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

V. Yermolchyk
on behalf of SANC team

JINR

VIII SPD Collaboration meeting
08 November 2024

Motivation

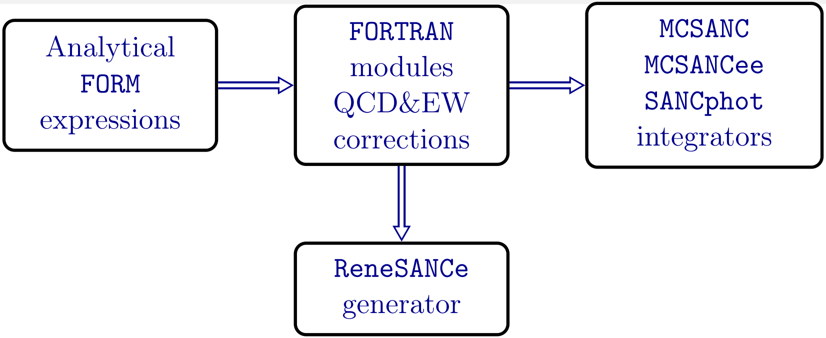
See Igor Denisenko talk:

Generators

- ~~**SPHINX**~~ (DY only)
- **ULYSSES** (multiquark correlations) – A. Zelenov, V. Kim, work in progress
- Simulation lambda polarization effects in unpolarized pp collision (V. Kim *et al.*)
- Simulation of elestic pp scattering (A. Galoyan, V. Uzhinzky)
- **For many processes of the first SPD first phase we lack signal modeling tools.**
- **HELAC-Onia** (polarized J/psi production)
- **KatTie** (talk by Alexey Chernyshev at P&MC, June 19)
- Code to **import HepMC events** as a SpdRoot generator **would be useful**

14 Report from the Physics Coordinator 05.11.24

The SANC framework and products family



Publications:

SANC – CPC 174 481-517
MCSANC – CPC 184 2343-2350; JETP Letters 103, 131-136
SANCphot – CPC 294 108929
ReneSANCe – CPC 256 107445; CPC 285 108646

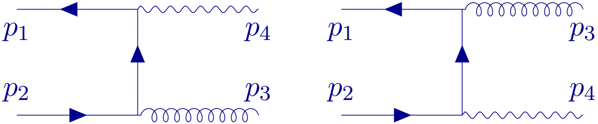
SANC products are available at http://sanc.jinr.ru/download.php
ReneSANCe is also available at http://renesance.hepforge.org

SANC advantages:

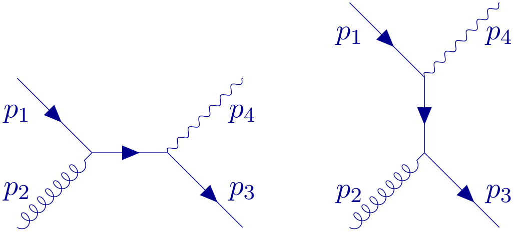
- full one-loop electroweak corrections
- higher order corrections
- massive case
- accounting for polarization effects
- full phase space operation
- results of ReneSANCe event generator are thoroughly cross checked
- output of ReneSANCe: events in LHEF, HepMC, HEPEVT or ROOT formats

Prompt photon production

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

- They carry information directly from the hard scattering process.
- Electromagnetic calorimeter (the energy resolution of electromagnetic calorimeters is generally better than that of hadronic calorimeters).
- Systematic errors in the photon energy scale are smaller.
- Relatively low event rate compared with the jet production, and many background sources from the jet production are not negligible.

Jets

- Hadronic + electromagnetic calorimeters.
- A jet algorithm to reconstruct a jet axis is needed.
- High systematic errors.

The problem we solved

The prompt photon production is a useful tool for extraction of gluon distribution function. Especially interesting is double-spin asymmetry for this process.

We implemented 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 in the `ReneSANCe` event generator.

