Di-photon and photon-hadron correlations at the LHC

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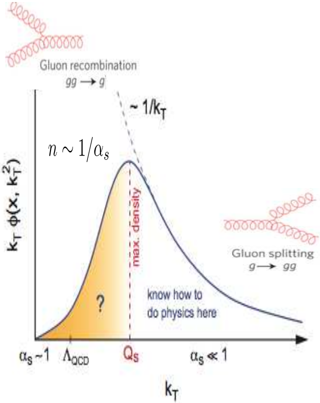
Outline

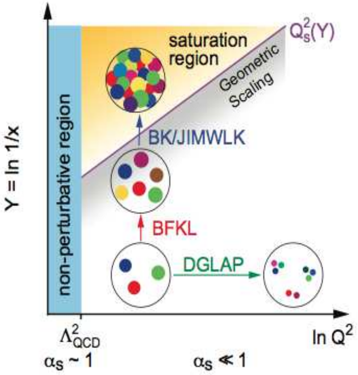
- Motivation, introduction to Color-Glass-Condensate (CGC)/saturation.

- Why di-photon and photon-hadron production in p+A collisions can be considered as golden channels to discriminate among different scenarios?.

- Di-photon and photon-hadron production in high-energy p+A collisions from the CGC.

Road map of strong interaction

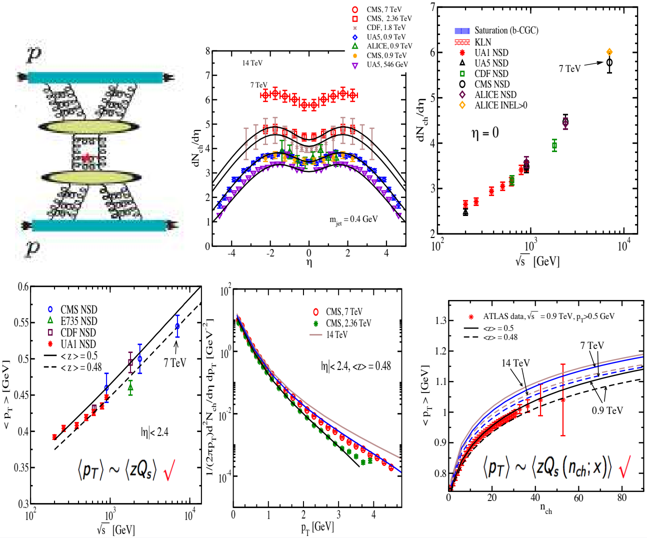




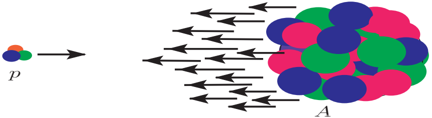
- Is the CGC perturbative approach reliable & systematic at the small-x?
  Yes.
- **What are the signatures of the gluon saturation phenomenon at HERA, RHIC, LHC, LHeC, EIC and FCC?**
  See talk by: **Nestor Armesto**

p+p@LHC from the CGC/saturation

Comparing CGC predictions with 7 TeV data: Levin, Rezaeian, arXiv:1005.0631

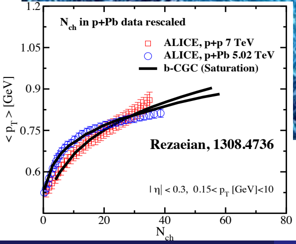


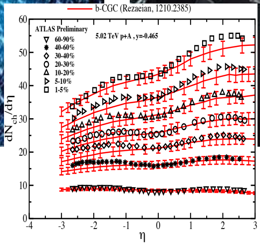
k_T-factorization+ the dipole scattering amplitude constrained by DIS data.

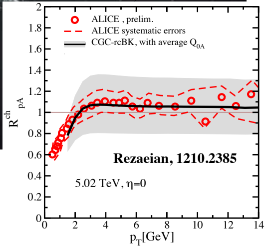


Color−Glass−Condensate in pPb

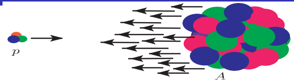
Collective flow in pPb collisions



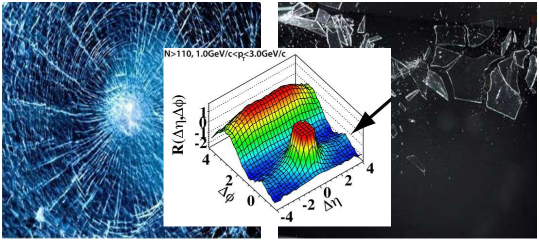




What is origin of the observed Ridge phenomenon in p+p(A) collisions?

