Color Class Condensate from electron-proton DIS to pA collisions

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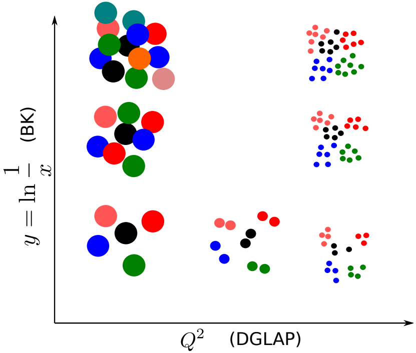
Introduction



- Study QCD at high energies
- Evolution in x (energy): BK equation
- Saturation phenomena described by CGC
- Saturation scale Q_s = characteristic momentum scale

pA is interesting as $Q_s^2 \sim A^{1/3}$.

Setting up the baseline

CGC offers a consistent framework to describe small-x data.

- Non-perturbative input: dipole amplitude at $x = x_0$
- rcBK equation gives energy (Bjorken x) evolution

Compute

- DIS
- Single inclusive hadron production in pp and pA
- Dihadron correlations, ...

In this talk: Use only HERA DIS data as an input and go consistently to pA collisions

T. Lappi, H.M, arXiv:1309.6963

Fitting

Solve rcBK with modified MV model initial condition

$$N_p(r, y=0) = 1 - \exp\left[\frac{-(r^2 Q_{sp}^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda_{\mathrm{QCD}}} + e_c \cdot e\right)\right],$$

$$\alpha_s(r^2) = \frac{12\pi}{(33 - 2N_f)\ln \frac{4C^2}{r^2\Lambda_{\mathrm{QCD}}^2}}.$$

Compute σ_r (or F_2), assume factorizable proton impact parameter profile

$$\sigma_{T,L}^{\gamma^* p} = \sigma_0 \int \mathrm{d}z |\Psi_{\gamma^* \to q\bar{q}}^{T,L}|^2 N(r, y)$$

Fit different models:

- MV with $\gamma \equiv 1, e_c \equiv 1$.
- MV^γ with $e_c \equiv 1$, fit γ (AAMQS collaboration, arXiv:1012.4408).
- MV^e with $\gamma \equiv 1$, fit e_c (NEW).

Fit result

Fit to HERA σ_r data at $Q^2 < 50\,\mathrm{GeV}^2, x < 0.01$ (MV$^\gamma$ fit by AAMQS).

	$\frac{\chi^2}{\text{d.o.f}}$	Q^2_{s0} [GeV^2]	Q^2_{s} [GeV^2]	γ	C^2	e_c	$\sigma_0/2$ [mb]
MV	2.76	0.104	0.139	1	14.5	1	18.81
MV$^\gamma$	1.18	0.165	0.245	1.135	6.35	1	16.45
MV^e	1.15	0.060	0.238	1	7.2	18.9	16.36

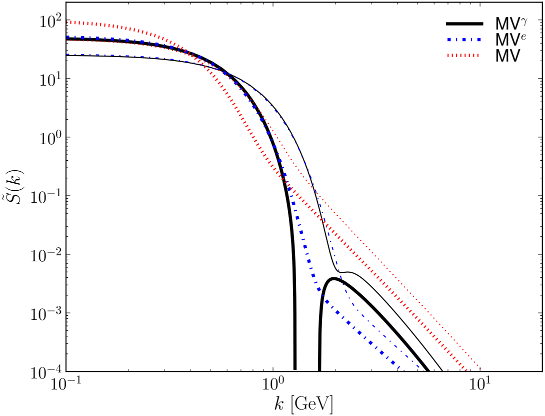
- Fit quality is significantly improved when also fitting γ or e_c.

- MV$^\gamma$: Fourier transform of $1 - N(r)$ ($\sim$ ugd) negative at large k

+ MV^e: Positive (next slide)

+ MV^e without γ is easier to generalize for nuclei.

