Nuclear enhancement and suppression of diffractive structure functions at high energies

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DIS 2009

Outline

- Computing F_2^D in the dipole model (IPsat) ,
- Results vs. β, Q^2, $x_{\mathbb{P}}$, A.

Talk based on: H. Kowalski, T. L., C. Marquet and R. Venugopalan, Phys. Rev. C **78** (2008) 045201, [arXiv:0805.4071 [hep-ph]].

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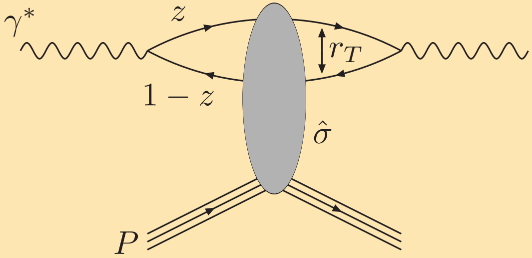
Context: measure diffraction in eA at EIC

See **`http://www.eic.bnl.gov/`**

Also first evaluation of F_2^D in ep with IPsat parametrization

DIS in dipole frame



Use:

- S-matrix real
- optical theorem

- $\Psi^{\gamma}_{L,T} \sim K_{0,1}\left(\sqrt{z(1-z)}Q|\mathbf{r}_T|\right)$
  - momentum scale $Q^2 \sim 1/\mathbf{r}_T{}^2$
- Diffractive: t is FT of $\mathbf{b}_T$.

See talk by A. Luszczak

Observables from dipole cross section

$$\sigma_{\rm dip}(x, \mathbf{r}_T, \mathbf{\Delta}) = \int \mathrm{d}^2\mathbf{b}_T \frac{\mathrm{d}^2\sigma_{\rm dip}(x, \mathbf{r}_T, \mathbf{b}_T)}{\mathrm{d}^2\mathbf{b}_T} e^{i\mathbf{b}_T\cdot\mathbf{\Delta}}, \qquad \mathbf{\Delta}^2 = -t$$

▼

Inclusive

$$\sigma_{L,T}^{\gamma^* p} = \int \mathrm{d}^2\mathbf{r}_T \int \mathrm{d}z \left|\Psi_{L,T}^{\gamma}(Q^2, \mathbf{r}_T, z)\right|^2 \sigma_{\rm dip}(x, \mathbf{r}_T)$$

Observables from dipole cross section

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Inclusive **diffractive** (elastic dipole–target)

$$\sigma_{L,T}^{\gamma^* p} = \int \mathrm{d}^2\mathbf{r}_T \int \mathrm{d}z \left|\Psi_{L,T}^{\gamma}(Q^2, \mathbf{r}_T, z)\right|^2 \sigma_{\text{dip}}(x, \mathbf{r}_T)$$

$$\frac{\sigma_{L,T}^{D,tot}}{\mathrm{d}t} = \frac{1}{16\pi} \int \mathrm{d}^2\mathbf{r}_T \int \mathrm{d}z \left|\Psi_{L,T}^{\gamma}(Q^2, \mathbf{r}_T, z)\right|^2 \sigma_{\text{dip}}^2(x, \mathbf{r}_T, \boldsymbol{\Delta})$$

Observables from dipole cross section

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Inclusive diffractive (elastic dipole–target) **exclusive diff.**

$$\sigma_{L,T}^{\gamma^* p} = \int \mathrm{d}^2\mathbf{r}_T \int \mathrm{d}z \left|\Psi_{L,T}^{\gamma}(Q^2, \mathbf{r}_T, z)\right|^2 \sigma_{\rm dip}(x, \mathbf{r}_T)$$

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$$\frac{\sigma_{L,T}^{D,V}}{\mathrm{d}t} = \frac{1}{16\pi} \left|\int \mathrm{d}^2\mathbf{r}_T \int \mathrm{d}z \left(\Psi^{\gamma}\Psi^{*V}\right)_{L,T} \sigma_{\rm dip}(x, \mathbf{r}_T, \boldsymbol{\Delta})\right|^2$$

IPsat model: protons

Use here the IPsat model Kowalski, Teaney

- DGLAP evolution: improves description of large Q^2.
- Consistent $\mathbf{b}_T$ dependence for total and diffractive
  (no separate B_D and σ_0)

$$\sigma_{\text{dip}} = 2 \int d^2\mathbf{b}_T \left(1 - \exp\overbrace{\left\{-\frac{\pi^2}{2N_c}\alpha_s(\mu^2)xg(x,\mu^2)T_p(\mathbf{b}_T)\mathbf{r}_T{}^2\right\}}^{-\mathbf{r}_T{}^2 Q_s^2/4}\right)$$

