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.

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

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

Fits are available for quark Sivers functions (QSFs):
Anselmino et. al., Eur. Phys. J. A 39, 89 (2009)
Anselmino et. al., Phys. Rev. D 72, 094007 (2005)

A first indirect estimate of the gluon Sivers function (GSF):
D'Alesio, Murgia, and Pisano, J. High Energy Phys. 09 (2015) 119

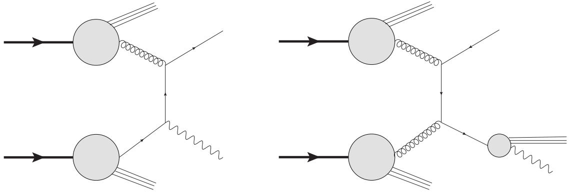
Processes proposed to probe GSF —
Open charm and closed production:
Godbole, Kaushik, and Misra, Phys. Rev. D 97, 076001 (2018)
Godbole, Kaushik, and Misra, Phys. Rev. D 94, 114022 (2016)
Godbole, Kaushik, A. Misra, and Rawoot, Phys. Rev. D 91, 014005 (2015)
Godbole, Misra, Mukherjee, and Rawoot, Phys. Rev. D 85, 094013 (2012)

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, $gq \to \gamma q$ and quark-antiquark annihilation $q\bar{q} \to \gamma g$
  — $\mathcal{O}(\alpha_{em}\alpha_s)$
- **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 $(q, g \to \gamma + X)$
  — effectively $\mathcal{O}(\alpha_{em}\alpha_s)$



Isolation cuts can be applied to separate out thsese contributions.

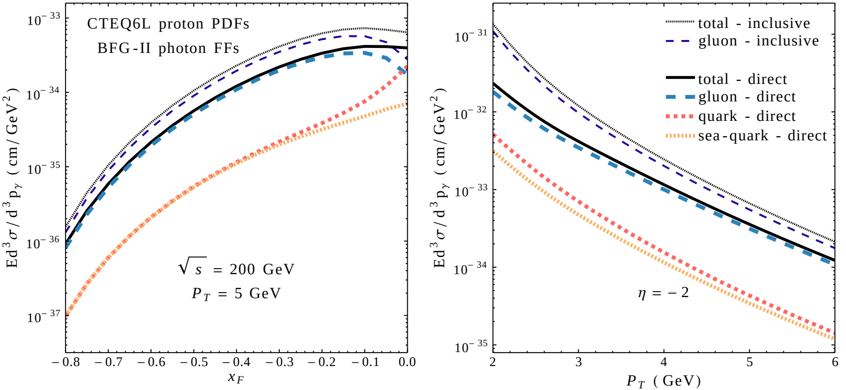
Direct photon as a probe of gluon distribution

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.

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 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 Λ_{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 $pp \to \gamma, \pi + X$ (complemented with proper NLO K-factors); better than collinear LO or NLO calculations.
- Provides a good description on SSA in $pp \to \pi + X$

Asymmetry in a GPM framework

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

$$d\sigma^{\uparrow} + d\sigma^{\downarrow} = \frac{E_\gamma \, d\sigma^{p^{\uparrow}p\to\gamma X}}{d^3\boldsymbol{p}_\gamma} + \frac{E_\gamma \, d\sigma^{p^{\downarrow}p\to\gamma X}}{d^3\boldsymbol{p}_\gamma}$$

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

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

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = \frac{E_\gamma \, d\sigma^{p^{\uparrow}p\to\gamma X}}{d^3\boldsymbol{p}_\gamma} - \frac{E_\gamma \, d\sigma^{p^{\downarrow}p\to\gamma X}}{d^3\boldsymbol{p}_\gamma}$$

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

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

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:

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

D'Alesio , Murgia and Pisano, J. High Energ. Phys. (2015) 2015: 119.
Sivers function satisfies the positivity bound

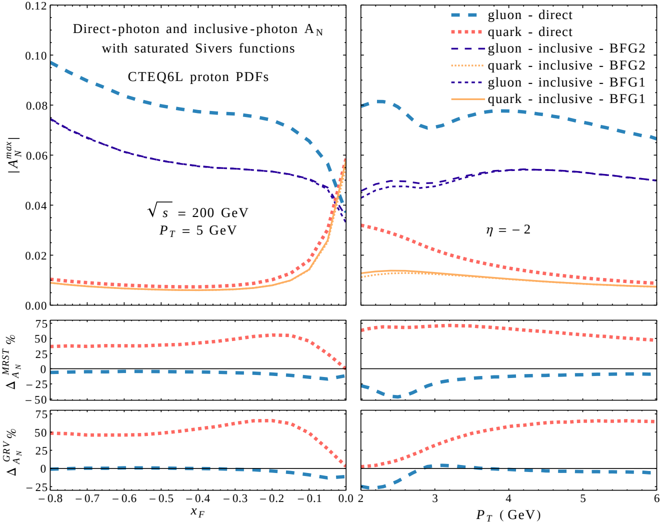
$$\frac{|\Delta^N f_{i/p^\uparrow}(x, k_\perp)|}{2f_{i/p}(x, k_\perp)} \leq 1\,\forall\, x, k_\perp$$

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 $p^{\uparrow}p \to \gamma + X$ in GPM



Conclusions

- 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.

