Isolated photon production in proton-nucleus collisions at forward rapidity

T. Lappi
tuomas.v.v.lappi@jyu.fi

University of Jyväskylä, Finland

Quark Matter, Venezia, May 2018
Introduction

Motivation

- Initial stage of AA-collision: color field of small-x gluons $\Rightarrow$ glasma
- Independently measure this color field with dilute probe:
  - Deep inelastic scattering
  - Proton-nucleus (and pp) at forward rapidity — this talk
  - Signals for gluon saturation?
  - Difference between collinear and small-x evolution?

Outline of this talk: based on work with B. Ducloué & H. Mäntysaari

- Dilute probe and small-x color field: eikonal scattering
- Isolated photons Ducloué, T.L. Mäntysaari, arXiv:1710.02206
- Other fwd observables: $J/\Psi$, single inclusive hadrons
- Speculation: this is LO, what could change at NLO?
Eikonal scattering off target of glue

How to measure small-x glue?
- Dilute probe through target color field
- At high energy interaction is eikonal

Eikonal scattering amplitude: Wilson line $V$

$$V = \mathbb{P} \exp \left\{ -ig \int_{x^+}^{x^+} dy^+ A^{-}(y^+, x^-, x) \right\} \approx V(x) \in SU(N_c)$$

- Many observables need color dipole amplitude

$$\mathcal{N}(|x - y|) = 1 - \left\langle \frac{1}{N_c} \text{Tr} \, V^\dagger(x) V(y) \right\rangle$$

from color transparency to saturation

- $1/Q_s = \text{correlation length}$, $Q_s = \text{gluon intrinsic } k_T$
Where do we get Wilson lines?

Use here MV\(e\) parametrization from T.L., Mäntysaari, \texttt{arXiv:1309.6963}

- Initial condition for protons at \(x_0 = 0.01\)

\[
N(r) = 1 - e^{-\frac{(r^2 Q_s^2)}{4} \ln \left( \frac{1}{\Lambda_{\text{QCD}}} + e_c \cdot e \right)}
\]

(3 fit parameters \(Q_s, e_c, \sigma_0 = \text{proton area})

- \(x < x_0\) predicted by leading order, running coupling Balitsky-Kovchegov equation

(1 fit parameter: scale in \(\alpha_s\))

- Parameters fit to HERA \(F_2\) data

(just like parton distributions are)

- Protons to nuclei: optical Glauber at \(x_0\), no additional free parameters

Small subset of HERA \(F_2\) data
Photon production at forward rapidity

- Incoming quark passes through color field and emits photon

\[ \frac{dN^{pA\rightarrow X}}{d^2k \, dy_\gamma} = \sum_q \frac{e_q^2 \alpha_{em}}{\pi (2\pi)^3} \int_{q,x_p} \frac{z^2 [1 + (1 - z)^2]}{1 + (1 - z)^2} \frac{q(x_p, \mu^2)}{k^2} \frac{(k + q)^2}{[zq - (1 - z)k]^2} S(k + q, x_g) \]

\[ z = \frac{|k|}{x_p \sqrt{s}} e^{y_\gamma} \quad x_p = \frac{|k| e^{y_\gamma} + |q| e^{y_q}}{\sqrt{s}} \quad x_g = \frac{|k| e^{-y_\gamma} + |q| e^{-y_q}}{\sqrt{s}} \]

- Differential photon multiplicity \( \text{Gelis, Jalilian-Marian} \hepph/0205037 \) for large \( y_\gamma \)}
Photon production at forward rapidity

- Incoming quark passes through color field and emits photon

- Differential photon multiplicity for large $y_\gamma$

\[
\frac{dN_{pA\rightarrow \gamma X}}{d^2k \ dy_\gamma} = \sum_q \frac{e_q^2 \alpha_{em}}{\pi (2\pi)^3} \int_{q,x_p} z^2 [1 + (1 - z)^2] \frac{q(x_p, \mu^2)}{k^2} \frac{(k + q)^2}{[zq - (1 - z)k]^2} S(k + q, x_g)
\]

