Prompt Photon Production as a probe of Gluon Sivers Function

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Based on:

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

“Gluon Sivers Function and Transverse Single Spin Asymmetries in $e + p \uparrow \rightarrow \gamma + X$”, SP, Rohini M. Godbole, Abhiram Kaushik, Anuradha Misra, and Vaibhav S. Rawoot (in preparation)
Sivers asymmetry

- Sivers effect: The distribution of quarks and gluons in a spin-1/2 hadron that is polarised transversely to its momentum need not be left-right symmetric with respect to the plane spanned by its momentum and spin directions.
- It results in angular asymmetries of produced particles.
- Single Transverse-spin asymmetry (SSA) is defined as the ratio of the difference and the sum of the cross sections when the hadron’s spin vector $S_\perp$ is flipped.

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\Delta\sigma}{2d\sigma}$$
The Sivers function, $\Delta^N f_{i/p}^\uparrow(x, k_\perp; Q)$ describes the azimuthal anisotropy in the transverse momentum distribution of an unpolarised parton in a transversely polarised hadron.

\[
f_{i/h}^\uparrow(x, k_\perp, S; Q) = f_{i/h}(x, k_\perp; Q) + \frac{1}{2} \Delta^N f_{i/h}^\uparrow(x, k_\perp; Q) S.(\hat{P} \times \hat{k}_\perp) = f_{i/h}(x, k_\perp; Q) + \frac{1}{2} \Delta^N f_{i/h}^\uparrow(x, k_\perp; Q) \cos \phi_\perp
\]

Fits are available for quark Sivers functions (QSFs):


A first indirect estimate of the gluon Sivers function (GSF):


Processes proposed to probe GSF —
Open charm and closed production:


In this talk, we are interested in seeing if direct photon production in proton-proton and electron-proton collisions can provide information on the poorly known gluon Sivers function (GSF).
Prompt photons at RHIC

Prompt photons in proton-proton collisions have two contributions:

- **Direct Contributions:** photons produced at the hard scattering through QCD Compton process, \( gq \rightarrow \gamma q \) and quark-antiquark annihilation \( q\bar{q} \rightarrow \gamma g \)
  
  \[ \mathcal{O}(\alpha_{em}\alpha_s) \]

- **Fragmentation Contributions:** photons produced at leading order through the standard 2-to-2 QCD parton scattering processes with the final-state parton fragmenting into a photon \( (q, g \rightarrow \gamma + X) \)
  
  \[ \mathcal{O}(\alpha_{em}\alpha_s) \]

Isolation cuts can be applied to separate out these contributions.
Direct photon production in pp collisions is dominated by QCD Compton process, $gq \rightarrow \gamma q$

For this reason Schmidt, Soffer and Yang suggested that 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 $gq \rightarrow \gamma q$, with the gluon coming from the polarised proton.

Cross-section for prompt-photons at RHIC

CTEQ6L proton PDFs
BFG-II photon FFs

$s = 200$ GeV
$P_T = 5$ GeV

Plot above shows cross-section for direct-photon components (thick lines) as well inclusive (direct+fragmentation, thin lines) photons.
Asymmetry in a Generalized Parton Model (GPM)

So far, TMD factorization has been demonstrated only for processes which have two scales:

- Hard scale (e.g. virtuality of the photon in the DY)
- Soft scale (of the order of $\Lambda_{QCD}$)

*M. G. Echevarria, “Proper TMD factorization for quarkonia production: $pp \rightarrow \eta_c$ as a study case”, arXiv:1907.06494*

Generalized Parton Model (GPM) based on the assumptions:

- *TMD factorization holds* for single hard scale process.
- TMDs are *process independent*. 
Successes of GPM:

- Reasonable agreement with a large set of experimental data for unpolarized cross sections for $pp \rightarrow \gamma, \pi + X$ (complemented with proper NLO K-factors); better than collinear LO or NLO calculations.
- Provides a good description on SSA in $pp \rightarrow \pi + X$
Asymmetry in a GPM framework

