Gluon saturation at LHC from CGC

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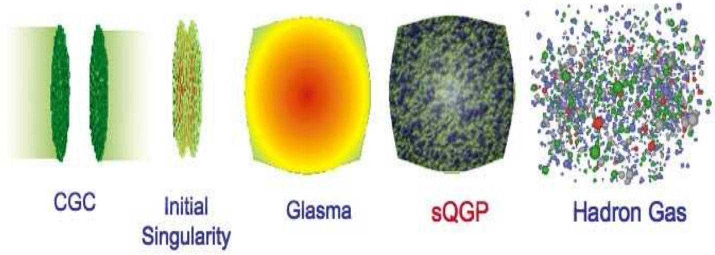
Workshop on Hadron-Hadron & Cosmic-Ray interactions at multi-TeV
29 Nov-3 Dec 2010,ECT*, Trento

Based on references

- Levin and A.H.R,"*Gluon saturation and inclusive hadron production at LHC*", PRD **82**, 014022 (2010),arXiv:1007.2430.
- Levin and A.H.R, "*Hadron multiplicity in pp and AA collisions at LHC from the Color Glass Condensate*",PRD **82**, 054003 (2010), arXiv:1005.0631.
- Kormilitzin, Levin and A.H.R. "*On the Nuclear Modification Factor at RHIC and LHC*",arXiv:1011.1248.

Outline

- Inclusive hadron production in *pp* collisions at the LHC.
- Compare with the recent LHC data from ALICE, ATLAS, CMS. Is there any indication of gluon saturation at the LHC?
- Inclusive hadron production in *AA* collisions at the LHC. What would be the implication of ALICE new data on *AA*?.

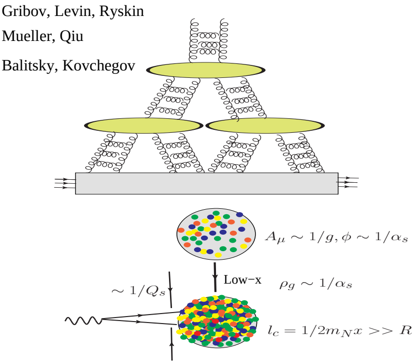


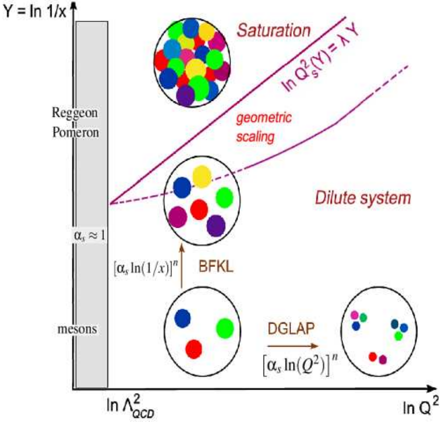
Color-Glass-Condensate (CGC)

The CGC is the universal limit for the components of a hadron wavefunction which is highly coherent and extremely high-energy density ensemble of gluons.

For recent review:
McLerran, arXiv:1011.3203; arXiv:1011.3204
Gelis, Iancu, Jalilian-Marian and Venugopalan, arXiv:1002.0333.

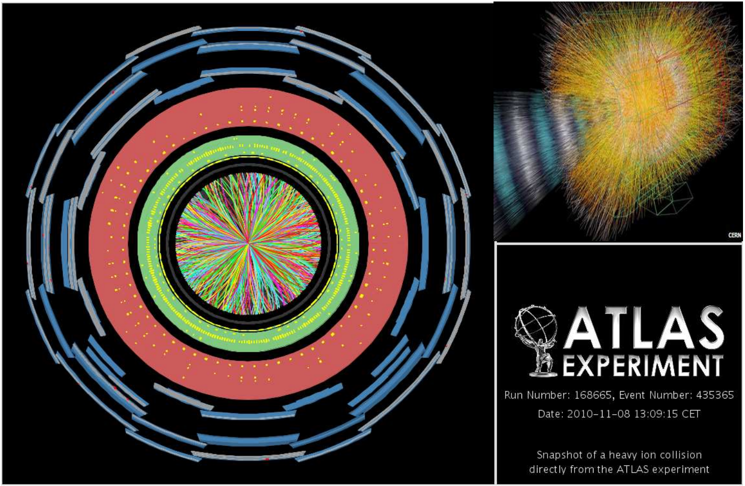
Gluon saturation





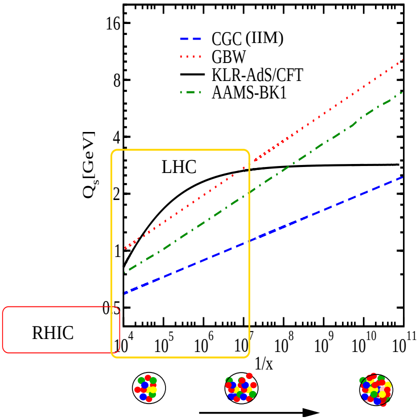
- Increasing Q^2: Density decreases, partons keep their identity.
- Increasing $1/x$: Density in the transverse grows, evolution is nonlinear.
- Hard processes develop over large longitudinal distances $l_c \sim 1/2m_N x$.

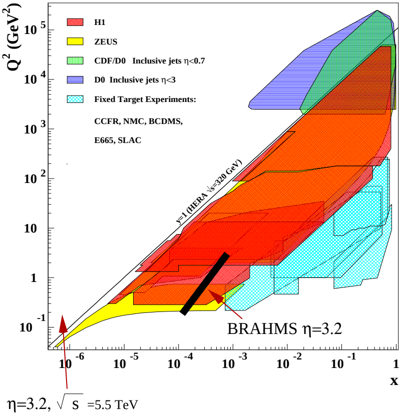
Small-x physics is very relevant at the LHC



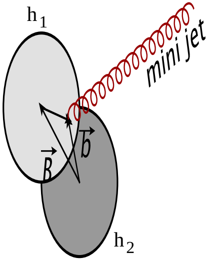
The bulk of particle production comes from very low-x ($p_T \leq 2$ GeV):
$x_2 = \frac{p_T}{\sqrt{s}} e^{-\eta}$.

