Isolated Photons at Hadron Colliders at $O(\alpha\alpha_s^2)(\II)$: Spin Dependent Case

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Abstract

The cross section for inclusive prompt photon production with polarized hadron beams is calculated at order $\alpha\alpha_s^2$ using the phase space slicing or analytic/Monte Carlo method. Isolation cuts are placed on the photon and the results are compared to a previous fully analytic calculation. Numerical results for the isolated cross section are presented for $\bar{p}p \rightarrow \gamma + X$ at RHIC center-of-mass energies with plausible isolation parameters using the most modern polarized parton densities evolved in next-to-leading order QCD. The perturbative stability of the asymmetries and scale dependence of the results are briefly discussed.
I. INTRODUCTION

Prompt photon production is at the top of the list of the most important processes to be studied at the BNL Relativistic Heavy Ion Collider (RHIC) which is expected to start taking data in the next few years. It is well established as one of the main processes which is sensitive to the polarized gluon density of the proton $\Delta G$. This is mainly because the cross section is dominated by the quark-gluon scattering process $qq \rightarrow \gamma + X$ which contributes at leading order (LO). Another factor in the importance of this process is that photons are in principle experimentally more simple to detect, and hence the kinematic variables can be more accurately determined as compared to high transverse momentum ($p_T$) jets, for example. Unfortunately, in practice this is not always the case. At collider energies experimentalists are forced to impose isolation cuts on the photon in order to accurately detect it from among the copious hadronic debris produced simultaneously in the high energy collisions. In effect what is detected in many cases is a photon in a jet, where the jet energy is restricted by the isolation cuts.

The isolation procedure has proved difficult to implement in a theoretically consistent way especially on the component of the cross section where the photon is produced by bremsstrahlung off a final state parton, the fragmentation component. This happens to be the component of the cross section most affected by the isolation procedure since the photon is always accompanied by a jet in this case. These difficulties have restricted the usefulness of prompt photon production for extracting information on gluon distributions in the unpolarized case since they highlight the fact that isolation is not yet theoretically fully understood. In fact there is at present some controversy pertaining to the use of the conventional factorization theorem in the infrared regions of phase space for the fragmentation contribution in NLO [1,2] when isolation cuts are imposed.

Since in spite of these difficulties prompt photon production has proved useful for helping to constrain the unpolarized gluon distributions, it has been suggested that it might also be useful in the case of the polarized gluon distribution $\Delta G$ [3], about which little or no
experimental information is presently available. The spin structure of nucleons has been a
topic of much activity ever since the European Muon Collaboration (EMC) first published
results of a measurement of the first moment of the spin-dependent proton structure function
\( g_1^p(x, Q^2) \) \[4\], obtained from polarized deep inelastic scattering experiments. The results were
in disagreement with the Ellis-Jaffe sum rule which is based on the naive parton model \[5\] and
suggested that much less of the nucleon spin was carried by quarks than would be expected
from this model. Since that time much progress has been made on the understanding of the
problem on the theoretical front and new more precise data have also become available, which
on average reduces somewhat the discrepancy with parton model expectations \[6\] although
still leaving a very significant one. Most of the progress that can be made from purely
theoretical investigations alone has now been achieved and therefore activity is at present
more focussed on obtaining more precise experimental information on the spin structure of
the nucleons.

Deep inelastic scattering processes do not directly probe the gluon structure of hadrons
since photons do not couple directly to gluons, and hence only limited further information
on \( \Delta G \) can be obtained from this source via processes such as heavy quark or two jet
production. One must therefore look at other scattering processes which involve a direct
gluon coupling. Prompt photon production is one such process, but others have also been
suggested and some have been calculated in NLO \[7,8\]. In this context, inclusive prompt
photon production with polarized beam and target, \( p\bar{p} \rightarrow \gamma + X \), was first examined in LO
\[3\] and shown to be sensitive to \( \Delta G \). Sizeable asymmetries were also predicted, indicating
a sensitivity to polarization effects. The NLO corrections were calculated in \[9\] and \[10\],
numerical estimates were also presented and it was established that the LO results were
perturbatively stable.

