Some CGC predictions in pA collisions and signature of saturation

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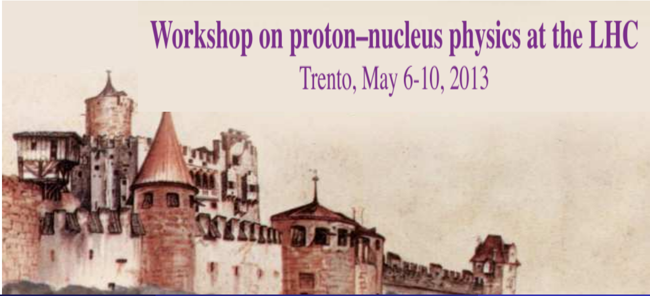
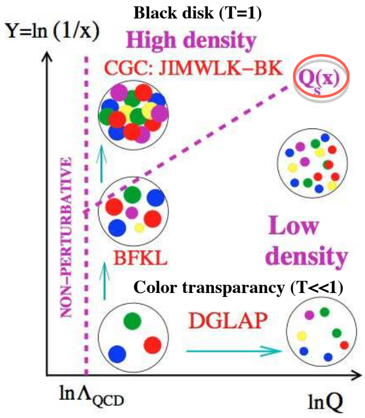
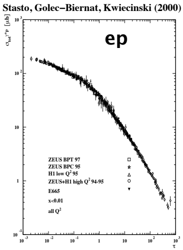
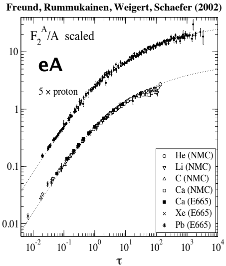


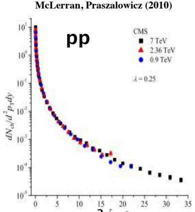
Gribov, Levin, Ryskin (83); Mueller, Qiu (86); **McLerran, Venugopalan (94)**

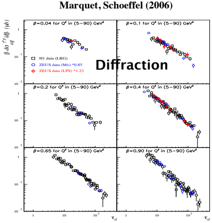
30 Years ago **20 Years ago**











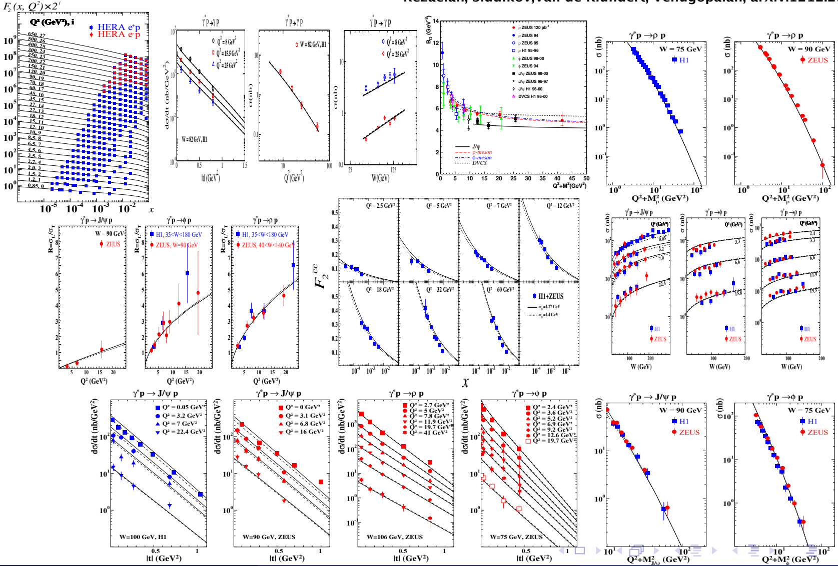
Q^2/Q_s^2

- The geometric scaling observed in different reactions can be naturally(and only) explained in the CGC approach→ universality at small-x.

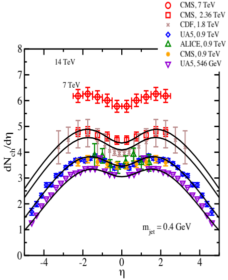
e+p ($x < 0.01$)

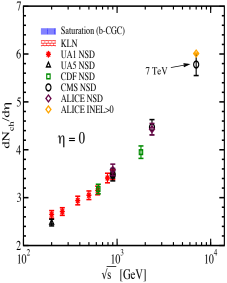
A unified description of x, Q^2, W and t dependence of inclusive & exclusive data

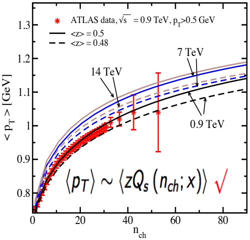
Rezaeian, Siddikov,Van de Klundert, Venugopalan, arXiv:1212.2974

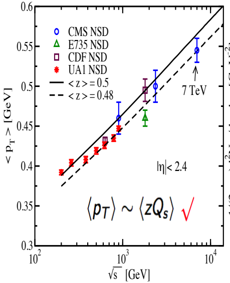


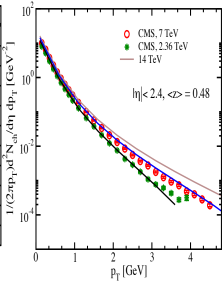
Comparing CGC predictions with 7 TeV data: Levin, Rezaeian, PRD82, arXiv:1005.0631

