Illuminating the impact-parameter dependence of UPC dijet photoproduction

Petja Paakkinen

in collab. with K. J. Eskola, V. Guzey, I. Helenius & H. Paukkunen

University of Jyväskylä

AoF CoE in Quark Matter
partner in ERC AdG YoctoLHC

Quark Matter 2023

6 September 2023

UPCs as probes of nuclei

In ultra-peripheral heavy-ion collisions (UPCs), two nuclei pass each other at an impact parameter larger than the sum of their radii

- ➔ hadronic interactions suppressed

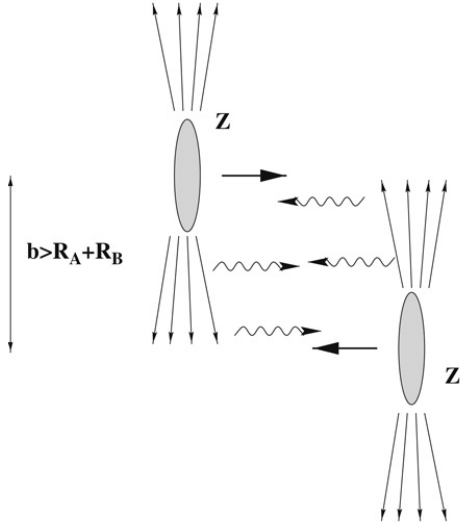
Hard interactions of one nucleus with the e.m. field of the other can be described in equivalent photon approximation

- ➔ access to photo-nuclear processes

A "new" way to probe nuclear contents!

Bertulani, Klein & Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271
Baltz et al., Phys. Rept. 458 (2008) 1
Contreras & Tapia Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012
Klein & Mäntysaari, Nature Rev. Phys. 1 (2019) 662

Baltz et al., Phys. Rept. 458 (2008) 1



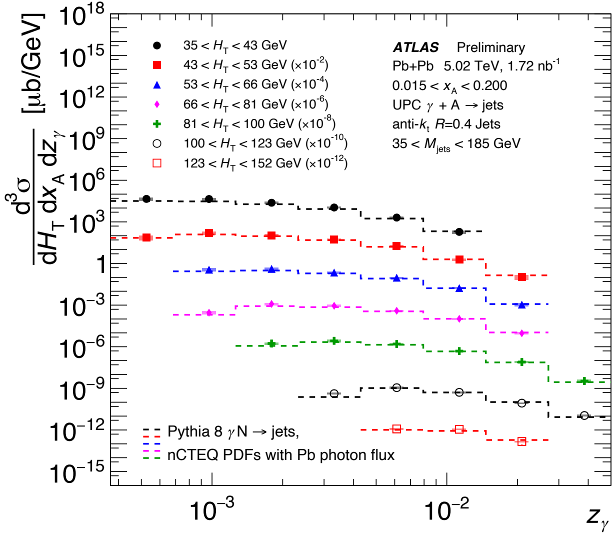
Inclusive dijets in UPCs

Dijet photoproduction in UPCs has been promoted as a probe of nuclear PDFs

Strikman, Vogt & White, PRL 96 (2006) 082001

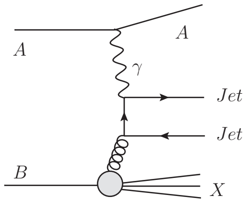
ATLAS measurement now fully unfolded!

ATLAS-CONF-2022-021

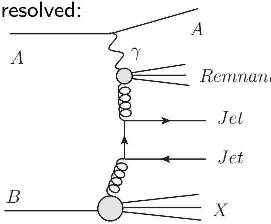


Guzey & Klasen, PRC 99 (2019) 065202

direct:



resolved:



Triple differential in

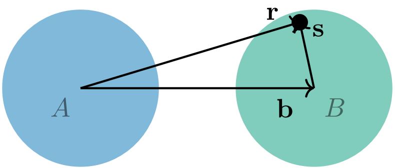
$$H_{\mathrm{T}} = \sum_{i\in\mathrm{jets}} p_{\mathrm{T},i}, \quad z_\gamma = \frac{M_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{+y_{\mathrm{jets}}},$$

$$x_A = \frac{M_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{-y_{\mathrm{jets}}}$$

Previous NLO predictions have been performed in a pointlike approximation

→ Can/should we do better?

