Diffractive PDFs

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Based on Frankfurt, Guzey, Stasto, Strikman, “Selected topics in diffraction with protons and nuclei: past, present, and future”, Rep. Prog. Phys. 85 (2022) 126301 [2203.12289 [hep-ph]]

Outline:

- Collinear factorization and diffractive PDFs
- Diffractive PDFs from global fits
- Diffractive dijet photoproduction at HERA and factorization breaking
- Nuclear diffractive PDFs in eA diffractive DIS
- Outlook and summary

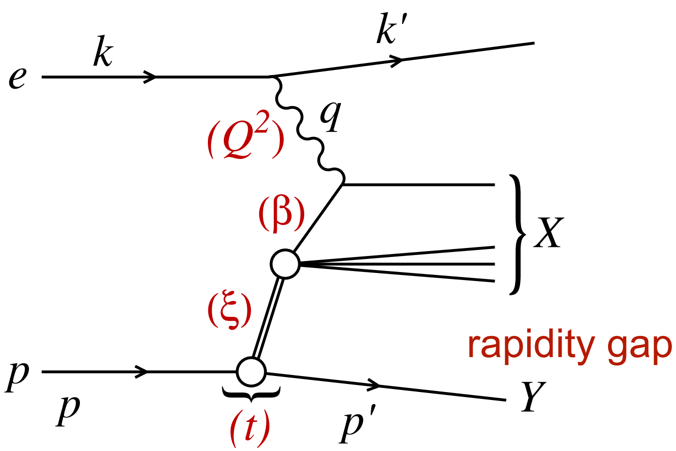
Diffraction in ep DIS at HERA

• Diffractive scattering at high energies → target intact and rapidity gap, i.e., large region in a detector with no activity.

• Present in both soft [elastic pp scattering] and hard [ep deep inelastic scattering (DIS)] processes.

• Challenging in QCD due to enhanced HT/non-linear effects.

• Classic and most studied example: diffraction in ep DIS at HERA → one of main HERA results that diffraction ~10-15% of total DIS cross section.



Standard DIS variables:

$$q^2 = -Q^2, \qquad x = \frac{Q^2}{2p\cdot q}, \qquad W^2 = (p+q)^2, \qquad y = \frac{p\cdot q}{p\cdot k},$$

Additional diffraction-specific variables:

$$t = (p-p')^2, \qquad \xi = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}, \qquad \beta = \frac{Q^2}{Q^2 + M_X^2 - t},$$

• Reduced DIS cross section in terms of diffractive structure functions:

$$\sigma_{\rm red}^{\rm D(4)} = F_2^{\rm D(4)}(\beta,\xi,Q^2,t) - \frac{y^2}{Y_+} F_{\rm L}^{\rm D(4)}(\beta,\xi,Q^2,t)$$

$$Y_+ = 1 + (1-y)^2$$

Collinear factorization in diffractive DIS

• Similarly to inclusive DIS → collinear factorization for diffractive DIS, Collins, PRD 57 (1998) 3051, PRD 61 (2000) 019902 (erratum).

• Diffractive cross section given by convolution of coefficient functions (same as in inclusive case) with diffractive parton distributions (PDFs):

$$F_{2/L}^{D(4)}(\beta,\xi,Q^2,t)=\sum_i\int_\beta^1\frac{dz}{z}C_{2/L,i}(\beta/z,Q^2)f_i^D(z,\xi,Q^2,t)$$

• Similarly to inclusive case, operator definition for diffractive PDFs:

$$f_i^D(z,\xi,Q^2,t)=\frac{1}{4\pi}\frac{1}{2}\sum_s\int dy^-e^{-izp^+y^-}\sum_{X,s'}\langle p,s|\bar{\psi}(0,y^-,\mathbf{0}_T)|p',s';X\rangle\gamma^+\langle p',s';X|\psi(0)|p,s\rangle$$

• Diffractive PDFs = conditional probabilities of finding partons in the proton, provided that it scatters into the final system Y with momentum p'.

• Similarly to inclusive case, diffractive PDF are universal (probed in inclusive diffraction, diffractive jet production, etc.) and obey Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations at fixed ξ and t.

Diffractive PDFs from global fits

• Diffractive PDFs given by long-distance matrix elements → non-perturbative and need to be extracted from data using global QCD fits.

• Depend on 4 kinematic variables, c.f. usual PDFs → need simplifications.

• Proton vertex (Regge) factorization, Ingelman, Schlein, PLB 152 (1985) 256, for the leading Pomeron and sub-leading ($\xi \geq 0.03$) Reggeon contributions:

$$f_i^D(z,\xi,Q^2,t) = f_{I\!P}(\xi,t) f_i^{I\!P}(z,Q^2) + f_{I\!R}(\xi,t) f_i^{I\!R}(z,Q^2)$$

• The fluxes motivated by Regge theory:

$$f^p_{\mathbb{P},\mathbb{R}}(\xi,t) = A_{\mathbb{P},\mathbb{R}} \frac{\mathrm{e}^{B_{\mathbb{P},\mathbb{R}} t}}{\xi^{2\alpha_{\mathbb{P},\mathbb{R}}(t)-1}}, \qquad \alpha_{\mathbb{P},\mathbb{R}}(t) = \alpha_{\mathbb{P},\mathbb{R}}(0) + \alpha'_{\mathbb{P},\mathbb{R}}$$

• Simple form for sea quark (valence =0) and gluon PDFs of the Pomeron:

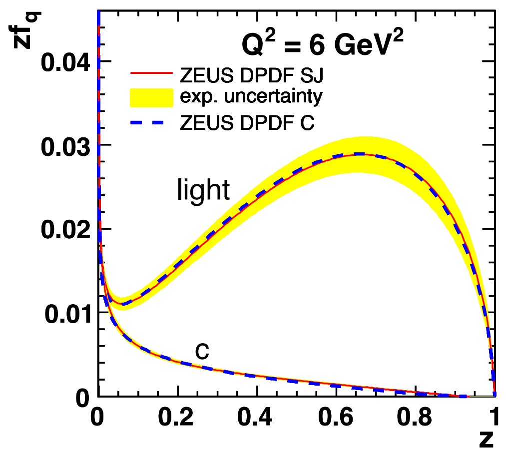
$$z f_i^{\mathbb{P}}(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i}$$

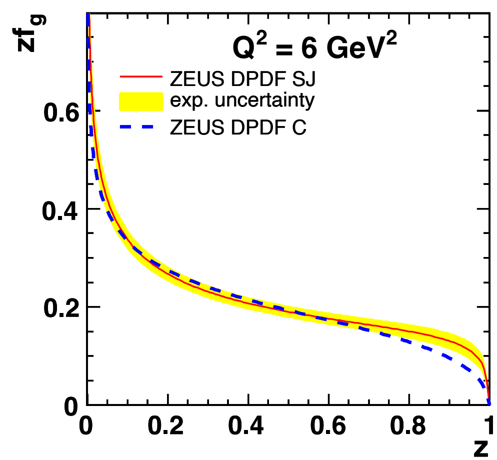
• $f_u^{I\!P} = f_d^{I\!P} = f_s^{I\!P}$, and massless heavy flavors in the variable flavor scheme generated through DGLAP evolution.