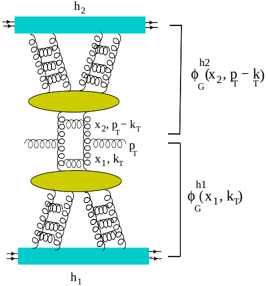
Small-x physics (and HERA) is relevant at the LHC





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.





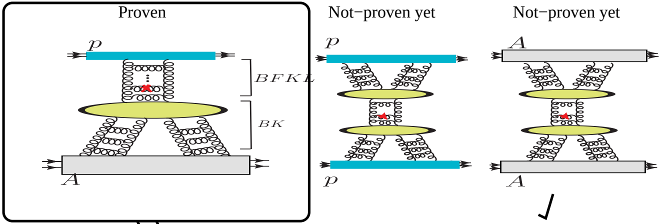
$$\frac{d\sigma^{mini-jet}}{dy\, d^2 p_T} = \frac{2\alpha_s}{C_F} \frac{1}{p_T^2} \int d^2 \vec{k}_T\ \phi_G^{h_1}\left(x_1; \vec{k}_T\right)\ \phi_G^{h_2}\left(x_2; \vec{p}_T - \vec{k}_T\right),$$

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

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

Kovchegov and Tuchin, 2002

- The relation between unintegrated-gluon density $\phi_G^{h_i}$ and the forward-dipole amplitude N is not a simple Fourier transformation.
- Impact-parameter dependence is not trivial.



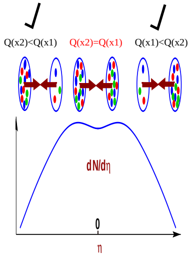
Kt−factorization was proven: diluted−dense

pT, Q_s >> μ (soft scale)

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

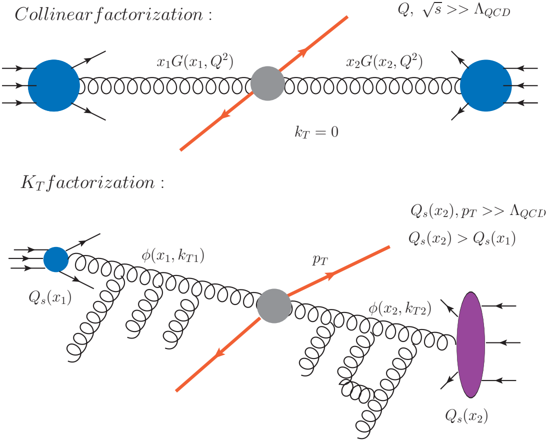
Kt−factorization might be violated for:

pt < Q(x1) ~ Q(x2)

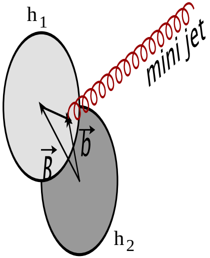


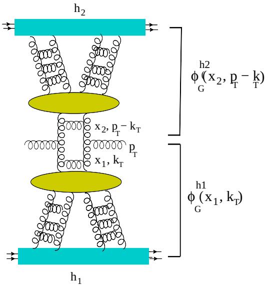
In pA collisions: Kovchegov and Mueller (98); M. A. Braun (2000); Kovchegov and Tuchin (2002); Dumitru and McLerran (2002); Blaizot, Gelis and Venugopalan (2004).

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



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





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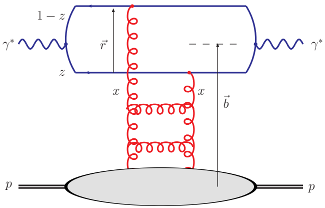
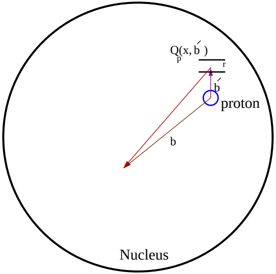
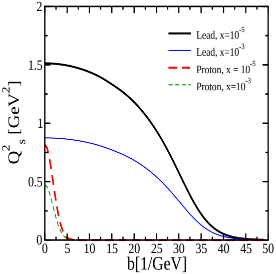
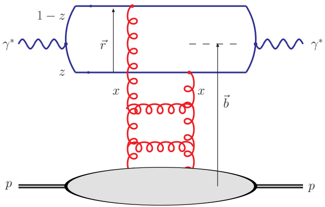


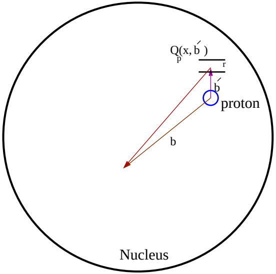


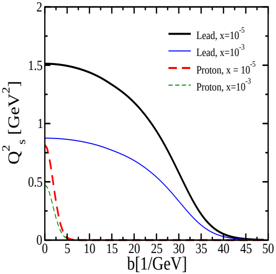


Impact-parameter dependent dipole-proton amplitude

b-CGC; describes HERA data $x < 0.01$, $Q^2 < 40$ GeV^2 with $\chi^2 = 0.92$.







