Probing Gluon Saturation via Semi-Inclusive DIS at the EIC

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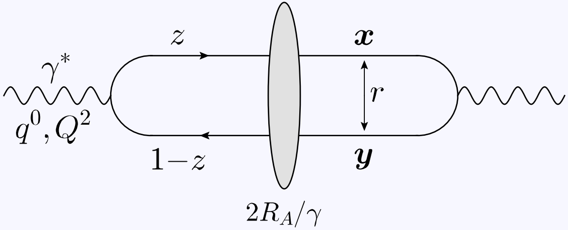
E. Iancu, A.H. Mueller, DT, S.Y. Wei arXiv:2012.08562

Outline

- Dipole picture/factorization of DIS at small-x
- Single Inclusive DIS: "tag" one fermion $z, k_\perp$
- Elastic scattering, photon wavefunction at small $k_\perp$
- Broadening and power law tail at high $k_\perp$
- Cronin peak and evolution
- Scaling, strong-z dependence in $k_\perp$-integrated cross section
- Conclusion & outlook

Dipole Picture of DIS at small-x

High energy scattering conveniently studied in dipole picture

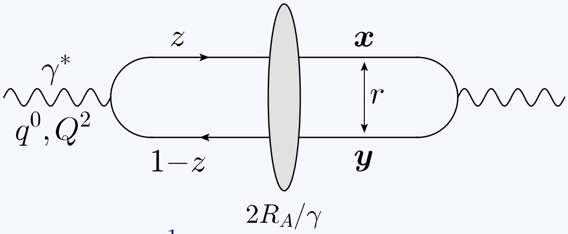


$$q^\mu = \left(\sqrt{q^2 - Q^2}, \mathbf{0}, q\right) \qquad \& \qquad P_N^\mu = \left(\sqrt{P^2 + M^2}, \mathbf{0}, -P\right)$$

Photon coherent time larger than hadron longitudinal extent

$$\tau_{\gamma^*} \sim \frac{2q^0}{Q^2} \gg \frac{2R_A M}{P} \sim \frac{A^{1/3}}{P} \rightsquigarrow x = \frac{2P \cdot q}{Q^2} \ll A^{1/3}$$

DIPOLE FACTORIZATION OF DIS AT SMALL-x

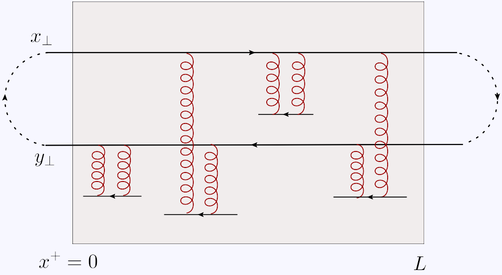


$$\sigma_{\mathrm{L,T}}^{\gamma^* A} = 2 \int \mathrm{d}^2\boldsymbol{r} \int_0^1 \mathrm{d}z \left| \Psi_{\mathrm{L,T}}(r, z; Q^2) \right|^2 \int \mathrm{d}^2\boldsymbol{b}\, T(\boldsymbol{b}, \boldsymbol{r}, x)$$

- Photon WF has support for $r\bar{Q} \lesssim 1$, with $\bar{Q}^2 = z(1-z)Q^2$
- Fermions' typical transverse momentum $k_\perp^2 \sim \bar{Q}^2$
- Elastic amplitude $T = 1 - S$ contains QCD dynamics

$$S = \frac{1}{N_c} \left\langle \mathrm{Tr}\big[V(\boldsymbol{x}) V^\dagger(\boldsymbol{y})\big] \right\rangle_x$$

Color Glass Condensate I : MV model



- Multiple scattering off valence quarks at initial $x_0 \sim 10^{-2}$

$$S(r) = \exp\left[-\frac{r^2 Q_A^2}{4}\,\ln\frac{1}{r^2\Lambda^2}\right] \quad \text{with} \quad Q_A^2 = \frac{2\alpha_s^2 C_F A^{1/3}}{R_p^2}$$