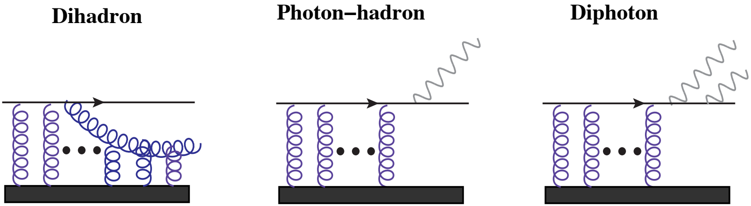


Color–Glass–Condensate in pPb | Collective flow in pPb collisions

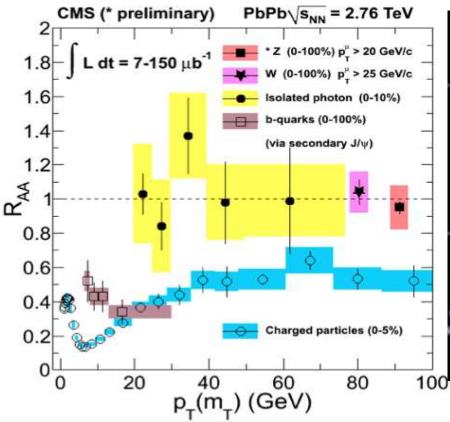


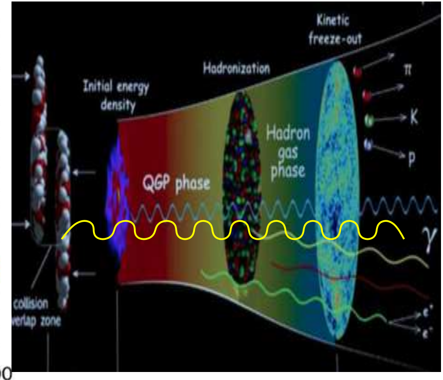
- Does the ridge phenomenon in p+p(A) collisions mainly come from initial-state or final-state effects?
- Is the "ridge" universal phenomenon for all different two-particle productions in p+p(A) collisions?
- What is nature of high multiplicity events in p+p(A) collisions?

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

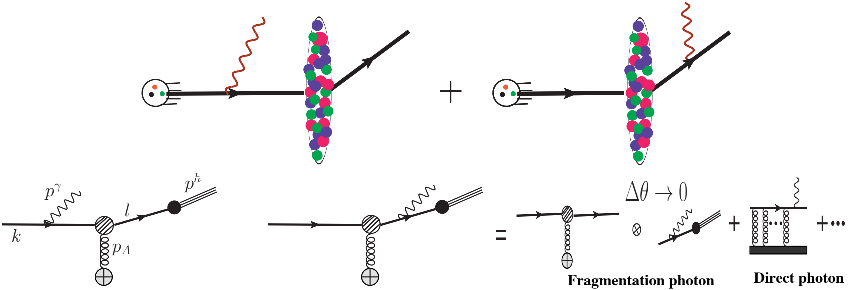


- Soft gluons are scattered out of the projectile wave function by directly scattering on a saturated target.
  Photons do not scatter themselves, but rather decohere from the scattered quarks.
- **Virtual photons do not directly interact with the gluons inside target.**
- **Final-state effects are absent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





- 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.**

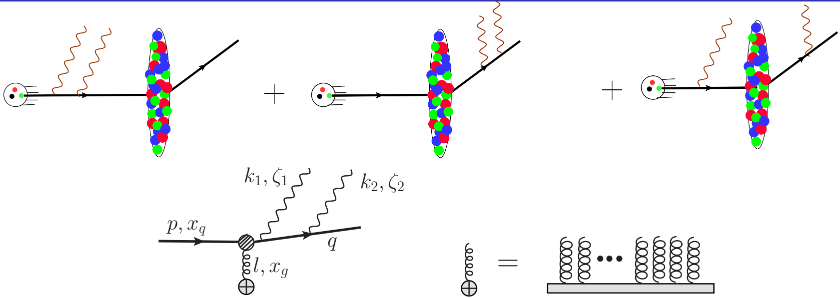


Gelis, Jalilian-Marian, hep-ph/0205037; Baier, Mueller, Schiff, hep-ph/0403201; Jalilian-Marian, Rezaeian, arXiv:1204.1319; Kovner, Rezaeian, arXiv:1404.5632.

