Di-photon correlations in dilute-dense collisions from the CGC

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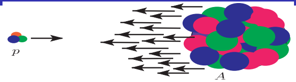
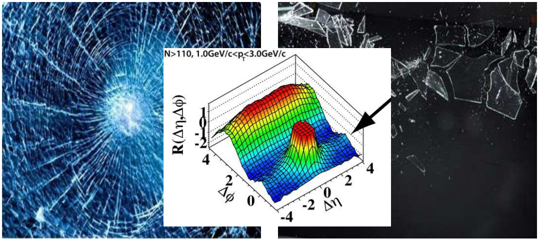
In collaboration with: **Alex Kovner**

What is origin of the observed Ridge phenomenon in p+p(A) collisions?



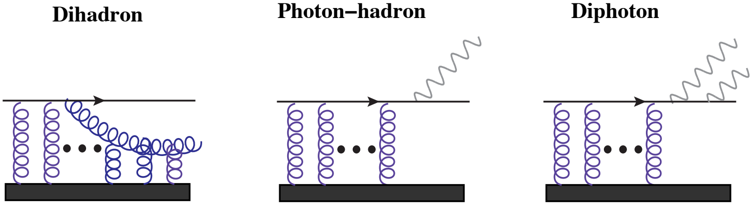
Color–Glass–Condensate in pPb **Collective flow in pPb collisions**



- Does the ridge phenomenon in p+p(A) collisions mainly come from initial-state or final-state effects?
- Is the "ridge" universal phenomenon, for all different two-particle productions in p+p(A) collisions?
- What is nature of high multiplicity events in p+p(A) collisions?

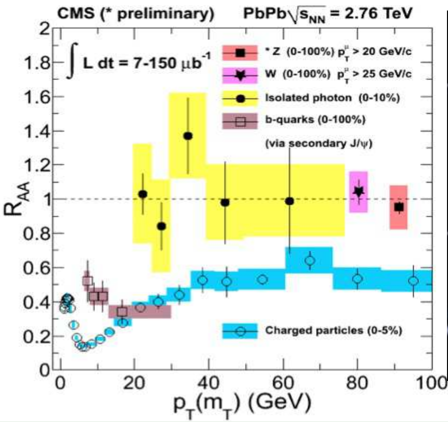
Measurements of di-photon and photon-hadron correlations in p+p(A) collisions can address these questions.

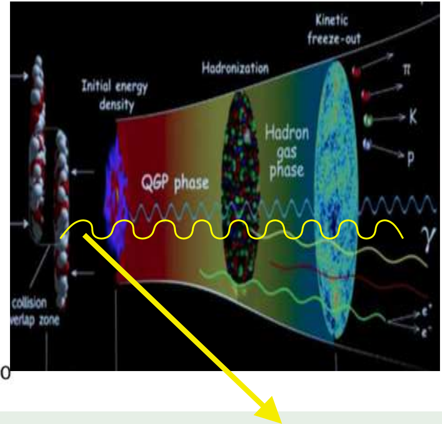
Dihadron v. photon-hadron v. diphoton production in the CGC



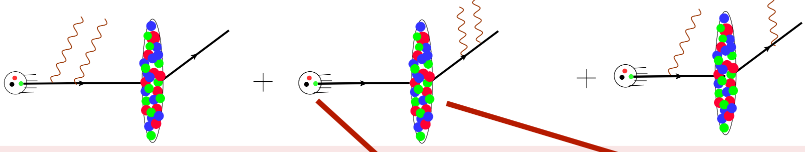
- Soft gluons are scattered out of the projectile wave function by directly scattering on a saturated target.
  Photons do not scatter themselves, but rather decohere from the scattered quarks.
- **Virtual photons do not directly interact with the gluons inside target.**
- **Final-state effects are absent in the photon production, no initial-final state interference, and no hadronization.**