Impact-parameter dependent dipole-proton amplitude

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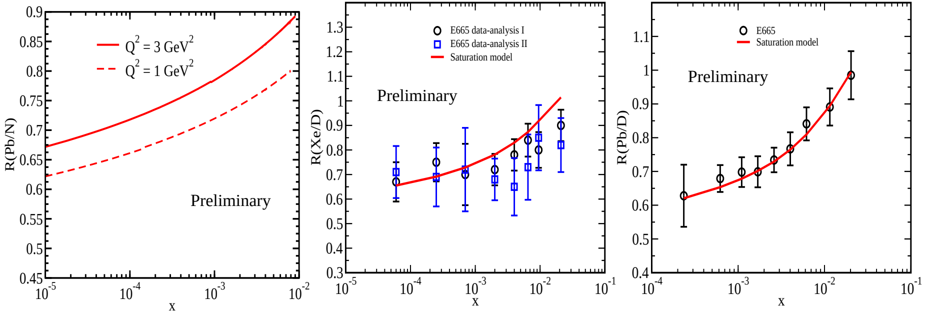
Impact-parameter dependent dipole-nuclear amplitude

The only difference between p and A is the saturation scale: $Q_{sp} \rightarrow Q_{sA}$.

$Q_A^2\,(x;b) \;=\; \int d^2\vec{b}'\;\, T_A\left(\vec{b}-\vec{b}'\right)\; Q_p^2\,(x;b')$.

Note: we have $Q_A^2 \approx Q_p^2 A^{1/3}$ since typical $b' << b \sim R_A$.



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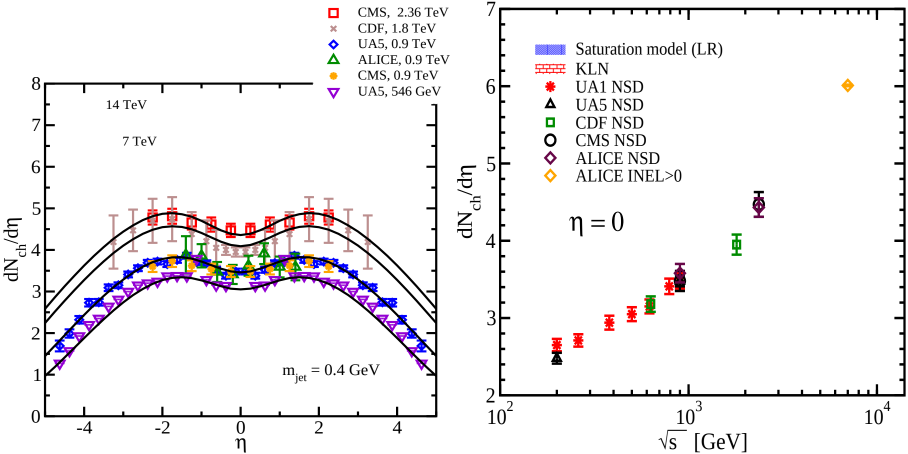
$$\frac{dN_{\text{hadrons}}}{d\eta} = \frac{\mathcal{C}}{\sigma_{nsd}} \int d^2p_T\, h[\eta] \frac{d\sigma^{mini-jet}}{dy\, d^2p_T}$$

1. Hadronization at $p_T \leq 2$ GeV: Local Parton-Hadron duality namely hadronization is a soft processes and cannot change the direction of emitted radiations ($\mathcal{C}$-factor). It works for e^+e^- annihilation into hadrons and etc...
2. Calculate $\sigma_{nsd} = \sigma_{tot} - \sigma_{el} - \sigma_{sd} - \sigma_{dd}$ in the same framework. Geometrical scaling: $\sigma_{nsd} = M\pi \left\langle \vec{b}^2_{jet} \right\rangle$ = Area of interaction.
3. Introduce mini-jet mass m_{jet} to regulaize the inclusive gluon cross-section (Pre-hadronization leads to the appearance of the mini jet mass).

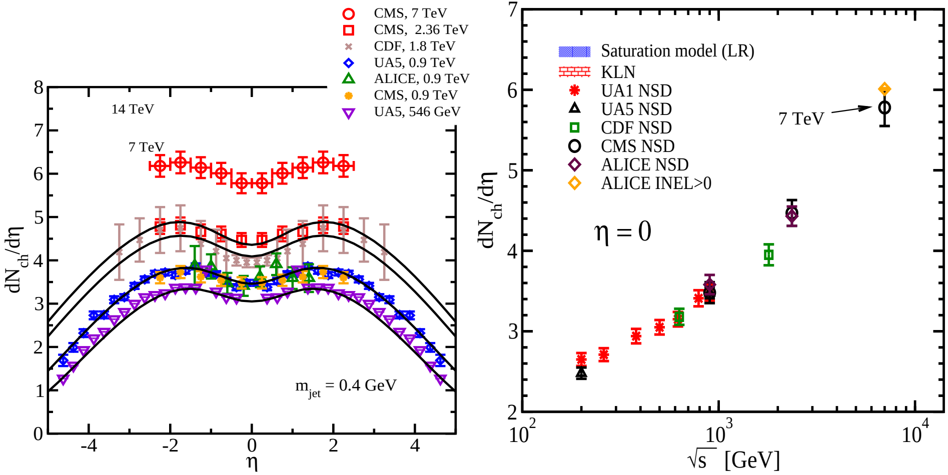
We have only two free parameters $\mathcal{C}$ and m_{jet} which will be fixed with the multiplicity data at low energy.

