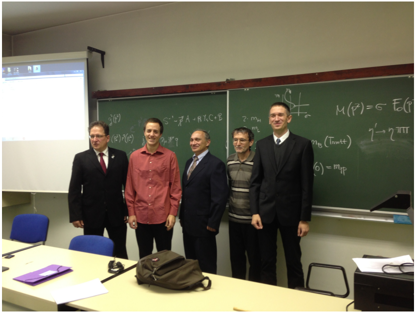
Photon production in high energy p+A collisions as a probe of Color Glass Condensate

Sanjin Benić (Kyoto)

SB, Fukushima, Garcia-Montero, Venugopalan, JHEP **1701**, (2017) 115
SB, Dumitru, Phys. Rev. D **97** (2018) no. 1, 014012
SB, Fukushima, Garcia-Montero, Venugopalan, Phys. Lett. B **791**, (2019) 11

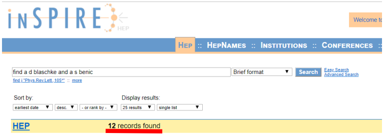
40th Max Born Symposium, Wrocław, October 11, 2019

Happy birthday David!



Supervisor: - Prof. dr. sc. Dubravko Klabučar, University of Zagreb

Committee:
1. Doc. dr. sc. Davor Horvatić, University of Zagreb
2. Prof. dr. sc. Dubravko Klabučar, University of Zagreb
3. Prof. dr. sc. Mirko Planinić, University of Zagreb
4. Prof. dr. sc. David Blaschke, Wrocław University
5. Dr. sc. Dalibor Kekez, Senior Research Associate, Ruđer Bošković Institute



Contents

- CGC
- photon production in CGC
- inclusive photon in p+p and p+A
- γ-jet angular correlations

Photon - a precious tool in high energy physics

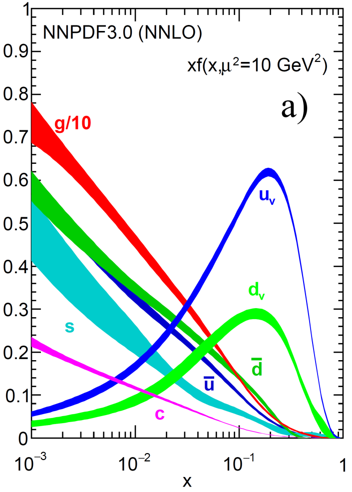
- A+A - thermal γ as a probe of QGP
- e+p, p+p - isolated (and/or direct) γ as a pQCD benchmark
- this work: p+A, (e+A) - γ as a probe of cold nuclear matter effects

- vs hadrons

1. better theoretical control
2. smaller cross sections by α_e

Proton at high energy

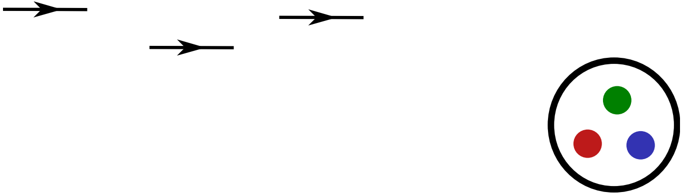
- ..is dominated by gluons ($x \sim Q^2/s$)



