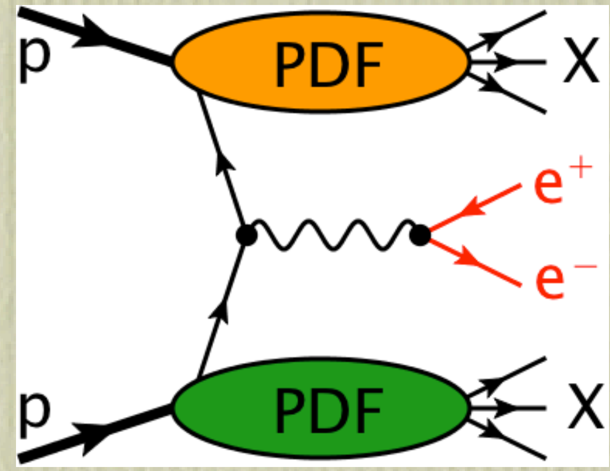
T-odd TMDs and Initial/Final State Interactions

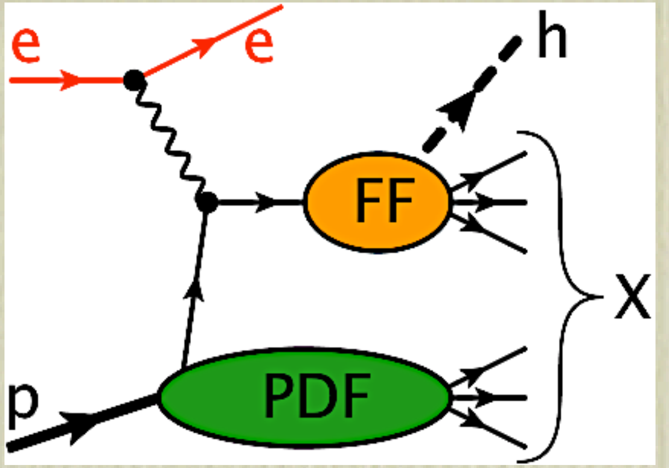
Marc Schlegel
Tuebingen University

TRANSVERSITY2011, Losinj, Croatia, Aug. 29, 2011

Quark TMDs in Drell-Yan & SIDIS

"intrinsic" transverse parton momentum through small final state transverse momenta





$q_T \ll Q$ $\qquad$ $P_{hT} \ll Q$

TMD factorization (tree-level)

Drell-Yan

$$W^{\mu\nu} \sim \int d^2k_{aT} d^2k_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} - \vec{q}_T)\, \mathrm{Tr}[\gamma^\mu \Phi(x_a, \vec{k}_{aT}) \gamma^\nu \bar{\Phi}(x_b, \vec{k}_{bT})]$$

SIDIS

$$W^{\mu\nu} \sim \int d^2k_T d^2p_T\, \delta^{(2)}(\vec{k}_T - \vec{p}_T - \vec{P}_{hT}/z)\, \mathrm{Tr}[\gamma^\mu \Phi(x, \vec{k}_T) \gamma^\nu \Delta(z, \vec{p}_T)]$$

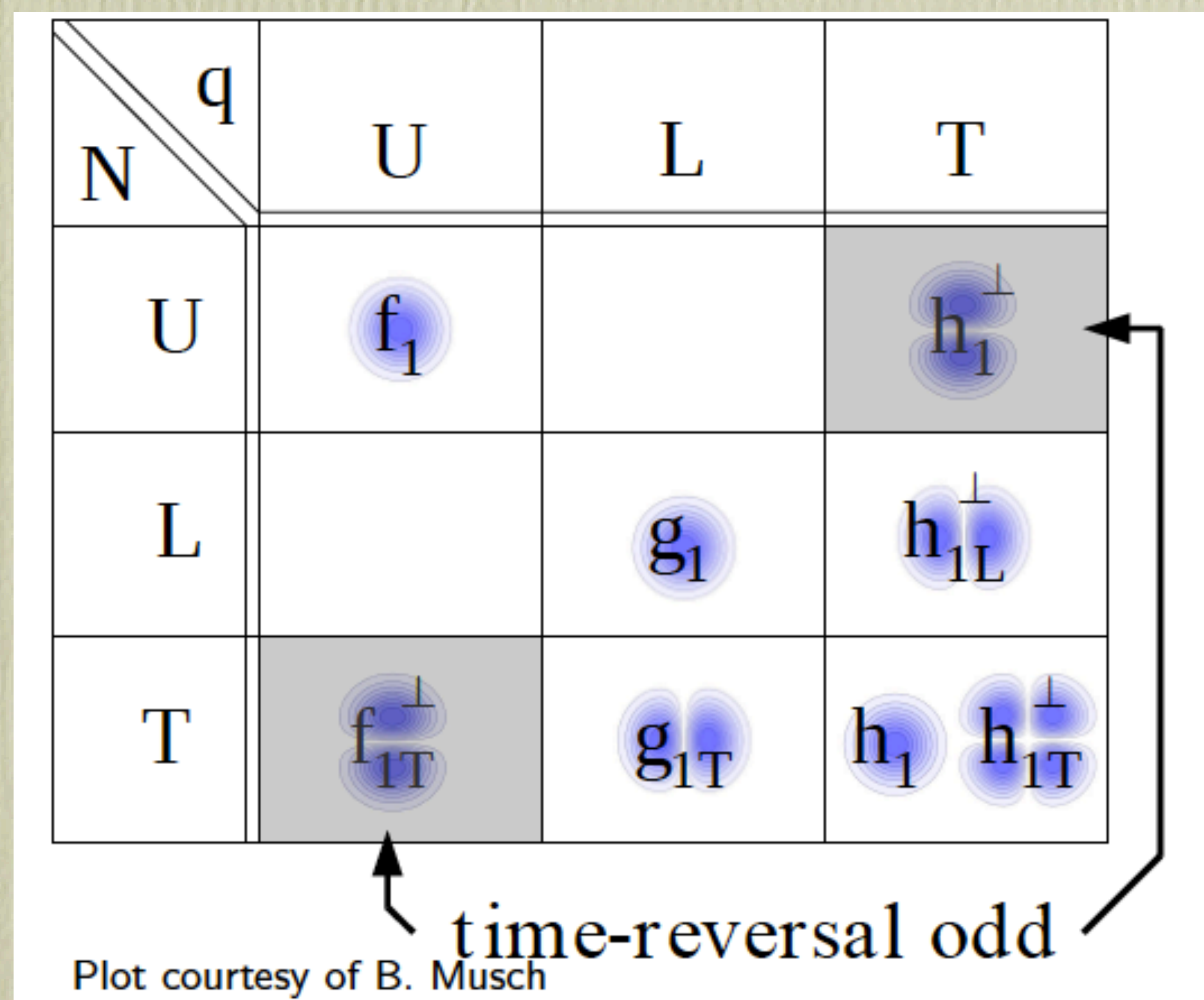
(Naive) definition of the quark TMD correlator

$$\Phi_{ij}(x,\vec{k}_T;S) = \int \frac{dz^- d^2 z_T}{2(2\pi)^3}\, e^{ik\cdot z} \langle P,S|\, \bar{\psi}_j(0) \mathcal{W}_{\mathrm{SIDIS/DY}}[0,z]\, \psi_i(z)\, |P,S\rangle \Big|_{z^+=0}$$

→ correct definition: see Mert Aybat's talk

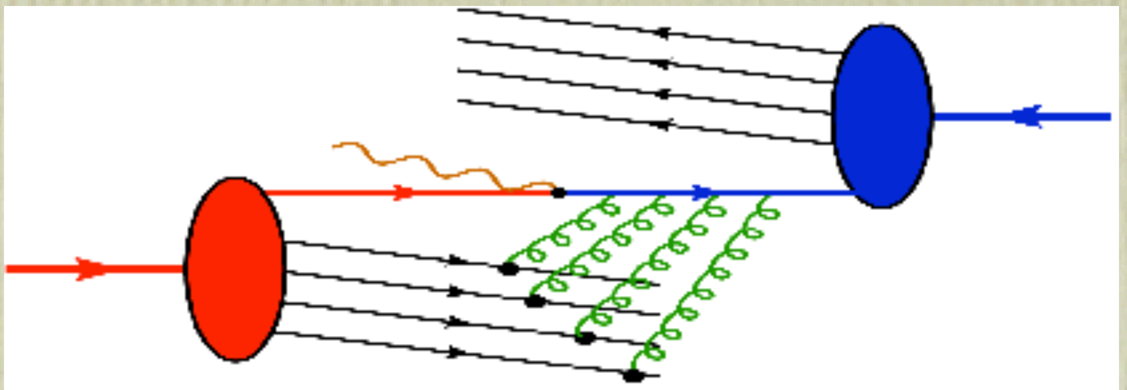
Projection of correlator on $\gamma^+,\ \gamma^+\gamma_5,\ \gamma^+\gamma^\perp\gamma_5$