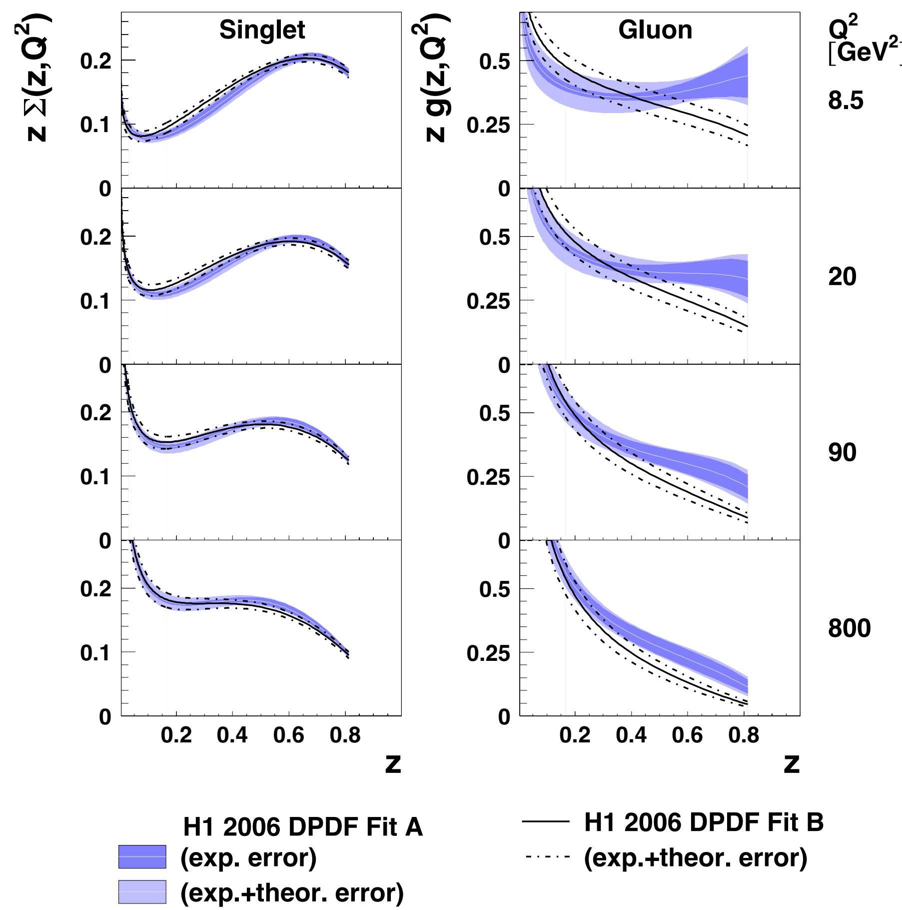
• Reggeon $f_i^{I\!R}$ taken from pion PDFs → can be better constrained at EIC, Armesto, Newman, Slominski, Stasto, PRD 110 (2024) 5, 054039.

Diffractive PDFs from global fits (2)

• Most notable examples are ZEUS and H1 analyses of their own data, Chekanov et al, NPB 831 (2010) 1; Aktas et al, EPJC 48 (2006) 715.



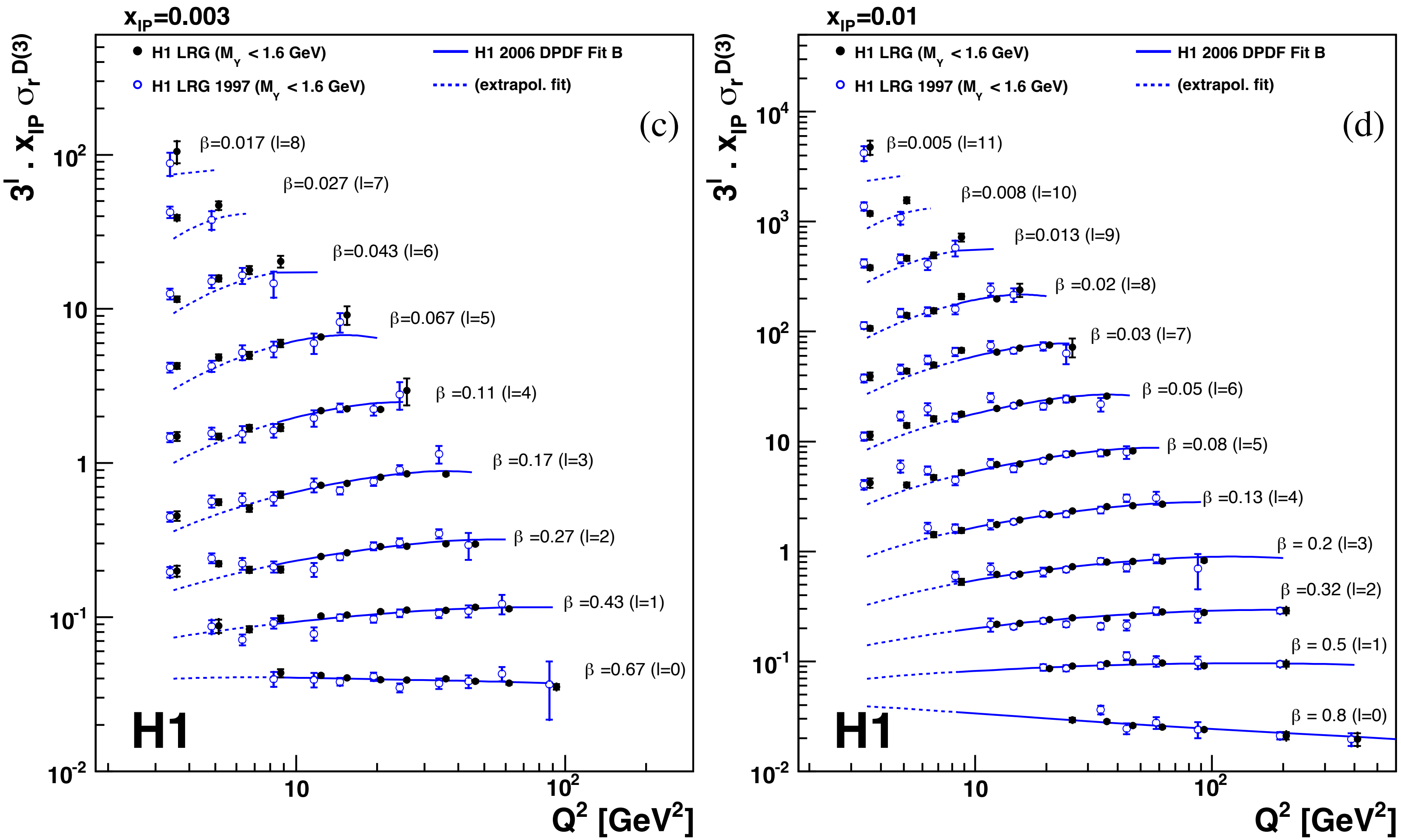




• Diffractive gluon PDF >> quark PDFs, but poorly constrained at large z → need to include data on diffractive dijets → favor ZEUS C and H1 B fits.