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

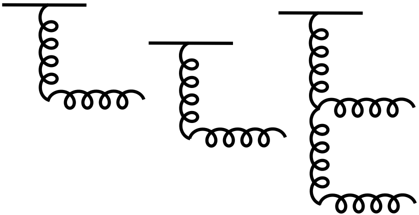
Proton at high energy

- at low energy proton is mostly valence quarks



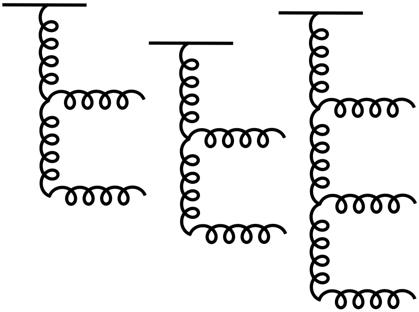
Proton at high energy

- as energy is increased new partons are emitted



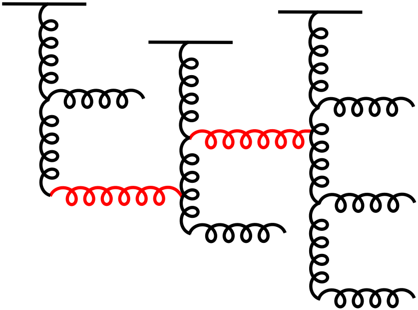
Proton at high energy

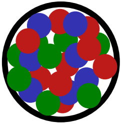
- as long as parton density is low the evolution is linear



Proton at high energy

- at high energy parton density becomes large and recombination is possible





recombination $\sim$ emission

gluon saturation

Color Glass Condensate

- universally appears at high energies $x \ll 1$

$$\frac{\alpha_S}{Q_S^2} \times \frac{x f_g(x, Q_S^2)}{\pi R^2} \sim 1$$

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

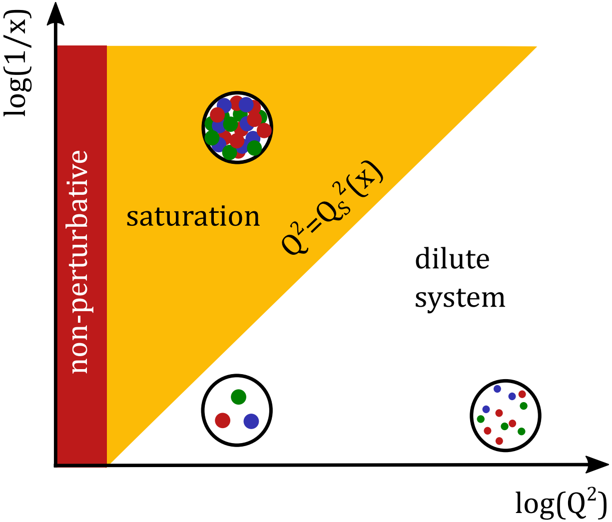
$Q_S^2 \sim$ density of gluons

$Q_S^2 \sim$ typical gluon $k_\perp$ (transverse size)$^{-1}$

- uniquely sensitive to non-Abelian physics

Gribov, Levin, Ryskin, Phys. Rept. **100**, 1 (1983)

QCD phase space diagram



CGC at colliders

- weak coupling framework if $Q_S^2 \gg \Lambda_{\rm QCD}^2$
- enhance Q_S^2:

  higher energies $Q_S^2(x) \sim 1/x^{0.3}$

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

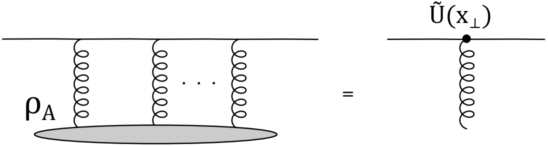
- RHIC: $Q_S \sim 1 - 2$ GeV

  LHC: $Q_S \sim 2 - 3$ GeV

- CGC cross sections modified (typically suppressed) with respect to their pQCD counterparts in a few GeV range

Scattering off the CGC

- large gluon density → classical approximation
- high energies → eikonal scattering



$$\tilde{U}(\mathbf{x}_\perp) = \mathcal{P}\exp\left[ig\int_{x^+}\mathcal{A}^-(x)\right]$$

$$= 1 + ig\int_{x^+}\mathcal{A}^-(x) + (ig)^2\int_{x^+x'^+}\theta(x^+ - x'^+)\mathcal{A}^-(x)\mathcal{A}^-(x') + \cdots$$

