Ridge and Multiplicity at the LHC in pp and AA collisions from the CGC/saturation

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Outline

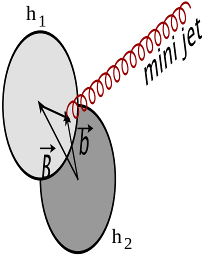
- Compare with the recent LHC data from ALICE, ATLAS, CMS.
  Is there any indication of saturation at the recent LHC data in pp?
- Inclusive hadron production in AA collisions at the LHC.
  What would be the implication of the LHC new data on AA collisions?
- The Ridge at the LHC in pp collisions
  Does it originate from the BFKL or the saturation?

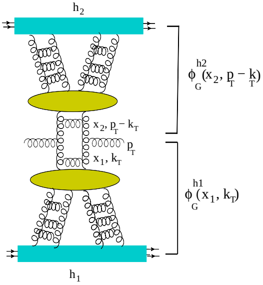
Based on references

- Levin and A.H.R, arXiv:1105.3275,
  "The Ridge from the BFKL evolution and beyond".
- Levin and A.H.R, PRD in press, arXiv:1102.2385.
- Levin and A.H.R, PRD **82**, 014022 (2010), arXiv:1007.2430.
- Levin and A.H.R, PRD **82**, 054003 (2010), arXiv:1005.0631.

Other related works (not all) that I will not cover:

- McLerran and Praszalowicz, arXiv:1006.4293. Michal Praszalowicz's talk
- Tribedy and Venugopalan, NPA **850**, 136 (2011).
- Lappi, arXiv:1104.3725.
- Albacete and Dumitru, arXiv:1011.5161. Javier Albacete's talk
- Kovner and Lublinsky, PRD **83**, 034017 (2011). Michael Lublinsky's talk
- Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi and Venugopalan, PLB **697** (2011) 21.
- Dumitru, Jalilian-Marian and Petreska, arXiv:1105.4155.
- See also talks by: Fabio Dominguez and Cyrille Marquet





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

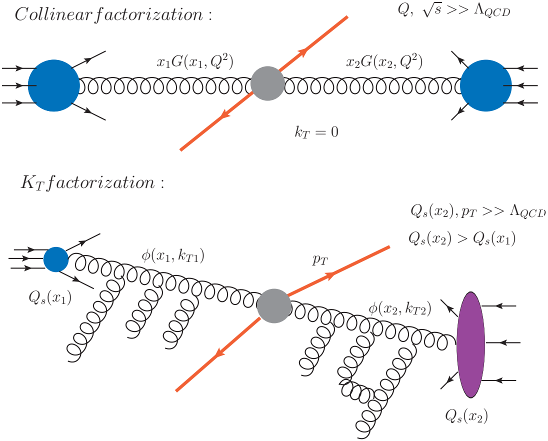
$$\phi_G^{h_i}\left(x_i;\vec{k}_T\right) = \frac{1}{\alpha_s}\frac{C_F}{(2\pi)^3}\int d^2\vec{b}\, d^2\vec{r}_T e^{i\vec{k}_T\cdot\vec{r}_T}\ \nabla_T^2\, N_G^{h_i}\left(x_i;r_T;b\right),$$

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

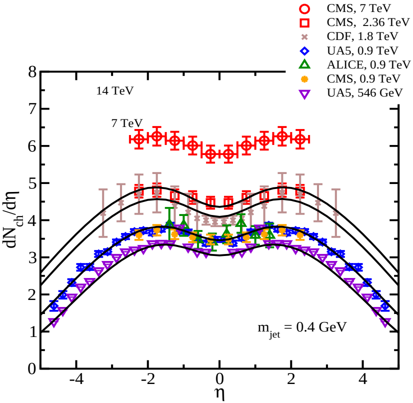
Kovchegov and Tuchin, 2002

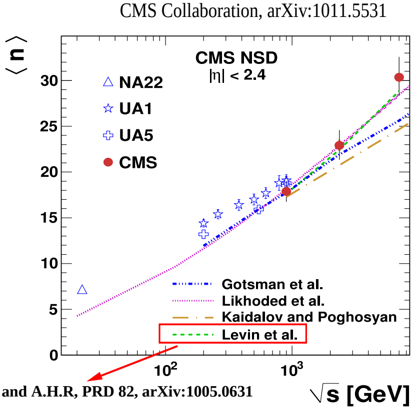
- Impact-parameter dependence of Q_s is important.