For *direct photons*, we can write the denominator and numerator of $A_n$ as,

$$d\sigma^\uparrow + d\sigma^\downarrow = \frac{E_\gamma d\sigma_{p^\uparrow p \to \gamma X}}{d^3p_\gamma} + \frac{E_\gamma d\sigma_{p^\downarrow p \to \gamma X}}{d^3p_\gamma}$$

$$= \frac{2\pi\alpha_s\alpha_{em}}{\hat{s}^2} \sum_{a,b=g,q,\bar{q}} \int dxa d^2k_a dx_b d^2k_b \hat{f}_{a/p}(x_a, k_{\perp a}) \hat{f}_{b/p}(x_b, k_{\perp b})$$

$$\times \frac{\hat{s}}{x_ax_b s} H^U_{ab \to \gamma d} \frac{\hat{s}}{\pi} \delta(\hat{s} + \hat{t} + \hat{u})$$

$$d\sigma^\uparrow - d\sigma^\downarrow = \frac{E_\gamma d\sigma_{p^\uparrow p \to \gamma X}}{d^3p_\gamma} - \frac{E_\gamma d\sigma_{p^\downarrow p \to \gamma X}}{d^3p_\gamma}$$

$$= \frac{\pi\alpha_s\alpha_{em}}{\hat{s}^2} \sum_{a,b=g,q,\bar{q}} \int dxa d^2k_a dx_b d^2k_b \Delta^N f_{a/p}^\uparrow(x_a, k_{\perp a}) f_{b/p}(x_b, k_{\perp b})$$

$$\times \frac{\hat{s}}{x_ax_b s} H^U_{ab \to \gamma d} \frac{\hat{s}}{\pi} \delta(\hat{s} + \hat{t} + \hat{u})$$
Parametrisation of TMDs

For the unpolarised TMDs we adopt the commonly used form with the collinear PDF multiplied by a Gaussian transverse momentum dependence

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

with \( \langle k_\perp^2 \rangle = 0.25 \ \text{GeV}^2 \).

Sivers:

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


Sivers function satisfies the positivity bound

\[ \frac{|\Delta^N f_{i/p}(x, k_\perp)|}{2 f_{i/p}(x, k_\perp)} \leq 1 \ \forall \ x, k_\perp \]
Quark and gluon Sivers functions with the positivity bound saturated, viz. $\mathcal{N}_i(x) = 1$.

Using the saturated Sivers functions for quarks and gluons allows us to study —

- The general *kinematic dependencies of the asymmetry* and the *relative importances of quark and gluon contributions* to the asymmetry.
- How *uncertainties in the knowledge of the collinear, unpolarised gluon and sea quark densities* might impact the probe.
Results for SSA in $p^{↑}p \rightarrow \gamma + X$ in GPM

Direct-photon and inclusive-photon $A_N$
with saturated Sivers functions

CTEQ6L proton PDFs

$\sqrt{s} = 200$ GeV
$P_T = 5$ GeV

$\eta = -2$

$|A_N^{\text{max}}|$ vs $x_F$

$\Delta A_N^{\text{MRST}}$ vs $x_F$

$\Delta A_N^{\text{GRV}}$ vs $x_F$

$\Delta A_N^{\text{BFG1}}$ vs $x_F$

$\Delta A_N^{\text{BFG2}}$ vs $x_F$

$\Delta A_N^{\text{BFG1}}$ vs $P_T$

$\Delta A_N^{\text{BFG2}}$ vs $P_T$

$\Delta A_N^{\text{CTEQ6L}}$ vs $P_T$
Conclusions

- Gluon contribution dominates in the $x_F < 0$ (backward) region.
- Saturated gluon Sivers function gives asymmetries of up to 8–10%.
- Results sensitive to choice of collinear PDFs.
- Inclusion of fragmentation photons dilutes the asymmetry somewhat.
Colour-Gauge Invariant Generalised Parton Model (CGI-GPM)

- Takes into account effects of initial-state (IS) and final-state (FS) interactions between the struck parton and spectators from the polarized proton on the numerator of the asymmetry.
- These interactions make TMD densities to be process dependent.

\[ \Delta^N f_{q/p^\uparrow} \bigg|_{\text{SIDIS}} = - \Delta^N f_{q/p^\uparrow} \bigg|_{\text{DY}} \]

In Colour-Gauge Invariant Generalised Parton Model (CGI-GPM), process dependence of the Sivers function is shifted to the squared hard partonic scattering amplitude under one-gluon exchange approximation.


