_{1T}^{\perp(1)}(x)$ "T-odd"

Transverse Polarization: "Subleading Twist"

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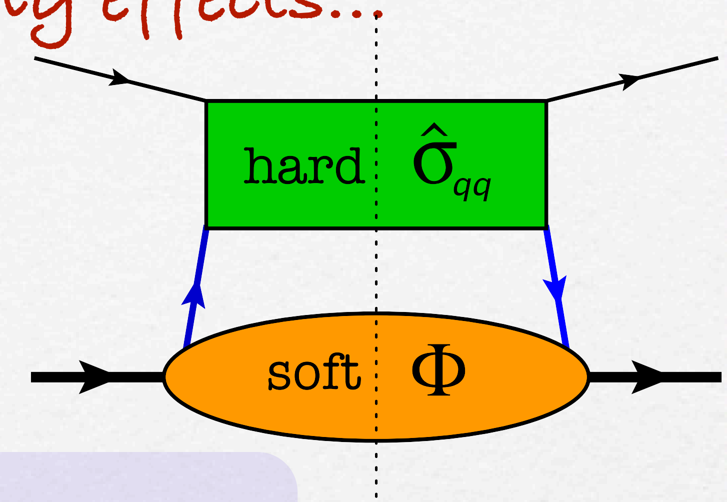

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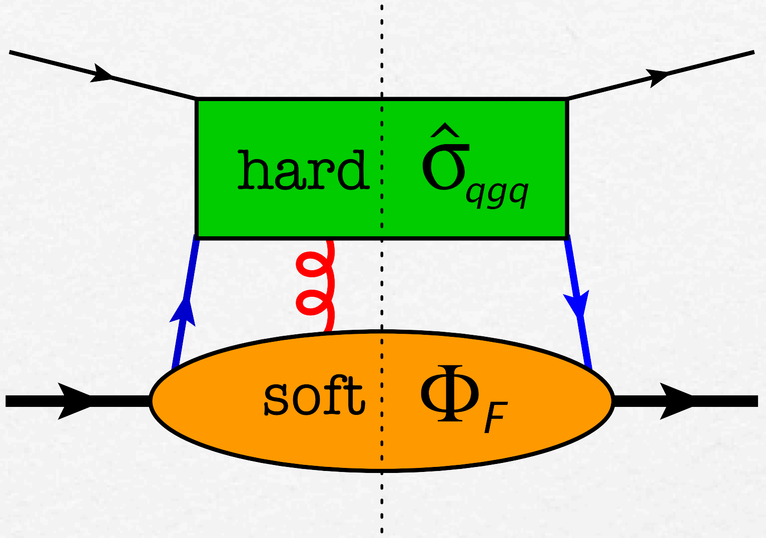
$$\Phi_{\partial}(x) = \int d^2k_T\ k_T\ \Phi(x, k_T) \longrightarrow \begin{cases} g_{1T}^{(1)}(x) & \text{"T-even"} \\ f_{1T}^{\perp(1)}(x) & \text{"T-odd"} \end{cases}$$

"quark mass effect" $\frac{m_q}{Q} h_1(x_B)$ chiral-odd, transversity

Quark-Gluon Correlations

"dynamical twist-3"

$$\boxed{\hat{\sigma}_{qgq} \otimes \Phi_F = \int dx \int dx' \; \hat{\sigma}_{qgq}(x,x') \; \Phi_F(x,x')}$$



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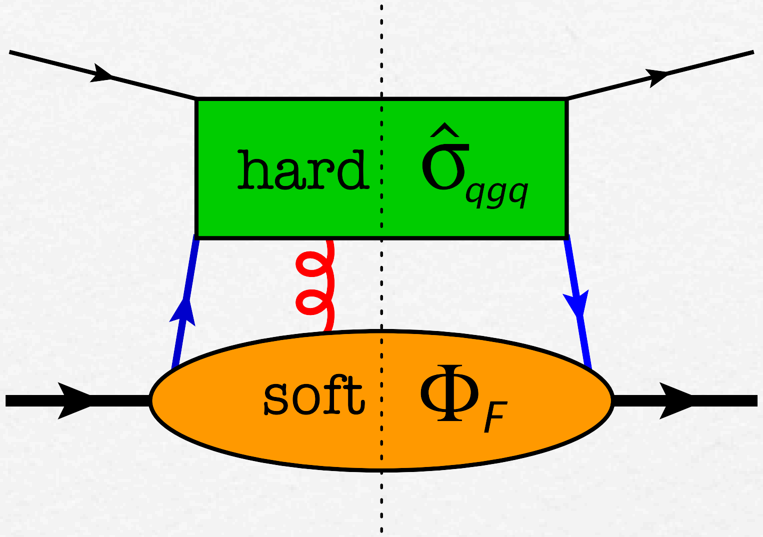
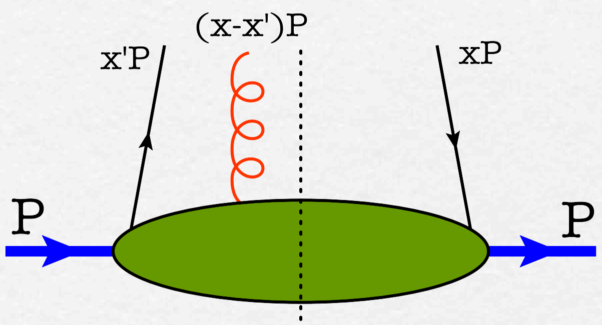


Quark-Gluon Correlation Functions

(ETQS-matrix elements)



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

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

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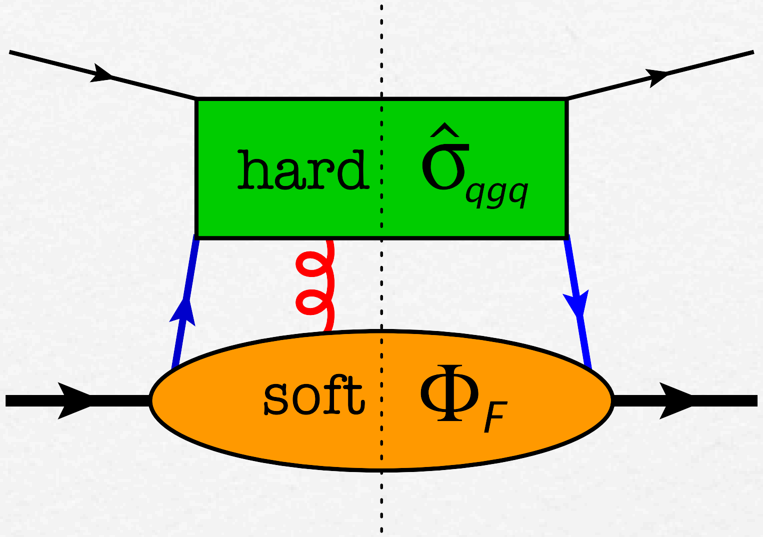

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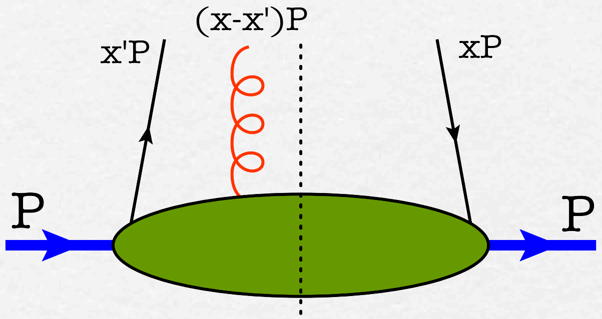

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relevant for $g_2 \leftrightarrow \sigma_{LT}$

$$x\tilde{g}_T^q(x) = \mathrm{P}\int_0^1 dx' \; \frac{G_F^q(x,x') + \tilde{G}_T^q(x,x')}{2(x'-x)}$$

Relation between twist-3 effects

QCD-equation of motion: $$\boxed{x\tilde{g}_T^q(x) = x g_T^q(x) - g_{1T}^{(1),q}(x) - \frac{m_q}{M} h_1^q(x)}$$

Relation Sivers vs. ETQS: $$\boxed{f_{1T,\mathrm{DIS}}^{\perp(1)}(x) = \frac{\pi}{2} G_F(x,x)}$$

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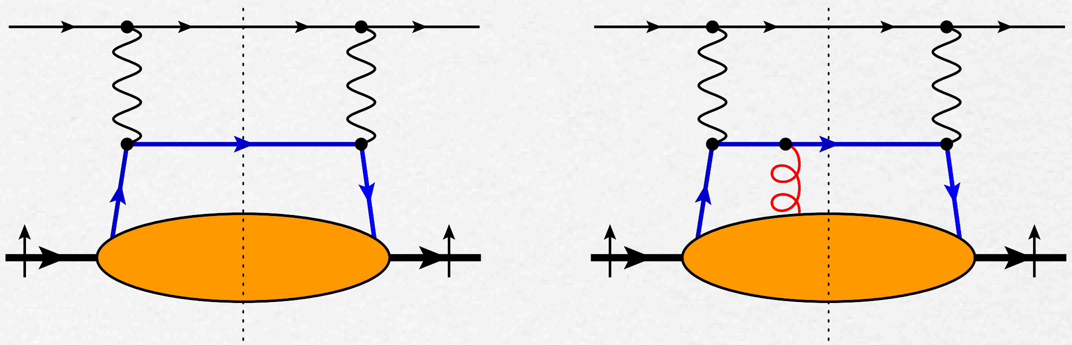
One-Photon Exchange

Hard part to LO:



Double-Spin Asymmetry:

$$\boxed{d\sigma_{LT} \propto x g_T(x) + g_{1T}^{(1)}(x) + \frac{m_q}{M} h_1(x) + x\tilde{g}_T(x) = 2x g_T(x)}$$

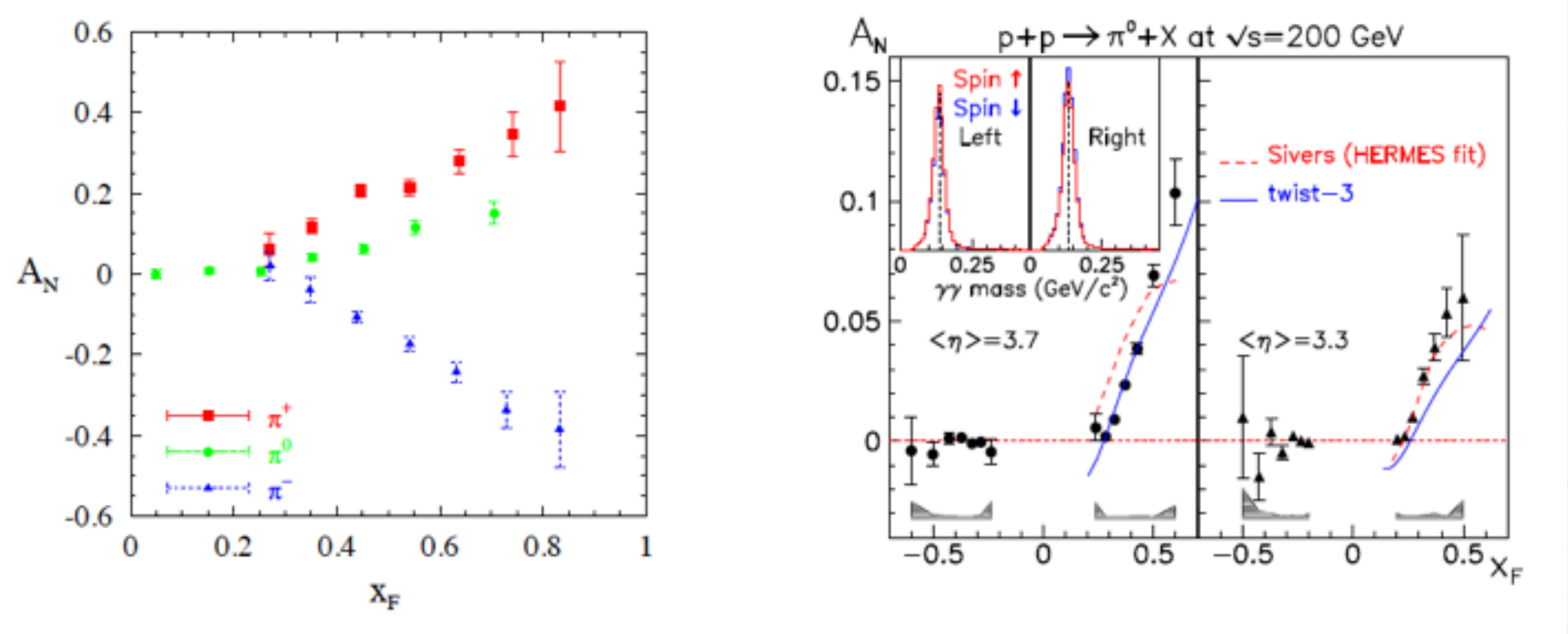
Single-Spin Asymmetry: $$\boxed{d\sigma_{UT} \propto f_{1T}^{\perp(1)}(x) - \frac{\pi}{2} G_F(x,x) = 0}$$

