Dijet photoproduction and transverse-plane geometry in ultra-peripheral nuclear collisions

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UPCs as probes of nuclei

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

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

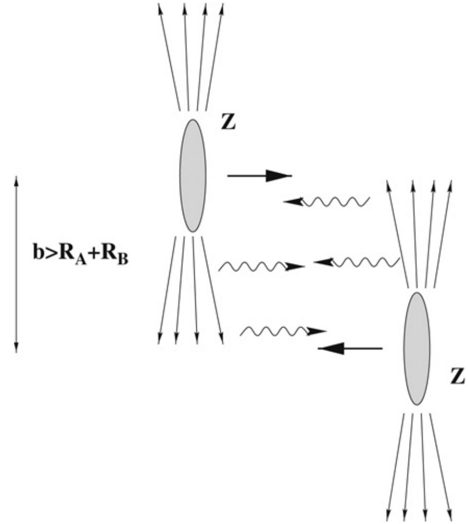
→ hadronic interactions suppressed

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



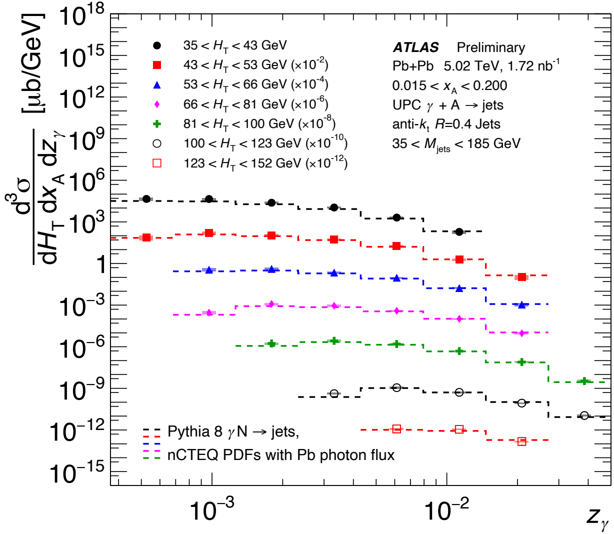
Inclusive dijets in UPCs

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

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

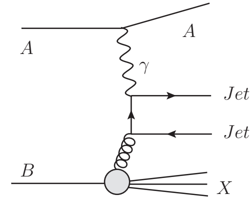
ATLAS measurement now fully unfolded!

ATLAS-CONF-2022-021

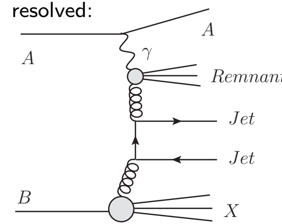


Guzey & Klasen, PRC 99 (2019) 065202

direct:



resolved:



Triple differential in

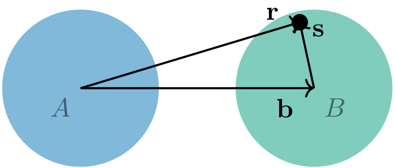
$$H_{\mathrm{T}} = \sum_{i \in \mathrm{jets}} p_{\mathrm{T},i}, \quad z_\gamma = \frac{M_{\mathrm{jets}}}{\sqrt{s_{\mathrm{NN}}}} e^{+y_{\mathrm{jets}}},$$

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

Previous NLO predictions have been performed in a pointlike approximation

→ Can/should we do better?

Impact-parameter dependence of UPC dijet production

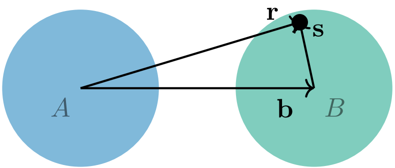


We use an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
Greiner et al., PRC 51 (1995) 911

The inclusive UPC dijet cross section can be written as:

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



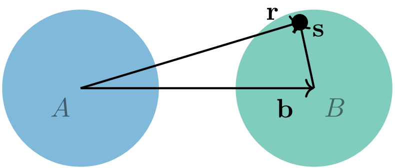
We use an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
Greiner et al., PRC 51 (1995) 911

Survival 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

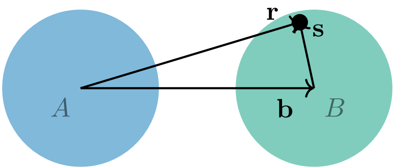


We use an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
Greiner et al., PRC 51 (1995) 911

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

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



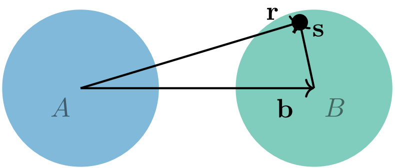
We use an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
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



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Greiner et al., PRC 51 (1995) 911

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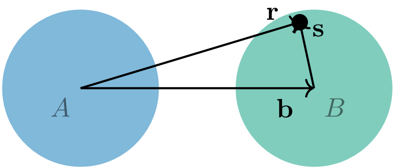
Nuclear PDF:
Density of partons type j within the nucleus
at distance $\mathbf{s}$ from the center

Impact-parameter dependence of UPC dijet production



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Baron & Baur, PRC 48 (1993) 1999
Greiner et al., PRC 51 (1995) 911

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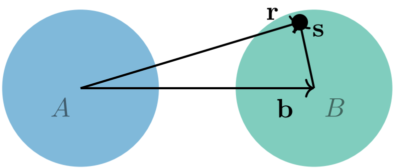
$$\otimes \int \mathrm{d}^2\mathbf{s}\, f_{j/B}(x, Q^2, \mathbf{s}) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'} \delta(\mathbf{r}-\mathbf{s}-\mathbf{b})$$

Partonic cross section (NLO pQCD):
Production rate for the dijet system
from partons i and j

Frixione & Ridolfi, NPB 507 (1997) 315

Impact-parameter dependence of UPC dijet production



We use an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
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 $f_{j/B}(x, Q^2, \mathbf{s}) = \frac{1}{B}\, T_B(\mathbf{s}) \times f_{j/B}(x, Q^2)$, we can write

