CGC photon production at NLO in p+A collisions

Sanjin Benić (YITP)

SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701**, (2017) 115
SB, Dumitru, Phys. Rev. D **97** (2018) no. 1, 014012
SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

INT, Seattle, November 13, 2018

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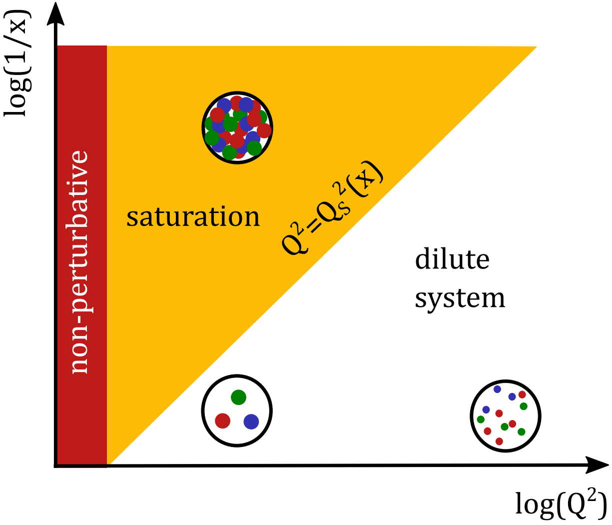
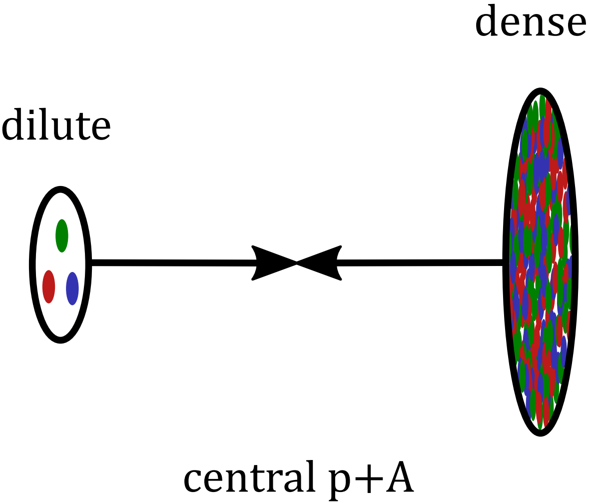
- NLO photon formula in CGC
- inclusive photon in p+p (and p+A)
- photon-jet angular correlations

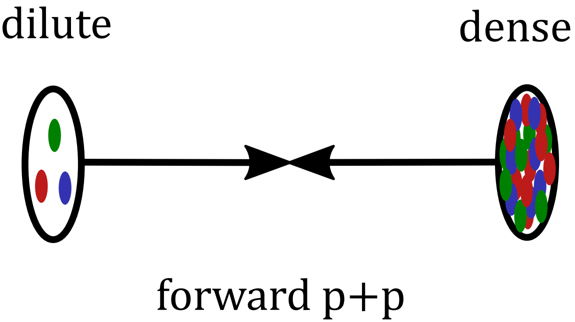
QCD phase space diagram



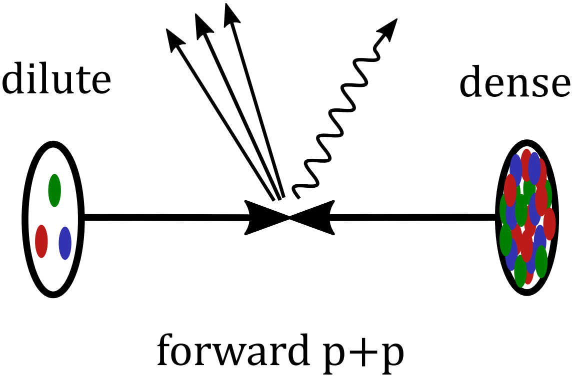
Dilute-dense collision



Dilute-dense collision

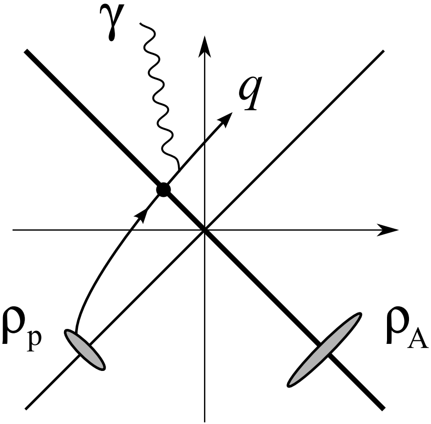


Dilute-dense collision



LO $q \to q\gamma$

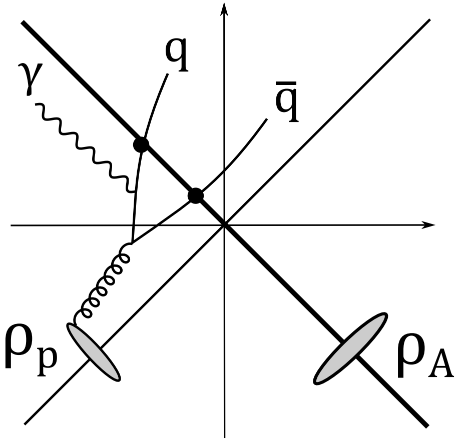
- valence quark bremsstrahung $O(\alpha_e)$



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

NLO $g \to q\bar{q}\gamma$

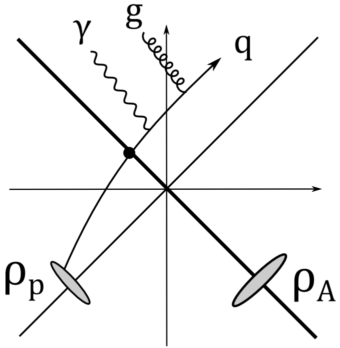
- sea quark bremsstrahlung $O(\alpha_e \alpha_S)$