→ Two-Photon Exchange

Transverse Single Target Spin Asymmetry (Experiments)

Transverse SSA in pp-collisions

Transverse SSA in pion-production $p + p^{\uparrow} \to \pi + X$



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

- sizeable effect at large x_F (and large P_T... (?))
- cannot be explained in the naive parton model

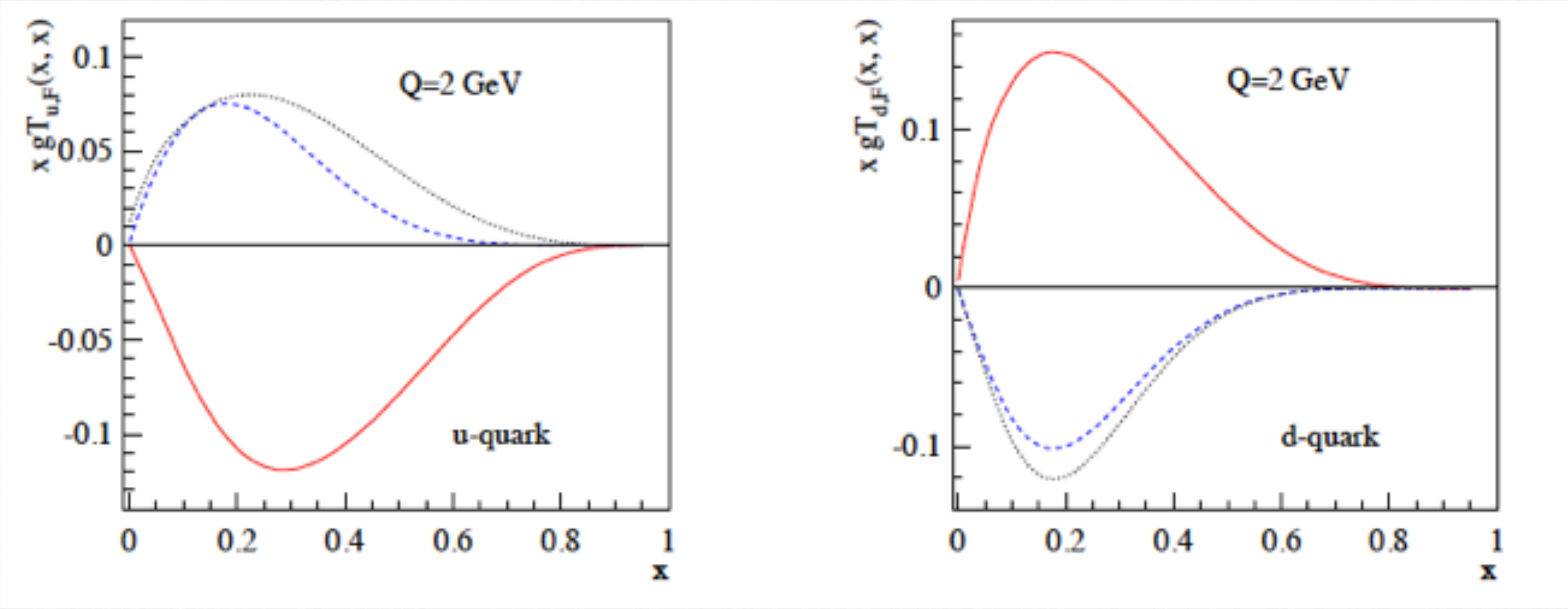
  [Kane, Pumplin, Repko]

  → explained by ETQS - functions...
- However: complicated → many contributions ("chiral-odd", Fragmentation...) (unlike DIS...)

"Sign - mismatch"

[Kang, Qiu, Vogelsang, Yuan]

Comparison of pp- and SIDIS-data via relation $\boxed{f_{1T,\mathrm{DIS}}^{\perp(1)}(x) = \frac{\pi}{2} G_F(x,x)}$



"Direct" extraction of $G_F(x,x)$ from $pp^\uparrow \to \pi X$ (RHIC)

"Indirect" extraction from $ep^\uparrow \to e\pi X$ (HERMES+COMPASS)

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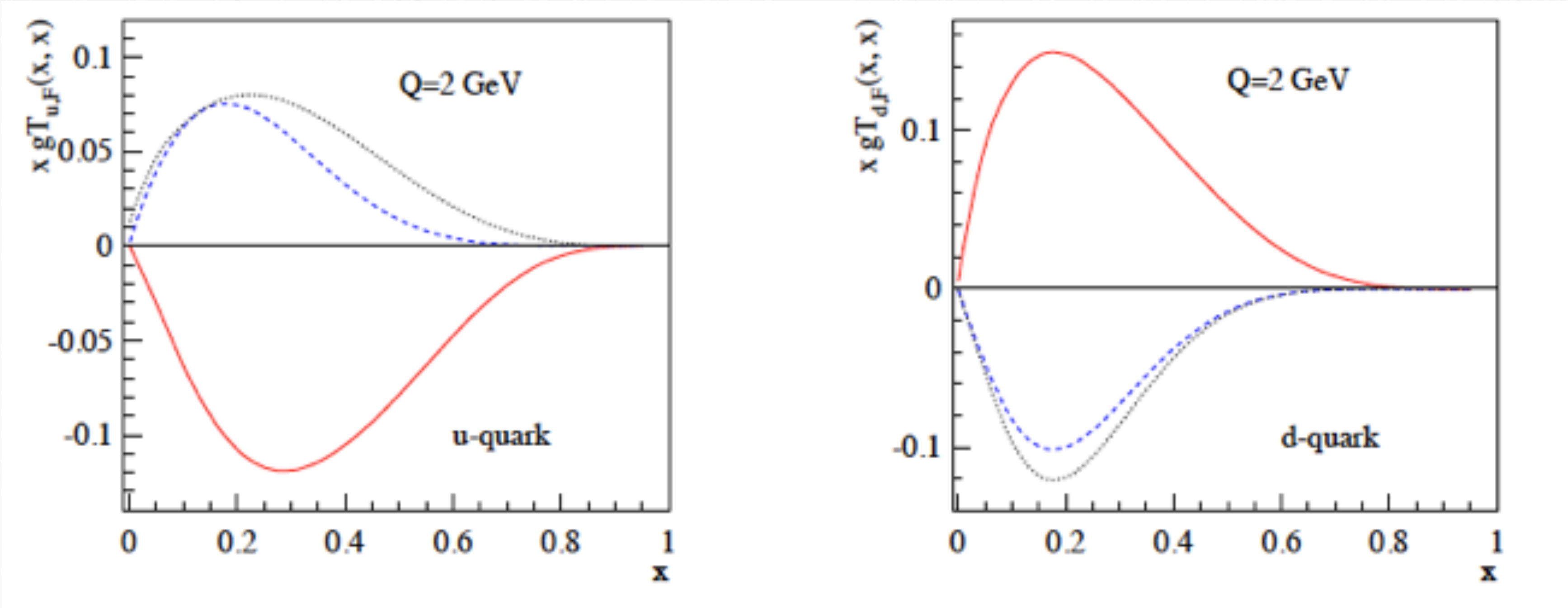

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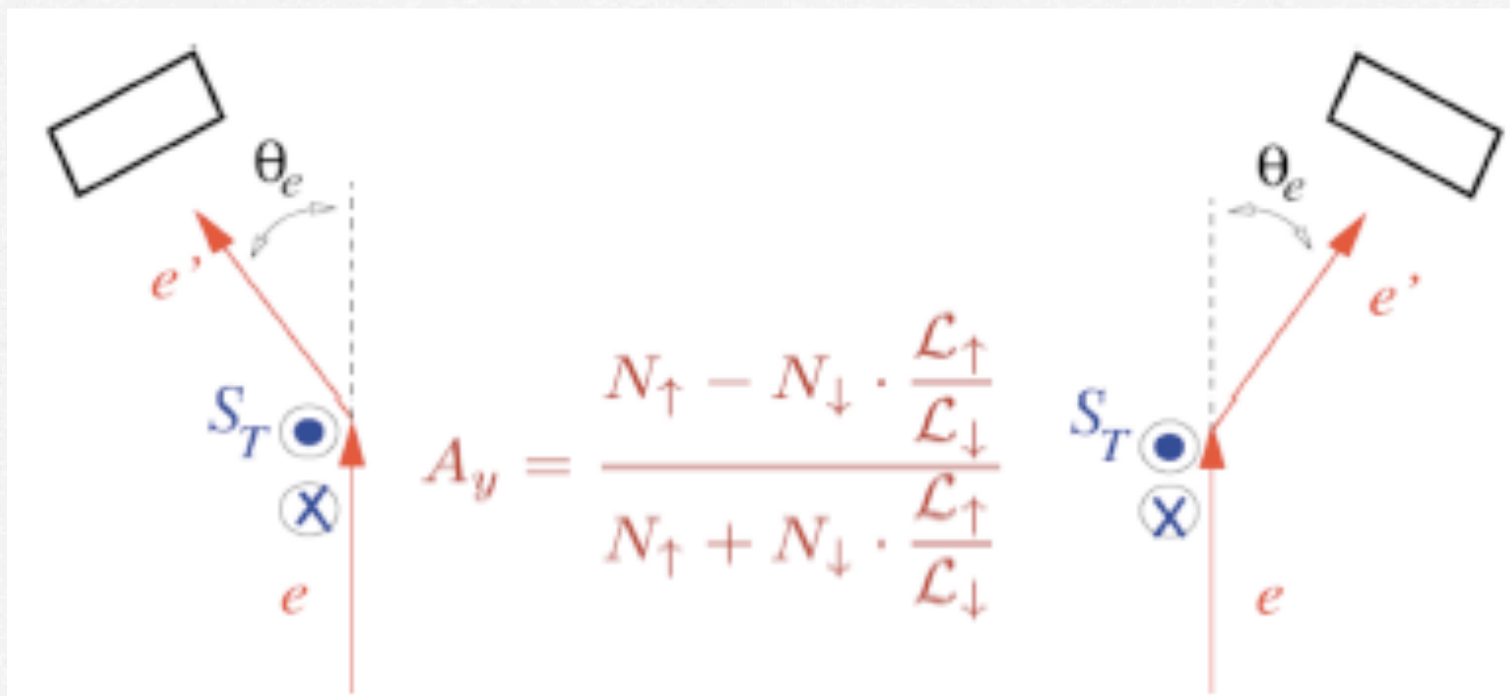
pp-data: other (than Sivers) effects dominant? Fragmentation? [Anselmino et al., Metz et al.]

ep-data: Sivers function only constraint for $x<0.4$: Nodes? [Kang, Prokudin; Boer]

DIS data on A_{UT} may help to solve the puzzle...