Levin and A.H.R., PRD 82, 014022 (2010)[arXiv:1005.0631]



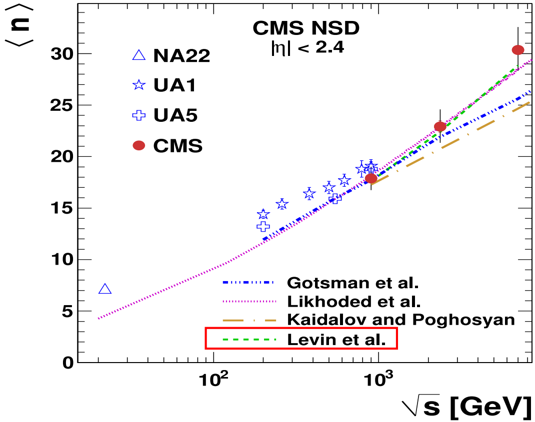
- Only $dN/d\eta$ data for *pp* at $\sqrt{s} = 546$ GeV was used to fit two parameters. Results at other energies/rapidities are predictions.
- The band indicates about 2% theoretical error.

Hadron multiplicity in *pp* collisions with 7 TeV data



- Saturation model predictions: Levin and A.H.R.,PRD 82, arXiv:1005.0631
- CMS collaboration with 7 TeV: PRL 105, arXiv:1005.3299

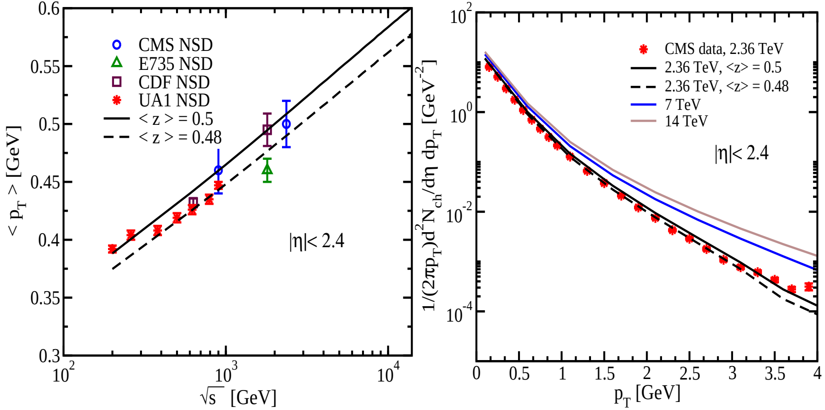
CMS Collaboration, arXiv:1011.5531



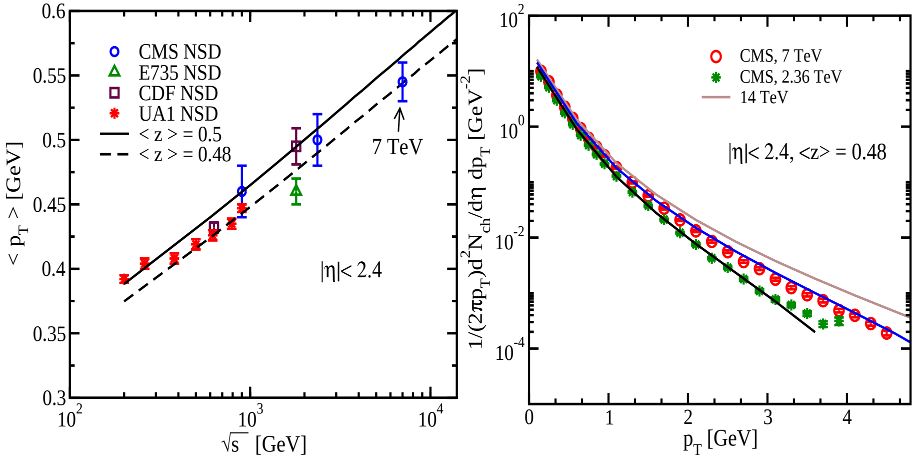
- In the above plot,it was assumed a fixed mini-jet $m_{jet} = 0.4$ GeV for all energies and rapidities. But $m_{jet}^2 \simeq 2\mu < p_T >$, and $< p_T > \sim Q_s$ makes the agreement between CGC model prediction and CMS even more striking.

Differential yield of charged hadrons in *pp* collisions without 7 TeV data

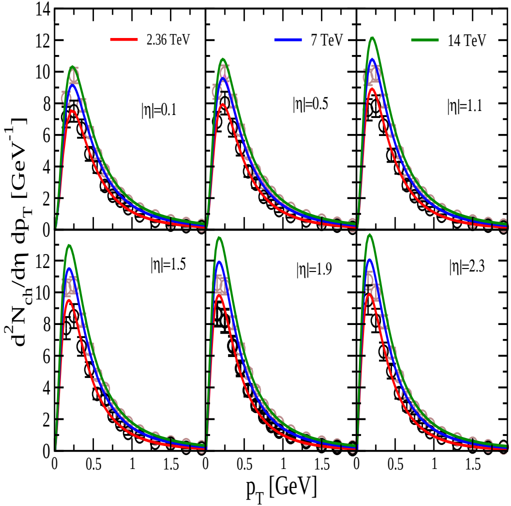
Levin and A.H.R., PRD 82, 014022 (2010)[arXiv:1005.0631]



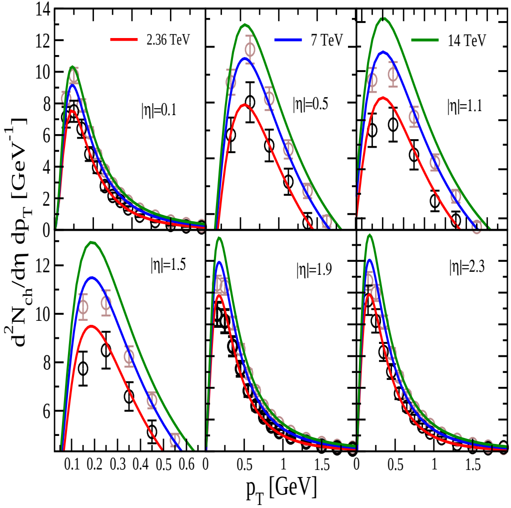
- $\langle p_{\text{hadron},T}\rangle = \sqrt{\langle z p_{\text{jet},T}\rangle^2 + \langle p_{\text{intrinsic},T}\rangle^2}$, z is the fraction of energy of the mini-jet carried by the hadron. $\langle p_{\text{intrinsic},T}\rangle = m_\pi$, $\langle z\rangle = 0.48 \div 0.5$.


