Diffractive PDFs

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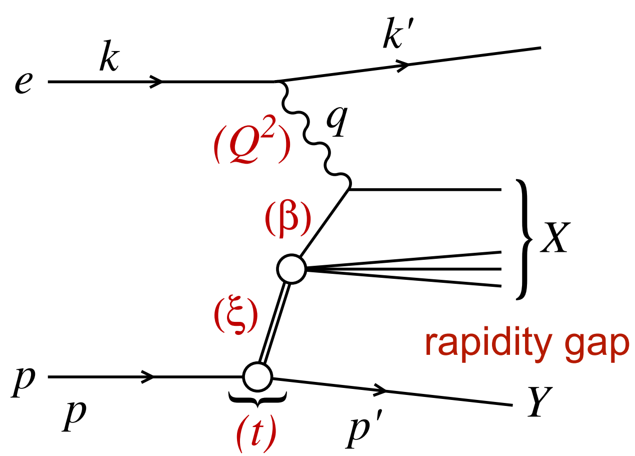
Based on Frankfurt, Guzey, Stasto, Strikman, "Selected topics in diffraction with protons and nuclei: past, present, and future", Rep. Prog. Phys. 85 (2022) 126301 [2203.12289 [hep-ph]]

Outline:

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

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 DIS) processes.
- Challenging in QCD due to enhanced HT/non-linear effects.
- Classic and most studied example: diffraction in ep DIS at HERA.



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 needs 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, in terms of leading Pomeron and sub-leading ($\xi \geq 0.03$) Reggeon terms:

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

- The fluxes in the form motivated by Regge theory:

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

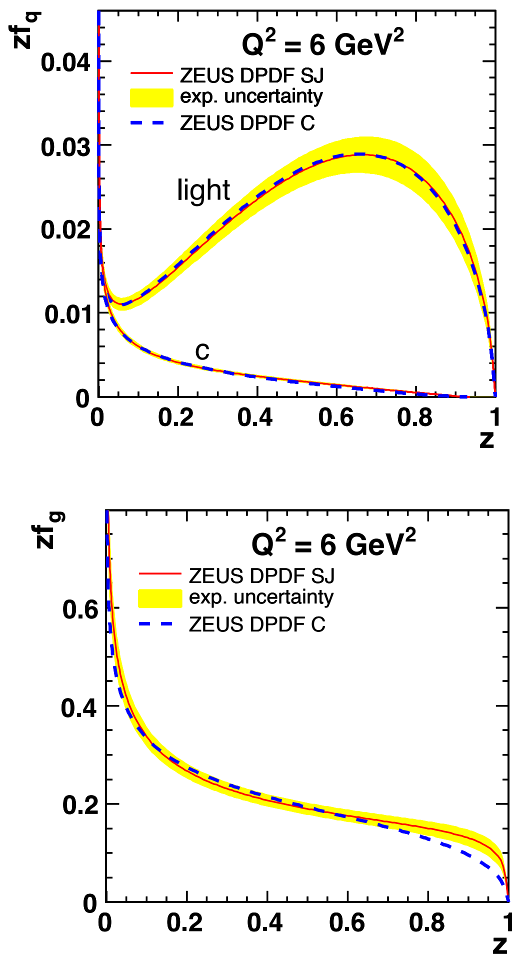
- Simple form for sea quark (valence =0) and gluon PDFs of the Pomeron:

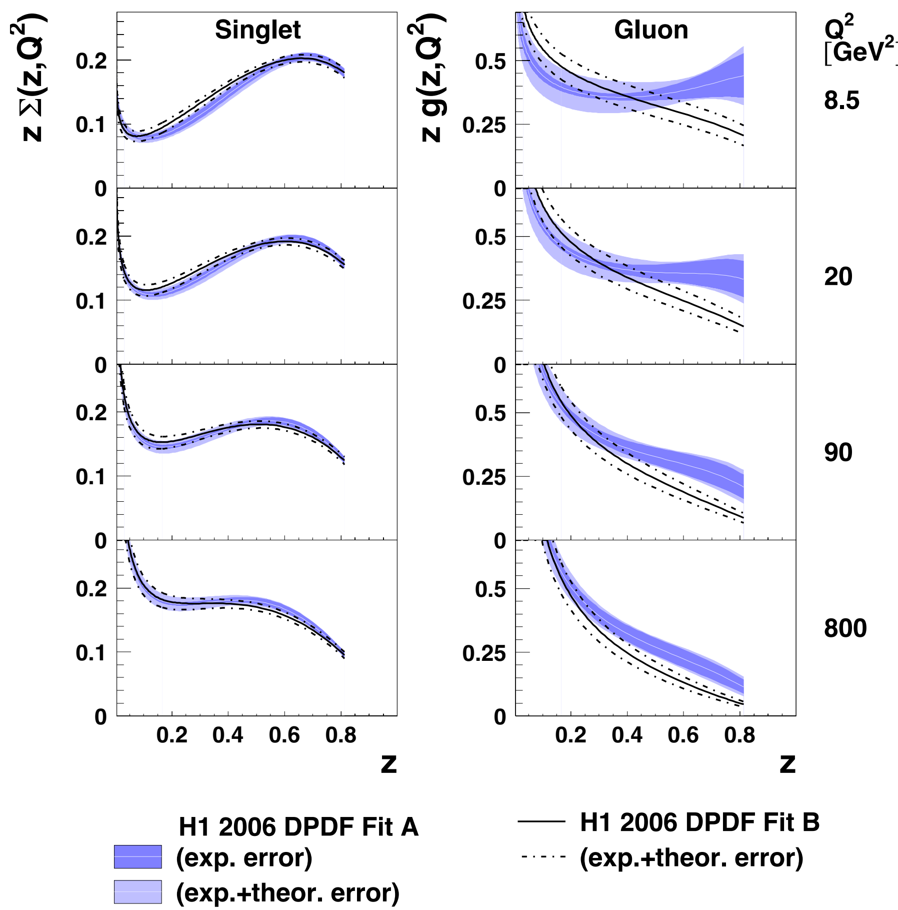
$$z f_i^{\mathbb{P}}(z,\mu_0^2) = A_i z^{B_i}(1-z)^{C_i}$$

