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

Workshop on proton-nucleus collisions at the LHC
Trento 2013

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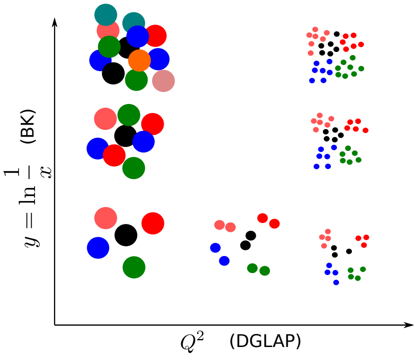
6.5.2013

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: Fit MV model only to HERA data and go consistently to pA! (work in progress)

MV model (no anomalous dimension) because it can be generalized to nuclei unambiguously.

Fitting

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

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

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

Compute $\sigma_r(\sigma_T, \sigma_L)$ [or F_2]; assume factorizable impact parameter profile for proton.

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

Fitting

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

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

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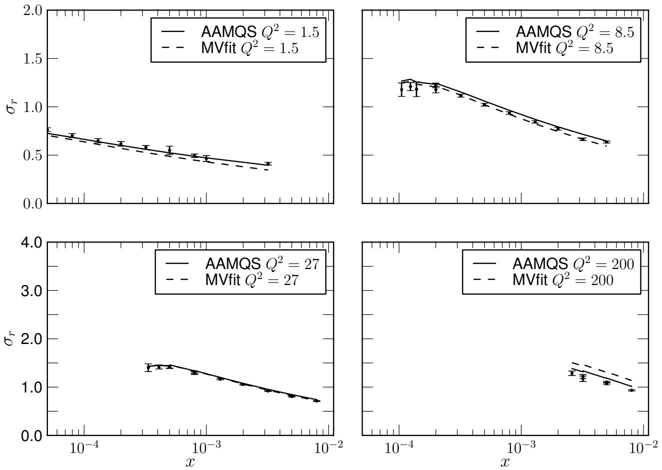
$$\sigma_{T,L}^{\gamma^* p} = \sigma_0 \int \mathrm{d}z |\Psi_{\gamma^* \to q\bar{q}}^{T,L}|^2 N(r, y)$$

Fit: (χ^2/d.o.f ≈ 3, not as good as AAMQS with $\gamma > 1$)

- Initial saturation scale $Q_{sp}^2 = 0.12\,\mathrm{GeV}^2$
- Λ_{QCD}: $C^2 = 6$
- Proton DIS area $\sigma_0/2 = 16\,\mathrm{mb}$ (factor 2 from optical theorem)

Fit result



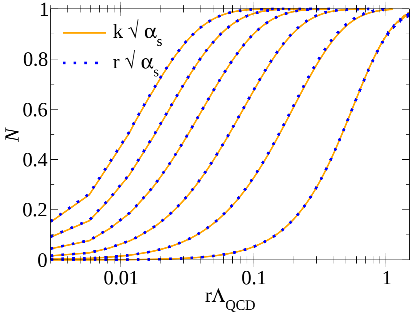
Fitted to $Q^2 < 50\,\mathrm{GeV}^2$, HERA data: arXiv:0911.0884, AAMQS fit: 1012.4408

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 from JIMWLK
Solid: momentum space α_s
Dashed: $4C^2 = 4e^{-2\gamma_E}$



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

Single inclusive hadron production from CGC

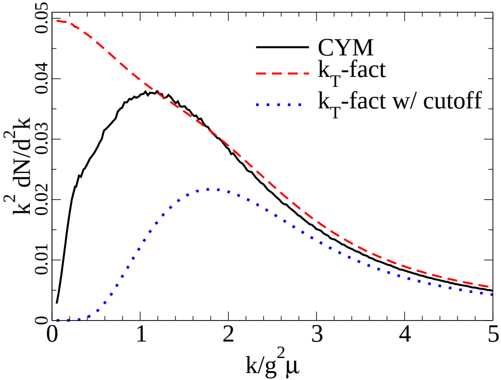
Go to pp. The "correct" k_T factorization:

