Inclusive and diffractive dijet photoproduction at EIC in NLO QCD

AoF CoE in Quark Matter

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In collaboration with M. Klasen, PRC 102 (2020) 6, 065201 and JHEP05 (2020) 074

Outline:

- Dijet photoproduction in QCD
- Inclusive dijet photoproduction in eA scattering at EIC: kinematic reach, nuclear effects
- Diffractive dijet production in ep/eA scattering at EIC: kinematic reach, factorization breaking, nuclear diffractive PDFs
- Summary

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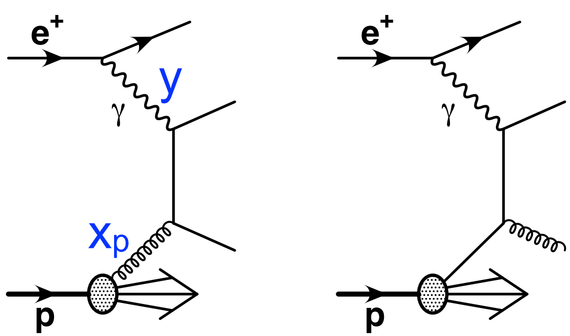
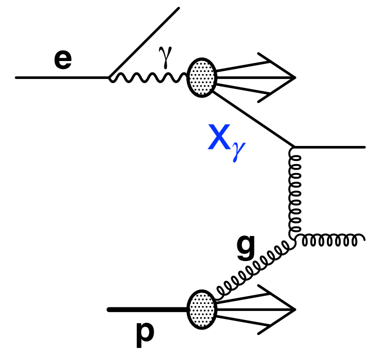
Dijet photoproduction in QCD

• 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 dijet photoproduction:

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

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

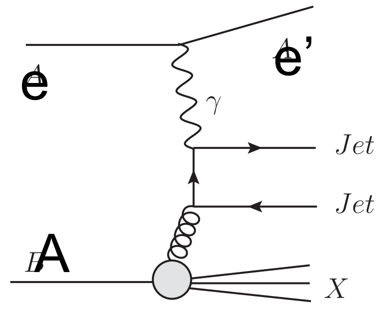
- Access to photon structure, constraints on the gluon PDF of the photon, which are complimentary to those from $F_2^{\gamma}(x,Q^2)$ in e+e-, Nisius, Phys. Rept. 332 (2000) 165.

- At EIC with nuclear targets, one will be able to probe usual and diffractive **nuclear PDFs**

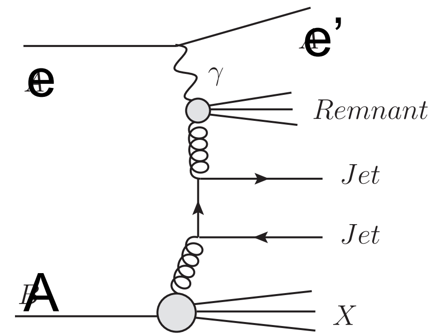
Inclusive dijet photoproduction in NLO pQCD

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

• Typical LO graphs:



direct-photon



resolved-photon

• In framework of collinear factorization of perturbative QCD, the cross section is 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

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

Photon flux in Weizsäcker-Williams approximation

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

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

Proton/ nucleus 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 hadronization corrections from Monte Carlo (LO + parton showers), Helenius, arXiv:1806.07246 and arXiv:1811.10931; Helenius and Rasmusen, EPJC 79 (2019) 413.

Inclusive dijet photoproduction in NLO pQCD(2)

• Numerical implementation using parton-level Monte Carlo developed by Klasen and Kramer, Klasen, Rev. Mod. Phys. 74 (2002) 1221, Klasen, Kramer, Z. Phys. C 72 (1996) 107, Z. Phys. C 76 (1997) 67; EPJC 71 (2011) 1774; Klasen, Kleinwort, Kramer, EPJC direct 1 (1998) 1, 1

• Anti-kT jet cone/clustering algorithm (at most 2 partons in a jet) with radius R=0.4.

• Photon PDFs from stand-alone GRV photon PDFs, Gluck, Reya, PRD 60 (1999) 054019.

• Proton/nucleus PDFs from LHAPDF (nCTEQ15, EPPS16).

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

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

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

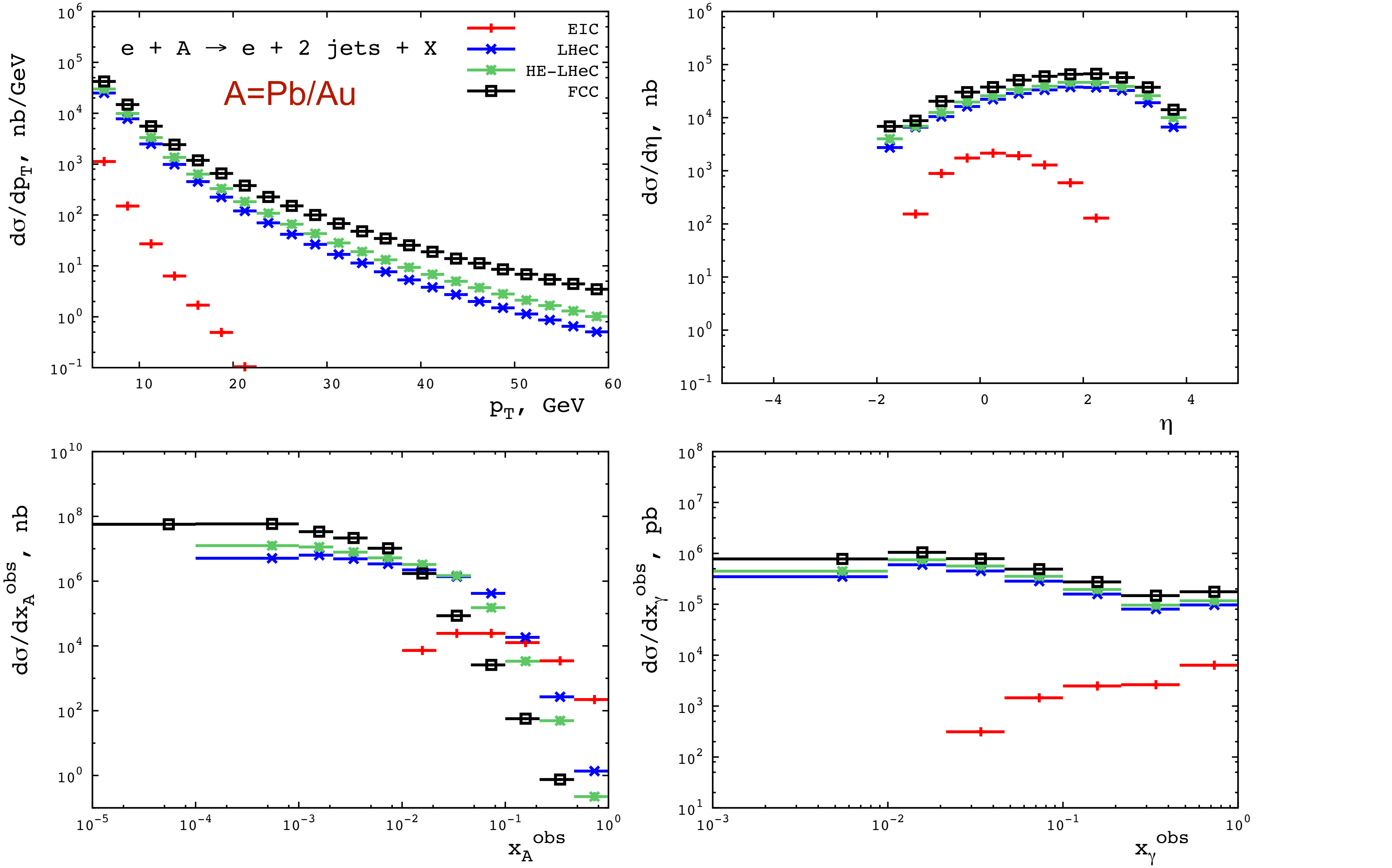
• Assumed p_T > 5 GeV (HERA)

