SSA with photon observables

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University of Tübingen

Physics at AFTER
using the LHC beams, ECT*, Feb. 6, 2013

Why (transverse) SSA?

Two important experimental observations for TSSAs

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

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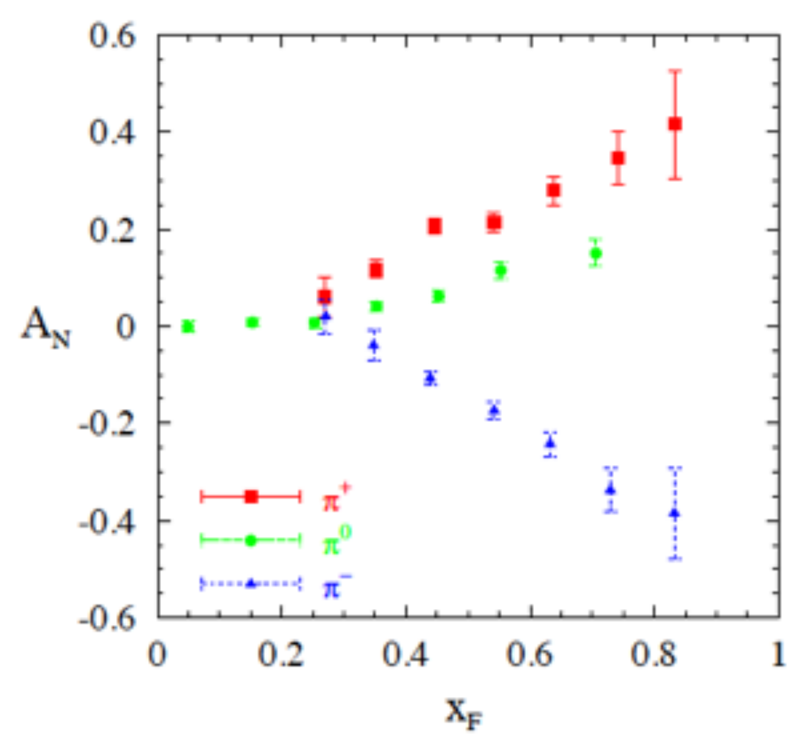
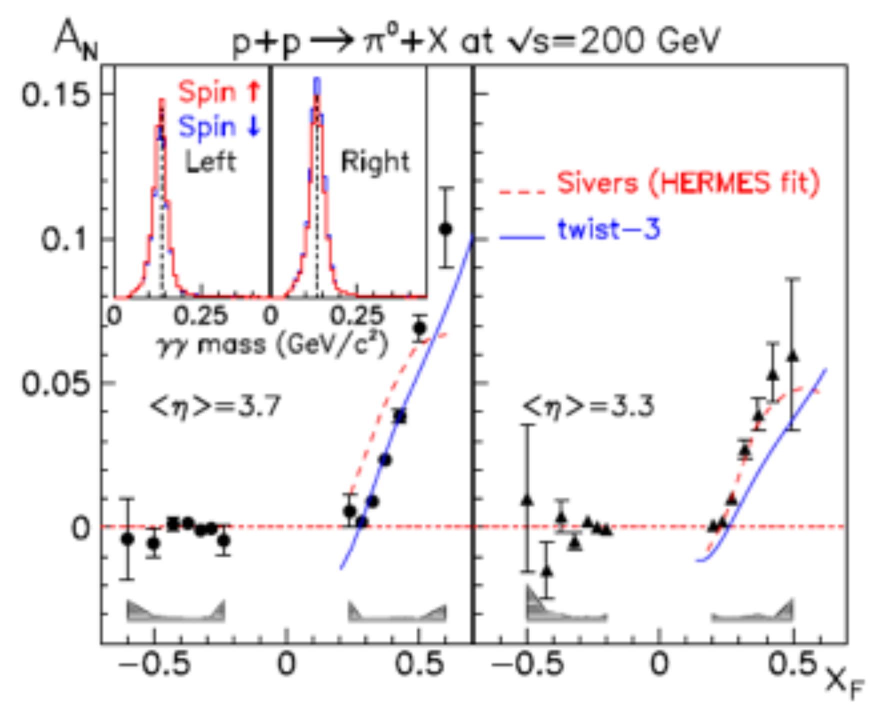
$$A_N = A_{UT} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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



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



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

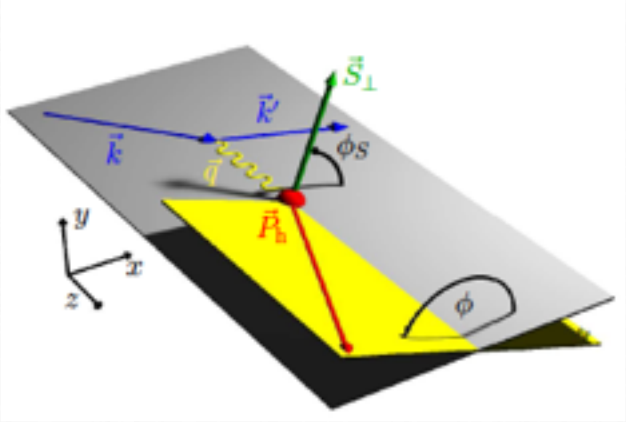
- sizeable effect at large x_F (and large P_T... (?))
- cannot be explained in the naive parton model [Kane, Repko]

➙ collinear twist-3 framework

2) Transverse SSA in semi-inclusive DIS

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

("Sivers", "Collins" effect...)



$$d\sigma_{UT}^{\rm SIDIS} = F_{UT}^{\sin(\phi-\phi_S)} \sin(\phi - \phi_S)$$

$$+ F_{UT}^{\sin(\phi+\phi_S)} \sin(\phi + \phi_S) + \ldots$$

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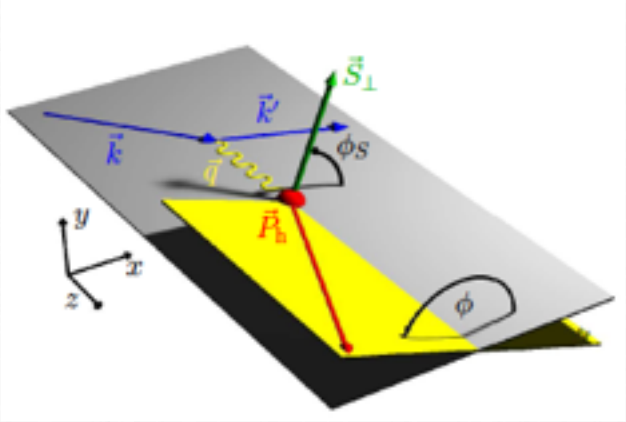

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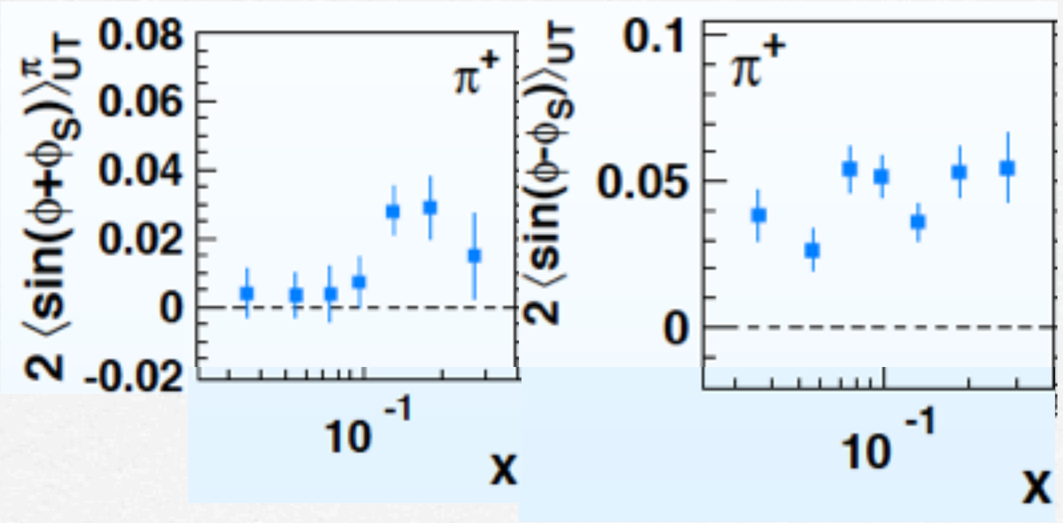
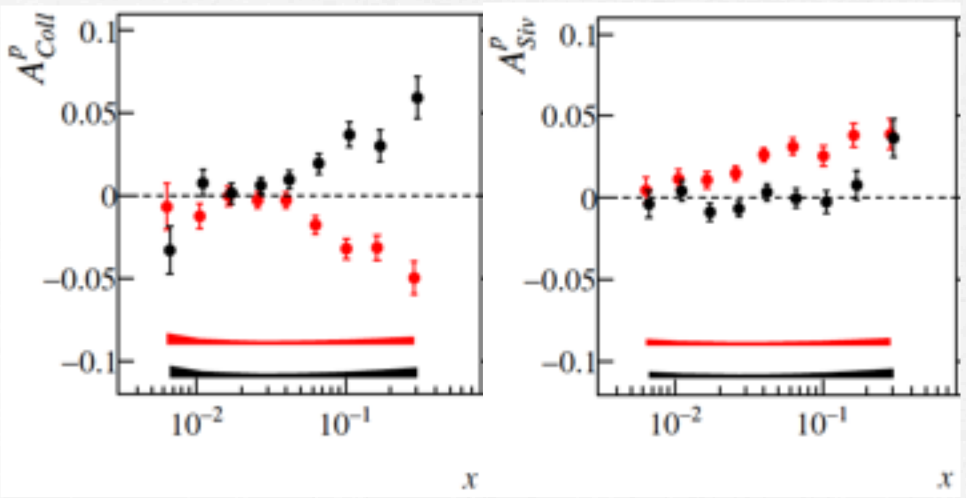


