Probing the gluon Sivers function through direct photon production at RHIC

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Publications

The work presented in these slides is based on:

“Probing the gluon Sivers function through direct photon production at RHIC”, Rohini M. Godbole, AK, Anuradha Misra and Siddhesh Padval, *Phys. Rev. D* 99 (2019), 014003

Sivers function

The Sivers function is a transverse-momentum dependent PDF describing an azimuthal anisotropy in the $\boldsymbol{k}_\perp$ distribution of an unpolarized parton in a transversely polarized nucleon — it arises out of a spin-orbit coupling between the proton's spin and the parton's orbit.

$$f_{a/p^\uparrow}(x, \boldsymbol{k}_\perp) = f_{a/p}(x, k_\perp) + \Delta^N f_{a/p^\uparrow}(x, k_\perp)\ \mathbf{S}.(\mathbf{p} \times \mathbf{k}_\perp)$$

D. Sivers, Phys. Rev. D41, 83 (1990); 43, 261 (1991)

Anisotropy at parton level $\longrightarrow$ single transverse-spin asymmetry in final state

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

In this talk, we are interested in seeing if direct photon production in pp collisions can provide information on the poorly known gluon Sivers function (GSF).

Production of prompt photons at RHIC: $p^{\uparrow}p \rightarrow \gamma + X$

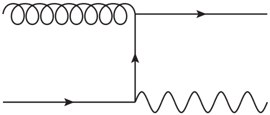
Prompt-photons are of two types:

- Direct photons: photons produced either at the hard scattering (through QCD Compton process, $gq \rightarrow \gamma q$ and $q\bar{q}$ annihilation $q\bar{q} \rightarrow \gamma g$) — $\mathcal{O}(\alpha_s \alpha_{\text{em}})$
- Fragmentation photons: produced in fragmentation of final state partons ($q, g \rightarrow \gamma + X$) — effectively at $\mathcal{O}(\alpha_s \alpha_{\text{em}})$ — need knowledge of fragmentation functions to calculate

Direct photons can be identified by applying isolation cone — but this is not perfect and does not completely eliminate fragmentation photons.

Production of prompt-photons in *pp* collions

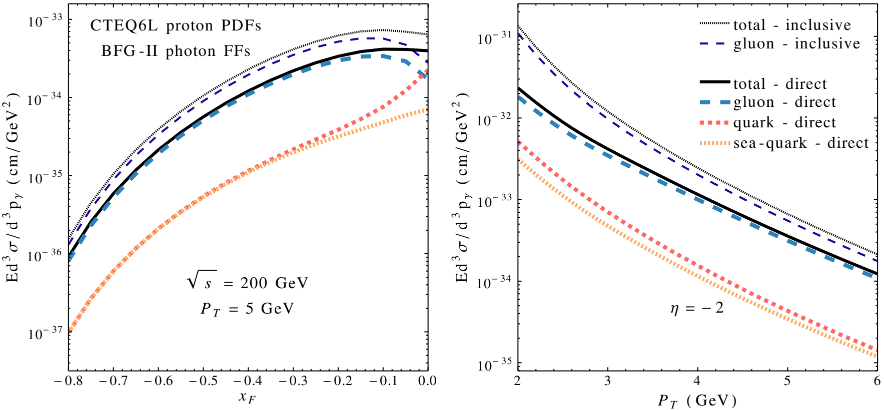
Direct photon production dominated by $gq \to \gamma q$ at RHIC kinematics — gives direct access to gluons — no issues with poorly known fragmentation functions



For this reason Schmidt, Soffer and Yang suggested direct-photon production in the *backward* hemisphere (i.e., in $x_F, y < 0$ with the transversely polarised proton taken as going *forward*) could give access to the GSF — production dominated by the $gq \to \gamma q$, with the gluon coming from the polarised proton.

I. Schmidt, J. Soffer and J. J. Yang, Phys. Lett. B 612, 258 (2005)

Cross-section for prompt-photons at RHIC



Plot above shows cross-section for direct-photon components (thick lines) as well inclusive (direct+fragmentation, thin lines) photons.

