Particle Production in CGC

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Based on works with
S. Benic, O. Garcia-Montero, R. Venugopalan
N. Tanji

— Saturation: Recent developments, new ideas and Measurements —

Talk Plan

Photons in *pA* at high energies

- □ Leading-order — Bremsstrahlung (***quarks***)

  Gelis-Jalilian-Marian hep-ph/0205037

- □ Next-leading-order — Annihilation/Bremsstrahlung (***gluons***)

  Benic-Fukushima arXiv:1602.01989
  Benic-Fukushima-Garcia-Montero-Venugopalan arXiv:1609.09424

Semi-CGC regime where the latter is overwhelming!

Quarks in *AA* at small proper time

- □ Proper-time expansion (glasma)

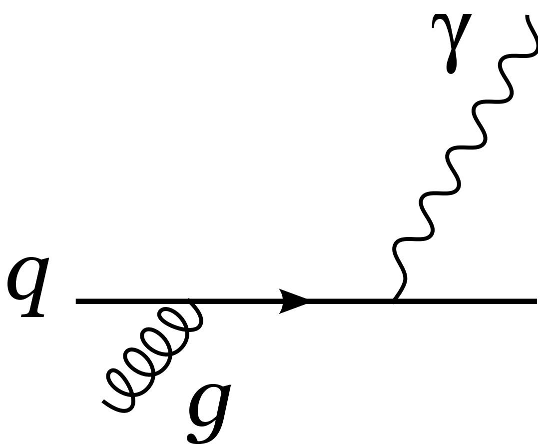
  Fries-Kapusta-Li nucl-th/0604054 / arXiv:1602.09060
  Fukushima-Fujii-Hidaka arXiv:0811.0437

- □ Quark sector — quark production / **chirality** production

  Gelis-Tanji arXiv:1506.03327 / Fukushima-Tanji ?????

Photon Production

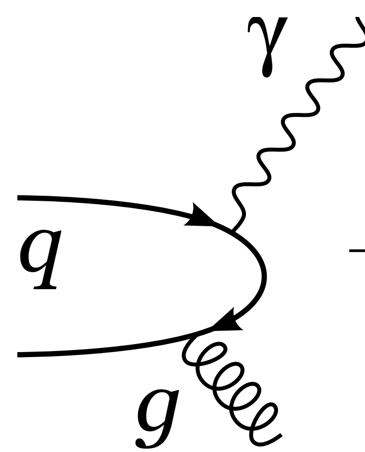
Compton Scattering



$$\propto \ \alpha_e \alpha_s \, n_q (1 - n_q) n_g$$

$$(qg \ \rightarrow \ q\gamma)$$

Annihilation



+ crossed

+ ~~LPM~~

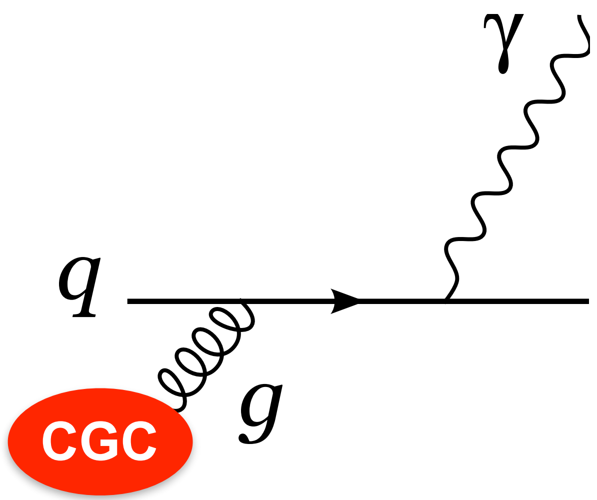
large N_c

$$\propto \ \alpha_e \alpha_s \, n_q n_{\bar{q}} (1 + n_g)$$

$$(q\bar{q} \ \rightarrow \ g\gamma)$$

Photon Production with CGC

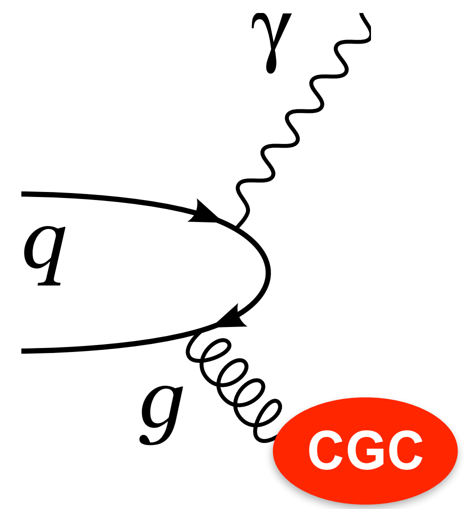
Compton Scattering



$$\propto \; \alpha_e \alpha_s \, n_q (1 - n_q) \alpha_s^{-1}$$

$$\sim \alpha_e n_q (1 - n_q)$$

Annihilation

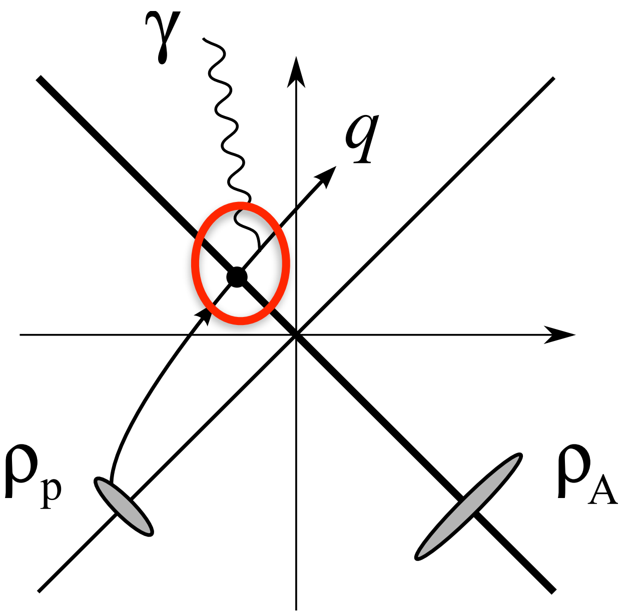


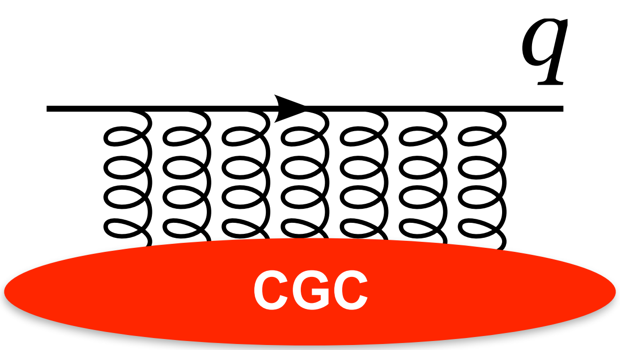
$$\propto \; \alpha_e \alpha_s \, n_q n_{\bar{q}} \alpha_s^{-1}$$

$$\sim \alpha_e n_q n_{\bar{q}}$$

Photon Production with CGC

Gauge choice: $A \sim \rho_{\mathrm{A}} \sim \delta(x^{+})$ **Gelis-Mehtar-Tani (2006)**

