Photon production from the Color Glass Condensate in pA collisions

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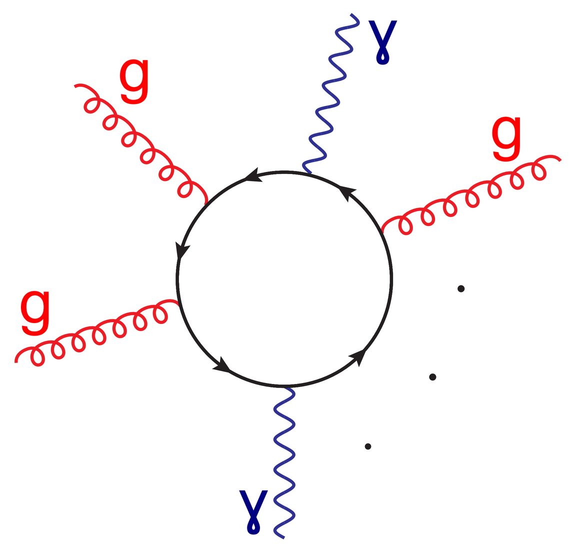
Quark Matter 2015 - XXV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Sep. 27-Oct. 3, 2015, Kobe, Japan

Motivation

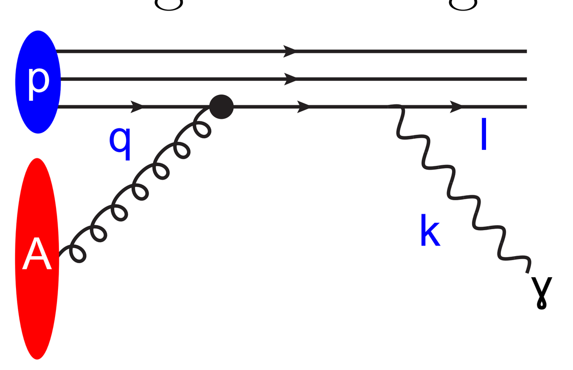
The photon puzzle is an excess in multiplicity of soft photons and a large photon v_2: PHENIX Collaboration, PRL 104 (2010) 132301, PRL 109 (2012) 122302.

- photons produced in all stages of the heavy ion collisions
  $\to$ probe the initial state
- "photon puzzle" $\to$ find new sources of photons
- goal: saturation physics from photons
- CGC phase $\to$ gluon dominated
  $\to$ photons from virtual quarks!
- small coupling compensated by $A^\mu \sim 1/g$ color fields
  $\to$ loops as important as trees!



An interesting possibility is that this type of diagrams are sensitive to the anomaly. Some ideas about this have recently been discussed in the context of the chiral (Fukushima, Mameda, PRD 86 (2012) 071501) and the scale anomaly (Basar, Kharzeev, Shuryak, PRC 90 (2014) 1, 014905).

- Bremsstrahlung $\to$ leading order diagram



Gelis, Jalilian-Marian, PRD 66 (2002) 014021.

Classical gluon field in pA

- CGC formalism:
  small-x partons $\to$ classical gluon field $\mathcal{A}$
  large-x partons $\to$ sources ρ
- $\rho_p \ll \rho_A \to$ small perturbation
- solve Yang-Mills equations in light-cone gauge $A^+ = 0$

$$\mathcal{A}^\mu = \mathcal{A}^\mu_{(0)} + \mathcal{A}^\mu_{(1)} + \mathcal{O}(\rho_p^2)$$

where the non-zero components are

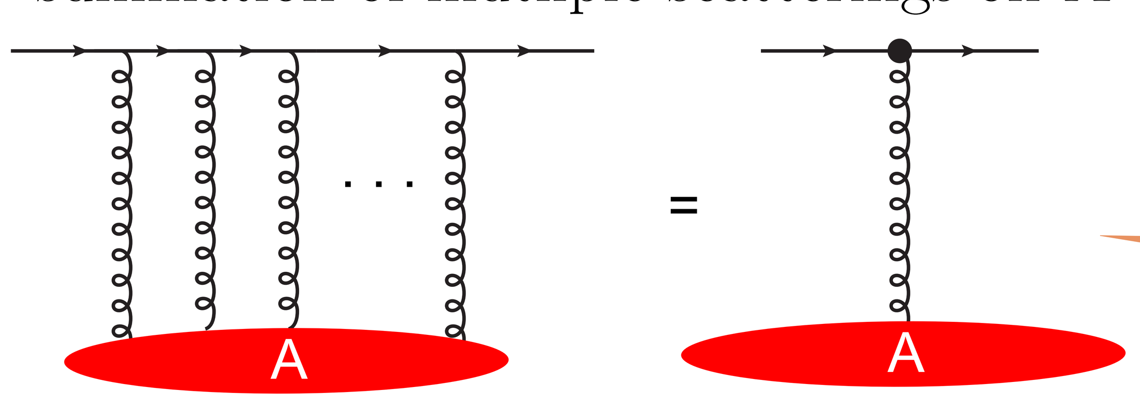
$$\mathcal{A}^-_{(0)} = -\delta(x^+)\frac{1}{\boldsymbol{\partial}^2_\perp}\rho_A(\mathbf{x}_\perp)$$

