# Workshop on Double Parton Scattering and the 3D structure of hadrons

# Cold Nuclear Matter Effects: from the LHC to the EIC







Exclusive quarkonium production in UPCs and nPDFs

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## Contents

State-of-the-art experimental measurements from ep to AA

Exclusive  $J/\psi$  photoproduction from experiments past&present

pQCD theory framework for AA UPCs

J/ψ in PbPb Y in PbPb

Infamous scale-stability problem in NLO pQCD

Collinear factorisation + High-energy factorisation + LL GPD evolution

CAF, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, Phys.Lett.B 859 (2024) 139117

Exclusive J/ψ photoproduction to date (fixed target+ **ep**, pp, pPb)



ep@HERA:

hep-ex/0201043, hep-ex/0404008, hep-ex/0510016, hep-ex/0404008



Tagged electron => measure photon virtuality. Here, discuss photoproduction (quasi-real photons)

Photon fluctuation into heavy-quark pair, producing J/psi via two-parton colour-singlet exchange

Exclusive J/ψ photoproduction to date (fixed target+ ep, **pp**, pPb)



## Exclusive J/ $\psi$ photoproduction to date (fixed target+ ep, pp, **pPb**)



pPb@LHC: 1406.7819, 1809.03235 , 2304.12403

-For pp, have more lumi. but more pileup than pPb

-For pp, have  $W_+/W_-$  ambiguity,

#### very much less so for pPb

-For pp, more model dependence in survival factor/photon flux combination

-For pp, more contamination from Odderon-pomeron due to relatively smaller impact parameter

**ALICE**: Exclusive J/ψ photoproduction in pPb at 5.02 & 8.16 TeV

### 5.02TeV at both semi-forward, forward & midrapidity (wrt to p directn)

pPb (2.5 < y < 4)Pbp (-3.6 < y < -2.6) } yield ~70-400 depend. on rapidity and lumi Lint: 4-8 nb<sup>-1</sup>

8.16 TeV forward only (wrt to p directn)



Forward Direction

## This talk $\longrightarrow$ Exclusive J/ $\psi$ photoproduction off Pb (UPC **PbPb**)



ALICE has measured the coherent production of  $J/\psi$  across 3 orders of magnitude in Bjorken-x

The new ALICE data is consistent with ALICE measurements from Run 1 and with CMS results from Run 2

The new ALICE data extends the reach in the centre-of-mass energy of the photon-Pb system by more than 300 GeV

**Scope**: Discuss pQCD formulism + results for exclusive quarkonium production in AA UPCs, sensitivity to nPDFs

### Framework

- Fluctuation of incoming photon into pair of heavy quarks
- Pair interacts with proton P (or nucleus N) via twoparton colour-singlet exchange
- Modelling of heavy-quark pair recombination into time-like exclusive vector meson made within NRQCD



$$F_{q/g} \otimes C_{q/g} \otimes \phi_{Q\bar{Q}}^V$$

NRQCD:  $\phi(z) \sim \delta(z-1/2)$ 

#### **Coefficient functions**

$$A \propto \int_{-1}^{1} \mathrm{d}x \left[ C_g(x,\xi) F_g(x,\xi) + \sum_{q=u,d,s} C_q(x,\xi) F_q(x,\xi) \right]$$

Photoproduction (on-shell photon) pp/pA/AA

Factorisation not proven but holds to fixed-order NLO Ivanov, Schäfer, Szymanowski, Krasnikov, 04 & Jones, 14 (thesis)

Electroproduction (off-shell photon) ep/eA

Chen, Qiao, 19 CAF, <u>Gracey</u>, Jones, <u>Teubner</u>, 21



large x at some initial scale  $\mu_0$  controls effectively the region of small x at the hard scale ~MV /2, MV.

This allows to consider that most of the  $\xi$  dependence at ~MV /2, MV arises from the evolution.