Fourier transform of the ICs



- Thick lines: Fundamental representation
- Thin lines: Adjoint representation

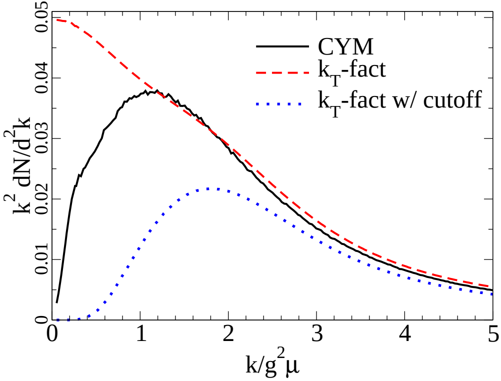
Single inclusive hadron production from CGC

Single inclusive particle production in pp using the k_T factorization:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_T \mathrm{d}y} = \frac{2\alpha_s}{C_\mathrm{F} p_T^2} \int \mathrm{d}^2 q_T \frac{\varphi_{x_1}(q_T)}{q_T^2} \frac{\varphi_{x_2}(k_T - q_T)}{(k_T - q_T)^2}$$

.

- Agrees with CYM for $p_T \gtrsim Q_s$
- φ_{x_1,x_2}: dipole (not WW) UGD of hadron 1/2. $\varphi(k_T) \sim \frac{\sigma_0}{2} k^4 \int \mathrm{d}^2 r e^{ikr}[1 - N(r)]$



Blaizot, Lappi, Mehtar-Tani, arXiv:1005.0955

Single inclusive hadron production from CGC

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_T \mathrm{d}y} = \frac{2\alpha_s}{C_\mathrm{F} p_T^2} \int \mathrm{d}^2 q_T \frac{\varphi_{x_1}(q_T)}{q_T^2} \frac{\varphi_{x_2}(p_T - q_T)}{(p_T - q_T)^2}$$

Assuming that $p_T \gg Q_s$ we get the hybrid formalism
(Note: $\varphi \sim \sigma_0/2 =$ proton DIS area).

$$\frac{\mathrm{d}N}{\mathrm{d}y\mathrm{d}^2 p_T} = \frac{\sigma_0/2}{\sigma_\mathrm{inel}} \frac{1}{(2\pi)^2} xg(x, Q^2) \tilde{S}(p_T),$$

where

$$xg(x, Q^2) = \frac{C_\mathrm{F} \sigma_0/2}{2\pi^2 \alpha_s} \int^{Q^2} \frac{\mathrm{d}^2 q_T}{(2\pi)^2} q_T^2 \tilde{S}(q_T),$$

(or e.g. CTEQ) and $\tilde{S}$ is Fourier transform of $1 - N(r)$ (adj. rep.).

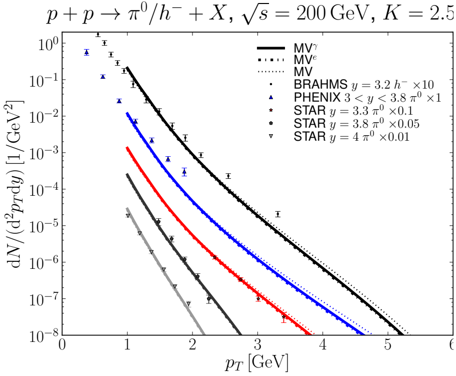
Normalization factor

At RHIC (LHC) $(\sigma_0/2)/\sigma_\mathrm{inel} \sim 0.4$ (0.3)

Single inclusive hadron production from CGC

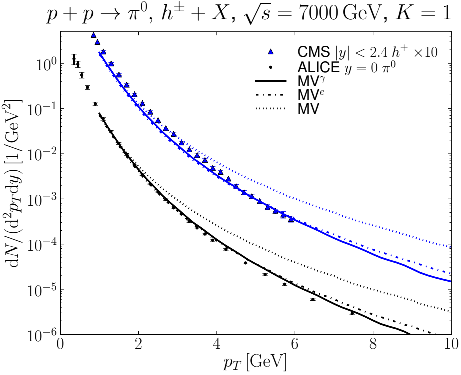
MV^γ and MV^e models work with the LHC data, MV does not.