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



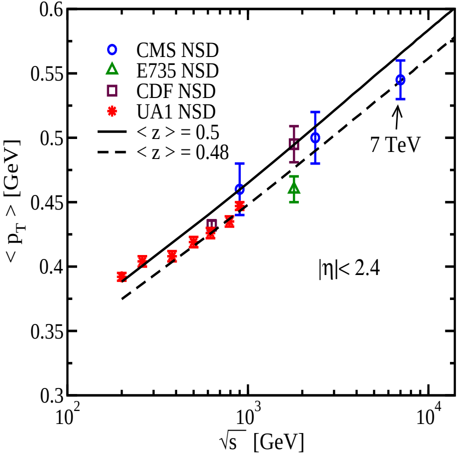
Φ is not the canonical unintegrated gluon density, is it universal?

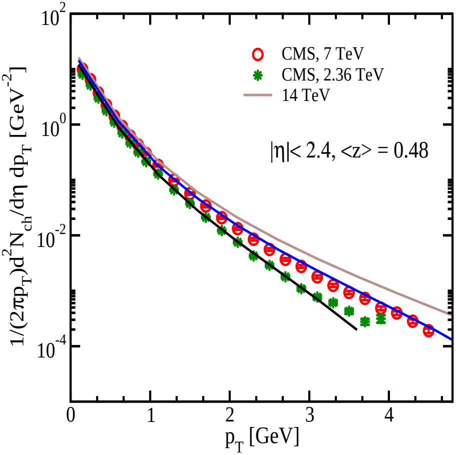




- In the above plot,it was assumed a fixed mini-jet $m_{jet} = 0.4$ GeV for all energies and rapidities.

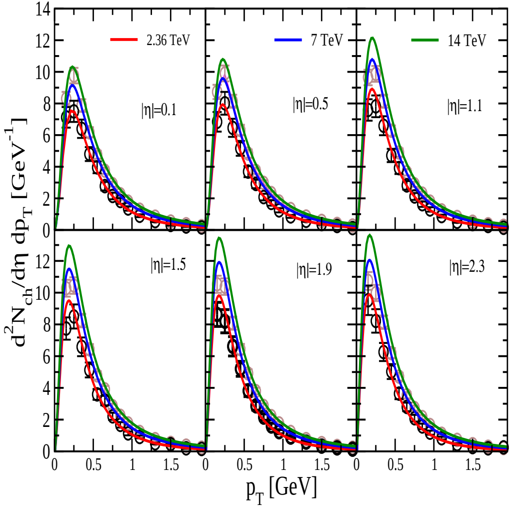
Differential yield of charged hadrons in *pp* collisions





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

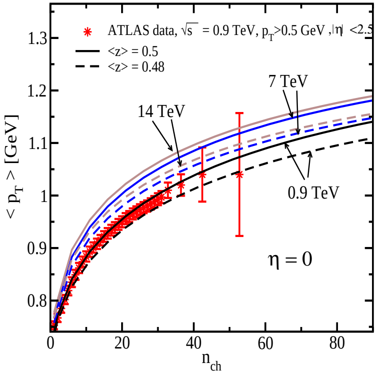
Differential yield of charged hadrons in *pp* collisions

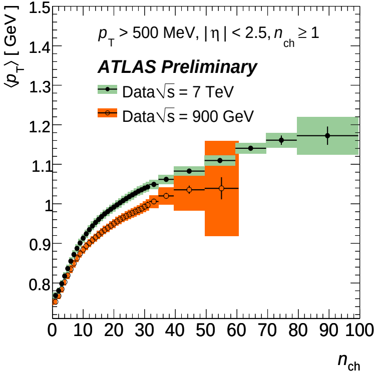


- The position of the peak is approximately at $p_T \simeq m_{jet}\langle z\rangle$ $\surd$.

