Isolated photon-hadron production in high energy *pp* and *pA* collisions at RHIC and LHC

REVESTRUCTURE workshop 2023

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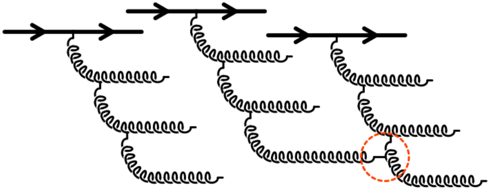
July 10^{th} 2023

Based on Phys. Rev. D 105, 114052 (2022)

Motivation: The photon as a tool in pp and pA collisions

- $p + A \to \gamma + h$ as a probe of cold nuclear matter effects
- Complements *hh* production
- γh vs. *hh* as a probe:
  1. Better theoretical control
  2. Downside: smaller cross sections by α_e vs. α_s
- Isolated photons - exclusion of fragmentation photons via isolation cone around the photon, $R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$

Gluon saturation



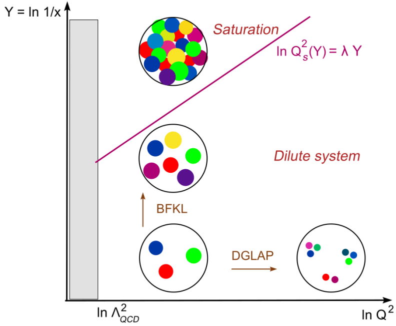
- At high energy, the parton density becomes large
- Gluon emission and recombination processes balance out

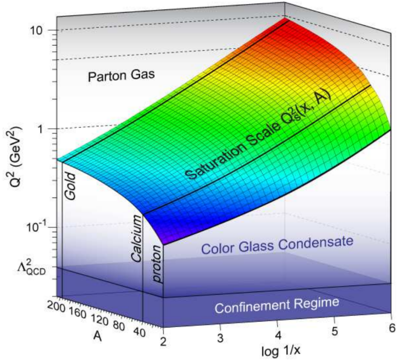
- Emergent saturation scale:

$$Q_s^2(x) \sim A^{1/3}/x^{0.3} \sim 1 - 2GeV$$

- See also Samuel Wallons and Eric Andreas Vivodas talks on Tuesday

Phase space diagram of QCD



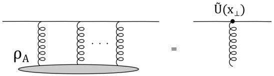


- Dependence of saturation on rapidity, transverse momentum and A of the target; $x \propto 1/\sqrt{s}$

Venugopalan, J.Phys.G 35 (2008) 104003.

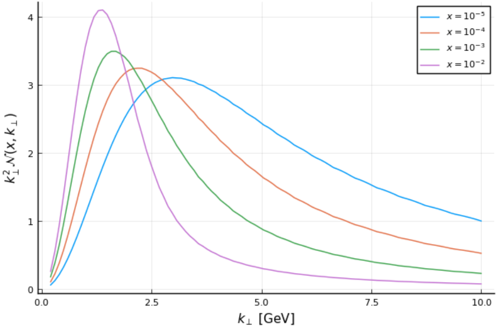
Gluon correlators

- High energy - eikonal scattering of partons on the nucleus
- Representation of gluon shockwave through effective vertex
- Gluon distributions are correlators of Wilson lines:



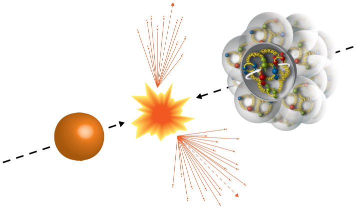
$$\tilde{U}(x_\perp) = \mathcal{P} \exp \left[ig \int_{x^+} A_a^-(x) t_a \right]$$

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



Description of pA scattering

- Dilute-dense approximation: the proton is a simple projectile, the nucleus is a dense and saturated target described by CGC
- Hybrid framework: parton from the proton has initial $k_\perp = 0$: description through standard collinear PDFs
- Key consequence: intrinsic imbalance momentum of the process ($|k_\perp| \sim Q_S$) comes from the gluons in the nucleus