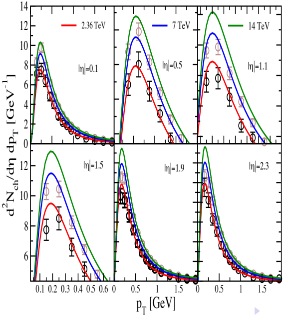






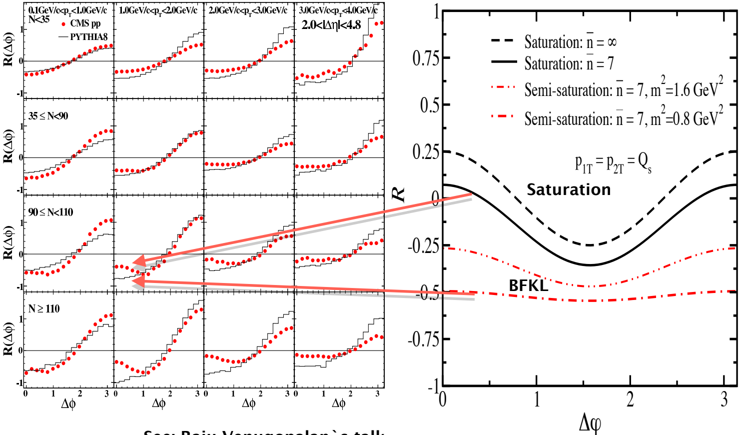






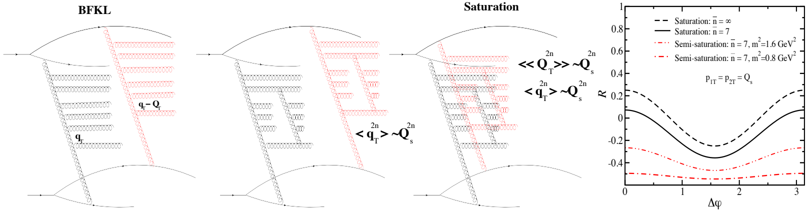
CMS Collaboration, JHEP 1009, arXiv:1009.4122

Levin, Rezaeian, PRD84, arXiv:1105.3275



See: Raju Venugopalan`s talk

- A pronounced ridge-like structure emerges by going from the BFKL to the saturation region, although BFKL can also generate azimuthal correlations.
- See also:Kovner and Lublinsky (2010); Dusling and Venugopalan(2013)



Rezaeian, Levin, arXiv:1105.3275

Deep in saturation $\longrightarrow v_2^{saturation}$

$$\mathcal{R}\left(\Delta\varphi; y_1, y_2\right) = \frac{\frac{dN}{dy_1 d^2\vec{p}_{1,T}\, dy_2 d^2\vec{p}_{2,T}}}{\frac{d^2N}{dy_1 d^2\vec{p}_{1,T}}\;\frac{d^2N}{dy_2 d^2\vec{p}_{2,T}}} - 1 = \frac{\overline{n}(\overline{n}-1)}{2\,\overline{n}^2}\left\{1 + \frac{1}{2}\left(2 + \cos\left(2\Delta\varphi\right)\right)\right\} - 1,$$

with $\overline{n} \approx E\left(N/\langle N\rangle\right)$, and $p_{1T} = p_{2T} = Q_T = Q_s$

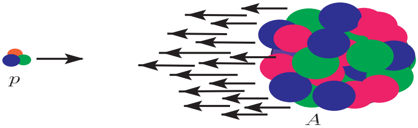
Semi-saturation (saturation within pomeron showers) $\longrightarrow v_2^{semi-saturation}$

$$\mathcal{R}\left(\Delta\varphi; y_1, y_2\right) = \frac{\overline{n}(\overline{n}-1)}{2\,\overline{n}^2}\left\{1 + \frac{m^4}{30\,Q_s^4}\left(2 + \cos\left(2\Delta\varphi\right)\right)\right\} - 1.$$

with $p_{1T} = p_{2T} = Q_s$

$$v_2^{saturation} \approx 0.2 > v_2^{semi-saturation} \approx 0.01$$

⟵ **Initial−State effect**

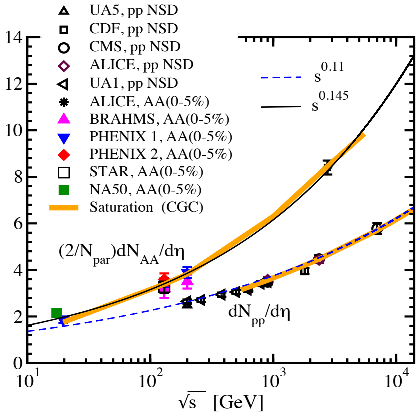


Color–Glass–Condensate in pPb

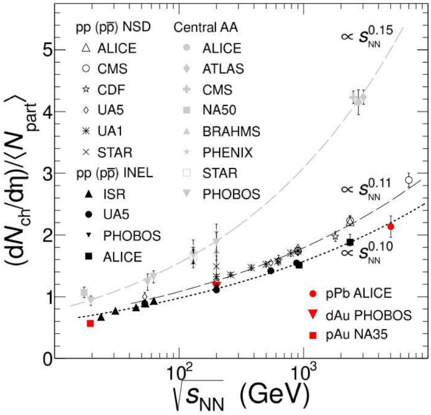
Collective flow in pPb collisions

Which one we have seen at the LHC??

