# Photon-jet Ridge @p+A


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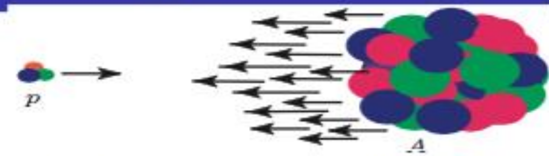
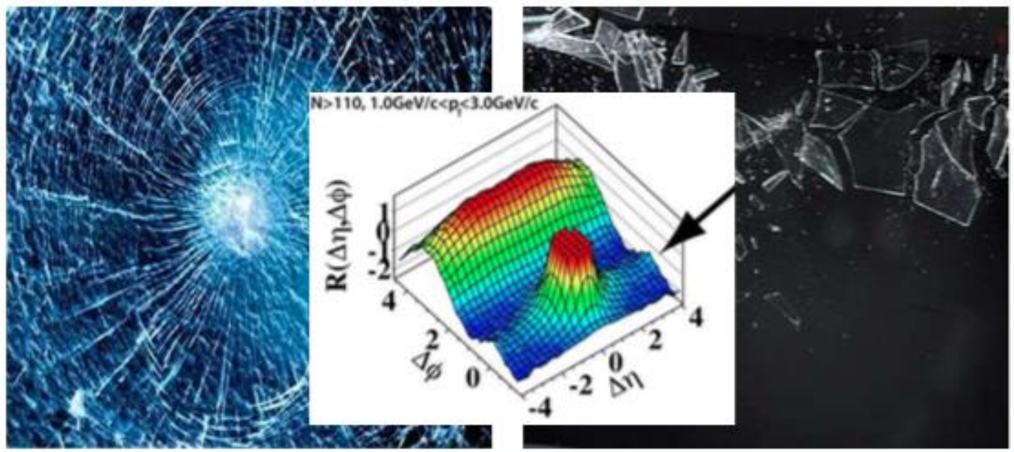
# What is origin of the observed Ridge phenomenon in p+p(A) collisions?




Color–Glass–Condensate in pPb

Collective flow in pPb collisions




Motivation:

**See talk by Alex Kovner**

- 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? di-photon, photon-jet, etc.

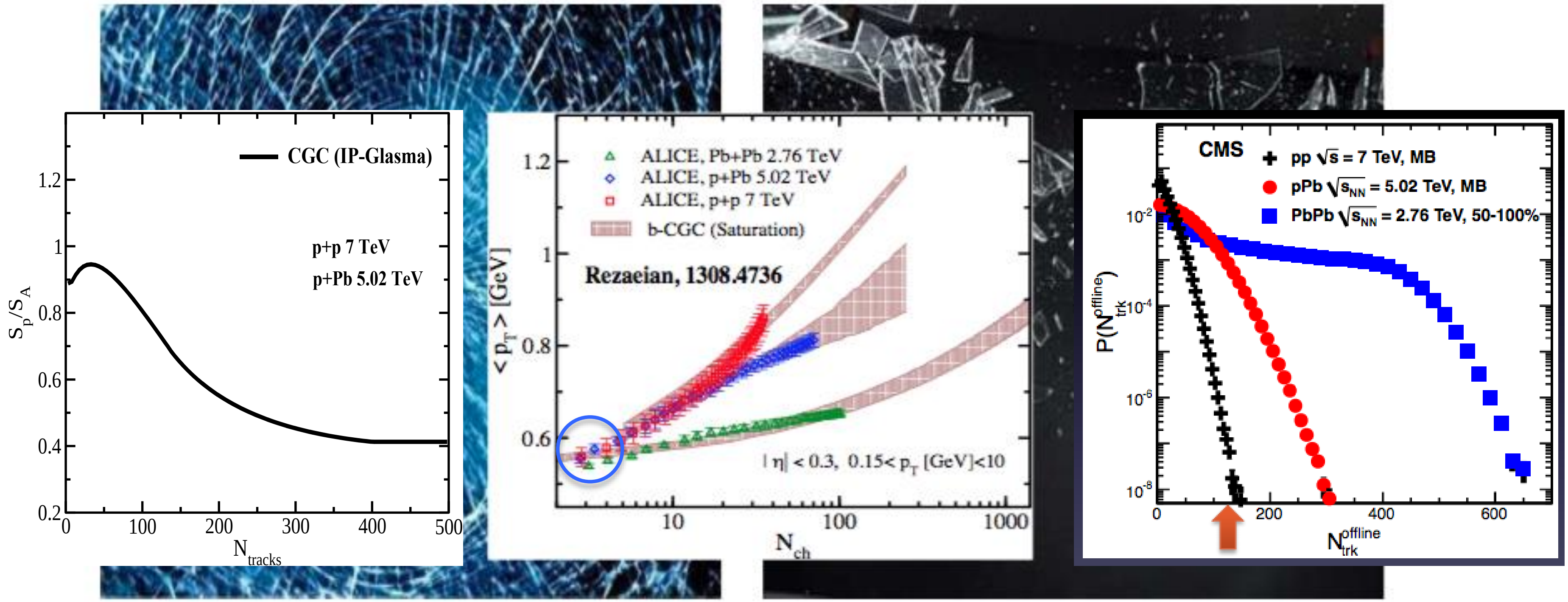
**Photon-jet Ridge: Rezaeian, PRD in press, arXiv:1603.07354.** → This talk

**Di-photon Ridge: Kovner, Rezaeian, PRD92, arXiv:1508.02412.**

## *Back-of-the-envelope measurements:* Initial-state v. final-state!

**Increase v. flatness of $\langle p_T \rangle (N_{ch})$**

$$\langle p_T \rangle (N_{ch}) : \ K_T - \text{Factorization}, \ \text{and} \ Q^2_{s,min} \rightarrow Q^2_{s,min} \times N_{ch}/\langle N_{ch} \rangle$$

