Inclusive hadron production at the LHC from the Color-Glass-Condensate

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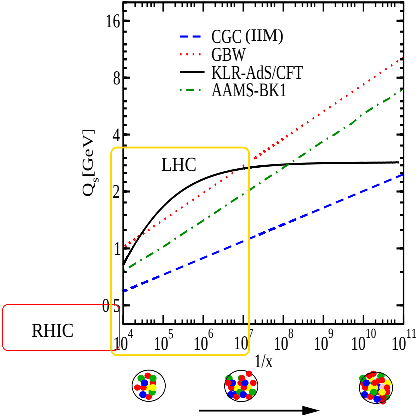
Outline

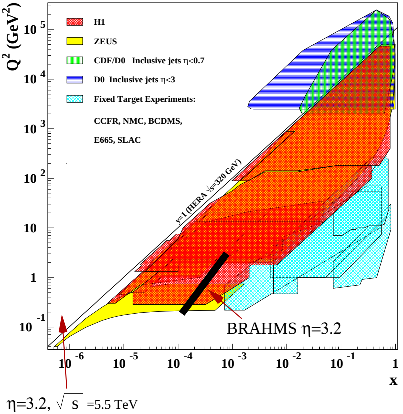
- Inclusive hadron production in *pp* collisions at the LHC.
  Is there any indication of saturation at the recent LHC data in pp?
- Inclusive hadron production in *AA* collisions at the LHC.
  What would be the implication of the LHC new data on *AA* collisions?
- The Ridge at the LHC in *pp* collisions
  Does it originate from the BFKL or the saturation?
- Inclusive hadron production in *pA* collisions at RHIC and the LHC.
  Revise/update the previous studies

Based on references

- Levin and A.H.R, PRD **82**, 014022 (2010), arXiv:1007.2430.
- Levin and A.H.R, PRD **82**, 054003 (2010), arXiv:1005.0631.
- Levin and A.H.R, PRD **84**, 034031 (2011), arXiv:1105.3275.
- Levin and A.H.R, PRD **83**, 114001 (2011), arXiv:1102.2385.
- Jalilian-Marian and A.H.R, arXiv:1110.2810

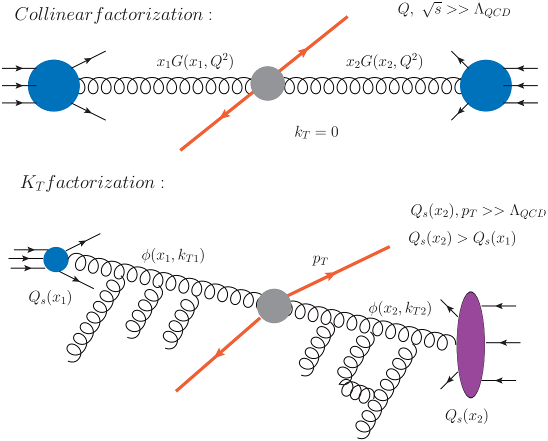
Small-x physics (and HERA) is relevant at the LHC



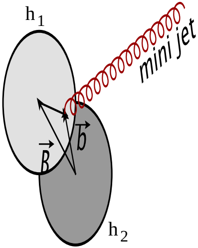


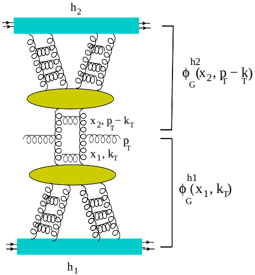
The bulk of particle production comes from very low-x ($p_T \leq 2$ GeV):
$x_2 = \frac{p_T}{\sqrt{s}} e^{-\eta}$. LHC box: $p_T = 1$ GeV, $\sqrt{s} = 5.5$ TeV, $0 < \eta < 7$
Nuclear targets amplify small-x effects: higher gluon-density.

K_T-factorization and universality of $G(x, Q^2)$ and $\phi(x, k_T)$



Φ is not the canonical unintegrated gluon density, is it universal?





$$\frac{d\sigma^{mini-jet}}{dy\, d^2 p_T} = \frac{2\alpha_s}{C_F}\frac{1}{p_T^2}\int d^2\vec{k}_T\ \phi_G^{h_1}\left(x_1;\vec{k}_T\right)\ \phi_G^{h_2}\left(x_2;\vec{p}_T-\vec{k}_T\right),$$

$$\phi_G^{h_i}\left(x_i;\vec{k}_T\right) = \frac{1}{\alpha_s}\frac{C_F}{(2\pi)^3}\int d^2\vec{b}\, d^2\vec{r}_T\, e^{i\vec{k}_T\cdot\vec{r}_T}\ \nabla_T^2\, N_G^{h_i}\left(x_i;r_T;b\right),$$

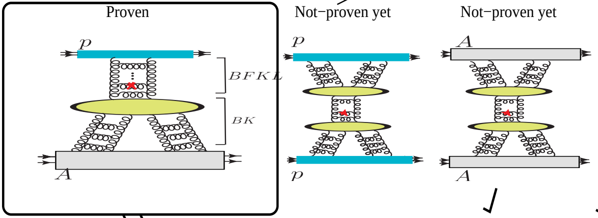
$$N_G^{h_i}\left(x_i;r_T;b\right) = 2\,N\left(x_i;r_T;b\right) - N^2\left(x_i;r_T;b\right).\ \ \text{(connection to BK eq and DIS)}$$

