Isolated photon-hadron production in high energy $pp$ and $pA$ collisions

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Motivations

- $\gamma h$ angular correlations as a probe of high energy nuclear wavefunction
- Imbalance momentum
  \[ k_\perp \equiv k_{\gamma \perp} + \frac{P_{h \perp}}{Z_h} \]
  \[ k_\perp^2 \sim Q_S^2 \sim A^{1/3} \]
- Complements $hh$ productions
  $\rightarrow$ see previous talk by Cyrille Marquet
Motivations

- recent data on isolated $\gamma h^{\pm}$ from PHENIX and ALICE at mid-rapidity

**PHENIX ($pp$)**

- $\sqrt{s} = 200, 510$ GeV
- $k_{\gamma\perp} = 5 - 15$ GeV
- $P_{h\perp} = 0.5 - 10$ GeV

**ALICE ($pp$ & $pPb$)**

- $\sqrt{s} = 5.02$ TeV
- $k_{\gamma\perp} = 12 - 40$ GeV
- $P_{h\perp} = 0.5 - 10$ GeV

PHENIX, PRD 95, no. 7, 072002 (2017)
PHENIX, PRD 98, no. 7, 072004 (2018)
ALICE, PRC 102, 044908 (2020)

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Motivations

• $x_{\text{RHIC}} \sim 10^{-2}$, $x_{\text{LHC}} \sim 10^{-3}$
  $\rightarrow$ small-$x$ effects $\rightarrow$ CGC

• imbalance momentum: $k_{\perp} \equiv k_{\gamma\perp} + \frac{P_{h\perp}}{z_h}$

• hard scale: $Q \sim k_{\text{trig}\perp}$

• for kinematics when $Q \gg k_{\perp}$
  $\rightarrow$ Sudakov (double) logs $\alpha_s \log^2(\frac{Q^2}{k_{\perp}^2})$
  important

• try to interpret the PHENIX and ALICE data in the context of CGC + Sudakov
Generic considerations

- \( qg \rightarrow q\gamma \) in collinear pQCD

\[
\frac{d\sigma}{d^2k_{\gamma\perp}d\eta_{\gamma}d^2P_{h\perp}d\eta_h} = \sum_q e_q^2 \int \frac{dz_h}{z_h^2} D_q(z_h, \mu^2) x_p f_q(x_p, \mu^2) x_A f_g(x_A, \mu^2) \alpha_s \hat{\sigma} \delta^{(2)}(k_{\perp})
\]

\( \gamma h \) emerge back-to-back
Generic considerations

• $q g \rightarrow q \gamma$ in CGC

\[ d\sigma \over d^2 k_{\gamma \perp} d\eta_{\gamma} d^2 P_{h \perp} d\eta_h \]

\[ = (\pi R_A^2) \sum_q \int_0^1 \frac{dz_h}{z_h^2} D_q(z_h, \mu^2) \frac{e_q^2 N_c}{8\pi^4} x_p f_q(x_p, \mu^2) k_{\perp}^2 \tilde{N}_{A, Y_A}(k_{\perp}) \hat{\sigma} \]

\[ \tilde{N}_{A, Y_A}(k_{\perp}) \equiv \int d^2 b_{\perp} e^{ik_{\perp} \cdot b_{\perp}} \text{tr} \left\langle \bar{U}(b_{\perp}) \bar{U}^\dagger(0) \right\rangle_{Y_A} / N_c \]

→ broadening of the away side peak

Kopeliovich, Tarasov, Schafer, PRC 59, 1609-1619 (1999)
Gelis, Jalilian-Marian, PRD 66 014021 (2002)
Baier, Mueller, Schiff, NPA 741 358-380 (2004)
Previous phenomenological works

- a generic feature: dip at $\Delta \phi = \pi$
- due to dipole UGD

$$\varphi_{DP}(k_\perp) \sim k_\perp^2 \tilde{N}(k_\perp) \sim k_\perp^2 / Q_S^2$$

- in contrast to $hh$ correlations that probe the WW UGD

$$\varphi_{WW}(k_\perp) \sim \log(Q_S^2 / k_\perp^2)$$

Jalilian-Marian, Rezaeian, PRD 86 034016 (2012)
Stasto, Xiao, Zaslavsky, PRD 86 014009 (2012)
Rezaeian, PRD 86 094016 (2012)
Goncalves, Lima, Pasechnik, Sumbera, PRD 101 no. 9 094019 (2020)
**Lesson from $hh$ correlations**

- Giacalone et al: *away side peak is too narrow in comparison to the data*

- see also previous talk by Cyrille Marquet

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Albacete, Giacalone, Marquet, Matas, PRD 99 014002 (2019)
Lesson from $hh$ correlations

- Wei et al: Sudakov resummation broadens the away side peak $\rightarrow$ agrees with the data!
- see also previous talk by Cyrille Marquet
Sudakov resummation

- two particle production: two scale problem
  \[ \rightarrow \text{imbalance } k_\perp \text{ and a hard scale } \equiv Q \]

\[ Q^2 \equiv x_p x_A s \sim k_{\text{trig}_\perp}^2 \]

- account for soft gluon radiations

\[ \frac{d\sigma^{(0)}}{d^2 k_\perp} \propto \delta^{(2)}(k_\perp) \]
Sudakov resummation

- two particle production $\rightarrow$ two scale problem
  $\rightarrow$ imbalance $k_{\perp}$ and a hard scale $\equiv Q$

$$Q^2 \equiv x_p x_A s \sim k_{\text{trig}}^2$$

- account for soft gluon radiations

$$\frac{d\sigma^{(1)}}{d^2 k_{\perp}} \propto \int_{k_{g\perp}} \frac{\alpha_s}{k_{g\perp}^2} \log \frac{Q^2}{k_{g\perp}^2} \times \delta^{(2)}(k_{g\perp} + k_{\perp})$$