→ 8 quark TMDs

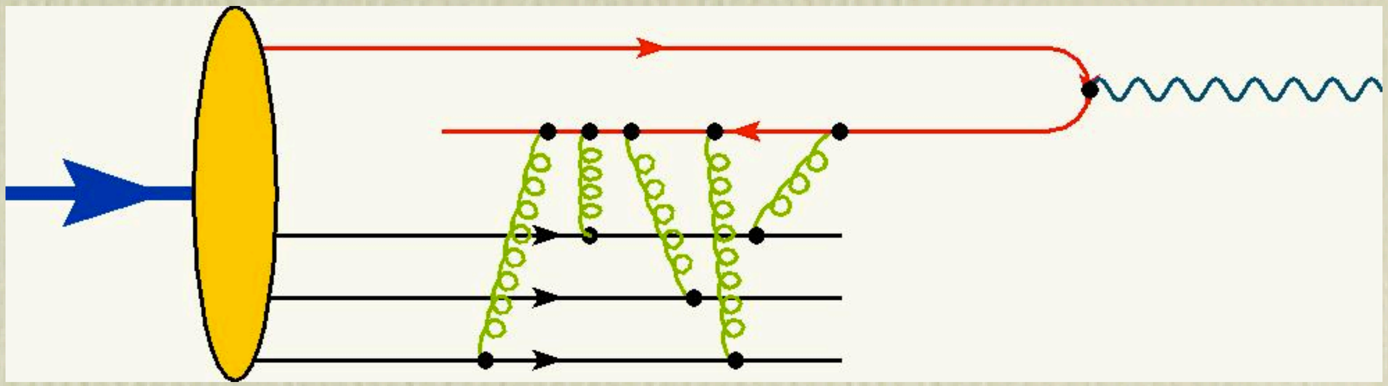


Physics of the Wilson line

Initial State Interactions: Drell-Yan

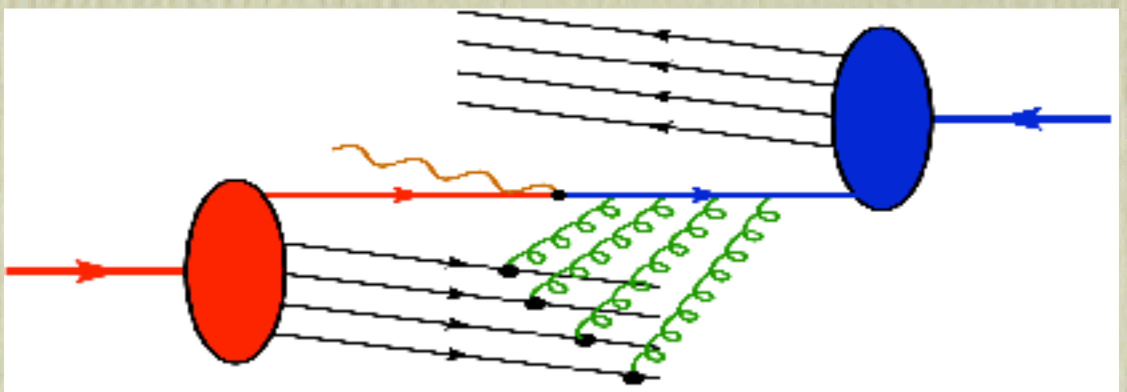


Final State Interactions: SIDIS

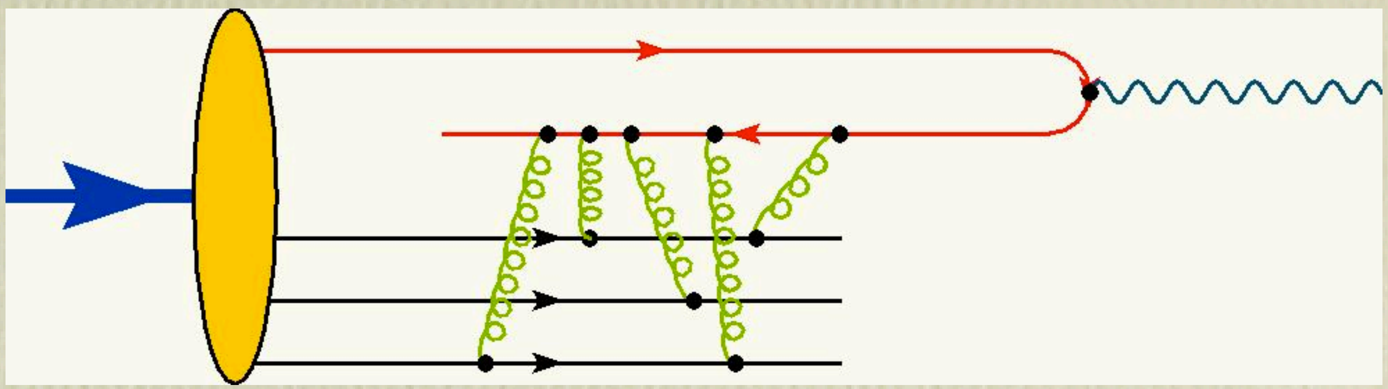


Physics of the Wilson line

Initial State Interactions: Drell-Yan



Final State Interactions: SIDIS



$\mathcal{PT}$ - Transformation on the quark correlator → ISI ⇔ FSI

→ sign switch of Sivers and Boer-Mulder function "T-odd"

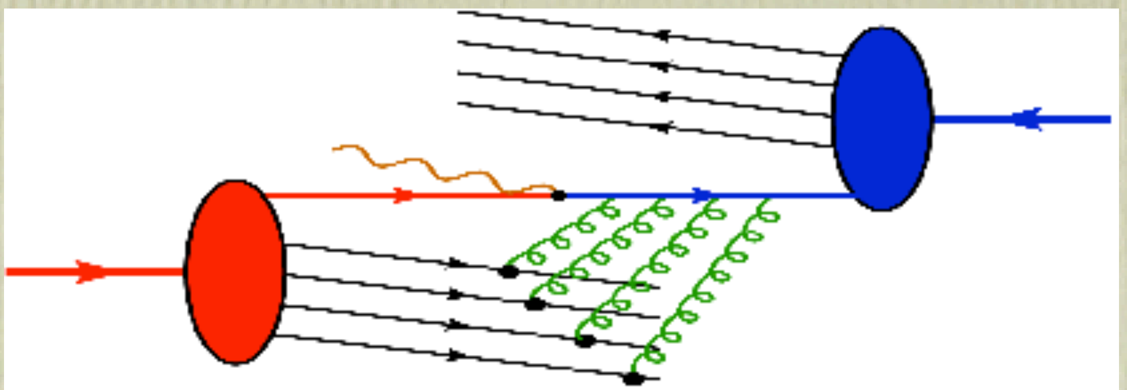
$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$$

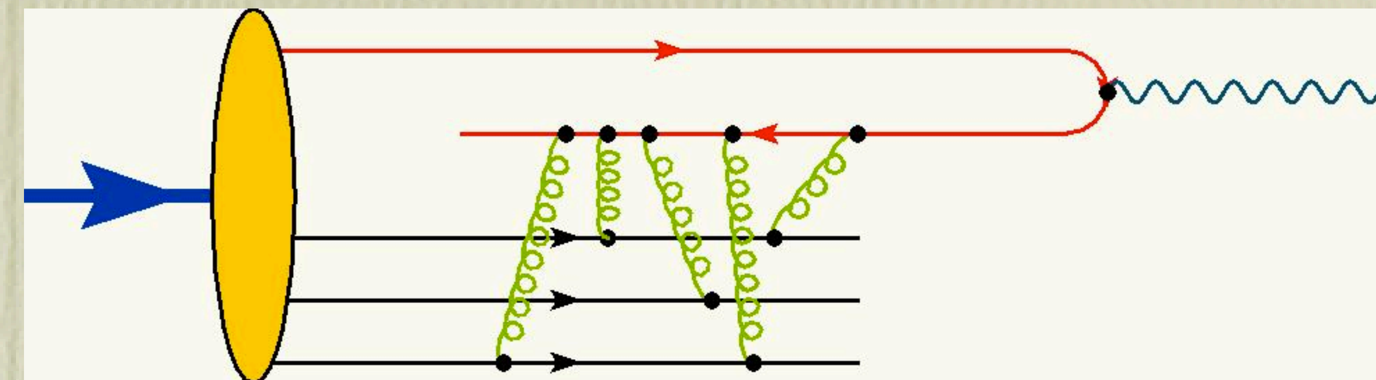
$$h_{1}^{\perp}\Big|_{DIS} = -h_{1}^{\perp}\Big|_{DY}$$

Physics of the Wilson line

Initial State Interactions: Drell-Yan

Final State Interactions: SIDIS





$\mathcal{PT}$ - Transformation on the quark correlator → ISI ⇔ FSI

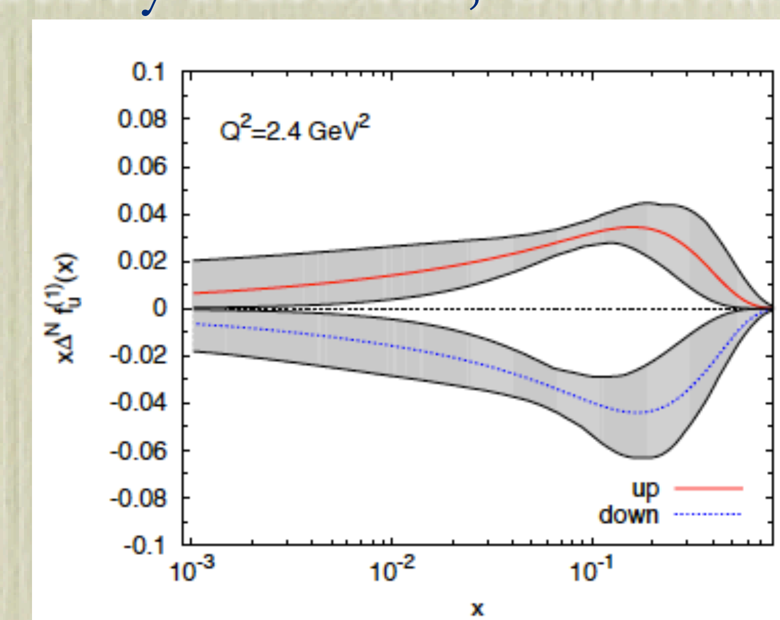
→ sign switch of Sivers and Boer-Mulder function "T-odd"

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY} \qquad h_1^{\perp}\Big|_{DIS} = -h_1^{\perp}\Big|_{DY}$$

"T-odd" TMDs generate / appear in observables

→ e.g. transverse SSA in SIDIS (measured by HERMES, COMPASS etc.) or DY

$$A_{UT}^{\mathrm{SIDIS}} \propto \frac{[f_{1T}^{\perp,q} \otimes D_1^q]}{[f_1^q \otimes D_1^q]}$$

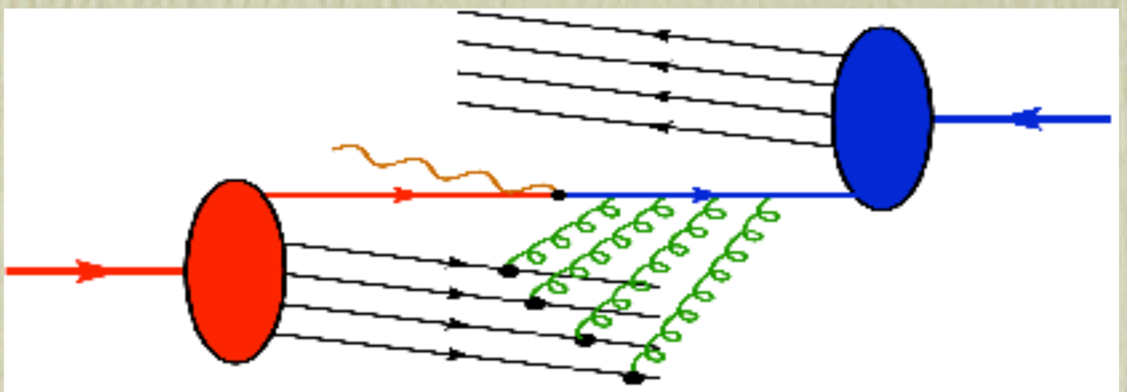


most recent param. from [Anselmino et al., 1107.4446]

