Jets in UPCs

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Based on work in collaboration with **M. Klasen**,
JHEP 04 (2016) 158; EPJ C 76 (2016) 8, 467; PRC 99 (2019) 6, 065202;
EPJ C 79 (2019) 5, 396; PRD 104 (2021) 11, 114013

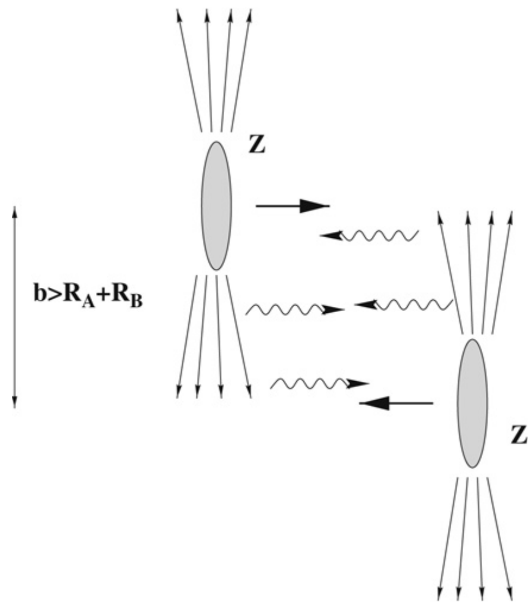
Outline:

- Ultraperipheral collisions (UPCs)
- Inclusive dijet photoproduction in Pb-Pb UPCs at the LHC and nuclear PDFs
- Diffractive dijet photoproduction in Pb-Pb UPCs at the LHC

CFNS Adhoc Workshop: Target fragmentation and diffraction physics with novel processes: Ultraperipheral, electron-ion, and hadron collisions,
Online meeting, Feb 9-11, 2022

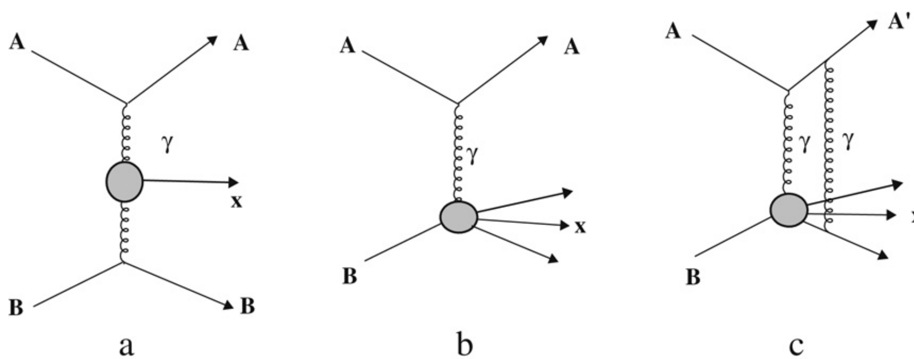
Ultraperipheral collisions

- Ultraperipheral collisions (UPCs): ions interact at large impact parameters $b >> R_A+R_B$ → hadron interactions suppressed → interaction via quasi-real photons in Weizsäcker-Williams equivalent photon approximation, Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15 (1975) 181



- UPCs@LHC allow one to study $\gamma\gamma$, γp and γA interactions at unprecedentedly high energies (energy frontier) reaching: $W_{\gamma p}$=5 TeV, $W_{\gamma A}$=700 GeV/A, $W_{\gamma\gamma}$=4.2 TeV

- UPCs can be used to study open questions of proton and nucleus structure in QCD and search for new physics.

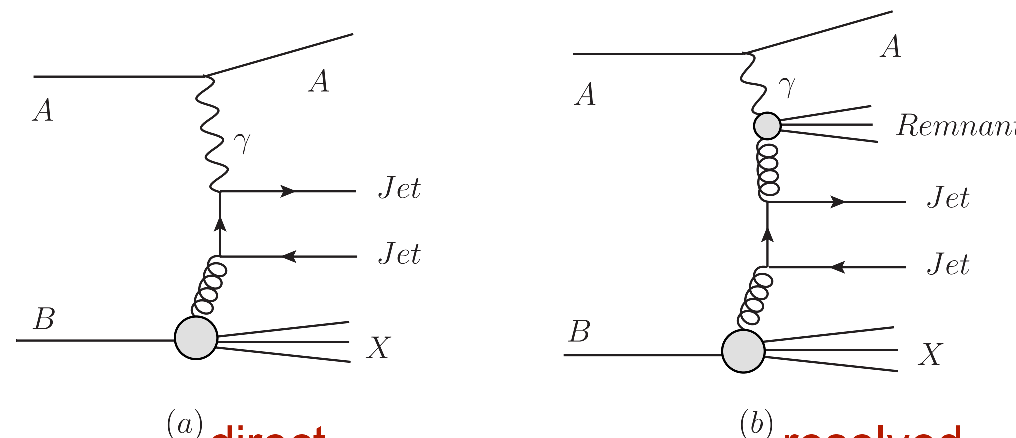


Bertulani, Klein, Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271; Baltz et al, Phys. Rept. 480 (2008) 1; Contreras and Tapia-Takaki, Int. J. Mod. Phys. A 30 (2015) 1542012; Snowmass LoI, Klein et al, arXiv:2009.03838

