Prospects for measurements of gluon TDMs

Daniël Boer

Transversity 2017

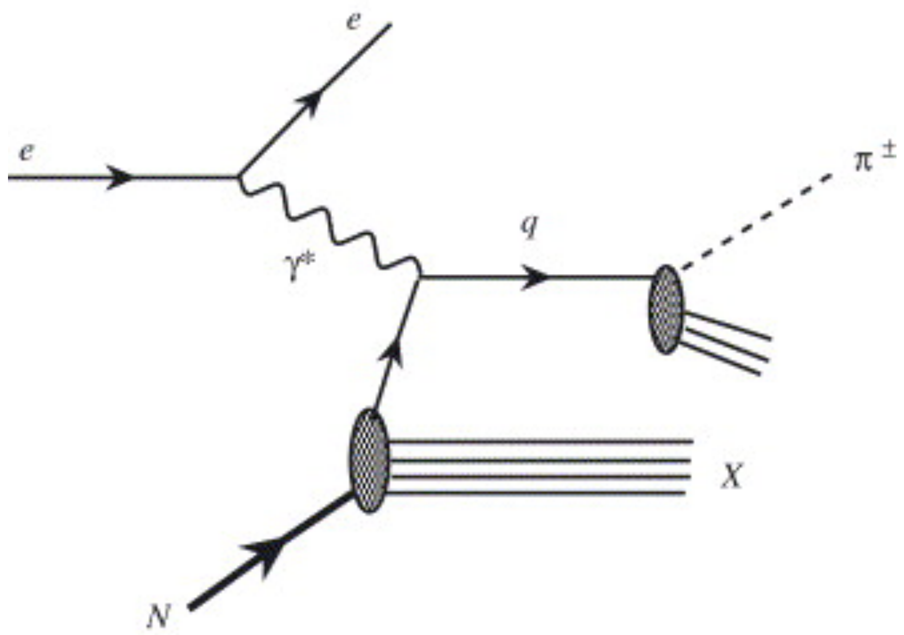
Frascati, December 14, 2017

university of groningen

Typical TMD processes

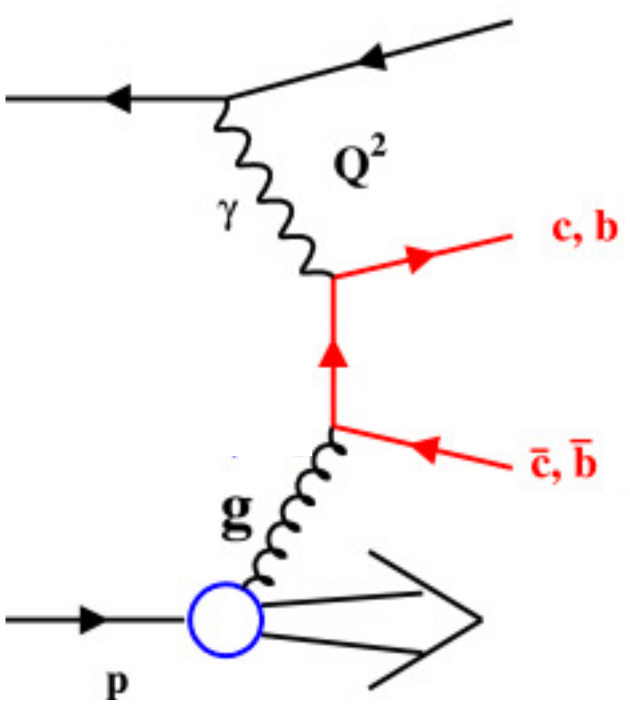
Semi-inclusive DIS is a process sensitive to the transverse momentum of quarks

$$e\, p \to e'\, h\, X$$



D-meson pair production is sensitive to transverse momentum of gluons

$$e\, p \to e'\, D\, \bar{D}\, X$$



Gluons TMDs

The gluon correlator:

$$\Gamma_g^{\mu\nu[\mathcal{U},\mathcal{U}']}(x,k_T) \equiv \mathrm{F.T.}\langle P|\mathrm{Tr}_c\left[F^{+\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$

For unpolarized protons:

$$\Gamma_U^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{x}{2}\left\{-g_T^{\mu\nu} f_1^g(x,\boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{p}_T^2}{2M_p^2}\right) h_1^{\perp\,g}(x,\boldsymbol{p}_T^2)\right\}$$

unpolarized gluon TMD

linearly polarized gluon TMD

Gluons inside *unpolarized* protons can be polarized!

For transversely polarized protons:

gluon Sivers TMD

$$\Gamma_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{x}{2}\left\{g_T^{\mu\nu}\frac{\epsilon_T^{\rho\sigma}\,p_{T\rho}\,S_{T\sigma}}{M_p} f_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2) + \ldots\right\}$$

[Mulders, Rodrigues '01]

Process dependence of gluon TMDs

The color flow in a process may lead to different correlators in different processes

$$\Gamma_g^{\mu\nu[\mathcal{U},\mathcal{U}']}(x,k_T) \equiv \text{F.T.}\langle P|\text{Tr}_c\left[F^{+\nu}(0)\,\mathcal{U}_{[0,\xi]}\,F^{+\mu}(\xi)\,\mathcal{U}'_{[\xi,0]}\right]|P\rangle$$

$$\mathcal{U}_{\mathcal{C}}[0,\xi] = \mathcal{P}\exp\left(-ig\int_{\mathcal{C}[0,\xi]} ds_\mu\, A^\mu(s)\right) \qquad\qquad \xi = [0^+,\xi^-,\boldsymbol{\xi}_T]$$

Gauge links arise from the initial and/or final state interactions (ISI/FSI) in a process

[Collins & Soper, 1983; D.B. & Mulders, 2000; Brodsky, Hwang & Schmidt, 2002; Collins, 2002; Belitsky, X. Ji & F. Yuan, 2003; D.B., Mulders & Pijlman, 2003]

This has observable effects, as was first shown for Sivers effect asymmetries

[Brodsky, Hwang & Schmidt, 2002; Collins, 2002; Belitsky, Ji & Yuan, 2003]