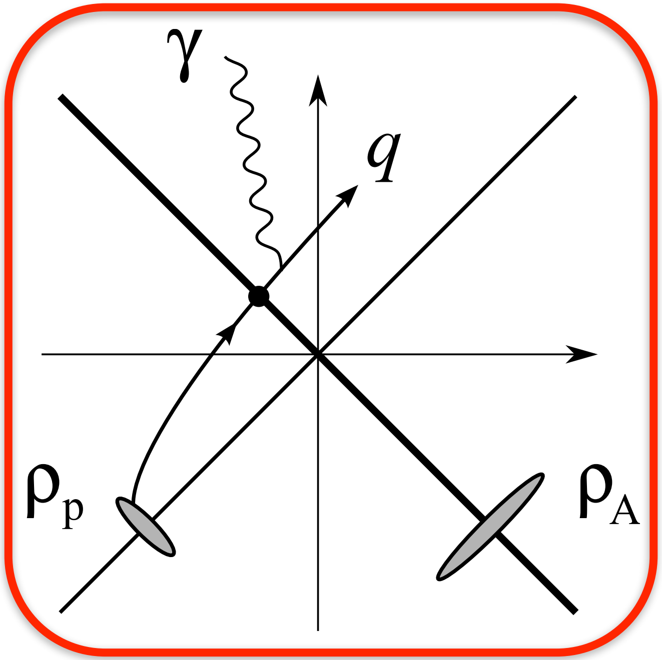




$$U \sim 1 + igA + \frac{1}{2}(igA)^2 + \cdots$$

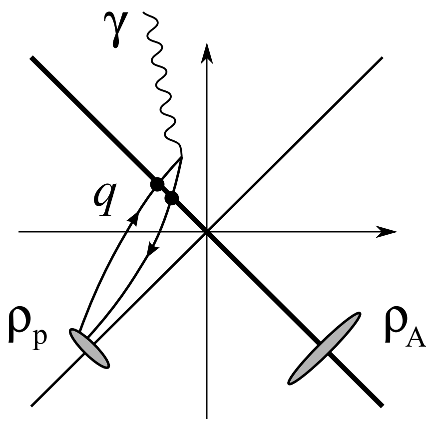
Leading-order Process

Gelis-Jalilian-Marian (2002)



$$\sim \ \alpha_e n_q \langle \underline{UU^\dagger} \rangle$$

Multiple Scattering with CGC



$$\sim \ \alpha_e n_q n_{\bar{q}} \langle UU^\dagger UU^\dagger \rangle$$

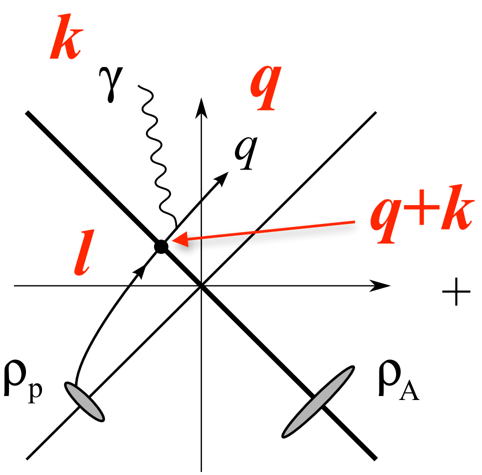
Suppressed by quark distribution

Leading-order Process

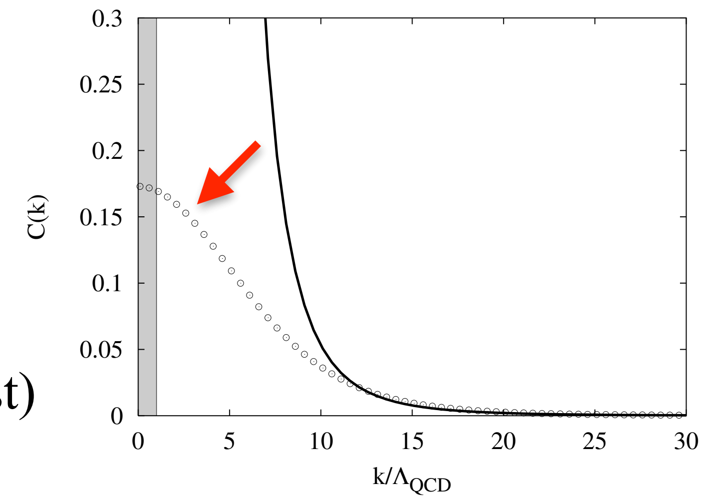
$$\frac{1}{A_\perp}\frac{d\sigma^{q\to q\gamma}}{d^2\boldsymbol{k}_\perp} = \frac{2\alpha_e}{(2\pi)^4\boldsymbol{k}_\perp^2}\int_0^1 dz\,\frac{1+(1-z)^2}{z}\int d^2\boldsymbol{l}_\perp\,\frac{\boldsymbol{l}_\perp^2 C(\boldsymbol{l}_\perp)}{(\boldsymbol{l}_\perp-\boldsymbol{k}_\perp/z)^2}$$

$$C(\boldsymbol{l}_\perp) \equiv \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp} e^{-B_2(\boldsymbol{x}_\perp)} = \int d^2\boldsymbol{x}_\perp e^{i\boldsymbol{l}_\perp\cdot\boldsymbol{x}_\perp}\left\langle U(0)U^\dagger(\boldsymbol{x}_\perp)\right\rangle_\rho$$

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

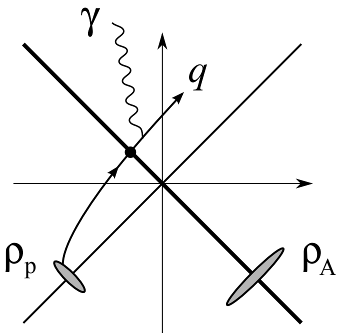


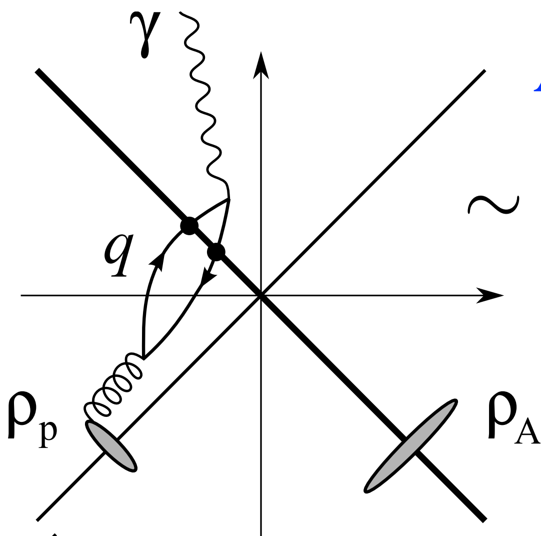
+ crossed diagram
(photon emitted first)



Gelis-Jalilian-Marian (2002)

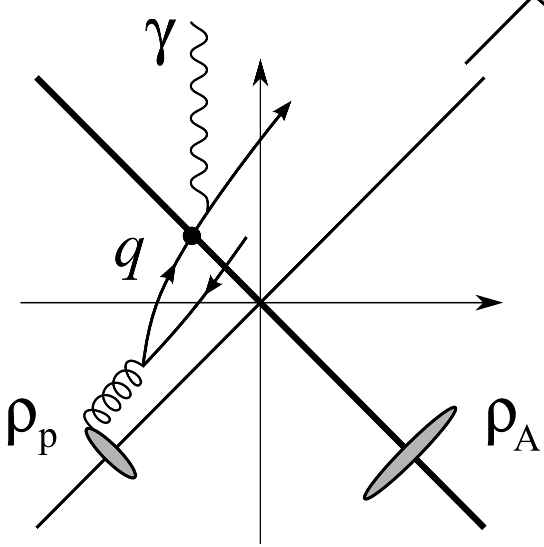
“Higher”-order Processes





Annihilation

$$\sim \ \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$$



Bremsstrahlung

$$\sim \ \alpha_e \delta n_q \langle U U^\dagger \rangle \quad \text{(evolution)}$$

$$\sim \ \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$$

“Higher”-order Processes

LO: $\sim \alpha_e n_q \langle U U^\dagger \rangle$

NLO: $\sim \alpha_e \langle (g\rho_p)^2 \rangle \langle U U^\dagger U U^\dagger \rangle$