COMPASS:



- Effect on the percent-level
- usually discussed in TMD-framework

Collinear Twist-3 approach to SSA

Collinear Twist-3 approach for SSA in pQCD

- applicable to 1-particle inclusive processes (one hard scale Q):

$$p + p^{\uparrow} \to \pi, l, \gamma, \text{jet} + X \qquad e + p^{\uparrow} \to \pi, l, \gamma, \text{jet} + X$$

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- 2-(or more...)particle inclusive processes
  - ➝ second scale: Transverse Momentum q_T
    - ➝ integrated (weighted) observables

$$\int d^2q_T \, w(q_T) \frac{d\sigma_{UT}}{d^2q_T} \equiv \langle w(q_T) \rangle_{UT}$$

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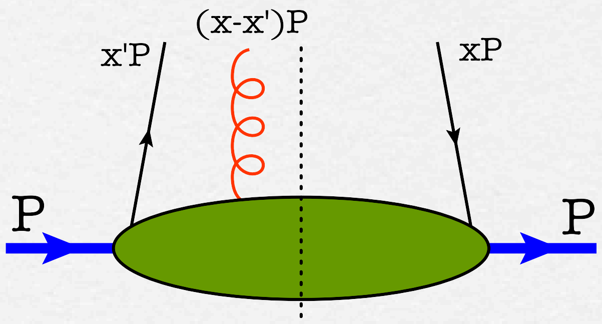
Quark-Gluon Correlation Functions

(ETQS-matrix elements)



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

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

Direct-Photon Production

- $p+p^{\uparrow}$- process: most data from π-production (RHIC) → complicated, many contributions...
- $p+p^{\uparrow} \rightarrow \gamma+X$: theoretically cleaner /Simpler → AFTER (?)

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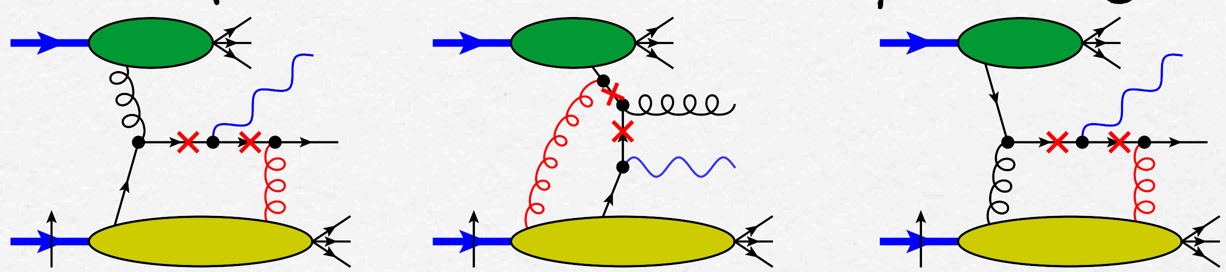
Twist-3 factorization: Sample diagrams



worked out by many people: Qiu, Sterman; Kouvaris, Vogelsang, Yuan; Koike, Yoshida; ...

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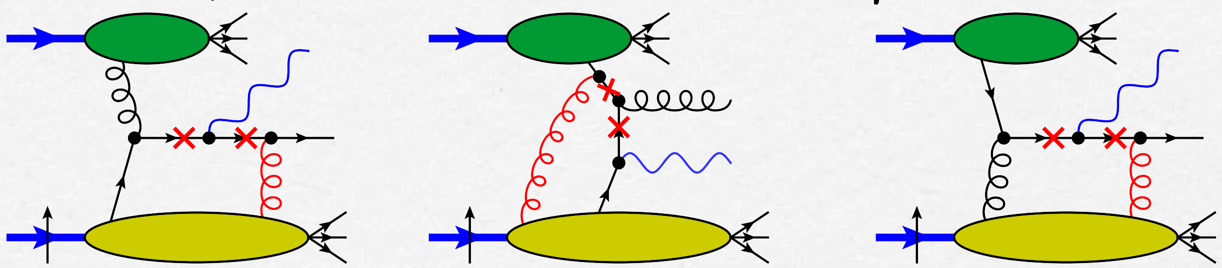

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SSA: needs imaginary part in the hard part

➞ propagators may go on-shell

$$\frac{1}{p^2 + i\epsilon} = \mathrm{P}\frac{1}{p^2} - i\pi\delta(p^2)$$

"Soft-Gluon Poles" $G_F(x, x)$

"Soft-Fermion Poles" $G_F(x, 0)$

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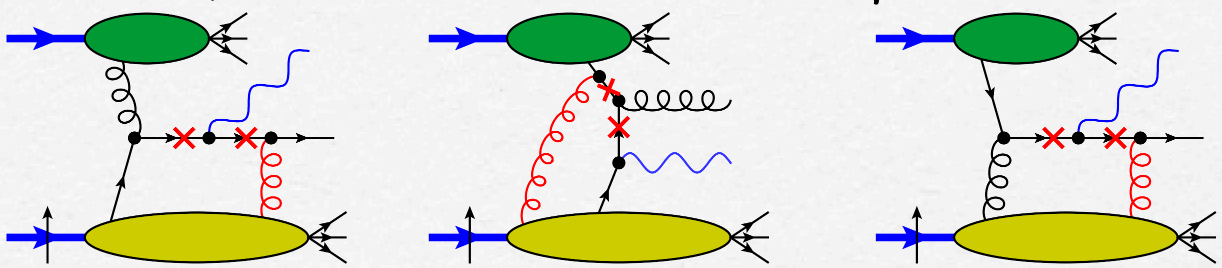

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Typical Twist-3 pQCD form at LO:

$$E\frac{d\Delta\sigma}{d^3q_\gamma} \propto \int \frac{dx'}{x'} \int \frac{dx}{x} f_1^{q/g}(x') \left[G_F^{q/g}(x,x) - x\frac{d}{dx}G_F^{q/g}(x,x)\right] \hat{H}^{SGP}(x,x') + \ldots$$

Predictions from Fits

[Kouvaris, Qiu, Vogelsang, Yuan]

Input from fits of RHIC π-production data (“Soft-Gluon Pole” only)

$$\boxed{G_F^q(x,x) = N^q\, x^\alpha (1-x)^\beta f_1^q(x)}$$

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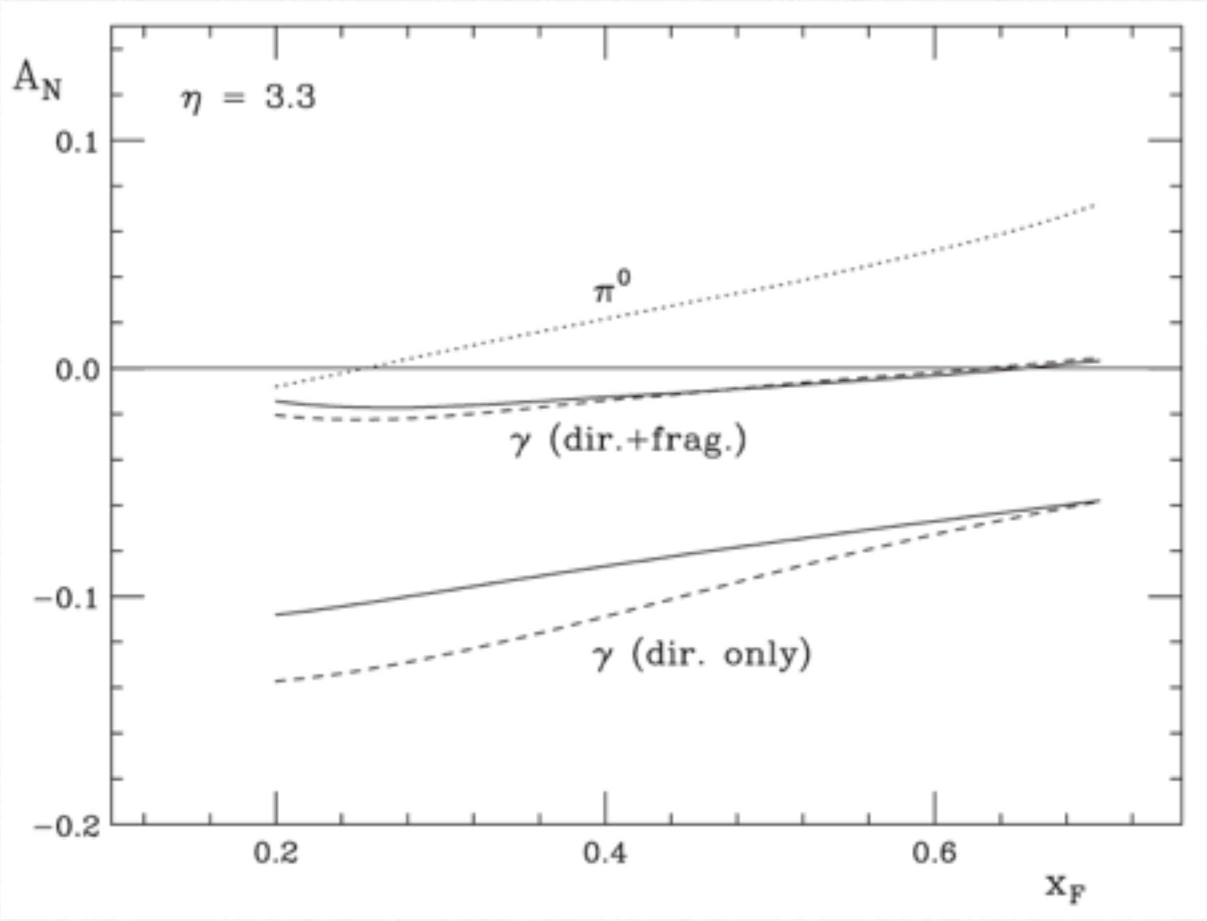
LO prediction for direct and prompt photon SSA



→ Expect SSA of up to 10 %!