In \[9\] and \[10\] the phase space integrations were carried out analytically, hence isolation
restrictions could not be imposed. Furthermore, at that time only LO parton distributions
were available so a fully consistent NLO analysis could not be performed. Recently, due to
the calculation of the spin dependent splitting functions at NLO \[11\], new polarized parton
distributions evolved fully in NLO QCD, which take into account all recent data have become available [12–15]. In these analyses different assumptions are made about both the size and shape of $\Delta G$ which is hardly constrained by the available data. This is reflected in the fact that in general they each give more than one parametrization of the polarized parton densities each having a different input for $\Delta G$. In [17] we recently provided estimates for the polarized non-isolated prompt photon cross section at energies relevant for the proposed HERA-$\bar{N}$ collider, using these new polarized parton distributions. In this paper this analysis is extended the case of the RHIC collider with the inclusion of isolation restrictions on the photon. In this case the calculation is carried out using the Monte Carlo method. Recently [16] the analytic calculation of [9] was updated to include the use of NLO structure functions. In this calculation the authors chose to completely ignore the fragmentation contributions, and of course isolation effects are not included since the calculation was done analytically.

In [19] the results of the analytic and Monte Carlo methods of calculating both the inclusive and isolated cross sections were compared for both the polarized and unpolarized cases and exact agreement was found as expected for the inclusive case. For the isolated case agreement was found over a wide range of the isolation parameters for centrally produced photons. As expected there are regions where the analytic method breaks down. It gives results in disagreement with the Monte Carlo method for very large ($R \geq 1$) or very small ($R \leq 0.1$) isolation cone sizes, or at rapidities away from the central regions. It is therefore useful to calculate the polarized cross section using the more robust and flexible Monte Carlo method, particularly since the values of the isolation parameters necessary for RHIC have not yet been decided. If it turns out that they are chosen outside the range where the analytic calculation is valid then it will be useful to have the Monte Carlo calculation. The details of the calculation can be found in [8] where it was applied to prompt photon plus jet production.

In the unpolarized case the cross section was first calculated in [20] using the Monte Carlo method, and this calculation is thus the second calculation in this case. A new feature in the present calculation is that the various subprocess contributions are kept separate which
allows one to tell how much of the cross section is due to $qg$ or $q\bar{q}$ scattering, for example. This information could be useful if one is interested in the sensitivity of the cross section to the gluon distribution. For the polarized case, the present calculation is the first using this method.

The only major drawback of the present calculation is that the fragmentation contributions can only be calculated in LO since the matrix elements for the NLO case have not yet been calculated. In this study an attempt is made to assess the importance of these contributions at RHIC center-of-mass (cms) energies. Since RHIC is expected to run at different cms energies between 50 and 500 GeV, it is possible that the fragmentation contributions may not be numerically important at the lower energies, thereby reducing the need to impose isolation cuts on the photon, or at least reducing the theoretical uncertainty from incomplete calculations of these contributions.

The rest of this paper is as follows; in section II a brief theoretical background to the calculations is given in order to make the paper as self contained as possible. In section III numerical results are presented for the polarized and unpolarized cross sections at RHIC, and in section IV the conclusions are given.

II. ISOLATED PROMPT PHOTONS

In this section a brief description of the ingredients used in the calculation of the inclusive and isolated prompt photon cross sections is given in order to make the paper as self contained as possible. More details of the calculation can be found in refs. [8][9]. Only the polarized case is discussed explicitly but all the arguments are valid in the unpolarized case with the replacements discussed at the end of the section.

Contributions to the prompt photon cross section are usually separated into two classes in both LO and NLO. There are the so-called direct processes, $ab \rightarrow \gamma c$ in LO and $ab \rightarrow \gamma cd$, in NLO, $a, b, c$ and $d$ referring to partons, where the photon is produced directly in the hard scattering. In addition there are the fragmentation contributions where the photon
is produced via bremsstrahlung off a final state quark or gluon, $ab \to cd(e)$ followed by $c- \to \gamma + X$ for instance.