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

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

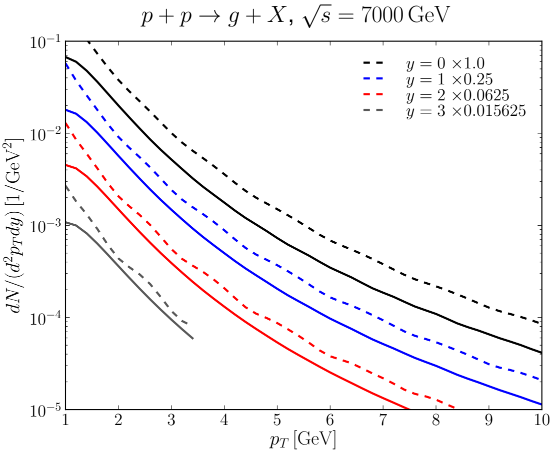
$$xg(x, Q^2) = \frac{C_\mathrm{F} \sigma_0/2}{2\pi^2 \alpha_s} \int^{Q^2} \frac{\mathrm{d}^2 q_T}{(2\pi)^2} q_T^2 \tilde{S}(q_T),$$

(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)

k_T factorization vs hybrid formalism

At midrapidity k_T factorization (dashed lines) $\sim 2\times$ hybrid (with xg from UGD, solid lines). Smaller difference at forward rapidities. Same p_T slope.



pp data and K factors

Questions

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

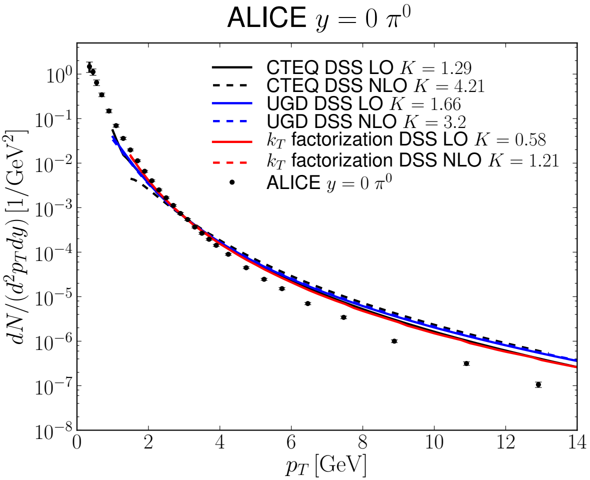
- What K factor is needed? (and is one enough?)
- What is the p_T slope?

Now correct normalization, so K factor tells how much the LO result differs from data!

Single inclusive pp data and K factors

All models give same p_T slope but different normalization

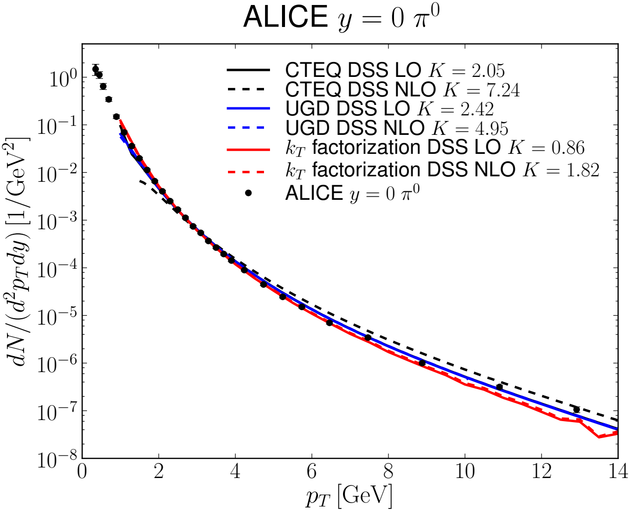
p_T slope does not work very well at large p_T



Data: arXiv:1205.5724

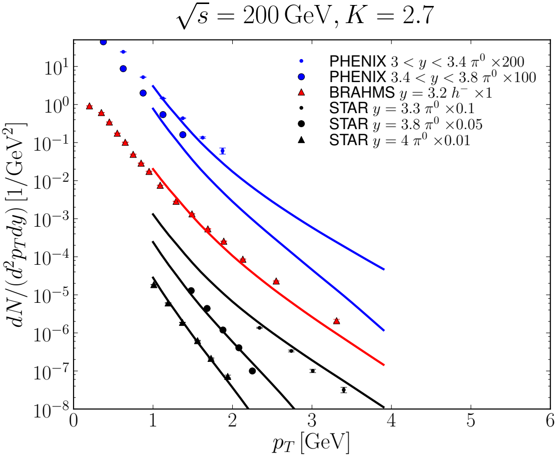
Single inclusive pp data and K factors

AAMQS would work much better, but anomalous dimension makes it difficult to generalize to nuclei.