- $f_u^{I\!P} = f_d^{I\!P} = f_s^{I\!P}$, 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.

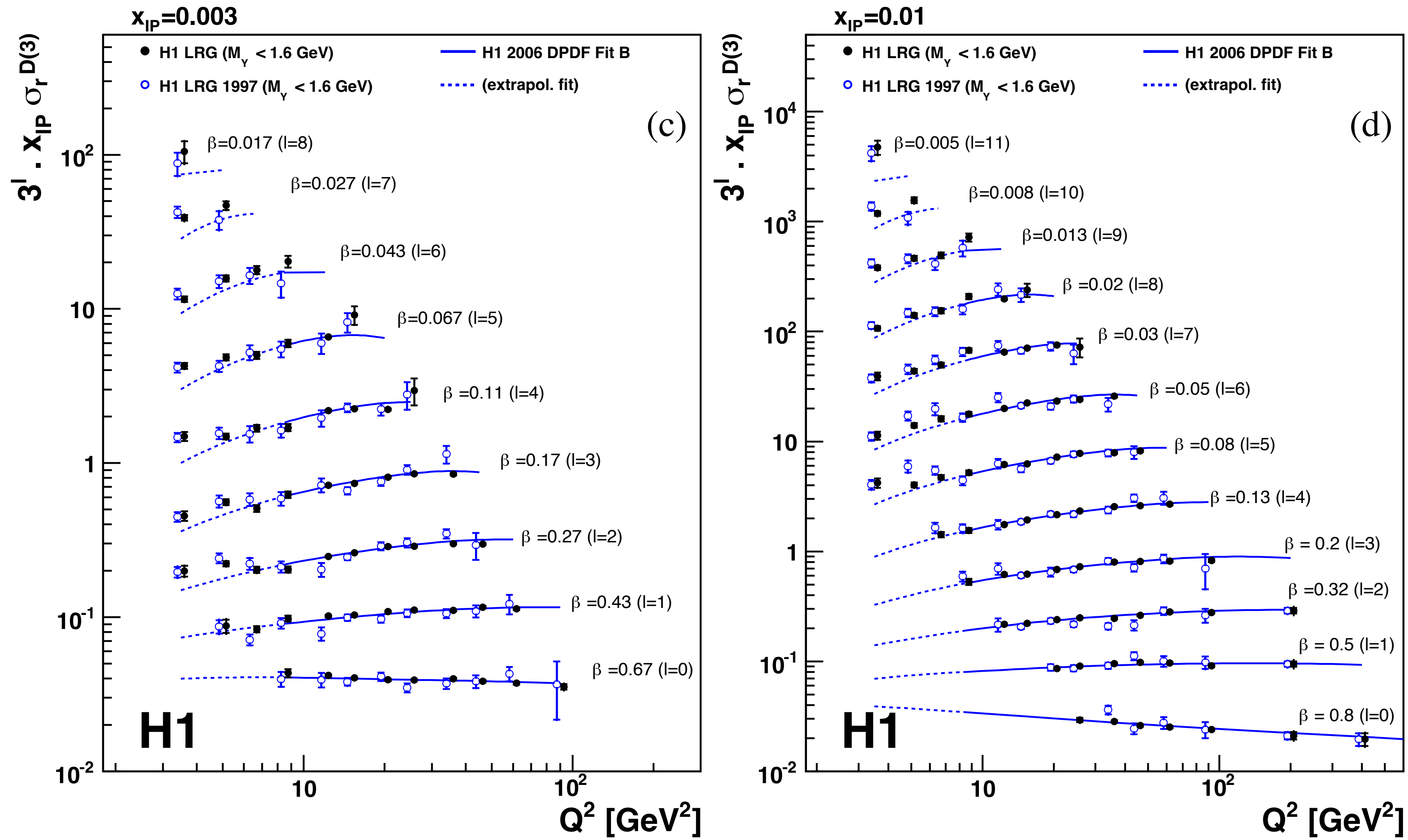




• Diffractive gluon PDF >> quark PDFs, but poorly constrained at large z → need to include data on diffractive dijets → favor ZEUS C and H1 B fits.