$$\mathcal{A}^i_{(1<)}(x) = \theta(-x^+)\theta(x^-)\frac{\partial^i}{\boldsymbol{\partial}^2_\perp}\rho_p(\mathbf{x}_\perp)$$

Gelis, Mehtar-Tani, PRD 73 (2006) 034019, Fukushima, Hidaka, NPA 813 (2008) 171.

Quark propagator in the field of a single nucleus

- summation of mutliple scatterings on A



McLerran, Venugopalan, PRD 59 (1999) 094002.

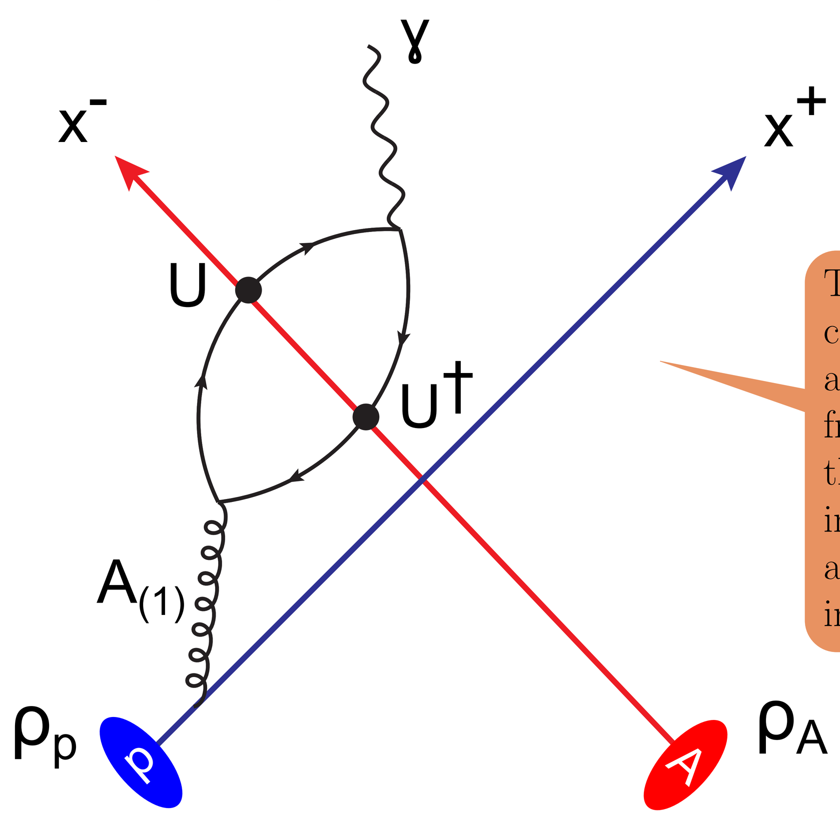
$$S_{(0)}(x,y) = S_F(x-y) + i\theta(x^+)\theta(-y^+)\int d^4z\,\delta(z^+)(U(\mathbf{z}_\perp)-1)S_F(x-z)\not{n}S_F(z-y)$$
$$- i\theta(-x^+)\theta(y^+)\int d^4z\,\delta(z^+)(U^\dagger(\mathbf{z}_\perp)-1)S_F(x-z)\not{n}S_F(z-y)$$

$$U(\mathbf{x}_\perp) \equiv \mathcal{P}_{x^+}\exp\left[ig^2\int_{-\infty}^{\infty}dx^+\mathcal{A}^-_{(0)}(x)\right] = \exp\left[-ig^2\frac{1}{\boldsymbol{\partial}^2_\perp}\rho_A(\mathbf{x}_\perp)\right]$$

