Gluon TMDs: status and outlook

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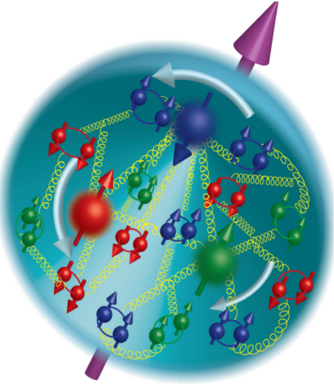


Gluon content of proton and deuteron with the Spin Physics Detector at the NICA collider

30 September - 1 October 2020

Gluon TMDs and factorization

Gluon TMDs

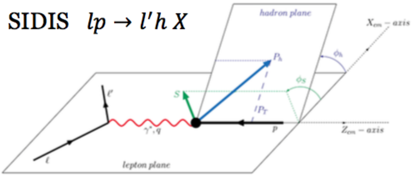
GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

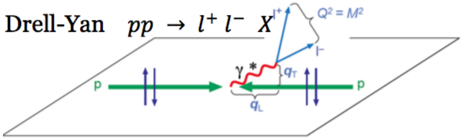
Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Rodrigues, PRD 63 (2001)
Meissner, Metz, Goeke, PRD 76 (2007)

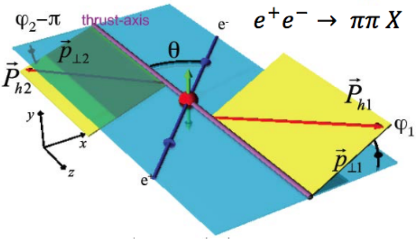
- $h_1^{\perp\, g}$: T-even distribution of linearly polarized gluons inside an unp. hadron
- $f_{1T}^{\perp\, g}$: T-odd gluon Sivers function
- $h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2}\, h_{1T}^{\perp\, g}$ does not survive under p_T integration, unlike transversity

In contrast to quark TMDs, gluon TMDs are almost unknown

Two scale processes $Q^2 \gg q_T^2$







Factorization proven

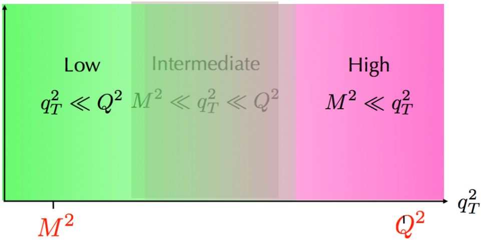
All orders in α_s

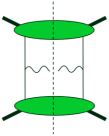
Leading order in powers of $1/Q$ (twist)

Collins, Cambridge University Press (2011)

Three physical scales, two theoretical tools

Bacchetta, Boer, Diehl, Mulders, JHEP 08 (2008)
Bacchetta, Bozzi, Echevarria, CP, Prokudin, Radici, PLB 797 (2019)
Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)

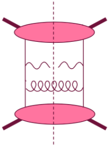




TMD

Do they describe the same dynamics or two competing mechanisms in the intermediate region?

(i.e., interpolation or sum?)

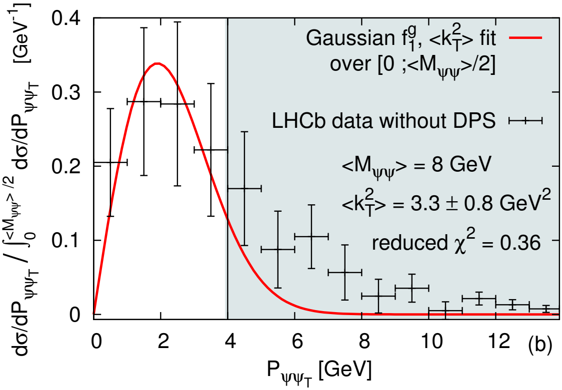


collinear PDF

Useful to test assumptions on TMD factorization

$q_T = P_T^{\Psi\Psi} \leq M_{\Psi\Psi}/2$ in order to have two different scales

Color Singlet production mechanism $\Longrightarrow$: $[-,-]$ gauge link structure (like DY)



Lansberg, CP, Scarpa, Schlegel, PLB 784 (2018)
LHCb Coll., JHEP 06 (2017)

