Associated forward photon-jet production as a probe of the nuclear unintegrated glue

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Outline

Inelastic production as excitation of beam partons

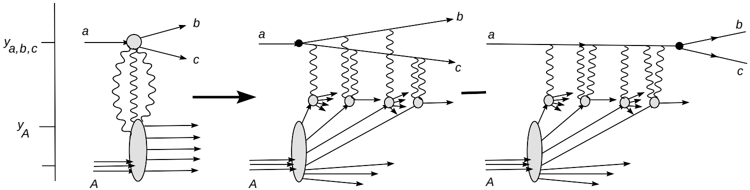
Unintegrated gluon distribution of a nucleus: salient features

Linear $k_\perp$–factorization for $q\gamma$–dijets

Nuclear broadening of the acoplanarity distribution

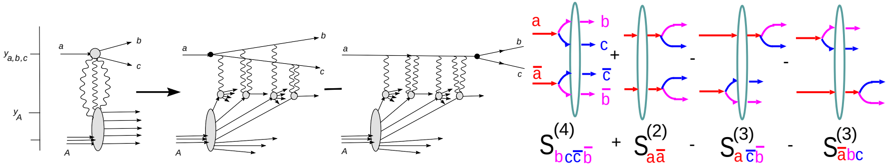
based on collaboration work with N. Nikolaev, B.G. Zakharov and V.R. Zoller NSZZ J.Exp.Theor.Phys.97 (2003); NS Phys.Rev.D71 (2005); NSZ Phys.Rev.Lett.95 (2005); NSZZ Phys.Rev.D72(2005); NSZ Phys.Rev.D72 (2005); NS Phys.Rev.D74(2006).

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



- For $y_{a,b,c} \gtrsim \log(2R_A m_N) = \log(1/x_A)$, $x_A \sim 0.01$, the breakup $a \rightarrow bc$ is coherent over the whole nucleus.
- Partons move along straight–line trajectories. Impact parameters $\boldsymbol{b}_i$ conserved in the interaction.
- Interactions with the nucleus *before* and *after* the virtual decay interfere destructively.
- In DIS on heavy nuclei: diffraction/total $\sim 30\%$ implies large unitarity/rescattering effects Nikolaev, WS, Zakharov, Zoller (2007).

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.

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:

$$\Gamma(\boldsymbol{b}, x_A, \boldsymbol{r}) = 1 - \exp[-\sigma(x_A, \boldsymbol{r}) T_A(\boldsymbol{b})/2] = \int d^2\boldsymbol{p}[1 - e^{i\boldsymbol{p}\boldsymbol{r}}]\phi(\boldsymbol{b}, x_A, \boldsymbol{p}).$$

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

$$\phi(\boldsymbol{b}, x_A, \boldsymbol{p}) = \sum w_j(\boldsymbol{b}, x_A) f^{(j)}(x_A, \boldsymbol{p}) \,,\; f^{(1)}(x, \boldsymbol{p}) = \frac{4\pi\alpha_S}{N_c} \frac{1}{\boldsymbol{p}^4} \frac{\partial G(x, \boldsymbol{p}^2)}{\partial \log(\boldsymbol{p}^2)}$$

- collective glue of j overlapping nucleons :

$$f^{(j)}(x_A, \boldsymbol{p}) = \int \Big[\prod^{j} d^2\boldsymbol{\kappa}_i f^{(1)}(x_A, \boldsymbol{\kappa}_i)\Big] \delta^{(2)}(\boldsymbol{p} - \sum \boldsymbol{\kappa}_i)$$

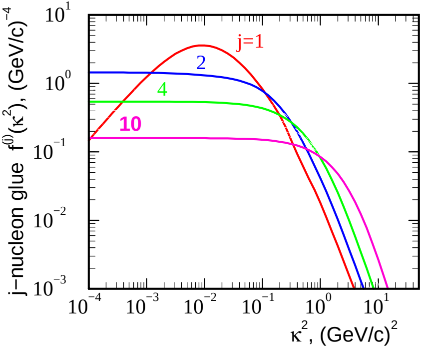
- probab. to find j overlapping nucleons

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

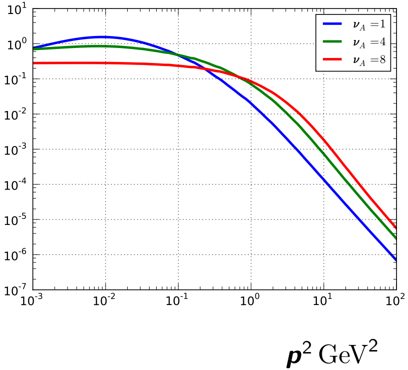
- impact parameter $\boldsymbol{b} \to$ effective opacity ν_A, $q^2 =$ the relevant hard scale.