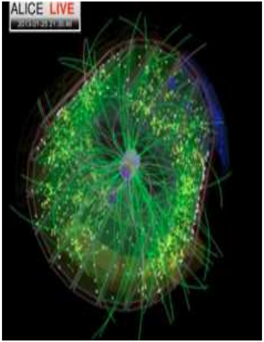
Levin, Rezaeian, arXiv:1102.2385

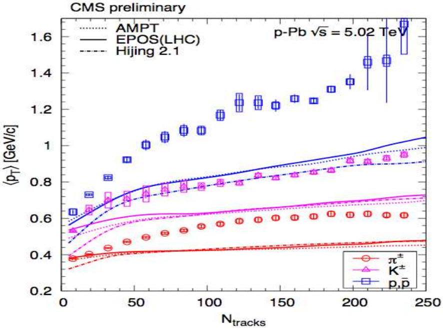


ALICE collaboration, arXiv:1210.3615

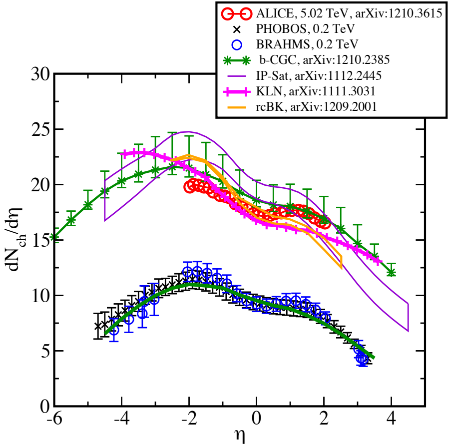


$$\frac{dN_h}{d\eta} \propto Q_s^2 \propto s^{\lambda/2} = s^{0.10\div0.145}$$



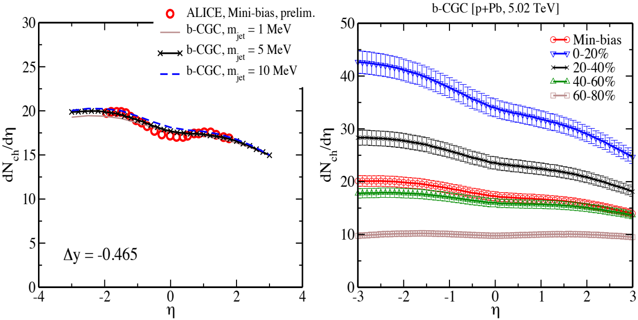


- **Most of the produced particles have $p_T < 2$ GeV**
- x: fraction of target momentum carried by parton
  Mind that:exact definition of x is different for different processes.
- $x \approx p_T/\sqrt{s} \approx 10^{-2}$ at RHIC ($\sqrt{s} = 200$ GeV, $\eta = 0$)
- $x \approx p_T/\sqrt{s} \approx 10^{-4}$ at the LHC ($\sqrt{s} = 5$ TeV, $\eta = 0$)



- All models employed K_T-factorization but with different saturation models.
- Two free parameters mini-jet mass m_{jet} and overall normalization (are related to hadronization) cannot be uniquely fixed by only RHIC data $\Longrightarrow 5 \div 15\%$ uncertaintes.

Rezaeian, PLB718 [arXiv:1210.2385]

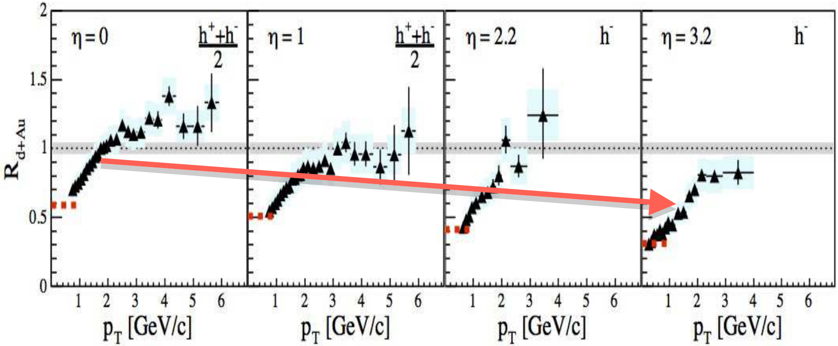


- In b-CGC saturation model: $m_{jet} = m_{\text{current quark}}$ gives a good description of both RHIC and ALICE data.
- Centrality dependence of multiplicity a very non-trivial test of saturation dynamics: **up to a factor of 2 different from mini-bias; from very asymmetric to symmetric distribution.**
- In above predictions a fixed mini-jet mass was used at all centralities (may bring some uncertainties in calculation).

Signatures of the CGC in d+A@RHIC: Initial-state effect

$$R_{pA}(\eta, p_\perp) \equiv \frac{1}{N_{coll}} \frac{\left.\frac{dN_h}{d^2p_\perp d\eta}\right|_{pA}}{\left.\frac{dN_h}{d^2p_\perp d\eta}\right|_{pp}} \simeq \frac{1}{A^{1/3}} \frac{\Phi_A(Y, p_\perp)}{\Phi_p(Y, p_\perp)} \, .$$

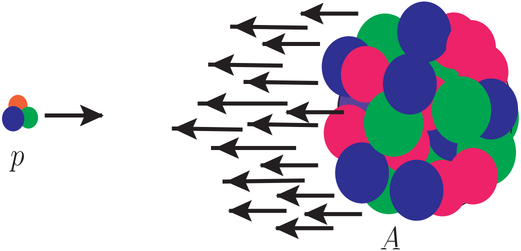
- Suppression of single inclusive hadron production at forward rapidities