• Studied the energy configurations corresponding to EIC, LHeC, and FCC →

	E_e (GeV)	E_A (TeV)	$\sqrt{s}$ (GeV)
EIC	21	0.1	92
LHeC	60	2.76	812
HE-LHeC	60	4.93	1,088
FCC	60	19.7	2,174

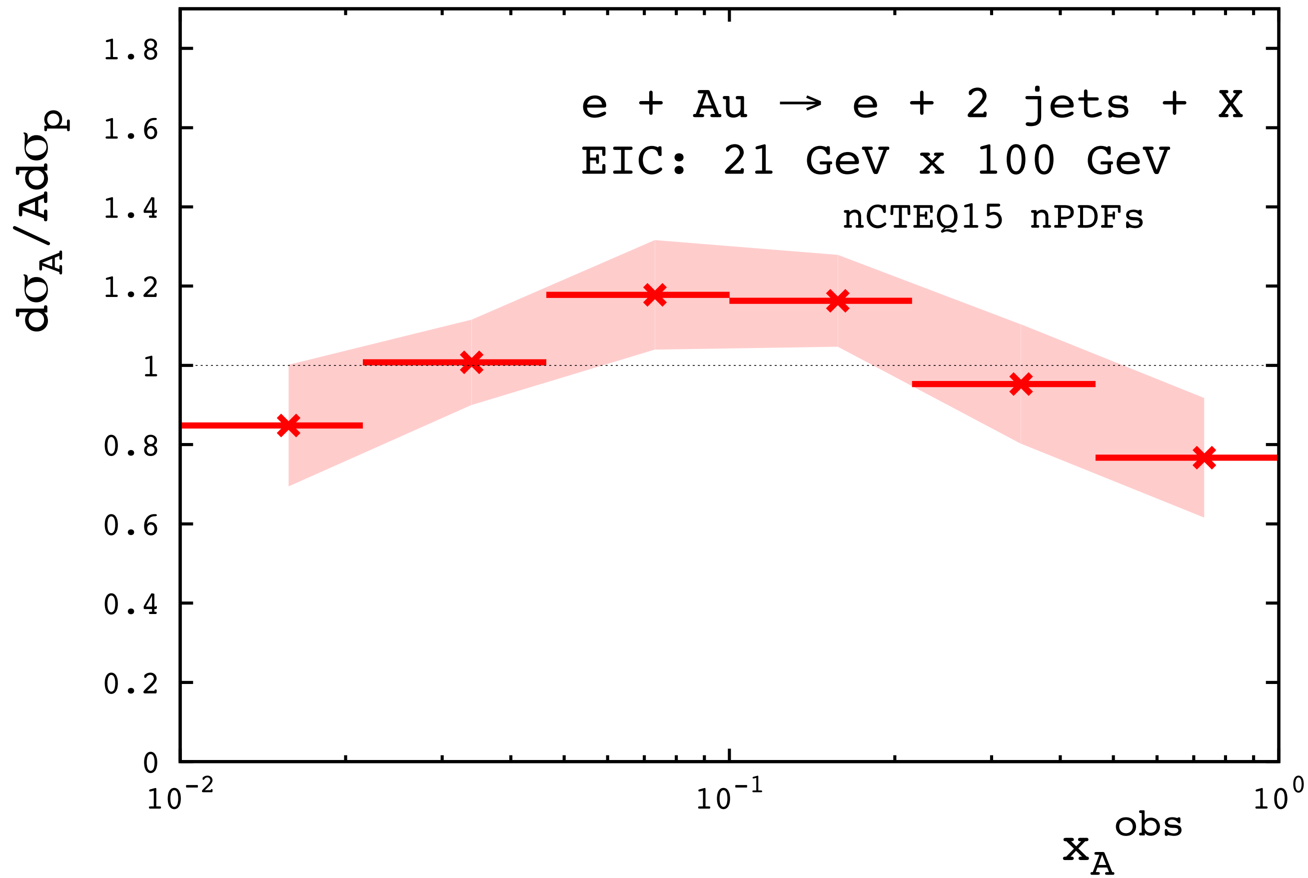
NLO QCD predictions for EIC, LHeC and FCC

- Distributions in dijet average transverse momentum $p_T = (p_{T1}+p_{T2})/2$, average rapidity $\eta = (\eta_1+\eta_2)/2$, and observed parton momentum fractions in the photon and nucleus, x_γ^{obs} and x_A^{obs}



- EIC Kinematic reach: $5 < \bar{p}_T < 20$ GeV, $-2 < \bar{\eta} < 3$, $0.03 < x_\gamma^{obs} < 1$, $0.01 < x_A^{obs} < 1$
- Kinematic coverage dramatically expands for LHeC, HE-LHeC, and FCC.

Nuclear modifications of dijet cross section



- Ratio of the dijet cross sections on a nucleus and proton exhibits x_A dependence similar to that of the ratio of the gluon distributions $g_A(x,\mu^2)/[Ag_p(x,\mu^2)]$ with 10-20% nuclear modifications.

- Similar behavior with nCTEQ15 and EPPS16 nPDFs.

- Statistical uncertainty of these measurements at EIC is expected to be 1-2% → this process can be used to reduce uncertainties of nPDFs (shown by red band).

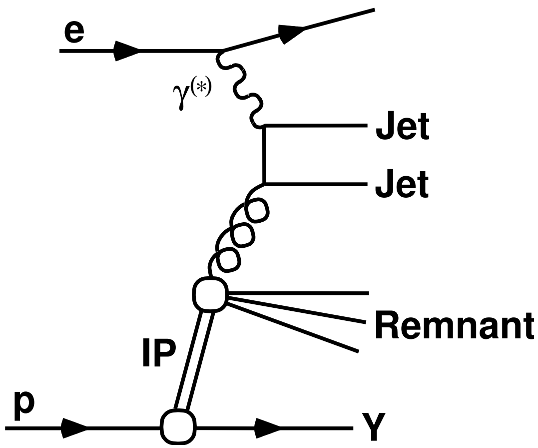
- Note that the ATLAS UPC data reaches down to x_A ~0.005.

