Probing nuclear parton distribution functions with heavy-flavour production (HQ4nPDF)

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IJCLab-IFJ PAN workshop

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Outline

Plan of co-PhD — Overview

Objectives & Timeline

- 1.5 years in IJCLab and 1.5 years in IFJ PAN.
- Geometry of nuclear PDFs (impact-parameter dependence).
- Radiative corrections to $g \to \mathcal{Q} + g + g$ Fragmentation Functions($\leftrightarrow$ K.Lynch's PhD).
- Investigation of the relation between t-dependence and its Fourier analogue b-dependence in Exclusive J/ψ photoproduction.
- Study of the connection between nPDFs and SRCs (Short-Range Correlations).

Last October I started as a joint PhD between IFJ PAN and IJCLab.

Plan of PhD — Overview

Year 1–2 @ IJCLab

- Build a full b-dependent nPDF framework using Glauber MC, centrality classes (N_{anc}, N_{out}), and impact-parameter–dependent nuclear geometry.
- FF: Reproduce the LO results. Generate the virtual emission amplitudes at NLO.
- Investigate the theoretical link between t-dependence and Fourier-transform b-dependence in coherent J/ψ photoproduction.

Year 2–3 @ IFJ PAN

- Compute the virtual emission corrections.
- Explore constraints from coherent photoproduction (Pb, Au, pPb, dAu) including impact-parameter imaging.
- Implement SRC-motivated nuclear modifications and test their consistency with EMC-region phenomenology.

Project A: Collinear Factorization and Nuclear PDFs

Collinear Factorization for hadronic or nuclear inclusive cross sections involving a hard scale $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$

$$d\sigma^{AB \to k+X} = \sum_{i,j,X'} f_i^A(Q^2) \otimes f_j^B(Q^2) \otimes d\hat{\sigma}^{\,ij \to k+X'} + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

- **Proton PDFs** of parton i (non-perturbative and universal).
- $\hat{\sigma}$ — parton-level matrix element (calculable in pQCD).
- $\mathcal{O}\left(\frac{1}{Q^2}\right)$ — non-leading terms controlling factorization accuracy.

- **nPDFs** (**PDFs of bound nucleons in nuclei**) are **not** equal to the sum of free-nucleon PDFs.
  - Observable evidence for nuclear modifications.
  - Nuclear mass-number (A) dependence added on top of the usual x and Q^2 dependence of proton PDFs.

Project A

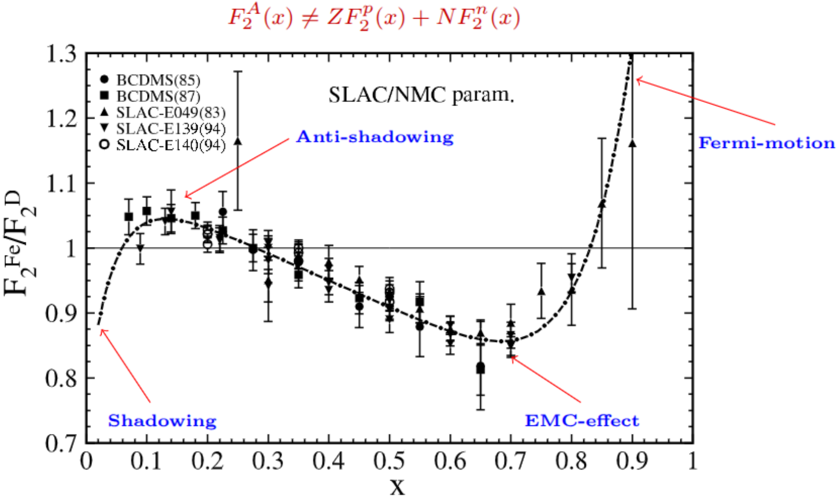


Figure 1: Reminder on Nuclear PDFs

Project A: Goal and Collaboration Overview

- **Goal of the study:**
  - Determine how **gluon shadowing varies with impact parameter** inside nuclei.
  - Relate spatial dependence to the **local nucleon density** (thickness function $T_A(b)$).
  - Use **two complementary observables** — centrality-dependent single J/ψ production and double-parton-scattering ($D^0 D^0$) in pA — to extract this dependence.
- **Collaborating groups:**
  - IFJ PAN (A. Kusina, S. Delorme)
  - IJCLab / Université Paris-Saclay (J.-P. Lansberg)
  - LPTHE / Sorbonne Université (H.-S. Shao)
- **My contribution:**
  - **Derive centrality classes of RHIC and LHC experiments (PHENIX, ALICE, LHCb, etc) from multiplicity** for both minimum-bias and hard-process events.
  - Computed event-by-event **impact-parameter distributions**, using TGlauberMC for data and my codes to use them in order to match each centrality class to a consistent b-range.
  - Produced the **centrality–b maps** required to test the spatial dependence of gluon shadowing.