Single inclusive pp data and K factors

MV-fit: RHIC data roughly works with a single K factor (LHC $K = 1.3$) (PHENIX data would prefer larger, STAR smaller)



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 (small r up to logarithms)

$$\sigma_{\text{dip}}^{p} = \sigma_0 N \sim \sigma_0 r^2 Q_{sp}^2/4.$$

Write the dipole-nucleus cross section (correct 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: $N_A \sim r^2 Q_{s_A}^2/4$

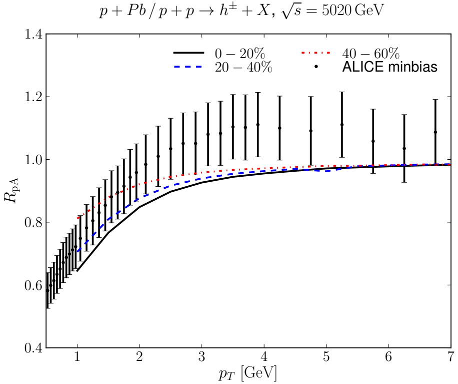
$$Q_{sA}^2(b) = \frac{\sigma_0}{2} A T_A(b) Q_{sp}^2.$$

From proton to nucleus

$$Q_{sA}^2(b) = \frac{\sigma_0}{2} A T_A(b) Q_{sp}^2.$$

$R_{pA}(y=0) \to 1$ at large p_T independently of $\sqrt{s_{NN}}$!.

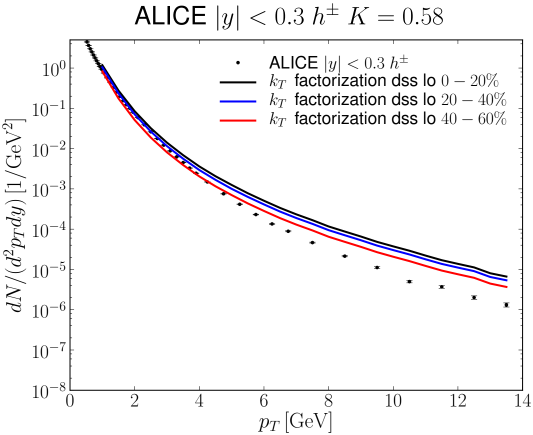
Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)



DATA: ALICE, 1210.4520

ALICE $p + Pb$ spectrum, k_T factorization

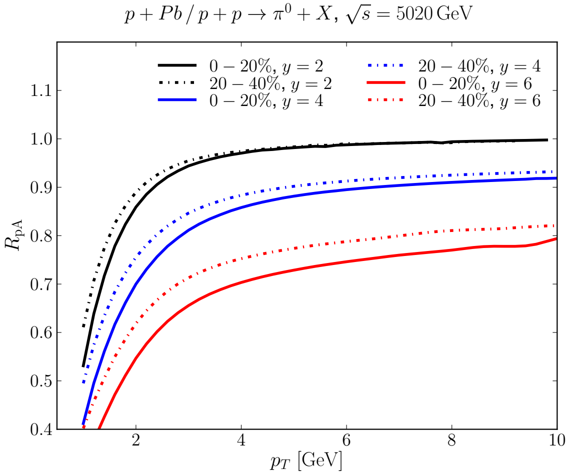
K factor fitted to pp data. Again slope does not work at large p_T.
k_T factorization and hybrid formalism give same result (with different K).