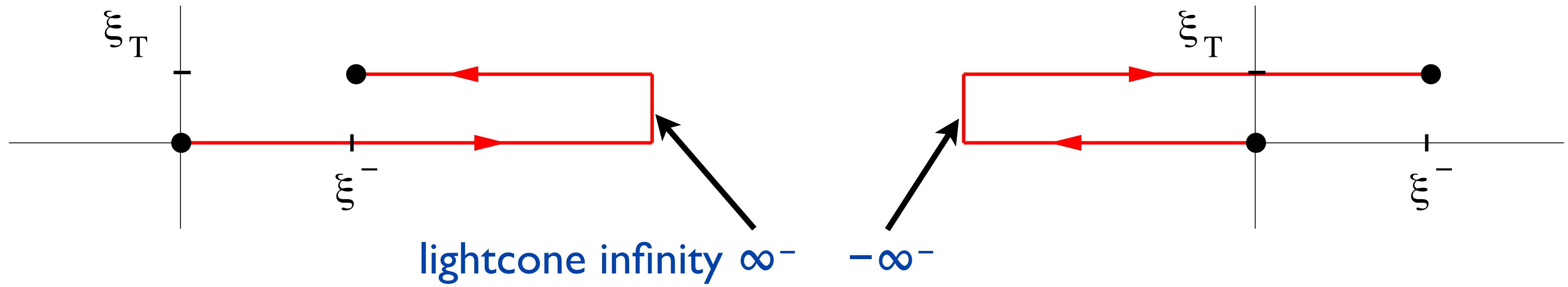
This even affects unpolarized gluon TMDs, as was first realized in a small-x context

[Dominguez, Marquet, Xiao, Yuan, 2011]

Process dependence of Sivers TMDs

SIDIS | DY

FSI lead to a future pointing Wilson line (+ link), whereas ISI to past pointing (− link)



One can use parity and time reversal invariance to relate these

$$f_{1T}^{\perp q[\mathrm{SIDIS}]}(x, k_T^2) = -f_{1T}^{\perp q[\mathrm{DY}]}(x, k_T^2)$$

[Collins '02]

A similar sign change relation for gluon Sivers functions holds, but due to the appearance of two gauge links, there are more possibilities

For most processes of interest there are 2 link combinations to consider: [+,+] and [+,−], because [−,−] and [−,+] are related

More complicated structures often only enter in processes where TMD factorization is questionable anyway

Sign change relation for gluon Sivers TMD

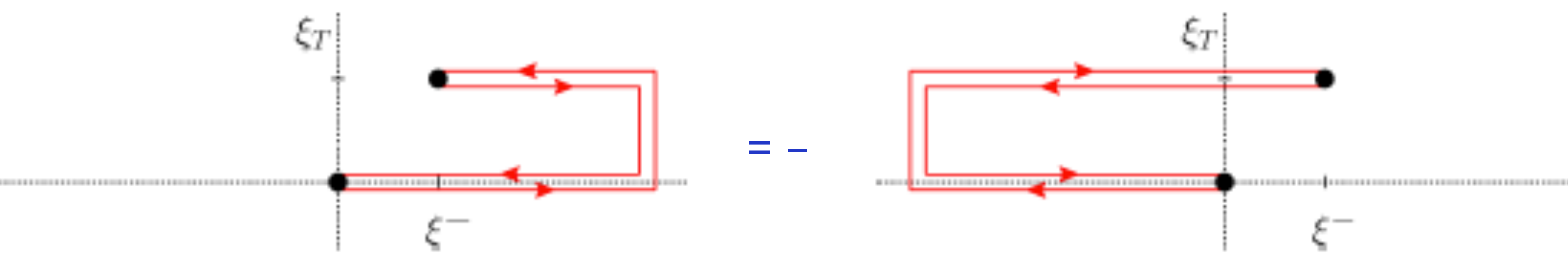
$e\,p^{\uparrow} \to e'\,Q\bar{Q}\,X$ $\quad\quad$ $\gamma^*\,g \to Q\bar{Q}$ probes [+,+]

$p^{\uparrow}\,p \to \gamma\,\gamma\,X$

Qiu, Schlegel, Vogelsang, 2011

In the kinematic regime where pair rapidity is central, one effectively selects the subprocess:

$g\,g \to \gamma\,\gamma$ probes [−,−]



$$f_{1T}^{\perp\, g\,[e\,p^{\uparrow}\to e'\,Q\,\overline{Q}\,X]}(x, p_T^2) = -f_{1T}^{\perp\, g\,[p^{\uparrow}\,p\to\gamma\,\gamma\,X]}(x, p_T^2)$$

EIC $\quad\quad$ RHIC

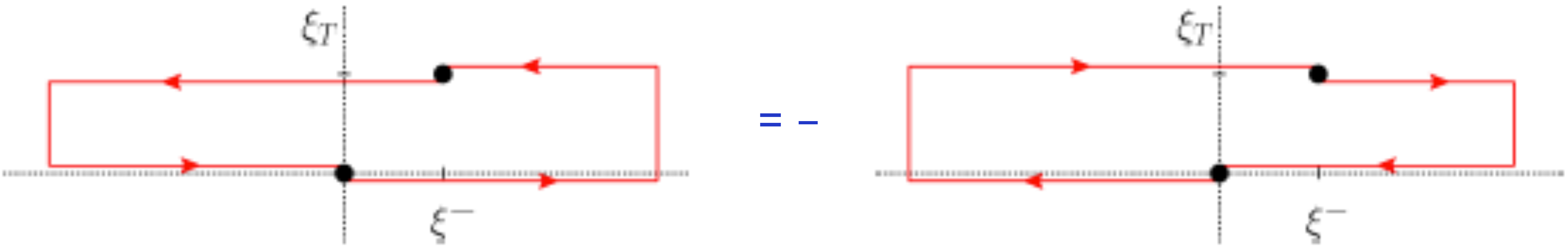
D.B., Mulders, Pisano, J. Zhou, 2016

f and d type gluon Sivers TMD

$e\,p^{\uparrow} \to e'\,Q\bar{Q}\,X$ $\gamma^*\,g \to Q\bar{Q}$ probes [+,+]

