

Hadron and prompt photon production in pA collisions at the LHC from the CGC

A. Rezaeian

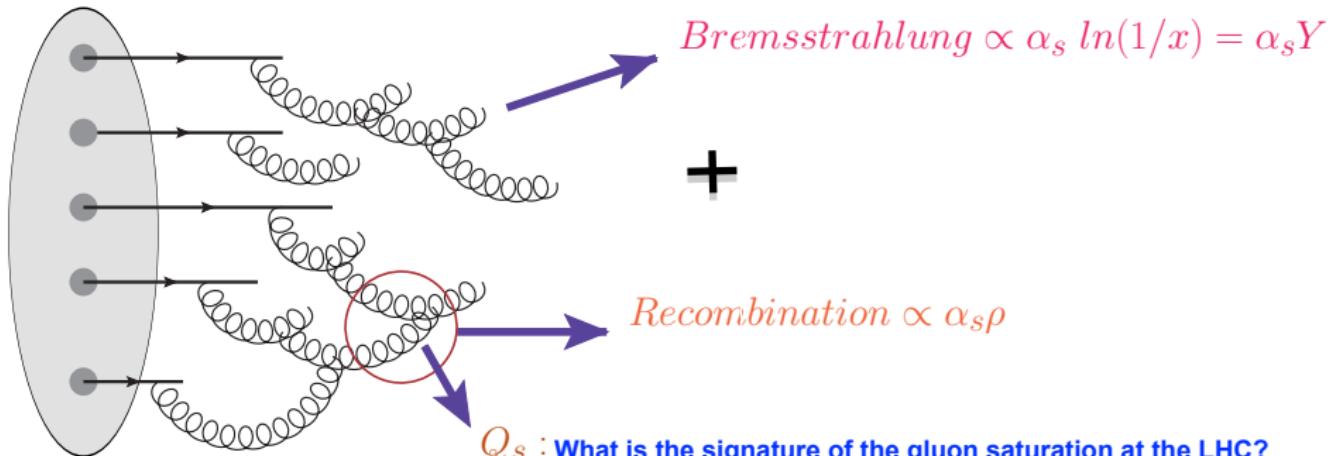
Universidad Tecnica Federico Santa Maria

Hard Probes 2012, Cagliari, Italy

Based on references

- Jalilian-Marian and AR, arXiv:1204.1319.
- Jalilian-Marian and AR, PRD **85**, 014017 (2012); arXiv:1110.2810.
- AR, PRD **85**, 014028 (2012); arXiv:1111.2312.

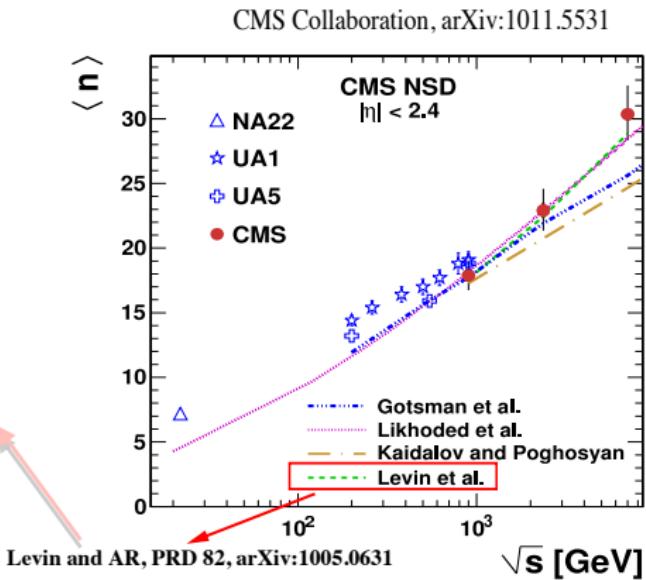
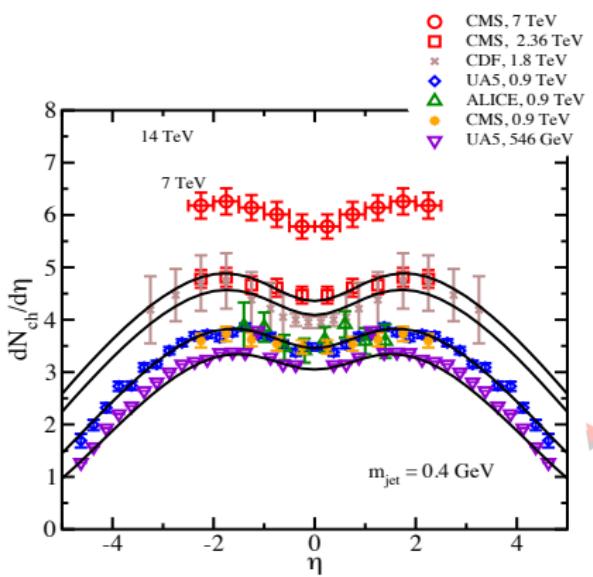
Nuclear/proton wavefunction at high energies



- BK-JIMWLK renormalization evolution sum systematically leading logs $(\alpha_s Y)^n$ and high parton density $(\alpha_s \rho)^n$.
- Successful CGC/Saturation phenomenology at: HERA ep; eA; RHIC dA & AA; and already the LHC pp & AA collisions.

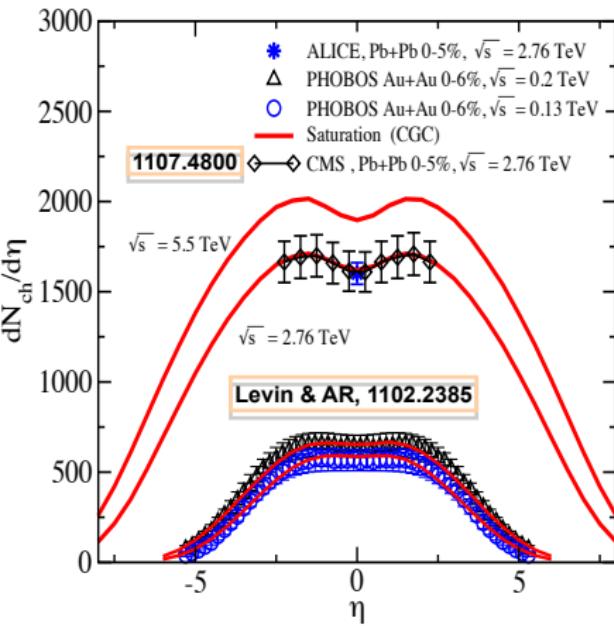
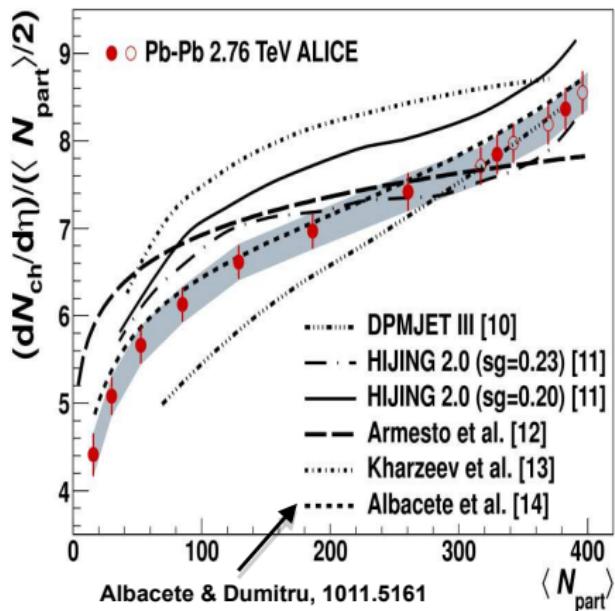
Pedagogia review: Kovchegov and Levin, "Quantum Chromodynamics at High Energy" (Cambridge Univ. press, 2012)

CGC-based prediction for the LHC pp collisions



- Correct energy/rapidity dependence in pp collisions.

