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

ACHT workshop 2023

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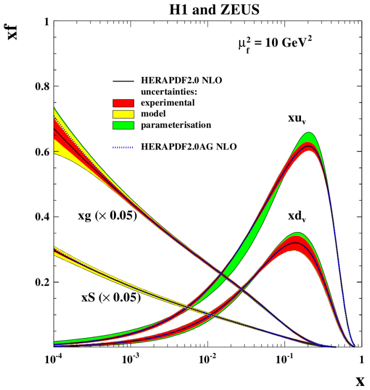
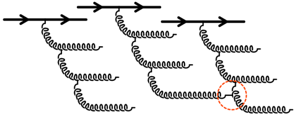
Based on S. Benić, O. Garcia-Montero, AP: Phys. Rev. D 105, 114052 (2022)

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:

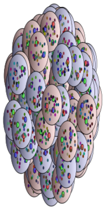
$$Q_s^2(x) \sim A^{1/3}/x^{0.3} \sim 1 \ \mathrm{GeV}$$

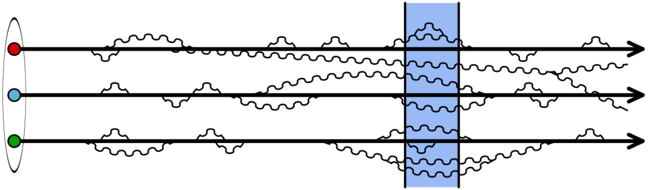
Color Glass Condensate (CGC)

- Light cone coordinates: $x^{\pm} = (x^0 \pm x^3)/\sqrt{2}$, $\mathbf{x}_\perp = (x_1, x_2)$
- Parent gluons (average lifetime Δx_p^+) frozen by Lorentz dilation, sources for fields (cascading gluons with $\Delta x^+ \ll \Delta x_p^+$) - glass-like hierarchy of time scales
- Averaging over color source configurations:

$$\langle \mathcal{O} \rangle = \int [D\rho]\, W[\rho]\, \mathcal{O}[\rho]$$

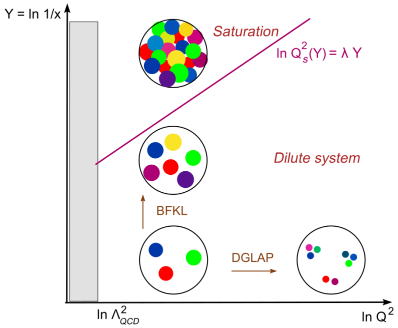
- Evolution of weight functional W (i.e. separate evolution of gluons as field sources and dynamical fields) described by small-x renormalization group equations

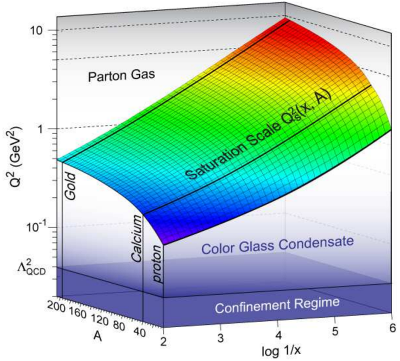




- Effectively, a probe sees this target as a gluon wall
- See also Eric Andreas Vivoda's talk tomorrow

Phase space diagram of QCD





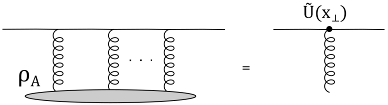
Venugopalan, J.Phys.G 35 (2008) 104003.

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

Gluon correlators

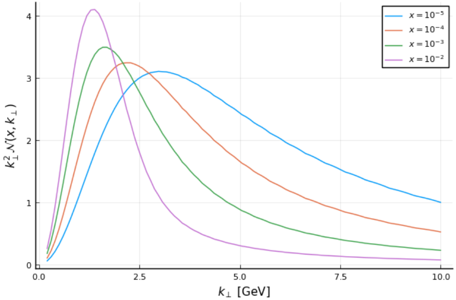
- High energy - eikonal scattering of partons on the nucleus
- Representation of gluon shockwave through effective vertex - Wilson lines (fundamental and adjoint)
- Gluon distributions are color-averaged correlators of Wilson lines!

