Inclusive and diffractive dijet photoproduction in Pb-Pb UPCs at the LHC

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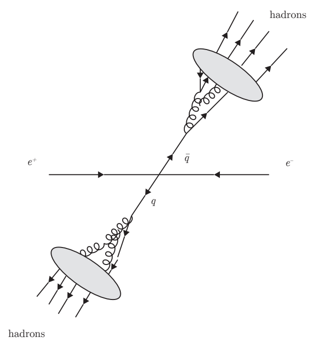
Based on work in collaboration with **M. Klasen** (U. of Münster, Germany),
JHEP 04 (2016) 158; EPJ C 76 (2016) 8, 467; PRC 99 (2019) 6, 065202; EPJ C 79 (2019) 5, 396;
PRD 104 (2021) 11, 114013

Outline:

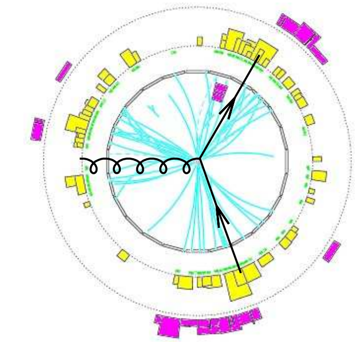
- Jets in QCD and dijet photoproduction in collinear factorization and NLO pQCD
- Inclusive dijet photoproduction in Pb-Pb UPCs at the LHC and nuclear PDFs
- Diffractive dijet photoproduction in Pb-Pb UPCs at the LHC: nuclear diffractive PDFs and QCD factorization breaking

UPC 2023: International workshop on the physocs of Ultra-Peripheral Collisions, 11-15 October, 2023, Playa del Carmen, Mexico

Jets in QCD



• Jets are collimated sprays of hadrons (π, K, p, …) produced in high-energy e+e-, lepton-hadron, and hadron-hadron collisions,
Salam, arXiv:1011.5131; Sapeta, arXiv:1511.09336; Laenen, arXiv:1708.00770



• Jets have been instrumental is establishing QCD and concepts af asymptotic freedom (factorization) and confinement (hadronization).

• Classic example: 3-jet events in e+e- annihilation → existence of gluons.

• Studies of jet production remain an active field of QCD studies at colliders:

- precision extraction of $\alpha_S(M_Z)$ from HERA data on ep DIS, H1 Coll. EPJC 75 (2015) 2, 65; ZEUS Coll., NPB 864 (2012) 1

- global QCD fits of parton distribution functions **(PDFs) of the proton** using ep DIS@HERA, anti-pp@Tevatron, and pp@LHC, NNPDF4.0, EPJC 82 (2022) 4, 428; CT18, PRD 103 (2021) 1, 014013, **nuclear PDFs** using dijets in pA@LHC, EPPS21, EPJC 82 (2022) 5, 413, and **photon PDFs**, Slominski, Abramowicz, Levy, EPJC 45 (2006) 633.

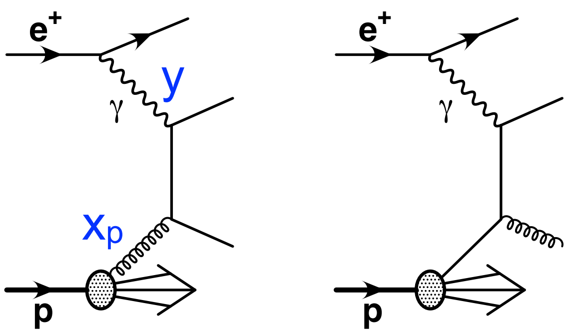
- search for small-x BFKL and saturation physics using forward dijet production at LHC, 2022 Snowmass Summer Study, arXiv:2203.08129 and at EIC, Boussarie, Mäntysaari, Salazar, Schenke, JHEP 09 (2021) 178

- Standard Model background for many new physics processes.

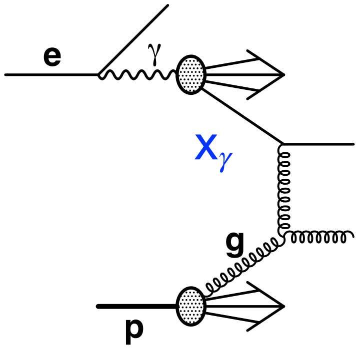
Jet photoproduction in QCD

• All information on jet photoproduction comes from ep scattering at HERA, Newman, Wing, Rev. Mod. Phys. 86 (2014) 3, 1037; Butterworth, Wing, Rept. Prog. Phys. 68 (2005) 2773; Klein, Yoshida, Prog. Part. Nucl. Phys. 61 (2008) 343 + prelim. data on Pb-Pb UPCs@LHC, ATLAS-CONF-2017-011, ATLAS-CONF-2022-021

• Typical leading-order (LO) Feynman graphs: direct-photon and resolved-photon contributions. The separation is not unique beyond LO, but is still useful.



direct-photon



resolved-photon

• Main interests in studying jet photoproduction:

- Cross section is sensitive to quark and gluon structure at the same order. When combined DIS cross section, provides of additional constraints on the gluon PDF, ZEUS, EPJC 42 (2005) 1

- Test of QCD factorization and its violation (in case of diffractive dijet photoproduction)

- Access to photon structure, constraints on the gluon PDF of the photon, which are complimentary to those from $F_2^{\gamma}(x,Q^2)$ in e+e-, Nisius, Phys. Rept. 332 (2000) 165; Slominski, Abramowicz, Levy, EPJC 45 (2006) 633

Dijet photoproduction in NLO pQCD

• In photoproduction, jet transverse momentum provides hard scale $\mu_R=\mu_F=E_T$

• In framework of collinear factorization of perturbative QCD, cross sections are known to next-to-leading order (NLO) accuracy, Aurenche at al. EPJC 17 (2000) 413; Frixione, Ridolfi, NPB 507 (1997) 315; Klasen, Kramer, Z. Phys. C 76 (1997) 67

• Dijet cross section in NLO pQCD:

$$d\sigma_{ep\to e+\text{jets}+X} = \sum_{a,b} \int_0^1 dx_\gamma \int_0^1 dx_p \, f_{\gamma/e} \, f_{b/\gamma}(x_\gamma, \mu_{F\gamma}) \, f_{a/p}(x_p, \mu_{Fp}) \, d\hat{\sigma}_{ab\to cd}(x_\gamma, x_p, \alpha_s(\mu_R), \mu_{F\gamma}, \mu_{Fp}, \mu_R)$$

Photon flux in Weizsäcker-Williams approx.

$$f_{\gamma/e}(y) = \frac{\alpha}{2\pi}\left[\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{\max}(1-y)}{m_e^2 y^2} + 2m_e^2 y\left(\frac{1-y}{m_e^2 y^2} - \frac{1}{Q^2_{\max}}\right)\right]$$

Photon PDFs for resolved photon; in b=γ case, $f_{b/\gamma}=\delta(1-x_\gamma)$ for Born and virtual corr.

