Saturation or collectivity in p+A collisions at RHIC and LHC

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Situation
Observables
Long-range longitudinal fluctuations / correlations
Conclusions

The situation in p+A:

$C_2(\Delta\varphi)$	hydro	CGC	
$v_2(p_t)$	hydro	CGC	
$v_3(p_t)$	hydro		CGC for quarks
$v_{2,3}$ vs N_{track}	hydro		
$\langle p_t \rangle$ vs N_{track}	hydro	geom. scaling	
v_2 mass splitting	hydro		
$v_2\{2,4,6,8\}$	hydro	CGC ?	>0 up to 6 GeV [CMS]
$v_2(p_t)$ in d+Au	hydro		
$v_3(p_t)$ in He3+Au	hydro		
p+p	ampt	CGC ?	

Hydro is running strong. At high $p_t > 1-2$ GeV it is questionable.

Uncertain status of hydro in p+p. AMPT describes well p+p ridge.

Local sources of correlations (domains etc.) seem to have problem with d+Au and He3+Au (the more sources the smaller v_n).

in my opinion

Successful hydro ?
Unconvincing CGC ?

CGC ⇔ dense partonic system ⇒ scatterings of partons ⇒ "hydro" ?

hydro-like behavior

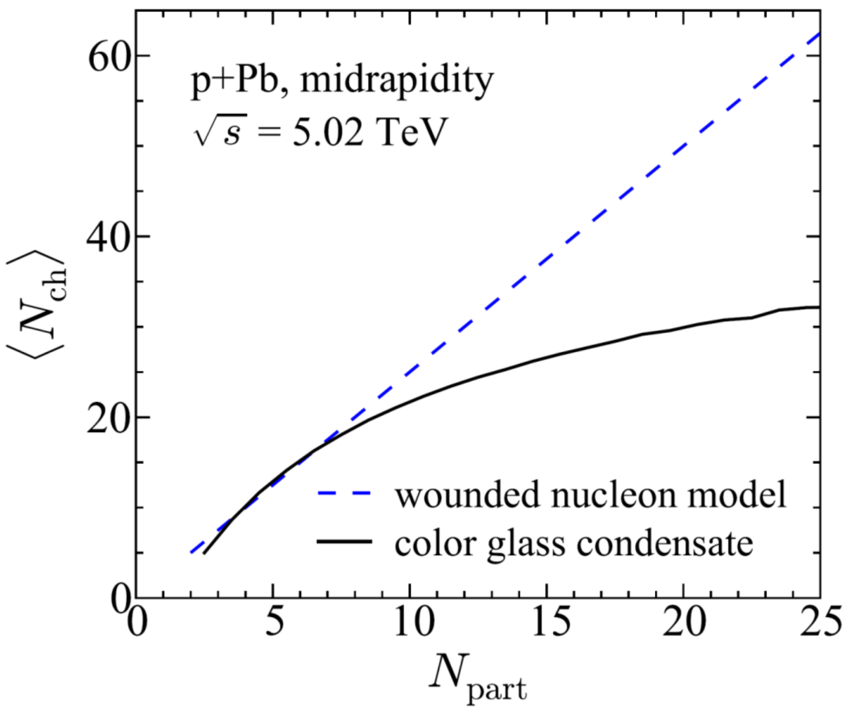
P. Bozek, PRC 85 (2012) 014911
E. Shuryak, I. Zahed, PRC 88 (2013) 044915
K. Dusling, R. Venugopalan, PRD 87 (2013), 094034
A. Dumitru, A.V. Giannini, NPA 933 (2014) 212
V. Skokov, PRD 91 (2015) 054014
G.L. Ma, AB, PLB 739 (2014) 209