Salient features of the nuclear unintegrated glue

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



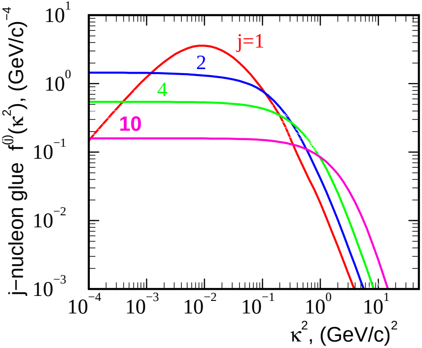
nuclear glue $\phi(\nu_A, x_A, \boldsymbol{p})$



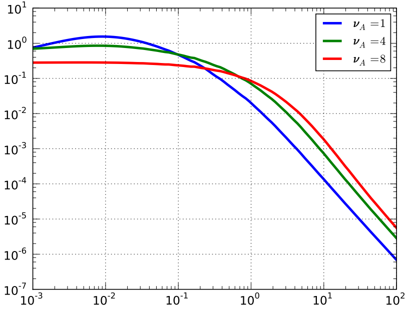
- a plateau at small $\boldsymbol{p}^2$, which displays shadowing: $\phi(\nu_A, x_A, \boldsymbol{p}) \propto 1/\nu_A$
- transition from plateau to tail is controlled by the saturation scale $Q_A^2(\nu_A, x)$

Salient features of the nuclear unintegrated glue

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



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



- using that $f(x_A, \boldsymbol{p}^2) \sim \boldsymbol{p}^{-2\gamma}$, $\gamma \approx 2$ manifestly positive higher twist at large $\boldsymbol{p}^2$:

$$\phi(\nu_A, x_A, \boldsymbol{p}) = \nu_A f(x_A, \boldsymbol{p}) \cdot \left(1 + \nu_A \frac{2\pi^2\gamma^2\alpha_S(\boldsymbol{p}^2)G(x_A, \boldsymbol{p}^2)}{N_c \boldsymbol{p}^2} + \dots\right)$$

Nikolaev, WS & Schwiete (2000)

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 free nucleon:

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

- the collinear pole gives rise to a fragmentation piece:

$$\frac{2(2\pi)^2 d\sigma_N(q \to q\gamma)}{dz d^2\boldsymbol{p}} = \underbrace{f(x, \frac{\boldsymbol{p}}{z})}_{q \to q} \times \underbrace{\int d^2\boldsymbol{k} |\psi(z, \boldsymbol{k})|^2}_{\text{fragmentation } q \to \gamma}$$

Nikolaev, WS (2005)

- extract the "monojet contribution" by decomposing

$$\frac{1}{(\boldsymbol{p} - z\boldsymbol{\Delta})^2 + \varepsilon^2} = \frac{1}{\boldsymbol{p}^2 + \varepsilon^2} \theta(\boldsymbol{p}^2 - z^2\boldsymbol{\Delta}^2) + \mathcal{L}(\boldsymbol{p}, z\boldsymbol{\Delta})$$

- with

$$\int d^2\boldsymbol{\Delta} f(\boldsymbol{\Delta}) \, \mathcal{L}(\boldsymbol{p}, z\boldsymbol{\Delta}) = \frac{\pi}{z^2} f(\frac{\boldsymbol{p}}{z}) \log(\boldsymbol{p}^2/\varepsilon^2)$$

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
- nuclear excess cross section:

$$\frac{d\delta\sigma_A}{d^2\boldsymbol{b} d^2\boldsymbol{p} d^2\boldsymbol{\Delta}} = \frac{d\sigma_A}{d^2\boldsymbol{b} d^2\boldsymbol{p} d^2\boldsymbol{\Delta}} - T(\boldsymbol{b}) \frac{d\sigma_N}{d^2\boldsymbol{b} d^2\boldsymbol{p} d^2\boldsymbol{\Delta}} \,,$$

$$\langle \boldsymbol{\Delta}^2 d\sigma \rangle_A - \langle \boldsymbol{\Delta}^2 d\sigma \rangle_N = \int d^2\boldsymbol{\Delta}\, \boldsymbol{\Delta}^2 \frac{d\delta\sigma_A}{d^2\boldsymbol{b} d^2\boldsymbol{p} d^2\boldsymbol{\Delta}}$$

nuclear broadening (eliminate the collinear pole !)