Transverse Target Asymmetry in DIS

- Conceptually simple experimental setup
- DIS: well understood process



Left-Right Asymmetry

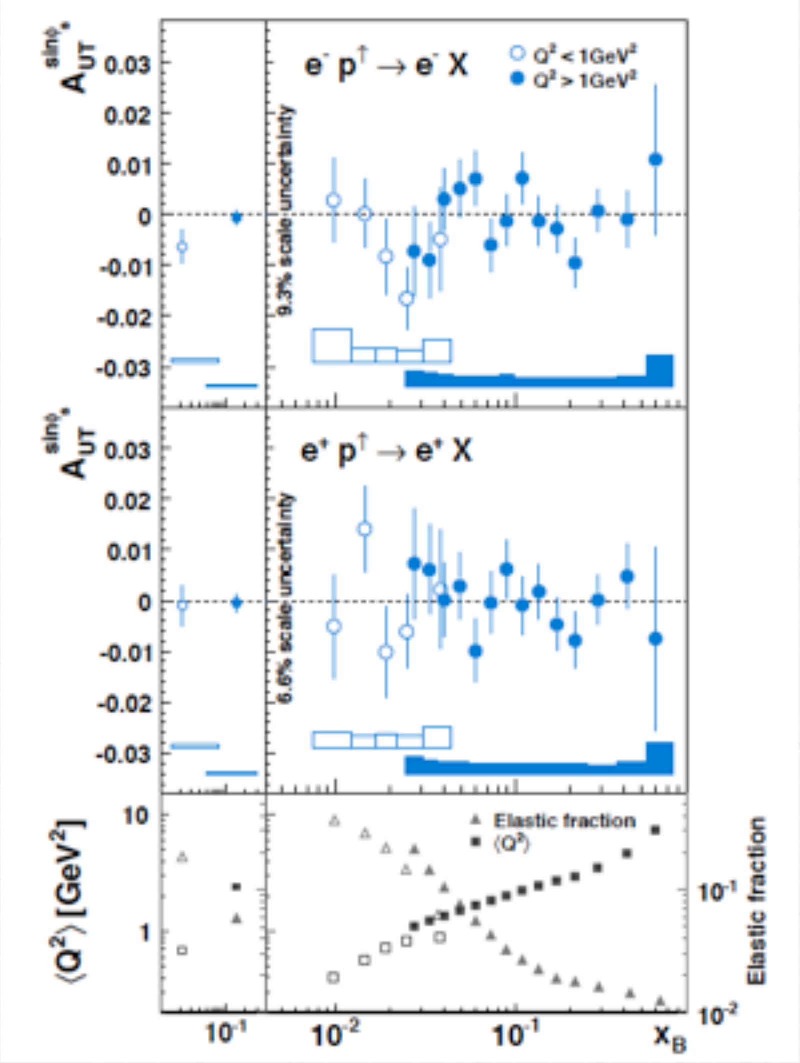
However: SSA small → need good statistics (precision measurement)

Past and ongoing measurements:

Past and ongoing measurements:

HERMES

(Proceedings SPIN2010)



pol. proton target

→ consistent with zero

Past and ongoing measurements:

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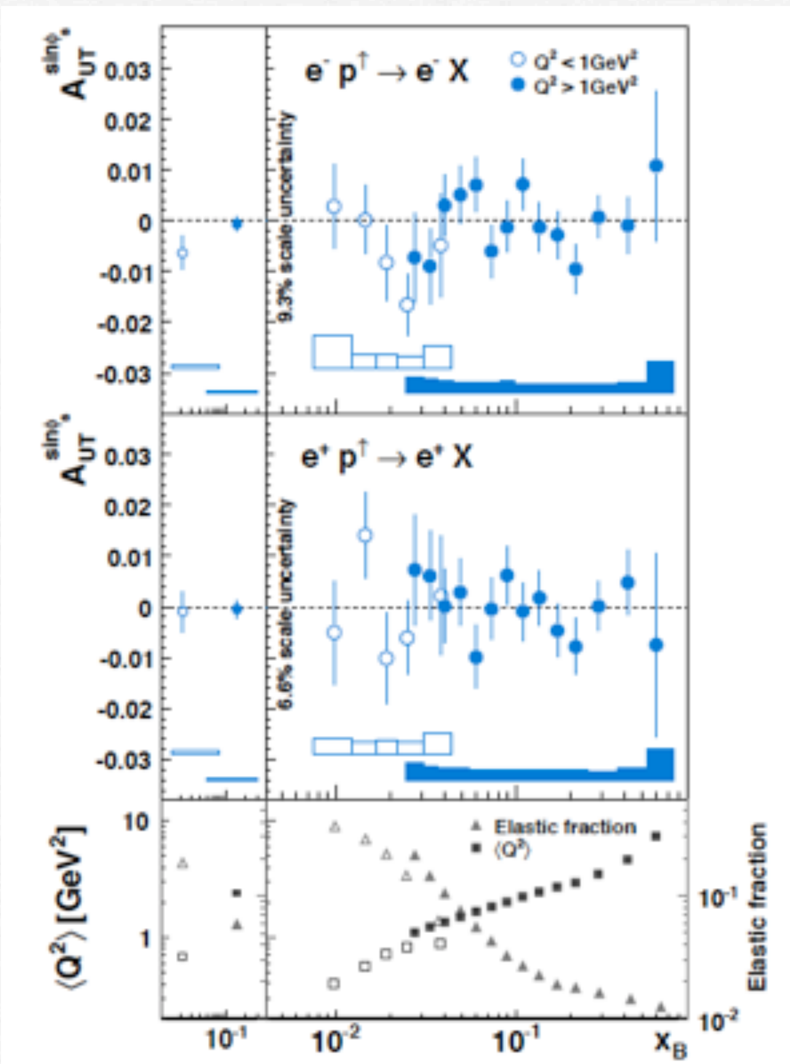

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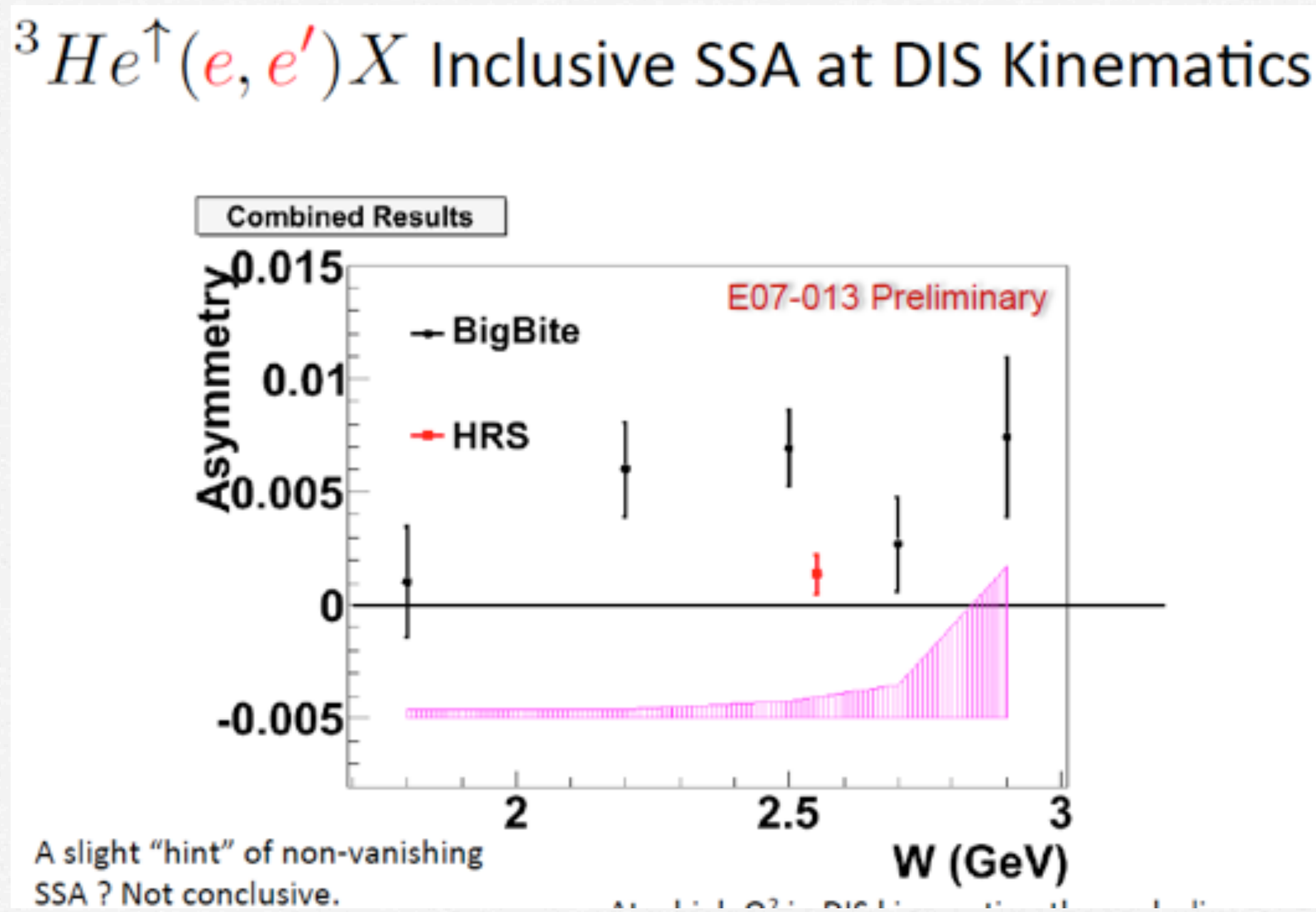
→ consistent with zero

JLab (preliminary)

(Talk by X. Jiang QCD-N'12)



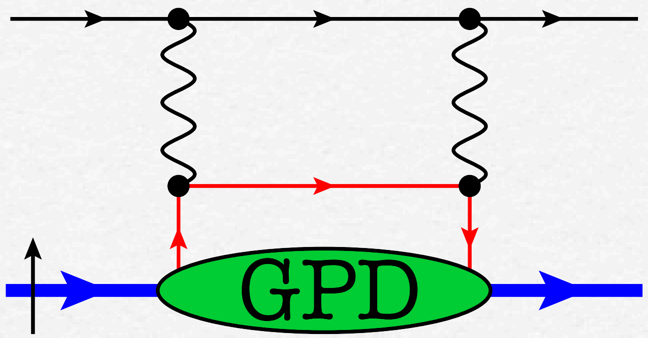
pol. Helium (~ Neutron) target

→ "hints" of non-zero SSA

Transverse Single Target Spin Asymmetry (Theory)

Transverse Single-Spin Asymmetry in Exclusive Scattering

[Chen, Afanasev, Brodsky, Carlson, Vanderhaeghen, PRL 93 (2004) 122301; PRD 72 (2005) 013008]



Spin Component normal to scattering plane ➛ Asymmetry

$$\boxed{A_n \propto \int_{-1}^{1} \frac{\mathrm{d}x}{x}\, \Im[\hat{\sigma}](x) \sum_q e_q^2 \left(H^q \left[G_E - \sqrt{\tfrac{1+\varepsilon}{2\varepsilon}} G_M \right] + E^q \left[G_E - \tfrac{Q^2}{4M^2} \sqrt{\tfrac{1+\varepsilon}{2\varepsilon}} G_M \right] \right)}$$

➛ Alternative way to access GPDs

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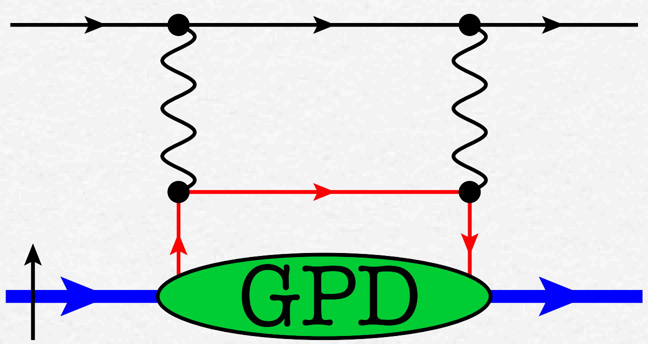

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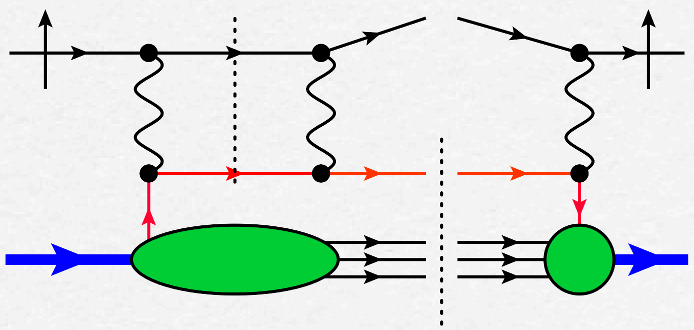
Transverse Single-Beam Spin Asymmetry in DIS

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



Transversely polarized lepton ➛ lepton mass effect

$$\boxed{A_{TU} \propto \alpha_{\mathrm{em}} \frac{m_l}{Q} \sum_q e_q^3\, x_B\, f_1^q(x_B)}$$

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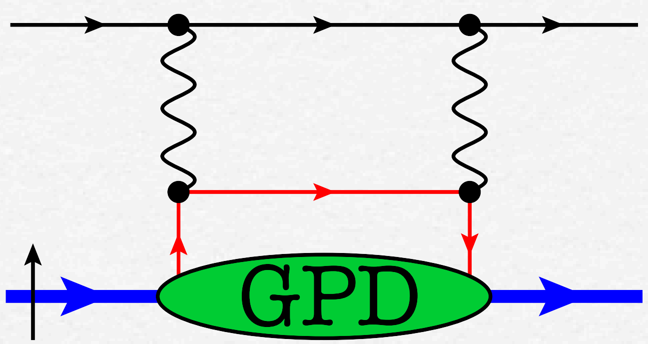

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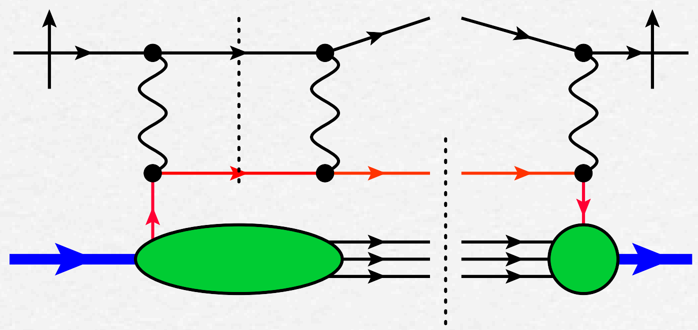