Proposals for extracting the gluon Sivers function at COMPASS

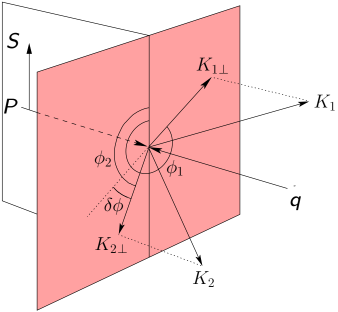
Talk by J. Matousek

Heavy quark pair production at an EIC

Gluon TMDs probed directly in $e(\ell) + p(P,S) \to e(\ell') + Q(K_1) + \overline{Q}(K_2) + X$

Boer, Brodsky, Mulders, CP, PRL 106 (2011)
CP, Boer, Brodsky, Mulders, JHEP 10 (2013)
Boer, Mulders, CP, Zhou, JHEP 1608 (2016)

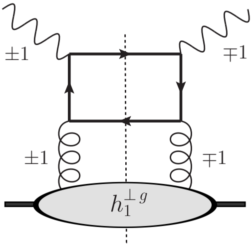
- the $Q\overline{Q}$ pair is almost back to back in the plane $\perp$ to q and P
- $q \equiv \ell - \ell'$: four-momentum of the exchanged virtual photon γ^*



$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp}$$

$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2$$

$\Longrightarrow$ Correlation limit: $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, $\quad |\boldsymbol{K}_\perp| \approx |\boldsymbol{K}_{1\perp}| \approx |\boldsymbol{K}_{2\perp}|$



$\phi_T, \phi_\perp, \phi_S$ azimuthal angles of $q_T, K_\perp, S_T$

At LO in pQCD: only $\gamma^* g \to Q\overline{Q}$ contributes

$$\mathrm{d}\sigma(\phi_S, \phi_T, \phi_\perp) = \mathrm{d}\sigma^U(\phi_T, \phi_\perp) + \mathrm{d}\sigma^T(\phi_S, \phi_T, \phi_\perp)$$

Angular structure of the unpolarized cross section for $ep \to e' Q\overline{Q}X$, $\quad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\frac{\mathrm{d}\sigma^U}{\mathrm{d}^2\boldsymbol{q}_T\,\mathrm{d}^2\boldsymbol{K}_\perp} \propto \left\{A_0^U + A_1^U \cos\phi_\perp + A_2^U \cos 2\phi_\perp\right\} f_1^g(x, \boldsymbol{q}_T^2) + \frac{\boldsymbol{q}_T^2}{M_p^2}\, h_1^{\perp\, g}(x, \boldsymbol{q}_T^2)$$
$$\times \left\{B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_\perp) + B_2^U \cos 2(\phi_T - \phi_\perp) + B_3^U \cos(2\phi_T - 3\phi_\perp) + B_4^U \cos 2(\phi_T - 2\phi_\perp)\right\}$$

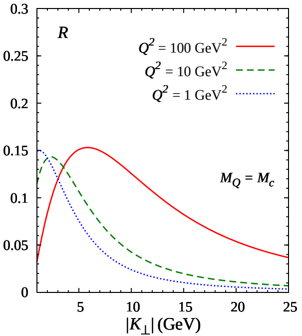
The different contributions can be isolated by defining

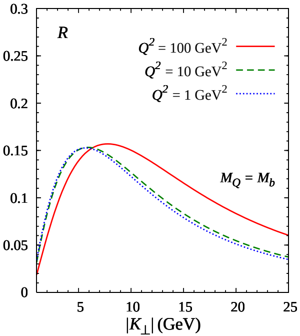
$$\langle W(\phi_\perp, \phi_T)\rangle = \frac{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\, W(\phi_\perp, \phi_T)\,\mathrm{d}\sigma}{\int \mathrm{d}\phi_\perp \mathrm{d}\phi_T\,\mathrm{d}\sigma}, \qquad W = \cos 2\phi_T,\ \cos 2(\phi_\perp - \phi_T), \ldots$$

Positivity bound for $h_1^{\perp g}$: $|h_1^{\perp g}(x, \boldsymbol{p}_T^2)| \leq \frac{2M_p^2}{\boldsymbol{p}_T^2} f_1^g(x, \boldsymbol{p}_T^2)$