Diffractive dijet photoproduction in NLO QCD

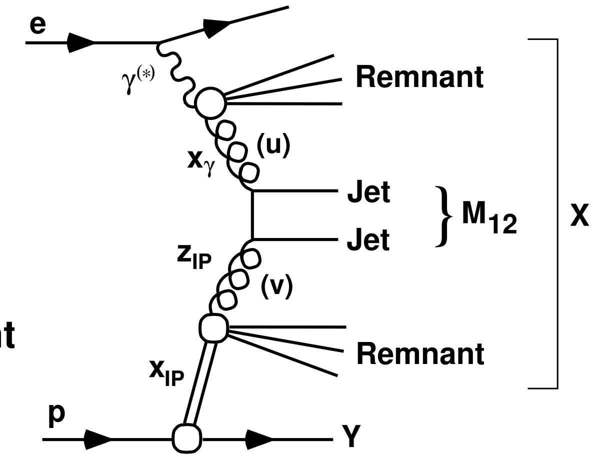
- At HERA, diffraction makes up 10-15% of the total DIS cross section, Newman, Wing, Rev. Mod. Phys. 86 (2014) 1037 (2014) → expected to be significant also at EIC.

- Diffractive dijet photoproduction:

  Characterized by large rapidity gap between the forward proton (excitation Y) and the rest of hadronic activity X.



direct-photon



resolved-photon

- Similarly to inclusive case, cross section is known to NLO accuracy Klasen, Kramer, Salesch, Z. Phys. C 68, 113 (1995); Klasen, Kramer, Z. Phys. C 72, 107 (1996), Z. Phys. C 76, 67 (1997); Klasen, Rev. Mod. Phys. 74, 1221 (2002)

$$d\sigma = \sum_{a,b} \int dy \int dx_\gamma \int dt \int dx_{I\!P} \int dz_{I\!P} f_{\gamma/e}(y) f_{a/\gamma}(x_\gamma, M_\gamma^2) f_{I\!P/p}(x_{I\!P}, t) f_{b/I\!P}(z_{I\!P}, M_{I\!P}^2) d\hat{\sigma}_{ab}^{(n)}$$

Photon flux in Weizsäcker-Williams approximation

Photon PDFs for resolved photon;
in a=γ case, $f_{a/\gamma}=\delta(1-x_\gamma)$

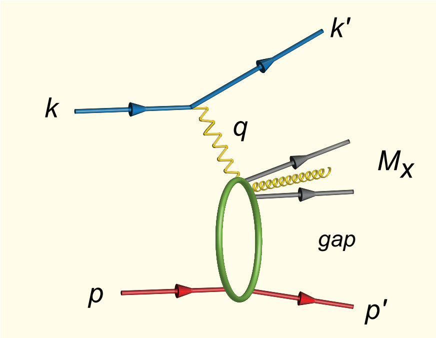
“Pomeron” flux motivated by Regge theory:

$$f_{I\!P/p}(x_{I\!P}, t) = A_{I\!P} \cdot \frac{e^{B_{I\!P} t}}{x_{I\!P}^{2\alpha_{I\!P}(t)-1}};$$

Diffractive PDFs from HERA

hard partonic cross section

Diffractive dijet photoproduction in NLO QCD(2)



- QCD factorization theorem for diffraction, Collins, PRD 57, 3051 (1998); PRD 61, 019902 (2000) → universal diffractive parton distributions.

- Have been extracted from HERA data using global QCD fits, Aktas at al. [H1 Coll.], EPJ C48, 715 (2006) and EPJC 48, 749 (2006); Chekanov at al. [ZEUS Coll.], NPB 831, 1 (2010)

- Universality has been successfully tested in diffractive dijet and open charm product in DIS, Aktas at al. [H1 Coll.], JHEP 10, 042 (2007); EPJ C 71, 549 (2010); EPJ C 50, 1 (2007); Chekanov et al. [ZEUS Coll.], EPJ C 52, 813 (2007); Chekanov at al. [ZEUS Coll.], NPB 831, 1 (2010)

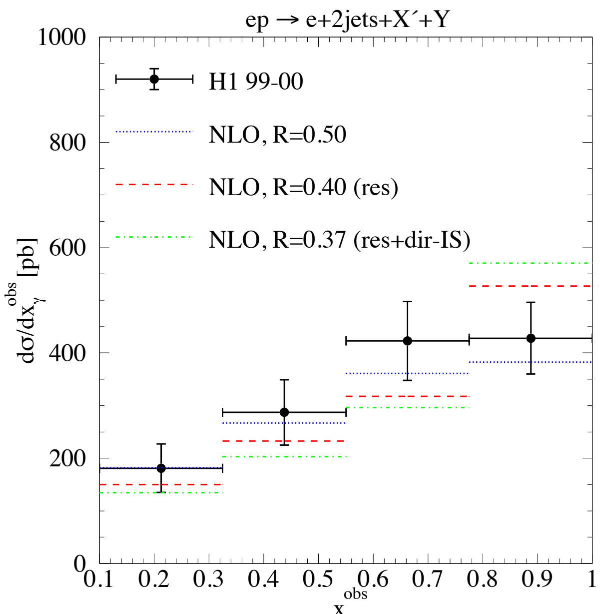
- At the same time, NLO pQCD QCD overestimates cross sections of diffractive dijet photoproduction at HERA by **factor 2**→ factorization breaking, Aktas at al. [H1 Coll.], EPJ C 71, 549 (2007); Aaron et al. [H1 Coll.], EPJ C 70, 15 (2010); Andreev et al. [H1 Coll.], JHEP 05, 056 (2015); Chekanov at al. [ZEUS Coll.], EPJ C 55, 177 (2008).

- Mechanism of factorization breaking remains unknown:

- global suppression factor R ≈ 0.5

- suppression of only the resolved photon contribution by R ≈ 0.34 as expected in hadron-hadron scattering, Kaidalov, Khoze, Martin, Ryskin, PLB 567, 61 (2003); Klasen, Kramer, EPJ C 70, 91 (2010),

- a flavor-dependent combination of these mechanisms, Guzey, Klasen, EPJ C 76, 467 (2016)



Diffractive dijet photoproduction in NLO QCD at EIC

- Cross section as a function of the average transverse momentum $\overline{p_T} = (p_{T1}+p_{T2})/2$, proton momentum fraction loss x_P, parton momentum fractions in the photon and Pomeron in terms of their observed hadronic estimators:

$$x_\gamma^{\rm obs} = \frac{p_{T1}\, e^{-\eta_1} + p_{T2}\, e^{-\eta_2}}{2yE_e} \quad \text{and} \quad z_{I\!P}^{\rm obs} = \frac{p_{T1}\, e^{\eta_1} + p_{T2}\, e^{\eta_2}}{2x_{I\!P}E_p}$$

- Jets using the anti-k_T formalism with distance parameter R=1.