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 (σ^{++}, σ^{+-}, σ^{-+}, σ^{--}) of the hadron-hadron cross section:

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

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

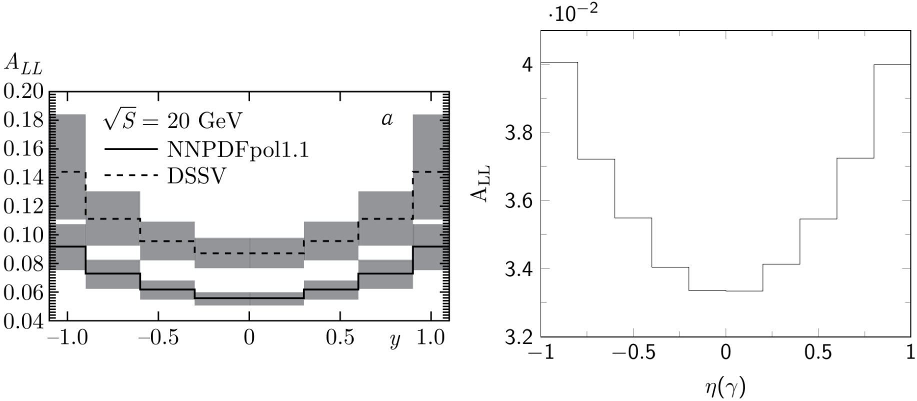
$$\mathrm{A_{L(LL)}}(Y) = \frac{\Delta d\sigma_{\mathrm{L(LL)}}/d\eta_\gamma}{d\sigma/d\eta_\gamma}, \quad \Delta\mathrm{A_L} = \mathrm{A_L^{NLO}} - \mathrm{A_L^{LO}},$$

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

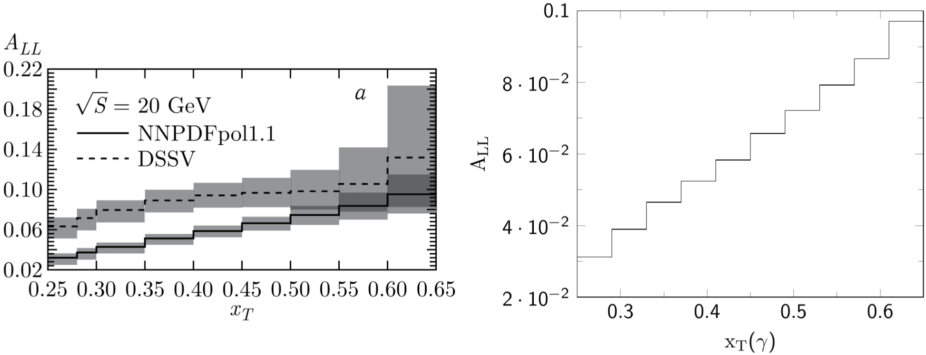
$$\eta_\gamma = -\ln\left(\tan\frac{\vartheta_\gamma}{2}\right).$$

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.

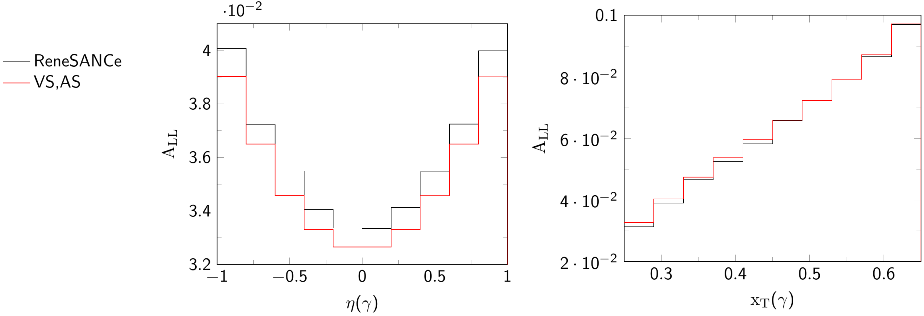
Results and comparison with "Phys.Part.Nucl.Lett. 20 (2023) 3, 400-403". Double-spin asymmetry versus photon rapidity.



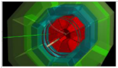
Results and comparison with "Phys.Part.Nucl.Lett. 20 (2023) 3, 400-403". Double-spin asymmetry versus $x_T = 2p_T/\sqrt{S}$.



Results of comparison in private communication with Vladimir Saleev and Alexandra Shipilova. Double-spin asymmetry versus photon rapidity and x_T.



Is it possible to compare with Sphinx?



SPHINX, SPINX-TT

Some history:

- ❑ **First reference:**

SPHINX, MONTE CARLO PROGRAM FOR POLARISED NUCLEON-NUCLEON COLLISIONS. S. GULLENSTERN, P. GORNICKI, L. MANKIEWICZ, A. SCHAFER, COMP. PHYS. COMMUN. 87 (1995) 416

- ❑ **Last developments were done by O. Martin (Regensburg University, A. Shafer supervision) around 1999**
- ❑ **Homepage was lost. Only intermediate versions of SPHINX v 1.1 and SPHINX-TT from late 1996 are in hands. As well as initial version from CPC. Also PhD Thesis from O.Martin might contain details.**

The SPHINX Home Page

The SPHINX project started in the early 90's with the aim to develop a Monte Carlo Simulation for polarized nucleon-nucleon collisions. As a basis for the program Pythia 5.6 and Jetset 7.3 were chosen.The new versions Pythia 6.1 can be obtained from Torbjorn Sjostrand or from CERN.