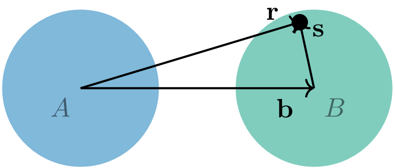
Impact-parameter dependence of UPC dijet production



Let's assume an impact-parameter dependent factorization similar to
Greiner et al., PRC 51 (1995) 911

The inclusive UPC dijet cross section can be written as:

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\,\Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'}\delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

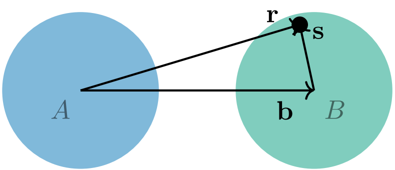


Let's assume an impact-parameter dependent factorization similar to
Greiner et al., PRC 51 (1995) 911

Nuclear suppression factor:
Probability for having no hadronic interaction at impact parameter $\mathbf{b}$

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Impact-parameter dependence of UPC dijet production

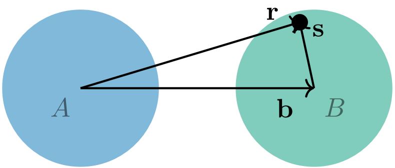


<u>Let's assume</u> an impact-parameter dependent factorization similar to
Greiner et al., PRC 51 (1995) 911

Photon flux:
The number of photons at radius $\mathbf{r}$
from the emitting nucleus

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2)$$
$$\otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'}\delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Impact-parameter dependence of UPC dijet production

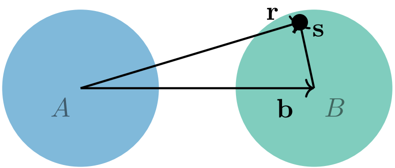


Let's assume an impact-parameter dependent factorization similar to
Greiner et al., PRC 51 (1995) 911

Photon PDF:
Density of partons type i within the photon

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\,\Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2)$$
$$\otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Impact-parameter dependence of UPC dijet production

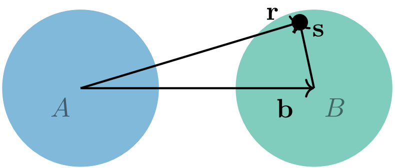


Let's assume an impact-parameter dependent factorization similar to
Greiner et al., PRC 51 (1995) 911

$$
\begin{aligned}
\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \\
\otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})
\end{aligned}
$$

Nuclear PDF:
Density of partons type j within the nucleus
at distance s from the center

Impact-parameter dependence of UPC dijet production

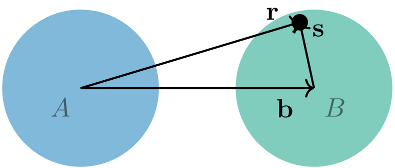


Let's assume an impact-parameter dependent factorization similar to Greiner et al., PRC 51 (1995) 911

$$
\mathrm{d}\sigma^{AB\to A+\text{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\, \Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\text{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})
$$

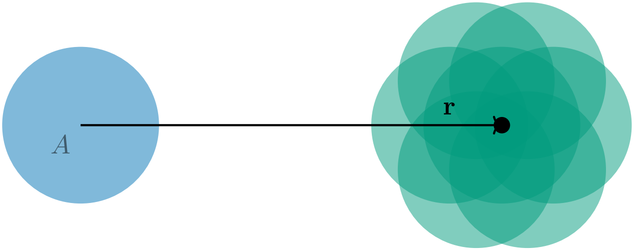
Partonic cross section:
Production rate for the dijet system
from partons i and j

Impact-parameter dependence of UPC dijet production



Let's assume an impact-parameter dependent factorization similar to

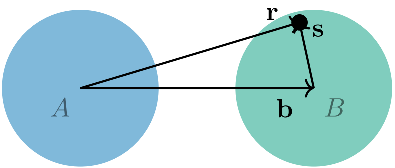
Greiner et al., PRC 51 (1995) 911



$|\mathbf{r}| \sim |\mathbf{b}| \gg |\mathbf{s}| \sim R_B$ 'far-passing'

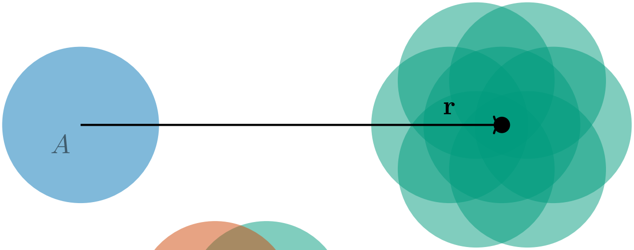
➔ any $\mathbf{s}$ equally allowed

Impact-parameter dependence of UPC dijet production



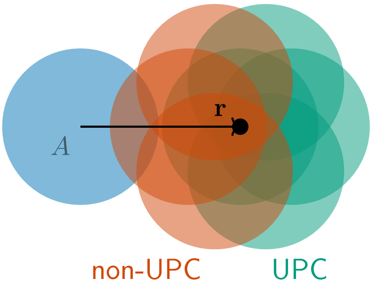
Let's assume an impact-parameter dependent factorization similar to