$p^{\uparrow}\,p \to \gamma\,\mathrm{jet}\,X$

In the kinematic regime where gluons in the polarized proton dominate, one effectively selects the subprocess: $g\,q \to \gamma\,q$ probes [+,−]



These processes probe 2 distinct, *independent* gluon Sivers functions

Related to the antisymmetric (f^{abc}) and symmetric (d^{abc}) color structures

Bomhof, Mulders, 2007; Buffing, Mukherjee, Mulders, 2013

Conclusion: gluon Sivers TMD studies at EIC and at RHIC or AFTER@LHC can be related or complementary, depending on the processes considered

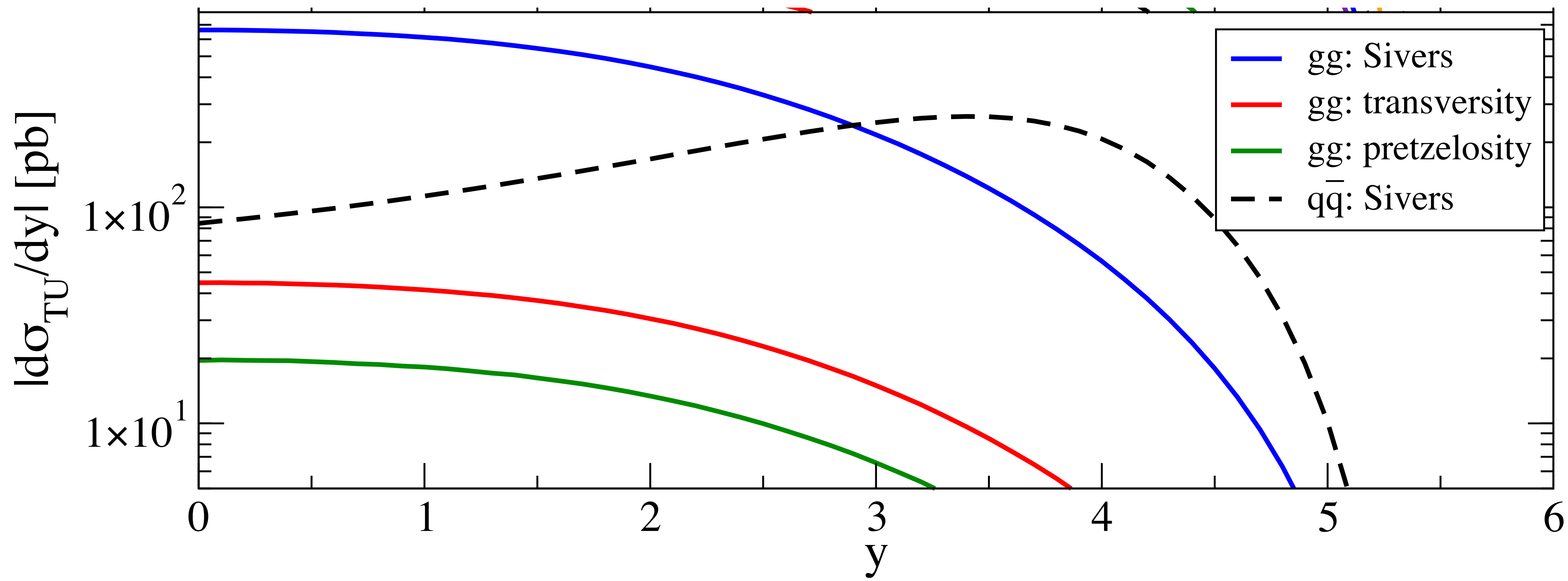
D.B., Lorcé, Pisano & J. Zhou, 2015

Gluon Sivers effect in double γ production

$f_{1T}^{\perp\, g\, [-,-]}$

[Qiu, Schlegel, Vogelsang, 2011]

$p^{\uparrow} p \rightarrow \gamma\gamma X$



$\sqrt{s}$=500 GeV, $p_T^{\gamma} \geq 1$ GeV, integrated over $4 < Q^2 < 30$ GeV^2, $0 \leq q_T \leq 1$ GeV

At photon pair rapidity y < 3 gluon Sivers dominates and max($d\sigma_{TU}/d\sigma_{UU}$) ~ 30-50%

The more direct probe at EIC through open heavy quark production is bounded by 1

$$e\, p^{\uparrow} \rightarrow e'\, Q\bar{Q}\, X \qquad A_N^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p} \frac{f_{1T}^{\perp\, g}(x, \boldsymbol{q}_T^2)}{f_1^g(x, \boldsymbol{q}_T^2)}$$