(Blaizot, Gelis, Venugopalan, Nucl. Phys. A743 (2004), 13)



$$\tilde{U}(x_\perp) = \mathcal{P}\exp\left[ig\int_{x^+} A_a^-(x)t_a\right] \Longrightarrow \tilde{\mathcal{N}}_{A,Y_A}(k_\perp) = \frac{1}{N_c}\int_{\mathbf{y}_\perp} e^{ik_\perp y_\perp}\langle \tilde{U}(\mathbf{y}_\perp)\tilde{U}^\dagger(0)\rangle_{x_A},$$

$$U^{ab}(x_\perp) = \mathcal{P}\exp\left[ig\int_{x^+} A_c^-(x)T_c^{ab}\right] \Longrightarrow \mathcal{N}_{A,Y_A}(k_\perp)\delta^{ab} = \frac{1}{N_c}\int_{\mathbf{y}_\perp} e^{ik_\perp y_\perp}\langle U(\mathbf{y}_\perp)U^\dagger(0)\rangle_{x_A}^{ab}$$



- Dipole unintegrated gluon distribution (UGD):
- $\varphi_{DP,Y_A}(k_\perp) \sim k_\perp^2 \mathcal{N}_{A,Y_A}(k_\perp)$
- $\varphi_{DP,Y_A}(k_\perp) \overset{k_\perp \to \infty}{\sim} Q_s^2/k_\perp^2$, and $\varphi_{DP,Y_A}(k_\perp) \overset{k_\perp \to 0}{\sim} k_\perp^2$
- Dependence on $k_\perp$, evolution in Björken x versus Q^2 - BFKL hierarchy versus DGLAP equations
- In some processes (hh, jet-jet etc.) we can probe the Weizsäcker-Williams (WW) UGD: $\varphi_{WW}(k_\perp) \overset{k_\perp \to 0}{\sim} \log(Q_s^2/k_\perp^2)$
- Relation between UGDs and collinear PDFs:

$$xf_g(x) = \frac{1}{\pi^2} \int_{\mathbf{k}_\perp} \varphi_{Y_A}(\mathbf{k}_\perp)$$

Balitsky-Kovchegov equation

- $\tilde{\mathcal{N}}_{A,Y_A}(k_\perp)$ is the Fourier transform of the solution to the running-coupling Balitsky-Kovchegov equation:

$$\frac{\partial \tilde{\mathcal{N}}_Y(r_\perp)}{\partial Y} = \int_{\mathbf{r}_{1\perp}} K(r_\perp, r_{1\perp})\Big(\tilde{\mathcal{N}}_Y(r_{1\perp}) + \tilde{\mathcal{N}}_Y(r_{2\perp}) - \tilde{\mathcal{N}}_Y(r_\perp) - \tilde{\mathcal{N}}_Y(r_{1\perp})\tilde{\mathcal{N}}_Y(r_{2\perp})\Big)$$

$$K(r_\perp, r_{1\perp}) = \frac{N_C \alpha_s(r_\perp^2)}{2\pi^2}\left[\frac{r_\perp^2}{r_{1\perp}^2 r_{2\perp}^2} + \frac{1}{r_{1\perp}^2}\left(\frac{\alpha_s(r_{1\perp}^2)}{\alpha_s(r_{2\perp}^2)} - 1\right) + \frac{1}{r_{2\perp}^2}\left(\frac{\alpha_s(r_{2\perp}^2)}{\alpha_s(r_{1\perp}^2)} - 1\right)\right]$$

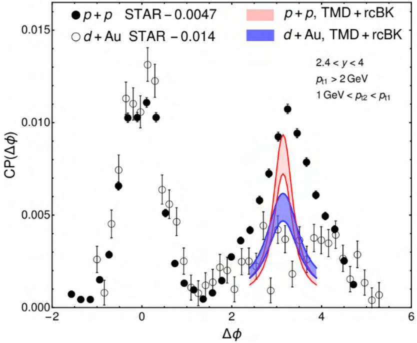
(Jalilian-Marian, Kovchegov, Prog.Part.Nucl.Phys. 56 (2006), 104-231)