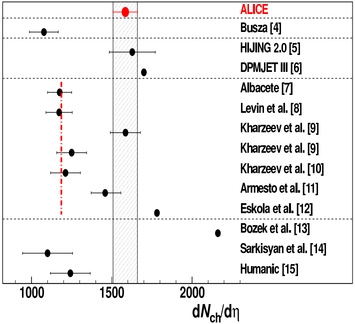
Average p_T as a function of number of charged particles

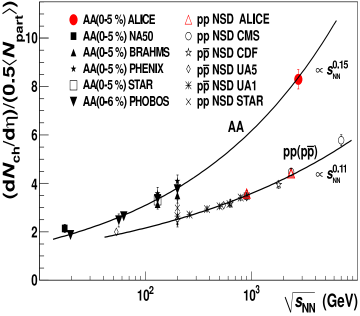
Levin and A.H.R., PRD 82, 014022 (2010)





- $\langle p_T \rangle \sim \langle zQ_s\,(n_{ch}; x)\rangle$ $\surd$





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?

- Old prescription: *MLLA* gluon decays+hadronization are *naively* taken into account by only a pre-factor $\mathcal{C}$ 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:

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

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

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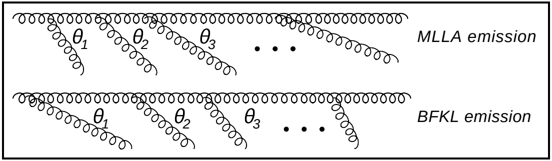
- The MLLA+LPHD→ good description of hadron multiplicity in e^+e^- and *ep* collisions. Dokshitzer, Khoze, Troian and Ochs *et al.* 1998.
- The K_t-factorization+MLLA+LPHD→ good description of hadron multiplicity in *pp* and *AA* collisions.



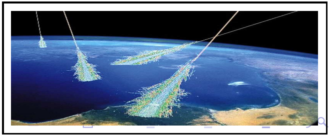
- BFKL type gluon emissions (included in the K_T-factorization):

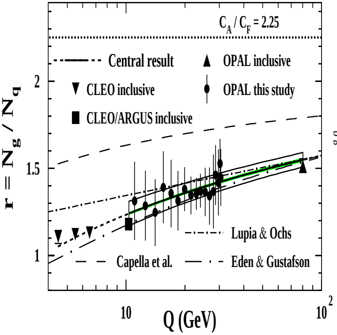
$$p^+ > k_1^+ > k_2^+ > ... > k_n^+,$$
$$p_T \sim k_{T1} \sim k_{T2} ... \sim k_{Tn},$$
$$\theta_1 < \theta_2 < \theta_3 < ... < \theta_n.$$

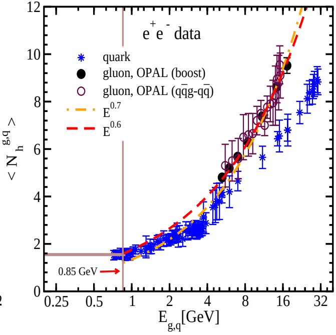
- MLLA type gluon emissions (reproduces N_h^{Gluon}):
  This kinematics is not included in the K_T factorization scheme.