Dutrieux, Winn, Bertone Phys.Rev.D 107 (2023) 11, 114019

GPDs ~ PDFs at small  $\xi$ 

### Framework for AA



#### Photon flux

$$k\frac{dN_{\gamma}^{A}(k)}{dk} = \int d^{2}\vec{b} N_{\gamma}^{A}(k,\vec{b})\Gamma_{AA}(\vec{b})$$

Guzey&Zhalov JHEP 02 (2014) 046

Number of equivalent WW photons of energy k at a transverse distance b from the center of a nucleus A with Z protons:

$$N_{\gamma}^{A}(k, ec{b}) = rac{Z^{2} lpha_{ ext{e.m.}}}{\pi^{2}} \Bigg| \int_{0}^{\infty} dk_{\perp} rac{k_{\perp}^{2} ilde{F}_{A}(k_{\perp}^{2} + k^{2}/\gamma_{L}^{2})}{k_{\perp}^{2} + k^{2}/\gamma_{L}^{2}} J_{1}(|ec{b}|k_{\perp}) \Bigg|^{2}$$

Glauber probability for no hadronic interactions:

$$\Gamma_{AA}(\vec{b}) = \exp[-\sigma_{NN}(s_{NN})T_{AA}(\vec{b})]$$

total n-n int. cross section

nuclear overlap function

$$k \frac{dN_{\gamma}^{A}(k)}{dk} = \int d^{2}\vec{b}N_{\gamma}^{A}(k,\vec{b})\Gamma_{AA}(\vec{b}) \qquad \text{UPC bmin > 2 RA > 18fm} \\ \text{for PbPb} \\ + k \frac{dN_{\gamma/Z}^{\text{pl}}(k)}{dk} \bigg|_{b_{\text{min}}} - k \frac{dN_{\gamma/Z}^{\text{pl}}(k)}{dk} \bigg|_{b_{\text{min}}} \\ = k \frac{dN_{\gamma/Z}^{\text{pl}}(k)}{dk} \bigg|_{b_{\text{min}}} + \int_{0}^{b_{\text{min}}} d^{2}\vec{b} N_{\gamma}^{A}(k,\vec{b})\Gamma_{AA}(\vec{b}) \\ + \int_{b_{\text{min}}}^{\infty} d^{2}\vec{b} \left[ N_{\gamma}^{A}(k,\vec{b})\Gamma_{AA}(\vec{b}) - N_{\gamma/Z}^{\text{pl}}(k,\vec{b}) \right].$$

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**Scale sensitivity** Set  $\mu_F = \mu_R = \mu$ , vary  $\mu$ from  $M_{J/\psi}/2 = m_c$  to  $M_{J/\psi} = 2m_c$ Huge scale dependence (!)

Optimal scale can be found which ~reproduces ALICE central, CMS and LHCb data at two centre-of-mass energies

Large scale uncertainty observed in original work of Ivanov et al. twenty years ago!

Ivanov, <u>Schäfer</u>, <u>Szymanowski</u>, <u>Krasnikov</u>, 04

Eskola,CAF, Löytäinen, Guzey, Paukkunen Phys.Rev.C 106 (2022) 3, 035202 Phys.Rev.C 107 (2023) 4, 044912



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see later for various approaches to alleviate this

Eskola,CAF, Löytäinen, Guzey, Paukkunen Phys.Rev.C 106 (2022) 3, 035202 Phys.Rev.C 107 (2023) 4, 044912

#### **Quarks & gluons decomposition** $\mathcal{M} = \mathcal{M}_G^{ ext{LO}} + \mathcal{M}_G^{ ext{NLO}} + \mathcal{M}_Q^{ ext{NLO}}$ Full $|M|^2$ NLO with EPPS16 $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ Only Gluons $\frac{d\sigma}{dy}$ (Pb+Pb $\rightarrow$ Pb+// $\Psi$ +Pb) [mb] $\mu_F = \mu_R = 2.37 \text{ GeV}$ Only Quarks Interference 3. Only gluons **Only quarks** 2 $|\mathcal{M}|^2 = |\mathcal{M}_G^{\mathrm{LO}} + \mathcal{M}_G^{\mathrm{NLO}}|^2 + |\mathcal{M}_Q^{\mathrm{NLO}}|^2$ $+2\left[\operatorname{Re}(\mathcal{M}_{G}^{\mathrm{LO}}+\mathcal{M}_{G}^{\mathrm{NLO}})\operatorname{Re}(\mathcal{M}_{Q}^{\mathrm{NLO}})\right]$ 1. + Im $(\mathcal{M}_{G}^{\mathrm{LO}} + \mathcal{M}_{G}^{\mathrm{NLO}})$ Im $(\mathcal{M}_{Q}^{\mathrm{NLO}})$ . 0 Interference Eskola, CAF, Löytäinen, Guzey, Paukkunen $^{-2}$ -6-4 6 0 2 Phys.Rev.C 106 (2022) 3,035202 y Phys.Rev.C 107 (2023) 4,044912

