Nonlinear $k_\perp$–factorization and the unintegrated gluon distribution of a nucleus

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Outline

Color dipole cross section $\longrightarrow$ unintegrated gluon distribution

Unintegrated gluon distribution of a nucleus: boundary condition

Nonlinear small-x evolution of the nuclear glue

Small–x evolution of quasielastic diffraction

How photon-jet correlations can probe the nuclear unintegrated glue

Summary and outlook

References

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color dipole cross section ↔ unintegrated glue

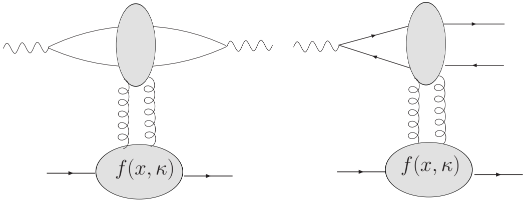
- at high energies, when $\Lambda_{QCD} \ll p_\perp \ll \sqrt{s}$, we should take parton transverse momenta explicitly into account → unintegrated parton distributions.
- equivalence of color dipole-cross section and unintegrated gluon distribution (Nikolaev & Zakharov '94):

$$\int \frac{d^2\boldsymbol{r}}{(2\pi)^2}\,\sigma(x,\boldsymbol{r})\,\exp(-i\boldsymbol{p}\boldsymbol{r}) = \sigma_0(x)\,\delta^{(2)}(\boldsymbol{p}) - f(x,\boldsymbol{p})$$

$$f(x,\boldsymbol{p}) = \frac{4\pi\alpha_S}{N_c}\,\frac{1}{\boldsymbol{p}^4}\,\frac{\partial G(x,\boldsymbol{p}^2)}{\partial \log \boldsymbol{p}^2};\;\; \sigma_0(x) = \int d^2\boldsymbol{p}\, f(x,\boldsymbol{p})\,.$$

- nb: diffractive amplitude $\propto \int d^2\boldsymbol{r}\exp(-i\boldsymbol{q}\boldsymbol{r})\,\sigma(x,\boldsymbol{r})\,\psi_{q\bar{q}}(z,\boldsymbol{r})$,

  $\boldsymbol{q}$ = transverse momentum of q or $\bar{q}$ diffractive jet.



small-x evolution: adding $q\bar{q}(ng)$ Fock-states:

Nikolaev & Zakharov '94, Mueller '94

- as we increase energy Fock states $q\bar{q}g, q\bar{q}gg, \dots q\bar{q}(ng)$ with strongly ordered light–cone momenta $z_n \ll \dots \ll z_2 \ll z_1 \ll 1$ will be coherent over the target.
- their effect can be resummed and absorbed into the x–dependent dipole cross section:

$$\frac{\partial \sigma(x, \boldsymbol{r})}{\partial \log(1/x)} = \int d^2\boldsymbol{\rho} K(\boldsymbol{\rho}, \boldsymbol{\rho} + \boldsymbol{r}) \Big[\sigma_{q\bar{q}g}(x, \boldsymbol{\rho}, \boldsymbol{r}) - \sigma(x, \boldsymbol{r})\Big]$$

$$\sigma_{q\bar{q}g}(x, \boldsymbol{\rho}, \boldsymbol{r}) = \frac{N_c^2}{N_c^2 - 1}[\sigma(x, \boldsymbol{\rho}) + \sigma(x, \boldsymbol{\rho} + \boldsymbol{r})] - \frac{1}{N_c^2 - 1}\sigma(x, \boldsymbol{r})$$

$$K(\boldsymbol{\rho}, \boldsymbol{\rho} + \boldsymbol{r}) \propto \Big|\psi(\boldsymbol{\rho}) - \psi(\boldsymbol{\rho} + \boldsymbol{r})\Big|^2, \; \psi(\boldsymbol{\rho}) = \frac{\sqrt{C_F \alpha_S}}{\pi} \frac{\boldsymbol{\rho}}{\boldsymbol{\rho}^2} F(\mu_G \boldsymbol{\rho})$$

- $\mu_G^2 \sim 0.5\,\mathrm{GeV}^2$, 'gluon mass' - a smooth cutoff for long wavelength gluons, which respects 'gauge cancellations'.