Greiner et al., PRC 51 (1995) 911



$|\mathbf{r}| \sim |\mathbf{b}| \gg |\mathbf{s}| \sim R_B$ 'far-passing'

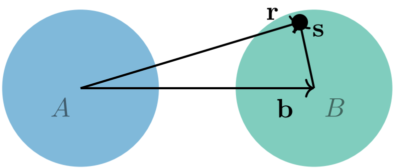
➔ any $\mathbf{s}$ equally allowed



$|\mathbf{r}| \sim |\mathbf{b}| \sim |\mathbf{s}| \sim R_B$ 'close-encounter'

➔ restricted $\mathbf{s}$ phase space for UPC events

Impact-parameter dependence of UPC dijet production



Let's assume an impact-parameter dependent factorization similar to Greiner et al., PRC 51 (1995) 911

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \int \mathrm{d}^2\mathbf{b}\,\Gamma_{AB}(\mathbf{b}) \int \mathrm{d}^2\mathbf{r}\, f_{\gamma/A}(y,\mathbf{r}) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x,Q^2,\mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'}\delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Now, if $f_{j/B}(x,Q^2,\mathbf{s}) = \frac{1}{B}\,T_B(\mathbf{s})\cdot f_{j/B}(x,Q^2)$, we can write

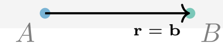
$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} f^{\mathrm{eff}}_{\gamma/A}(y) \otimes f_{i/\gamma}(x_\gamma,Q^2) \otimes f_{j/B}(x,Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'}$$

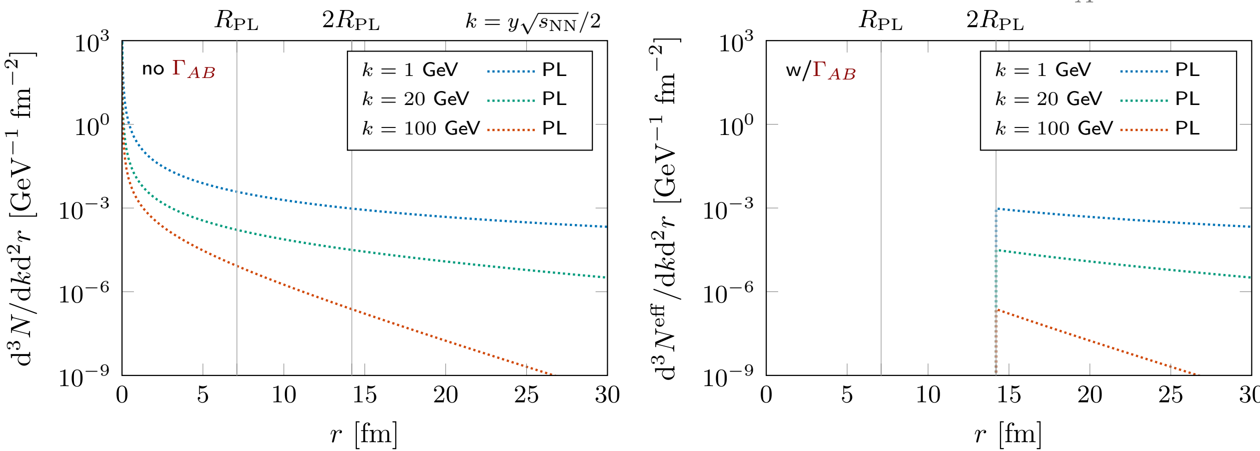
where the effective photon flux reads

$$f^{\mathrm{eff}}_{\gamma/A}(y) = \frac{1}{B}\int \mathrm{d}^2\mathbf{r} \int \mathrm{d}^2\mathbf{s}\, f_{\gamma/A}(y,\mathbf{r})\, T_B(\mathbf{s})\, \Gamma_{AB}(\mathbf{r}-\mathbf{s})$$

as in ATLAS-CONF-2022-021 (see Appendix A)

Effective photon flux in UPC PbPb (1: PL approx.)