Inclusive prompt photon v. hadron production



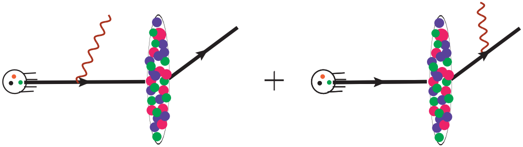


- Photons can be produced at different stages of collisions (prompt, thermal, decay). Here I only discuss prompt photon coming from hard collisions in small-x region.
- In AA collisions all hadrons are strongly quenched except prompt photon → **prompt photon can be a good probe of initial-state effects.**



$$\frac{d\sigma^{pA\to\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{b}\,d^2\mathbf{k}_{1T}\,d\eta_1\,d^2\mathbf{k}_{2T}\,d\eta_2} = \alpha_{em}^2 \int_{x_q^{min}}^{1} dx_q\, f(x_q,\mu_I^2) \int d^2\mathbf{l}_T\, \mathcal{H}\left(\mathbf{k}_{1T},\mathbf{k}_{2T},\mathbf{l}_T,\zeta_1,\zeta_2\right) N_F(l_T,x_g)$$

- Di-photon production in p+A collisions at LO: $\mathcal{H}$ **is a few pages formula**, Kovner and Rezaeian, **arXiv:1508.02412**, arXiv:1404.5632.

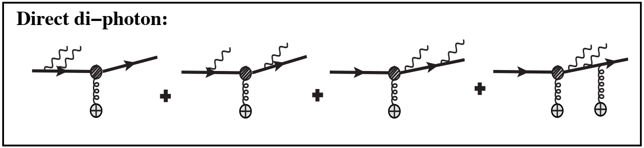


$$\frac{d\sigma^{pA\to\gamma(k)X}}{d^2\mathbf{b}\,d^2\mathbf{k}_T\,d\eta} = \alpha_{em} \int_{x_q^{min}}^{1} dx_q\, f(x_q,\mu_I^2) \int d^2\mathbf{l}_T\, \mathcal{H}\left(\mathbf{k}_T,\mathbf{l}_T,\zeta\right) N_F(l_T,x_g)$$

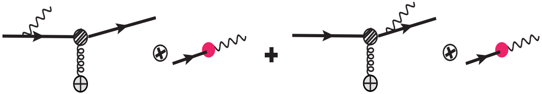
- Single photon production in p+A collisions at LO: Gelis, Jalilian-Marian, hep-ph/0205037; Baier, Mueller, Schiff, hep-ph/0403201; Kovner, Rezaeian, arXiv:1404.5632.

Inclusive prompt di-photon production in high-energy p+A collisions

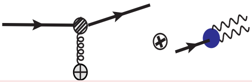
Direct di−photon:



Single fragmentation di−photon:



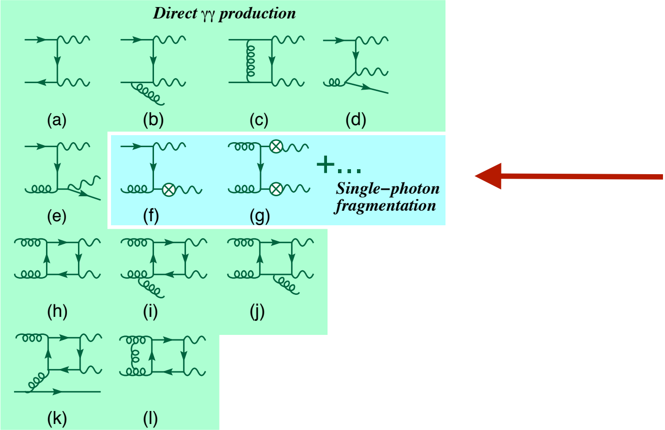
Double fragmentation di−photon:



$$\frac{d\sigma^{pA\rightarrow\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}=\frac{d\sigma^{\text{Direct}}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}+\frac{d\sigma^{\text{Fragmentation}}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}.$$