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

NLO $q \to qg\gamma$

- $O(\alpha_e \alpha_S)$

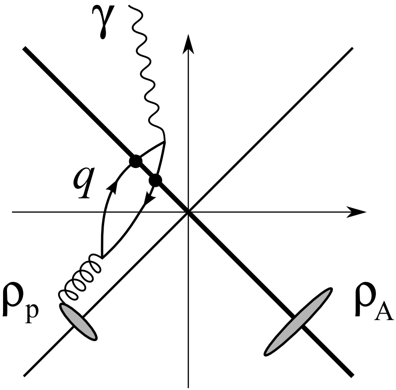


- suppressed as $f_q \ll f_g$

Altinoluk, Armesto, Kovner, Lublinsky, Petreska, JHEP **1804** (2018) 063
Altinoluk, Boussarie, Marquet, Taels, 1810.11273

NLO $g \to q^* \bar{q}^* \to \gamma$

- $O(\alpha_e \alpha_S)$



- suppressed due to quark loop

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

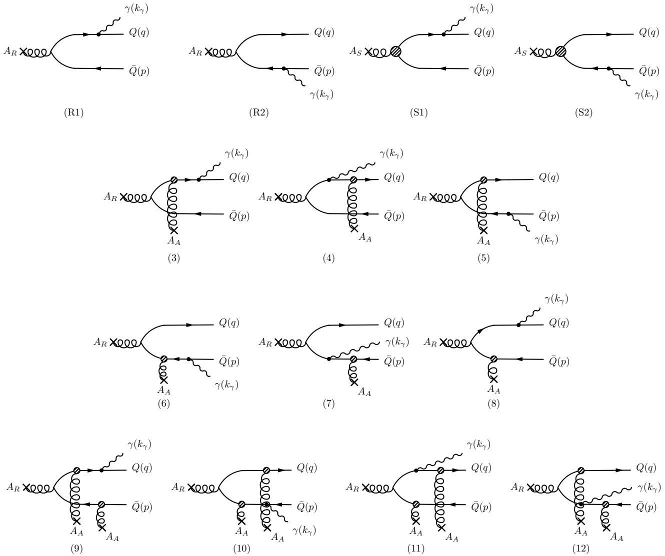
LO - cross section

$$\frac{d\sigma^{q\to q\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma d^2\mathbf{p}_\perp d\eta_p} = (\pi R_A^2)\sum_{f,\bar{f}}\frac{\alpha_e q_f^2}{64\pi^4}\int_{x_{p,\min}}^1 dx_p f_{q,f}(x_p,Q^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{p}_\perp+\mathbf{k}_{\gamma\perp})$$
$$\times\frac{1}{p^+l^+}\Bigg\{-4m_f^2\left[\frac{l^{+2}}{(p\cdot k_\gamma)^2}+\frac{p^{+2}}{(l\cdot k_\gamma)^2}+\frac{k_\gamma^{+2}}{(l\cdot k_\gamma)(p\cdot k_\gamma)}\right]$$
$$+4\left(l^{+2}+p^{+2}\right)\left[\frac{l\cdot p}{(l\cdot k_\gamma)(p\cdot k_\gamma)}+\frac{1}{p\cdot k_\gamma}-\frac{1}{l\cdot k_\gamma}\right]\Bigg\}\delta(l^+-p^+-k_\gamma^+)$$

$$\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp) = \frac{1}{N_c}\int_{\mathbf{y}_\perp} e^{i\mathbf{k}_\perp\cdot\mathbf{y}_\perp}\langle\tilde{U}(\mathbf{y}_\perp)\tilde{U}^\dagger(0)\rangle_{x_A}$$

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

NLO - diagrams



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

NLO - cross section

$$
\begin{aligned}
&\frac{d\sigma^{g\to q\bar{q}\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma d^2\mathbf{q}_\perp d\eta_q d^2\mathbf{p}_\perp d\eta_p} = \frac{\alpha_e\alpha_S^2 q_f^2}{256\pi^8 C_F}\\
&\times \int_{\mathbf{k}_{1\perp}\mathbf{k}_{2\perp}} (2\pi)^2\delta^{(2)}(\mathbf{P}_\perp - \mathbf{k}_{1\perp} - \mathbf{k}_{2\perp})\frac{\varphi_p(\mathbf{k}_{1\perp})}{k_{1\perp}^2 k_{2\perp}^2}\\
&\times \Bigg\{\int_{\mathbf{k}_\perp\mathbf{k}'_\perp} \mathrm{Tr}[(\not{q}+m)T^\mu_{q\bar{q}}(\mathbf{k}_{1\perp},\mathbf{k}_\perp)(-\not{p}+m)\gamma^0 T^\dagger_{q\bar{q}\mu}(\mathbf{k}_{1\perp},\mathbf{k}'_\perp)\gamma^0]\\
&\times \phi_A^{q\bar{q},q\bar{q}}(\mathbf{k}_\perp,\mathbf{k}_{2\perp}-\mathbf{k}_\perp;\mathbf{k}'_\perp,\mathbf{k}_{2\perp}-\mathbf{k}'_\perp)\\
&+\int_{\mathbf{k}_\perp} \mathrm{Tr}[(\not{q}+m)T^\mu_{q\bar{q}}(\mathbf{k}_{1\perp},\mathbf{k}_\perp)(-\not{p}+m)\gamma^0 T^\dagger_{g\mu}(\mathbf{k}_{1\perp})\gamma^0]\\
&\times \phi_A^{q\bar{q},g}(\mathbf{k}_\perp,\mathbf{k}_{2\perp}-\mathbf{k}_\perp;\mathbf{k}_{2\perp}) + \mathrm{h.\,c.}\\
&+\mathrm{Tr}[(\not{q}+m)T^\mu_g(\mathbf{k}_{1\perp})(-\not{p}+m)\gamma^0 T^\dagger_{g\mu}(\mathbf{k}_{1\perp})\gamma^0]\phi_A^{g,g}(\mathbf{k}_{1\perp})\Bigg\}
\end{aligned}
$$

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

NLO - 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)