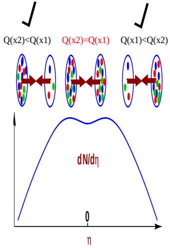
Kovchegov and Tuchin (2002)

- Recent developments for ϕ or N from the BK:
  Balitsky and Chirilli (2008); Berger and Stasto (2010)
  Kuokkanen, Rummukainen and Weigert (2011)

Reliability of the K_T-factorization

We have already data from the LHC: pp and AA collisions





Kt−factorization was proven: diluted−dense

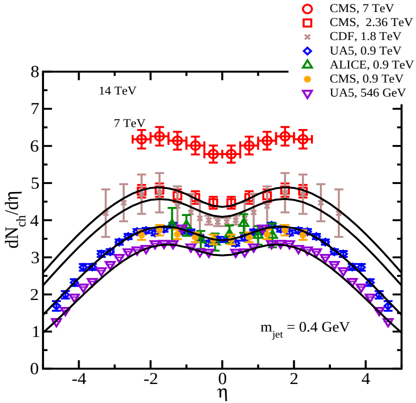
pT, Q_s >> μ (soft scale)

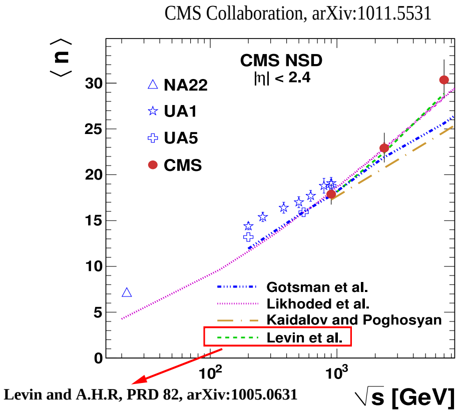
When we have three scales: Q(x1), Q(x2), pT

Kt−factorization might be violated for:

pt < Q(x1) ~ Q(x2)

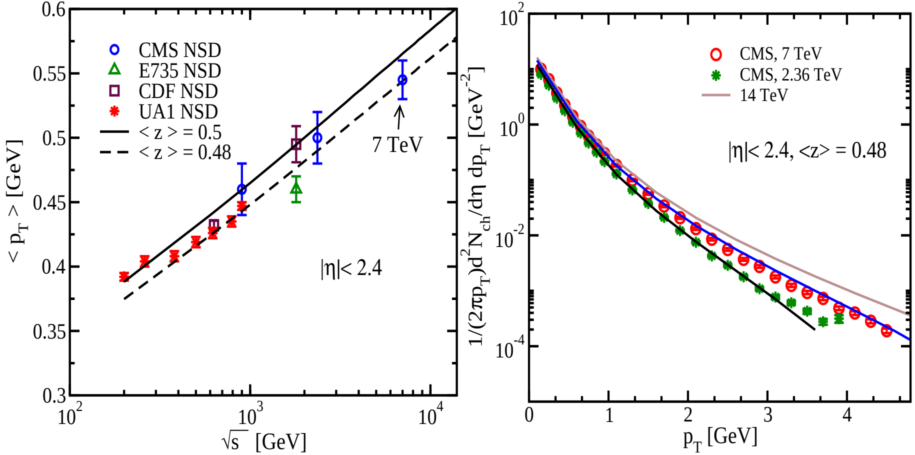
In pA collisions: Kovchegov and Mueller (98); M. A. Braun (2000); Kovchegov and Tuchin (2002); Dumitru and McLerran (2002); Blaizot, Gelis and Venugopalan (2004).



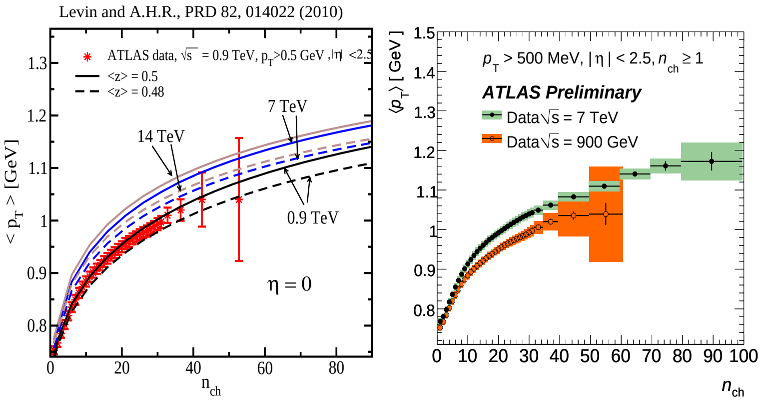


- In the above plot,it was assumed a fixed mini-jet $m_{jet} = 0.4$ GeV for all energies and rapidities.

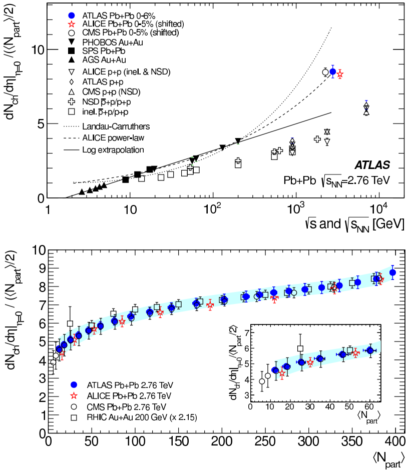
Differential yield of charged hadrons in *pp* collisions



- Saturation predictions: Levin and A.H.R.,PRD 82, arXiv:1005.0631
- $\langle p_T \rangle \sim \langle z Q_s \rangle$ √