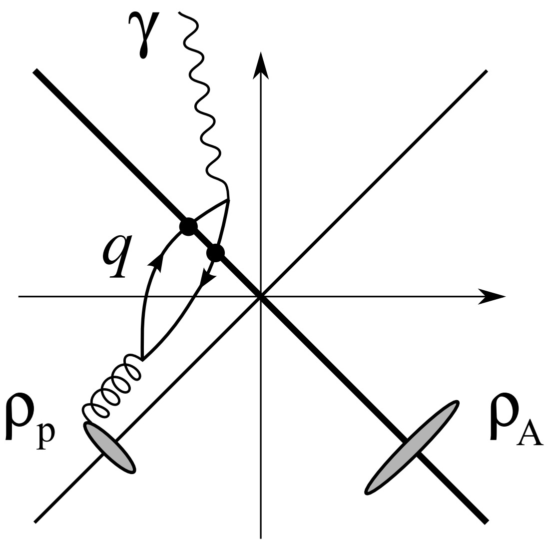
$$(g\rho_p)^2 < g\rho_p \sim n_q$$

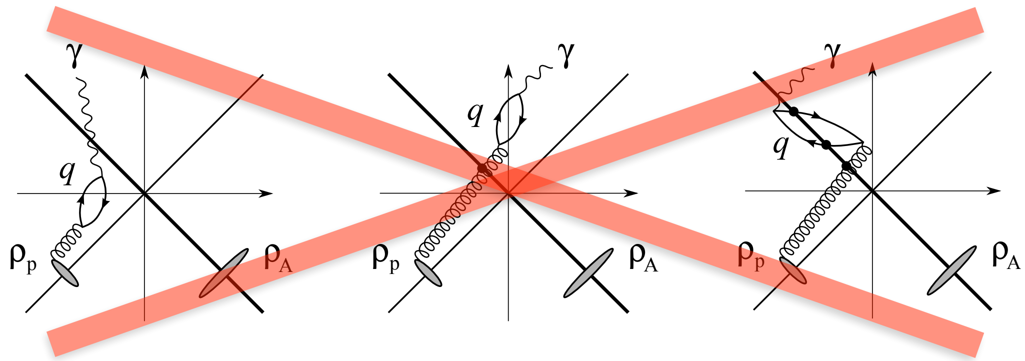
NLO is overwhelming but the pA expansion still works

Systematic calculations feasible
Not small corrections but dominant at high energies
pA photon (hopefully) coming very soon

Annihilation Diagram

Benic-Fukushima (2016)





$$\mathcal{M}_\lambda(\boldsymbol{k}) \equiv \langle \boldsymbol{k}, \lambda|\Omega\rangle = eg\int d^4x\, d^4y\, e^{ik\cdot x}\, \mathrm{Tr}\big[\not\epsilon(\boldsymbol{k},\lambda) S(x,y) \not{\mathcal{A}}_{(1)}(y) S(y,x)\big]$$

Known

$$\sim S_F\, \gamma^+ U\, S_F$$

ρ_p + propagator

Annihilation Diagram

Benic-Fukushima (2016)

✔ Ward identity:

$$\mathcal{M}_\lambda(\boldsymbol{k}) = \frac{eg^2}{4\pi^3}\int_0^1 dx \int d^2\boldsymbol{u}_\perp\, d^2\boldsymbol{v}_\perp \int \frac{d^2\boldsymbol{p}_\perp}{(2\pi)^2}\, e^{-i(\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)\cdot[\boldsymbol{v}_\perp + a(x)\boldsymbol{u}_\perp]}$$
$$\times \frac{\rho_p^a(\boldsymbol{p}_\perp)}{p_\perp^2}\,\mathrm{Tr}_c\Big[U\Big(\boldsymbol{v}_\perp + \frac{\boldsymbol{u}_\perp}{2}\Big) T_F^a U^\dagger\Big(\boldsymbol{v}_\perp - \frac{\boldsymbol{u}_\perp}{2}\Big)\Big]$$
$$\times \big[\hat{u}_\lambda p_\perp \Psi_1(\boldsymbol{p}_\perp, \boldsymbol{u}_\perp, x) + p_\lambda \Psi_2(\boldsymbol{p}_\perp, \boldsymbol{u}_\perp, x)\big]\ ,$$

Looks complicated but the structure is intuitive

$$\Psi_1(\boldsymbol{p}_\perp, \boldsymbol{u}_\perp, x) \equiv -4ia(x)b(x)p_\perp K_0(m_p(x)u_\perp)mK_1(mu_\perp)$$
$$\qquad + 4b(x)\hat{\boldsymbol{p}}_\perp\cdot\hat{\boldsymbol{u}}_\perp m_p(x)K_1(m_p(x)u_\perp)mK_1(mu_\perp)$$
$$\Psi_2(\boldsymbol{p}_\perp, \boldsymbol{u}_\perp, x) \equiv mK_1(mu_\perp)m_p(x)K_1(m_p(x)u_\perp)$$
$$\qquad + m^2K_0(mu_\perp)K_0(m_p(x)u_\perp)\ .$$

$$a(x) \equiv x - \tfrac{1}{2}$$
$$b(x) \equiv x(1-x)$$
$$m_p^2(x) \equiv m^2 + b(x)p_\perp^2$$

Annihilation Diagram

Benic-Fukushima (2016)

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

Master formula **Fukushima-Hidaka arXiv:0704.2806**

$$\big\langle U(\boldsymbol{x}_{1\perp})_{\beta_1\alpha_1} U(\boldsymbol{x}_{2\perp})_{\beta_2\alpha_2} \cdots U(\boldsymbol{x}_{n\perp})_{\beta_n\alpha_n} \big\rangle = \exp[-(H_0 + V)]_{\beta_1\cdots\beta_n;\alpha_1\cdots\alpha_n}$$

$$H_0 = Q_\mathrm{s}^2 \frac{2N_\mathrm{c}}{N_\mathrm{c}^2 - 1} \left(\sum_{k=1}^{n} t_k^a \right)^2 L(0,0)$$

$$V = -Q_\mathrm{s}^2 \frac{2N_\mathrm{c}}{N_\mathrm{c}^2 - 1} \sum_{i>j} t_i^a \, t_j^a \; \varGamma(\boldsymbol{x}_{i\perp}, \boldsymbol{x}_{j\perp})$$

Annihilation Diagram

Benic-Fukushima (2016)