- enhanced when $Q^2 \gg k_{\perp}^2$

$\rightarrow$ Sudakov resummation

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

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Sudakov resummation

- Sudakov effect on top of CGC
  - Mueller, Xiao, Yuan, PRL 110 082301 (2013)
  - Stasto, Wei, Xiao, Yuan, PLB 784 301-306 (2018)
  - Marquet, Wei, Xiao, PLB 802 135253 (2020)
  - Zhao, Xu, Chen, Zhang, Wu, PRD 104, no, 114032 (2021)
  - van Hameren, Kotko, Kutak, Sapeta, PLB 814 136078 (2021)

- employed in $b_{\perp}$-space

\[ k_{\perp}^2 \tilde{N}_{A,Y_A}(k_{\perp}) D_q(z_h, \mu^2) f_q(x_p, \mu^2) \]

\[ \rightarrow \int d^2 b_{\perp} e^{i k_{\perp} \cdot b_{\perp}} \partial^2_{b_{\perp}} \tilde{N}_{A,Y_A}(b_{\perp}) D_q(z_h, \mu_b^2) f_q(x_p, \mu_b^2) e^{-S_{Sud}(b_{\perp}, Q)} \]

- Sudakov factor

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

- $A$ and $B \rightarrow$ channel dependent coefficients
- for $qg \rightarrow q\gamma$

\[ A = \frac{\alpha_S(\bar{\mu}^2)}{\pi} \left( C_F + \frac{C_A}{2} \right) \quad B = -\frac{\alpha_S(\bar{\mu}^2)}{\pi} \frac{3}{2} C_F \]
Computation setup

- $D_q(z_h, \mu^2) \rightarrow \text{DSS}$
  de Florian, Sassot, Stratmann, PRD 75, 114010 (2007)

- $x_p f_q(x_p, \mu^2) \rightarrow \text{CTEQ6M}$
  Pumplin, Stump, Huston, Lai, Nadolsky, Tung, JHEP 07, 012 (2002)

- $\tilde{N}_A, \gamma_A(k_{\perp}) \rightarrow \text{AAMQS}$
  Albacete, Armesto, Milhano, Quiroga-Arias, Salgado, EPJC 71, 1705 (2011)

- $b^*$ prescription $\mu_b > 2 e^{-\gamma_E} / b_{\text{max}}$

  $S_{\text{Sud}}(b_{\perp}, Q) \rightarrow S_{\text{Sud}}(b_{\perp}, Q) + S_{\text{non-pert}}(b_{\perp}, Q)$

- $S_{\text{non-pert}}(b_{\perp}, Q) \rightarrow \text{SIYY}$
  Sun, Isaacson, Yuan, IJMPA 33 no. 11, 1841006 (2018)
Angular corr’s: CGC vs CGC+Sud

self-normalized cross section

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Delta \phi} \]

\[ p + p \]
\[ \sqrt{s} = 200 \text{ GeV} \]
\[ |\eta| < 0.35 \]
\[ 5 < k_{\perp} < 7 \text{ GeV} \]
\[ 2 < P_{h\perp} < 5 \text{ GeV} \]

- dip at \( \Delta \phi = \pi \)
\[ \varphi_{DP}(k_{\perp}) \sim k_{\perp}^2/Q_S^2 \]

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Angular corr’s: CGC vs CGC + Sud

- washed away by Sudakov!!

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Angular corr’s: PHENIX $pp$ 200 GeV

- self-normalized results in $k_{\gamma \perp} \times P_{h \perp}$ bins

mostly sensitive to CGC+Snon-pert

mostly sensitive to SSud
PHENIX predictions

- \( pp \) vs \( pA @ PHENIX: \)
  - lowest (5 – 7 GeV) & highest (12 – 15 GeV) \( k_{\gamma \perp} \) bins

- \( Q_{S0, A}^2 = 3 Q_{S0, p}^2 \)

- nuclear effect at most \( \sim 10\% \)

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**ALICE $pp$ and $pA$ 5.02 TeV**

- $k_{\gamma\perp} = 12 - 40$ GeV
  - $\rightarrow$ nuclear effect barely visible for ALICE kinematics

**ALICE, PRC 102, 044908 (2020)**
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ALICE - predictions

- *pp vs pA @ ALICE*

  lower $k_{\gamma \perp}$ → more symmetric kinematics

  \[ \text{decrease } k_{\gamma \perp} \]

- nuclear effect at most $\sim 10\%$

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\( p_{\text{out}} \)-distributions: PHENIX

\[
p_{\text{out}} \equiv P_{h\perp} \sin(\Delta \phi) \quad x_E \equiv -\frac{P_{h\perp}}{k_{\gamma\perp}} \cos(\Delta \phi)
\]

- close to the away side peak (\( \Delta \phi \simeq \pi \)):

\[
p_{\text{out}} \sim z_h k_{\perp} \quad x_E \sim z_h
\]

\( \rightarrow \) proxy for intrinsic \( k_{\perp} \)
$p_{\text{out}}$-distributions: widths

- extracted by fitting to a Gaussian in the range $|p_{\text{out}}| < 1.1 \pm 0.2$ GeV

- best description with CGC+Sud

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Conclusions

- $\gamma h$ production in a CGC+Sud framework → a reasonable description of the data
- caveat: this may not be the only way to interpret the data
- modest nuclear effect $\sim 10\%$
- future works: Drell-Yan, NLO corrections, systematic errors etc..
Widths: $pA$ vs. $pp$

- Up to 0.15 GeV$^2$ broader widths in $pA$ vs $pp$ for $x_E < 0.4$

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