Photon at NLO as a CGC probe in p+A collisions

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Nucl. Phys. A **958** (2017) 1 (1602.01989)
JHEP **1701** (2017) 115 (1609.09424)

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GHP Workshop, Washington, USA, Feb. 1 - Feb. 3 2017

Color Glass Condensate

- universal form of matter at $x \ll 1$

  $\rightarrow$ **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

- nuclear enhancement $Q_S^2 \sim A^{1/3}$

Motivation

- p+A

  p → known

  A → unknown

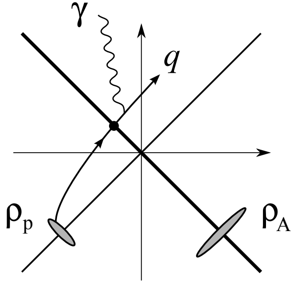
- forward hadron and di-hadron production, quarkonia production, ...

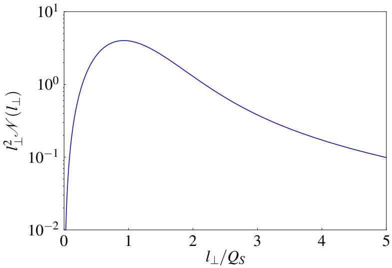
  Kharzeev, Levin, McLerran, Phys. Lett. B **561** (2003) 93
  Albacete, Armesto, Kovner, Salgado, Wiedemann, Phys. Rev. Lett. **92** (2004) 082001
  Marquet, Nucl. Phys. A **796** (2007) 41
  Dominguez, Marquet, Xiao, Yuan, Phys. Rev. D **83** (2011) 105005
  Fujii, Gelis, Venugopalan, Nucl. Phys. A **780** (2006) 146
  Ma, Venugopalan Zhang, Phys. Rev. D **92** (2015) 071901
  GHP 2017 talk: Watanabe (HI: Onia II)
  ...

- photon → clean probes

Photon in pA: LO

- valence quark bremsstrahung $O(\alpha_e)$





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

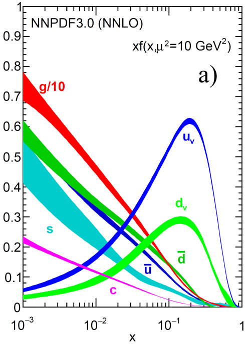
color dipole: $\int_{\mathbf{x}_\perp} e^{i\mathbf{l}_\perp\cdot\mathbf{x}_\perp}\langle U(0)U^\dagger(\mathbf{x}_\perp)\rangle$

Kopeliovich, Tarasov, Schaefer, Phys. Rev. C **59** (1999) 1609
Gelis, Jalilian-Marian, Phys. Rev. D **66** (2002) 014021
Baier, Mueller, Schiff, Nucl. Phys. A **741** (2004) 358

Photon in pA

- high energy (small x)

  $\to$ more likely to pull out a gluon than a quark from the proton



$\to$ **new emission processes**

Particle Data Group, Chin. Phys. C **40** (2016) no.10, 100001

Power counting

- proton: gluons more abundant than quarks

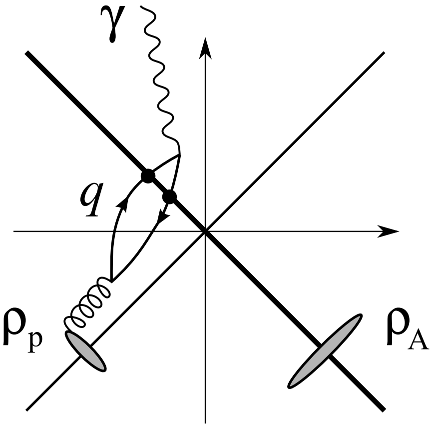
$$f_q \ll f_g$$

- nucleus dense, proton dilute

$$\rho_p \ll \rho_A$$

Photon in pA: NLO

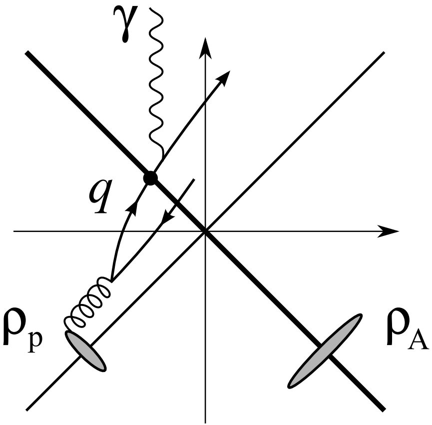
- annihilation $O(\alpha_e \alpha_S)$



SB, Fukushima, Nucl. Phys. A **958** (2017) 1
SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115

