The gluon Sivers function and its process dependence from RHIC data

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TORINO

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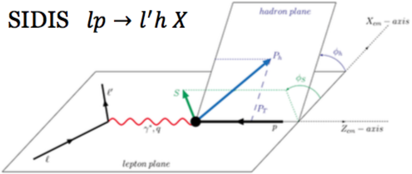
INFN CAGLIARI

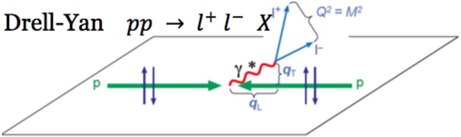
The TMD Generalized Parton Model

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

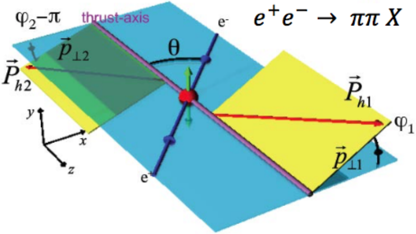
SIDIS $lp \to l'h\,X$



Drell-Yan $pp \to l^+ l^- X$

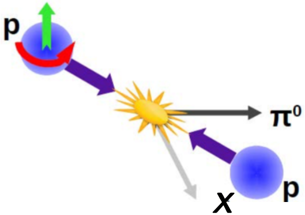


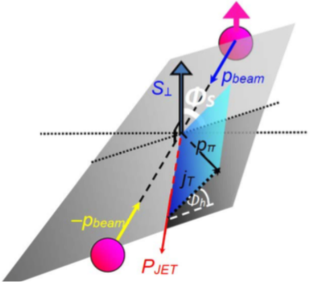
$e^+e^- \to \pi\pi\,X$



Factorization proven

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)

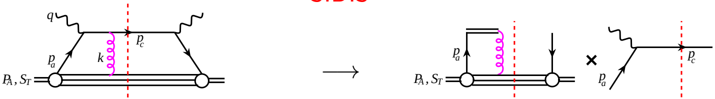
- Spin & $k_\perp$-dependent distribution and fragmentation functions as in TMD scheme
- $k_\perp$-dependence included in the hard scattering, unlike in the TMD formalism
- Universality and TMD factorization: assumption to be tested

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

Gamberg, Kang, PLB 696 (2011)

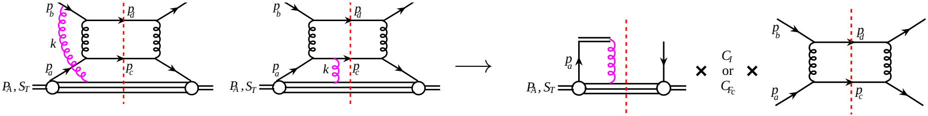
One-gluon exchange approx.: LO term of of the α_S expansion of the gauge link

SIDIS



$f_{1T}^{\perp q\,[\mathrm{SIDIS}]}$ × Hard part

$qq' \to qq'$



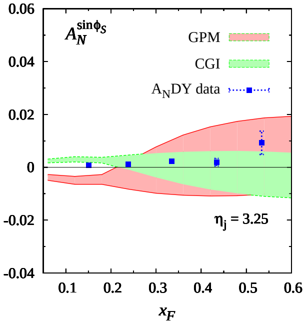
$f_{1T}^{\perp q\,[\mathrm{SIDIS}]}$ × (CF × Hard part)

$f_{1T}^{\perp q[\mathrm{SIDIS}]}$ is universal, process dependence absorbed in *modified* hard functions

The CGI-GPM recovers the relation $f_{1T}^{\perp\,[DY]} = -f_{1T}^{\perp\,[SIDIS]}$

In the CGI-GPM TMDs are process dependent, different predictions w.r.t. GPM

Gamberg, Kang, PLB 696 (2011)
D'Alesio, Gamberg, Kang, Murgia, CP, PLB 704 (2011)



$p^\uparrow p \to \text{jet}\, X$

$(\sqrt{s} = 500$ GeV$)$

Extension of the CGI-GPM to the gluon Sivers function is now completed

D'Alesio, Murgia, CP, Taels, PRD 96 (2017)
D'Alesio, Flore, Murgia, CP, PRD 99 (2019)