Asymmetry in a GPM framework

We first considered the asymmetry in this process ($p^{\uparrow}p \to \gamma + X$) in the context of a generalised parton model framework. That is, assuming that

- that a description in terms of TMDs can be used to describe this single hard scale process
- and that the TMDs can be treated as being universal

$$
\begin{aligned}
d\sigma^{\uparrow} - d\sigma^{\downarrow} &= \frac{\pi\alpha_s\alpha_{\rm em}}{\hat{s}^2}\sum_{a,b=g,q,\bar{q}}\int dx_a d^2\boldsymbol{k}_{\perp a} dx_b d^2\boldsymbol{k}_{\perp b}\ \Delta^N f_{a/p^{\uparrow}}(x_a,\boldsymbol{k}_{\perp a}) f_{b/p}(x_b,k_{\perp b}) \\
&\times \frac{\hat{s}}{x_a x_b s} H^U_{ab\to\gamma d}\frac{\hat{s}}{\pi}\delta(\hat{s}+\hat{t}+\hat{u})
\end{aligned}
$$

$$
\begin{aligned}
d\sigma^{\uparrow} + d\sigma^{\downarrow} &= \frac{\pi\alpha_s\alpha_{\rm em}}{\hat{s}^2}\sum_{a,b=g,q,\bar{q}}\int dx_a d^2\boldsymbol{k}_{\perp a} dx_b d^2\boldsymbol{k}_{\perp b}\ f_{a/p^{\uparrow}}(x_a,\boldsymbol{k}_{\perp a}) f_{b/p}(x_b,k_{\perp b}) \\
&\times \frac{\hat{s}}{x_a x_b s} H^U_{ab\to\gamma d}\frac{\hat{s}}{\pi}\delta(\hat{s}+\hat{t}+\hat{u})
\end{aligned}
$$

Parametrisation of TMDs

We used a factorised $k_\perp$-dependence for the TMDs.

Unpolarised TMD:

$$f_{i/p}(x, \mathbf{k}_\perp; Q) = f_{i/p}(x, Q) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}$$

with $\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2$

Sivers:

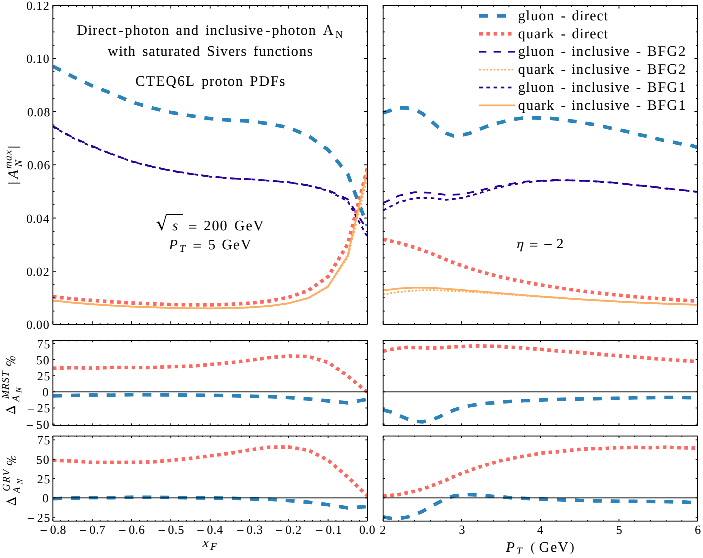
$$\Delta^N f_{i/p^\uparrow}(x, k_\perp; Q) = 2\mathcal{N}_i(x) f_{i/p}(x, Q) \frac{\sqrt{2e}}{\pi} \sqrt{\frac{1-\rho}{\rho}} k_\perp \frac{e^{-k_\perp^2/\rho\langle k_\perp^2 \rangle}}{\langle k_\perp^2 \rangle^{3/2}}$$

We consider the maximal gluon Sivers function as allowed by the positivity bound

$$\frac{|\Delta^N f_{g/p^\uparrow}(x, \mathbf{k}_\perp)|}{2 f_{g/p}(x, \mathbf{k}_\perp)} \leq 1$$

i.e. $\mathcal{N}_g(x) = 1$.