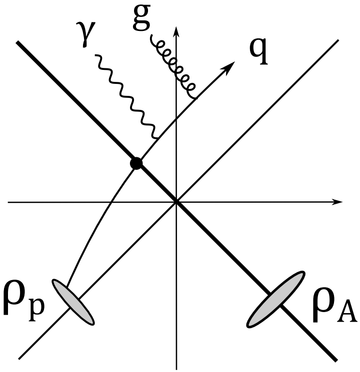
Photon in pA: NLO

- bremsstrahlung by produced $q\bar{q}$ $O(\alpha_e \alpha_S)$



Photon in pA: NLO

- photon+gluon bremsstrahlung $O(\alpha_e \alpha_S)$



- suppressed as $f_q \ll f_g$

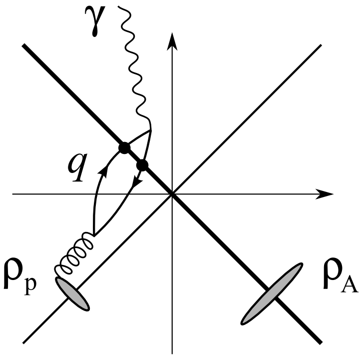
SB, Fukushima, Nucl. Phys. A **958** (2017) 1
SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115

Annihilation - amplitude

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

Annihilation - amplitude

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



Annihilation - rate

$$\frac{dN}{d^2\mathbf{k}_{\gamma\perp}d\eta_{k_\gamma}} = \frac{\alpha_e\,\alpha_S}{16\pi^8}\frac{N_c}{N_c^2-1}\int_0^1 dx\,dx'\int_{\mathbf{y}_\perp\mathbf{y}'_\perp\mathbf{z}_\perp\mathbf{z}'_\perp} e^{i\mathbf{k}_{\gamma\perp}\cdot\mathbf{r}_\perp}$$
$$\times\, S(\mathbf{y}_\perp,\mathbf{z}_\perp,\mathbf{y}'_\perp,\mathbf{z}'_\perp)\int_{\mathbf{k}_{1\perp}} e^{-i\mathbf{k}_{1\perp}\cdot\mathbf{r}_\perp}\varphi_p(\mathbf{k}_{1\perp})$$
$$\times\left[\hat{\mathbf{u}}_\perp\cdot\hat{\mathbf{u}}'_\perp\Psi_1\Psi_1'^* + \Psi_2\Psi_2'^* + 2\hat{\mathbf{u}}_\perp\cdot\hat{\mathbf{k}}_{1\perp}\Psi_1\Psi_2'^*\right]$$

- unintegrated gluon distribution

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

- multi-gluon correlator

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

SB, Fukushima, Nucl. Phys. A **958** (2017) 1

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

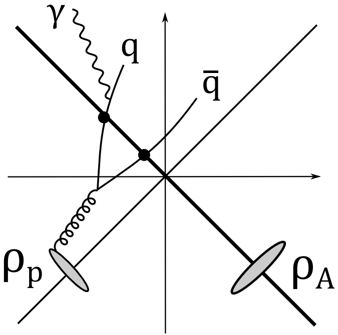
$$
\begin{aligned}
\mathcal{M}_\lambda(\mathbf{k}_\gamma, \mathbf{q}, \mathbf{p}) &= ieg \int_{xyz} e^{ik\cdot x + iq\cdot y + ip\cdot z}\, \bar{u}(\mathbf{q})(i\vec{\not\partial}_y - m) \\
&\times \Big\{ S_{(0)}(y,w)\not{\mathcal{A}}_{(1)}(w) S_{(0)}(w,x)\not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x,z) \\
&+ S_{(0)}(y,x)\not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x,w)\not{\mathcal{A}}_{(1)}(w) S_{(0)}(w,z) \Big\} (i\overleftarrow{\not\partial}_z + m) v(\mathbf{p})
\end{aligned}
$$