Dijet photoproduction in UPCs@LHC

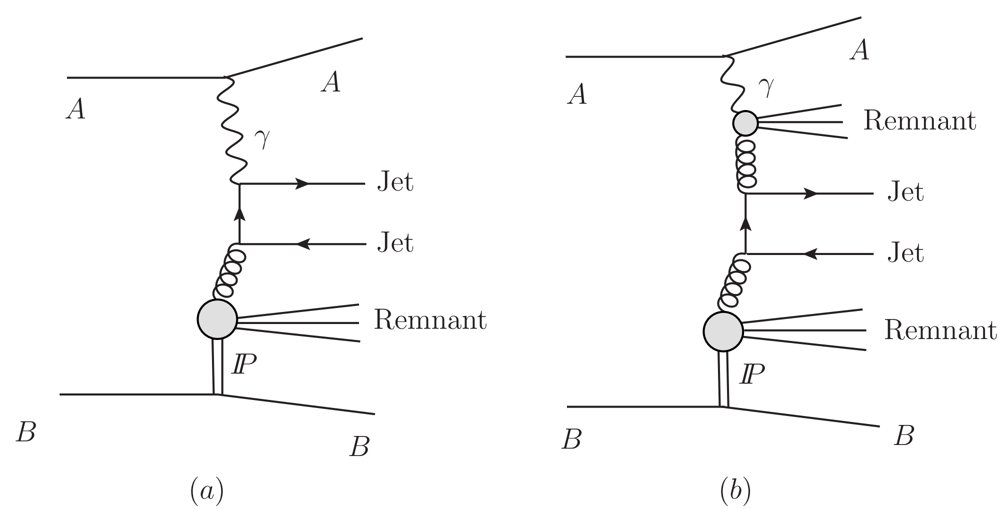
• The focus of UPC measurements@LHC has been exclusive (coherent) photoproduction of charmonia (J/ψ, ψ') and light vector mesons (ρ) → new constraints on the gluon density at small x down to $x_p \sim 6\times10^{-6}$ and $x_A \sim 6\times10^{-4}$.

• Poorly constrained nuclear parton distribution functions (PDFs) and photon PDFs can also be studied in **inclusive dijet photoproduction** in Pb-Pb UPCs, ATLAS-CONF-2017-011



(a) direct (b) resolved

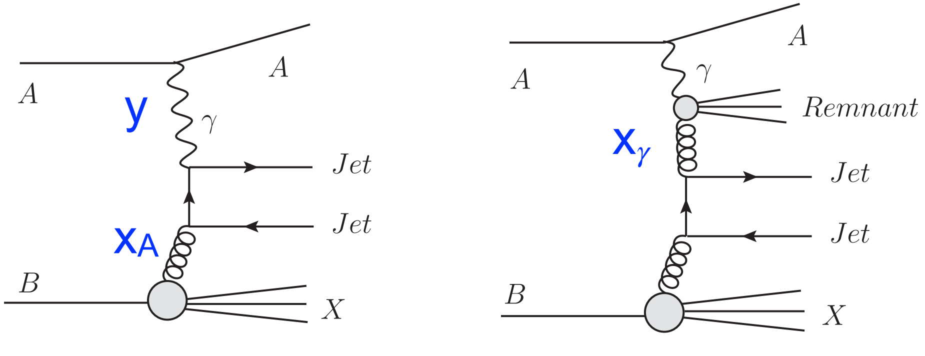
• Requiring intact nuclear target, one can study **diffractive dijet photoproduction** in Pb-Pb UPCs → access to novel nuclear diffractive PDFs and mechanism of QCD factorization breaking, Guzey, Klasen, JHEP 04 (2016) 158



(a) (b)

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC

- Cross section of dijet photoproduction using collinear factorization and next-to-leading (NLO) pQCD, which is successful for HERA data on dijet photoproduction in ep scattering, Klasen, Kramer, Z.Phys. C 72 (1996) 107, Z. Phys. C 76 (1997) 67; Klasen, Rev. Mod. Phys. 74 (2002) 1221; Klasen, Kramer, EPJC 71 (2011) 1774



(a) direct

(b) resolved

$$d\sigma(AA \to A + 2\text{jets} + X) =$$

$$\sum_{a,b} \int dy \int dx_\gamma \int dx_A f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/A}(x_A, \mu^2) d\hat{\sigma}_{ab\to\text{jets}}$$

Photon flux from QED:
- high intensity ~ Z^2
- high photon energy ~ γ_L

Photon PDFs (resolved photon), from e+e- data

Nuclear PDFs (nCTEQ15, EPPS16)

Hard parton cross section

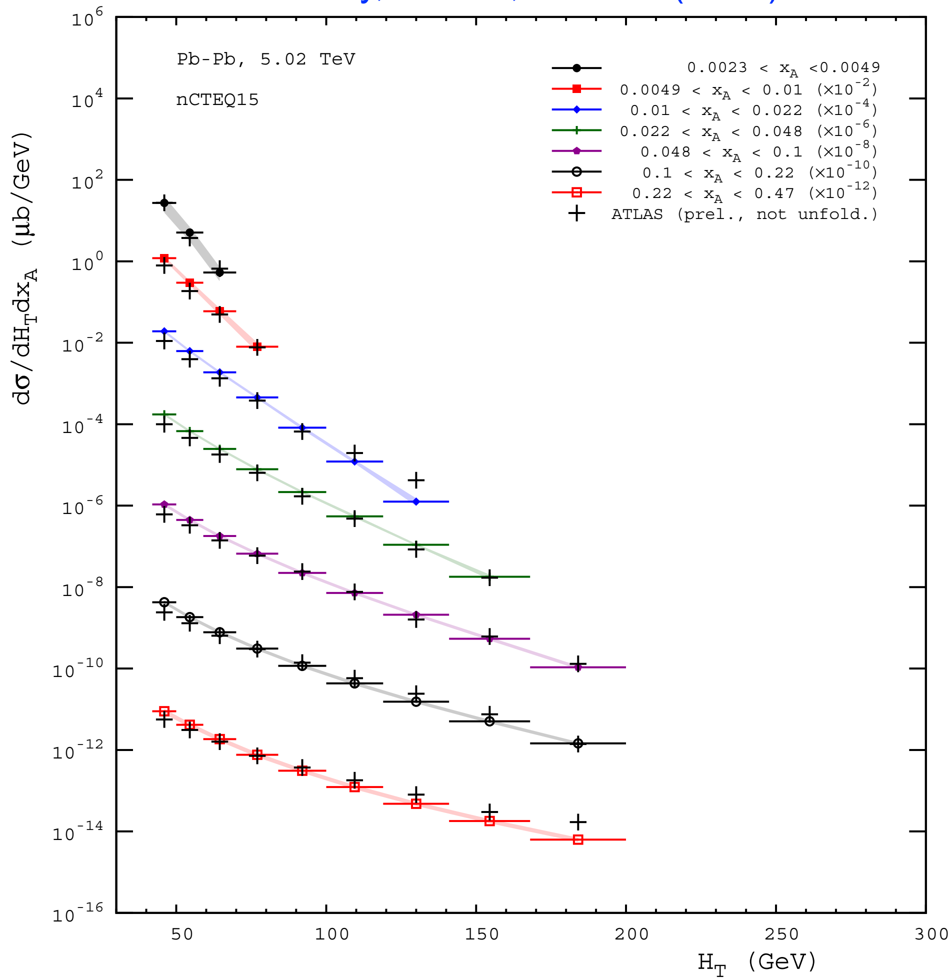
$$f_{\gamma/A}(y) = \frac{2\alpha_{\text{e.m.}} Z^2}{\pi} \frac{1}{y} \left[\zeta K_0(\zeta) K_1(\zeta) - \frac{\zeta^2}{2}(K_1^2(\zeta) - K_0^2(\zeta)) \right]$$