Gluon Sivers function constrained from available data on $p^\uparrow p \to \pi^0 X$ and $p^\uparrow p \to DX$; predictions for $p^\uparrow p \to J/\psi X$ and $p^\uparrow p \to \gamma X$ at RHIC

Talk by F. Murgia, WG7

Two independent gluon Sivers functions 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

Bomhof, Mulders, JHEP 0702 (2007)
Buffing, Mukherjee, Mulders, PRD 88 (2013)

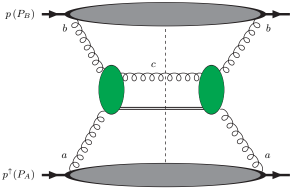
The two distributions have a different behavior under charge conjugation

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)

In the Color Singlet Model, the dominant production channel is $gg \to J/\psi\, g$

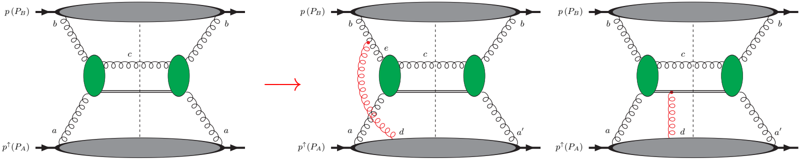


$$A_N \equiv \frac{\mathrm{d}\sigma^{\uparrow} - \mathrm{d}\sigma^{\downarrow}}{\mathrm{d}\sigma^{\uparrow} + \mathrm{d}\sigma^{\downarrow}} \equiv \frac{\mathrm{d}\Delta\sigma}{2\mathrm{d}\sigma}$$

$$\mathrm{d}\Delta\sigma^{\mathrm{GPM}} = \frac{2\alpha_s^3}{s} \int \frac{\mathrm{d}x_a}{x_a} \frac{\mathrm{d}x_b}{x_b}\, \mathrm{d}^2\boldsymbol{k}_{\perp a}\, \mathrm{d}^2\boldsymbol{k}_{\perp b}\, \delta(\hat{s} + \hat{t} + \hat{u} - M^2)$$
$$\times \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp g}(x_a, k_{\perp a}) \cos\phi_a\, f_{g/p}(x_b, k_{\perp b})\, H^U_{gg\to J/\psi g}(\hat{s}, \hat{t}, \hat{u})$$

$f_{1T}^{\perp g}$: Gluon Sivers function (one and process independent)

GPM | CGI-GPM

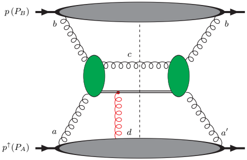


C_U | $C_I^{(f/d)}$ | $C_{F_c}^{(f/d)}$ [Color Factors]

$$[\text{GPM}]\;\; f_{1T}^{\perp\, g}\, H^U_{gg\to J/\psi g} \longrightarrow f_{1T}^{\perp\, g\,(f)} H^{\text{Inc}\,(f)}_{gg\to J/\psi g} + f_{1T}^{\perp\, g\,(d)} H^{\text{Inc}\,(d)}_{gg\to J/\psi g} \;\; [\text{CGI}-\text{GPM}]$$

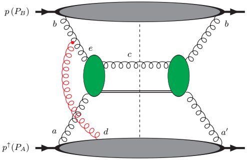
Two independent, universal $f_{1T}^{\perp}$'s, process dependence shifted into new hard parts

$$H^{\text{Inc}\,(f/d)}_{gg\to J/\psi g} \equiv \frac{C_I^{(f/d)} + C_{F_c}^{(f/d)}}{C_U}\, H^U_{gg\to J/\psi g}$$



$c\bar{c}$ pair in a color singlet state, no FSIs: $C_{F_c}^{(f)} = C_{F_d}^{(d)} = 0$

F. Yuan, PRD 78 (2003)



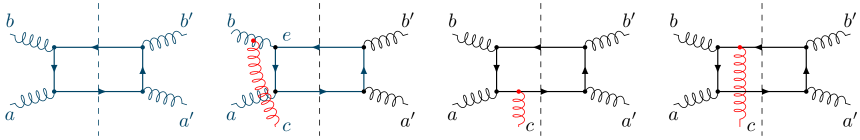
$$C_I^{(f)} = -\tfrac{1}{2}\, C_U \qquad C_I^{(d)} = 0$$

