Probing the Color Glass Condensate: from single inclusive baseline to dihadron correlations

High energy, high density and hot QCD
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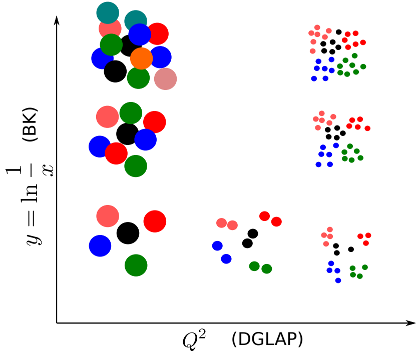
Content

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

Fitting

Solve rcBK with MV$^\gamma$ model initial condition (MV: $\gamma \equiv 1$)

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

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

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

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

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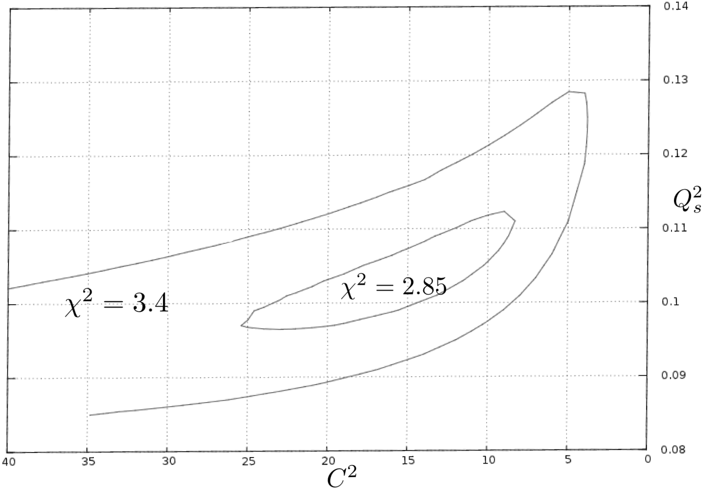
Fit: (MV: χ^2/d.o.f ≈ 2.7, AAMQS with $\gamma > 1$: χ^2/d.o.f ~ 1.17)

- Initial saturation scale Q_{sp}^2: $0.165\,\mathrm{GeV}^2$ (AAMQS), $0.11\,\mathrm{GeV}^2$ (MV)
- Λ_{QCD}: $C^2 \sim 6$, Proton DIS area $\sigma_0/2 \sim 16\,\mathrm{mb}$

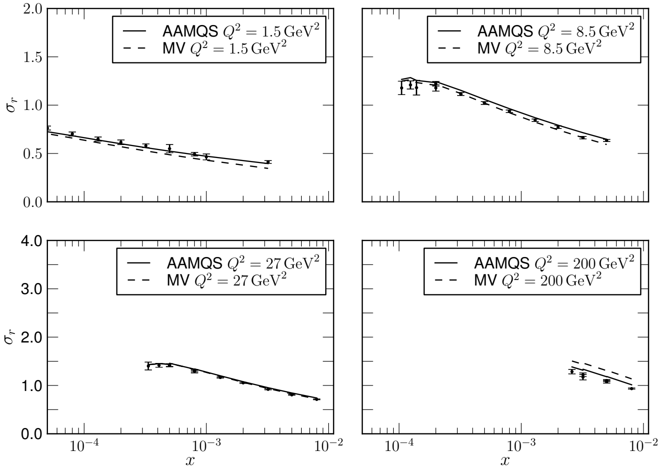
AAMQS: Albacete, Armesto, Milhano, Quiroga-Arias, Salgado, 2011, arXiv: 1012.4408.