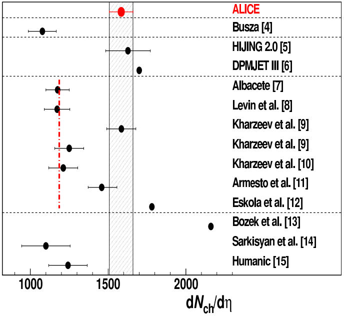


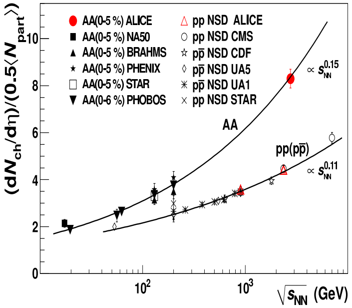
- $\langle p_T \rangle \sim \langle z Q_s\left(n_{ch}; x\right) \rangle$ √



The power-law behaviour in *AA* is so different from *pp* collisions.

ALICE collaboration, arXiv:1011.3916





The power-law behaviour in *AA* is so different from *pp* collisions.

1. Saturation approaches are based on the K_T factorization.
2. On average saturation results are consistent with each others regardless of what saturation model one has used, e.g. b-CGC, rcBK, etc...

Something universal might be then missing in the K_t factorization approach?

Some effects neglected in all saturation-based predictions shown in previous plot:

1. The effects of fluctuations and pre-hadronization
2. Gluon to hadron conversion and jet fragmentation effects
3. Soft effects due to correlations and peripheral collisions,....
4. Gluon cascade effects before hadronization:
   - Levin and A.H.R. (2011)
   - Lapii (2011)
5. Realistic (Monte-Carlo) implementation of geometrical fluctuations and the shape of nuclei:
   - Albacete and Dumitru (2011)

- Old prescription: motivated by the Local-parton-hadron duality

$$\frac{dN_h}{d\eta\, d^2p_T} \propto \frac{dN^{Gluon}}{dy\, d^2p_T} \times \mathcal{C}$$

- The correct prescription: *MLLA* gluon decays should be incorporated

$$\frac{dN_h}{d\eta\, d^2p_T} \propto \frac{dN^{Gluon}}{dy\, d^2p_T} \otimes N_h^{Gluon}(E_{jet}) \times \mathcal{C},$$

$$\frac{dN_h}{d\eta} \propto \sigma_s Q_s^2 \times N_h^{Gluon}(Q_s),$$

- $N_h^{Gluon}(E_{jet})$: Can be obtained from e^+e^- data or pQCD within the MLLA scheme (not included into the K_T-factorization).

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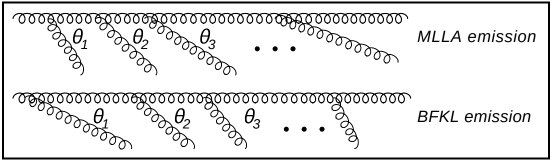
- The MLLA+LPHD→ good description of hadron multiplicity in e^+e^- and *ep* collisions. Dokshitzer, Khoze, Troian and Ochs *et al.* 1998.
- The K_t-factorization+MLLA+LPHD→ good description of hadron multiplicity in *pp* and *AA* collisions.



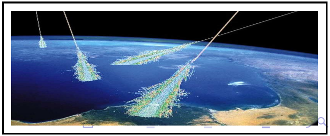
- BFKL type gluon emissions (included in the K_T-factorization):

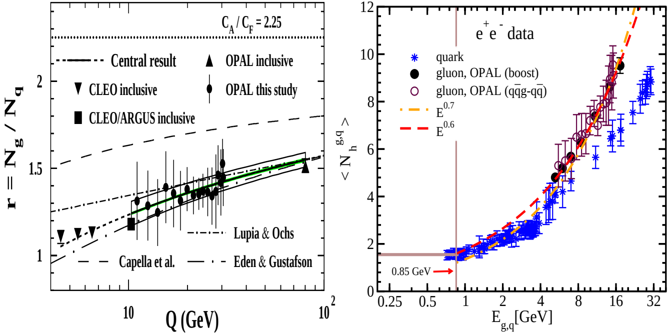
$$p^+ > k_1^+ > k_2^+ > ... > k_n^+,$$
$$p_T \sim k_{T1} \sim k_{T2} ... \sim k_{Tn},$$
$$\theta_1 < \theta_2 < \theta_3 < ... < \theta_n.$$

- MLLA type gluon emissions (reproduces N_h^{Gluon}):
This kinematics is not included in the K_T factorization scheme.

$$p^+ > k_1^+ > k_2^+ > ... > k_n^+,$$
$$p_T >> k_{T1} >> k_{T2} ... >> k_{Tn},$$
$$\theta_1 > \theta_2 > \theta_3 > ... > \theta_n.$$

Similar to Chudakov effect (1955) in QED



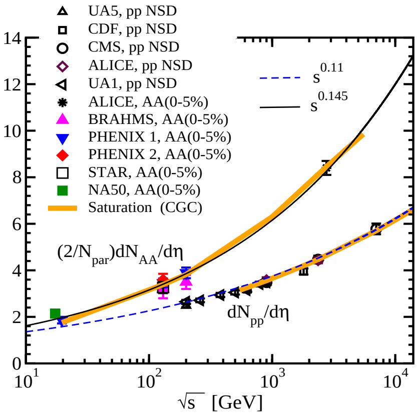


- $\langle N_h^{Gluon} \rangle \propto E_{jet}^{\delta}$, with $\delta = 0.6 \div 0.7$ for $E_{jet} \geq 0.85 \div 1$ GeV

$$\frac{dN_h}{d\eta}(pp) \propto Q_s^2 \propto s^{\lambda/2} = s^{0.11} \quad \text{for} \quad Qs \leq 0.85 \div 1 \text{ GeV}$$