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

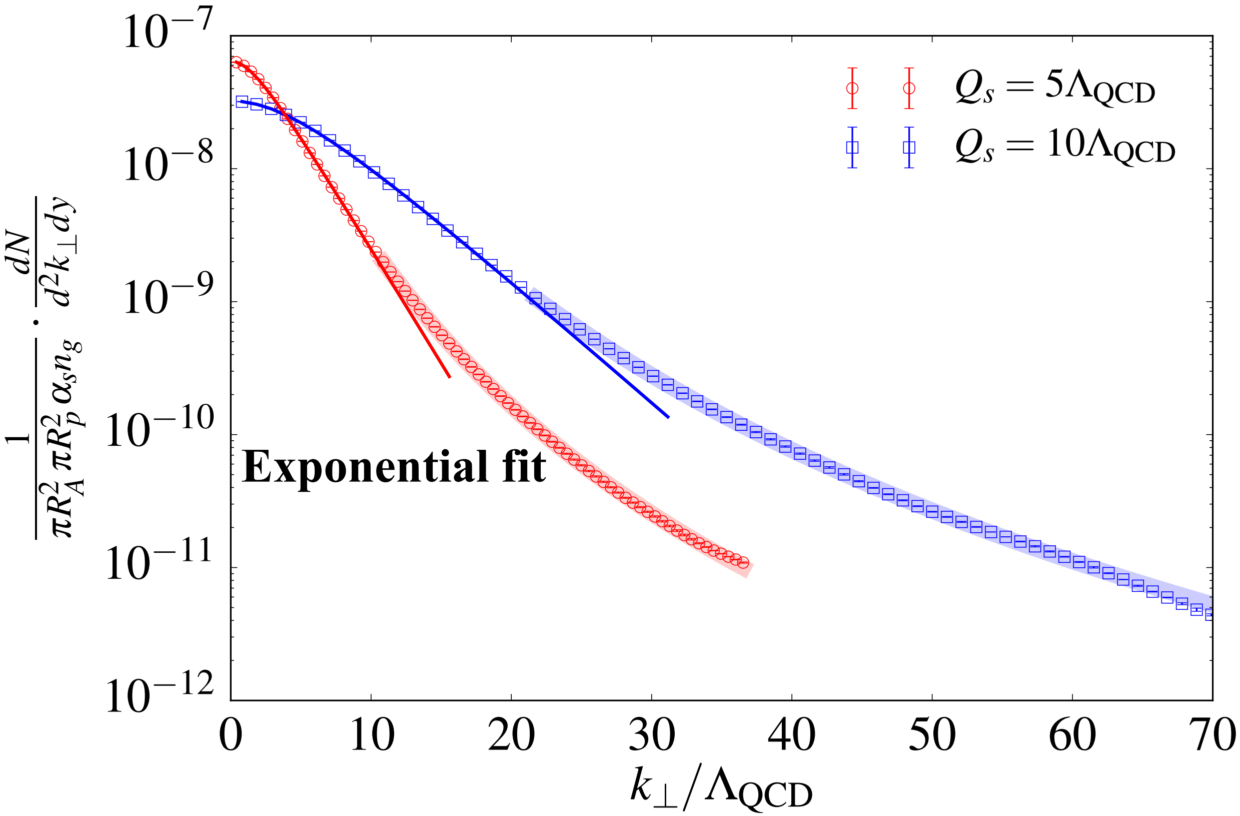
Color average in MV

$$\frac{1}{N_c}\frac{(N_c^2-1)(\beta-\alpha)}{\sqrt{N_c^2(\alpha-\gamma)^2-4(\alpha-\beta)(\beta-\gamma)}}$$
$$\times\exp\left[-\frac{2\beta+(N_c^2-2)(\alpha+\gamma)}{N_c^2-1}\right]$$
$$\times\sinh\left[\frac{N_c}{N_c^2-1}\sqrt{N_c^2(\alpha-\gamma)^2-4(\alpha-\beta)(\beta-\gamma)}\right]$$

α, β, γ : combinations of $\dfrac{1}{2\pi}\dfrac{Q_s^2}{\Lambda_{\mathrm{QCD}}^2}\Big[1-x_\perp\Lambda_{\mathrm{QCD}}K_1(x_\perp\Lambda_{\mathrm{QCD}})\Big]$

Annihilation Diagram

Benic-Fukushima (2016)



8-dim numerical integration (Monte-Carlo)

UV tail behaves numerically like:

$$(k^2 + (1.3Q_s)^2)^{-2.4}$$

Caveat

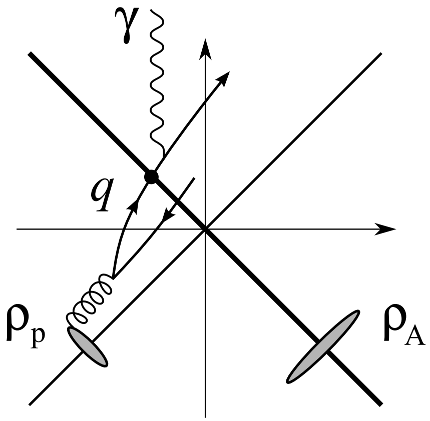
Caveat

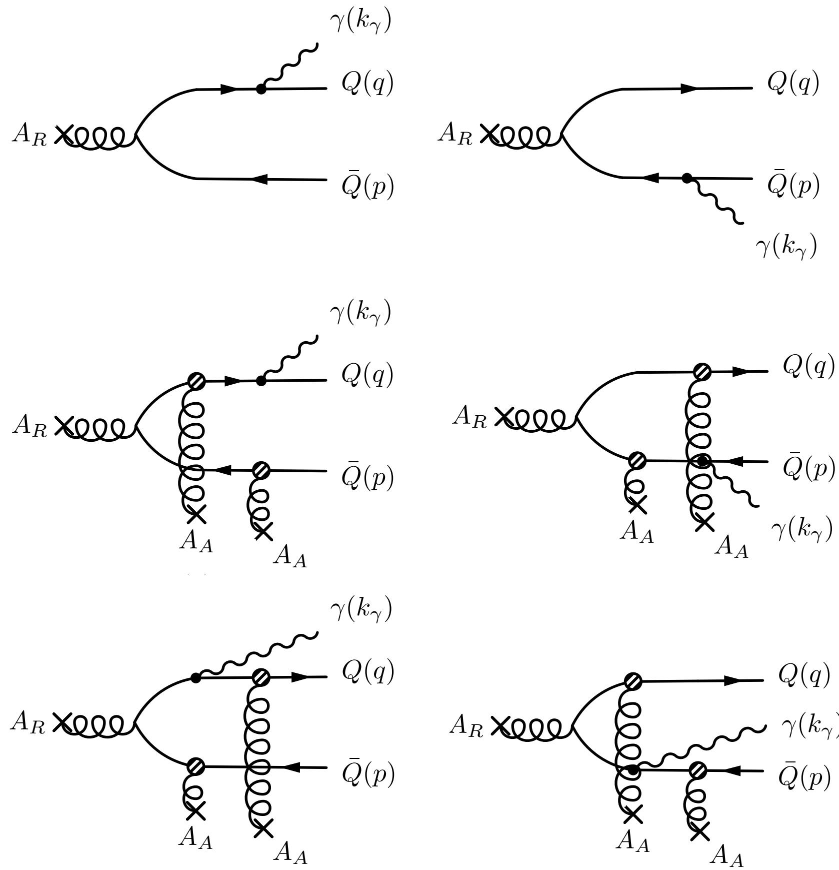
Loops vanish for *u*, *d*, *s* quarks

$$q_u + q_d + q_s = 0$$

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)



