Production of prompt photons in the collision of longitudinally polarized proton beams at NICA

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Introduction

The Spin Physics Detector of NICA

- Polarized and unpolarized beams: pp, dd, pd, NN ...
- Unpolarized, longitudinally and transversely polarized modes (PDF, TMD, ...)
- Polarized physics at the $x > 0.1$

Structure of nucleons

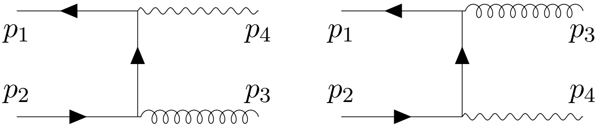
- The spin- and three-dimensional structures of nucleons
- The influence of gluons on the properties of nucleons
- Testing the Standard Model by searching for time invariance violation and parity violation
- ...

Processes

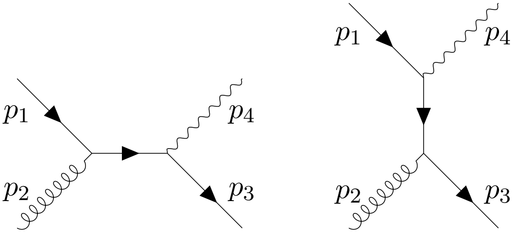
1. Charmonium production (J/Ψ and excited states $\Psi(2S)$, $\Psi(3770)$)
2. Open charm production ($gg \to c\bar{c}$, $q\bar{q} \to c\bar{c}$)
3. Prompt photons ($gq(\bar{q}) \to \gamma q(\bar{q}), q\bar{q} \to \gamma g$)

What are prompt photons?

Photons emerging from the hard parton scattering subprocess are called prompt photons.



Annihilation process $q\bar{q} \to \gamma g$.



Quark-gluon Compton process $qg \to q\gamma$.

Prompt photons vs Jets

Prompt photons

- Prompt photons production proceeds without fragmentation $\rightarrow$ low background sources;
- They carry information directly from the hard scattering process.
- We need only electromagnetic calorimeter;
- Systematic errors are small.

Jets

- Fragmentation $\rightarrow$ high rate of background sources;
- Hadronic + electromagnetic calorimeters;
- We need a jet algorithm to reconstruct a jet axis;
- High systematic errors.

The problem we solved

We estimated the leading order of prompt photons processes $pp \to g\gamma(+X)$ and $pp \to q(\bar{q})\gamma(+X)$ for the case of longitudinal polarization of initial states using `ReneSANCe` [10.1016/j.cpc.2022.108646], `MCSANC` [10.1016/j.cpc.2013.05.010] and `SANC` [arXiv:0812.4207].

In the near future we will also obtain the QCD-EW radiative corrections.

Hadronic and partonic levels

Hadronic level

$$d\sigma(\Lambda_1, \Lambda_2, s) = \sum_{p_1 p_2} \sum_{\lambda_1 \lambda_2} \int_0^1 \int_0^1 dx_1 dx_2 f_{p_1}^{\Lambda_1 \lambda_1}(x_1) \times f_{p_2}^{\Lambda_2 \lambda_2}(x_2)\, d\hat{\sigma}_{p_1 p_2}(\lambda_1, \lambda_2, \hat{s})$$

where $\Lambda_i = \pm 1$ and $\lambda_i = \pm 1$ are the helicities of each proton and quark (gluon) (p_1, p_2), respectively, with $\hat{s} = x_1 x_2 s$.

Parton distribution functions

Parton distributions $f_{p_i}^{\Lambda_i \lambda_i}$ can be obtained from unpolarized f_{p_i} and longitudinally polarized Δf_{p_i} PDFs: $f_{p_i}^{\Lambda_i \lambda_i} = \frac{1}{2}(f_{p_i} + \Lambda_i \lambda_i \Delta f_{p_i})$.

Partonic level

$$\bar{q}(p_1, \lambda_1) + q(p_2, \lambda_2) \to g(p_3, \lambda_3) + \gamma(p_4, \lambda_4)$$
$$q(\bar{q})(p_1, \lambda_1) + g(p_2, \lambda_2) \to q(\bar{q})(p_3, \lambda_3) + \gamma(p_4, \lambda_4)$$

Observables

Single- and double-spin combinations of polarized components $(\sigma^{++}, \sigma^{+-}, \sigma^{-+}, \sigma^{--})$ of the hadron-hadron cross section:

$$\Delta\sigma_{\rm L} = \frac{1}{4}\left(\sigma^{++} + \sigma^{+-} - \sigma^{-+} - \sigma^{--}\right),$$
$$\Delta\sigma_{\rm LL} = \frac{1}{4}\left(\sigma^{++} - \sigma^{+-} - \sigma^{-+} + \sigma^{--}\right),$$

Definitions of single-spin ($\mathrm{A_L}$) and double-spin ($\mathrm{A_{LL}}$) asymmetries:

$$\mathrm{A_{L(LL)}}(Y) = \frac{\Delta d\sigma_{\rm L(LL)}/d\eta_\gamma}{d\sigma/d\eta_\gamma}, \quad \Delta \mathrm{A_L} = \mathrm{A_L^{NLO}} - \mathrm{A_L^{LO}},$$

η_γ – pseudo-rapidity of lepton in the final state:

$$\eta_\gamma = -\ln\left(\tan\frac{\vartheta_\gamma}{2}\right).$$

Here ϑ_γ is the angle of the γ in the laboratory frame. The z-axis is directed along the momentum of the first proton.
These asymmetries are crucial because they provide insights into the spin structure of nucleons.

Kinematic cuts, input parameters and conditions

Numerical results were obtained using the Monte Carlo generator `ReneSANCe` [arXiv:2207.04332].