Experimentally, a prompt photon is considered isolated if inside a cone of radius $R$ centered on the photon the hadronic energy is less than $\epsilon E_\gamma$, where $E_\gamma$ is the photon energy and $\epsilon$ is the energy resolution parameter, typically $\epsilon \sim 0.1$. The radius of the circle defined by the isolation cone is given in the pseudo-rapidity $\eta$ and azimuthal angle $\phi$-plane by $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. In the case of a small cone the parameter used is the half angle of the cone, $\delta$, where $\delta \approx R$ for small rapidities of the photon. The exact relation is $R = \delta / \cosh \eta$.

A. The LO Case

In LO, $O(\alpha_\alpha s)$, the direct subprocesses contributing to the cross section are

\[ qq \to \gamma q \]
\[ q\bar{q} \to \gamma g. \]  \hspace{1cm} (2.1)

In addition there are the fragmentation processes

\[ qq \to gg \]
\[ qq \to qq \]
\[ qq' \to qq' \]
\[ q\bar{q} \to q\bar{q} \]
\[ q\bar{q} \to gg \]
\[ gg \to gg \]
\[ gg \to q\bar{q} \]  \hspace{1cm} (2.2)

where one of the final state partons fragments to produce the photon, i.e., $q(g) \to \gamma + X$.

In the direct processes in LO, the photon is always isolated since it must always balance
the transverse momentum $p_T$ of the other final state parton and is thus always in the opposite hemisphere. In this case the differential cross section is given by

$$E_\gamma \frac{d\Delta \sigma_{LO}^{\text{dir}}}{d^3 p_T} = \frac{1}{\pi S} \sum_{i,j} \int_0^1 \frac{dv}{1-v} \int_{VW/v}^1 \Delta f_1^i(x_1, M^2) \Delta f_2^j(x_2, M^2) \frac{1}{v} \frac{d\Delta \sigma_{ij-\gamma}}{dv} \delta(1-w) \quad (2.3)$$

where $S = (P_1 + P_2)^2$, $V = 1 + T/S$, $W = -U/(T + S)$, $v = 1 + \hat{t}/\hat{s}$, $w = -\hat{u}/(\hat{t} + \hat{s})$, $\hat{s} = x_1 x_2 S$, and $T = (P_1 - P_\gamma)^2$ and $U = (P_2 - P_\gamma)^2$. As usual the Mandelstam variables are defined in the upper case for the hadron-hadron system and in lower case in the parton-parton system. $P_1$ and $P_2$ are the momenta of the incoming hadrons and $f_1^i(x_1, M^2)$ and $f_2^j(x_2, M^2)$ represent the respective probabilities of finding parton $i$ and $j$ in hadrons 1 and 2 with momentum fractions $x_1$ and $x_2$ at scale $M^2$.

For the fragmentation processes, the photon is always produced nearly collinearly to the fragmenting parton and an isolation cut must be placed on the cross section to remove the remnants of the fragmenting parton if it has more energy than $\epsilon E_\gamma$. In this case this restriction is quite easy to implement. The inclusive differential cross section is given by

$$E_\gamma \frac{d\Delta \sigma_{\text{frag}}^{\text{incl}}}{d^3 p_T} = \frac{1}{\pi S} \sum_{i,j,l} \int_0^1 \frac{dz}{z^2} \int_{VW/z}^1 \frac{dv}{1-v} \int_{VW/vz}^1 \frac{dw}{w} \Delta f_1^i(x_1, M^2) \Delta f_2^j(x_2, M^2) \times \frac{1}{v} \frac{d\Delta \sigma_{ij-\gamma}}{dv} \delta(1-w) D_{\gamma/l}^j(z, M_f^2), \quad (2.4)$$