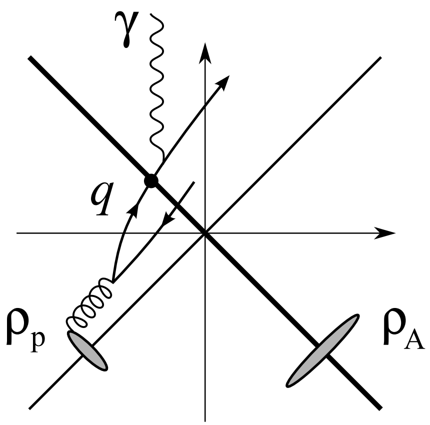


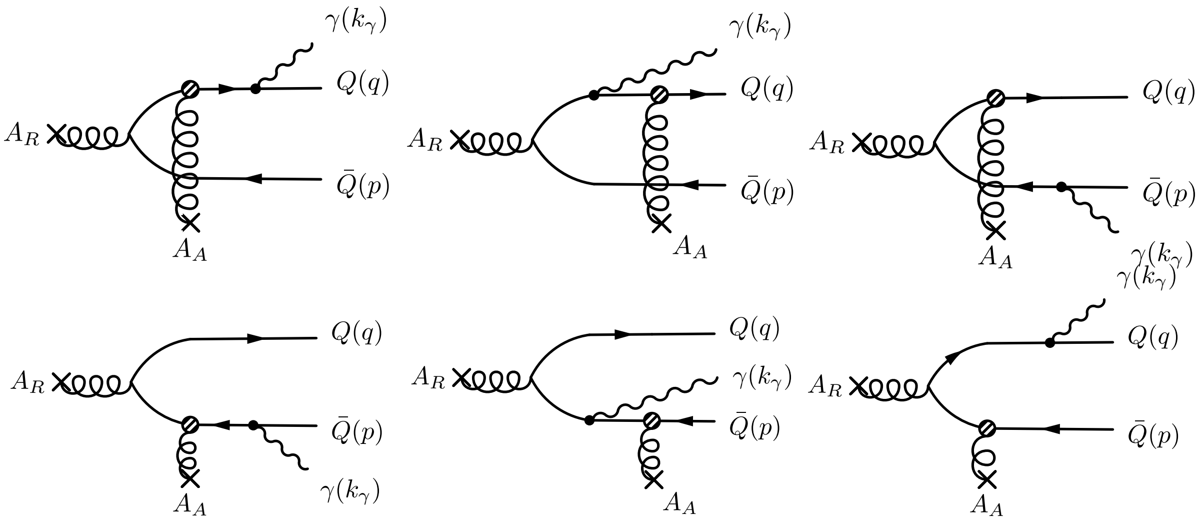
$$\sim \; U_{ad}$$

$$\sim \; U t^a U^\dagger$$

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)

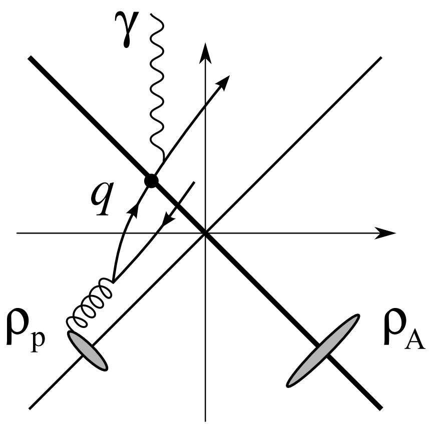


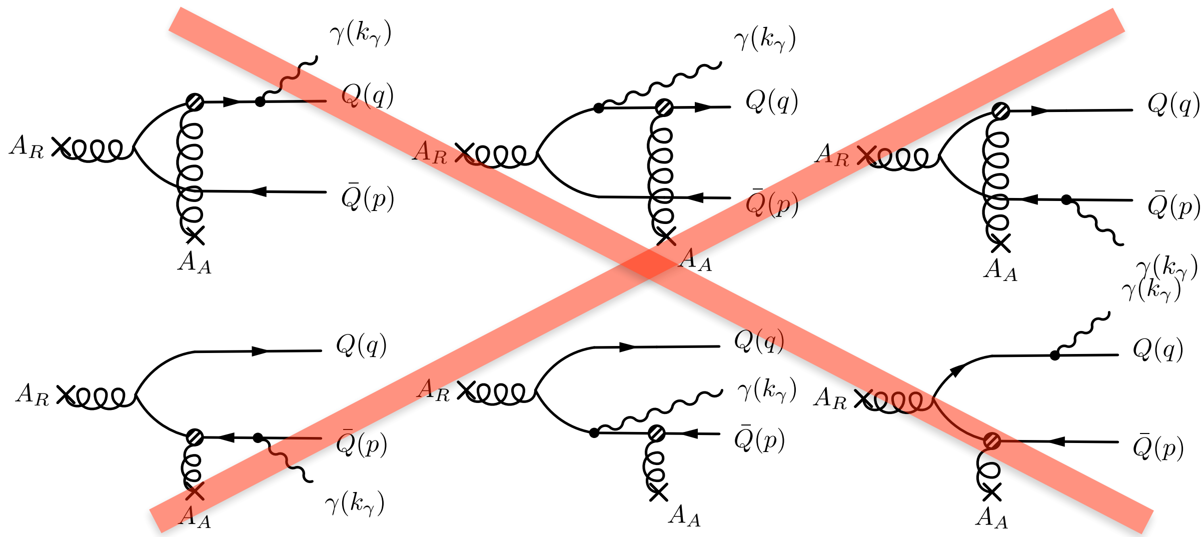


$$\sim\ U,\ U^\dagger$$

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)





$$\sim\ U,\ U^\dagger$$

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)

$$\mathcal{M}^\mu(\boldsymbol{p},\boldsymbol{q},\boldsymbol{k}_\gamma) = -q_f e g^2 \int_{\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp}} \int_{\boldsymbol{x}_\perp \boldsymbol{y}_\perp} \frac{\rho_p^a(\boldsymbol{k}_{1\perp})}{\boldsymbol{k}_{1\perp}^2}\, \mathrm{e}^{\mathrm{i}\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp + \mathrm{i}(\boldsymbol{P}_\perp - \boldsymbol{k}_\perp - \boldsymbol{k}_{1\perp})\cdot\boldsymbol{y}_\perp}$$

$$\times\, \bar{u}(\boldsymbol{q})\big\{T_g^\mu(\boldsymbol{k}_{1\perp})U(\boldsymbol{x}_\perp)^{ba}t^b + T_{q\bar{q}}^\mu(\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp})\tilde{U}(\boldsymbol{x}_\perp)t^a\tilde{U}^\dagger(\boldsymbol{y}_\perp)\big\}v(\boldsymbol{p})$$

Structure is simple but the full expression is…

Necessary conditions for correctness

- ✔ Gauge invariance (Coulomb/Light-cone)
- ✔ Ward identity: $k_{\gamma\mu}\mathcal{M}^\mu(\boldsymbol{p},\boldsymbol{q},\boldsymbol{k}_\gamma) = 0$
  satisfied separately for T_g and T_{qq}
- ✔ Leading-twist (perturbative)
- ✔ Soft-photon limit (Low-Burnett-Kroll theorem)