0.6
0.55
0.5
0.45
0.4
0.35
0.3
10^2
10^3
10^4
$\sqrt{s}$ [GeV]
$< p_T >$ [GeV]
CMS NSD
E735 NSD
CDF NSD
UA1 NSD
< z > = 0.5
< z > = 0.48
7 TeV
$|\eta|< 2.4$
10^2
10^0
10^{-2}
10^{-4}
0
1
2
3
4
p_T [GeV]
$1/(2\pi p_T)d^2N_{ch}/d\eta\, dp_T$ [GeV^{-2}]
CMS, 7 TeV
CMS, 2.36 TeV
14 TeV
$|\eta|< 2.4$, $<z>$ = 0.48

Differential yield of charged hadrons in *pp* collisions with 7 TeV data



- The position of the peak is approximately at $p_T \simeq m_{jet}\langle z \rangle$.
- CMS 7 TeV data confirmed the prediction for the position of the peak.



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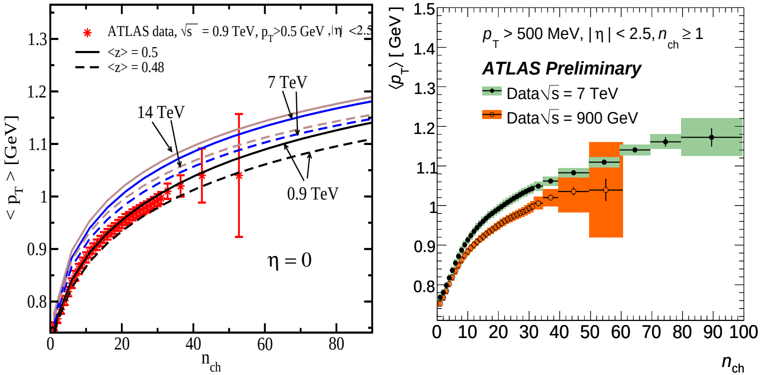
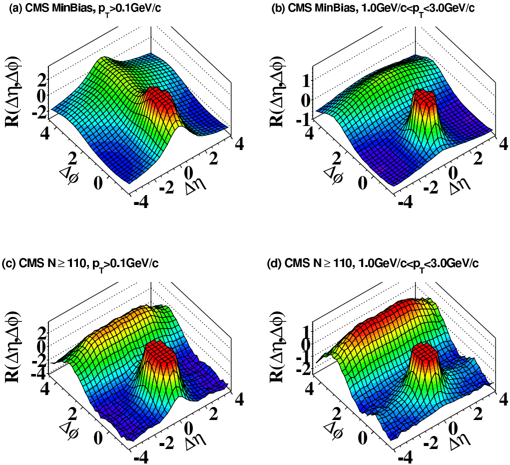
Average p_T as a function of number of charged particles

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

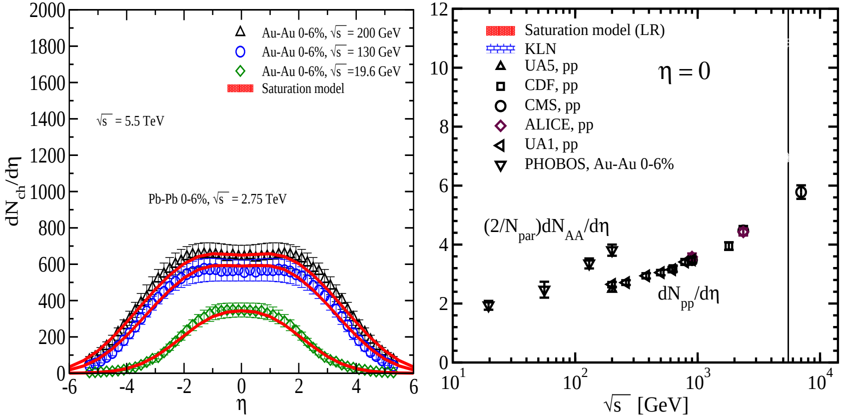


The ridge in *pp* collisions at the LHC from the CGC

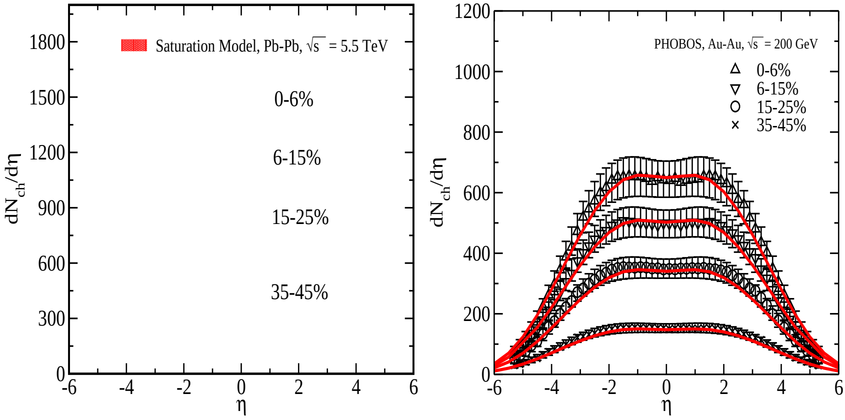


- Can be understood in the CGC framework of gluon saturation: Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi and Venugopalan, arXiv:1009.5295