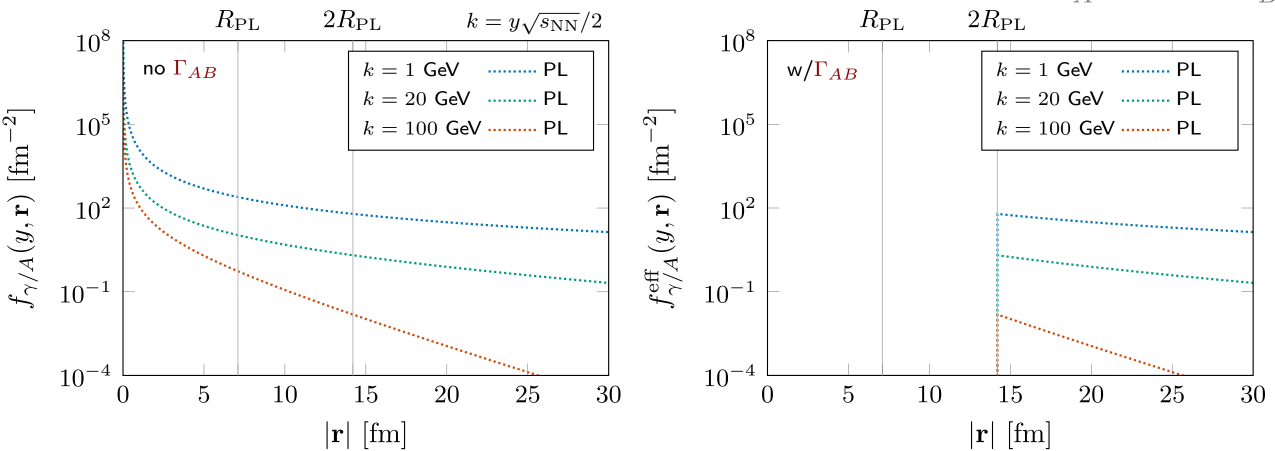
$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} f^{\mathrm{eff}}_{\gamma/A}(y) \otimes f_{i/\gamma}(x_\gamma, Q^2) \otimes f_{j/B}(x, Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'}$$

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.)

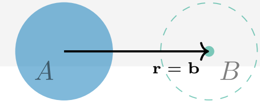


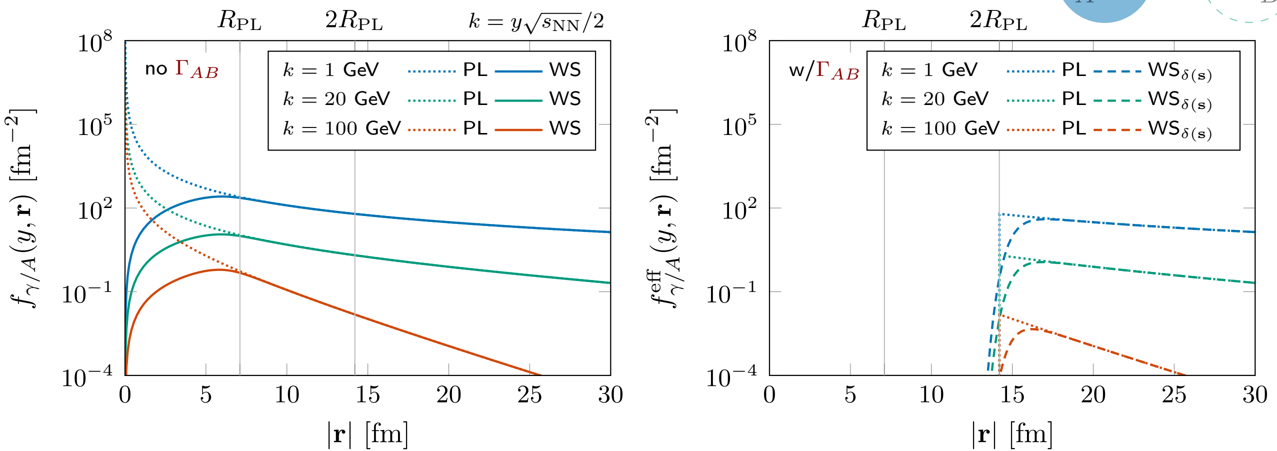
Pointlike (PL) approximation: $T_B(\mathbf{s}) = B\delta(\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \theta(|\mathbf{b}| - b_{\rm min})$, $b_{\rm min} = 2R_{\rm PL} = 14.2$ fm

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

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

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



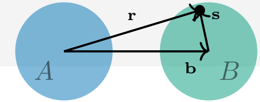


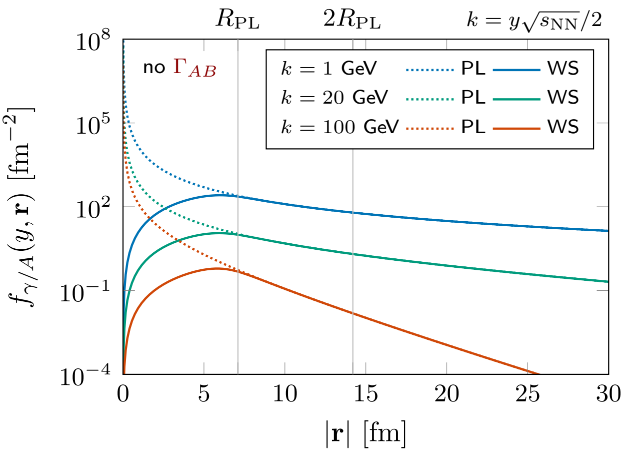
Woods-Saxon source on point-like target (WS$_{\delta(\mathbf{s})}$): $T_B(\mathbf{s}) = B\delta(\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \exp[-\sigma_{\rm NN}\, T_{AB}^{\rm WS}(\mathbf{b})]$

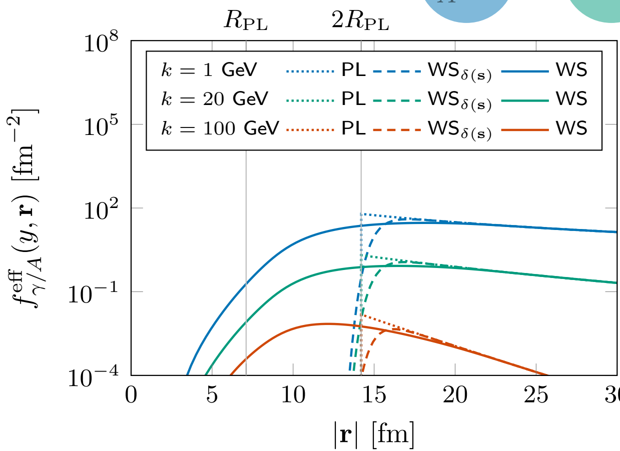
$$\Rightarrow f_{\gamma/A}^{\mathrm{eff,WS}_{\delta(\mathbf{s})}}(y) = \int \mathrm{d}^2\mathbf{r}\, \underbrace{f_{\gamma/A}^{\rm WS}(y,\mathbf{r})}_{= \frac{Z^2\alpha_{\rm e.m.}}{\pi^2}\frac{1}{y}\left|\int_0^\infty \frac{\mathrm{d}k_\perp k_\perp^2}{k_\perp^2+(ym_p)^2} F^{\rm WS}(k_\perp^2+(ym_p)^2)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