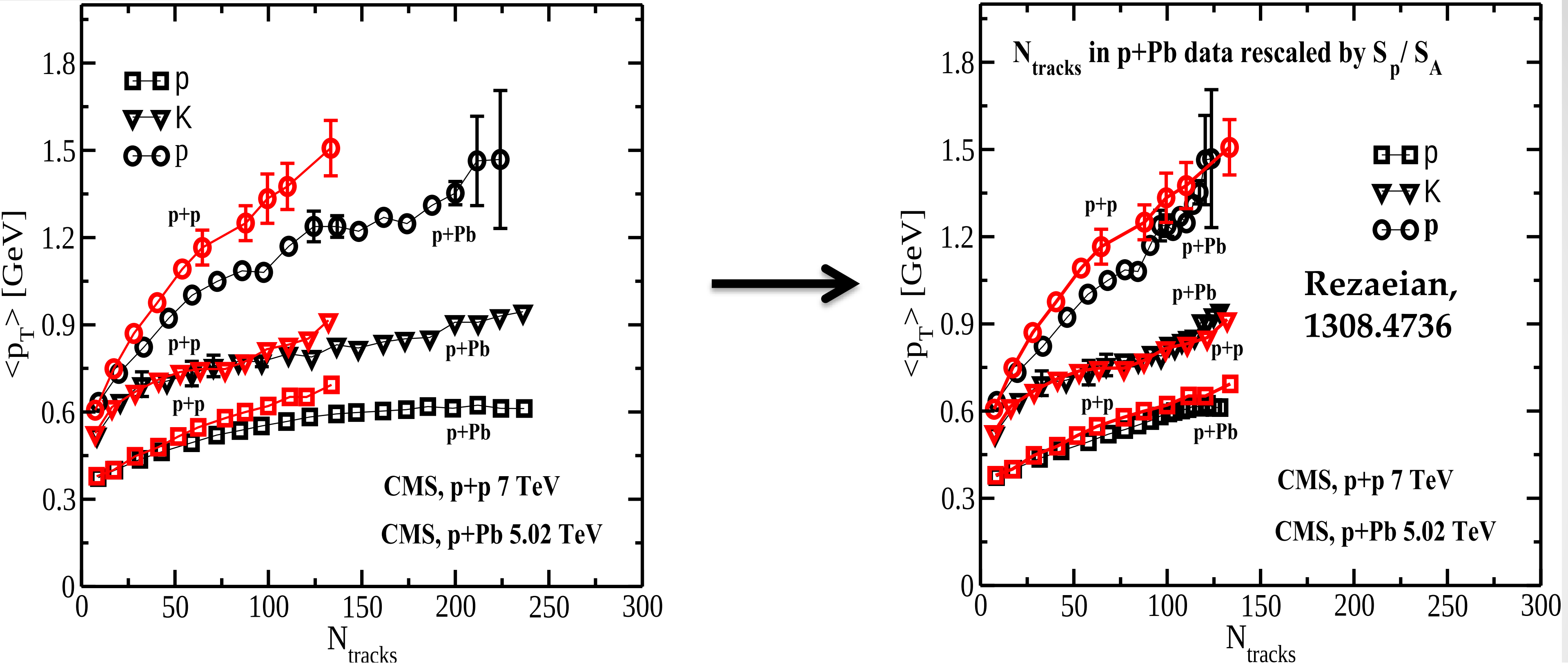



Different system sizes:

$$S_{eff}(N_{cri}) = Const. \longrightarrow \begin{array}{l} \langle N_{ch} \rangle^{Pb+Pb} > \langle N_{ch} \rangle^{p+Pb} > \langle N_{ch} \rangle^{p+p}, \\ N_{cri}^{Pb+Pb} > N_{cri}^{p+Pb} > N_{cri}^{p+p}, \end{array}$$

**Two competing effects: saturation scale and effective interactions area.**
**A event with the same multiplicity in pp, pA and AA does not necessarily correspond to the same system.**

# Geometric scaling in p+Pb@LHC

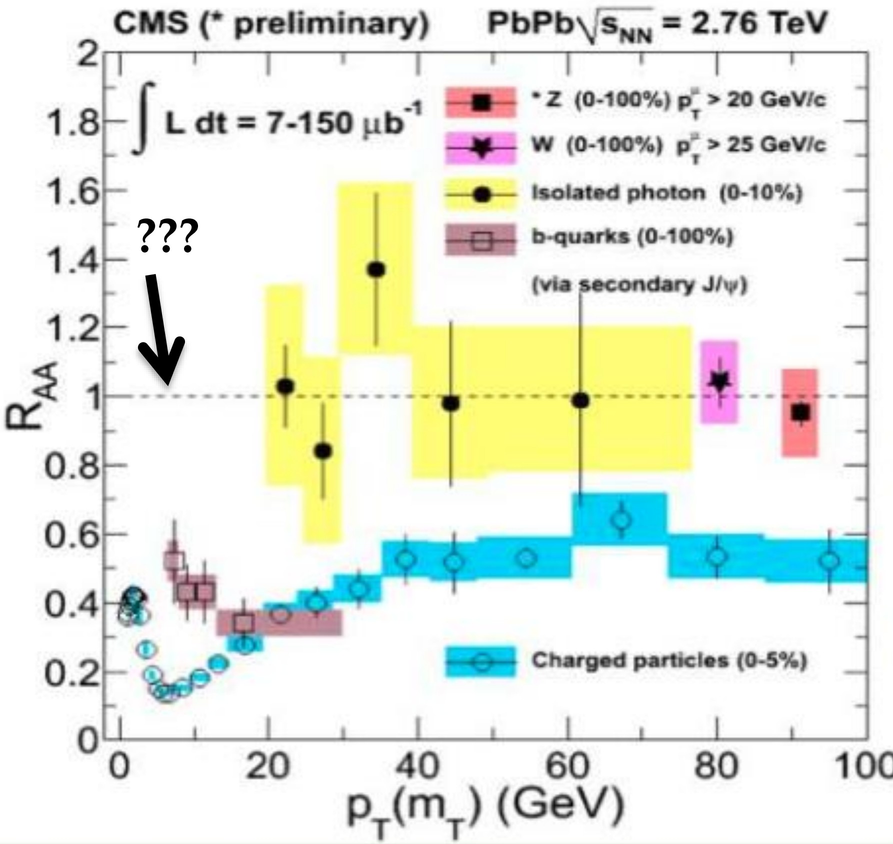


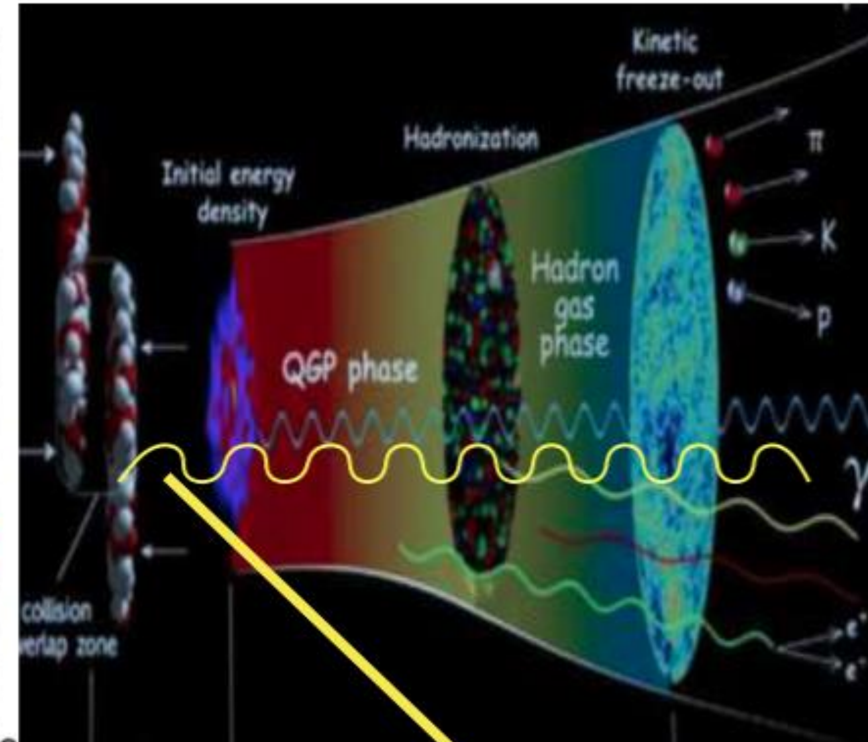

$$N^{p+p}_{tracks} \propto S_p Q^2_{s,min}(x) \quad \text{and} \quad N^{p+Pb}_{tracks} \propto S_A Q^2_{s,min}(x) \longrightarrow N^{p+p}_{tracks} \approx K \frac{S_p}{S_A} N^{p+Pb}_{tracks}$$

**McLerrran, Praszalowich, Schenke, arXiv:1306.2350; A. R., arXiv:1308.4736.**

- Can final-state type approaches like hydrodynamic explain this scaling phenomenon?