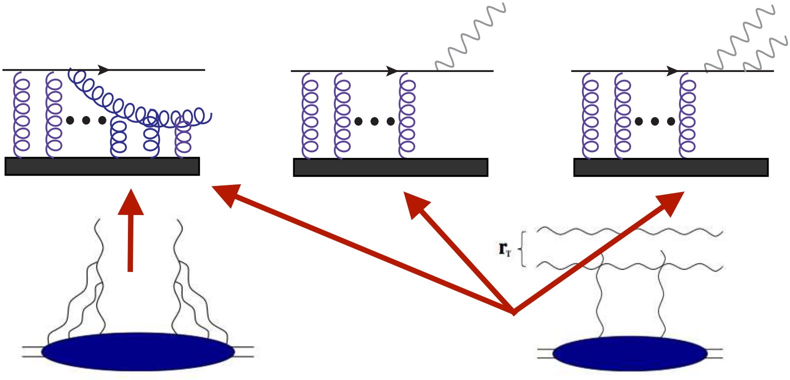
Both single and double fragmentation di-photon contributions, as well direct di-photon part are sensitive to the saturation dynamics via $N_F(x_g, l_T)$.

Inclusive di-photon production in p+p collisions (pQCD:NLO)



$$\frac{d\sigma^{pA\rightarrow\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}=\frac{d\sigma^{\text{Direct}}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}+\frac{d\sigma^{\text{Fragmentation}}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}.$$

Two-particle production in p+A collisions from the CGC



Dihadron

Photon–hadron

Diphoton

Weizsacker–Williams (WW) gluon distribution (quadropole)
counts the number of gluons (never measured)

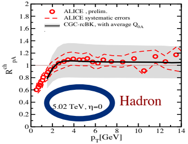
Color dipole gluon distribution (dipole)
appears in F_2 , F_L structure funtions (measured)

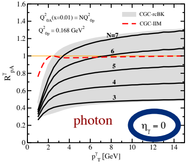
Dihadron v. photon-hadron v. diphoton production in the CGC

- In contrast to dihadron production, photon-hadron and diphoton cross section depend only on the dipole amplitude (not WW gluon distribution).

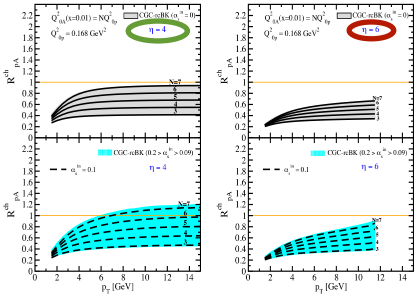
Inclusive direct photon v. hadron production in p+A collisions at the LHC

Rezaeian, PLB718, arXiv:1210.2385

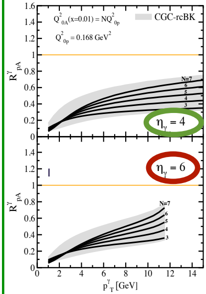



Inclusive prompt photon, 5 TeV

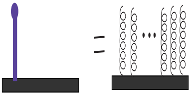
Hadron, 5 TeV



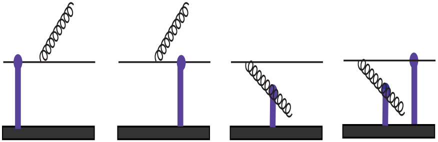
Direct photon, 5 TeV



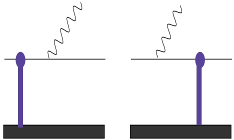
Main input: BK evolution Eq.



Typical diagrams for gluon production:



Inclusive photon production at LO

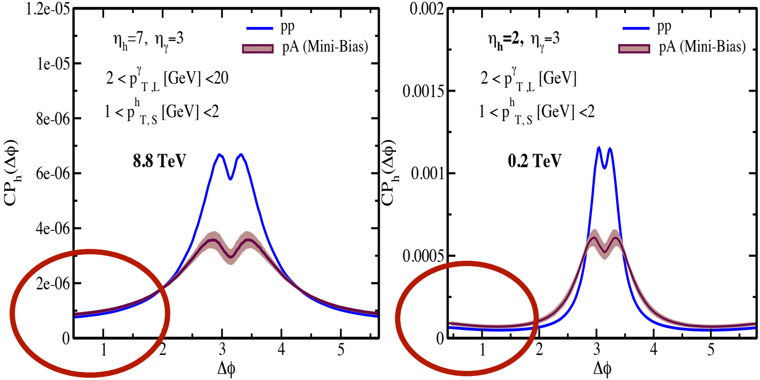


$$R_{pA}(p_T >> 1) = \frac{Q^2_{0A} S_A}{Q^2_{0p} A S_p} \approx \frac{Q^2_{0A}}{Q^2_{0p} A^{1/3}} \to 1, \qquad \checkmark$$