Diffractive PDFs from global fits (3)

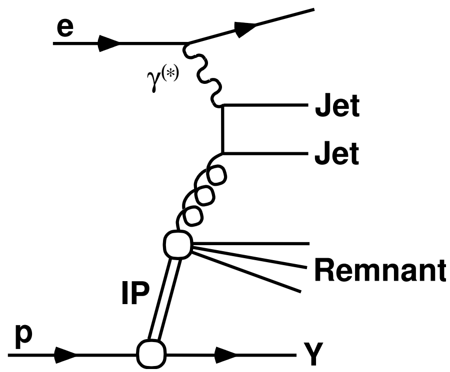
- Good description of original and more recent H1 data, Aaron et al, EPJC 72 (2012) 2074



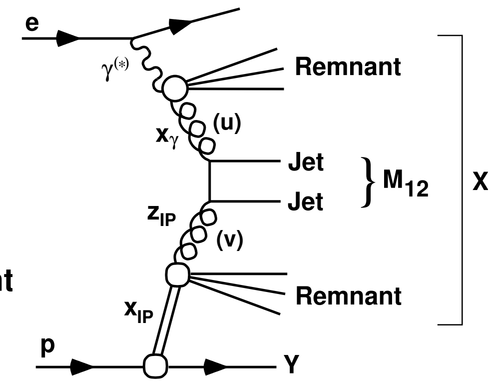
- Comparison of LRG with proton-tagged cross section measurement → **~20%** contribution of proton dissociation.

Diffractive dijet photoproduction

- Collinear fact: same diffractive PDFs for pQCD description of various processes.
- Diffractive dijet electro- and photoproduction in ep scattering → constraints on gluon distribution.



direct-photon



resolved-photon

- 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)

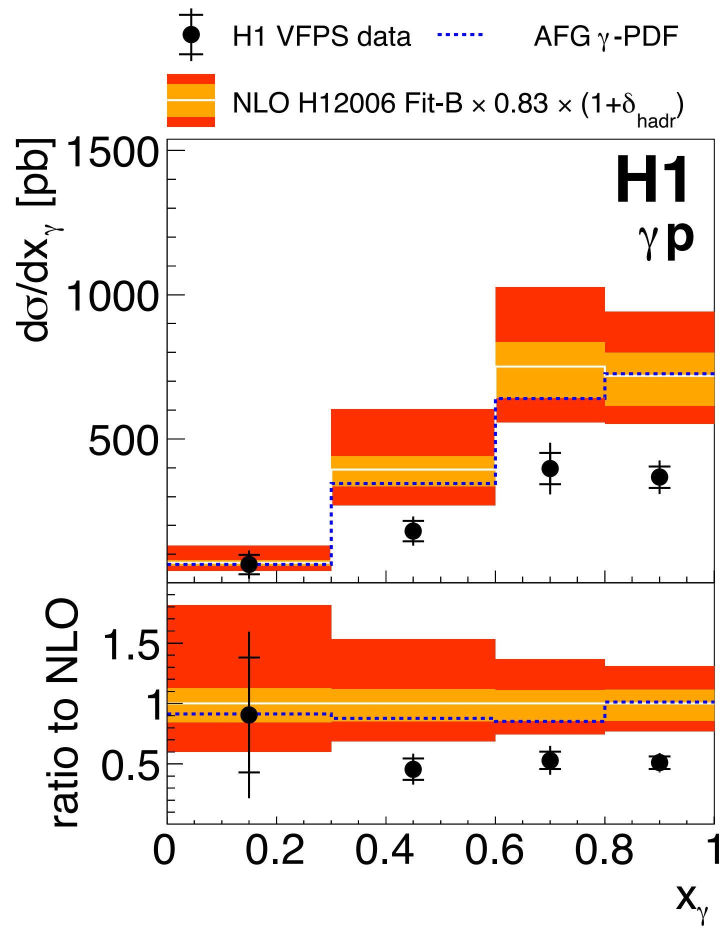
$$d\sigma = \sum_{a,b} \int dy \int dx_\gamma \int dt \int dx_{I\!P} \int dz_{I\!P} f_{\gamma/e}(y) f_{a/\gamma}(x_\gamma, M_\gamma^2) f_{I\!P/p}(x_{I\!P}, t) f_{b/I\!P}(z_{I\!P}, M_{I\!P}^2) d\hat{\sigma}_{ab}^{(n)}$$

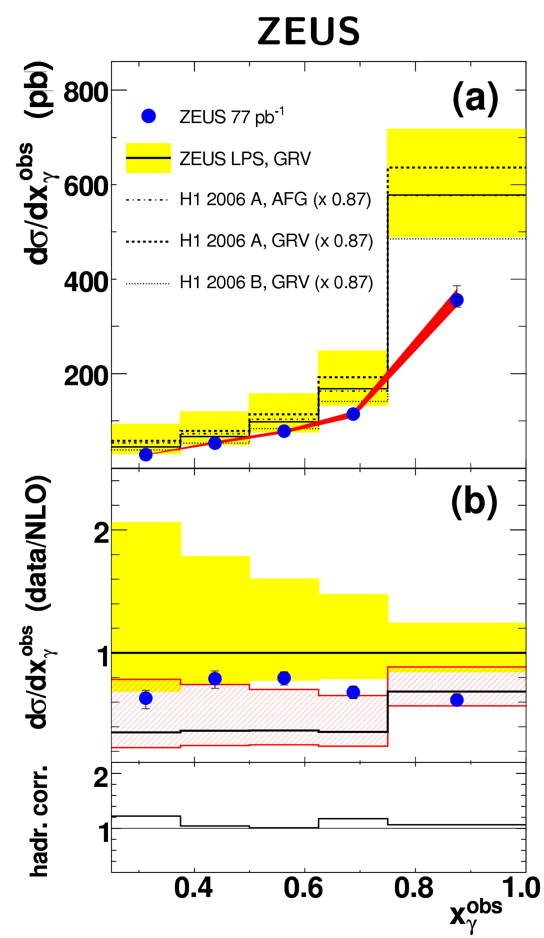
- $f_{\gamma/e}(y)$: Photon flux in Weizsäcker-Williams approximation
- $f_{a/\gamma}(x_\gamma, M_\gamma^2)$: Photon PDFs for resolved photon; in a=γ case, $f_{a/\gamma}=\delta(1-x_\gamma)$
- $f_{I\!P/p}(x_{I\!P}, t)$: "Pomeron" flux
- $f_{b/I\!P}(z_{I\!P}, M_{I\!P}^2)$: Diffractive PDFs
- $d\hat{\sigma}_{ab}^{(n)}$: Hard partonic cross section

Diffractive dijet photoproduction (2)

• Universality of diffractive PDFs 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).