J/ψ

Apparent quark contribution dominant at mid-rapidity (!) -LO & NLO gluon amplitudes tend to cancel - feature of NLO

Structure of amplitude detailed, interplaying between photoproduction cross section, photon flux, form factor and  $W_+/W_-$  components

Caveat: may anticipate different picture at NNLO so be careful with interpretation



# J/ψ

Nuclear+free baseline PDF uncertainties encompass available data both at Run I and Run II energies nicely

Wider distribution in underlying error sets for nNNPDF3.0 & nCTEQ15WZSIH compared to EPPS21 gives larger uncertainties

Newer LHCb 2018 data points more in line with ALICE fwd ones

Eskola,CAF, Löytäinen, Guzey, Paukkunen Phys.Rev.C 106 (2022) 3, 035202 Phys.Rev.C 107 (2023) 4, 044912 Y

Data-driven approach

$$\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W) = \left[\frac{\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p \to \Upsilon p}(W)}\right]_{\mathrm{pQCD}} \sigma_{\mathrm{fit}}^{\gamma p \to \Upsilon p}(W)$$

Overall normalisation from HERA-data fit





Less complicated interplay than in J/\u03c6 case, gluon dominated Eskola,CAF, Löytäinen, Guzey, Paukkunen Eur.Phys.J.C 83 (2023) 8,758

Data-driven approach

$$\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W) = \left[\frac{\sigma^{\gamma \mathrm{Pb} \to \Upsilon \mathrm{Pb}}(W)}{\sigma^{\gamma p \to \Upsilon p}(W)}\right]_{\mathrm{pQCD}} \sigma_{\mathrm{fit}}^{\gamma p \to \Upsilon p}(W)$$

Overall normalisation from HERA-data fit



#### **Nuclear modification factor**



pQCD ratio R normalised by R' to elim. nuclear and proton form factor effects central R'xR follows shape and normalisation of central Rg -> dominance of gluon contribution

results confirms expectation we are sensitive to input nuclear and free PDFs through ratio Various scale dependence approaches

Scale fixing Jones et al., J.Phys.G 43 (2016) 3, 035002 LLA resummation Ivanov 0712.3193 Ivanov et al., 1601.07338

#### here discuss

• Integration of Collinear Factorisation (CF) with High-energy Factorisation (HEF)

=> to

C<sub>qq</sub> in D

in a manner consistent with the NLO DGLAP evolution of GPDs in CF allows for a consistent matching procedure

CAF, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, Phys.Lett.B 859 (2024) 139117



$$C_{g}^{\text{HEF}}\left(\frac{\xi}{x}\right) = \frac{-i\pi}{2} \frac{F_{\text{LO}}}{\left(\frac{\xi}{x}\right)} \int_{0}^{\infty} d\mathbf{q}_{T}^{2} C_{gi}\left(\frac{\xi}{x}, \mathbf{q}_{T}^{2}, \mu_{F}, \mu_{R}\right) h(\mathbf{q}_{T}^{2}),$$

$$h(\mathbf{q}_{T}^{2}) = \frac{M^{2}}{M^{2} + 4\mathbf{q}_{T}^{2}} \quad \longleftarrow \text{ process-dependent factor}$$

$$LLA \text{ in } x/\xi; a_{S}^{n} \ln^{n-1} x/\xi *F(Q^{2}), \text{ exact in } Q.$$

$$=> \text{ Cgi in } LLA \text{ in } x/\xi \text{ contains } Q \text{ dep terms not included in DGLAP}$$

$$=> \text{ to be consistent with NLO DGLAP we truncate this resummation to the Double-Leading-Logarithmic (DLA) approximation (intersection of LLA in x and Q^{2}).$$

$$HEF DLA \text{ resummation of terms } \sim a_{S}^{n} \ln^{n-1} x/\xi \ln^{n-1} \mu_{F} \text{ at } integrand \text{ level to the imaginary part of Cgi}$$