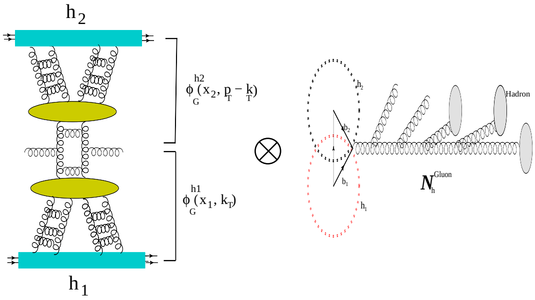
$$\frac{dN_h}{d\eta}(AA) \propto Q_s^2 \times (E_{jet} \propto Q_s)^{0.65} = s^{0.145} \quad \text{for} \quad Qs > 0.85 \div 1 \text{ GeV}$$

The energy-dependence of charged hadron multiplicity in *pp* and *AA* collisions



$$\frac{dN_h}{d\eta}(pp) \quad \propto \quad Q_s^2 \propto s^{\lambda/2} = s^{0.11} \quad \text{for} \quad Qs \leq 0.85 \div 1 \text{ GeV}$$

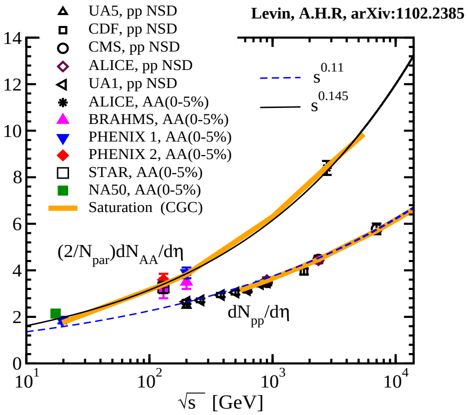
$$\frac{dN_h}{d\eta}(AA) \quad \propto \quad Q_s^2 \times (E_{jet} \propto Q_s)^{0.65} = s^{0.145} \quad \text{for} \quad Qs > 0.85 \div 1 \text{ GeV}$$



$$\frac{dN_h}{d\eta}(AA \text{ or } pp) = \frac{\mathcal{C}}{\sigma_s}\int d^2p_T\; h[\eta]\; \frac{d\sigma^{Gluon}}{dy\, d^2p_T}(AA \text{ or } pp)\;\; \mathcal{N}_h^{Gluon}(\overline{Q}_s),$$

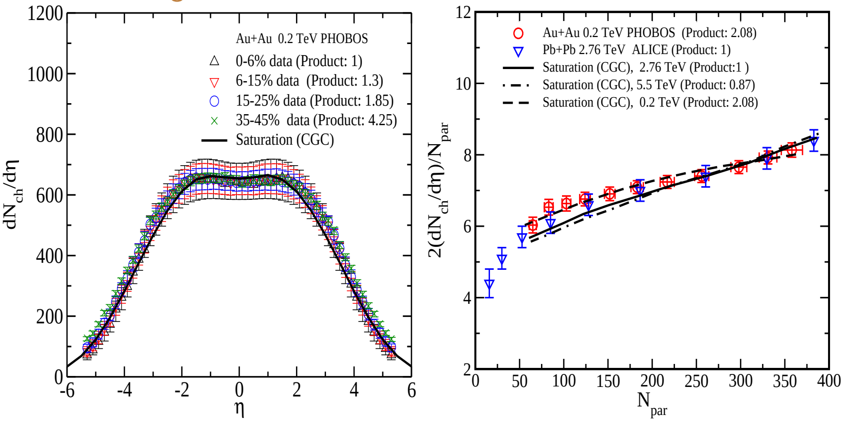
$$\mathcal{N}_h^{Gluon}(\overline{Q}_{A,p}) = C_0 \begin{cases} \left(\frac{\overline{Q}_{A,p}}{0.85}\right)^{0.65} & \text{for} \quad \overline{Q}_{A,p} \geq 0.85 \text{ GeV;} \\ 1 \quad \text{for} \quad \overline{Q}_{A,p} < 0.85, \end{cases}$$

$$\overline{Q}_{A,p} = \left(\frac{Q^2_{A,p}(x_1, b) + Q^2_{A,p}(x_2, b_-)}{2}\right)^{1/2},$$

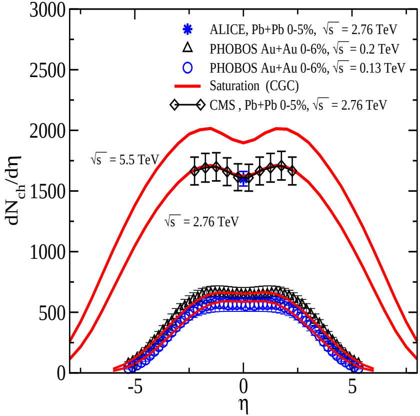


- The *pp* theory curve is from Levin and A.H.R.,PRD 82, arXiv:1005.0631 and will not change in new scheme as $Q_s(pp) < 1$ GeV.
- The gluon-decay effects in the final initial-state (before hadronization) bring extra $20 - 25\%$ contribution. This is not final-state effect as gluon decays are in the presence of the saturation scale $Q_s > 1$ GeV.