MV model fit

Fit to HERA σ_r data, bestfit $\chi^2 \approx 2.7$ With L. Korkeala



Fit result



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

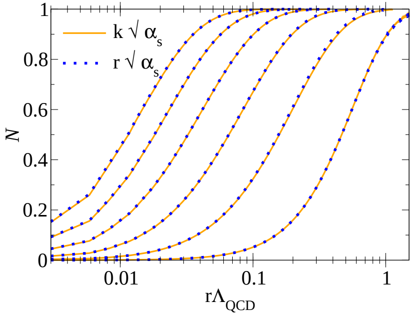
Value of Λ_{QCD}

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

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



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Single inclusive hadron production from CGC

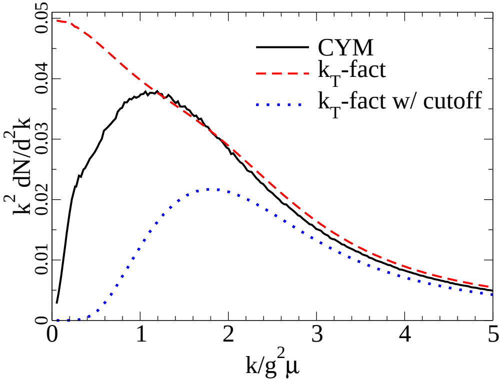
Go to pp. The "correct" k_T factorization:

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

φ_{x_1,x_2}: dipole (not WW) UGD of hadron 1/2.
Obtainable from dipole amplitude N.

$\varphi(k_T) \sim$
$\frac{\sigma_0}{2} k^4 \int \mathrm{d}^2 r e^{ikr} [1 - N(r)]$

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 transfer of $1 - N(r)$ (adj. rep.).

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

pp data and K factors

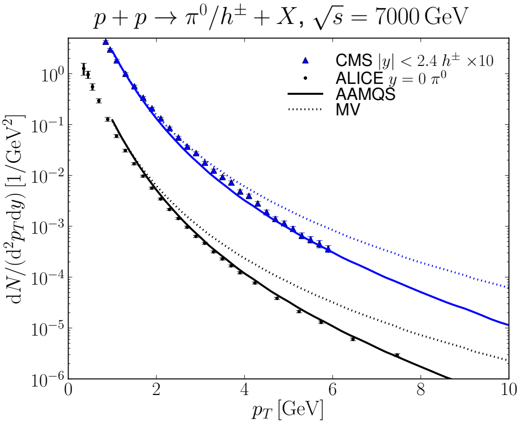
Questions

Use information only from *ep* DIS and compute pp and pA observables.

- What K factor is needed? (and is one enough?)
- Does the p_T slope agree with the data?

Now normalization computed correctly, so K factors tells how much the LO calculation differs from the data.

LHC pp data works with $K_{k_T\text{-fact}} = 1$ and clearly favours AAMQS ($\gamma > 1$)

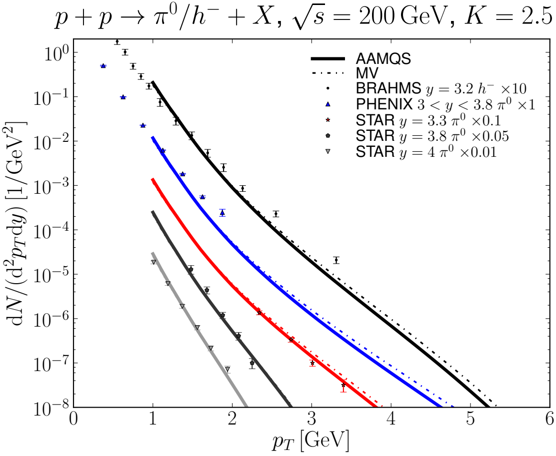


k_T factorization, Data: arXiv:1205.5724 (ALICE), arXiv:1005.3299 (CMS)

Hybrid formalism: $\approx$ same slope but requires $K_{\text{hybrid}} \sim 2$.

Single inclusive pp data

RHIC data requires $K_{\text{hybrid}} \sim 2.5$, small difference between AAMQS and MV initial conditions.



Hybrid, LO CTEQ, LO DSS

STAR: nucl-ex/0602011, BRAHMS: nucl-ex/0403005 PHENIX: B. Meredith (PhD Thesis)

From proton to nucleus

Question

What is the saturation scale of the nucleus?