➔ 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)





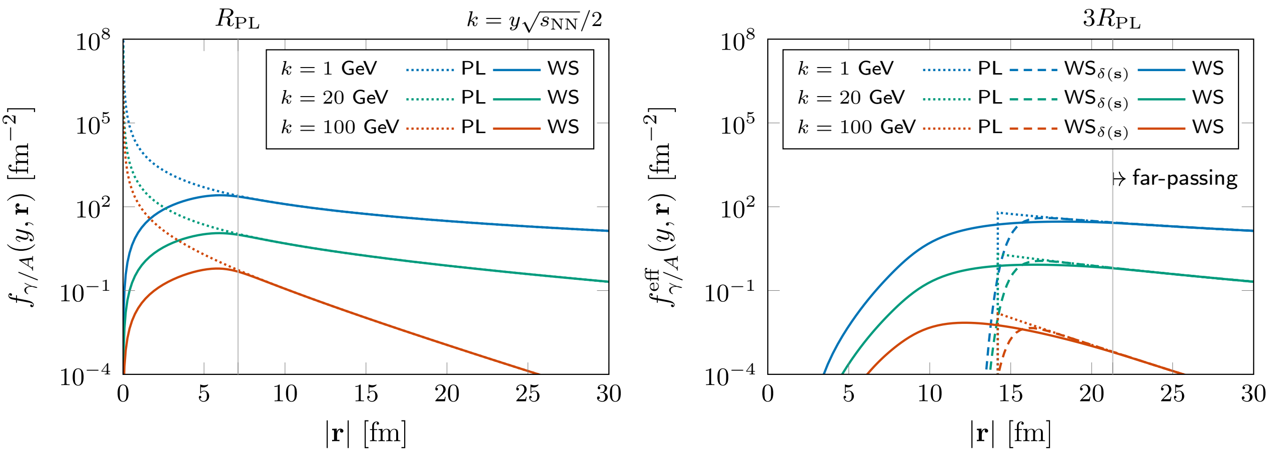


Woods-Saxon nuclear profile (WS): $T_B(\mathbf{s}) = \int \mathrm{d}z \rho_B^{\rm WS}(z,\mathbf{s})$, $\Gamma_{AB}(\mathbf{b}) = \exp[-\sigma_{\rm NN} T_{AB}^{\rm WS}(\mathbf{b})]$

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

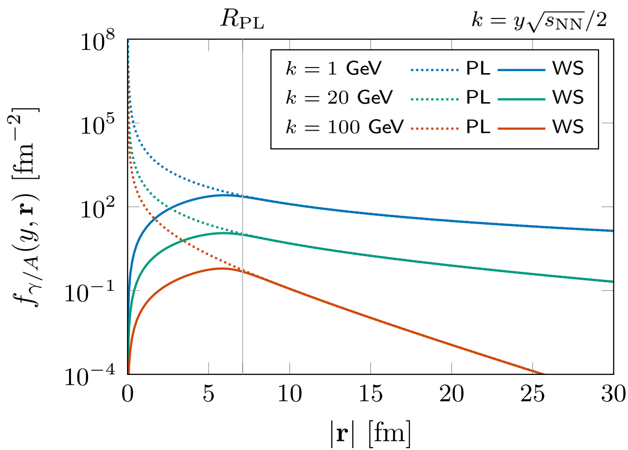
➔ Accounting for the s dependence important at small $|\mathbf{r}|$!