The first part of the project was the development of an event generator for collisions of longitudinally polarized hadrons, which was called SPHINX (Simulation for Polarized Hadronic INteract(X)ions).The main authors of this program are Stefan Güllenstern and Axel Saalfeld. The photoproduction part was programmed by Oliver Martin.

News about SPHINX:

- 02 Dec 1996: Release of SPHINX version 1.1. New parametrizations of polarized and unpolarized parton distribution functions are available now. A new interface to pdflib 4.0 and higher versions is also provided. A severe error in the initial state shower subroutine was corrected (the bug basically turned off initial state showering after several hundred events).
- 3 Mar 1997: error in common block in JETSET 7.3 fixed , did not effect results
- 7 Apr 1997: SPHINX version 1.2 can be downloaded. The new features include polarized electrons or photons as beam particles, a choice of two model parton distributions of the polarized photon and the necessary partonic subprocesses for photoproduction of jets.
- 18 Apr 1997: error in PYSSPA corrected which caused an infinite loop after several million events. The version of the corrected code is 1.201 .
- 20 May 1997: Glueck, Reya, Stratmann, Vogelsang leading order and next to leading order parametrizations of polarized pdfs of the proton included (Phys. Rev. D53 (1996) 4775). The version of the new code is 1.202 .
- 24 August 1998: SPHINX might be used as polarized event generator for the preparation of the Spin Program at the polarized RHIC collider. Starting mid-september 1998, a workshop will be held at Brookhaven National Lab with the aim to further enhance SPHINX, upgrade it to PYTHIA 6.1 and compare results to NLO QCD calculations.

News about SPHINX TT:

- 12 Nov 1996: The first official SPHINX TT version is available. A new interface to pdflib 4.0 and higher versions is included now.
- 3 Mar 1997: error in common block in JETSET 7.3 fixed , did not effect results

Sphinx

Recovery work on `Sphinx`

- Found last version 1.202.
- Switch to modified Jetset 7.4.10 (not works with bundled Jetset 7.3).
- Found flags to compile using gfortran-7 (to overcome numerical overflow and common blocks alignment problems).
- Add binding to LHAPDF to use modern PDFs.
- Problem with CERNlib and nanoCERNlib, so use FBOOK for histograming.

Limitations of `Sphinx`

- Polarization effects only for initial state.
- Decays of resonances are generated uniformly in most cases.
- No longer supported.

Processes available in Sphinx

Table 1: List of processes implemented in the polarized mode.

ISUB	Process	Comment
1	$q_i\bar{q}_i \to \gamma^*/Z^0$	quark-antiquark annihilation into virtual γ^*/Z^0
2	$q_i\bar{q}_j \to W^\pm$	annihilation into charged vector boson
11	$q_iq_j \to q_iq_j$	(anti-)quark – (anti-)quark scattering; annihilation diagram not included
12	$q_i\bar{q}_i \to q_k\bar{q}_k$	annihilation process
13	$q_i\bar{q}_i \to gg$	annihilation into gluon pair
14	$q_i\bar{q}_i \to g\gamma$	annihilation into gluon and prompt γ
15	$q_i\bar{q}_i \to gZ^0$	annihilation into gluon and Z^0
16	$q_i\bar{q}_j \to gW^\pm$	annihilation into gluon and $W^\pm$
18	$q_i\bar{q}_i \to \gamma\gamma$	annihilation into γ pair
19	$q_i\bar{q}_i \to \gamma Z^0$	annihilation into γ and Z^0
20	$q_i\bar{q}_i \to \gamma W^\pm$	annihilation into γ and $W^\pm$
28	$q_ig \to q_ig$	(anti-)quark – gluon scattering
29	$q_ig \to q_i\gamma$	prompt γ production in (anti-)quark – gluon scattering
30	$q_ig \to q_iZ^0$	Z^0 production in (anti-)quark – gluon scattering
31	$q_ig \to q_jW^\pm$	$W^\pm$ production in (anti-)quark – gluon scattering
33	$f_i\gamma \to f_ig$	scattering of fermion and real photon
34	$f_i\gamma \to f_i\gamma$	scattering of fermion and real photon
53	$gg \to q_k\bar{q}_k$	gluon fusion
54	$g\gamma \to q_k\bar{q}_k$	fusion of gluon and real photon
68	$gg \to gg$	gluon – gluon scattering

Comparison with Sphinx. Kinematic cuts, input parameters.