$qg \to \gamma h^{\pm}$ cross section

$$\frac{d\sigma^{pA\to\gamma h}_{CGC}}{d^2\mathbf{k}_{\gamma\perp} d\eta_\gamma d^2\mathbf{P}_{h\perp} d\eta_h} = (\pi R_A^2) \sum_q \frac{e_q^2 N_c}{8\pi^4} \int_0^1 \frac{dz_h}{z_h^2} D_q(z_h, \mu^2) x_p f_q(x_p, \mu^2) k_\perp^2 \tilde{\mathcal{N}}_{A,Y_A}(\mathbf{k}_\perp) \hat{\sigma}$$

$$\hat{\sigma} = \frac{\alpha_e}{2N_c} \frac{P_{q\gamma}}{q \cdot k_\gamma} \frac{z^2}{\mathbf{k}_{\gamma\perp}^2}, \quad P_{q\gamma} = \frac{1 + (1-z)^2}{z}, \quad z = \frac{k_\gamma^+}{q^+ + k_\gamma^+}.$$

- Imbalance momentum: $\mathbf{k}_\perp = \mathbf{k}_{\gamma\perp} + \mathbf{q}_\perp$, $q = P_h/z_h \implies \mathbf{k}_\perp^2 \sim Q_s^2 \sim A^{1/3}$

(Gelis, Jalilian-Marian, Phys.Rev.D 66 014021 (2002))

Target distributions

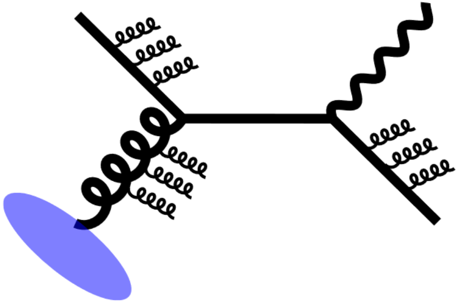
MV^{γ} model - evolution of the following initial condition via the rcBK equation:

$$\tilde{\mathcal{N}}_{Y_0}(x_\perp) = \exp\left\{-\frac{(x_\perp^2 Q_{s0}^2)^{\gamma}}{4}\ln\left(\frac{1}{x_\perp \Lambda_{IR}} + e\right)\right\}$$

- $\tilde{\mathcal{N}}_{Y_A}(\mathbf{k}_\perp)$ from AAMQS (Albacete, Armesto, Milhano, Quiroga-Arias, Salgado, EPJC 71, 1705 (2011))
- $D_q(z_h, \mu^2)$ from DSS (de Florian, Sassot, Stratmann, PRD 75, 114010 (2007))
- $x_p f_q(x_p, \mu^2)$ from CTEQ6M (Pumplin, Stump, Huston, Lai, Nadolsky, Tung, JHEP 07, 012 (2002))

General consideration of soft gluon radiation

- Processes with partons should include soft gluon radiation



- Sudakov double logarithm - result of the incomplete cancellation of divergences from real and virtual contributions:

$$\frac{d\sigma}{dk_\perp^2} \propto 1 - C\alpha_S \ln^2\left(Q^2/k_\perp^2\right) + \mathcal{O}(\alpha_S^2),$$

- Q = hard scale of the process, $k_\perp$ = final state transverse momentum

Sudakov soft gluon resummation

- Breakdown of perturbative expansion avoided by Sudakov resummation:

$$\frac{d\sigma}{dk_\perp^2} \propto F(k_\perp) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} \left(C\alpha_S \ln^2 \frac{Q^2}{k_\perp^2} \right)^n = \exp\left[-C\alpha_S \ln^2 \frac{Q^2}{k_\perp^2} \right]$$

- Cross section suppression for $Q^2 \gg \mathbf{k}_\perp^2$

(Collins, Soper, Sterman, NPB 250 199-224 (1985))

