kT factorisation and quarkonium production in the LHC era

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

Stéphane Delorme
(on behalf of the 12-147 collaboration)

COPIN-IN2P3 Workshop 2023

Warsaw University of Technology

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Scientists in the collaboration

- IN2P3 scientists:
  - J.P. Lansberg (IJCLAB)
  - S. Wallon (IJCLAB)
  - M. Nefedov (IJCLAB, post-doc)
  - C. Flett (IJCLAB, post-doc)
  - S. Nabeebaccus (IJCLAB, post-doc)
  - Y. Yedelkina (IJCLAB, Ph. D student)
  - E. Li (IJCLAB, Ph. D student)
  - J. Bor (IJCLAB, Ph. D student)
- COPIN scientists:
  - A. Kusina (IFJ PAN)
  - D. Kikoła (WUT)
  - J. Wagner (NCBJ)
  - L. Szymanowski (NCBJ)
  - A. van Hameren (IFJ PAN)
  - S. Delorme (IFJPAN, post-doc)
  - A. Colpani Serri (WUT, Ph. D student)
  - A. Safronov (WUT, Ph. D student)
  - L. Manna (WUT, Ph. D student)

Exchanges in 2023

- 0 days approved for IN2P3 scientists in COPIN
- 34 days approved for COPIN scientists in France
  - A. Colpani Serri (7 days)
  - S. Delorme (7 days)
  - K. Kutak (4 days)
  - A. van Hameren (4 days)
  - T. Altinoluk (4 days)
  - G. Beuf (4 days)
  - L. Manna (4 days)
- A. Colpani Serri stayed for 3 weeks to attend doctoral school lectures in IJCLab
- L. Manna stayed for 3 weeks in September in IJCLab
- J. Wagner stayed for 2 weeks in Ecole Polytechnique
- L. Szymanowski stayed for several weeks in France

Workshops/Meetings

- Quarkonia As Tools 2023, 4–14 Jan 2023, Aussois, France
- QCD Evolution Workshop 2023, Orsay, France, 22–26 May 2023
- NLOAccess/Precisonium annual meeting, 20 - 24 Nov 2023, CERN
- Quarkonia As Tools 2024, 7–13 Jan 2024, Aussois, France
- Workshop on overlap between QCD resummations 14 Jan - 17 Jan 2024, Aussois, France

- Usually from 5 to 15 participants from COPIN/IN2P3 (e.g. for QaT2024: S. Delorme, L. Manna, A. Colpani Serri, A. Safronov, A. Matyja on the polish side)

Ph.D students

- A. Colpani Serri: Works in WUT under the supervision of D. Kikoła (+ partial co-supervision of J.P. Lansberg) on the extension of Madgraph to TMD factorisation and to quarkonium production. Also works with C. Flett and J. Bor.
- A. Safronov: Works in WUT under the supervision of D. Kikoła (+ partial co-supervision of J.P. Lansberg) on the implementation of the computation of cross sections in proton-nucleus collisions in Madgraph at NLO.
- L. Manna: Works in WUT under the supervision of D. Kikoła (+ partial co-supervision of J.P. Lansberg) on the implementartion of the computation of cross sections in photon-hadron and lepton-hadron collisions in Madgraph at NLO.
- Strongly consolidate the contribution of WUT in NLOAccess (EU-funded Virtual Access for automated pQCD computations).

Ph.D students

- Y. Yedelkina: Works in IJCLAB on the quarkonium production with QCD corrections. Works with M. Nefedov
- E. Li: Works in IJCLAB under the supervision of S. Wallon and L. Szymanowski on probing gluon saturation in semi-hard γ(*) + p/A processes. Defended her Ph. D on 19/10/2023.
- J. Bor: Connected to COPIN-IN2P3, works on TMD factorization with A. Colpani Serri
- K. Lynch: Also connected to the collaboration, works on inclusive photoproduction at the LHC in UPC (related to the work of A. Safronov, L. Manna and A. Colpani Serri)

Problem: Perturbative instability of quarkonium total cross sections

Inclusive η_c-hadroproduction [Mangano *et.al.*, '97, ..., Lansberg, Ozcelik, '20]

$$p+p \to c\bar{c}\left[{}^1S_0^{[1]}\right]+X,\ \text{LO: } g(p_1)+g(p_2) \to c\bar{c}\left[{}^1S_0^{[1]}\right],$$

$$\sigma(\sqrt{s_{pp}}) = f_i(x_1,\mu_F)\otimes f_j(x_2,\mu_F)\otimes\hat{\sigma}(z),$$

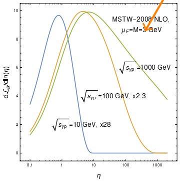
where $z = \frac{M^2}{\hat{s}}$ with $\hat{s} = (p_1+p_2)^2$.