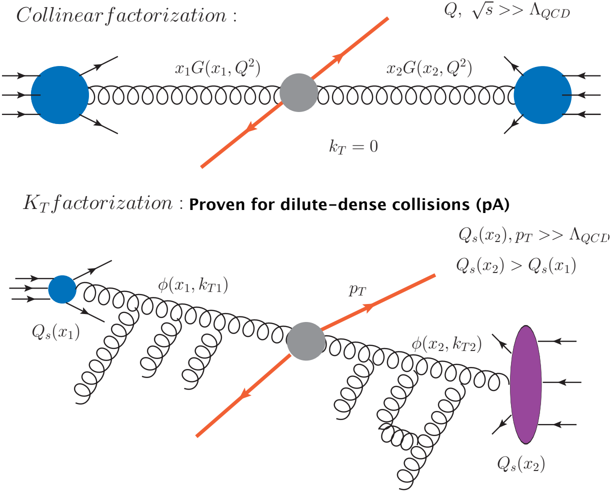
p+A@LHC Sep 2012 & Feb 2013

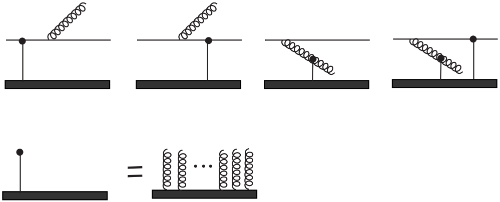
$y^{RHIC}_{forward} \Leftrightarrow y^{LHC}_{mid-rapidity}$

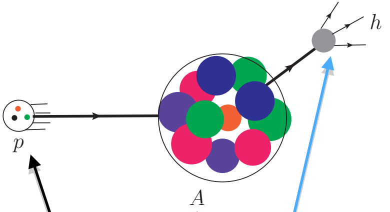
Suppression or not?



- At a fixed rapidity, Kinematic-limit for particle production at RHIC and the LHC are different.


$Collinear factorization :$
$Q, \sqrt{s} >> \Lambda_{QCD}$
$x_1G(x_1, Q^2)$
$x_2G(x_2, Q^2)$
$k_T = 0$
$K_T factorization$: **Proven for dilute-dense collisions (pA)**
$Q_s(x_2), p_T >> \Lambda_{QCD}$
$Q_s(x_2) > Q_s(x_1)$
$\phi(x_1, k_{T1})$
p_T
$Q_s(x_1)$
$\phi(x_2, k_{T2})$
$Q_s(x_2)$





Dumitru, Hayashigaki, Jalilian-Marian,hep-ph/0506308; Altinoluk, Kovner, arXiv:1102.5327; Chirilli, Xiao, Yuan,arXiv:1112.1061

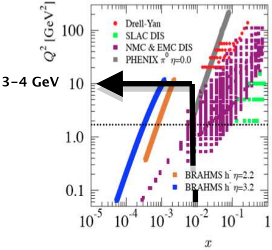
$$\frac{dN^{pA\to hX}}{d^2p_T d\eta} = \frac{K}{(2\pi)^2}\left[\int_{x_F}^{1}\frac{dz}{z^2}\left[x_1 f_g(x_1,Q^2)N_A(x_2,\frac{p_T}{z})D_{h/g}(z,Q) + \Sigma_q x_1 f_q(x_1,Q^2)N_F(x_2,\frac{p_T}{z})D_{h/q}(z,Q)\right]\right.$$
$$\left. + \int_{x_F}^{1}\frac{dz}{z^2}\frac{\alpha_s^{in}}{2\pi^2}\frac{z^4}{p_T^4}\int_{k_T^2<Q^2} d^2k_T k_T^2 N_F(k_T,x_2)\int_{x_1}^{1}\frac{d\xi}{\xi}\Sigma_{i,j=q,\bar{q},g} w_{i/j}(\xi)P_{i/j}(\xi)x_1 f_j(\frac{x_1}{\xi},Q)D_{h/i}(z,Q)\right]$$

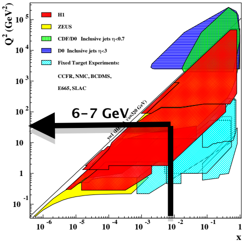
$$\frac{\partial\mathcal{N}_{A(F)}(r,x)}{\partial\ln(x_0/x)} = \int d^2\vec{r}_1\ K^{\rm run}(\vec{r},\vec{r}_1,\vec{r}_2)\left[\mathcal{N}_{A(F)}(r_1,x)+\mathcal{N}_{A(F)}(r_2,x)-\mathcal{N}_{A(F)}(r,x)-\mathcal{N}_{A(F)}(r_1,x)\,\mathcal{N}_{A(F)}(r_2,x)\right]$$

Balitsky–Kovchegov Eq.

Initial condition: $\mathcal{N}(r,Y=0) = 1-\exp\left[-\frac{\left(r^2\,Q_{0s}^2\right)^{\gamma}}{4}\ln\left(\frac{1}{\Lambda\,r}+e\right)\right]$

Albacete et. al, arXiv:1012.4408



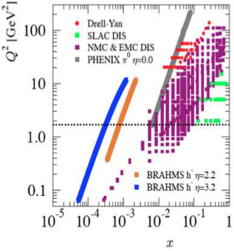


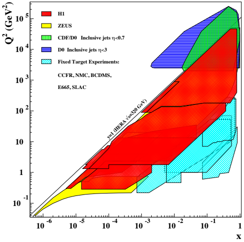
- Available data (HERA+RHIC+LHC) cannot **uniquely** determine the initial condition (initial saturation scale) of the BK equation.