Proton PDFs

2→2 and 2→3 hard parton scattering cross section

• This parton-level cross section assumes massless quarks and for comparison with data, needs to be supplemented with hadronization corrections from Monte Carlo (LO + parton showers), Helenius, arXiv:1806.07246 and arXiv:1811.10931; Helenius and Rasmusen, EPJC 79 (2019) 413.

• Parton momentum fractions are determined using their hadron-level estimates based on measured jet transverse energies $E_{T1,2}$ and rapidities $\eta_{1,2}$.

$$x_\gamma^{\text{obs}} = \frac{p_{T,1}e^{-\eta_1} + p_{T,2}e^{-\eta_2}}{2yE_e}$$

$$x_A^{\text{obs}} = \frac{p_{T,1}e^{\eta_1} + p_{T,2}e^{\eta_2}}{2E_A},$$

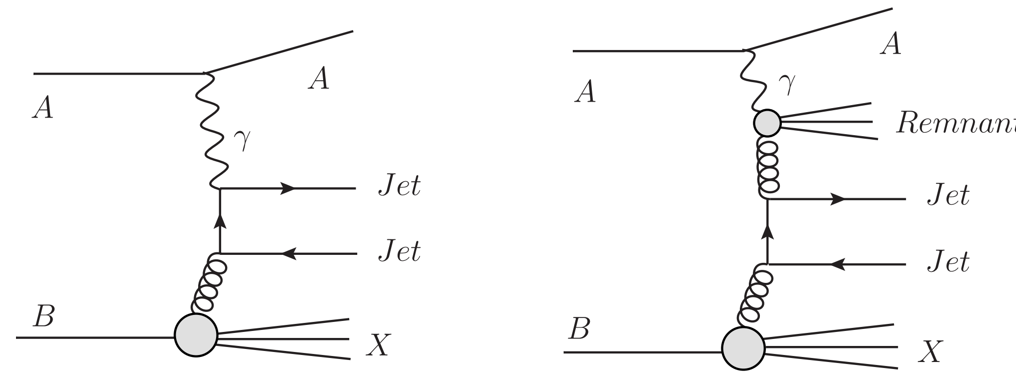
Dijet photoproduction in UPCs@LHC

• 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 $x_A \sim 10^{-5}$.

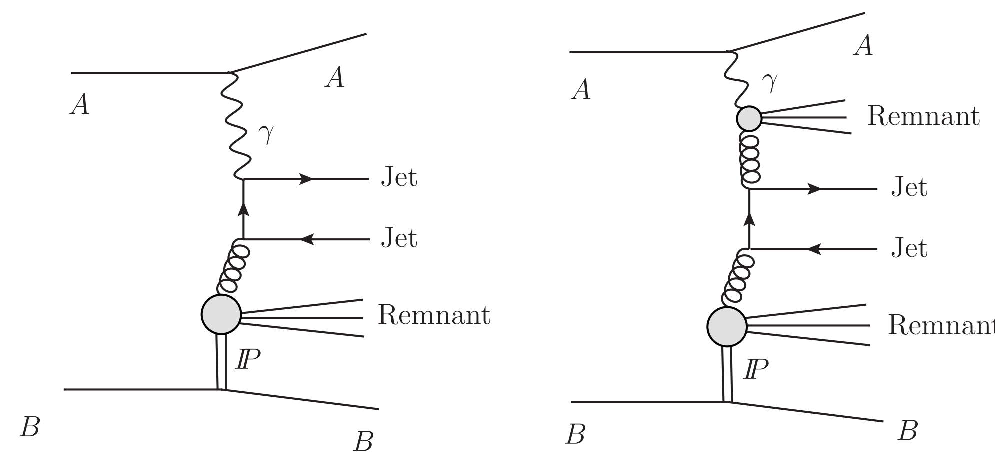
• Nuclear and photon PDFs can also be studied in **inclusive dijet photoproduction** in Pb-Pb UPCs, ATLAS-CONF-2017-011, ATLAS-CONF-2022-021

• Requiring intact nuclear target → **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

• First LO pQCD calculations of heavy-flavor jets in UPCs, Strikman, Vogt, White, PRL 96 (2006) 082001 → very large rates for inclusive and diffractive (~20%) dijets.



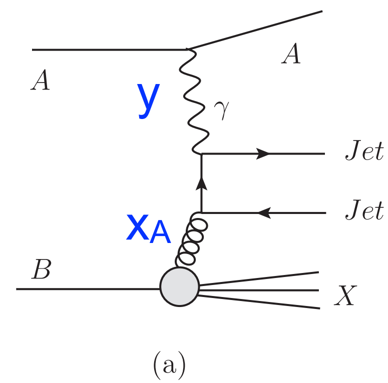
(a) direct (b) resolved



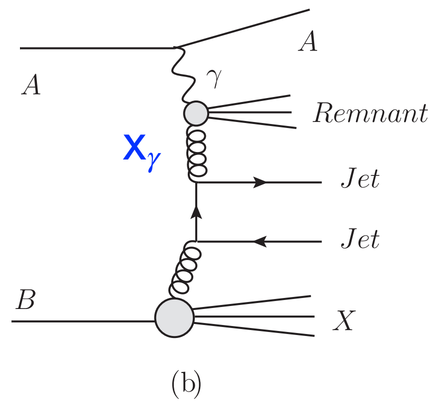
(a) (b)

Inclusive dijet photoproduction in Pb-Pb UPCs@LHC

- Cross section of dijet photoproduction using collinear factorization and 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



direct



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 (GRVHO) (resolved photon), from e+e- data

Nuclear PDFs (nCTEQ15, EPPS16)