Bremsstrahlung Diagram

Parametric form of the final expression

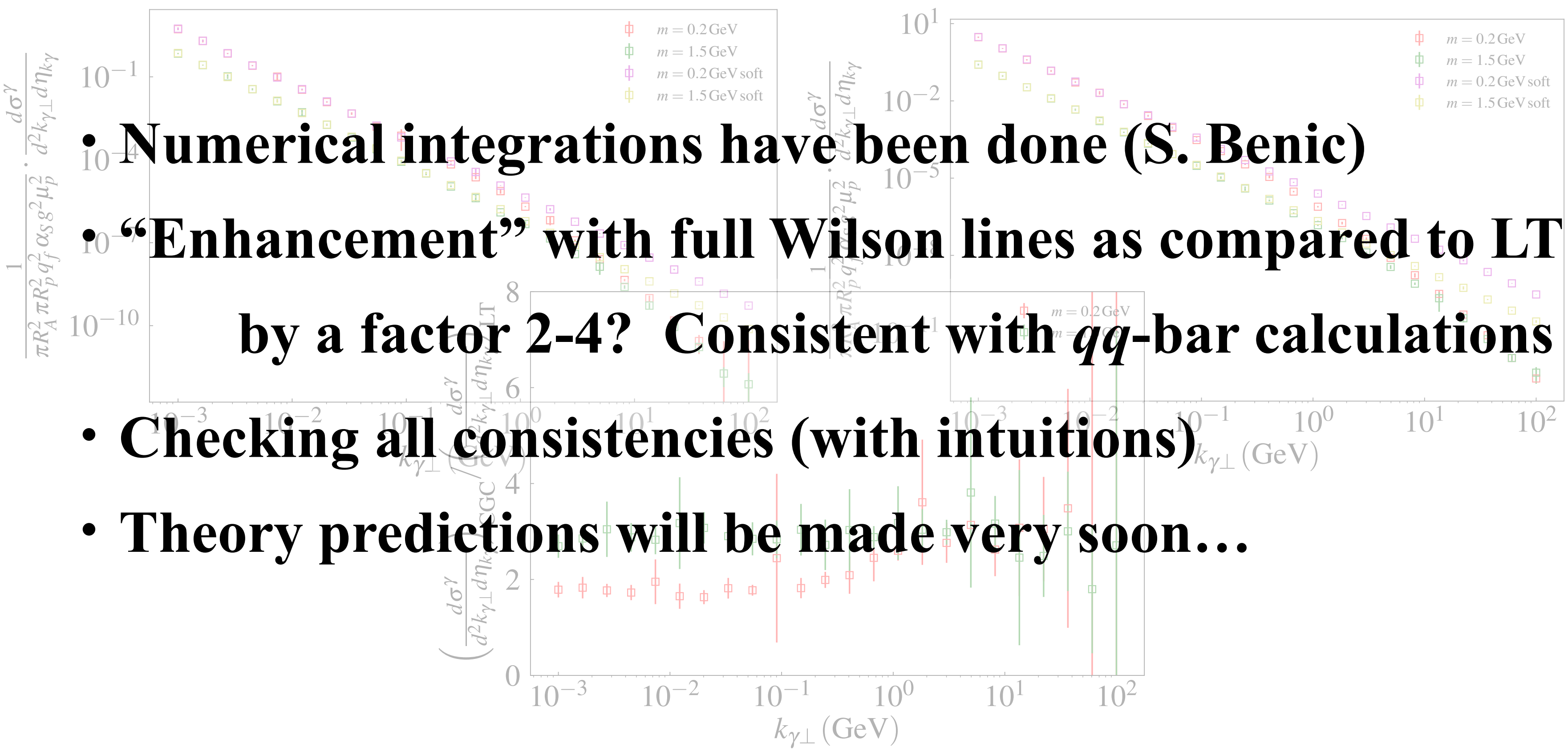
$$\frac{\mathrm{d}\sigma^{\gamma}}{\mathrm{d}^2\boldsymbol{k}_{\gamma\perp}\mathrm{d}\eta_{k_\gamma}} = \frac{\alpha_e\alpha_S^2 q_f^2}{16\pi^4 C_F}\int_0^{\infty}\frac{\mathrm{d}q^+}{q^+}\frac{\mathrm{d}p^+}{p^+}\int_{\boldsymbol{k}_{1\perp}\boldsymbol{k}_{2\perp}\boldsymbol{q}_\perp\boldsymbol{p}_\perp}(2\pi)^2\delta^{(2)}(\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp}-\boldsymbol{k}_{2\perp})\,\frac{\varphi_p(\boldsymbol{k}_{1\perp})}{\boldsymbol{k}_{1\perp}^2\boldsymbol{k}_{2\perp}^2}$$
$$\times\Big\{\tau_{g,g}(\boldsymbol{k}_{1\perp};\boldsymbol{k}_{1\perp})\phi_A^{g,g}(\boldsymbol{k}_{2\perp})+\int_{\boldsymbol{k}_\perp}2\mathrm{Re}\big[\tau_{g,q\bar{q}}(\boldsymbol{k}_{1\perp};\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp})\big]\,\phi_A^{q\bar{q},g}(\boldsymbol{k}_\perp,\boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp;\boldsymbol{k}_{2\perp})$$
$$+\int_{\boldsymbol{k}_\perp\boldsymbol{k}'_\perp}\tau_{q\bar{q},q\bar{q}}(\boldsymbol{k}_\perp,\boldsymbol{k}_{1\perp};\boldsymbol{k}'_\perp,\boldsymbol{k}_{1\perp})\,\phi_A^{q\bar{q},q\bar{q}}(\boldsymbol{k}_\perp,\boldsymbol{k}_{2\perp}-\boldsymbol{k}_\perp;\boldsymbol{k}'_\perp,\boldsymbol{k}_{2\perp}-\boldsymbol{k}'_\perp)\Big\}\,.$$

Leading twist → k_t-factorized form

$$\frac{\mathrm{d}\sigma^{\gamma}}{\mathrm{d}^6K_\perp\mathrm{d}^3\eta_K} = \frac{\alpha_e\alpha_S^2 q_f^2}{256\pi^8 N_c(N_c^2-1)}\int_{\boldsymbol{k}_{1\perp}\boldsymbol{k}_{2\perp}}(2\pi)^2\delta^{(2)}(\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp}-\boldsymbol{k}_{2\perp})\,\frac{\varphi_p(Y_p,\boldsymbol{k}_{1\perp})\varphi_A(Y_A,\boldsymbol{k}_{2\perp})}{\boldsymbol{k}_{1\perp}^2\boldsymbol{k}_{2\perp}^2}\,\Theta(\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp})$$

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)

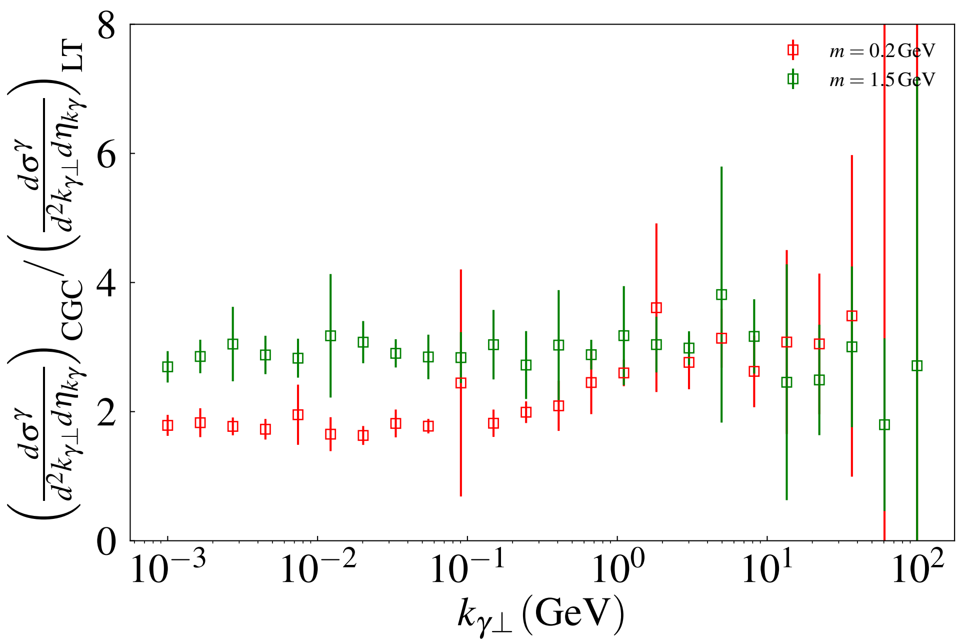


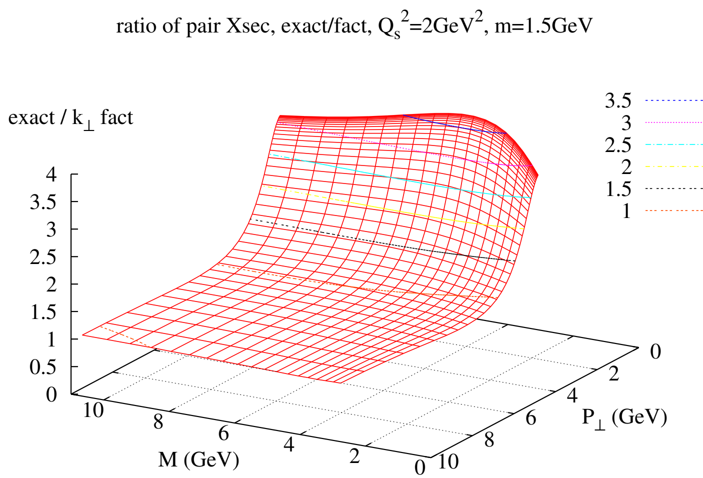
- **Numerical integrations have been done (S. Benic)**
- **“Enhancement” with full Wilson lines as compared to LT by a factor 2-4? Consistent with *qq*-bar calculations**
- **Checking all consistencies (with intuitions)**
- **Theory predictions will be made very soon…**

