Dipole amplitude with uncertainty estimate from HERA data and applications in Color Glass Condensate phenomenology

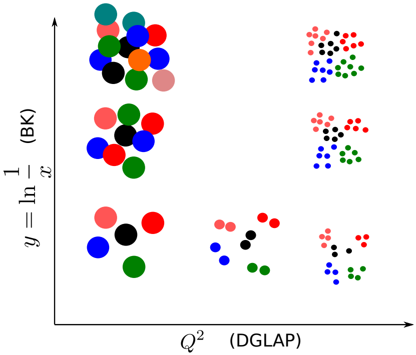
DIS 2014

Heikki Mäntysaari

University of Jyväskylä
Department of Physics

1.5.2014

Introduction



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

Setting up the baseline

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

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

Compute

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

Fit setup

Solve rcBK with modified MV model initial condition

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

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

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 Q_s^2, σ_0, C^2 and consider different parametrizations:

- 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, T. Lappi, H.M, 1309.6963).

Fit result

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

	χ^2/N	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

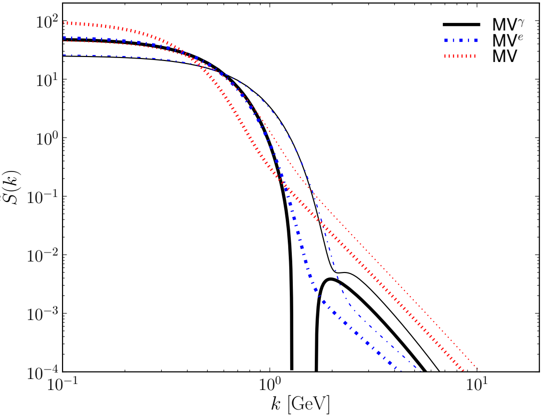
Much better fit with modified MV models.

- Inclusion of heavy quarks: AAMQS takes separate $\sigma_{0,c}$, we do not want to introduce extra parameters $\Rightarrow \chi^2/N \sim 2$, work in progress...

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

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

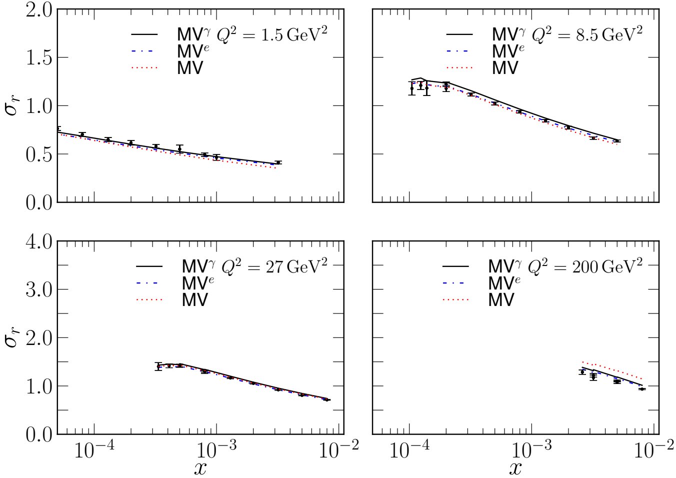
Fourier transform of the ICs



- Thick lines: fundamental representation, thin lines: adjoint

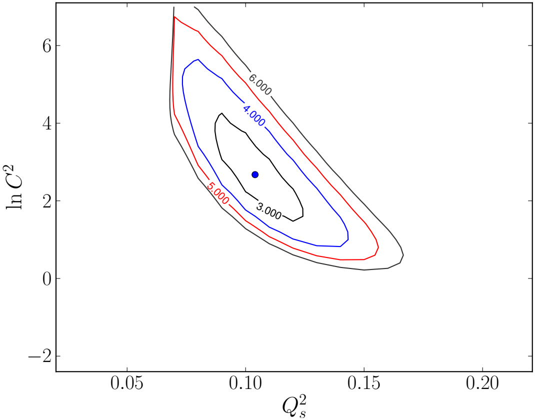
MV^e: smoother inteprolation between saturation region and large-k power law behavior.