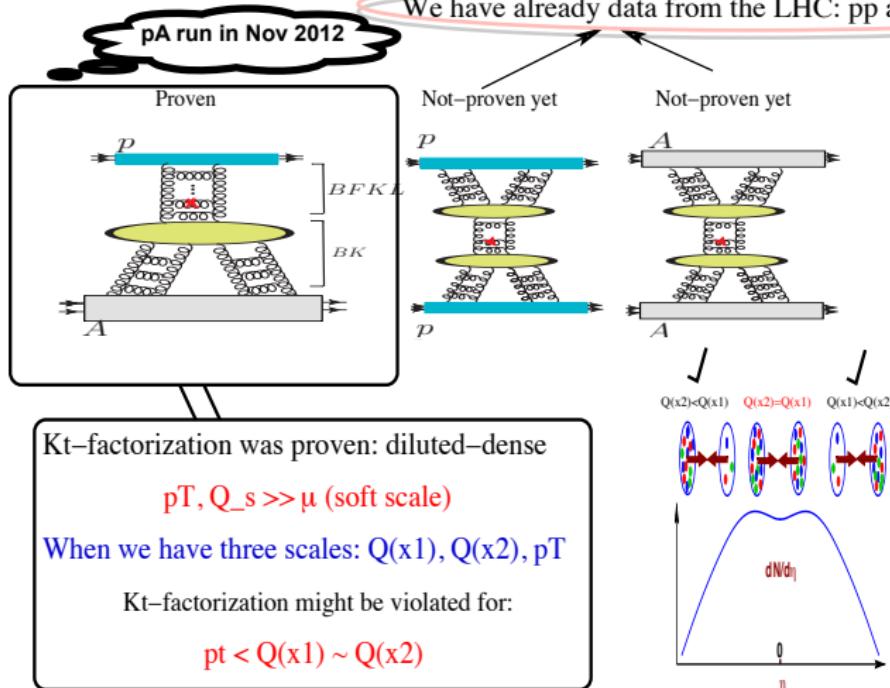
CGC-based prediction for the LHC AA collisions



- Correct centrality/rapidity dependence in AA collisions.

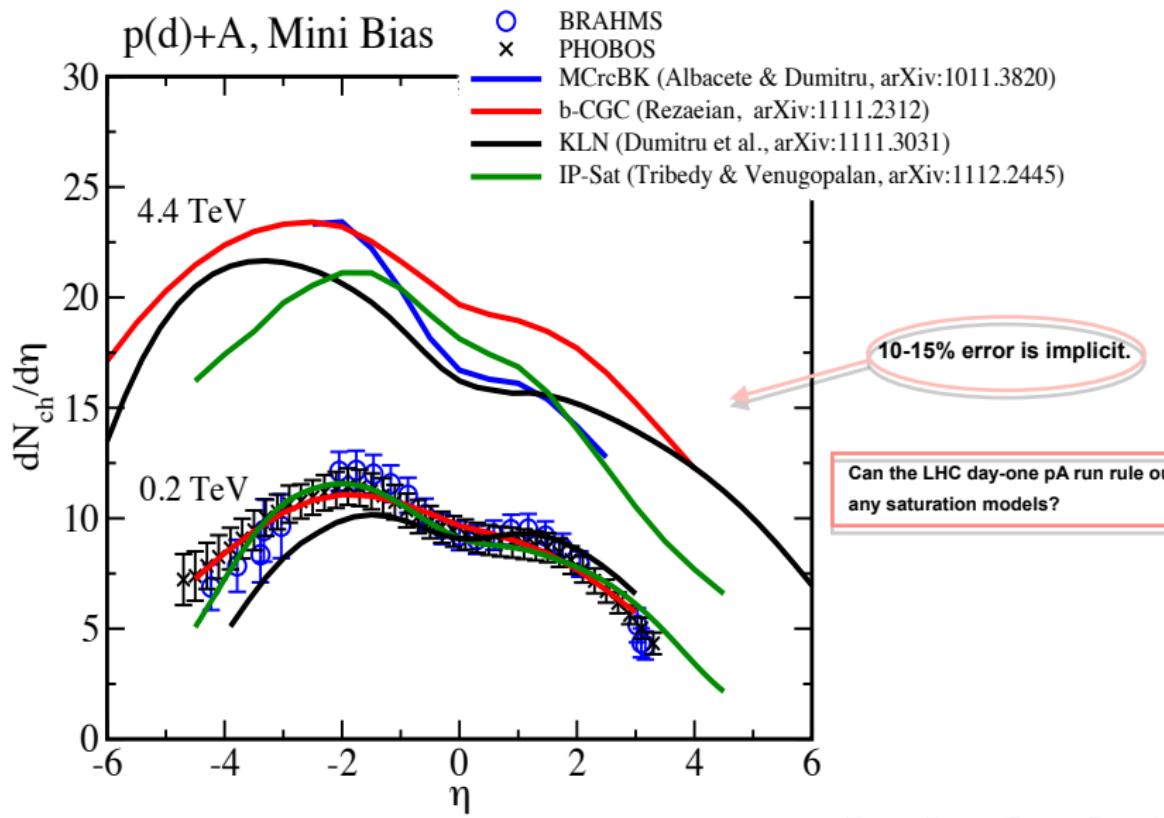
See also: Tribedy and Venugopalan (2011).

pA collisions: A good test of k_T -factorization and saturation physics

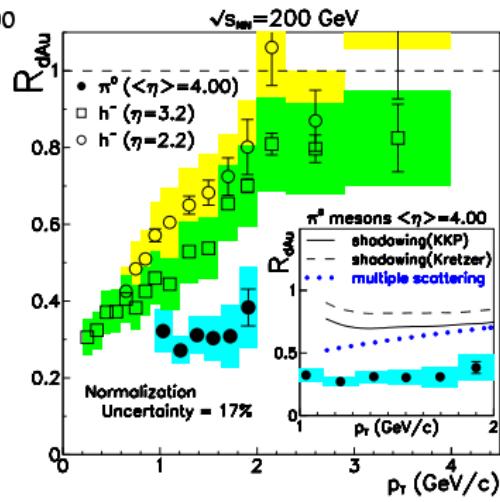
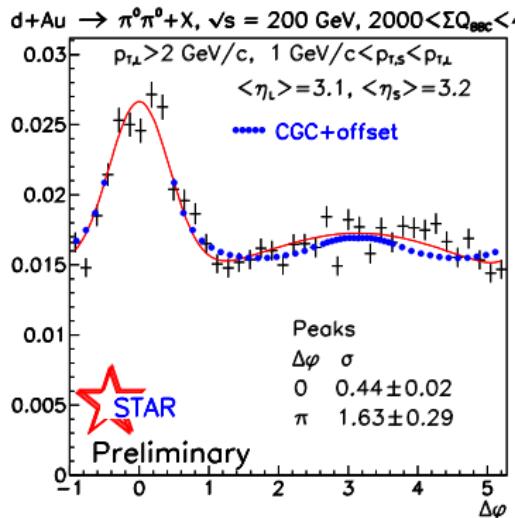


In pA collisions: Kovchegov and Mueller (98); M. A. Braun (2000); Kovchegov and Tuchin (2002); Dumitru and McLerran (2002); Blaizot, Gelis and Venugopalan (2004).