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4 parameters fit to HERA data

- $xg(x,\mu^2)$ is evolved with DGLAP, 2 parameters
- $\mu^2 = \frac{4}{{\mathbf{r}_T}^2} + \mu_0^2$
- Gaussian $T_p(\mathbf{b}_T)$ ▶ B_D

IPsat: nuclei

Straightforward generalization to nuclei:

$$\frac{\mathrm{d}\sigma^A_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T} = 2\left(1 - \exp\left\{-\frac{\pi^2}{2N_\mathrm{c}}\alpha_\mathrm{s}(\mu^2)xg(x,\mu^2)\sum_{i=1}^{A} T_p(\mathbf{b}_T - \mathbf{b}_{T\,i})\mathbf{r}_T{}^2\right\}\right)$$

$\mathbf{b}_{T\,i}$: nucleon positions ▶ average $\langle\cdot\rangle_\mathrm{N}$ from Woods-Saxon;

no additional nuclear parameters

IPsat: nuclei

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$\mathbf{b}_{T\,i}$: nucleon positions ▶ average $\langle\cdot\rangle_N$ from Woods-Saxon; **no additional nuclear parameters**

$R_p \sim 0.6\text{fm} \ll d_{NN}$

▶ **lumpy** nucleus seen in **incoherent** diffraction $\left\langle \left(\sigma^A_{\text{dip}}\right)^2 \right\rangle_N$

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$R_p \sim 0.6\text{fm} \ll d_{NN}$

▶ **lumpy** nucleus seen in **incoherent** diffraction $\left\langle \left(\sigma^A_{\mathrm{dip}}\right)^2 \right\rangle_N$

Coherent: Glauber

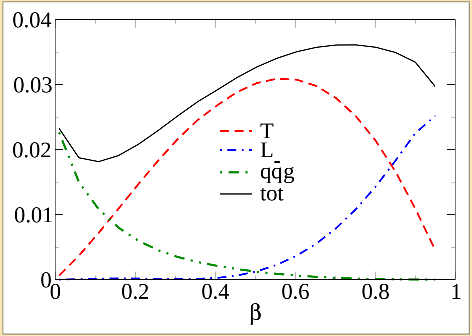
$$\left\langle \frac{\mathrm{d}\sigma^A_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T} \right\rangle_N \approx_{A\to\infty} 2\left[1 - e^{-\frac{AT_A(\mathbf{b}_T)}{2}\sigma^p_{\mathrm{dip}}}\right]$$

Diffractive structure function $F_2^D(x_{\mathbb{P}}, \beta, Q^2)$

$$\beta = \frac{Q^2}{M_X^2 + Q^2} \qquad x_{\mathbb{P}} = \frac{M_X^2 + Q^2}{W^2 + Q^2} \qquad x = \beta x_{\mathbb{P}}$$

Essential regimes:

- $\beta \ll 1$: dominated by higher Fock ($q\bar{q}g$ etc.)
- $\beta \sim 0.5$: dominated by transverse $q\bar{q}$
- $\beta \to 1$: longitudinal $q\bar{q}$.



(Proton, $Q^2 = 5\text{GeV}^2$, $x_{\mathbb{P}} = 10^{-3}$)

Computing F_2^D: $q\bar{q}$

$$x_{\mathbb{P}}F_2^D = \underbrace{x_{\mathbb{P}}F_{T,q\bar{q}}^D + x_{\mathbb{P}}F_{L,q\bar{q}}^D}_{\alpha_s^0} + \underbrace{x_{\mathbb{P}}F_{T,q\bar{q}g}^D}_{\alpha_s} + \underbrace{\text{higher Fock states}}_{\alpha_s^2}$$

Need Bessel transform of dipole cross section

$$\Phi_n = \int d^2\mathbf{b}_T \left[\int_0^\infty dr\, rK_n(\varepsilon r)J_n(kr)\frac{d\sigma_{\text{dip}}}{d^2\mathbf{b}_T}(\mathbf{b}_T, \mathbf{r}_T, x_{\mathbb{P}})\right]^2,$$