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

Similar to Chudakov effect (1955) in QED



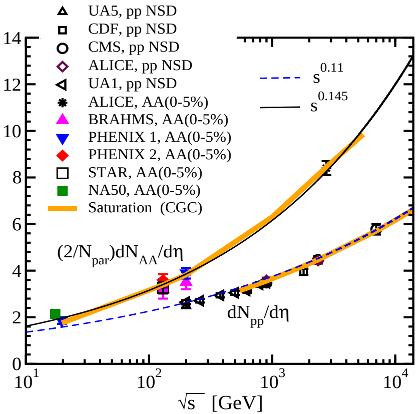




- $\langle N_h^{Gluon} \rangle \propto E_{jet}^{\delta}$, with $\delta = 0.6 \div 0.7$ for $E_{jet} \geq 0.85 \div 1$ GeV

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

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



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

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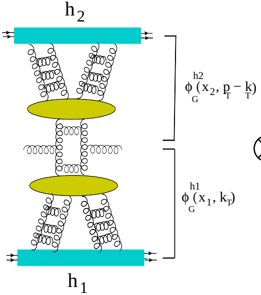

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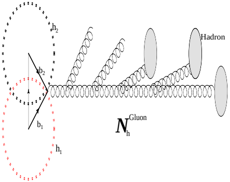


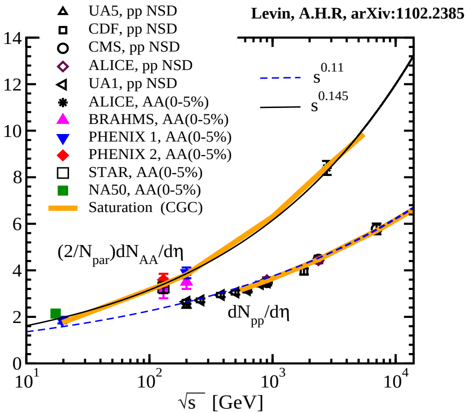
$$\frac{dN_h}{d\eta}(AA \text{ or } pp) = \frac{\mathcal{C}}{\sigma_s}\int d^2p_T\, h[\eta]\, \frac{d\sigma^{Gluon}}{dy\, d^2p_T}(AA \text{ or } pp)\ \mathcal{N}_h^{Gluon}(\overline{Q}_s),$$

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

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

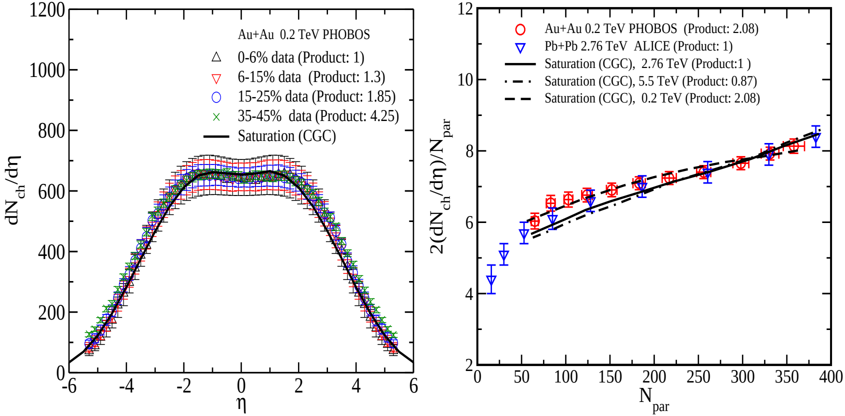
We have only two free parameters $\mathcal{C}$ and m_{jet} which will be fixed with the multiplicity data at low energy.

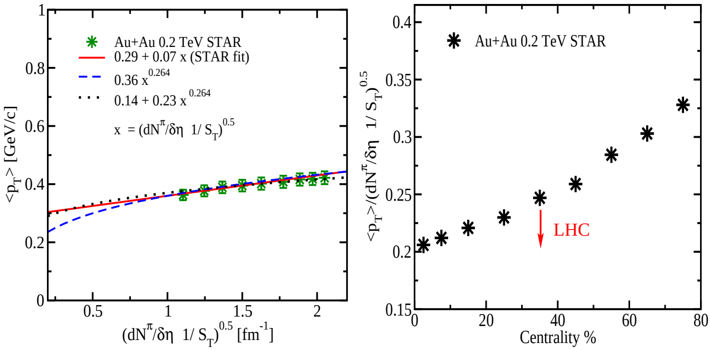
Hadron multiplicity in *pp* and *AA* collisions within the CGC



- 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.

