Isolated photon production in proton-nucleus collisions at forward rapidity

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Introduction

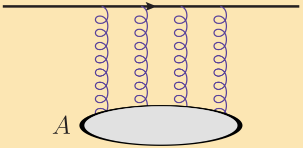
Motivation

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

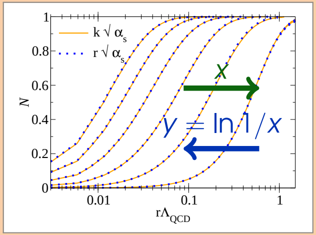
$$V = \mathbb{P}\exp\left\{-ig\int^{x^+} \mathrm{d}y^+ A^-(y^+,x^-,\mathbf{x})\right\} \underset{x^+\to\infty}{\approx} V(\mathbf{x}) \in \mathrm{SU}(N_\mathrm{c})$$

- Many observables need color dipole amplitude

$$\mathcal{N}(|\mathbf{x}-\mathbf{y}|) = 1 - \left\langle \frac{1}{N_\mathrm{c}} \operatorname{Tr} V^\dagger(\mathbf{x}) V(\mathbf{y}) \right\rangle$$

from color transparency to saturation

- $1/Q_\mathrm{s}$ = **correlation length**, Q_s = gluon **intrinsic** k_T



Where do we get Wilson lines?

Use here MV^e parametrization from

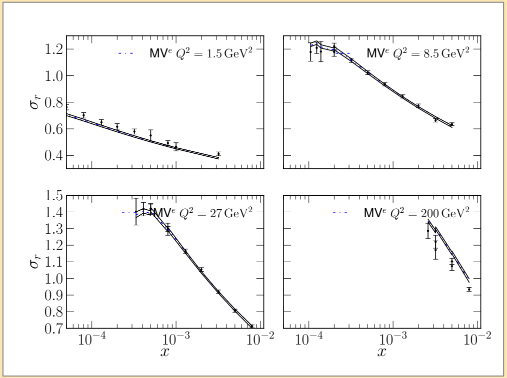
T.L., Mäntysaari, `arXiv:1309.6963`

- Initial condition for protons at $x_0 = 0.01$

$$N(r) = 1 - e^{-\frac{(r^2 Q_{s0}^2)}{4} \ln\left(\frac{1}{r\Lambda_{QCD}} + e_c \cdot e\right)}$$

(3 fit parameters $Q_{s0}, e_c, \sigma_0 =$ proton area)

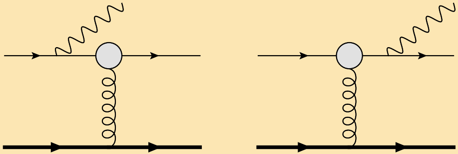
- $x < x_0$ **predicted** by leading order, running coupling **Balitsky-Kovchegov equation**
  (1 fit parameter: scale in α_s)
- Parameters fit to HERA F_2 data
  (just like parton distributions are)
- Protons to nuclei: optical Glauber at x_0, no additional free parameters



Small subset of HERA F_2 data

Photon production at forward rapidity

- Incoming quark passes through color field and emits photon



- Differential photon multiplicity Gelis, Jalilian-Marian `hep-ph/0205037` for large y_γ

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

$$z = \frac{|\mathbf{k}|}{x_p\sqrt{s}}e^{y_\gamma} \qquad x_p = \frac{|\mathbf{k}|e^{y_\gamma}+|\mathbf{q}|e^{y_q}}{\sqrt{s}} \qquad \boxed{x_g = \frac{|\mathbf{k}|e^{-y_\gamma}+|\mathbf{q}|e^{-y_q}}{\sqrt{s}}}$$

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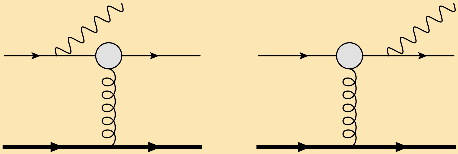

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- Target at $x_g \ll 1$: $\quad S_{x_g}(\mathbf{x}-\mathbf{y}) = 1 - N_{x_g}(\mathbf{x}-\mathbf{y}) \implies$ Fourier transform $S(\mathbf{k},x_g)$