where $D_{\gamma/l}^j(z, M_f^2)$ represents the probability that the parton labelled $l$ fragments to a photon with a momentum fraction $z$ of its own momentum at scale $M_f^2$ (note that $D_{\gamma/l}^j(z, M_f^2)$ is the usual unpolarized fragmentation function, since the final state is not polarized). This is the non-perturbative fragmentation function which must be obtained from experiment at some scale and evolved to $M_f^2$ using the usual evolution equations. This means that in order to obtain the isolated cross section we simply have to cut on the variable $z$. If isolation is defined in the usual way by only accepting events with hadronic energy less than fraction $\epsilon$ in a cone of radius $R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ drawn in the pseudo-rapidity azimuthal angle plane around the photon, then the hadronic remnants of the fragmenting parton will always automatically be inside the cone with the photon, for suitable choices of $M_f$, and the isolated cross section is given by the equation
\[
E_\gamma \frac{d\sigma^{isol}_{\text{frag}}}{d^3p_\gamma} = \frac{1}{\pi S} \sum_{i,j,l} \int_{\text{Max}[z_{\text{min}},(1+\epsilon)/V]}^{1} \frac{dz}{z^2} \int_{VW/vz}^{1-(1-V)/z} \frac{dv}{1-v} \int_{vW/vz}^{1} \frac{dw}{w} \\
\times \Delta f_1(x_1, M^2) \Delta f_2(x_2, M^2) \frac{1}{v} \frac{d\sigma_{ij \rightarrow \ell}}{dv} \delta(1-w) D'_\ell(z, M_f^2),
\]

(2.5)

where \(z_{\text{min}} = 1-V+VW\). It is also suggested that the fragmentation scale should be replaced by \((RM_f)\) or \((\delta M_f)\) in order to ensure that all fragmentation remnants are radiated inside the cone [22], but this argument is not universally accepted. It was shown in [21] that the choice is numerically irrelevant, since the dependence of the cross section on the fragmentation scale is negligible after isolation in NLO.

**B. The NLO Case**

1. **The Non-Fragmentation Contribution**

In NLO order, \(O(\alpha_s^2)\), there are virtual corrections to the LO non-fragmentation processes of eq.(2.1), as well as the further three-body processes:

\[
g + q \rightarrow g + q + \gamma \quad (2.6a)
\]

\[
g + g \rightarrow q + \bar{q} + \gamma \quad (2.6b)
\]

\[
q + \bar{q} \rightarrow g + g + \gamma \quad (2.6c)
\]

\[
q + q \rightarrow q + q + \gamma \quad (2.6d)
\]

\[
\bar{q} + q \rightarrow \bar{q} + q + \gamma \quad (2.6e)
\]

\[
q + \bar{q} \rightarrow q' + \bar{q}' + \gamma \quad (2.6f)
\]

\[
q + q' \rightarrow q + q' + \gamma \quad (2.6g)
\]

In principle the fragmentation processes of eq.(2.2) should now be calculated to \(O(\alpha_s^3)\) and convoluted with the NLO photon fragmentation functions whose leading behaviour is \(O(\alpha/\alpha_s)\), but the hard subprocess matrix elements are not yet available in the polarized case, hence, in both the polarized and unpolarized cases, we include the leading order contributions to these processes only. Numerically the fragmentation processes are not as significant except
at low $p_T$ after isolation cuts are implemented, but for a theoretically consistent calculation they should nevertheless be included as they help to reduce scale dependences, and as was demonstrated in ref. [18] they also help to improve the agreement between theory and experiment in the low $p_T^\gamma$ region.