Computing F_2^{D}: $q\bar{q}$

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$$\Phi_n = \int \mathrm{d}^2\mathbf{b}_T \left[\int_0^\infty \mathrm{d}r r K_n(\varepsilon r) J_n(kr) \frac{\mathrm{d}\sigma_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T}(\mathbf{b}_T, \mathbf{r}_T, x_{\mathbb{P}})\right]^2,$$

Transverse part of $q\bar{q}$

$$x_{\mathbb{P}}F_{T,q\bar{q}}^{\mathrm{D}}(x_{\mathbb{P}}, \beta, Q^2) = \frac{N_c Q^4}{16\pi^3\beta} \sum_f e_f^2 \int_{z_0}^{1/2} \mathrm{d}z z(1-z) \times \left[\varepsilon^2(z^2 + (1-z)^2)\Phi_1 + m_f^2\Phi_0\right]$$

Computing F_2^{D}: $q\bar{q}$

$$x_{\mathbb{P}} F_2^{\mathrm{D}} = \underbrace{x_{\mathbb{P}} F_{T,q\bar{q}}^{\mathrm{D}} + x_{\mathbb{P}} F_{L,q\bar{q}}^{\mathrm{D}}}_{\alpha_s^0} + \underbrace{x_{\mathbb{P}} F_{T,q\bar{q}g}^{\mathrm{D}}}_{\alpha_s} + \underbrace{\text{higher Fock states}}_{\alpha_s^2}$$

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Longitudinal part of $q\bar{q}$

$$x_{\mathbb{P}} F_{L,q\bar{q}}^{\mathrm{D}}(x_{\mathbb{P}}, \beta, Q^2) = \frac{N_c Q^6}{4\pi^3\beta} \sum_f e_f^2 \int_{z_0}^{1/2} \mathrm{d}z z^3 (1-z)^3 \Phi_0$$

Computing F_2^{D}: $q\bar{q}$

$$x_{\mathbb{P}} F_2^{\mathrm{D}} = \underbrace{x_{\mathbb{P}} F_{T,q\bar{q}}^{\mathrm{D}} + x_{\mathbb{P}} F_{L,q\bar{q}}^{\mathrm{D}}}_{\alpha_s^0} + \underbrace{x_{\mathbb{P}} F_{T,q\bar{q}g}^{\mathrm{D}}}_{\alpha_s} + \underbrace{\text{higher Fock states}}_{\alpha_s^2}$$

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$\int \mathrm{d}t$ from $-\infty$ to 0 ▶ “easy” evaluation integrating over $\mathbf{b}_T$.

Incoherent: $\int \mathrm{d}^2\mathbf{b}_T$ really 2-dimensional.

Computing F_2^{D} II: $q\bar{q}g$ – component
Combine two known limits

Large Q^2, finite β ("GBW" Golec-Biernat, Wusthoff)

$$x_{\mathbb{P}} F_{T,q\bar{q}g}^{\mathrm{D}\,(\mathrm{GBW})} = \frac{\alpha_s \beta}{8\pi^4} \sum_f e_f^2 \int \mathrm{d}^2\mathbf{b}_T \int_\beta^1 \mathrm{d}z \left[\left(1 - \frac{\beta}{z}\right)^2 + \left(\frac{\beta}{z}\right)^2 \right]$$

$$\times \int_0^{Q^2} \mathrm{d}k^2 k^4 \ln \frac{Q^2}{k^2} \left[\int_0^\infty \mathrm{d}r r K_2(\sqrt{z}kr) J_2(\sqrt{1-z}kr) \frac{\mathrm{d}\tilde{\sigma}_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{b}_T}(\mathbf{b}_T, \mathbf{r}_T, x_{\mathbb{P}}) \right]^2$$

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$$x_{\mathbb{P}} F^{\mathrm{D\,(GBW)}}_{T,q\bar{q}g} = \frac{\alpha_s \beta}{8\pi^4} \sum_f e_f^2 \int \mathrm{d}^2\mathbf{b}_T \int_\beta^1 \mathrm{d}z \left[\left(1-\frac{\beta}{z}\right)^2 + \left(\frac{\beta}{z}\right)^2\right]$$