The scaling is not new, similar to the observed effect at RHIC

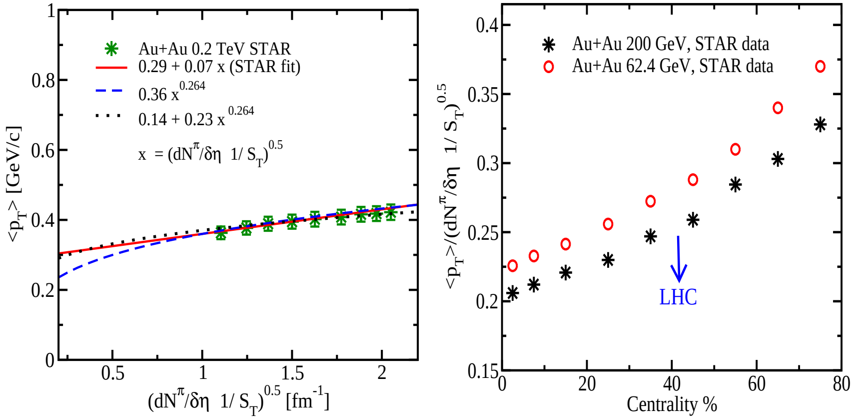


Levin and A.H.R, PRD **83**, 114001 (2011), arXiv:1102.2385.



Predictions from: Levin and A.H.R, PRD **83**, 114001 (2011), arXiv:1102.2385.

LHC Data:CMS collaboration: 1107.4800

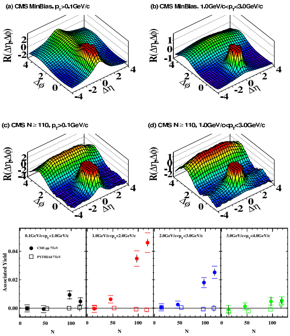


- In the KLN type approach: $\langle p_T\rangle/\sqrt{(dN/d\eta)/\sigma_s} \sim 1$
  In our approach: $\langle p_T\rangle/\sqrt{(dN/d\eta)/\sigma_s} \sim \frac{1}{n\sqrt{n}}$ with $n \sim N_h^{Gluon}$ for $Q_s \geq 1$ $\quad\rightarrow$ more suppression for more central collisions or higher energies.

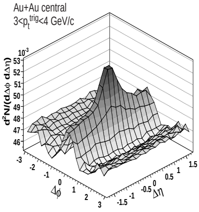
- In the KLN type approach: $x = \sqrt{(dN/d\eta)/S_T} \rightarrow \langle p_T\rangle \sim x$.
  In our approach: $\langle p_T\rangle \sim x^{0.264}$ when $Q_s \geq 1$ GeV.

At the LHC in 7 TeV *pp* collisions ridge-type structure was found

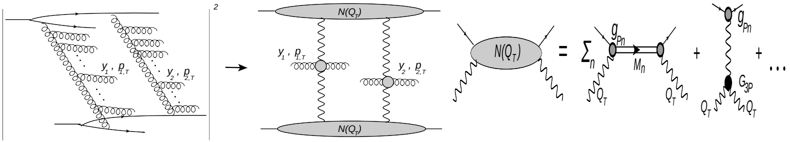
7 TeV PP



0.2 TeV AA



- Ridge at high multiplicity event selections in *pp* collisions at the LHC has a similar structure as in *AA* collisions at RHIC: Is it initial or final state phenomenon?
- v2 due to color-dipole orientation:"*Azimuthal Asymmetry of pions in pp and pA collisions*", Kopeliovich, A.H.R and Schmidt, PRD 78, 114009 (2008).



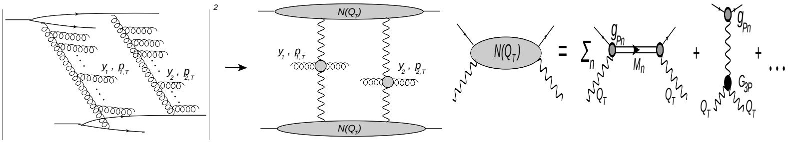
$$\frac{d\sigma}{dy_1\, d^2\vec{p}_1\; dy_2\, d^2\vec{p}_2} = \frac{1}{2}\int d^2\vec{Q}_T\; N^2_{Ph}(Q_T^2)\,\frac{d\sigma}{dy_1\, d^2\vec{p}_1}\left(\vec{Q}_T\right)\frac{d\sigma}{dy_2\, d^2\vec{p}_2}\left(-\vec{Q}_T\right)$$

$$\frac{d\sigma\,(Q_T)}{dy d^2\vec{p}_T} = 4\frac{2\alpha_s}{C_F}\int d^2\vec{q}_T K\left(\vec{Q}_T;\vec{q}_T,\vec{q'}_T\right)\frac{1}{q_T'^2(\vec{Q}-\vec{q})^2_T}\,\phi\left(Y-y,\vec{q}_T,\vec{Q}_T-\vec{q}_T\right)\phi\left(y,\vec{q}_T-\vec{p}_T,\vec{Q}_T-\vec{q}_T+\vec{p}_T\right)$$

$$\begin{aligned}\frac{\partial\phi\left(y,\vec{q'}_T,\vec{Q}_T-\vec{q}'_T\right)}{\partial y} &= \frac{\bar{\alpha}_s}{\pi}\Big\{\int d^2\vec{q''}\; K\left(\vec{Q}_T;\vec{q'}_T,\vec{q''}_T\right)\frac{1}{q_T''^2\,(\vec{Q}-\vec{q'})^2_T}\,\phi\left(y,\vec{q''}_T,\vec{Q}_T-\vec{q''}_T\right)\\ &- \left(\frac{q_T'^2}{(q'')^2_T\,(\vec{q'}-\vec{q''})^2_T}+\frac{(\vec{Q}-\vec{q'})^2_T}{(q'')^2_T\,(\vec{Q}-\vec{q'}-\vec{q''})^2_T}\right)\phi\left(y,\vec{q'}_T,\vec{Q}_T-\vec{q}'_T\right)\Big\},\end{aligned}$$

Related papers: Kovner and Lublinsky (2011).

Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi and Venugopalan (2011)



$$\frac{d\sigma}{dy_1\, d^2\vec{p}_1\; dy_2\, d^2\vec{p}_2} = \frac{1}{2}\int d^2\vec{Q}_T\; N^2_{Ph}(Q_T^2)\frac{d\sigma}{dy_1\, d^2\vec{p}_1}\left(\vec{Q}_T\right)\frac{d\sigma}{dy_2\, d^2\vec{p}_2}\left(-\vec{Q}_T\right)$$

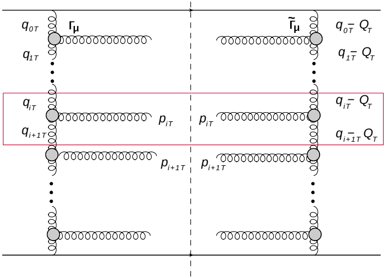
$$\frac{d\sigma\,(Q_T)}{dy d^2\vec{p}_T} = 4\frac{2\alpha_s}{C_F}\int d^2\vec{q}_T K\left(\vec{Q}_T;\vec{q}_T,\vec{q'}_T\right)\frac{1}{q'^2_T(\vec{Q}-\vec{q})^2_T}\phi\left(Y-y,\vec{q}_T,\vec{Q}_T-\vec{q}_T\right)\phi\left(y,\vec{q}_T-\vec{p}_T,\vec{Q}_T-\vec{q}_T+\vec{p}_T\right)$$

- Angular correlations stem from the $\vec{Q}_T$ integration. For example:

$$\frac{d\sigma}{dy_i\, d^2\vec{p}_i}(Q_T) \propto \vec{Q}_T\cdot\vec{p}_{i,T}\,\frac{d\tilde{\sigma}}{d^2y_i\, d^2\vec{p}_i},$$

$$\frac{d\sigma}{dy_1\, d^2\vec{p}_{1,T}\; dy_2\, d^2\vec{p}_{2,T}} \propto \vec{p}_{1,T}\cdot\vec{p}_{2,T}(\pi/2)\int dQ_T^2\; N^2_{Ph}(Q_T^2)\,\frac{d\tilde{\sigma}}{dy_1\, d^2\vec{p}_{1,T}}\left(Q_T^2\right)\frac{d\tilde{\sigma}}{dy_2\, d^2\vec{p}_{2,T}}\left(Q_T^2\right).$$

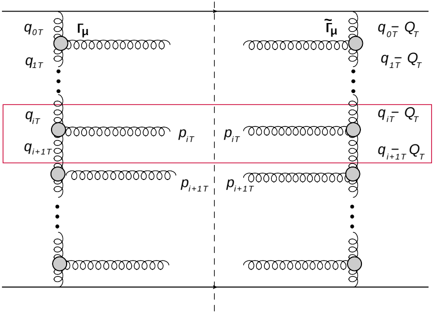
- These azimuthal correlations have long-range nature and will survive the BFKL leading log-s resummation.
- These correlations have no $1/N_c$ suppression



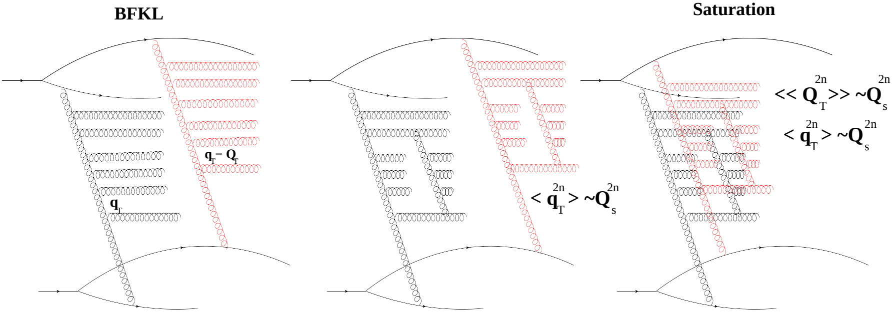
The azimuthal correlations between $\vec{Q}_T$ and $\vec{p}_{i,T}$ can be seen in the ith-rung:

$$\frac{K\left(\vec{Q}_T, \vec{q}_{i,T}, \vec{q}_{i+1,T}\right)}{(\vec{q}_{i+1,T} - \vec{p}_i)^2(\vec{q}_{i+1,T} - \vec{p}_i - \vec{Q}_T)^2 q^2_{i+1,T}(\vec{q}_{i+1,T} - \vec{Q}_T)^2}$$

$$\times \quad \left(\frac{\beta_i}{\beta_{i+1}}\right)^{\epsilon_G(\vec{q}_{i+1,T})+\epsilon_G\left(\vec{q}_{i+1,T}-\vec{Q}_T\right)} \left(\frac{\beta_{i-1}}{\beta_i}\right)^{\epsilon_G(\vec{q}_{i+1,T}-\vec{p}_i)+\epsilon_G\left(\vec{q}_{i+1,T}-\vec{p}_i-\vec{Q}_T\right)} .$$