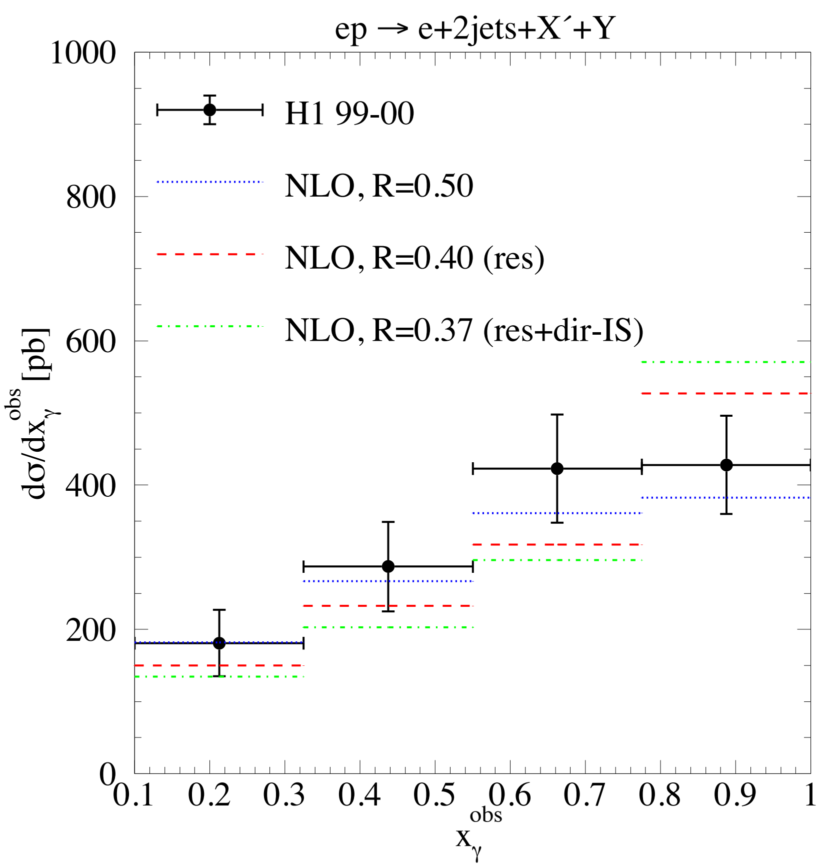
Factorization breaking

- Mechanism of this factorization breaking remains unknown:

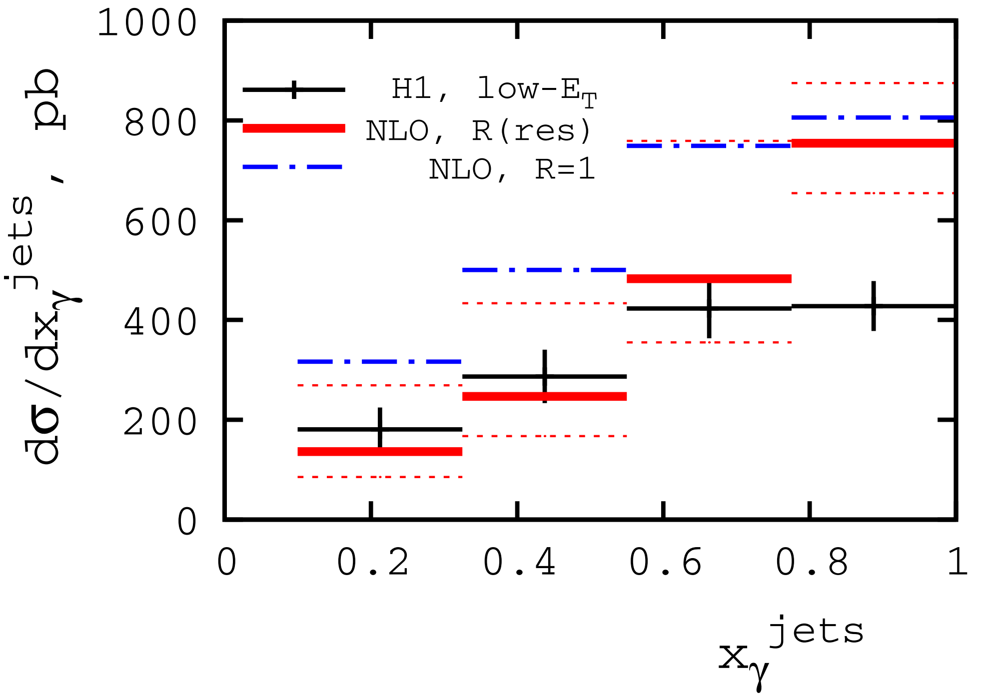
- global suppression factor R ≈ 0.5

- suppression of only 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)

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



$$S_i^2(x_\gamma) \to \begin{cases} 1, & i = c, \\ A_q\, x_\gamma + 0.34, & i = u, d, s, \\ A_g\, x_\gamma + 0.34, & i = g, \end{cases}$$

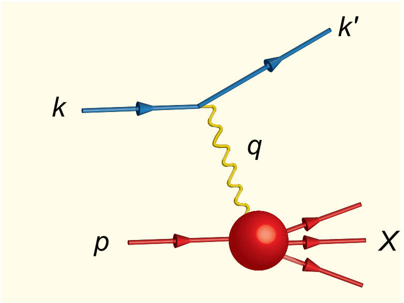


Diffraction in DIS on nuclei

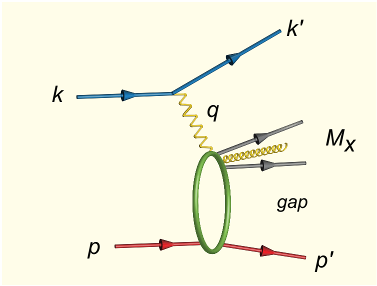
- Never been measured at HERA, but will be at the Electron-Ion Collider (EIC).

- Besides accessing nuclear diffractive PDFs for the first time, enhanced sensitivity to non-linear effects, e.g., gluon saturation in heavy nuclei.

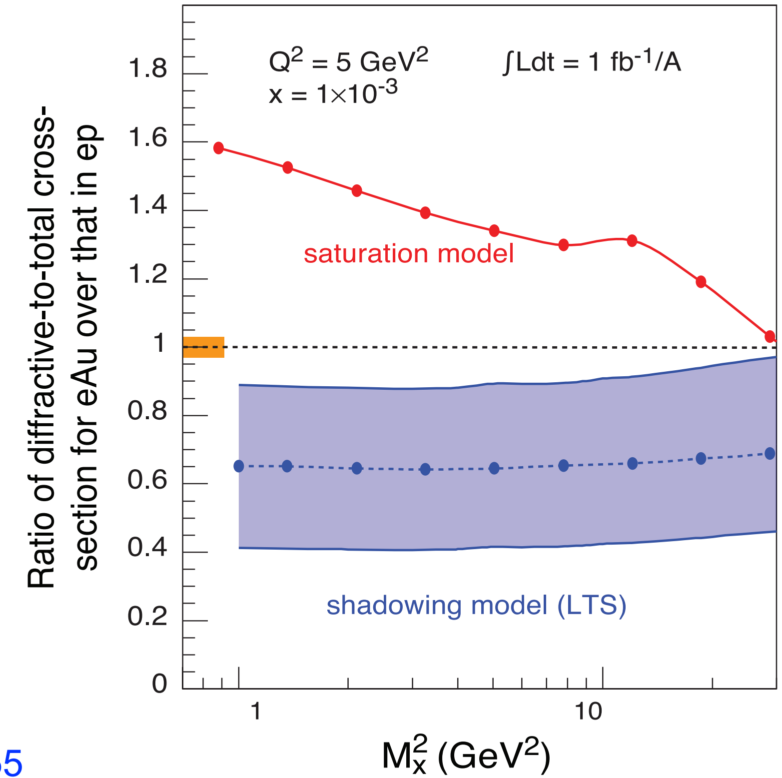
- Sensitive observable is the ratio of diffractive to total DIS cross sections for a heavy nucleus and the proton, Accardi et al., EPJ A52 (2016) 9, 268 [1212.1701 [hep-ex]]:



Total DIS



Diffractive DIS



- Predicted to be:
  - $R_{\text{diff/tot}} > 1$ due to nuclear enhancement of saturation scale $Q^2_{s,A}$, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303; Lappi, Le, Mäntysaari, PRD 108 (2023 114023
  - $R_{\text{diff/tot}} < 1$ due to strong leading twist nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