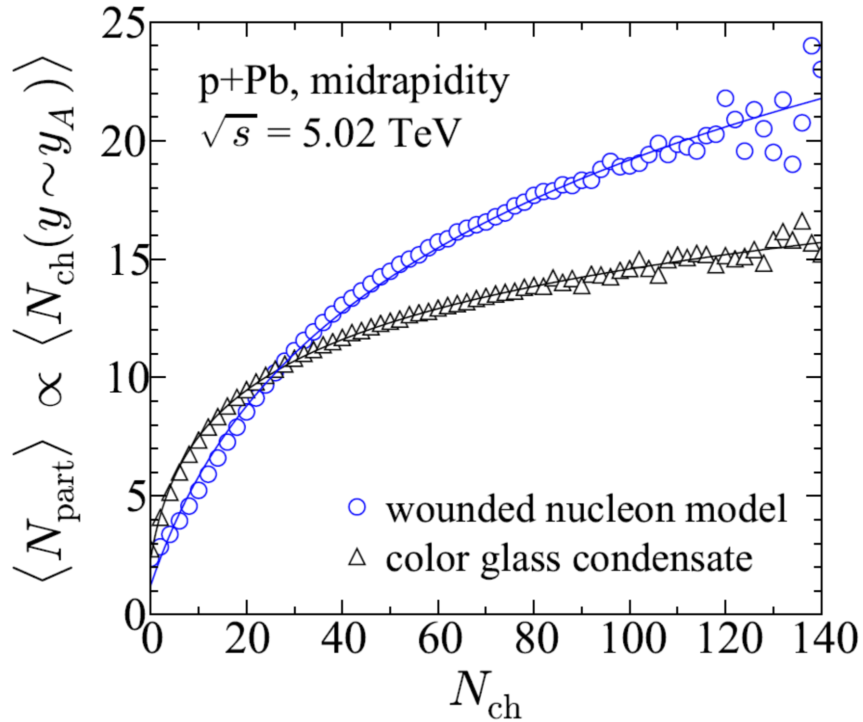
Possible tests of initial vs. final state physics.