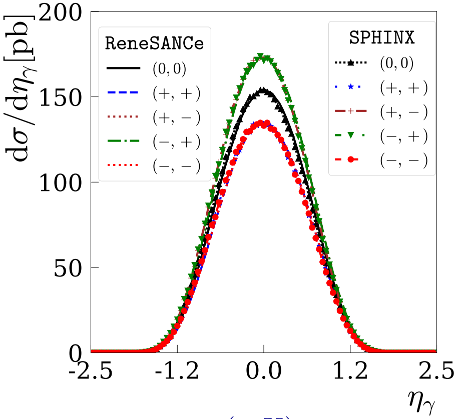
Input parameters and conditions:

1. $\alpha = 137.035999084$, $\alpha_s = 0.1176$; energy of c.m.s. is $\sqrt{s_0} = 20$ 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].

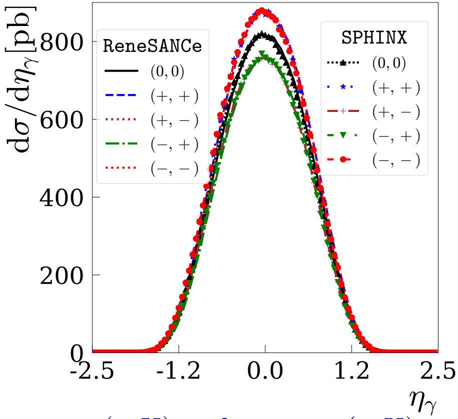
Kinematic cut:

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

The differential cross sections and comparison with Sphinx



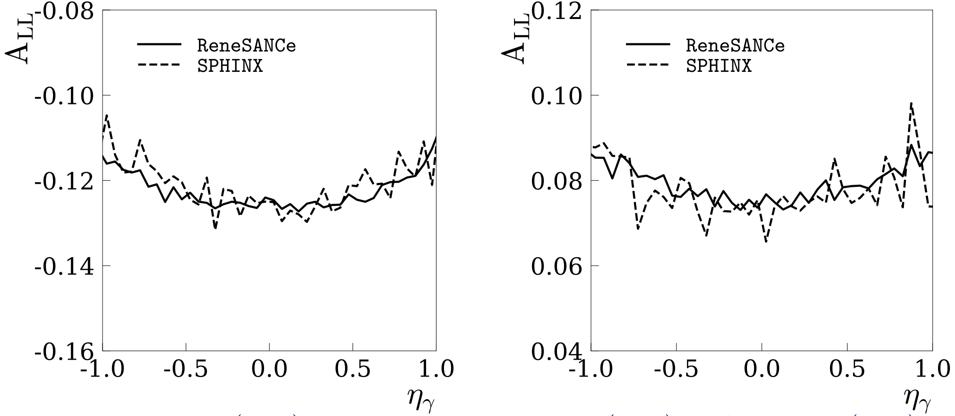
$pp \to g\gamma(+X)$



$pp \to q\gamma(+X)$ 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.

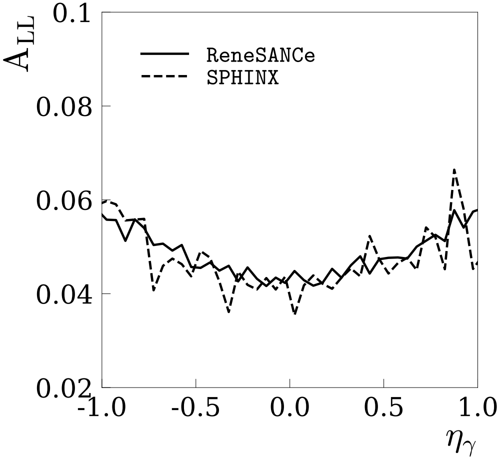
Double-spin asymmetries and comparison with Sphinx



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

Conclusion

- The implementation of processes of interest for SPD has begun in the Monte Carlo event generator `ReneSANCe`.
- 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.
- The next steps are to complete the calculation of QCD radiative corrections for prompt photons and implement another processes from `Sphinx` list.

Thank you for paying attention!