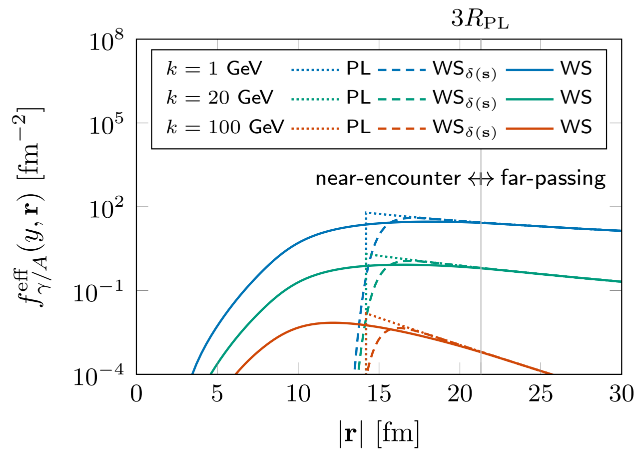
Effective photon flux in UPC PbPb



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

Effective photon flux in UPC PbPb

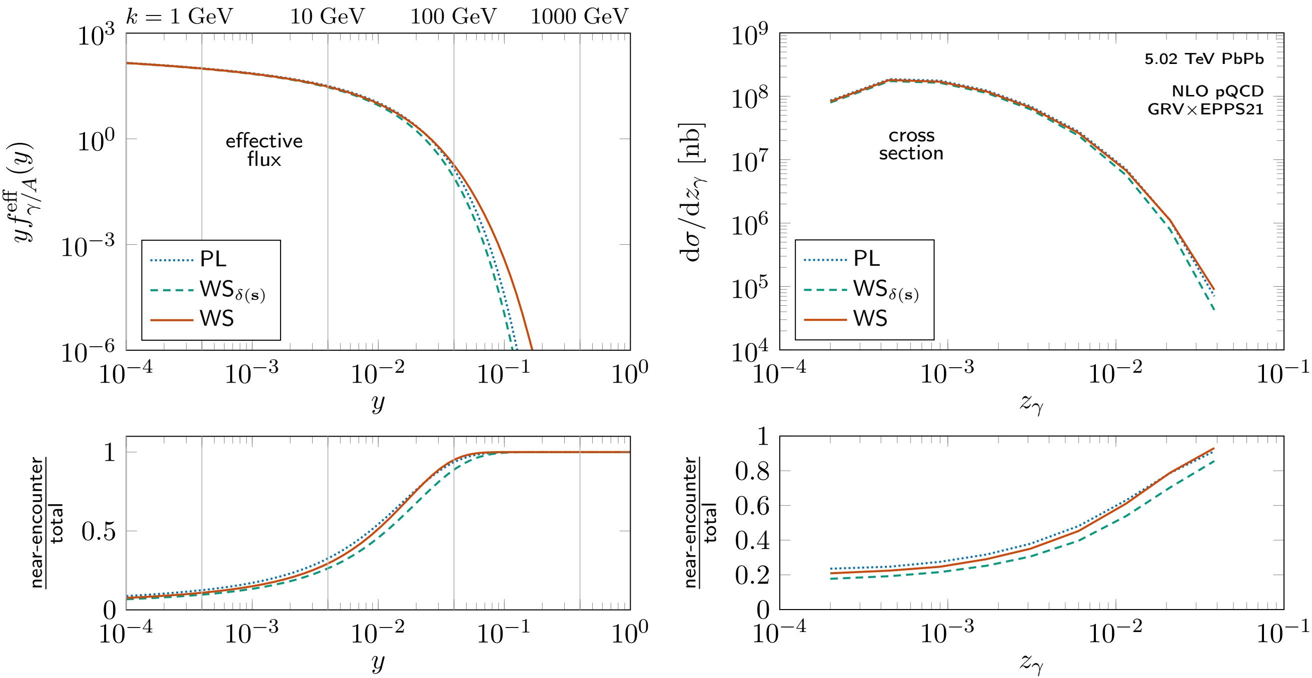




For the 'far-passing' events with $|\mathbf{r}| > 3R_{\mathrm{PL}}$ the PL approximation works fine...

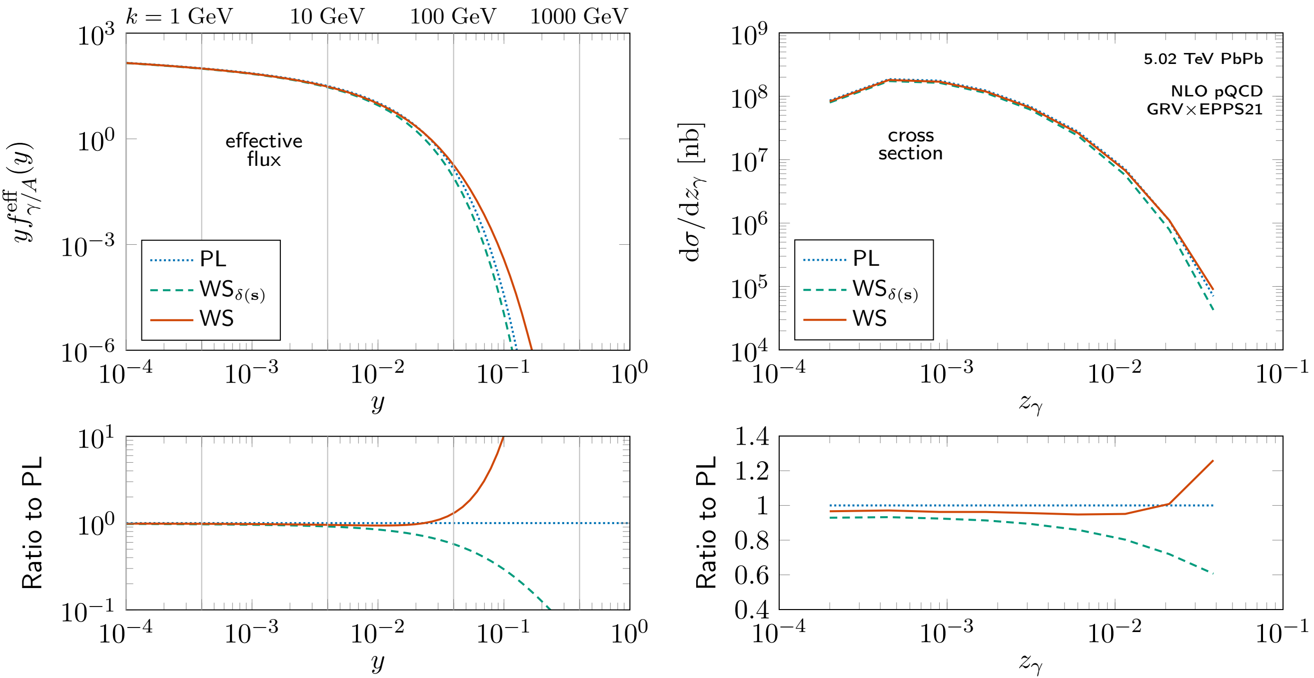
...but producing high-p_{T} jets requires sufficient energy from the photon which enhances sensitivity to the 'near-encounter' region

Effective photon flux and UPC dijet cross section

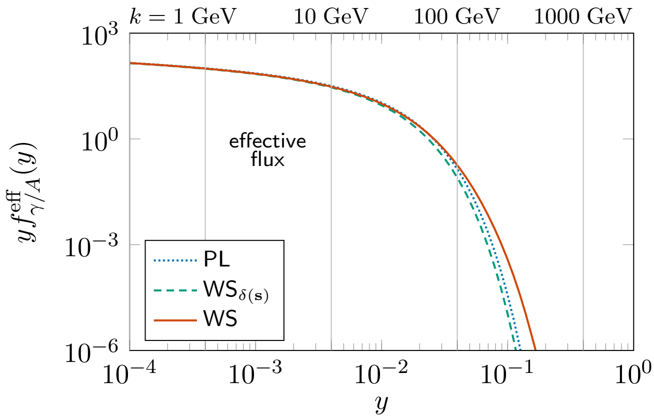


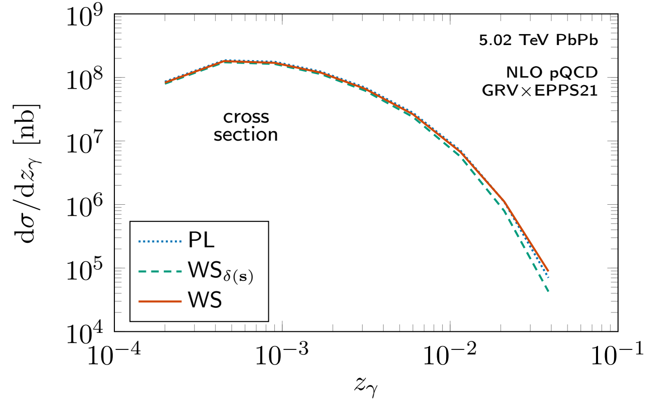
➔ Most of the events with large z_γ (correspondingly small x_A) come from small $|\mathbf{r}|$!