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

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

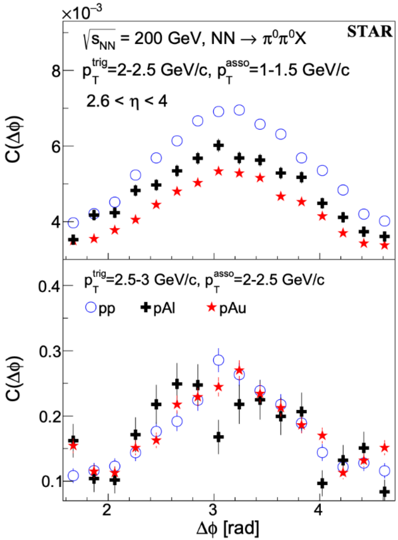
Indicators of gluon saturation from experiments

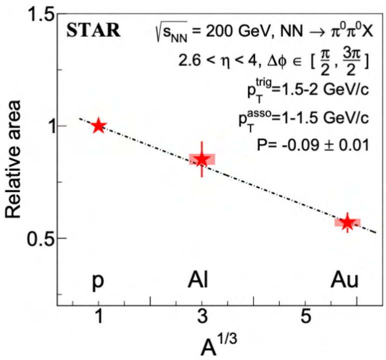
- Angular correlations of particle pairs - peak broadening at $\Delta\phi = \pi$ for pA compared to pp collisions
- Effect of multiple parton scatterings (weaker back-to-back correlation of final state particles with momenta $k_{1\perp}$ and $k_{2\perp}$) in the regime $|k_\perp| = |k_{1\perp} + k_{2\perp}| \sim Q_S$



Dihadron angular correlations

(Albacete, Giacalone, Marquet, Matas, PRD 99 014002 (2019))

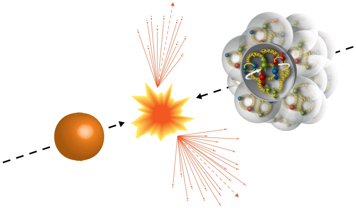




Dihadron angular correlations for varying targets (nuclei) and the comparison of areas under the curves (STAR Collaboration, Phys. Rev. Lett. 129, 092501 (2022))

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

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

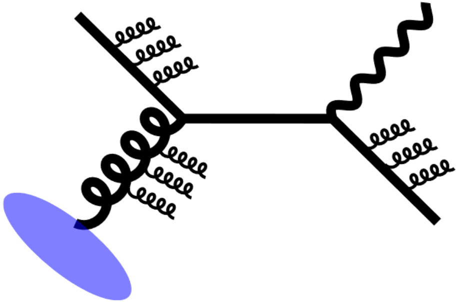
$$\hat{\sigma} = \frac{\alpha_e}{2N_c}\frac{P_{q\gamma}}{q\cdot k_\gamma}\frac{z^2}{\mathbf{k}_{\gamma\perp}^2}, \quad P_{q\gamma} = \frac{1+(1-z)^2}{z}, \quad z = \frac{k_\gamma^+}{q^+ + k_\gamma^+}.$$

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

- Imbalance momentum: $\mathbf{k}_\perp = \mathbf{k}_{\gamma\perp} + \mathbf{q}_\perp$, $q = P_h/z_h \implies \mathbf{k}_\perp^2 \sim Q_s^2 \sim A^{1/3}$
- CGC parameters fitted to HERA and CMS data in (Albacete, Armesto, Milhano, Quiroga-Arias, Salgado, EPJC 71, 1705 (2011))

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:

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

- 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))

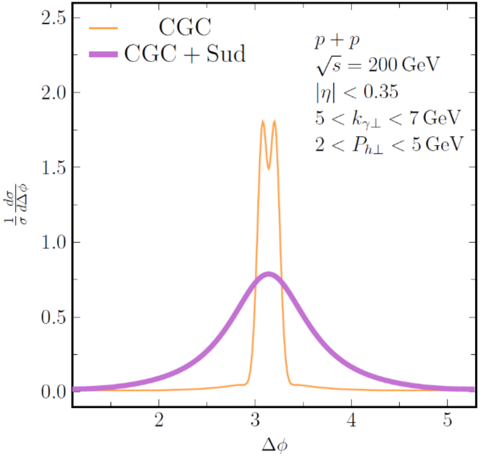
- Sudakov factor (for $qg \to q\gamma$):