The suppression of the inclusive prompt photon and inclusive hadron production in p+A collisions at the LHC are rather similar.

Near-side $\gamma - \pi^0$ correlations in p+p(A) collisions

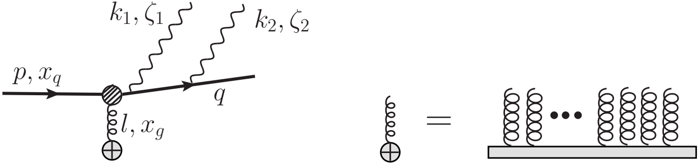
Rezaeian,PRD86, arXiv:1209.0478



- **No ridge-like structure at the near-side for photon-hadron correlations in p+p(A) minimum-bias collisions at RHIC and the LHC from the CGC.**

Inclusive di-photon production in p+A collisions from the CGC

Kovner and Rezaeian, arXiv:1508.02412.



$$\frac{d\sigma^{pA\to h(q')\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{b}d^2\mathbf{k}_{1T}d\eta_1 d^2\mathbf{k}_{2T}d\eta_2} = \alpha_{em}^2 \int_{x_q^{min}}^{1} dx_q\, f(x_q, \mu_I^2) \int d^2 l_T\, \mathcal{H}(k_1, k_2, l, \zeta_1, \zeta_2)\, N_F(l_T, x_g)$$

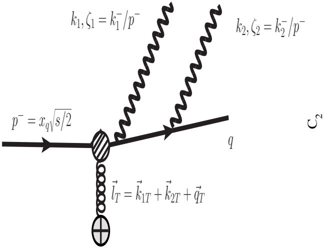
$$x_g = \frac{1}{x_q s}\left[\frac{k_{1T}^2}{z_1} + \frac{k_{2T}^2}{z_2(1-z_1)} + \frac{|\mathbf{l_T} - \mathbf{k}_1 - \mathbf{k_2}|^2}{1 - z_1 - z_2 + z_1 z_2}\right],$$

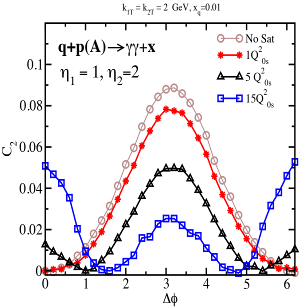
$$\zeta_1 = \frac{k_1^-}{p^-} = \frac{k_{1T}}{x_q\sqrt{s}} e^{\eta_{\gamma_1}},$$

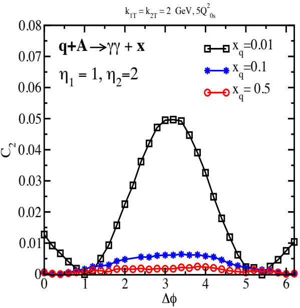
$$\zeta_2 = \frac{k_2^-}{p^- - k_1^-} = \frac{k_{2T}}{x_q(1-z_1)\sqrt{s}} e^{\eta_{\gamma_2}}$$

$$x_q^{min} = Max\left(\frac{k_{1T}e^{\eta_{\gamma_1}}}{\sqrt{s}}, \frac{k_{2T}e^{\eta_{\gamma_2}}}{\sqrt{s} - k_{1T}e^{\eta_{\gamma_1}}}\right).$$