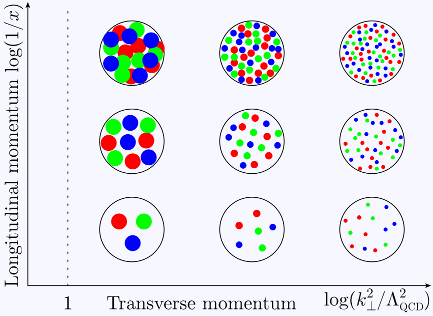
- Enhanced color charged density squared

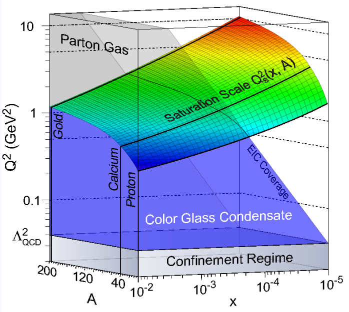
- Unitarity/saturation when $S(r \sim 2/Q_s) \sim 1/2$

$$Q_s^2 \sim Q_A^2 \ln\frac{Q_A^2}{\Lambda^2} \simeq A^{1/3} \ln A^{1/3}$$

Color Glass Condensate II : BK - JIMWLK

Weak coupling non-linear evolution in $\ln x_0/x$: NLO + collinear

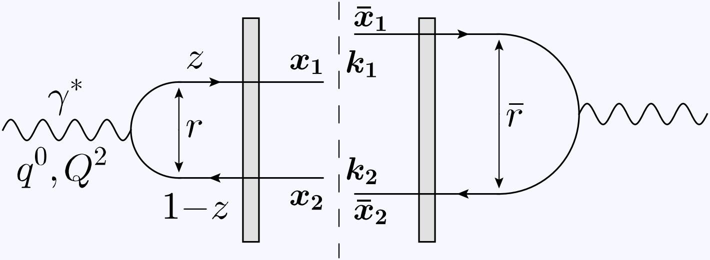




$$Q_s^2(A,x) \sim \Lambda_{\rm QCD}^2 A^{1/3} \left(\frac{x_0}{x}\right)^{\lambda_s} \qquad \text{with} \qquad \lambda_s = 0.2 \div 0.25$$

Q_s^2 at small-x and/or large A (much) larger than $\Lambda_{\rm QCD} \sim 0.2{\rm GeV}$

Forward Dijets in eA Collisions



$q\bar{q}$ fluctuation "on-shell" due to scattering with nucleus

Measure $\boldsymbol{k}_1$, $\boldsymbol{k}_2$ and $z, 1-z$ of outgoing particles

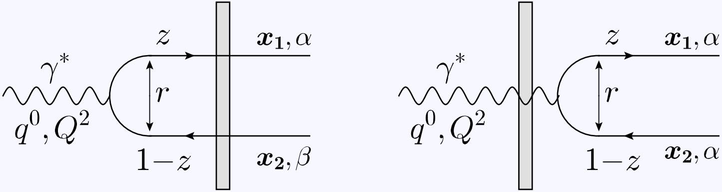
Coordinate space to transverse momenta via FTs $\boldsymbol{x}_i - \bar{\boldsymbol{x}}_i \to \boldsymbol{k}_i$

Final transverse momenta get two contributions:

(i) Initial momentum from γ^* splitting $k_\perp^2 \sim z(1-z)Q^2$

(ii) Modified by scattering with nucleus $k_\perp^2 \sim Q_s^2$

Splitting can occur before or after the scattering with nucleus



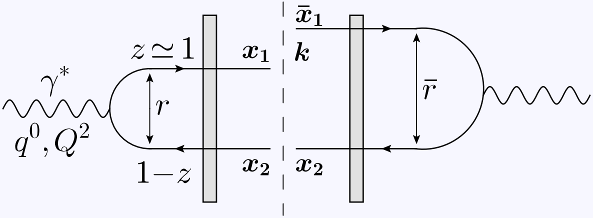
$$\mathcal{A} \sim \int \mathrm{d}^2\boldsymbol{x}_1 \mathrm{d}^2\boldsymbol{x}_2\, \mathrm{e}^{-\mathrm{i}(\boldsymbol{k}_1\cdot\boldsymbol{x}_1+\boldsymbol{k}_2\cdot\boldsymbol{x}_2)}\Psi\big(r, z; Q^2\big)\big[V(\boldsymbol{x}_1)V^\dagger(\boldsymbol{x}_2) - 1\big]_{\alpha\beta}$$