RHIC



Hybrid formalism, LO CTEQ&DSS

LHC



k_T factorization, LO DSS

From proton to nucleus

Initial condition for nuclei: Glauber (dilute limit $\sigma_{\text{dip}}^A \sim A\sigma_{\text{dip}}^p$)

$$N_A(b,r) = 1 - \exp\left[-AT_A(b)\frac{\sigma_0}{2}\frac{(r^2Q_{sp}^2)^\gamma}{4}\ln\left(\frac{1}{\Lambda_{\text{QCD}}r} + e_c \cdot e\right)\right].$$

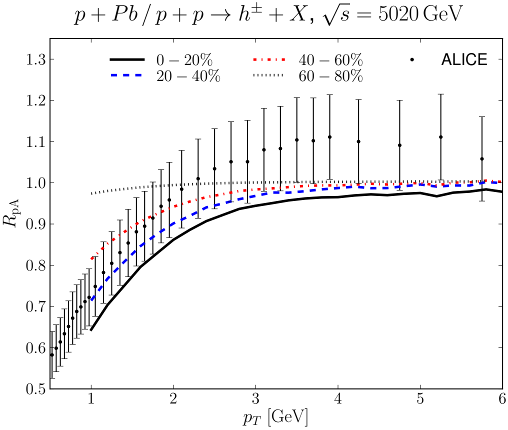
No additional nuclear parameters

- σ_0 from DIS
- T_A: standard Woods-Saxon

$\Rightarrow$ prediction for $Q_s^2(b)$.

From proton to nucleus: R_{pA}

Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)

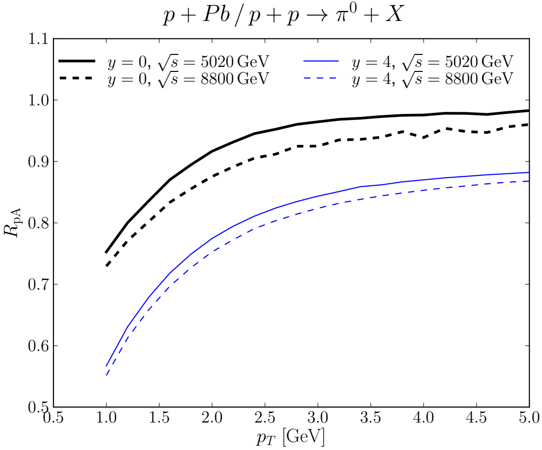


DATA: ALICE, 1210.4520

MV, MV$^{\gamma}$ and MV^{e} give ≈ same R_{pA}

Energy dependence of R_{pA}

Midrapidity $R_{pA} \to 1$ at large p_T independently of $\sqrt{s_{NN}}$!.

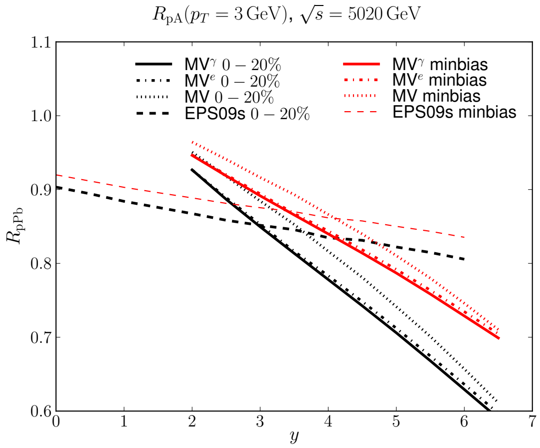


R_{pA} at $y = 0$ (k_T factorization) and at $y = 4$ (hybrid formalism)

CGC vs pQCD (EPS09s)

CGC predicts faster centrality and especially rapidity evolution than EPS09s-NLO pQCD

EPS09s calculations by I. Helenius



CGC: Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

Conclusions

- New initial condition MV^e fitted to HERA data.
- MV model must be modified (include γ or e_c) in order describe LHC pp and pA spectra
- Using only ep DIS as an input we compute single particle production in pp and pA.
- Single inclusive spectrum: absolute normalization
- Centrality and rapidity dependent predictions for R_{pA}
  - Faster rapidity evolution than predicted by NLO pQCD calculations (EPS09s).

BACKUPS

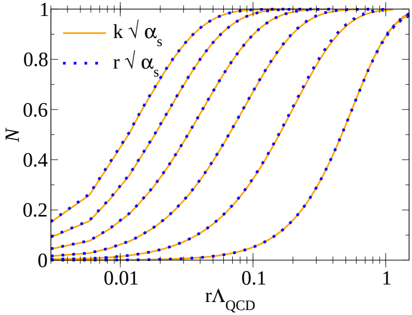
Value of Λ_{QCD}

$$\alpha_s(r^2) = \frac{12\pi}{(33 - 2N_f)\ln \frac{4C^2}{r^2\Lambda_{QCD}^2}}.$$

Fit result: $C^2 \sim 6$.
Analytically (Kovchegov, Weigert, 2007): $4C^2 = 4e^{-2\gamma_E}$
$\Rightarrow$ Effectively $\Lambda_{QCD} \sim 50\,\mathrm{MeV}$?? (NLO effects $\rightarrow$ slower evolution?)