Hard parton cross section

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

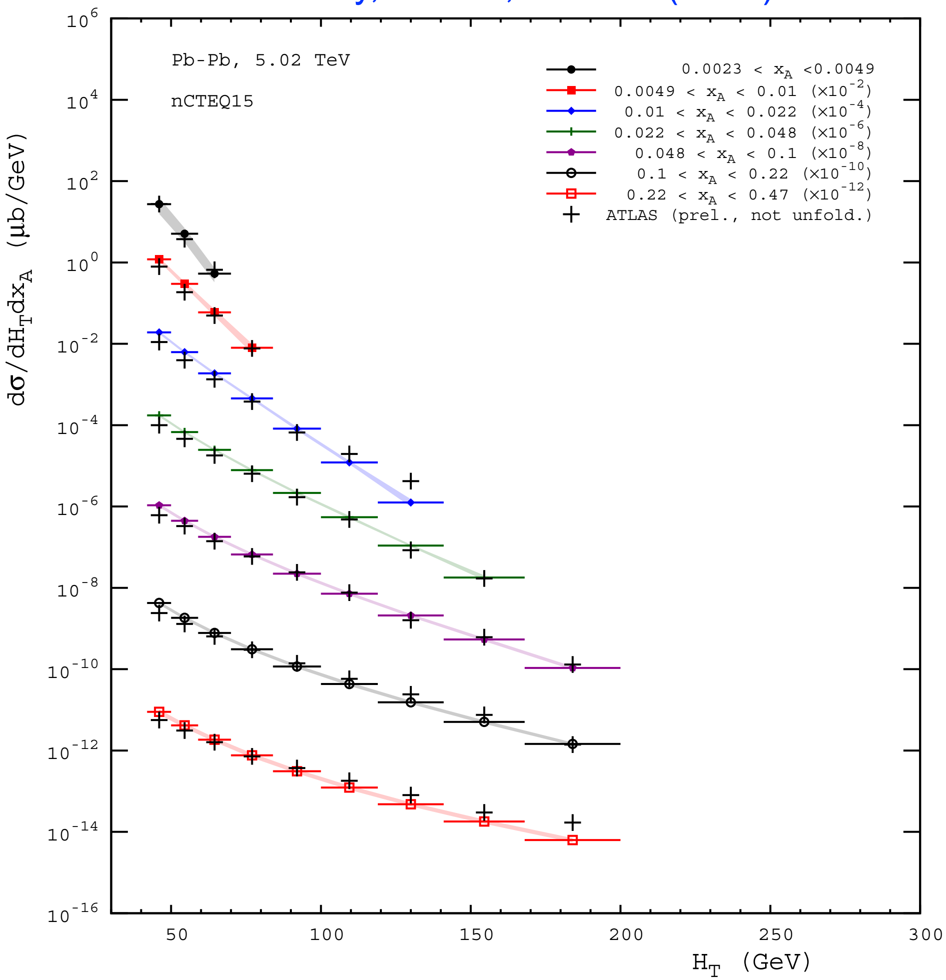
$$\zeta = y m_p b_{\min} \approx y m_p (2R_A)$$

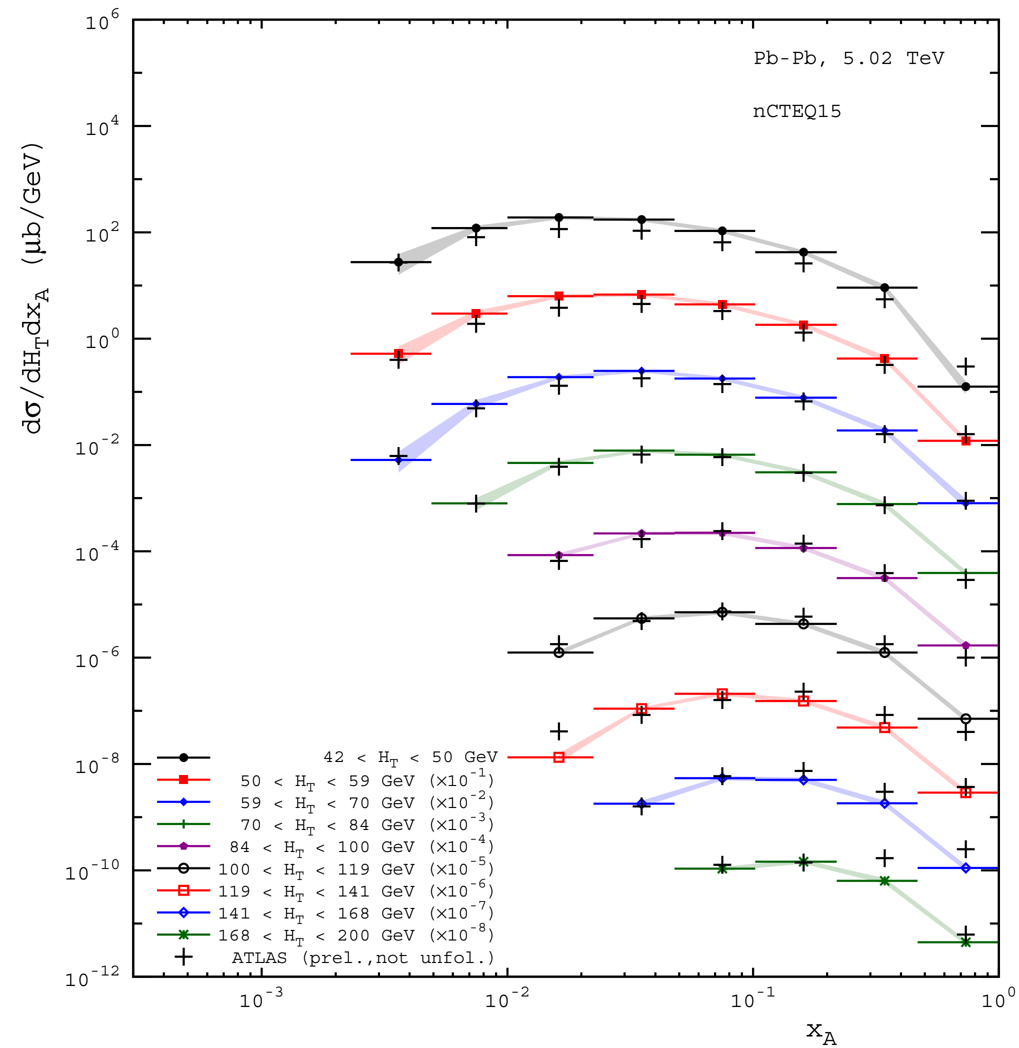
See talk P. Paakkinen

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

- NLO pQCD vs. ATLAS data as a function of the dijet transverse 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