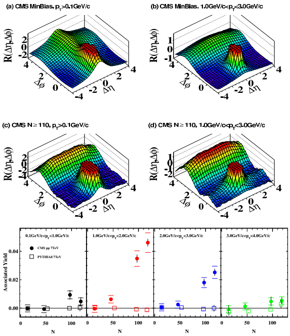
Levin and A.H.R., PRD in press, arXiv:1102.2385



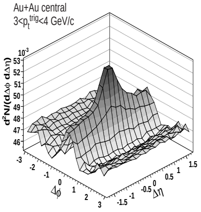


- In the KLN type approach: $\langle p_T\rangle/\sqrt{(dN/d\eta)/\sigma_s} \sim 1$
  In our approach: $\langle p_T\rangle/\sqrt{(dN/d\eta)/\sigma_s} \sim \frac{1}{n\sqrt{n}}$ with $n \sim N_h^{Gluon}$ for $Q_s \geq 1$ $\rightarrow$ more suppression for more central collisions or higher energies.
- In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

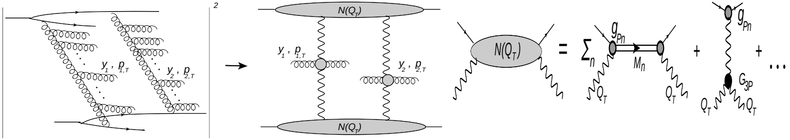
7 TeV PP



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).

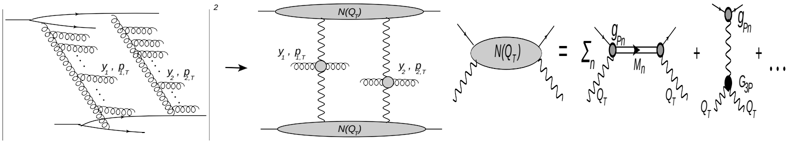


$$\frac{d\sigma}{dy_1\, d^2\vec{p}_1\, dy_2\, d^2\vec{p}_2} = \frac{1}{2}\int d^2\vec{Q}_T\, N^2_{\mathbb{P}h}(Q_T^2)\frac{d\sigma}{dy_1\, d^2\vec{p}_1}\left(\vec{Q}_T\right)\frac{d\sigma}{dy_2\, d^2\vec{p}_2}\left(-\vec{Q}_T\right)$$

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

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

$$-\left(\frac{q'^2_T}{(q'')^2_T\,(\vec{q'}-\vec{q''})^2_T}+\frac{(\vec{Q}-\vec{q'})^2_T}{(q'')^2_T\,(\vec{Q}-\vec{q'}-\vec{q''})^2_T}\right)\phi\left(y,\vec{q'}_T,\vec{Q}_T-\vec{q}'_T\right)\Big\},$$



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

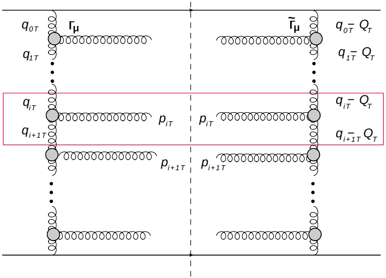
$$\frac{d\sigma\,(Q_T)}{dy d^2\vec{p}_T} = 4\frac{2\alpha_s}{C_F}\int d^2\vec{q}_T K\left(\vec{Q}_T;\vec{q}_T,\vec{q'}_T\right)\frac{1}{q'^2_T(\vec{Q}-\vec{q})^2_T}\phi\left(Y-y,\vec{q}_T,\vec{Q}_T-\vec{q}_T\right)\phi\left(y,\vec{q}_T-\vec{p}_T,\vec{Q}_T-\vec{q}_T+\vec{p}_T\right)$$