Diffractive PDFs from global fits (3)

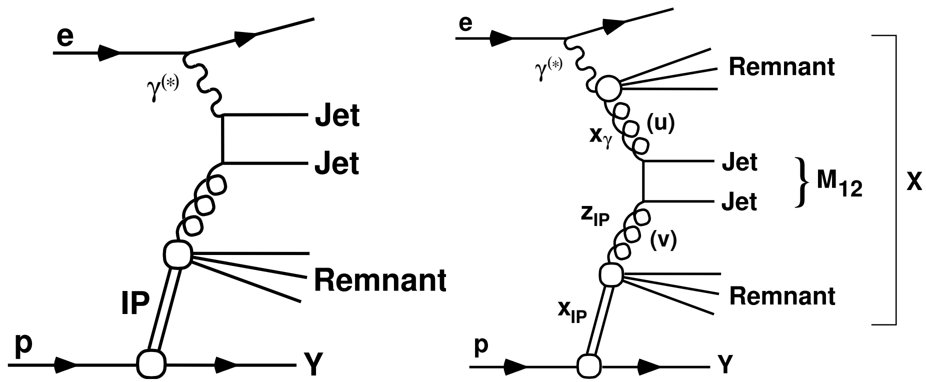
- Good description of original and more recent H1 data, Aaron et al, EPJC 72 (2012) 2074



- 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)

