Photon from the Color Glass Condensate in the pA collision

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SCHOOL OF SCIENCE
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Motivation

- photon $\rightarrow$ clean probes
- in pA $\rightarrow$ initial state
- **goal of this work**

  saturation effects in photon spectrum

Color Glass Condensate

- universal form of matter at

$$x \ll 1 \,, \quad Q^2 = \text{fixed}$$

$\rightarrow$ **saturation scale** Q_s^2

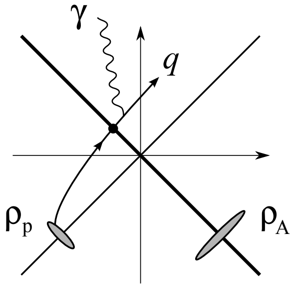
$$\frac{\alpha_s}{Q_s^2}\frac{xf_g(x, Q_s^2)}{\pi R^2} \sim 1$$

$\rightarrow$ large gluon occupation number

$\rightarrow$ classical color fields

Photon in pA

- valence quark bremsstrahung $O(\alpha)$



- Gelis – Jalilian-Marian formula

$$\frac{1}{\pi R_A^2}\frac{d\sigma^{q\to q\gamma}}{d^2k_\perp} = \frac{\alpha}{\pi}\frac{1}{k_\perp^2}\int_0^1 dz \frac{1+(1-z)^2}{z}\int_{l_\perp} C(\mathbf{l}_\perp)\frac{l_\perp^2}{(\mathbf{l}_\perp - \mathbf{k}_\perp/z)^2}$$

color dipole: $\int_{x_\perp} e^{i\mathbf{l}_\perp\cdot\mathbf{x}_\perp}\langle U(0)U^\dagger(\mathbf{x}_\perp)\rangle$

Gelis, Jalilian-Marian, Phys. Rev. D **66** (2002) 014021

Photon in pA

- but: high energy (small x)
  $\rightarrow$ gluon component of the proton wave function becomes dominant