...in momentum space it is BFKL:

- the equivalence of dipole and momentum space approaches extends to the small-x evolution:

$$\begin{aligned}\frac{\partial f(x,\boldsymbol{p})}{\partial \log(1/x)} &= 2\int d^2\boldsymbol{\kappa}\, K(\boldsymbol{p},\boldsymbol{p}+\boldsymbol{\kappa})\, f(x,\boldsymbol{\kappa}) - f(x,\boldsymbol{p}) \int d^2\boldsymbol{\kappa}\, K(\boldsymbol{\kappa},\boldsymbol{\kappa}+\boldsymbol{p}) \\ &= \mathcal{K}_{BFKL} \otimes f(x,\boldsymbol{p})\end{aligned}$$

- the kernel:

$$K(\boldsymbol{p}_1,\boldsymbol{p}_2) = K_0 \cdot \left|\frac{\boldsymbol{p}_1}{\boldsymbol{p}_1^2+\mu_G^2} - \frac{\boldsymbol{p}_2}{\boldsymbol{p}_2^2+\mu_G^2}\right|^2, \; K_0 = \frac{C_A \alpha_S}{2\pi^2}$$

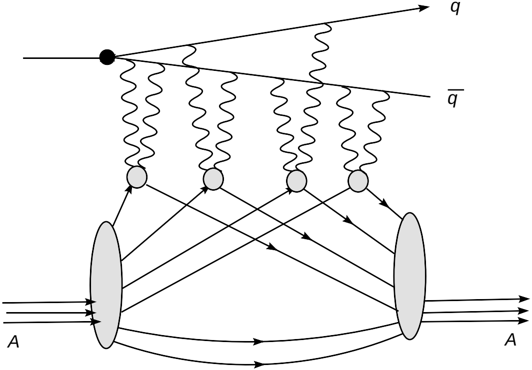
- nonperturbative parameters: μ_G, freezing of α_S.

unintegrated glue of a nucleus:

- amplitude for scattering of a $q\bar{q}$ dipole $\boldsymbol{r}$ off a nucleus at fixed impact parameter $\boldsymbol{b} \leftrightarrow$ the nuclear unintegrated glue:

$$\int \frac{d^2\boldsymbol{r}}{(2\pi)^2} \Gamma(\boldsymbol{b}, x, \boldsymbol{r}) \exp(-i\boldsymbol{pr}) = (1 - w_0(\boldsymbol{b}, x))\, \delta^{(2)}(\boldsymbol{p}) - \phi(\boldsymbol{b}, x, \boldsymbol{p})$$

- a physical observable: hard diffractive dijets in $\pi A \to Jet_1 Jet_2 A$ acquire $\boldsymbol{p}$ from gluons $\to$ diffractive amplitude directly proportional to $\phi(\boldsymbol{b}, x, \boldsymbol{p})$.



Nuclear unintegrated glue at $x \sim x_A$

- at not too small $x \sim x_A = (R_A m_p)^{-1} \sim 0.01$ only the $\bar{q}q$ state is coherent over the nucleus, and $\Gamma(\boldsymbol{b}, x, \boldsymbol{r})$ can be constructed from Glauber-Gribov theory:

$$\Gamma(\boldsymbol{b}, x_A, \boldsymbol{r}) = 1 - \exp[-\sigma(x_A, \boldsymbol{r}) T_A(\boldsymbol{b})/2] \,.$$

- nuclear coherent glue per unit area in impact parameter space:

$$\phi(\boldsymbol{b}, x_A, \boldsymbol{p}) = \sum w_j(\boldsymbol{b}, x_A) f^{(j)}(x_A, \boldsymbol{p})$$

- collective glue of j overlapping nucleons :

$$f^{(j)}(x_A, \boldsymbol{p}) = \int \Big[\prod^{j} d^2\boldsymbol{\kappa}_i f(x_A, \boldsymbol{\kappa}_i) \Big] \delta^{(2)}(\boldsymbol{p} - \sum \kappa_i)$$