Only $f_{1T}^{\perp\, g\, (f)}$ contributes to A_N

$$\mathrm{d}\Delta\sigma^{\mathrm{CGI}} = \frac{2\alpha_s^3}{s} \int \frac{\mathrm{d}x_a}{x_a}\, \frac{\mathrm{d}x_b}{x_b}\, \mathrm{d}^2\boldsymbol{k}_{\perp a}\, \mathrm{d}^2\boldsymbol{k}_{\perp b}\, \delta(\hat{s}+\hat{t}+\hat{u}-M^2)$$
$$\times \left(-\frac{k_{\perp\, a}}{M_p}\right) f_{1T}^{\perp\, g\, (f)}(x_a, k_{\perp a}) \cos\phi_a\, f_{g/p}(x_b, k_{\perp b})\, H^{\mathrm{Inc}\,(f)}_{gg\to J/\psi g}(\hat{s}, \hat{t}, \hat{u})$$

$$H^{\mathrm{Inc}\,(f)}_{gg\to J/\psi g} = -\frac{1}{2}\, H^{U}_{gg\to J/\psi g}$$

LO channels are $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$. Color factors for $gg \to c\bar{c}$:



Agreement with *gluonic pole strenghts* calculated for $p^\uparrow p \to h\, h\, X$

$$C_G^{(f/d)} \equiv \frac{C_I^{(f/d)} + C_{F_c}^{(f/d)} + C_{F_d}^{(f/d)}}{C_U}$$

Bomhof, Mulders, JHEP 0702 (2007)

Agreement with twist-three results for $p^\uparrow p \to D X$

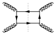
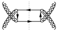
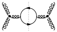
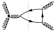
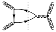
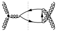
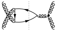
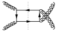
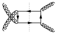
Kang, Qiu, Vogelsang, Yuan, PRD 78 (2008)

Both $f_{1T}^{\perp\, g\,(f)}$ and $f_{1T}^{\perp\, g\,(d)}$ contribute to $A_N(p^\uparrow p \to D X)$

Gluon Sivers function in $p^{\uparrow} p \to D X$

Color factors for $gg \to c\bar{c}$

$$C_I^{\mathrm{Inc}\,(f/d)} \equiv C_I^{(f/d)} + C_{F_c}^{(f/d)}$$

D	C_U	$C_I^{(f)}$	$C_{Fc}^{(f)}$	$C_{F_d}^{(f)}$	$C^{\mathrm{Inc}\,(f)}$	$C_I^{(d)}$	$C_{F_c}^{(d)}$	$C_{F_d}^{(d)}$	$C^{\mathrm{Inc}\,(d)}$
	$\frac{1}{4N_c}$	$-\frac{N_c}{8(N_c^2-1)}$	$\frac{1}{8N_c}$	$-\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	$\frac{1}{8N_c}$	$\frac{1}{8N_c(N_c^2-1)}$	$\frac{2N_c^2-1}{8N_c(N_c^2-1)}$
	$\frac{1}{4N_c}$	$-\frac{N_c}{8(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	$\frac{1}{8N_c}$	$-\frac{N_c^2+1}{8N_c(N_c^2-1)}$	$-\frac{N_c}{8(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c}$	$-\frac{N_c^2+1}{8N_c(N_c^2-1)}$
	$\frac{N_c}{2(N_c^2-1)}$	$-\frac{N_c}{4(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	$-\frac{N_c}{8(N_c^2-1)}$	0	$\frac{N_c}{8(N_c^2-1)}$	$-\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$
	$\frac{N_c}{4(N_c^2-1)}$	$-\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	0	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	$\frac{N_c}{4(N_c^2-1)}$
	$\frac{N_c}{4(N_c^2-1)}$	$-\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	0	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	$\frac{N_c}{4(N_c^2-1)}$
	$-\frac{N_c}{4(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	$-\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$
	$-\frac{N_c}{4(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	$-\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$	0	$\frac{N_c}{8(N_c^2-1)}$	$\frac{N_c}{8(N_c^2-1)}$
	$-\frac{1}{4N_c(N_c^2-1)}$	0	$-\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	0	$-\frac{1}{8N_c(N_c^2-1)}$	$\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$
	$-\frac{1}{4N_c(N_c^2-1)}$	0	$-\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$	0	$-\frac{1}{8N_c(N_c^2-1)}$	$\frac{1}{8N_c(N_c^2-1)}$	$-\frac{1}{8N_c(N_c^2-1)}$