NLO - consistency checks

- photon Ward identity
- NLO soft photon factorization

$$\mathcal{M}^{\mu}(\mathbf{p},\mathbf{q},\mathbf{k}_{\gamma}) = -q_f e \left(\frac{p^{\mu}}{p\cdot k_{\gamma}} - \frac{q^{\mu}}{q\cdot k_{\gamma}}\right)\mathcal{M}(\mathbf{p},\mathbf{q})$$

- NLO calculation in $A^{+}=0$ and $\partial_{\mu}A^{\mu}=0$ gauges

- $k_{\perp}$-factorization and pQCD results recovered in appropriate limits

Multi-gluon correlators at large N_c

- large N_c: gluon correlators $\rightarrow$ dipoles

$$\frac{2N_c\alpha_S}{\mathbf{k}_{2\perp}^2}\,\phi_A^{q\bar{q},q\bar{q}}(Y_A,\mathbf{k}_\perp,\mathbf{k}_{2\perp}-\mathbf{k}_\perp;\mathbf{k}'_\perp,\mathbf{k}_{2\perp}-\mathbf{k}'_\perp)$$
$$=\frac{N_c^2}{2}(2\pi)^2\delta^{(2)}(\mathbf{k}_\perp-\mathbf{k}'_\perp)(\pi R_A^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_{2\perp}-\mathbf{k}_\perp)$$

$$\frac{2N_c\alpha_S}{\mathbf{k}_{2\perp}^2}\,\phi_{A,Y_A}^{q\bar{q},g}(Y_A,\mathbf{k}_\perp,\mathbf{k}_{2\perp}-\mathbf{k}_\perp;\mathbf{k}'_\perp)=\frac{N_c^2}{2}(\pi R_A^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_{2\perp}-\mathbf{k}_\perp)$$

$$\frac{2N_c\alpha_S}{\mathbf{k}_{2\perp}^2}\,\phi_A^{g,g}(Y_A,\mathbf{k}_{2\perp})=\frac{N_c^2}{2}(\pi R_A^2)\int_{\mathbf{k}_\perp}\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_{2\perp}-\mathbf{k}_\perp)$$

Inclusive photon cross section

$$\frac{d\sigma^{g\rightarrow q\bar{q}\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_f \frac{\alpha_e\alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)}\int_{\eta_q\eta_p}\int_{\mathbf{q}_\perp\mathbf{p}_\perp\mathbf{k}_{1\perp}\mathbf{k}_\perp}\frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}^2}$$
$$\times\,\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{P}_\perp-\mathbf{k}_{1\perp}-\mathbf{k}_\perp)\Theta^{g\rightarrow q\bar{q}\gamma}(\mathbf{k}_\perp,\mathbf{k}_{1\perp})$$

Inclusive photon cross section

$$\frac{d\sigma^{g\to q\bar{q}\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_f \frac{\alpha_e\alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)}\int_{\eta_q\eta_p}\int_{\mathbf{q}_\perp\mathbf{p}_\perp\mathbf{k}_{1\perp}\mathbf{k}_\perp}\frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}^2}$$
$$\times\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{P}_\perp-\mathbf{k}_{1\perp}-\mathbf{k}_\perp)\Theta^{g\to q\bar{q}\gamma}(\mathbf{k}_\perp,\mathbf{k}_{1\perp})$$

$$\frac{d\sigma^{q\to q\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_{f,\bar{f}}\frac{\alpha_e q_f^2}{16\pi^2}\int_{\mathbf{p}_\perp}\int_{x_{p,\min}}^1 dx_p f_{q,f}(x_p,Q^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{p}_\perp+\mathbf{k}_{\gamma\perp})\Theta^{q\to q\gamma}$$

Inclusive photon cross section

$$\frac{d\sigma^{g\to q\bar{q}\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_f \frac{\alpha_e\alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)}\int_{\eta_q\eta_p}\int_{\mathbf{q}_\perp\mathbf{p}_\perp\mathbf{k}_{1\perp}\mathbf{k}_\perp}\frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}^2}$$
$$\times\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{P}_\perp-\mathbf{k}_{1\perp}-\mathbf{k}_\perp)\Theta^{g\to q\bar{q}\gamma}(\mathbf{k}_\perp,\mathbf{k}_{1\perp})$$

$$\frac{d\sigma^{q\to q\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_{f=u,d}\frac{\alpha_e q_f^2}{16\pi^2}\int_{\mathbf{p}_\perp}\int_{x_{p,\mathrm{min}}}^1 dx_p f_{q,f}^{\mathrm{val}}(x_p,Q^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{p}_\perp+\mathbf{k}_{\gamma\perp})\Theta^{q\to q\gamma}$$

- use $f_{q,f}^{\mathrm{val}}(x_p,Q^2)$ for LO

Evolution and initial condition

- running coupling BK
- initial condition at $x = 0.01$

$$\mathcal{N}_{Y_p=0}(\mathbf{x}_\perp) = \exp\left\{-\frac{[x_\perp^2 (Q_{S0}^p)^2]^\gamma}{2} \log\left(\frac{1}{x_\perp \Lambda_{\text{IR}}} + e\right)\right\}$$

- MV IC:

$$\Lambda_{\text{IR}} = 0.241\,\text{GeV} \quad \gamma = 1.0 \quad (Q_{S0}^p)^2 = 0.2\,\text{GeV}^2$$

(good description of J/Ψ production)

Ma, Venugopalan, Phys. Rev. Lett. **113** (2014) no.19, 192301
Ma, Venugopalan, Watanabe, Zhang, Phys. Rev. C **97** (2018) no.1, 014909
Ma, Tribedy, Venugopalan, Watanabe, Phys. Rev. D **98** (2018) no.7, 074025