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

Photon flux in Weizsäcker-Williams approximation

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

"Pomeron" flux

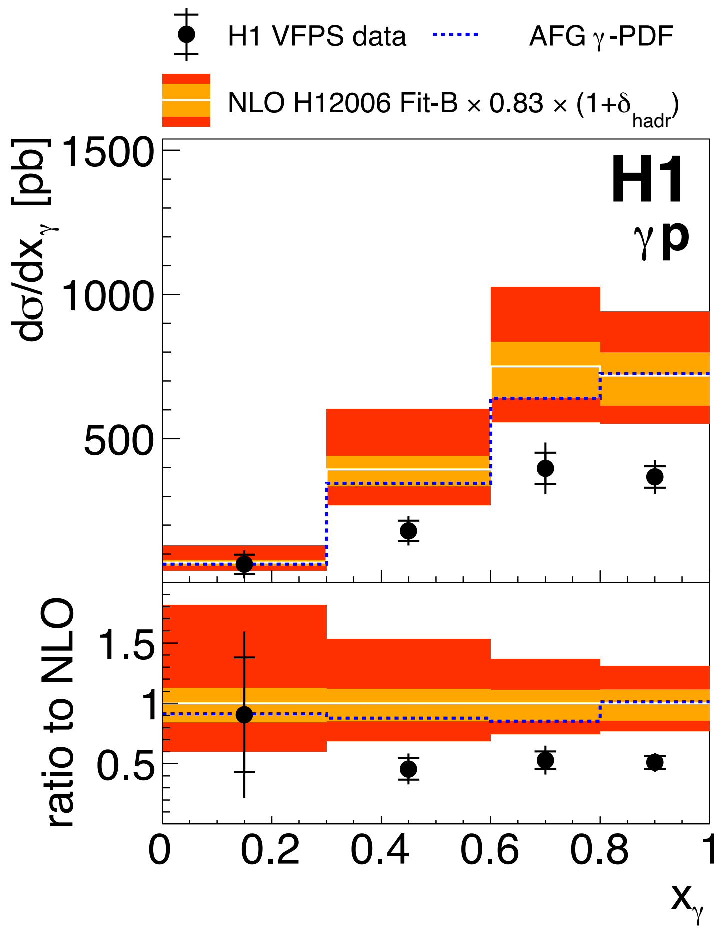
Diffractive PDFs

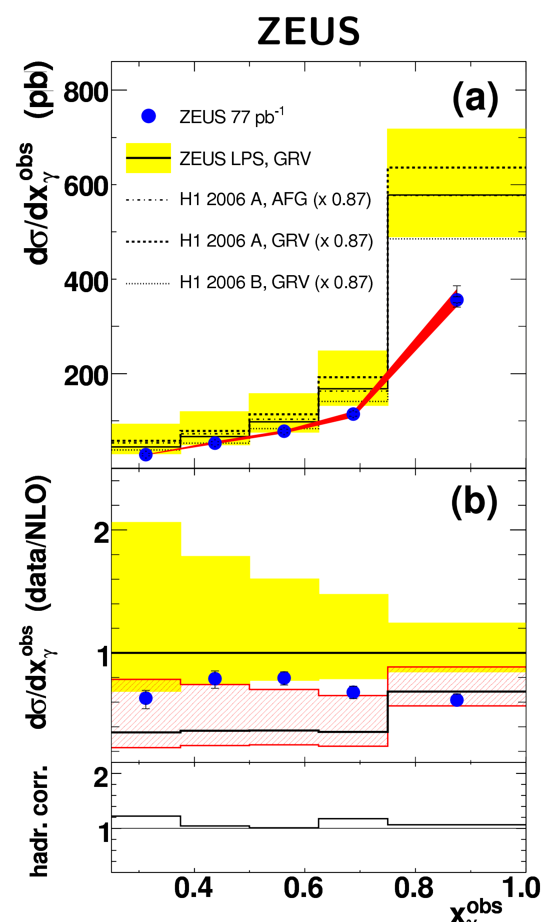
Hard partonic cross section

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

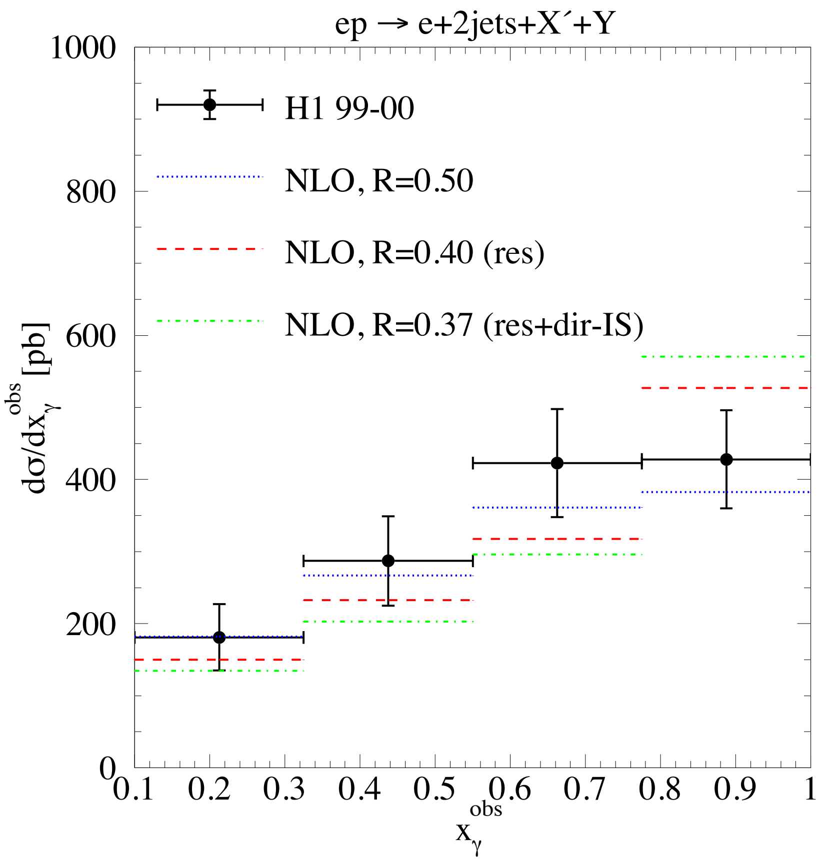
- Mechanism of this factorization breaking remains unknown:

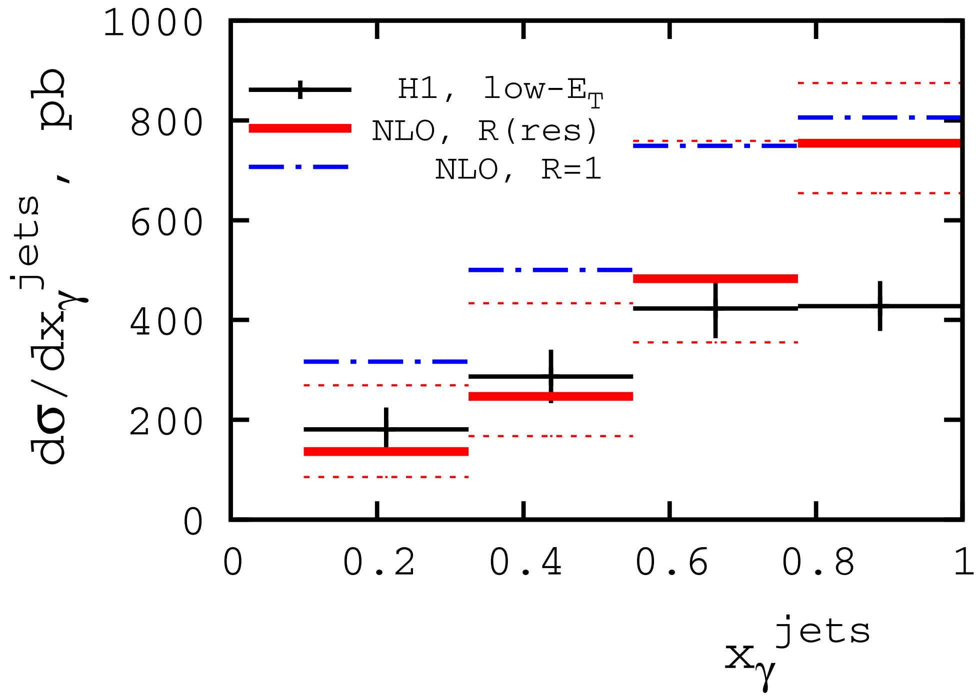
- global suppression factor R ≈ 0.5

- 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)