Photon production at forward rapidity

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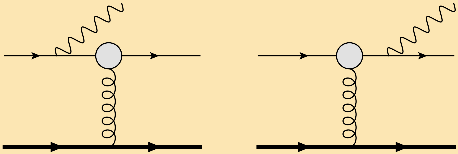

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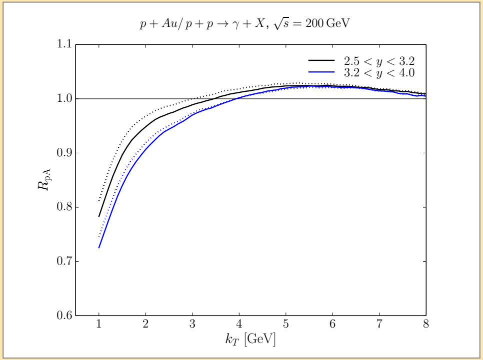
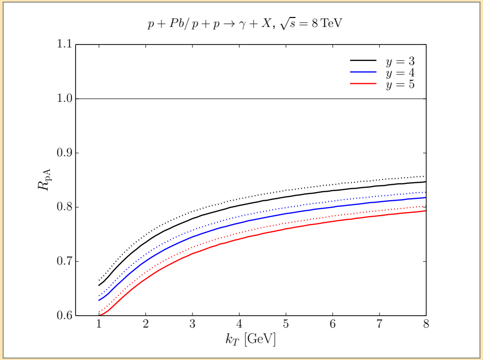
- Target at $x_g \ll 1$: $S_{x_g}(\mathbf{x}-\mathbf{y}) = 1 - N_{x_g}(\mathbf{x}-\mathbf{y}) \Longrightarrow$ Fourier transform $S(\mathbf{k},x_g)$
- Probe: collinear (large x_p) quark distribution $q(x_p,\mu^2)$
- Impose isolation cut $\sqrt{(y_\gamma-y_q)^2+(\phi_\gamma-\phi_q)^2} > R$

Isolated photon R_{pA}

Ducloué, T.L. Mäntysaari, arXiv:1710.02206



RHIC energy, close to x_0



LHC energy: evolved to $x \ll x_0$

See effects of saturation and small-x evolution

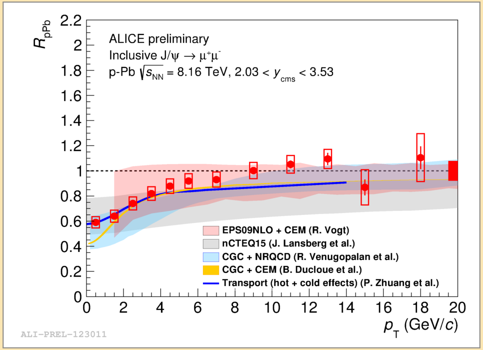
- Saturation: suppression at low $k_T{}^{\gamma} \lesssim Q_s$: already at x_0 (RHIC)
- Evolution: suppression extends to large k_T: "geometric scaling" in action