$$\langle \boldsymbol{\Delta}^2 \rangle_{A-N} = \frac{\langle \boldsymbol{\Delta}^2 d\sigma \rangle_A - \langle \boldsymbol{\Delta}^2 d\sigma \rangle_N}{T(\boldsymbol{b}) \int d^2\boldsymbol{\Delta}\, (d\sigma_N / d^2\boldsymbol{p} d^2\boldsymbol{\Delta})} \,.$$

Nuclear broadening of the acoplanarity distribution

Using the higher twist expansion for the tail of the nuclear glue:

$$\phi(\boldsymbol{b}, x_A, \boldsymbol{\Delta}) = \frac{1}{2} T(\boldsymbol{b}) \, f(x_A, \boldsymbol{\Delta}) \cdot \Big(1 + T(\boldsymbol{b}) \frac{2\pi^2 \gamma^2 \alpha_S(\boldsymbol{\Delta}^2) G(x_A, \boldsymbol{\Delta}^2)}{N_c \boldsymbol{\Delta}^2} + \dots \Big) \, ,$$

and the large $\boldsymbol{p}$ form of the "quark tagged" photon spectrum on the free nucleon

$$\frac{2(2\pi)^2 d\sigma_N(q^* \to q\gamma)}{dz d^2\boldsymbol{p}} == \frac{z^2 P_{\gamma q}(z)}{p^4} \int^{\boldsymbol{p}^2/z^2} d^2\boldsymbol{\Delta} \, \boldsymbol{\Delta}^2 f(x, \boldsymbol{\Delta}) \, ,$$

we obtain the nuclear broadening

$$\begin{aligned} \langle \boldsymbol{\Delta}^2 \rangle_{A-N} &\approx \frac{2\pi^2\gamma^2}{N_c} \alpha_S(\boldsymbol{p}^2) G(x_A, \boldsymbol{p}^2) T(\boldsymbol{b}) \\ &\approx Q_A^2(\boldsymbol{b}, x) \cdot \frac{\gamma^2}{2} \cdot \frac{\alpha_S(\boldsymbol{p}^2) G(x_A, \boldsymbol{p}^2)}{\alpha_S(Q_A^2) G(x_A, Q_A^2)} \, . \end{aligned}$$

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

- on the nucleus:

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

- the (parton-level) 'nuclear modification factor' doesn't depend on $\boldsymbol{p}$:

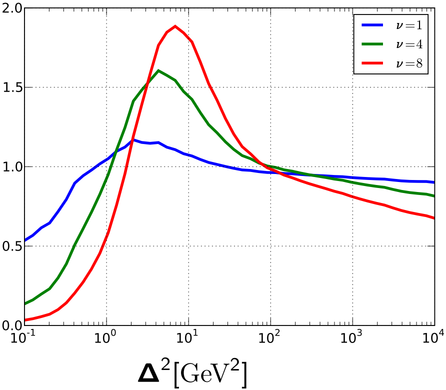
$$R_{pA}(\nu_A, \boldsymbol{p}, \boldsymbol{\Delta}) = \frac{d\sigma_A}{T_A(\boldsymbol{b}) d\sigma_N} = \frac{\phi(\nu_A, x, \boldsymbol{\Delta})}{\nu_A f(x, \boldsymbol{\Delta})}$$

- similarly the central-to-peripheral ratio:

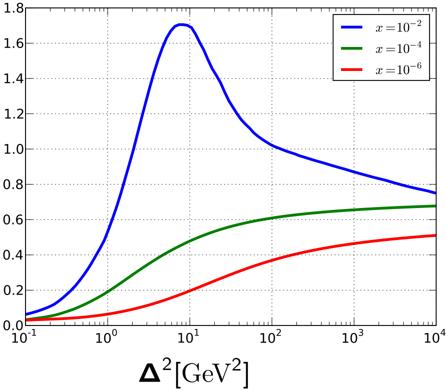
$$R_{CP}(\nu_>, \nu_<, \boldsymbol{p}, \boldsymbol{\Delta}) = \frac{\nu_< \,\phi(\nu_>, x, \boldsymbol{\Delta})}{\nu_> \,\phi(\nu_<, x, \boldsymbol{\Delta})}$$

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

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



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



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

Summary

- cross section for direct photons tagged by a quark jet fulfills a *linear* $k_\perp$–factorization formula.
- γ-jet correlations in the proton fragmentation region can map out the unintegrated gluon distribution $\longrightarrow$ experimental determination of the saturation scale.
- we derived the relation between the nuclear broadening of the acoplanarity momentum distribution and the saturation scale at $x \sim x_A$.
- small-x evolution can dilute the broadening effect.