It can be used to estimate maximal values of the asymmetries

Upper bounds on $R \equiv |\langle \cos 2(\phi_T - \phi_\perp) \rangle|$ at $y = 0.01$





CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013)
Boer, Brodsky, Mulders, CP, PRL 106 (2011)

Spin asymmetries in $ep^{\uparrow} \to e' Q\overline{Q}X$

Angular structure of the single polarized cross section for $ep^{\uparrow} \to e' Q\overline{Q}X$, $\quad |\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$

$$\mathrm{d}\sigma^T \propto \sin(\phi_S - \phi_T)\Big[A_0^T + A_1^T \cos\phi_\perp + A_2^T \cos 2\phi_\perp\Big] f_{1T}^{\perp\,g} + \cos(\phi_S - \phi_T)\Big[B_0^T \sin 2\phi_T$$
$$+ B_1^T \sin(2\phi_T - \phi_\perp) + B_2^T \sin 2(\phi_T - \phi_\perp) + B_3^T \sin(2\phi_T - 3\phi_\perp) + B_4^T \sin(2\phi_T - 4\phi_\perp)\Big] h_{1T}^{\perp\,g}$$
$$+ \Big[B_0'^{\,T} \sin(\phi_S + \phi_T) + B_1'^{\,T} \sin(\phi_S + \phi_T - \phi_\perp) + B_2'^{\,T} \sin(\phi_S + \phi_T - 2\phi_\perp)$$
$$+ B_3'^{\,T} \sin(\phi_S + \phi_T - 3\phi_\perp) + B_4'^{\,T} \sin(\phi_S + \phi_T - 4\phi_\perp)\Big] h_{1T}^{g}$$

The ϕ_S dependent terms can be singled out by means of azimuthal moments A_N^W

$$A_N^{W(\phi_S,\phi_T)} \equiv 2\,\frac{\int \mathrm{d}\phi_T\,\mathrm{d}\phi_\perp\, W(\phi_S,\phi_T)\,\mathrm{d}\sigma_T(\phi_S,\,\phi_T,\,\phi_\perp)}{\int \mathrm{d}\phi_T\,\mathrm{d}\phi_\perp\,\mathrm{d}\sigma_U(\phi_T,\phi_\perp)}$$

$$A_N^{\sin(\phi_S-\phi_T)} \propto \frac{f_{1T}^{\perp\,g}}{f_1^g} \qquad A_N^{\sin(\phi_S+\phi_T)} \propto \frac{h_1^g}{f_1^g} \qquad A_N^{\sin(\phi_S-3\phi_T)} \propto \frac{h_{1T}^{\perp\,g}}{f_1^g}$$

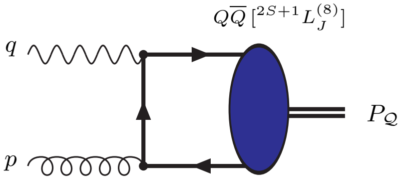
Same modulations as in SIDIS for quark TMDs ($\phi_T \to \phi_h$)

Quarkonium production at the EIC

$e\, p^{\uparrow} \to e'\, \mathcal{Q}\, X$ with $\mathcal{Q}$ either a J/ψ or a Υ meson, with $P^2_{\mathcal{Q}T} \ll M^2_{\mathcal{Q}} \sim Q^2$

Bacchetta, Boer, CP, Taels, EPJ C 80 (2020)

At $\mathcal{O}(\alpha_s)$ color octet (CO) production dominates in the v-expansion of NRQCD

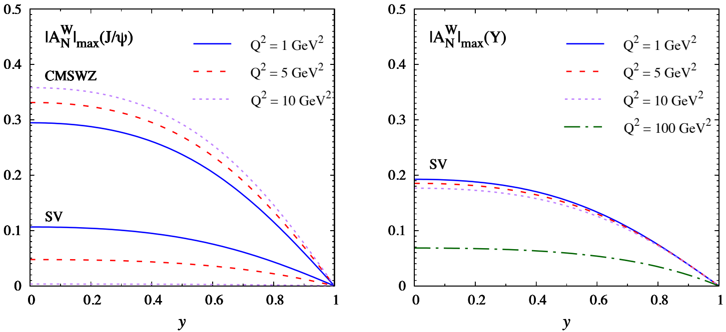


Theoretically described by Color Evaporation Model or NRQCD

Godbole, Misra, Mukherjee, Rawoot, PRD 85 (2012)
Godbole, Kaushik, Misra, Rawoot, PRD 91 (2015)
Mukherjee, Rajesh, EPJC 77 (2017)
Rajesh, Kishore, Mukherjee, PRD 98 (2018)