Saturation/CGC based predictions for charged hadron multiplicity in pA collisions



- Suppression of single inclusive hadron production at forward rapidity in dAu.
Kharzeev, Levin, McLerran, '02; Kharzeev, Kovchegov, Tuchin, '03;
Albacete, Armesto, Kovner, Salgado, Wiedemann, '03; Baier, Kovner,
Wiedemann, '03....
- Disappearance of the away side jet peak in dihadron production at forward
rapidity in dAu. Albacete, Marquet, '10; Tuchin; '10, Stasto, Xiao, Yuan, '11



Back-of-envelope estimation of R_{pA}^h in the saturation region

$$\frac{d\sigma^{pA \rightarrow hX}}{dy d^2 p_t} = \frac{2\alpha_s}{C_F} \frac{1}{p_t^2} \int d^2 \vec{k}_t \phi^p(x_1; \vec{k}_t) \phi^A(x_2; \vec{p}_t - \vec{k}_t),$$

Deep inside saturation, $p_t < Q_s$:

$$\frac{d\sigma^{pA \rightarrow hX}}{d\eta d^2 p_t} \sim \frac{S_A S_p Q_s^2}{p_t^2} \quad \frac{d\sigma^{pp \rightarrow hX}}{d\eta d^2 p_t} \sim \frac{S_p^2 Q_s^2}{p_t^2}$$

$$R_{pA} = \frac{\frac{d\sigma^{pA}}{d\eta d^2 p_t}}{A \frac{d\sigma^{pp}}{d\eta d^2 p_t}} = \frac{S_A}{AS_p} \sim A^{-1/3} = 0.17 \quad (A = 208)$$

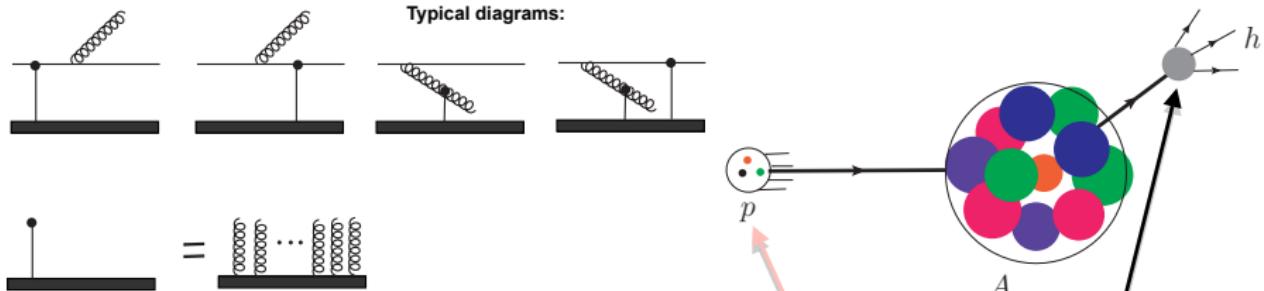
In extended geometric scaling region: $Q_s < p_t < p_{geom}$:

$$R_{pA} \sim A^{-1/6} = 0.41 \quad (A = 208)$$

Kharzeev, Kovchegov, Tuchin, '03

What is the rapidity/energy/centrality correction of the above naive estimate?

Inclusive hadron production in pA collisions; revisited



Dumitru et. al. (2006)

Altinoluk and Kovner (2011)

Jalilian-Marian and AR (2011)

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

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

$$K^{\text{run}}(\vec{r}, \vec{r}_1, \vec{r}_2) = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left[\frac{1}{r_1^2} \left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2} \left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]$$

Albacete-Kovchegov (2007)

Albacete et. al. (2011)

For relevance of the BK evolution: see Javier Albacete's talk

Inclusive hadron production in pA collisions

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

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

$$K^{\text{run}}(\vec{r}, \vec{r}_1, \vec{r}_2) = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left[\frac{1}{r_1^2} \left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2} \left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]$$

The only external input:

- From DIS: $Q_{0p}^2 \approx 0.15 \div 0.2 \text{ GeV}^2$, From RHIC: $Q_{0p}^2 \approx 0.15 \div 0.336 \text{ GeV}^2$.
- From DIS & RHIC: $Q_{0A}^2 \approx 3 \div 4 Q_{0p}^2$.

$$Q_{sA}^2 \propto A^\alpha Q_{sp}^2$$

- Empirical geometric scaling and DIS data:

Armesto, Salgado and Wiedemann (2004):

$$Q_{sA}^2 = c_1 A^{4/9} Q_{sp}^2 \implies Q_{sA}^2 \approx 3.1 Q_{sp}^2$$

- BK-JIMWLK equation and DIS data

McLerran and Venugopalan (1994), Albacete et al. (2010), Dusling, Gelis, Lappi and Venugopalan (2010), AR, Levin (2010)

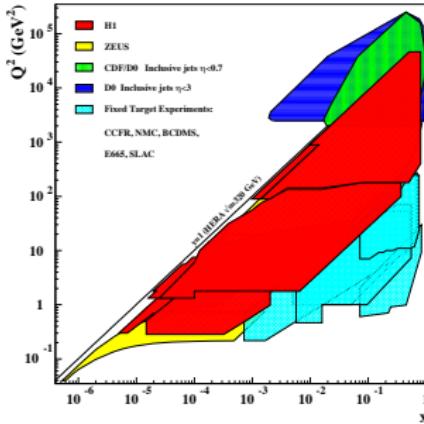
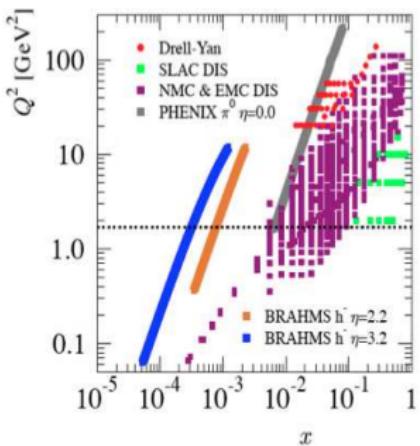
$$Q_{sA}^2 = c_2 A^{1/3} Q_{sp}^2 \implies Q_{sA}^2 \approx 2.96 Q_{sp}^2$$

- Running-coupling BFKL evolution near the saturation boundary

Mueller (2003): $Q_{sA}^2 = c_3 A^0 Q_{sp}^2$, is **independent** of A .