From proton to nucleus

Start from the dipole-proton cross section

$$\sigma_{\text{dip}}^{p} = \sigma_0 N \sim \sigma_0 \frac{(r^2 Q_{sp}^2)^\gamma}{4} \ln\left(\frac{1}{\Lambda_{\text{QCD}} r} + e\right).$$

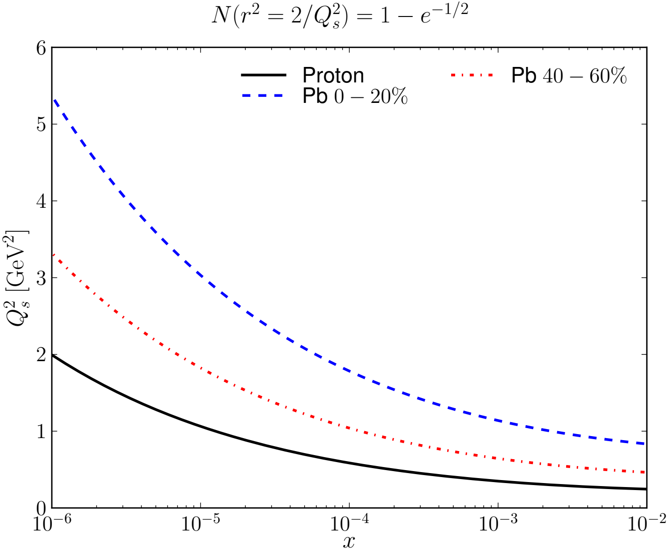
Dipole-nucleus cross section by glauberization (dilute limit $\sigma_{\text{dip}}^{A} \sim A\sigma_{\text{dip}}^{p}$)

$$\frac{\mathrm{d}\sigma_{\text{dip}}^{A}}{\mathrm{d}^2 b} = 2N_A(b) = 2\left(1 - \exp\left[\frac{-AT_A(b)}{2}\sigma_{\text{dip}}^{p}\right]\right).$$

Require: $N_A \to 1$ at large dipoles

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

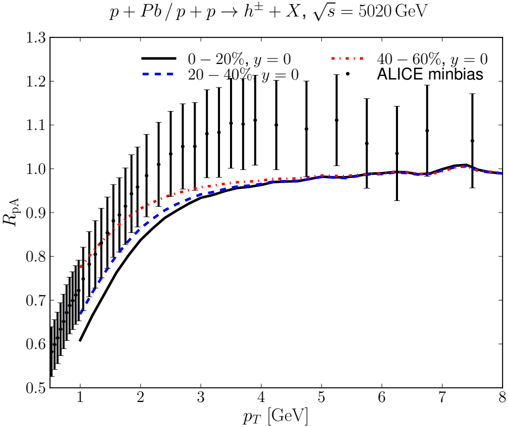
From proton to nucleus: saturation scale



From proton to nucleus

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

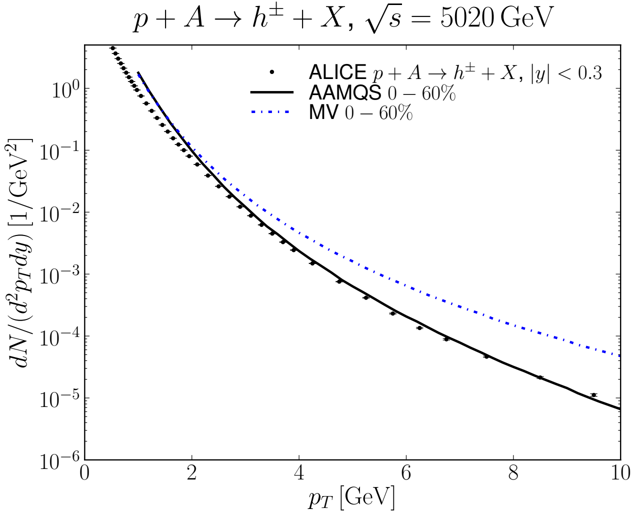
Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)