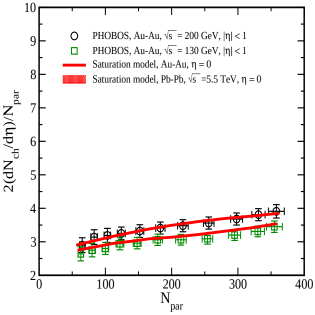
Levin and A.H.R, PRD **82**, 014022 (2010)[arXiv:1007.2430]

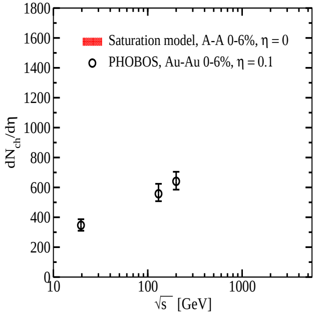


Centrality dependence at RHIC and LHC in *AA* collisions



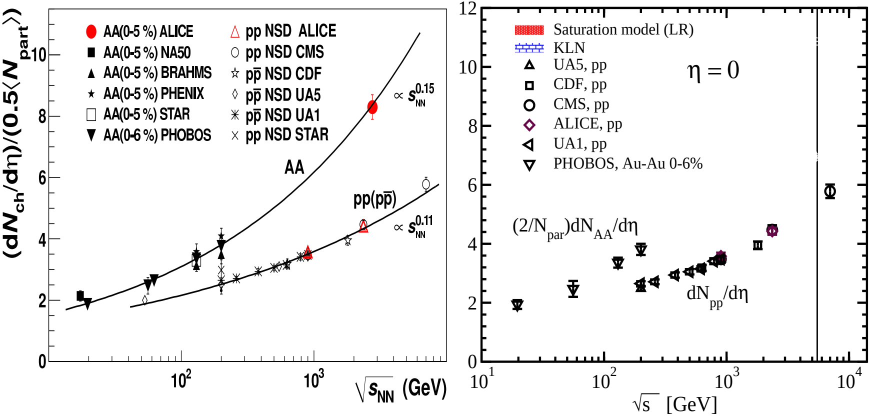
Energy and N_{par} dependence in AA collisions



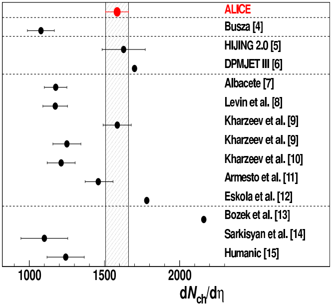


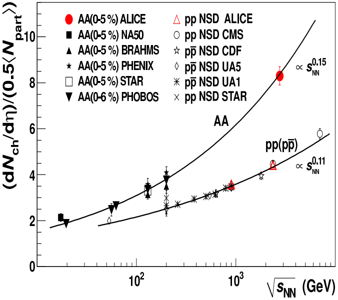
Predictions for Pb+Pb collisions at the LHC at $\eta = 0$

- $0 - 6\%$ centrality bin ($B \leq 3.7$ fm):
  $\sqrt{s} = 2.75$ TeV : $dN_{AA}/d\eta = 1152 \pm 81$
  $\sqrt{s} = 5.5$ TeV : $dN_{AA}/d\eta = 1314 \pm 92$
- $0 - 5\%$, $\sqrt{s} = 2.76$ TeV: $dN_{AA}/d\eta = 1172 \pm 82$
- ALICE: $0 - 5\% \rightarrow N_{par} = 381$, Our: $0 - 5\% \rightarrow N_{par} = 374$



- *pp* is for mini-bias NSD, *AA* is $0-5\%$, what is the value of σ^{pp}_{inel} at 2.76 TeV?. why at $0-5\%$ $N_{part}=381$ not 374?(this is not related to saturation).





ALICE $0-5\%$ corresponds to $N_{part} = 381$ while our (Levin et al) $N_{part} = 374$. Therefore, our actual prediction for the same centrality bin will be higher.

The surprises are:

- The power-law behaviour in *AA* is so different from *pp*.
- The models that describes DIS for proton, DIS for nucleus, the LHC data for proton and RHIC data apparently failed to describe the ALICE data with the same accuracy.

Kharzeev, Levin and Nardi (2001-2004) approach was very successful at RHIC.

- We used a different relation between the unintegrated gluon-density and the forward dipole-nucleon amplitude in the k_t-factorization.
- We keep impact-parameter dependence of the k_t-factorization.
- The relative increase of the σ_{nsd} was calculated in our approach while in the KLN approach was taken from soft high-energy interactions.

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- We employed an impact-parameter dependent saturation model which was obtained from a fit to low Bjorken-x HERA data (no more freedom).
- In the KLN: the LHC saturation momentum was found via an extrapolation of the energy dependence of the saturation scale at RHIC in the BFKL region.

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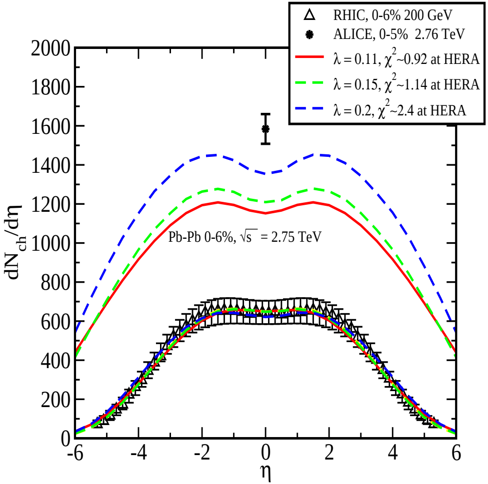
- We described *pp*, *ep* and *eA* data within the same model.



- Looks like it is difficult to describe at the same time HERA, RHIC and ALICE!!