Effective photon flux and UPC dijet cross section



➔ Full WS cross section larger than $\mathrm{WS}_{\delta(\mathbf{s})}$ by a factor 2 in the largest z_γ bin

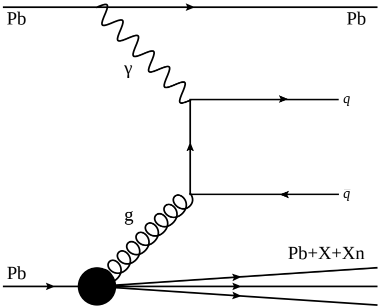




Note:

- All of this assumed that we can factorize $f_{j/B}(x, Q^2, \mathbf{s}) = \frac{1}{B} T_B(\mathbf{s}) \times f_{j/B}(x, Q^2)$, but this is a simplification – use impact-parameter dependent nPDFs (EPS09s, FGS10) instead.
- Here we have neglected the possibility of electromagnetic breakup through Coulomb excitations; Including it would modify the $\Gamma_{AB}(\mathbf{b})$ suppression factor.
  - → ATLAS measurement in 0nXn neutron class, must take this effect into account

Breakup-class modelling



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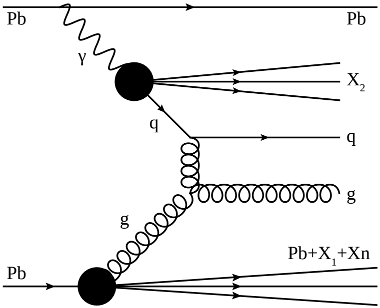


Require 0 neutrons in one direction

Require $X > 0$ neutrons in opposite direction

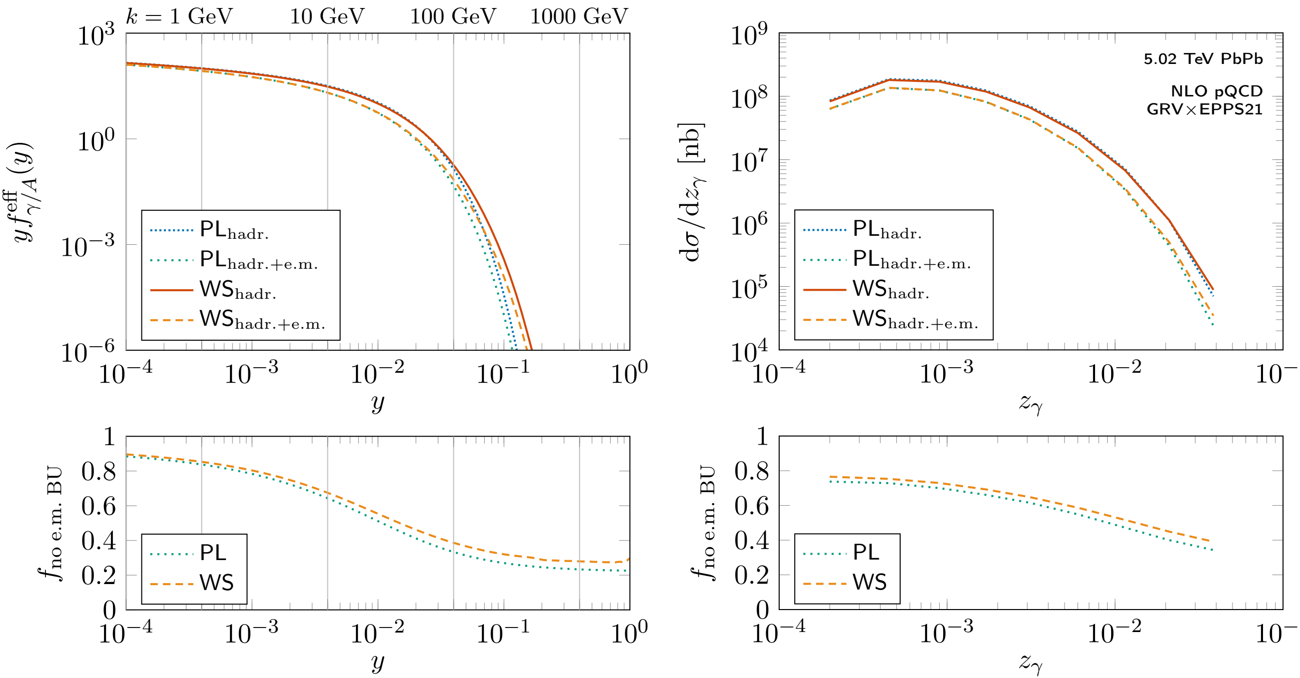
Poissonian probability for *no* electromagnetic breakup of nucleus A through Coulomb excitations:

$$\Gamma^{\text{e.m.}}_{AB}(\mathbf{b}) = \exp\left[-\int_0^1 \mathrm{d}y\, f_{\gamma/B}(y,\mathbf{b})\,\sigma_{\gamma A\to A^*}(\sqrt{y\, s_{\text{NN}}})\right]$$