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

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

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

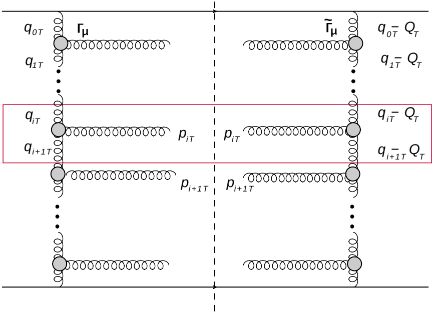
- These azimuthal correlations have long-range nature and will survive the BFKL leading log-s resummation.
- These correlations have no $1/N_c$ suppression



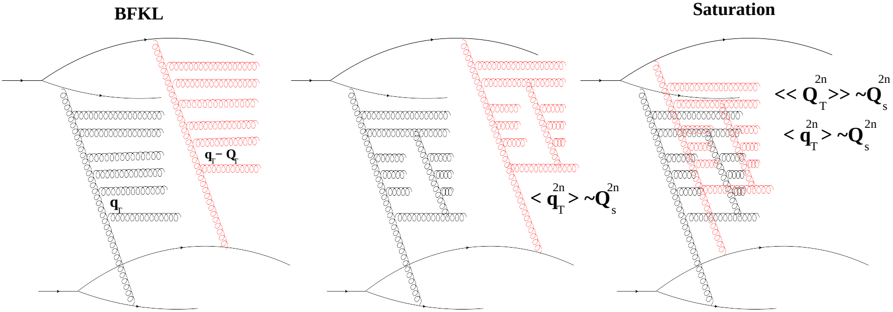
The azimuthal correlations between $\vec{Q}_T$ and $\vec{p}_{i,T}$ can be seen in the ith-rung:

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

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



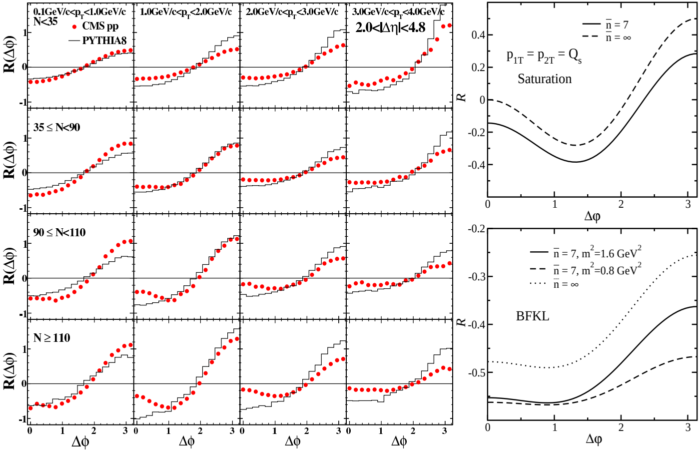
$$\frac{d\sigma}{dy_1\, dy_2\, d^2\vec{p}_{1,T}\, d^2\vec{p}_{2,T}} = \mathcal{N}\Big(1 - \frac{1}{2}\, p_{1,T}\, p_{2,T}\, \langle\langle Q_T^2\rangle\rangle\, \langle\frac{1}{q^2}\rangle^2 \cos\Delta\varphi + \frac{1}{2}\, p_{1,T}^2\, p_{2,T}^2\, \langle\langle Q_T^4\rangle\rangle\, \langle\frac{1}{q^4}\rangle^2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



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

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

Levin and A.H.R., arXiv:1105.3275



- A pronounced ridge-like structure emerges by going from the BFKL to the saturation region.
- This is fully consistent with the fact that the saturation/CGC approach provides an adequate description of other 7 TeV data in pp collisions.

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 gluon-decay effects in the final **initial-state** (before hadronization) bring extra $20 - 25\%$ contribution when $Q_s > 1$ GeV. This is not final-state effect as gluon decays are in the presence of the saturation scale $Q_s > 1$ GeV.
  - The K_t-factorization+MLLA+LPHD$\rightarrow$ good description of hadron multiplicity in pp and AA collisions from RHIC to the LHC.

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.

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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.