  $\rightarrow$ **new emission processes**

Power counting

- proton: gluons more abundant than quarks

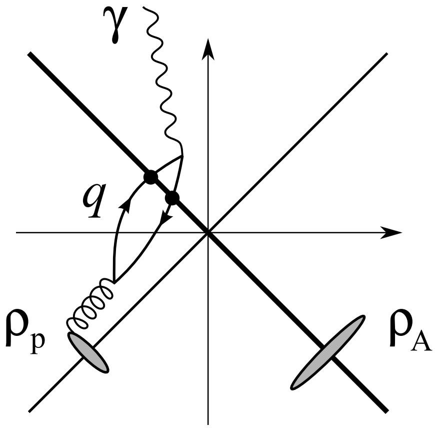
$$f_q \ll f_g$$

- nucleus dense, proton dilute

$$\rho_p \ll \rho_A$$

Photon in pA

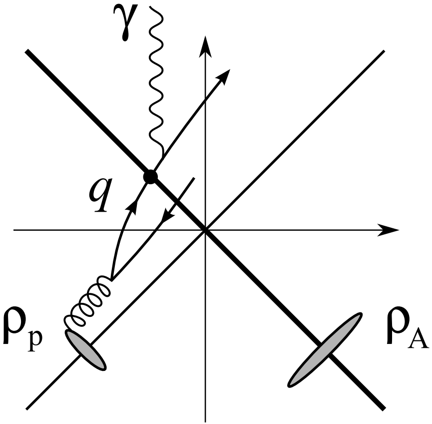
- annihilation $O(\alpha\alpha_s)$



SB, Fukushima, arXiv:1602.01989

Photon in pA

- bremsstrahlung from produced $\bar{q}q$ $O(\alpha\alpha_s)$

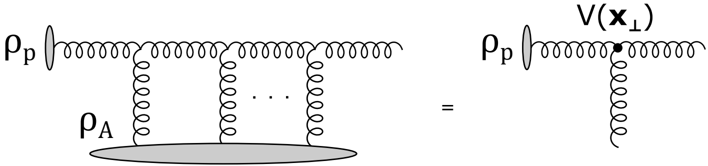


SB, Fukushima, arXiv:1602.01989

pA CGC Feynman rules

- light-cone gauge: $n^\mu \mathcal{A}_\mu = 0$, $n^\mu \equiv \delta^{\mu -}$

1. background gluon field $\mathcal{A}_{(1)}(x)$

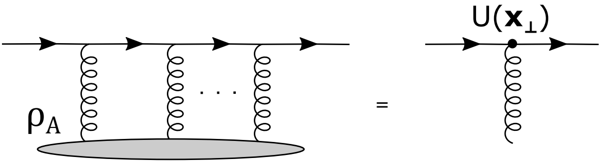


Gelis, Mehtar-Tani, Phys. Rev. D **73** (2006) 034019
Fukushima and Hidaka, Nucl. Phys. A **813** (2008) 171

pA CGC Feynman rules

- light-cone gauge: $n^\mu \mathcal{A}_\mu = 0$, $n^\mu \equiv \delta^{\mu-}$

2. quark propagator $S_{(0)}(x, y)$



Baltz, McLerran, Phys. Rev. C **58** (1998) 1679

Annihilation - amplitude

$$\mathcal{M}_\lambda(\boldsymbol{k}) = eg \int_{xy} e^{ik\cdot x}\, \mathrm{Tr}\left[\not\epsilon_\lambda(\mathbf{k}) S_{(0)}(x,y) \not{\mathcal{A}}_{(1)}(y) S_{(0)}(y,x)\right]$$

Annihilation - amplitude

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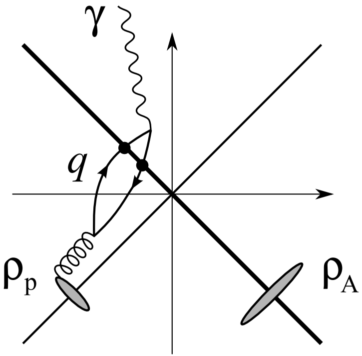

Annihilation - rate

$$\frac{1}{\pi R_A^2}\frac{dN}{d^2\mathbf{k}_\perp dy} = \frac{\alpha\,\alpha_s}{16\pi^8}\frac{N_c}{N_c^2-1}\int_{xx'}\int_{\mathbf{u}_\perp\mathbf{u}'_\perp\mathbf{w}_\perp} e^{-i\mathbf{k}_\perp\cdot\mathbf{r}_\perp}$$
$$\times\, S\left(\mathbf{u}_\perp - \frac{\mathbf{v}_\perp}{2}, \mathbf{u}_\perp + \frac{\mathbf{v}_\perp}{2}, \mathbf{u}'_\perp - \frac{\mathbf{v}'_\perp}{2}, \mathbf{u}'_\perp + \frac{\mathbf{v}'_\perp}{2}\right)$$
$$\times \int_{\mathbf{l}_\perp} e^{i\mathbf{l}_\perp\cdot\mathbf{r}_\perp}\varphi_p(l_\perp)\left(\hat{\mathbf{u}}_\perp\cdot\hat{\mathbf{u}}'_\perp\Psi_1\Psi_1'^{*} + \Psi_2\Psi_2'^{*} + 2\hat{\mathbf{u}}_\perp\cdot\hat{\mathbf{l}}_\perp\Psi_1\Psi_2'^{*}\right)$$

- unintegrated gluon distribution

$$g^2\left\langle\rho_p^a(\mathbf{l}_\perp)\rho_p^{a'}(\mathbf{l}_\perp)\right\rangle \equiv \frac{\delta^{aa'}}{\pi(N_c^2-1)} l_\perp^2\,\varphi_p(l_\perp)$$

- inelastic quadrupole

$$S(\mathbf{y}_\perp,\mathbf{z}_\perp,\mathbf{y}'_\perp,\mathbf{z}'_\perp) \equiv \frac{1}{N_c}\left\langle \mathrm{Tr}_c\left[U(\mathbf{y}_\perp)T_F^a U^\dagger(\mathbf{z}_\perp)\right]\mathrm{Tr}_c\left[U(\mathbf{z}'_\perp)T_F^a U^\dagger(\mathbf{y}'_\perp)\right]\right\rangle$$