$$\frac{d\sigma^{p\,A\to h(p^h)\,\gamma(p^\gamma)\,X}}{d^2\mathbf{b_T}\,d^2\mathbf{p_T}^\gamma\,d^2\mathbf{p_T}^h\,d\eta_\gamma\,d\eta_h} = \frac{e_q^2\,\alpha_{em}}{\sqrt{2}(4\pi^4)}\int_{z_f^{min}}^1 \frac{dz_f}{z_f^2}\int dx_q\, f_q(x_q,Q^2)\frac{1+(\frac{l^-}{k^-})^2}{[p^-\,\mathbf{l_T}-l^-\mathbf{p_T}^\gamma]^2}\, N_F(|\mathbf{l_T}+\mathbf{p_T}^\gamma|,x_g)\,D_{h/q}(z_f,Q^2)$$

$$\delta[x_q - \frac{l_T}{\sqrt{S}}e^{\eta_h} - \frac{p_T^\gamma}{\sqrt{S}}e^{\eta_\gamma}]\left[2l^-p^-\,\mathbf{l_T}\cdot\mathbf{p_T}^\gamma + p^-(k^- - p^-)\,l_T^2 + l^-(k^- - l^-)\,(p_T^\gamma)^2\right]\frac{p^-}{(p_T^\gamma)^2\sqrt{S}}$$

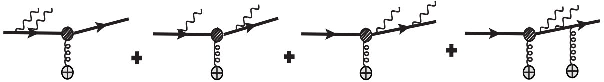
$$\frac{\partial N_{A(F)}(r,x)}{\partial\ln(x_0/x)} = \int d^2\mathbf{r}_1\;K^{\rm run}(\mathbf{r},\mathbf{r}_1,\mathbf{r}_2)\left[N_{A(F)}(r_1,x)+N_{A(F)}(r_2,x)-N_{A(F)}(r,x)-N_{A(F)}(r_1,x)\,N_{A(F)}(r_2,x)\right]$$



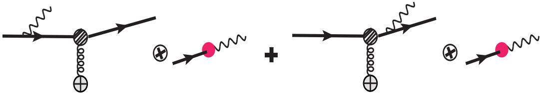
$$\frac{d\sigma^{pA\rightarrow h(q')\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{b}d^2\mathbf{k}_{1T}d\eta_1 d^2\mathbf{k}_{2T}d\eta_2} = \alpha_{em}^2 \int_{x_q^{min}}^1 dx_q f(x_q, \mu_I^2) \int d^2 l_T \mathcal{H}(k_1, k_2, l, \zeta_1, \zeta_2)\, N_F(l_T, x_g)$$

- Soft approximation (radiated photons are soft compared to momentum transfer to target): In soft approximation: $\mathcal{H}$ **is a few lines formula.** Kovner and Rezaeian, **arXiv:1404.5632**.
- Full calculation in p+A collisions at LO: $\mathcal{H}$ **is a few pages formula**, Kovner and Rezaeian, **arXiv:1508.02412**.
  In this talk I show the numerical results of complete calculation.

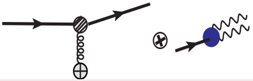
Direct di−photon:



Single fragmentation di−photon:



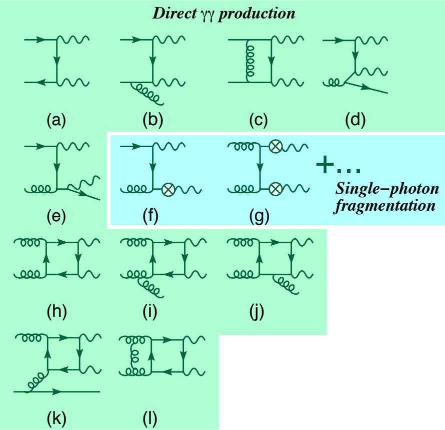
Double fragmentation di−photon:



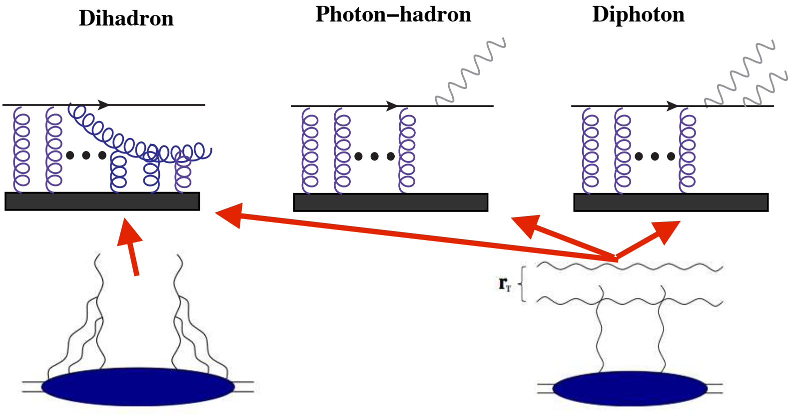
$$\frac{d\sigma^{pA\to\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}} = \frac{d\sigma^{\text{Direct}}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}} + \frac{d\sigma^{\text{Fragmentation}}}{d^2\mathbf{k}_{1T}\,d\eta_{\gamma_1}\,d^2\mathbf{k}_{2T}\,d\eta_{\gamma_2}}.$$

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)



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



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

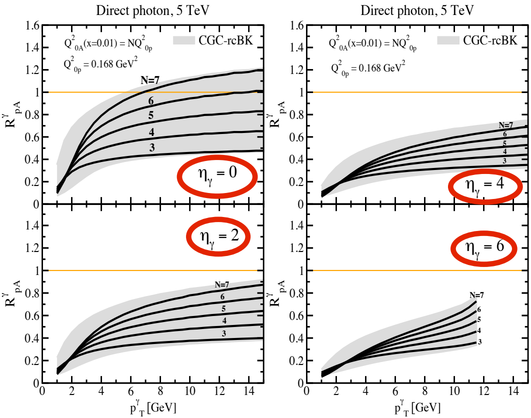
Color dipole gluon distribution (dipole)
appears in F_2 , F_L structure funtions (measured)

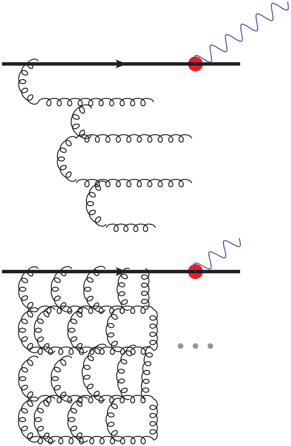
Dihadron v. photon-hadron v. diphoton production in the CGC

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

Direct photon production at the LHC in p+A collisions from the CGC

Rezaeian, arXiv:1210.2385





Prompt photons at forward rapidities in p+A collisions at the LHC are subject to suppression due to the gluon saturation.

$\gamma - h$ correlations via the coincidence probability in p+A collisions

Trigger particle is a prompt photon:

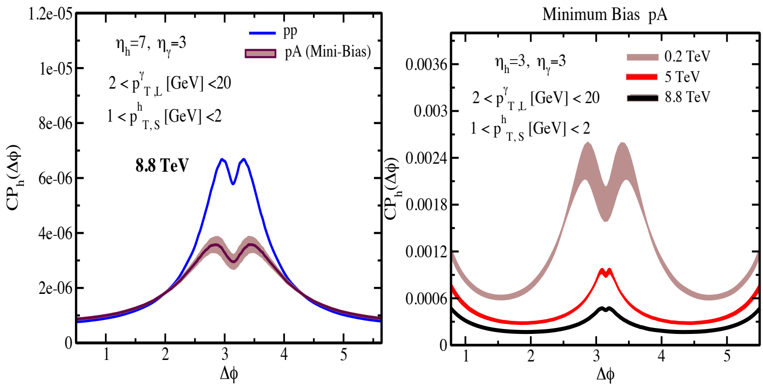
$$CP_h(\Delta\phi) = N_h^{\text{pair}}(\Delta\phi)/\underline{N_{\text{photon}}}$$

Trigger particle is a hadron:

$$CP_\gamma(\Delta\phi) = N_\gamma^{\text{pair}}(\Delta\phi)/\underline{N_{\text{hadron}}}$$