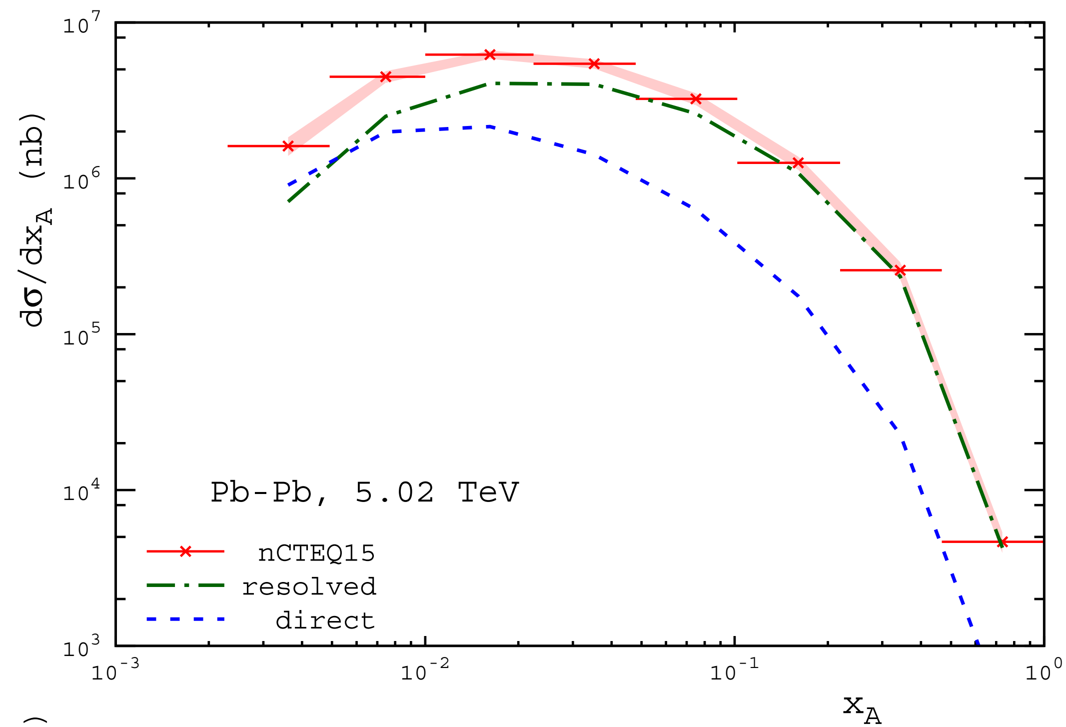


- Shape and normalization of ATLAS data, ATLAS-CONF-2017-011 reproduced well (data not corrected for detector response).
- We haven't compared to the more recent unfolded data, ATLAS-CONF-2022-021.

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.

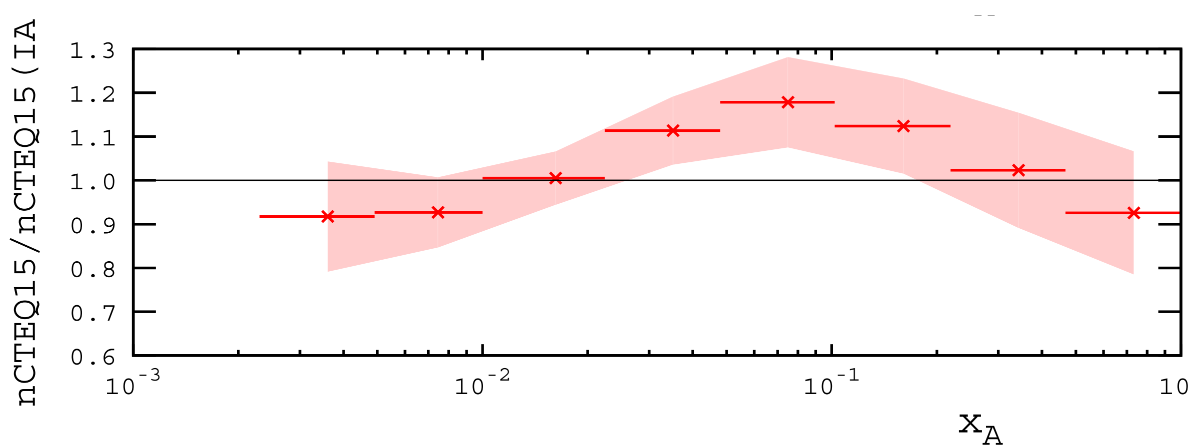
See talk I. Helenius



- Nuclear modifications: shape of 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; Guzey, Klasen, PRC 102 (2020) 6, 065201.

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

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



Constraints on nPDFs from dijet photoproduction

- Potential of inclusive dijet photoproduction in Pb-Pb UPCs to constrain nPDFs can be assessed using Bayesian reweighting 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:

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

- $\chi 2$ for each k using our calculations with central nPDFs as pseudo-data (need to assign some error eps=5-15%)

- $\rightarrow$ statistical weights $\mathbf{w_k}$ for replicas to reproduces the pseudo-data with tolerance T

$$w_k = \frac{e^{-\frac{1}{2}\chi^2_k/T}}{\frac{1}{N_{\text{rep}}}\sum_i^{N_{\text{rep}}} e^{-\frac{1}{2}\chi^2_i/T}}$$