► Available data cannot **uniquely** determine the A -dependence of the saturation scale!.

$$Q_{sA}^2 \propto A^\alpha Q_{sp}^2$$



- Available data cannot **uniquely** determine the A -dependence of the initial saturation scale!. Need: **pA** run at the **LHC** with different **A**
- All available data with heavy nuclei are consistent with $Q_{0A}^2 \approx (3 \div 4) Q_{0p}^2$
What is role of geometrical fluctuations in the existing data? (Albacete, Dumitru and Nara)

Inclusive hadron production in pA collisions

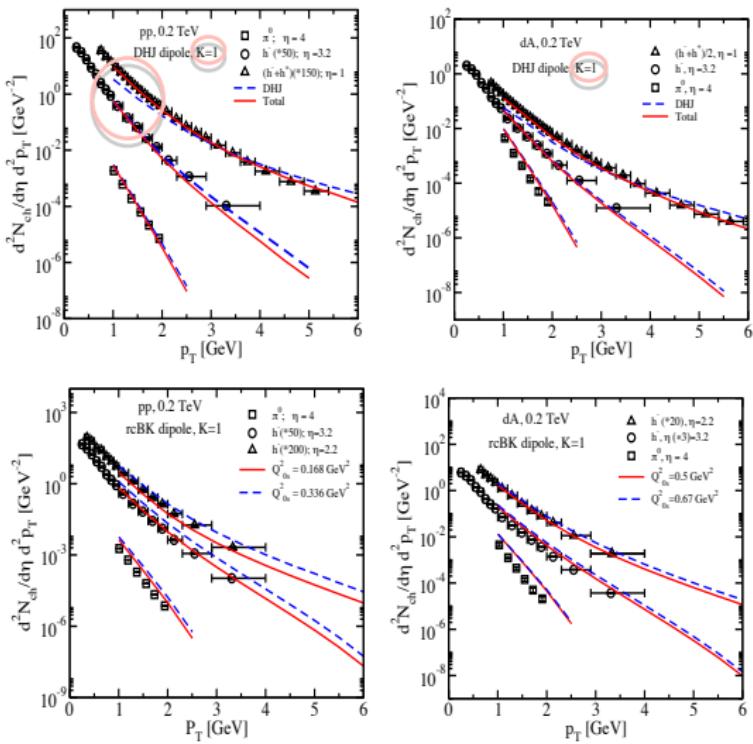
$$\frac{dN^{pA \rightarrow hX}}{d^2 p_T d\eta} = \frac{K}{(2\pi)^2} \left[\int_{x_F}^1 \frac{dz}{z^2} \left[x_1 f_g(x_1, Q^2) \textcolor{red}{N_A}(x_2, \frac{p_T}{z}) D_{h/g}(z, Q) + \sum_q x_1 f_q(x_1, Q^2) \textcolor{red}{N_F}(x_2, \frac{p_T}{z}) D_{h/q}(z, Q) \right] \right. \\ \left. + \int_{x_F}^1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

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

$$\textcolor{blue}{K^{\text{run}}}(\vec{r}, \vec{r}_1, \vec{r}_2) = \frac{N_c \alpha_s(r^2)}{2\pi^2} \left[\frac{1}{r_1^2} \left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1 \right) + \frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_2^2} \left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1 \right) \right]$$

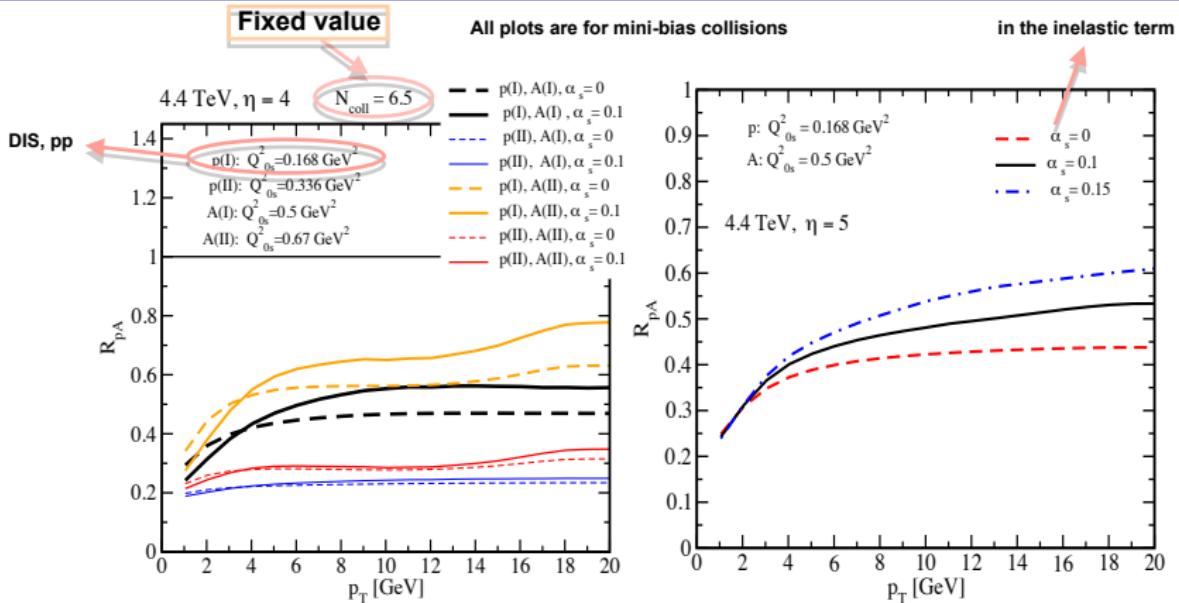
The only external input:

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- From DIS & RHIC: $Q_{0A}^2 \approx 3 \div 4 Q_{0p}^2$.
- N_{coll} in $R_{p(d)A}$ comes from soft physics (Glauber model) is **NOT** calculated from saturation physics (**possible normalization problem!**).



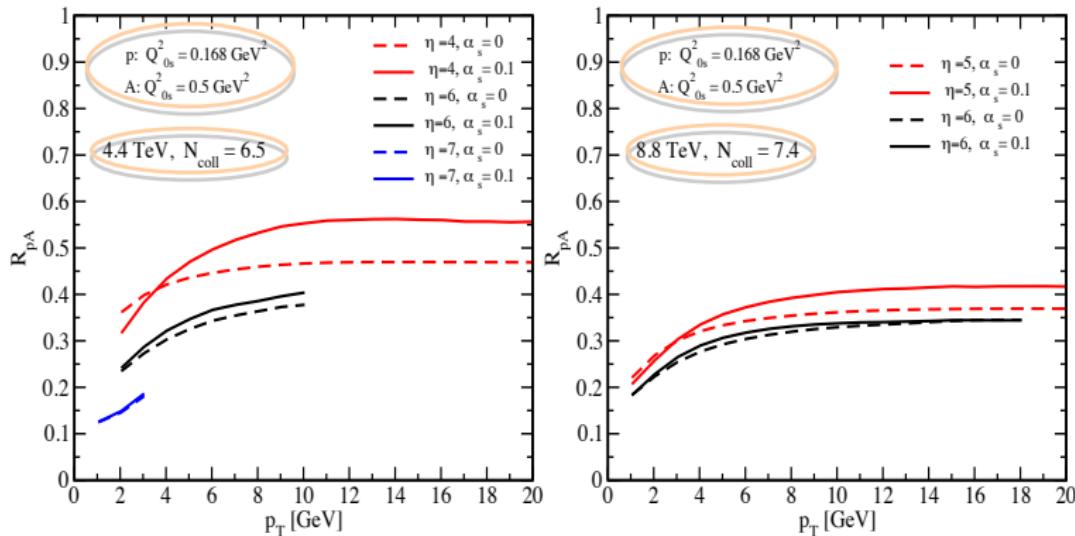
- The inelastic contribution (higher twist contributions) is important at $\eta \sim 0$.
- What is the role of cold matter energy loss which is not included in the above? Kopeliovich, Frankfurt, Strikman; and Neufeld-Vitev-Zhang.