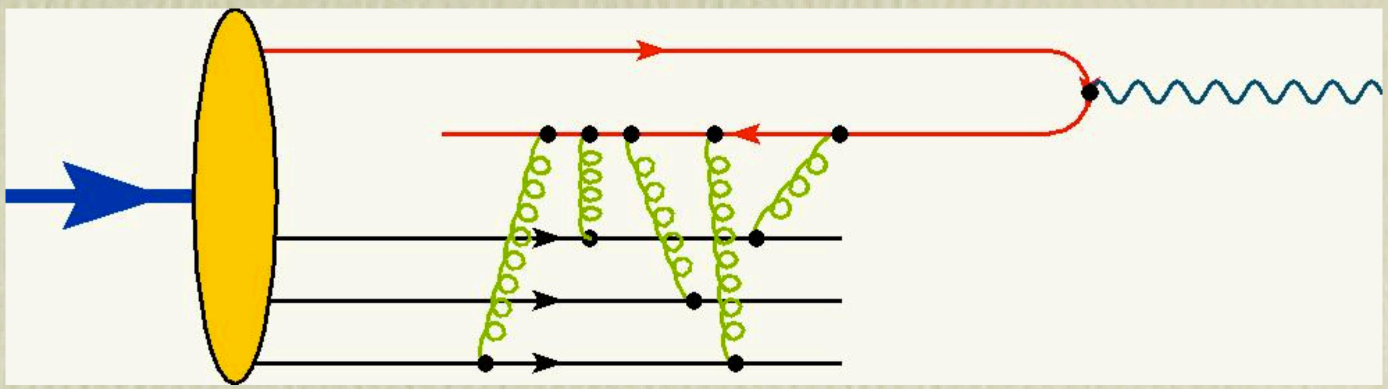
$$A_{UT}^{\mathrm{DY}} \propto \frac{[f_{1T}^{\perp,q} \otimes f_1^{\bar{q}}]}{[f_1^q \otimes f_1^{\bar{q}}]}$$

Physics of the Wilson line

Initial State Interactions: Drell-Yan



Final State Interactions: SIDIS



$\mathcal{PT}$ - Transformation on the quark correlator → ISI ⇔ FSI

→ sign switch of Sivers and Boer-Mulder function "T-odd"

$$f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY} \qquad h_1^{\perp}\Big|_{DIS} = -h_1^{\perp}\Big|_{DY}$$

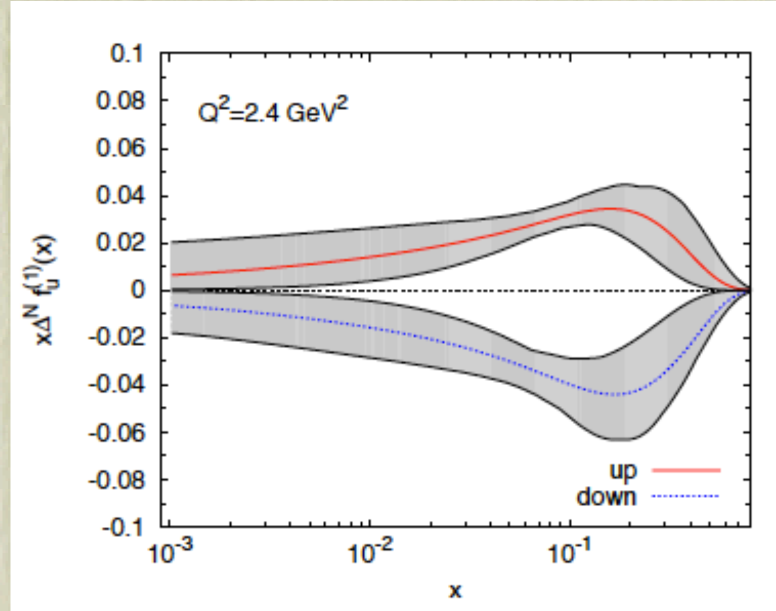
"T-odd" TMDs generate / appear in observables

→ e.g. transverse SSA in SIDIS (measured by HERMES, COMPASS etc.) or DY

$$A_{UT}^{\text{SIDIS}} \propto \frac{[f_{1T}^{\perp,q} \otimes D_1^q]}{[f_1^q \otimes D_1^q]}$$

−

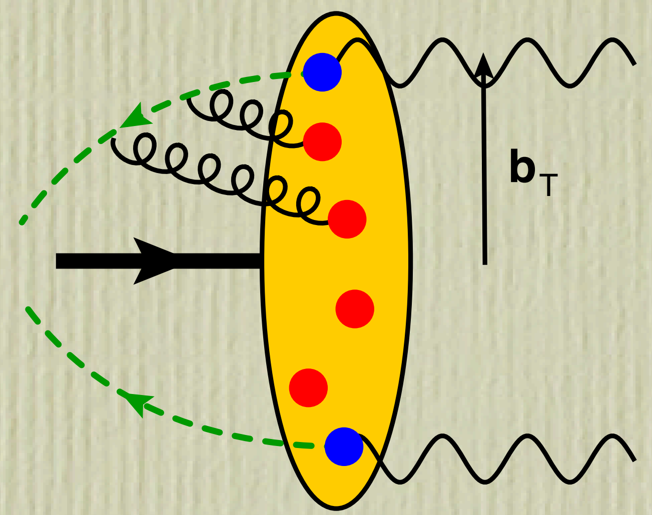
$$A_{UT}^{\text{DY}} \propto \frac{[f_{1T}^{\perp,q} \otimes f_1^{\bar{q}}]}{[f_1^q \otimes f_1^{\bar{q}}]}$$



most recent param. from [Anselmino et al., 1107.4446]

Intuitive picture of Sivers effect (M. Burkardt)

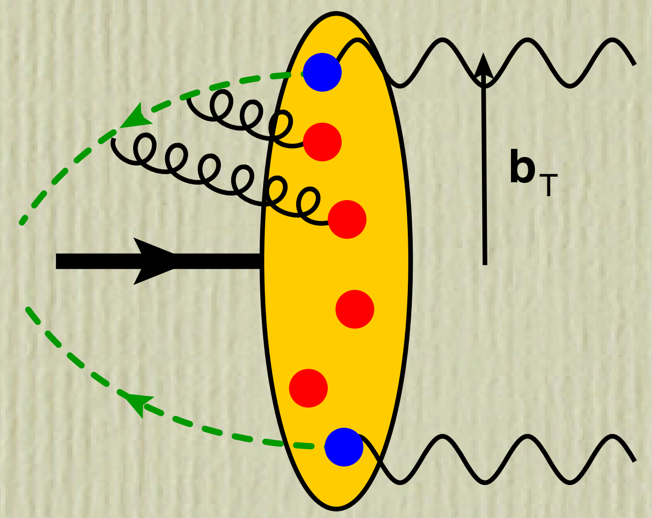
unpolarized



attr. FSI + eq. distributed quarks
= no net effect

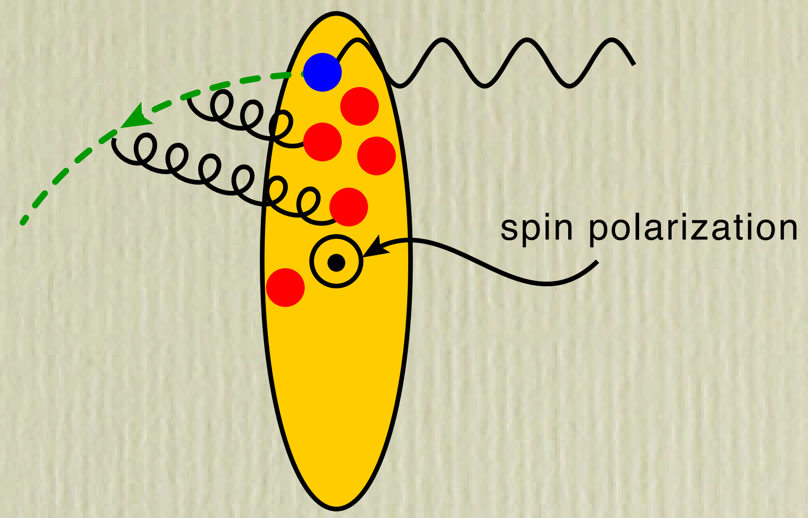
Intuitive picture of Sivers effect (M. Burkardt)

unpolarized



attr. FSI + eq. distributed quarks
= no net effect

transversely polarized

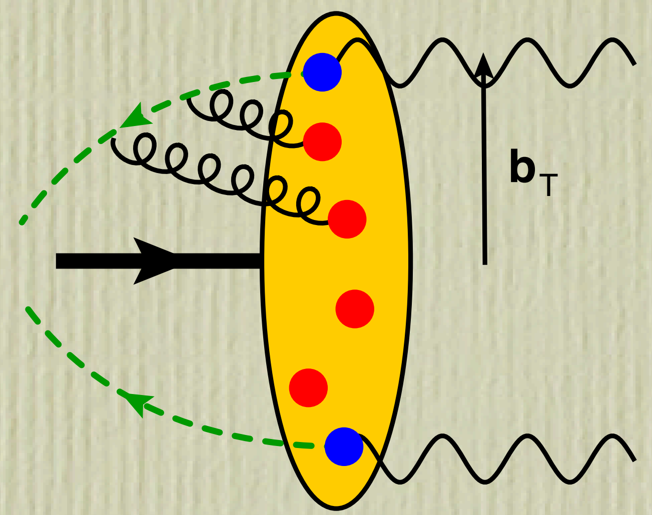


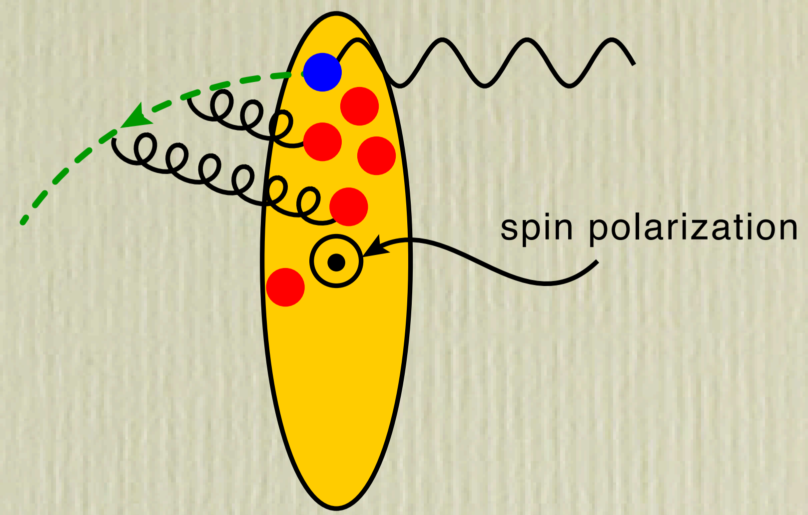
attr. FSI + distortion of distrib. (OAM)
= Sivers effect