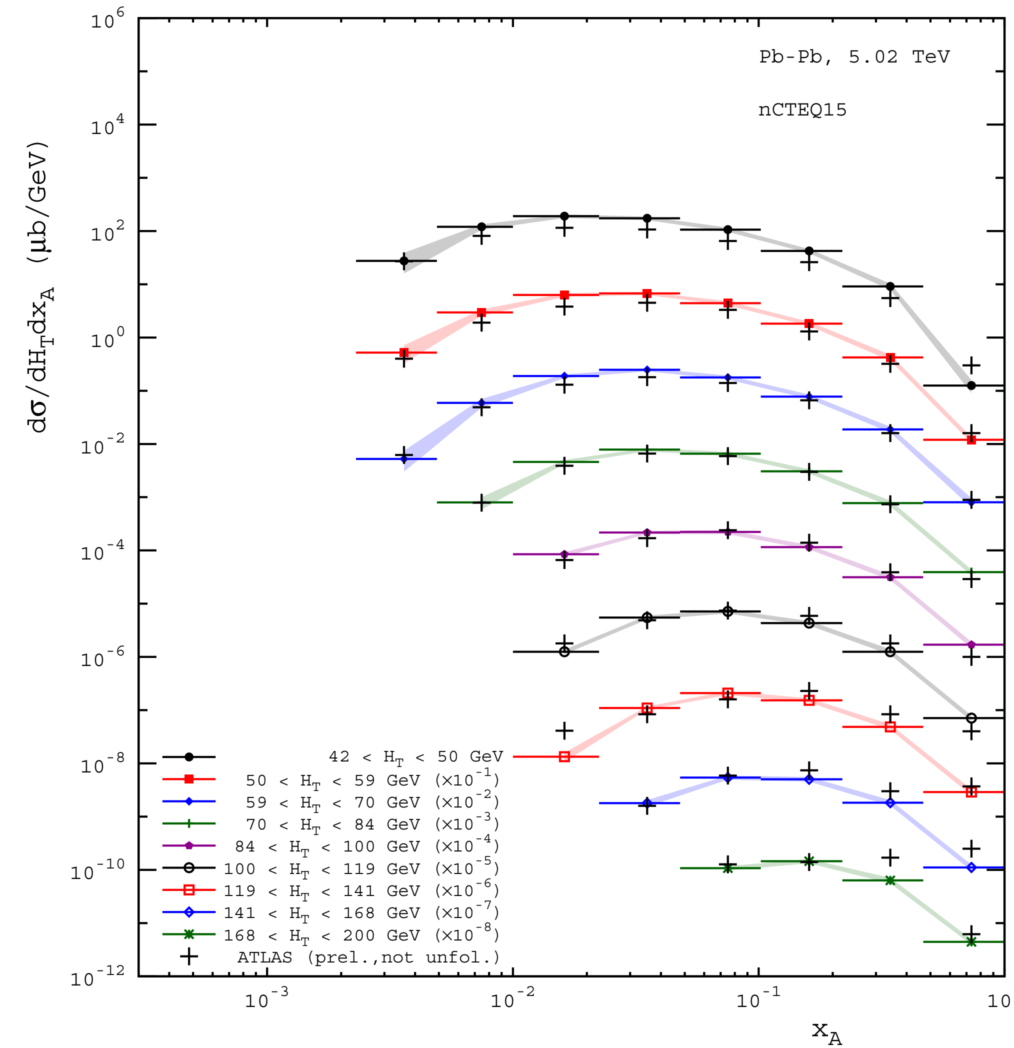
$$\zeta = y m_p b_{\min} \approx y m_p (2R_A)$$

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC (2)

- NLO pQCD vs. prelim. ATLAS data as function of dijet transv. momentum $H_T = E_T^{jet1} + E_T^{jet2}$ and nuclear momentum fraction $x_A = (m_{jets}/\sqrt{s_{NN}})e^{-y_{jets}}$