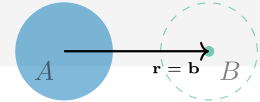


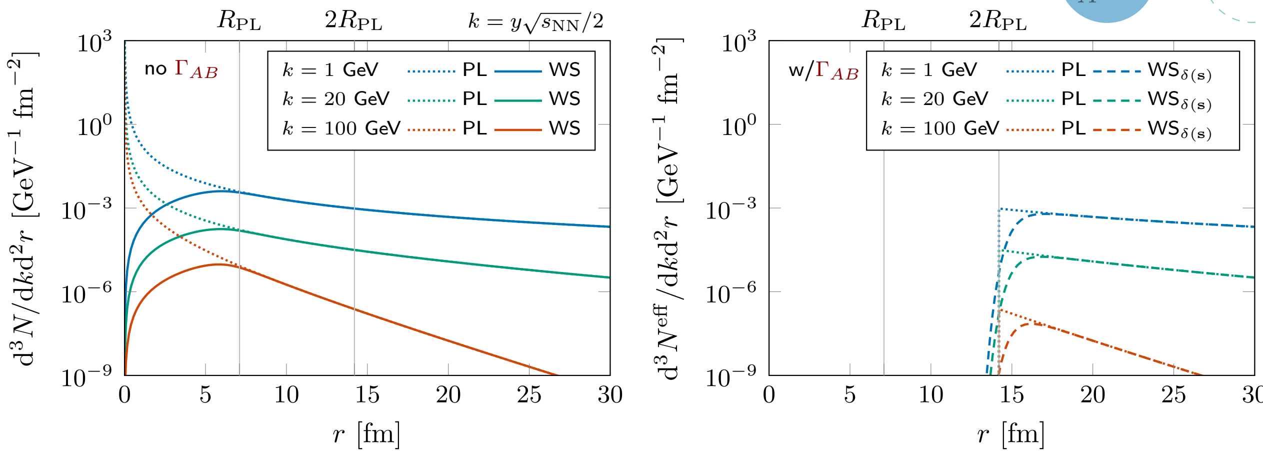
Pointlike (PL) approximation: $\quad T_B(\mathbf{s}) = B\delta(\mathbf{s}), \quad \Gamma_{AB}(\mathbf{b}) = \theta(|\mathbf{b}| - b_{\min}), \quad b_{\min} = 2R_{\mathrm{PL}} = 14.2$ fm

$$\Rightarrow f^{\mathrm{eff,PL}}_{\gamma/A}(y) = \int \mathrm{d}^2\mathbf{r}\, \underbrace{f^{\mathrm{PL}}_{\gamma/A}(y,\mathbf{r})}_{= \frac{Z^2\alpha_{\mathrm{e.m.}}}{\pi^2} m_p^2 y [K_1^2(\zeta) + \frac{1}{\gamma_L} K_0^2(\zeta)]_{\zeta = y m_p |\mathbf{r}|}} \theta(|\mathbf{r}| - b_{\min}) = \frac{2Z^2\alpha_{\mathrm{e.m.}}}{\pi y}\left[\zeta K_0(\zeta) K_1(\zeta) - \frac{\zeta^2}{2}[K_1^2(\zeta) - K_0^2(\zeta)]\right]_{\zeta = y m_p b_{\min}}$$

➔ Coincides with Guzey & Klasen, PRC 99 (2019) 065202

Effective photon flux in UPC PbPb (2: WS with $T_B(\mathbf{s}) = B\delta(\mathbf{s})$)