➔ take from Starlight

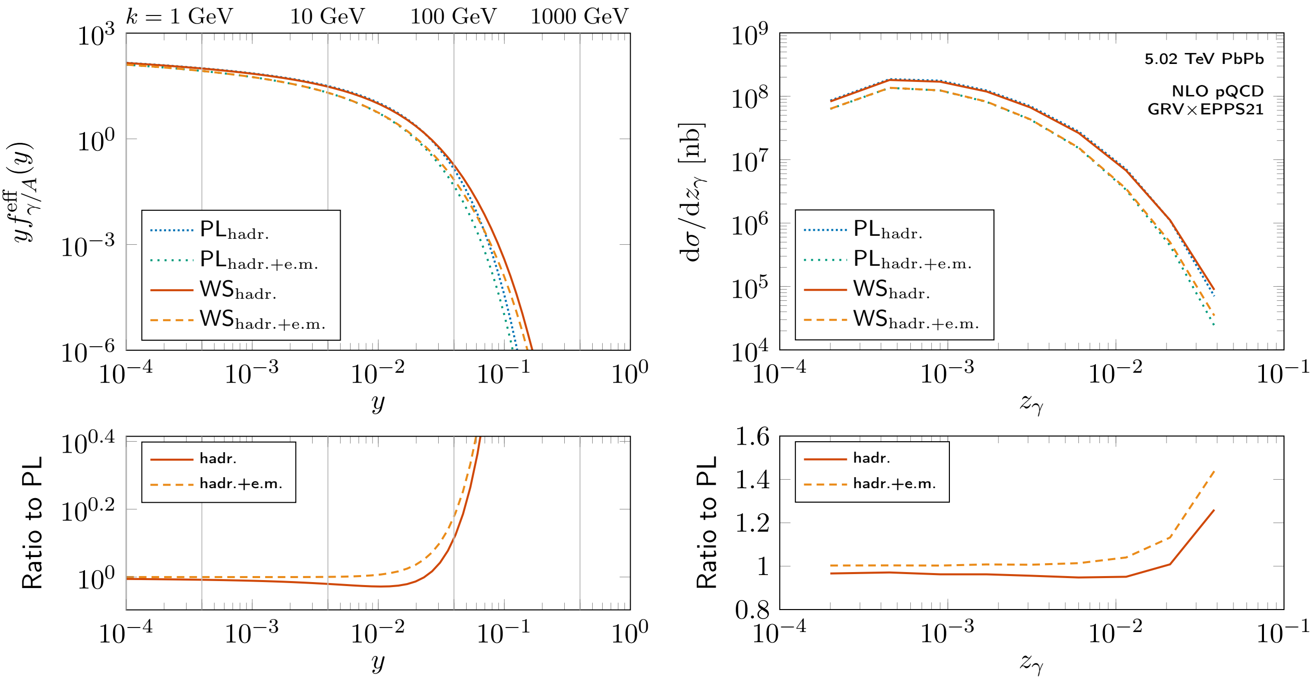
Baltz, Klein & Nystrand, PRL 89 (2002) 012301
Klein et al., Comput. Phys. Commun. 212 (2017) 258

The total survival factor is then $\Gamma^{\text{hadr.+e.m.}}_{AB}(\mathbf{b}) = \Gamma^{\text{e.m.}}_{AB}(\mathbf{b})\Gamma^{\text{hadr.}}_{AB}(\mathbf{b})$



➔ Breakup-class modelling necessary for apples to apples comparison with data

Effective photon flux and UPC dijet cross section w/ breakup classes



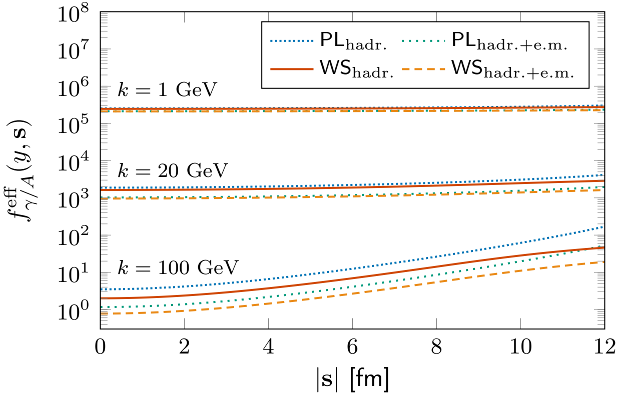
➔ Difference between PL and WS approximations survives after the e.m. breakup modelling

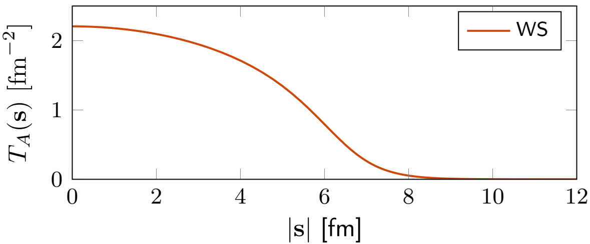
Note that it is possible to reorganise:

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

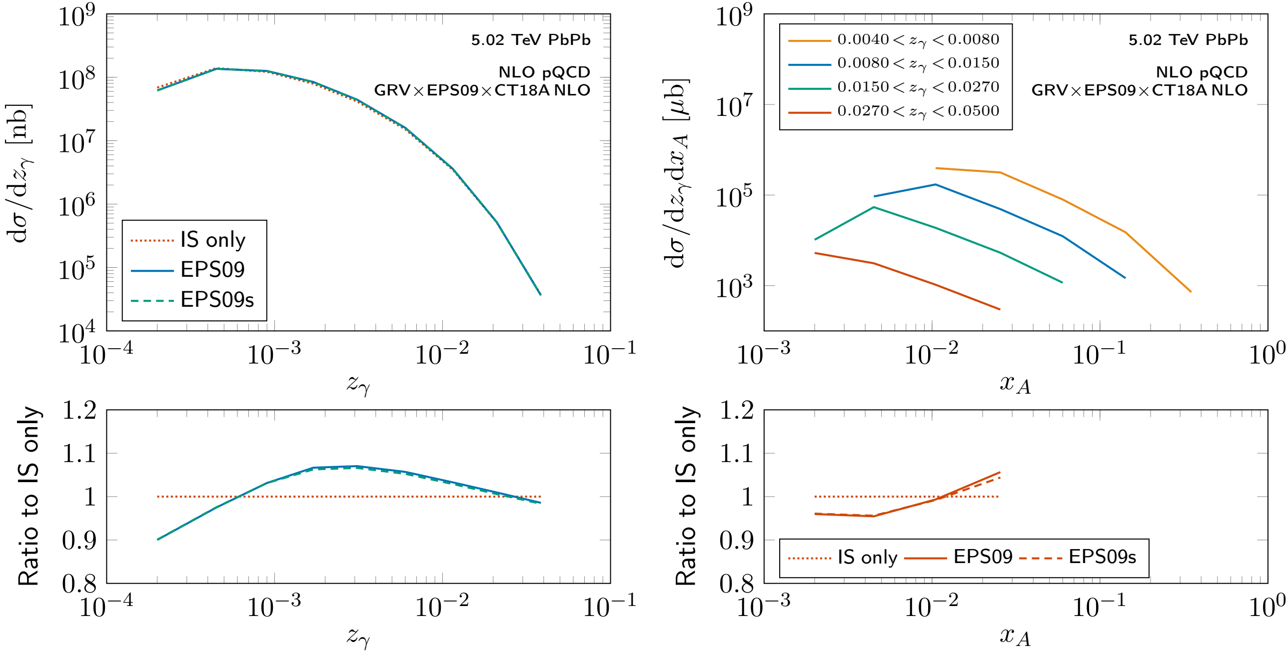
where $f^{\mathrm{eff}}_{\gamma/A}(y,\mathbf{s})$ sets how the nuclear partons are sampled:

- If it is constant in s over support of $f_{j/B}(x, Q^2, \mathbf{s})$, then one recovers ordinary non-spatial nPDFs.
- If not, then one needs to use spatially dependent nPDFs.