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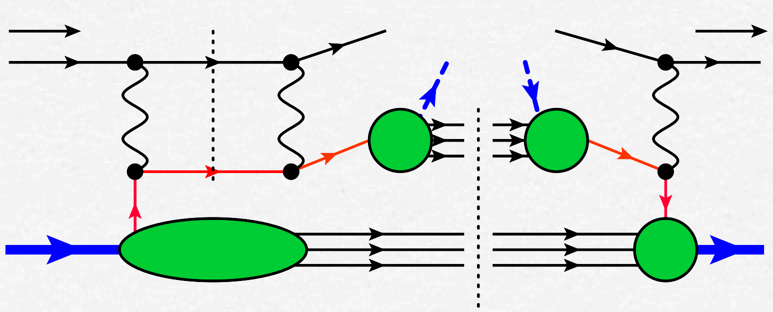
Longitudinal Single-Beam Spin Asymmetry in SIDIS

[M.S., Metz, arXiv:0902.0781]

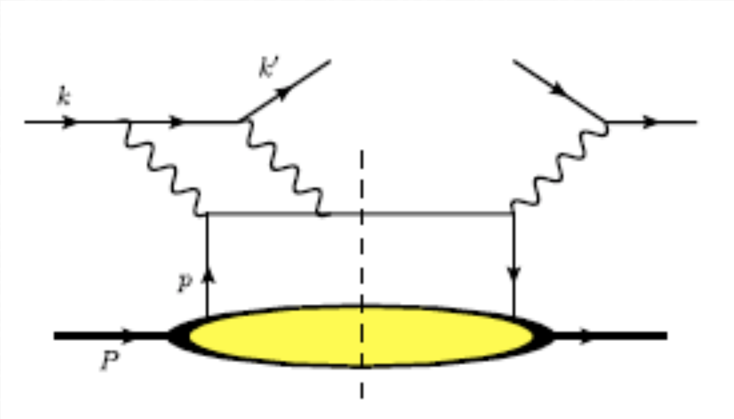


Long. pol. lepton ➛ "Boer-Mulders effect"

$$\boxed{A_{LU}^{\sin(2\phi)} \propto \alpha_{\mathrm{em}} \sin(2\phi) \sum_q e_q^3\, [h_1^{\perp q} \otimes H_1^{\perp q}]}$$

➛ absent in One-Photon Exchange

Single Transverse-Target-Spin Asymmetry



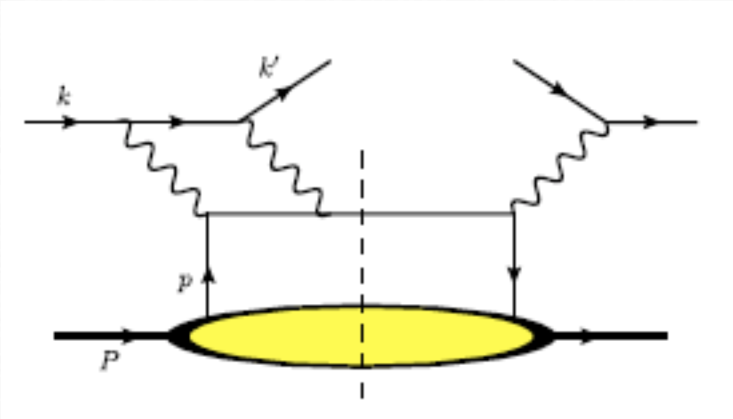
naive calculation (imaginary part):

[Metz, M.S., Goeke, PLB643,319]

$$\hat{\sigma}_{UT}\left(x g_T - g_{1T}^{(1)} - \frac{m_q}{M} h_1\right) \longrightarrow \hat{\sigma}_{UT}\; x\tilde{g}_T$$

soft divergence → 1/ε - pole!

Single Transverse-Target-Spin Asymmetry



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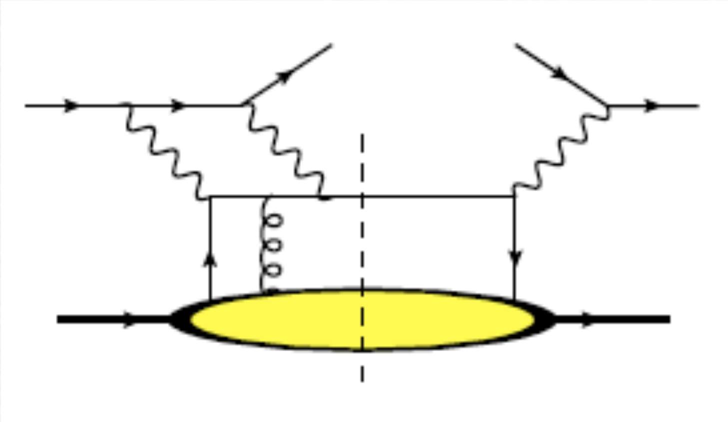


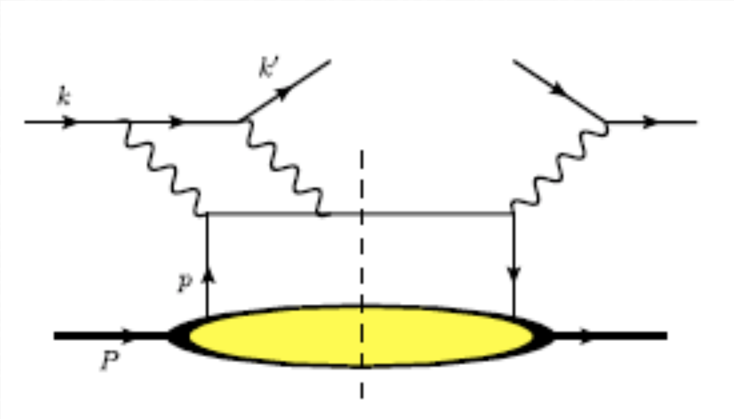
need to include Quark-Gluon Correlations:

$$\boxed{\mathcal{P}\int_0^1 dx' \, \frac{\hat{\sigma}_1(x') G_F(x', x_B) + \hat{\sigma}_2(x') \tilde{G}_F(x', x_B)}{(x' - x_B)}}$$

- $1/\varepsilon$-pole cancels!

- Integral diverges for $x' \to x_B$, not well regularized!

Single Transverse-Target-Spin Asymmetry

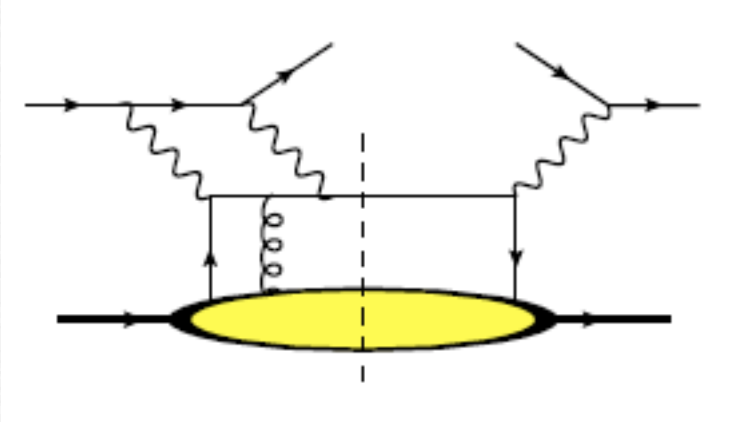


naive calculation (imaginary part):

[Metz, M.S., Goeke, PLB643,319]

$$\hat{\sigma}_{UT}\left(x g_T - g_{1T}^{(1)} - \frac{m_q}{M} h_1\right) \longrightarrow \hat{\sigma}_{UT}\, x\tilde{g}_T$$

soft divergence → 1/ε - pole!



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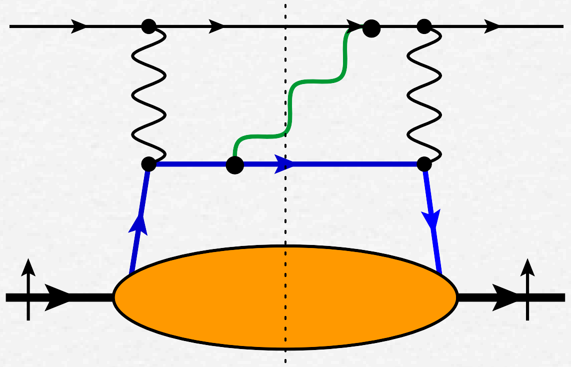
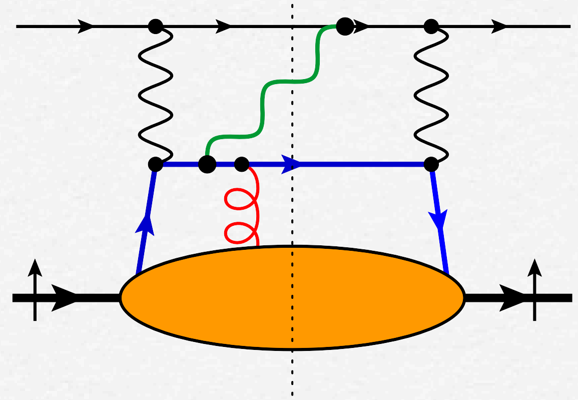
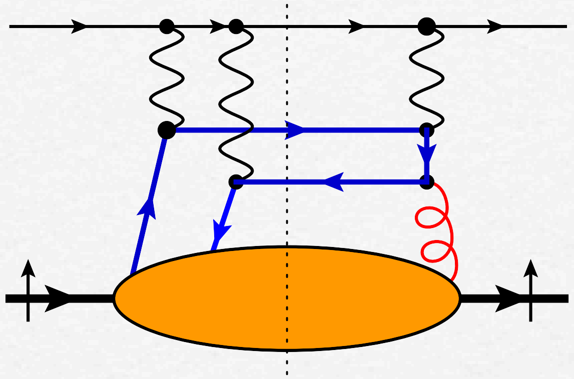
more contributions needed...

real photon emission:



(Sivers function only)





"qqg"

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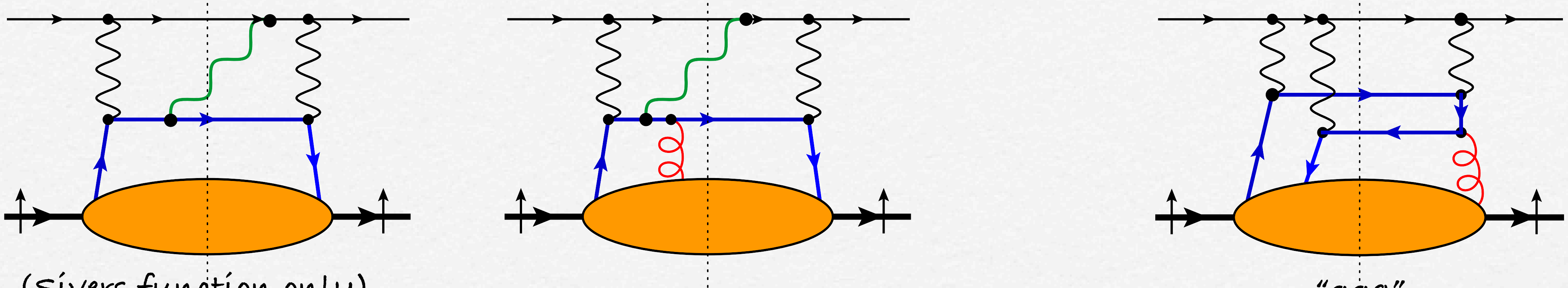

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3 kinds of contributions (propagators onshell)

Soft Gluon Poles $G_F(x,x)$

→ cancels after adding Sivers contribution

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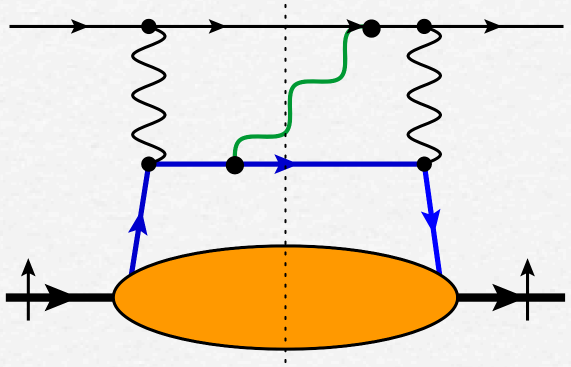