$$\mathcal{C}_{gg}^{(\mathrm{DL})}\left(\frac{\xi}{x},\mathbf{q}_{T}^{2},\mu_{F}^{2},\mu_{R}^{2}\right) = \frac{\hat{\alpha}_{s}}{\mathbf{q}_{T}^{2}} \begin{cases} J_{0}\left(2\sqrt{\hat{\alpha}_{s}\ln\left(\frac{x}{\xi}\right)\ln\left(\frac{\mu_{F}^{2}}{\mathbf{q}_{T}^{2}}\right)\right) & \text{if } \mathbf{q}_{T}^{2} < \mu_{F}^{2}, \\ I_{0}\left(2\sqrt{\hat{\alpha}_{s}\ln\left(\frac{x}{\xi}\right)\ln\left(\frac{\mathbf{q}_{T}}{\mu_{F}^{2}}\right)\right) & \text{if } \mathbf{q}_{T}^{2} > \mu_{F}^{2}. \end{cases}$$

 $\implies$  resums terms scaling like  $(\hat{\alpha}_s \ln(x/\xi) \ln(\mu_F^2/\mathbf{q}_T^2))^n$  to all orders in perturbation theory. at amplitude level

Integration of Collinear Factorisation (CF) with High-energy Factorisation (HEF)

in a manner consistent with the NLO DGLAP evolution of GPDs in CF allows for a consistent matching procedure

CAF, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, Phys.Lett.B 859 (2024) 139117



Convert (\*) to Mellin space, insert into CgHEF to get its Mellin-space rep and then invert again:

$$C_{g}^{\text{HEF}}\left(\frac{\xi}{x}\right) = \frac{-i\pi\hat{\alpha}_{s}F_{\text{LO}}}{2\left|\frac{\xi}{x}\right|}\sqrt{\frac{L_{\mu}}{L_{x}}}\left\{I_{1}\left(2\sqrt{L_{x}L_{\mu}}\right) - 2\sum_{k=1}^{\infty}\text{Li}_{2k}(-1)\left(\frac{L_{x}}{L_{\mu}}\right)^{k}I_{2k-1}\left(2\sqrt{L_{x}L_{\mu}}\right)\right\}$$
  
where  $L_{\mu} = \ln[M^{2}/(4\mu_{F}^{2})]$  and  $L_{x} = \hat{\alpha}_{s}\ln\left|\frac{x}{\xi}\right|.$ 

This yields, when expanded in  $\alpha_s$ ,

$$C_{g}^{\mathsf{HEF}}\left(\frac{\xi}{x}\right) = \frac{-i\pi F_{\mathsf{LO}}}{2} \left( \underbrace{\delta\left(\left|\frac{\xi}{x}\right| - 1\right) + \frac{\hat{\alpha}_{s}}{\left|\frac{\xi}{x}\right|} \ln\left(\frac{M^{2}}{4\mu_{F}^{2}}\right)}_{\rightarrow C_{g}^{\mathsf{asy.}}} + \frac{\hat{\alpha}_{s}^{2}}{\left|\frac{\xi}{x}\right|} \ln\frac{1}{\left|\frac{\xi}{x}\right|} \left[\frac{\pi^{2}}{6} + \frac{1}{2}\ln^{2}\left(\frac{M^{2}}{4\mu_{F}^{2}}\right)\right] + \dots \right)$$

first two terms match the LO and NLO CF results at small  $\xi$ 

Quark coefficient function:

$$C_q^{\mathsf{HEF}}\left(\frac{\xi}{x}\right) = \frac{2C_F}{C_A}C_g^{\mathsf{HEF}}\left(\frac{\xi}{x}\right)$$

#### Integration of Collinear Factorisation (CF) with High-energy Factorisation (HEF)

in a manner consistent with the NLO DGLAP evolution of <u>GPDs</u> in CF allows for a consistent matching procedure CAF, <u>Lansberg</u>, <u>Nabeebaccus</u>, <u>Nefedov</u>, <u>Sznajder</u>, Wagner, <u>Phys.Lett.B</u> 859 (2024) 139117