The direct contribution to the inclusive cross section is given by

$$E_\gamma \frac{d\Delta\sigma^{\text{incl}}}{d^3p_\gamma} = \frac{1}{\pi S} \sum_{ij} \int_{VW}^V \frac{dv}{1-v} \int_{VW/v}^1 \frac{dw}{w} \Delta f_1^i(x_1, M^2) \Delta f_2^j(x_2, M^2) \times \left[ \frac{1}{v} \frac{d\Delta\hat{s}_{ij}\to\gamma}{dv} \delta(1-w) + \frac{\alpha_s(\mu^2)}{2\pi} \Delta K_{ij\to\gamma}(\hat{s}, v, w, \mu^2, M^2, M_f^2) \right],$$

(2.7)

where $\Delta K_{ij\to\gamma}(\hat{s}, v, w, \mu^2, M^2, M_f^2)$ represents the higher corrections to the hard subprocess cross sections calculated in [10] and $\mu$ is the renormalization scale.

In [21] the isolated cross section is first written as the inclusive cross section minus a subtraction piece, along the lines suggested in [22]:

$$E_\gamma \frac{d\Delta\sigma^{\text{isol}}}{d^3p_\gamma} = E_\gamma \frac{d\Delta\sigma^{\text{incl}}}{d^3p_\gamma} - E_\gamma \frac{d\Delta\sigma^{\text{sub}}}{d^3p_\gamma},$$

(2.8)

$E_\gamma \frac{d\Delta\sigma^{\text{sub}}}{d^3p_\gamma}$ being the cross section for producing a prompt photon with energy $E_\gamma$ which is accompanied by more hadronic energy than $\epsilon E_\gamma$ inside the cone. The question is then how to calculate the subtraction piece. In [21] it is calculated by an approximate analytic method for a small cone of half angle $\delta$ as well as for a cone of radius $R$ as defined above using Monte Carlo integration methods. The complete details of the calculation can be found in ref. [21].

The final form for the subtraction piece assuming a small cone of half angle $\delta$ is given by

$$E_\gamma \frac{d^3\Delta\sigma^{\text{sub}}}{d^3p_\gamma} = A \ln \delta + B + C\delta^2 \ln \epsilon,$$

(2.9)

where $A, B$ and $C$ are functions of the kinematic variables of the photon and $\epsilon$. A detailed study was then made of the difference between the analytic and numerical Monte Carlo subtraction pieces for various values of the isolation parameters $\epsilon$ and $\delta$ at $\sqrt{S} = 1$ TeV. It was found that the small cone approximation was within 10% of the Monte Carlo results for the subtraction piece except for very large values of $\epsilon$ and $\delta$, greater than 0.25 and 0.8 respectively. This translated into a very small error for the full isolated cross section even
for large values of the parameters, as the subtraction piece is numerically much smaller than the inclusive piece.

The Monte Carlo method of calculation differs from the method outlined above in some important ways. The phase space is only integrated over analytically in those regions where soft collinear singularities occur. These are cancelled or subtracted in the usual way leaving the rest of the phase space to be integrated over numerically. The flexibility of the method lies in the fact that any infrared safe experimental cuts can be imposed on the phase space by imposing restrictions on the regions which are integrated over numerically by Monte Carlo methods. Thus it is straightforward to impose isolation cuts on the photon in this case without making any further approximations.

In ref. [19] a detailed comparison of the results of the analytic and Monte Carlo methods was made for both the inclusive and isolated cross sections, and agreement was found. A similar comparison was made for the polarized case with the same results, but since the comparisons follow along the exact same lines as that presented in [13] with similar results the details will not be repeated in this paper.

C. Polarized vs Unpolarized Cases

When the initial hadrons are longitudinally polarized, all the usual formulas used in the spin averaged case can be taken over, expect that now the hard subprocess cross sections and the parton distributions must be replaced by the corresponding spin dependent versions. For example the polarized hard subprocess matrix elements in LO used in eqs.(2.3-2.5) and (2.7) were defined by

\[
\frac{d\Delta\hat{\sigma}}{dv} = \frac{1}{2} \left[ \frac{d\hat{\sigma}(++)}{dv} - \frac{d\hat{\sigma}(+-)}{dv} \right],
\]

(2.10)

where +, – denote the helicities of the initial partons. The usual spin averaged versions are defined by

\[
\frac{d\hat{\sigma}}{dv} = \frac{1}{2} \left[ \frac{d\hat{\sigma}(++)}{dv} + \frac{d\hat{\sigma}(+-)}{dv} \right].
\]