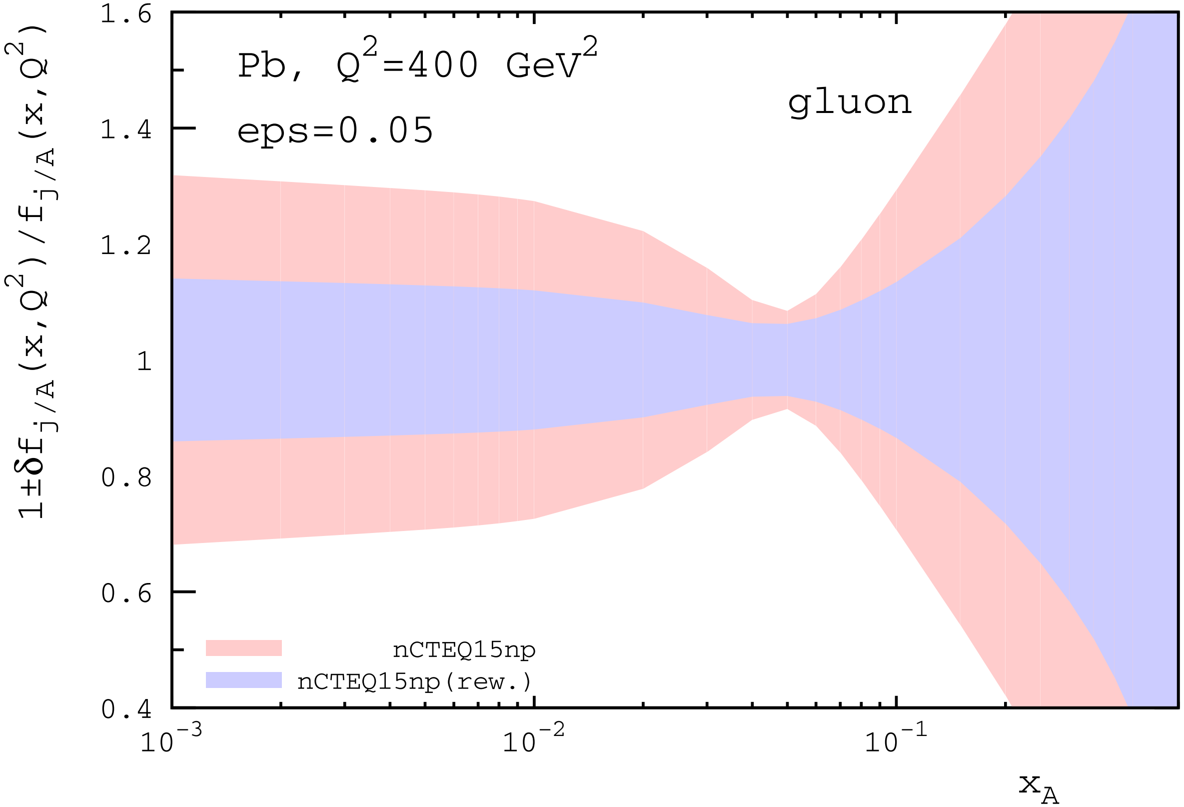
Constraints on nPDFs from dijet photoproduction (2)

- Re-weighted PDFs and their uncertainties:

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

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

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

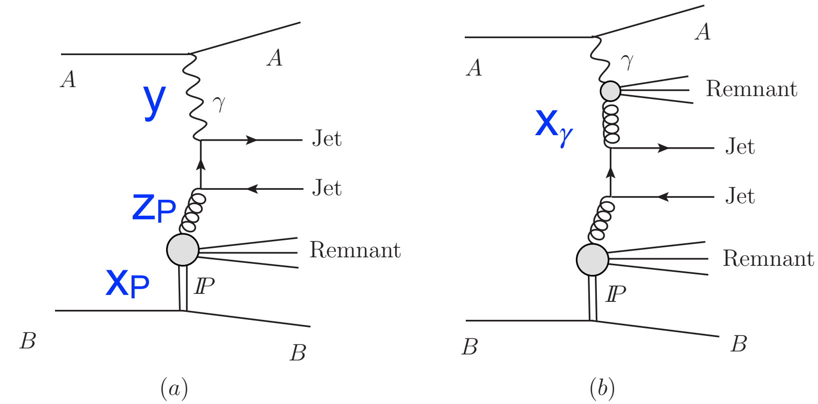


Guzey, Klasen, EPJ C 79 (2019) 5, 396

- 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

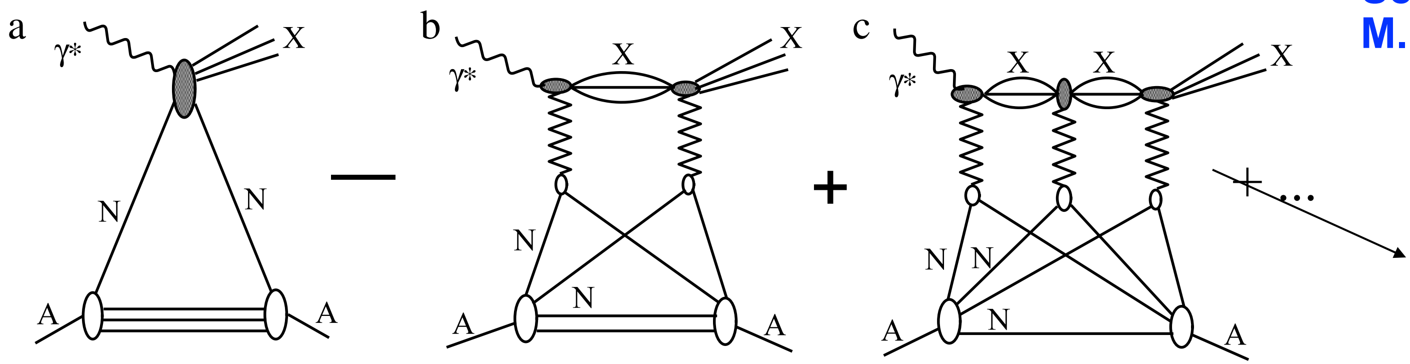
$$f_{b/A}^{D(4)}(x_P, z_P, t, \mu^2) = R_b(x_P, z_P, \mu^2) A^2 F_A^2(t) f_{b/p}^{D(4)}(x_P, z_P, t=0, \mu^2)$$

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

Leading twist approach to nuclear shadowing

- Combination of Gribov-Glauber theory with QCD factorization theorems for inclusive and diffractive DIS → prediction for small-x nPDFs at input scale Q_0,
  Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