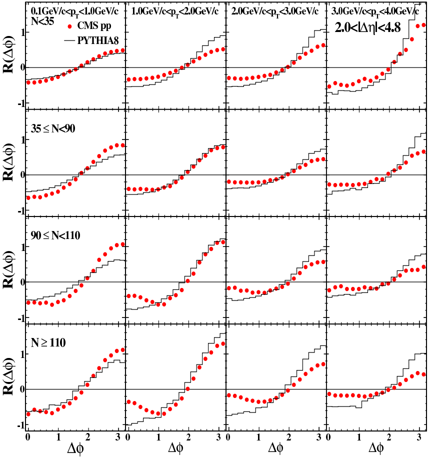


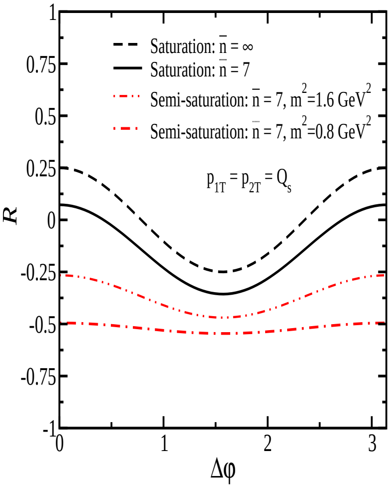
$$\frac{d\sigma}{dy_1\, dy_2\, d^2\vec{p}_{1,T}\, d^2\vec{p}_{2,T}} \approx \mathcal{N}\left(1 + \frac{1}{2}\, p_{1,T}^2\, p_{2,T}^2\, \langle\langle Q_T^4 \rangle\rangle\, \langle \frac{1}{q^4} \rangle^2 (2 + \cos(2\Delta\varphi))\right)$$



$$\langle \frac{1}{q_T^{2n}} \rangle = \frac{\int \frac{d^2\vec{q}_T}{q_T^{2n}} \phi(Y-y,\vec{q}_T,-\vec{q}_T)\,\phi(y,\vec{q}_T-\vec{p}_T,\vec{p}_T-\vec{q}_T)}{\int d^2\vec{q}_T \phi(Y-y,\vec{q}_T,-\vec{q}_T)\,\phi(y,\vec{q}_T-\vec{p}_T,\vec{p}_T-\vec{q}_T)},$$

$$\langle\langle Q_T^{2n} \rangle\rangle = \frac{\int d^2\vec{Q}_T\; Q_T^{2n}\, N_{Ph}^2(Q_T^2)}{\int d^2\vec{Q}_T\, N_{Ph}^2(Q_T^2)}.$$

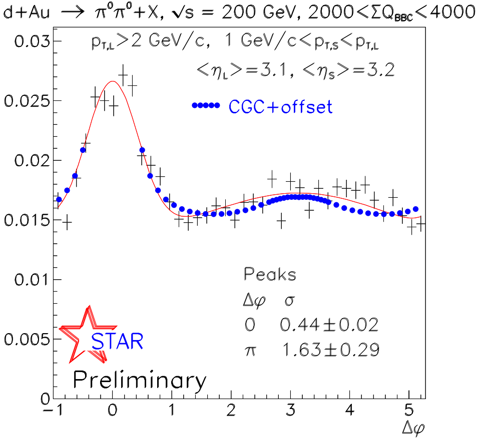


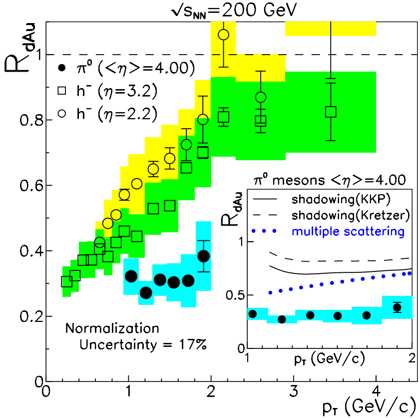


- A pronounced ridge-like structure emerges by going from the BFKL to the saturation region ($\bar{n} = N/\langle N \rangle >> 1$)
- This is fully consistent with the fact that the saturation/CGC approach provides an adequate description of other 7 TeV data in pp collisions.

Two most spectacular signatures of the CGC at RHIC

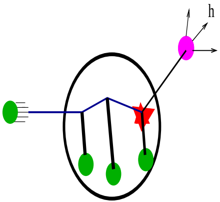
- Suppression of single inclusive hadron production at forward rapidity in d+Au
- Disappearance of the away side jet peak in dihadron production at forward rapidity in d+Au

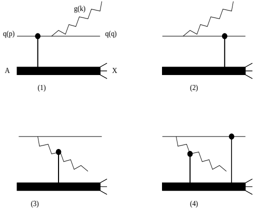




The state of the art

- Suppression of single inclusive hadron production at forward rapidity in d+Au:
  - ➤ A big piece of inelastic term at leading twist level had been missed out!! Albacete and Marquet (2010); Altinoluk and Kovner (2011); Jalilian-Marian and A.H.R. (2011)
- Disappearance of the away side jet peak in dihadron production at forward rapidity in d+Au:
  - ➤ The effects of multi-gluon correlators have been too oversimplified!! Marquet (2007); Albacete *et al.* (2010); Dumitru *et al.* (2011); Stasto *et al.* (2011); Iancu *et al.* (2011)