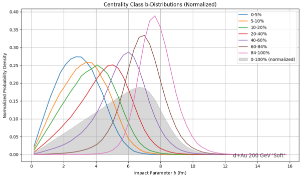
Project A: b-distributions and Centrality Classes

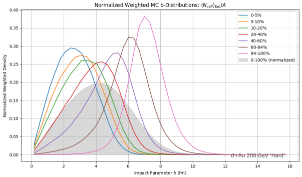
Inputs

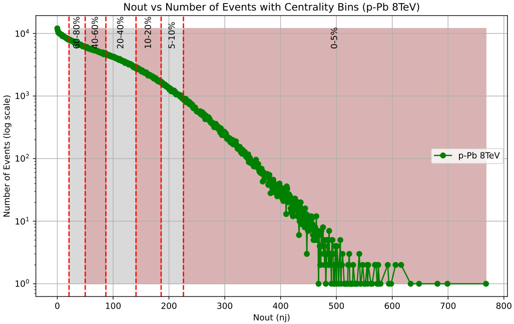
- **Type of collision**: e.g. d–Au
- **Energy**: $\sqrt{s_{NN}} = $ GeV/TeV (set value)
- **Number of events**: N_{evt} (set value)

Outputs

- For every centrality class `.dat` file with per–event: $\{N_{\mathrm{part}}, N_{\mathrm{coll}}, b\}$.
- Distributions: b, N_{part}, and N_{coll}.
- Averages: $\langle N_{\mathrm{coll}} \rangle$, $\langle N_{\mathrm{part}} \rangle$.
- Centrality classes (most violent $\rightarrow$ central, less violent $\rightarrow$ peripheral) based on multiplicity.
- Results provided for both **minimum bias** and **hard** events.







Project A: Methodology

Parameters

$$N_{\text{anc}} \;=\; f \times N_{\text{part}} \;+\; (1-f) \times N_{\text{coll}}$$

$$P_{p,k}(n) = \frac{(n+k-1)!}{n!\,(k-1)!}\; p^{\,k}\,(1-p)^{n}$$

- f: fraction of particle production attributed to participants.
- μ: mean particles produced per participant.
- k: width of the NBD (multiplicity fluctuations).

Methodology of Analysis

- For every event, compute N_{anc}.
- Use NBD to draw the created-particle counts; repeat N_{anc} times and sum for the event.
- Label the event by this sum, denoted N_{out}.
- Define 10 centrality classes by sorting on N_{out} and assign each event to a class.
- For each class, compute N_{coll}, N_{part}, b and their averages.

Project B: t-dependence and its connections with b-dependence

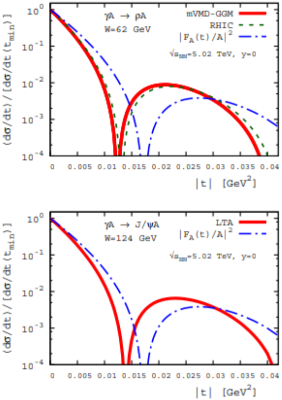
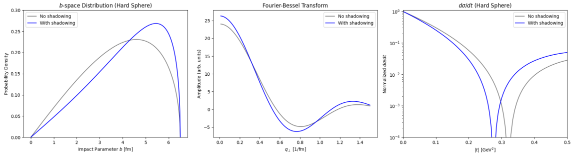


Figure 2: V. Guzey, M. Strikman, M. Zhalov, Phys. Rev. C 95 (2017) 025204



- Gusey et al used coherent $\gamma A \to VA$ photoproduction to extract **gluon transverse distributions**.
- They showed that nuclear shadowing **shifts diffractive minima** because of the broadening of $g_A(x, b)$.
- We reproduced the logic by computing *b*-**space profiles**, then performing the **Fourier–Bessel transform** to obtain *t*–space patterns.