DATA: ALICE, 1210.4520

ALICE $p + Pb$ spectrum, k_T factorization

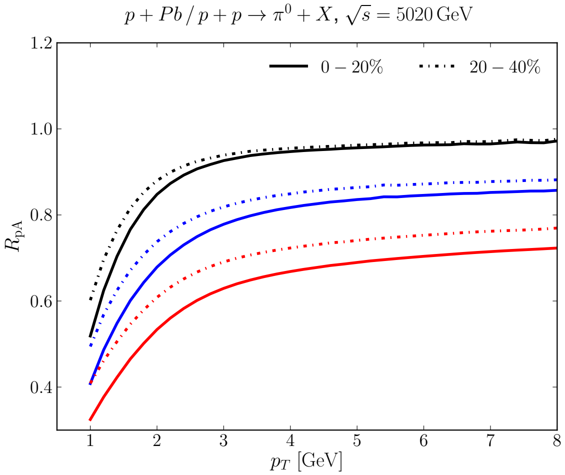
p+Pb yield favours anomalous dimension, no K factor required ($K = 1$).



k_T factorization, DATA: ALICE, 1210.4520

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

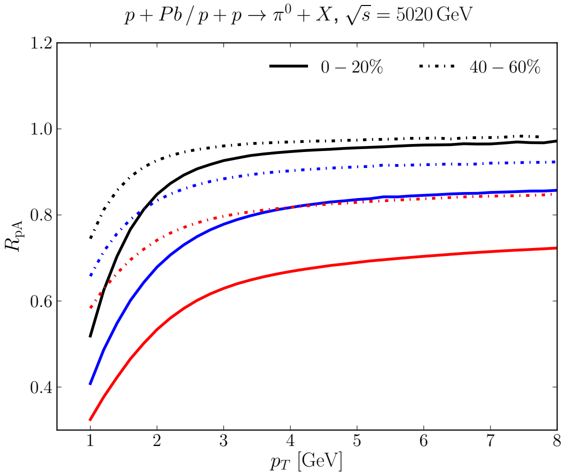
Centrality dependence increases at forward rapidities ($y = 2, 4, 6$)



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

Rapidity dependence of R_{pA}: $0 - 20\%$ vs $40 - 60\%$

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

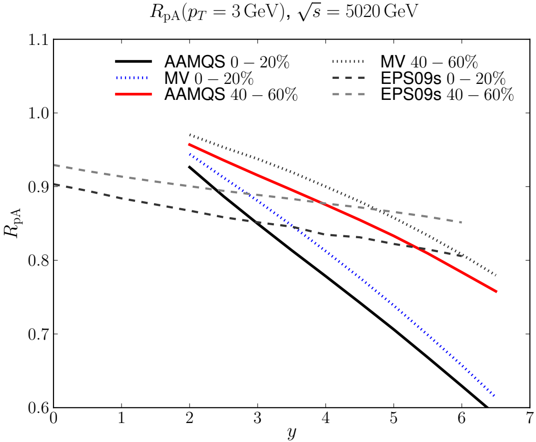


Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

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.

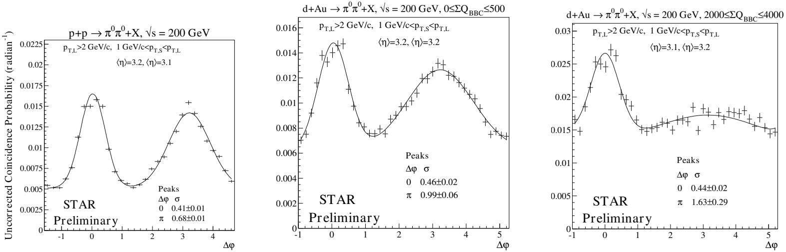
R_{pA}

- Centrality dependence is larger at forward rapidities
- No Cronin peak at midrapidity (LHC)
- Large suppression at more forward rapidities
- Much faster rapidity evolution than in EPS09s
- Larger dependence on centrality than in EPS09s