Di-photon correlations in q+A collisions at the LHC 5 TeV



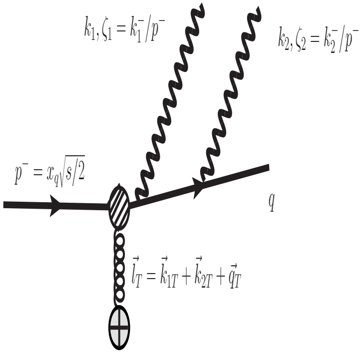


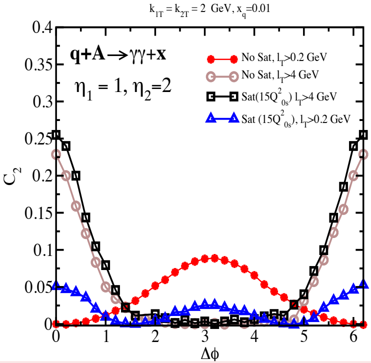


$$C_2(\Delta\phi, k_{1T}, k_{2T}, \eta_1, \eta_2) = \frac{d\sigma^{pA\to\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}d\eta_{\gamma_2}}[\Delta\phi] / \int_0^{2\pi} d\Delta\phi \frac{d\sigma^{pA\to\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}d\eta_{\gamma_2}} - C_{ZYAM}$$

- Near-side and away-side correlations are enhanced at small $x_q \to 0$ or large $\zeta_1, \zeta_2 \to 1$. At large x_q, near-side correlations diminish and only away-side peak survives.
- Near-side correlations are enhanced while away-side correlations are suppressed by increasing the saturation scale Q_s.

Di-photon correlations in q+A collisions at the LHC 5 TeV



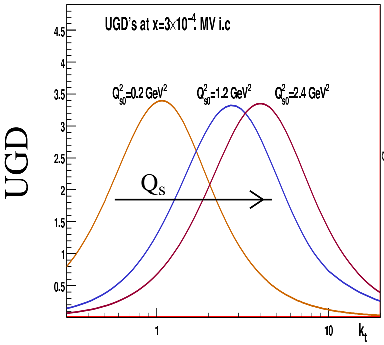


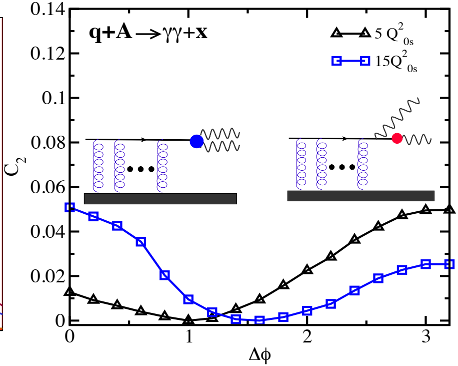
- At the near-side, the main contribution comes from large momentum transfer to target l_T, while away-side correlations come from low l_T.

$$\frac{d\sigma^{qA\to h(q')\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{b}\, d^2\mathbf{k}_{1T}\, d\eta_1\, d^2\mathbf{k}_{2T}\, d\eta_2} = \alpha_{em}^2 \int_{l_T > l_T^{Min}} d^2 l_T\, \mathcal{H}\left(k_1, k_2, l, \zeta_1, \zeta_2\right) N_F(l_T, x_g)$$

- Near-side peak mainly comes from double-fragmentation contribution while away-side peak comes from the single fragmentation contribution.

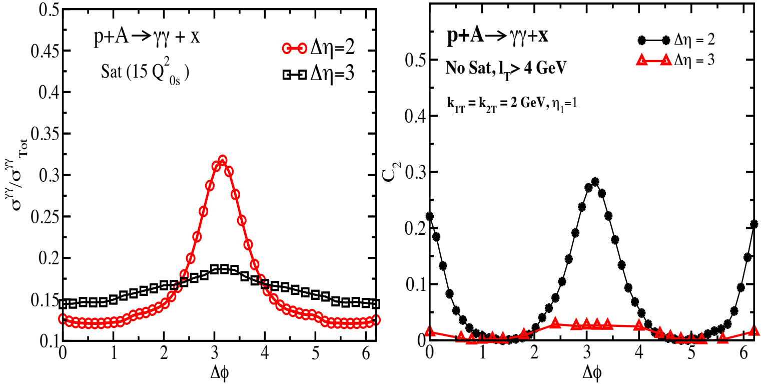
Di-photon correlations in q+A collisions at the LHC 5 TeV