$f_{1T}^{\perp\, g\, [+,+]}$

D.B., Pisano, Mulders, J. Zhou, 2016

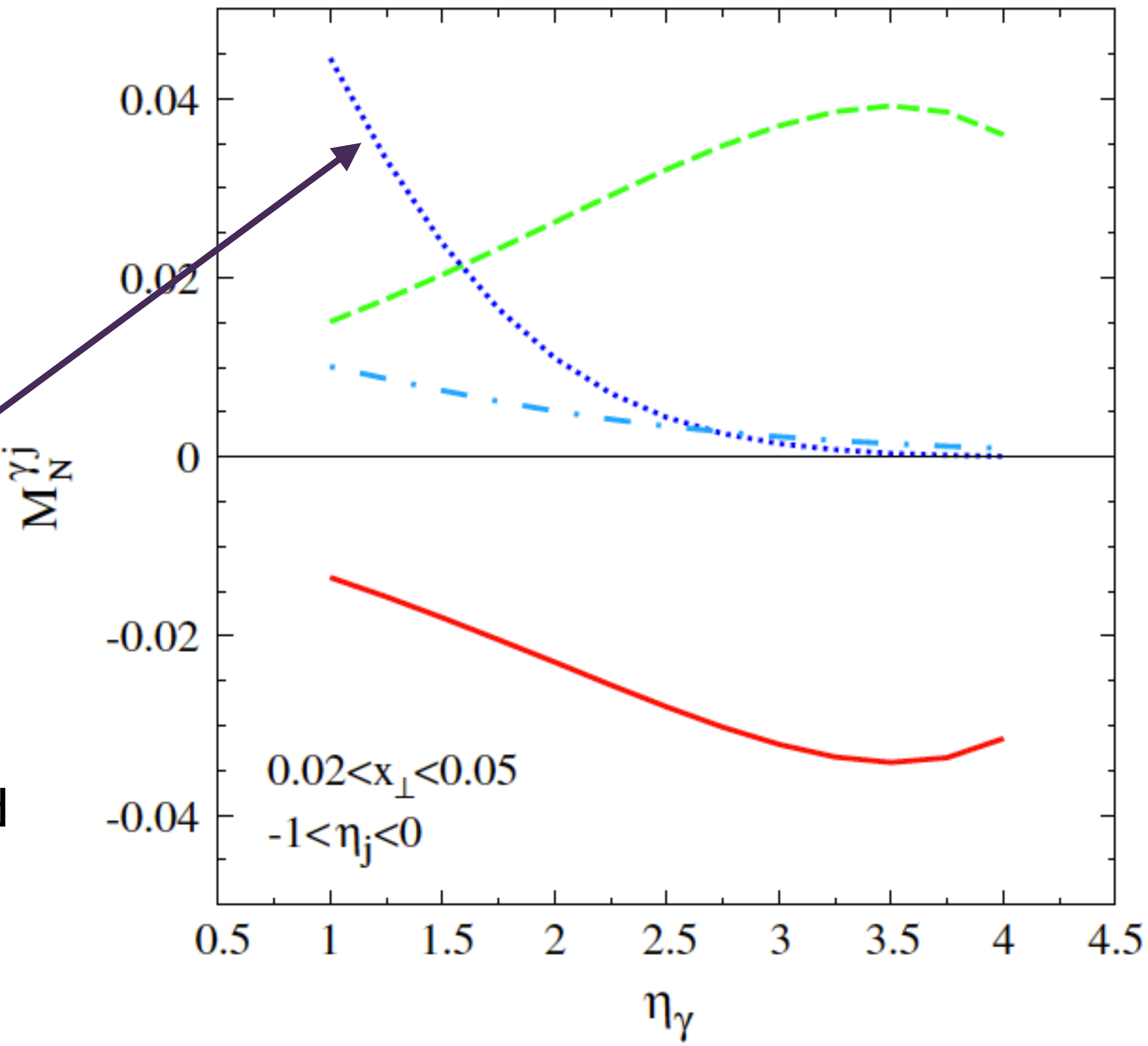
Gluon Sivers effect in γ jet production

[Bacchetta, Bomhof, D'Alesio, Mulders, Murgia, 2007]

$f_{1T}^{\perp g\,[+,-]}$

$p^{\uparrow}p \to \gamma$ *jet X*

maximum contribution from the gluon Sivers function (absolute value)



Prediction for the azimuthal moment at $\sqrt{s}$=200 GeV, $p_T^{\gamma} \geq 1$ GeV, integrated over $-1 \leq \eta_j \leq 0$, $0.02 \leq x_\perp \leq 0.05$

$$M_N^{\gamma j}(\eta_\gamma, \eta_j, x_\perp) = \frac{\int d\phi_j\, d\phi_\gamma \frac{2|\boldsymbol{K}_{\gamma\perp}|}{M} \sin(\delta\phi) \cos(\phi_\gamma) \frac{d\sigma}{d\phi_j\, d\phi_\gamma}}{\int d\phi_j\, d\phi_\gamma \frac{d\sigma}{d\phi_j\, d\phi_\gamma}}$$

Small gluon Sivers effect?

Experiments suggest gluon Sivers (which one?) is small, but not necessarily tiny:

- Burkardt sum rule already (approximately) satisfied by up and down quarks

$$\sum_{a=q,g} \int f_{1T}^{\perp(1)a}(x)\, dx = 0$$

- small Sivers asymmetry in SIDIS on deuteron target by COMPASS
  [Brodsky & Gardner, 2006]

- small A_N at midrapidity at RHIC (small gluon Sivers function in the GPM)
  [Anselmino, D'Alesio, Melis & Murgia, 2006; D'Alesio, Murgia, Pisano, 2015]

- COMPASS using high-p_T hadron pairs measured the gluon Sivers asymmetry:
  $A^{Siv} = -0.23 \pm 0.08$ (stat) ± 0.05 (syst) at $\langle x_g \rangle = 0.15$
  [C. Adolph et al., PLB 2017]

Gluon Sivers function is constrained to be $\lesssim$ 30% of nonsinglet quark Sivers function

D.B., Lorcé, Pisano & J. Zhou, 2015

This is its natural size, being $1/N_c$ suppressed at $x \sim 1/N_c$, like the flavor singlet u+d
[Efremov, Goeke, Menzel, Metz, Schweitzer, 2005]

Gluon Sivers effect in p↑A collisions

Another interesting option is backward hadron production in p↑p or p↑A

A_N is not a TMD factorizing process, except at small x (shown at one-loop order)

Chirilli, Xiao, Yuan, PRL & PRD 2012

It probes the dipole-type Sivers function $f_{1T}^{\perp\, g\, [+,-]}$

$$\Gamma^{[+,-]\, ij}(x,\boldsymbol{k}_T) \xrightarrow{x\to 0} \frac{k_T^i k_T^j}{2\pi L}\Gamma_0^{[\Box]}(\boldsymbol{k}_T)$$

a single Wilson loop matrix element

D.B., Cotogno, van Daal, Mulders, Signori & Ya-Jin Zhou, JHEP 2016

$$U^{[\Box]} = U^{[+]}_{[0,y]} U^{[-]}_{[y,0]}$$

At small x it can be identified with the *spin-dependent odderon* [J. Zhou, 2013]