Fit result



Fitted to $Q^2 < 50\,\mathrm{GeV}^2, x < 0.01$ HERA data (arXiv:0911.0884)

Fit parameters are correlated ⇒ error sets for the dipole amplitude.
Example: χ^2/d.o.f for the MV model, Q_s^2 and C^2 are correlated:



Uncertainty analysis

Hessian method: expand χ^2 around the minimum $\Rightarrow$ Hessian matrix H

$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j,$$

H is computed by fitting a quadratic function

$$f(a_i, a_j) = \chi_0^2 + c_i(a_i - a_i^0)^2 + c_j(a_j - a_j^0)^2 + c_{ij}(a_i - a_i^0)(a_j - a_j^0)$$

- Diagonalize $H \Rightarrow$ obtain a basis in which parameters are uncorrelated
- In the uncorrelated basis compute error sets S_k such that $\chi^2(S_k) - \chi_0^2 = \text{const.}$
- Evolve error sets using rcBK

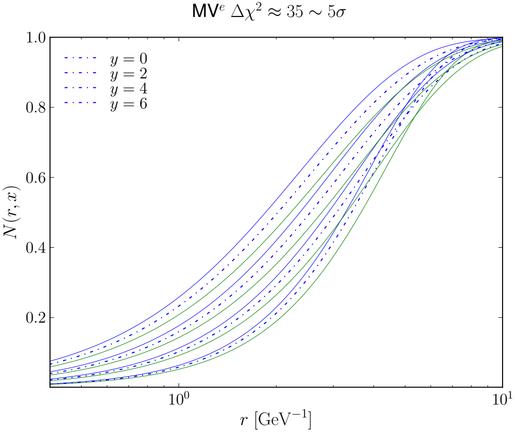
Uncertainty of any quantity X becomes

$$(\Delta X)^2 \approx \frac{1}{4} \sum_k [X(S_k^+) - X(S_k^-)]^2$$

Uncertainty analysis

Preliminary results

Dipole amplitude at initial $y = 0$ and at higher rapidities ($y = \ln \frac{1}{x}$)

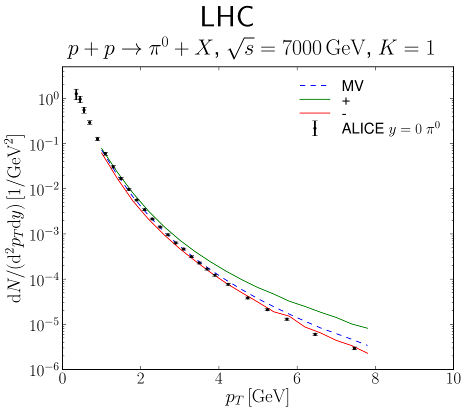


Single inclusive hadron production from CGC

k_T factorization, gluon production: Preliminary results

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_T \mathrm{d}y} = \frac{2\alpha_\mathrm{s}}{C_\mathrm{F} p_T^2} \int \mathrm{d}^2 q_T \frac{\varphi_1(q_T)}{q_T^2} \frac{\varphi_2(k_T - q_T)}{(k_T - q_T)^2}$$

- Convolute with PDF and FF $\Rightarrow$ hadron spectrum.
- φ_i: Unintegrated (transverse momentum dependent) gluon distribution of hadron i.
- $\varphi(k_T) \sim k_T^4 \int \mathrm{d}^2 r e^{ik \cdot r}[1 - N(r)]$



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).

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

xg: is collinear factorization gluon distribution (computable from $\tilde{S}$)
$\tilde{S}$ is Fourier transform of $1 - N(r)$ (adj. rep.).

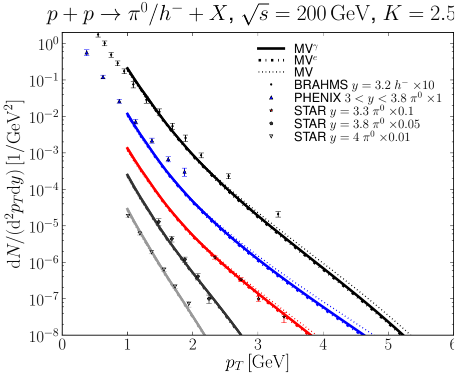
Normalization factor

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

Single inclusive hadron production from CGC

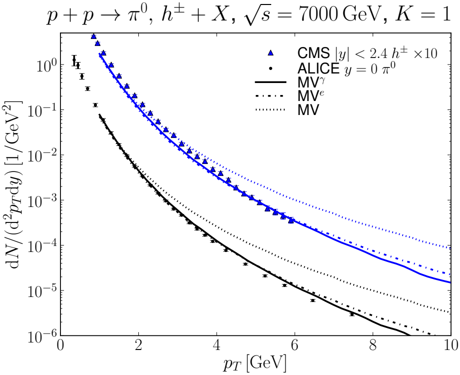
MV model result is not consistent with the LHC data, modifications required.