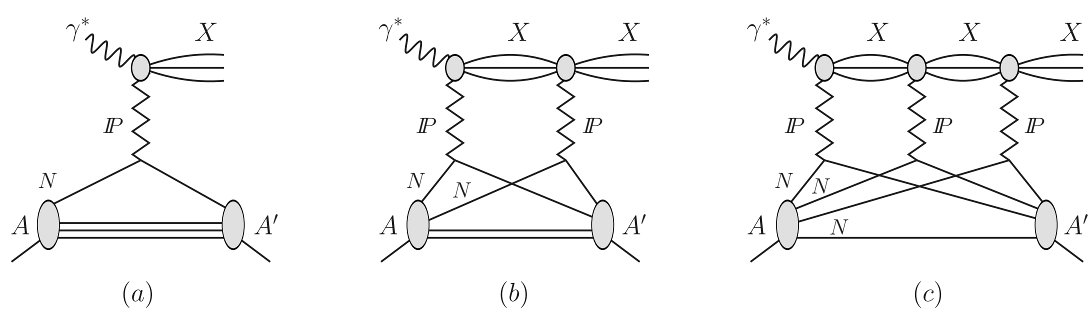
Leading twist approach to nuclear shadowing

- Nuclear shadowing: suppression of nuclear PDFs $f_{i/A}(x,Q^2)/[A f_{i/p}(x,Q^2)] < 1$

- LTA = method to calculate various nuclear parton distributions at small x (usual, generalized, diffractive), Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255 $\rightarrow$ alternative to global fits of PDFs.

- Based on:
  - Gribov-Glauber model of NS for soft hadron-nucleus scattering
  - QCD factorization theorems for inclusive and diffractive DIS.

- $\gamma^* + A \rightarrow X + A'$ amplitude is a series of diffractive scattering off $i = 1,2,\ldots,A$ target nucleons:



- Coherent diffraction $A' = A$:

$$\sigma_{\gamma^* A\to XA} = \int d^2\vec{b}\,|\Gamma_{\gamma^* A\to XA}(\vec{b})|^2 = 4\pi \frac{d\sigma_{\gamma^* N\to XN}(t=0)}{dt}\int d^2\vec{b}\left|\int dz\rho_A(\vec{b},z)e^{iz\Delta_{\gamma^* X}}e^{-\frac{1-i\eta}{2}\sigma_{\text{soft}}\int_z^\infty dz'\rho_A(\vec{b},z')}\right|^2$$

diffractive cross section on proton measured at HERA

nuclear density

model-dependent cross section

LTA to nuclear shadowing (2)

- Apply collinear QCD factorization for diffractive DIS, Collins, PRD 57 (1998); PRD 61 (2000) 019902 $\longrightarrow$ from structure function to parton distributions:

$$f_{i/A}^{D(3)}(x,x_{I\!P},Q^2)=4\pi f_{i/p}^{D(4)}(x,x_{I\!P},Q^2,t=0)\int d^2\vec{b}\left|\int dz\rho_A(\vec{b},z)e^{izx_{I\!P}m_N}e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)\int_z^\infty dz'\rho_A(\vec{b},z')}\right|^2$$

$$=f_{i/p}^{D(3)}(x,x_{I\!P},Q^2)\frac{1}{\sigma^i_{\rm el}(x)}\int d^2\vec{b}\left|1-e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)T_A(\vec{b})}\right|^2$$

$$\sigma_{\rm el}(x)=\frac{[\sigma_{\rm soft}(x)]^2}{16\pi B_{\rm diff}}$$

$$T_A(\vec{b})=\int dz\rho(\vec{b},z)$$

- Transparent interpretation: nuclear diffractive PDFs suppressed (shadowed) in proportion to the nuclear elastic cross section.

- Similarly for quasi-elastic scattering using completeness final states A' :

$$\sigma_{\gamma^*A\to XA'}=\int d^2\vec{b}\,\langle A|\left|\Gamma_{\gamma^*A\to XA}(\vec{b})\right|^2|A\rangle=\sigma_{\gamma^*N\to XN}\frac{1}{\sigma_{\rm el}}\int d^2\vec{b}\left(\left|1-e^{-\frac{1-i\eta}{2}\sigma_{\rm soft}T_A(\vec{b})}\right|^2+e^{-\sigma_{\rm in}T_A(\vec{b})}-e^{-\sigma_{\rm soft}T_A(\vec{b})}\right)$$

$\downarrow$

$$\tilde{f}_{i/A}^{D(3)}(x,x_{I\!P},Q^2)=f_{i/p}^{D(3)}(x,x_{I\!P},Q^2)\frac{1}{\sigma^i_{\rm el}(x)}\int d^2\vec{b}\left(\left|1-e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)T_A(\vec{b})}\right|^2+e^{-\sigma^i_{\rm in}(x)T_A(\vec{b})}-e^{-\sigma^i_{\rm soft}(x)T_A(\vec{b})}\right)$$

$$\sigma_{\rm in}(x)=\sigma_{\rm soft}(x)-\sigma_{\rm el}(x)$$

- In this case, NS is given by sum of elastic and inelastic nuclear cross sections.

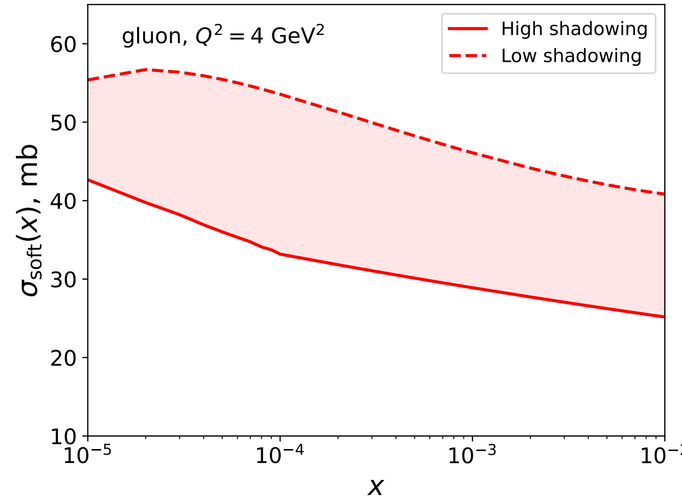
LTA predictions for nuclear diffractive PDFs

- Assumed that diffractive intermediate states X do not mix → one free parameter $\sigma^i_{\text{soft}}(x)$ → controls size and uncertainties of LTA predictions.