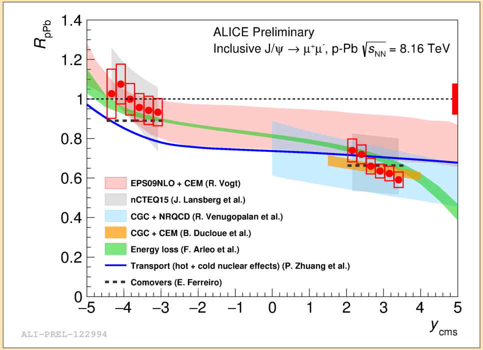
R_{pA} for inclusive J/ψ

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

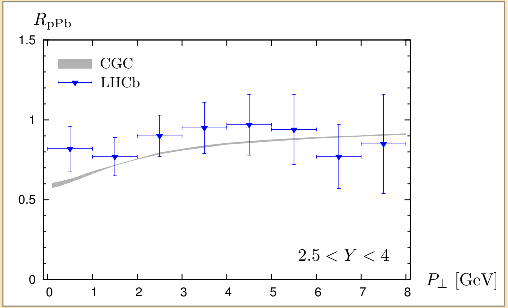
Here J/Ψ in forward pA collisions

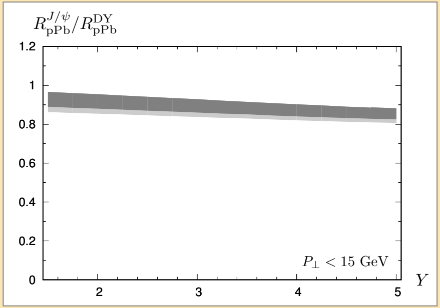




CGC+CEM calculation Ducloué et al `arXiv:1503.02789`, `arXiv:1605.05680`

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:

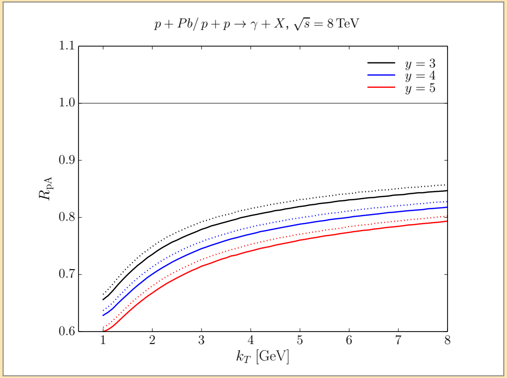
J/ψ R_{pA} over Drell-Yan R_{pA}

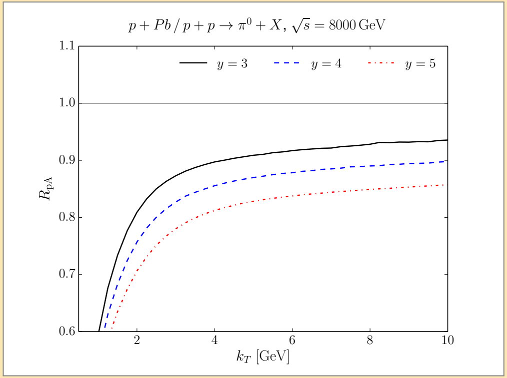
Ducloué `arXiv:1701.08730`

(Very different in CNM energy loss models)

Light hadrons: almost same story

Comparison at forward LHC kinematics:





Photons

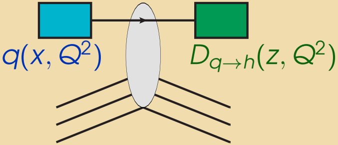
π^0 $\Longrightarrow$ suppression not as large

Why is π^0 different than photons?

Kinematics of process is different in LO CGC power counting

LO CGC processes are:

Pions

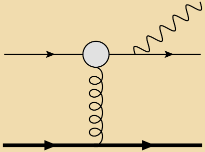


$1 \to 1$ kinematics:

Large pion p_T

always from target gluon $k_T \gg Q_s$

Photons



$1 \to 2$ kinematics:

Even large photon p_T

can have target gluon $k_T \lesssim Q_s$

$\Longrightarrow$ more suppression

At NLO also light hadron production is $1 \to 2$ $\Longrightarrow$ 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" γ in coordinate or momentum space:

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

Consequence for R_{pA} at high p_T:

$${Q_{s,A}}^2 \sim A^{1/3} {Q_{s,p}}^2 \quad \& \quad \frac{\mathrm{d}N}{\mathrm{d}^2\mathbf{p}} \sim \left(\frac{Q_s^2}{p^2}\right)^{\gamma} \quad \Longrightarrow \quad R_{pA} \sim \frac{1}{A^{1/3}} \frac{\mathrm{d}N_A/\,\mathrm{d}^2\mathbf{p}}{\mathrm{d}N_p/\,\mathrm{d}^2\mathbf{p}} \sim A^{\frac{1}{3}(\gamma-1)}$$

- Nuclear suppression at large p_T results from decrease in anomalous dimension from initial $\gamma = 1$ @ $x_0 \Longrightarrow \gamma < 1$ at small x **"geometric scaling"**
- This happens very fast in LO BK

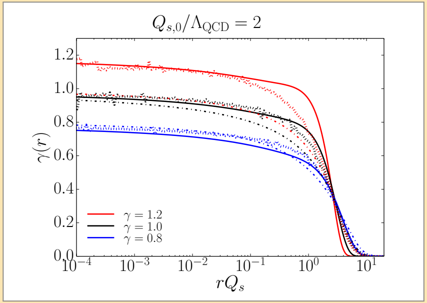
Speculation: what could happen with NLO evolution?