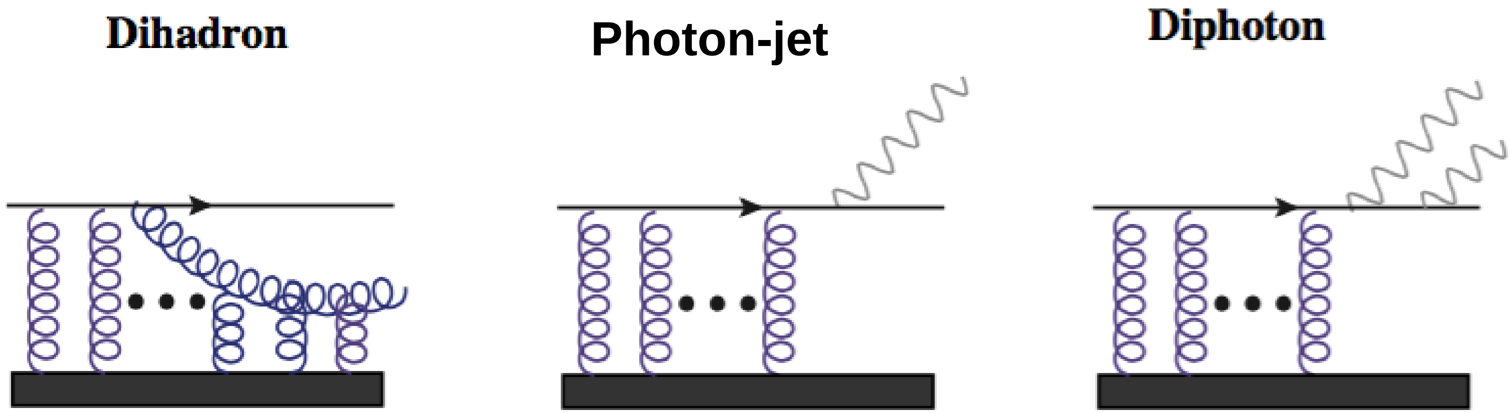
# Prompt Photon @A+A



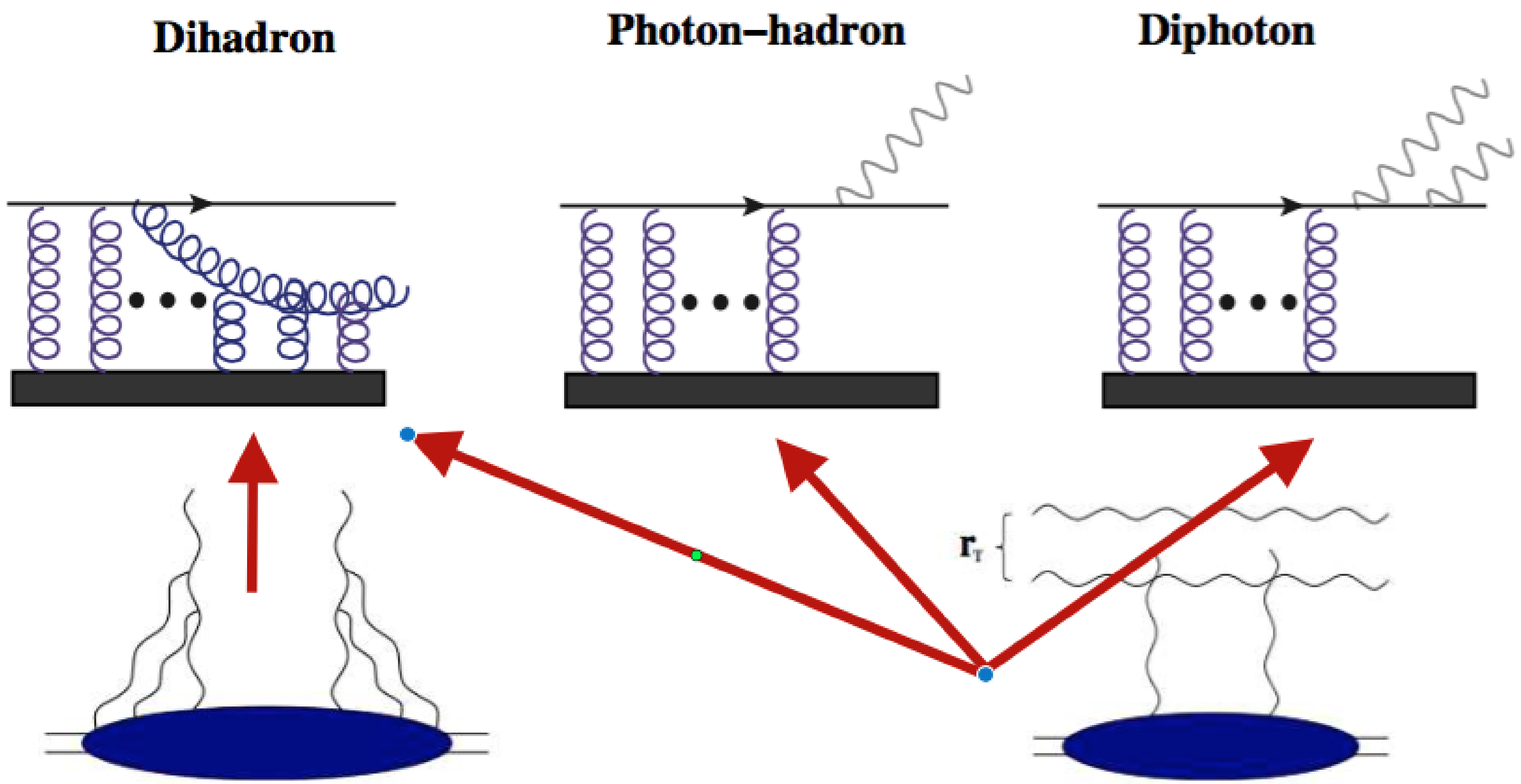

- Photons can be produced at different stages of collisions (prompt, thermal, decay). Here I only discuss prompt photon coming from hard collisions in small-x region.
- In AA collisions all hadrons are strongly quenched except prompt photon → **prompt photon can be a good probe of initial-state effects.**