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

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

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

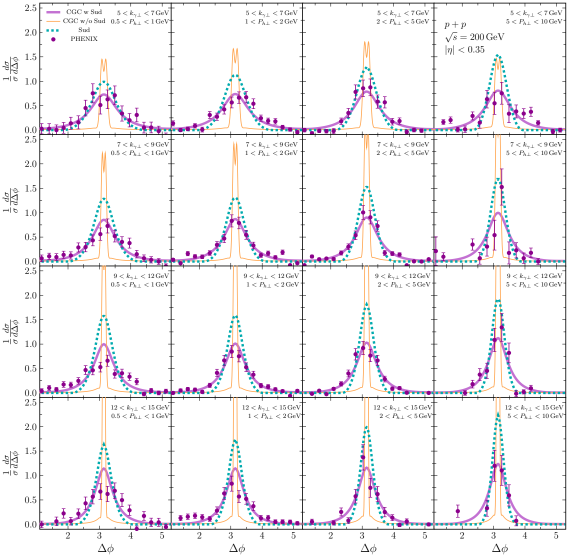
Comparison of CGC vs CGC+Sudakov angular correlations



- Generic CGC prediction: double peak structure at $\Delta\phi \sim \pi$
- Adding Sudakov effects broadens the distribution and destroys that structure

(Benić, Garcia-Montero, AP, Phys. Rev. D 105, 114052 (2022))

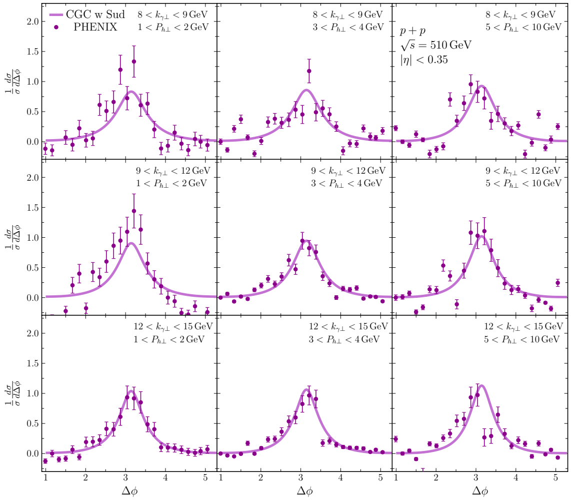
Self-normalized angular correlations



- PHENIX $pp \to \gamma h^{\pm}$, $\sqrt{s} = 200$ GeV at central rapidity
- 5 GeV $< k_{\gamma\perp} <$ 15 GeV
- 0.5 GeV $< P_{h\perp} <$ 10 GeV

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

Self-normalized angular correlations

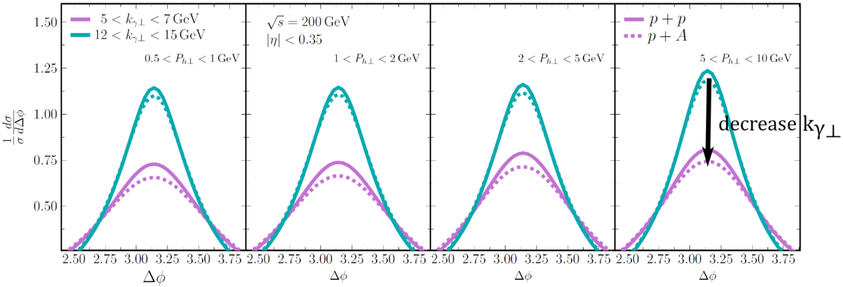


- PHENIX $pp \to \gamma h^{\pm}$, $\sqrt{s} = 510$ GeV at central rapidity
- 8 GeV $< k_{\gamma\perp} <$ 12 GeV
- 1 GeV $< P_{h\perp} <$ 10 GeV