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

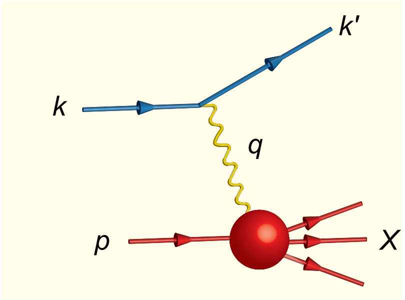




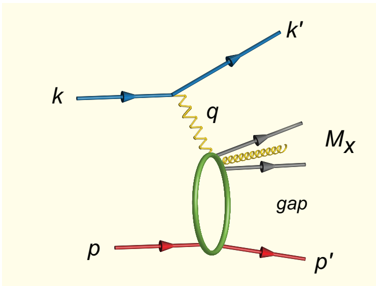
Diffraction in DIS on nuclei

- The planned Electron-Ion Collider (EIC) in USA has potential to discriminate among approaches of NS due to:
  - wide $x - Q^2$ coverage
  - measurement of longitudinal structure function $F_L^A(x, Q^2)$ sensitive to gluons
  - for the first time measurement of hard diffraction in nuclear DIS.

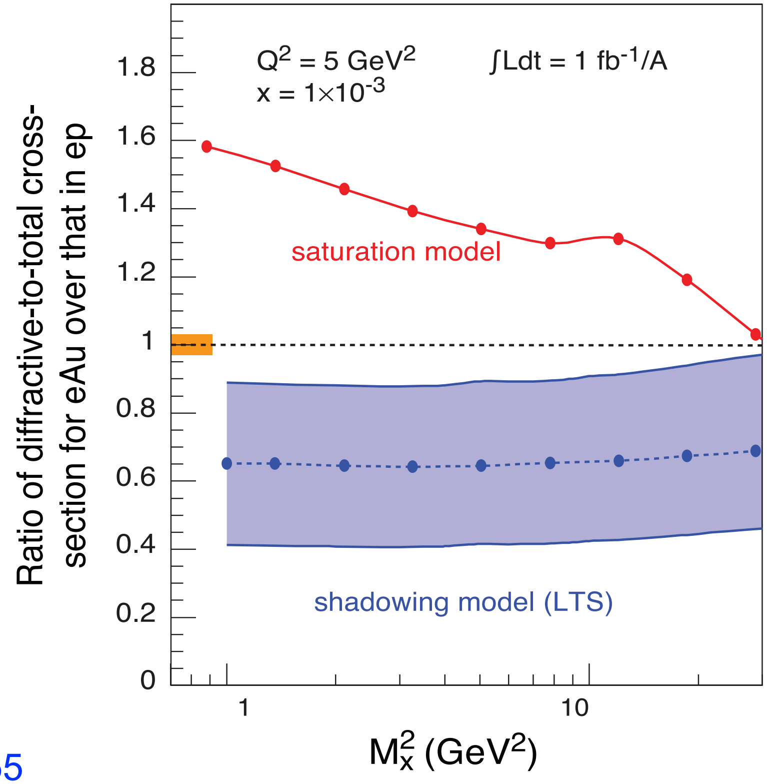
- Sensitive observable is the ratio of diffractive to total DIS cross sections for a heavy nucleus and the proton, Accardi et al., EPJ A52 (2016) 9, 268 [1212.1701 [hep-ex]]:



Total DIS



Diffractive DIS



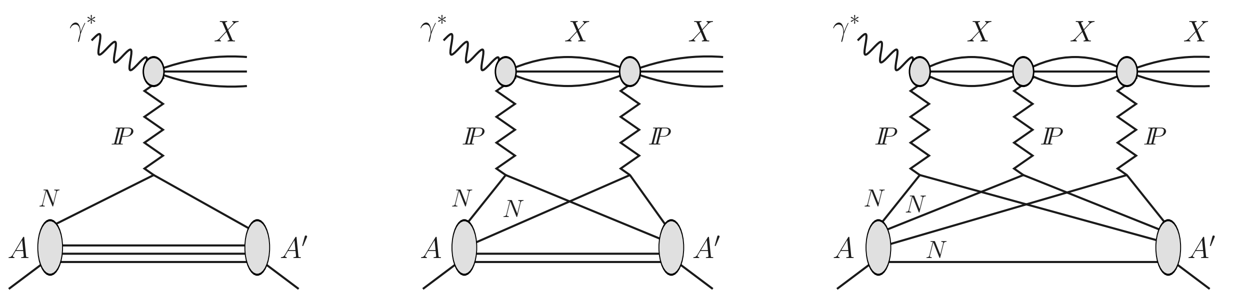
- Predicted to be:
  - $R_{\rm diff/tot} > 1$ due to nuclear enhancement of saturation scale $Q^2_{s,A}$, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303; Lappi, Le, Mäntysaari, PRD 108 (2023 114023
  - $R_{\rm diff/tot} < 1$ due to strong leading twist nuclear shadowing, Frankfurt, Guzey, Strikman,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