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Small $\beta \to 0$, large N_c, ("MS" Munier, Shoshi)

$$x_{\mathbb{P}} F^{\mathrm{D\,(MS)}}_{T,q\bar{q}g} = \frac{C_F \alpha_s Q^2}{4\pi^4 \alpha_{\mathrm{em}}} \int \mathrm{d}^2\mathbf{b}_T\, \mathrm{d}^2\mathbf{r}_T\, \mathrm{d}^2\mathbf{r}_T{}' \int_0^1 \mathrm{d}z \left|\Psi_T^{\gamma^*}(r, Q, z)\right|^2$$

$$\frac{\mathbf{r}_T{}^2}{(\mathbf{r}_T{}')^2(\mathbf{r}_T - \mathbf{r}_T{}')^2} \left[\mathcal{N}(\mathbf{r}_T{}') + \mathcal{N}(\mathbf{r}_T - \mathbf{r}_T{}') - \mathcal{N}(\mathbf{r}_T) - \mathcal{N}(\mathbf{r}_T{}')\mathcal{N}(\mathbf{r}_T - \mathbf{r}_T{}')\right]^2$$

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Interpolate between these Marquet 2007

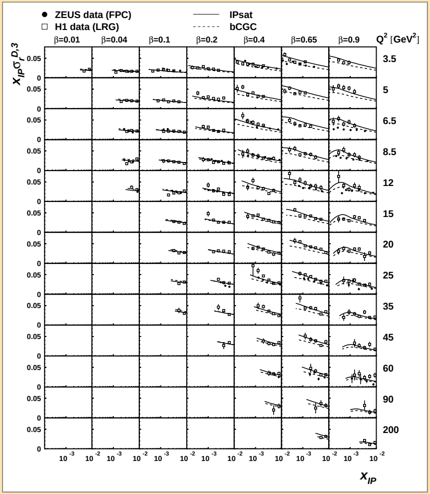
$$x_{\mathbb{P}} F_2^{\mathrm{D}}(x_{\mathbb{P}}, \beta, Q^2) = \frac{x_{\mathbb{P}} F_{T,q\bar{q}g}^{\mathrm{D\,(GBW)}}(x_{\mathbb{P}}, \beta, Q^2) \times x_{\mathbb{P}} F_{T,q\bar{q}g}^{\mathrm{D\,(MS)}}(x_{\mathbb{P}}, Q^2)}{x_{\mathbb{P}} F_{T,q\bar{q}g}^{\mathrm{D\,(GBW)}}(x_{\mathbb{P}}, \beta = 0, Q^2)}.$$

First: HERA data

Agree with HERA ep data ($x_{\mathbb{P}} < 0.01$) with $\chi^2/\text{d.o.f.} \sim 1$.

Need small $\alpha_s = 0.14$
(coefficient of the $q\bar{q}g$-term)
use same value for nuclei.

- Mostly cancels in ratios
- Larger $q\bar{q}g$: natural from b-dependence
  (more on this next slide)



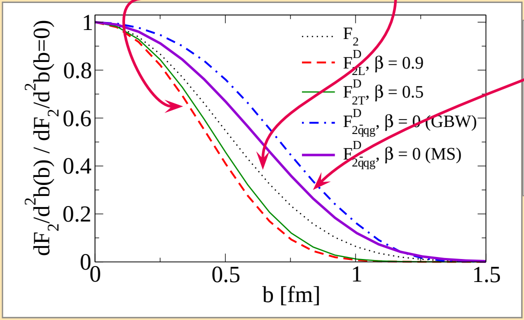
$\mathbf{b}_T$–dependence of different components

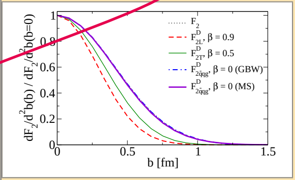
Dominant impact parameters different

$$b^{\text{diff}}(q\bar{q}) < b^{\text{incl}} < b^{\text{diff}}(q\bar{q}g)$$

Integrand vs. $\mathbf{b}_T$ for

diff. $q\bar{q}$ — inclusive — diff $q\bar{q}g$





$Q^2 = 1\text{GeV}^2$

$Q^2 = 100\text{GeV}^2$

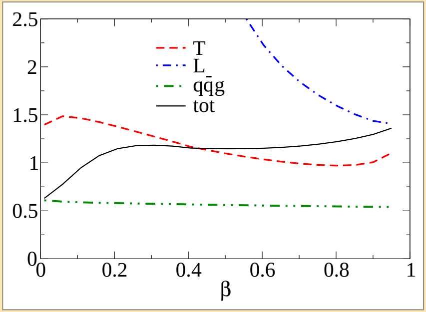
$(x_{\mathbb{P}} = 10^{-3})$

Results: β-dependence

Ratios of nucleus/proton

$$\frac{F^{D}_{2A(x)}}{AF^{D}_{2p(x)}} \text{ with } x = L,\ T(q\bar{q}),\ q\bar{q}g,\ \text{tot.}$$

- $\beta \ll 1$: $q\bar{q}g$ strongly suppressed (black disk limit)
- $\beta \sim 0.5$: transverse $q\bar{q}$ enhanced.
- $\beta \to 1$: longitudinal $q\bar{q}$ very much enhanced.