(2.11)
LO matrix elements for the direct and fragmentation processes have been presented in many places (see eg. [17]) and the NLO ones integrated analytically over phase are given in the appendix of [10]. The unintegrated three-body matrix elements are collected in the appendix of [8]. The polarized parton distributions are similarly defined by

$$\Delta f_{ia}^i(x, M^2) = f_{a,+}^i(x, M^2) - f_{a,-}^i(x, M^2),$$

(2.12)

where $f_{a,\pm}^i(x, M^2)$ is the distribution of parton type $i$ with positive (+) or negative (-) helicity in hadron $a$, whereas the usual unpolarized ones are given by

$$f_{ia}^i(x, M^2) = f_{a,+}^i(x, M^2) + f_{a,-}^i(x, M^2).$$

(2.13)

### III. NUMERICAL RESULTS

In this section predictions for the isolated prompt photon cross section for polarized proton-proton collision at RHIC energies are investigated. The fragmentation contribution is always estimated with LO matrix elements for both the polarized and unpolarized cases, although NLO structure and fragmentation functions are used throughout. The renormalization, factorization, and fragmentation scales are always set to a common value $\mu = p_T^\gamma$ unless otherwise stated. The fragmentation functions evolved in NLO from ref. [23] are used throughout. There are various parametrizations of the polarized proton densities at NLO on the market [12–14]. In ref. [13] three different sets are parametrized (the GS sets), all fitting the DIS data, but due to the freedom in fixing the various flavour of quark densities as well as the gluon densities, the actual distributions differ. In this paper the three GS distributions (GSA, GSB and GSC) are used and the predictions using them compared. For the unpolarized cross sections, the CTEQ4M [24] distributions are used throughout. The NLO expression for $\alpha_s$ is always used and four quark flavors are assumed although no contribution from initial charm quark scattering is included in the calculations. The value of $\Lambda$ used is chosen to correspond with the unpolarized parton parametrization used.
A. Isolated Prompt Photons at RHIC

RHIC is expected to run at center of mass energies between $\sqrt{s} = 50$ and 500 GeV. At the lower energies the fragmentation contribution to prompt photon production is expected to be much less. This has two important consequences. First, since the matrix elements for the fragmentation contribution in the polarized case are still unknown the estimates using LO matrix elements should be more reliable, and secondly, there will be less need to place isolation restrictions on the cross section at lower energies, thereby avoiding all the attendant uncertainties.

In Figs.1a and 1b the isolated and non-isolated cross sections for prompt photon production are compared at 50 and 500 GeV at an average rapidity $y = 0$. The GSA polarized distributions is used and the isolation parameters used are $R = 1.0$ and $\epsilon = 2$ GeV/$p_T$. As expected to $\sqrt{s} = 50$ GeV the effect of isolation on the cross section is negligible, whereas at 500 GeV it is more significant. The total rates are also substantial enough to be measured out to $p_T^\gamma = 15 - 20$ GeV at $\sqrt{s} = 50$ GeV and $50 - 60$ GeV at $\sqrt{s} = 500$ GeV.