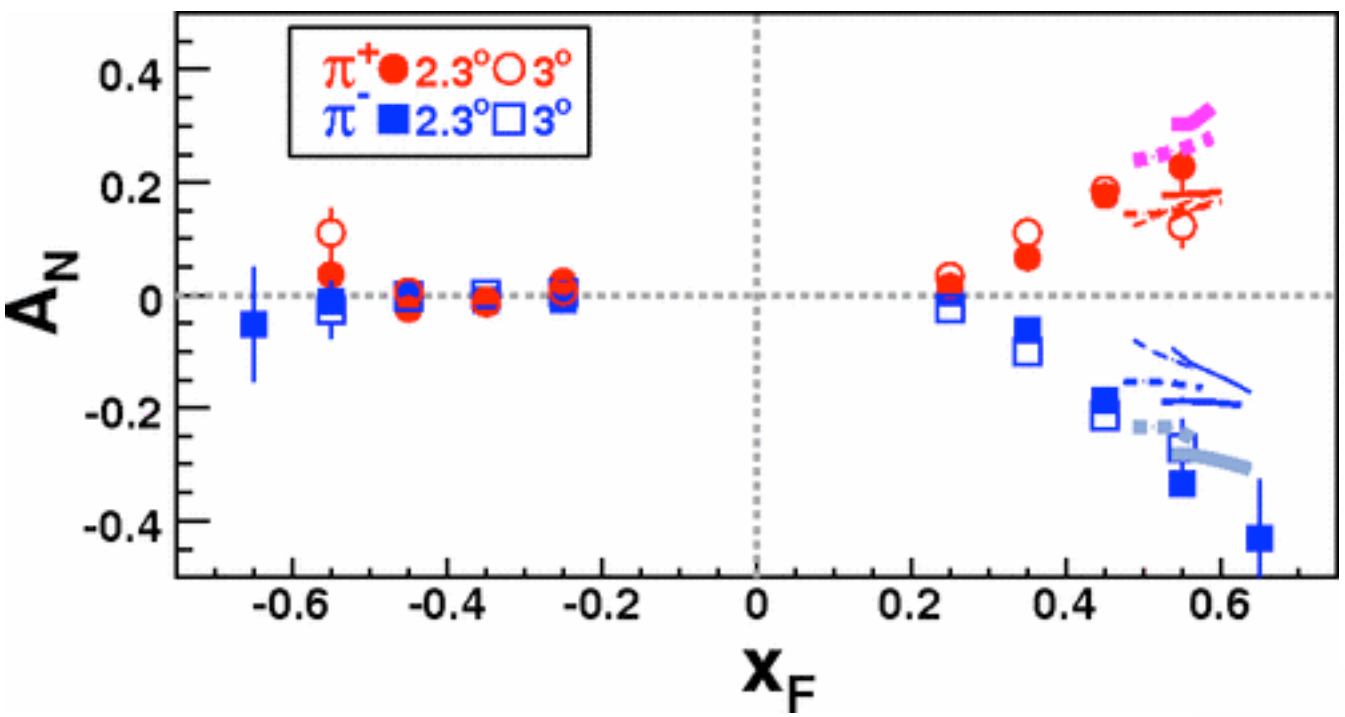
$$\Gamma^{(T-\mathrm{odd})}_{(d)} \equiv \left(\Gamma^{[+,-]} - \Gamma^{[-,+]}\right) \propto \mathrm{F.T.}\, \langle P, S_T | \mathrm{Tr}\left[U^{[\Box]}(0_T, y_T) - U^{[\Box]\dagger}(0_T, y_T)\right] | P, S_T\rangle$$

D.B., Echevarria, Mulders, J. Zhou, PRL 2016

It is the only relevant contribution in A_N at negative x_F, as opposed to the many contributions at positive x_F

The imaginary part of the Wilson loop determines the gluonic single spin asymmetry

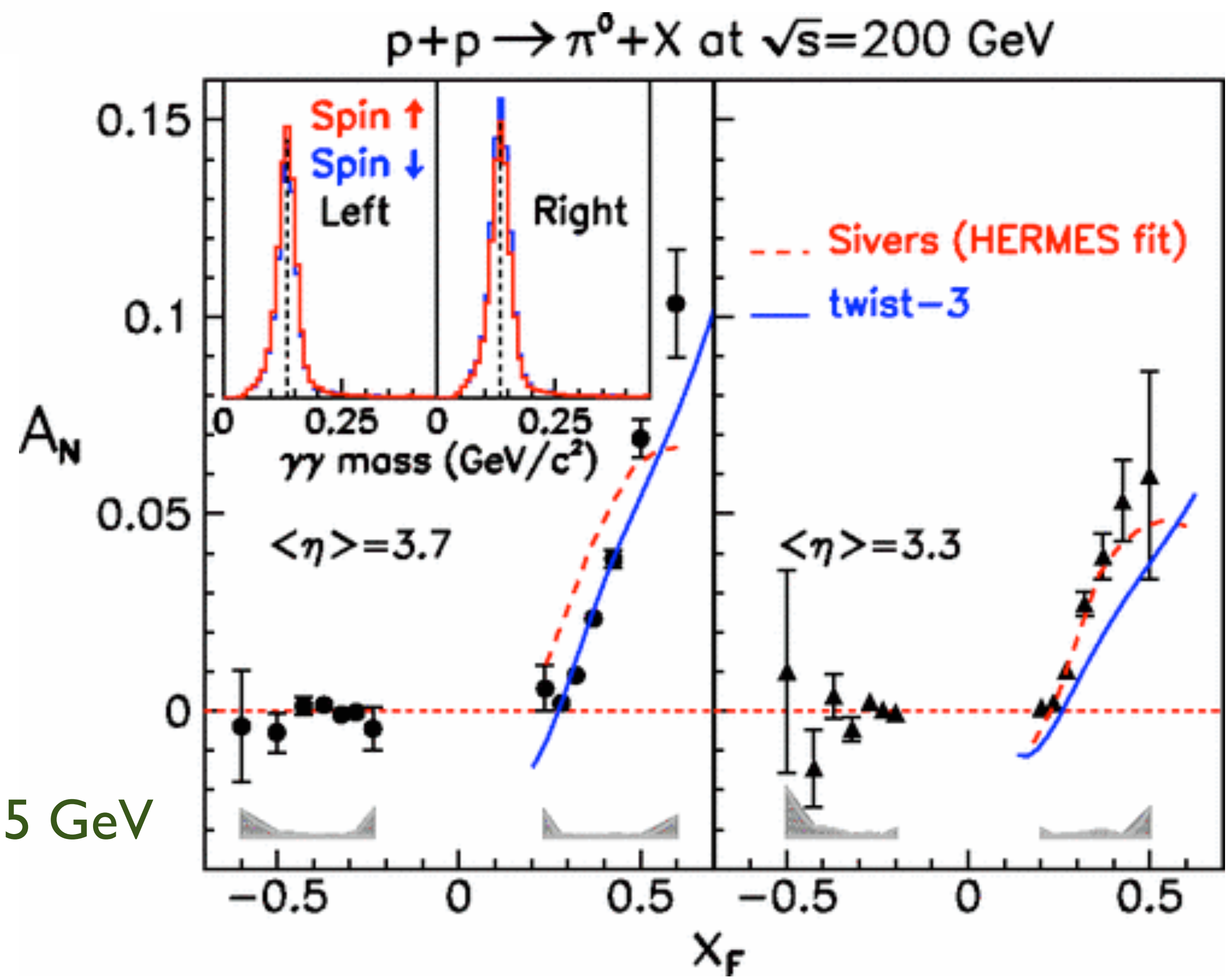
$p^{\uparrow}p \to h^{\pm}\, X$ at $x_F < 0$