  For proton: $p_t \leq 6$ GeV, $x \leq 0.01$: $Q^2_{0p} \approx 0.168\,\text{GeV}^2$ with $\gamma \approx 1.119$

- For heavy nuclei: $Q^2_{0A} = \mathbf{c} A^{1/3}\ Q^2_{0p}$,

  $p_t \leq 4$ GeV, $x \leq 0.01$: $\mathbf{c} \approx 0.5 \Longrightarrow Q^2_{0A} \approx (3 \div 4) Q^2_{0p}$





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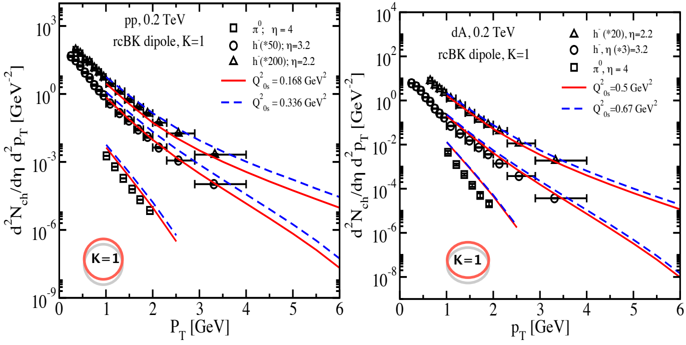
$p_t \leq 4$ GeV, $x \leq 0.01$: $\mathbf{c} \approx 0.5 \Longrightarrow Q^2_{0A} \approx (3 \div 4) Q^2_{0p}$

$$R^{ch}_{pA}(p_T >> 1) = \frac{Q^2_{0A} S_A}{Q^2_{0p} A S_p} \approx \frac{Q^2_{0A}}{Q^2_{0p} A^{1/3}} \to 1 \Longrightarrow Q^2_{0A} = \mathbf{c}A^{1/3}\; Q^2_{0p} \text{ with } \mathbf{c} \approx 1$$

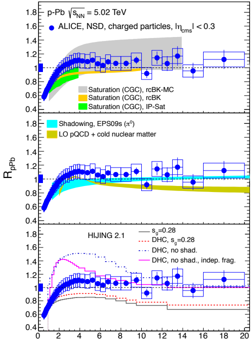
$\mathbf{c} \approx 0.5 \div 1 \Longrightarrow Q^2_{0A} = N Q^2_{0p}$ with $N = 3 \div 7$.

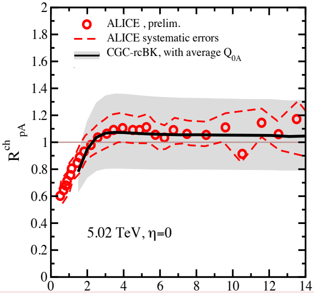
Jalilian-Marian, Rezaeian, arXiv:1110.2810



- What is the role of cold matter energy loss which is not included in the above (nuclear effect in deuteron was also ignored)?.

CGC predictions for R^h_{pA} in p+Pb@LHC and ALICE data

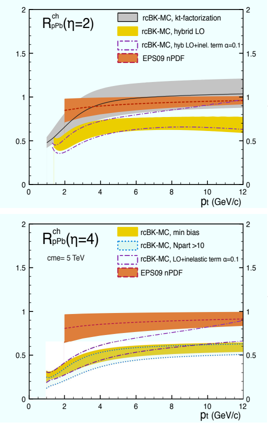




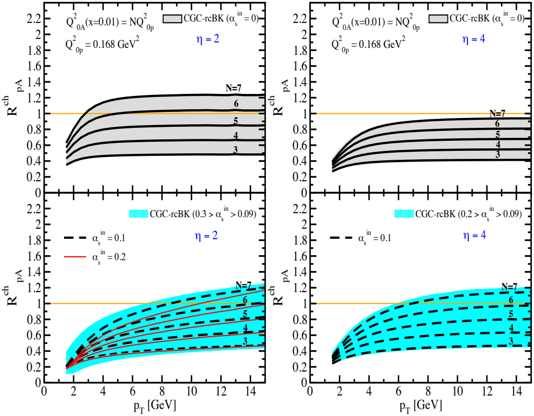
- 3 independent CGC results: Tribedy-Venugopalan(2011);Albacete-Dumitru-Fujii-Nara(2012); Rezaeian(2012) .
- The black curve corresponds to $Q^2_{0A} = NQ^2_{0p}$ with the average $N = 5$: Rezaeian,arXiv:1210.2385.
- Data seem to rule out any (or strong) Cronin-type peak!.
- If R^h_{pA} remains above one at high-p_T $\rightarrow$ possible tension with Npdf.