Amplitude

- 0th order in ρ_p: $\mathcal{A}^\mu$ pure gauge $\to \langle \mathbf{p},\lambda|\Omega_{\rm in}\rangle = 0$
- 1st order in ρ_p: $\mathcal{A}^\mu$ develops transverse components

$$\langle \mathbf{p},\lambda|\Omega_{\rm in}\rangle = e_f g\epsilon_\mu(\mathbf{p},\lambda)\int d^4x\int d^4y\, e^{ip\cdot x}\mathcal{A}^a_{(1)\nu}(y)\langle\Omega_{\rm out}|TJ^\mu_{\rm QED}(x)J^{\nu a}_{\rm QCD}(y)|\Omega_{\rm in}\rangle_{\mathcal{A}_{(0)}}$$
$$= -e_f g\epsilon_\mu(\mathbf{p},\lambda)\int d^4x\int d^4y\, e^{ip\cdot x}\mathcal{A}^a_{(1)\nu}(y)\,{\rm Tr}[\gamma^\mu S_{(0)}(x,y)\gamma^\nu T^a_F S_{(0)}(y,x)]\,.$$



The only non-zero contribution to the amplitude comes from the case when the photon vertex is in the region $x^+ > 0$ and the gluon vertex in the region $x^+ < 0$.

- gluon momenta $\to 0$, chiral limit

$$\langle \mathbf{p},\lambda|\Omega_{\rm in}\rangle = \frac{2e_f g}{\pi}\int_{\mathbf{q}_\perp}\int_{\mathbf{k}_\perp}\int_{\mathbf{l}_\perp}\frac{\mathcal{T}}{(\mathbf{k}_\perp+\mathbf{l}_\perp)^2}\int_0^1 dx\frac{(x\mathbf{p}_\perp+\mathbf{q}_\perp)\cdot\boldsymbol{\epsilon}_\perp}{(x\mathbf{p}_\perp-\mathbf{q}_\perp)^2}$$

$$\mathcal{T} \equiv {\rm Tr}[U(\mathbf{q}_\perp+\mathbf{k}_\perp)\rho_p(-\mathbf{k}_\perp-\mathbf{l}_\perp)U^\dagger(-\mathbf{l}_\perp+\mathbf{q}_\perp-\mathbf{p}_\perp)]$$

Photon multiplicity

$$\frac{dN}{d^2p_\perp dy} = \frac{1}{4\pi}\frac{1}{(2\pi)^2}\sum_\lambda|\langle\mathbf{p},\lambda|\Omega_{\rm in}\rangle|^2$$

- color average $\to$ Mclerran-Venugopalan model
- proton

$$\langle\rho^a_p(\mathbf{k}_{1\perp})\rho^{b*}_p(\mathbf{k}_{2\perp})\rangle_{\rho_p} = (2\pi)^2\delta^{ab}g^2\mu_p^2\delta^{(2)}(\mathbf{k}_{1\perp}-\mathbf{k}_{2\perp})$$

- nucleus
  singlet contribution + large N_c limit

$$\langle{\rm Tr}\left[U(\mathbf{x}_{1\perp})T^a_F U^\dagger(\mathbf{x}_{2\perp})\right]{\rm Tr}\left[U(\mathbf{x}_{3\perp})T^b_F U^\dagger(\mathbf{x}_{4\perp})\right]\rangle_{\rho_A} = \frac{\delta^{ab}}{2}\frac{1}{N_c}\frac{\alpha-\beta}{\alpha-\gamma}\left(e^{-2Q_s^2\alpha}-e^{-2Q_s^2\gamma}\right)$$

$$2Q_s^2\alpha = B_2(\mathbf{x}_{1\perp}-\mathbf{x}_{4\perp}) + B_2(\mathbf{x}_{2\perp}-\mathbf{x}_{3\perp})$$
$$2Q_s^2\beta = B_2(\mathbf{x}_{1\perp}-\mathbf{x}_{3\perp}) + B_2(\mathbf{x}_{2\perp}-\mathbf{x}_{4\perp})$$
$$2Q_s^2\gamma = B_2(\mathbf{x}_{1\perp}-\mathbf{x}_{2\perp}) + B_2(\mathbf{x}_{3\perp}-\mathbf{x}_{4\perp})$$

$$B_2(\mathbf{x}_\perp-\mathbf{y}_\perp) = Q_s^2\int d^2z_\perp[G_0(\mathbf{x}_\perp-\mathbf{z}_\perp)-G_0(\mathbf{z}_\perp-\mathbf{y}_\perp)]^2$$

- Q_s: saturation scale

Summary

- analytic expression for photon multiplicity in pA within CGC
- leading order $\to$ bremsstrahlung, but at high energy gluon content of the proton dominates
  $\to$ photon production through quark loop in that limit should resemble more the AA case
- numerical evaluation underway

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