BRAHMS, 2008 $\sqrt{s}$ = 62.4 GeV
low p_T, up to roughly 1.2 GeV
where gg channel dominates

spin-dependent odderon is C-odd,
whereas gg in the CS state is C-even

expect smaller asymmetries
in neutral pion and jet production



STAR, 2008
$\sqrt{s}$ = 200 GeV
p_T between 1 and 3.5 GeV

Unpolarized gluon TMDs

WW vs DP

For most processes of interest there are 2 relevant unpolarized gluon distributions

Dominguez, Marquet, Xiao, Yuan, 2011

$$xG^{(1)}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[+]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle \quad [+,+]$$

$$xG^{(2)}(x,k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P|\mathrm{Tr}\left[F^{+i}(\xi^-,\xi_\perp)\mathcal{U}^{[-]\dagger}F^{+i}(0)\mathcal{U}^{[+]}\right]|P\rangle \quad [+,-]$$

For unpolarized gluons [+,+] = [−,−] and [+,−] = [−,+]

At small x the two correspond to the Weizsäcker-Williams (WW) and dipole (DP) distributions, which are generally different in magnitude and width:

$$xG^{(1)}(x,k_\perp) = -\frac{2}{\alpha_S}\int \frac{d^2v}{(2\pi)^2}\frac{d^2v'}{(2\pi)^2}\, e^{-ik_\perp\cdot(v-v')}\left\langle \mathrm{Tr}\left[\partial_i U(v)\right]U^\dagger(v')\left[\partial_i U(v')\right]U^\dagger(v)\right\rangle_{x_g} \quad \text{WW}$$

$$xG^{(2)}(x,q_\perp) = \frac{q_\perp^2 N_c}{2\pi^2\alpha_s} S_\perp \int \frac{d^2r_\perp}{(2\pi)^2} e^{-iq_\perp\cdot r_\perp}\frac{1}{N_c}\left\langle \mathrm{Tr}U(0)U^\dagger(r_\perp)\right\rangle_{x_g} \quad \text{DP}$$

Different processes probe one or the other or a mixture, so this can be tested

WW vs DP

Selection of processes that probe the WW or DP unpolarized gluon TMD:

	DIS	DY	SIDIS	$pA \to \gamma\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$f_1^{g\,[+,+]}$ (WW)	$\times$	$\times$	$\times$	$\times$	$\surd$	$\surd$	$\surd$
$f_1^{g\,[+,-]}$ (DP)	$\surd$	$\surd$	$\surd$	$\surd$	$\times$	$\times$	$\times$

Dijet production in pA probes a combination of 6 distinct unpolarized gluon TMDs

Akcakaya, Schäfer, Zhou, 2013; Kotko, Kutak, Marquet, Petreska, Sapeta, van Hameren, 2015

Also, it generally suffers from factorization breaking contributions

Collins, Qiu, 2007; Rogers, Mulders, 2010

Single color singlet (CS) J/ψ or ϒ production from two gluons is not allowed by the Landau-Yang theorem, while color octet (CO) production involves a more complicated link structure. C-even (pseudo-)scalar quarkonium production is easier