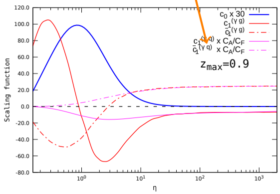
Inclusive J/ψ-photoproduction [Krämer, '96, ...,Colpani Serri *et.al*, '21]

$$\gamma+p \to c\bar{c}\left[{}^3S_1^{[1]}\right]+X,\ \text{LO: } \gamma(q)+g(p_1) \to c\bar{c}\left[{}^3S_1^{[1]}\right]+g,$$

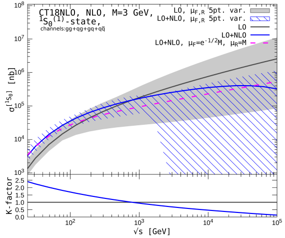
$$\sigma(\sqrt{s_{\gamma p}}) = f_i(x_1,\mu_F)\otimes\hat{\sigma}(\eta),$$

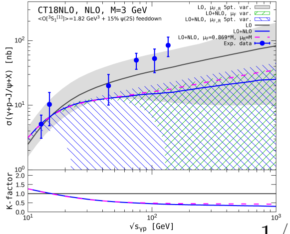
where $\eta = \frac{\hat{s}-M^2}{M^2}$ with $\hat{s} = (q+p_1)^2$, $z = \frac{pP}{qP}$.





At sufficiently high energy, the $\mu_{F,R}$-variation band of NLO computation blows-up:



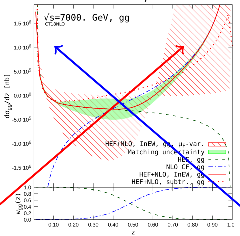


Solution: Matching between High-Energy Factorisation and NLO

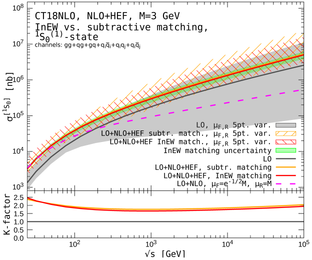
We resum corrections $\propto \alpha_s^n \ln^{n-1}(\hat{s}/M^2)$ to $\hat{\sigma}(\hat{s})$ using HEF and smoothly match it with NLO CF by the *Inverse-Error Weighting Method.*

η_c-hadroproduction [Lansberg, Nefedov, Ozcelik 21']

$z = M^2/\hat{s}$:

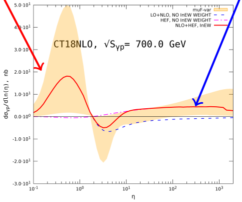


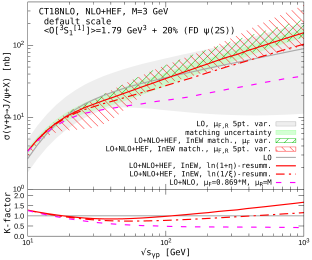
NLO **HEF**



J/ψ-photoproduction [Lansberg et al. 23']

$\eta = (\hat{s} - M^2)/M^2$:





Collaborative activities

- Visit of A. van Hameren (IFJ PAN, Krakov) to IJClab, Orsay on 14/08-18/08/2023, funded by the Marie Sklodowska Curie action "RadCor4HEF" (grant agreement t No. 101065263)
- Participation of A. van Hameren (IFJ PAN, Krakov), K. Kutak (IFJ PAN, Krakow), G. Beuf (NCBJ, Warsaw) and T. Altinoluk (NCBJ, Warsaw) in the "Mini-Workshop on the overlap between QCD resummations" in the Centre Paul Langevin (CNRS) in Aussois (France) on 14th - 17th of January 2024. Funded by COPIN.