Bremsstrahlung Diagram

Benic-Fukushima-Garcia-Montero-Venugopalan (2016)

Preliminary





Fujii-Gelis-Venugopalan (2006)

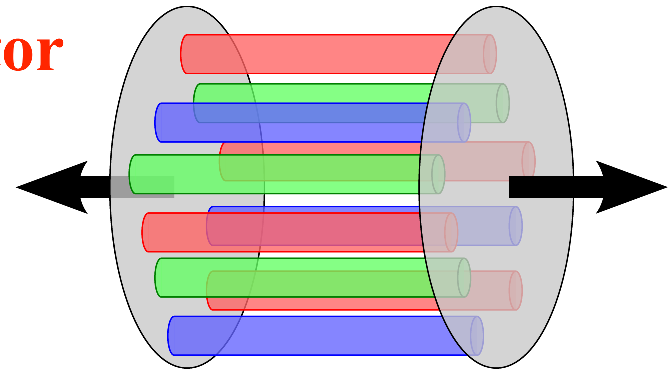
Quarks in AA

Analytically calculable up to $\tau = 0^+$

Initial condition for the gluon sector

$$A_{i(0)} = \alpha_i^{(1)} + \alpha_i^{(2)}\,, \qquad A_{\eta(0)} = 0$$

$$E^i_{(0)} = 0\,, \qquad E^\eta_{(0)} = ig\big[\alpha_i^{(1)}, \alpha_i^{(2)}\big]$$



Kovner-McLerran-Weigert (1995)

What do we know about quarks on CGC?

Initial condition for the quark sector
How μ_5 distributes (anomalous hydro)?

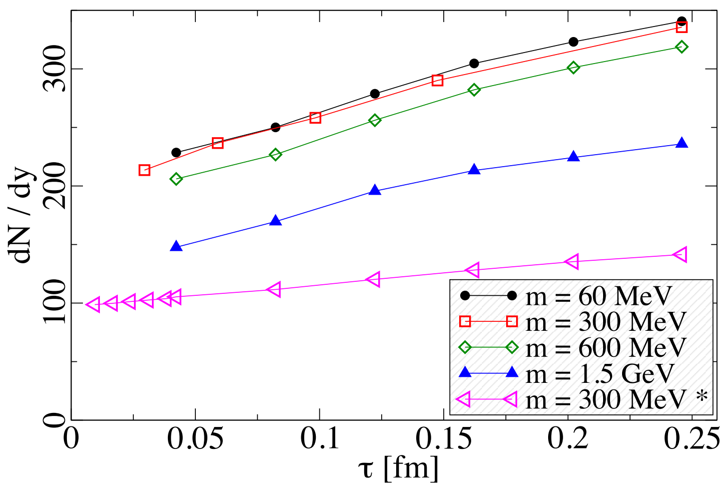
Quarks in AA

Gelis-Kajantie-Lappi (2005)

Amplitude from *anti-particles* to *particles*

$$M_\tau(p,q) \equiv \int \frac{\tau \mathrm{d}z \mathrm{d}^2\mathbf{x}_T}{\sqrt{\tau^2+z^2}} \phi^\dagger_{\mathbf{p}}(\tau,\mathbf{x})\gamma^0\gamma^\tau\psi_{\mathbf{q}}(\tau,\mathbf{x})$$

$$\frac{dN}{dy} = \int \frac{\mathrm{d}y_p \mathrm{d}^2\mathbf{p}_T}{2\,(2\pi)^3}\frac{\mathrm{d}y_q \mathrm{d}^2\mathbf{q}_T}{2\,(2\pi)^3}\delta\left(y-y_p\right)\left|M_\tau(p,q)\right|^2$$



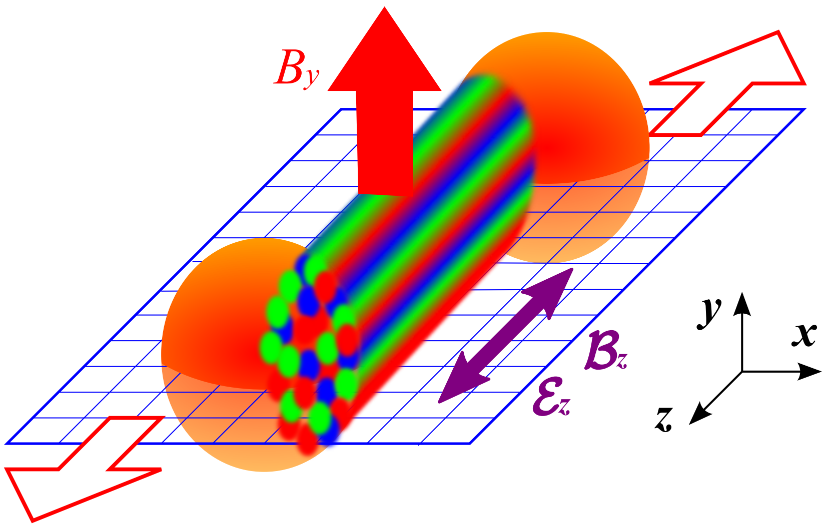
$$\psi_{\mathbf{q}}(t\to-\infty,\mathbf{x}) = e^{iq\cdot x}v(q)$$

$$\phi_{\mathbf{p}}(x) = e^{-ip\cdot x}u(p)$$

Quarks in AA

A substantial portion of particle production at $\tau = 0^+$?

If this is true, and if the glasma is true (color fluxtubes), chirality fluctuations (local parity violation) at $\tau = 0^+$?



Fukushima-Kharzeev-Warringa (2009)

Quarks in AA

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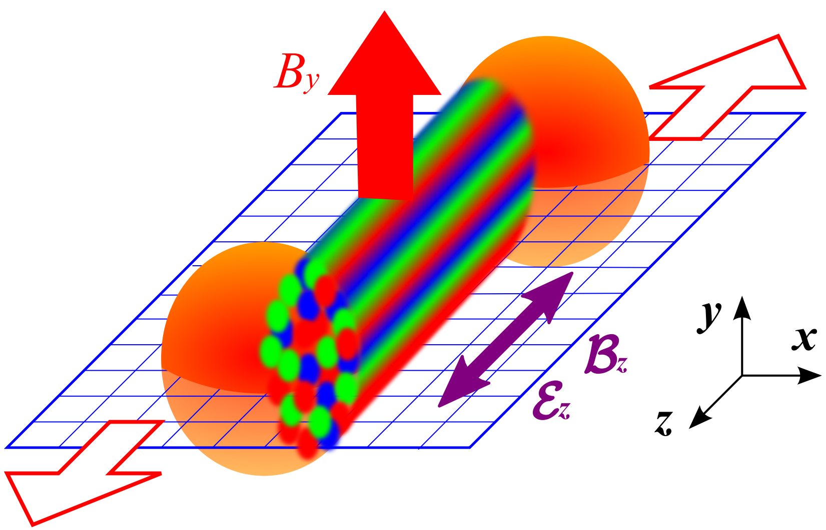


Fukushima-Kharzeev-Warringa (2009)

The answer is negative

Chirality $\sim \sqrt{\tau}$ at most

Fukushima-Tanji (coming soon)

Quarks in AA

Gelis-Tanji (2015)