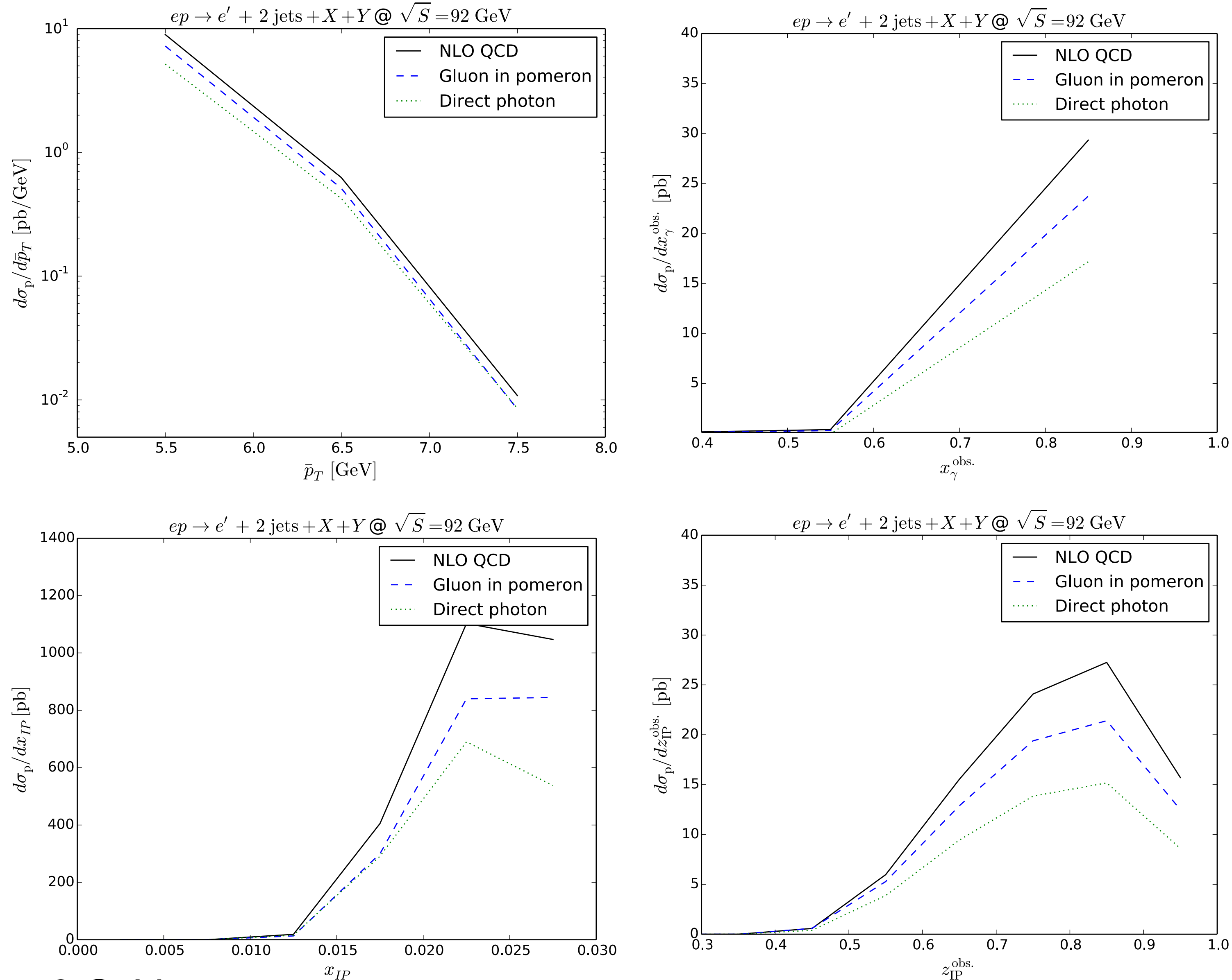
- Using HERA experience, assume $p_{T1} > 5$ GeV and $p_{T2} > 4.5$ GeV → will require good resolution of hadronic jet energy and subtraction of underlying event to avoid large hadronization corrections.

- Generic cuts: $0 < y < 1$, $Q^2 < 0.1$ GeV^2, $|t| < 1$ GeV^2, $M_Y < 1.6$ GeV and $-4 < \eta_{1,2} < 4$.

- Two scenarios: default with $x_P < 0.03$ (Pomeron) and extended with $x_P < 0.1$ (Pomeron+Reggeon) to access sub-leading Reggeon contribution.

- The base configuration is **Ee=21 GeV** and **Ep=100 GeV** ($\sqrt{s} \sim 92$ GeV). To extend the kinematic coverage and study factorization breaking, we also used Ee=18 GeV and Ep=275 GeV ($\sqrt{s} \sim 141$ GeV).