- Target at $x_g \ll 1$: $S_{x_g}(x - y) = 1 - N_{x_g}(x - y) \implies$ Fourier transform $S(k, x_g)$
Photon production at forward rapidity

- Incoming quark passes through color field and emits photon

\[ \frac{dN^{pA \to \gamma X}}{d^2k \, dy_{\gamma}} = \sum_q \frac{e_q^2 \alpha_{em}}{\pi(2\pi)^3} \int_{q,x_p} z^2 [1 + (1 - z)^2] \frac{q(x_p, \mu^2)}{k^2} \frac{(k + q)^2}{[zq - (1 - z)k]^2} S(k + q, x_g) \]

\[ z = \frac{|k|}{x_p \sqrt{s}} e^{y_{\gamma}} \quad x_p = \frac{|k| e^{y_{\gamma}} + |q| e^{-y_q}}{\sqrt{s}} \]

- Differential photon multiplicity \( Gelis, Jalilian-Marian \) \( hep-ph/0205037 \) for large \( y_{\gamma} \)

- Target at \( x_g \ll 1: \quad S_{x_g}(x - y) = 1 - N_{x_g}(x - y) \quad \Rightarrow \quad \text{Fourier transform } S(k, x_g) \)

- Probe: collinear (large \( x_p \)) quark distribution \( q(x_p, \mu^2) \)

- Impose isolation cut \( \sqrt{(y_{\gamma} - y_q)^2 + (\phi_{\gamma} - \phi_q)^2} > R \)
Isolated photon $R_{pA}$
Duclouë, T.L. Mäntysaari, arXiv:1710.02206

$R_{pA}$

$p + Au/p + p \rightarrow \gamma + X, \sqrt{s} = 200$ GeV

$0.6 < k_T [\text{GeV}] < 0.7$

$2.5 < y < 3.2$

$3.2 < y < 4.0$

$p + Pb/p + p \rightarrow \gamma + X, \sqrt{s} = 8$ TeV

$0.6 < k_T [\text{GeV}] < 0.7$

$y = 3$

$y = 4$

$y = 5$

RHIC energy, close to $x_0$

LHC energy: evolved to $x \ll x_0$

See effects of saturation and small-$x$ evolution

- Saturation: suppression at low $k_T \gamma \lesssim Q_s$: already at $x_0$ (RHIC)
- Evolution: suppression extends to large $k_T$: “geometric scaling” in action
$R_{pA}$ for inclusive J/$\psi$

**Same features in different process, calculated with exactly same target color field**

- Suppression at low $p_T$ from saturation
- Forward $y$ @ LHC: also suppression at high $p_T$ from evolution

Here J/$\psi$ in forward pA collisions

More $R_{pA}$’s: Drell-Yan, $D$-mesons: very much same story

$R_{pA}$ for $D$-mesons
Ducloué, T.L. Mäntysaari, arXiv:1612.04585
(This plot: LHCb data preliminary)

Double ratio:
$J/\psi$ $R_{pA}$ over Drell-Yan $R_{pA}$
Ducloué arXiv:1701.08730
(Very different in CNM energy loss models)
Light hadrons: almost same story

Comparison at forward LHC kinematics:

\[ p + Pb/p + p \rightarrow \gamma + X, \sqrt{s} = 8 \text{ TeV} \]

\[ p + Pb/p + p \rightarrow \pi^0 + X, \sqrt{s} = 8000 \text{ GeV} \]

Photons \[\Rightarrow\] suppression not as large
Why is $\pi^0$ different than photons?

Kinematics of process is different in LO CGC power counting

LO CGC processes are:

**Pions**

$$q(x, Q^2) \rightarrow D_{q\rightarrow h}(z, Q^2)$$

1 $\rightarrow$ 1 kinematics:
Large pion $p_T$ always from target gluon $k_T \gg Q_s$

**Photons**

1 $\rightarrow$ 2 kinematics:
Even large photon $p_T$ can have target gluon $k_T \lesssim Q_s$

$\Rightarrow$ more suppression

At NLO also light hadron production is 1 $\rightarrow$ 2 $\Rightarrow$ expect effect on $R_{pA}$

next talk Ducloué
Why nuclear suppression even at large momenta?