- High shadowing: given by probability of diffraction

$$\sigma^i_{\text{soft}}(x) \approx \sigma_2(x) \equiv \frac{16\pi}{f_{i/p}(x)} \int_x^{0.1} \frac{dx_{I\!P}}{x_{I\!P}} f^{D(4)}_{i/p}(x, x_{I\!P}, t=0)$$

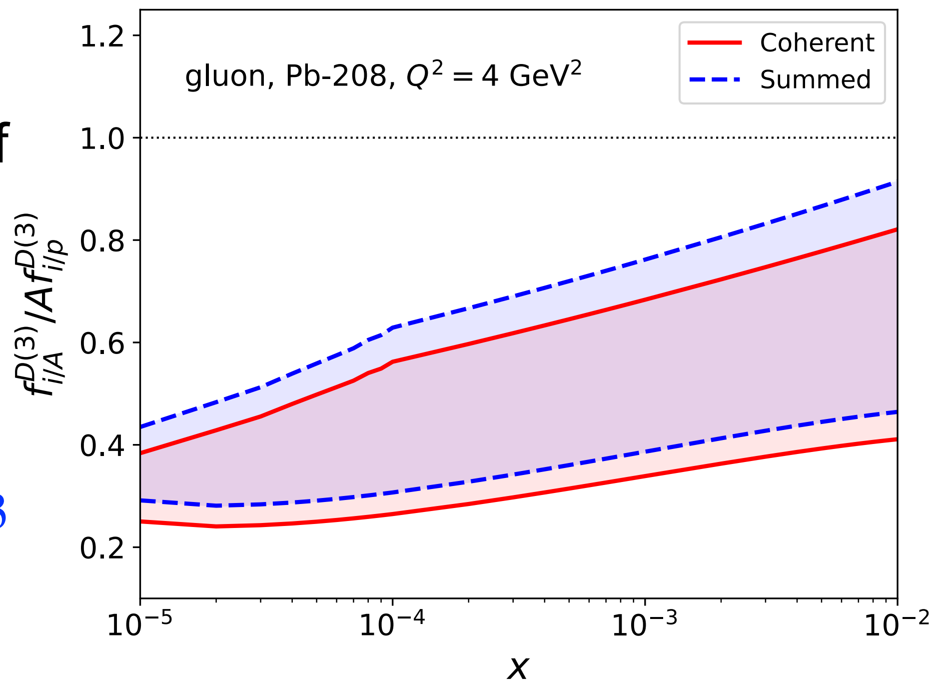
- Low shadowing: calculated using model for hadronic structure of ρ meson.



- In LTA, nuclear shadowing driven by diffraction on proton → 10-15% probability of diffraction in DIS@HERA leads to large suppression of nuclear PDFs at small x.

- Compare to impulse approximation (IA):

$$\frac{f^{D(3)}_{i/A}}{A f^{D(3)}_{i/p}} = \frac{4\pi B_{\text{diff}}}{A} \int d^2\vec{b}\,(T_A(\vec{b}))^2 = \frac{B_{\text{diff}}}{A} \int dt F^2_A(t) = 4.3$$

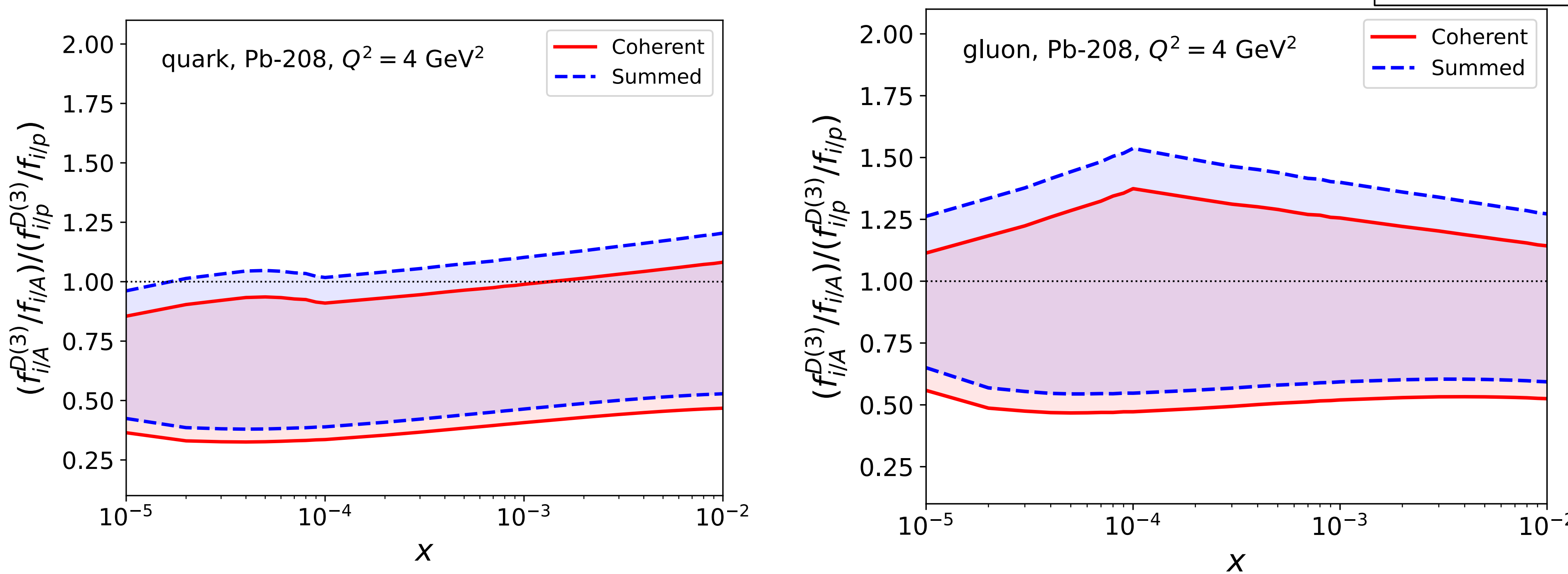


LTA predictions for $R_{diff/tot}$

- Combine LTA predictions for diffractive and usual nuclear PDFs:

$$\frac{f_{i/A}^{D(3)}(x, x_{I\!P}, Q^2)/f_{i/A}(x, Q^2)}{f_{i/p}^{D(3)}(x, x_{I\!P}, Q^2)/f_{i/p}(x, Q^2)} = \frac{\sigma_{\text{soft}}^i(x)}{\sigma_{\text{el}}^i(x)} \frac{\int d^2\vec{b} \left| 1 - e^{-\frac{1-i\eta}{2}\sigma_{\text{soft}}^i(x) T_A(\vec{b})} \right|^2}{2(1-\lambda^i(x))\Re e \int d^2\vec{b} \left(1 - e^{-\frac{1-i\eta}{2}\sigma_{\text{soft}}^i(x) T_A(\vec{b})} \right) + \lambda^i(x) A \sigma_{\text{soft}}^i(x)}$$