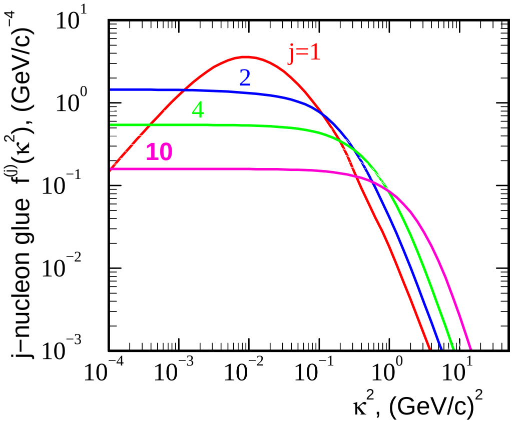
- probab. to find j overlapping nucleons

$$w_j(\boldsymbol{b}, x_A) = \frac{\nu_A^j(\boldsymbol{b}, x_A)}{j!} \exp[-\nu_A(\boldsymbol{b}, x_A)] \,, \; \nu_A(\boldsymbol{b}, x_A) = \frac{1}{2} \alpha_S(q^2) \, \sigma_0(x_A) \, T_A(\boldsymbol{b}) \,,$$

- impact parameter $\boldsymbol{b} \to$ effective opacity ν_A, $q^2 =$ the relevant hard scale.

Nuclear unintegrated glue: salient features

collective glue $f^{(j)}(x_A, \boldsymbol{\kappa})$



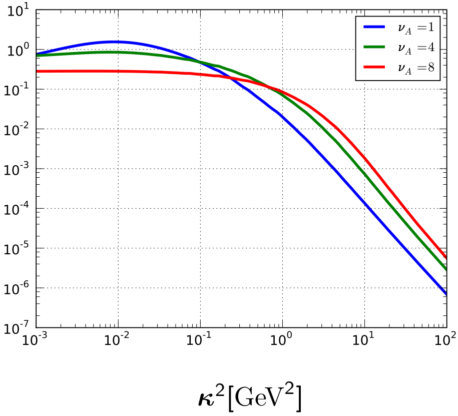
- nuclear coherent glue per unit area in impact parameter space:

$$\phi(\nu_A, x_A, \boldsymbol{\kappa}) = \sum w_j(\nu_A) f^{(j)}(x_A, \boldsymbol{\kappa})$$

- typical scale: the saturation scale $Q_A^2 \sim 0.8 \div 1.5$ GeV^2 for realistic glue and heavy nuclei.
- large–$\boldsymbol{\kappa}^2$ Cronin–type antishadowing enhancement
- furnishes linear $k_\perp$–factorization of inclusive deep inelastic, forward single jets in DIS, and diffractive dijets.
- straightforward unitarity cut interpretation.

Nuclear unintegrated glue: salient features, $x_A = 0.01$

collective nuclear glue $\phi(\nu_A, x_A, \boldsymbol{\kappa})$



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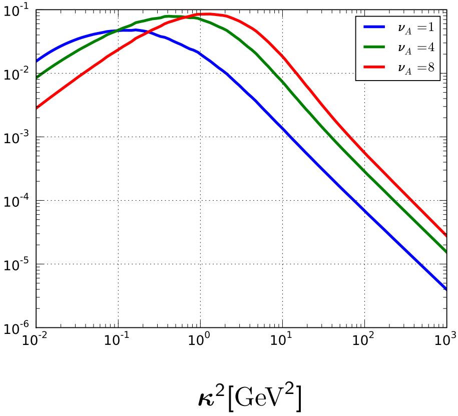
saturation scale grows with ν_A, $x_A = 0.01$

$$\boldsymbol{\kappa}^2\,\phi(\nu_A, x_A, \boldsymbol{\kappa}) \propto \partial G_A(x_A, \boldsymbol{\kappa}^2)/\partial \boldsymbol{\kappa}^2$$