Results depend on the quite uncertain CO $^1S_0$ and ^3P_J LDMEs

Upper bounds for $\langle \cos 2\phi_T \rangle$ and A_N^W with $W = \sin(\phi_S + \phi_T)$, $\sin(\phi_S - 3\phi_T)$



$\langle \cos 2\phi_T \rangle$ still sizeable at small x, using the MV model as a starting input for $h_1^{\perp g}$ and f_1^g at $x = 10^{-2}$ and evolve them with the JIMWLK equations

Bacchetta, Boer, CP, Taels, EPJ C 80 (2020)
Marquet, Rosnel, Taels, PRD 97 (2018)

The Sivers asymmetry does not depend on the CO NRQCD LDMEs

$$A^{\sin(\phi_S-\phi_T)} = \frac{|\boldsymbol{q}_T|}{M_p}\,\frac{f_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}{f_1^g(x,\boldsymbol{q}_T^2)}$$

The other asymmetries depend on them, but one can consider ratios of asymmetries to cancel them out

$$\frac{A^{\cos 2\phi_T}}{A^{\sin(\phi_S+\phi_T)}} = \frac{\boldsymbol{q}_T^2}{M_p^2}\,\frac{h_1^{\perp\,g}(x,\boldsymbol{q}_T^2)}{h_1^g(x,\boldsymbol{q}_T^2)}$$

$$\frac{A^{\cos 2\phi_T}}{A^{\sin(\phi_S-3\phi_T)}} = -\frac{1}{2}\,\frac{h_1^{\perp\,g}(x,\boldsymbol{q}_T^2)}{h_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}$$

$$\frac{A^{\sin(\phi_S-3\phi_T)}}{A^{\sin(\phi_S+\phi_T)}} = -\frac{\boldsymbol{q}_T^2}{2M_p^2}\,\frac{h_{1T}^{\perp\,g}(x,\boldsymbol{q}_T^2)}{h_1^g(x,\boldsymbol{q}_T^2)}$$

Same relations hold for $e\,p \to e'\,Q\,\overline{Q}\,X$

Boer, Mulders, CP, Zhou, JHEP 08 (2016)
CP, Boer, Brodsky, Buffing, Mulders, JHEP 1310 (2013)
Boer, Brodsky, Mulders, CP, PRL 106 (2011)

One can consider ratios where the TMDs cancel out and one can obtain new experimental information on the CO NRQCD LDMEs

It requires comparison with $e\,p^{\uparrow} \to e'\,Q\,\overline{Q}\,X$

$$\mathcal{R}^{\cos 2\phi} = \frac{\int \mathrm{d}\phi_T \cos 2\phi_T \, \mathrm{d}\sigma^{\mathcal{Q}}(\phi_S, \phi_T)}{\int \mathrm{d}\phi_T \, \mathrm{d}\phi_\perp \cos 2\phi_T \, \mathrm{d}\sigma^{Q\overline{Q}}(\phi_S, \phi_T, \phi_\perp)}$$

$$\mathcal{R} = \frac{\int \mathrm{d}\phi_T \, \mathrm{d}\sigma^{\mathcal{Q}}(\phi_S, \phi_T)}{\int \mathrm{d}\phi_T \, \mathrm{d}\phi_\perp \, \mathrm{d}\sigma^{Q\overline{Q}}(\phi_S, \phi_T, \phi_\perp)}$$

Two observables depending on two unknowns: $\mathcal{O}_8^S \equiv \langle 0|\mathcal{O}_8^{\mathcal{Q}}(^1S_0)|0\rangle$
$\mathcal{O}_8^P \equiv \langle 0|\mathcal{O}_8^{\mathcal{Q}}(^3P_0)|0\rangle$