Main conclusion:

The CGC approach provided correct predictions for 7 TeV data for pp

- Multiplicity distribution.
- Inclusive charged-hadron transverse-momentum distribution.
- The position of peak in differential yield.
- Average transverse momentum of the produced hadron on energy and hadron multiplicities.
- It also describes *ep*, *eA* and *AA* (at RHIC) within the same model.

Main conclusion:

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If ALICE data on AA will be confirmed by ATLAS and CMS:

- Saturation models gave correct predictions for multiplicity in AA collisions at the LHC within about less than 20% error. Indeed, this is not horribly bad given the simplicity of the approach.
  - What is the role of final-state effects?
  - How the mini-jet mas changes with energy/rapidity in a very dense medium?.
  - What is the effects of fluctuations and pre-hadronization?

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  - What is the effects of fluctuations and pre-hadronization?
- Recall: gluon production in AA collisions is still an open problem in the CGC.
  - We should examine more carefully the k_T factorization for AA collisions.

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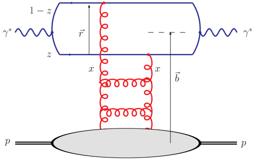
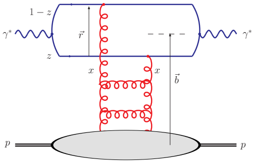
  - What is the effects of fluctuations and pre-hadronization?
- Recall: gluon production in *AA* collisions is still an open problem in the CGC.
  - We should examine more carefully the k_T factorization for *AA* collisions.
- We should rethink about saturation models, how it changes from *ep*, *pp*, *eA* collisions to *AA* collisions.



Kt-factorization depends on impact-parameter. Moreover, impact-parameter dependence is crucial here in order to relate $d\sigma/dy \rightarrow dN/dy$.



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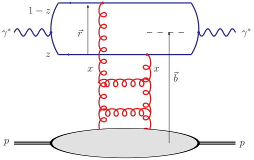
- *b*-dependent numerical solution to the BK eq is not yet available.
- Higher-order corrections to the BK(or JIMWLK) eq is not yet available.



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- b-dependent numerical solution to the BK eq is not yet available.
- Higher-order corrections to the BK(or JIMWLK) eq is not yet available.
- We use b-CGC dipole model which satisfies all well-known properties of the low-x physics (and BK eq): geometric-scaling, etc...

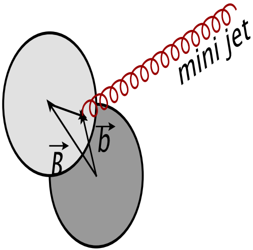
$$N\left(Y;r;b\right) = \begin{cases} N_0 \left(\frac{\mathcal{Z}}{2}\right)^{2\left(\gamma_s + \frac{1}{\kappa\lambda Y}\ln\left(\frac{2}{\mathcal{Z}}\right)\right)} & \text{for } \mathcal{Z} = rQ_s(x) \leq 2\,; \\ 1 - \exp\left(-A\ln^2\left(B\mathcal{Z}\right)\right) & \text{for } \mathcal{Z} = rQ_s(x) > 2\,; \end{cases}$$

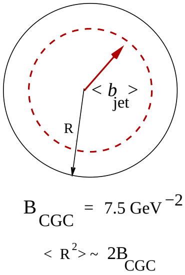
$$Q_s(x;b) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}} \exp\left\{-\frac{b^2}{4(1-\gamma_{cr})B_{CGC}}\right\} \qquad \lambda = 0.11$$

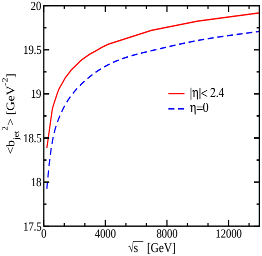
Watt and Kowalski (2008); Iancu, Itakura and Munier (2004).

$$\frac{dN_{\text{hadrons}}}{d\eta} = h[\eta]\frac{\mathcal{C}}{\sigma_{nsd}}\int d^2p_T\,\frac{d\sigma^{mini-jet}}{dy\,d^2p_T}$$

- 5: In past (e.g. KLN's papers) $\sigma_{nsd} = \sigma_{tot} - \sigma_{el} - \sigma_{sd} - \sigma_{dd}$ taken from soft interaction models. But this is not consistent within the same picture!! Note: experimental data on σ_{dd} is very limited, σ_{sd} is measured with rather large errors and even for the total cross-section σ_{tot} we have two values at the Tevatron.
- $\sigma_{nsd} = M\pi\left\langle \vec{b}^2_{jet}\right\rangle$ = Area of interaction
  - The geometric-scaling: partons are distributed uniformly in the transverse plane in the wave-function of a fast hadron in a such way that the wave-function generates a uniform distribution of the produced partons after the interaction with the target. Therefore, the NSD (inelastic) cross-section is proportional to the area occupied by partons.
  - The elastic (diffractive) cross-section corresponds to a rare event where the target does not destroy (only partially) the coherence of the gluons in the wave-function.