# Two-particle production




- 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.**

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



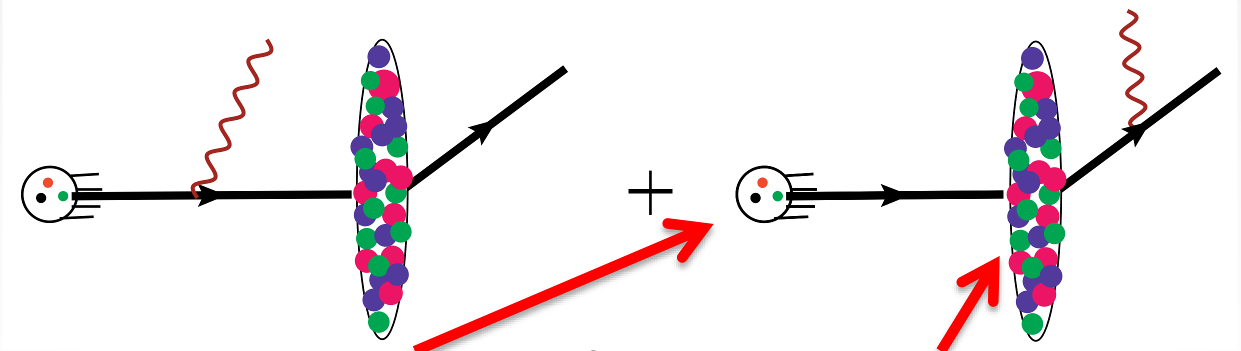

**Weizsacker–Williams (WW) gluon distribution (quadropole) counts the number of gluons (never measured)**

**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).

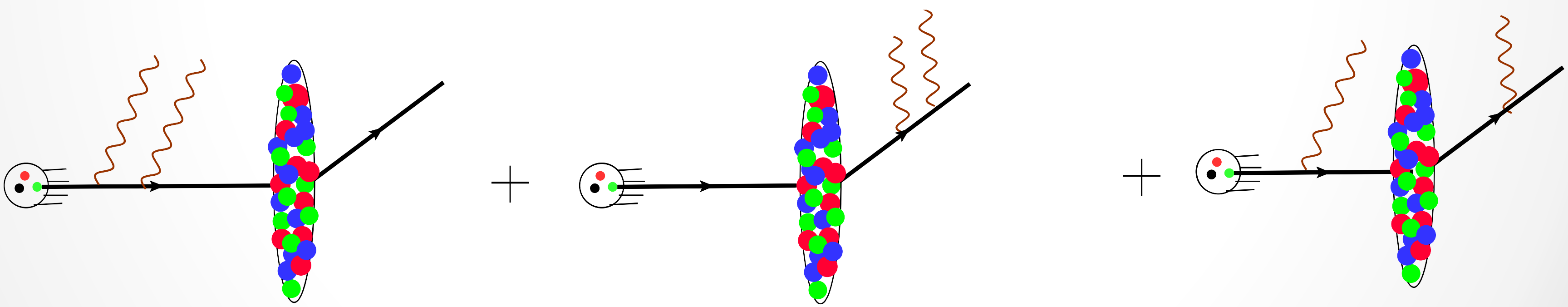
## Prompt Photon+Jet production in p+A collisions at LO:



$$\sigma = \alpha_{em} F(x_q, \mu^2) \otimes \mathcal{H}^{\gamma} \otimes N_F(x_g, p_T)$$

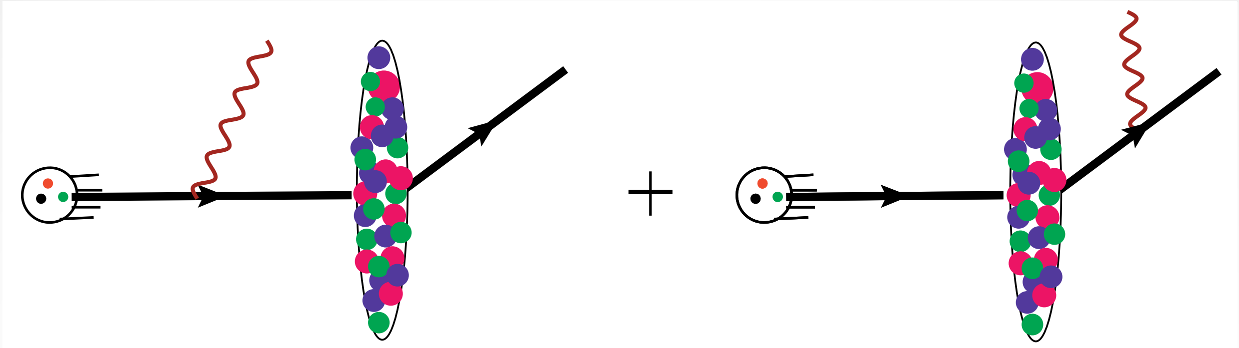
**Gelis, Jalilian-Marian, hep-ph/0205037; Baier, Mueller, Schiff, hep-ph/0403201; Kovner, Rezaeian, arXiv:1404.5632.**

## Prompt Diphoton+Jet production in p+A collisions at LO:



$$\sigma = \alpha_{em}^2 F(x_q, \mu^2) \otimes \mathcal{H}^{\gamma\gamma} \otimes N_F(x_g, p_T)$$

**Kovner, Rezaeian, arXiv:1404.5632; arXiv:1508.02412.**



## Prompt Photon+Jet production in p+A collisions at LO from the CGC:

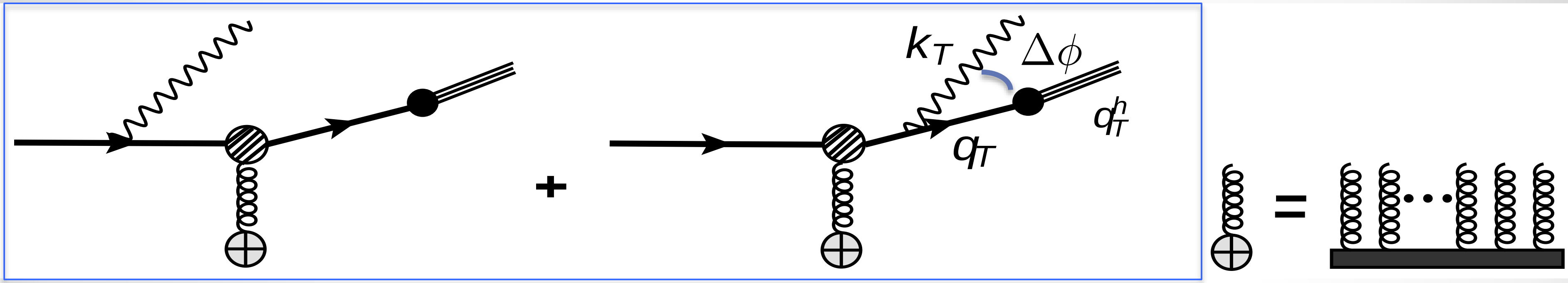
*Theory*:

- Gelis, Jalilian-Marian, *PRD66*, hep-ph/0205037.
- Baier, Mueller, Schiff, *NPA741*, hep-ph/0403201.
- Kovner, Rezaeian, *PRD92*, arXiv:1404.5632.

*Phenomenology*:

- Jalilian-Marian, Rezaeian, *PRD86*, arXiv:1204.1319. ← Away-side Corr.
- Staśto, Xiao, Zaslavsky, *PRD86*, arXiv:1204.4861. ← DY
- Rezaeian, *PRD86*, arXiv:1209.0478; *PLB718*, arXiv:1210.2385. ← R_pA
- Rezaeian, *PRD in press*, arXiv:1603.07354 ← Ridge

# Origin of Photon-Jet Ridge




$$\frac{d\sigma^{p+A\to\gamma(k)+\mathrm{jet}(q)+X}}{d^2\mathbf{b}_T\, d^2\mathbf{k}_T\, d\eta^\gamma\, d^2\mathbf{q}_T\, d\eta^{jet}} \propto |\mathbf{q}_T+\mathbf{k}_T|^2 N_F(b_T, |\mathbf{q}_T+\mathbf{k}_T|, x_g).$$

## Condition 1:

If $p_T^{total} = |\mathbf{q}_T+\mathbf{k}_T| \approx 0 \longrightarrow \sigma^{p+A\to\gamma(k)+\mathrm{jet}(q)+X} \approx 0.$