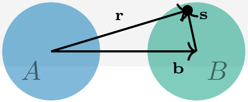


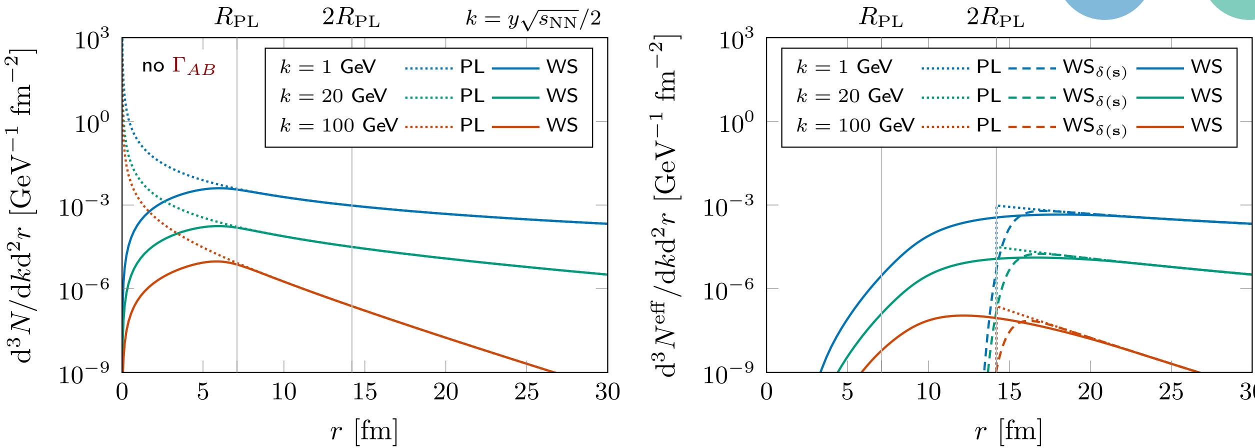
Woods-Saxon source on point-like target ($\mathrm{WS}_{\delta(\mathbf{s})}$): $T_B(\mathbf{s}) = B\delta(\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \exp[-\sigma_{\mathrm{NN}}\,T_{AB}^{\mathrm{WS}}(\mathbf{b})]$

$$\Rightarrow f_{\gamma/A}^{\mathrm{eff},\mathrm{WS}_{\delta(\mathbf{s})}}(y) = \int \mathrm{d}^2\mathbf{r}\ \underbrace{f_{\gamma/A}^{\mathrm{WS}}(y,\mathbf{r})}_{=\frac{Z^2\alpha_{\mathrm{e.m.}}}{\pi^2}\frac{1}{y}\left|\int_0^\infty \frac{\mathrm{d}k_\perp k_\perp^2}{k_\perp^2+(ym_p)^2} F^{\mathrm{WS}}(k_\perp^2+(ym_p)^2) J_1(|\mathbf{r}|k_\perp)\right|^2}\ \Gamma_{AB}(\mathbf{r})$$

➔ cf. Guzey & Zhalov, JHEP 02 (2014) 046; Zha et al., PLB 781 (2018) 182; Eskola et al., PRC 106 (2022) 035202

Effective photon flux in UPC PbPb (3: Full WS profile)



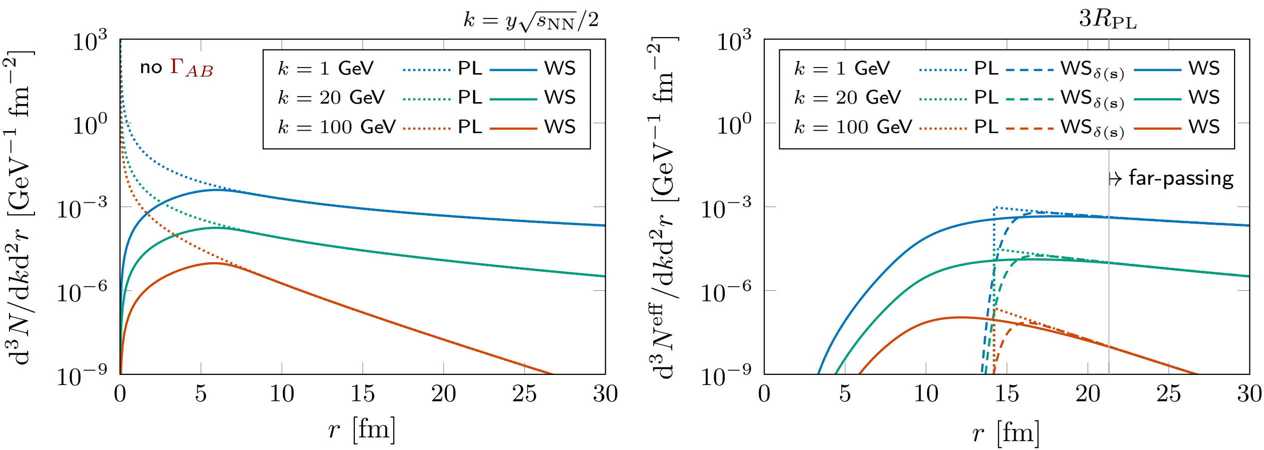


Woods-Saxon nuclear profile (WS): $T_B(\mathbf{s}) = \int \mathrm{d}z \rho_B^{\mathrm{WS}}(z,\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \exp[-\sigma_{\mathrm{NN}} T_{AB}^{\mathrm{WS}}(\mathbf{b})]$