Transversity GPDs (chiral-odd GPDs) are completely unknown experimentally. We have proposed the exclusive photoproduction of a photon-meson pair with large invariant mass to extract them:

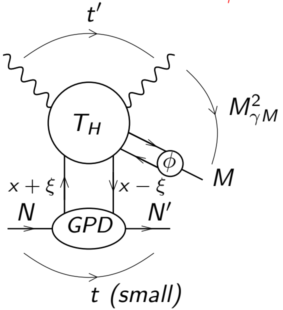
- $\gamma N \to \gamma M N'$:

  R. Boussarie, G. Duplančić, S. Nabeebaccus, K. Passek-Kumerički, B. Pire, L. Szymanowski, S. Wallon: [1609.03830, 1809.08104, 2212.00655, 2302.12026]

Moreover, the richer kinematics of the process allows the sensitivity of GPDs wrt x to be probed (beyond moment-type dependence, e.g. in DVCS): J. Qiu, Z. Yu: [2305.15397]

Exclusive photoproduction of γ-meson pair with large invariant mass

- Consider the process $\gamma N \to \gamma M N'$, M =meson. Collinear factorisation of the amplitude at large $M^2_{\gamma M}$, t', u', and small t.



Factorised formula:

$$\mathcal{A} = \int_{-1}^{1} dx \int_{0}^{1} dz \; T(x,\xi,z) \; H(x,\xi,t) \; \Phi_M(z)$$

$T(x,\xi,z)$: Coefficient function (Hard), computed in pQCD
$H(x,\xi,t)$: GPD (soft)
$\Phi_M(z)$: Distribution amplitude of outgoing meson

Exclusive photoproduction of γ-meson pair with large invariant mass

- Mesons considered in the final state: $\pi^{\pm}$, $\rho^{\pm,0}_{L,T}$.
- Leading order and leading twist.
- Cross-section (and polarisation asymmetries wrt to incoming photon) differential in $(-u')$ and $M^2_{\gamma M}$, and evaluated at $(-t) = (-t)_{\min}$, covering $S_{\gamma N}$ from $\sim 4\,\text{GeV}^2$ to $20000\,\text{GeV}^2$.
- Very good statistics at various experiments, such as JLab, COMPASS, future EIC and LHC in ultra-peripheral collisions (UPCs).
- Small ξ studies can also be done using experimental data from collider experiments.

Extension of the calculation to NLO
Quark GPD case

At LO, there are 20 diagrams, but at NLO, this goes up to 422!
$\Longrightarrow$ Necessary to automate!
Our approach:

1. Generate diagrams using FeynArts
2. Reduce tensor loop integrals (which can go up to 6-point functions!) to a basis of *known scalar master integrals*.
   $\Longrightarrow$ Use ROLI (Reduction Of Loop Integrals), a private code based on Integration-By-Parts (IBP) reduction developed by Goran Duplancic, which is based on B. Nizic, G. Duplancic [hep-ph/0303184] .
3. Include GPD evolution and observe explicitly the cancellation of IR divergences.
4. Perform convolution over momentum fractions x (GPD) and z (DA).

Computation very similar to B. Nizic, G. Duplancic [hep-ph/0607069] for $\gamma\gamma \to \pi^+\pi^-$ ... except ...

- No $i\epsilon$ factors needed when calculating the convolution of coefficient function with 2 DAs in the $\gamma\gamma \to \pi^+\pi^-$ case.
- In $\gamma N \to \gamma MN$, since poles of propagators are crossed during the convolution, one requires $i\epsilon$ factors to be in place in arguments of logs and dilogs (easy), as well as in denominators (hard).
- Denominators can appear both through the IBP reduction procedure, or through the evalutation of master integrals themselves, where naive analytic continuation $(p_i^2 \to p_i^2 + i\epsilon)$ does NOT lead to the correct prescription! [B. Nizic, G. Duplancic: hep-ph/0006249]

Extension of the calculation to NLO
Quark GPD case

- Finally, need to deal with numerical instabilities in convolution integral: These instabilities are present even in the $\gamma\gamma \to \pi^+\pi^-$ calculation, due to the introduction of spurious singularities that should cancel in the end...
- With $i\epsilon$ in denominators, the situation becomes much more complicated.
- This was actually a significant bottleneck in the NLO computation of $\gamma N \to \gamma\gamma N$, performed by O. Grocholski, B. Pire, P. Sznajder, L. Szymanowski, J. Wagner [2110.00048, 2204.00396], where a finite $i\epsilon$ was kept for the numerics.
$\implies$ However, calculation significantly simpler than our case, since only one convolution integration to perform, and also have up to 5-point functions to reduce.