- gluon distributions are correlators of Wilson lines
- gluon dipole

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

Generalized gluon distributions

- Balitsky-Kovchegov (BK) equation ($T = 1 - \tilde{\mathcal{N}}$, $Y \sim \log x$)

$$\frac{\partial T_Y(\mathbf{x}_\perp)}{\partial Y} = \int_{\mathbf{x}_{1\perp}} \mathcal{K}(\mathbf{x}_\perp, \mathbf{x}_{1\perp})[T_Y(\mathbf{x}_{1\perp}) + T_Y(\mathbf{x}_{2\perp}) - T_Y(\mathbf{x}_\perp) - T_Y(\mathbf{x}_{1\perp}) T_Y(\mathbf{x}_{2\perp})]$$

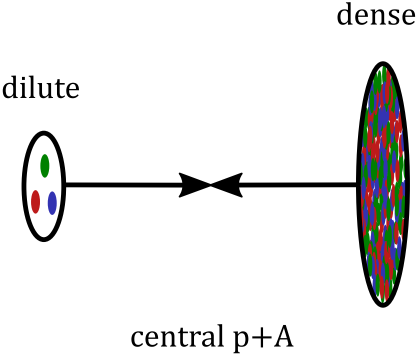
- T_Y^2 term $\to$ recombination: tames the exponential growth of the distribution with energy

$$f_g(x; Q^2) \sim \int_0^{Q^2} dk_\perp^2 \, \tilde{\mathcal{N}}_Y(k_\perp)$$

Balitsky, Nucl. Phys. B **463**, 99 (1996)
Kovchegov, Phys. Rev. D **61**, 074018 (2000)

Dilute-dense collision

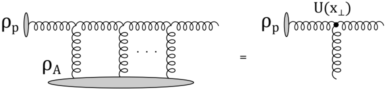
- proton: simple, "known", probe
- gluon density in the target enhanced $Q_S^2 \sim A^{1/3}$
- scattering off the target to all orders in α_S



CGC Feynman rules

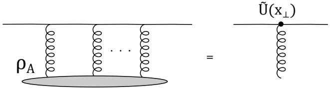
- YM equations with sources localized on the light-cone

$$[D_\mu, \mathcal{F}^{\mu\nu}] = g\delta^{\nu +}\delta(x^-)\rho_p(\mathbf{x}_\perp) + g\delta^{\nu -}\delta(x^+)\rho_A(\mathbf{x}_\perp)$$



- order-by-order in ρ_p, to all orders in ρ_A: $\rho_p \ll \rho_A$
- quark propagator in the background target field

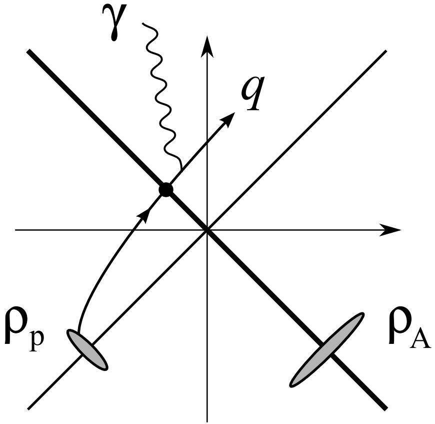
$$S(x,y) = S_F(x-y)$$
$$+ i\theta(x^+)\theta(-y^+)\int_z \delta(z^+)(\tilde{U}(\mathbf{z}_\perp) - 1)S_F(x-z)\gamma^+ S_F(z-y)$$
$$- i\theta(-x^+)\theta(y^+)\int d^4z\delta(z^+)(\tilde{U}(\mathbf{z}_\perp) - 1)^\dagger S_F(x-z)\gamma^+ S_F(z-y)$$



Gelis, Mehtar-Tani, Phys. Rev. D **73** (2006) 034019
Baltz, McLerran, Phys. Rev. C **58** (1998) 1679