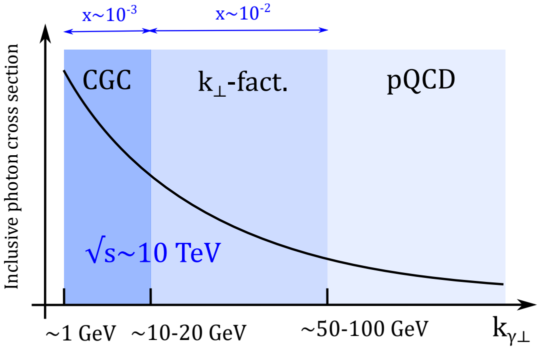
Isolated photons

$$\sqrt{(\phi - \phi_\gamma)^2 + (\eta - \eta_\gamma)^2} > R$$

- hadronic activity inside the cone below some threshold
- suppresses fragmentation photons
- we use $R = 0.4$

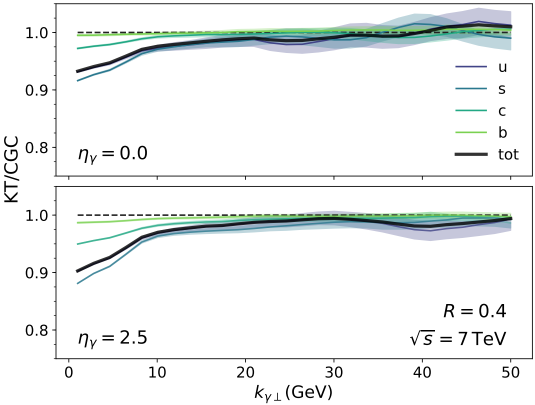
$p + p$ @ LHC

- $p + p \to \gamma + X$ @ 2.76, 7 & 13 TeV
- ATLAS, CMS: $k_{\gamma\perp} \gtrsim 20$ GeV



$\to$ small-x physics

NLO: $k_\perp$-factorized vs CGC



SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

Inclusive photon cross section

$$\frac{d\sigma^{g\to q\bar{q}\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_f \frac{\alpha_e \alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)}\int_{\eta_q\eta_p}\int_{\mathbf{q}_\perp\mathbf{p}_\perp\mathbf{k}_{1\perp}\mathbf{k}_\perp}\frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}^2}$$
$$\times\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{P}_\perp-\mathbf{k}_{1\perp}-\mathbf{k}_\perp)\Theta^{g\to q\bar{q}\gamma}(\mathbf{k}_\perp,\mathbf{k}_{1\perp})$$

$$\frac{d\sigma^{q\to q\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_{f=u,d}\frac{\alpha_e q_f^2}{16\pi^2}\int_{\mathbf{p}_\perp}\int_{x_{p,\mathrm{min}}}^1 dx_p f_{q,f}^{\mathrm{val}}(x_p,Q^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{p}_\perp+\mathbf{k}_{\gamma\perp})\Theta^{q\to q\gamma}$$

- use $f_{q,f}^{\mathrm{val}}(x_p,Q^2)$ for LO

Inclusive photon cross section

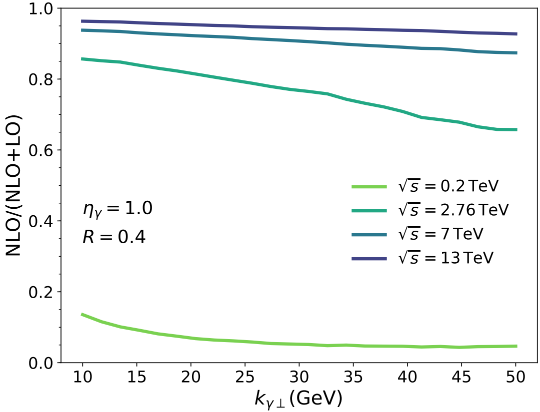
$$\frac{d\sigma^{g\to q\bar{q}\gamma}_{k_\perp-\text{fact}}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_f \frac{\alpha_e\alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)}\int_{\eta_q\eta_p}\int_{\mathbf{q}_\perp\mathbf{p}_\perp\mathbf{k}_{1\perp}} \frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}^2}$$
$$\times\,\mathcal{N}_{A,Y_A}(\mathbf{P}_\perp-\mathbf{k}_{1\perp})\Theta^{g\to q\bar{q}\gamma}_{k_\perp-\text{fact}}$$

$$\frac{d\sigma^{q\to q\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_{f=u,d}\frac{\alpha_e q_f^2}{16\pi^2}\int_{\mathbf{p}_\perp}\int_{x_{p,\text{min}}}^1 dx_p f^{\text{val}}_{q,f}(x_p,Q^2)\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{p}_\perp+\mathbf{k}_{\gamma\perp})\Theta^{q\to q\gamma}$$

- use $f^{\text{val}}_{q,f}(x_p,Q^2)$ for LO

LO vs NLO: collision energy

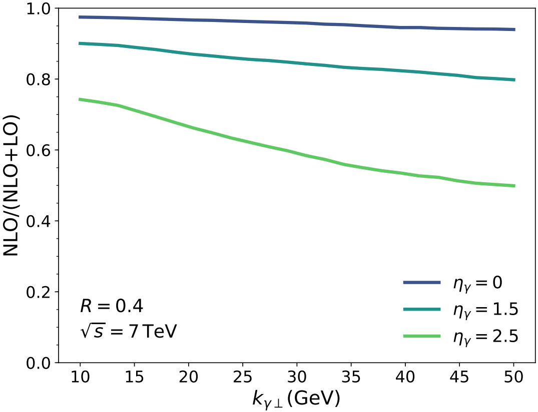
- $x_p \sim \frac{k_{\gamma\perp}}{\sqrt{s}} e^{\eta_\gamma} \quad x_A \sim \frac{k_{\gamma\perp}}{\sqrt{s}} e^{-\eta_\gamma}$



SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

LO vs NLO: rapidity

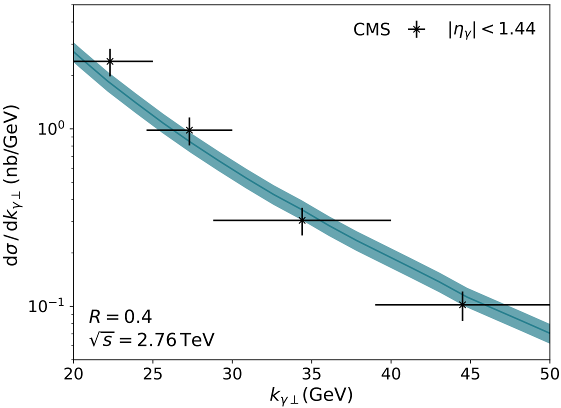
- $x_p \sim \frac{k_{\gamma\perp}}{\sqrt{s}} e^{\eta_\gamma} \quad x_A \sim \frac{k_{\gamma\perp}}{\sqrt{s}} e^{-\eta_\gamma}$



SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

p+p $\sqrt{s} = 2.76$ TeV

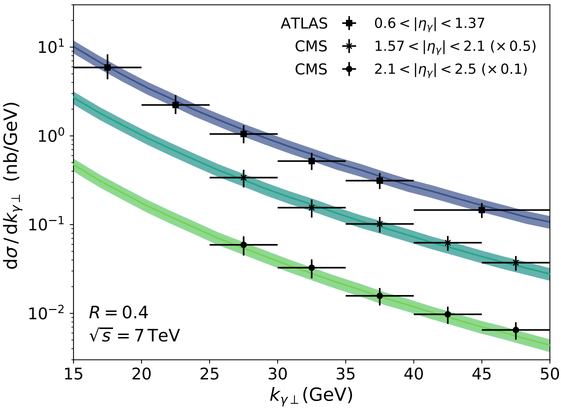
- K factor: $K = 2.4$



CMS, Phys. Lett. B **710**, 256 (2012)
SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

p+p $\sqrt{s} = 7$ TeV

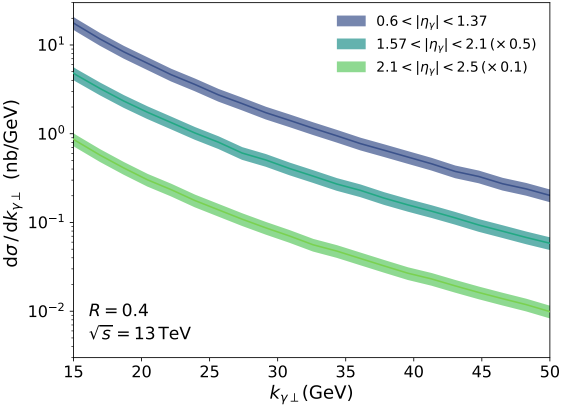
- K factor: $K = 2.4$



ATLAS, Phys. Rev. D **83**, 052005 (2011)
SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

p+p $\sqrt{s} = 13$ TeV

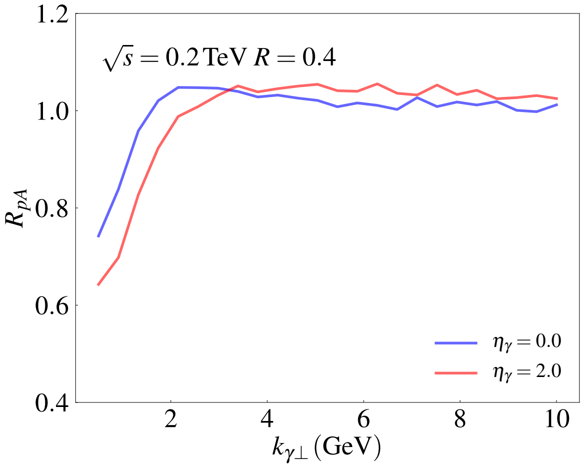
- K factor: $K = 2.4$



ATLAS, Phys. Rev. D **83**, 052005 (2011)
CMS, Phys. Rev. D **84** (2011) 052011
SB, Fukushima, Garcia-Montero, Venugopalan, 1807.03806

$p + A \sqrt{s} = 0.2$ TeV (preliminary)

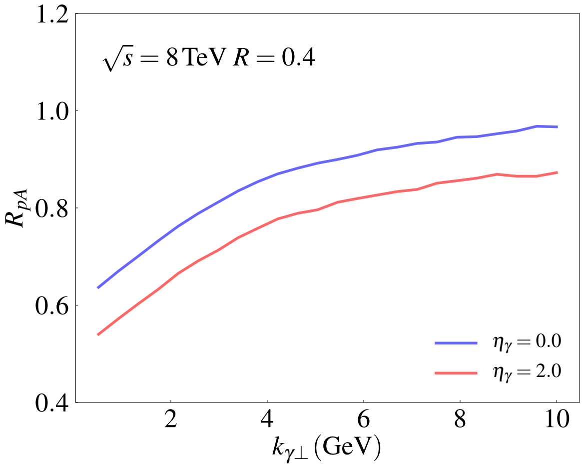
- $(Q_{S,0}^A)^2 = 3(Q_{S,0}^p)^2$



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

$p + A$ $\sqrt{s} = 8$ TeV (preliminary)

- $(Q_{S,0}^A)^2 = 3(Q_{S,0}^p)^2$



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

Back-to-back kinematics

- γ-jet final state: $\mathbf{k}_{\gamma\perp}, \mathbf{p}_\perp \gg Q_S$

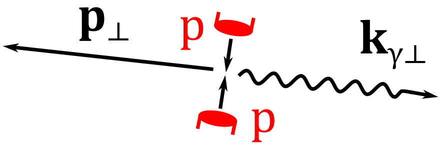
$$\mathbf{Q}_\perp \equiv \mathbf{k}_{\gamma\perp} + \mathbf{p}_\perp \qquad \tilde{\mathbf{P}}_\perp \equiv \frac{1}{2}(\mathbf{p}_\perp - \mathbf{k}_{\gamma\perp})$$