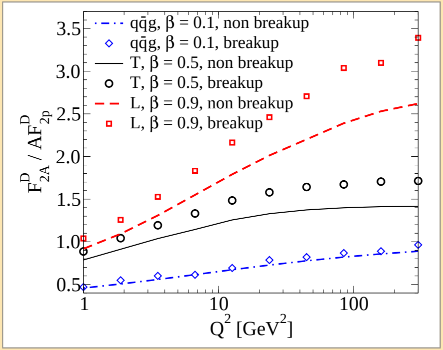
(Au at $Q^2 = 5\text{GeV}^2$ and $x_{\mathbb{P}} = 10^{-3}$)

Results: Q^2-dependence

Nuclei have smaller Q^2/Q_s^2 at same $x_{\mathbb{P}}, Q^2$

▶ Nuclear enhancement of F_2^D's grows with Q^2

- Non breakup = coherent
- Breakup = coherent + incoherent

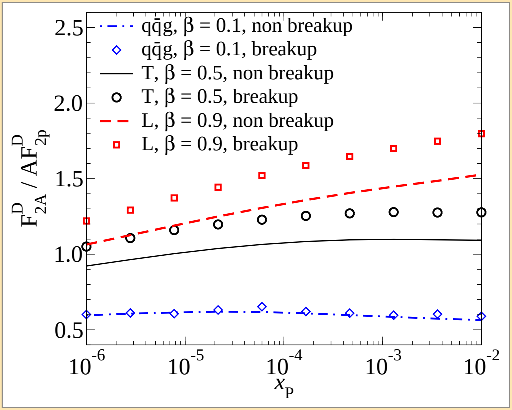


(Au at $x_{\mathbb{P}} = 10^{-3}$)

Results: $x_{\mathbb{P}}$-dependence

At smaller $x_{\mathbb{P}}$ also proton closer to black disk limit

▶ smaller enhancement in $q\bar{q}$-components.

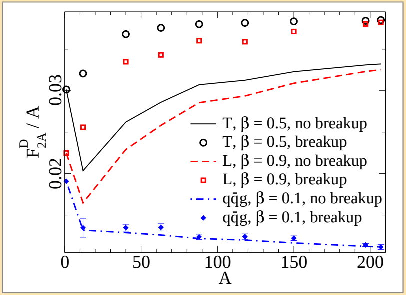


(Au at $Q^2 = 5\text{GeV}^2$)

Results: A-dependence

Small A more dilute than p: coherent diff. suppressed

(Different components at $x_{\mathbb{P}} = 10^{-3}$ and $Q^2 = 5\text{GeV}^2$)



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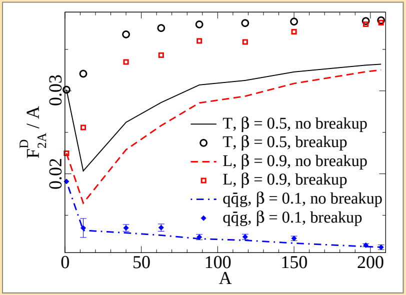

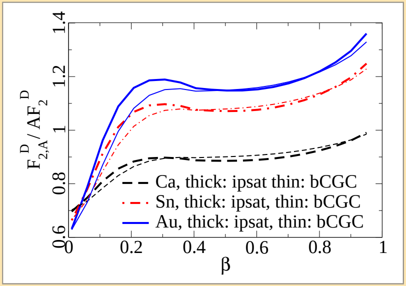

(Different nuclei vs β)

Conclusions

Computed diffractive structure functions F_2^{D} for nuclei

- Realistic b-dependence essential
- Nuclear suppression at small β, enhancement at large β
- Large A close to black disk: diffraction enhanced
- Coherent diffraction at small A suppressed by diluteness

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Further questions:

- t-dependence in nuclei?
- Beyond Glauber-like (independent scattering) treatment of nucleons?

Thank you.