$$\lambda^i(x) = 1 - \sigma_2^i(x)/\sigma_{\text{soft}}^i(x)$$

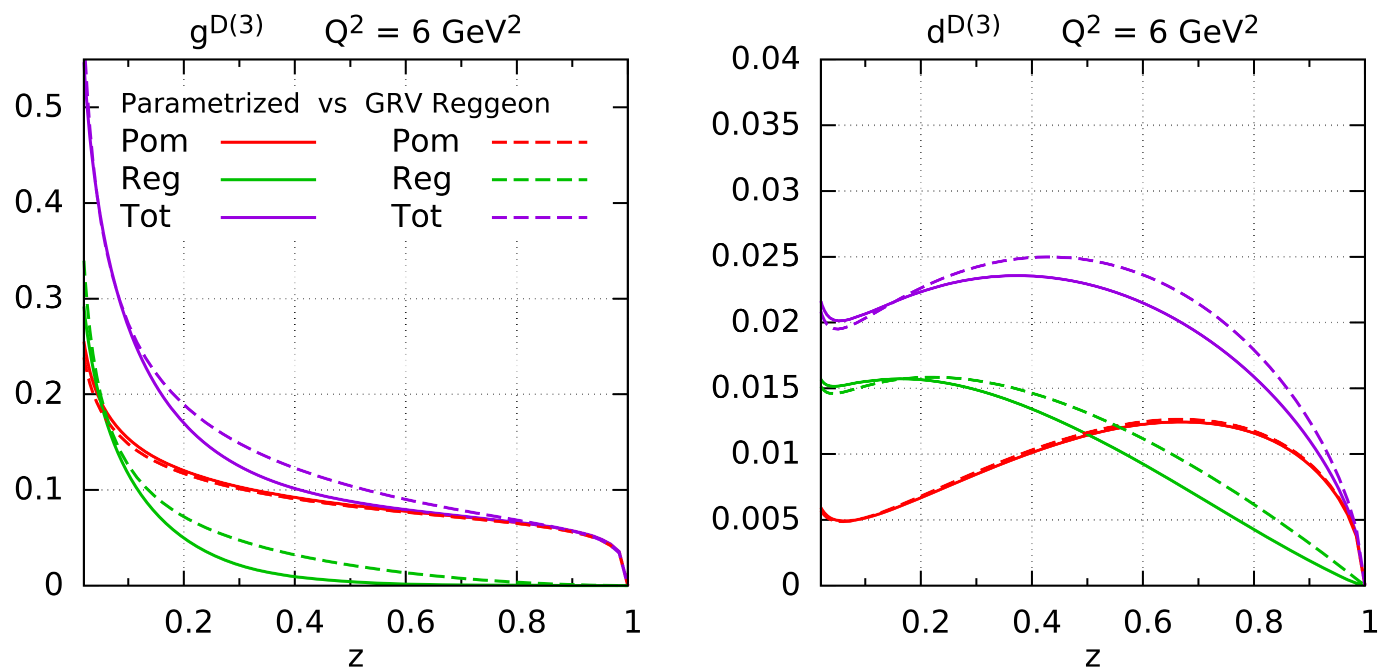


- Suppression $R_{\text{diff/tot}} \approx 0.5 - 1$ (quarks) and $R_{\text{diff/tot}} \approx 0.5 - 1.3$ (gluons) due to interplay of large leading twist nuclear shadowing for diffractive and usual nuclear PDFs.

Outlook: diffraction at EIC

- Several recent global QCD fits for proton diffractive PDFs using all (inclusive+dijets) HERA data, Salajeghen at al., PRD 107 (2024) 9, 093038; PRD 106 (2022) 5, 054012

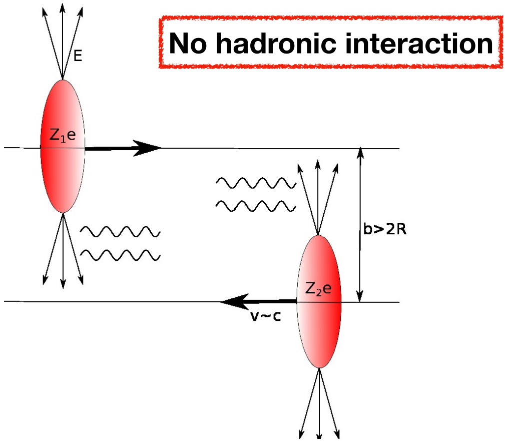
- Further progress possible at the Electron-Ion Collider (EIC) $\to \sqrt{s_{ep}} \sim 100$ GeV lower than at HERA $\to$ constrain sub-leading (Reggeon) contribution at large ξ, Armesto, Newman, Slominski, Stasto, PRD 110 (2024) 5, 054039



$\xi = 0.1$

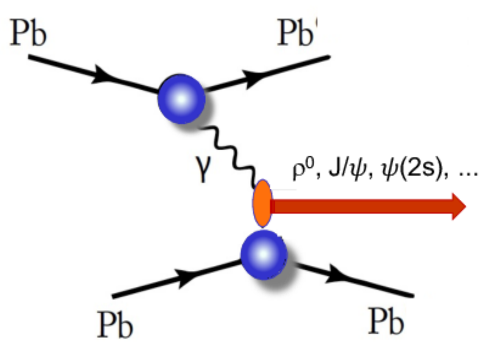
- Similarly, NLO pQCD predicts10-35% contribution of sub-leading Reggeon trajectory for $x_P > 0.06$ in diffractive dijet photoprofuction at EIC, Guzey, Klasen, JHEP 05 (2020) 074

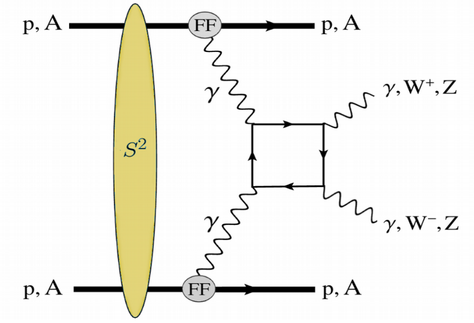
Outlook: diffraction in UPC at LHC



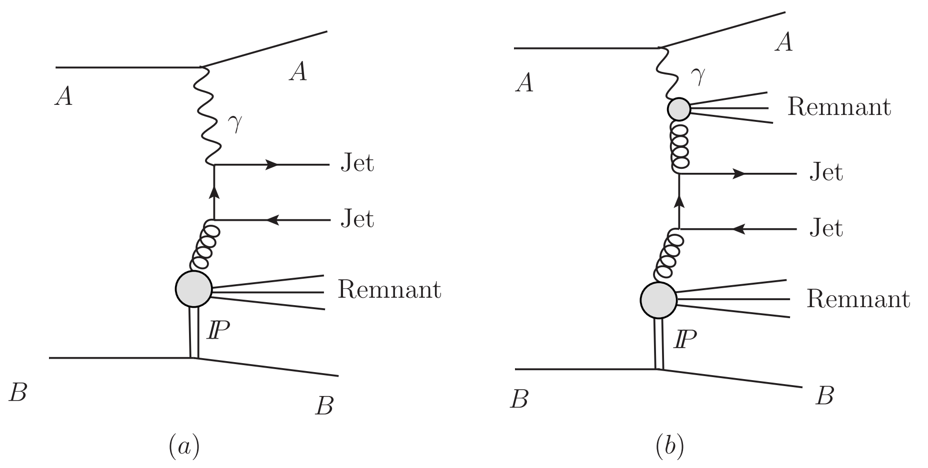
- Ultraperipheral collisions (UPCs) at large transverse distances $|\vec{b}| \gg 2R_A$ → interaction via quasi-real photons → LHC is a high-energy *photon collider* → can be used to test predictions for EIC.

- Photon-nucleus (proton) and photon-photon scattering in UPCs:





- Recent ATLAS measurement in 0nXn channel, Aad at al, 2409.11060 [nucl-ex] → can be extended to 0n0n channel probing nuclear diffractive PDFs.