- correlation limit

$$Q_\perp \ll \tilde{P}_\perp$$

Angular correlations

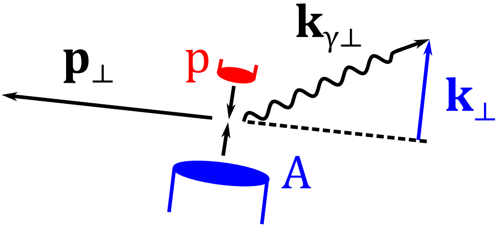
- dilute-dilute: back-to-back emissions



Angular correlations

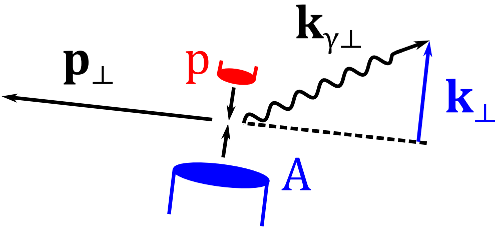
- dilute-dense: transverse kick from CGC

  $\to$ momentum imbalance



Angular correlations

- dilute-dense: transverse kick from CGC
  $\rightarrow$ momentum imbalance



- angular correlations

$$\cos\phi = \frac{\mathbf{Q}_\perp \cdot \tilde{\mathbf{P}}_\perp}{Q_\perp \tilde{P}_\perp} \qquad a_n \equiv \langle \cos\, n\phi \rangle$$

LO

$$\frac{d\sigma^{q\to q\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma d^2\mathbf{p}_\perp d\eta_p} = \sum_{f,\bar{f}} \frac{\alpha_e q_f^2}{32\pi^5}\int_{x_{p,\min}}^1 dx_p f_{q,f}(x_p,\mu^2)$$
$$\times \frac{1}{l^+}\left(l^{+2}+p^{+2}\right)\left[\frac{l\cdot p}{(l\cdot k_\gamma)(p\cdot k_\gamma)}+\frac{1}{p\cdot k_\gamma}-\frac{1}{l\cdot k_\gamma}\right]\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{p}_\perp+\mathbf{k}_{\gamma\perp})$$
$$\times(2\pi)\delta(l^+-p^+-k_\gamma^+)$$

LO

$$\frac{d\sigma^{q\to q\gamma}}{d^2\tilde{\mathbf{P}}_\perp d^2\mathbf{Q}_\perp d\eta_\gamma d\eta_p} = \sum_{f,\bar{f}} \frac{\alpha_e q_f^2}{16\pi^5} \int_{x_{p,\min}}^1 dx_p f_{q,f}(x_p,\mu^2) \frac{(1-z_q)^2+z_q^2}{z_q}$$

$$\frac{z_q(1-z_q)^2 Q_\perp^2}{\left(\frac{1}{2}\mathbf{Q}_\perp - \tilde{\mathbf{P}}_\perp\right)^2 \left[\left(\frac{1}{2}-z_q\right)\mathbf{Q}_\perp + \tilde{\mathbf{P}}_\perp\right]^2} \tilde{\mathcal{N}}_{A,Y_A}(\mathbf{Q}_\perp)\,(2\pi)p^+\delta(l^+ - p^+ - k_\gamma^+)$$

LO

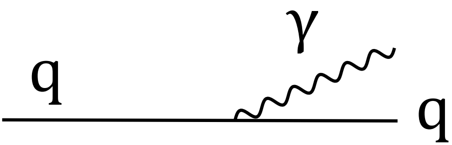
$$\frac{d\sigma^{q\to q\gamma}}{d^2\tilde{\mathbf{P}}_\perp d^2\mathbf{Q}_\perp d\eta_\gamma d\eta_p} = \sum_{f,\bar{f}} \frac{\alpha_e q_f^2}{16\pi^5} \int_{x_{p,\min}}^1 dx_p f_{q,f}(x_p,\mu^2) \frac{(1-z_q)^2 + z_q^2}{z_q}$$

$$\frac{z_q(1-z_q)^2 Q_\perp^2}{\left(\frac{1}{2}\mathbf{Q}_\perp - \tilde{\mathbf{P}}_\perp\right)^2 \left[\left(\frac{1}{2}-z_q\right)\mathbf{Q}_\perp + \tilde{\mathbf{P}}_\perp\right]^2} \mathcal{N}_{A,Y_A}(\mathbf{Q}_\perp)\,(2\pi)p^+\delta(l^+ - p^+ - k_\gamma^+)$$

- isotropic to $Q_\perp^2/Q_S^2$
- $\cos\phi$ dependence @ $(Q_\perp^2/Q_S^2)\times(Q_\perp/\tilde{P}_\perp)$
- a_n's NOT sensitive to $\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{Q}_\perp)$

LO

- photon typically emitted collinearly to the jet



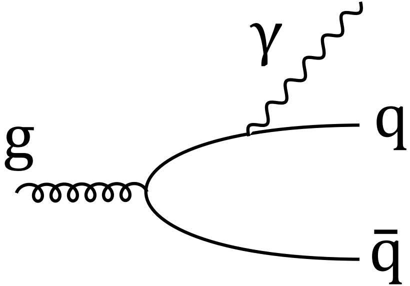
- anti-collinear (B2B) emissions?

Jalilian-Marian, Rezaeian, Phys. Rev. D **86**, 034016 (2012)

NLO @ B2B

- B2B emissions @ NLO? → Yes!!

- select γ-jet events (no γ-dijet!!)
- isolate γ from the jet



SB, Dumitru, Phys. Rev. D **97** (2018) no.1, 014012

NLO @ B2B

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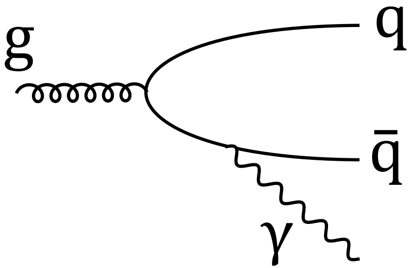

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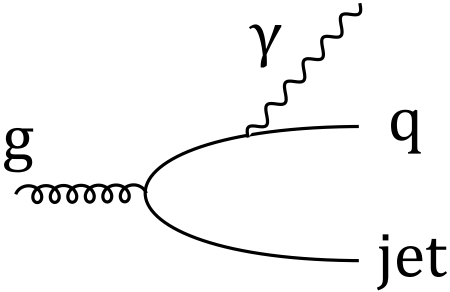
NLO @ B2B

- B2B emissions @ NLO? $\rightarrow$ Yes!!
- select γ-jet events (no γ-dijet!!)