Intuitive picture of Sivers effect (M. Burkardt)

unpolarized

transversely polarized





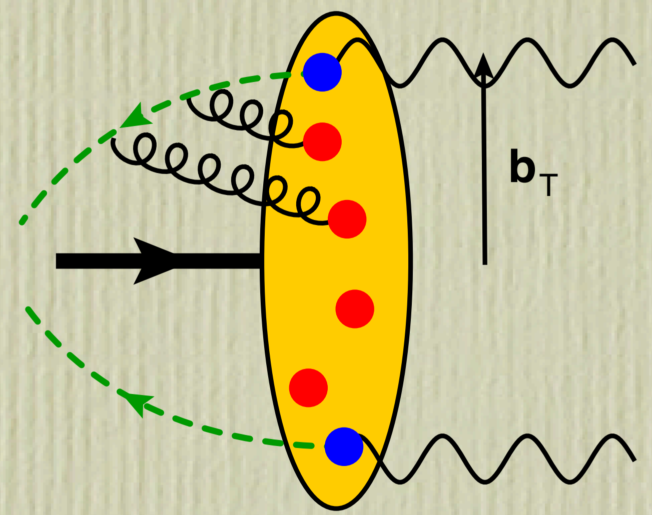
attr. FSI + eq. distributed quarks
= no net effect

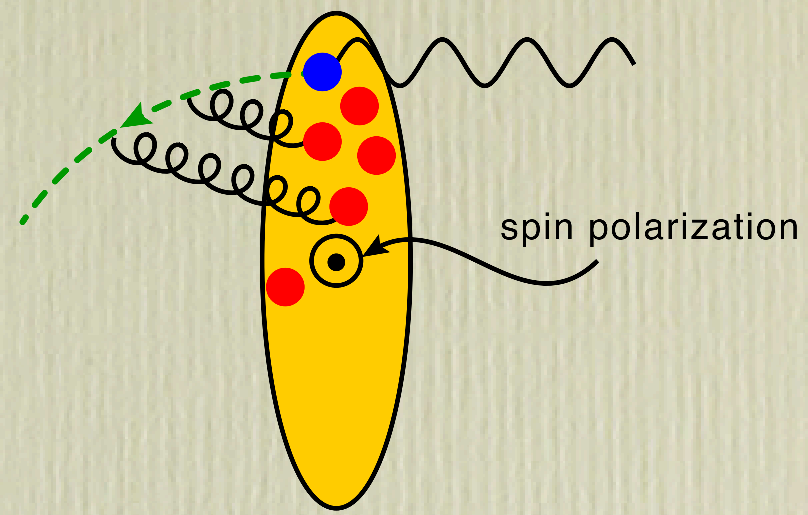
attr. FSI + distortion of distrib. (OAM)
= Sivers effect

$$\langle k_T^i \rangle = -M \epsilon_T^{ij} S_T^j \, f_{1T}^{\perp,(1)}(x) \simeq \int d^2 b_T \, \mathcal{I}^i(x, \vec{b}_T) \, \frac{\vec{b}_T \times \vec{S}_T}{M} \, \frac{\partial}{\partial b_T^2} \mathcal{E}(x, \vec{b}_T^2)$$

Not a model-independent relation (but valid in certain models...)

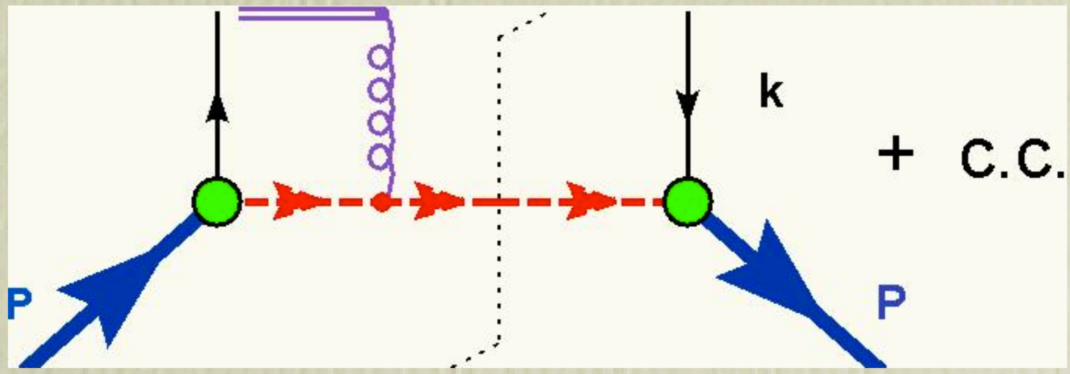
Intuitive picture of Sivers effect (M. Burkardt)





$$\langle k_T^i \rangle = -M \epsilon_T^{ij} S_T^j \, f_{1T}^{\perp,(1)}(x) \simeq \int d^2 b_T \, \mathcal{I}^i(x, \vec{b}_T) \, \frac{\vec{b}_T \times \vec{S}_T}{M} \, \frac{\partial}{\partial b_T^2} \mathcal{E}(x, \vec{b}_T^2)$$

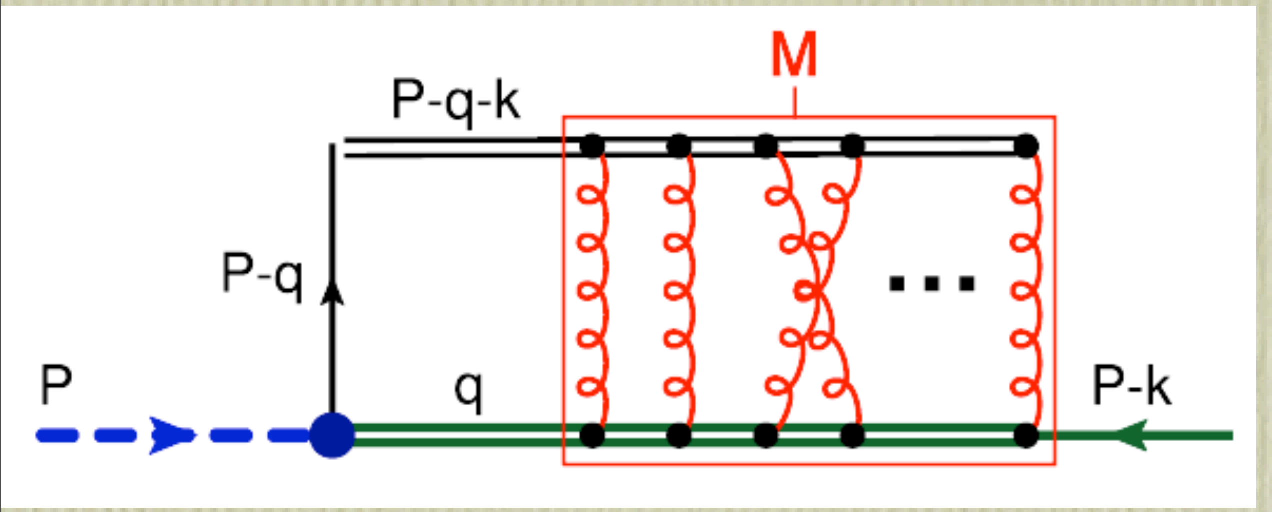
Not a model-independent relation (but valid in certain models...)



→ Lensing function calculable

Beyond the one gluon exchange...

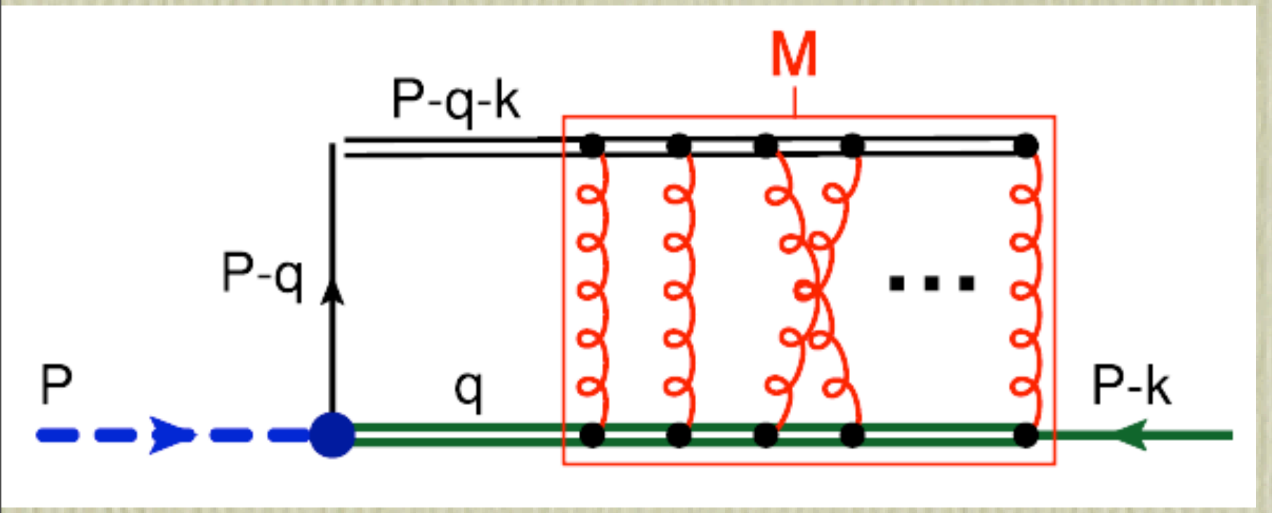
[Gamberg, M.S., PLB 685,95; 1012.3395; see also Courtoy, Scopetta, Vento, EPJA 47,49]



- Use spectator model to identify Lensing function
- Sum up soft gluons using non-perturbative eikonal methods
- Use input from Dyson-Schwinger eqs. for SU(3) running coupling and non-pert. gluon propagator
  ➙ Lensing Function without free parameters!
- Impact parameter GPD from models, parameterization

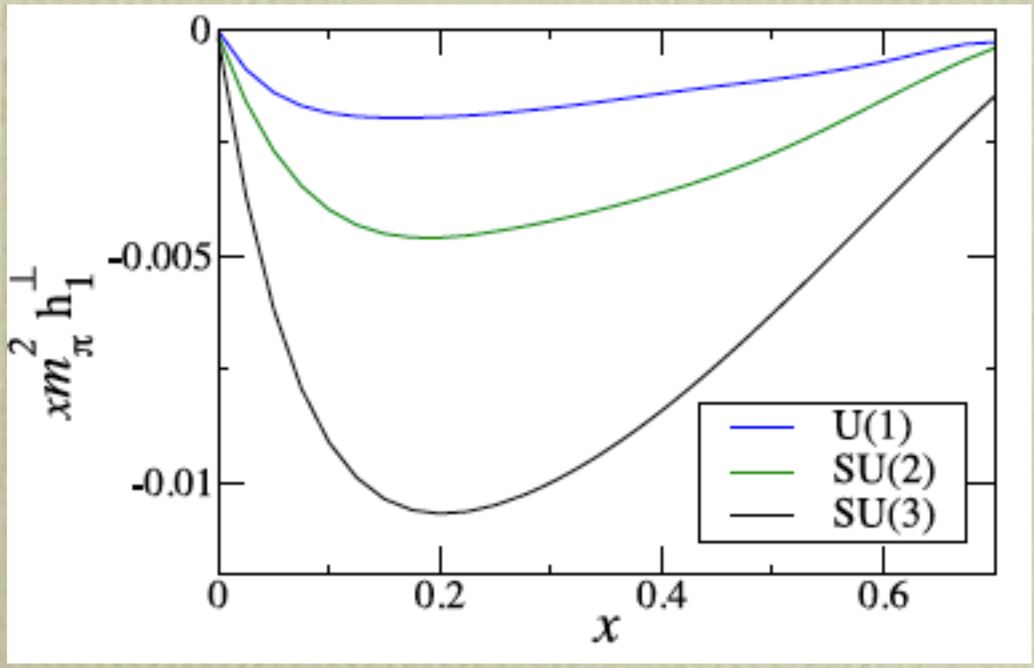
Beyond the one gluon exchange...