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

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

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

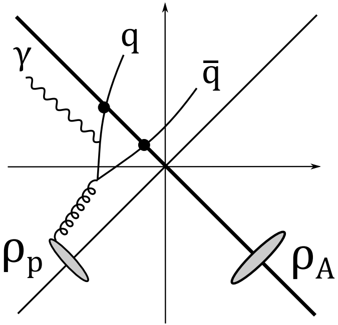
$$\left. + S_{(0)}(y, x) \not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x, w) \not{\mathcal{A}}_{(1)}(w) S_{(0)}(w, z) \right\} (i\overleftarrow{\not\partial}_z + m) v(\mathbf{p})$$



SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115

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

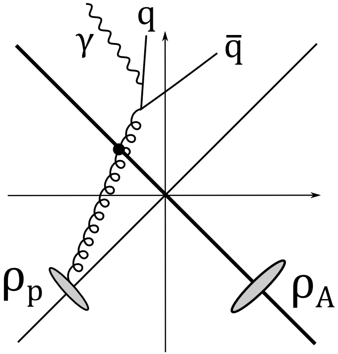
$$\mathcal{M}_\lambda(\mathbf{k}_\gamma, \mathbf{q}, \mathbf{p}) = ieg \int_{xyz} e^{ik\cdot x + iq\cdot y + ip\cdot z} \bar{u}(\mathbf{q})(i\overrightarrow{\not\partial}_y - m)$$
$$\times \Big\{ S_{(0)}(y,w) \not{\mathcal{A}}_{(1)}(w) S_{(0)}(w,x) \not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x,z)$$
$$+ S_{(0)}(y,x) \not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x,w) \not{\mathcal{A}}_{(1)}(w) S_{(0)}(w,z) \Big\} (i\overleftarrow{\not\partial}_z + m) v(\mathbf{p})$$



SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115

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

$$\mathcal{M}_\lambda(\mathbf{k}_\gamma, \mathbf{q}, \mathbf{p}) = ieg \int_{xyz} e^{ik\cdot x + iq\cdot y + ip\cdot z} \bar{u}(\mathbf{q})(i\vec{\not\partial}_y - m)$$
$$\times \Big\{ S_{(0)}(y,w)\not{\mathcal{A}}_{(1)}(w) S_{(0)}(w,x) \not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x,z)$$
$$+ S_{(0)}(y,x)\not\epsilon_\lambda(\mathbf{k}_\gamma) S_{(0)}(x,w)\not{\mathcal{A}}_{(1)}(w) S_{(0)}(w,z)\Big\}(i\overleftarrow{\not\partial}_z + m)v(\mathbf{p})$$



SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115

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

$$\frac{d\sigma}{d^2\mathbf{k}_{\gamma\perp} d\eta_{k_\gamma} d^2\mathbf{q}_\perp d\eta_q d^2\mathbf{p}_\perp d\eta_p} = \frac{\alpha_e \alpha_S^2}{256\pi^8 C_F}$$

$$\times \int_{\mathbf{k}_{1\perp}\mathbf{k}_{2\perp}} (2\pi)^2 \delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2 k_{2\perp}^2}$$

$$\times \Bigg\{ \int_{\mathbf{k}_\perp \mathbf{k}'_\perp} \mathrm{Tr}[(\not{q} + m) T^\mu_{q\bar{q}}(\mathbf{k}_{1\perp}, \mathbf{k}_\perp)(-\not{p} + m)\gamma^0 T^\dagger_{q\bar{q}\mu}(\mathbf{k}_{1\perp}, \mathbf{k}'_\perp)\gamma^0]$$

$$\times \phi_A^{q\bar{q},q\bar{q}}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}'_\perp, \mathbf{k}_{2\perp} - \mathbf{k}'_\perp)$$

$$+ \int_{\mathbf{k}_\perp} \mathrm{Tr}[(\not{q} + m) T^\mu_{q\bar{q}}(\mathbf{k}_{1\perp}, \mathbf{k}_\perp)(-\not{p} + m)\gamma^0 T^\dagger_{g\mu}(\mathbf{k}_{1\perp})\gamma^0]$$

$$\times \phi_A^{q\bar{q},g}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}_{2\perp}) + \mathrm{h.c.}$$

$$+ \mathrm{Tr}[(\not{q} + m) T^\mu_g(\mathbf{k}_{1\perp})(-\not{p} + m)\gamma^0 T^\dagger_{g\mu}(\mathbf{k}_{1\perp})\gamma^0]\phi_A^{g,g}(\mathbf{k}_{1\perp}) \Bigg\},$$

SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115
Garcia-Montero, Master thesis (2016)