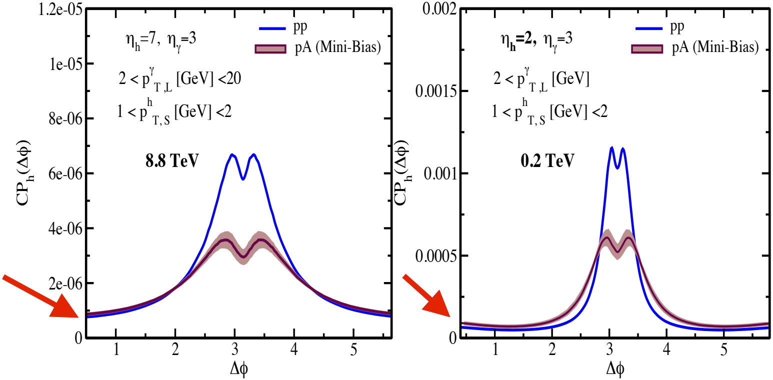
Rezaeian,PRD86, arXiv:1209.0478

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



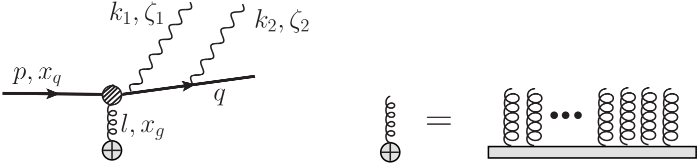
- Existence of the saturation scale unbalances the back-to-back correlations.
- Denser nuclei **or/and** Higher energy **or/and** Lower transverse momentum $\rightarrow$ larger saturation scale $\rightarrow$ more suppression of away-side correlations.
- The double peak structure becomes stronger and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

Rezaeian,PRD86, arXiv:1209.0478



- **No ridge-like structure at the near-side for photon-hadron correlations in p+p and p+A collisions at RHIC and the LHC.**

Kovner and Rezaeian, arXiv:1508.02412.



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

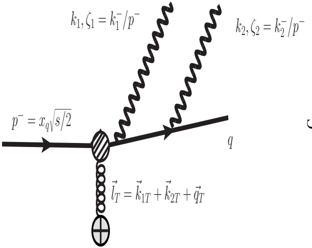
$$x_g = \frac{1}{x_q s}\left[\frac{k_{1T}^2}{z_1} + \frac{k_{2T}^2}{z_2(1-z_1)} + \frac{|\mathbf{l_T} - \mathbf{k}_1 - \mathbf{k_2}|^2}{1 - z_1 - z_2 + z_1 z_2}\right],$$

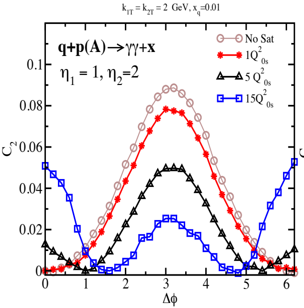
$$\zeta_1 = \frac{k_1^-}{p^-} = \frac{k_{1T}}{x_q\sqrt{s}} e^{\eta_{\gamma_1}},$$

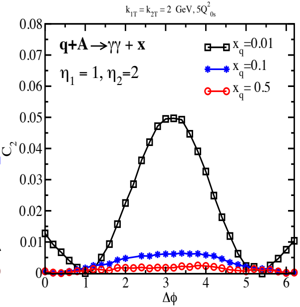
$$\zeta_2 = \frac{k_2^-}{p^- - k_1^-} = \frac{k_{2T}}{x_q(1-z_1)\sqrt{s}} e^{\eta_{\gamma_2}}$$

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

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

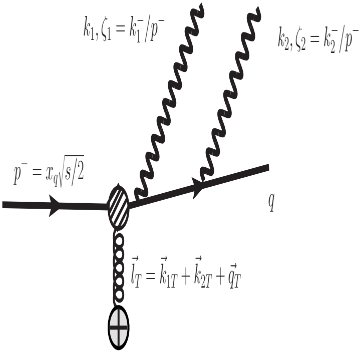


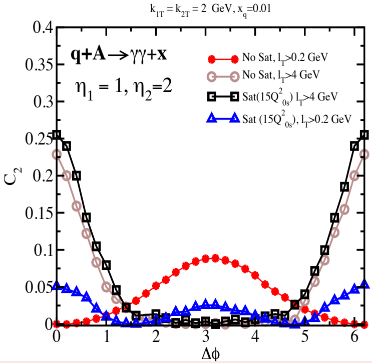




$$C_2(\Delta\phi, k_{1T}, k_{2T}, \eta_1, \eta_2) = \frac{d\sigma^{pA\to\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}\, d\eta_{\gamma_1}\, d^2\mathbf{k}_{2T}\, d\eta_{\gamma_2}}[\Delta\phi] / \int_0^{2\pi} d\Delta\phi \frac{d\sigma^{pA\to\gamma(k_1)\gamma(k_2)X}}{d^2\mathbf{k}_{1T}\, d\eta_{\gamma_1}\,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

- 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.