Typically $|\boldsymbol{k}_1 + \boldsymbol{k}_2| \sim Q_s$ and $\alpha \neq \beta$: inelastic scattering

If $\boldsymbol{k}_1 + \boldsymbol{k}_2 = 0$ and $\alpha = \beta$: elastic scattering

Integrate over $\boldsymbol{k}_2 \rightsquigarrow \bar{\boldsymbol{x}}_2 = \boldsymbol{x}_2$: SIDIS cross section

Expressions like total DIS, only additional dependence $\mathrm{J}_{0,1}(k_\perp r)$



Key point: if $z \to 1$, can have $Q^2 \gg Q_s^2$ with $z(1-z)Q^2 \lesssim Q_s^2$

Then $r_{\max} Q_s \sim Q_s/\bar{Q} \gtrsim 1$: scattering sensitive to saturation

Decreasing $1-z$ probes the saturation regime

Elastic Scattering at low-$\boldsymbol{k}$

Example: elastic scattering in limiting case $k_\perp^2, \bar{Q}^2 \ll Q_s^2$

$$\mathcal{A}_{\rm el} \sim \int {\rm d}r\, r\, {\rm J}_1(k_\perp r){\rm K}_1(\bar{Q}r)T(r)$$

In general depends on three scales $k_\perp^2, \bar{Q}^2, Q_s^2$ entering integrand

Phase and wavefunction have support even when T is close to 1

$$1/Q_s < r < 1/k_\perp, 1/\bar{Q}$$

Calculated exactly

$$\frac{{\rm d}\sigma_{\rm el,T}}{{\rm d}z{\rm d}^2\boldsymbol{k}} \sim \left| \int {\rm d}r\, r\, {\rm J}_1(k_\perp r){\rm K}_1(\bar{Q}r) \right|^2 \sim \frac{k_\perp^2}{(k_\perp^2 + \bar{Q}^2)^2}$$

Black disk limit scattering “measures” photon WF

Inelastic Scattering and Broadening at $\boldsymbol{k} \sim Q_s$

Inelastic scattering is sensitive to interference

$$\frac{\mathrm{d}\sigma_{\rm inel}}{\mathrm{d}z\mathrm{d}^2\boldsymbol{k}} \sim \int_{\boldsymbol{r},\boldsymbol{r}'} \mathrm{e}^{-\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{r}-\boldsymbol{r}')}\Psi\big(r,z;Q^2\big)\Psi^*\big(r',z;Q^2\big)[S(\boldsymbol{r}-\boldsymbol{r}')-S(\boldsymbol{r})S(-\boldsymbol{r}')]$$

Regime of interest $\bar{Q}^2 \ll k_\perp^2 \lesssim Q_s^2$

Log-regime $1/Q_s \ll r, r' \ll 1/\bar{Q}$ with $|\boldsymbol{r}-\boldsymbol{r}'| \sim 1/Q_s$ much smaller

Interference term $S(\boldsymbol{r}-\boldsymbol{r}')$ dominates and of order $\mathcal{O}(1)$

$$\frac{\mathrm{d}\sigma_{\rm inel,T}}{\mathrm{d}z\mathrm{d}^2\boldsymbol{k}} \sim \ln\frac{Q_s^2}{\bar{Q}^2}\,\frac{1}{\pi Q_s^2}\exp(-k_\perp^2/Q_s^2) \qquad \text{vs} \qquad \frac{\mathrm{d}\sigma_{\rm el,T}}{\mathrm{d}z\mathrm{d}^2\boldsymbol{k}} \sim \frac{1}{k_\perp^2}$$

(i) Transverse momentum broadening

(ii) Elastic more significant (parametrically) for $\bar{Q}^2 \ll k_\perp^2 \lesssim Q_s^2$

Hard Scattering and power-law at high-$\boldsymbol{k}$

When $k_\perp^2 \gg Q_s^2 \gg \bar{Q}^2$, again inelastic scattering and the interference term dominate