Guzey, Klasen, PRC 99 (2019) 065202

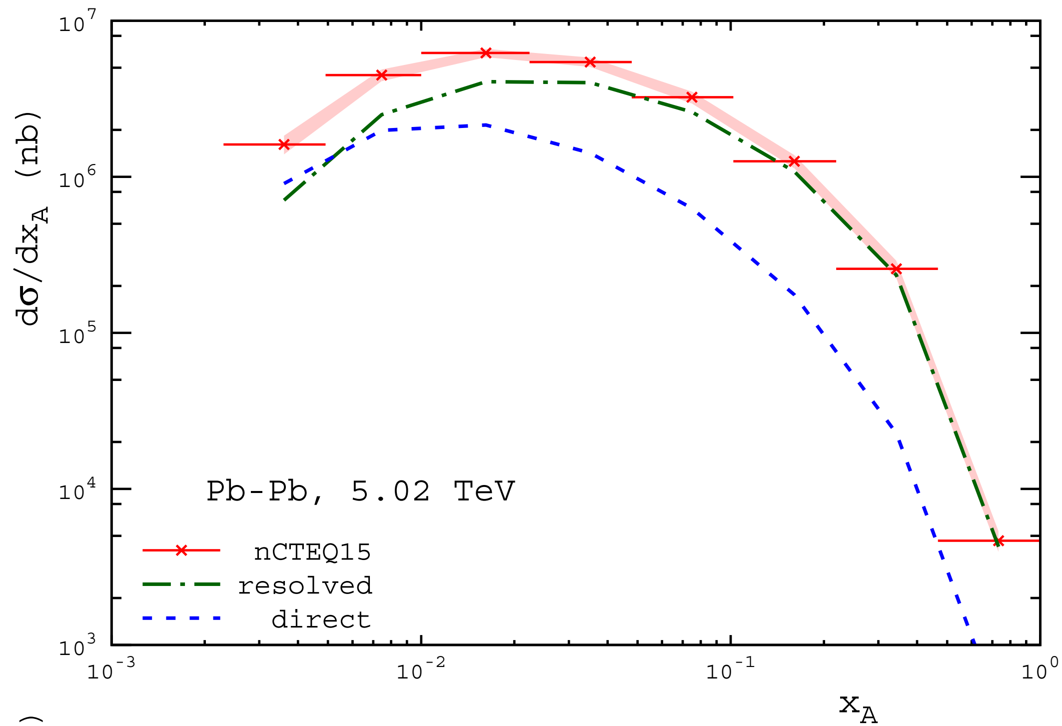




- Shape and normalization of the ATLAS data are reproduced well. Note that the data is preliminary and has not been corrected for detector response.

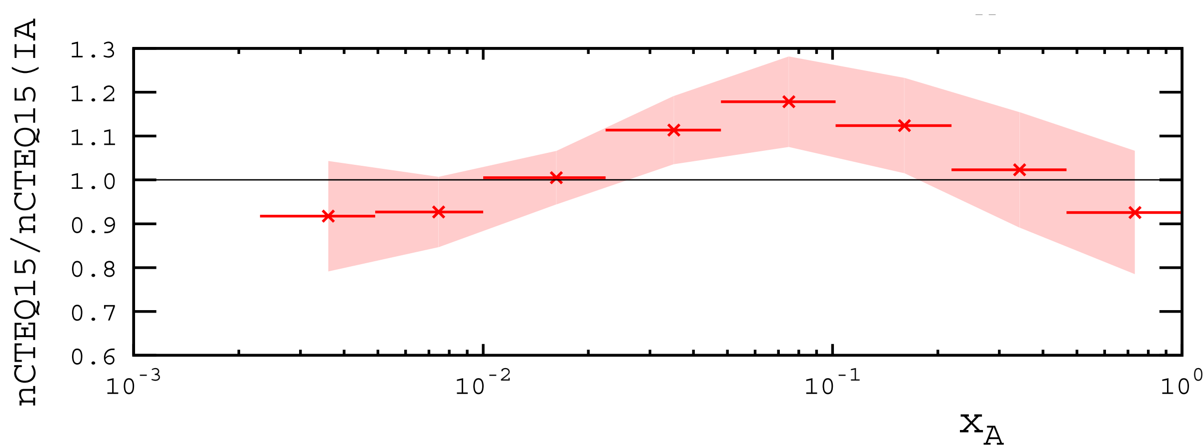
Inclusive dijet photoproduction in Pb-Pb UPCs@LHC (3)

- Resolved vs. direct photon contributions: resolved photons dominate for $x_A > 0.01$; resolved and direct are compatible for $x_A < 0.01$ → similar trend in leading order (LO) analysis in PYTHIA8 framework, Helenius, Rasmusen, EPJ C 79 (2019) 5, 413



- Nuclear modifications: shape of $R = \dfrac{d\sigma(AA \to A + 2\text{jets} + X)}{d\sigma^{\text{IA}}(AA \to A + 2\text{jets} + X)}$ repeats that of $R_g(x) = g_A/Ag_N$: 10% shadowing for $x_A < 0.01$, 20% antishadowing at $x_A \sim 0.1$, 5-10% EMC effect for large x_A → can be compared to predictions for EIC, Klasen, Kovarik, PRD 97 (2018) 114013

$$f_{b/A}^{\text{IA}} = Z f_{b/p} + (A - Z) f_{b/n}$$



Constraints on nPDFs from dijet photoproduction

- To quantity the power of inclusive dijet photoproduction in Pb-Pb UPCs to constrain nPDFs, one can use the statistical method of Bayesian reweighting commonly used for pA data, Armesto et al. JHEP 1311 (2013) 015; Paukkunen, Zurita, JHEP 1412 (2014) 100; Kusina et al, EPJC 77 (2017) 488

- Using error nPDFs, one generates N (N=10,000) replicas:

$$f^k_{j/A}(x,Q^2) = f^0_{j/A}(x,Q^2) + \frac{1}{2}\sum_{i=1}^{N}\left[f^{i+}_{j/A}(x,Q^2) - f^{i-}_{j/A}(x,Q^2)\right] R_{ki}$$

central value — error PDFs — random numbers

- Calculate the cross section for each replica:

$$\frac{d\sigma^k}{dx_A} = \sum_{a,b}\int_{y_{\min}}^{y_{\max}} dy \int_0^1 dx_\gamma f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma,\mu^2) f^k_{b/B}(x_A,\mu^2) d\hat{\sigma}(ab \to \text{jets})$$

- The essence of reweighting is to find the statistical weights **w_k** quantifying how well the k's replica reproduces the data. In our case, as data we take **pseudo-data** obtained using the central value of nPDFs.