In figs.1c and 1d the ratio $\sigma^{\text{frag}}/\sigma^{\text{full}}$, where $\sigma^{\text{frag}}$ is the fragmentation contribution to the cross section and $\sigma^{\text{full}}$ is the sum of direct and fragmentation contributions, are plotted vs $p_T^\gamma$. This is done for both the isolated and non-isolated cases. The ratio is typically less than 15% for the unpolarized and less than 10% for the polarized case at $\sqrt{s} = 50$ GeV, and falls with increasing $p_T^\gamma$. Isolation cuts have the effect of reducing the ratio only slightly at this energy. At $\sqrt{s} = 500$ GeV the situation is very different. For the range of $p_T^\gamma$ shown, before isolation, the fragmentation contribution makes up to around 50% of the cross section at low $p_T^\gamma$ and is still significant at medium values of $p_T^\gamma$. Once isolation cuts are imposed the fragmentation contribution falls dramatically as one might expect. The fragmentation contributions seem to be more important for the polarized case before isolation, but after isolation the ratio is similar for both the polarized and unpolarized cases. It turn out that this effect is mostly due to the interplay between the various subprocess contributions and depends significantly on the choice of parton distributions made.
In figs. 2a and 2b predictions for the polarized isolated cross section are compared for the GSA, GSB and GSC parametrizations of the parton distributions at $\sqrt{s} = 50$ and 500 GeV respectively at average rapidity $y = 0$. The corresponding asymmetries, defined as the ratio of the polarized to the unpolarized cross section are plotted in figs. 2c and 2d. Larger asymmetries are preferred as they indicate that the cross section is sensitive to polarization effects. The GSA and GSB distributions give rather similar predictions at both cms energies in the low $p_T^\gamma$ region but tend to diverge as $p_T^\gamma$ increases, whereas the GSC predictions are very different at all $p_T^\gamma$ values. In both cases GSC predicts negative cross sections for part of the $p_T^\gamma$ range covered. This is because in this case $\Delta G$ is negative over part of the $x$-range at input [13].

The asymmetry plots reflect the differences between the three parametrizations. There is a wide spread in the three curves of figs. 2c and 2d as $p_T^\gamma$ increases. The differences should be experimentally distinguishable. In fig. 2d the solid line is the predicted asymmetry for the non-isolated cross section using the GSA parametrization. It is very similar to the isolated prediction, although the corresponding cross sections are very different in magnitude. This indicates that the predictions for the asymmetries do not depend very much on whether the photon is isolated or not although the actual sizes of the cross sections are significantly affected at higher cms energies.

Figs. 3a and 3b show the rapidity distributions of the isolated cross section for the various parametrizations at a fixed value of $p_T^\gamma = 10$ GeV at $\sqrt{s} = 50$ and 500 GeV respectively. The unpolarized cross section is also shown. Again the three parametrizations of the polarized proton distributions give distinguishable results. This is reflected in the asymmetry plots in figs. 3c and 3d which show differences in both shapes and sizes. Changing the factorization/renormalization scales do not have a substantial effect on the asymmetries although the individual cross sections can increase by as much as 50% if $\mu^2 = (p_T^\gamma/2)^2$ is used. Including fragmentation contributions fully at NLO would likely reduce this scale sensitivity and thus improve the reliability of the predictions for the cross sections.
IV. CONCLUSIONS

The cross section for prompt photon production was presented at RHIC cms energies using polarized proton densities evolved in NLO QCD for the first time. The calculation was performed using the Monte Carlo method and compared to a previous calculation using purely analytic methods and agreement was found. The Monte Carlo method used allowed the inclusion of isolation cuts on the direct component of the cross section in NLO without any further approximations. The fragmentation contribution was estimated in LO where isolation is trivial to implement.

The cross section was studied at two cms energies, \(\sqrt{s} = 50\) and \(500\) GeV, typical for the RHIC collider. At \(\sqrt{s} = 50\) GeV, the fragmentation contributions which can only be estimated in LO were found to be small and isolation hardly change the predictions. At \(\sqrt{s} = 500\) GeV, fragmentation contributes up to 50\% of the cross section before isolation, and thus imposition of the isolation cuts substantially reduced the cross section. This means that the predictions presented here for the cross sections are more likely to be reliable at lower cms energies. It turned out that the asymmetries were hardly affected by isolation since both the polarized and unpolarized cross sections are similarly affected and the effect cancelled out in the ratio. A similar effect was found when the factorization/renormalization scales were varied. Thus the asymmetries are the most stable predictions of this calculation, and it can be anticipated that even the inclusion of higher order corrections to the fragmentation contributions are unlikely to change them very much.