Project C: Radiative corrections to $g \to \mathcal{Q} + g + g$ Fragmentation Functions

Impact of relativistic corrections to high-P_T prompt-$\psi(2S)$ production at hadron colliders

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[3]*School of Physics, University College Dublin, Dublin 4, Ireland*

- Relativistic corrections to prompt $\psi(2S)$ at high P_T studied using leading-power factorization with NRQCD fragmentation functions evolved to NLL accuracy.
- Corrections significantly enhance the gluon-fragmentation channel; effects are moderate for the charm channel.
- A full theoretical–parametric uncertainty analysis is performed.
- Predictions agree well with ATLAS and CMS without requiring color-octet terms.

Project C: Radiative corrections to $g \to \mathcal{Q} + g + g$ Fragmentation Functions

Goal

Compute the full radiative NLO corrections (virtual + real) to gluon $\to$ J/ψ fragmentation in full QCD.

- Collaboration: Jean-Philippe Lansberg, Maxim Nefedov, Aleksander Kusina, Chris Flett, Y.-Q. Ma *et al.*
- We develop the NLO corrections for the gluon $\to$ $^3S_1$ channel beyond the LO relativistic studies of Lynch *et al.*
- **So far:** LO gluon $\to$ J/ψ fragmentation fully reproduced and validated.
- **Current work:** building the **virtual NLO amplitudes** with Maxim Nefedov in full QCD .
- **Real-emission is for:** Chris Flett will derive the complete $g \to Q\bar{Q}gg$ real amplitudes.

Project D: SRC-motivated nuclear PDFs

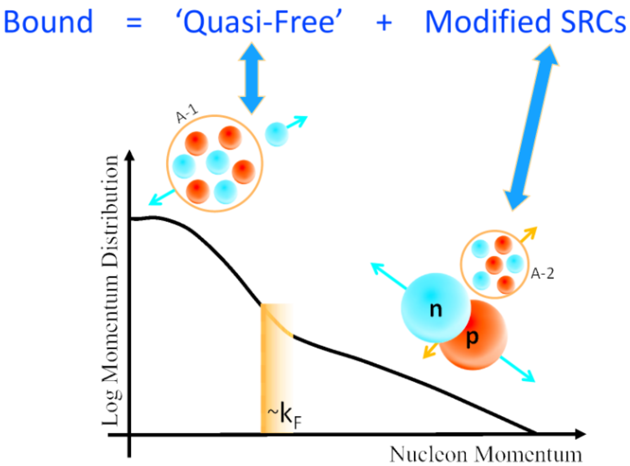
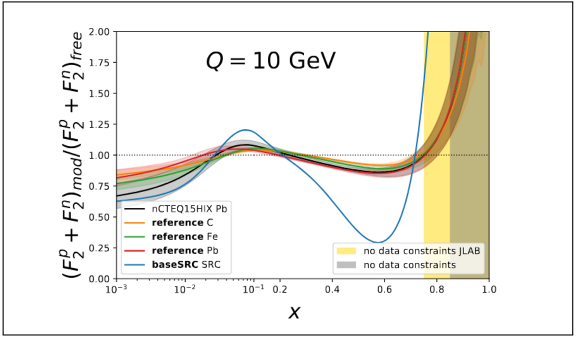


Figure 3: Or Hen, 4th International Workshop on Quantitative Challenges in SRC & EMC Effect Research, CEA France, 03/02/2023.

Project D: Short-Range Correlations (SRCs)

- **SRCs arise from nucleon pairs at very short distances** (typically $r \lesssim 1$ fm), where the strong force becomes highly repulsive or tensor-dominated.
- **Tensor and isospin-dependent interactions** are the main drivers of SRCs. In particular, *np* pairs dominate over *pp* or *nn* pairs due to strong tensor forces.
- **SRC pairs are concentrated near the nuclear center**, where the local density and overlap probabilities are highest.
- **No fixed momentum threshold:** SRCs generate high-momentum tails ($k > k_F$), while for $k < k_F$ the momentum distribution is dominated by mean-field (shell-model) nucleons.

Project D: SRC-motivated nuclear PDFs



- The simple SRC-based picture of nPDFs leads to comparable or better data description than the traditional nPDF parameterization.
- This suggests that the SRC framework points toward a deeper underlying description of the nuclear dynamics.
- Aim to continue on the work on SRC-motivated nPDFs of my advisor Aleksander Kusina.
- Have followed a summer school on Florida International University on the topic and have discussed with Wim Cosyn.