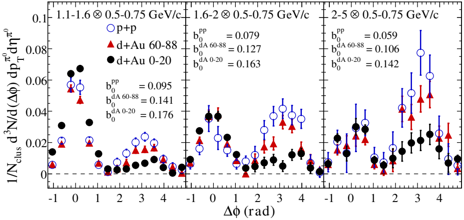
Dihadron correlations

RHIC, two particle collision vs. $\Delta\phi$: away side peak goes away

p+p peripheral d+Au central d+Au



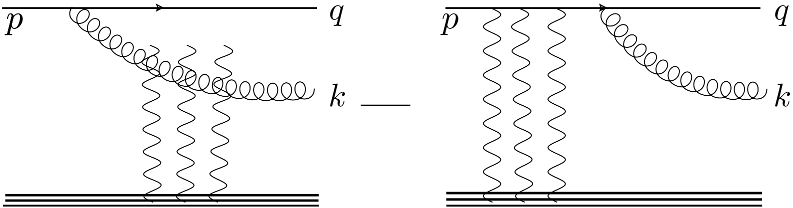
STAR, 1102.0931



PHENIX, 1105.5112

Dihadron production from CGC

CGC description: quark emits a gluon and scatters off the target.
Momentum transfer $\sim Q_s \Rightarrow$ explains disappearance of the away side peak



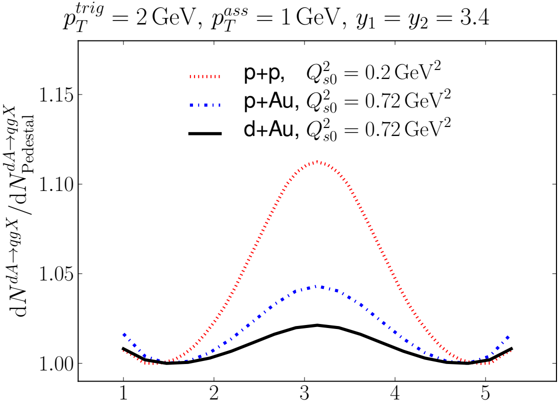
$$Q_s^2 \approx A^{1/3} \left(\frac{x}{x_0}\right)^{-0.3} Q_{s0}^2$$

- Requires dipole amplitude and quadrupole (Gaussian approximation).
- Also uncorrelated double parton scattering (formally IR divergent).

Dihadrons at RHIC

In nucleus saturation scale is significantly larger

$\Rightarrow$ Back-to-back structure is washed out.



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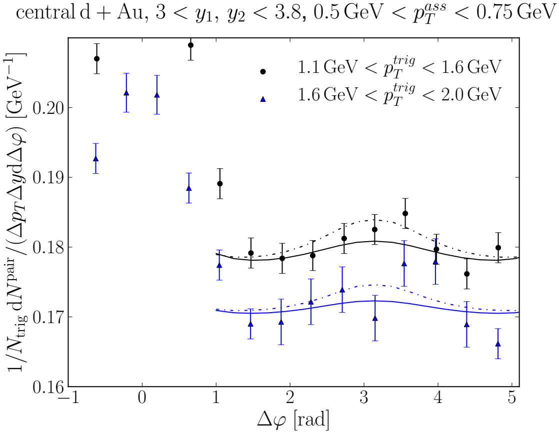
Note: here MV model with initial condition $Q_{sA}^2 \approx N_{\text{bin}}^{pA} Q_{sp}^2$

Dihadrons at RHIC

Relatively good description of the PHENIX data (STAR data also works)