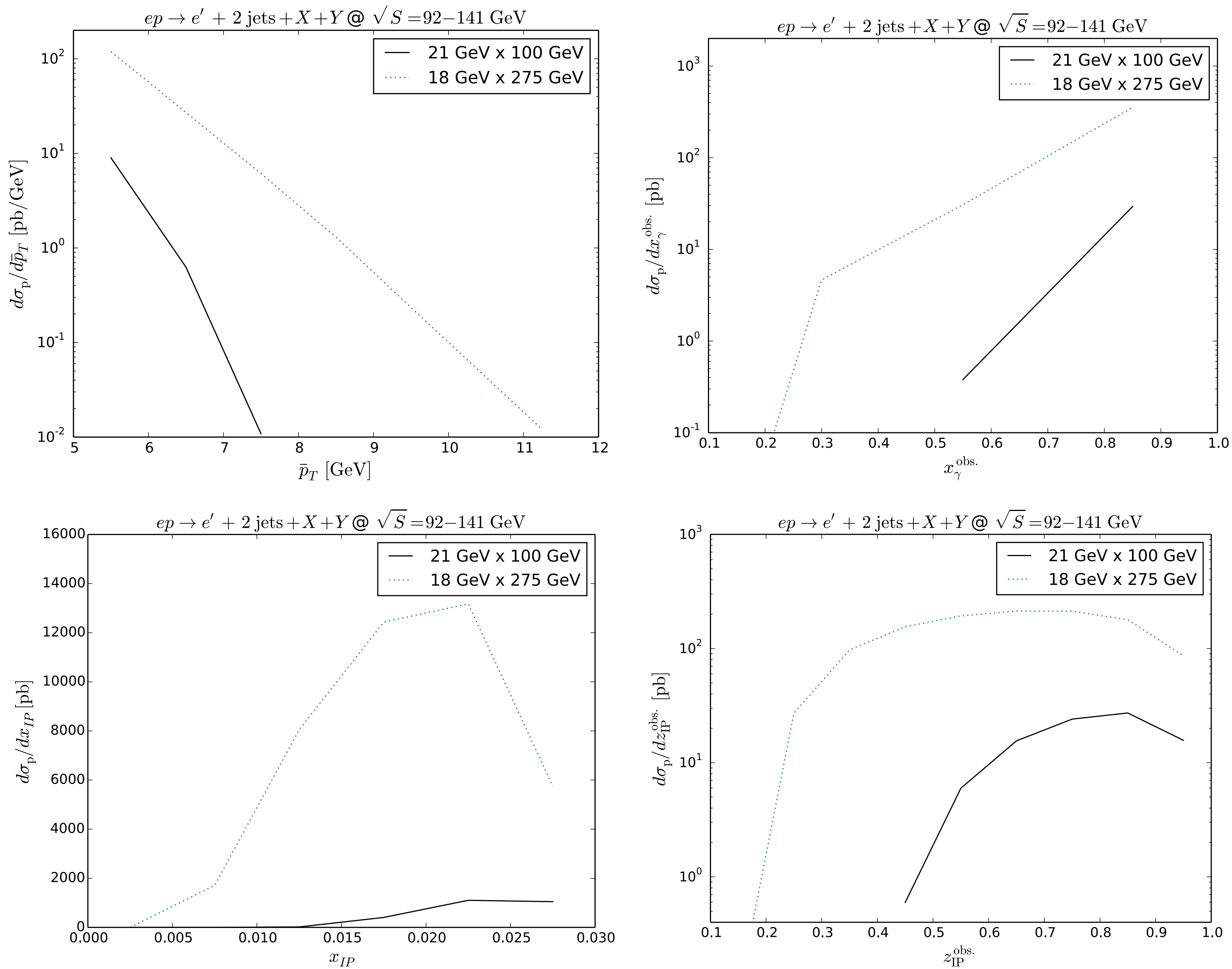
NLO QCD predictions for EIC: √s=92 GeV



- <u>Main features:</u>

- $\overline{p_T}$ coverage up to 8 GeV
- dominated by direct photon contribution and large $x_\gamma > 0.5$ → challenging to address factorization breaking
- dominated by large x_P and z_P → probes mostly diffractive gluon density.

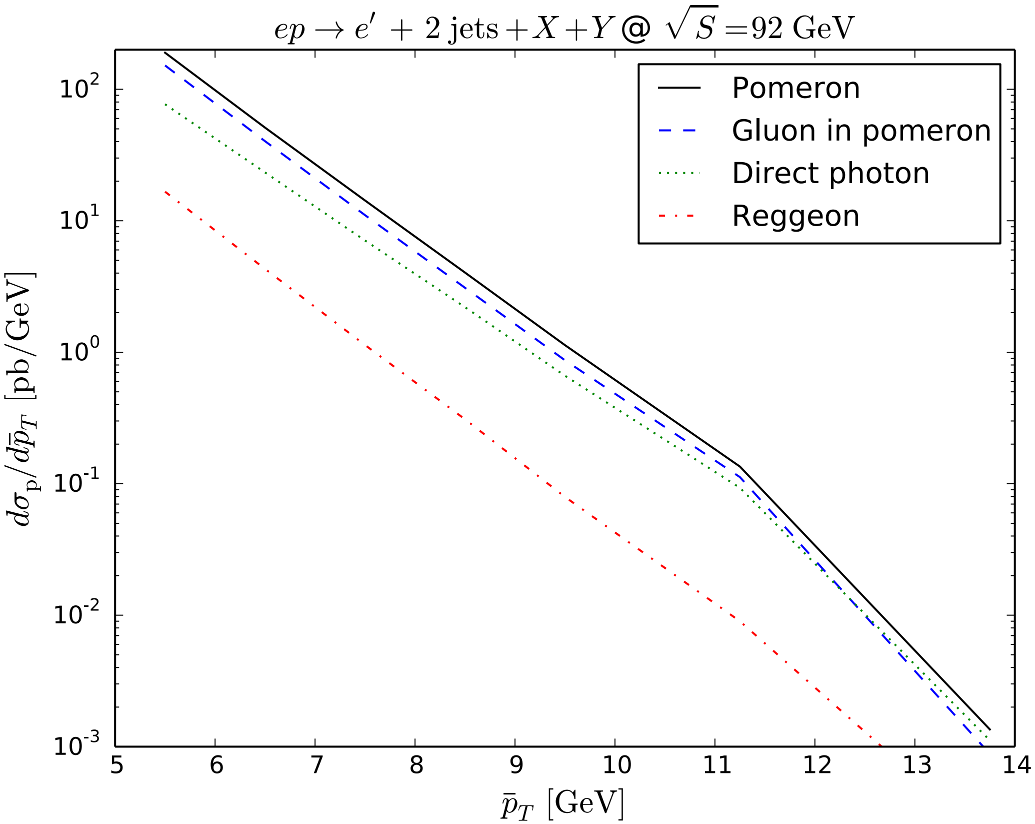
NLO QCD predictions for EIC: √s=92 vs 141 GeV