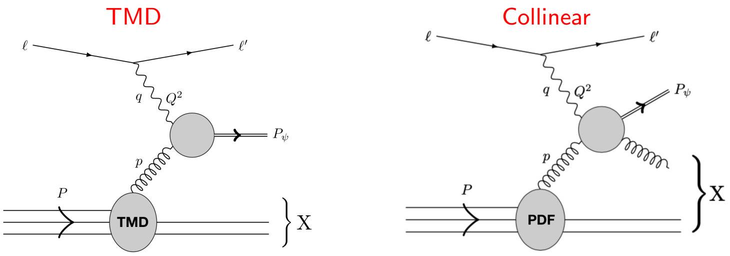
$$\mathcal{R}^{\cos 2\phi} = \frac{27\pi^2}{4} \frac{1}{M_Q} \left[\mathcal{O}_8^S - \frac{1}{M_Q^2} \mathcal{O}_8^P\right]$$

$$\mathcal{R} = \frac{27\,\pi^2}{4} \frac{1}{M_Q} \frac{[1 + (1-y)^2]\,\mathcal{O}_8^S + (10 - 10y + 3y^2)\,\mathcal{O}_8^P / M_Q^2}{26 - 26y + 9y^2}$$

Plus similar (but different) equations for polarized quarkonium production

So far we neglected smearing effects in quarkonium formation, which are included in the *shape functions* $\Delta^{[n]}$ (TMD generalizations of NRQCD LDMEs)

Echevarria, JHEP 10 (2019)
Fleming, Makris, Mehen, JHEP 04 (2020)



$P^2_{\psi T} \ll \mu^2$

$M_p^2 \ll P^2_{\psi T}$

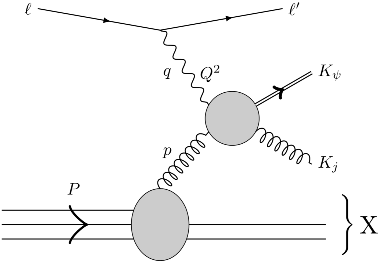
Imposing the matching of the TMD and collinear results in overlapping kinematic region $\mu^2 \gg P^2_{\mathcal{Q}T} \gg M_p^2$: $\quad f_1^g \longrightarrow \mathcal{C}[f_1^g\,\Delta^{[n]}]$

$$\Delta^{[n]}(\boldsymbol{k}_T^2, \mu^2) = \frac{\alpha_s}{2\pi^2 \boldsymbol{k}_T^2}\, C_A\, \langle 0|\mathcal{O}_8^Q(n)|0\rangle\, \ln\frac{\mu^2}{\boldsymbol{k}_T^2} \qquad k_T^2 \gg M_p^2$$

Boer, D'Alesio, Murgia, CP, Taels, JHEP 09 (2020)

$J/\psi+$ jet production in SIDIS can be studied in a TMD framework in the correlation limit $|\boldsymbol{q}_T| \ll |\boldsymbol{K}_\perp|$, along the same lines as jet-jet and $Q\overline{Q}$ production

D'Alesio, Murgia, CP, Taels, PRD 99 (2019)



$$\boldsymbol{q}_T \equiv \boldsymbol{K}_{\psi\perp} + \boldsymbol{K}_{j\perp}$$

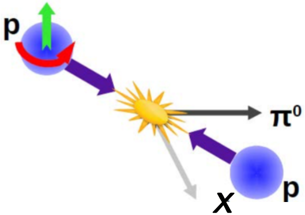
$$\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{\psi\perp} - \boldsymbol{K}_{j\perp})/2$$

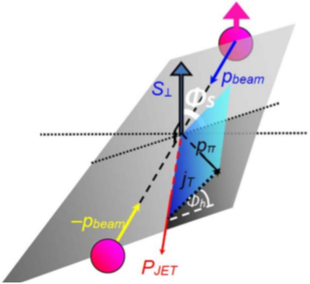
$\phi_T, \phi_\perp, \phi_S$: azimuthal angles of $q_T, K_\perp, S_T$

$$A_N^{\sin(\phi_S-\phi_T)} \propto \frac{f_{1T}^{\perp\, g}}{f_1^g} \qquad A_N^{\sin(\phi_S+\phi_T)} \propto \frac{h_1^g}{f_1^g} \qquad A_N^{\sin(\phi_S-3\phi_T)} \propto \frac{h_{1T}^{\perp\, g}}{f_1^g}$$