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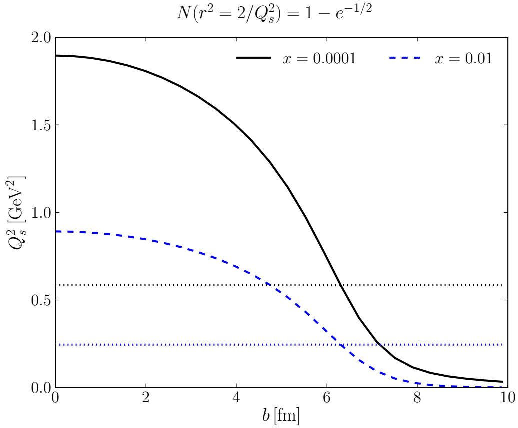
Conclusions

- Using only ep DIS as an input we compute single particle production in pp and pA.
- Good description of RHIC and LHC single inclusive spectra.
- Different K factor required for RHIC and LHC
- MV model initial condition works with DIS and RHIC data, but LHC data favours anomalous dimension.
- Centrality and rapidity dependent predictions for R_{pA}, faster evolution than predicted by NLO pQCD calculations (EPS09s).
- Dihadron correlations at RHIC are well understood, LHC forward-forward data will be interesting.

BACKUPS

Impact parameter dependence of the saturation scale



Quadrupole operator

$$Q = N_c^{-1}\langle \mathrm{Tr}\, U(b)U^\dagger(b')U(x')U^\dagger(x)\rangle,\ S = S^{(2)} = N_c^{-1}\langle \mathrm{Tr}\, U(x)U^\dagger(x')\rangle$$

Motivation for approximations

Dipole amplitude S is easy to obtain from BK $\Rightarrow$ approximation depending only on dipole amplitude is much easier for practical work

Approximating the quadrupole Q

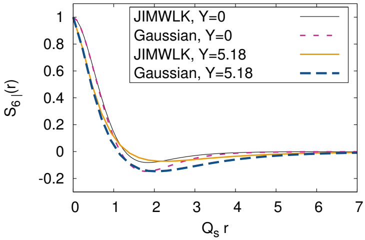
- Naive Large-N_c $Q(b, b', x', x) = \frac{1}{2}[S(x, b)S(x', b') + S(x, x')S(b, b')]$ previous phenomenology: w.o. inelastic contribution $S(x, x')S(b, b')$
- Gaussian approximation (and large-N_c limit)

Gaussian approximation: assume that the correlators of the color charges are Gaussian $\Rightarrow$ depends only on two-point functions

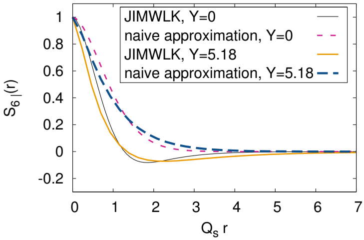
- We use the full Gaussian approximation which includes the inelastic contribution

Quadrupole operator

Comparison with full JIMWLK evolution



(a) Gaussian



(b) Naive

T. Lappi et al. 1108.4764

- Gaussian approximation is accurate, Naive Large-N_c is not.

Dihadron production from CGC

CGC calculation by C. Marquet (Nucl.Phys. A796 (2007)), $q \to qg$ (at the LHC need also $g \to gg$):

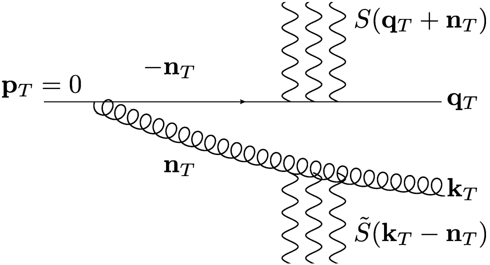
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 k_T \mathrm{d}^2 q_T \mathrm{d}y_q \mathrm{d}y_k} \sim xq(x,\mu^2) \int \frac{\mathrm{d}^2 x}{(2\pi)^2} \frac{\mathrm{d}^2 x'}{(2\pi)^2} \frac{\mathrm{d}^2 b}{(2\pi)^2} \frac{\mathrm{d}^2 b'}{(2\pi)^2} e^{ik_T(x'-x)} e^{iq_T(b'-b)} |\phi^{q\to qg}(x-b, x'-b')|^2 \left\{ S^{(6)} - S^{(3)} - S^{(3)} + S^{(2)} \right\}$$