Constraints on nPDFs from dijet photoproduction (2)

- To do this, one first calculates the chi-square:

$$\chi_k^2 = \sum_{j=1}^{N_{\rm data}} \frac{(d\sigma^0/dx_A - d\sigma^k/dx_A)^2}{\sigma_j^2}$$

error on pseudo-data

- and then forms the weights **w_k**:

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\rm rep}}\sum_i^{N_{\rm rep}} e^{-\frac{1}{2}\chi_i^2/T}}$$

T=tolerance associated with a given set of nPDFs

- Then one calculates the new, weighted average cross section and its error:

$$\left\langle \frac{d\sigma}{dx_A} \right\rangle_{\rm new} = \frac{1}{N_{\rm rep}} \sum_{k=1}^{N_{\rm rep}} w_k \frac{d\sigma^k}{dx_A} \, ,$$

$$\delta \left\langle \frac{d\sigma}{dx_A} \right\rangle_{\rm new} = \sqrt{\frac{1}{N_{\rm rep}} \sum_k w_k \left(\frac{d\sigma^k}{dx_A} - \left\langle \frac{d\sigma}{dx_A} \right\rangle_{\rm new} \right)^2}$$

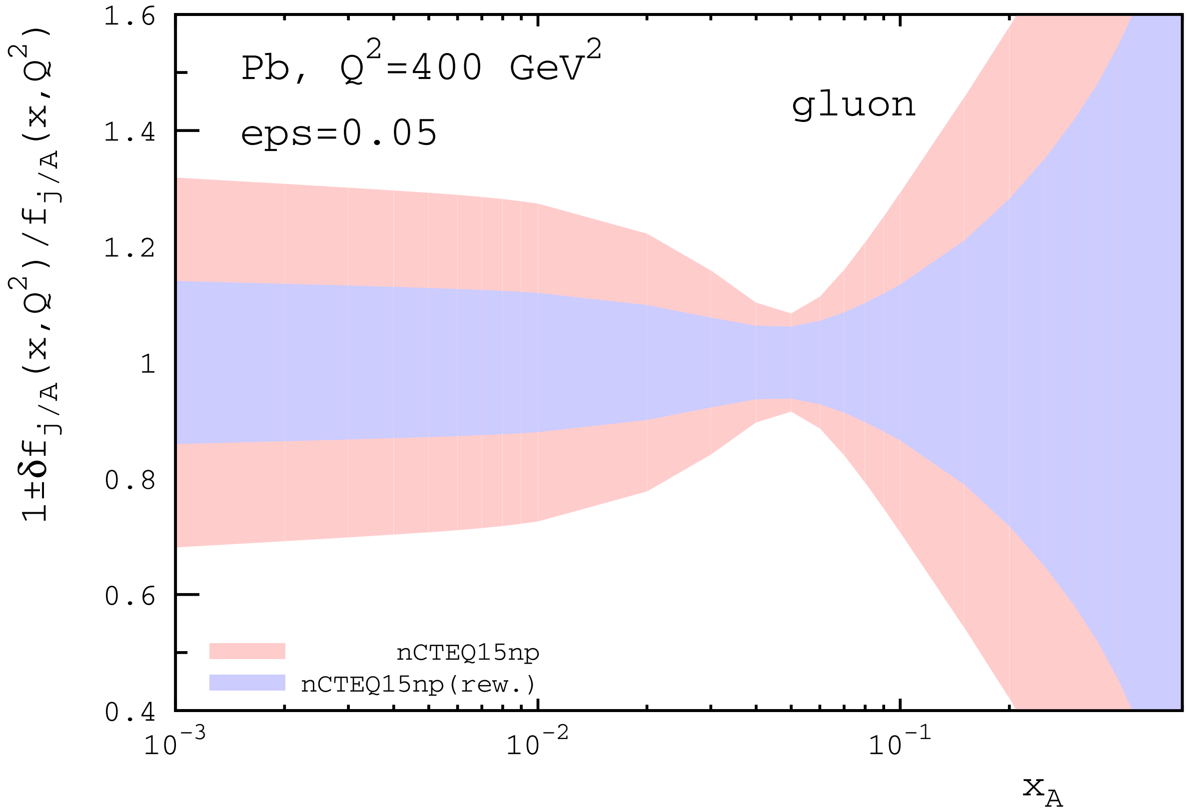
Constraints on nPDFs from dijet photoproduction (3)

- Similarly for nPDFs:

$$\langle f_{j/A}(x,Q^2)\rangle_{\rm new} = \frac{1}{N_{\rm rep}}\sum_{k=1}^{N_{\rm rep}} w_k f^k_{j/A}(x,Q^2)\,,$$

$$\delta\langle f_{j/A}(x,Q^2)\rangle_{\rm new} = \sqrt{\frac{1}{N_{\rm rep}}\sum_{k=1}^{N_{\rm rep}} w_k\left(f^k_{j/A} - \langle f_{j/A}(x,Q^2)\rangle_{\rm new}\right)^2}$$

- This quantifies the effect of the pseudo-data on nPDFs and their uncertainties.