Implementation of the Sudakov resummation

- Effectively we are replacing the CGC, FF and PDF distributions with a $b_\perp$ integral ($k_\perp$ convolution) - joint resummation:

$$k_\perp^2 \tilde{\mathcal{N}}_{A,Y_A}(k_\perp) D_q\left(z_h, \mu^2\right) f_q\left(x_p, \mu^2\right) \to \int_{\mathbf{b}_\perp} e^{ik_\perp \cdot b_\perp} \partial^2_{b\perp} \tilde{\mathcal{N}}_{A,Y_A}(b_\perp) D_q\left(z_h, \mu_b^2\right) f_q\left(x_p, \mu_b^2\right) e^{-S_{Sud}(b_\perp, Q)}$$

(Mueller, Xiao, Yuan, PRL 110 082301 (2013)), (Stasto, Wei, Xiao, Yuan, PLB 784 301-306 (2018))

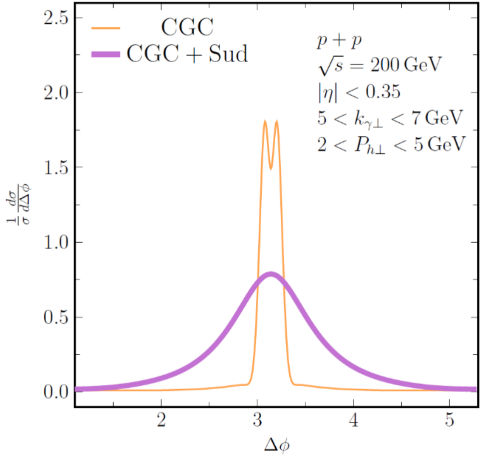
- Sudakov factor (for $qg \to q\gamma$):

$$S_{\mathrm{Sud}}(b_\perp, Q) = \int_{\mu_b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[A \log\left(\frac{Q^2}{\bar{\mu}^2}\right) + B\right] + S_{non-pert}(b_\perp, Q),$$

$$A = \frac{\alpha_s(\bar{\mu}^2)}{\pi}(C_F + C_A/2), \quad B = -\frac{3\alpha_s(\bar{\mu}^2)}{2\pi} C_F$$

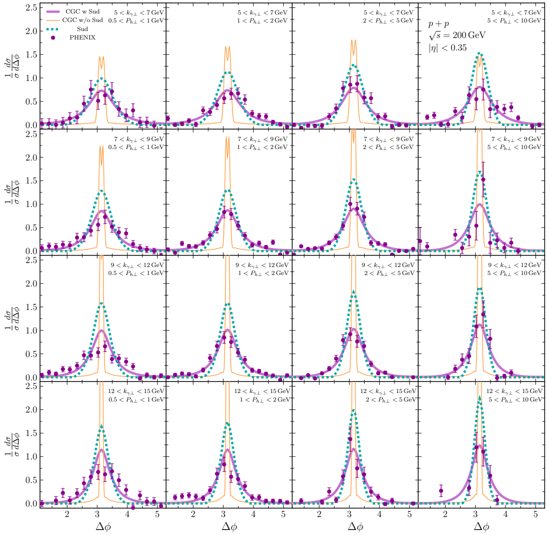
- $\mu_b > 2e^{-\gamma_E}/b_{\max}$, $S_{non-pert}(\mathbf{b}_\perp, Q)$ prescribed by (Sun, Isaacson, Yuan, Yuan, IJMPA 33 no. 11, 1841006 (2018))

Comparison of CGC vs CGC+Sudakov angular correlations



- Generic CGC prediction: double peak structure at $\Delta\phi \sim \pi$
- Adding Sudakov effects seems to broaden the distribution and destroy that structure