SB, Dumitru, Phys. Rev. D **97** (2018) no.1, 014012

NLO @ B2B

- B2B emissions @ NLO? $\rightarrow$ Yes!!

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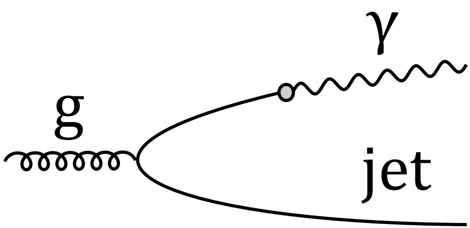

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NLO @ B2B: amplitude

- $k_{1\perp} \ll Q_S^p \ll \tilde{P}_\perp$
- $k_\perp \sim |\mathbf{k}_{2\perp} - \mathbf{k}_\perp| \sim k_{2\perp} \sim Q_S^A \ll \tilde{P}_\perp$

- expand using Ward identities

$$\mathcal{M}^\mu = -q_f e g^2 \int_{\mathbf{k}_\perp \mathbf{k}_{1\perp}} \int_{\mathbf{x}_\perp \mathbf{y}_\perp} \frac{\rho_p^a(\mathbf{k}_{1\perp})}{k_{1\perp}^2} e^{i\mathbf{k}_\perp \cdot \mathbf{x}_\perp + i(\mathbf{P}_\perp - \mathbf{k}_\perp - \mathbf{k}_{1\perp})\cdot \mathbf{y}_\perp}$$

$$\times \bar{u}(\mathbf{q}) \Big\{ k_{1 i_1} k_{2 i_2} R_g^{\mu i_1 i_2} U(\mathbf{x}_\perp)^{ba} t^b$$

$$+ \left[k_{1 i_1} k_{i_2} R_q^{\mu i_1 i_2} + k_{1 i_1} (k_2 - k)_{i_2} R_{\bar{q}}^{\mu i_1 i_2} \right] \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \Big\} v(\mathbf{p})$$

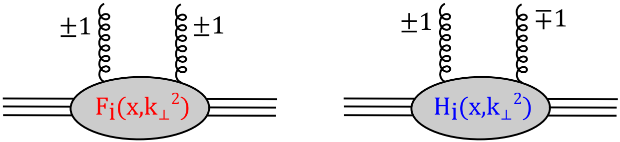
NLO @ B2B: nuclear distributions

$$C(x_A, \mathbf{x}_\perp, \mathbf{y}_\perp, \mathbf{y}'_\perp, \mathbf{x}'_\perp) \equiv \mathrm{tr}\left\langle \tilde{U}(\mathbf{x}_\perp) t^a \tilde{U}^\dagger(\mathbf{y}_\perp) \tilde{U}(\mathbf{y}'_\perp) t^a \tilde{U}^\dagger(\mathbf{x}'_\perp) \right\rangle_{x_A}$$

$$\int_{\mathbf{x}_\perp \mathbf{x}'_\perp} e^{i\mathbf{k}_{2\perp}\cdot(\mathbf{x}_\perp - \mathbf{x}'_\perp)} \left[\frac{\partial^2 C(x_A, \mathbf{x}_\perp, \mathbf{y}_\perp, \mathbf{y}'_\perp, \mathbf{x}'_\perp)}{\partial x^i \partial x'^{i'}} \right]_{\mathbf{x}_\perp = \mathbf{y}_\perp, \mathbf{x}'_\perp = \mathbf{y}'_\perp}$$

$$\equiv \frac{1}{2}\delta^{ii'} F_1(x_A, k_{2\perp}^2) + \left(\frac{k_{2\perp}^i k_{2\perp}^{i'}}{k_{2\perp}^2} - \frac{1}{2}\delta^{ii'} \right) H_1(x_A, k_{2\perp}^2)$$

- F_i = unpolarized gluons
- H_i = linearly polarized gluons



Akcakaya, Schäfer, Zhou, Phys. Rev. D **87**, 5, 054010 (2013)
Marquet, Roiesnel, Taels, Phys. Rev. D **97**, 1, 014004 (2018)

NLO @ B2B: cross section 1/2

- integrate over photon-quark collinear singularity

$$z \equiv \frac{k_\gamma^+}{k_\gamma^+ + q^+} \qquad \zeta \equiv \frac{k_\gamma^+}{p^+}$$

$$\mathbf{P}_\perp = \mathbf{p}_\perp + \frac{1}{z}\mathbf{k}_{\gamma\perp} = -\frac{1-z}{z}\tilde{\mathbf{P}}_\perp + \frac{1+z}{2z}\mathbf{Q}_\perp$$

- $1 - z \ll 1 \to P_\perp \ll \tilde{P}_\perp$

NLO @ B2B: cross section 2/2

$$
\frac{d\sigma^{g\to q\bar{q}\gamma}}{d^2\tilde{\mathbf{P}}_\perp d^2\mathbf{Q}_\perp d\eta_p d\eta_\gamma dz} = \sum_f \frac{\alpha_e \alpha_S q_f^2}{64\pi^4 N_c(N_c^2-1)} \frac{1}{z(1-z)} x_p f_{g,p}\left(x_p, P_\perp^2\right)
\times \frac{1}{2\pi}\frac{1+(1-z)^2}{z}\log\left(\frac{P_\perp^2}{\Lambda_{\overline{\rm MS}}^2}\right)
\times \frac{\zeta(1-z)(1+z)^4}{(\zeta+z)^6}\frac{1}{\tilde{P}_\perp^4}\Bigg\{(\zeta^4+6\zeta^2 z^2+z^4)F_1\left(x_A, P_\perp^2\right)
- 2\zeta z(\zeta-z)^2 F_2\left(x_A, P_\perp^2\right) - 4\zeta^2 z^2 F_3\left(x_A, P_\perp^2\right)
+ 2\zeta z(\zeta-z)^2\left[\frac{(\mathbf{P}_\perp\cdot\tilde{\mathbf{P}}_\perp)^2}{P_\perp^2\tilde{P}_\perp^2}-\frac{1}{2}\right]
\times\left[-H_1\left(x_A, P_\perp^2\right) - H_2\left(x_A, P_\perp^2\right) + H_3\left(x_A, P_\perp^2\right)\right]\Bigg\}
$$