D'Alesio, Murgia, Pisano, Taels, PRD 96 (2017)

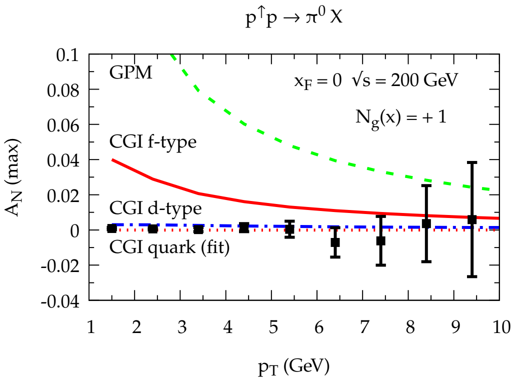
Modified hard functions $H^{\mathrm{Inc}\,(f/d)}$ are not simply proportional to H_U

Similar tables and results for all the channels in $p^{\uparrow} p \to \pi X$

D'Alesio, Flore, Murgia, Pisano, Taels, PRD 99 (2019)

Comparison with data and results

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

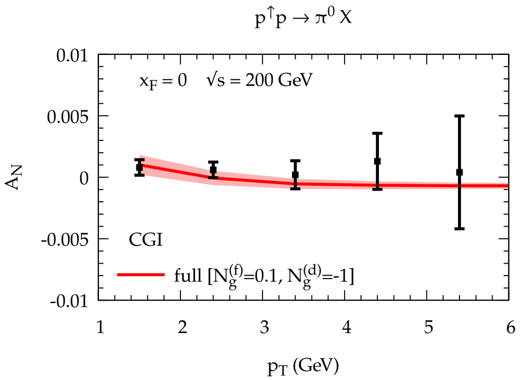


Maximized GSFs ($N_g = +1$)

PHENIX Collaboration, PRD 90 (2014)

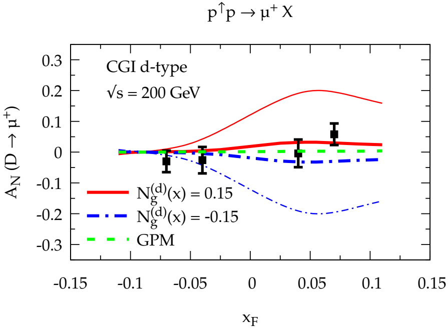
The f-type GSF is dominant in the CGI-GPM approach

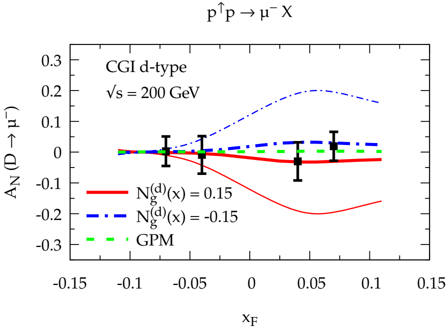
Reduced f-type GSF ($N_g^{(f)} = 0.1$), negative saturated d-type GSF ($N_g^{(d)} = -1$)



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: $N_g^{(d)} = -0.15 \Rightarrow N_g^{(f)} = +0.05$

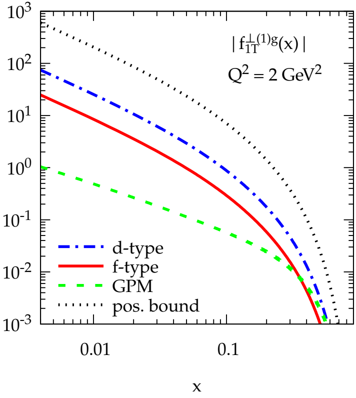




PHENIX Collaboration, PRD 95 (2017)

Muon SSAs obtained from our D-meson estimates by Jeongsu Bok (PHENIX)

First $k_\perp$-moment of the GSFs



- First attempt towards an extraction of the (process dependent) GSFs
- Data are not sufficient to discriminate between the GPM and the CGI-GPM