Sensitivity of R_{pA} to the initial saturation scale and α_s



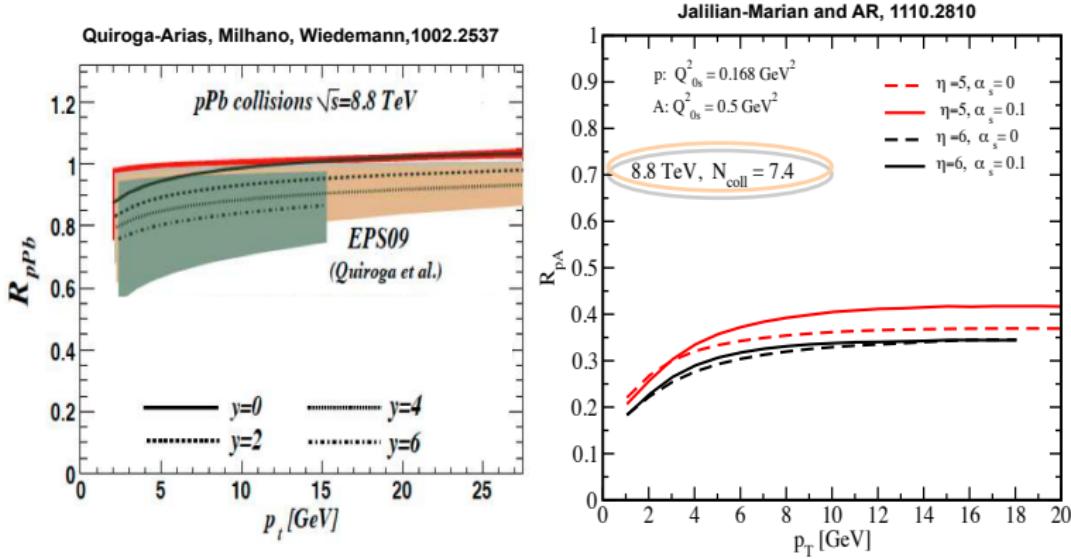
- Inclusion of these inelastic terms makes R_{pA} grow faster with increasing transverse momentum.
- R_{pA} is sensitive to the initial saturation scale and small- x evolution.

Predictions for the LHC at forward rapidity



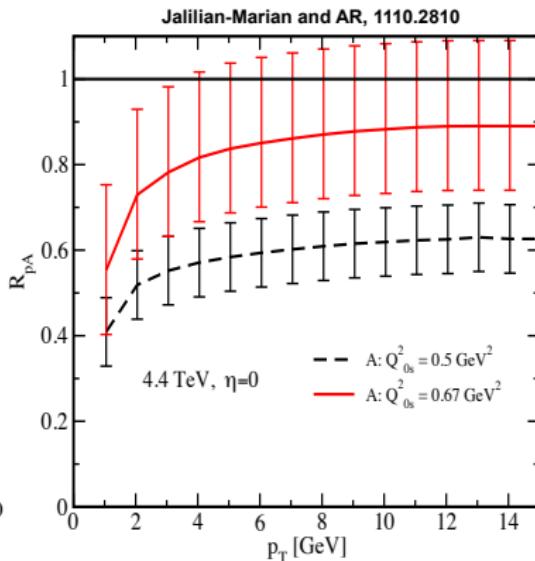
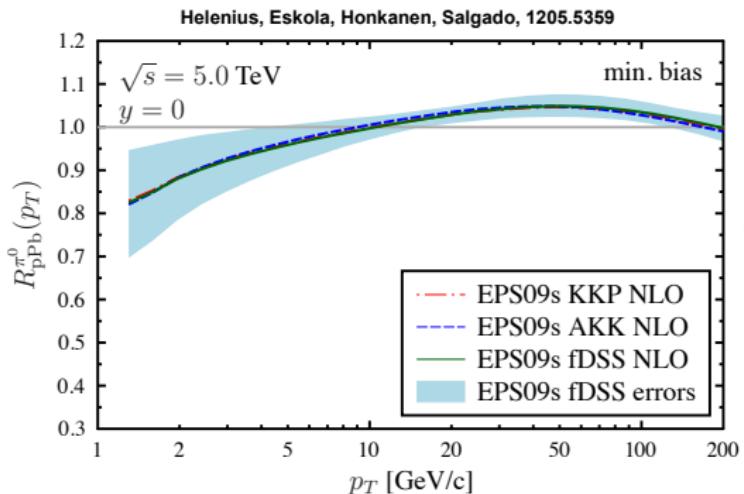
- Uncertainties due to the choice of Q_{0s} and α_s are reduced at forward rapidity at the LHC.
- The energy-dependence of R_{pA} from 4.4 to 8.8 TeV is rather weak.

Collinear (parton model) v. k_t -factorization (CGC) at the LHC forward rapidities



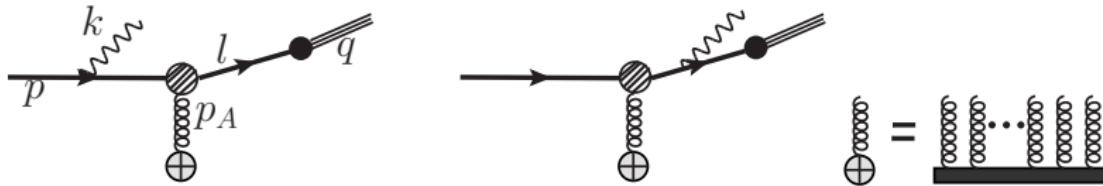
- The CGC predicts substantial more suppression for inclusive hadron production at forward rapidity at the LHC compared to the standard parton model approach.

Collinear (parton model) v. k_t -factorization (CGC) at the LHC



- Higher order corrections beyond leading twist approximation become important.
- The uncertainties due to initial saturation scale produces large uncertainties for R_{pA} at $\eta = 0$.
- Our description of hadron production in pp collisions (reference) at midrapidity is less reliable.

Photon-hadron production in high-energy pA collisions



Gelis and Jalilian-Marian (2002)

Jalilian-Marian and AR (2012)

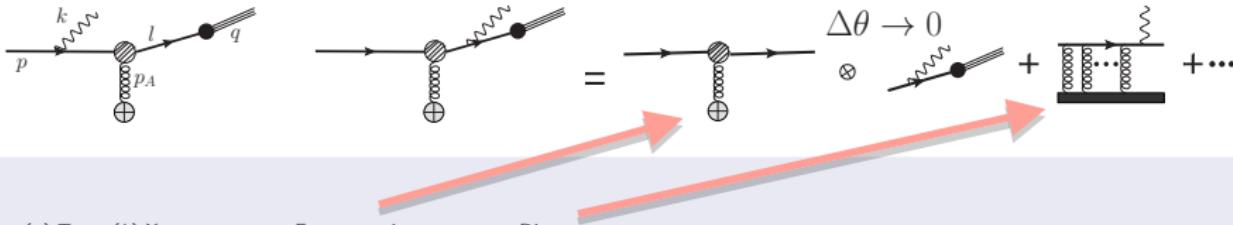
$$\frac{d\sigma^{q(p)} p(A) \rightarrow q(l) \gamma(k) X}{d^2 \vec{b}_t d\vec{k}_t^2 dl_t^2 dy_\gamma dy_l d\theta} = \frac{e_q^2 \alpha_{em}}{\sqrt{2}(2\pi)^3} \frac{k^-}{k_t^2 \sqrt{S}} \frac{1 + (\frac{l^-}{p^-})^2}{[k^- \vec{l}_t - l^- \vec{k}_t]^2}$$

$$\delta[x_q - \frac{l_t}{\sqrt{S}} e^{y_l} - \frac{k_t}{\sqrt{S}} e^{y_\gamma}] \left[2l^- k^- \vec{l}_t \cdot \vec{k}_t + k^- (p^- - k^-) l_t^2 + l^- (p^- - l^-) k_t^2 \right]$$

$$\int d^2 \vec{r}_t e^{i(\vec{l}_t + \vec{k}_t) \cdot \vec{r}_t} N_F(\vec{b}_t, \vec{r}_t, x_g),$$

$$\frac{d\sigma^p p(A) \rightarrow \gamma(k) h(q) X}{d^2 \vec{b}_t dk_t^2 dq_t^2 d\eta_\gamma d\eta_h d\theta} = \int_{z_f^{\min}}^1 \frac{dz_f}{z_f^2} \int dx_q f(x_q, Q^2) \frac{d\sigma^q p(A) \rightarrow \gamma q X}{d^2 \vec{b}_t dk_t^2 dl_t^2 d\eta_\gamma d\eta_h d\theta} D_{h/q}(z_f, Q^2)$$