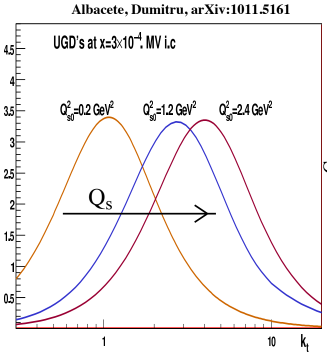


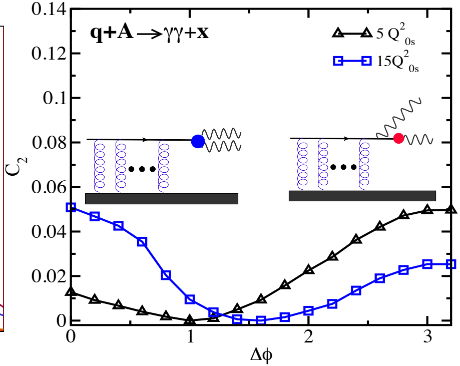


- At the near-side, the main contribution comes from large momentum transfer to target l_T, while away-side correlations come from low l_T.

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

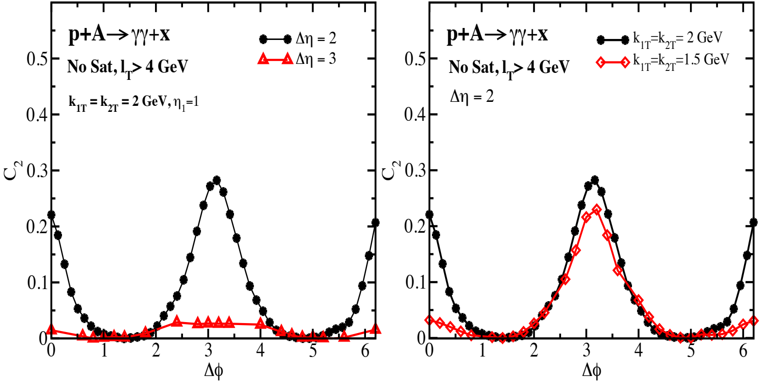
- Near-side peak mainly comes from double-fragmentation contribution while away-side peak comes from the single fragmentation contribution.



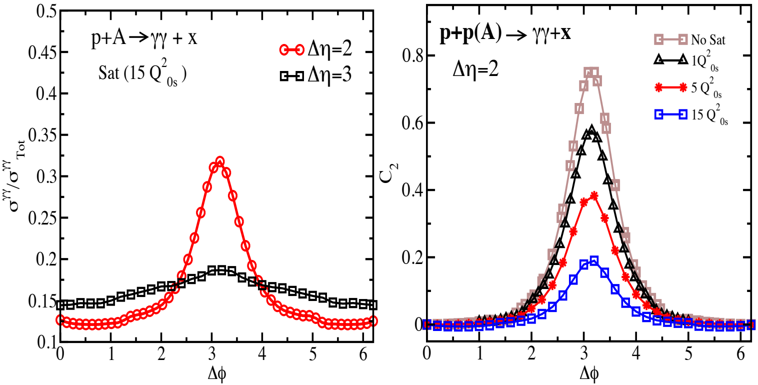


- A larger saturation scale shifts the main contribution of integrand to higher $l_T \Longrightarrow$ enhances the double-fragmentation contribution and the near-side peak while suppresses the single-fragmentation contribution and the away-side correlations (unbalance the back-to-back).