SB, Fukushima, arXiv:1602.01989

Remarks

- ✓ photon Ward identity
- ✓ Furry theorem (vanishing of $gg \to \gamma$)
- ✓ UV finite (lowest order is $ggg \to \gamma$)
- ✓ collinear factorization on the proton side
- chiral limit

SB, Fukushima, arXiv:1602.01989

Brems from produced $\bar{q}q$ - amplitude

$$
\mathcal{M}_\lambda(\mathbf{k},\mathbf{q},\mathbf{p}) = ieg\int_{xyz} e^{ik\cdot x+iq\cdot y+ip\cdot z}\bar{u}(\mathbf{q})(i\vec{\not{\partial}}_y - m)
$$

$$
\times\Big\{S_{(0)}(y,w)\not{\mathcal{A}}_{(1)}(w)S_{(0)}(w,x)\not{\epsilon}_\lambda(\mathbf{k})S_{(0)}(x,z)
$$

$$
+ S_{(0)}(y,x)\not{\epsilon}_\lambda(\mathbf{k})S_{(0)}(x,w)\not{\mathcal{A}}_{(1)}(w)S_{(0)}(w,z)\Big\}(i\overleftarrow{\not{\partial}}_z + m)v(\mathbf{p})
$$

Brems from produced $\bar{q}q$ - amplitude

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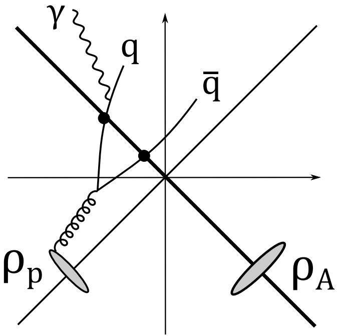
$$+ S_{(0)}(y,x)\not\epsilon_\lambda(\mathbf{k})S_{(0)}(x,w)\not{\mathcal{A}}_{(1)}(w)S_{(0)}(w,z)\Big\}(i\overleftarrow{\not\partial}_z + m)v(\mathbf{p})$$



SB, Fukushima, Garcia-Montero, Venugopalan, in preparation

Brems from produced $\bar{q}q$ - amplitude

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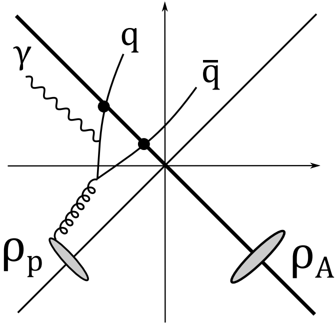
$$\times\Big\{S_{(0)}(y,w)\not\mathcal{A}_{(1)}(w)S_{(0)}(w,x)\not\epsilon_\lambda(\mathbf{k})S_{(0)}(x,z)$$

$$+\,S_{(0)}(y,x)\not\epsilon_\lambda(\mathbf{k})S_{(0)}(x,w)\not\mathcal{A}_{(1)}(w)S_{(0)}(w,z)\Big\}(i\overleftarrow{\not\partial}_z + m)v(\mathbf{p})$$



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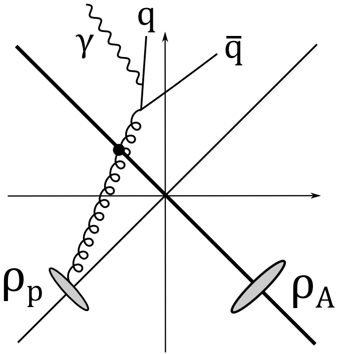
Brems from produced $\bar{q}q$ - amplitude