Prompt photon production in high-energy pA collisions



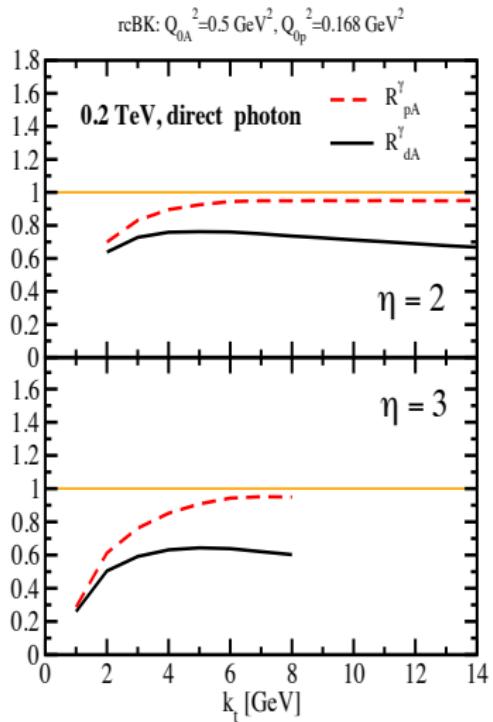
$$\frac{d\sigma^{q(p)} T \rightarrow \gamma(k) X}{d^2 \vec{b}_t d^2 \vec{k}_t d\eta_\gamma} = \frac{d\sigma^{\text{Fragmentation}}}{d^2 \vec{b}_t d^2 \vec{k}_t d\eta_\gamma} + \frac{d\sigma^{\text{Direct}}}{d^2 \vec{b}_t d^2 \vec{k}_t d\eta_\gamma}$$

$$= \frac{1}{(2\pi)^2} \frac{1}{z} D_{\gamma/q}(z, k_t^2) N_F(x_g, b_t, k_t/z) + \frac{e_q^2 \alpha_{em}}{\pi (2\pi)^3} z^2 [1 + (1-z)^2] \frac{1}{k_t^4} \int^{k_t^2} d^2 \vec{l}_t l_t^2 N_F(\bar{x}_g, b_t, l_t)$$

- 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 \rightarrow non-trivial isospin effect.

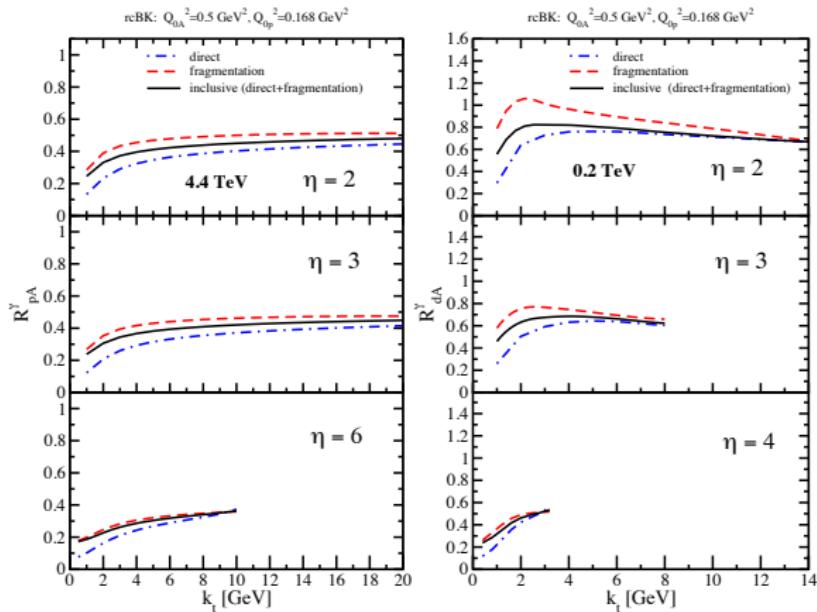
pA vs. dA at RHIC

Jalilian-Marian and AR, 1204.1319



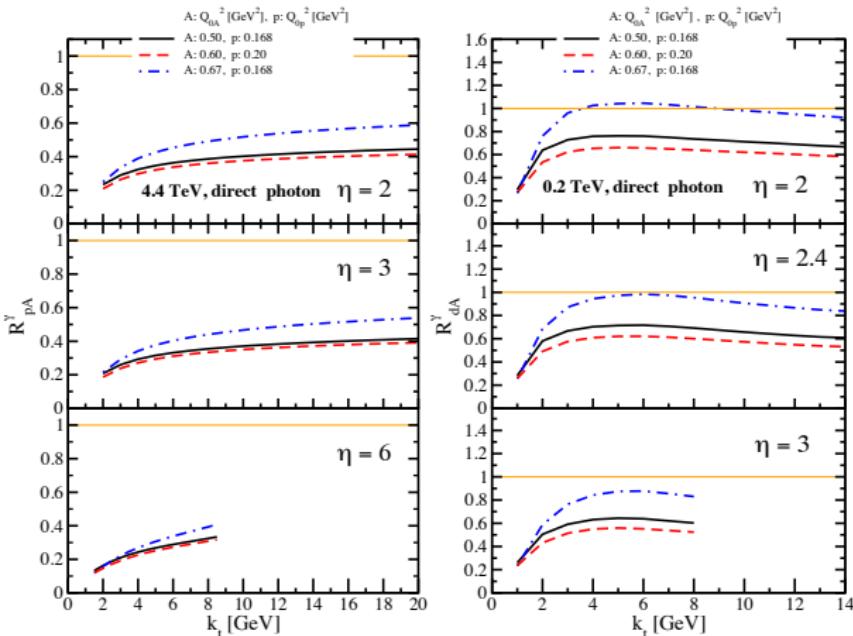
- Sizable isospin effect \rightarrow suppression at high transverse momentum (NOT due to saturation effect).