Outlook: diffraction in UPC at LHC (2)

• Besides nuclear diffractive PDFs, heavy nucleus can be used to suppress the resolved photon contribution → new handle on mechanism of factorization breaking, Guzey, Klasen, JHEP 04 (2016) 158

• Suppression factor for resolved photon: $R(\text{res.}) = \dfrac{\int d^2b\, |\mathcal{A}_{\gamma T\to VT}(W,b)|^2 P_{VT}(W,b)}{\int d^2b\, |\mathcal{A}_{\gamma T\to VT}(W,b)|^2}$

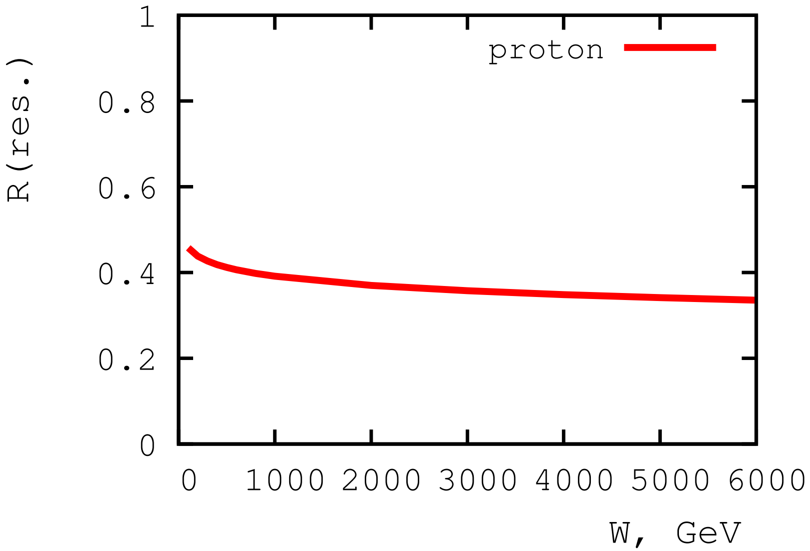
VM photoproduction in Glauber model

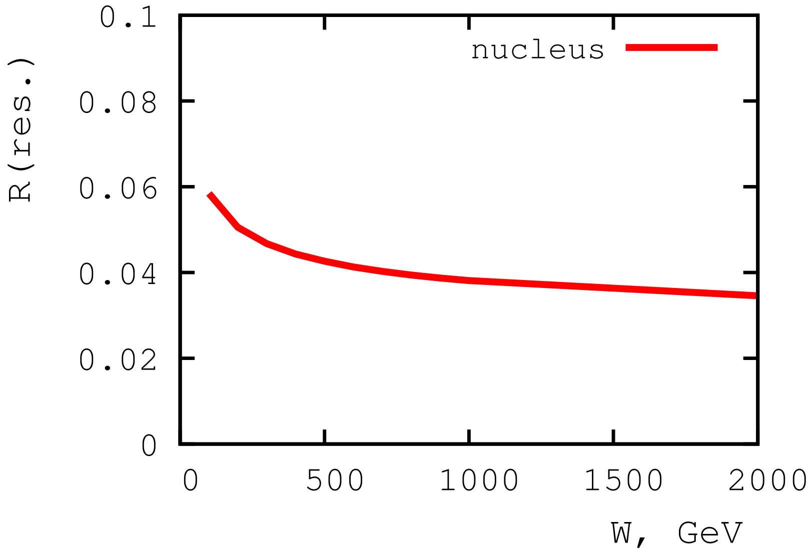
$$\mathcal{A}_{\gamma A\to VA}(W,b) = \frac{e}{f_V}\left(1 - e^{-\frac{\sigma_{\rho N}(W)}{2}T_A(b)}\right)$$

Probability to not have strong interactions

$$P_{VA}(W,b) = e^{-\sigma_{\rho N}(W)T_A(b)}$$

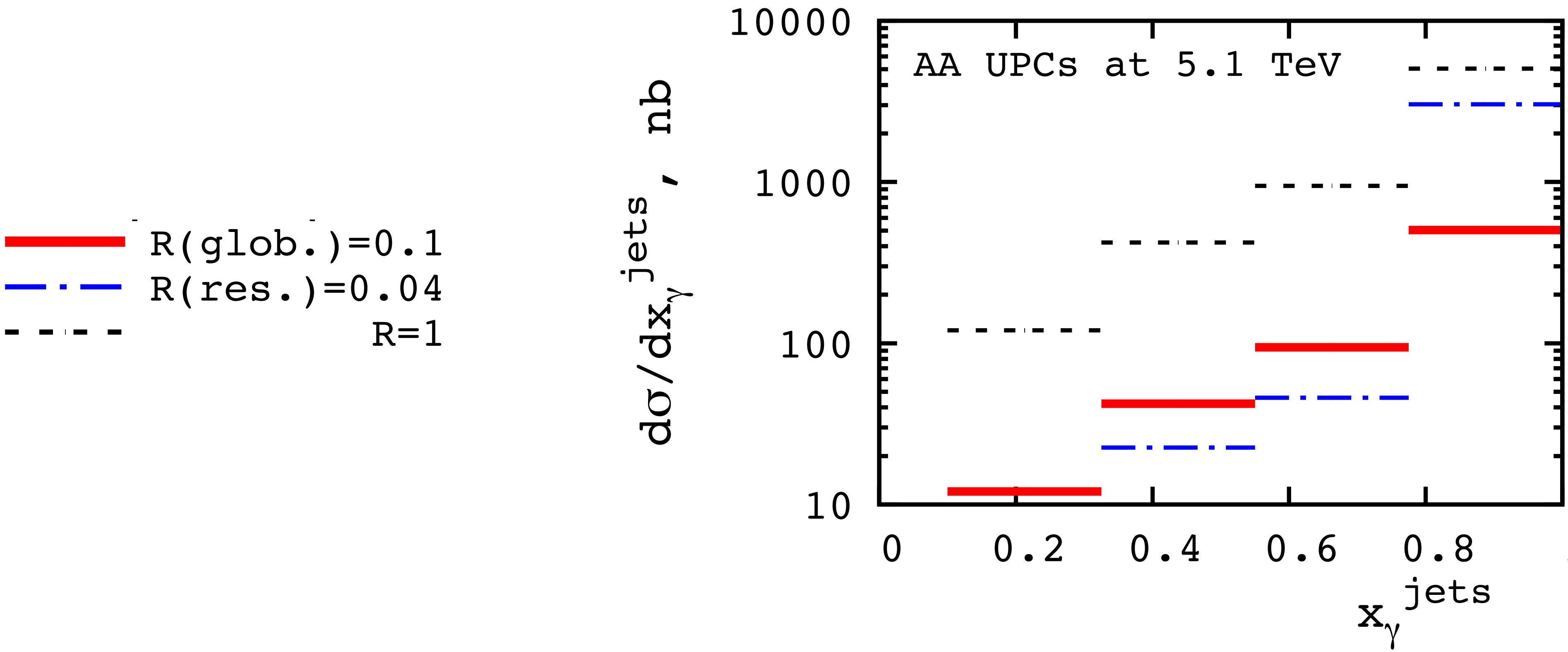
• Suppression factor: proton vs. nucleus





Outlook: diffraction in UPC at LHC (3)

- It is much easier to break up nucleus and fill the rapidity gap → $R(\mathrm{res})_A \ll \mathrm{R(res)}_p$
- NLO pQCD predictions for diffractive dijet photoproduction in Pb-Pb UPCs at LHC, Guzey, Klasen, JHEP 04 (2016) 158



Summary

• Diffractive PDFs is a standard tool of perturbative QCD.

• In the proton case, they are extracted using global fits to HERA data.

• Further progress at EIC for the sub-leading contribution for large ξ.

• In the nuclear case, diffractive PDFs never been measured → will be at EIC and can be in Pb-Pb UPCs at LHC.

• Open question: mechanism of factorization breaking in diffractive dijet photoproduction → can be addressed in UPCs at LHC.

• Diffraction in ep and eA can be alternatively addressed in the dipole model, where the emphasis on the gluon saturation.