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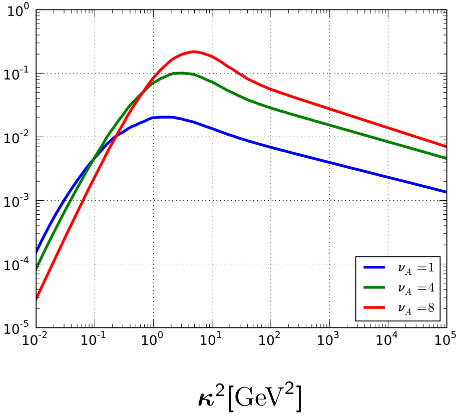
...behaviour at large κ^2, $x_A = 0.01$

$$\boldsymbol{\kappa}^4\,\phi(\nu_A, x_A, \boldsymbol{\kappa}) \propto \partial G_A(x_A, \boldsymbol{\kappa}^2)/\partial \log \boldsymbol{\kappa}^2$$



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Nuclear unintegrated glue: small-x evolution

- again, add the $q\bar{q}g$ Fock-state:
- small–x evolution Balitsky–Kovchegov '96–'98:

$$\Gamma_{q\bar{q},A}(\nu_A, x_A, \boldsymbol{r}) \to \Gamma_{q\bar{q},A}(\nu_A, x_A, \boldsymbol{r}) + \log(x_A/x)\delta\Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{r})$$

$$\delta\Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{r}) \propto \int d^2\rho K(\boldsymbol{\rho}, \boldsymbol{\rho}+\boldsymbol{r})\Big(\Gamma_{q\bar{q}g,A}(\nu_A, \boldsymbol{\rho}, \boldsymbol{r}) - \Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{r})\Big)$$

$$\Gamma_{q\bar{q}g,A}(\nu_A, \boldsymbol{\rho}, \boldsymbol{r}) = \Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{\rho}) + \Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{\rho}+\boldsymbol{r}) - \Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{\rho})\Gamma_{q\bar{q},A}(\nu_A, \boldsymbol{\rho}+\boldsymbol{r})$$

- evolution of unintegrated glue:

$$\frac{\partial\phi(\nu_A, x, \boldsymbol{p})}{\partial\log(1/x)} = \mathcal{K}_{BFKL} \otimes \phi(\nu_A, x, \boldsymbol{p}) + \mathcal{Q}[\phi](\nu_A, x, \boldsymbol{p})$$

$$\mathcal{Q}[\phi](\nu_A,x,\boldsymbol{p}) = \int d^2\boldsymbol{q}\, d^2\boldsymbol{\kappa}\, \phi(\nu_A,x,\boldsymbol{q}) \Big\{ \Big[K(\boldsymbol{p}+\boldsymbol{\kappa},\boldsymbol{p}+\boldsymbol{q}) - K(\boldsymbol{p},\boldsymbol{\kappa}+\boldsymbol{p}) - K(\boldsymbol{p},\boldsymbol{q}+\boldsymbol{p})\Big]\phi(\nu_A,x,\boldsymbol{\kappa}) - \phi(\nu_A,x,\boldsymbol{p})\Big[K(\boldsymbol{\kappa},\boldsymbol{\kappa}+\boldsymbol{q}+\boldsymbol{p}) - K(\boldsymbol{\kappa},\boldsymbol{\kappa}+\boldsymbol{p})\Big]\Big\}$$

properties of the nonlinear term:

- first piece of the nonlinear term looks like a diffractive cut of a triple-Pomeron vertex Nikolaev & WS '05:

$$\int d^2\boldsymbol{q} d^2\boldsymbol{\kappa}\phi(\nu_A, x, \boldsymbol{q})\Big[K(\boldsymbol{p}+\boldsymbol{\kappa}, \boldsymbol{p}+\boldsymbol{q}) - K(\boldsymbol{p}, \boldsymbol{\kappa}+\boldsymbol{p}) - K(\boldsymbol{p}, \boldsymbol{q}+\boldsymbol{p})\Big]\phi(\nu_A, x, \boldsymbol{\kappa})$$

$$= -2K_0\Big|\int d^2\boldsymbol{\kappa}\,\phi(\nu_A, x, \boldsymbol{\kappa})\Big[\frac{\boldsymbol{p}}{\boldsymbol{p}^2+\mu_G^2} - \frac{\boldsymbol{p}+\boldsymbol{\kappa}}{(\boldsymbol{p}+\boldsymbol{\kappa})^2+\mu_G^2}\Big]\Big|^2$$