Direct vs. fragmentation vs. inclusive prompt photon at RHIC and the LHC



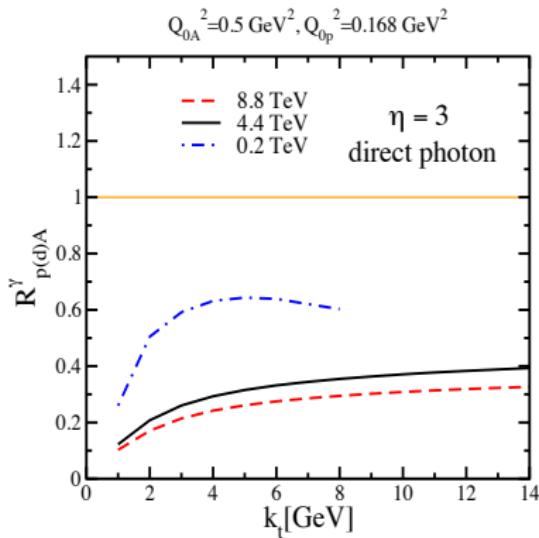
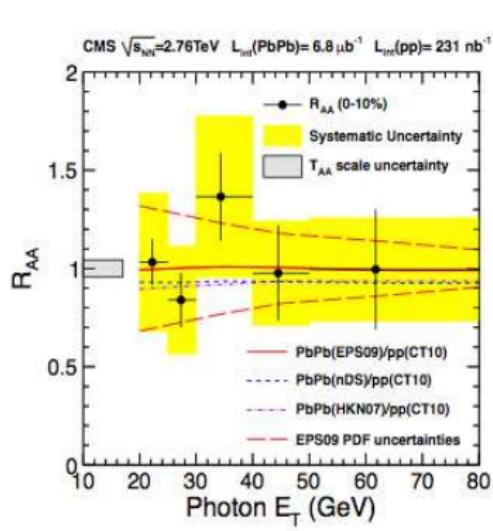
- Direct photon $R_{p(d)A}^{\gamma}$ is more sensitive to the saturation effects \rightarrow more suppression.
- At very forward rapidity $R_{p(d)A}^{\gamma}$ of direct photon and inclusive prompt photon are similar.

Sensitivity to the initial saturation scale Q_{0s}



- It is sensitive to $Q_{0s} \rightarrow$ probes small- x dynamics.
- Uncertainties due to Q_{0s} is reduced at higher energy and more forward collisions.

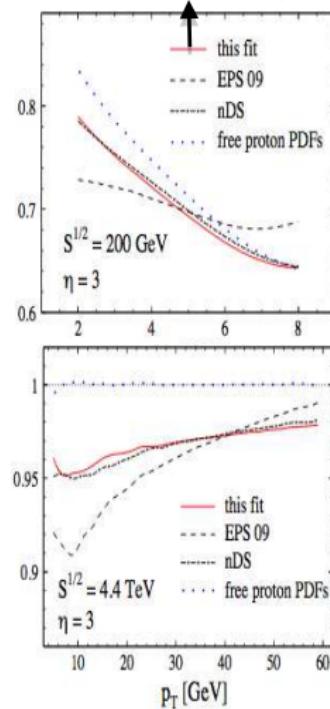
pA at forward-rapidity vs. AA ($\eta = 0$) at the LHC



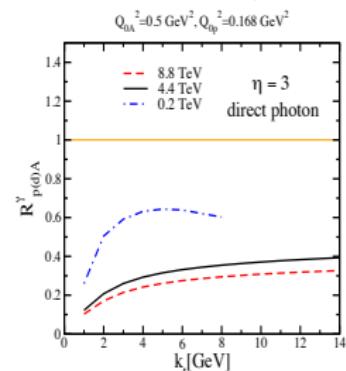
- The suppression at the LHC is impressive given that at the LHC isospin effect is not important (projectile is proton).
- Prompt photon is cleaner probe of initial-state effect: no hadronization.
- There was no suppression for R_{AA}^γ at the LHC in AA collisions at **high-pt and mid-rapidity**.

Collinear v. k_t -factorization (CGC) at the LHC and prompt photon

Florian, Sassot, Stratmann, Zurita, 1112.6324



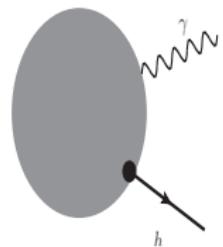
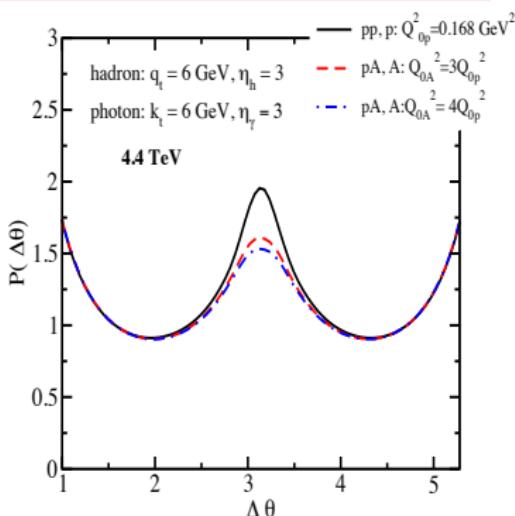
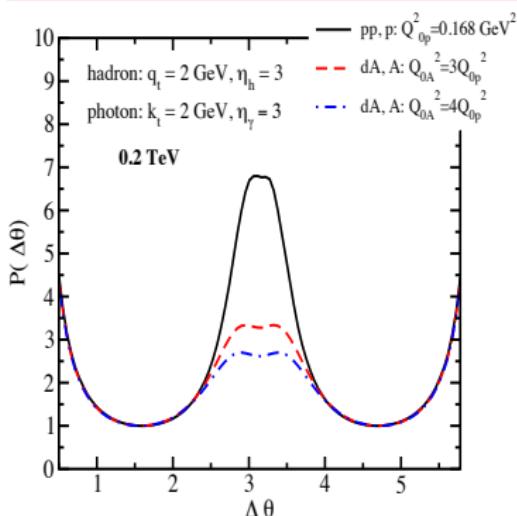
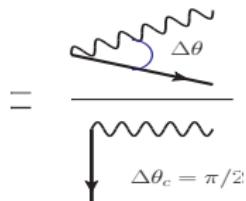
Jalilian-Marian and AR, 1204.1319



- The CGC prediction for R_{pA}^{γ} are very different both at RHIC and the LHC from collinear factorization results.

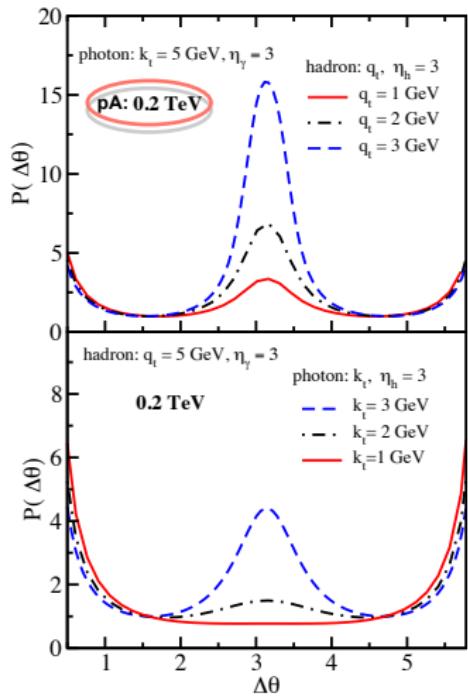
Photon-hadron azimuthal correlations; suppression of away-side correlations

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



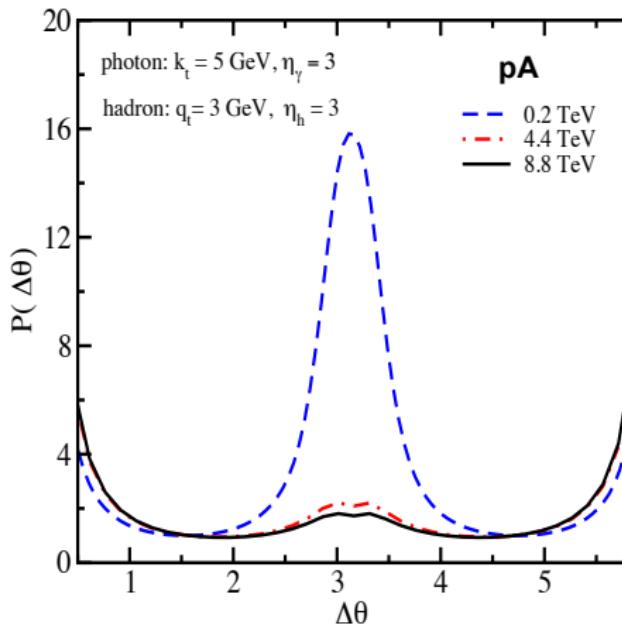
- Denser nuclei (or bigger saturation scale) → more suppression of away-side correlations.