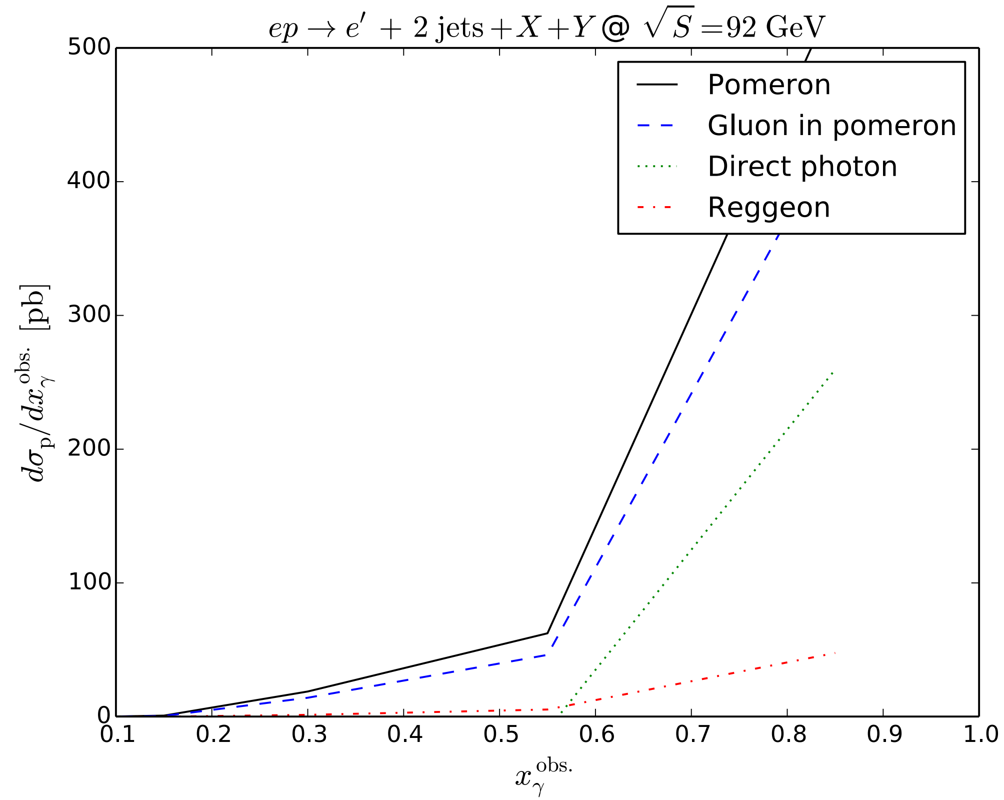


- <u>Main features:</u>

- p_T coverage up to 12 GeV
- extended coverage in other variables: $0.2 < x_\gamma < 1$, $0.2 < z_P < 1$
- cross section now larger by 1-2 orders of magnitude → increased statistics and precision!

NLO QCD predictions for EIC: extended $x_{I\!P} < 0.1$



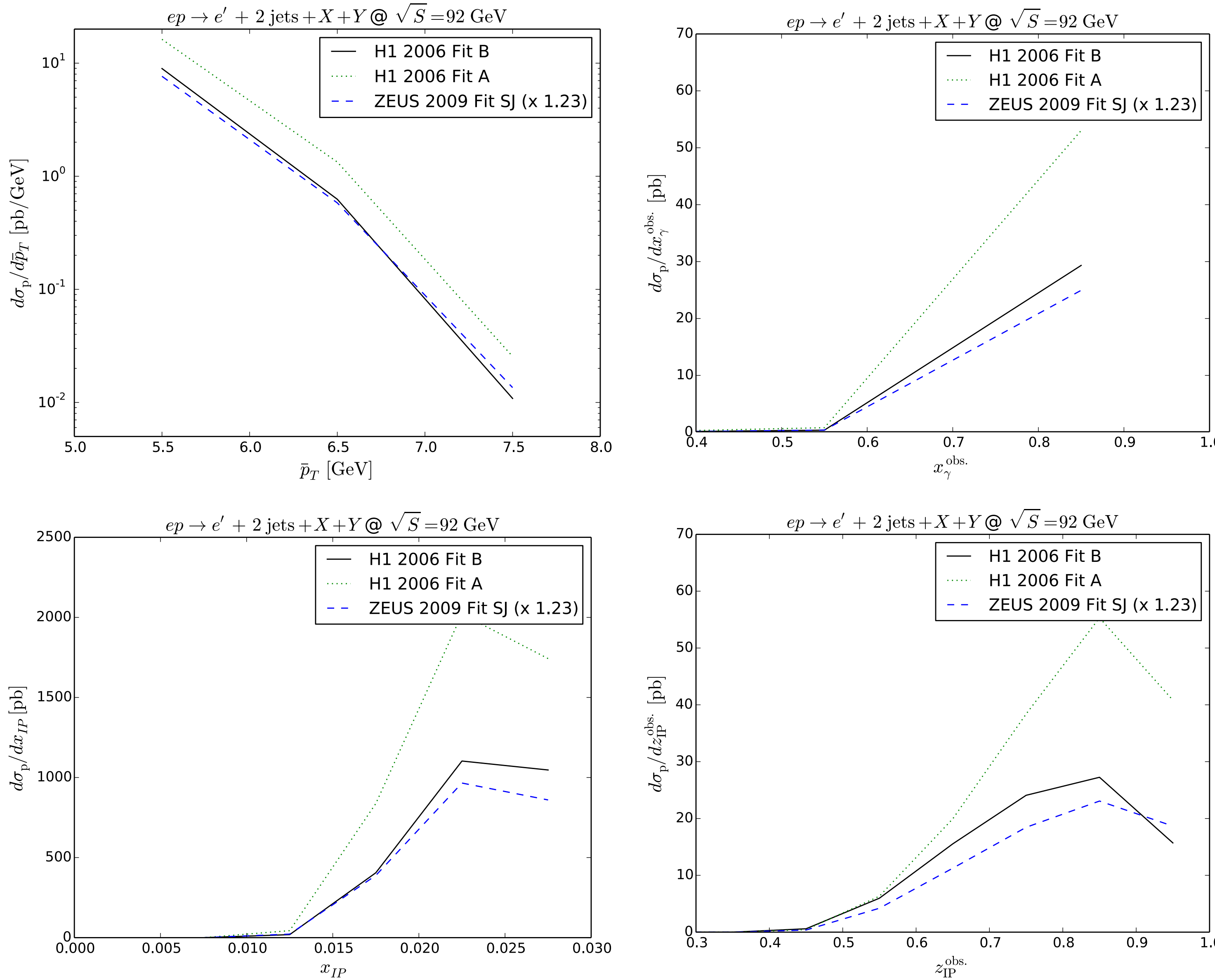


- <u>Main features:</u>

- p_T coverage is now up to 14 GeV → more advantageous than increasing √s !
- photon momentum fraction down to $x_\gamma > 0.1$ → resolved photon also contributes
- 10-35% contribution of sub-leading Reggeon trajectory for $x_{I\!P} > 0.06$.