$$\Rightarrow f_{\gamma/A}^{\mathrm{eff,WS}}(y) = \int \mathrm{d}^2\mathbf{r}\ \underbrace{f_{\gamma/A}^{\mathrm{WS}}(y,\mathbf{r})}_{=\frac{Z^2\alpha_{\mathrm{e.m.}}}{\pi^2}\frac{1}{y}\left|\int_0^\infty \frac{\mathrm{d}k_\perp k_\perp^2}{k_\perp^2+(ym_p)^2} F^{\mathrm{WS}}(k_\perp^2+(ym_p)^2) J_1(|\mathbf{r}|k_\perp)\right|^2}\ \Gamma_{AB}^{\mathrm{eff}}(\mathbf{r}), \quad \text{where} \quad \Gamma_{AB}^{\mathrm{eff}}(\mathbf{r}) = \frac{1}{B}\int \mathrm{d}^2\mathbf{s}\, T_B(\mathbf{s})\, \Gamma_{AB}(\mathbf{r}-\mathbf{s})$$

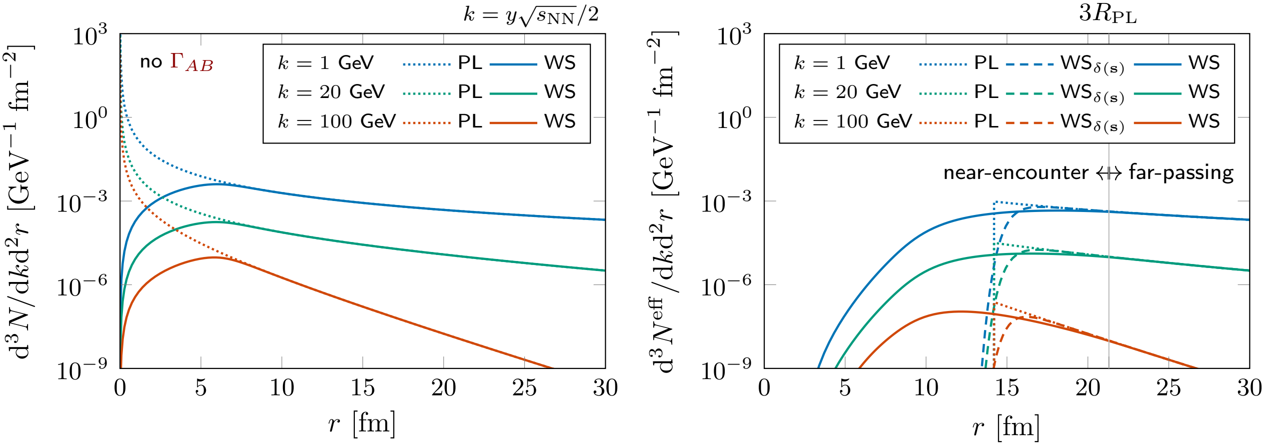
➔ Accounting for the s dependence important at small $|\mathbf{r}|$!

Effective photon flux in UPC PbPb



For the 'far-passing' events with $|\mathbf{r}| > 3R_{\rm PL}$ the PL approximation works fine. . .