$$\mathcal{M}_\lambda(\mathbf{k},\mathbf{q},\mathbf{p}) = ieg\int_{xyz} e^{ik\cdot x+iq\cdot y+ip\cdot z}\bar{u}(\mathbf{q})(i\vec{\partial\!\!\!/}_y - m)$$
$$\times\Big\{S_{(0)}(y,w)\mathcal{A\!\!\!/}_{(1)}(w)S_{(0)}(w,x)\epsilon\!\!\!/_\lambda(\mathbf{k})S_{(0)}(x,z)$$
$$+ S_{(0)}(y,x)\epsilon\!\!\!/_\lambda(\mathbf{k})S_{(0)}(x,w)\mathcal{A\!\!\!/}_{(1)}(w)S_{(0)}(w,z)\Big\}(i\overleftarrow{\partial\!\!\!/}_z + m)v(\mathbf{p})$$



SB, Fukushima, Garcia-Montero, Venugopalan, in preparation

Brems from produced $\bar{q}q$ - rate

$$\frac{1}{\pi R_A^2}\frac{d\sigma}{d^2\mathbf{k}_\perp dy\, d^2\mathbf{q}_\perp dy_q\, d^2\mathbf{p}_\perp dy_p} = -\frac{\alpha\alpha_s N_c}{256\pi^8(N_c^2-1)}\int_{\mathbf{l}_\perp \mathbf{s}_\perp \mathbf{s}'_\perp}\frac{\varphi_p(l_\perp)}{l_\perp^2}$$

$$\times\int_{\mathbf{u}_\perp \mathbf{u}'_\perp \mathbf{w}_\perp} e^{i\left(\mathbf{s}_\perp+\frac{\mathbf{l}_\perp-\mathbf{P}_\perp}{2}\right)\cdot\mathbf{u}_\perp} e^{-i\left(\mathbf{s}'_\perp+\frac{\mathbf{l}_\perp-\mathbf{P}_\perp}{2}\right)\cdot\mathbf{u}'_\perp} e^{i(\mathbf{l}_\perp-\mathbf{P}_\perp)\cdot\mathbf{w}_\perp}$$

$$\times C\left(\mathbf{u}_\perp-\frac{\mathbf{v}_\perp}{2},\mathbf{u}_\perp+\frac{\mathbf{v}_\perp}{2},\mathbf{u}'_\perp-\frac{\mathbf{v}'_\perp}{2},\mathbf{u}'_\perp+\frac{\mathbf{v}'_\perp}{2}\right)$$

$$\times\Big\{C_\mu(P,\mathbf{l}_\perp,\mathbf{P}_\perp-\mathbf{l}_\perp)C_{\mu'}(P,\mathbf{l}_\perp,\mathbf{P}_\perp-\mathbf{l}_\perp)\mathrm{Tr}_D\left[(\not{q}+m)R_g^{\mu\nu}(\not{p}-m)\overline{R}_{g\nu}^{\mu'}\right]$$

$$+\frac{l_i}{P^+}\frac{l_{i'}}{P^+}\mathrm{Tr}_D\left[(\not{q}+m)R_{\bar{q}q}^{i\nu}(\mathbf{l}_\perp,\mathbf{s}_\perp)(\not{p}-m)\overline{R}_{\bar{q}q\nu}^{i'}(\mathbf{l}_\perp,\mathbf{s}'_\perp)\right]$$

$$+\frac{l_{i'}}{P^+}C_\mu(P,\mathbf{l}_\perp,\mathbf{P}_\perp-\mathbf{l}_\perp)\mathrm{Tr}_D\left[(\not{q}+m)R_g^{\mu\nu}(\not{p}-m)\overline{R}_{\bar{q}q\nu}^{i'}(\mathbf{l}_\perp,\mathbf{s}'_\perp)\right]+\mathrm{h.c.}\Big\}$$

- same Wilson line product as in $\bar{q}q$ production

$$C(\mathbf{y}_\perp,\mathbf{z}_\perp,\mathbf{y}'_\perp,\mathbf{z}'_\perp)\equiv\frac{1}{N_c}\left\langle\mathrm{Tr}_c\left[U(\mathbf{y}_\perp)T_F^a U^\dagger(\mathbf{z}_\perp)U(\mathbf{z}'_\perp)T_F^a U^\dagger(\mathbf{y}'_\perp)\right]\right\rangle$$