Local Minimum

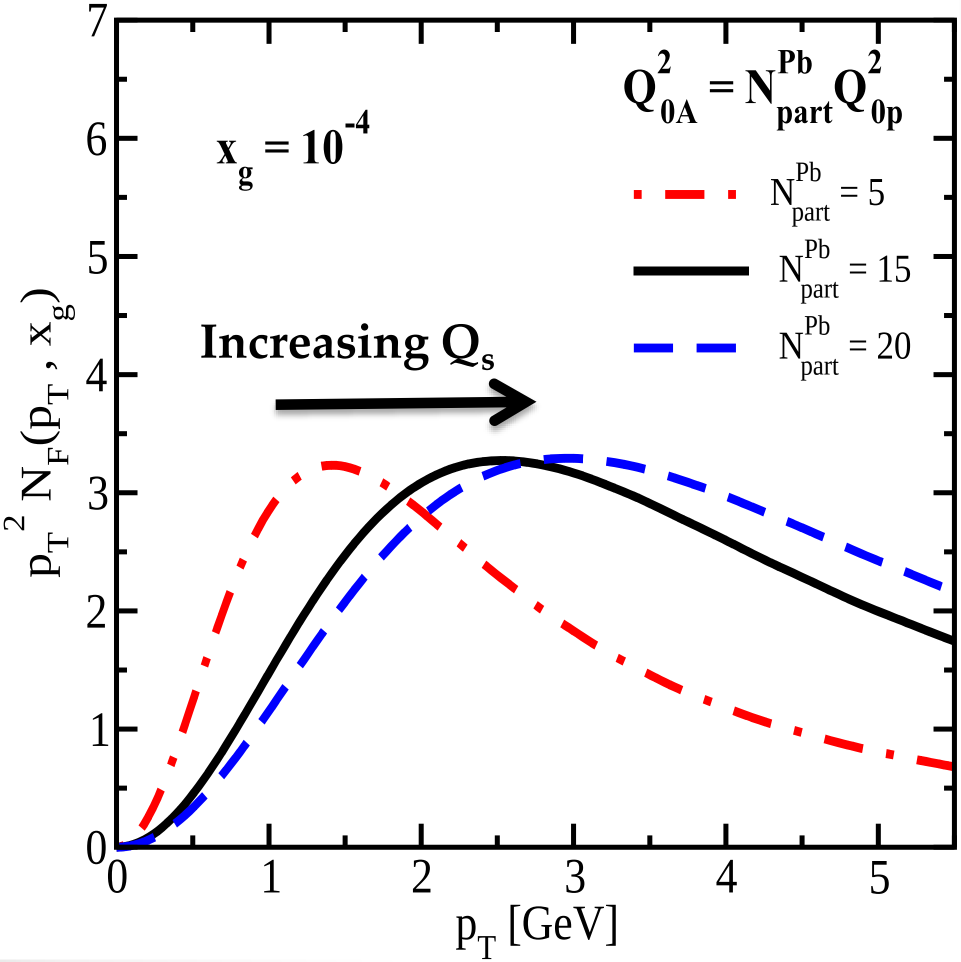
This condition can be satisfied for away-side correlations: $\Delta\phi = \pi$ for $q_T \sim k_T$

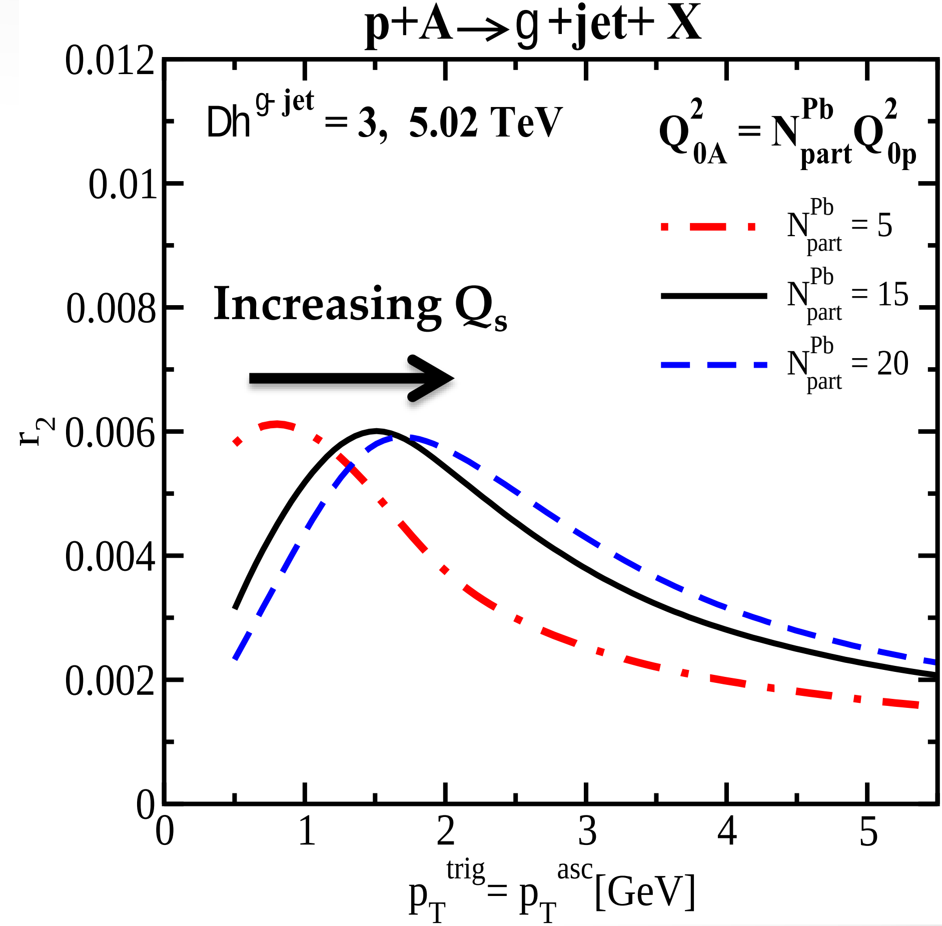
## Condition 2:

If $p_T^{\mathrm{total}} = |\mathbf{q}_T+\mathbf{k}_T| \approx Q_s$ then $\sigma^{p+A\to\gamma(k)+\mathrm{jet}(q)+X} \longrightarrow$ Maximum.

Local Maximum

This condition can be satisfied for near-side correlations: $\Delta\phi = 0$ for $q_T \sim k_T \sim Q_s/2$




$$r_2(p_T^{\text{trig}}, \eta^{\gamma}, p_T^{\text{asc}}, \eta^{jet}, \Delta\phi) = \left. \frac{2\pi q_T^2 \frac{dN^{p+A\to\gamma(k)+\text{jet}(q)+X}}{d^2\mathbf{k}_T\, d\eta^{\gamma}\, d^2\mathbf{q}_T\, d\eta^{jet}}}{\frac{dN^{p+A\to\gamma(k)+X}}{d^2\mathbf{k}_T d\eta^{\gamma}}} \right|_{k_T=p_T^{\text{trig}},\, q_T=p_T^{\text{asc}}} .$$