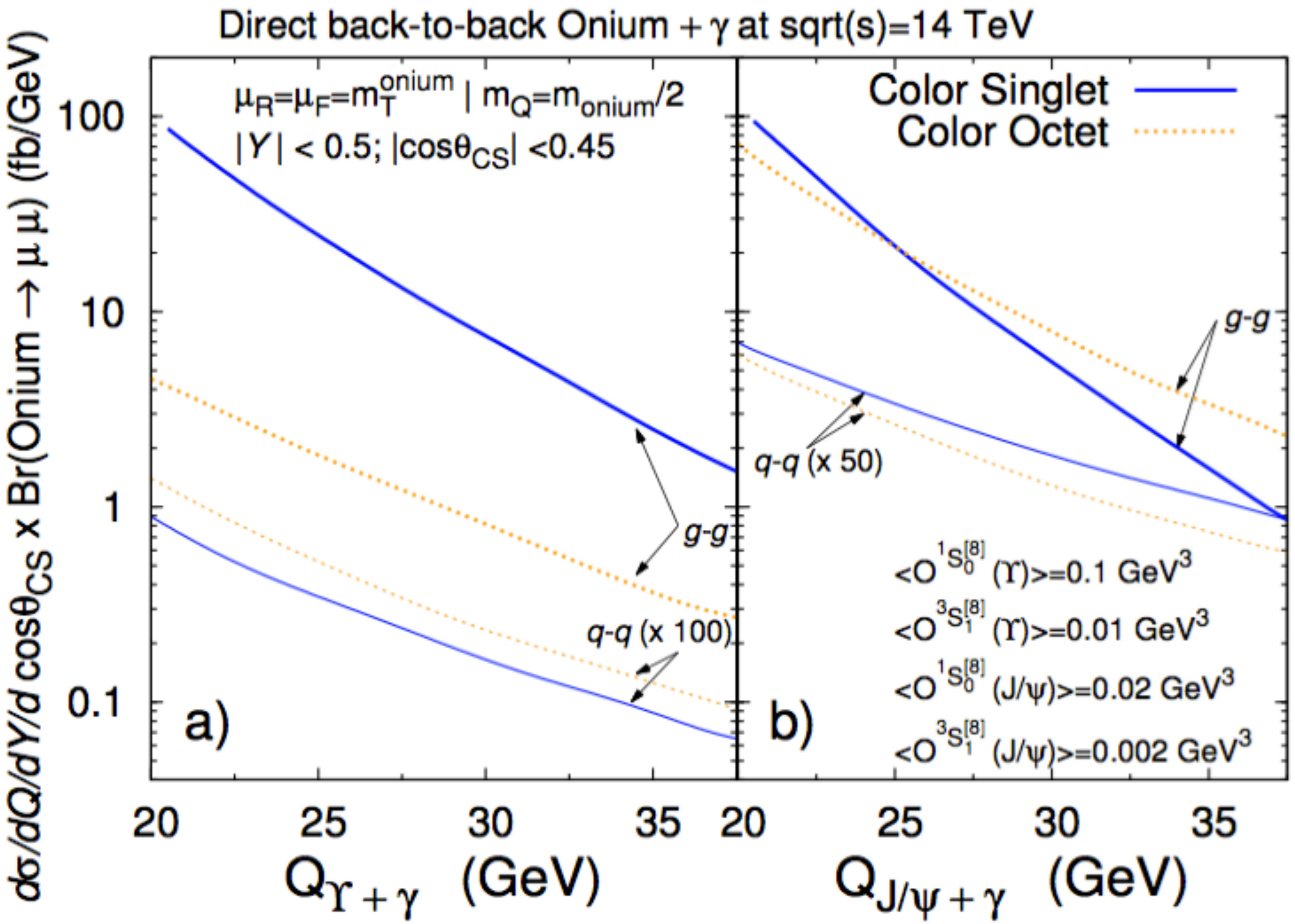
D.B., Pisano, 2012

CS vs CO

In ϒ+γ production the color singlet contribution dominates and in J/ψ+γ production for a specific range of invariant mass of the pair

den Dunnen, Lansberg, Pisano, Schlegel, PRL 2014

$$f_1^{g\,[+,+]}$$



Linearly polarized gluons in unpolarized hadrons

Probes of linear gluon polarization

$h_1^{\perp g}$ is more difficult to extract, as it cannot be probed in DIS, DY, SIDIS, nor in inclusive hadron or γ+jet production in pp or pA collisions

Selection of processes that probe the WW or DP linearly polarized gluon TMD:

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\mathrm{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp\,g\,[+,+]}$ (WW)	$\surd$	$\times$	$\surd$	$\surd$	$\surd$
$h_1^{\perp\,g\,[+,-]}$ (DP)	$\times$	$\surd$	$\times$	$\times$	$\times$

% level at RHIC
Qiu, Schlegel, Vogelsang, 2011

10% level at EIC
D.B., Brodsky, Pisano, Mulders, 2011;
Dumitru, Lappi, Skokov, 2015;
D.B., Pisano, Mulders, J. Zhou, 2016

10% level for η_Q and
% level for Higgs at LHC
D.B. & den Dunnen, 2014;
Echevarria, Kasemets, Mulders, Pisano, 2015

EIC and RHIC/LHC can probe the same $h_1^{\perp g}$

Higgs and $0^{\pm +}$ quarkonium production uses the angular *independent* p_T distribution

All other suggestions use angular modulations

γ^*-jet production

$h_1^{\perp g}$ is power suppressed in *pp*→ *γ jet X* [D.B, Mulders, Pisano, 2008]

It is not power suppressed in *pp*→ *γ* jet X if* $Q^2 \sim P_{\perp,jet}^2$ [D.B, Mulders, Zhou & Zhou, 2017]

Consider $Q^2 \sim P_{\perp,jet}^2$ also to avoid a three-scale problem

	$pp \to \gamma\,\gamma\,X$	$pA \to \gamma^*\,\text{jet}\,X$	$e\,p \to e'\,Q\,\overline{Q}\,X$ $e\,p \to e'\,j_1\,j_2\,X$	$pp \to \eta_{c,b}\,X$ $pp \to H\,X$	$pp \to J/\psi\,\gamma\,X$ $pp \to \Upsilon\,\gamma\,X$
$h_1^{\perp g\,[+,+]}$ (WW)	$\surd$	$\times$	$\surd$	$\surd$	$\surd$
$h_1^{\perp g\,[+,-]}$ (DP)	$\times$	$\surd$	$\times$	$\times$	$\times$

pp→ *γ* jet X* offers a *unique* opportunity to study the Wilson loop matrix element for unpolarized protons, *if* TMD factorization holds (at least at small x)

At high gluon density (large A and/or small x) the DP linear gluon polarization is expected to become maximal, as was first shown in the MV model for the CGC

$$x h_{1,DP}^{\perp g}(x,k_\perp) = 2x f_{1,DP}^{g}(x,k_\perp)$$

[Metz & Jian Zhou, 2011; D.B., Cotogno, van Daal, Mulders, Signori & Ya-Jin Zhou, 2016]

Azimuthal asymmetry in γ^*-jet production

Linear gluon polarization *not* power suppressed in pp$\rightarrow\gamma^*$ jet X for $Q^2 \sim P_{\perp,jet}^2$ leading to a $\cos(2\varphi)$ asymmetry, where $\varphi=\varphi_T-\varphi_\perp$

Some processes may become effectively TMD factorizing at small x (small-x factorization or hybrid factorization)

[Mueller, 1990 & 1994; Kovchegov & Mueller, 1998; Chirilli, Xiao, Yuan, 2012; Mueller, Xiao, Yuan, 2013]

In a hybrid factorization approach (assumed to be applicable at small x) at LO:

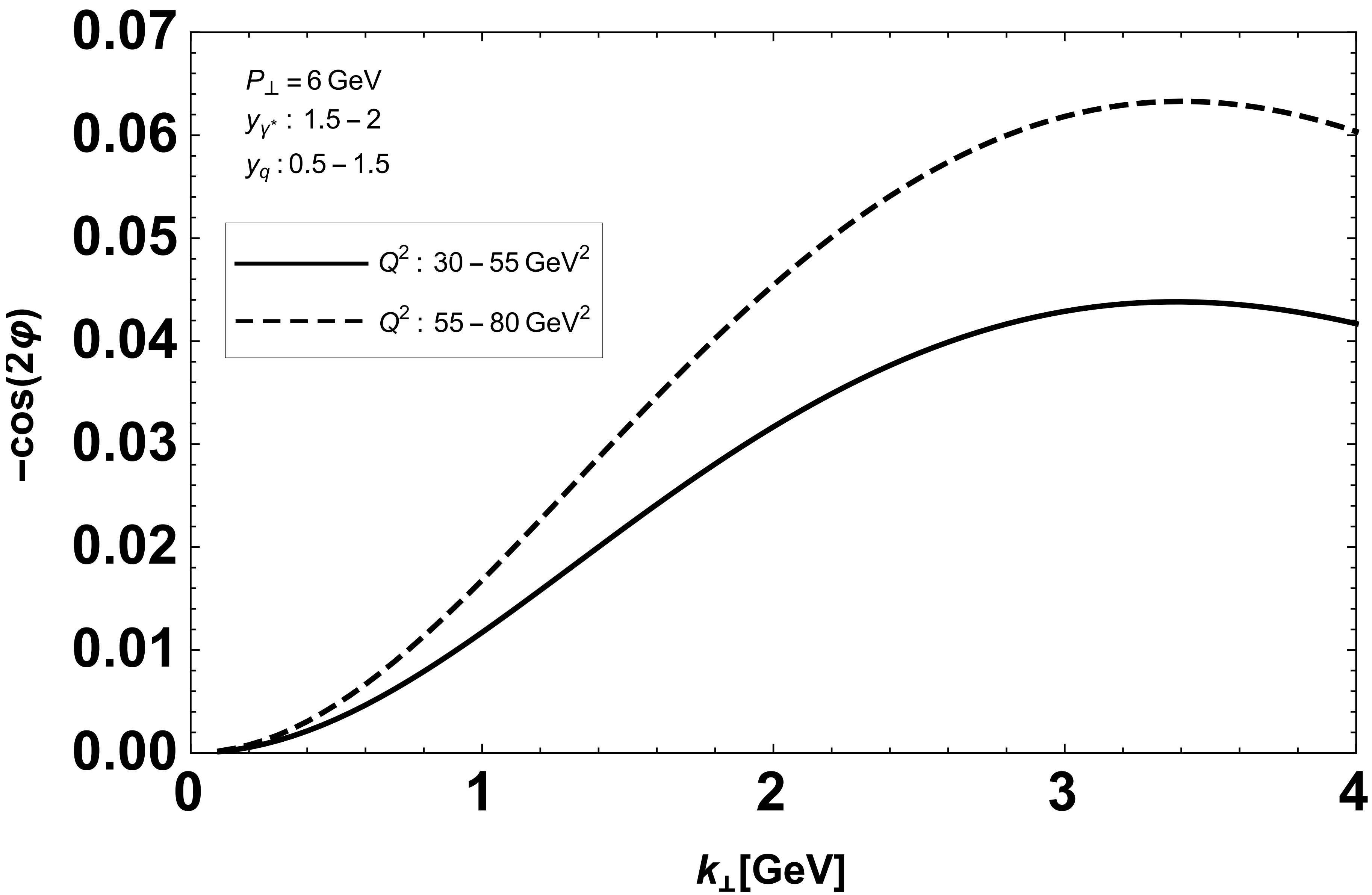
$$\frac{d\sigma^{pA\to\gamma^* qX}}{dP.S} = \sum_q x_p f_1^q(x_p)\left\{x f_1^g(x,k_\perp) H_{\rm Born} + \cos(2\phi)\, x h_1^{\perp g}(x,k_\perp) H_{\rm Born}^{\cos(2\phi)}\right\}$$

This leads to a sizeable asymmetry:

$$\frac{H_{\rm Born}^{\cos(2\phi)}}{H_{\rm Born}} \approx -0.1 \text{ for } z = 0.5 \;\&\; Q = P_\perp = 6 \text{ GeV}$$

[D.B, Mulders, Jian Zhou & Ya-Jin Zhou, 2017]

Sudakov suppression of linear gluon polarization



$\approx -0.1 \cdot 0.4$

Despite the maximal DP linear gluon polarization at small x, there is Sudakov suppression of the cos(2φ) asymmetry in pA→γ^* jet X: ~5% asymmetry at RHIC

D.B., Mulders, Jian Zhou & Ya-Jin Zhou, 2017

It becomes effectively power suppressed as Q~P⊥ increases from 6 to 90 GeV

Conclusions

Conclusions

- Gluon TMD measurements generally require higher energy collisions, less inclusive observables (particle pair correlations) and several processes (process dependence)

- For the [+,+] unpolarized gluon TMD one can exploit quarkonium-γ production at the LHC; for the [+,−] jet-γ production could be used

- The [+,+] linearly polarization gluon TMD can be measured in pp collisions (percent level effects in Higgs production, much larger in scalar quarkonium production) and in ep collisions, where also its sign can be determined

- The [+,−] linearly polarization gluon TMD can be probed in γ^*-jet production. At small x it becomes maximally polarized, but there is significant Sudakov suppression

- The two distinct gluon Sivers TMDs can be measured in $p^\uparrow p$ and $p^\uparrow A$ collisions (RHIC & AFTER@LHC), the [+,+]-type allows for a sign-change test w.r.t. $ep^\uparrow$ (EIC)

- As $x \to 0$ the [+,−] gluon Sivers TMD becomes the spin-dependent odderon, a T-odd and C-odd single Wilson loop matrix element that fully determines A_N at negative x_F