Tri-Gluon contributions

[Koike, Yoshida]

Two Twist-3 Glue-Glue correlation function:

$$\mathcal{FT}[\langle P,S|F^{+i}(0)\,F^{+j}(\lambda n)\,F^{+k}(\eta n)|P,S\rangle] \rightarrow O(x,x'),\, N(x,x')$$

LO-contribution from Tri-Gluon correlations to direct-γ SSA

$$d\Delta\sigma^{\gamma} \propto f_1(x') \otimes (1 - \tfrac{x}{2}\tfrac{d}{dx})\big((O(x,x) + O(x,0)) - (N(x,x) + N(x,0))\big)$$

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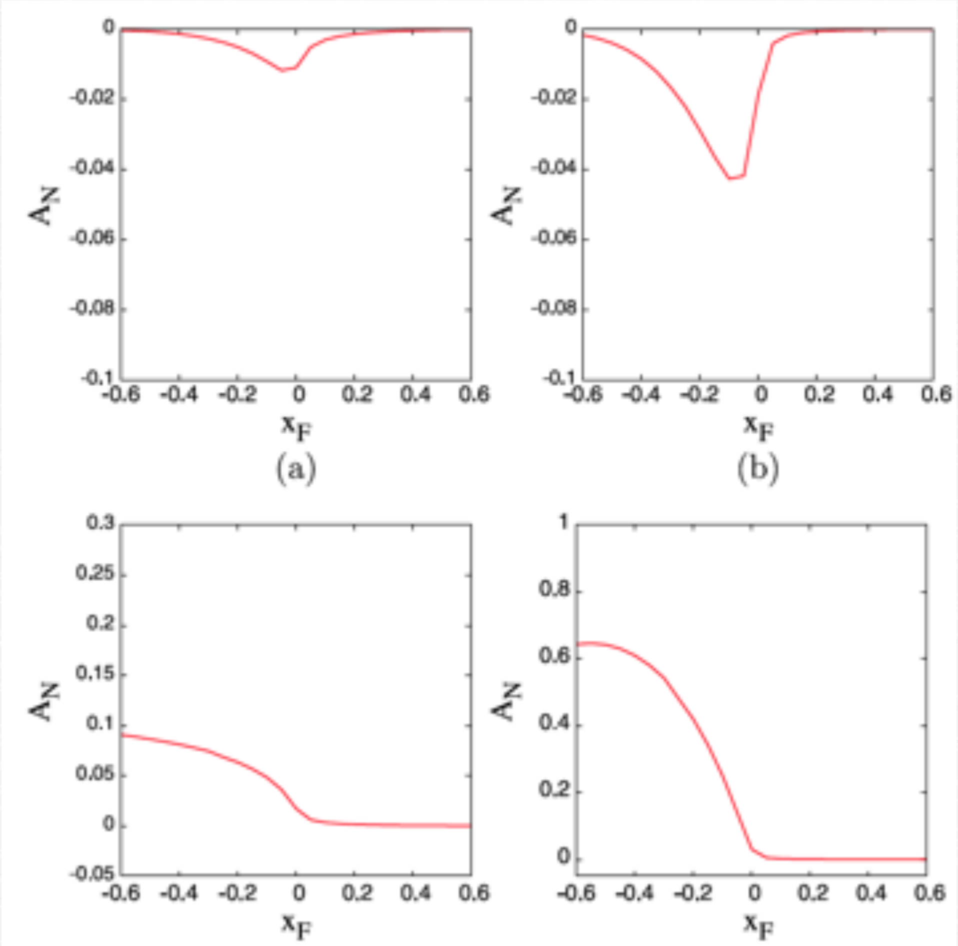

upper left: $O(x) = N(x)$ $\quad O(x) = 0.004\,xG(x)$

upper right: $O(x) = N(x)$ $\quad O(x) = 0.001\,\sqrt{x}G(x)$

lower left: $O(x) = -N(x)$ $\quad O(x) = 0.004\,xG(x)$

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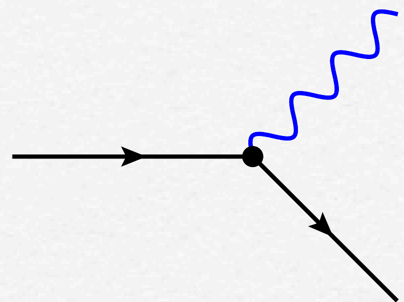
large in backward direction

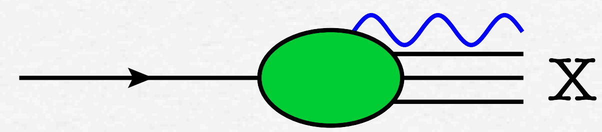
$x_F < 0$!

Photon fragmentation

- Photon observables ➙ contamination from fragmention photons



direct



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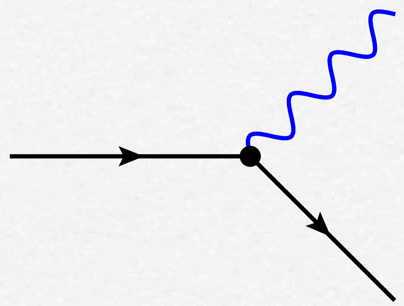

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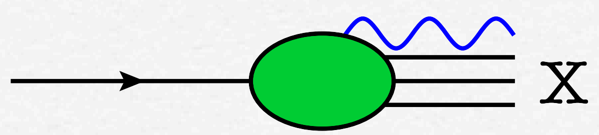

fragmentation

- Direct photons → isolation cuts, lowers event rate
- Direct photons: “Sivers” SSA, Frag. photons: “Sivers” + “Collins”

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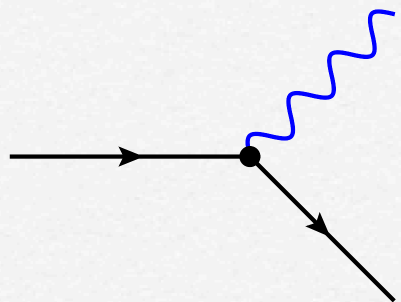

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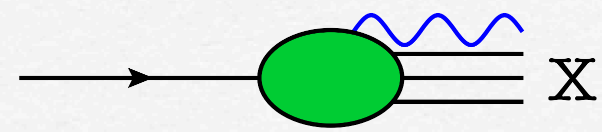
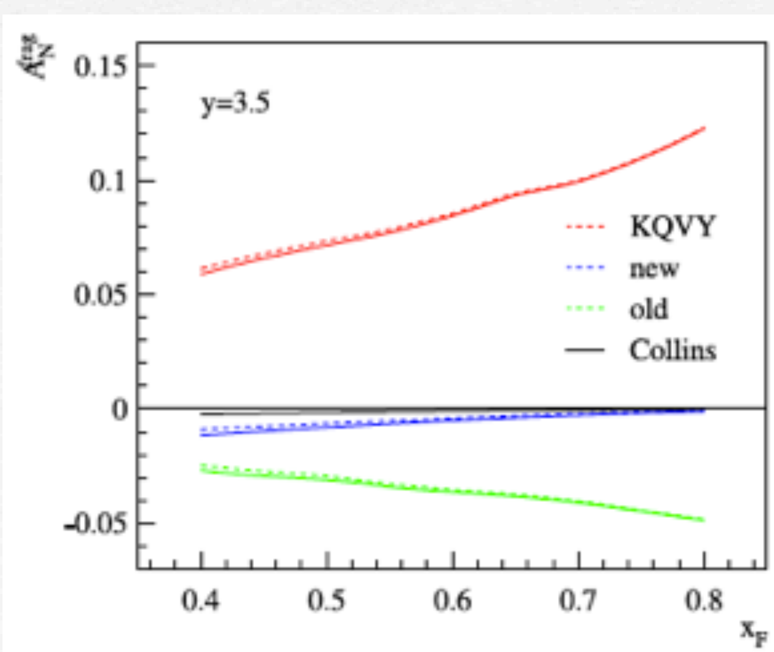
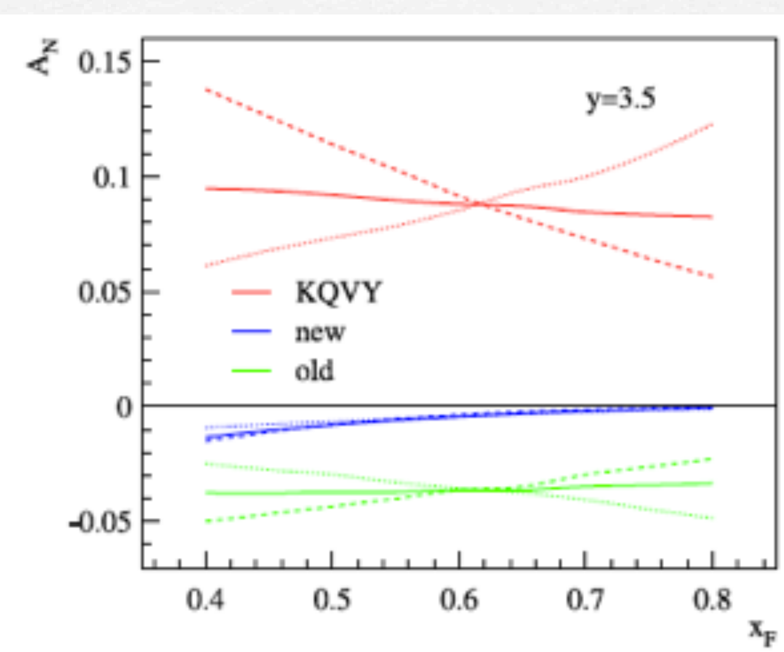


fragmentation

- Direct photons ➙ isolation cuts, lowers event rate
- Direct photons: "Sivers" SSA, Frag. photons: "Sivers" + "Collins"
  - Recent model calculation of unpol. and Collins FFs [Gamberg, Kang]