Brems: multi-gluon correlators

$$\int_{\mathbf{k}_\perp \mathbf{k}'_\perp} \int_{\mathbf{x}_\perp \mathbf{x}'_\perp \mathbf{y}_\perp \mathbf{y}'_\perp} e^{i(\mathbf{k}_\perp \cdot \mathbf{x}_\perp - \mathbf{k}'_\perp \cdot \mathbf{x}'_\perp) + i(\mathbf{k}_{2\perp} - \mathbf{k}_\perp)\cdot \mathbf{y}_\perp - i(\mathbf{k}_{2\perp} - \mathbf{k}'_\perp)\cdot \mathbf{y}'_\perp}$$

$$\times \delta^{aa'} \mathrm{Tr}\left\langle t^b U^{ba}(\mathbf{x}_\perp) t^{b'} U^{\dagger a' b'}(\mathbf{x}'_\perp)\right\rangle \equiv \frac{2N_c \alpha_S}{\mathbf{k}_{2\perp}^2} \phi_A^{g,g}(\mathbf{k}_{2\perp})$$

$$\int_{\mathbf{k}'_\perp} \int_{\mathbf{x}_\perp \mathbf{x}'_\perp \mathbf{y}_\perp \mathbf{y}'_\perp} e^{i(\mathbf{k}_\perp \cdot \mathbf{x}_\perp - \mathbf{k}'_\perp \cdot \mathbf{x}'_\perp) + i(\mathbf{k}_{2\perp} - \mathbf{k}_\perp)\cdot \mathbf{y}_\perp - i(\mathbf{k}_{2\perp} - \mathbf{k}'_\perp)\cdot \mathbf{y}'_\perp}$$

$$\times \delta^{aa'} \mathrm{Tr}\left\langle \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) t^{b'} U^{\dagger a' b'}(\mathbf{x}'_\perp)\right\rangle \equiv \frac{2N_c \alpha_S}{\mathbf{k}_{2\perp}^2} \phi_A^{q\bar{q},g}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}_{2\perp})$$

$$\int_{\mathbf{x}_\perp \mathbf{x}'_\perp \mathbf{y}_\perp \mathbf{y}'_\perp} e^{i(\mathbf{k}_\perp \cdot \mathbf{x}_\perp - \mathbf{k}'_\perp \cdot \mathbf{x}'_\perp) + i(\mathbf{k}_{2\perp} - \mathbf{k}_\perp)\cdot \mathbf{y}_\perp - i(\mathbf{k}_{2\perp} - \mathbf{k}'_\perp)\cdot \mathbf{y}'_\perp}$$

$$\times \delta^{aa'} \mathrm{Tr}\left\langle \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \tilde{U}(\mathbf{y}'_\perp) t^{a'} \tilde{U}^\dagger(\mathbf{x}'_\perp)\right\rangle$$

$$\equiv \frac{2N_c \alpha_S}{\mathbf{k}_{2\perp}^2} \phi_A^{q\bar{q},q\bar{q}}(\mathbf{k}_\perp, \mathbf{k}_{2\perp} - \mathbf{k}_\perp; \mathbf{k}'_\perp, \mathbf{k}_{2\perp} - \mathbf{k}'_\perp)$$

Blaizot, Gelis, Venugopalan, Nucl. Phys. A **743** (2004) 57
SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701** (2017) 115
Garcia-Montero, Master thesis (2016)

Leading twist

- bremsstrahlung: $gg \to q\bar{q}\gamma$
- $\mathbf{k}_\perp$ factorization

$$\frac{d\sigma}{d^2\mathbf{k}_{\gamma\perp}d\eta_{k_\gamma}d^2\mathbf{q}_\perp d\eta_q d^2\mathbf{p}_\perp d\eta_p} = \frac{\alpha_e\alpha_S^2 q_f^2}{256\pi^8 N_c(N_c^2-1)}$$
$$\times \int_{\mathbf{k}_{1\perp}\mathbf{k}_{2\perp}} (2\pi)^2\delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp}) \frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})\varphi_A(Y_A,\mathbf{k}_{2\perp})}{\mathbf{k}_{1\perp}^2\mathbf{k}_{2\perp}^2}\Theta(\mathbf{k}_{1\perp},\mathbf{k}_{2\perp})$$