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

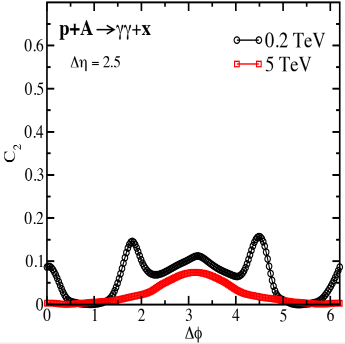


- The correlations strongly depend on the lower cut on the total transfer momentum l_T, and transverse momentum of the produced di-photon. **One may enhance the near-side peak by isolation cut techniques!.**
- Di-photon correlations extend up to $\Delta\eta \approx 2$ at the LHC.

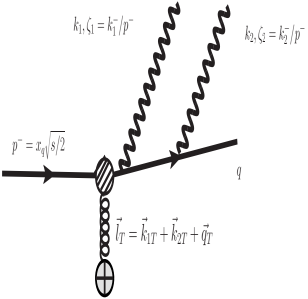


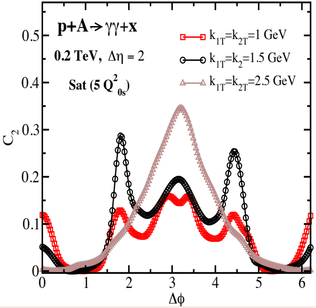
- The near-side correlations and peak are partly washed away at the LHC by integrating over x_q (or convolution with pdf), remember only at very small x_q we have a ridge-type structure here.
- The back-to-back (de)-correlations in prompt di-photon production are suppressed by increasing the saturation scale.

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



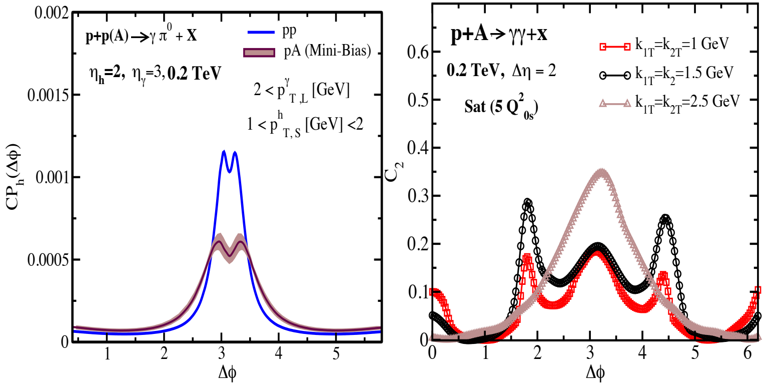
- Di-photon correlations at near-side at the RHIC has a **ridge-like** structure: the effect is extended upto $\Delta\eta \approx 3$.
- Di-photon correlations at near-side is larger at RHIC (0.2 TeV) compared to the LHC (5 TeV).
- The di-photon ridge disappears in the non-saturation model, it shows up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





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.

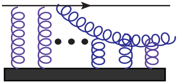
Away-side double-peak structure for Electromagnetic Probes



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.

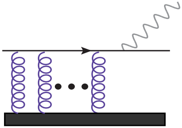
Dihadron



Measured at RHIC

PHENIX & STAR (2011)

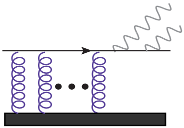
Photon–hadron



Not yet measured

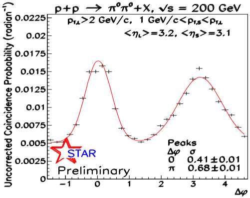
Jalilian–Marian, Rezaeian (2012)

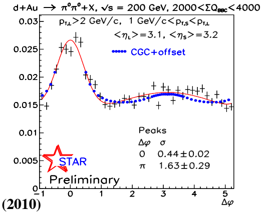
Diphoton



Not yet measured

Kovner, Rezaeian (2014)





Marquet (2007) **Albacete, Marquet (2010)**

Lappi, Mantysaari (2013)

Stasto, Xiao, Yuan (2014)

Plots: Braidot, arXiv:1008.3989

- 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) come from different mechanisms and is NOT universal.

Conclusion:

Di-photon and photon-hadron production in p+A collisions can be considered as a golden channel to discriminate among different scenarios.

- The prompt di-photon corrections exhibit long-range in rapidity near-side azimuthal collimation ("ridge") in p+A collisions at RHIC.
- The effect disappears at the LHC or is significantly weaker at the LHC (using isolation cut techniques and criteria).
- There is no ridge effect for photon-hadron correlations.
- Prompt di-photon and photon-hadron correlations also exhibit some distinct novel features, including the emergence of away side double-peak structure at intermediate transverse momenta.