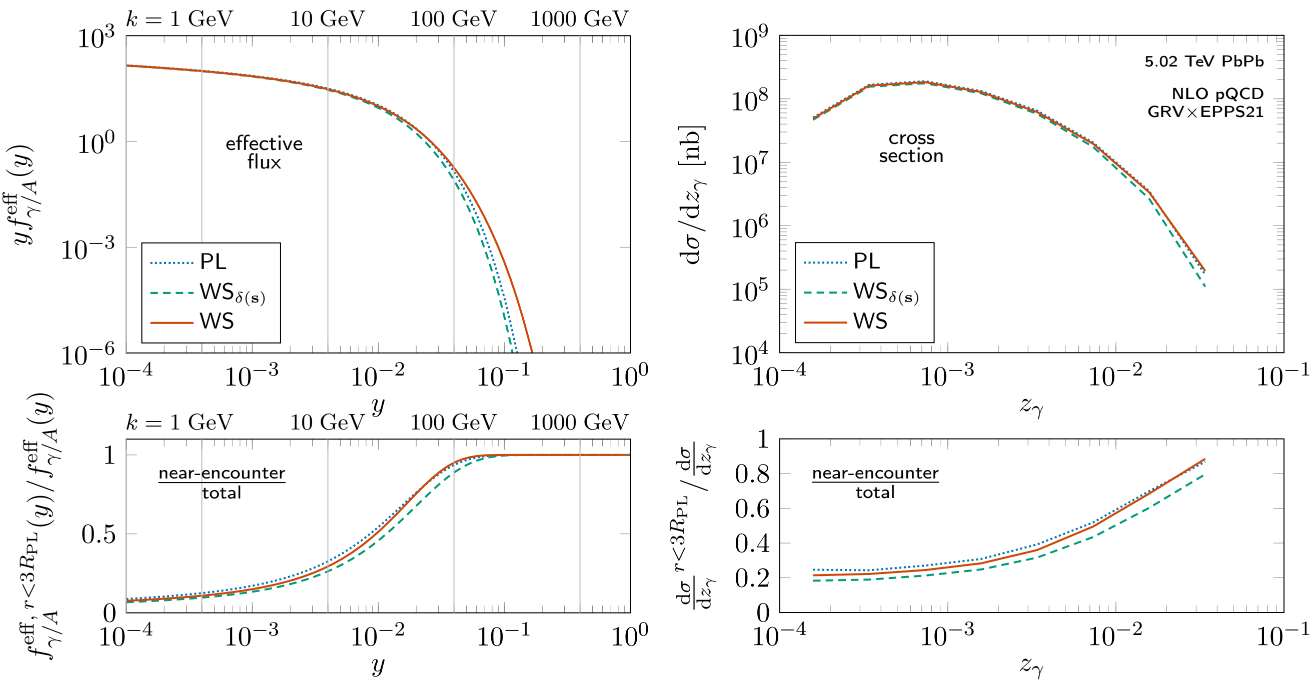
Effective photon flux in UPC PbPb



For the 'far-passing' events with $|\mathbf{r}| > 3R_{\mathrm{PL}}$ the PL approximation works fine. . .

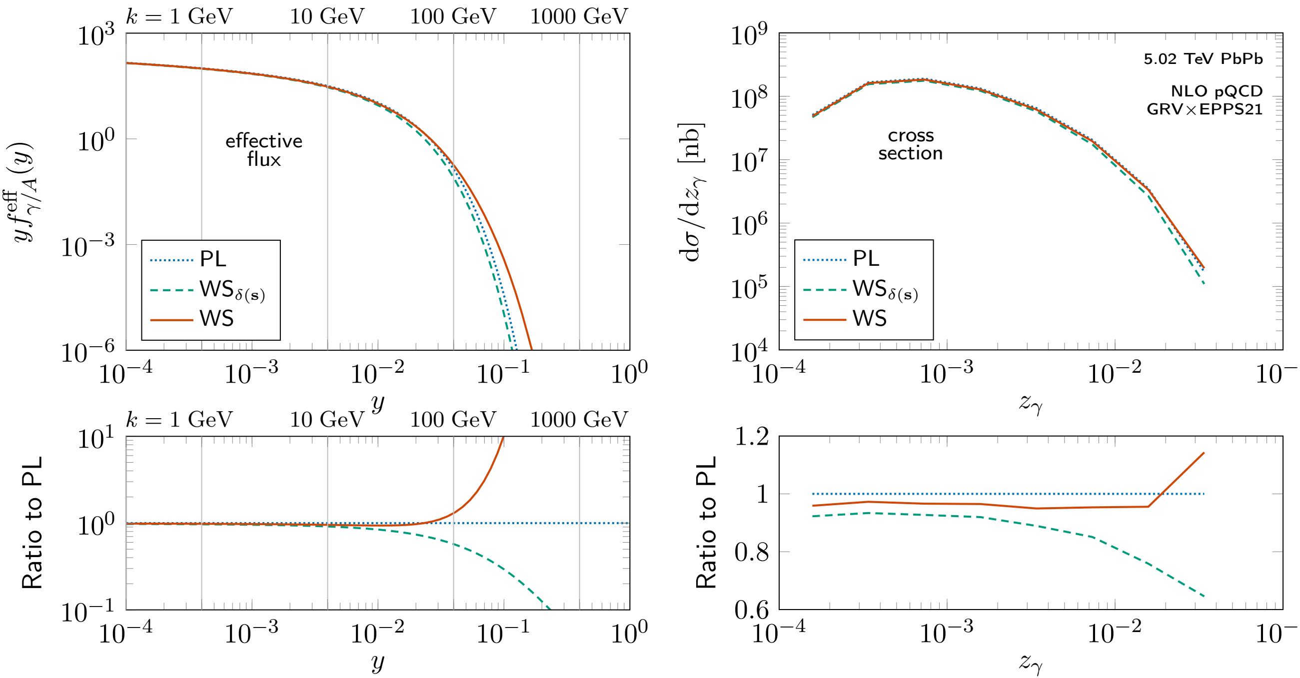
. . . but producing high-p_{T} jets requires sufficient energy from the photon which enhances sensitivity to the 'near-encounter' region