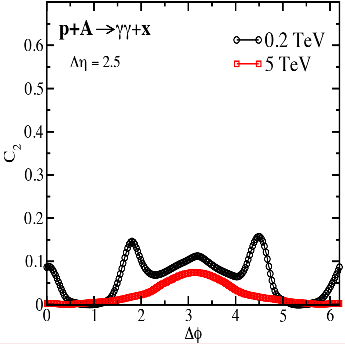
- A larger saturation scale shifts the main contribution of integrand to higher l_T $\Longrightarrow$ enhances the double-fragmentation contribution and the near-side peak while suppresses the single-fragmentation contribution and the away-side correlations (unbalance the back-to-back).

Di-photon correlations in p+A collisions at the LHC



- The near-side correlations and peak are partly washed away at the LHC by integrating over x_q (or convolution with pdf).
- The correlations strongly depend on the lower cut on the total transfer momentum l_T, and transverse momentum of the produced di-photon. **One may enhance the near-side peak by isolation cut techniques!.**

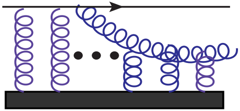
Di-photon correlations in p+A collisions at the RHIC



- Di-photon correlations at near-side at the RHIC has a **ridge-like** structure: the effect is extended upto $\Delta\eta \approx 3$.
- Di-photon correlations at near-side is larger at RHIC (0.2 TeV) compared to the LHC (5 TeV).
- The di-photon ridge disappears in the non-saturation model, it shows up at intermediate energy (RHIC) and it switches itself off at very high-energy and large rapidity interval.

Conclusion:

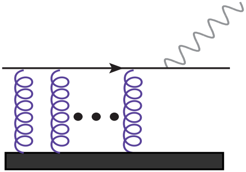
Dihadron



Measured at RHIC, LHC

PHENIX & STAR (2011)

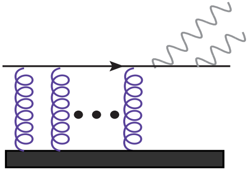
Photon–hadron



Not yet measured

Jalilian–Marian, Rezaeian (2012)

Diphoton

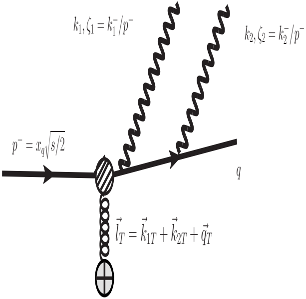


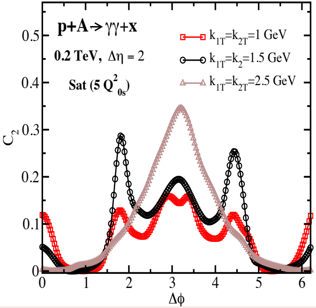
Not yet measured

Kovner, Rezaeian (2015)

- Back-to-back correlation gets suppressed due to the saturation scale. **This feature is universal to all semi-inclusive production shown above.**
- The near-side correlations (the ridge) for different two-particle productions come from **different mechanisms** and is **NOT universal**.
- There **is NO ridge-like** structure for di-photon and photon-hadron correlations at the **LHC** in p+A collisions from the initial-state physics.
- Such measurments can help to discriminate among initial- and final-state models.