$q \to q\gamma$

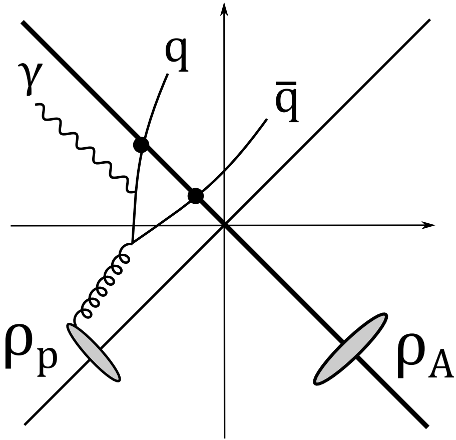
- valence quark bremsstrahung $O(\alpha_e)$



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

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

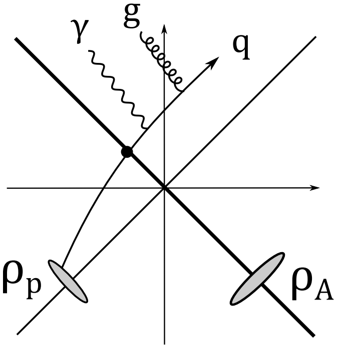
- sea quark bremsstrahlung $O(\alpha_e \alpha_S)$



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

$q \to qg\gamma$

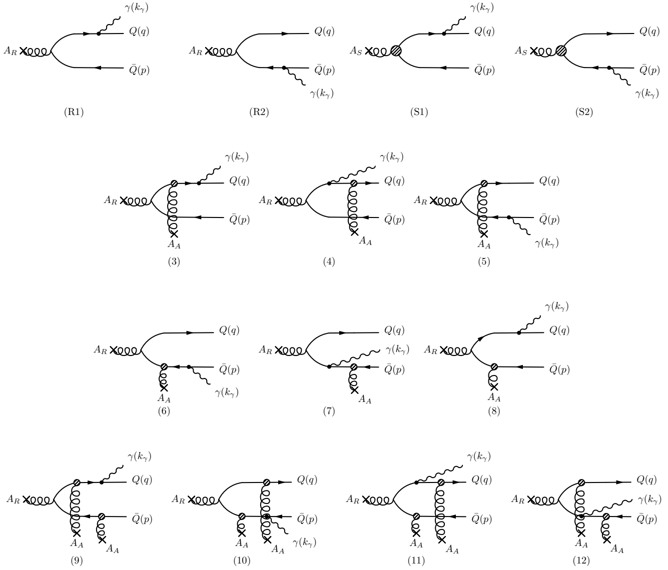
- $O(\alpha_e \alpha_S)$



- suppressed as $f_q \ll f_g$

Altinoluk, Armesto, Kovner, Lublinsky, Petreska, JHEP **1804** (2018) 063
Altinoluk, Boussarie, Marquet, Taels, JHEP **1907**, 079 (2019)