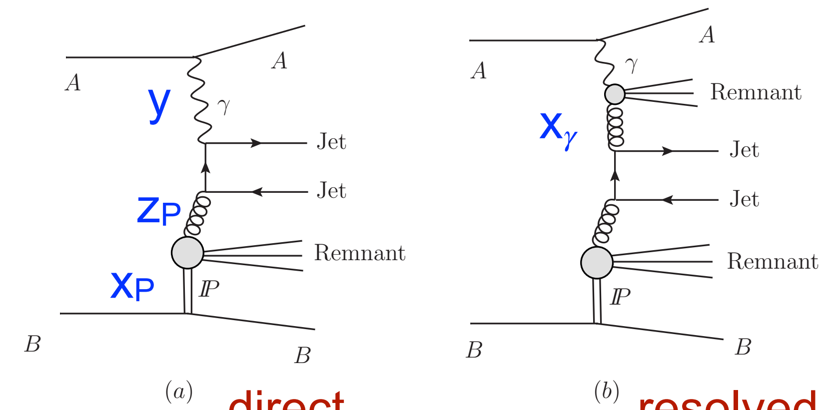


Guzey, Klasen, EPJ C 79 (2019) 5, 396

- Assuming 5% error → reduction of uncertainties by factor 2 at x_A=0.001.

Diffractive dijet photoproduction in Pb-Pb UPCs@LHC

- In framework of collinear factorization & NLO pQCD, it probes novel nuclear diffractive PDFs.
- Contribution of right-moving photon source:



$$d\sigma(AA \to A + 2\text{jets} + X + A)^{(+)} =$$

$$\sum_{a,b} \int dt \int dx_P \int dz_P \int dy \int dx_\gamma f_{\gamma/A}(y) f_{a/\gamma}(x_\gamma, \mu^2) f_{b/A}^{D(4)}(x_P, z_P, t, \mu^2) d\hat{\sigma}_{ab\to\text{jets}}$$

- Nuclear diffractive PDF $f_{b/A}^{D(4)}$= conditional probability to find parton b with mom. fraction z_P with respect to the diffractive exchange (pomeron) carrying mom. fraction x_P provided the nucleus remained intact with mom. transfer t.

- $f_{b/A}^{D(4)}$ is subject to nuclear modifications. The leading twist nuclear shadowing model predicts strong nuclear suppression (shadowing), Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

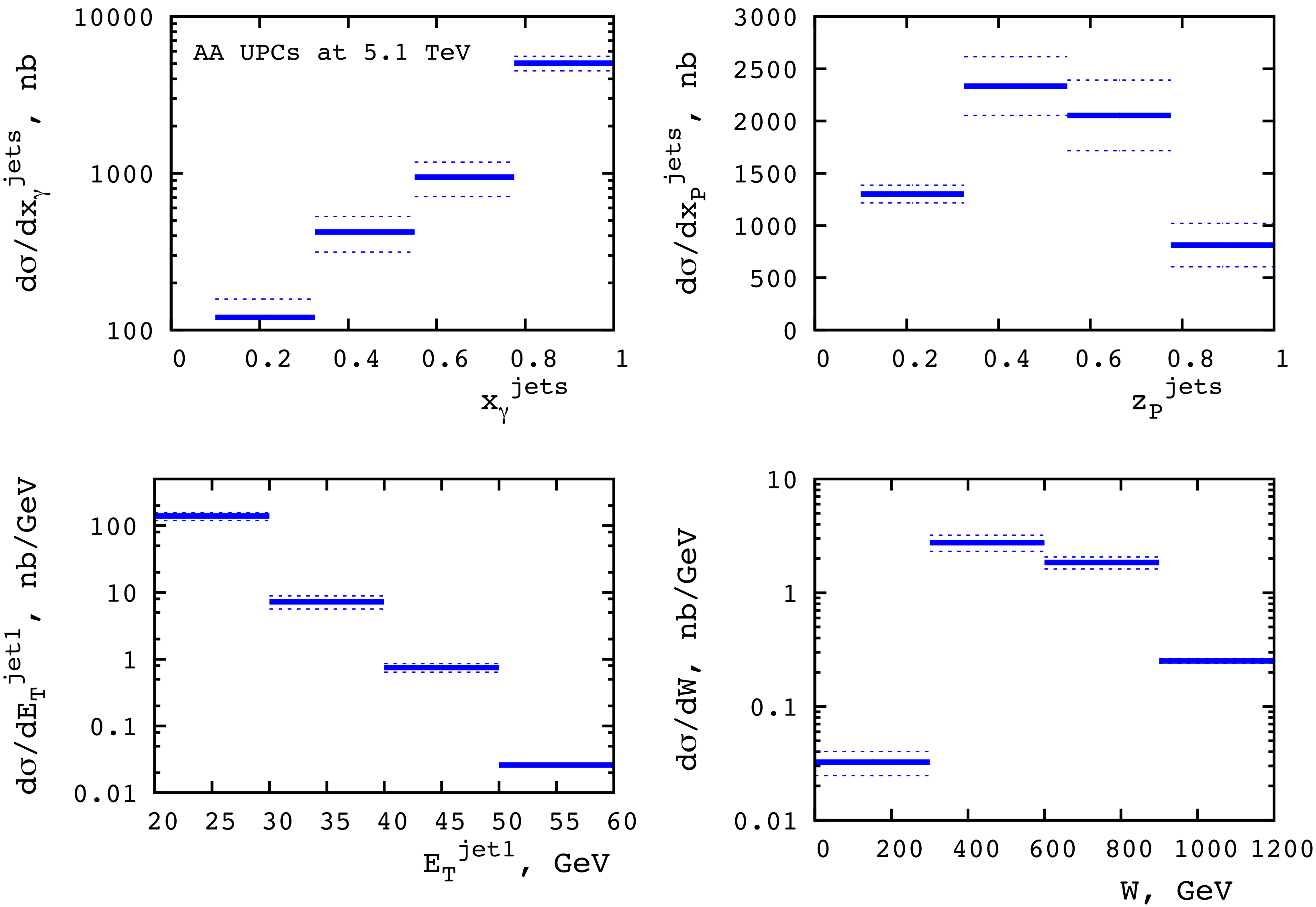
$$f_{b/A}^{D(4)}(x_P, z_P, t, \mu^2) = R_b(x_P, z_P, \mu^2) A^2 F_A^2(t) f_{b/p}^{D(4)}(x_P, z_P, t=0, \mu^2)$$

$$\approx 0.15 A^2 F_A^2(t) f_{b/p}^{D(4)}(x_P, z_P, t=0, \mu^2)$$

Diffractive dijet photoproduction in Pb-Pb UPCs@LHC (2)