DATA: ALICE, 1210.4520

Rapidity dependence of R_{pA}

Centrality dependence increases at forward rapidities



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

Rapidity dependence of R_{pA}

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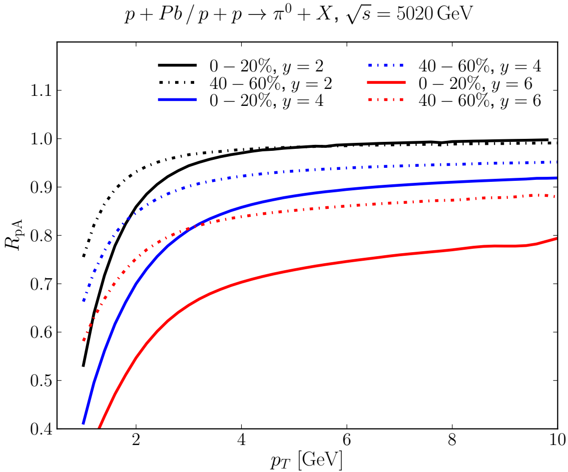
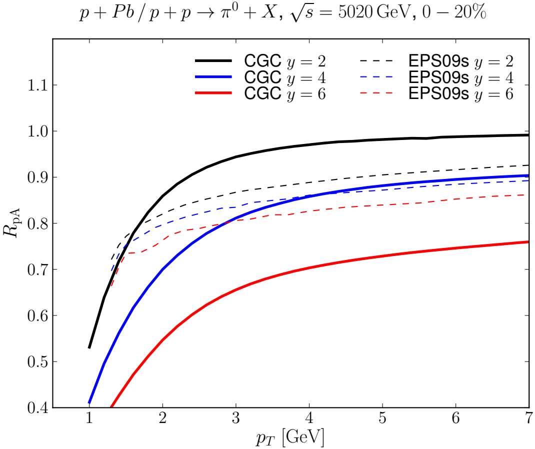


Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

CGC vs EPS09s

CGC predicts faster centrality and especially rapidity evolution than EPS09s (NLO pQCD by I. Helenius, see Ilkka's talk on Wednesday)

Central



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

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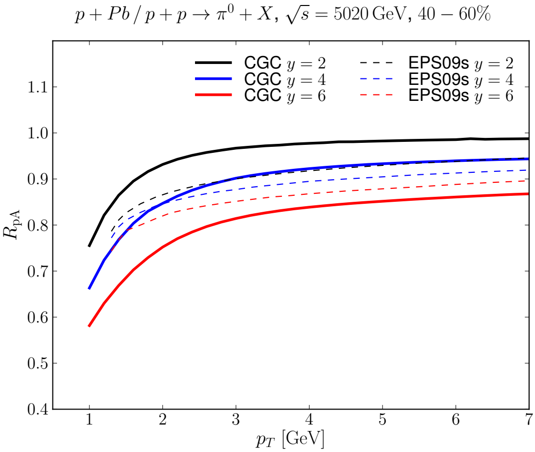
Peripheral



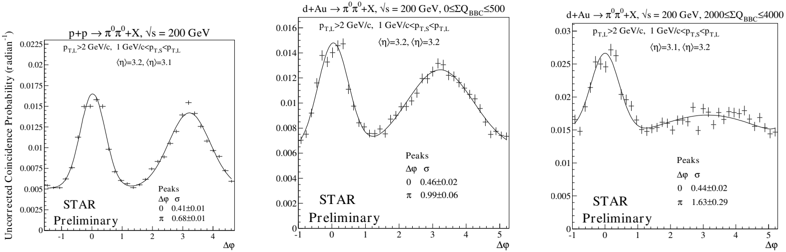
Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

R_{pA}

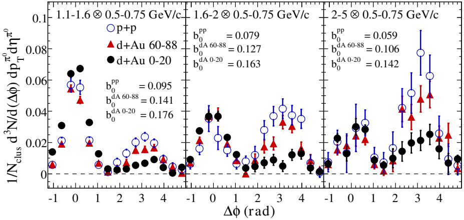
- Centrality dependence is larger at forward rapidities
- No Cronin peak at midrapidity (LHC)
- Large suppression at more forward rapidities
- Much faster rapidity evolution than in EPS09s
- Larger dependence on centrality than in EPS09s