RHIC



Hybrid formalism, LO CTEQ&DSS

LHC



k_T factorization, LO DSS

From proton to nucleus

Initial condition for nuclei: Optical Glauber

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

No additional nuclear parameters

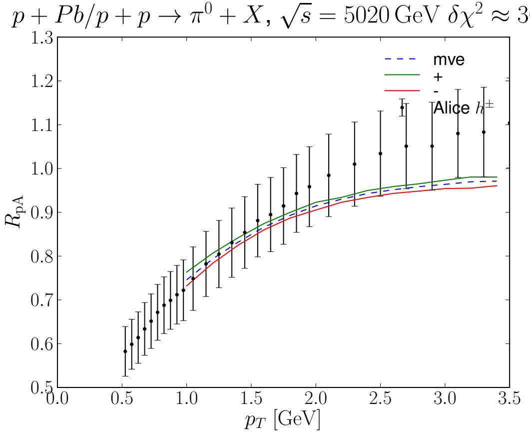
- σ_0 from DIS
- T_A: standard Woods-Saxon

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

Note: average dipole cross section obtained by integrating over fluctuating nucleon positions.

From proton to nucleus R_{pA}

Nuclear suppression factor $R_{pA} = \frac{\mathrm{d}N^{pA}}{N_{\text{bin}}\mathrm{d}N^{pp}}$
Results consistent with ALICE data, get explicitly $R_{pA} \to 1$ at large p_T.



DATA: ALICE, 1210.4520

Minimum bias, small dependence on initial condition.

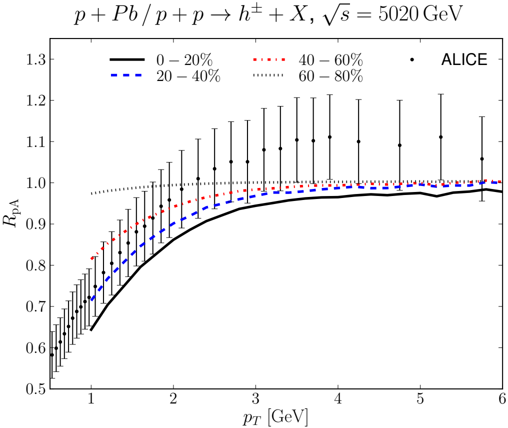
Conclusions

- CGC offers a consistent framework to describe small-x observables, non-perturbative input = dipole amplitude at initial x_0 required
- New initial condition MV^e fitted to HERA data
- Uncertainty estimates
- Generalization to pA collisions using only DIS data, agrees with the available R_{pA} data

BACKUPS

From proton to nucleus: R_{pA}, centrality dependence

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

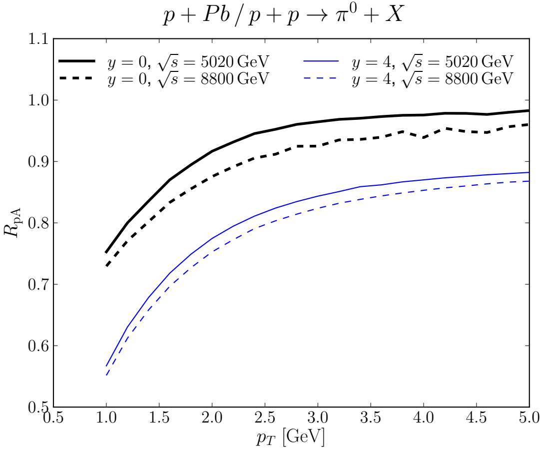


DATA: ALICE, 1210.4520

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 $\sqrt{s_{NN}}$!.

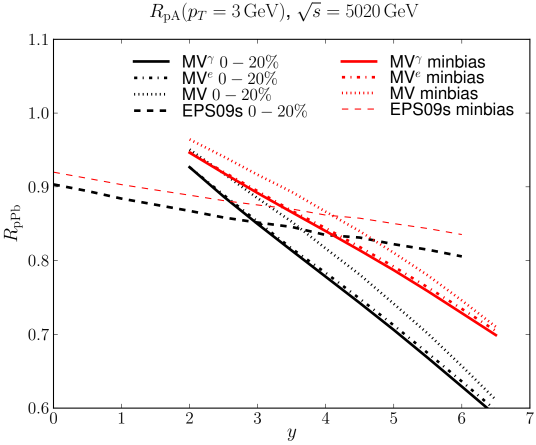


R_{pA} at $y = 0$ (k_T factorization) and at $y = 4$ (hybrid formalism)

CGC vs pQCD (EPS09s)

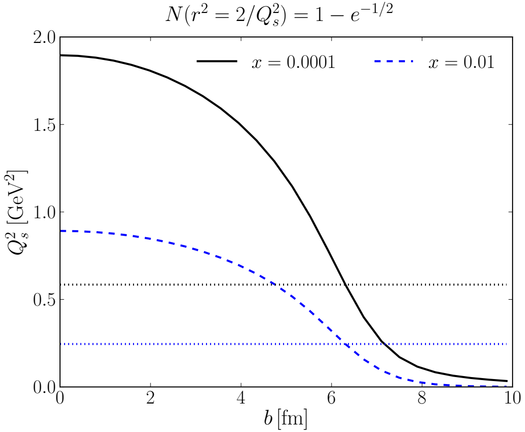
CGC predicts faster centrality and especially rapidity evolution than EPS09s-NLO pQCD