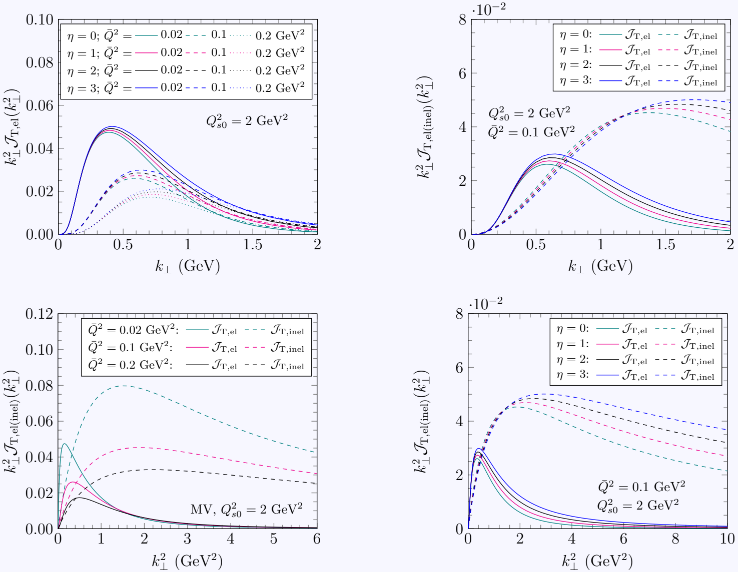
- Easy since can linearize
- Depends on the form of the amplitude
- Modulo logarithms:

$$\frac{\mathrm{d}\sigma_{\mathrm{inel,T}}}{\mathrm{d}z\mathrm{d}^2\boldsymbol{k}} \sim \frac{1}{k_\perp^2}\left(\frac{Q_s^2}{k_\perp^2}\right)^\gamma$$

  MV model: $\gamma = 1$, BK: $\gamma < 1$

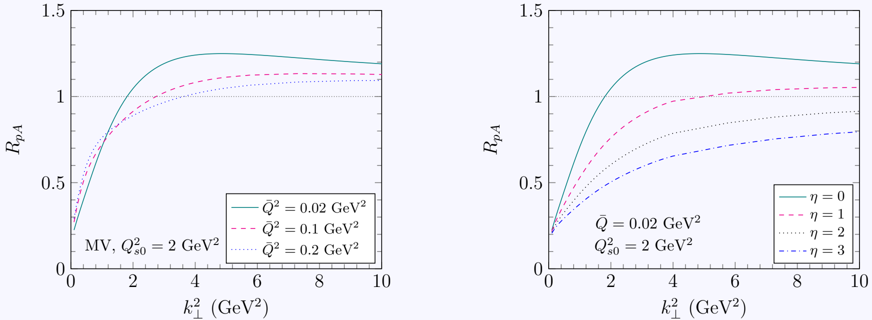
- Elastic (amplitude squared) power-suppressed

Elastic vs Inelastic



R_{pA} : Peak at large z and Evolution

SIDIS in eA divided by $A^{1/3}\times$ SIDIS in ep

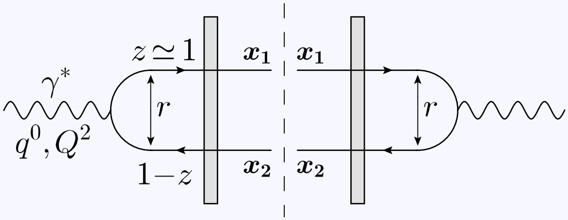


- MV model: $Q_A^2 = A^{1/3} Q_p^2$ at $\eta = 0$, peak for small $\bar{Q}^2/Q^2$
  $R_{pA}^{\max} \sim \ln Q_s^2(A)/\bar{Q}^2 > 1$

- Collinearly improved BK, quick disappearance of peak

$\boldsymbol{k}$-INTEGRATED CROSS SECTION

Integrate transverse momentum $\boldsymbol{k}$: DIS cross section at fixed $z \sim 1$