    ➙ Estimates of "prompt = dir. + frag." photon asymmetries:





dashed: direct photons
dotted: fragmentation photons
solid: prompt photons

Size and sign of prediction drastically depends on input for $G_F(x,x)$

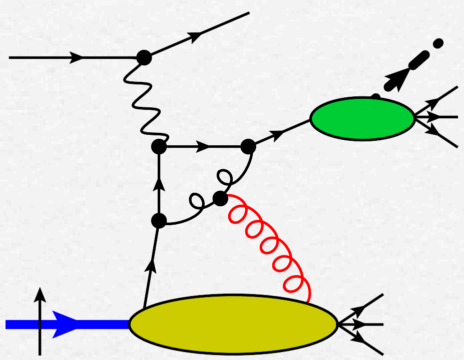
Twist-3 Formalism in $e + p^{\uparrow} \to e\ (+\ \pi) + X$

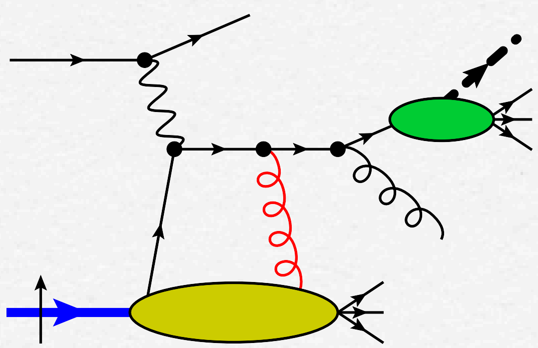
Twist-3 Formalism in $e + p^{\uparrow} \rightarrow e\ (+\ \pi) + X$

SIDIS at NLO [Kang, Vitev, Xing]

P_T - weighted SSA: "Sivers"

$$\langle P_T \rangle_{UT} = \int d^2 P_T\, (S_T \times P_T) \frac{d\sigma}{dP_T^2}$$





- Improves extractions of ETQS-functions
- Additional sensitivity at NLO to $G_F(x, x_B)$
- By product: re-derive evolution equations
- Test of universality

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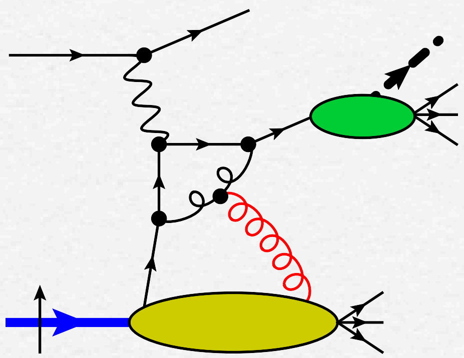

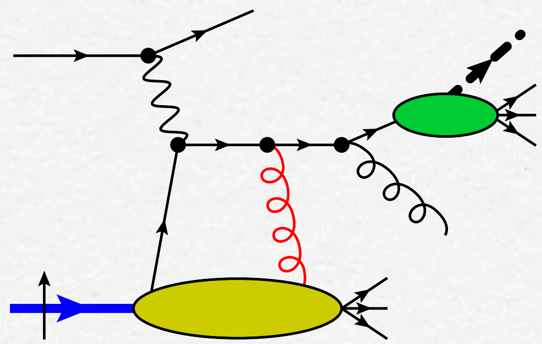

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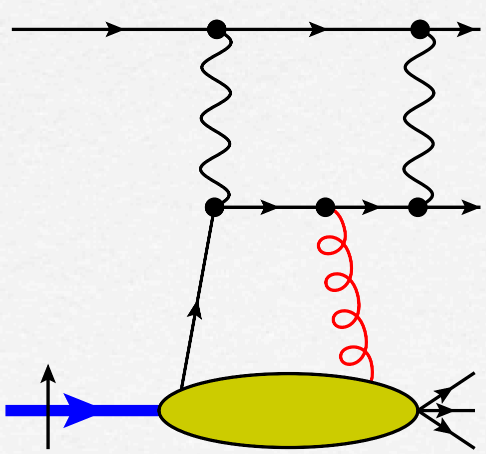
Two-Photon Exchange in incl. DIS [Metz, Pitonyak, Schäfer, M.S., Vogelsang, Zhou]



$$A_{UT} \propto \alpha_{\rm em} \frac{M}{Q} \Big[\int_0^1 dx \big(C_1\, G_F(x, x_B) + C_2 \tilde{G}_F(x, x_B) \big) + \big(1 - x_B \tfrac{d}{dx_B}\big) G_F^{\gamma}(x_B, x_B) \Big]$$

- Asymmetry suppressed by $\alpha = 1/137$
- Maybe feasible at JLab...
- In principle sensitivity to the full support of ETQS-functions.
- Contributions from Quark-Photon Correlations

  → may dominate at large x_B.

TMD approach to SSA

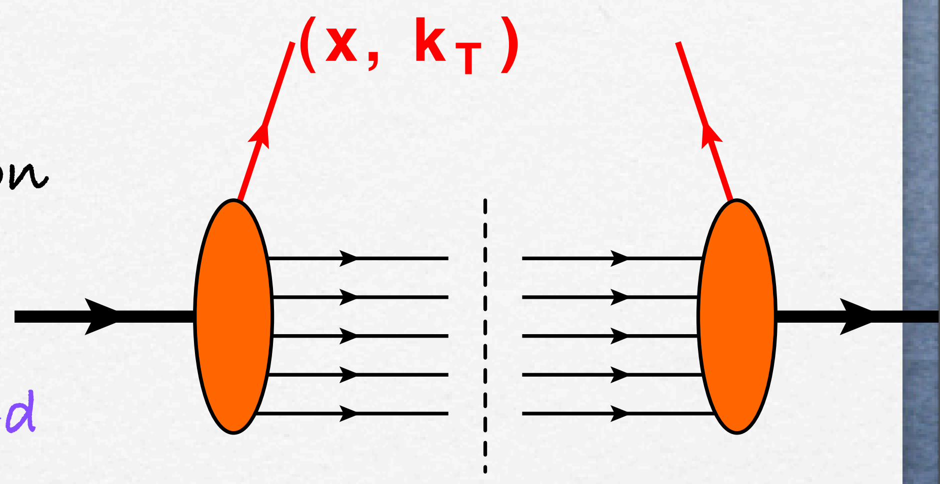
TMD approach:

applicable to semi-incl. (SIDIS, DY) processes at $q_T \sim \Lambda_{QCD}$

transverse momentum q_T from "intrinsic" transverse parton momentum k_T

→ different kind of factorization

→ study different aspects of hadron spin structure (e.g. 3-d momentum structure, spin-orbit correlations, etc.)



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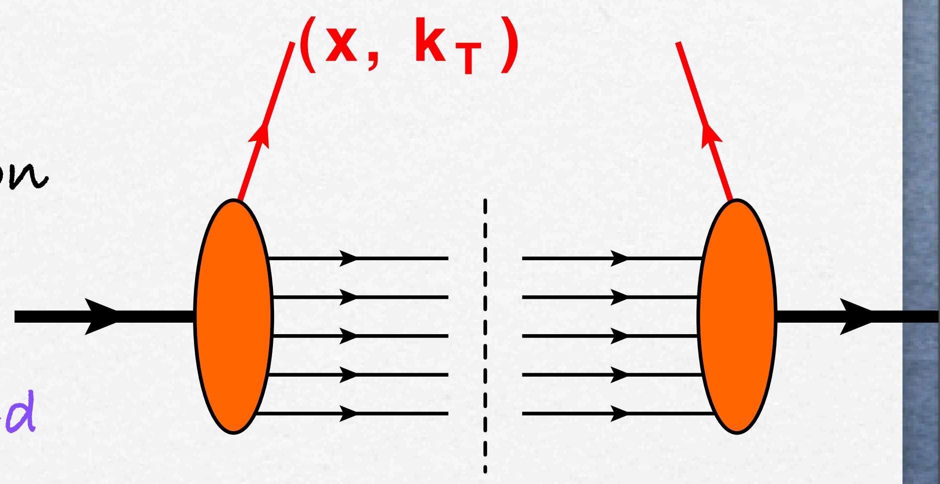
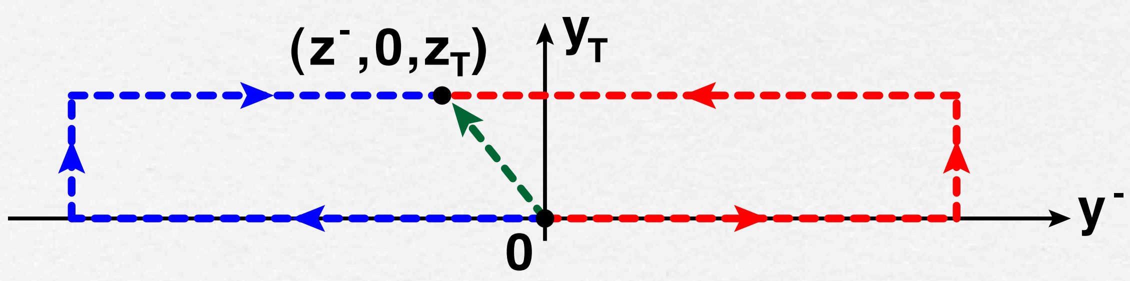


(Naive) definition of the quark TMD correlator

$$\Phi^{[\Gamma]}(x,k_T) = \int \frac{dz^- d^2 z_T}{2(2\pi)^3} e^{ik\cdot z} \langle P,S|\, \bar{q}(0)\, \Gamma\, \mathcal{W}[0,z]\, q(z)\, |P,S\rangle \Big|_{z^+=0}$$