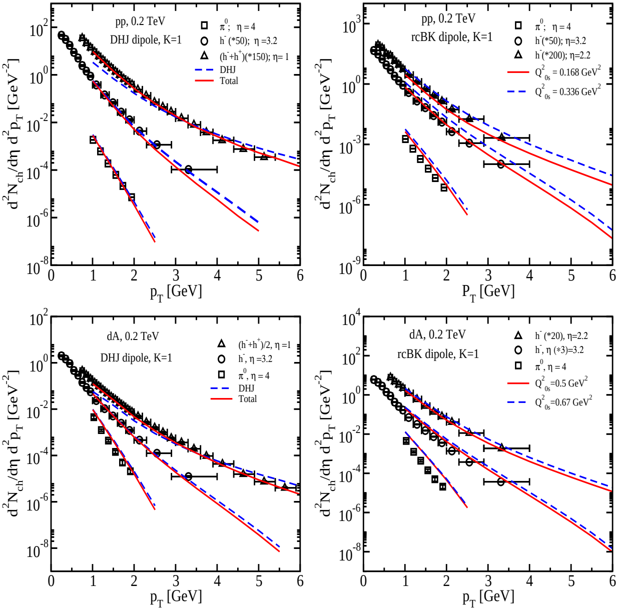


$$\frac{dN^{pA\to hX}}{d^2p_T d\eta} = \frac{K}{(2\pi)^2}\left[\int_{x_F}^{1}\frac{dz}{z^2}\left[x_1 f_g(x_1,Q^2)N_A(x_2,\frac{p_T}{z})D_{h/g}(z,Q)+\Sigma_q x_1 f_q(x_1,Q^2)N_F(x_2,\frac{p_T}{z})D_{h/q}(z,Q)\right]\right.$$
$$\left. + \int_{x_F}^{1}\frac{dz}{z^2}\frac{\alpha_s}{2\pi^2}\frac{z^4}{p_T^4}\int_{k_T^2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

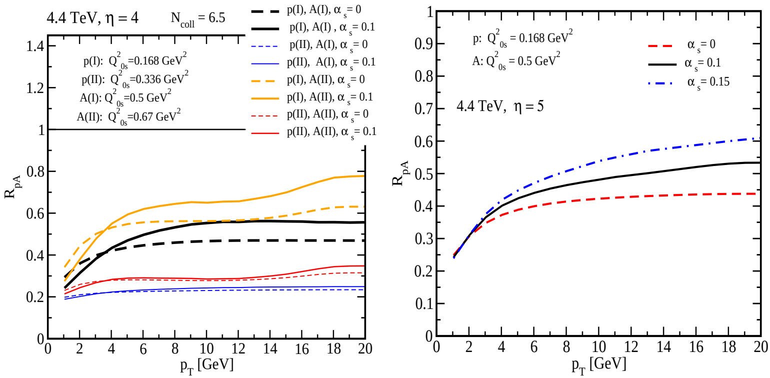
The same dipole amplitude $N_{A(F)}(x,k)$ appears in DIS and K_T-factorization

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

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

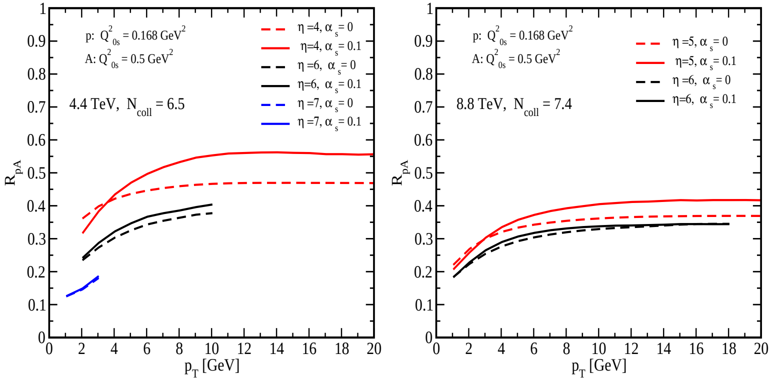


The inelastic contribution is important at about midrapidity.



- 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. Extracted from RHIC data for proton: $Q_{0s}^2 = 0.168 \div 0.336\ \text{GeV}^2$ and for gold: $Q_{0s}^2 = 0.5 \div 0.67\ \text{GeV}^2$.

Jalilian-Marian and A.H.R, arXiv:1110.2810



- 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.

conclusion:

The different power-law energy-dependence of charged hadron multiplicity in AA and pp collisions can be explained by inclusion of a strong angular-ordering in the gluon-decay cascade within the Color-Glass-Condensate approach.

- The K_t-factorization+MLLA$\rightarrow$ good description of hadron multiplicity in pp and AA collisions from RHIC to the LHC.

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The long-range rapidity correlations between the produced charged-hadron pairs from two BFKL parton showers generate considerable azimuthal angle correlations.

- These correlations have no $1/N_c$ suppression.
- A pronounced ridge-like structure emerges by going from the BFKL to the saturation region.

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R_{pA} measurement at the LHC in the forward rapidity region is a sensitive probe of the low-x dynamics.

- Inelastic contributions to single inclusive hadron production are significant at high transverse momentum and close to mid- rapidity. On the other hand, their contribution is very small in the forward rapidity region.