Leading twist approach to nuclear shadowing

- Method to calculate various nuclear parton distributions (usual, generalized, diffractive) as input for DGLAP evolution, Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255 $\rightarrow$ alternative to global fits of nPDFs.

- 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:



(a) (b) (c)

- 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:

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

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

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

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

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

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

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

$\downarrow$

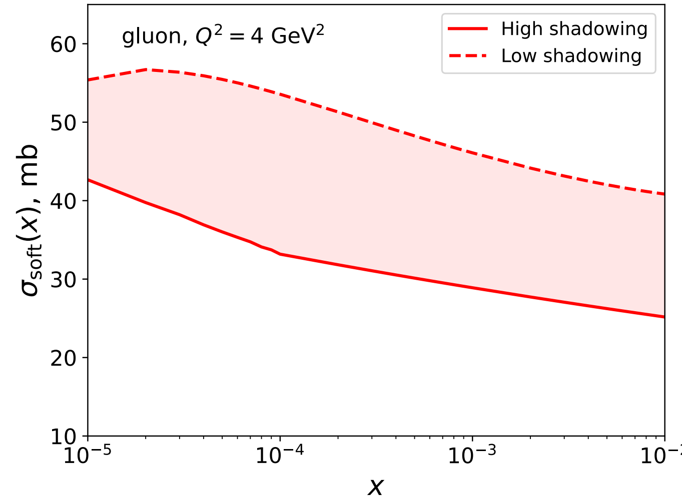
$$\tilde{f}_{i/A}^{D(3)}(x, x_{I\!P}, Q^2) = f_{i/p}^{D(3)}(x, x_{I\!P}, Q^2) \frac{1}{\sigma_{\rm el}^i(x)} \int d^2\vec{b} \left(\left| 1 - e^{-\frac{1-i\eta}{2}\sigma_{\rm soft}^i(x) T_A(\vec{b})} \right|^2 + e^{-\sigma_{\rm in}^i(x) T_A(\vec{b})} - e^{-\sigma_{\rm soft}^i(x) T_A(\vec{b})} \right)$$

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

- 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 $\sigma^{i}_{\rm soft}(x)$ → controls size and uncertainties of LTA predictions.



- High shadowing: given by probability of diffraction

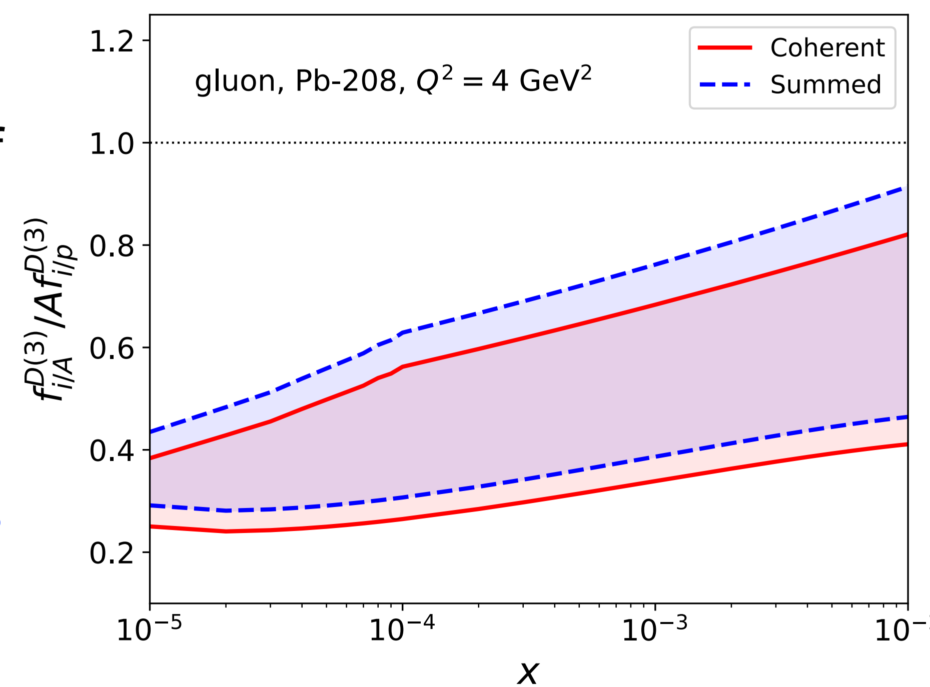
$$\sigma^{i}_{\rm soft}(x) \approx \sigma_2(x) \equiv \frac{16\pi}{f_{i/p}(x)} \int_x^{0.1} \frac{dx_{I\!P}}{x_{I\!P}} f^{D(4)}_{i/p}(x, x_{I\!P}, t=0)$$