Breakdown of collinear factorisation in $\pi^0\gamma$ pair photoproduction

- Unlike the channels considered before, having a π^0 meson in the final state allows the exchange of two gluons in the t-channel, due to its quantum number $J^{PC} = 0^{-+}$.
- Therefore, the amplitude becomes sensitive to gluon GPDs.
- Assuming collinear factorisation, we performed a calculation of the gluon GPD contribution, and found that it *diverges* at *leading order* and *leading twist*! This indicates a breakdown of collinear factorisation!
- In our very recent paper [S. Nabeebaccus, J. Schoenleber, L. Szymanowski, S. Wallon: 2311.09146], we were able to show that this is due to the existence of *Glauber gluon* ($|k_T|^2 \gg k^+k^-$) exchanges which remain trapped, preventing a *collinear* factorisation of the process.
- However, all processes we have previously studied are safe, since two-gluon exchanges are forbidden.

Heavy-quark constraints on nuclear PDFs

- nPDFs: essential link between measurable hadronic cross-sections and calculable cross-sections induced by partons
- More challenging than nucleon PDFs (not just a sum of nucleon PDFs)
- Determined by performing global analyses of experimental data
- Gluon content of nuclei very little known compared to quark content ($x < 10^{-3}$ region extrapolated from larger x region)
- Necessary for phenomenology of heavy-ion to determine the small-x gluon nPDFs and to reduce their uncertainties
- Recent study of the impact of heavy quark data
  $\Rightarrow$ Way to constrain gluon density down to $x = 7.10^{-6}$
  A. Kusina, J.P. Lansberg, I. Scheinbein, H.S. Shao, Phys.Rev.D 104 (2021) 1, 014010
  P. Duwentäster, T. Ježo, M. Klasen, K. Kovařík, A. Kusina, Phys.Rev.D 105 (2022) 11, 114043

Heavy-quark constraints on nuclear PDFs

- Focus on the spatial dependence of the gluon nPDFs
- Assumption that the spatially dependent nuclear modification can be determined by the local nucleon number density (thickness function)

$$R^A(\mathbf{b}, x, \mu_F) - 1 = (R^A(x, \mu_F) - 1)\, G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right),$$

with

$$\int T_A(\mathbf{b})\, G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) d^2\mathbf{b} = A.$$

We take:

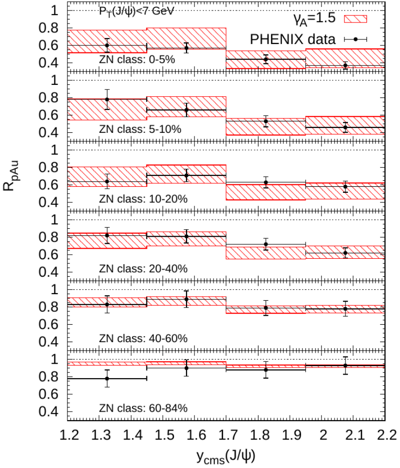
$$G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) \propto \left(\frac{T_A(\mathbf{b})}{T_A(0)}\right)^{\gamma_A},$$

with γ_A to be determined ($\gamma_A = 1$ often used in literature)

Heavy-quark constraints on nuclear PDFs

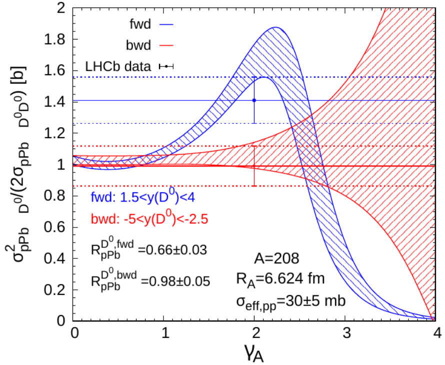
- 2 types of data are used:
  - Centrality dependent R_{pA} for single inclusive particle production (in our case pAu $\rightarrow$ J/Ψ forward data from PHENIX (RHIC) at $\sqrt{s_{NN}} = 200$ GeV)
    - forward: tension between nPDFs and backwards data
    - J/Ψ: Comover effect may be important for excited states like Ψ(2S)
    - RHIC: Large event-by-event fluctuations for LHC data.
  - Double Parton Scattering (DPS) in minimum bias pA collisions.
    - Choice of pPb $\rightarrow D^0 D^0$ LHCb data
    - pPb $\rightarrow J/\Psi D^0$ data also available but suffer from large SPS contamination.