Process dependent GSF in CGI-GPM is expressed as a linear combination of two independent and universal gluon distributions— $f$-type and $d$-type GSFs.

\[
H^{(f)}_{gq \to \gamma q} = H^{(f)}_{g \bar{q} \to \gamma \bar{q}} = -\frac{1}{2} H^U_{gq \to \gamma q}
\]

\[
H^{(d)}_{gq \to \gamma q} = -H^{(d)}_{g \bar{q} \to \gamma \bar{q}} = \frac{1}{2} H^U_{gq \to \gamma q}
\]

with,

\[
H^U_{gq \to \gamma q} = -\frac{e_q^2}{N_c} \left( \frac{\hat{u}}{\hat{s}} + \frac{\hat{s}}{\hat{u}} \right)
\]
$$H_{qq\rightarrow\gamma g}^{\text{mod}} = -H_{\bar{q}q\rightarrow\gamma g}^{\text{mod}} = \frac{e_q^2}{N_c^2} \left( \frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} \right)$$

$$H_{qg\rightarrow\gamma q}^{\text{mod}} = -H_{\bar{q}g\rightarrow\gamma q}^{\text{mod}} = -\frac{N_c}{N_c^2 - 1} e_q^2 \left( \frac{\hat{t}}{\hat{s}} + \frac{\hat{s}}{\hat{t}} \right)$$

with,

$$H_{qq\rightarrow\gamma g}^{U} = \frac{N_c^2 - 1}{N_c^2} e_q^2 \left( \frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} \right), \quad H_{qg\rightarrow\gamma q}^{U} = -\frac{N_c^2 - 1}{N_c} e_q^2 \left( \frac{\hat{t}}{\hat{s}} + \frac{\hat{s}}{\hat{t}} \right)$$
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 $x_F < 0.3$. 

In electron-proton collisions, prompt photons can be produced via:

- **Direct contribution**: $q\gamma \rightarrow \gamma q$
- **Fragmentation contributions**
- **Resolved contributions** —
  the photon emitted by the electron fluctuates into a partonic state and a gluon and/or a quark of this fluctuation takes part in the hard scattering.
For the Weizsäcker-Williams distribution function, $f_{\gamma/e}(x_{\gamma})$, following parametrization has been used.

$$f_{\gamma/e}(x_{\gamma}) = \frac{\alpha}{2\pi} \left[ 2m_e^2x_{\gamma} \left( \frac{1}{Q_{\text{min}}^2} - \frac{1}{Q_{\text{max}}^2} \right) + \frac{1 + (1 - x_{\gamma})^2}{x_{\gamma}} \ln \frac{Q_{\text{max}}^2}{Q_{\text{min}}^2} \right]$$

where $\alpha$ is the electromagnetic coupling and $Q_{\text{min}}^2 = m_e^2 \frac{x_{\gamma}^2}{1 - x_{\gamma}}$, $m_e$ being the electron mass.


And resolved distribution available in the literature (AFG)

Results for SSA in $e^- p^\uparrow \rightarrow \gamma + X$ (preliminary results)

Plot above shows unpolarised cross-section for direct-photon in electron-proton collisions at left and $|A_n^{\text{max}}|$ at right.
Conclusions

- Saturated QSF gives asymmetries of up to 8 to 12% while saturated GSF gives asymmetries of up to 1 to 2% in GPM.
- Negligible asymmetries due to quark Sivers function in CGI-GPM.
- No d-type GSF contribution in CGI-GPM.
- Only f-type GSF contributes (around 1%) to the asymmetry in CGI-GPM.
Thank you