- collinear

$$\frac{d\sigma}{d^2\mathbf{k}_{\gamma\perp}d\eta_{k_\gamma}d^2\mathbf{q}_\perp d\eta_q d^2\mathbf{p}_\perp d\eta_p} = \frac{1}{256\pi^4}(2\pi)^2\delta^{(2)}(\mathbf{p}_\perp + \mathbf{q}_\perp + \mathbf{k}_{\gamma\perp})$$
$$\times\, x_p f_{g,p}(x_p, Q^2)\, x_A f_{g,A}(x_A, Q^2)\, |\mathcal{M}_{gg\to q\bar{q}\gamma}|^2$$

$\to$ directly sensitive to nuclear gluon distributions

Color average

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

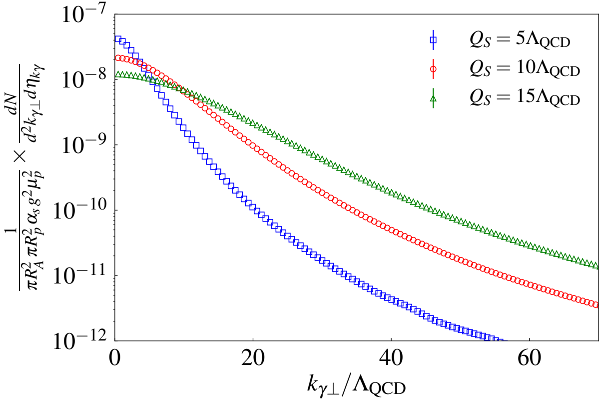
- McLerran-Venugopalan model

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

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

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

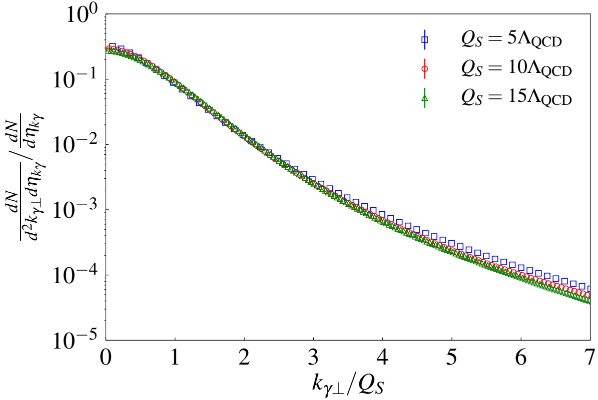
Annihilation: photon spectrum



- single flavor, chiral limit $m = 0$

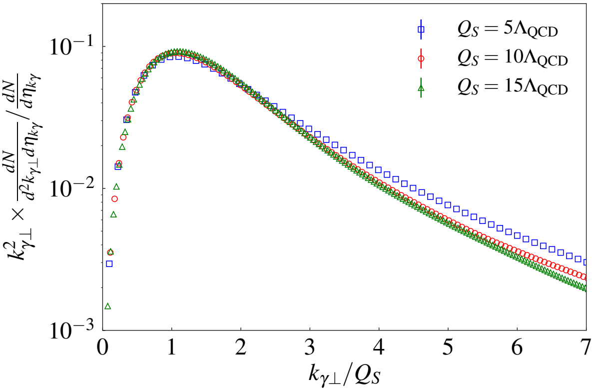
SB, Fukushima, Nucl. Phys. A **958** (2017) 1

Annihilation: geometric scaling



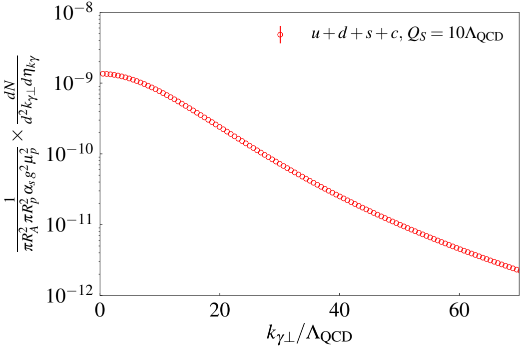
SB, Fukushima, Nucl. Phys. A **958** (2017) 1
Klein-Bösing, McLerran, Phys. Lett. B **734** (2014) 282