[Gamberg, M.S., PLB 685,95; 1012.3395; see also Courtoy, Scopetta, Vento, EPJA 47,49]



- Use spectator model to identify Lensing function
- Sum up soft gluons using non-perturbative eikonal methods
- Use input from Dyson-Schwinger eqs. for SU(3) running coupling and non-pert. gluon propagator
  ➞ Lensing Function without free parameters!
- Impact parameter GPD from models, parameterization

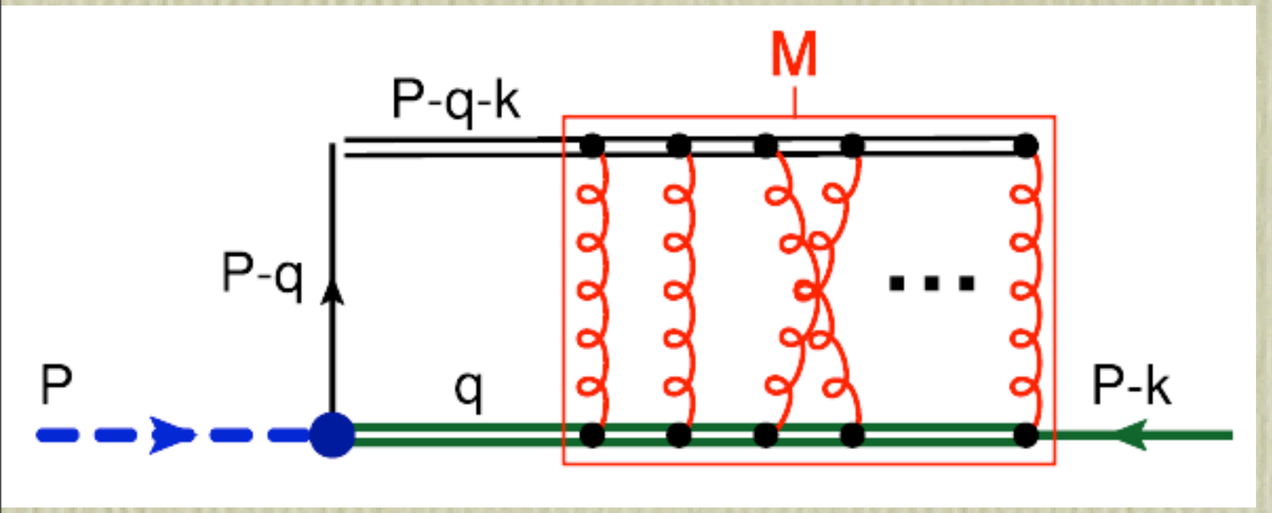
Pion Boer - Mulders



relevant for COMPASS DY

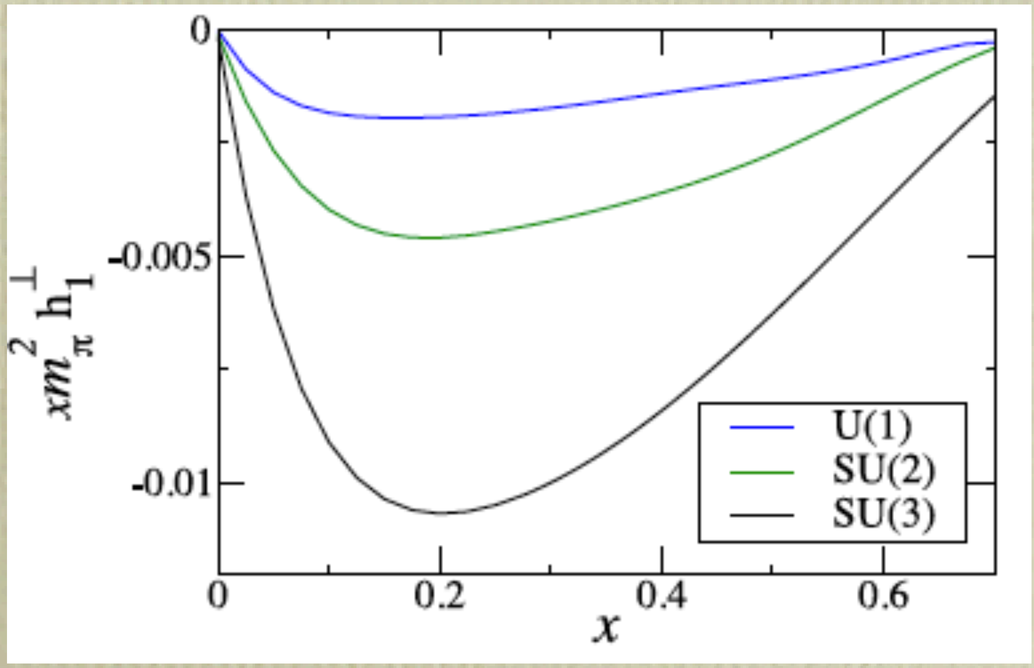
Beyond the one gluon exchange...

[Gamberg, M.S., PLB 685,95; 1012.3395; see also Courtoy, Scopetta, Vento, EPJA 47,49]

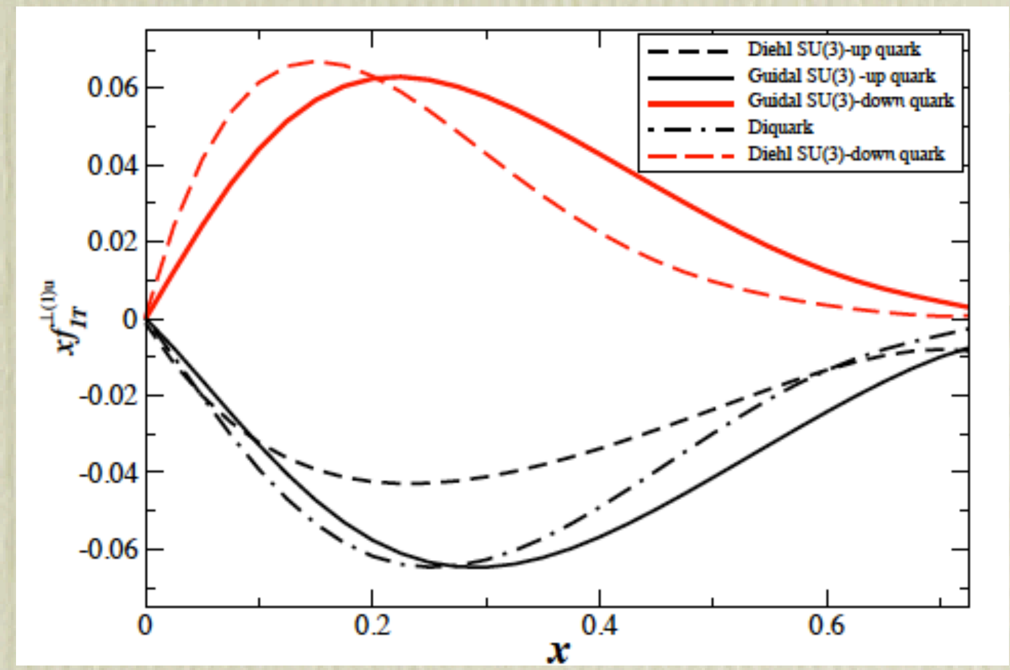


- Use spectator model to identify Lensing function
- Sum up soft gluons using non-perturbative eikonal methods
- Use input from Dyson-Schwinger eqs. for SU(3) running coupling and non-pert. gluon propagator ➞ Lensing Function without free parameters!
- Impact parameter GPD from models, parameterization

Pion Boer - Mulders



Proton Sivers



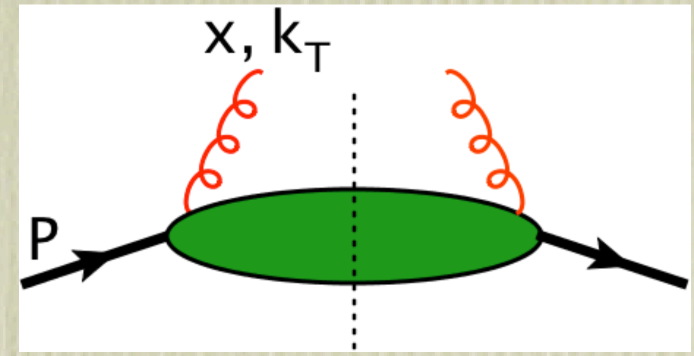
relevant for COMPASS DY

Eight Gluon TMDs

$$\Gamma^{ij}(x,\vec{k}_T) = \frac{1}{xP^+}\int \frac{dz^-\, d^2z_T}{(2\pi)^3}\, \mathrm{e}^{ik\cdot z}\langle P,S|\,F^{+i}(0)\,\mathcal{W}[0\,;\,z]\,F^{+j}(z)\,|P,S\rangle\Big|_{z^+=0}$$

$\Gamma^{[T-even]}(x,\vec{k}_T)$			$\Gamma^{[T-odd]}(x,\vec{k}_T)$	
		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, Rodriues, PRD 63,094021]