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

p+p peripheral d+Au central d+Au



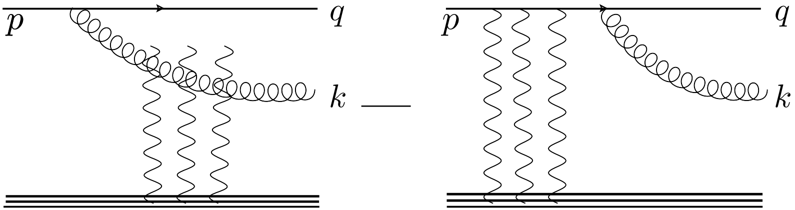
STAR, 1102.0931



PHENIX, 1105.5112

Dihadron production from CGC

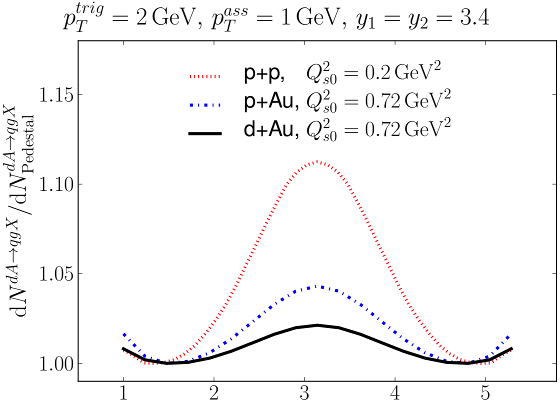
CGC description: quark emits a gluon and scatters off the target.
Momentum transfer $\sim Q_s \Rightarrow$ explains disappearance of the away side peak



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

Dihadrons at RHIC

In nucleus saturation scale is significantly larger
$\Rightarrow$ Back-to-back structure is washed out.



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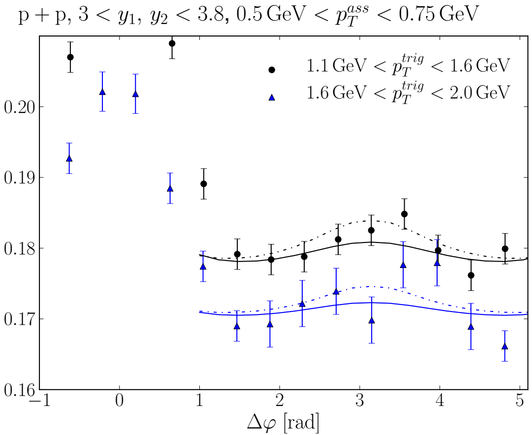
Note: here MV model with initial condition $Q_{sA}^2 \approx N_{\mathrm{bin}}^{pA} Q_{sp}^2$

Dihadrons at RHIC

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



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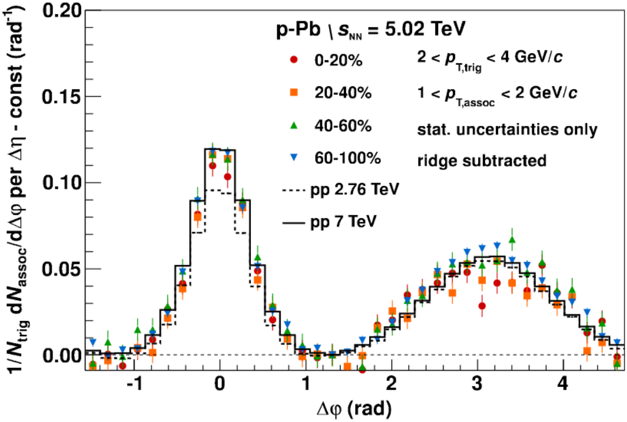
Dihadrons at the LHC

Where is the back-to-back suppression at the LHC? Forward-forward correlations would be very interesting...



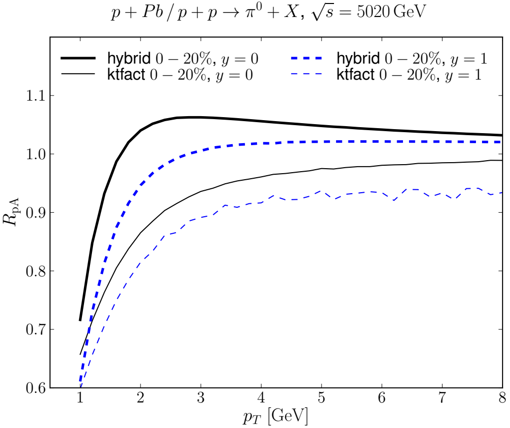
ALICE, Phys.Lett. B719 (2013) 29-41

Conclusions

- Using only ep DIS as an input we compute single particle production in pp and pA.
- Good description of RHIC single inclusive spectrum and LHC $R_{pA}(y = 0)$, LHC p_T slope does not work well.
- LHC spectra seem to favor 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 data will be interesting.