Results for SSA in $p^{\uparrow}p \rightarrow \gamma + X$



Results for SSA in $p^{\uparrow}p \rightarrow \gamma + X$

- Gluon contribution dominates in the $x_F < 0$ (backward) region.
- Saturated gluon Sivers function gives asymmetries of upto 8-10%.
- Results sensitive to choice of collinear PDFs.
- Inclusion of fragmentation photons dilutes the asymmetry somewhat.

Process dependence of GSF and QSF in $p^{\uparrow}p \to \gamma + X$

Next we relax the assumption that the TMDs are universal.

As is well known, they are not: $\Delta^N f_{q/p^{\uparrow}}|_{\text{SIDIS}} = -\Delta^N f_{q/p^{\uparrow}}|_{\text{DY}}$

This is due to process-dependent Wilson lines in the TMDs, i.e., process-dependent is due to initial state (IS) and final state (FS) interactions.

In more complicated processes (such as the one we consider), the effects of these initial and final state interactions are more complicated. It is not as simple as a sign change.

The Colour-Gauge Invariant Generalised Parton Model (CGI-GPM) formalism allows us to determine the manner in which the IS/FS interactions affect the universality of the Sivers functions.
Gamberg and Kang, Phys. Lett. B696 (2011) 109-118
D'Alesio, Murgia, Pisano and Taels., Phys. Rev. D96 036011 (2017)

Process dependence of GSF and QSF in $p^\uparrow p \to \gamma + X$

In this framework,

- the IS/FS effects can be absorbed into modified partonic hard parts,
- two independent GSFs — f-type and d-type can contribute.

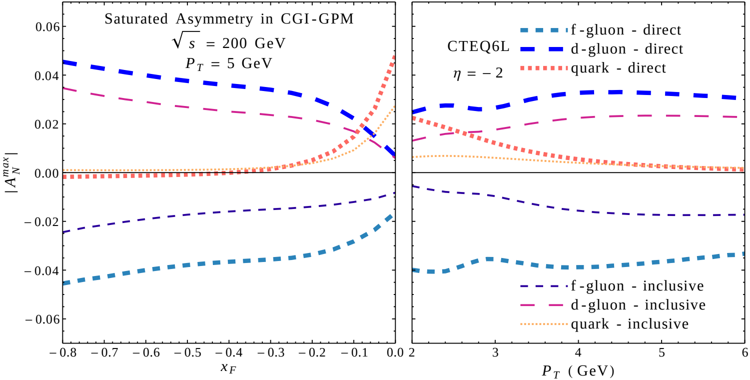
We calculated modified hard parts for photon production in gluon initiated processes $gq \to \gamma q$ and $g\bar{q} \to \gamma\bar{q}$, for both independent GSFs:

$$\begin{aligned} H^{(f)}_{gq\to\gamma q} &= H^{(f)}_{g\bar{q}\to\gamma\bar{q}} = -\frac{1}{2} H^{U}_{gq\to\gamma q} \\ H^{(d)}_{gq\to\gamma q} &= -H^{(d)}_{g\bar{q}\to\gamma\bar{q}} = \frac{1}{2} H^{U}_{gq\to\gamma q} \end{aligned}$$

where

$$H^{U}_{gq\to\gamma q} = -\frac{e_q^2}{N_c}\left[\frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}}\right]$$

Results for SSA in $p^{\uparrow}p \to \gamma + X$



- Inclusion of IS/FS effects with CGI-GPM leads to asymmetry estimates being roughly halved — around 3-4%
- However, dominance of gluon contribution over quark contribution increases significantly for $x_F < -0.3$.
- both f and d type GSFs can have non-zero contributions to this process

Conclusions

- Direct photon in the $x_F < 0$ region at RHIC could provide information on the gluon Sivers function.
- Burkardt Sum Rule constrains the f-type GSF — asymmetries of upto 0.1% — no bounds on asymmetry from d-type GSF (apart from positivity)

Thank you!