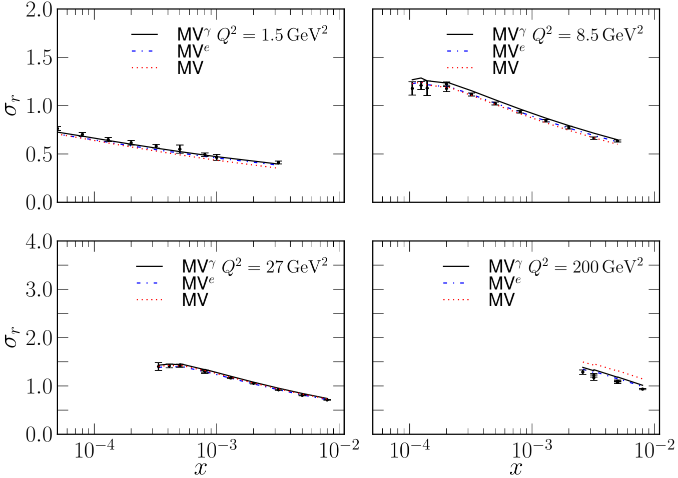
Dipole amplitude at various y from JIMWLK

- Solid: $\alpha_s(k)$ (standard)
- Dashed: $\alpha_s(r)$, $4C^2 = 4e^{-2\gamma_E}$



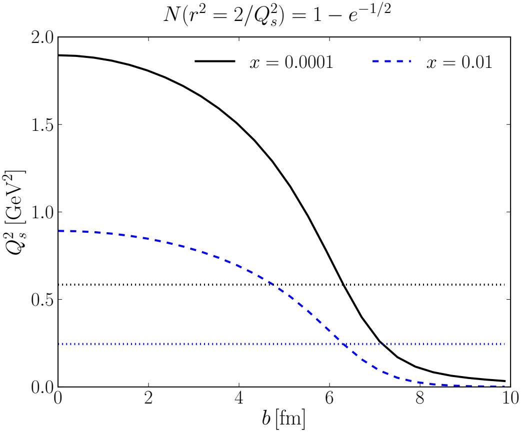
T. Lappi, H. M. Eur. Phys. J. C73 (2013) 2307

Fit result

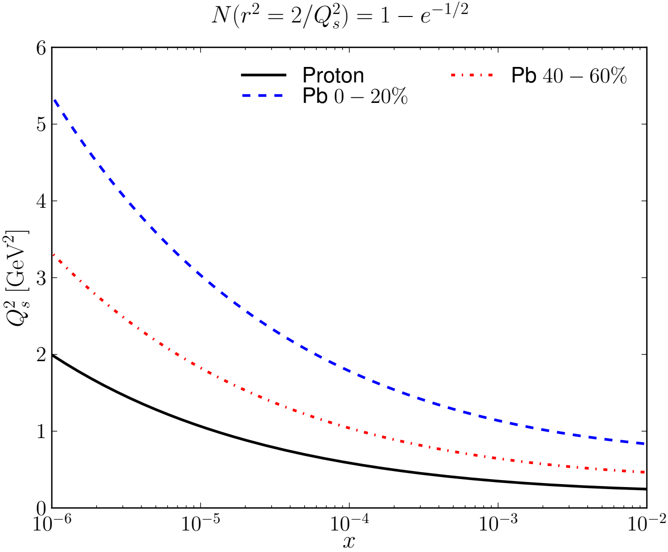


MV fitted to $Q^2 < 50\,\mathrm{GeV}^2$ HERA data (arXiv:0911.0884)