See talks B. Schenke, M. Strikman

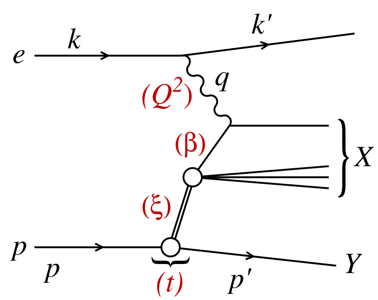


diffractive exchange

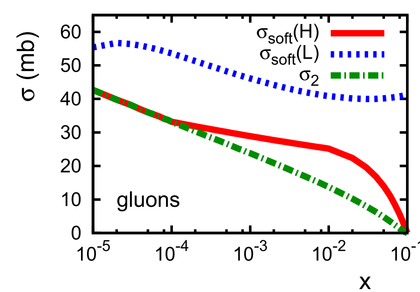
$$\beta f_{j/A}^{D(3)}(\beta,Q^2,x_{\mathbb{P}}) = 4\pi A^2 \beta f_{j/N}^{D(4)}(\beta,Q^2,x_{\mathbb{P}},t_{\min}) \int d^2b \left| \int_{-\infty}^{\infty} dz e^{i x_{\mathbb{P}} m_N z} e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^{j}(x,Q^2)\int_z^{\infty} dz' \rho_A(b,z')} \rho_A(b,z) \right|^2$$

j=q or g

N=2 term: proton diffractive PDFs from QCD analysis of HERA data



N ≥ 3 terms: model-dependent effective cross section



Spread in σ_{soft} → uncertainty of LTA predictions

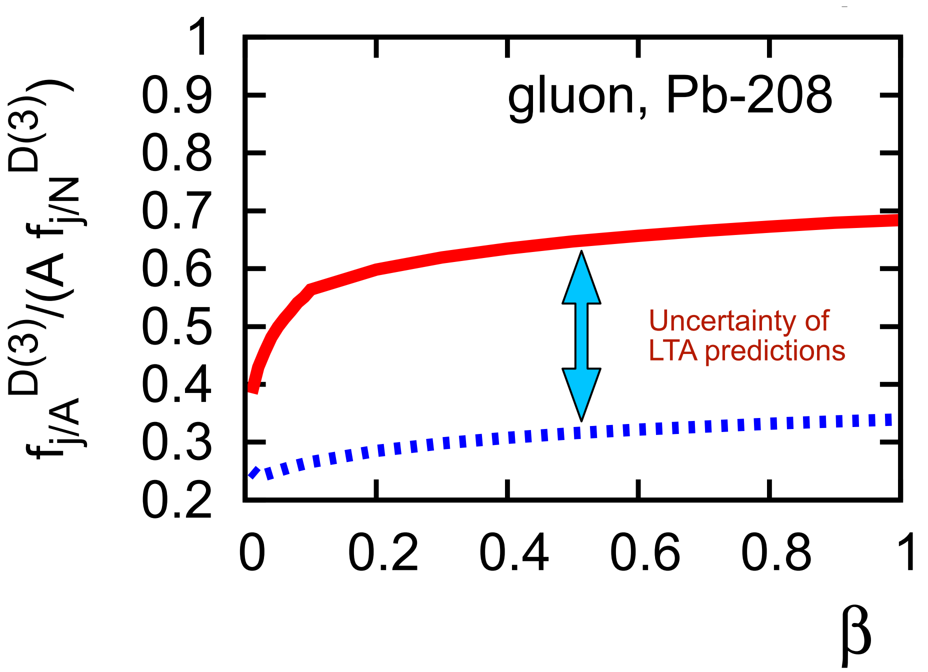
Nuclear density

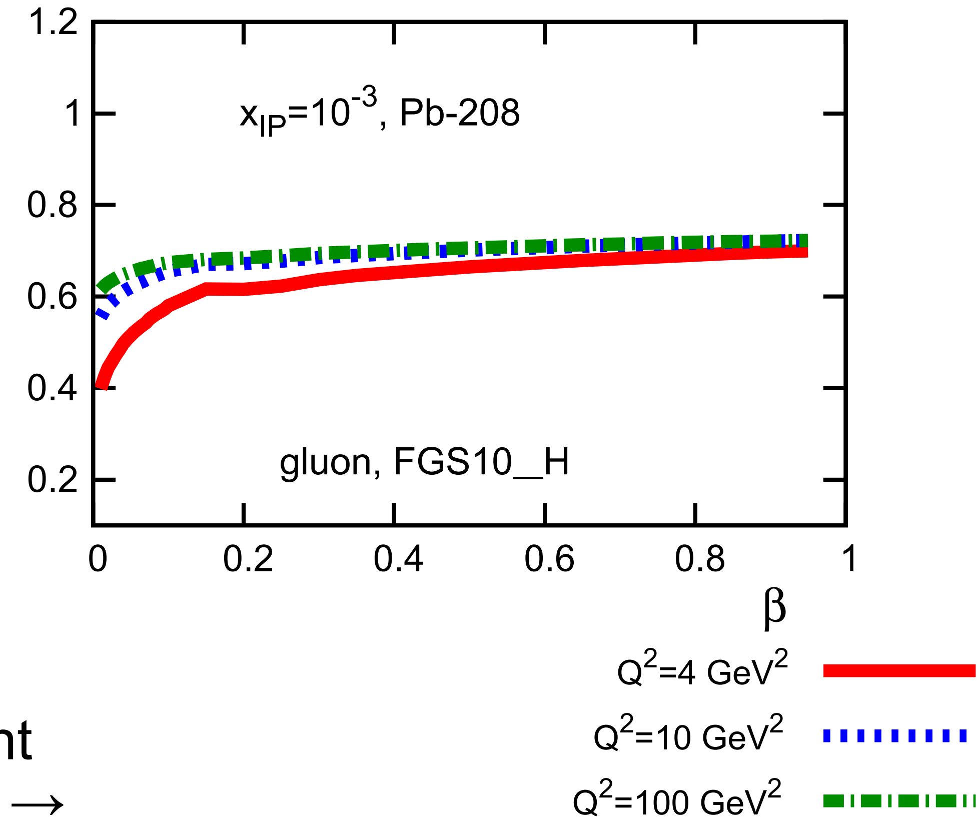
- Main feature: connects shadowing in eA with diffraction in ep.
- Can also be generalized to incoherent (quasi-elastic diffraction).

Leading twist approach to nuclear shadowing (2)

- HERA analysis: perturbative Pomeron is made mostly of gluons → LTA model naturally predicts large gluon nuclear shadowing.

- Nucleus/proton ratio of diffractive PDFs is a weak function of β, x_P and Q^2.