Understood for long time, see e.g. Albacete et al. hep-ph/0307179
Kharzeev at al hep-ph/0307037

Initial $x_0 \sim 0.01$ (close to) MV-model — many independent color charges

- Natural agnostic assumption, central limit theorem Gaussian
- Favored by fits to HERA data
- Leads to $xg(x, Q^2) \sim \ln Q^2$ like DGLAP

Evolution develops “anomalous dimension” $\gamma$ in coordinate or momentum space:

$$N(r) \sim r^{2\gamma} \quad \text{and} \quad k^2 S(k) \sim k^{-2\gamma} \quad \text{MV: } \gamma = 1$$

Consequence for $R_{pA}$ at high $p_T$:

$$Q_{s,A}^2 \sim A^{1/3} Q_{s,p}^2 \quad \text{and} \quad \frac{dN}{d^2p} \sim \left(\frac{Q_s^2}{p^2}\right)^\gamma \implies R_{pA} \sim \frac{1}{A^{1/3}} \frac{dN_A/d^2p}{dN_p/d^2p} \sim A_3^{1/(\gamma-1)}$$

- Nuclear suppression at large $p_T$ results from decrease in anomalous dimension from initial $\gamma = 1$ @ $x_0 \implies \gamma < 1$ at small $x$ “geometric scaling”
- This happens very fast in LO BK
Speculation: what could happen with NLO evolution?

- Yet no full NLO calculation of $R_{pA}$ (although progress is being made, need Fourier-positivity + HERA data + NLO BK collinear resummation + control of impact factors)
- But NLO evolution equations solved

Fate of geometric scaling at NLO

Calculate $\gamma(r) \equiv -\frac{d \ln N(r)}{d \ln r^2}$

- LO: fast to $\gamma \sim 0.8$
- NLO: stay at initial $\gamma$


- Solid: initial condition
- Dotted: $y = 5$ NLO
- Dot-dashed: $y = 5$ LO (rc)
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- LO $y = 0$ to $y = 5$

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**Fate of geometric scaling at NLO**

Calculate $\gamma(r) \equiv -\frac{d \ln N(r)}{d \ln r^2}$

- LO: fast to $\gamma \approx 0.8$
- NLO: stay at initial $\gamma$

- LO $y = 0$ to $y = 5$
- NLO $y = 0$ to $y = 5$


- Solid: initial condition
- Dotted: $y = 5$ NLO
- Dot-dashed: $y = 5$ LO (rc)
Conclusions

- By now quite large set of predictions for forward $pA$ in consistent framework: light hadrons (with fragmentation functions), real, virtual photons, heavy quarks
  - Intrinsically LO BK predicts fwd nuclear suppression
- Caveats: calculations so far LO
  - Kinematics different for $q, g$ vs. $Q\bar{Q}, \gamma, \gamma^*$ processes
  - Expect slower forward suppression from NLO BK evolution (but still no calculation)

Working on understanding these effects
(but predicting difficult, particularly in advance)

- Big picture: also multiparticle correlations (see e.g. talk Marquet)
Note on power counting and kinematics

Collinear $2 \rightarrow 2$ process, measure only 1 particle: integral over large $\Delta y = \ln \frac{x>}{x<}$

- In the CGC the power counting assumes $\alpha_s \ln \Delta y \sim 1$
  $\Rightarrow$ integrated gluon absorbed in BFKL/BK/JIMWLK-evolved target at $x<$

- The gluon recoil also gives intrinsic $k$ $\Rightarrow$ e.g. $J/\psi$ has $p_T$ distribution at LO in CGC (vs. only at NLO in collinear)
Inclusive $J/\psi$ in LHCb/ALICE kinematics: cross section

Cross sections for pPb Ducloué, T.L. Mäntysaari 1503.02789

Most of normalization uncertainty from scale in collinear PDF, and in $\alpha_s$. 