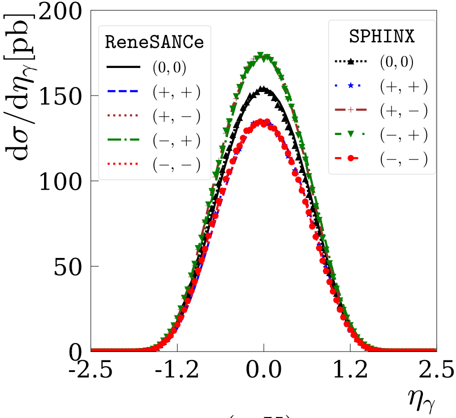
Input parameters and conditions:

1. $\alpha = 137.035999084$, $\alpha_s = 0.1176$; energy of c.m.s. is $\sqrt{s_0} = 20\,\text{GeV}$;
2. Set of input parameters [arXiv:2211.03561];
3. PDF: `NNPDF23_nlo_as_0119` for unpolarized parton distributions f_{q_i} и `NNPDFpol11_100` for longitudinally polarized parton distributions Δf_{q_i} from `LHAPDF6` library with factorization scale $\mu_F = \sqrt{s}$, where $s = x_1 x_2 s_0$ [arXiv:1406.5539].

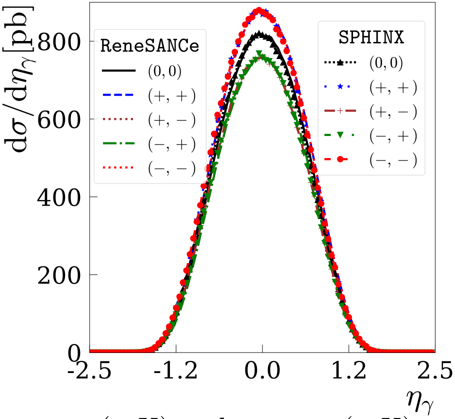
Kinematic cut:

$p_\perp > 2.5$ GeV for all processes of interest.

The differential cross sections and comparison with SPHINX [arXiv:hep-ph/9612278]



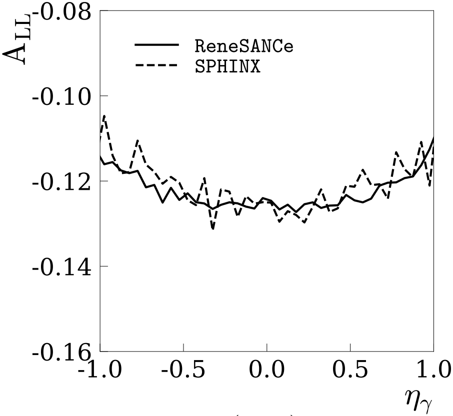
$pp \to g\gamma(+X)$



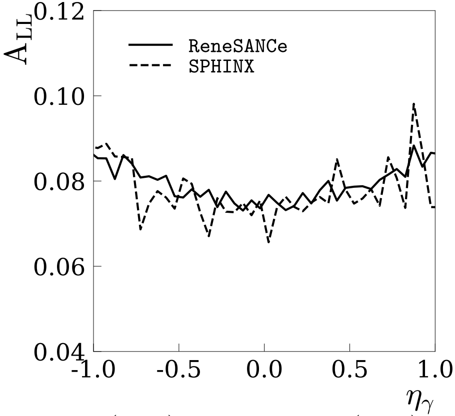
$pp \to q\gamma(+X)$ and $pp \to \bar{q}\gamma(+X)$

Differential cross section over pseudo-rapidity in the leading order for different values of polarization of the initial states.

Double-spin asymmetries and comparison with SPHINX



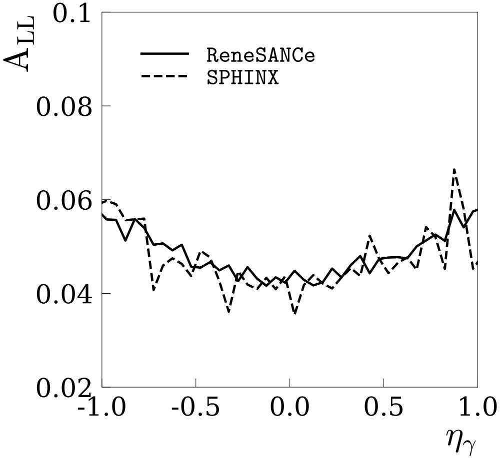
$pp \to g\gamma(+X)$



$pp \to q\gamma(+X)$ and $pp \to \bar{q}\gamma(+X)$

Double-spin asymmetries over pseudo-rapidity in the leading order.

Total double-spin asymmetries and comparison with SPHINX



Total double-spin asymmetry, including $pp \to g\gamma(+X)$ and $pp \to q\gamma(+X)$ and $pp \to \bar{q}\gamma(+X)$, over pseudo-rapidity in the leading order.

Comparison with "Письма в ЭЧАЯ. 2023. Т. 20, № 3(248). С. 417–421"

In addition to the comparison with the SPHINX program, there is a paper [Письма в ЭЧАЯ. 2023. Т. 20, № 3(248). С. 417–421], which presents results for double-spin asymmetries. The first results of comparison with it were unsatisfactory. Recently, authors reported that they had found an error. We are currently actively collaborating with them to achieve agreement on the results.

Conclusion

- The calculation of the leading order for prompt photons was performed.
- The behavior of polarized cross sections and double-spin asymmetries was investigated.
- Agreement with the SPHINX program was achieved at leading order for all processes of interest.
- The next steps are to complete the calculation of QCD-EW radiative corrections for prompt photons and to achieve agreement with [Письма в ЭЧАЯ. 2023. Т. 20, № 3(248). С. 417–421].

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Thank you for paying attention!