# Correlations via Coincidence probability

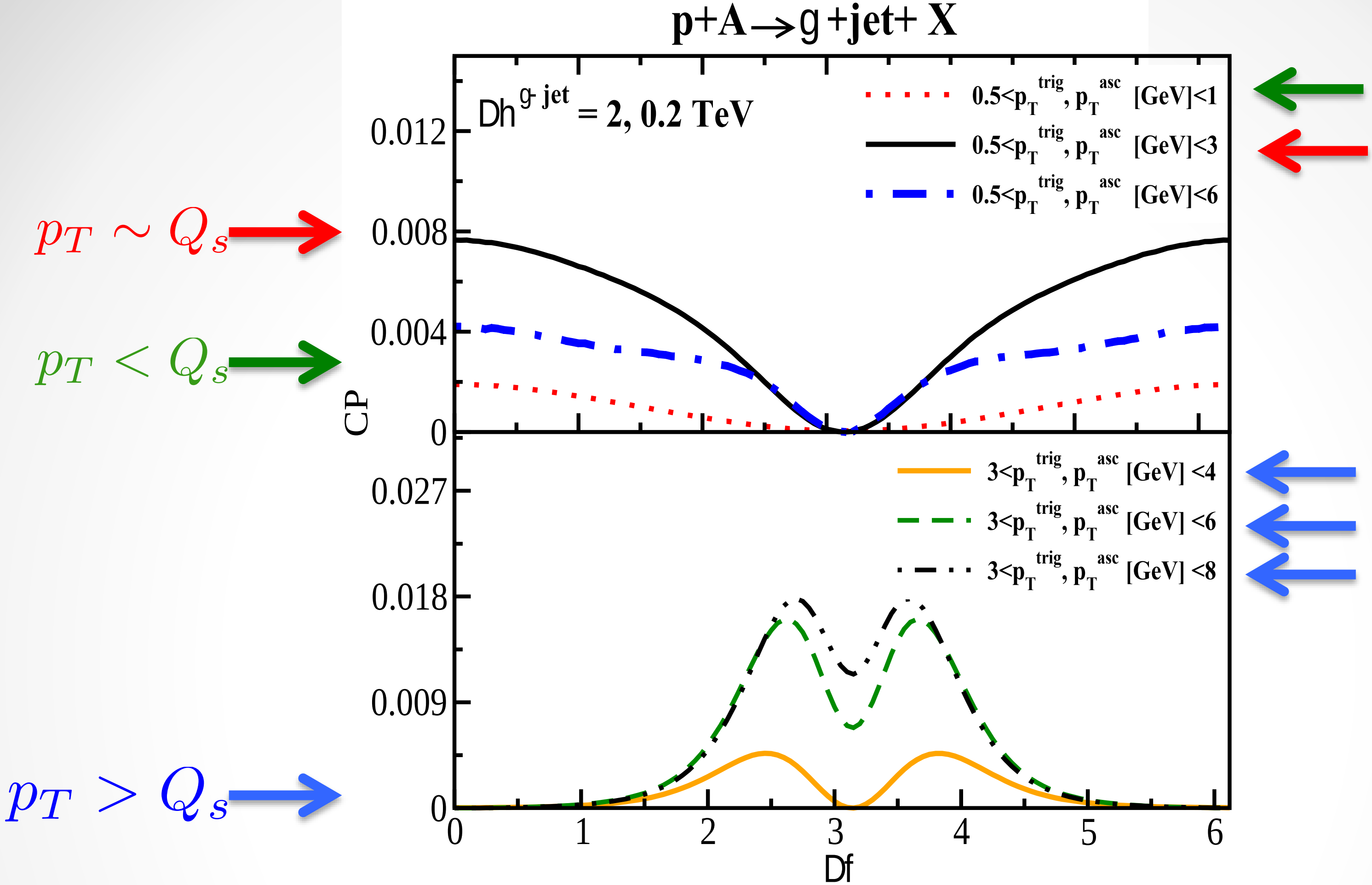
**Coincidence probability** **(Photon triggered):** → $CP(\Delta\phi) = N^{\text{photon-jet}}(\Delta\phi)/N^{\text{photon}}$

$$CP(p_T^{\text{trig(photon)}}, \eta^{\gamma}, p_T^{\text{asc(jet)}}, \eta^{jet}, \Delta\phi) = \frac{2\pi \int_{p_T^{\text{trig}}} dk_T k_T \int_{p_T^{\text{asc}}} dq_T q_T \frac{d\sigma^{p+A\to\gamma(k)+\text{jet}(q)+X}}{d^2\mathbf{b}_T\, d^2\mathbf{k}_T\, d\eta^{\gamma}\, d^2\mathbf{q}_T\, d\eta^{jet}}}{\int_{p_T^{\text{trig}}} d^2\mathbf{k}_T \frac{d\sigma^{p+A\to\gamma(k)+X}}{d^2\mathbf{b}_T d^2\mathbf{k}_T d\eta^{\gamma}}} - C_{\text{ZYAM}},$$

CP[γ (**trigger**) + Jet (**associated**)] > CP[ γ(**associated**) + Jet (**trigger**)]

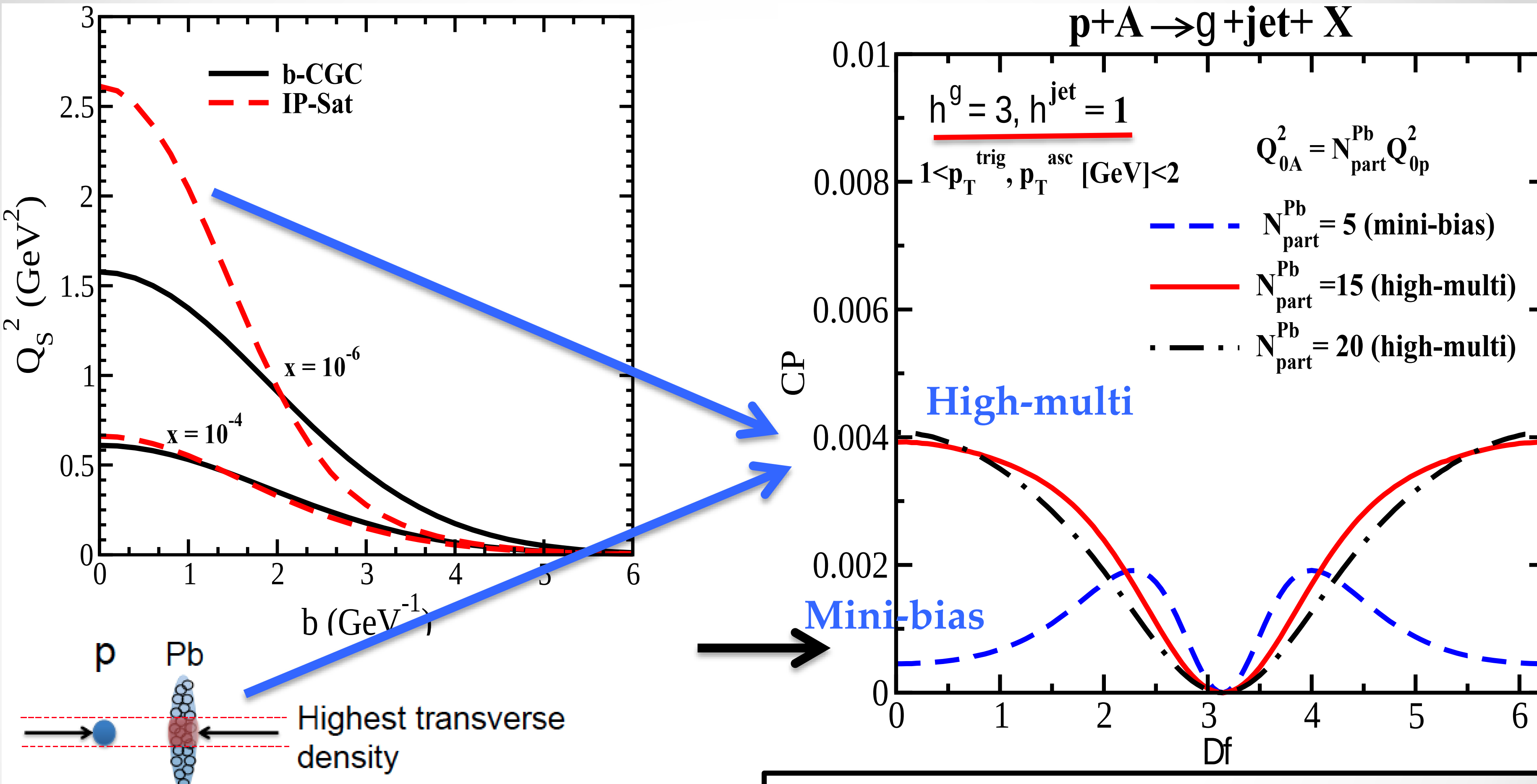
ZYAM subtraction: is not the same way as defined by ATLAS Coll. But this will not change the over-all physics here.