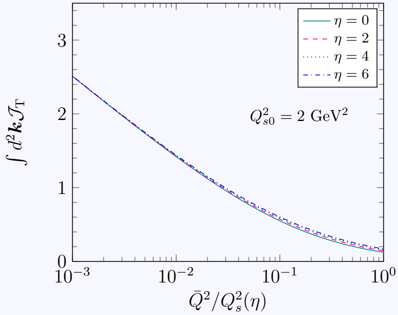


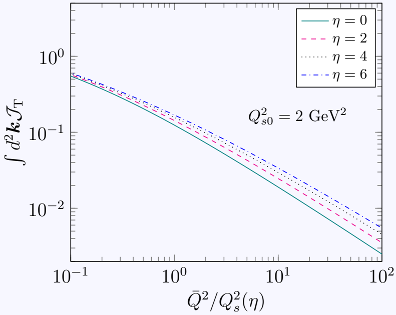
- For $\bar{Q}^2 \ll Q_s^2$, saturation, elastic $\sim$ inelastic
- For $\bar{Q}^2 \gg Q_s^2$, inelastic scattering, power-law tail

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to qX}}{\mathrm{d}z} \sim \ln \frac{Q_s^2}{\bar{Q}^2} \qquad \text{vs} \qquad \left(\frac{Q_s^2}{\bar{Q}^2}\right)^{\gamma} \ln \frac{\bar{Q}^2}{Q_s^2}$$

Scaling

Dependence only on the scaling variable $\bar{Q}^2/Q_s^2$



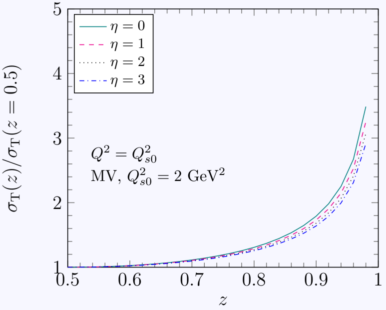


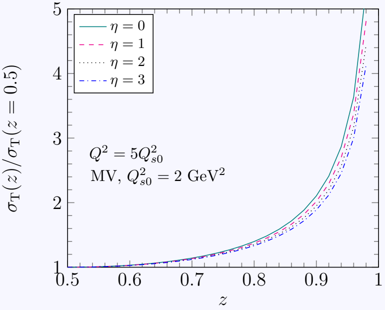
Perfect scaling at low $\bar{Q}^2$

Softening and asymptotic scaling at high $\bar{Q}^2$

Strong z-dependence

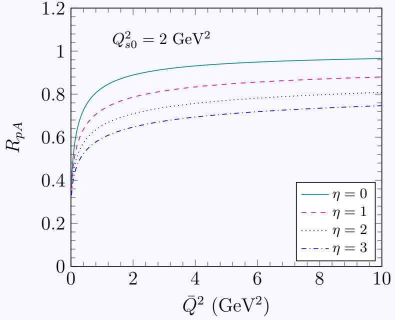
Fix Q^2 and study z-dependence

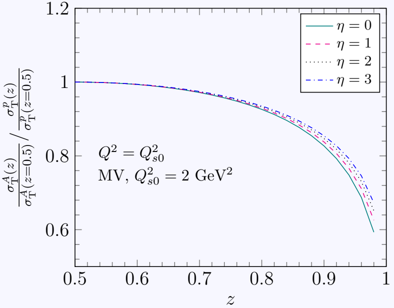




Not pronounced difference between logarithmic (left, saturation) and power-law divergence (right, weak scattering)

R_{pA} AND DOUBLE RATIO





- R_{pA} (as fn of $\bar{Q}^2$): suppression which increases
- Double ratio: different z-dependence now clearly visible

Conclusions

- Forward ($z \to 1$) SIDIS as a probe of gluon saturation
- Elastic scattering is significant at $k_\perp \ll Q_s$
- Inelastic scattering dominates at $k_\perp \gtrsim Q_s$

  Broadening at $k_\perp \sim Q_s$, power-law tail at $k_\perp \gg Q_s$
- R_{pA}: "wide peak" at $\eta = 0$, disappears with evolution
- $\boldsymbol{k}$-integrate cross section

  Strong z-dependence, elastic = inelastic at $\bar{Q} \ll Q_s$
- Outloook: fragmentation functions, jets?
- Hopefully visible effects at the EIC in selected observables