Effective photon flux and UPC dijet cross section



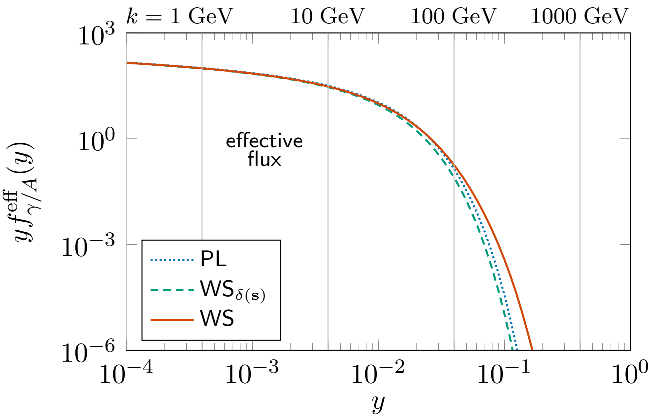
➔ most of the events with large z_γ (correspondingly small x_A) come from small $|\mathbf{r}|$!

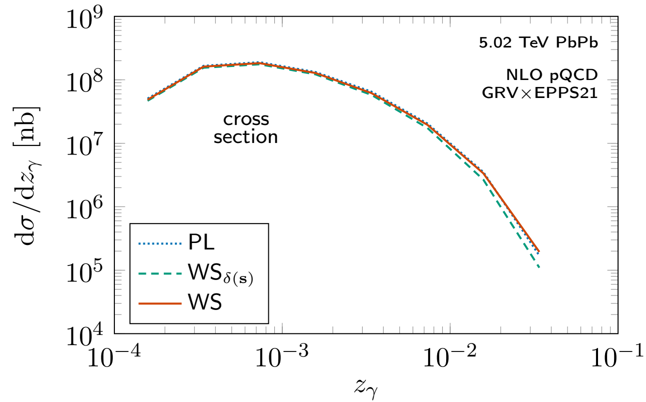
Effective photon flux and UPC dijet cross section



$\sim$ 40% effect in WS$_{\delta(\mathbf{s})}$ vs. full WS cross sections in the largest z_γ bin (but 10% for WS vs. PL)

Effective photon flux and UPC dijet cross section





Questions for further investigation:

- All of this assumed that we can factorize $f_{j/B}(x, Q^2, \mathbf{s}) = \frac{1}{B} T_B(\mathbf{s}) \cdot f_{j/B}(x, Q^2)$, but this is a simplification – use impact-parameter dependent nPDFs (EPS09s, FGS10) instead.
- How are then these objects we probe here in a (more or less) inclusive process related to the GPDs extracted from exclusive processes?
- Here we have neglected the possibility of electromagnetic breakup through Coulomb excitations; Including it would modify the $\Gamma_{AB}(\mathbf{b})$ suppression factor.

Summary

- In principle, *inclusive* dijet photoproduction off nuclei is a good probe for nuclear PDFs
- However, in UPCs impact-parameter space is restricted due to requirement of no nuclear overlap
- Due to requiring the production of high-p_{T} jets, significant part of the cross section comes from events where the nuclei pass each other at small impact parameters

→ Sensitivity to the nuclear transverse profile

→ Significant effect in the largest measured z_γ bins

- Will be interesting to study whether we can constrain impact-parameter dependent nPDFs this way
- Still have to include the e.m. breakup modelling to be able to compare directly with the data

Thank you!

Dijet photoproduction at EIC

The experimental condition for photoproduction at EIC is much simpler - depends only on electron scattering angle!

$$f_{\gamma/e}(y) = \frac{\alpha_{\text{e.m.}}}{2\pi}\left[\frac{1+(1-y)^2}{y}\log\frac{Q^2_{\max}(1-y)}{m_e^2 y^2} + 2m_e^2 y\left(\frac{1}{Q^2_{\max}} - \frac{1-y}{m_e^2 y^2}\right)\right],$$

where $Q^2_{\max}$ is the maximal photon virtuality

Probe nPDFs down to $x \sim 10^{-2}$

Klasen & Kovarik, PRD 97 (2018) 114013
Guzey & Klasen, PRC 102 (2020) 065201

Guzey & Klasen, PRC 102 (2020) 065201