CGC predictions for R^{h}_{pA} at 5 TeV: With two different modeling of Q_{0A}

Albacete, Dumitru, Fujii, Nara, arXiv:1209.2001

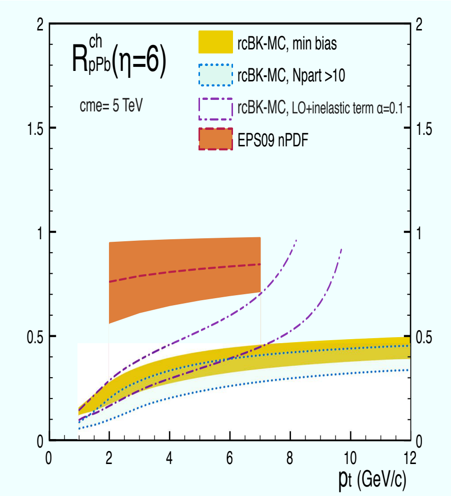


Rezaeian, arXiv:1210.2385

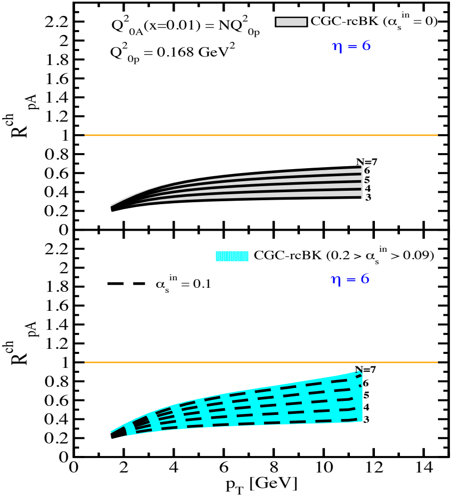


- Both approaches give a good description of all existing small-x data on nuclear target.
- In right panel: $Q^2_{0A} = NQ^2_{0p}$ (for mini-bias), one can readily extract N or Q_{0A} from data $\rightarrow$ **the uncertainties band will be then significantly reduced at other η and for all other observables.**

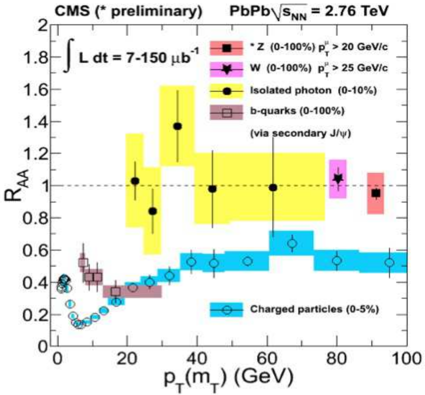
Albacete, Dumitru, Fujii, Nara, arXiv:1209.2001



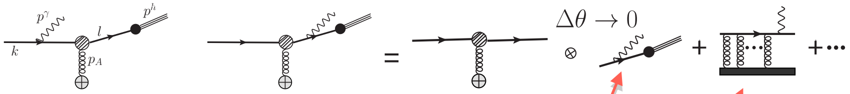
Rezaeian, arXiv:1210.2385



- CGC predicts more suppression than the collinear factorization for R^{ch}_{pA} at low p_T and very forward rapidities.



- In AA collisions all hadrons are strongly quenched except prompt photon → **prompt photon is a good probe of initial-state (Saturation) effect.**
- Prompt photon is free from hadronization mess.
- Semi-inclusive photon-hadron production (only dipole appears) **is better under control in the CGC approach** compared to dihadron production.



Gelis, Jalilian-Marian, hep-ph/0205037; Jalilian-Marian, Rezaeian, arXiv:1204.1319

$$\frac{d\sigma^{p\,A\to\gamma(p^\gamma)\,X}}{d^2\vec{b_T}\,d^2\vec{p_T}^{\,\gamma}\,d\eta_\gamma} = \frac{K}{(2\pi)^2}\Big[\int_{x_q^{min}}^{1} dx_q\, f_q(x_q,\,Q^2)\,\frac{1}{z}\,N_F(x_g,\,p_T^\gamma/z)D_{\gamma/q}(z,\,Q^2)$$

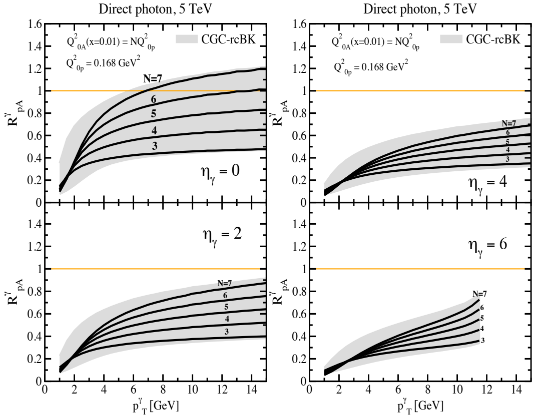
$$+\ \frac{e_q^2\,\alpha_{em}}{2\pi^2(p_T^\gamma)^4}\int_{x_q^{min}}^{1} dx_q\, f_q(x_q,\,Q^2)z^2[1+(1-z)^2]\int_{l_T^2<Q^2} d^2\vec{l_T}\ l_T^2\ N_F(\bar{x}_g,\,l_T)\Big],$$

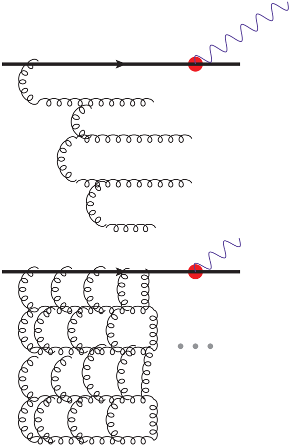
$$x_g = x_q\,e^{-2\,\eta_\gamma},\qquad \bar{x}_g = \frac{1}{x_q\,S}\left[\frac{(p_T^\gamma)^2}{z}+\frac{(l_T-p_T^\gamma)^2}{1-z}\right]\qquad z=\frac{p_T^\gamma}{x_q\sqrt{S}}\,e^{\eta_\gamma},\qquad \text{with}\qquad x_q^{min}=\frac{p_T^\gamma}{\sqrt{S}}\,e^{\eta_\gamma}.$$

- Both fragmentation and direct photon are sensitive to saturation via N_F. However, direct photon is more sensitive to the saturation effects.
- pA is different from dA (unlike hadron production) due to charge squared of quarks → non-trivial isospin effect.