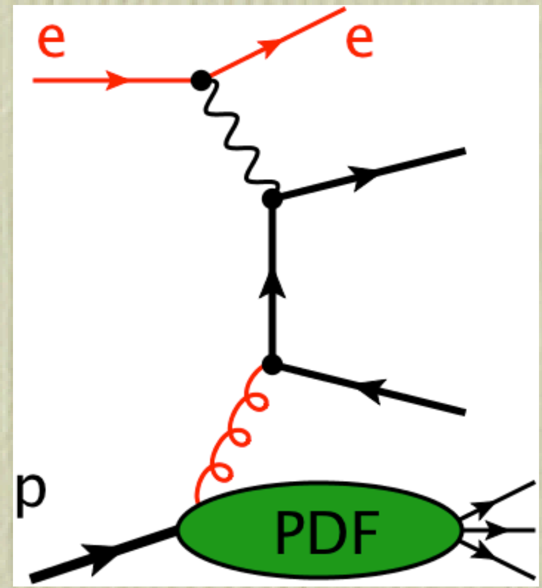
- ✳ linearly polarized gluons: T-even
- ✳ unpolarized gluons in transversely pol. proton: gluon Sivers function
- ✳ gluonic transversity / pretzelosity / wormgears: T-odd
- ✳ no chirality
- ✳ two collinear PDFs

Processes sensitive to gluon TMDs

Gluon TMDs do not appear in Drell-Yan or SIDIS

Processes sensitive to gluon TMDs

Gluon TMDs do not appear in Drell-Yan or SIDIS



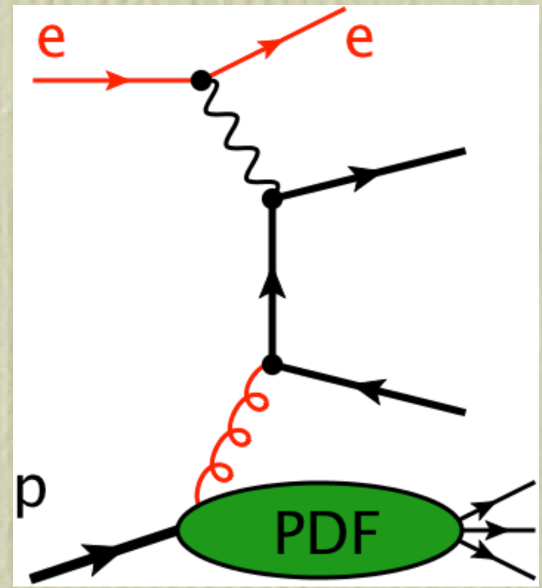
Heavy Quark production in ep - collisions

[Boer, Brodsky, Mulders, Pisano, PRL 106, 132001]

TMD factorization ok!
Spin dependent gluon TMDs: EIC
(Nucleon) spin independent gluon TMDs: EIC / HERA(?)

Processes sensitive to gluon TMDs

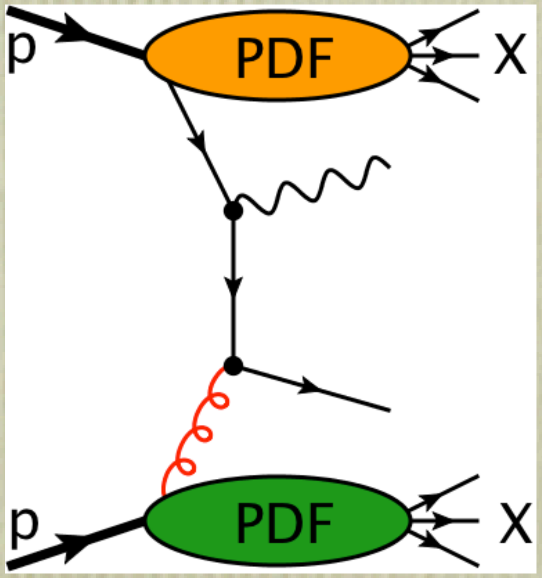
Gluon TMDs do not appear in Drell-Yan or SIDIS



Heavy Quark production in ep - collisions

[Boer, Brodsky, Mulders, Pisano, PRL 106, 132001]

TMD factorization ok!
Spin dependent gluon TMDs: EIC
(Nucleon) spin independent gluon TMDs: EIC / HERA(?)



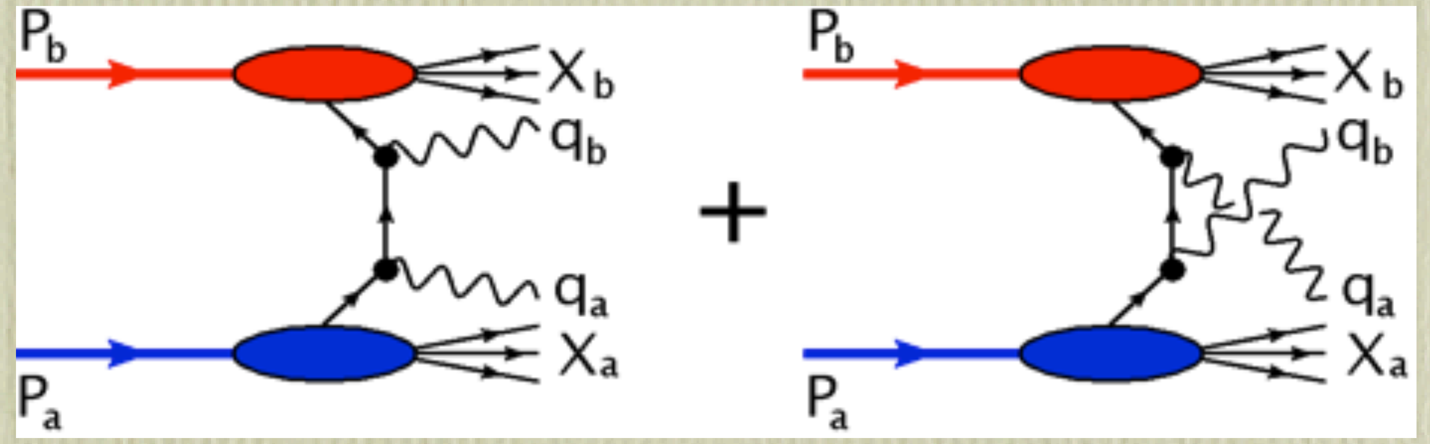
Jet / Hadron production in pp - collisions

Spin dependent processes feasible at RHIC
colored final states: problems with TMD factorization

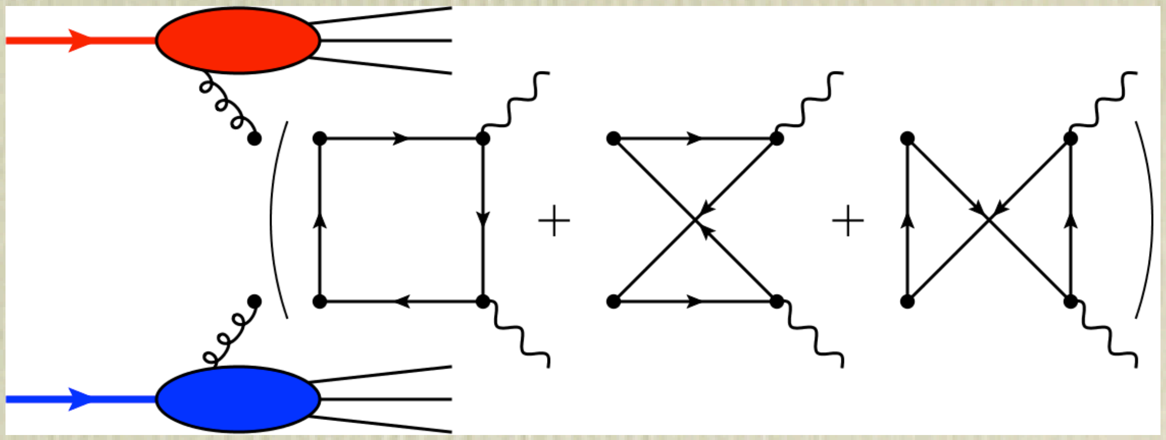
Photon pair production

[Qiu, M.S., Vogelsang, PRL 107, 062001]

quark TMDs



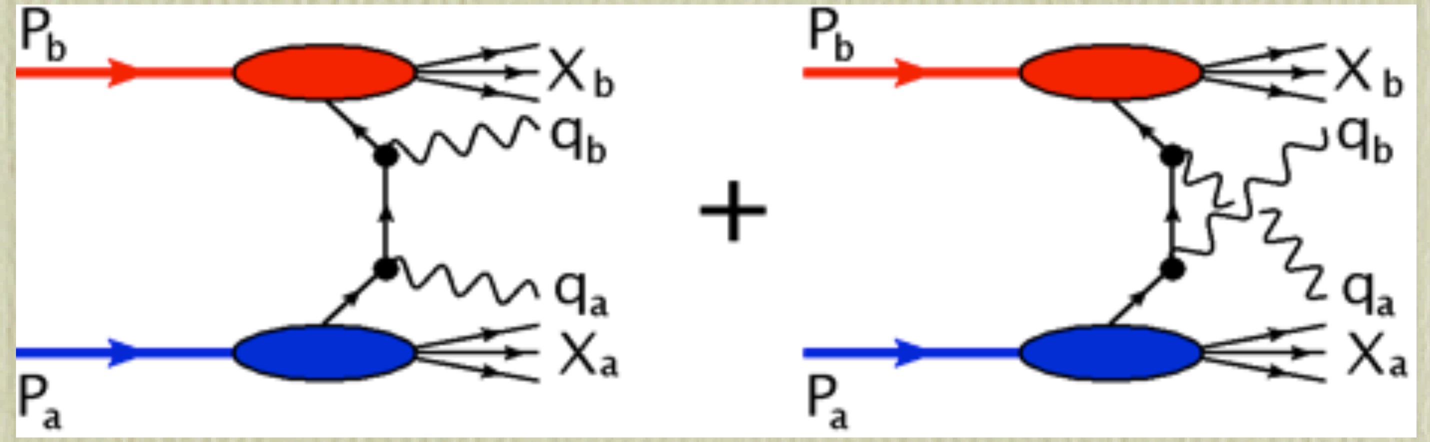
gluon TMDs at $O(\alpha_s^2)$



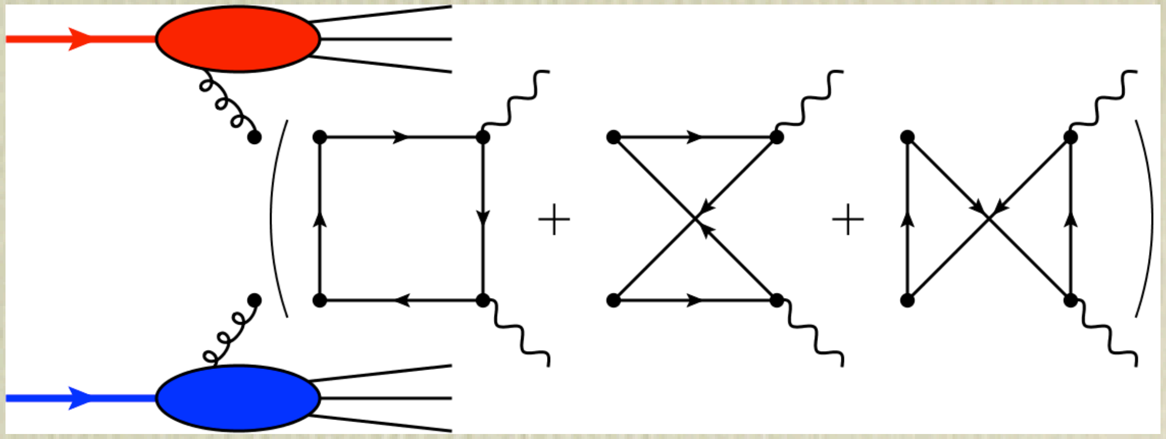
Photon pair production

[Qiu, M.S., Vogelsang, PRL 107, 062001]

quark TMDs



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



- no colored final state ⇒ TMD factorization ok
- gauge invariance ⇒ box finite ⇒ effectively tree-level
- potentially large gluon distributions
- new azimuthal observables