Photon-hadron azimuthal correlations; suppression with transverse momenta



- Lower transverse momentum \rightarrow more suppression of away-side correlations.

Photon-hadron azimuthal correlations; RHIC vs. the LHC



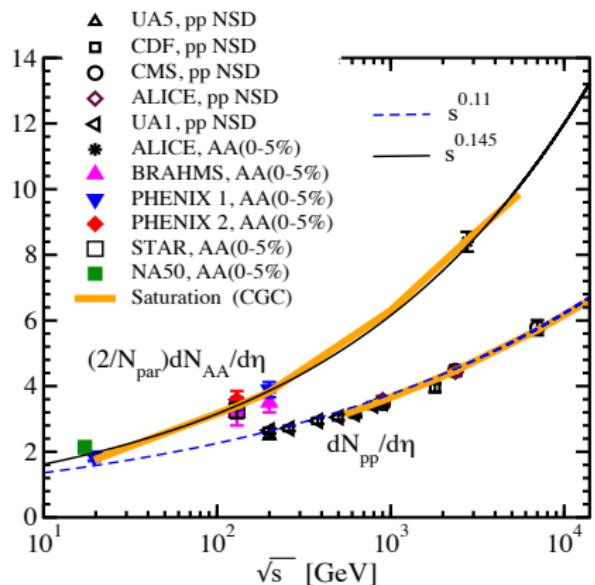
- Higher energy → more suppression of away-side correlations.

Conclusion:

$R_{pA}^{\gamma}, R_{pA}^h$ measurements at the LHC in the forward rapidity region are sensitive probes of the low-x dynamics.

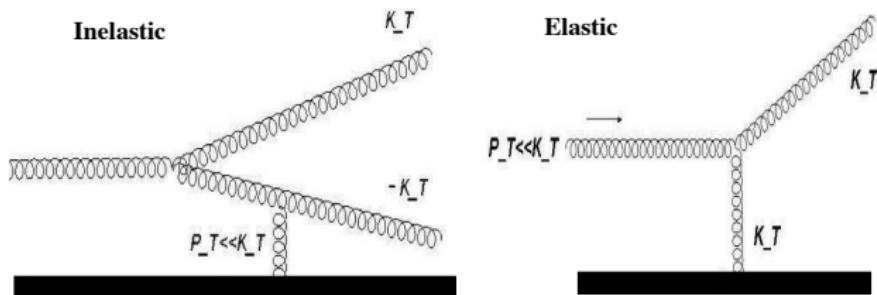
- Significant suppression of $R_{pA}^{\gamma}, R_{pA}^h$ at the LHC forward pA collisions.
- Strong suppression of the away-side peak in photon-hadron correlations at forward rapidities, similar to the observed mono-jet production in dA collisions at forward rapidity at RHIC.

Backup: The energy-dependence of multiplicity in pp and AA collisions



$$\frac{dN_h}{dn} \propto Q_s^2 \propto s^{0.11} \text{ for } Qs \leq 1 \text{ GeV}$$

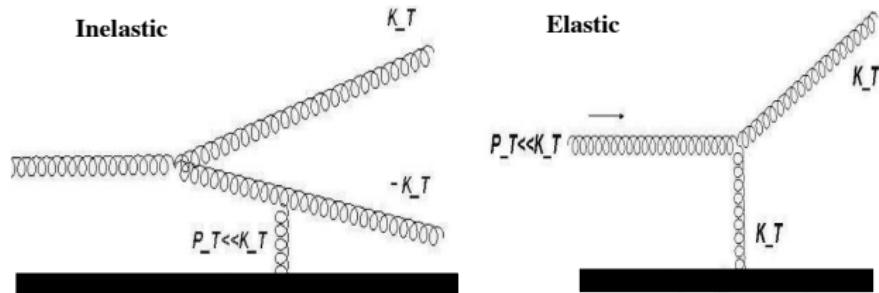
$$\frac{dN_h}{d\eta} \propto s^{0.11} * s^{0.035} = s^{0.145} \text{ for } Qs > 1 \text{ GeV}$$



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

- Elastic term $\approx N_{A,F}(x, p_T/z)$ and is sensitive to the saturation effect.

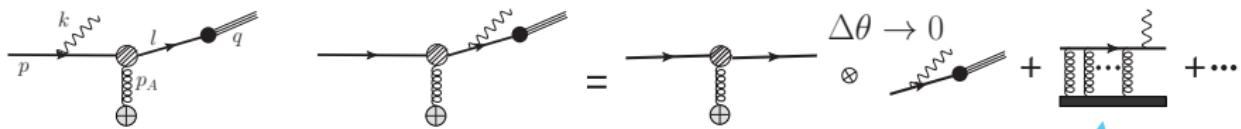
Backup: Inclusive hadron production in pA collisions; revisited



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

- Inelastic term $\approx \int_{k_T^2 < p_T^2} k_T^2 N_F(x, k_T) = f_{target}(x, p_T)$ and is sensitive to the saturation effect.

Backup: Prompt photon production in high-energy pA collisions



$$\frac{d\sigma^{q(p) T \rightarrow \gamma(k) X}}{d^2 \vec{b}_t d^2 \vec{k}_t d\eta_\gamma} = \frac{d\sigma^{\text{Fragmentation}}}{d^2 \vec{b}_t d^2 \vec{k}_t d\eta_\gamma} + \frac{d\sigma^{\text{Direct}}}{d^2 \vec{b}_t d^2 \vec{k}_t d\eta_\gamma}$$

$$= \frac{1}{(2\pi)^2} \frac{1}{z} D_{\gamma/q}(z, k_t^2) N_F(x_g, b_t, k_t/z) + \frac{e_q^2 \alpha_{em}}{\pi (2\pi)^3} z^2 [1 + (1-z)^2] \frac{1}{k_t^4} \int^{k_t^2} d^2 \vec{l}_t l_t^2 N_F(\bar{x}_g, b_t, l_t)$$

$$x_g = \frac{k_t^2}{z^2 x_q S} = x_q e^{-2\eta_\gamma}$$

$$\bar{x}_g = \frac{1}{x_q S} \left[\frac{k_t^2}{z} + \frac{(l_t - k_t)^2}{1-z} \right] \approx \frac{1}{x_q S} \frac{k_t^2}{z(1-z)},$$

$$z \equiv \frac{k^-}{p^-} = \frac{k_t}{x_q \sqrt{S}} e^{\eta_\gamma} = \frac{x_q^{\min}}{x_q} \quad \text{with} \quad x_q^{\min} = z_{\min} = \frac{k_t}{\sqrt{S}} e^{\eta_\gamma}.$$