→ Wilson line: process dependent, Initial / Final State Interactions



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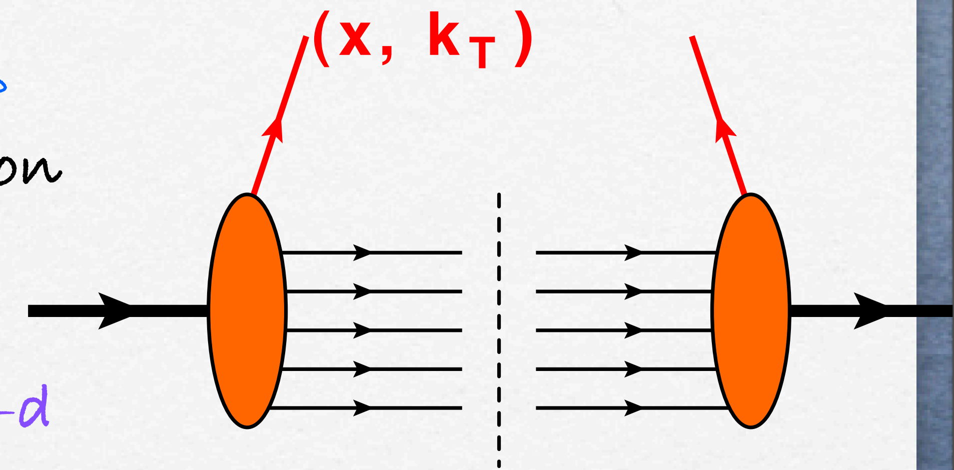

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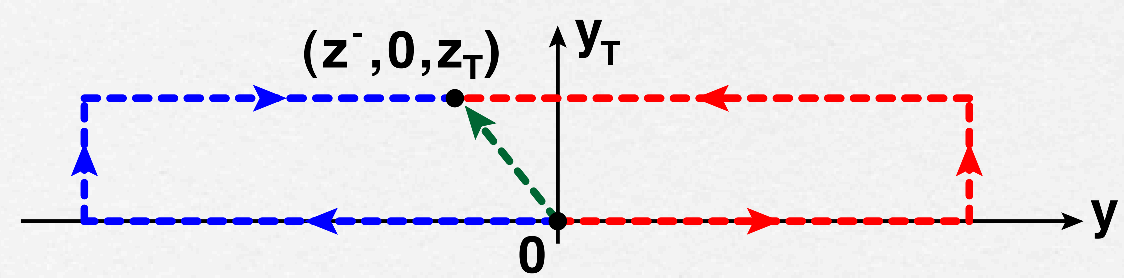
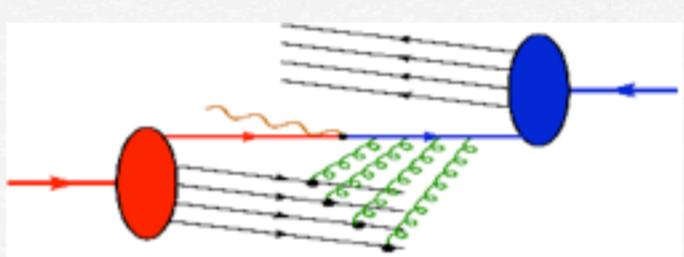
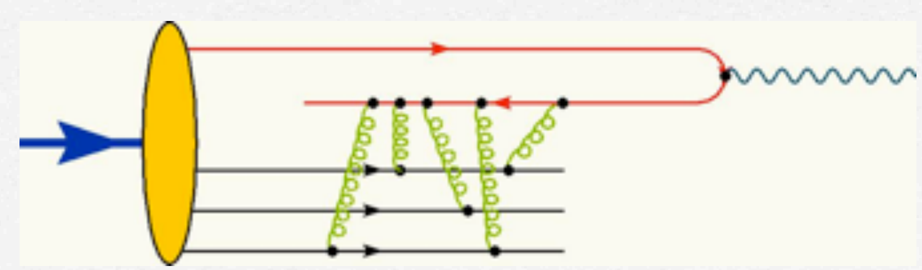


Initial State Interactions: Drell-Yan



Final State Interactions: SIDIS



Sivers-function

$$\Phi^{[\gamma^+]}(x, k_T) = f_1^q(x, k_T^2) - \frac{\epsilon_T^{\alpha\beta} k_{T\alpha} S_{T\beta}}{M} f_{1T}^{\perp q}(x, k_T^2)$$

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$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

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- Sivers-function generates transv. SSA in the TMD-approach "Sivers effect":

$$F_{UT}^{\sin(\phi-\phi_s)} \propto f_{1T}^{\perp} \otimes D_1 = \int d^2k_T d^2p_T\, \delta^{(2)}(k_T - p_T - P_{hT}/z)\, \frac{k_T \cdot P_{hT}}{M|P_{hT}|} f_{1T}^{\perp}(x, k_T^2) D_1(z, p_T^2)$$

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

- Sivers-function generates transv. SSA in the TMD-approach "Sivers effect":

$$F_{UT}^{\sin(\phi-\phi_s)} \propto f_{1T}^{\perp} \otimes D_1 = \int d^2k_T d^2p_T\, \delta^{(2)}(k_T - p_T - P_{hT}/z)\, \frac{k_T \cdot P_{hT}}{M|P_{hT}|} f_{1T}^{\perp}(x, k_T^2) D_1(z, p_T^2)$$

- relation to the Twist-3 approach:

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

- Twist-3 and TMD-approach to Sivers SSA shown to be equivalent in intermediate region $\Lambda_{QCD} \ll q_T \ll Q$

[Ji, Qiu, Vogelsang, Yuan; Bacchetta, Boer, Diehl, Mulders]

- "Sign mismatch" between pp- and SIDIS extractions...

TMD-approach in pp-processes

TMD factorization for photonic & leptonic final states

$$p + p^{\uparrow} \to \left((l\bar{l}),\, (\gamma\gamma), (\gamma Z), (ZZ), ...\right) + X$$

No TMD factorization for colored final states ($\pi+\pi$, $\gamma+$ jet, dijet...)!

[Collins, Qiu; Mulders, Rogers; ...]

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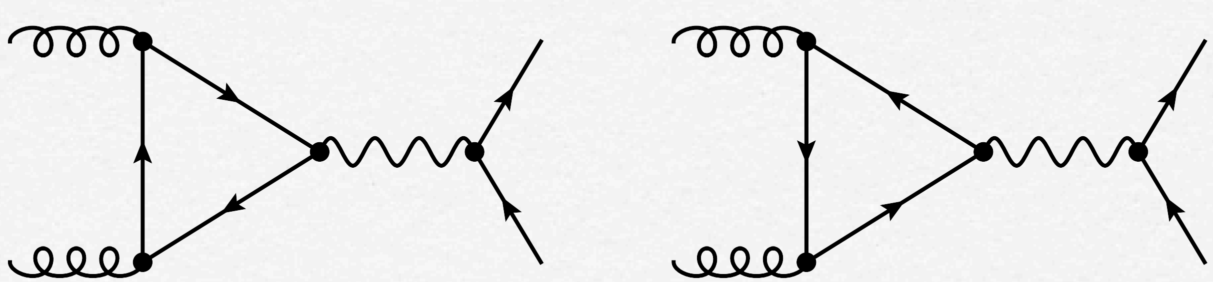
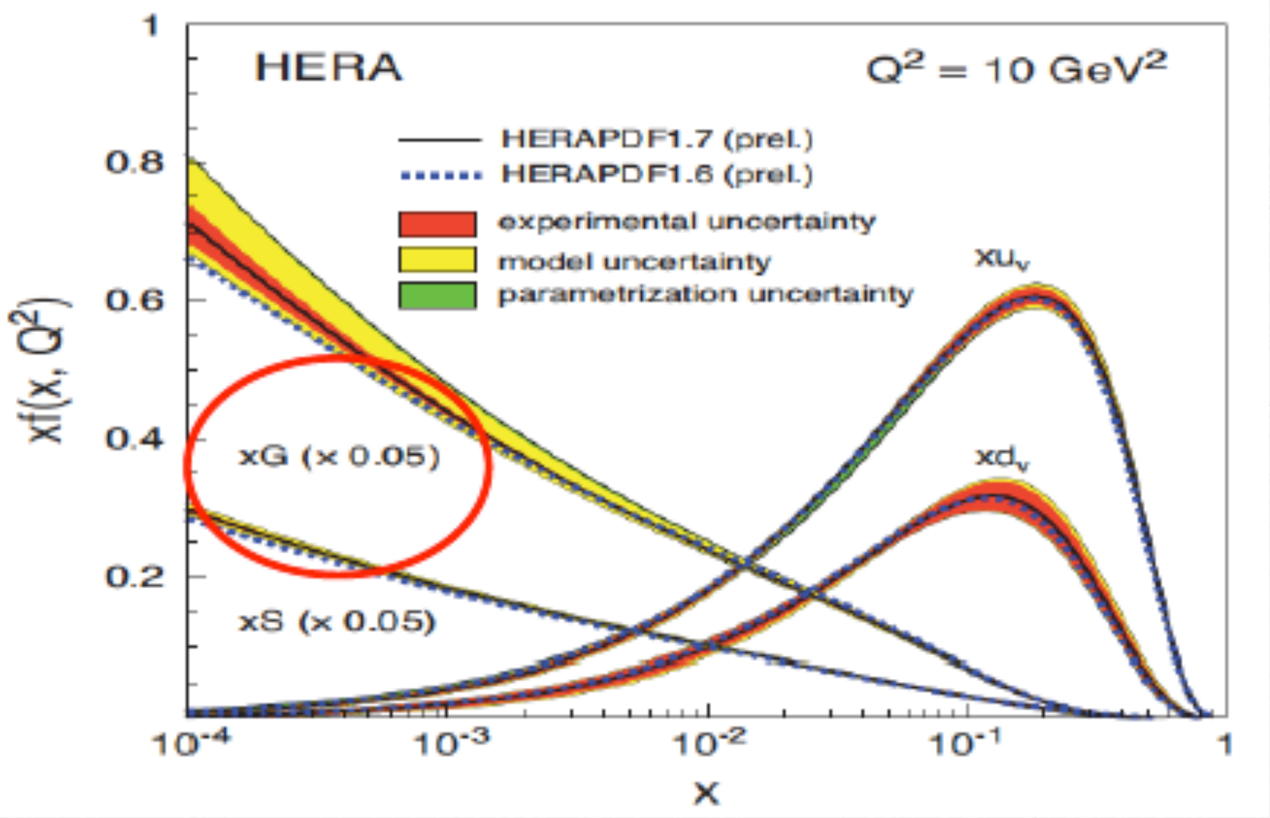
[Collins, Qiu; Mulders, Rogers; ...]