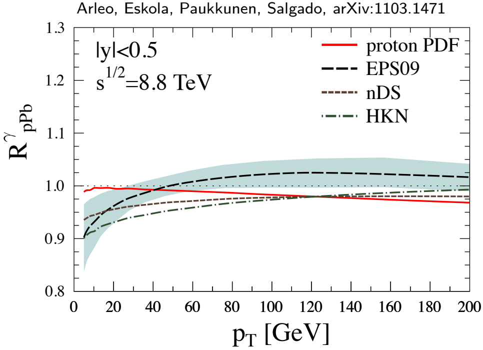
Direct photon production at the LHC in p+A collisions

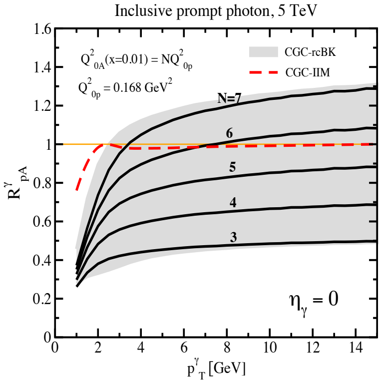
Rezaeian, arXiv:1210.2385





Prompt photons are not suppressed in QGP, but are subject to suppression in CGC medium due to gluon saturation.

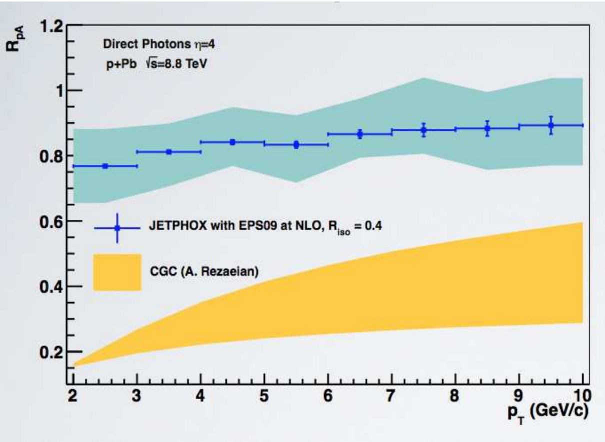




- To clearly discriminate between two approaches, forward rapidities measurements of R^{γ}_{pA} are needed.

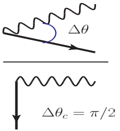
Direct photon production in p+A@LHC: Linear v. nonlinear

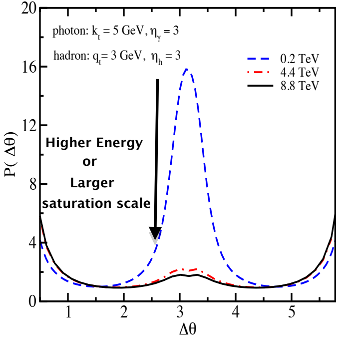
Peitzmann(for the ALICE collaboration), Forward Physics at the LHC, CERN 2013

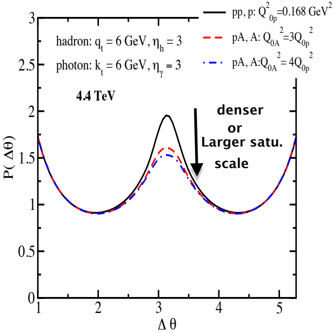


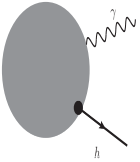
- At very forward rapidities, two approaches give very different results → The measurement is discriminatory.

$$P(\Delta\theta) = \frac{d\sigma^{p(d)\,T \to h(q)\,\gamma(k)\,X}}{d^2\vec{b}_t\, dk_t^2\, dq_t^2\, dy_\gamma\, dy_l\, d\theta}[\Delta\theta] \Big/ \frac{d\sigma^{p(d)\,T \to h(q)\,\gamma(k)\,X}}{d^2\vec{b}_t\, dk_t^2\, dq_t^2\, dy_\gamma\, dy_l\, d\theta}[\Delta\theta = \Delta\theta_c] =$$

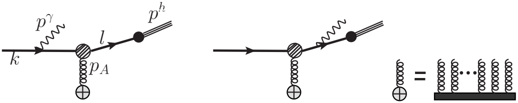




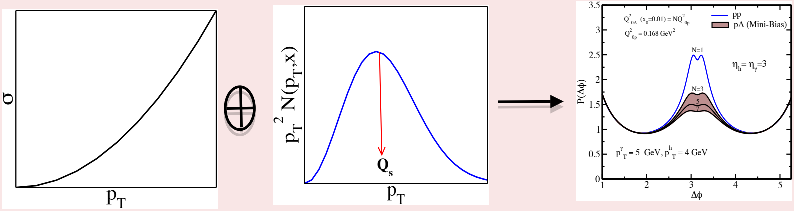




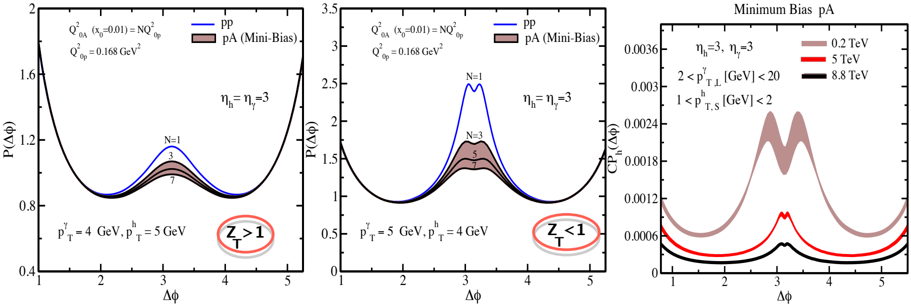
- Existence of the saturation scale unbalances the back-to-back correlations.
- Denser nuclei **or/and** Higher energy **or/and** Lower transverse momenta (larger saturation scale) $\rightarrow$ more suppression of away-side correlations.