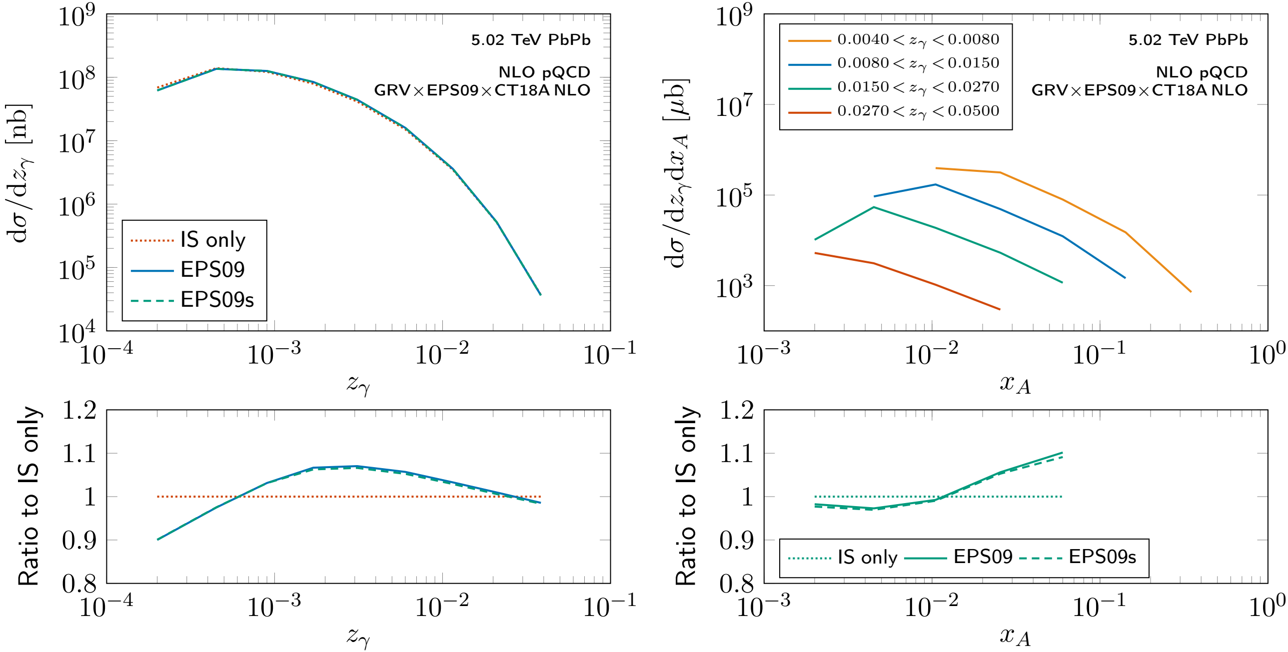


UPC dijet cross section w/ spatial dependence



➔ Spatial vs. non-spatial nPDFs only a small correction

UPC dijet cross section w/ spatial dependence



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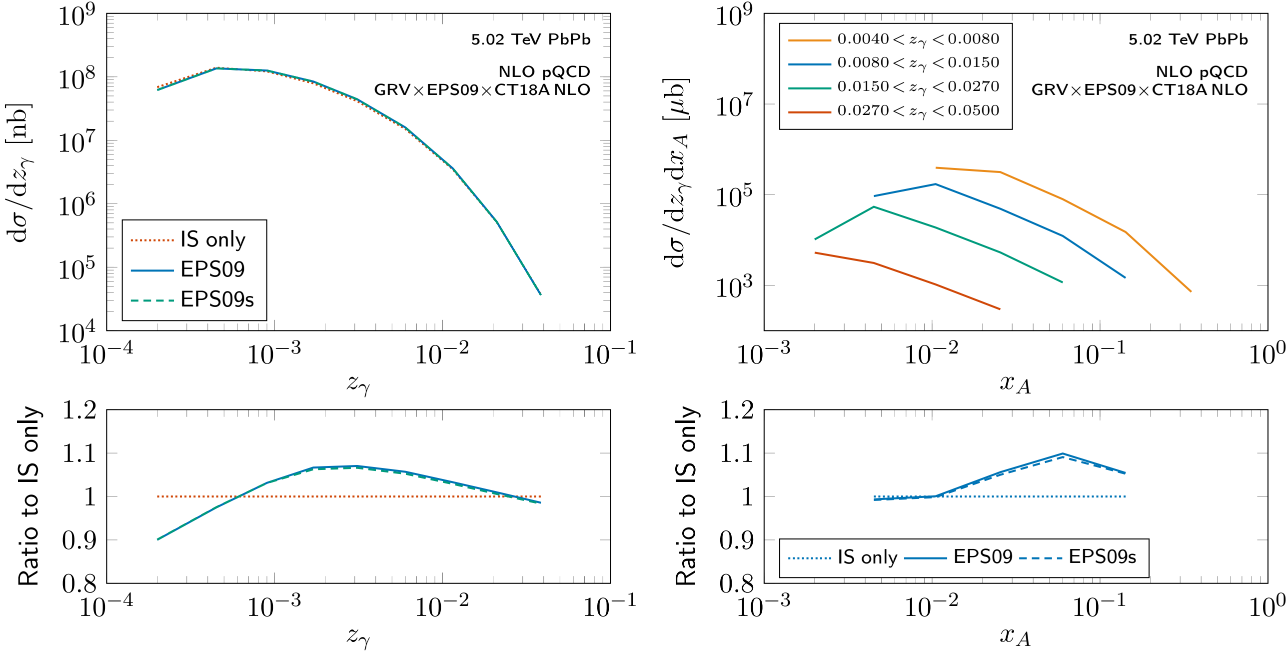