**See talk by Brian Cole**




**For $P_T^{Total} < Q_s$ or $P_T^{Total} > Q_s$ , away from the condition 2, the near-side correlations diminishes.**

# Density (multiplicity) dependence of the Ridge



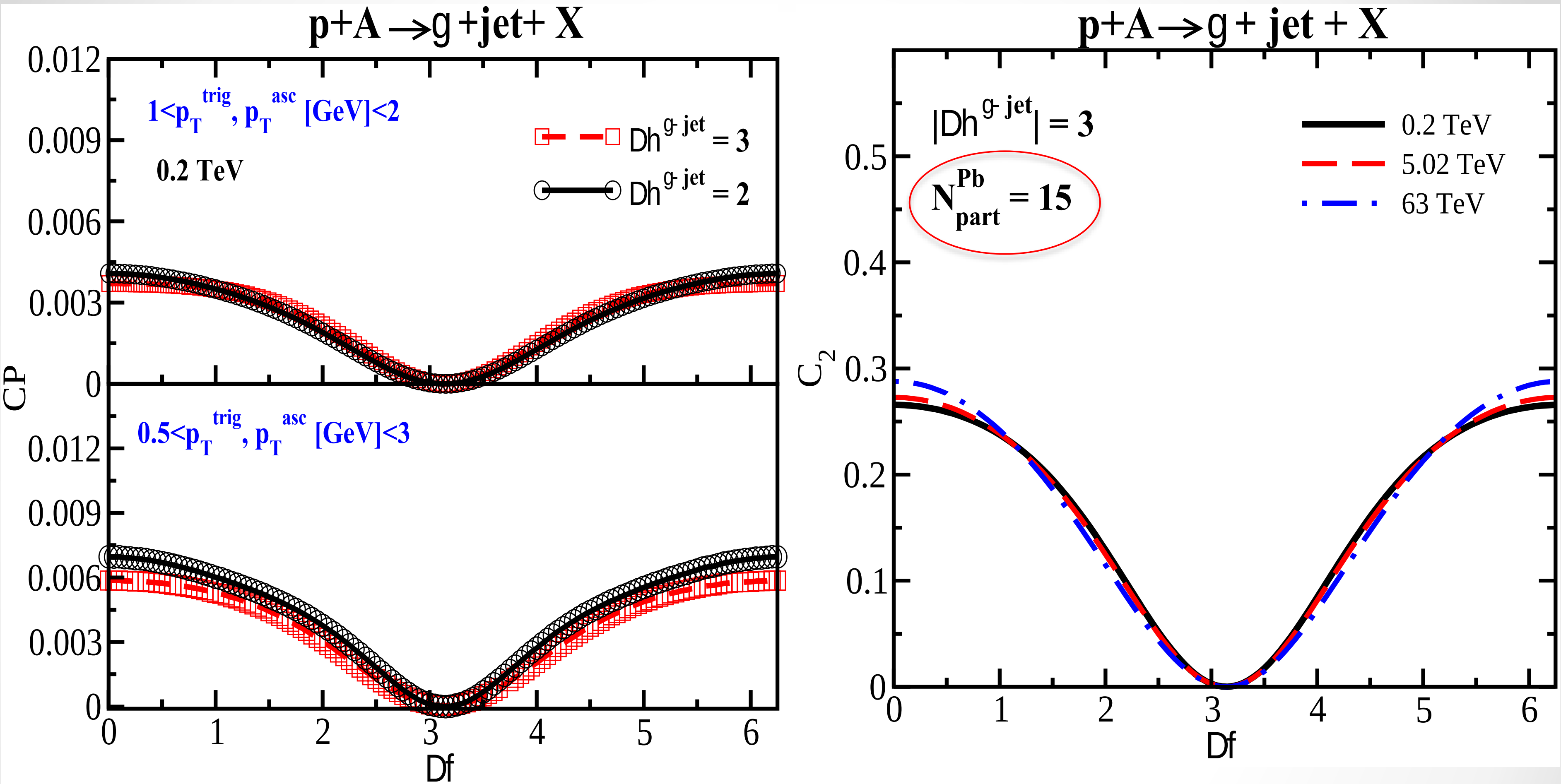

**At events with** $N^{pb}_{part}$**>10, near-side photon-jet correlations are maximum and does not change with multiplicity further.**
**At the same events, the di-hadron Ridge shows up (Dusling, Venugopalan, 2013).**

$$Q_0^2(\text{lead}) = N_{part}^{Pb}\ Q_0^2(\text{proton})$$

**# of "wounded" nucleons in lead nucleus**

$$N_{part}^{Pb} \approx 5 : \text{ minimum bias collisions}$$

# Rapidity and energy dependence of the Ridge



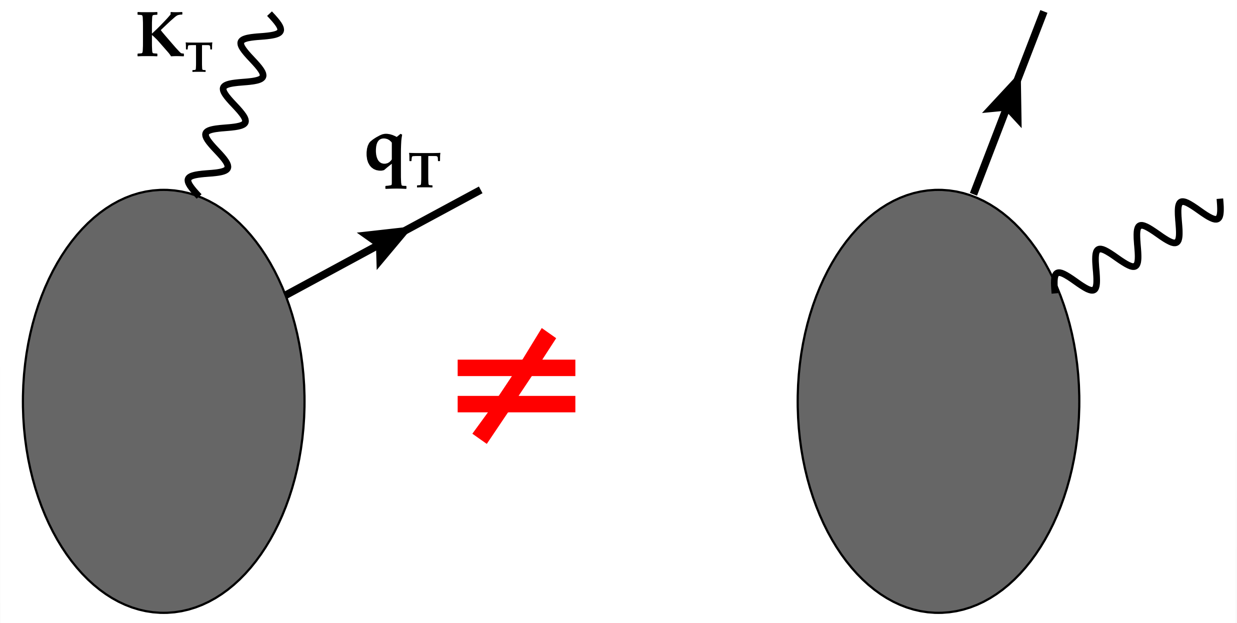

- ❑ The near-side and away-side photon-jet correlations practically do not change within $\Delta\eta^{\gamma-\text{jet}} \approx 2\text{–}4$ in high-multiplicity events.

- ❑ Although, $x_g$ changes from $10^{-3}$ to $10^{-6}$ , there is little energy dependence for the photon-jet ridge at high multiplicity events.