The TMD Generalized Parton Model

Phenomenological extension of the TMD formalism to processes like





$pp \to \pi X$

$(pp \to \mathrm{jet}\, X,\ pp \to \gamma X)$

Single scale processes

$pp \to \mathrm{jet}\, \pi X$

and more

Anselmino, Boglione, Murgia, PLB 362 (1995), ...
Aschenauer, D'Alesio, Murgia, EPJA52 (2016)

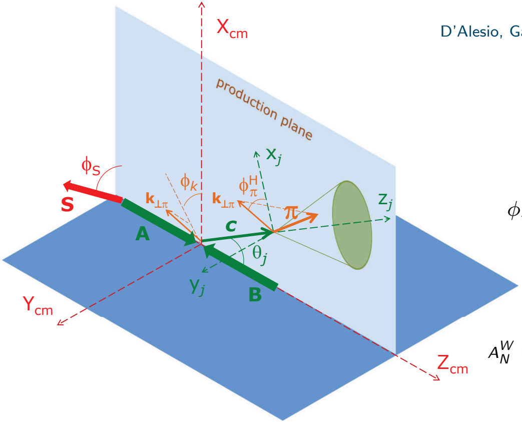
Transverse Momentum Dependent – Generalized Parton Model (GPM)

- Spin & $k_\perp$-dependent distribution and fragmentation functions as in TMD scheme
- Universality and TMD factorization: assumption to be tested

$$p_A(P_A;S) + p_B(P_B) \to \text{jet}(P_\text{j}) + \pi(P_\pi) + X$$

A is polarized with transverse spin $S = (0, \cos\phi_S, \sin\phi_S, 0)$

D'Alesio, Murgia, CP, PRD 83 (2011) 034021
D'Alesio, Gamberg, Kang, Murgia, CP, PLB 704 (2011) 637
D'Alesio, Murgia, CP, PEPAN 45 (2014) 676;
PLB 773 (2017) 300



ϕ_π^H: azimuthal distribution of the pion inside the jet, around the jet axis

$$A_N^W = 2\,\frac{\int \mathrm{d}\phi_S \mathrm{d}\phi_\pi^H W(\phi_S,\phi_\pi^H)[\mathrm{d}\sigma(\phi_S) - \mathrm{d}\sigma(\phi_S+\pi)]}{\int \mathrm{d}\phi_S \mathrm{d}\phi_\pi^H [\mathrm{d}\sigma(\phi_S) + \mathrm{d}\sigma(\phi_S+\pi)]}$$

$c.m.$ and helicity H frames: related by a rotation around Y_{cm} by θ_j, polar angle of the jet

- A_N^W in $p^{\uparrow}p \to \mathrm{jet}\,\pi\,X$ allows to single out the Collins and Sivers effects (as well as other TMDs), this is not possible in in $p^{\uparrow}p \to \pi\,X$

  Anselmino *et al.*, PRD 71 (2005) 014002;
  Anselmino *et al.*, PRD 73 (2006) 014020

- Jets coming from quark or gluon fragmentation could be identified
  - symmetric pion distribution: fragmentation of an unpolarized parton (D_1)
  - $\cos\phi_\pi^H$ distribution for a transversely polarized quark jet $(H_1^{\perp q})$
  - $\cos 2\phi_\pi^H$ distribution for a linearly polarized gluon jet $(H_1^{\perp g})$

- Complex measurement, but feasible and under consideration at RHIC

  STAR Collaboration, PRD 97 (2018)