- NLO pQCD predictions as a function of momentum fractions x_γ and z_P, leading jet transverse momentum E_T^{jet1}, and photon-nucleus energy W.

Guzey, Klasen, JHEP 04 (2016) 158

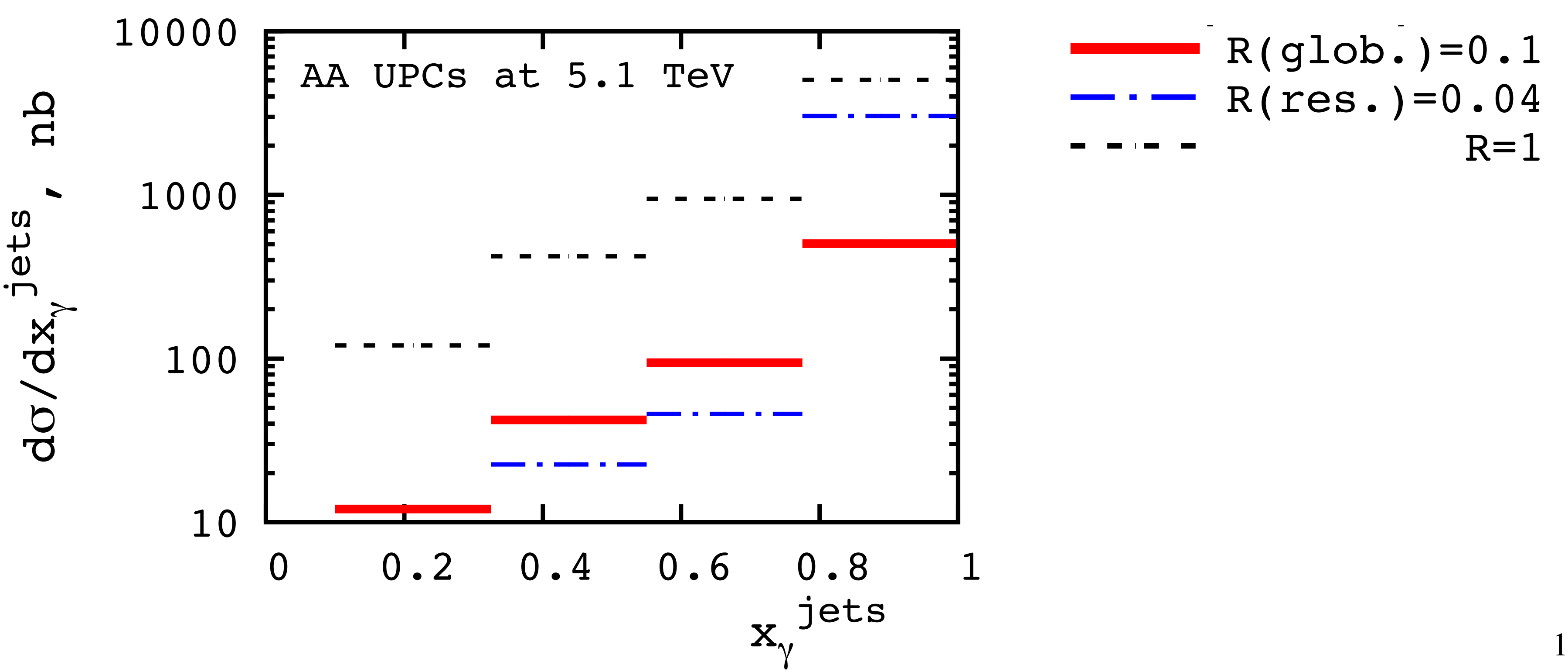


Diffractive dijet photoproduction in Pb-Pb UPCs@LHC (3)

- Analyses of diffractive dijet photoproduction in ep scattering@HERA → QCD factorization is broken, i.e., NLO calculations overestimate data by factor of ~2, Klasen, Kramer, EPJ C 38 (2004) 93; PRL 93 (2004) 232002; JPhys.G 31 (2005) 1391; MPLA 23 (2008) 1885; EPJ C 70 (2010) 91; PLB 508 (2001) 259; EPJ C 49 (2007) 957; PRD 80 (2009) 074006; Guzey, Klasen, EPJ C 76 (2016) 8, 467

- The pattern of unknown: either the global suppression factor R(glob.)=0.5 or the resolved-only suppression R(res.)=0.34, Kaidalov, Khoze, Martin, Ryskin, EPJ C 66 (2010) 373

- One can differentiate between these two scenarios by studying x_γ distribution in AA UPCs, Guzey, Klasen, JHEP 04 (2016) 158