- at large $\boldsymbol{p}^2$ the nonlinear term is a pure higher twist, it is dominated by the 'anticollinear' region $\boldsymbol{\kappa}^2 > \boldsymbol{p}^2$. It cannot be written as a square of the integrated gluon distribution.

$$\mathcal{Q}[\phi](\nu_A, x, \boldsymbol{p}) \approx -\frac{2K_0}{\boldsymbol{p}^2}\Big|\int_{\boldsymbol{p}^2}\frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^2}\phi(\nu_A, x, \boldsymbol{\kappa}^2)\Big|^2$$

$$-2K_0\phi(\nu_A, x, \boldsymbol{p}^2)\int_{\boldsymbol{p}^2}\frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^2}\int_{\boldsymbol{\kappa}^2} d^2\boldsymbol{q}\phi(\nu_A, x, \boldsymbol{q}^2)$$

- for the lowest 'conformal spin' component, it involves only 1-dim integrations, which greatly helps numerics.

Quasielastic diffractive production $\gamma^* A \to VA^*$

- diffractive production with breakup of the target nucleus, no particle production in the nuclear hemisphere:

$$\frac{d\sigma(\gamma_i^* A \to V_f A^*)}{d\boldsymbol{\Delta}^2}\Big|_{\boldsymbol{\Delta}^2=0} =$$
$$\sum_{A^* \neq A} \Big| \langle A^* \otimes V| \int d^2\boldsymbol{b}_+ d^2\boldsymbol{b}_- \Big(1 - \hat{S}_A(\boldsymbol{b}_+, \boldsymbol{b}_-)\Big)|A \otimes \gamma^*\rangle \Big|^2$$
$$= \int d^2\boldsymbol{b}\, T_A(\boldsymbol{b}) \Big| \langle V|\sigma(\boldsymbol{r}) \exp[-\frac{1}{2}\sigma(\boldsymbol{r}) T_A(\boldsymbol{b})]|\gamma^*\rangle \Big|^2 + \dots \qquad (2)$$

- a simple generalization of quasielastic pA scattering (Glauber & Matthiae, Czyż et al. 1970)
- incoherent sum over $\boldsymbol{b}$, effective diffraction operator:
  $\Omega(\boldsymbol{r}, \boldsymbol{b}) = \sigma(\boldsymbol{r}) \exp[-\frac{1}{2}\sigma(\boldsymbol{r}) T_A(\boldsymbol{b})]$
- valid at $x \sim x_A$

Quasielastic diffractive production $\gamma^* A \to V A^*$

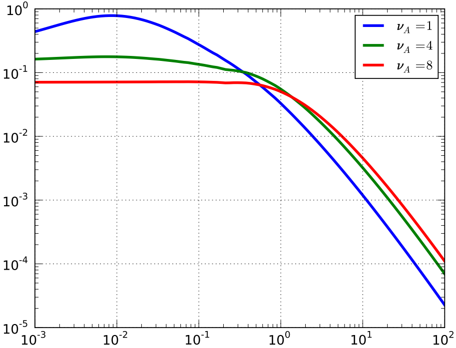
- for $x \ll x_A$ we must add the $q\bar{q}g$–Fock–state of the photon/vector meson, and absorb the effect of the gluon into the effective x–dependent diffraction operator $\Omega(x, \boldsymbol{r}, \boldsymbol{b})$.
- coupled equations for $\Omega(x, \boldsymbol{r}, \boldsymbol{b})$ and the $q\bar{q}$– S-matrix, $S_{q\bar{q}}(x, \boldsymbol{r}) = 1 - \Gamma_{q\bar{q}}(x, \boldsymbol{r})$:

$$
\begin{aligned}
\frac{\partial S_{q\bar{q}}(x,\boldsymbol{r})}{\partial \log(1/x)} &= \int d^2\boldsymbol{\rho} K(\boldsymbol{\rho}, \boldsymbol{\rho}+\boldsymbol{r}) \Big(S_{q\bar{q}}(x,\boldsymbol{\rho}) S_{q\bar{q}}(x,\boldsymbol{\rho}+\boldsymbol{r}) - S_{q\bar{q}}(x,\boldsymbol{r}) \Big) \\
\frac{\partial \Omega(x,\boldsymbol{r})}{\partial \log(1/x)} &= \int d^2\boldsymbol{\rho} K(\boldsymbol{\rho}, \boldsymbol{\rho}+\boldsymbol{r}) \Big(S_{q\bar{q}}(x,\boldsymbol{\rho}) \Omega(x,\boldsymbol{\rho}+\boldsymbol{r}) + S_{q\bar{q}}(x,\boldsymbol{\rho}+\boldsymbol{r}) \Omega(x,\boldsymbol{\rho}) \\
&\quad - \Omega(x,\boldsymbol{r}) \Big)
\end{aligned}
$$