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

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



T.L., H. Mäntysaari `arXiv:1601.06598`

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

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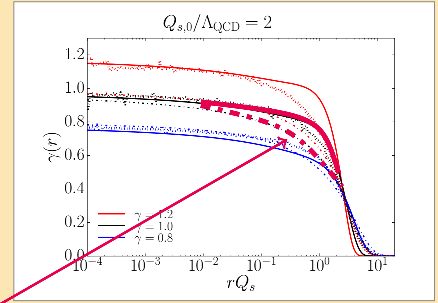

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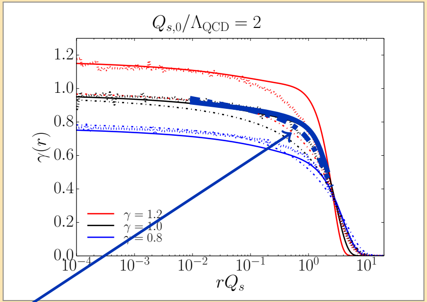

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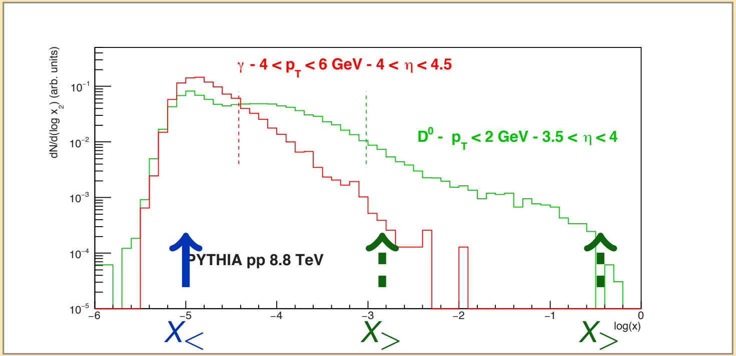
Conclusions

- 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

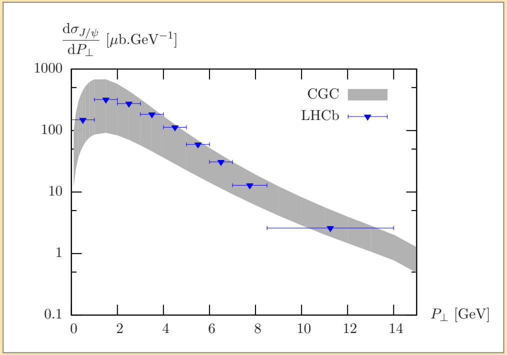
Collinear $2 \to 2$ process, measure only 1 particle: integral over large $\Delta y = \ln \frac{x_>}{x_<}$

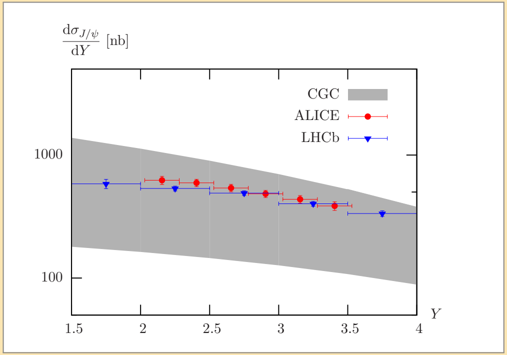


- In the CGC the power counting assumes $\alpha_s \ln \Delta y \sim 1$
  $\implies$ integrated gluon absorbed in BFKL/BK/JIMWKL-evolved target at $x_<$
- The gluon recoil also gives intrinsic $\mathbf{k}$ $\implies$ e.g. J/Ψ has p_T distribution at LO in CGC (vs. only at NLO in collinear)

Inclusive J/ψ 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 α_s