Centrality dependent R_{pA}



- $R_{pAu}(b_{min} < b < b_{max}) = 1 - r + rR_{pAu}$
- $r = \frac{\int_{b_{min}}^{b_{max}} T_A(\mathbf{b}) G\left(\frac{T_A(\mathbf{b})}{T_A(0)}\right) d^2\mathbf{b}}{\int_{b_{min}}^{b_{max}} T_A(\mathbf{b}) d^2\mathbf{b}}$
- R_{pAu} obtained from experiment (0-100% centrality)
- Best fit gives $\gamma_A = 1.50 \pm 0.10$ with χ^2/ndf = 0.64. (24 data points vs $y_{cms}(J/\Psi)$ and 96 vs $p_T(J/\Psi)$)
- Still work to do (correspondence between **b** and the centrality classes is more complex than what is done here)

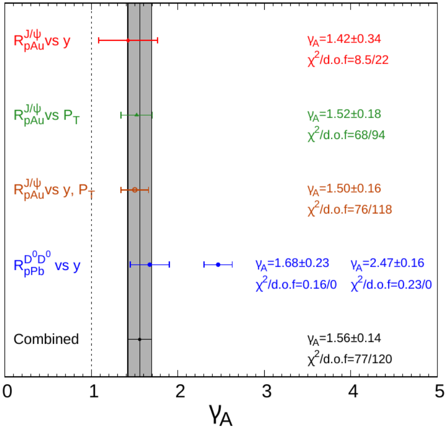
Minimum bias DPS



H.S. Shao, Phys. Rev. D 101 (2020) 5, 054036

- $R^{DPS}_{pPb\to D_0 D_0} = \frac{\sigma^{DPS}_{pPb\to D_0 D_0}}{A\sigma^{DPS}_{pp\to D_0 D_0}}$
  $=\Sigma^2_{i,j=1}\left(\hat{T}_{A,ij} + (A-1)\sigma_{eff,pp}\hat{T}^{(2)}_{A,ij}\right)\times$
  $\left(R^{D_0}_{pPb}\right)^{2-i}\left(R^{D_0}_{pPb}\right)^{2-j}$
- $\sigma_{eff,pp}$: effective pp cross-section without initial parton-parton correlations, measured from DPS in pp collisions
- $R^{D_0}_{pPb}$: Nuclear modification of single inclusive D_0 production (measured)
- 2 χ^2 minima: $\gamma_A = 1.68 \pm 0.23$ and $\gamma_A = 2.47 \pm 0.16$

Combined results



- 2 very different observables but compatible results
- Atomic numbers of lead and gold are close $\Rightarrow$ combination of fits
- Global fit gives $\gamma_A = 1.56 \pm 0.14$ (less than 10% relative uncertainty) $\Rightarrow$ Highly disfavors $\gamma_A = 0$ (and also $\gamma_A = 1$ to a lesser extent)

2024 activities

- Main activities in 2024:
  - Determination of gluon nuclear PDFs (A. Kusina, J.P. Lansberg, I. Schienbein, H.S. Shao, S. Delorme): paper to be submitted
  - QCD corrections to exclusive processes to study GPDs at NLO accuracy (C. Flett, S.Nabeebaccus, J. Wagner, L. Szymanowski, S. Wallon): 1 paper on 2-to-3 processes and one on quarkonium production
  - Ph. D in direct co-supervision between France and Poland: A. Safronov, L. Manna, A. Colpani Serri
  - 4 other Ph. D from IJCLAB involved in the scientific exchanges: J. Bor, Y. Yedelkina, K. Lynch, A.C. John Rubesh Rajan

2024 activities

- The MSCF EU project of M. Nefedov on High Energy/kT factorisation for quarkonium production (in collaboration with A. van Hameren)
- The EU Virtual Access NLOAccess between IJCLab, LPTHE, UCLouvain and WUT, with the inclusion of TMD factorisation by C. Flett and J. Bor (PI: J.P. Lansberg)
- Review on the quarkonium physics at the EIC (editors: J.P. Lansberg, M.Nefedov, D. Kikola)