- The boundary condition is $\Omega(x_A, \boldsymbol{r}) = \sigma(x_A, \boldsymbol{r}) S_{q\bar{q}}(x_A, \boldsymbol{r})$.
- Notice, that after small-x evolution $\Omega(x, \boldsymbol{r}) \neq \sigma(x, \boldsymbol{r}) S_{q\bar{q}}(x, \boldsymbol{r})$
- a similar set of coupled equations holds for the rapidity–gap evolution of the central diffractive process $pA \to p + \mathrm{Higgs} + A$, where it sums up all multipomeron diagrams.

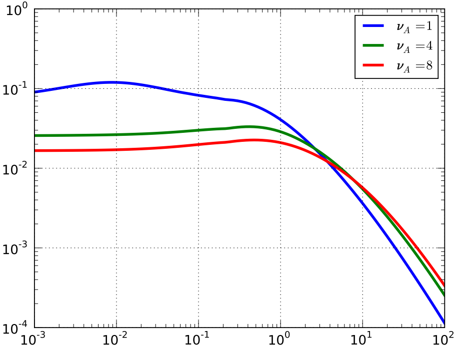
The evolved nuclear glue $\phi(\nu_A, x, \boldsymbol{p})$:

$\phi(\nu_A, x, \boldsymbol{p})$, $x = 10^{-4}$



$\boldsymbol{p}^2[\mathrm{GeV}^2]$

$\phi(\nu_A, x, \boldsymbol{p})$, $x = 10^{-6}$

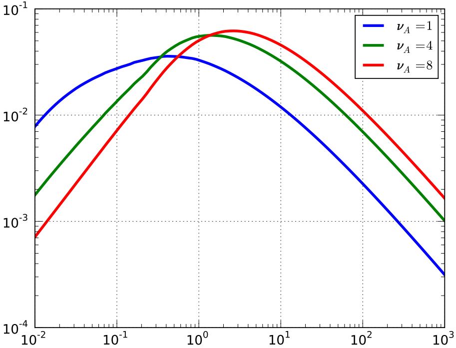


$\boldsymbol{p}^2[\mathrm{GeV}^2]$

- $\mu_G^2 = 0.5\mathrm{GeV}^2$, running α_S with 'freezing'.

Evolution of the saturation scale:

$\boldsymbol{p}^2\phi(\nu_A, x, \boldsymbol{p})$, $x = 10^{-4}$



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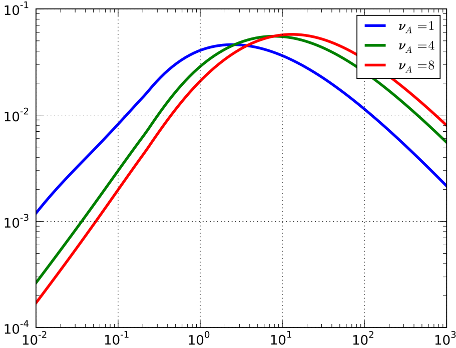
$\boldsymbol{p}^2\phi(\nu_A, x, \boldsymbol{p})$, $x = 10^{-6}$

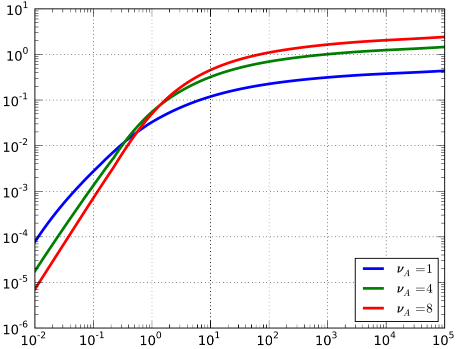


$\boldsymbol{p}^2[\mathrm{GeV}^2]$

- $\mu_G^2 = 0.5\mathrm{GeV}^2$, running α_S with 'freezing'.