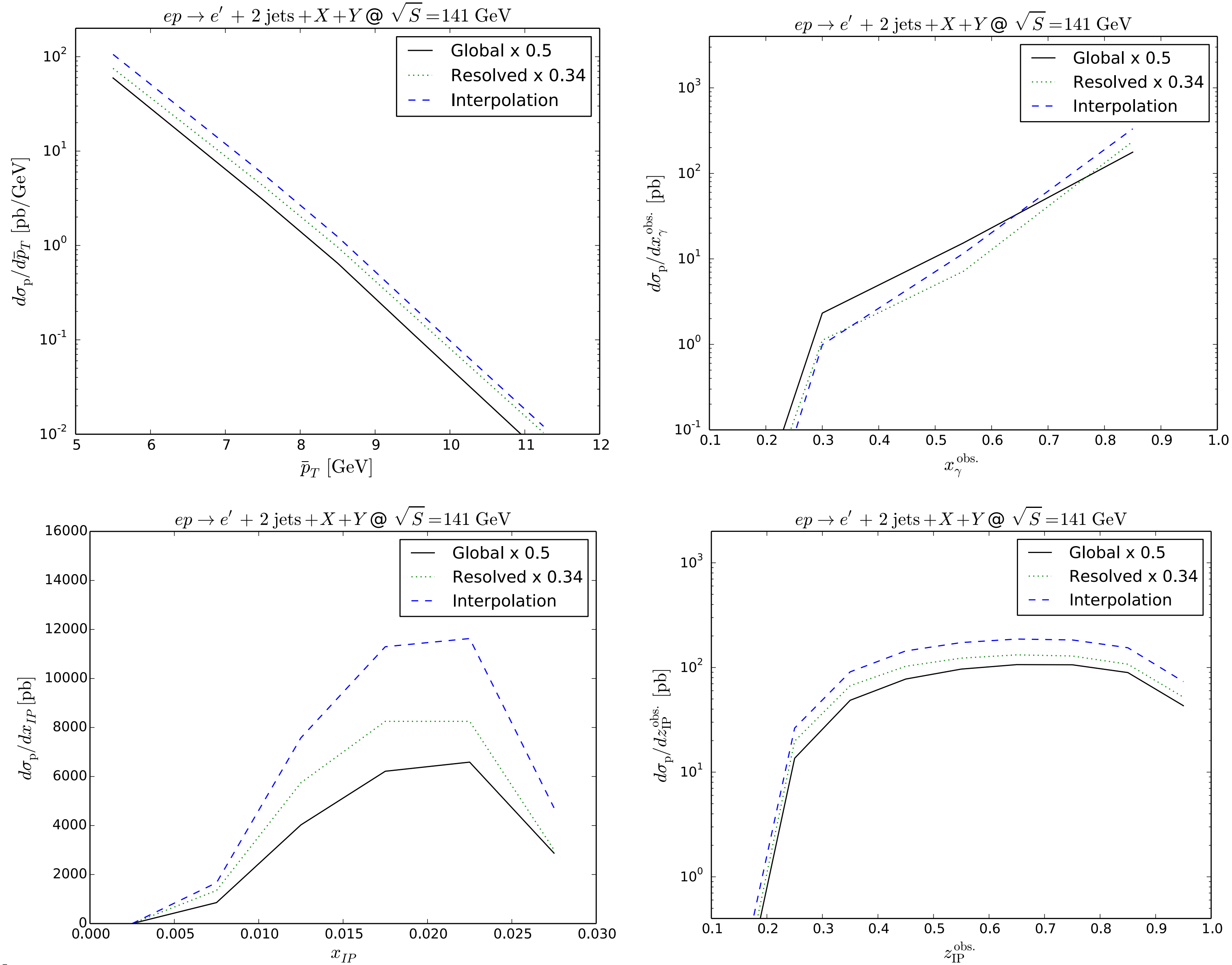
$$f_{i/p}^{D}(x, Q^2, x_{I\!P}, t) = f_{I\!P/p}(x_{I\!P}, t) \cdot f_{i/I\!P}(z_{I\!P}, Q^2) \; + \; n_{I\!R} \cdot f_{I\!R/p}(x_{I\!P}, t) \cdot f_{i/I\!R}(z_{I\!P}, Q^2)$$

QCD predictions for EIC: dependence on diffractive PDFs



- H1 Fit B and ZEUS SJ give similar predictions.
- Fit A predicts larger cross section due to larger diffractive gluon density at large z_P.

QCD predictions for EIC: factorization breaking



- <u>Main features:</u>

- Most promising observable is x_γ dependence → need wide coverage and high precision since the cross section drops.
- The rest of distributions differ mostly in normalization.

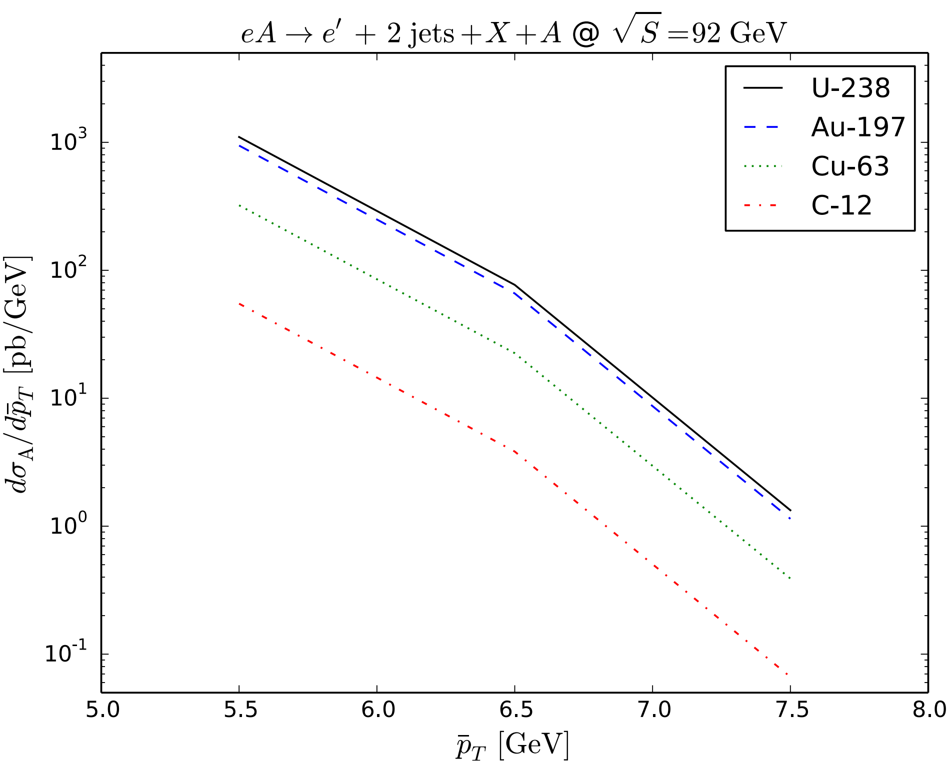
NLO QCD predictions for diffractive dijet photoproduction on nuclei at EIC

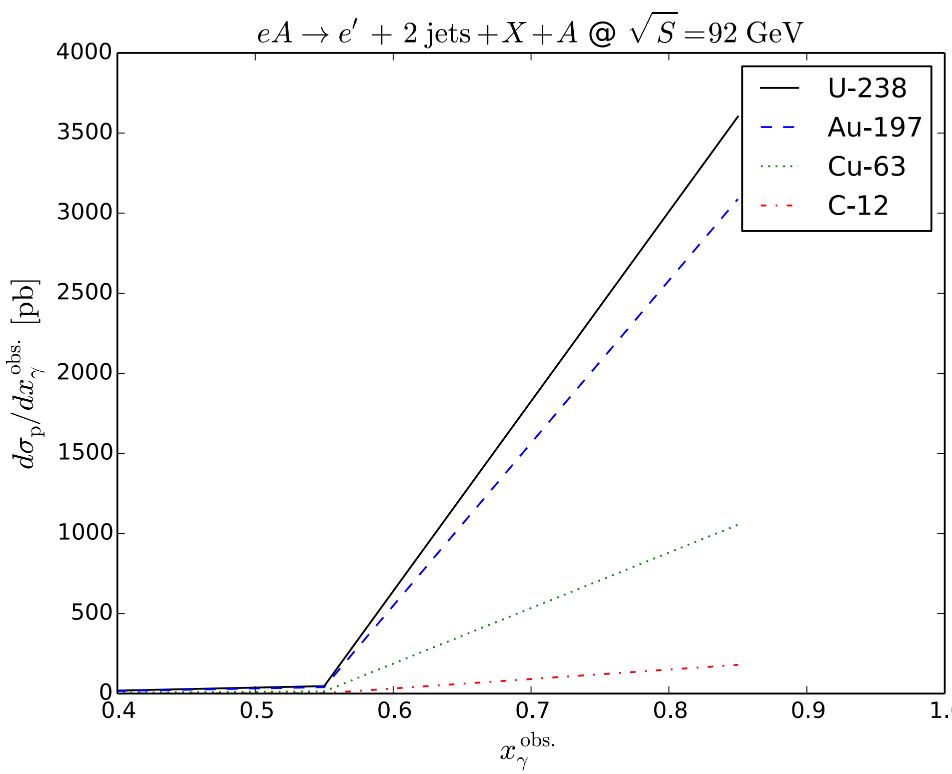
- For nuclear diffractive PDFs, used leading twist model of nuclear shadowing, Frankfurt, Guzey, Strikman, Phys Rep 512 (2012) 255