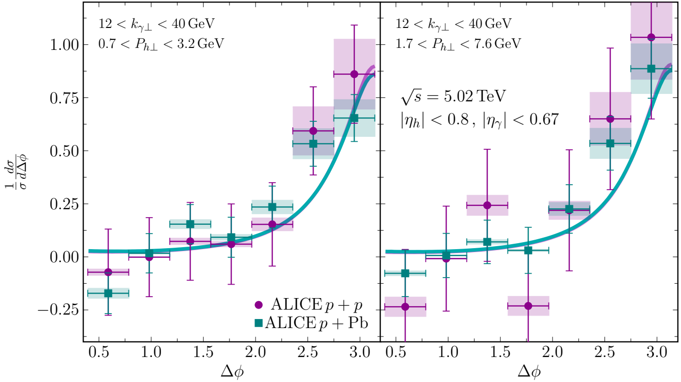
(PHENIX, PRD 95, no. 7, 072002 (2017))

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

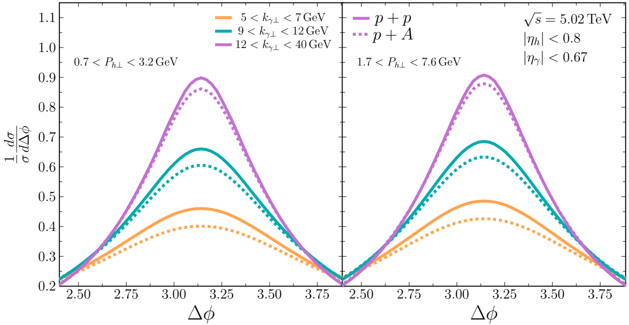


(ALICE, PRC 102, 044908 (2020))

- 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

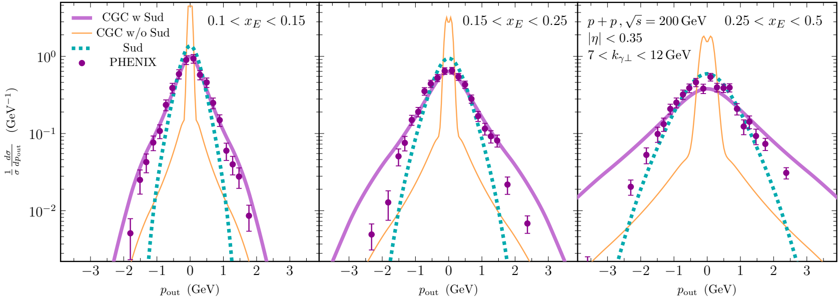
- *pp* vs *pA* - calculation for two more favorable $k_{\gamma\perp}$ bins (5-7 GeV and 9-12 GeV) as well as the existing one (12-40 GeV)
- Again, moderate nuclear effect visible in $\Delta\phi$ distribution broadening



Out-of-plane momentum distributions: PHENIX

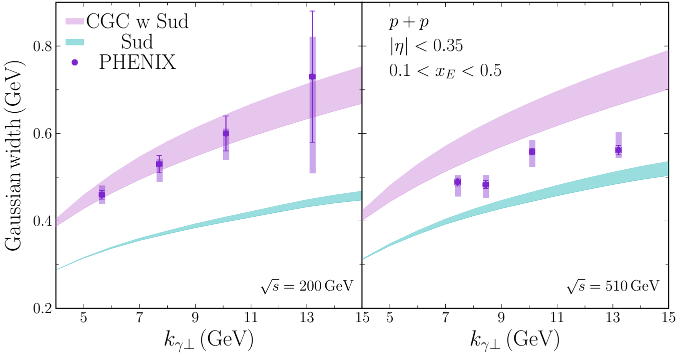
$$p_{out} = P_{h\perp} \sin(\Delta\phi), \quad x_E = -\frac{P_{h\perp}}{k_{\gamma\perp}} \cos(\Delta\phi)$$

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

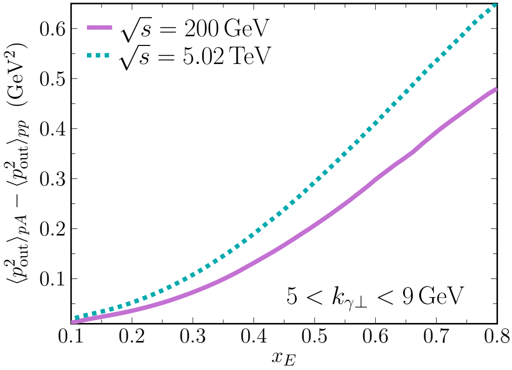


p_{out} distributions: Gaussian widths

- 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 at forward rapidity)