Anti-particle mode functions

$$\widetilde{\psi}^{-}_{\boldsymbol{k}_\perp \nu s a}(\tau \to 0^+) = -\frac{e^{i\pi/4}}{\sqrt{M_{\boldsymbol{k}}}} \int \frac{d^2\boldsymbol{p}_\perp}{(2\pi)^2} \frac{e^{i\boldsymbol{p}_\perp \cdot \boldsymbol{x}_\perp}}{M_{\boldsymbol{p}}}$$

$$\times \Bigg[e^{\pi\nu/2} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}} \right)^{i\nu} \Gamma(-i\nu + \tfrac{1}{2}) U_2^\dagger(\boldsymbol{x}_\perp) U_2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)\gamma^+$$

$$+ e^{-\pi\nu/2} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}} \right)^{-i\nu} \Gamma(i\nu + \tfrac{1}{2}) U_1^\dagger(\boldsymbol{x}_\perp) U_1(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)\gamma^- \Bigg]$$

$$\times (p^i \gamma^i + m) v_s(\boldsymbol{k}_\perp, y_k = 0)$$

Quarks in AA

Gelis-Tanji (2015)

Anti-particle mode functions

$$\tilde{\psi}^{-}_{\boldsymbol{k}_\perp \nu s a}(\tau \to 0^+) = -\frac{e^{i\pi/4}}{\sqrt{M_{\boldsymbol{k}}}} \int \frac{d^2\boldsymbol{p}_\perp}{(2\pi)^2} \frac{e^{i\boldsymbol{p}_\perp \cdot \boldsymbol{x}_\perp}}{M_{\boldsymbol{p}}}$$

$$\times \left[e^{\pi\nu/2} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}} \right)^{i\nu} \Gamma(-i\nu + \tfrac{1}{2}) \boxed{U_2^\dagger(\boldsymbol{x}_\perp) U_2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)} \gamma^+ \right.$$

$$\left. + e^{-\pi\nu/2} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}} \right)^{-i\nu} \Gamma(i\nu + \tfrac{1}{2}) \boxed{U_1^\dagger(\boldsymbol{x}_\perp) U_1(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)} \gamma^- \right]$$

$$\times (p^i \gamma^i + m) v_s(\boldsymbol{k}_\perp, y_k = 0)$$

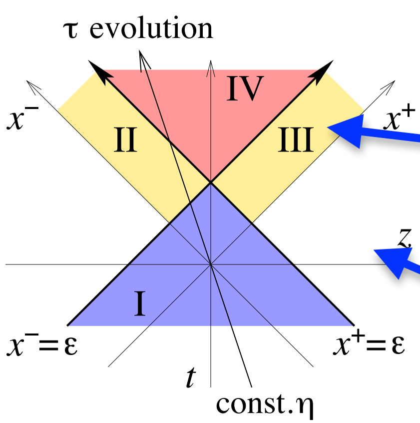
Quarks in AA

$$\widetilde{\psi}^{-}_{\boldsymbol{k}_\perp \nu s a}(\tau \to 0^+) = -\frac{e^{i\pi/4}}{\sqrt{M_{\boldsymbol{k}}}} \int \frac{d^2\boldsymbol{p}_\perp}{(2\pi)^2} \frac{e^{i\boldsymbol{p}_\perp \cdot \boldsymbol{x}_\perp}}{M_{\boldsymbol{p}}}$$

$$\times \Bigg[e^{\pi\nu/2} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}}\right)^{i\nu} \Gamma(-i\nu + \tfrac{1}{2}) \boxed{U_2^\dagger(\boldsymbol{x}_\perp) U_2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)} \gamma^+$$

$$+ e^{-\pi\nu/2} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}}\right)^{-i\nu} \Gamma(i\nu + \tfrac{1}{2}) \boxed{U_1^\dagger(\boldsymbol{x}_\perp) U_1(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)} \gamma^- \Bigg]$$

$$\times (p^i \gamma^i + m) v_s(\boldsymbol{k}_\perp, y_k = 0)$$



Eikonal *approx* → Color rotation
canceled from LC to FS

Pure-gauge → Gauge rotation (*full*)

Quarks in AA

Expectation values

$$\phi_{\boldsymbol{p}}^{(1)} = e^{-\frac{\pi\nu}{2}} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}}\right)^{-i\nu} \Gamma(i\nu + \tfrac{1}{2}) U_1^\dagger(\boldsymbol{x}_\perp) \widetilde{U}_1(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)$$

$$\phi_{\boldsymbol{p}}^{(2)} = e^{\frac{\pi\nu}{2}} \left(\frac{M_{\boldsymbol{p}}^2 \tau}{2M_{\boldsymbol{k}}}\right)^{i\nu} \Gamma(-i\nu + \tfrac{1}{2}) U_2^\dagger(\boldsymbol{x}_\perp) \widetilde{U}_2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp)$$

$$\langle 0|\overline{\widehat{\Psi}}(x) M \widehat{\Psi}(x)|0\rangle$$

$$= \frac{1}{2(2\pi)^2} \int d\nu \int_{\boldsymbol{k}_\perp} \frac{1}{M_{\boldsymbol{k}}} \int_{\boldsymbol{p}_\perp} \frac{1}{M_{\boldsymbol{p}}} \int_{\boldsymbol{q}_\perp} \frac{1}{M_{\boldsymbol{q}}} e^{-i(\boldsymbol{p}_\perp - \boldsymbol{q}_\perp)\cdot \boldsymbol{x}_\perp}$$

$$\times \operatorname{tr}\left[(q^i\gamma^i + m)(M_{\boldsymbol{k}}\gamma^0 - k^j\gamma^j - m)(p^l\gamma^l + m)\left(\phi_{\boldsymbol{p}}^{(2)\,\dagger}\gamma^+ + \phi_{\boldsymbol{p}}^{(1)\,\dagger}\gamma^-\right) M \left(\phi_{\boldsymbol{q}}^{(2)}\gamma^+ + \phi_{\boldsymbol{q}}^{(1)}\gamma^-\right)\right]$$

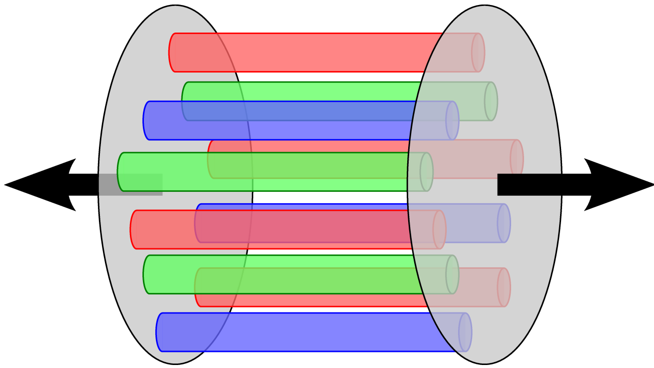
Easily shown:

Chirality / Longitudinal Current $\rightarrow$ Zero for any U_1, U_2

Transverse Currents $\rightarrow$ Non-zero for non-trivial U_1, U_2

Momentum kicks only on the transverse plane

Quarks in AA



Quarks at $\tau = 0^+$ do not feel any glasma fields at all…

Eikonal approximation is insensitive to the longitudinal fields

Eikonal approximation is "exact" in the thin pancake limit and in the $\tau = 0^+$ limit…

Transverse momentum dependent terms (higher twists) contribute to the chirality that grows as $\sim \sqrt{\tau}$

Summary

Photons in *pA* at high energies

- □ LO / NLO-Annihilation / NLO-Bremsstrahlung
- □ Numerical calculations partially done:
  CGC affects LO in IR
  CGC enhances NLO-Bremsstrahlung (**dominant**)
- □ Full predictions are coming very soon

Quarks in *AA* at small proper time

- □ Particle production not well-defined (unreliable)
- □ **Chirality production from higher twist effects at finite time** (vanishing at zero proper time)
- □ Fluctuations (current/chirality) still calculable (*B* dep?)