- Gluon-Gluon fusion at NNLO through loops
  → known to contribute in coll. factorization

- No gluon fusion in Drell-Yan
  (Furry's Theorem)

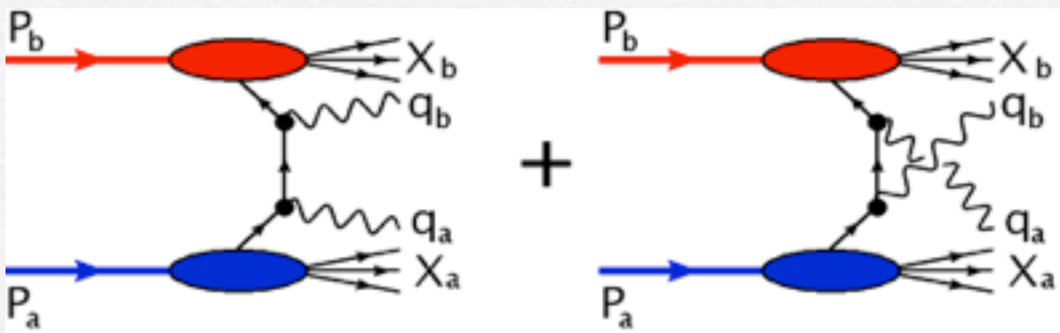




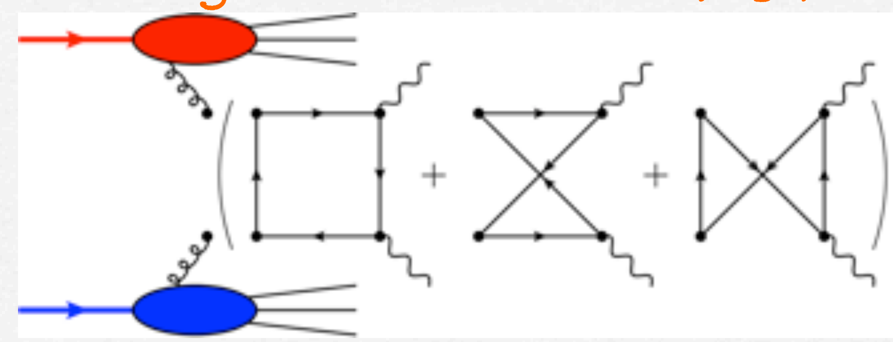
Photon Pair production

[Qiu, M.S., Vogelsang, PRL 107, 062001 (2011)]

quark TMDs



gluon TMDs at $O(\alpha_s^2)$



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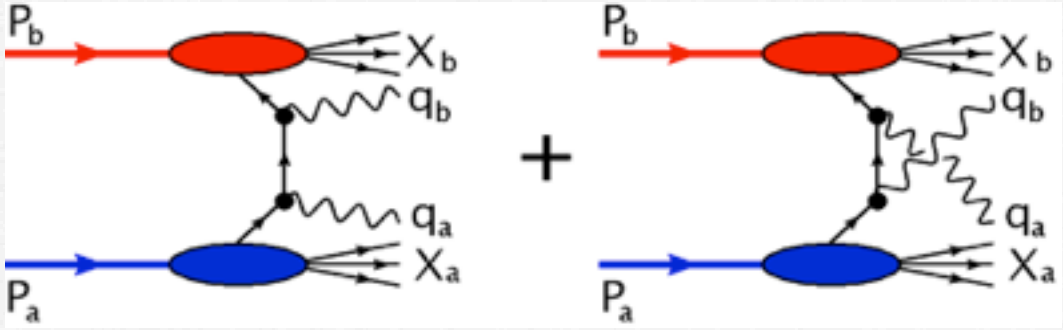

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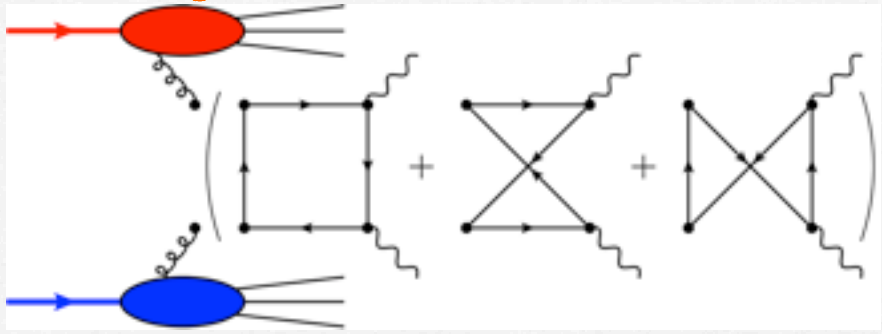

- Initial state interactions only, past-pointing Wilson lines
- gauge invariance ⇒ box finite ⇒ effectively tree-level

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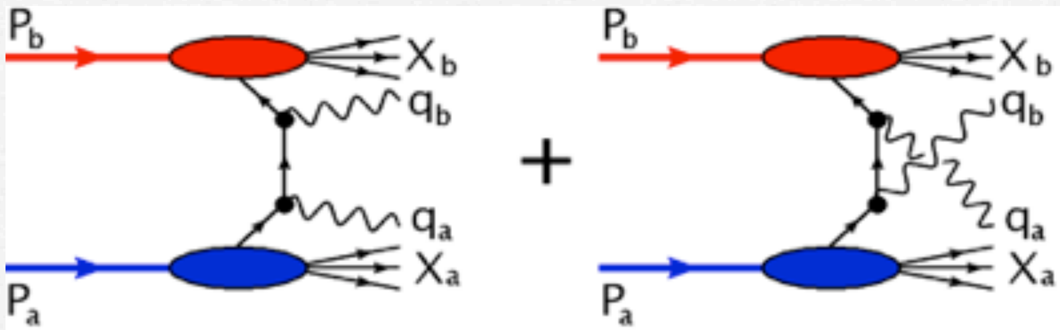

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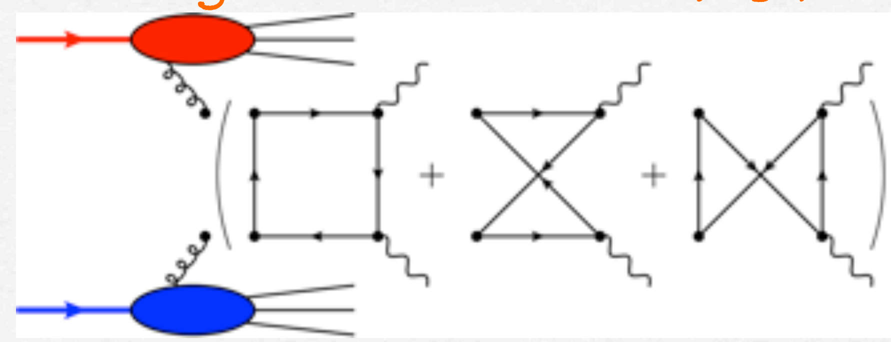
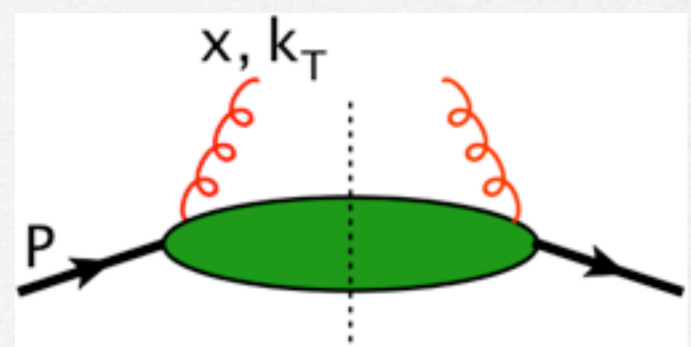


- Initial state interactions only, past-pointing Wilson lines
- gauge invariance ⇒ box finite ⇒ effectively tree-level

$\Gamma^{[T-even]}(x,\vec{k}_T)$			$\Gamma^{[T-odd]}(x,\vec{k}_T)$	
		flip		flip
U	f_1^g	$h_1^{\perp g}$		
L	$g_{1L}^{\perp g}$			$h_{1L}^{\perp g}$
T	$g_{1T}^{\perp g}$		$f_{1T}^{\perp g}$	h_1^g $h_{1T}^{\perp g}$

[Mulders, Rodrīues, PRD 63,094021]



- ✳ gluonic correspondence to "Boer-Mulders": T-even
- ✳ unpolarized gluons in transversely pol. proton: gluon Sivers function

Unpolarized pp→γγX Cross-Section at $q_T << Q$

$$\frac{d\sigma_{UU}}{d^4q\,d\Omega} \sim \left(\frac{2}{\sin^2\theta}\right)\left((1+\cos^2\theta)[f_1^q \otimes f_1^{\bar{q}}] + \cos(2\phi)\sin(2\theta)[h_1^{\perp q} \otimes h_1^{\perp \bar{q}}]\right)$$

quark contributions → almost identical to DY

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$$+\left(\frac{\alpha_s}{2\pi}\right)^2\Big(\mathcal{F}_1[f_1^g \otimes f_1^g] + \mathcal{F}_2[h_1^{\perp g} \otimes h_1^{\perp g}] + \cos(2\phi)\mathcal{F}_3[h_1^{\perp g} \otimes f_1^g + f_1^g \otimes h_1^{\perp g}] + \cos(4\phi)\mathcal{F}_4[h_1^{\perp g} \otimes h_1^{\perp g}]\Big)$$