Photon-hadron correlations have a double peak structure because:



1. If the projectile parton does not exchange transverse momentum with target, the production rate of photon-hadron goes to zero.
   $p_T = |\vec{l_T} + \vec{p_T}^{\gamma}| = 0 \to \sigma^{h\gamma}(q + A \to \gamma(p^\gamma) + q(l) + X) = 0$
2. Existence of saturation scale: $p_T^2 N_F(p_T, x_g)$ in $\sigma^{h\gamma}$ has a maximum at $p_T \sim Q_s$.
3. Because of convolution with fragmentation and parton distribution functions$\to$ local minimum will not be zero but gets smeared out.



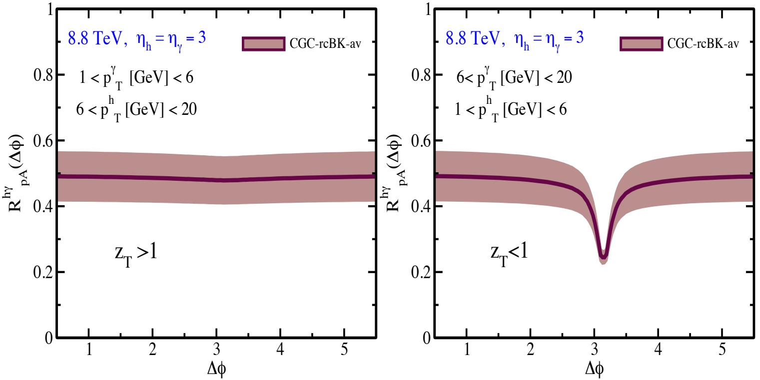
Rezaeian,PRD86, arXiv:1209.0478; PLB718, arXiv:1210.2385

Photon-hadron correlations have a double peak structure if:

$$z_T = \frac{p_T^h}{p_T^\gamma} \leq 1 \quad \text{and} \quad p_T^\gamma \frac{(e^{\eta_h} + e^{\eta_\gamma})}{\sqrt{S}} \leq 1.$$

Emergence of double peak structure is an excellent probe of saturation dynamics.

- **Challenge**: Standard (DGLAP-like) QCD calculations cannot reproduce none of $\gamma - \pi^0$ correlation features.



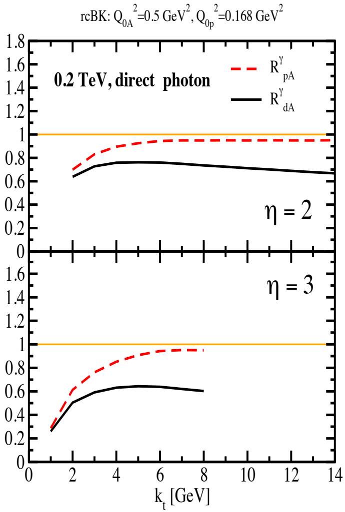
$p_T^h > p_T^\gamma$ $\qquad$ $p_T^h < p_T^\gamma$

Conclusion:

The CGC picture at RHIC and HERA at small-x is consistent with the LHC data (p+p, p+A, A+A) so far: the upcoming p+A data at the LHC is crucial test of gluon saturation/CGC.

- Await to be verified at the LHC:
  - Centrality dependence of the multiplicity distribution.
  - Suppression of inclusive charged hadron at *very* forward rapidities.
  - Suppression of inclusive (and direct) photon production at *very* forward rapidities.
  - Suppression of away-side photon-hadron (and dihadron) correlations at forward rapidities.
  - Appearance of double peak structure for away-side $\gamma - \pi^0$ correlations at forward rapidities.

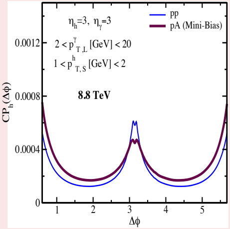
Backup: pA vs. dA at RHIC

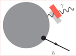


- Sizable isospin effect → suppression at high transverse momentum (NOT due to saturation effect).

$\pi^0 - \gamma$ coincidence probability in pA@LHC

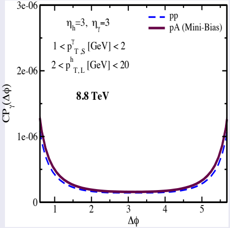
Trigger(leading) particle is a prompt photon ($p_T^h < p_T^\gamma$) :

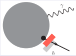




$$CP_h(\Delta\phi; p^h_{T,S}, p^\gamma_{T,L}; \eta_\gamma, \eta_h) = N_h^{\text{pair}}(\Delta\phi)/N_{\text{photon}}$$

Trigger particle is a hadron ($p_T^h > p_T^\gamma$):





$$CP_\gamma(\Delta\phi; p^\gamma_{T,S}, p^h_{T,L}; \eta_\gamma, \eta_h) = N_\gamma^{\text{pair}}(\Delta\phi)/N_{\text{hadron}}$$