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

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

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

$\mathcal{F}_i$ → non-trivial functions of cos(θ) and sin(θ)

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

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

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

$\mathcal{F}_i$ → non-trivial functions of cos(θ) and sin(θ)

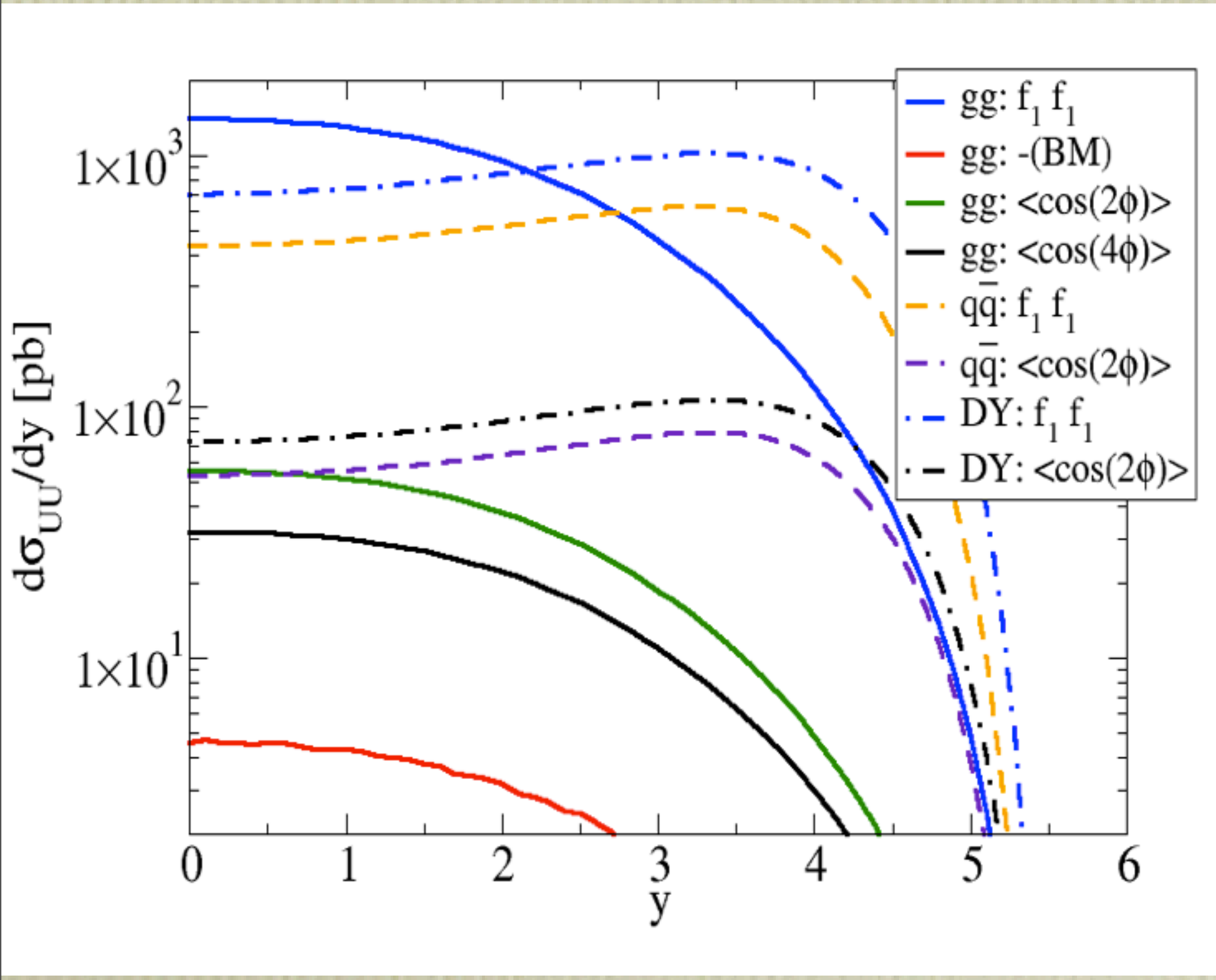
- Quark contribution similar to DY
  → only ISI / past-pointing Wilson line
- requires p_T / isolation cuts for the photons
- powerful in combination with DY
  map out quark TMDs in DY → gluon TMDs in γγ

Unpolarized pp→γγX Cross-Section at $q_T \ll Q$

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

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

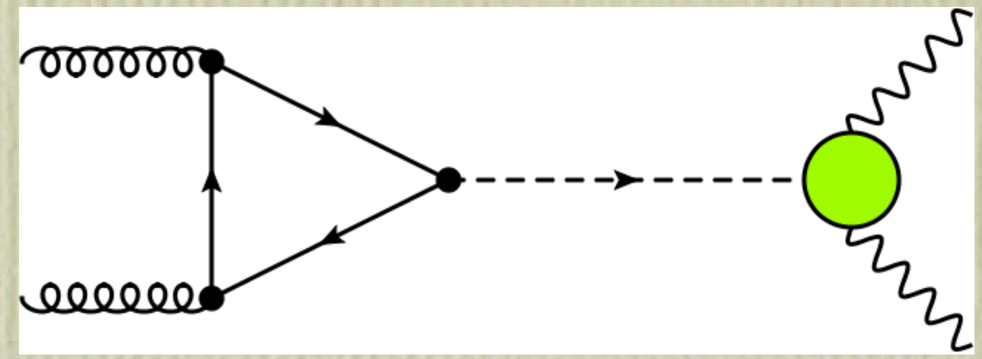
$\mathcal{F}_i$ → non-trivial functions of cos(θ) and sin(θ)



- Quark contribution similar to DY → only ISI / past-pointing Wilson line
- requires p_T / isolation cuts for the photons
- powerful in combination with DY map out quark TMDs in DY → gluon TMDs in γγ
- numerical estimates → Gaussian Ansatz + saturation of positivity bound
- cos(4ϕ) → only due to lin. pol. gluons → clean, ~1%
- cos(2ϕ) → determination of sign of $h_1^{\perp g}$

Linearly polarized gluons and Higgs production

[Boer, den Dunnen, Pisano, M.S., Vogelsang, in prep.]



ϕ - integrated cross section of Higgs + box:

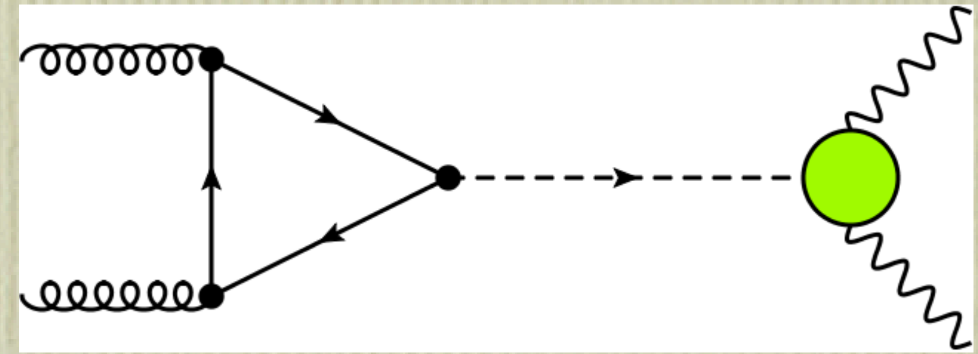
$$\int d\phi \frac{d\sigma^{gg}}{d^4q\, d\Omega} \propto \bar{\mathcal{F}}_1 \left[f_1^g \otimes f_1^g\right] + \bar{\mathcal{F}}_2 \left[h_1^{\perp g} \otimes h_1^{\perp g}\right]$$

Q ≠ m_H: $\bar{\mathcal{F}}_1 \gg \bar{\mathcal{F}}_2$ box dominant

Q ~ m_H : $\bar{\mathcal{F}}_1 \simeq \bar{\mathcal{F}}_2$ Higgs dominant (pole of the propagator)

Linearly polarized gluons and Higgs production

[Boer, den Dunnen, Pisano, M.S., Vogelsang, in prep.]



ϕ - integrated cross section of Higgs + box:

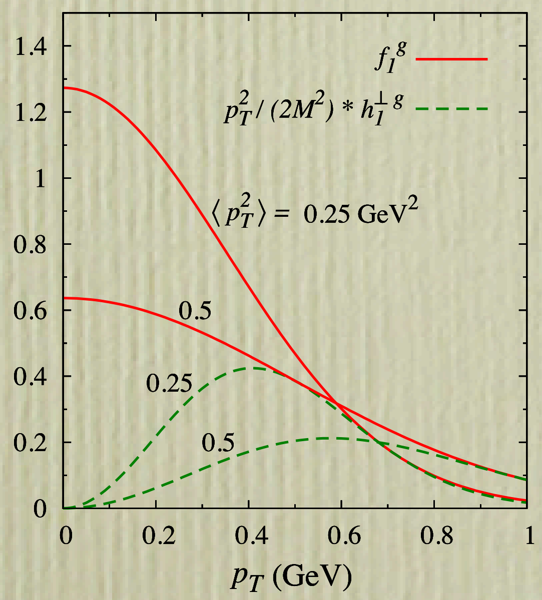
$$\int d\phi \frac{d\sigma^{gg}}{d^4q\, d\Omega} \propto \bar{\mathcal{F}}_1 \left[f_1^g \otimes f_1^g\right] + \bar{\mathcal{F}}_2 \left[h_1^{\perp g} \otimes h_1^{\perp g}\right]$$