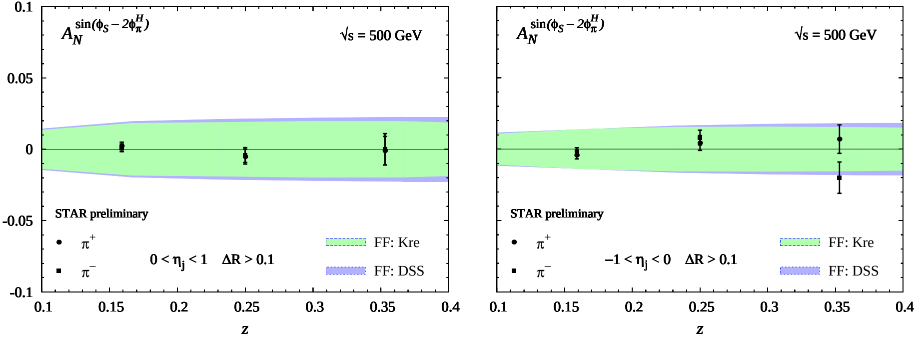
- Collinear + TMD factorization: intrinsic parton motion only in fragmentation, only Collins effect for quarks is at work

$$A_N^{\sin(\phi_S-\phi_\pi^H)} \sim h_1^q \; f_1 \; H_1^{\perp\, q}$$

F. Yuan, PRL 100 (2008) 032003
Kang, Liu, Ringer, Xing, JHEP 1711 (2017) 068
Kang, Prokudin, Ringer, Yuan, PLB 774 (2017) 635

$$A_N^{\sin(\phi_S - 2\phi_\pi^H)} \sim h_1^g \; f_1 \; H_1^{\perp\, g}$$

h_1^g, $H_1^{\perp g}$ are unknown; their positivity bounds $\longrightarrow$ upper bounds on $A_N^{\sin(\phi_S - 2\phi_\pi^H)} \approx 2\%$



[STAR Preliminary] R. Fatemi, QCD Evolution 2015

$\langle x_a \rangle \sim \langle x_b \rangle \sim 0.05\,;$ $\quad \langle k_{\perp\pi} \rangle \sim 0.3 - 0.6\ \text{GeV}\,;$ $\quad \langle P_{jT} \rangle \sim 7 - 8\ \text{GeV}$

$H_1^{\perp\, g}$: Collins-like FF can be determined separately from e^+e^- experiments

$h_1^g \neq h_1^{\perp\, g}$ (linearly polarized gluons inside an *unpolarized* proton)

The CGI-GPM takes into account the effects of initial and final state interactions

Gamberg, Kang, PLB 696 (2011)

Two independent gluon Sivers functions (GSFs) with first transverse moments

$$f_{1T}^{\perp(1)g\,(f/d)}(x) = \int \mathrm{d}^2\boldsymbol{k}_T\,\frac{k_T^2}{2M_p^2}\,f_{1T}^{\perp\,g\,(f/d)}(x,\boldsymbol{k}_T^2)$$

related to two different trigluon Qiu-Sterman functions $T_G^{(f/d)}$, involving the antisymmetric f_{abc} and symmetric d_{abc} color structures, respectively

D'Alesio, Murgia, CP, Taels, PRD 96 (2017)
Bomhof, Mulders, JHEP 0702 (2007)
Buffing, Mukherjee, Mulders, PRD 88 (2013)

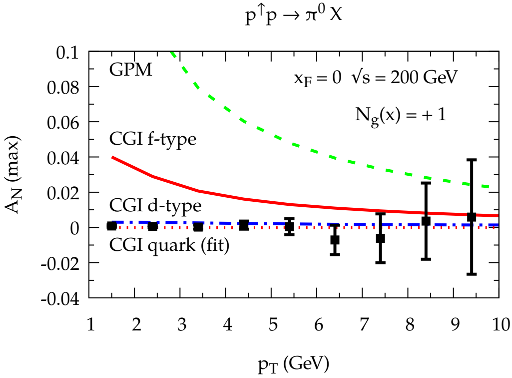
The two distributions have a different behavior under charge conjugation

The Burkardt sum rule constraints only the f-type gluon Sivers function

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

Boer, Lorcé, CP, Zhou, AHEP 2015 (2015)

Assumption: the GSFs have a factorized form in x-$k_\perp$, Gaussian $k_\perp$-dependence