$g \to q\bar{q}\gamma$ - diagrams



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

$g \to q\bar{q}\gamma$ - cross section

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

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

$g \to q\bar{q}\gamma$ - multi-gluon correlators

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

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

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

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

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

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

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

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

Multi-gluon correlators at large N_c

- large N_c: gluon correlators $\to$ dipoles

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

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

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

Inclusive photon cross section

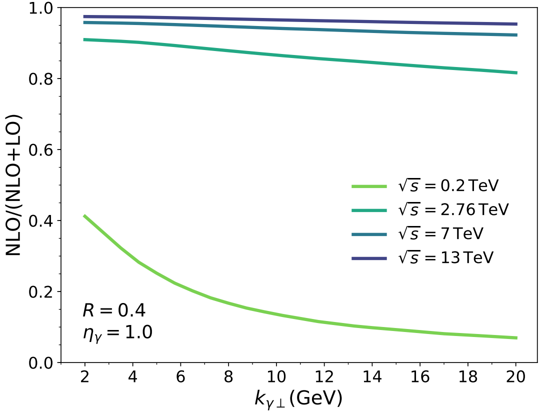
$$\frac{d\sigma^{g\to q\bar{q}\gamma}}{d^2\mathbf{k}_{\gamma\perp}d\eta_\gamma} = (\pi R_A^2)\sum_f \frac{\alpha_e\alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)}\int_{\eta_q\eta_p}\int_{\mathbf{q}_\perp\mathbf{p}_\perp\mathbf{k}_{1\perp}\mathbf{k}_\perp}\frac{\varphi_p(Y_p,\mathbf{k}_{1\perp})}{\mathbf{k}_{1\perp}^2}$$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

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

- nuclear effects contained in $\tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp)$

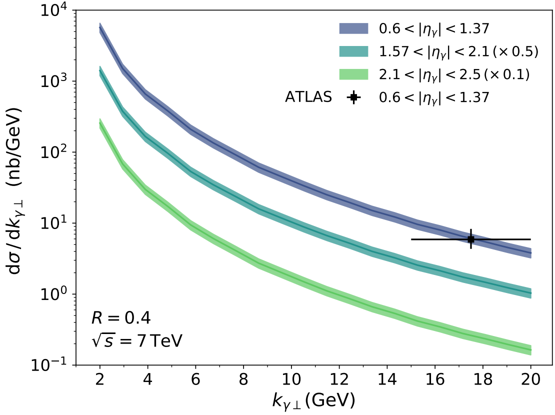
$q \to q\gamma$ vs $g \to q\bar{q}\gamma$: collision energy

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



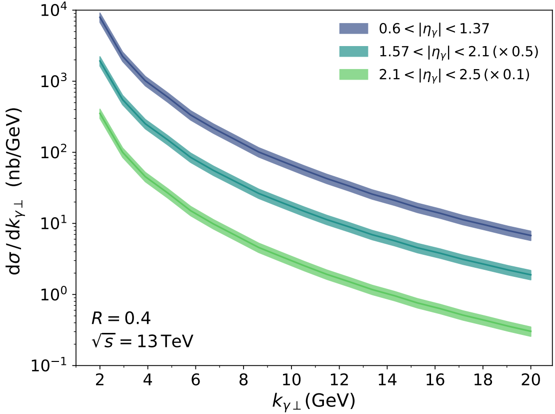
SB, Fukushima, Garcia-Montero, Venugopalan, Phys. Lett. B **791**, (2019) 11

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



SB, Fukushima, Garcia-Montero, Venugopalan, Phys. Lett. B **791**, (2019) 11

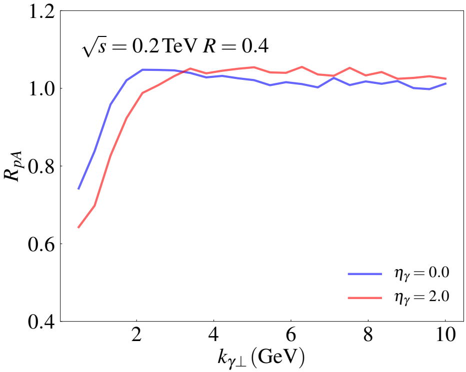
p+p $\sqrt{s} = 13$ TeV



SB, Fukushima, Garcia-Montero, Venugopalan, Phys. Lett. B **791**, (2019) 11

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

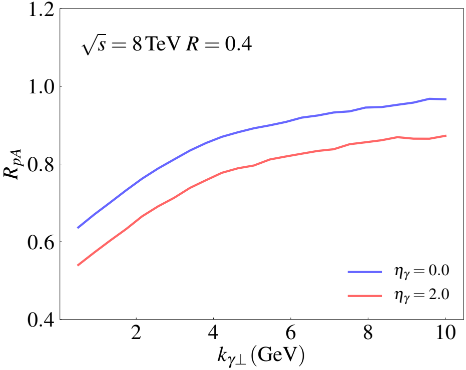
- $R_{pA} = d\sigma_{pA}/(A \times d\sigma_{pp})$
- Cronin peak at RHIC