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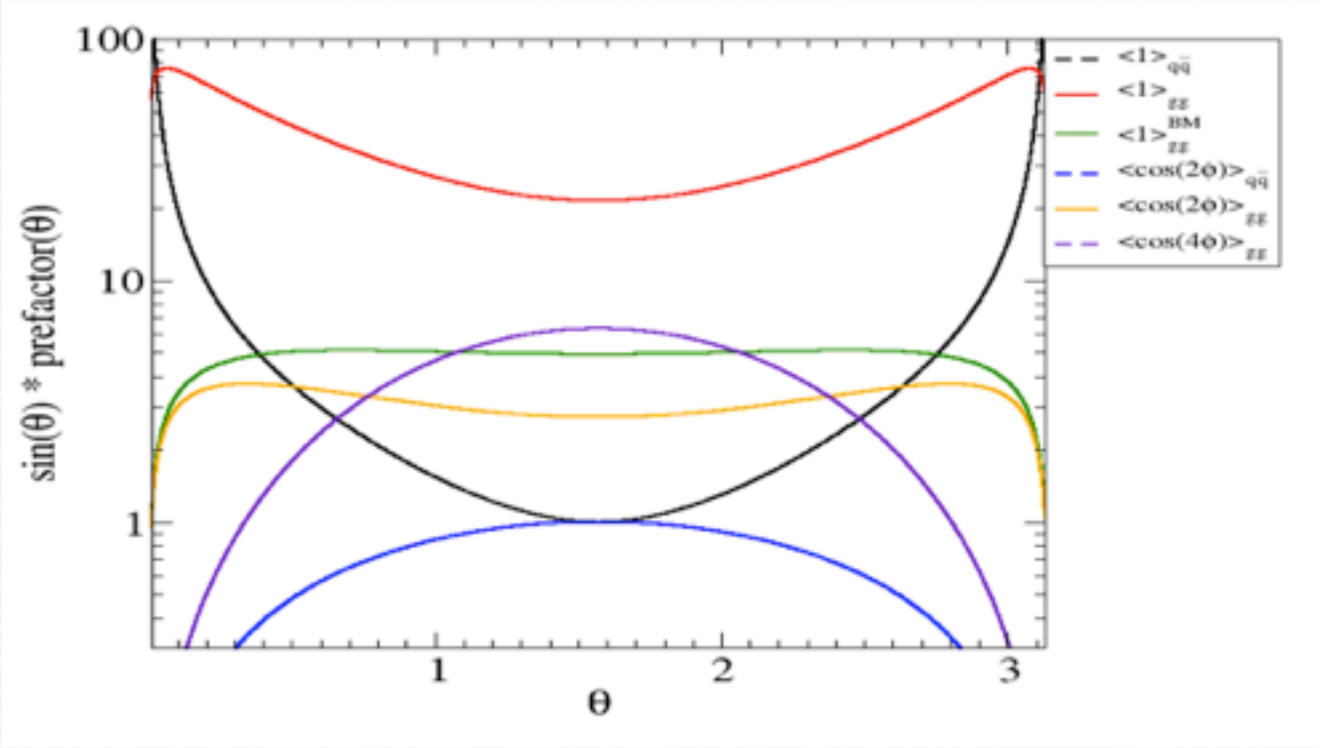


- cos(4φ) modulation a pure gluonic effect
- cos(2φ) ➞ sign of gluon $h_1^{\perp}$
- requires p_T isolation cuts for the photons
- powerful in combination with DY
  ➞ map out quark TMDs in DY
  → gluon TMDs in γγ

Numerical Estimate (Toy model)

RHIC energy: $\sqrt{S} = 500\,\mathrm{GeV}$

Positivity bounds

$$|h_1^{\perp,g}| \leq \frac{2M^2}{k_T^2} f_1^g \qquad |h_1^{\perp}, q| \leq \frac{M}{k_T} f_1^q$$

Gaussian ansatz:

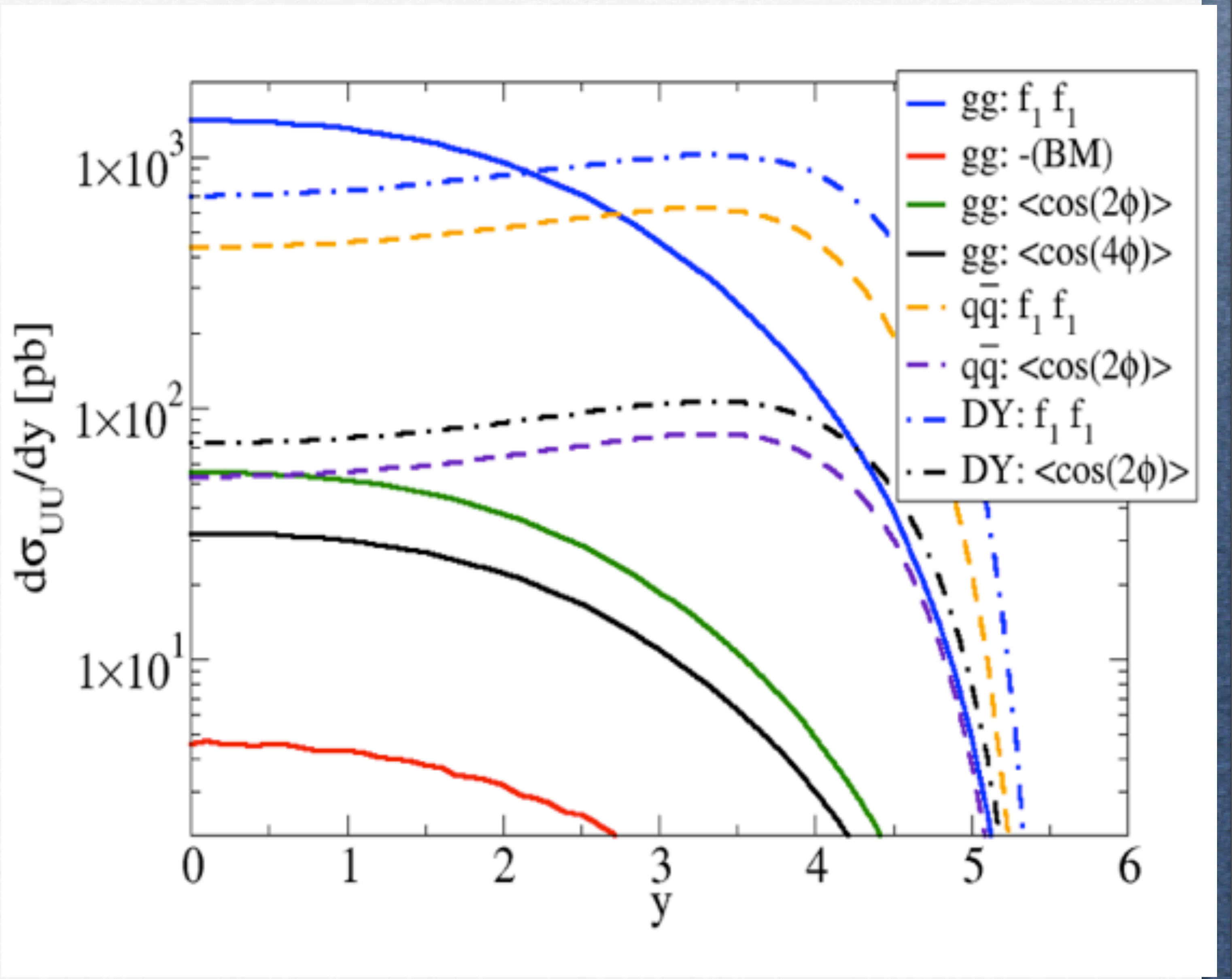
$$f_1^{q/g}(x, k_T^2) = f_1^{q/g}(x)\, \mathrm{e}^{-k_T^2/\langle k_{T,q/g}^2 \rangle}$$

Gaussian widths:

$$\langle k_{T,q}^2 \rangle = \langle k_{T,g}^2 \rangle = 0.5\,\mathrm{GeV}^2$$

p_T-cuts for each photon:

$$p_T^\gamma > 1\,\mathrm{GeV}$$



→ Gluon TMDs feasible at RHIC at mid-rapidity!

Gluon Sivers Effect

(Transverse) Spin dependent photon pair cross section:

$$\frac{d\sigma_{TU}}{d^4q\,d\Omega} \sim S_T \sin\phi_S \left[\frac{2}{\sin^2\theta}(1+\cos^2\theta)\,[f_{1T}^{\perp,q}\otimes f_1^{\bar{q}}] + \left(\frac{\alpha_s}{2\pi}\right)^2 \left(\mathcal{F}_1\,[f_{1T}^{\perp,g}\otimes f_1^g] + \mathcal{F}_2\,[h_1^g\otimes h_1^{\perp,g}] + \mathcal{F}_2\,[h_{1T}^{\perp,g}\otimes h_1^{\perp,g}]\right)\right] + \ldots$$