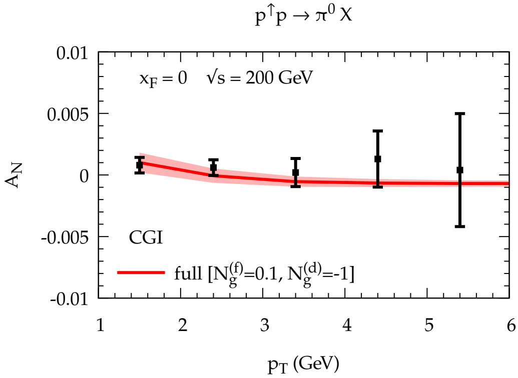
$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

Maximized GSFs ($N_g = +1$)

PHENIX Collaboration, PRD 90 (2014)

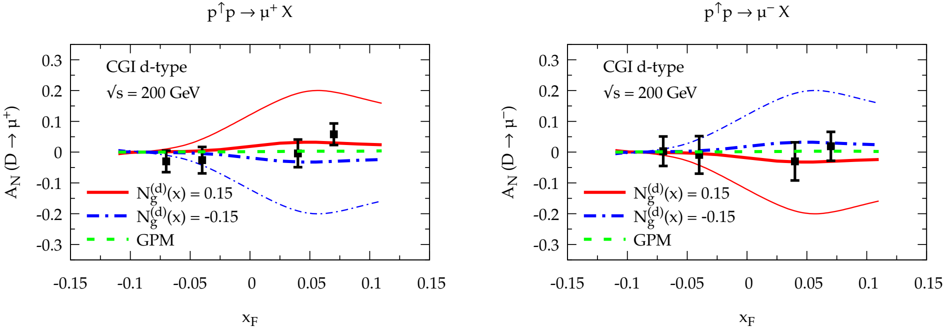
The f-type GSF is dominant in the CGI-GPM approach

Reduced f-type GSF ($N_g^{(f)} = 0.1$), negative saturated d-type GSF ($N_g^{(d)} = -1$)



Shaded area represents a $\pm 20\%$ uncertainty on $N_g^{(f)}$

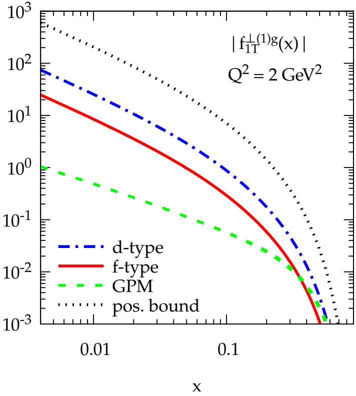
$f_{1T}^{\perp\,(d)}$ dominant, data imply $|N_g^{(d)}| \leq 0.15$; choice: $N_g^{(d)} = -0.15 \Rightarrow N_g^{(f)} = +0.05$



PHENIX Collaboration, PRD 95 (2017)

A_N for muons obtained from our D-meson estimates by Jeongsu Bok (PHENIX)

First $k_\perp$-moment of the GSFs



D'Alesio, Murgia, CP, JHEP 09 (2015)
D'Alesio, Flore, Murgia, CP, Taels, PRD 99 (2019)

- First attempt towards an extraction of the (process dependent) GSFs
- Data are not sufficient to discriminate between the GPM and the CGI-GPM
- The process $p^\uparrow p \to J/\psi\, X$ is also under study, data by PHENIX

D'Alesio, Murgia, CP, Rajesh, EPJC 79 (2019)
D'Alesio, Maxia, Murgia, CP, Rajesh, 2007.03353

Conclusions

- Azimuthal asymmetries in heavy quark pair and dijet production in DIS could probe WW-type gluon TMDs (similar to SIDIS for quark TMDs) with gauge-link structure $[+,+]$
- Quarkonia are good probes for gluon TMDs at the EIC, a first extraction of the unpolarized $[-,-]$ gluon TMD from LHC data on di-J/Ψ production
- Single scale processes like $p^{\uparrow}p \to \pi\, X$, $p^{\uparrow}p \to D\, X$, $p^{\uparrow}p \to J/\psi\, X$, ... can be studied within a GPM scheme or a collinear twist-3 approach
- Phenomenology and theory issues: process dependence, factorization breaking, TMD evolution, nonperturbative inputs $\Longrightarrow$ data needed from both *ep* and *pp* collisions (LHC, RHIC, NICA) at different energies