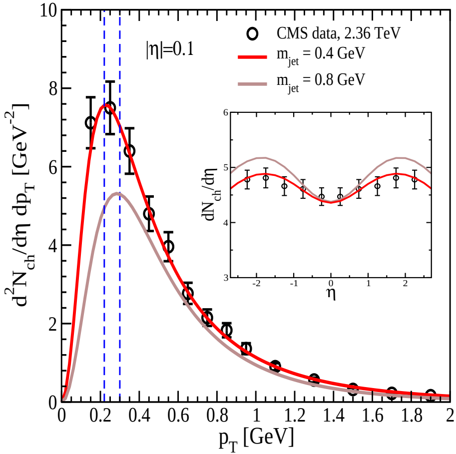




Geometrical-scaling of scattering amplitude:

- $\sigma_{nsd} = M\pi \left\langle \vec{b}^2_{jet} \right\rangle$ = Area of interaction

$$\left\langle \vec{b}^2_{jet} \right\rangle = \frac{\int \frac{d^2 p_T}{p_T^2} \int d^2\vec{b}\, d^2\vec{B}\, d^2 r_T \left(b^2 + |\vec{b} - \vec{B}|^2 \right) e^{i\vec{k}_T \cdot \vec{r}_T}\ \nabla^2_T N_G^{h_1}(x_1; r_T; b)\ \nabla^2_T N_G^{h_2}\left(x_2; r_T; |\vec{b} - \vec{B}| \right)}{\int \frac{d^2 p_T}{p_T^2} \int d^2\vec{b}\, d^2\vec{B}\, d^2 r_T\, e^{i\vec{k}_T \cdot \vec{r}_T}\ \nabla^2_T N_G^{h_1}(x_1; r_T; b)\ \nabla^2_T N_G^{h_2}\left(x_2; r_T; |\vec{b} - \vec{B}| \right)}.$$



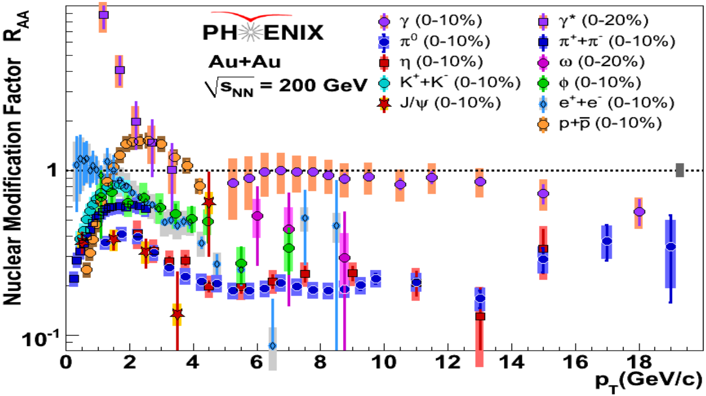
- $\frac{d^2N}{d\eta dp_T} \propto \frac{2\pi p_T}{p_T^2 + \langle z\rangle^2 m_{jet}^2}\mathcal{F}(x_1, x_2, p_T)$
- The position of the peak is then approximately at $p_T \simeq m_{jet}\langle z\rangle \approx 0.2$ GeV since we have $\langle z\rangle \approx 0.5$ and $m_{jet} \approx \sqrt{2\mu Q_s} \approx 0.4$ GeV

$$\frac{d\sigma}{dy\, d^2p_T}\|_{y=0}, = \frac{2C_F}{\alpha_s 2(2\pi)^3}\,\frac{1}{x_\perp^2}\int d^2b\, d^2B \int_{-\infty}^{+\infty} dz\, e^{-z}\, J_0\left(e^{\frac{1}{2}z}\, x_\perp\right)\, \nabla_z^2 N_G\left(z; b\right)\, \nabla_z^2 N_G\left(z; |\vec{b}-\vec{B}|\right)$$

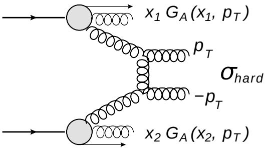
with $z = \ln\left(r^2 Q_s^2\right)$ and $x_\perp = p_T/Q_s$. K_T factorization has geometric-scaling property at $y = 0$.

$$R_{AA} \equiv \frac{1}{A^2}\,\frac{S_A^2}{S_p^2}\,\frac{\mathcal{T}\left(x_\perp\right)}{\mathcal{T}\left(x_\perp \frac{Q_{s,A}}{Q_{s,N}}\right)}$$

- Beyond the extended geometric-scaling region for $p_T > 3 \div 4\, Q_s$ one may expect that inclusive cross-section for AA and pp to be $\alpha_s(p_T^2)/p_T^4$ and $R_{AA} \to 1$. But this is not the case!



- What make R_{AA} to be so small even at high-p_T?
- What make R_{AA} to be flat at high-p_T?, what is the onset of flatness?
- Can it be calculated perturbatively?
  For the detailed answers see: Kormilitzin, Levin and A.H.R, arXiv:1011.1248



$$\frac{d\sigma_{AA}}{dy,\, d^2 p_T}|_{y=0} \quad = \quad A^2 \frac{\alpha_s^2(p_T)}{p_T^4}\, x_1 G_p\,(x_1 = 2p_T/\sqrt{s},\, p_T)\;\, x_2 G_p\,(x_2 = 2p_T/\sqrt{s},\, -p_T)$$

$$\xrightarrow{p_T >> Q_0} A^2 \frac{\alpha_s^2(p_T)}{p_T^4} \left(p_T^2/Q_0^2\right)^{2\gamma}$$

$$R_{AA}^g \quad \xrightarrow{\sqrt{s} \gg p_T \gg Q_s} \quad 1$$

$$R_{AA}^h \quad \xrightarrow{\sqrt{s} \gg p_T \gg Q_s} \quad \frac{\alpha_s^2\,(p_T/z_A)\,(p_T/z_A)^{4\alpha_s(p_T/z_A)}}{\alpha_s^2\,(p_T/z_h)\,(p_T/z_h)^{4\alpha_s(p_T/z_h)}} \times \left(\frac{z_A}{z_h}\right)^4.$$

- If $z_A = z_h$, then $R_{AA} = 1$.
- At RHIC $z_A/z_p \approx 0.76$ we have $R_{AA}^h \approx 0.3$ at high-p_T.
- R_{AA} is flat at high-p_T since p_T dependence mainly appears in α_s.

Backup: R_{AA} at RHIC and prediction for the LHC

Kormilitzin, Levin and A.H.R, arXiv:1011.1248