The three parametrizations for the polarized proton densities gave distinguishable results, particularly at higher \(p_T^\gamma\) values. This suggests that they should also be distinguishable in the experiment and that, as expected, prompt photon production will definitely prove useful in determining the size of \(\Delta G\).
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FIGURE CAPTIONS

[1] (a) The inclusive and isolated differential cross sections at $\sqrt{s} = 50$ GeV and rapidity averaged between $-0.5 \leq y \leq 0.5$ plotted vs photon $p_T$ for the polarized and unpolarized cases. (b) same as (a) at $\sqrt{s} = 500$ GeV. (c) ratios of the fragmentation contribution estimated with LO matrix elements to the full (direct plus fragmentation) of the polarized and unpolarized cross sections both before and after isolation cuts are implemented at $\sqrt{s} = 50$ GeV. (d) same as (a) at $\sqrt{s} = 500$ GeV.

[2] Polarized differential cross section at average rapidity $y = 0$ plotted vs photon $p_T$ at $\sqrt{s} = 50$ GeV as predicted using the GSA, GSB and GSC parametrizations of the polarized proton distributions. (b) same as (a) at $\sqrt{s} = 500$ GeV. (c) asymmetry plots vs photon $p_T$ for the cross sections given in (a) using the CTEQ4M proton distributions for the unpolarized cross section. (d) same as (c) but for the differential cross sections plotted in (b). The solid curve is for the non-isolated cross section predicted using the GSA polarized distributions.

[3] Rapidity distributions for the polarized and unpolarized differential cross sections at $p_T = 10$ GeV and $\sqrt{s} = 50$ GeV. (b) same as (a) at $\sqrt{s} = 500$ GeV. (c) and (d) asymmetry plots for the distributions plotted in (a) and (b) respectively.
Fig. 1a

\[ \frac{d(\Delta\sigma)}{dp_T dy} \text{ [pb/GeV]} \]

\( \sqrt{s} = 50 \text{ GeV} \)

- inclusive
- isolated

unpolarized

polarized

\( p_T \) (GeV)
Fig. 1b

\[ \frac{d\Delta\sigma}{d\Delta p_T dy} \text{ [pb/GeV]} \]

- **unpolarized**
- **polarized**

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

- **inclusive**
- **isolated**
Figure 1c

\( \frac{(\Delta)\sigma_{\text{frag}}}{(\Delta)\sigma_{\text{full}}} \) against \( p_T \) (GeV)

- **inclusive**
- **isolated**
- **unpol.**
- **pol.**

\( \sqrt{s} = 50 \text{ GeV} \)
(d) $\sqrt{s} = 500$ GeV

- inclusive
- isolated
- polarized

$(\Delta \sigma)_{\text{frag}} / (\Delta \sigma)_{\text{full}}$ vs $p_T$ (GeV)

Fig. 1d
\( \frac{d\Delta\sigma}{dp_T dy} \) [pb/GeV] vs. \( p_T \) (GeV)

- GSA
- GSB
- GSC (\( \times -1 \))

\( \sqrt{s} = 50 \) GeV

Fig. 2a
$d\Delta \sigma/dp_T dy$ [pb/GeV]

$p_T$ (GeV)

Fig. 2b
\( A_{LL} \) vs. \( p_T \) at \( \sqrt{s} = 500 \) GeV

Fig. 2d
Fig. 3a

\( \sqrt{s} = 50 \text{ GeV} \)

unpol. \( p_T = 10 \text{ GeV} \)
\( \sqrt{s} = 500 \text{ GeV} \)

\( p_T = 10 \text{ GeV} \)

\( \frac{d\Delta\sigma}{dp_Tdy} [\text{pb}/\text{GeV}] \)

- \( \text{GSA} \)
- \( \text{GSB} \)
- \( \text{GSC} \)

\( \eta \)

Fig. 3b
Fig. 3c

$\sqrt{s} = 50 \text{ GeV}$

$p_T = 10 \text{ GeV}$
Fig. 3d

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

\( p_T = 10 \text{ GeV} \)