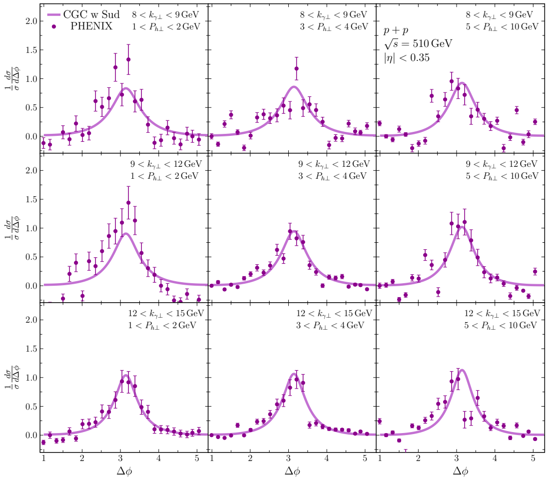
Self-normalized angular correlations



(PHENIX, PRD 98, no. 7, 072004 (2018))

- PHENIX $pp \to \gamma h^{\pm}$, $\sqrt{s} = 200$ GeV

Self-normalized angular correlations

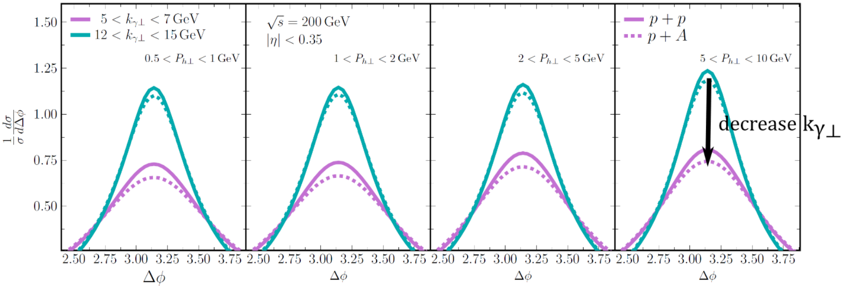


(PHENIX, PRD 95, no. 7, 072002 (2017))

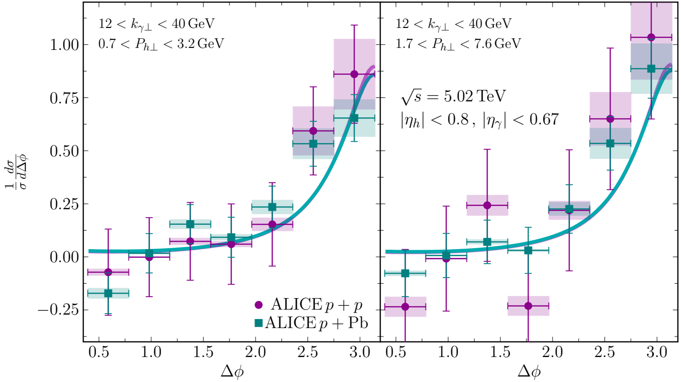
- PHENIX $pp \to \gamma h^{\pm}$, $\sqrt{s} = 510$ GeV

Predictions of nuclear effects at PHENIX

- *pp* vs *pA* - calculation for lowest (5-7 GeV) and highest (12-15 GeV) $k_{\gamma\perp}$ bins
- Modest nuclear effect (10%) - broadening of angular distribution
- Self normalized distribution - good for comparison with experimental data, but part of the physical information is lost



ALICE *pp* and *pA* angular correlations

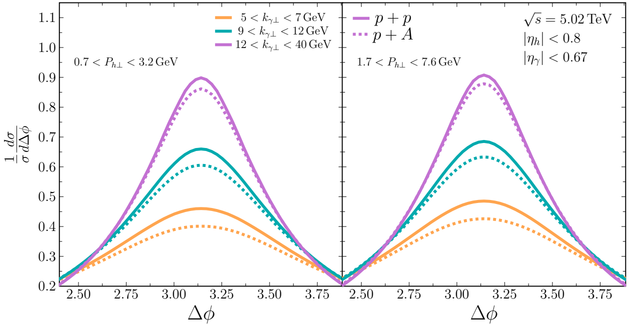


(ALICE, PRC 102, 044908 (2020))

- ALICE $pp/A \to \gamma h^{\pm}$, $\sqrt{s} = 5.02$ TeV
- Barely visible nuclear effect for this kinematics - we need lower $k_{\gamma\perp}$ resolution!