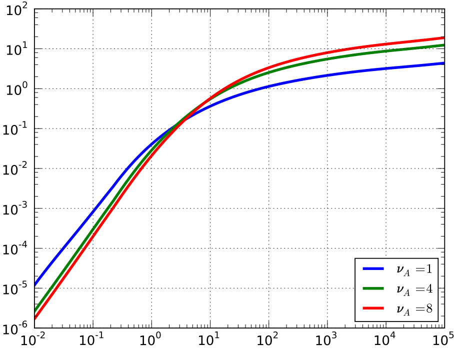
Large p^2–behaviour of the unintegrated glue:

$\boldsymbol{p}^4\phi(\nu_A, x, \boldsymbol{p})$, $x = 10^{-4}$



$\boldsymbol{p}^2[\mathrm{GeV}^2]$

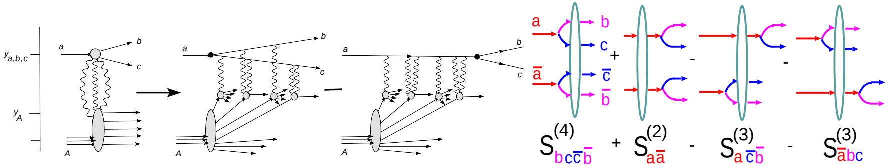
$\boldsymbol{p}^4\phi(\nu_A, x, \boldsymbol{p})$, $x = 10^{-6}$



$\boldsymbol{p}^2[\mathrm{GeV}^2]$

- the effective large-$\boldsymbol{p}^2$ 'anomalous dimension', $\gamma(x) > 2$ in $(\mu^2/\boldsymbol{p}^2)^{\gamma(x)}$ is due to the linear BFKL piece.

Production as excitation of beam partons $a \longrightarrow bc$



- To calculate dijet correlations, we need the two parton density matrix.
- In general this involves S–matrices of up to 4-parton states, and a coupled channel problem in the space of color representations. In momentum space, the pertinent observables are nonlinear functionals of the unintegrated nuclear glue.
- great simplification in $q \longrightarrow q\gamma$: γ does not interact, hence only 2-parton($q\bar{q}$) S-matrices are involved. Furthermore, the problem becomes an abelian one.
- $q \longrightarrow q\gamma$ satisfies a linear $k_\perp$-factorization theorem.

Linear $k_\perp$–factorization of $q \to q\gamma$

- on the free nucleon:

$$\frac{2(2\pi)^2 d\sigma_N(q \to q\gamma)}{dz d^2\boldsymbol{p} d^2\boldsymbol{\Delta}} = f(x, \boldsymbol{\Delta}) \Big| \psi(z, \boldsymbol{p}) - \psi(z, \boldsymbol{p} - z\boldsymbol{\Delta}) \Big|^2$$

with

$$\Big| \psi(z, \boldsymbol{p}_1) - \psi(z, \boldsymbol{p}_2) \Big|^2 = P_{\gamma q}(z) \Big| \frac{\boldsymbol{p}_1}{\boldsymbol{p}_1^2 + \varepsilon^2} - \frac{\boldsymbol{p}_2}{\boldsymbol{p}_2^2 + \varepsilon^2} \Big|^2$$

- $z, \boldsymbol{p} \to$ photon momentum, $\varepsilon^2 = z m_q^2$, $P_{\gamma q}(z) =$ splitting function
- $\boldsymbol{\Delta} = \boldsymbol{p} + \boldsymbol{p}_q$ =decorrelation momentum
- notice the collinear pole at $\boldsymbol{p} = z\boldsymbol{\Delta}$, from final state photon emission of the scattered quark.
- exact over the phase space of the γq–pair.
- decorrelation momentum distribution maps out the unintegrated glue