# Photon-jet v. two-hadron correlations

- **The cross-section of photon-jet production and the correlations are NOT symmetric with respect to the replacement of:**

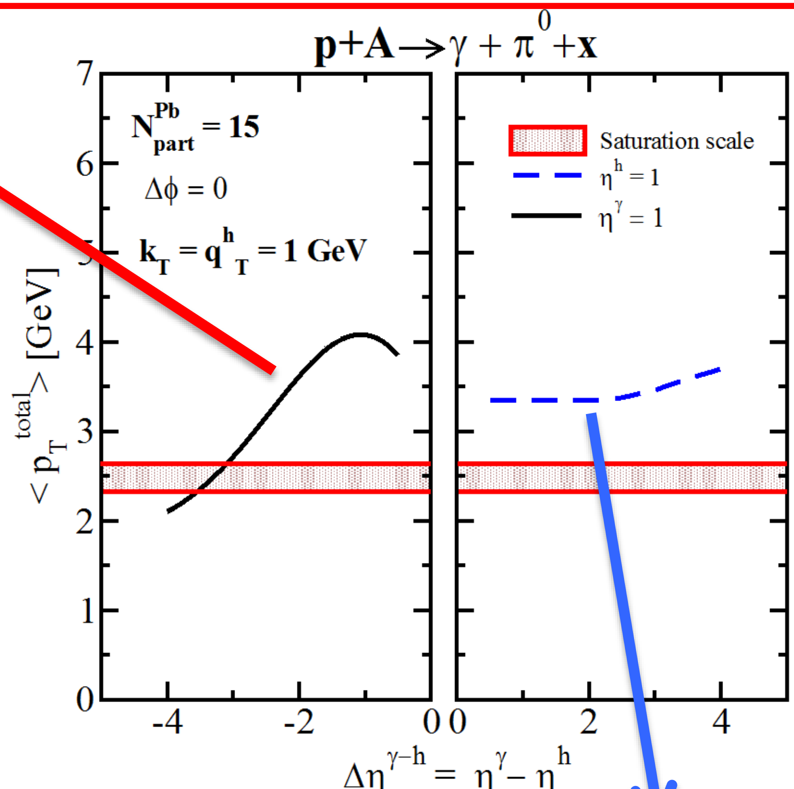
$$\eta^{\gamma} \longleftrightarrow \eta^{jet}, q_T \longleftrightarrow k_T$$



# Photon-hadron correlations

For $\eta^\gamma - \eta^h << 0 : \langle p_T^{total} = |k_T + q_T^h / z_h|\rangle \rightarrow Min,$ because $\langle z_h \rangle \rightarrow Max$

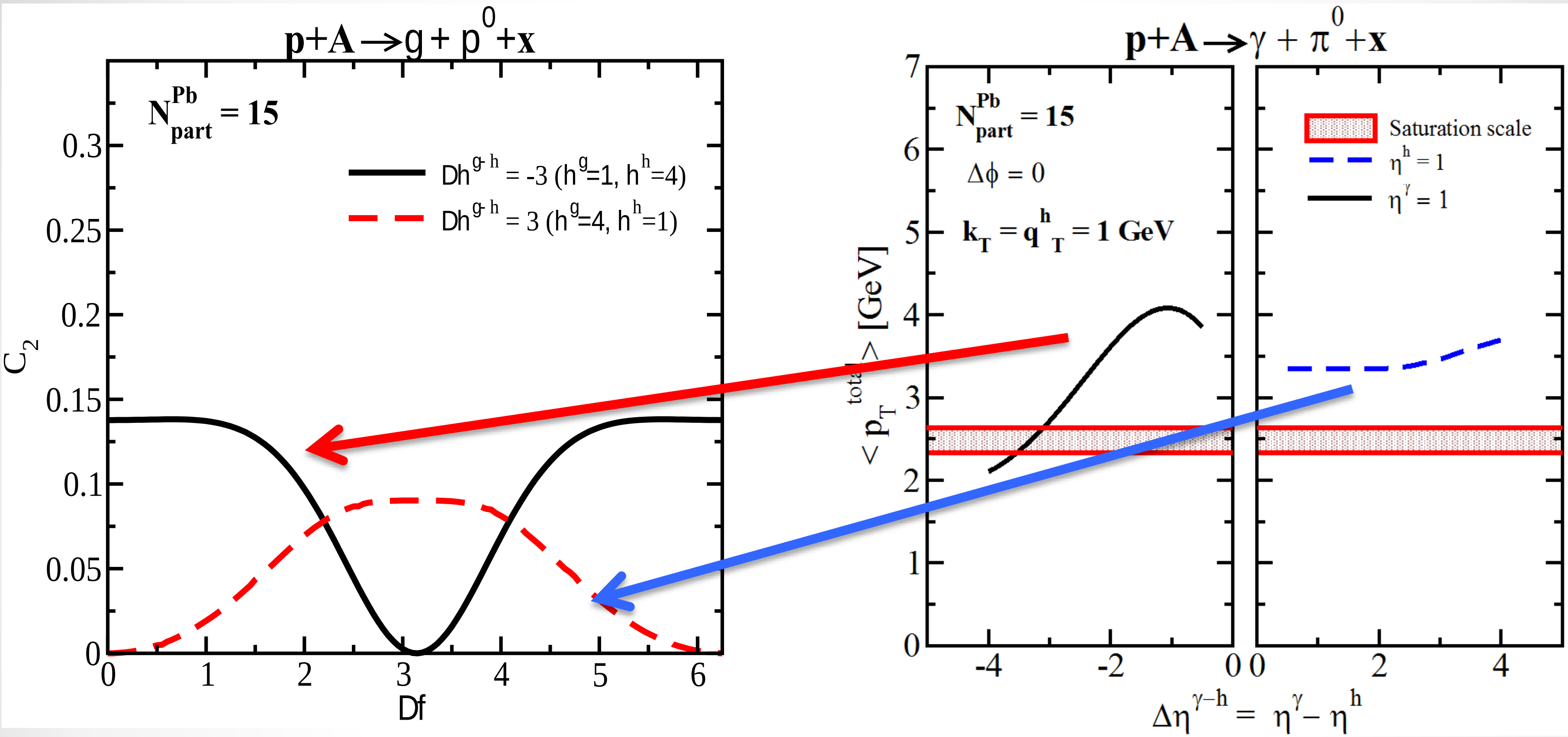
Ridge




No Ridge

For $\eta^\gamma - \eta^h >> 0 : \langle p_T^{total} = |k_T + q_T^h / z_h|\rangle \rightarrow const,$ because $\langle z_h \rangle \rightarrow const$

# Photon-hadron near-side correlations




**For** **photon-hadron** **production a ridge-like structure only exist for :**

$$\eta^h > \eta^\gamma$$

# Conclusion

- A ridge-type structure exists for pairs of prompt photon and jet production in high-multiplicity p+A collisions at both RHIC and the LHC.

The photon-jet collimation at near-side strongly depends on saturation dynamics and is **maximum** at:

- $P_T^{total} \sim Q_s \;\rightarrow\; p_T^{jet,\gamma} \approx 1 - 3 \text{ GeV}$
- $N_{part}^{Pb} > 5$
- $\eta^{\gamma - jet} \approx 2 - 5$

**These ridge-like features are strikingly similar to the observed ridge effect for di-hadron correlations at RHIC and the LHC.**

**In the Glasma approach of Dusling-Venugopalan: both projectile and target are in the saturation regime. Here only target is in the saturation regime!.**

- **Hadronization of jet has non-trivial effects on the photon-jet correlations.**
- **Photon-hadron correlations: the near-side collimation exists for $\eta^{\gamma} < \eta^{h}$.**