BACKUPS

R_{pA}, model dependence



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

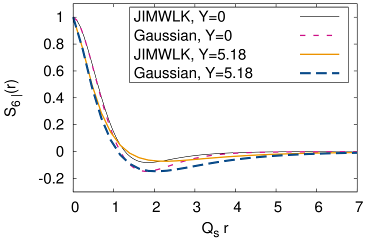
Approximating the quadrupole Q

- 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)

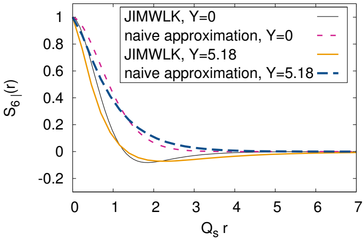
Gaussian approximation: assume that the correlators of the color charges are Gaussian $\Rightarrow$ depends only on two-point functions

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

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 $g \to gg$):

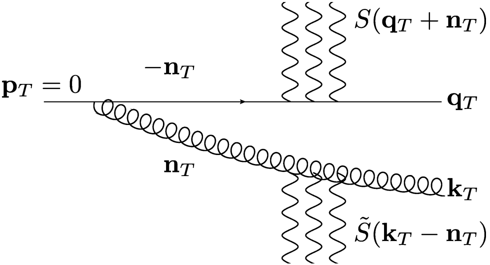
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 k_T \mathrm{d}^2 q_T \mathrm{d}y_q \mathrm{d}y_k} \sim xq(x,\mu^2) \int \frac{\mathrm{d}^2 x}{(2\pi)^2} \frac{\mathrm{d}^2 x'}{(2\pi)^2} \frac{\mathrm{d}^2 b}{(2\pi)^2} \frac{\mathrm{d}^2 b'}{(2\pi)^2} e^{ik_T(x'-x)} e^{iq_T(b'-b)}$$
$$|\phi^{q\to qg}(x-b, x'-b')|^2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

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

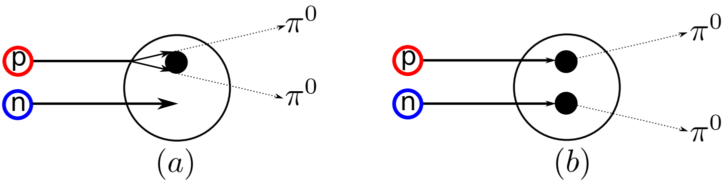


DPS in CGC framework: $S^{(6)}$ contains IR divergent contribution (gluon emitted far away from the quark), DPDF should cancel

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

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

Double parton scattering

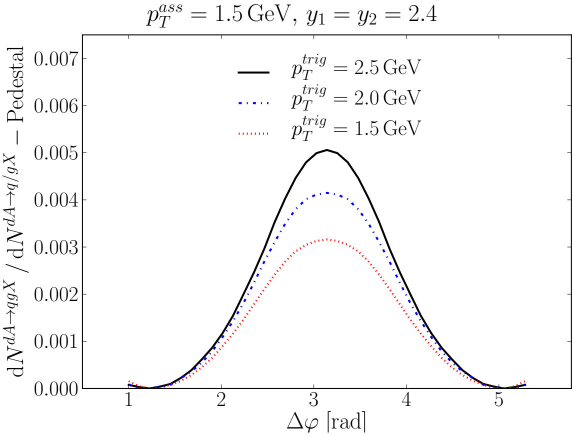


How to calculate DPS in CGC?

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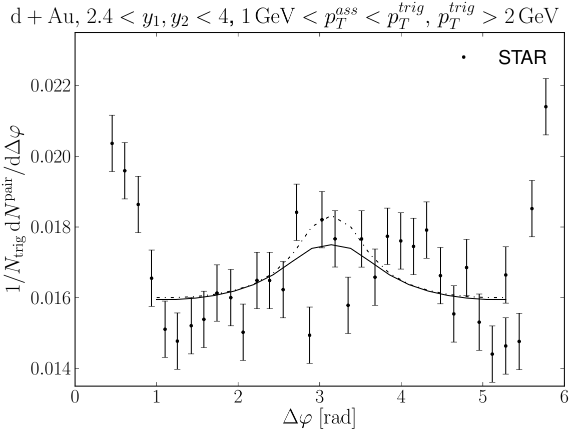
Note: here MV model with initial condition $Q_{sA}^2 \approx N_{\text{bin}}^{pA} Q_{sp}^2$

Dihadrons at RHIC

Relatively good description of the experimental data



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