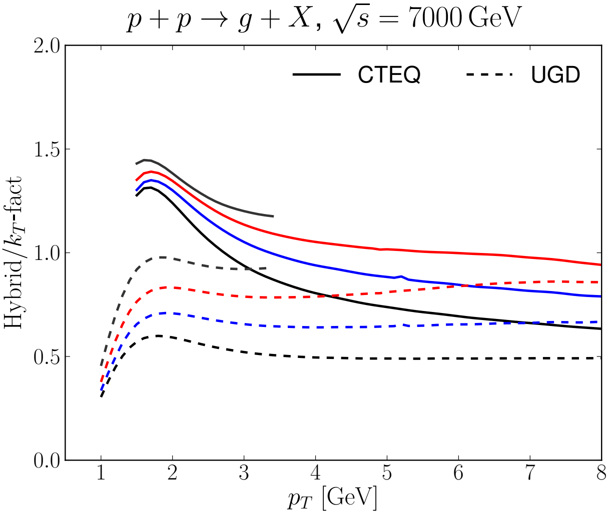
Impact parameter dependence of the saturation scale



From proton to nucleus: saturation scale

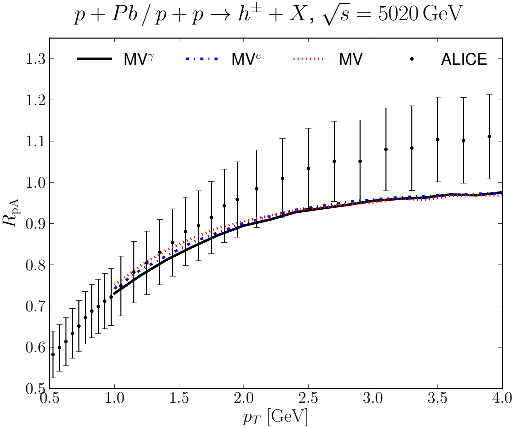


k_T factorization vs hybrid formalism



From proton to nucleus

Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)

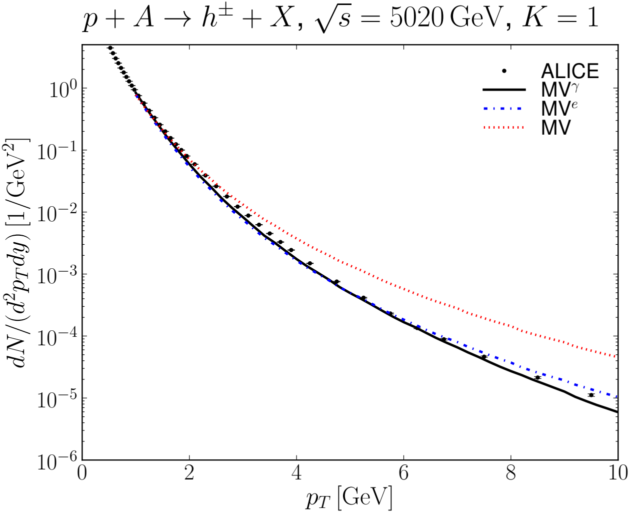


DATA: ALICE, 1210.4520

Minimum bias, small dependence on initial condition (also MV model works).

ALICE $p + Pb$ spectrum, k_T factorization

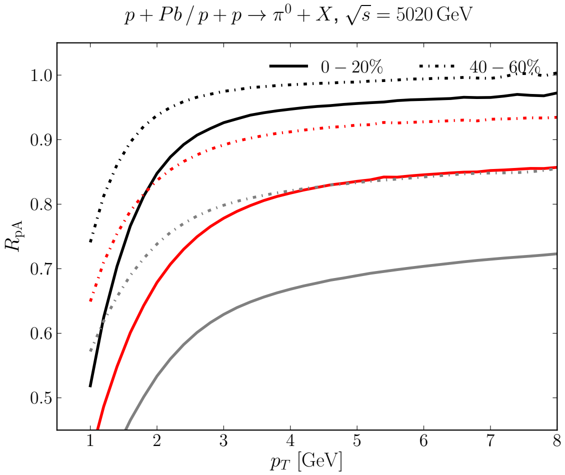
MV$^\gamma$ and MV^e model ICs work with ALICE data, MV does not.



k_T factorization, DATA: ALICE, 1210.4520

Rapidity dependence of R_{pA}: $0-20\%$ vs $20-40\%$

Centrality dependence increases at forward rapidities ($y = 2, 4, 6$)



Hybrid formalism, LO-CTEQ PDF, LO DSS FF.