Predictions of nuclear effects at ALICE

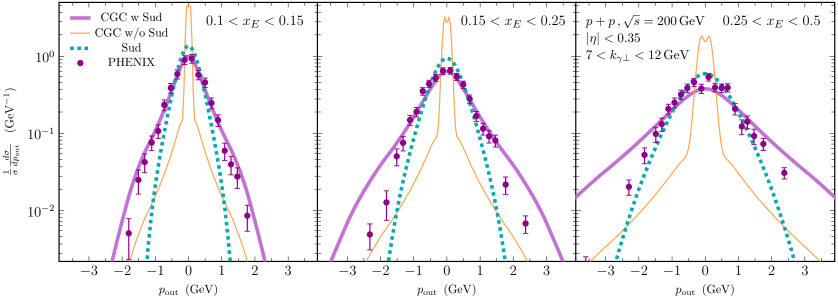
- *pp* vs *pA* - calculation for two more favorable $k_{\gamma\perp}$ bins (5-7 GeV and 9-12 GeV) as well as the existing one (12-40 GeV)
- Again, moderate nuclear effect visible in $\Delta\phi$ distribution broadening



Out-of-plane momentum distributions: PHENIX

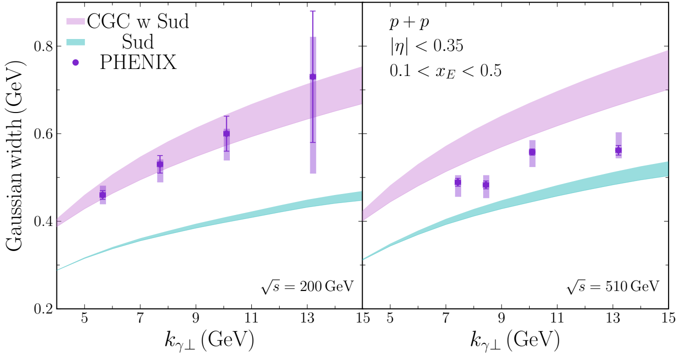
$$p_{out} = P_{h\perp}\sin(\Delta\phi), \quad x_E = -\frac{P_{h\perp}}{k_{\gamma\perp}}\cos(\Delta\phi)$$

- Close to $\Delta\phi \sim \pi$ we have $p_{out} \sim z_h k_\perp$, and $x_E \sim z_h$

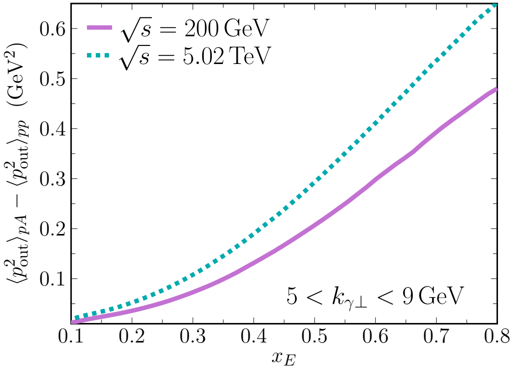


p_{out} distributions: Gaussian widths

- We extract the widths of the previous curves by fitting to a Gaussian in the range $p_{out} < 1.1 \pm 0.2$ GeV
- Best description with CGC+Sudakov



p_{out} distributions: pp vs. pA predictions



- Difference between pA and pp Gaussian widths squared - nuclear enhancement more pronounced at large x_E

Summary and outlook

- Benchmark results for γh production in the CGC+Sudakov framework
- Good description of RHIC and LHC data
- Are the predicted nuclear effects within experimental resolution?
- Further (and ongoing) inquiries:
  1. Study of inclusive Drell-Yan production
  2. Testing of systematic errors
  3. Comparison with future data (e.g. LHCb)