- 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):

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

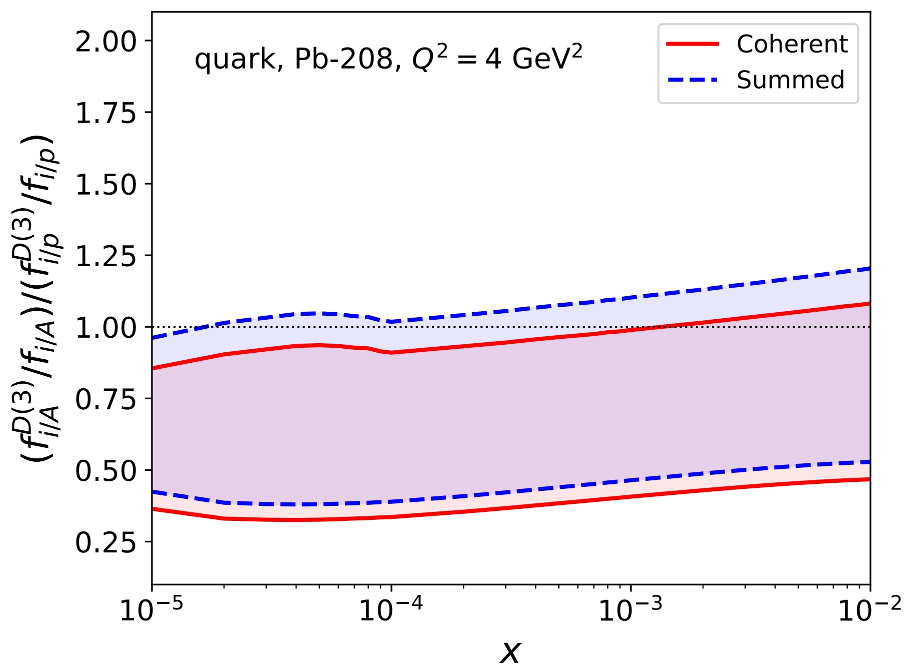


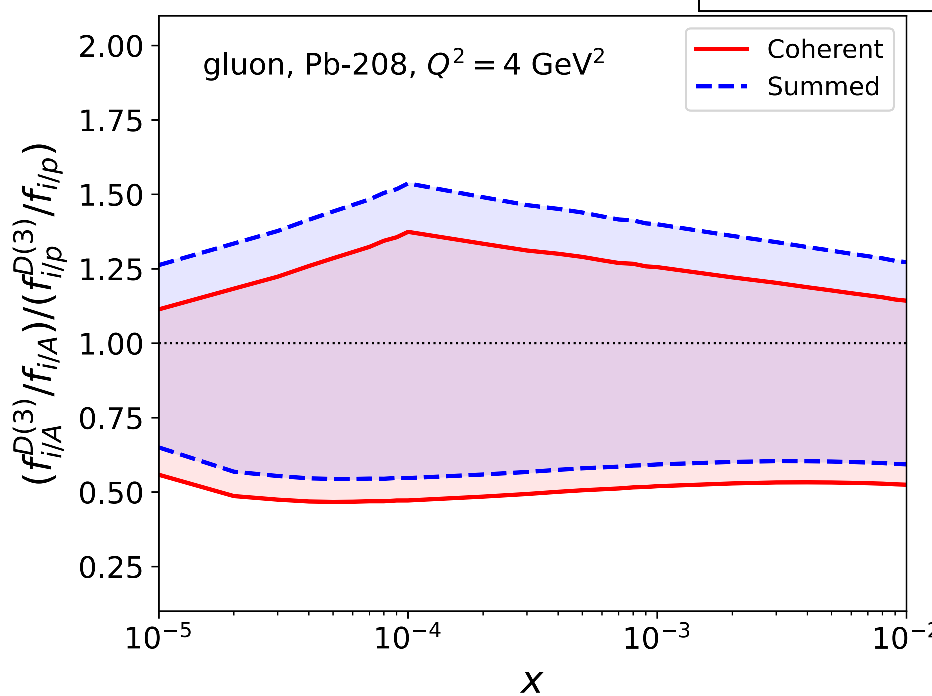
LTA predictions for $R_{diff/tot}$

- Combine LTA predictions for diffractive and usual nuclear PDFs:

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

$$\lambda^i(x) = 1 - \sigma^i_2(x)/\sigma^i_{\rm soft}(x)$$



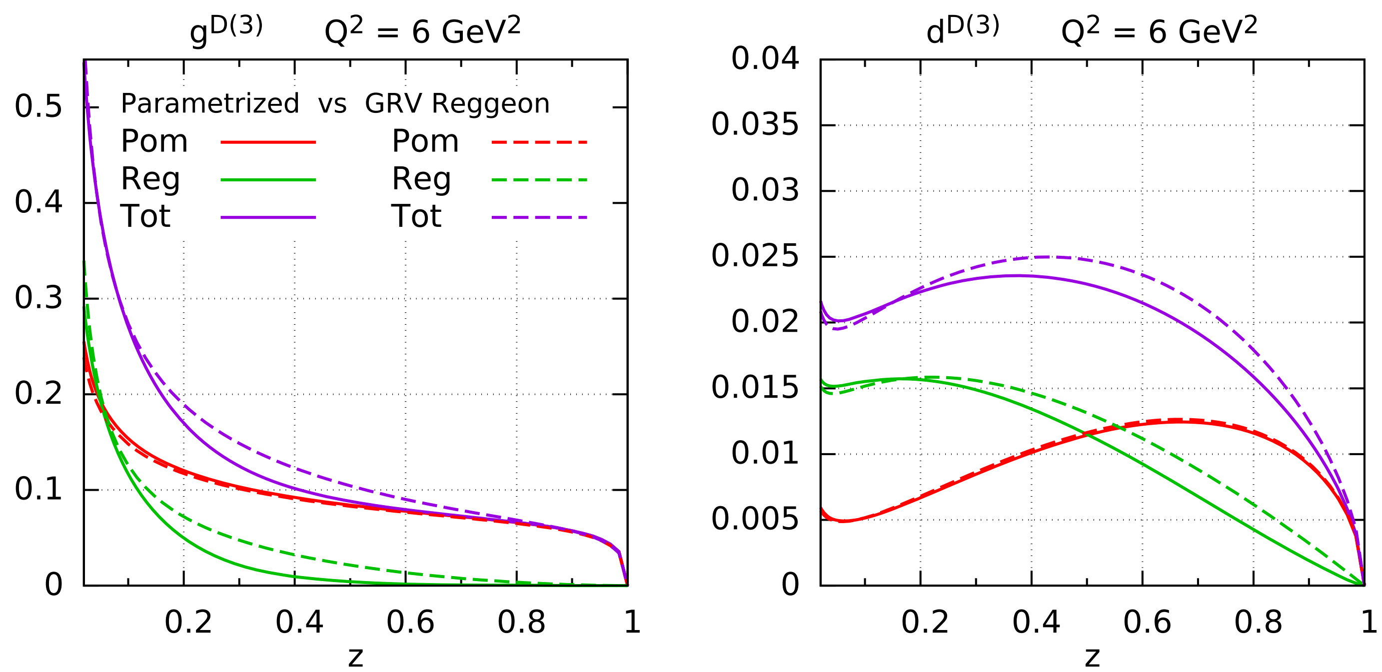


- Suppression $R_{\rm diff/tot} \approx 0.5-1$ (quarks) and $R_{\rm diff/tot} \approx 0.5-1.3$ (gluons) due to interplay of large leading twist nuclear shadowing for diffractive and usual nuclear PDFs.

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) $\rightarrow \sqrt{s_{NN}} \sim 100$ GeV lower than at HERA $\rightarrow$ constrain subleading (Reggeon) contribution at large ξ, Armesto, Newman, Slominski, Stasto, PRD 110 (2024) 5, 054039

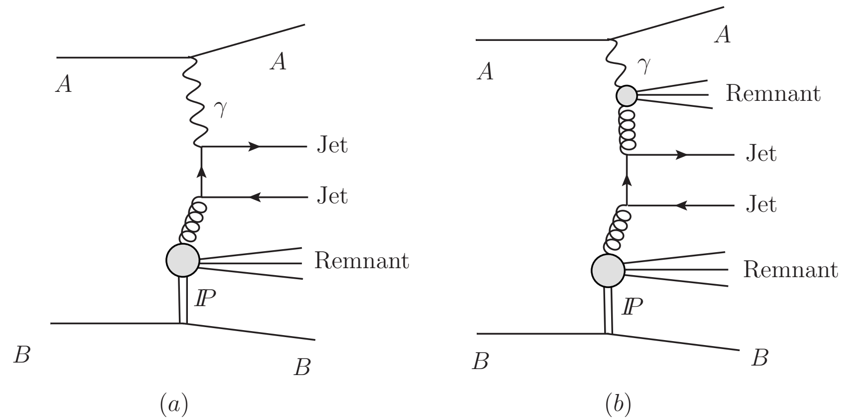


$\xi = 0.1$

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

Outlook: diffraction in UPC at LHC

• Predictions for EIC can be tested in ultraperipheral collisions (UPCs) at LHC.



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

• Nucleus can be used to suppress the resolved photon contribution → new handle on mechanism of factorization breaking, Guzey, Klasen, JHEP 04 (2016) 158