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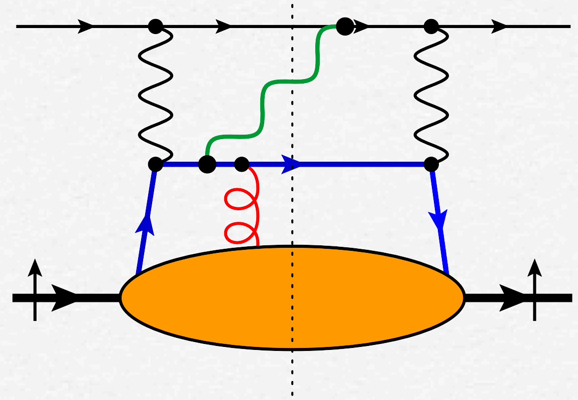

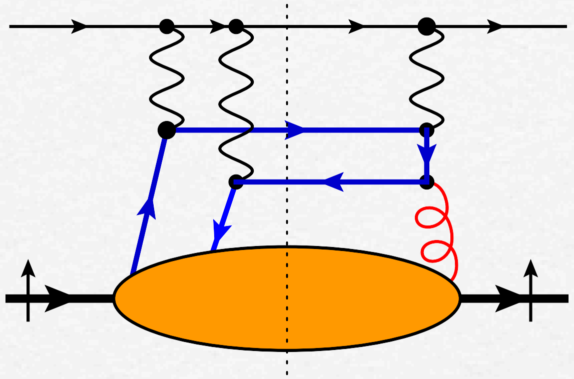

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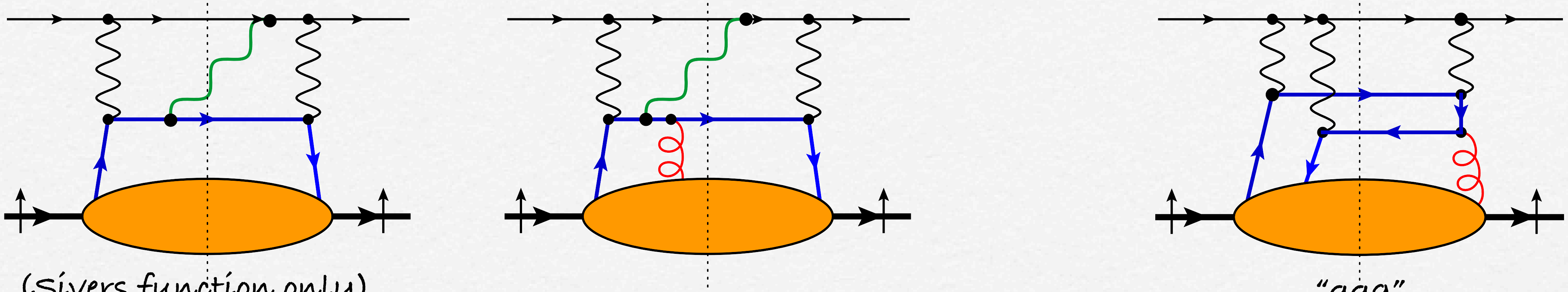

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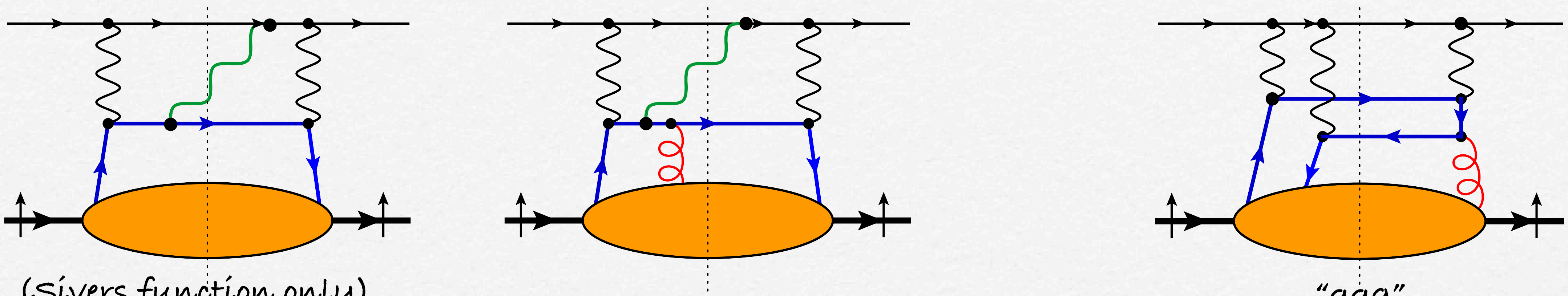
$$\boxed{\int_{x_B}^{1} dx \, \frac{\hat{\sigma}_1(x) G_F(x,x_B) + \hat{\sigma}_2(x) \tilde{G}_F(x,x_B)}{(x-x_B)}}$$

real photon emission:



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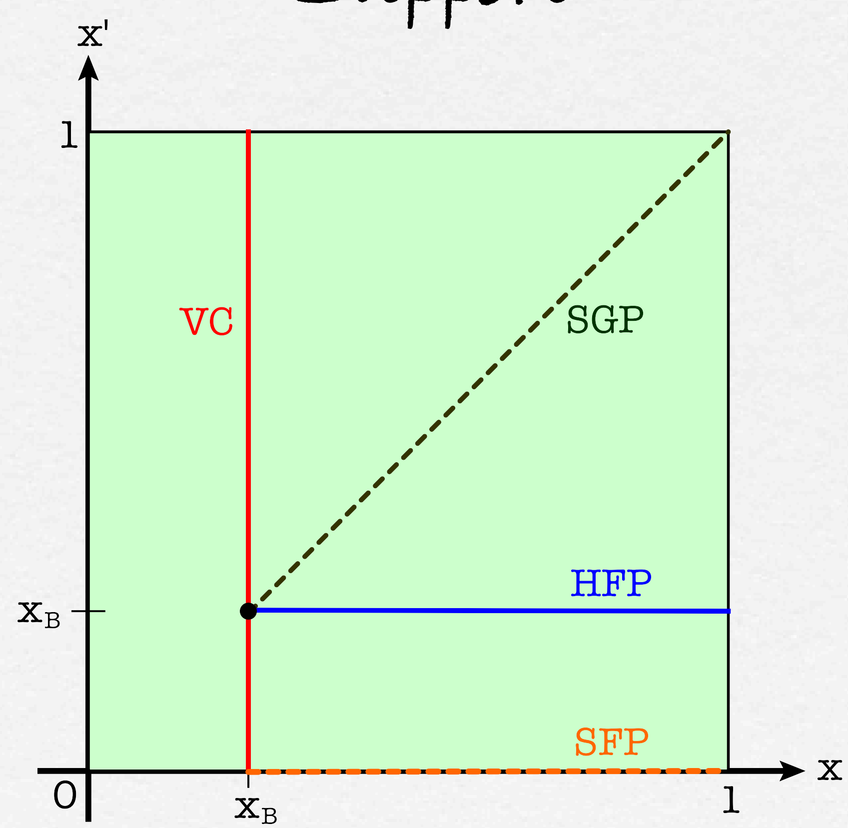
Support



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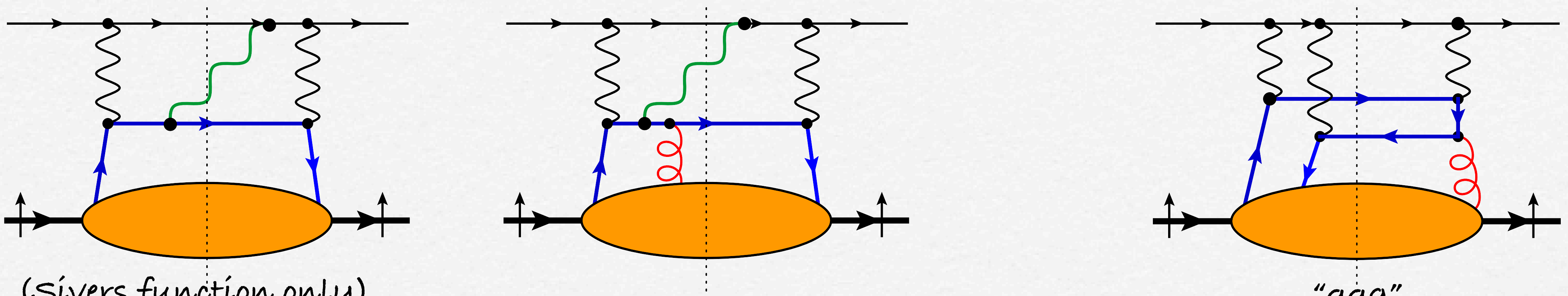

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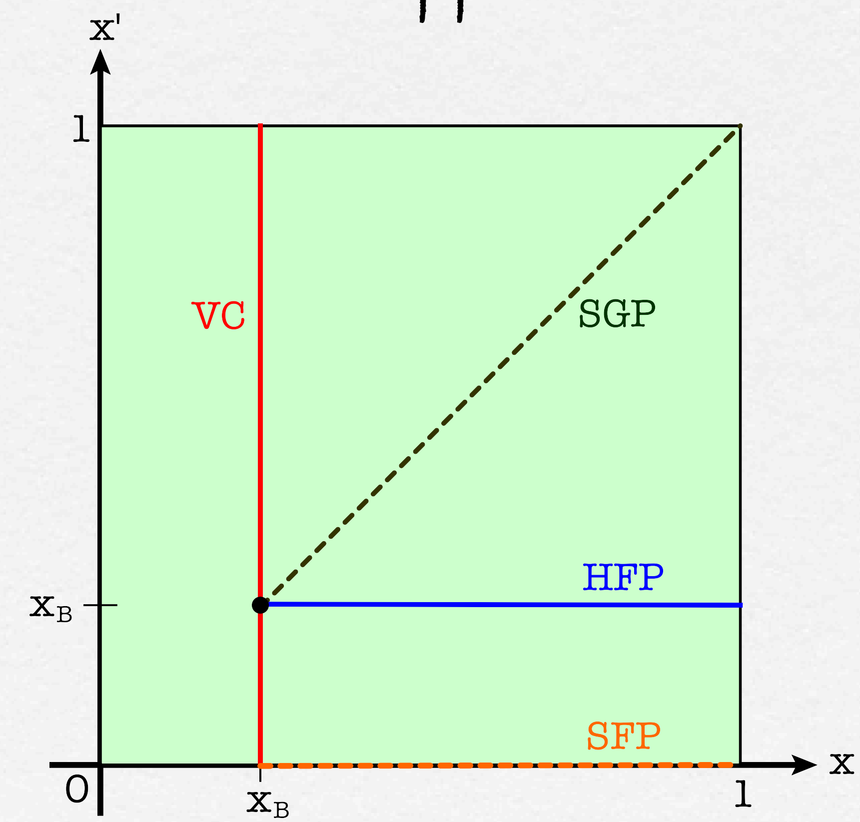
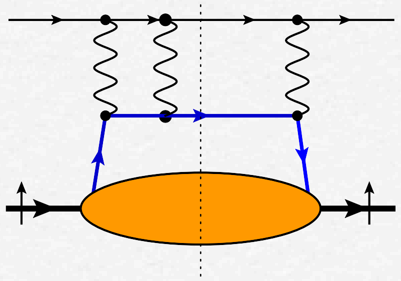


Integral diverges → even more contributions missing

real part of Two Photon Contribution at $x=x'=x_B$



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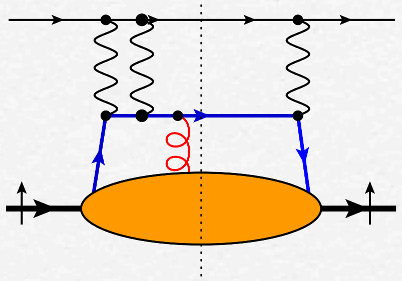
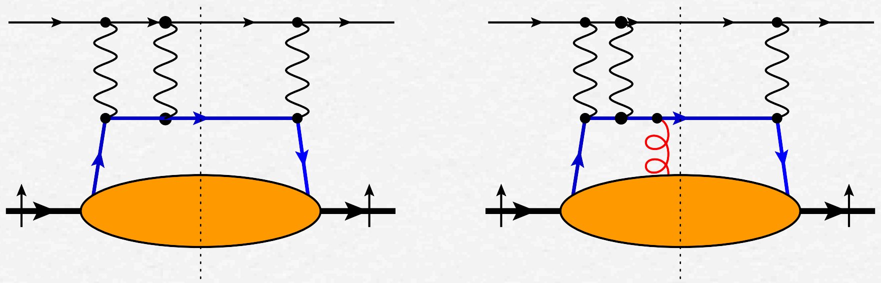


real part of Two Photon Contribution at x=x′=x$_B$



(Sivers function only)

Sum of all contribution

➛ well-behaved result, finite integral, no 1/ε poles!