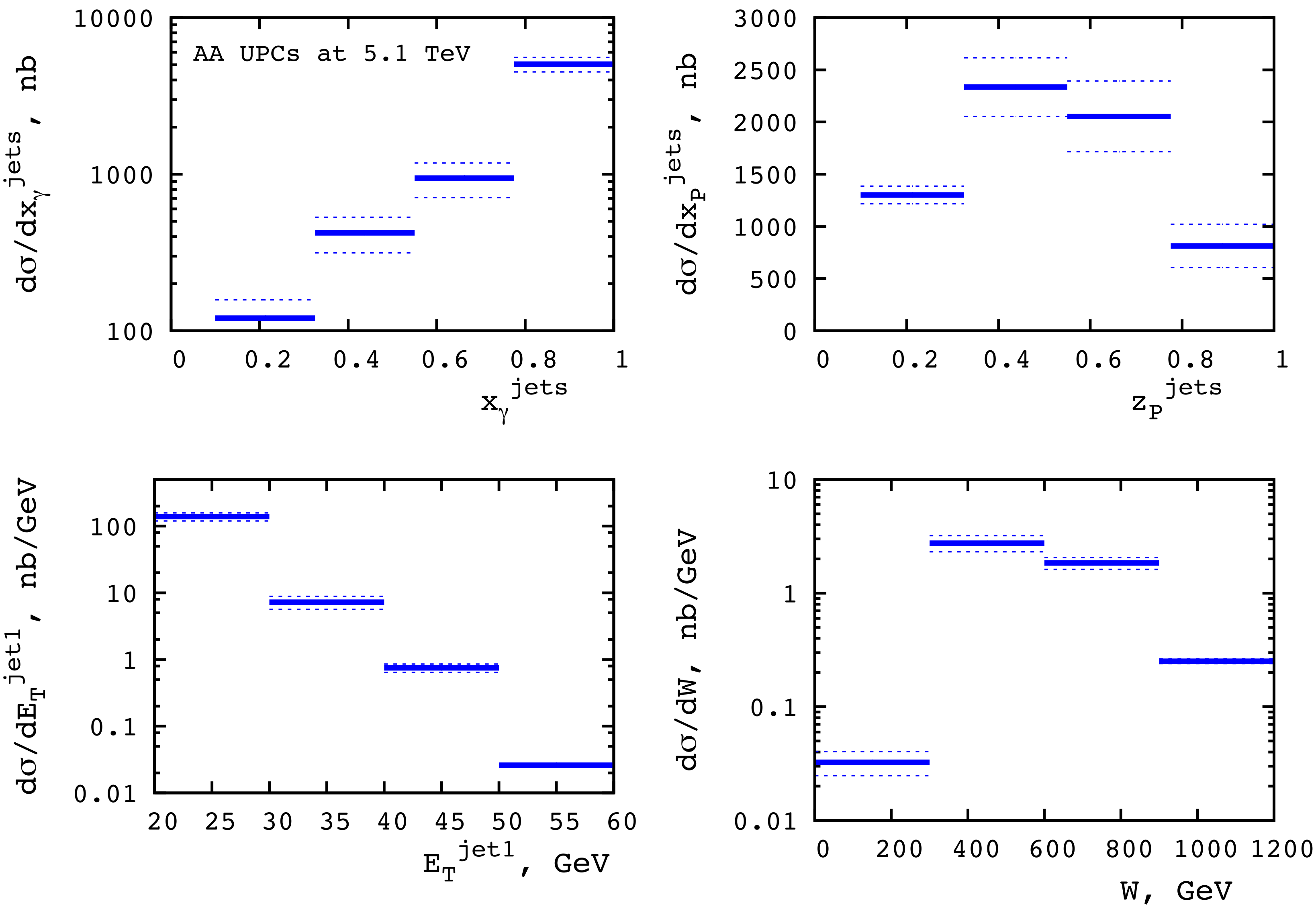
- → we approximate it by a single constant $R_b=0.15\text{-}0.30 < (R_g)^2=(0.6\text{-}0.7)^2=0.4\text{-}0.5$ → connection to strong shadowing in J/ψ case,

See talk E. Iancu

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

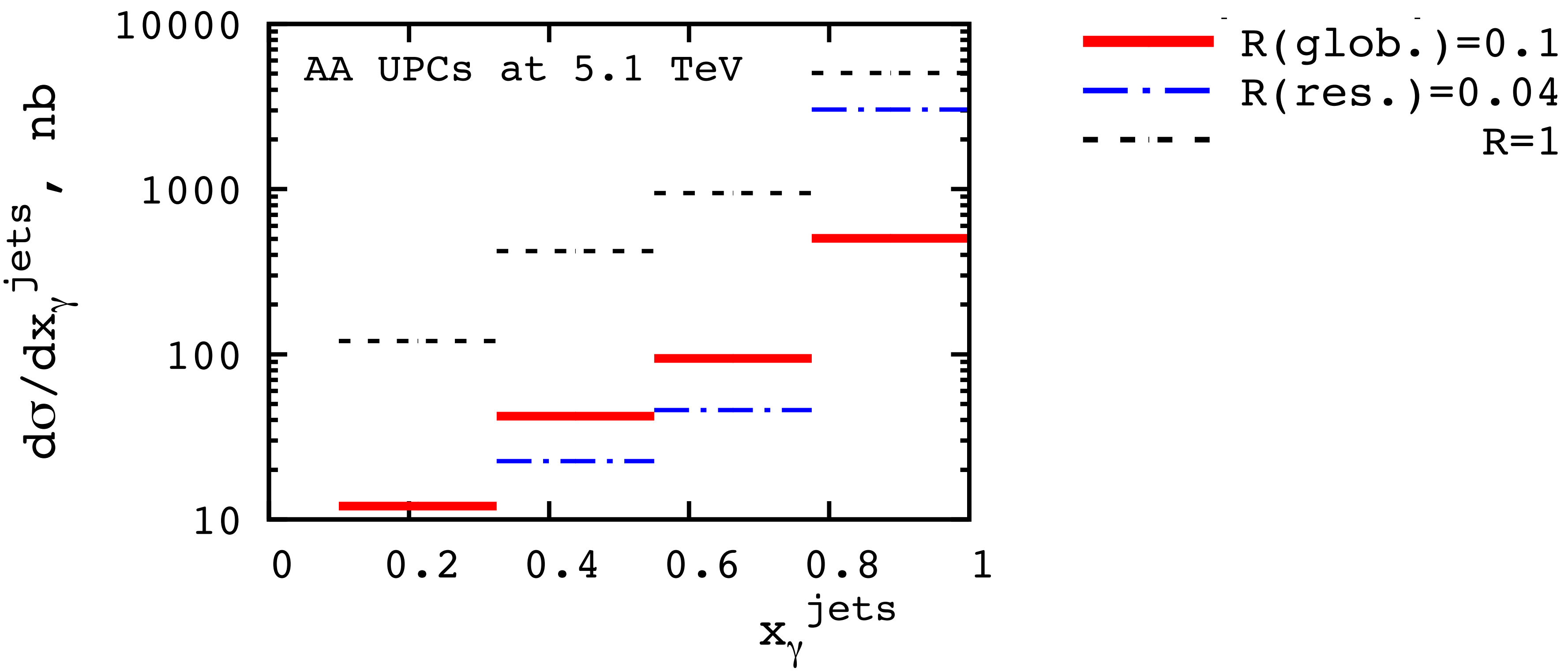


Diffractive dijet photoproduction in Pb-Pb UPCs@LHC (3)