Dipole amplitude N is not enough, need correlators of $n > 2$ Wilson lines

$$S^{(6)} \sim \langle \mathrm{Tr}\, U(b) U^\dagger(b') U(x') U^\dagger(x) \rangle \, \mathrm{Tr}\, U^\dagger(x) U(x')$$

$n > 2$: BK evolution equation $\to$ JIMWLK, or here: Gaussian approximation

Double parton scattering

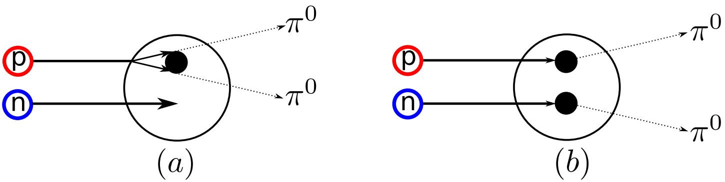


DPS in CGC framework: $S^{(6)}$ contains IR divergent contribution (gluon emitted far away from the quark), DPDF should cancel

$$\sim xf(x)\left[\int^{\Lambda} \mathrm{d}^2 n |\psi(n)|^2\right] \tilde{S}_A(k)\tilde{S}(q),$$

for $\Lambda \ll k, q$, ψ is the splitting function $q \to qg$. $\tilde{S}$: FT of S.

Double parton scattering

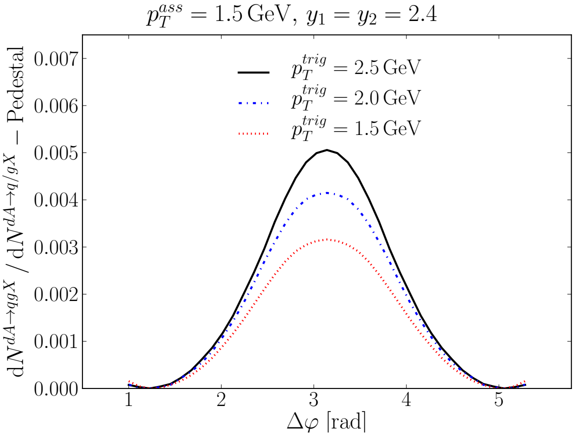


How to calculate DPS in CGC?

- Remove IR divergent contribution from $S^{(6)}$
- (a): assume DPDF $f(x_1, x_2) \sim f(x_1)f(x_2)$ with kinematical constraint $x_1 + x_2 < 1$
- (b): (single inclusive)^2, dominates in forward rapidities

Dihadrons at RHIC

Back-to-back peak disappears when trigger (or associate) particle $p_T \sim Q_s$.



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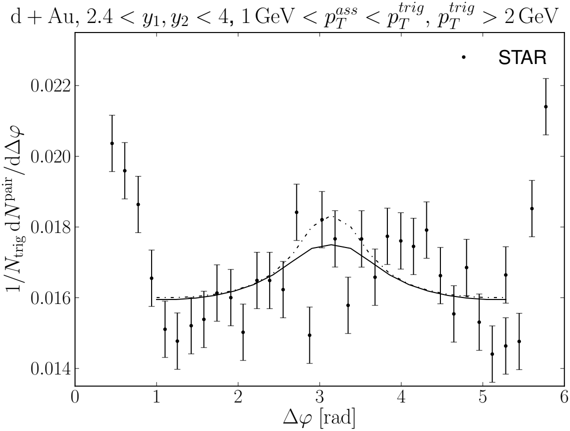
Note: here MV model with initial condition $Q_{sA}^2 \approx N_{\mathrm{bin}}^{pA} Q_{sp}^2$

Dihadrons at RHIC

Relatively good description of the experimental data



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