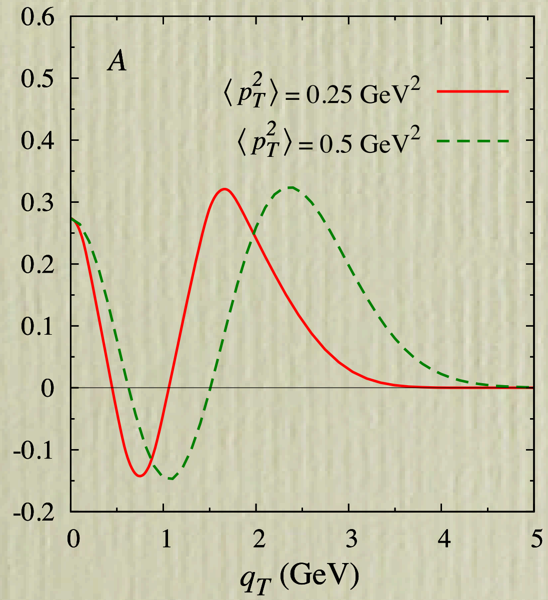
Q ≠ m_H: $\bar{\mathcal{F}}_1 \gg \bar{\mathcal{F}}_2$ box dominant

Q ~ m_H : $\bar{\mathcal{F}}_1 \simeq \bar{\mathcal{F}}_2$ Higgs dominant (pole of the propagator)

q_T-behaviour:

$$A = \frac{[h_1^{\perp g} \otimes h_1^{\perp g}]}{[f_1^g \otimes f_1^g]}$$

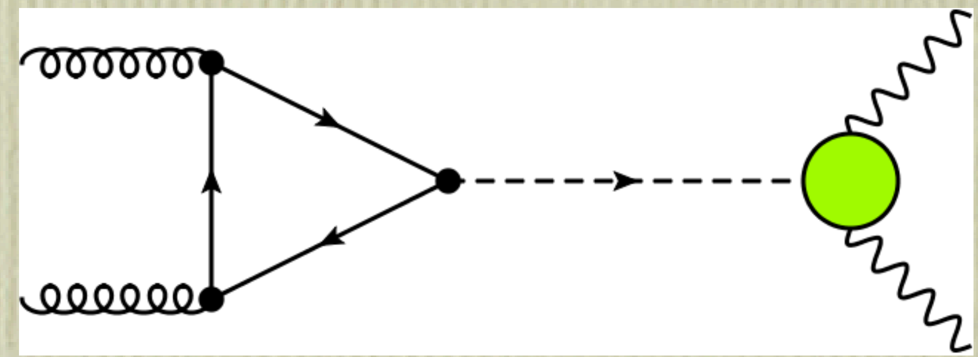




- sizeable contribution of lin. pol. gluons
- characteristic double node in q_T

Linearly polarized gluons and Higgs production

[Boer, den Dunnen, Pisano, M.S., Vogelsang, in prep.]



ϕ - integrated cross section of Higgs + box:

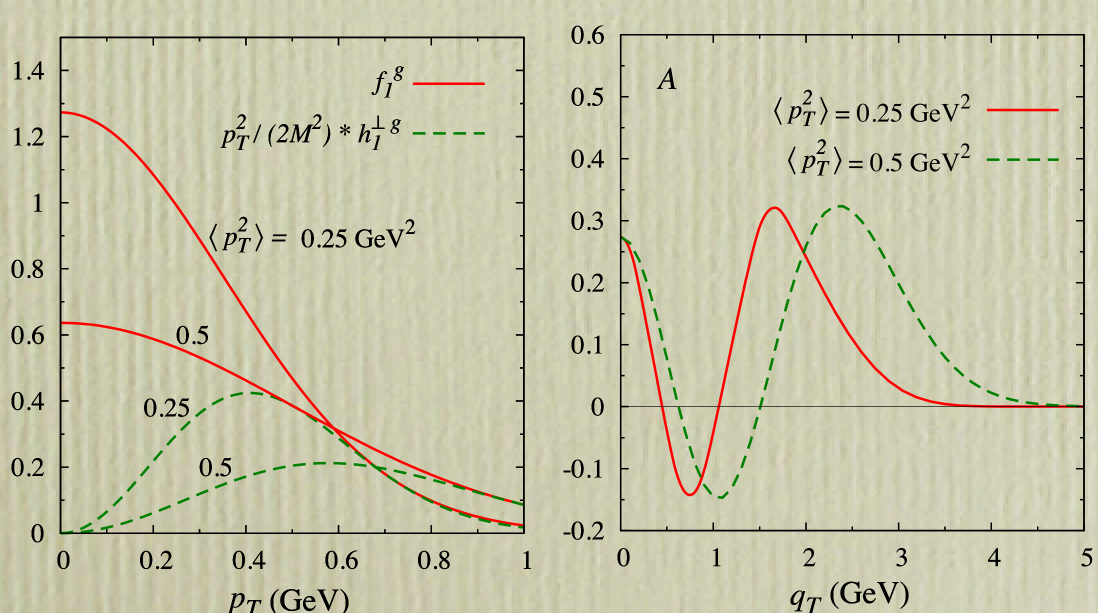
$$\int d\phi \frac{d\sigma^{gg}}{d^4q\, d\Omega} \propto \bar{\mathcal{F}}_1 \left[f_1^g \otimes f_1^g\right] + \bar{\mathcal{F}}_2 \left[h_1^{\perp g} \otimes h_1^{\perp g}\right]$$

Q ≠ m_H: $\bar{\mathcal{F}}_1 \gg \bar{\mathcal{F}}_2$ box dominant

Q ~ m_H : $\bar{\mathcal{F}}_1 \simeq \bar{\mathcal{F}}_2$ Higgs dominant (pole of the propagator)

q_T-behaviour:

$$A = \frac{[h_1^{\perp g} \otimes h_1^{\perp g}]}{[f_1^g \otimes f_1^g]}$$



- sizeable contribution of lin. pol. gluons
- characteristic double node in q_T

linearly polarized gluons sensitive to Higgs parity

$$[f_1^g \otimes f_1^g] \pm [h_1^{\perp g} \otimes h_1^{\perp g}]$$

+: scalar Higgs −: pseudoscalar Higgs

↓

precise q_T measurement may offer a way to determine Higgs parity

Gluon Sivers Effect

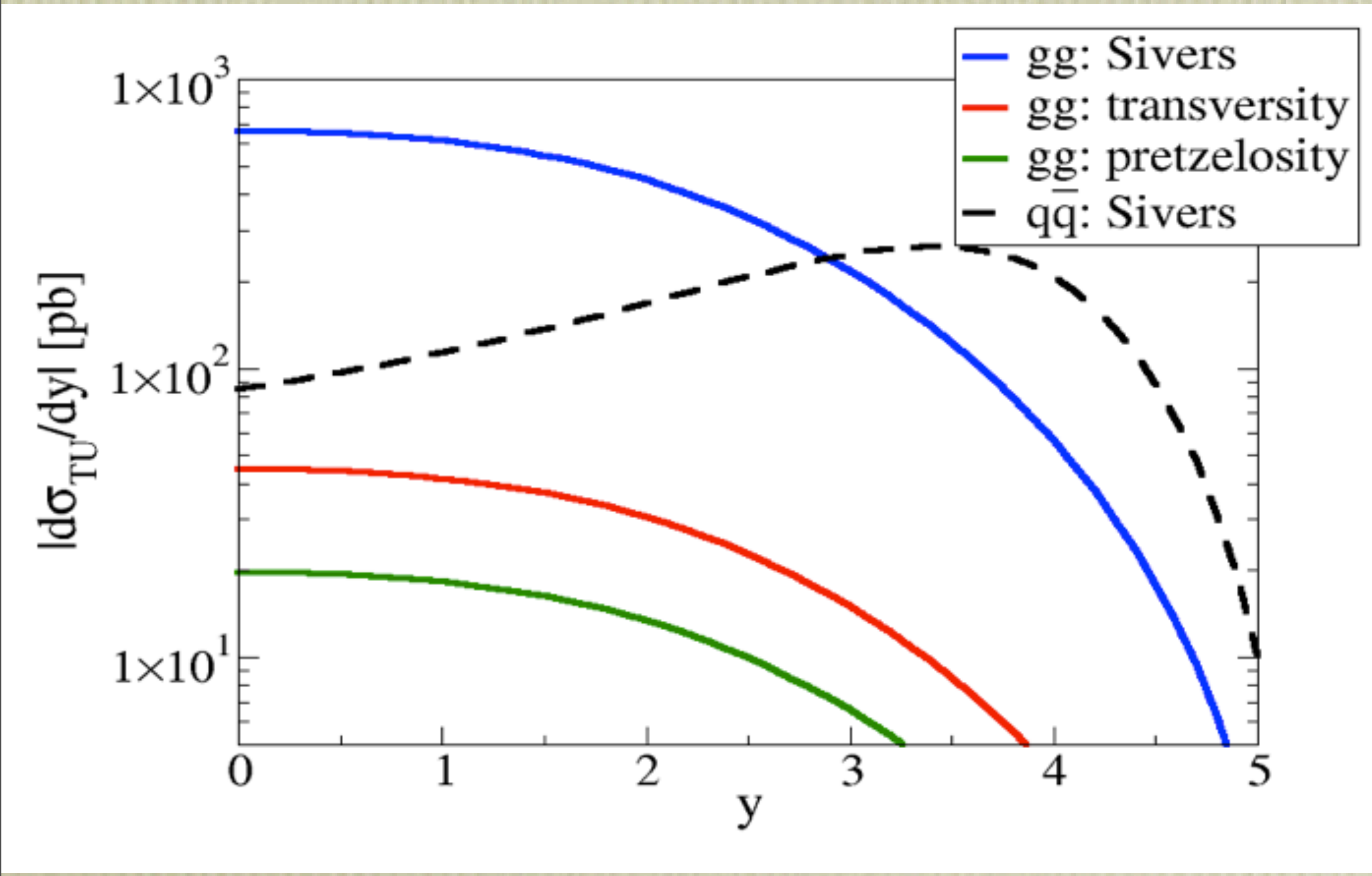
(Transverse) Spin dependent photon pair cross section:

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

Gluon Sivers Effect

(Transverse) Spin dependent photon pair cross section:

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



Estimates for RHIC 500 GeV

- Gaussian Ansatz + positivity bound for gluon and quark TMDs
- Flavor cancellation for quark Sivers func.: $f_{1T}^{\perp,u} \simeq -f_{1T}^{\perp,d}$ → 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
- Effects by gluon "transv. / pretzel." small

Summary

- T-odd TMDs generated by ISI/FSI → sign switch
- Relation of T-odd TMDs with IP GPDs studied in an eikonal model → reproduces Sivers function
- Gluon TMDs from Photon Pair Production at RHIC
- Lin. polarized Gluons may offer a way to determine parity of the Higgs boson
- Gluon Sivers function may be feasible at RHIC (if $\neq 0$)