Linear $k_\perp$–factorization of $q \to q\gamma$

- on the nucleus:

$$\frac{(2\pi)^2 d\sigma_A(q \to q\gamma)}{dz d^2\boldsymbol{p} d^2\boldsymbol{\Delta} d^2\boldsymbol{b}} = \phi(\nu_A, x, \boldsymbol{\Delta}) \Big| \psi(z, \boldsymbol{p}) - \psi(z, \boldsymbol{p} - z\boldsymbol{\Delta}) \Big|^2$$
$$+ w_0(\nu_A)\, \delta^{(2)}(\boldsymbol{\Delta}) \Big| \psi(z, \boldsymbol{p}) - \psi(z, \boldsymbol{p} - z\boldsymbol{\Delta}) \Big|^2$$

- a potential factorization violating diffractive contribution vanishes
- the (parton-level) 'nuclear modification factor' doesn't depend on $\boldsymbol{p}$:

$$R_{pA}(\nu_A, \boldsymbol{p}, \boldsymbol{\Delta}) = \frac{d\sigma_A}{T_A(\boldsymbol{b}) d\sigma_N} = \frac{\phi(\nu_A, x, \boldsymbol{\Delta})}{\nu_A f(x, \boldsymbol{\Delta})}$$

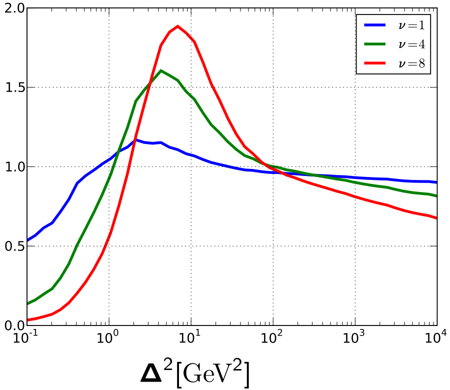
- similarly the central-to-peripheral ratio:

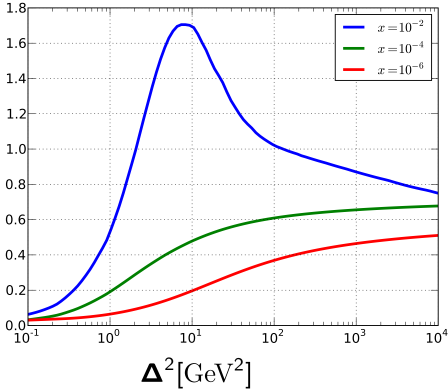
$$R_{CP}(\nu_>, \nu_<, \boldsymbol{p}, \boldsymbol{\Delta}) = \frac{\nu_< \phi(\nu_>, x, \boldsymbol{\Delta})}{\nu_> \phi(\nu_<, x, \boldsymbol{\Delta})}$$

R_{pA} (left panel), R_{CP} (right panel)

$$\frac{\phi(\nu_A, x, \mathbf{\Delta})}{\nu_A\, f(x, \mathbf{\Delta})},\ x = 0.01$$

$$\frac{\nu_<\, \phi(\nu_>, x, \mathbf{\Delta})}{\nu_>\, \phi(\nu_<, x, \mathbf{\Delta})},\ \nu_> = 8,\ \nu_< = 1$$





- left: a Cronin-type enhancement around the saturation scale
- ...which is quenched by small-x evolution (right panel)

Summary

- we presented numerical solutions of an impact parameter (or opacity-) dependent nonlinear evolution equation
- The diffraction operator for quasielastic diffractive processes obeys a novel evolution equation, coupled with the BK equation.
- γ-jet correlations in the proton fragmentation region can map out the unintegrated gluon distribution $\rightarrow$ experimental determination of the saturation scale

- Outlook
  - $\phi(\nu, x, \boldsymbol{p})$ as a universal 'saturation glue', even for the free nucleon:

$$f_N(x, \boldsymbol{p}) = 2 \int d^2\boldsymbol{b}\, \phi(\nu_N(\boldsymbol{b}), x, \boldsymbol{p})\,,\ \nu_N(\boldsymbol{b}) = \frac{1}{2}\alpha_S(q^2)\sigma_0 t_N(\boldsymbol{b})\,.$$

  - some fine tuning of the input $f(x_0, \boldsymbol{p})$,$\mu_G^2, \dots,$ nucleon profile $t_N(\boldsymbol{b})$ may be required