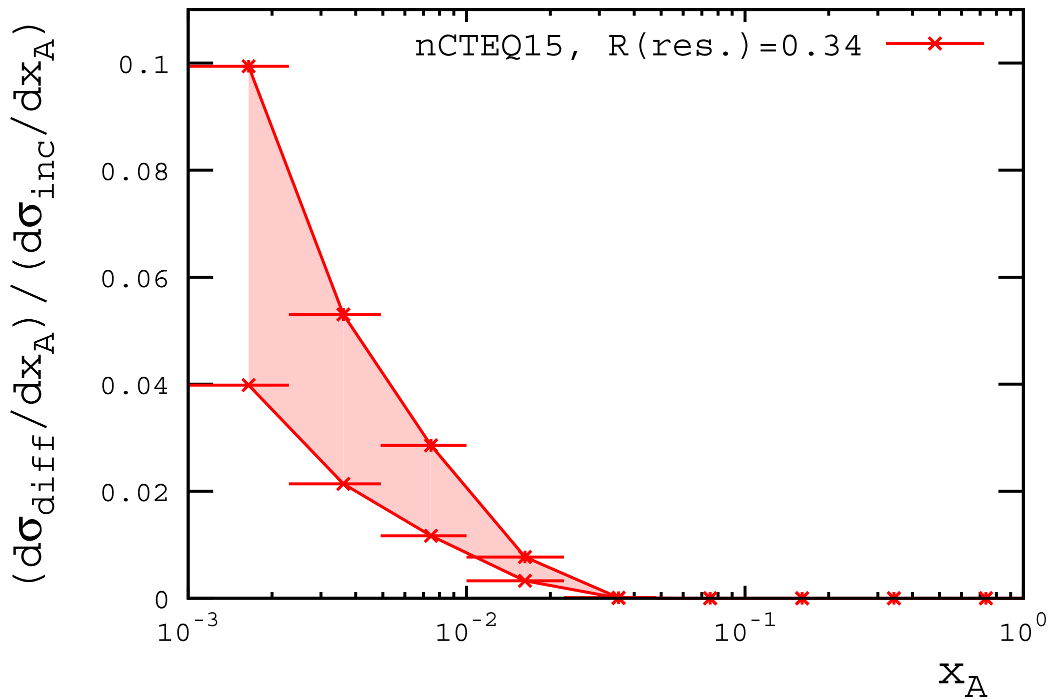


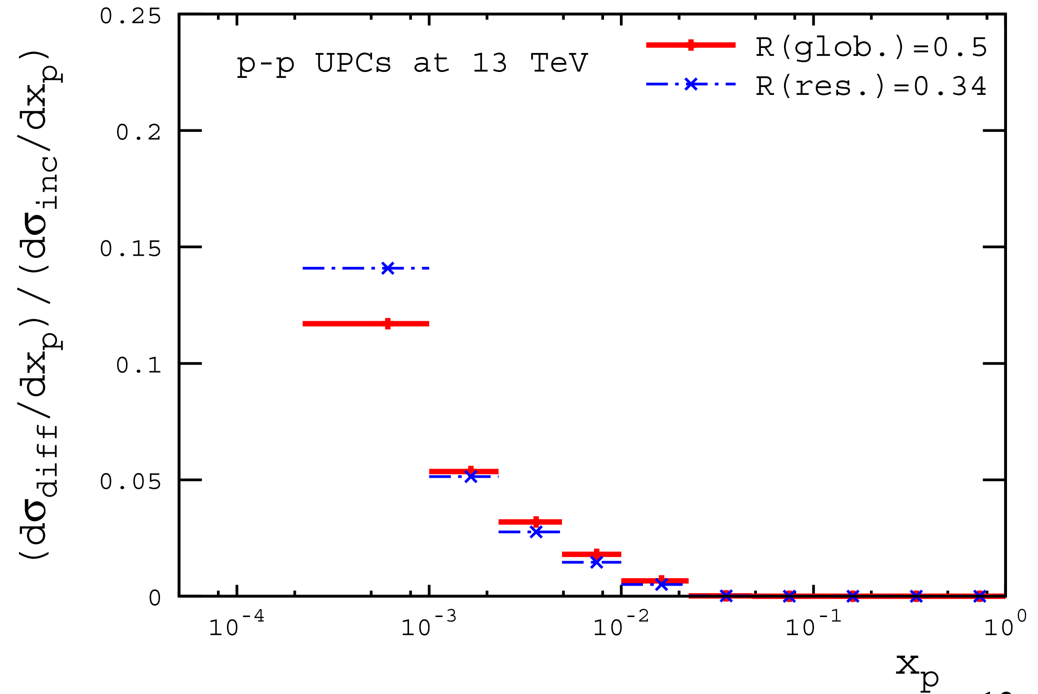
How large is the diffractive contribution?

- Diffractive contribution to inclusive dijet photoproduction in Pb-Pb UPCs in ATLAS kinematics does not exceed **5-10%** at small x_A, Guzey, Klasen, PRD 104 (2021) 11,114013

- This is the effect of restricted kinematics, $p_{T1} > 20$ GeV, $x_A > 0.001$ and large shadowing suppression of nuclear diffractive PDFs.

- This is not the case for pp UPCs, where the diffractive contribution can reach **10-15%** at $x_p \sim 5 \times 10^{-4}$.





Summary

• Nuclear PDFs are poorly constrained by available fixed-target and pA LHC data and, hence, there is growing interest in obtaining new constraints on them using hard photon-nucleus scattering in heavy ion UPCs a the LHC.

• Inclusive dijet photoproduction in Pb-Pb UPCs@LHC probes nPDFs down to x_A~0.005 and can reduce the current small-x_A uncertainties of the gluon distribution by factor of ~2.

• Diifractive dijet photoproduction in Pb-Pb UPCs@LHC accesses novel nuclear diffractive PDFs and may shed new light on mechanism of QCD factorization breaking in this process.

• Inclusive and diffractive dijet photoproduction on nuclei in the EIC kinematics has been studied in Guzey, Klasen, PRC 102 (2020) 6, 065201 and JHEP 05 (2020) 074.
It will cover more restricted kinematics: $x_A > 0.01$, $x_\gamma > 0.5$ → dominated by direct photon contribution → challenging to study factorization breaking.