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

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

- $R_{pA} = d\sigma_{pA}/(A \times d\sigma_{pp})$
- suppression at LHC



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

Back-to-back kinematics

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

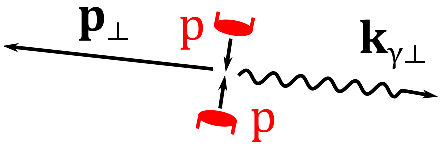
$$\mathbf{Q}_\perp \equiv \mathbf{k}_{\gamma\perp} + \mathbf{p}_\perp \qquad \tilde{\mathbf{P}}_\perp \equiv \frac{1}{2}(\mathbf{p}_\perp - \mathbf{k}_{\gamma\perp})$$

- correlation limit

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

Angular correlations

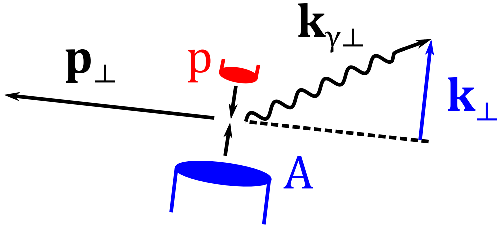
- dilute-dilute: back-to-back emissions



Angular correlations

- dilute-dense: transverse kick from CGC

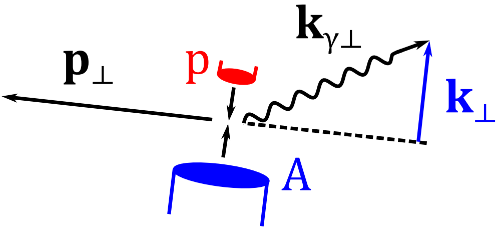
  $\rightarrow$ momentum imbalance



Angular correlations

- dilute-dense: transverse kick from CGC

  $\rightarrow$ momentum imbalance



- angular correlations

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

NLO @ B2B: angular correlations

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

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

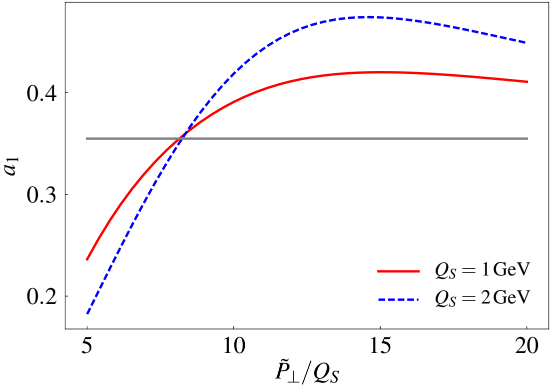
$$a_2 = \frac{(1+z)^2}{32(1-z)^2} \frac{Q_\perp^2}{\tilde{P}_\perp^2} \frac{(\zeta^4 + 6\zeta^2 z^2 + z^4) F_1^{(2,2)} - 2\zeta z(\zeta - z)^2 F_2^{(2,2)} - 4\zeta^2 z^2 F_3^{(2,2)}}{(\zeta^4 + 6\zeta^2 z^2 + z^4) F_1 - 2\zeta z(\zeta - z)^2 F_2 - 4\zeta^2 z^2 F_3}$$

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

  $\rightarrow$ can probe semi-hard scales!

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

Results



- gray line - no saturation
- saturation induces a non-trivial $\tilde{P}_\perp$ dependence, sensitive to Q_S

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

Conclusions

- full analytic formula for photon production from a gluon induced channel
- inclusive γ

  at the LHC gluon induced channel clearly dominate

  predictions for p+p and p+A
- γ-jet correlations

  $\rightarrow$ a_n's sensitive to saturation