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*.

$$\Delta^N f_{q/p^\uparrow}\Big|_{SIDIS} = - \Delta^N f_{q/p^\uparrow}\Big|_{DY}$$

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.

Gamberg and Kang, Phys. Lett. B696 (2011) 109-118
D'Alesio, Murgia, Pisano and Taels, Phys. Rev. D96 036011 (2017)

Process dependence of Sivers function in $p^{\uparrow}p \to \gamma + X$

Feynman rules in CGI-GPM: *D'Alesio, Murgia, Pisano and Taels, Phys. Rev. D96 036011 (2017)*

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,

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

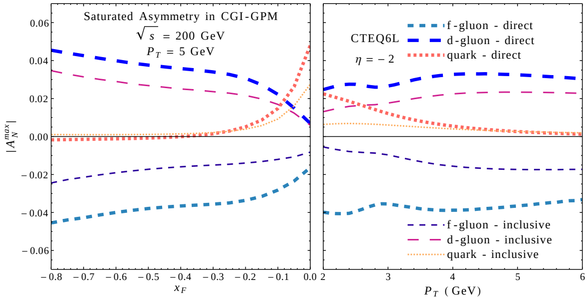
$$H^{mod}_{q\bar{q}\to\gamma g} = -H^{mod}_{\bar{q}q\to\gamma g} = \frac{e_q^2}{N_c^2}\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}}\right)$$

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

with,

$$H^{U}_{q\bar{q}\to\gamma g} = \frac{N_c^2 - 1}{N_c^2}e_q^2\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}}\right), \qquad H^{U}_{qg\to\gamma q} = -\frac{e_q^2}{N_c}\left(\frac{\hat{t}}{\hat{s}} + \frac{\hat{s}}{\hat{t}}\right)$$

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

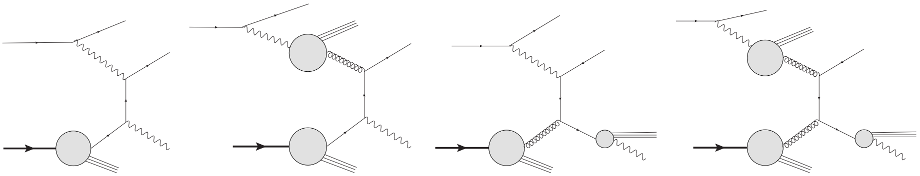


- Inclusion of IS/FS effects with CGI-GPM leads to asymmetry estimates being roughly halved — around $3 - 4\%$.
- However, dominance of gluon contribution over quark contribution increases significantly for $x_F < 0.3$.

Prompt photons at EIC

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

- Direct contribution: $q\gamma \to \gamma q$
- 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 Weizsäker-Williams distribution function, $f_{\gamma/e}(x_\gamma)$, following parametrization has been used.

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

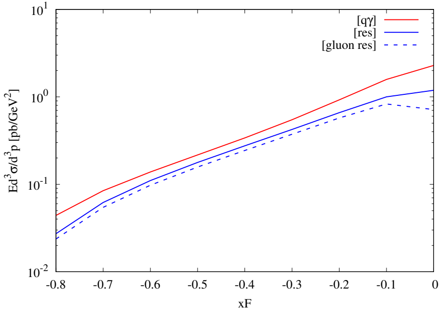
where α is the electromagnetic coupling and $Q_{min}^2 = m_e^2 \frac{x_\gamma^2}{1-x_\gamma}$, m_e being the electron mass.

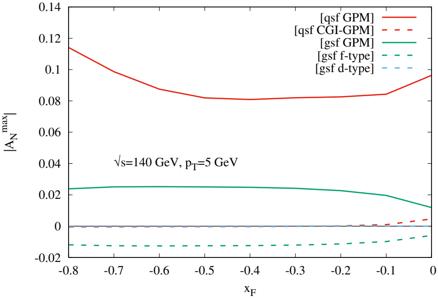
Frixione, Mangano, Nason, and Ridolfi, Phys. Lett. B319, 339 (1993)

And resolved distribution available in the literature (AFG)

Aurenche, Fontannaz, and Guillet, Eur. Phys. J. C (2005) 44: 395.

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





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

Conclusions

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

Thank you