SB, Dumitru, Phys. Rev. D **97** (2018) no.1, 014012

NLO @ B2B: angular correlations

- isotropic contribution $\sim (Q_\perp/\tilde{P}_\perp)^0$
- $a_n \equiv \langle \cos\ n\phi \rangle \sim Q_\perp^n/\tilde{P}_\perp^n$

$$a_1 = \frac{1+z}{4(1-z)} \frac{Q_\perp}{\tilde{P}_\perp} \frac{(\zeta^4+6\zeta^2z^2+z^4)F_1^{(1,1)} - 2\zeta z(\zeta-z)^2F_2^{(1,1)} - 4\zeta^2z^2F_3^{(1,1)}}{(\zeta^4+6\zeta^2z^2+z^4)F_1 - 2\zeta z(\zeta-z)^2F_2 - 4\zeta^2z^2F_3}$$

$$a_2 = \frac{(1+z)^2}{32(1-z)^2} \frac{Q_\perp^2}{\tilde{P}_\perp^2} \frac{(\zeta^4+6\zeta^2z^2+z^4)F_1^{(2,2)} - 2\zeta z(\zeta-z)^2F_2^{(2,2)} - 4\zeta^2z^2F_3^{(2,2)}}{(\zeta^4+6\zeta^2z^2+z^4)F_1 - 2\zeta z(\zeta-z)^2F_2 - 4\zeta^2z^2F_3}$$

- $F_i^{(a,b)} = F_i^{(a,b)}\left(x_A, (1-z)^2\tilde{P}_\perp^2/z^2\right)$

  $\rightarrow$ can probe semi-hard scales!

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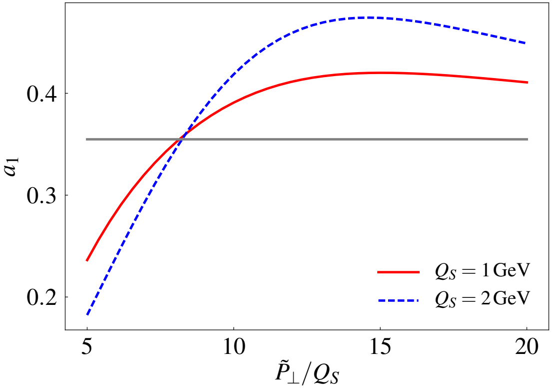
NLO @ B2B: results 1/2



- $\zeta = 1 \quad z = 0.75 \quad Q_\perp/\tilde{P}_\perp = 0.1$

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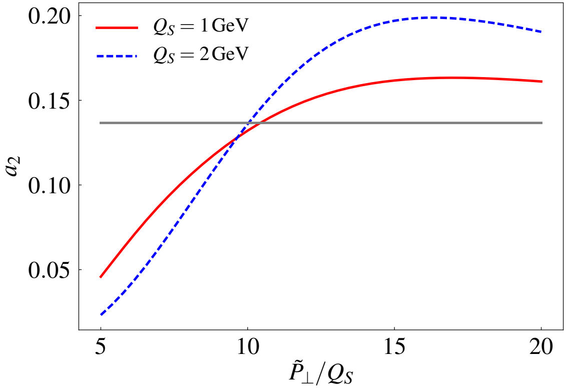
NLO @ B2B: results 2/2



- $\zeta = 1 \quad z = 0.75 \quad Q_\perp/\tilde{P}_\perp = 0.1$

SB, Dumitru, Phys. Rev. D **97** (2018) no.1, 014012

Conclusions

- inclusive γ

  $\rightarrow$ NLO dominates over LO @ LHC

  $\rightarrow$ fair description of CMS and ATLAS $p+p$ data at 2.76 and 7 TeV

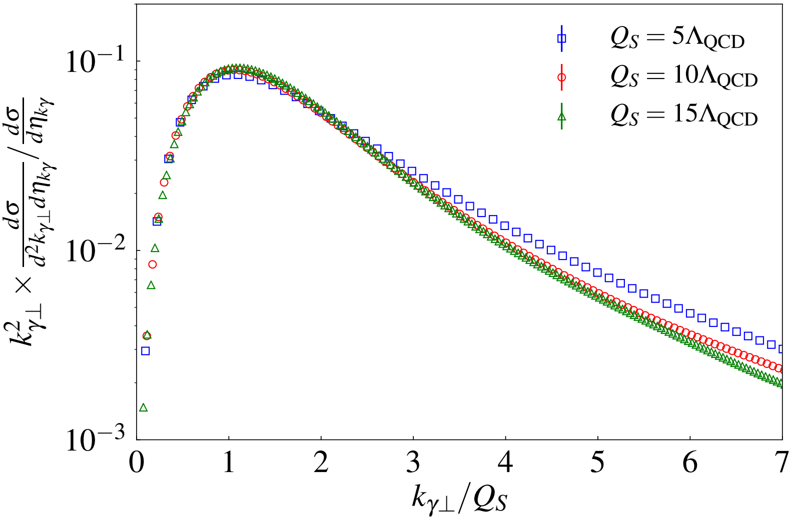
  $\rightarrow$ some $p+A$ predictions (work in progress)

- γ-jet correlations

  $\rightarrow$ a_n from LO NOT sensitive to saturation

  $\rightarrow$ a_n from NLO sensitive to saturation

$g \to q^* \bar{q}^* \to \gamma$ - sensitivity to Q_S



$g \to q\bar{q}\gamma$ - average x in the proton