Other IJCLab-IFJ PAN Collaborations

The impact of future *D*- and *B*-meson measurements with the SMOG2 program at LHCb on the determination of nuclear parton distribution functions

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A B S T R A C T

We perform an analysis of the potential impact of future *D*- and *B*-meson measurement within the SMOG2 fixed-target program at the LHCb experiment on nuclear parton distribution functions. Following [1], we assume that SMOG2 will collect data for five nuclear targets: He, Ne, Ar, Kr, Xe and hydrogen which will provide a baseline for constructing nuclear ratios. The analysis is performed by using the PDF reweighting method. We demonstrate that such a measurement will allow to considerably reduce the current uncertainties of the nuclear gluon distribution and, to some extent, even the uncertainties of the light sea-quark distributions. Furthermore, it will provide the first possibility to systematically study the current assumptions on the *A*-dependence of the nuclear parton distributions.

- SMOG2 will collect heavy-flavour data on many nuclear targets (He, Ne, Ar, Kr, Xe, H), letting us directly form nuclear ratios.
- Using PDF reweighting, these data can sharply reduce uncertainties on the gluon nPDF and also partially on the light sea quarks.
- This will allow, for the first time, a systematic test of the assumed *A*-dependence of nuclear PDFs.

Other IJCLab-IFJ PAN Collaborations

Automated NLO calculations for asymmetric hadron-hadron collisions in `MadGraph5_aMC@NLO`

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- Automated NLO QCD calculations for asymmetric hadron–hadron collisions inside `MadGraph5_aMC@NLO`.
- Framework supports different beam types (e.g. *p*–A, *p*–He, *p*–gas), enabling consistent NLO predictions.
- Provides a key tool for future fixed-target and collider programs such as SMOG2.

Other IJCLab-IFJ PAN Collaborations

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https://doi.org/10.1088/1361-6471/adeda5

Major Report

Physics with high-luminosity proton-nucleus collisions at the LHC*

D d'Enterria[1,†], C A Flett[2,†], I Grabowska-Bold[3,†], C Hadjidakis[2,†], P Kotko[3,†], A Kusina[4,†], J P Lansberg[2,†], R McNulty[5,†,**], M Rinaldi[6,†], L Bonechi[7,‡], R Bruce[8,‡], C Da Silva[9,‡], E G Ferreiro[10,‡], S Fichet[11,‡], L Harland-Lang[12,‡], G Innocenti[13,‡], F Jonas[14,‡], J M Jowett[1,15,‡], R Longo[16,‡], K Lynch[2,5,‡], C McGinn[13,‡], T Pierog[17,‡], M Pitt[1,‡], S Redaelli[8,‡], B Schenke[18,‡], I Schienbein[19,‡], M Stefaniak[20,‡], M Strikman[21,‡], L Szymanowski[22,‡], D Tapia Takaki[23,‡], C Van Hulse[24,‡] and S Wallon[2,‡]

Abstract

The physics case for the operation of high-luminosity proton-nucleus (*pA*) collisions at the CERN LHC is reviewed. The collection of $\mathcal{O}(1\text{–}10\,\mathrm{pb}^{-1})$ of proton-lead (*p*Pb) collisions at the LHC will provide unique physics opportunities in a broad range of topics including proton and nuclear parton distribution functions (PDFs and nPDFs), generalised parton distributions (GPDs), transverse momentum dependent PDFs (TMDs), low-x quantum chromodynamics and parton saturation, hadron spectroscopy, baseline studies for quark-gluon plasma and parton collectivity, double and triple parton scatterings, photon–photon collisions, and physics beyond the Standard Model; which are not otherwise as clearly accessible by exploiting data from any other colliding system at the LHC. This report summarises the accelerator aspects of high-luminosity *pA* operation at the LHC, as well as each of the physics topics outlined above, including the relevant experimental measurements that motivate much larger *pA* datasets than collected to date.

- High-luminosity pA running provides huge new datasets, especially for pPb.
- Enables studies of nPDFs, GPDs, TMDs, low-x QCD, saturation, spectroscopy, MPI, and more.
- Report explains why these measurements require large statistics and how HL pA makes them feasible.

HQ4nPDFs in a nutshell

- Draft made for first publication: Nuclear PDFs and their geometry- Can we associate this with t-dependence?.
- NLO calculations for the Fragmentation Function of a gluon to J/Psi and gg.
- Short range correlations. Can they be the missing piece of the puzzle for EMC effect?
- Thank you all for your talks — Your patience with my rookie physics presentation shows what a great community I have joined!