Annihilation: typical photon momentum



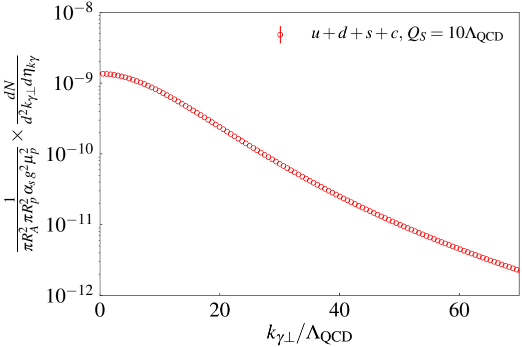
SB, Fukushima, Nucl. Phys. A **958** (2017) 1
Klein-Bösing, McLerran, Phys. Lett. B **734** (2014) 282

Annihilation: flavor effects



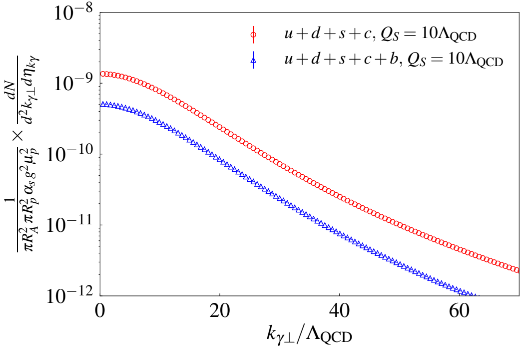
- $m_u, m_d, m_s \ll Q_S$
  $\rightarrow q_u \mathcal{M}_u + q_d \mathcal{M}_d + q_s \mathcal{M}_s \simeq 0$

Annihilation: flavor effects



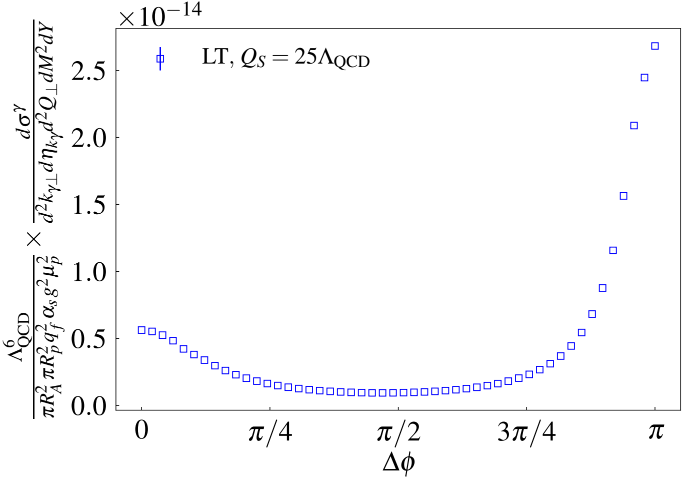
- $m_u, m_d, m_s \ll Q_S$
  $\rightarrow \mathcal{M} \simeq q_c \mathcal{M}_c + q_b \mathcal{M}_b$

Annihilation: flavor effects

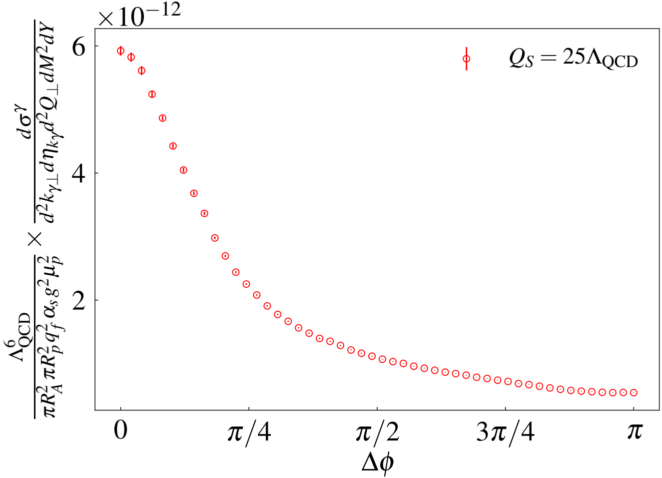


- $m_u, m_d, m_s \ll Q_S$
  $\to \mathcal{M} \simeq q_c\mathcal{M}_c + q_b\mathcal{M}_b$

Brems: $q\bar{q}$ - γ correlations (preliminary)



Brems: $q\bar{q}$ - γ correlations (preliminary)



Conclusions

- complete analytical result at $O(\alpha_e \alpha_S)$
- bremsstrahlung $\rightarrow$ nuclear gluon distribution functions
- annihilation $\rightarrow$ geometric scaling
- bremsstrahlung $\rightarrow$ angular correlations