- 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, or the flavor-dependent combination of the two, Guzey, Klasen, EPJ C 76 (2016) 8, 467

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



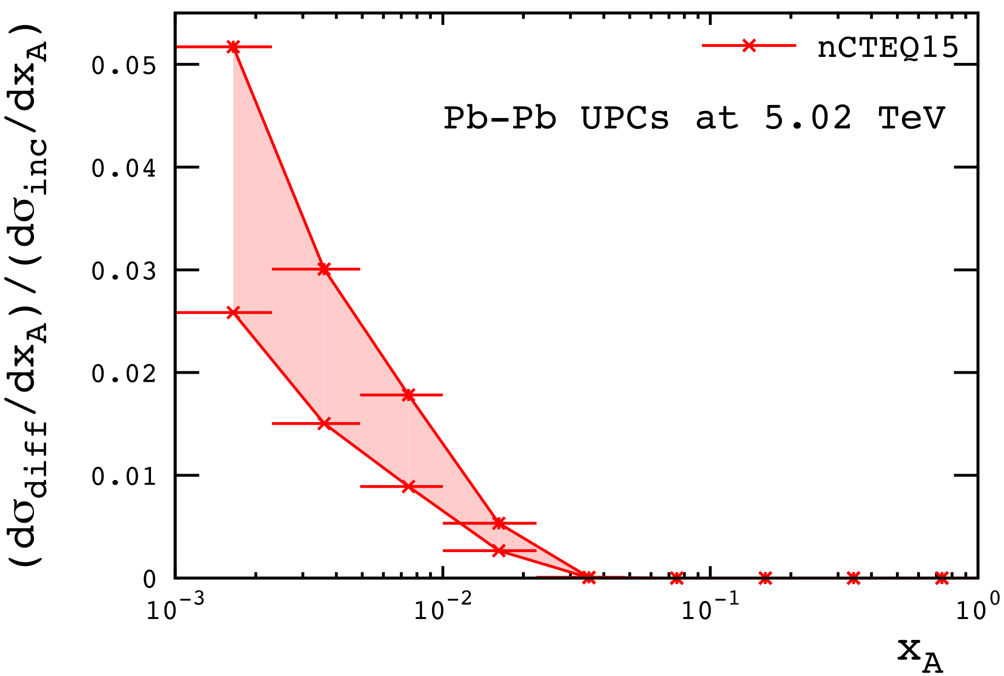
How large is the diffractive contribution?

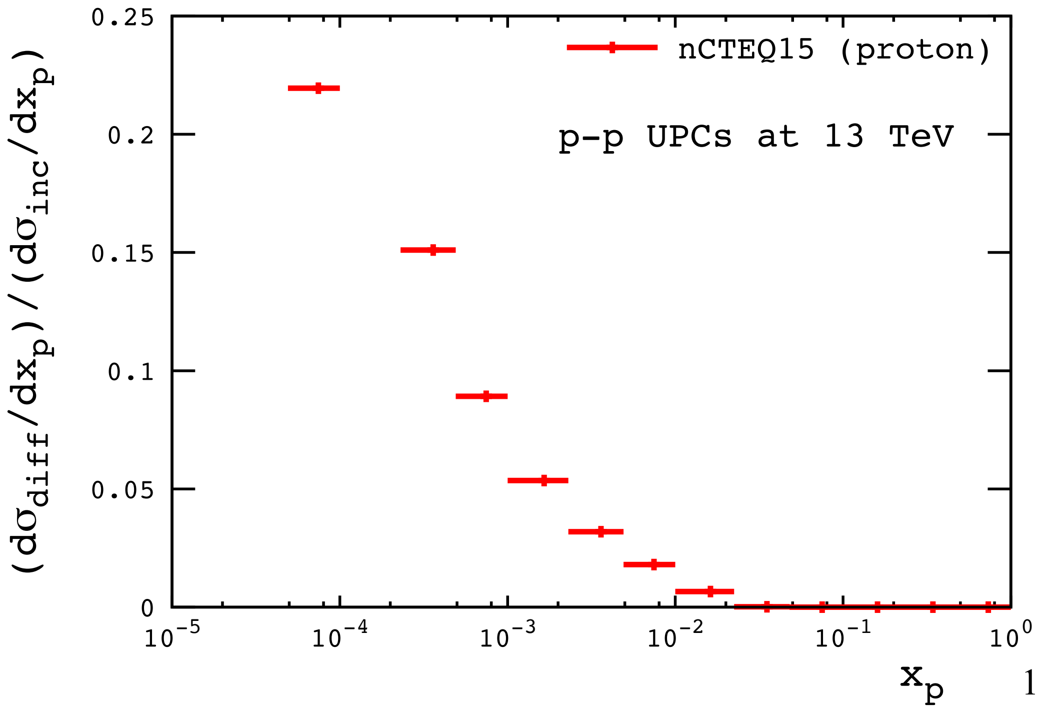
- Diffractive contribution to inclusive dijet photoproduction in Pb-Pb UPCs in ATLAS kinematics does not exceed **5%** at small x_A, Guzey, Klasen, PRD 104(2021) 11, 114013

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

- → the diffractive contribution and related ambiguity with the determination of the photon-emitting nucleus (invariant energy W) can be safely neglected.

- It is not the case for pp UPCs, where the diffractive contribution can reach **20-25%** at $x_p \sim 10^{-4}$.





Summary and Outlook

• Photoproduction of jets is a standard tool of QCD. Its theory is well-established in NLO pQCD and compares very well to HERA data.

• 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.

• Extraction of diffractive events is problematic due to ambiguity in photon source → can be solved by requiring $M_X \gg M_{dijet}$, Strikman, Vogt, White, PRL 96 (2006) 082001.

• Both processes can be viewed as precursors of analogous measurements at EIC, Guzey, Klasen, PRC 102 (2020) 6, 065201; JHEP 05 (2020) 074.