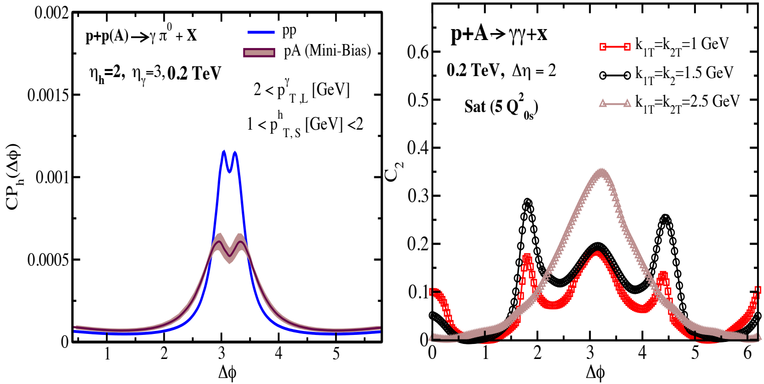
Backup: The origin of di-photon double-peak at $\Delta\phi = \pi$





1. Local minimum: $\sigma^{\gamma\gamma}(l_T \to 0) \to 0$.
2. Local maximum: single-fragmentation contribution is larger at lower l_T and has a maximum at $\Delta\phi = \pi$ (back-to-back).
3. Due to convolution with PDF and $N(x_g, l_T)$, the local min and max get smeared out (the double-peak structure appears within a kinematic region).
   e.g: a higher k_{1T} or k_{2T} excludes low-l_T region (condition 1) $\Longrightarrow$ double-peak structure disappears.

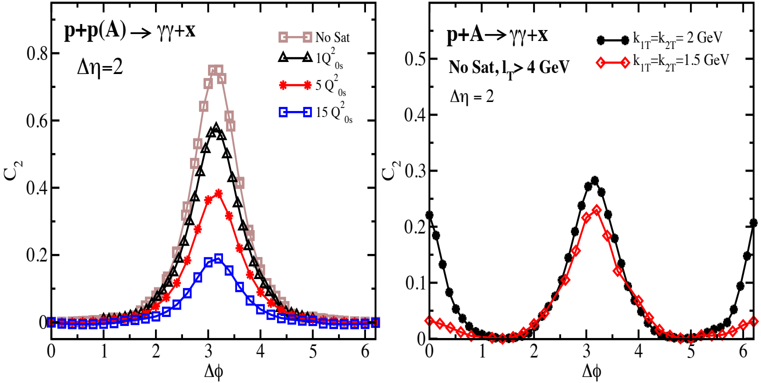
Backup: Away-side double-peak structure for Electromagnetic Probes



The away-side double-peak structure seems to be universal for EM probes:

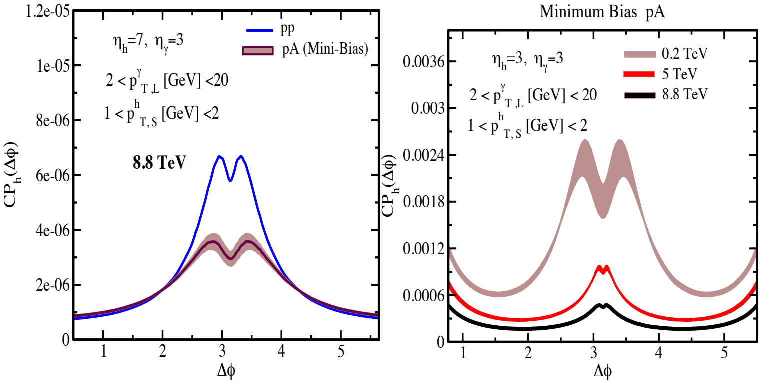
Di-photon correlations: Kovner and Rezaeian, arXiv:1508.02412.
Photon-π^0 correlations: Rezaeian, arXiv:1209.0478.
Drell-Yan Lepton-pair-π^0 correlations: Stasto, Xiao, Zaslavsky, arXiv:1204.4861.

Backup: Di-photon correlations in p+A collisions at the LHC



- The back-to-back (de)-correlations in prompt di-photon production are suppressed by increasing the saturation scale.

Backup: $\gamma - \pi^0$ away-side decorrelations in p+A collisions



- Existence of the saturation scale unbalances the back-to-back correlations.
- Denser nuclei **or/and** Higher energy **or/and** Lower transverse momentum → larger saturation scale → more suppression of away-side correlations.
- The double peak structure becomes stronger and wider at forward rapidities.