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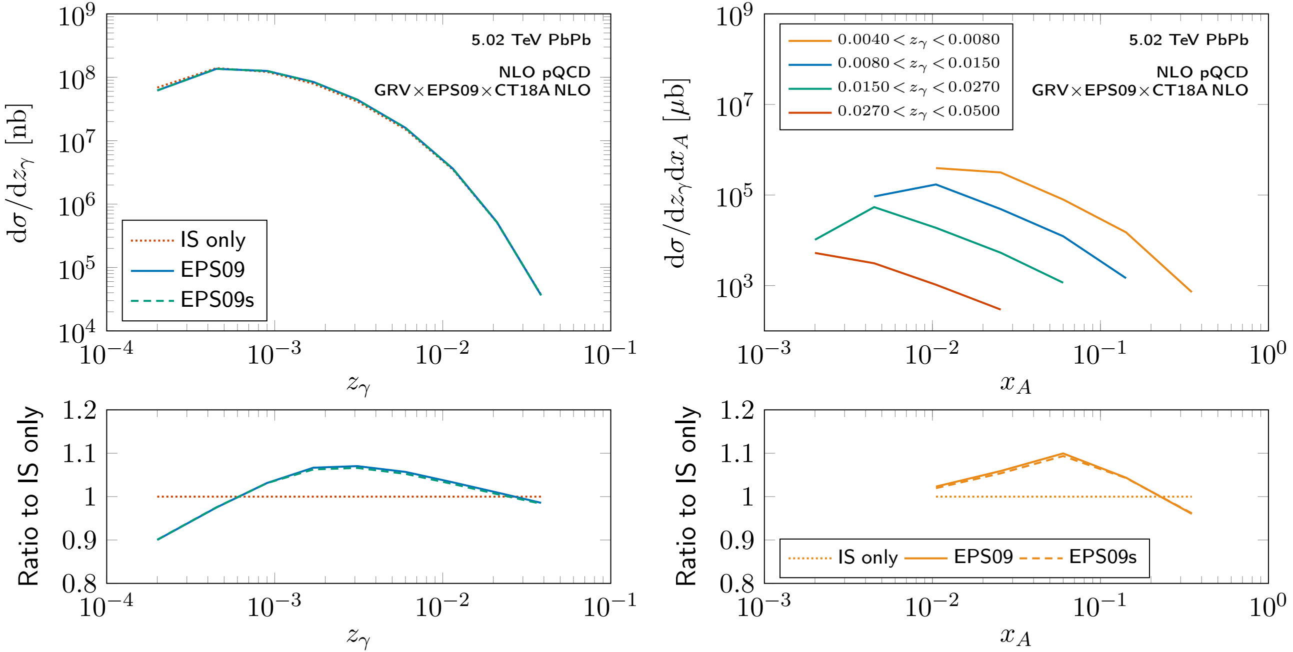
UPC dijet cross section w/ spatial dependence



➔ Spatial vs. non-spatial nPDFs only a small correction

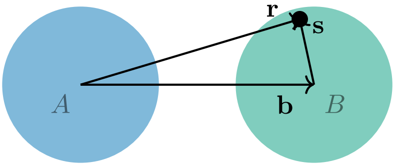
Summary

- 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
- We also studied impact of e.m. breakup modelling which is needed for direct comparison with data
- While energetic photons probe more on the edge of the target nucleus, we found that applying impact-parameter dependent nPDFs has only a small effect on the cross section

. . . expect paper in arXiv any day now

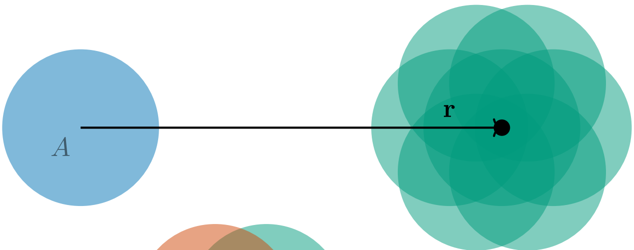
Thank you!

Impact-parameter dependence of UPC dijet production



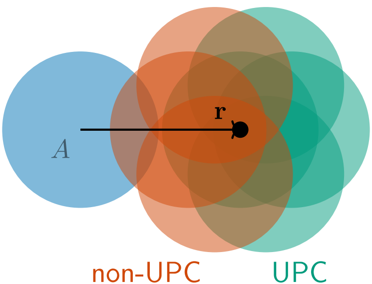
We use an impact-parameter dependent factorization similar to

Baron & Baur, PRC 48 (1993) 1999
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

EPS09s spatially dependent nPDFs

For EPS09s (Helenius et al., JHEP 07 (2012) 073) we have:

$$f_{j/B}(x,Q^2,\mathbf{s}) = \frac{1}{B} T_B(\mathbf{s}) \sum_{N\in B} r_j^{N/B}(x,Q^2,\mathbf{s}) f_{j/N}(x,Q^2)$$

with

$$r_j^{N/B}(x,Q^2,\mathbf{s}) = \sum_{m=0}^{4} c_m^{j/N}(x,Q^2)[T_B(\mathbf{s})]^m, \qquad c_0^{j/N}(x,Q^2) \equiv 1$$

The cross section then becomes

$$\mathrm{d}\sigma^{AB\to A+\mathrm{dijet}+X} = \sum_{i,j,X'} \sum_{m=0}^{4} f_{\gamma/A}^{\mathrm{eff},m}(y) \otimes f_{i/\gamma}(x_\gamma,Q^2) \otimes f_{j/B}^{m}(x,Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to\mathrm{dijet}+X'}$$

where

$$f_{\gamma/A}^{\mathrm{eff},m}(y) = \frac{1}{B}\int \mathrm{d}^2\mathbf{r} \int \mathrm{d}^2\mathbf{s}\, f_{\gamma/A}(y,\mathbf{r})\, [T_B(\mathbf{s})]^{m+1}\, \Gamma_{AB}^{\mathrm{hadr.+e.m.}}(\mathbf{r}-\mathbf{s})$$

$$f_{j/B}^{m}(x,Q^2) = \sum_{N\in B} c_m^{j/N}(x,Q^2) f_{j/N}(x,Q^2)$$

Dijet photoproduction at EIC

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

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

where $Q^2_{\rm max}$ 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