[M.S., PRD 87 (2013) 034006]

$$A_{UT} \propto \alpha_{\mathrm{em}} \frac{M}{Q} \sin \phi_s \left[\sum_q e_q^3 \int_0^1 dx \left(\hat{C}_+ G_F(x_B, x) + \hat{C}_- \tilde{G}_F(x_B, x) \right) \right]$$

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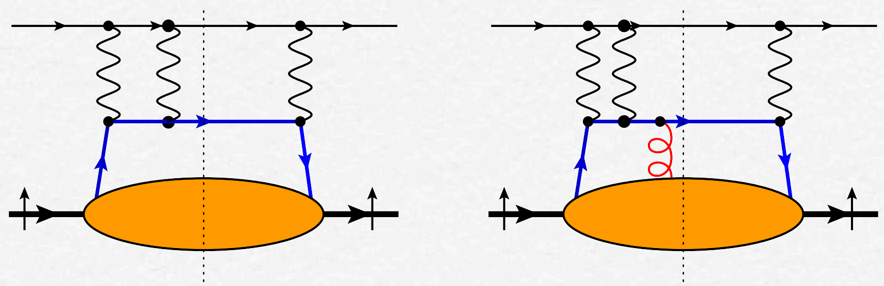

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Coefficient function well-defined, perturbatively calculable

$$\hat{C}_+(x,x_B,y)=\frac{\theta(x-x_B)}{(x-x_B)_+}f(y)+\mathrm{P}\frac{F_+(\frac{x}{x_B},y)}{x-x_B}+\delta(x-x_B)(f(y)\ln(\tfrac{1-x}{x})-(1-\tfrac{y}{2})^2)$$

$$\hat{C}_-(x,x_B,y)=\frac{\theta(x-x_B)}{(x-x_B)_+}f(y)+\mathrm{P}\frac{F_-(\frac{x}{x_B},y)}{x-x_B}$$

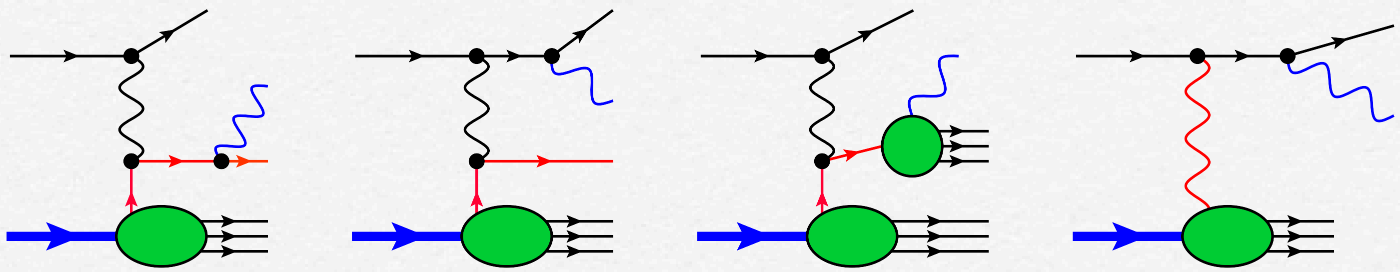
ETQS - matrix elements are probed at:

$x = x_B$ ➛ "Sivers effect"

$x \neq x_B$ ➛ sensitive to full support

Photon as a Parton:

Example: Photon SIDIS $e + N \to e' + \gamma + X$



Same order in α_{em}!

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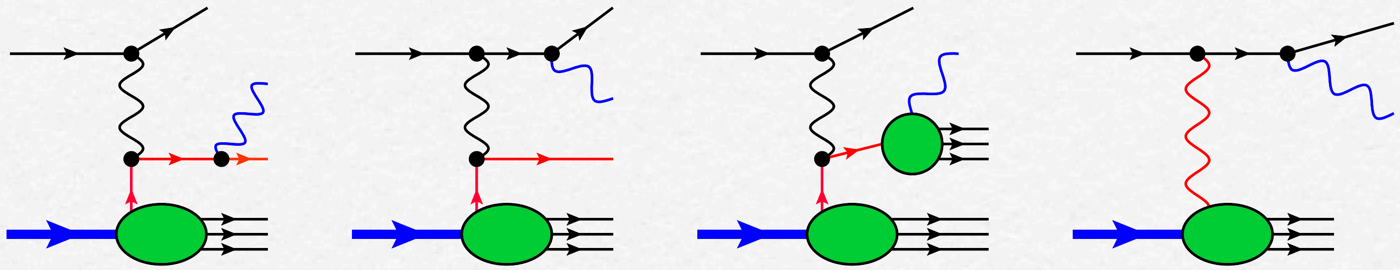
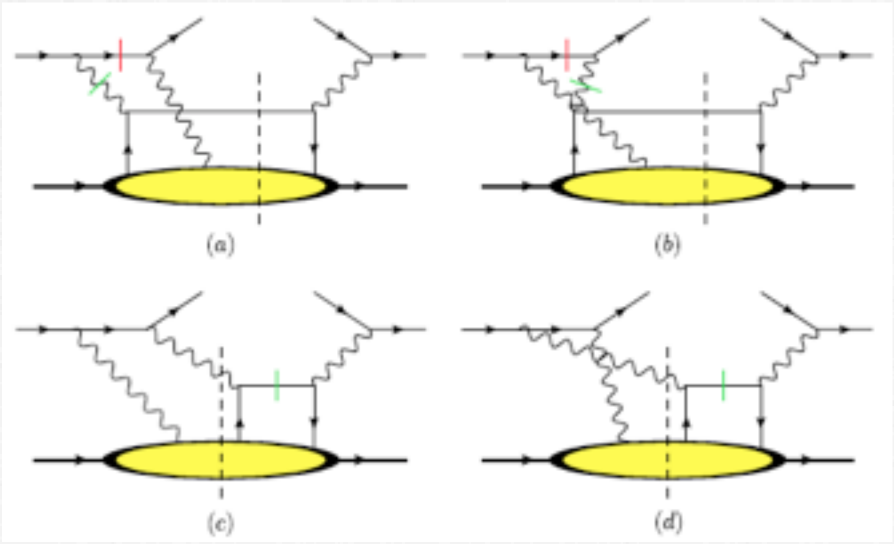


Same order in α_{em}!

"Quark-Photon Correlations"

[Metz, Pitonyak, Schäfer, M.S., Vogelsang, Zhou, PRD86,094039]



Asymmetry generated by
Quark-Photon Correlations

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

$$\boxed{E' \frac{d\sigma_{UT}}{d^3 l'} \propto \left(1 - x_B \frac{d}{dx_B}\right) G_F^{\gamma}(x_B, x_B)}$$

- "Soft-Photon Poles" contribute
- "Soft-Fermion Poles" cancel
- maybe dominant contribution

Adding all contributions: [M.S., PRD87,034006]

$$
\begin{aligned}
A_{UT} \quad = \quad -\alpha_{\rm em}\frac{M}{Q}\Bigg(& \frac{y}{\sqrt{1-y}f(y)}\,\frac{\sum e_q^3\ x_B(\hat{C}_+\otimes G_F+\hat{C}_-\otimes\tilde{G}_F)}{\sum e_q^2\ x_B f_1^q(x_B)} \\
& + \frac{y\sqrt{1-y}}{f(y)}\,\frac{\sum e_q^3\frac{m_q}{M}\ x_B h_1^q(x_B)}{\sum e_q^2\ x_B f_1^q(x_B)} \\
& + \frac{2-y}{2\sqrt{1-y}}\,\frac{\sum e_q^2\ x_B(1-x_B\frac{\mathrm{d}}{\mathrm{d}x_B})G_F^{\gamma,q}(x_B,x_B)}{\sum e_q^2\ x_B f_1^q(x_B)}\Bigg)
\end{aligned}
$$

Adding all contributions: [M.S., PRD87,034006]

$$A_{UT} = -\alpha_{\rm em}\frac{M}{Q}\left(\frac{y}{\sqrt{1-y}f(y)}\frac{\sum e_q^3\, x_B(\hat{C}_+\otimes G_F + \hat{C}_-\otimes \tilde{G}_F)}{\sum e_q^2\, x_B f_1^q(x_B)}\right.$$

$$+\frac{y\sqrt{1-y}}{f(y)}\frac{\sum e_q^3 \frac{m_q}{M}\, x_B h_1^q(x_B)}{\sum e_q^2\, x_B f_1^q(x_B)}$$

$$\left.+\frac{2-y}{2\sqrt{1-y}}\frac{\sum e_q^2\, x_B(1-x_B\frac{\mathrm{d}}{\mathrm{d}x_B})G_F^{\gamma,q}(x_B,x_B)}{\sum e_q^2\, x_B f_1^q(x_B)}\right)$$

What can we learn from this observable?

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What can we learn from this observable?

- information on the full support of ETQS - functions,
  test evolution of ETQS - functions [Braun et al.]

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- finite quark mass term ➞ transversity?

[Afanasev, Strikman, Weiss, PRD77,014028]

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- finite quark mass term → transversity?

[Afanasev, Strikman, Weiss, PRD77,014028]

- Quark - Photon correlation

(Theoretically) clean process:

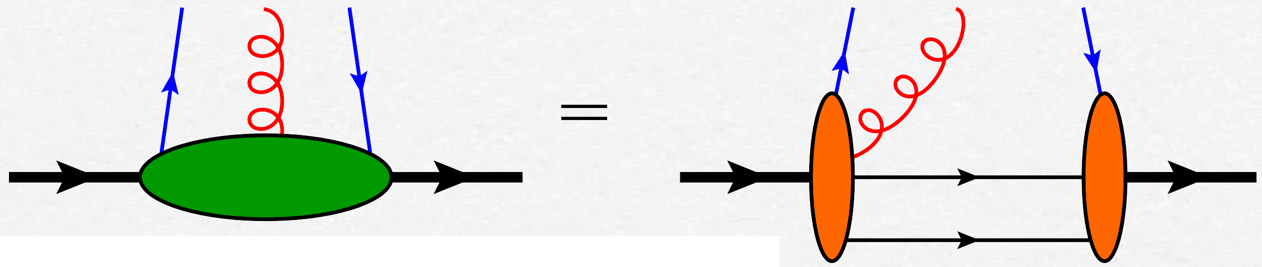
- no convolutions of non-perturbative functions (≠ pp-collisions)
- how to "disentangle" the effects?
- kinematical regimes where one contribution dominates?

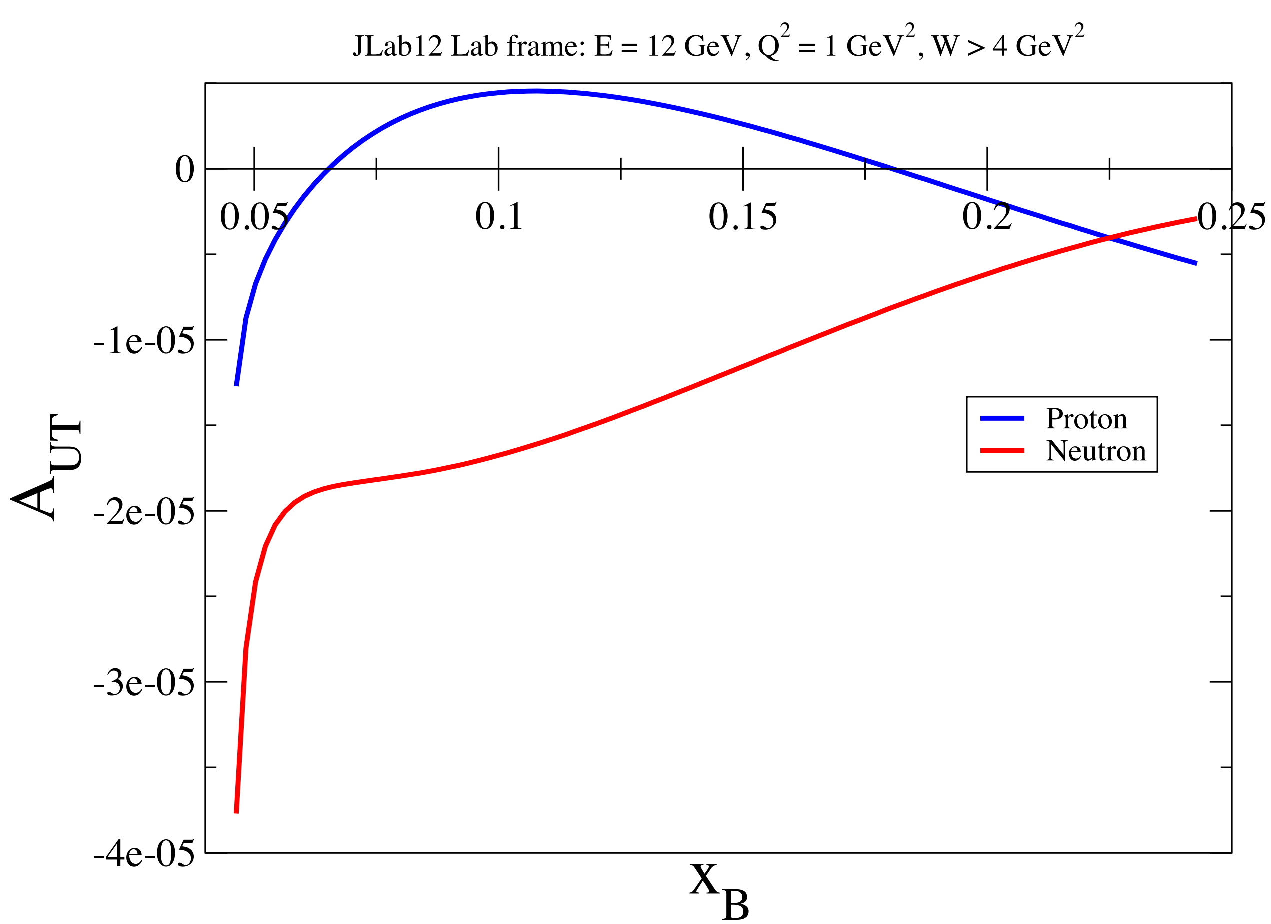
Models

Numerical estimate of "Quark-Gluon" contribution:

Test of the quark-gluon contribution → need input for ETQS - functions on full support

Model from Lightcone wave functions [Braun et al., PRD83, 094023]





[M.S., arXiv:1303.0978]

- Model input at $Q = 1$ GeV
- small ETQS - functions with

$$G_F^q(x,x) = 0$$ ✘

- JLab kinematics:

$E_{cm} = 12$ GeV

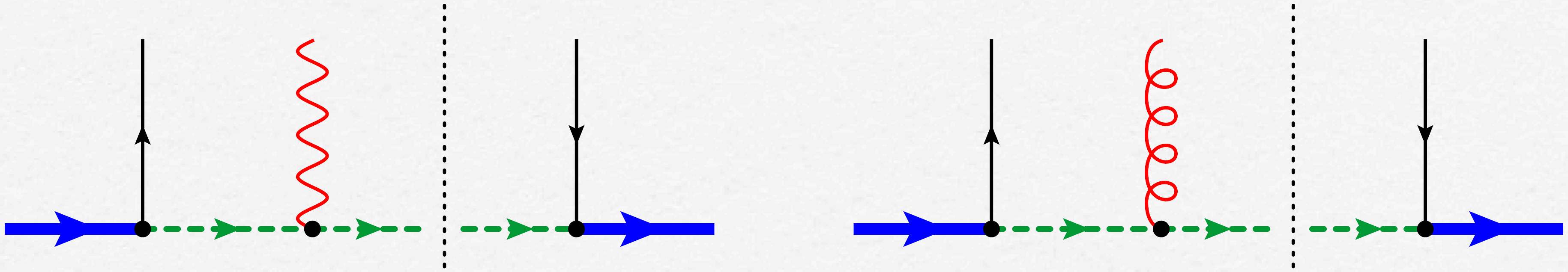
$W > 4$ GeV^2

- small effect from quark-gluon contr.

→ better model?

Quark-Photon correlations in a diquark spectator model

[Metz, Pitonyak, Schäfer, M.S., Vogelsang, Zhou, PRD86,094039]



Comparison of Quark-Photon and Quark-Gluon Correlation Functions

Proton:

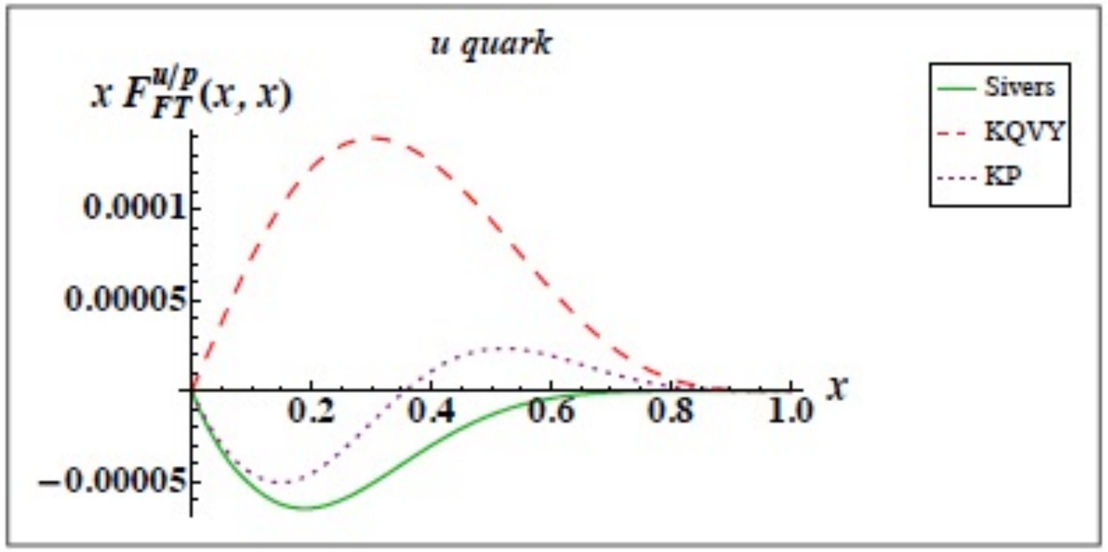
$$G_F^{\gamma,u/p}(x,x) = -\frac{G_F^{u/p}(x,x)}{12C_F\alpha_s} \;,\; G_F^{\gamma,d/p}(x,x) = -\frac{G_F^{d/p}(x,x)}{3C_F\alpha_s}$$

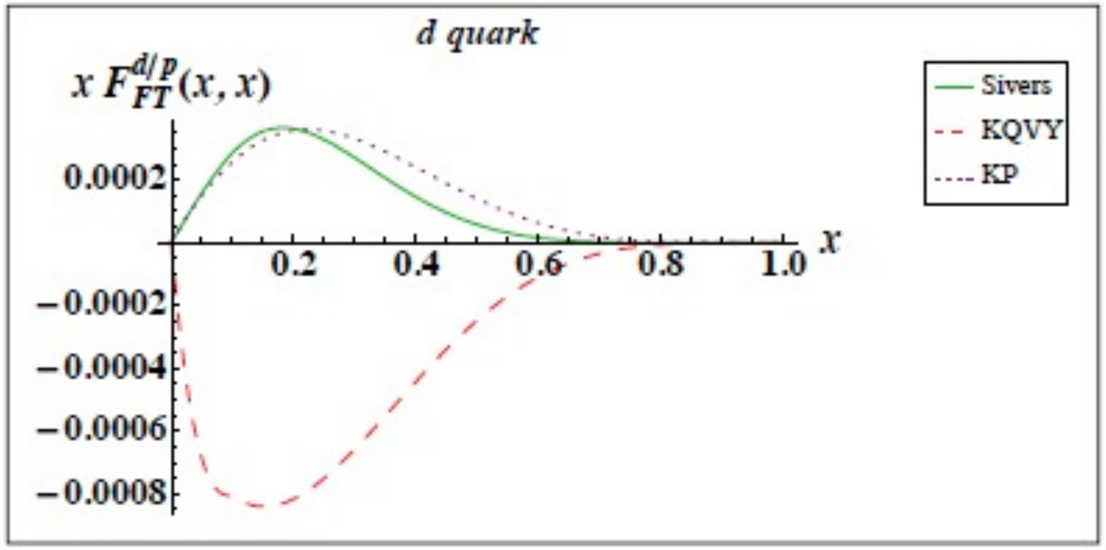
Neutron:

$$G_F^{\gamma,u/n}(x,x) = +\frac{G_F^{u/n}(x,x)}{6C_F\alpha_s} \;,\; G_F^{\gamma,d/n}(x,x) = -\frac{G_F^{d/n}(x,x)}{12C_F\alpha_s}$$

Input for $G_F(x,x)$ from parameterizations:

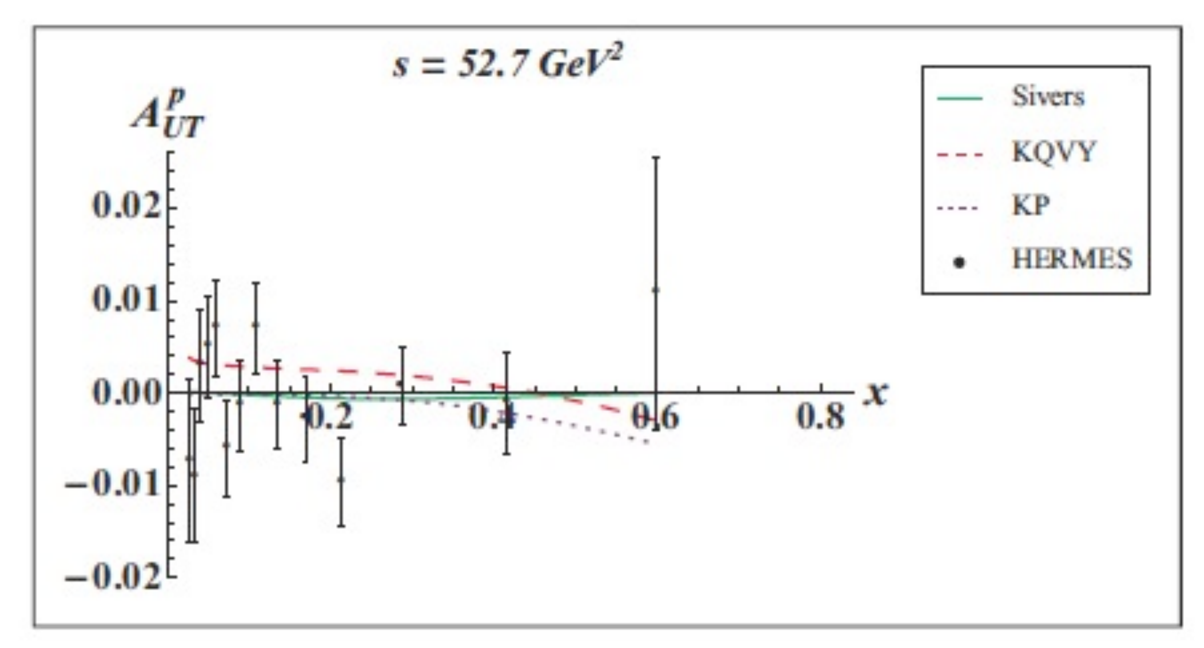
1) Sivers, 2) direct pp (KQVY), 3) pp+Sivers (KP)





Model predictions for the Quark-Photon Correlations

Proton asymmetry
in HERMES kinematics:



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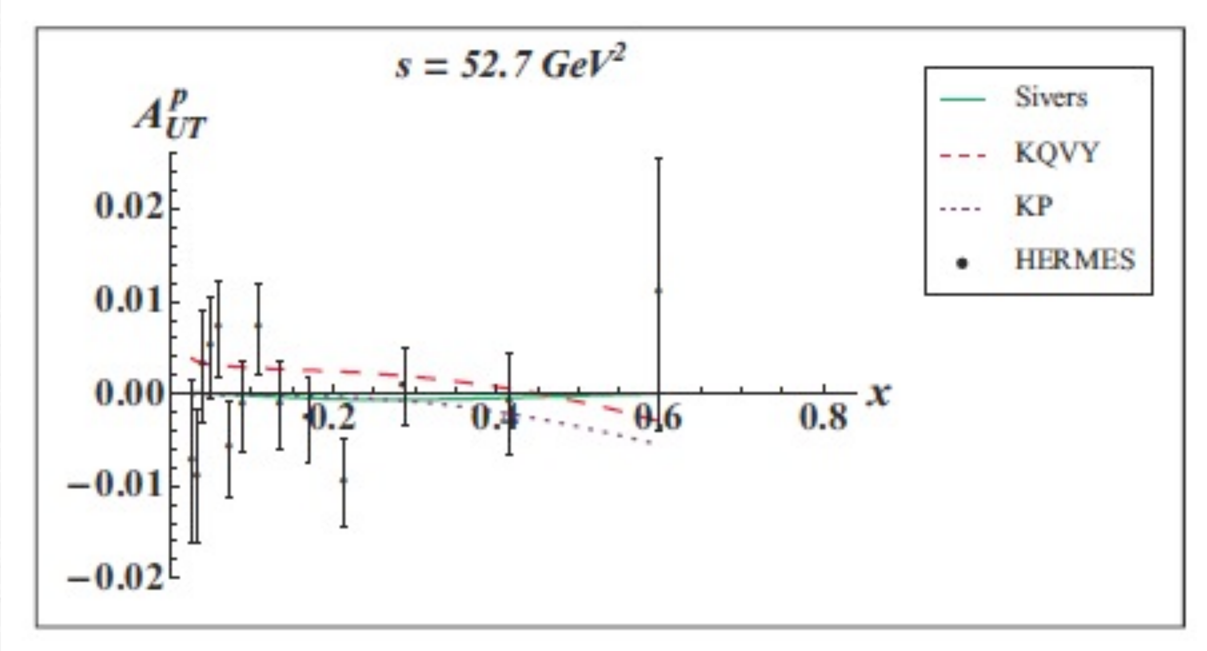
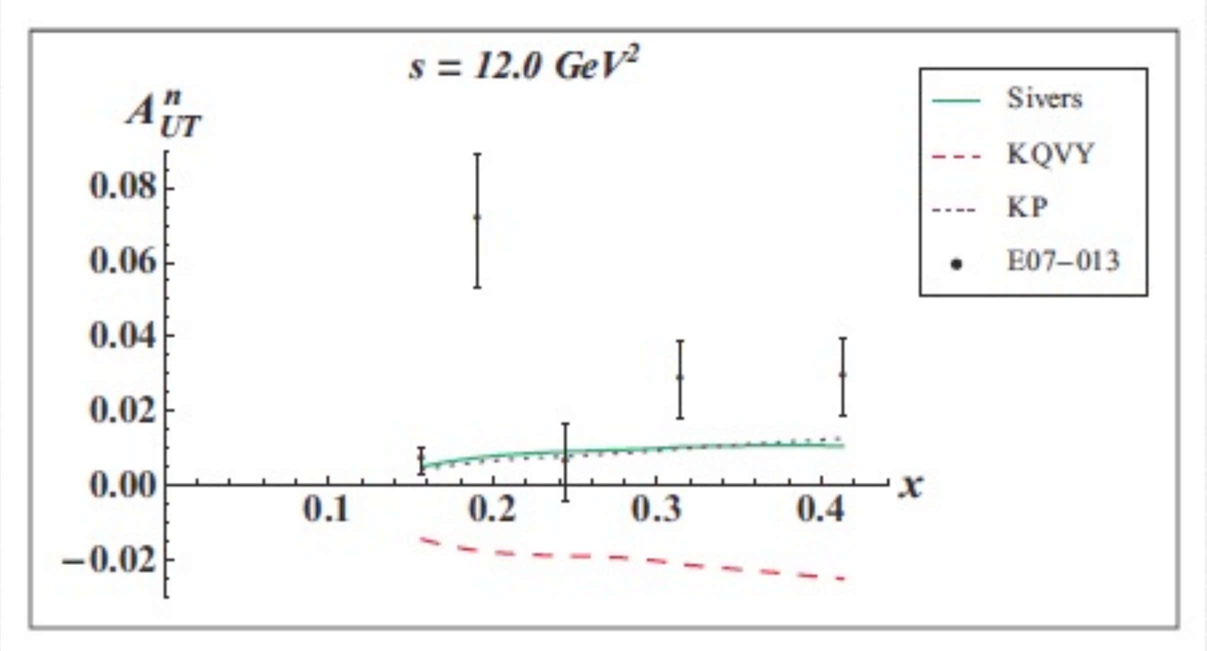


Neutron asymmetry
in JLAB HALL A kinematics:
(preliminary data)



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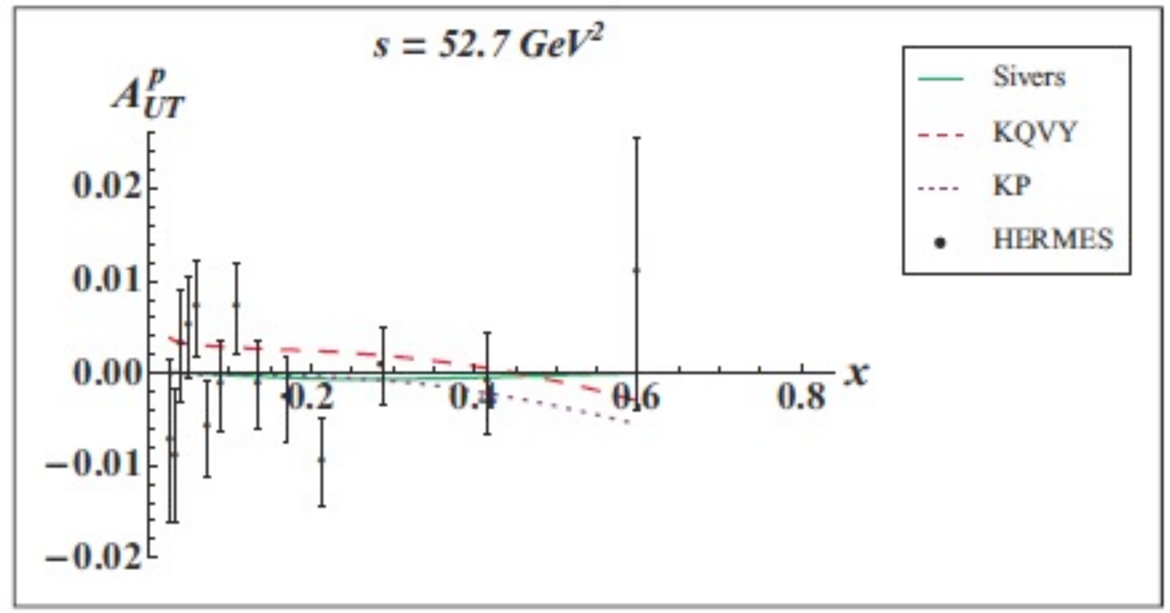

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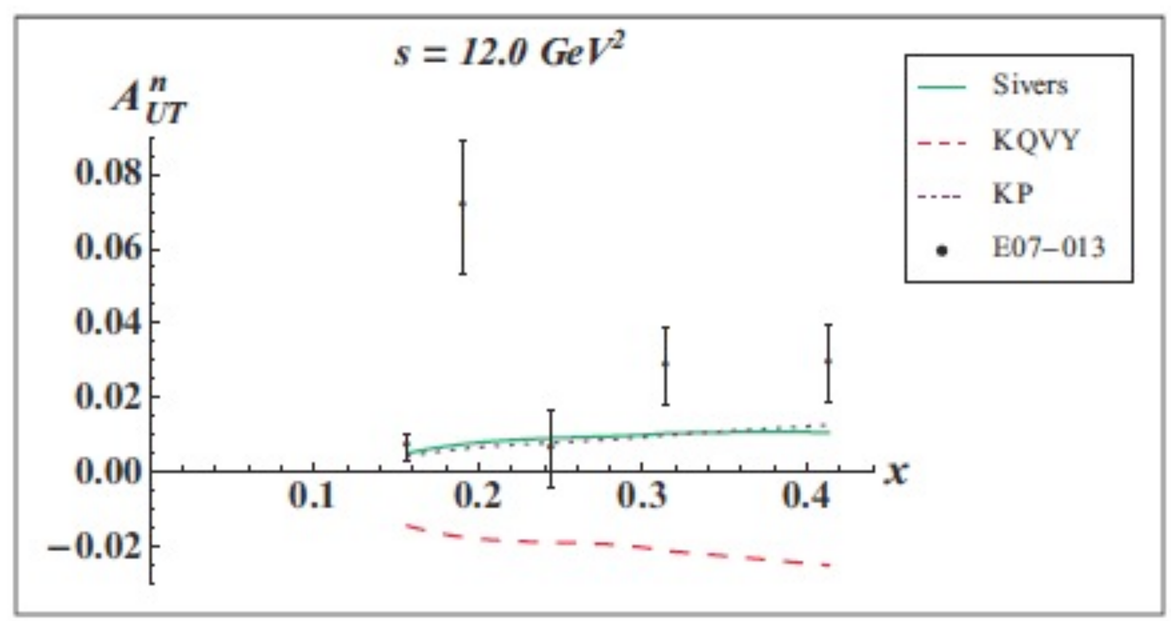
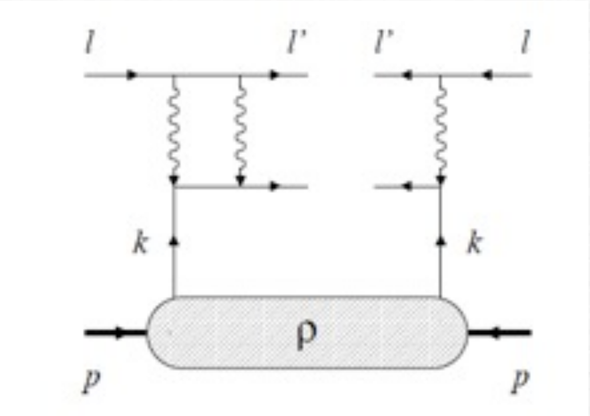


The model predictions are in qualitative agreement with data!

Quark mass effects

[Afanasev, Strikman, Weiss, PRD77,014028]



Model for the quark mass effects:

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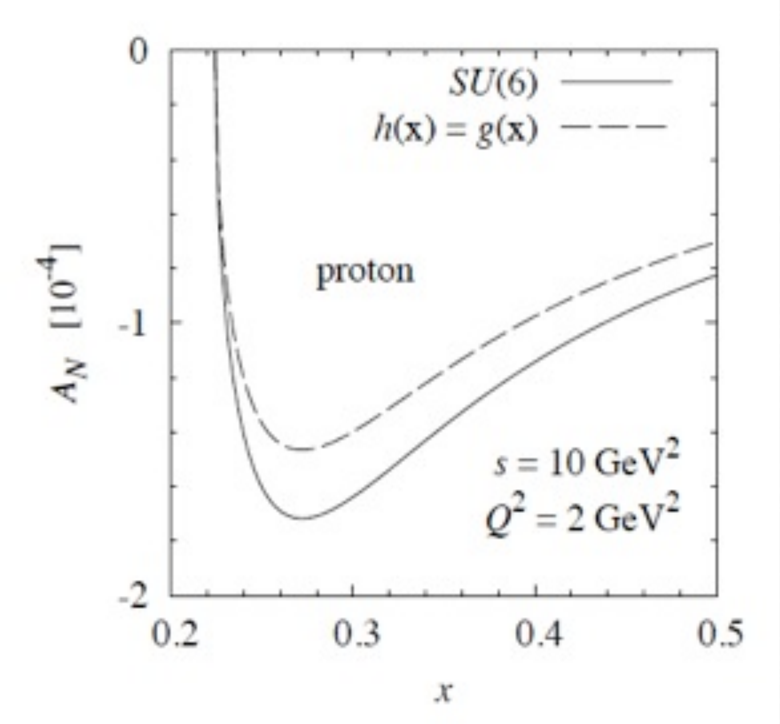
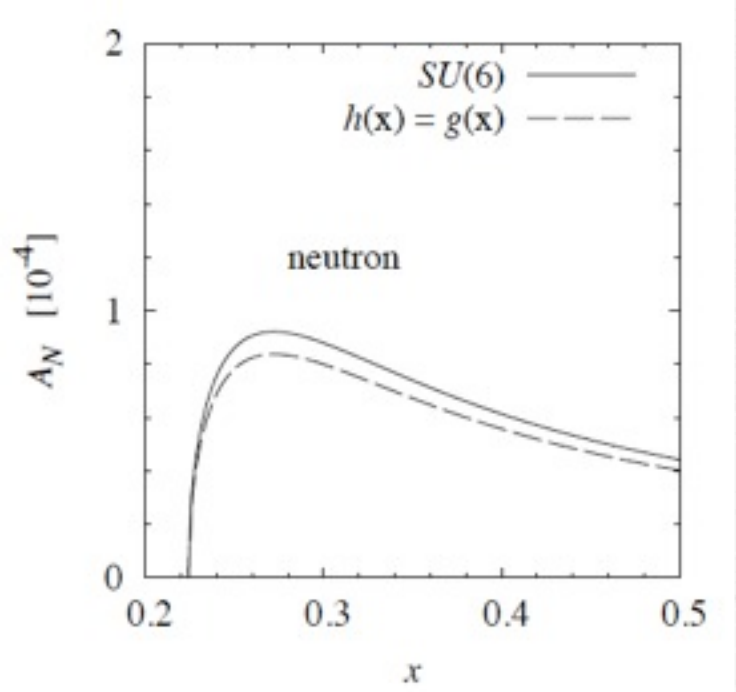
- non-perturbative vacuum effects: $m_{q,\rm current} \to m_{q,\rm constituent} \simeq 300$ MeV
- transversity from parameterization





→ effect of about 10^{-4}

Summary

- Transverse SSA in DIS generated by a Two-Photon Exchange
- it gives unique insight into the Twist-3 structure of the nucleon
  → full support on EQTS - functions
  → Quark-Photon correlations
  → test of our understanding of pQCD
- need data (possibly SSA≠0)!