$$f_{i/A}^{D}(z_{I\!P},Q^2,x_{I\!P}) \approx 16\pi B_{\rm diff} f_{i/p}^{D}(z_{I\!P},Q^2,x_{I\!P}) \int d^2\vec{b} \left| \frac{1-e^{-\frac{A}{2}(1-i\eta)\sigma_{\rm soft}^{i}(x,Q^2)T_A(b)}}{(1-i\eta)\sigma_{\rm soft}^{i}(x,Q^2)} \right|^2 .$$

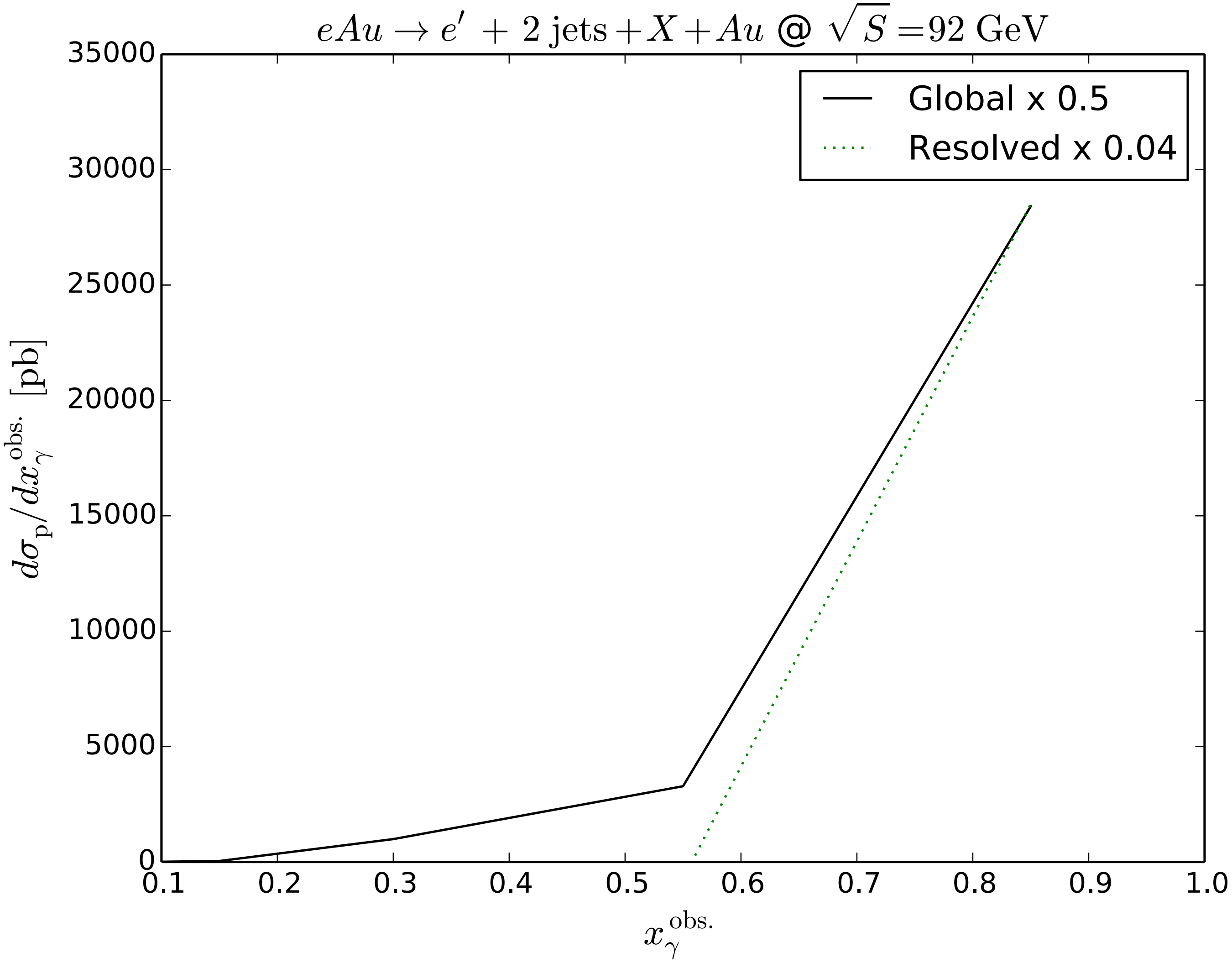
- Characterized by strong suppression of nuclear diffractive PDFs by factor R=0.65.

$$f_{i/A}^{D}(z_{I\!P},Q^2,x_{I\!P}) \approx AR(x,A) f_{i/p}^{D}(z_{I\!P},Q^2,x_{I\!P})$$





Diffractive dijet photoproduction on nuclei at EIC: factorization breaking



- x_γ dependence has the potential to distinguish between two used schemes of factorization breaking.

Summary

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

• Inclusive and diffractive dijet photoproduction at EIC is complimentary to inclusive and diffractive DIS@EIC and can help constrain proton and nucleus usual and diffractive PDFs.

• At EIC, the diffractive dijet photoproduction cross section is dominated by the direct photon contribution and gluon diffractive PDF.

• This process can help to solve the problem of the mechanism/pattern of factorization breaking in diffractive DIS: global suppression vs. resolved-only.

• For this, the most promising observable is x_γ dependence. To have wide coverage in x_γ, one needs the highest Ep and/or large range in x_P with an account with the sub-leading Reggeon contribution.

• Inclusive dijet photoproduction in Pb-Pb UPCs has been measured at the LHC: our NLO pQCD predictions describe well the preliminary ATLAS data, Guzey, Klasen, PRC 99 (2019) 6, 065202