EPS09s calculations by I. Helenius

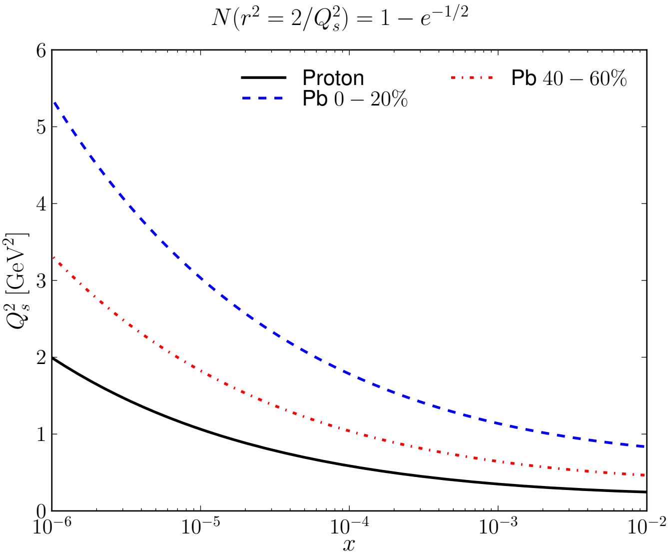


CGC: Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

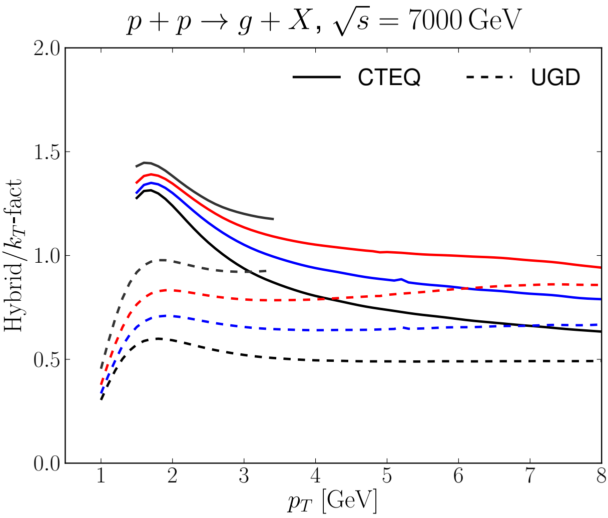
Impact parameter dependence of the saturation scale



From proton to nucleus: saturation scale

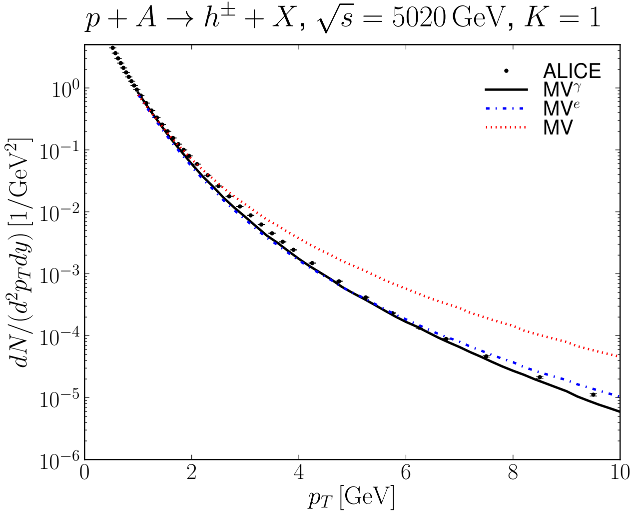


k_T factorization vs hybrid formalism



ALICE $p + Pb$ spectrum, k_T factorization

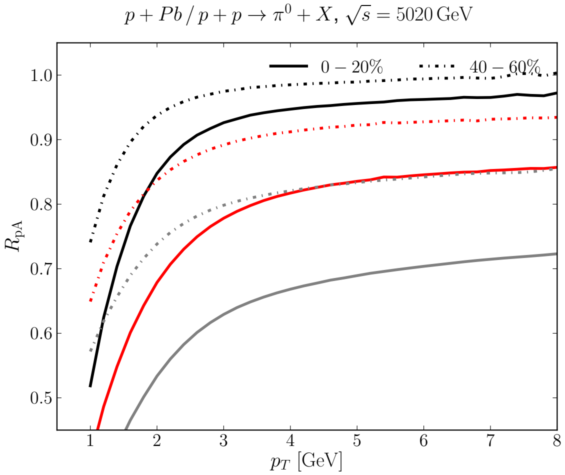
MV^γ and MV^e model ICs work with ALICE data, MV does not.



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.