$$C_{g,q}^{\text{match.}} \begin{pmatrix} \frac{\xi}{x} \end{pmatrix} = C_{g,q}^{\text{NLO CF}} \begin{pmatrix} \frac{\xi}{x} \end{pmatrix} - C_{g,q}^{\text{asy.}} \begin{pmatrix} \frac{\xi}{x} \end{pmatrix} + C_{g,q}^{\text{HEF}} \begin{pmatrix} \frac{\xi}{x} \end{pmatrix}$$
$$C_{g}^{\text{asy.}} \begin{pmatrix} \frac{\xi}{x} \end{pmatrix} = \frac{C_{A}}{2C_{F}} C_{q}^{\text{asy.}} \begin{pmatrix} \frac{\xi}{x} \end{pmatrix}$$
$$= \frac{-i\pi F_{\text{LO}}}{2} \left[ \delta \left( \left| \frac{\xi}{x} \right| - 1 \right) + \frac{\hat{\alpha}_{s}}{\left| \frac{\xi}{x} \right|} \ln \left( \frac{M^{2}}{4\mu_{F}^{2}} \right) \right]$$

first two terms in  $a_{\mbox{\scriptsize S}}$  expansion of CgHEF

Matching performed before x-integration



Υ

![](_page_21_Figure_0.jpeg)

Much milder scale dependence of resummed NLO CF + DLA HEF result

NLO CF + DLA HEF cures the instabilities of the NLO CF result

CAF, Lansberg, Nabeebaccus, Nefedov, Sznajder, Wagner, Phys.Lett.B 859 (2024) 139117

Variety of measurements of  $\gamma p \rightarrow J/\psi p$  from pp to pPb and  $\gamma Pb$  (from PbPb) from multiple experiments, and all consistent with each other

Implementation of NLO pQCD to exclusive photoproduction of  $J/\psi$  and Y in PbPb UPCs

## **J**/ψ

Large scale dependence & perturbative instabilities Complicated interplay of quarks and gluon over all rapidities, quark dominate at midrapidity, careful with interpretation

Y Milder scale dependence Gluon dominated over all rapidities First predictions, data-driven approach ratios less sensitive to scale uncertainties and GPD modeling

- High-energy resummation of large logarithms of In1/ξ matched consistently to NLO CF, employing full LL GPD evolution
- The NLO CF + DLA HEF results have a milder scale dependence

-> implications for future GPD/PDF extractions

->extend to NLLA, impact of relativistic corrections

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Thank you

#### Backup

![](_page_24_Figure_1.jpeg)

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# GPDs and the Shuvaev transform

# GPDs generalise PDFs: outgoing/incoming partons carry different

![](_page_25_Figure_2.jpeg)

Idea: Conformal moments of GPDs = Mellin moments of PDFs

(up to corrections of O(xi^2) @ LO and O(xi) @ NLO)

- Construct GPD grids in multidimensional parameter space x, xi/x, gsg with forward PDFs from LHAPDF
- Costly computationally due to slowly converging double integral transform
- Regge theory considerations => <u>Shuvaev</u> transform valid in space-like (DGLAP) region only. In time-like (ERBL) region imaginary part of coefficient function is zero

#### NLO:

![](_page_26_Figure_1.jpeg)

Increasing uncertainty with increasing energy, oscillatory energy dependence (!)

Poor perturbative convergence, observed also in original Ivanov, relative hierarchy of M vs. muF gives negative or positive term Schäfer, Szymanowski, Krasnikov, 04 twenty years ago

**High-energy limit**  $W_{\gamma p}^2 \gg M^2 \quad (\xi \to 0)$ 

$$\mathcal{T}_{\mathsf{NLO}}^{\mu\nu} \supset i\pi \frac{g_{\perp}^{\mu\nu}F_{LO}}{\xi} \left[ H_g(\xi,\xi) + \frac{\alpha_s(\mu_R)C_A}{\pi} \ln\left(\frac{M^2}{4\mu_F^2}\right) \int_{\xi}^1 \frac{dx}{x} H_g(x,\xi) + \frac{\alpha_s(\mu_R)C_A}{\pi} \frac{C_F}{C_A} \ln\left(\frac{M^2}{4\mu_F^2}\right) \int_{\xi}^1 dx \left(H_q(x,\xi) - H_q(-x,\xi)\right) \right]$$

both terms scale  $\sim \alpha_s \ln(1/\xi) \ln\left(\frac{M^2}{4\mu_c^2}\right)$ 

motivated few approaches to try to alleviate scale dependence