SB, Fukushima, Garcia-Montero, Venugopalan, in preparation

Remarks

- ✓ photon Ward identity
- ✓ soft photon theorem
- ✓ collinear factorization
- ✓ Lorenz gauge: $\partial_\mu \mathcal{A}^\mu = 0$
- ✓ leading twist matches to $gg \to \bar{q}q\gamma$ from $k_\perp$-factorization

Garcia-Montero, Master thesis (2016)

Baranov, Lipatov, Zotov, Phys. Rev. D **77** (2008) 074024

SB, Fukushima, Garcia-Montero, Venugopalan, in preparation

Color average

$$\left\langle \mathcal{O}[\rho_p, \rho_A] \right\rangle = \int [d\rho_p][d\rho_A] W_p[x_p; \rho_p] W_A[x_A; \rho_A] \mathcal{O}[\rho_p, \rho_A]$$

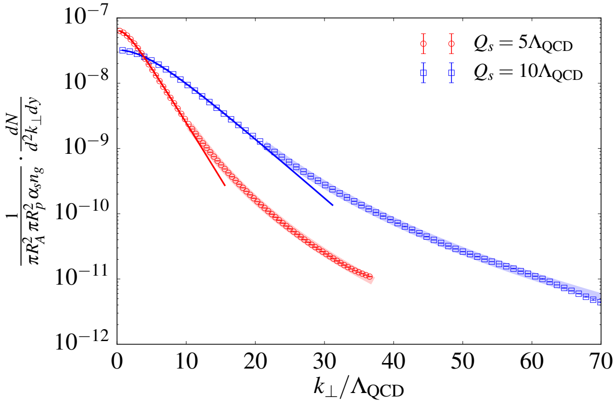
- McLerran-Venugopalan model

$$\left\langle \rho_A^a(\mathbf{x}_\perp)\rho_A^b(\mathbf{y}_\perp) \right\rangle = g^2 \delta^{ab} \mu_A^2 \delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp)$$

$$Q_s^2 \equiv \frac{N_c^2 - 1}{4N_c} g^4 \mu_A^2$$

- reasonable for x $\sim 10^{-2}$
- x evolution $\rightarrow$ JIMWLK

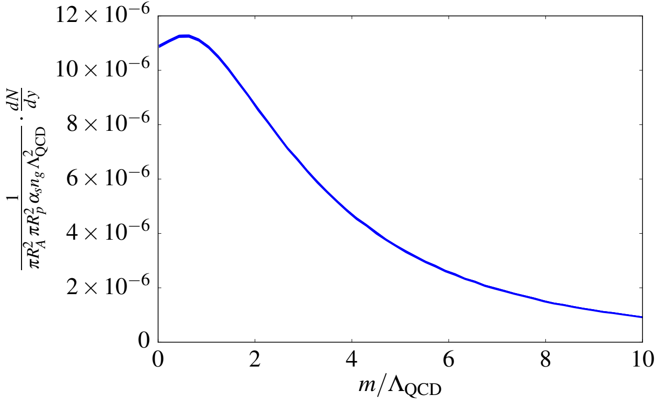
Annihilation - photon spectrum



- single flavor, chiral limit
- thin lines: $\exp\left(-\sqrt{k_\perp^2 + (0.5Q_s)^2}/0.5Q_s\right)$
- thick lines: $(\log(k_\perp/Q_s))^{1.5}/k_\perp^{5.6}$

SB, Fukushima, arXiv:1602.01989

Annihilation - mass dependence



- fit $(\log(m/\Lambda_{\mathrm{QCD}}))^{1.8}/m^{2.6}$
- mass corrections important

SB, Fukushima, arXiv:1602.01989

Conclusions and outlook

- ✓ complete analytical result at $O(\alpha\alpha_s)$
- ✓ numerical evaluation of the annihilation diagram

- sensitivity to quadrupole gluon correlators

- phenomenological applications

  bremsstrahlung - numerical evaluation

  x evolution