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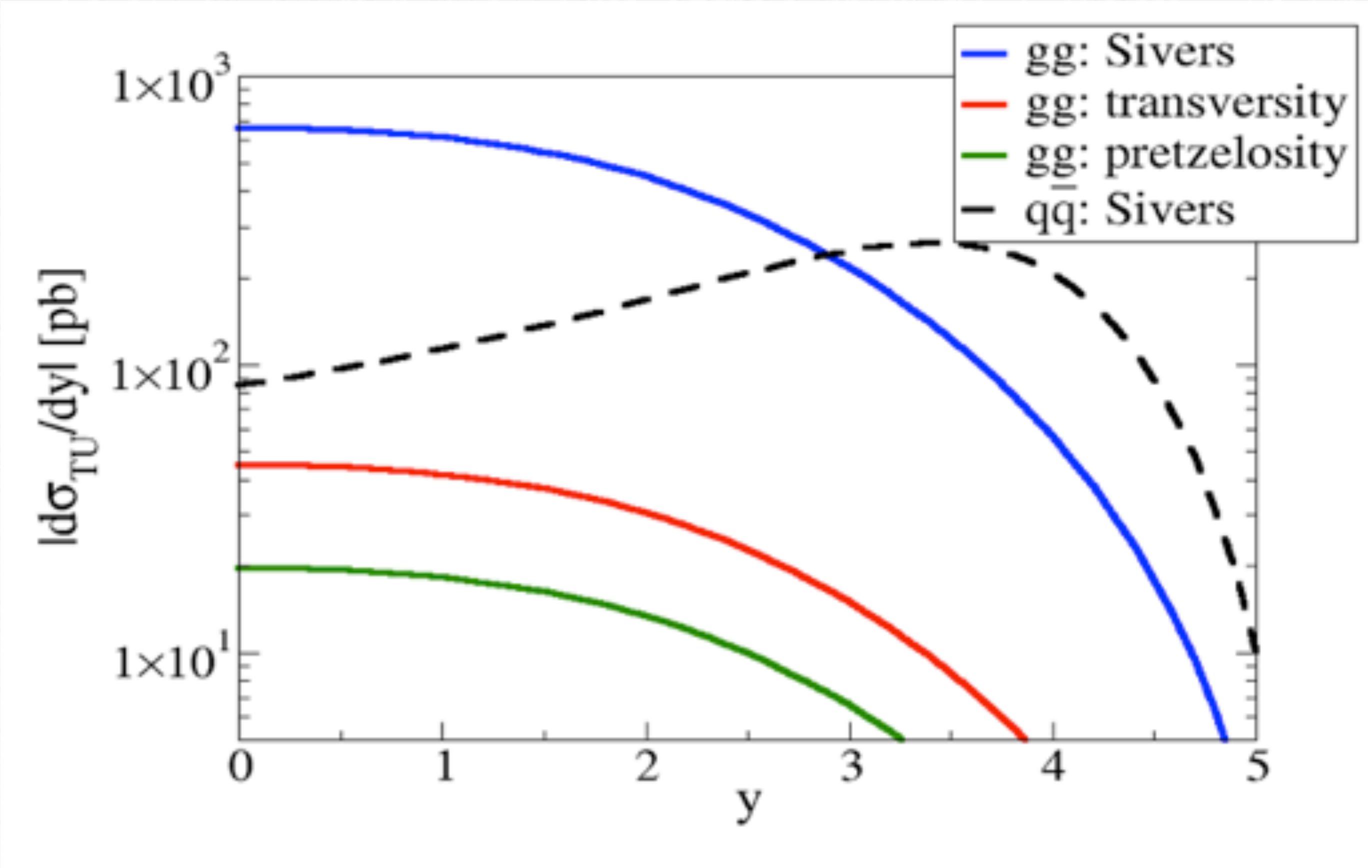
Estimates for RHIC 500 GeV



- Gaussian Ansatz + positivity bound for gluon and quark TMDs
- Flavor cancellation for quark Sivers func.: $f_{1T}^{\perp,u} \simeq -f_{1T}^{\perp,d}$ → exploit bound only for u-quarks
- Sign not fixed by bound → quark and gluon Sivers effect could add.
- Gluons dominate at mid-rapidity, quarks at large rapidity

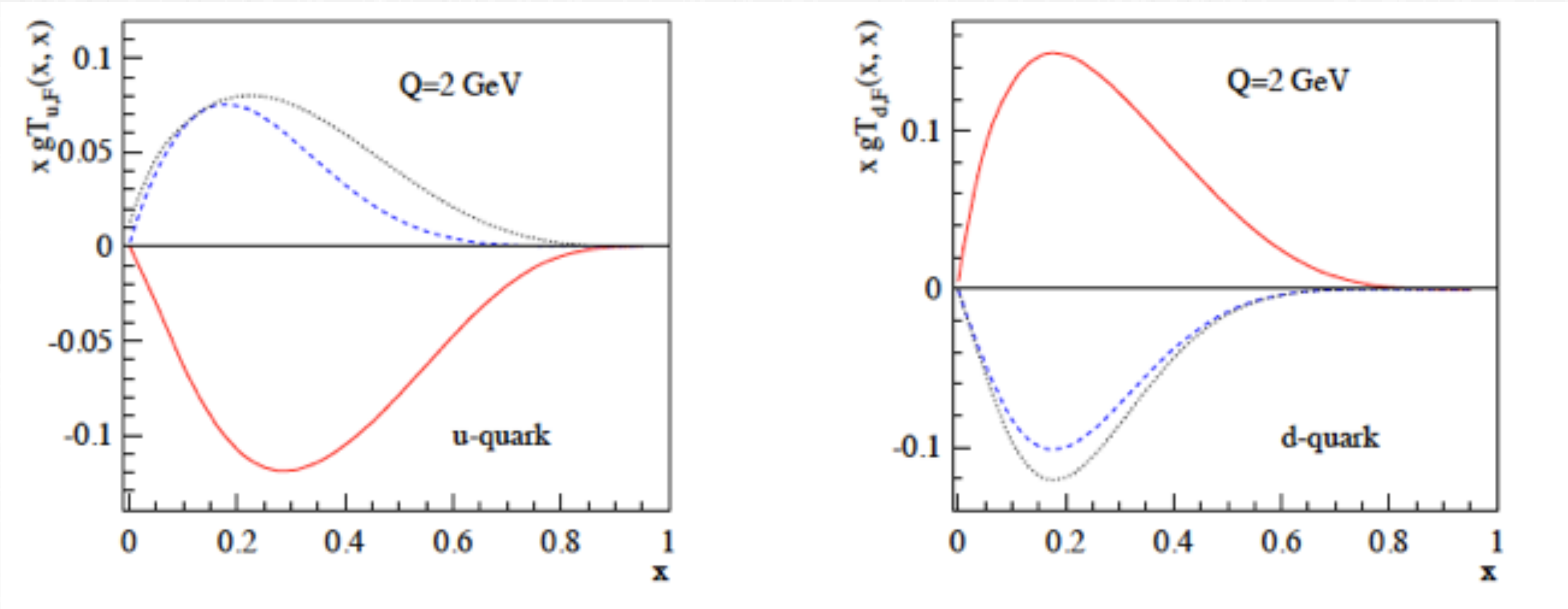
Summary

- Transverse SSA give unique insight into the Twist-3 structure of the nucleon
  ➝ test of our understanding of pQCD
- Photon Observables: theoretically simple, experimentally challenging ➝ AFTER
- Direct photon SSA
  ➝ quark-gluon and multi-gluon correlations
- Diphoton SSA ➝ gluon Sivers function

"Sign - mismatch"

[Kang, Qiu, Vogelsang, Yuan]

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



"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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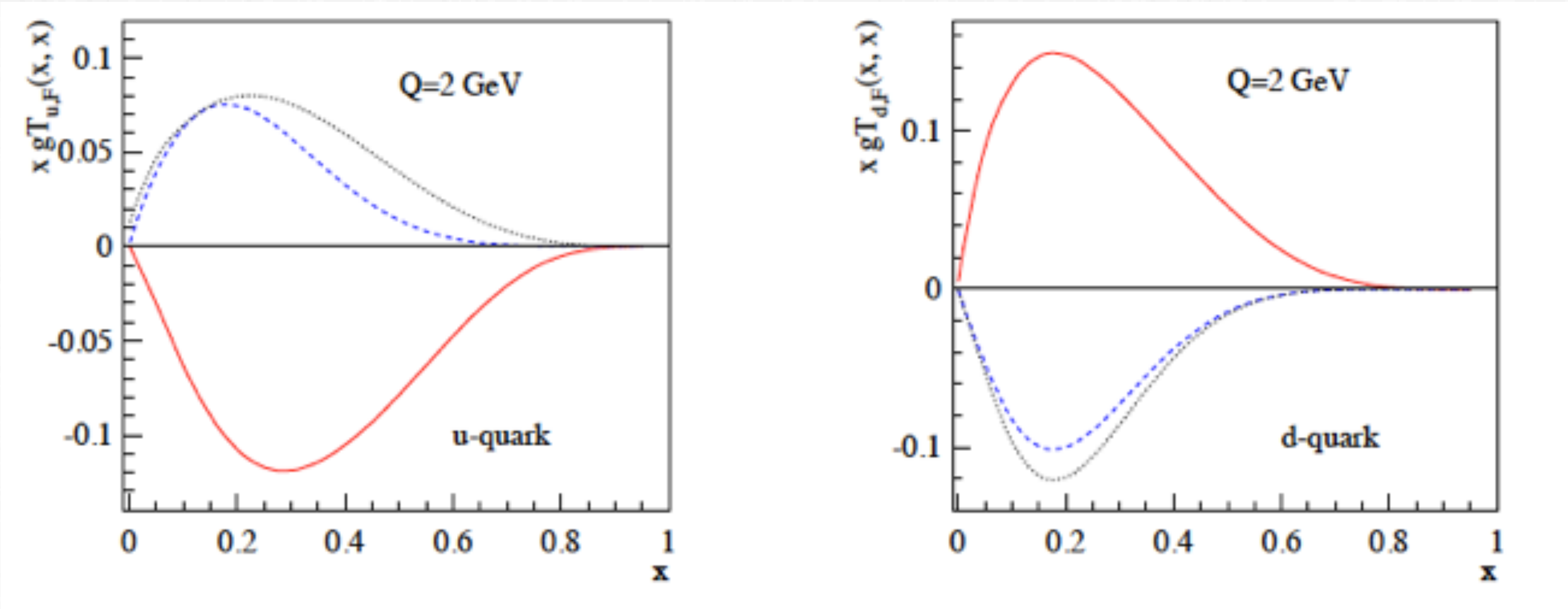

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pp-data: other (than Sivers) effects dominant? Fragmentation? [Anselmino et al., Metz et al.]

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

More data from other processes (Direct photon...) may help to solve the puzzle...