CGC: $\langle N_{pA} \rangle \sim \ln(N_{part})$ checked in rcBK, IP-Glasma, KLN

WNM: $\langle N_{pA} \rangle \sim N_{part}$

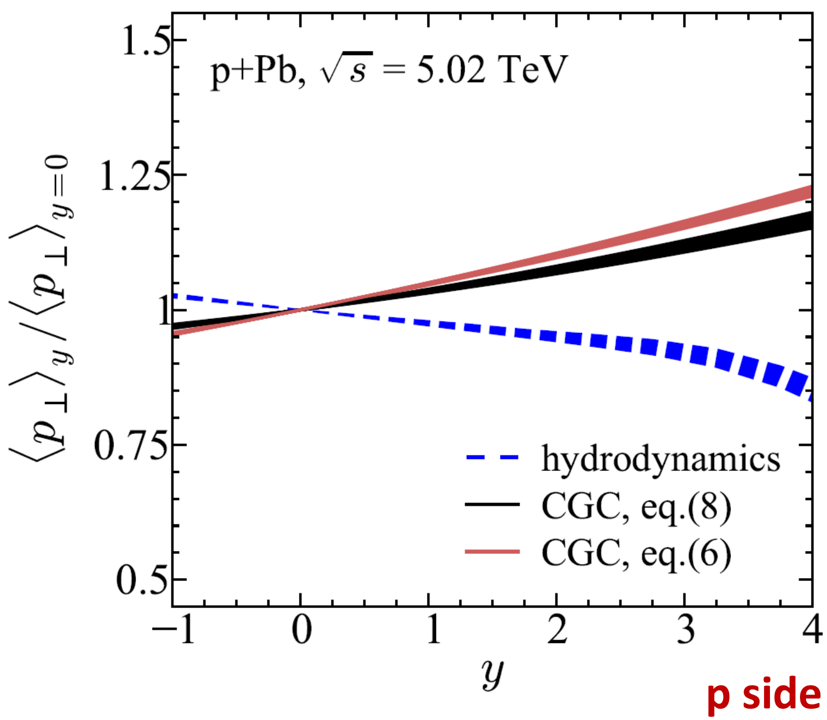
thanks to B.Schenke

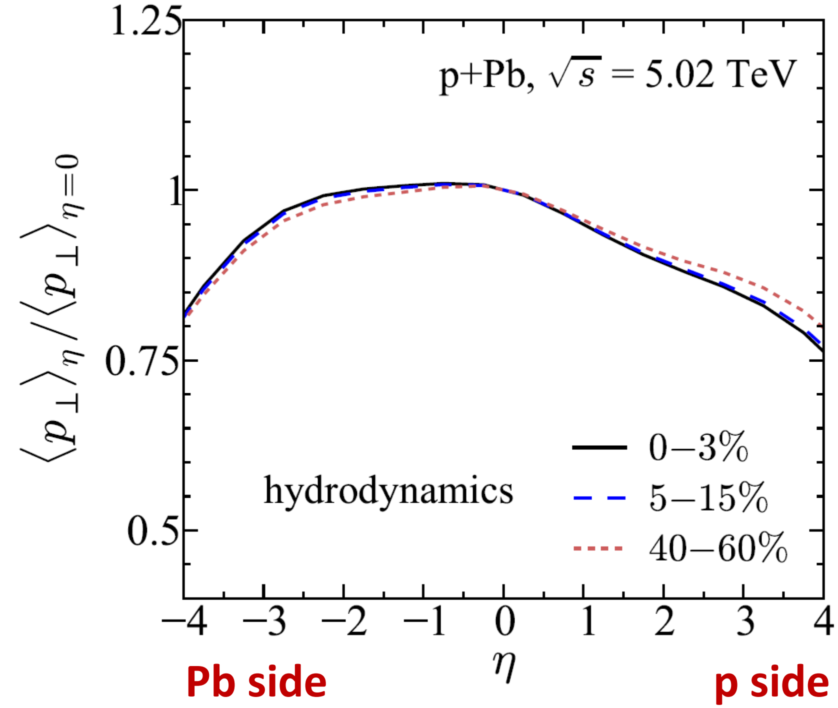




AB, V.Skokov, PRL 111 (2013) 182301

$\langle p_T \rangle$ versus η on proton side

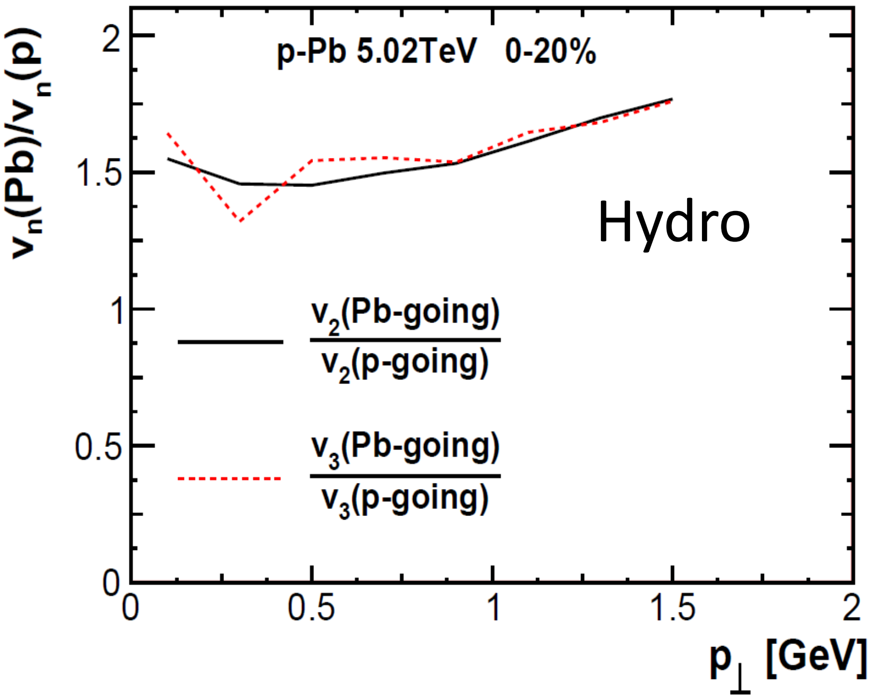


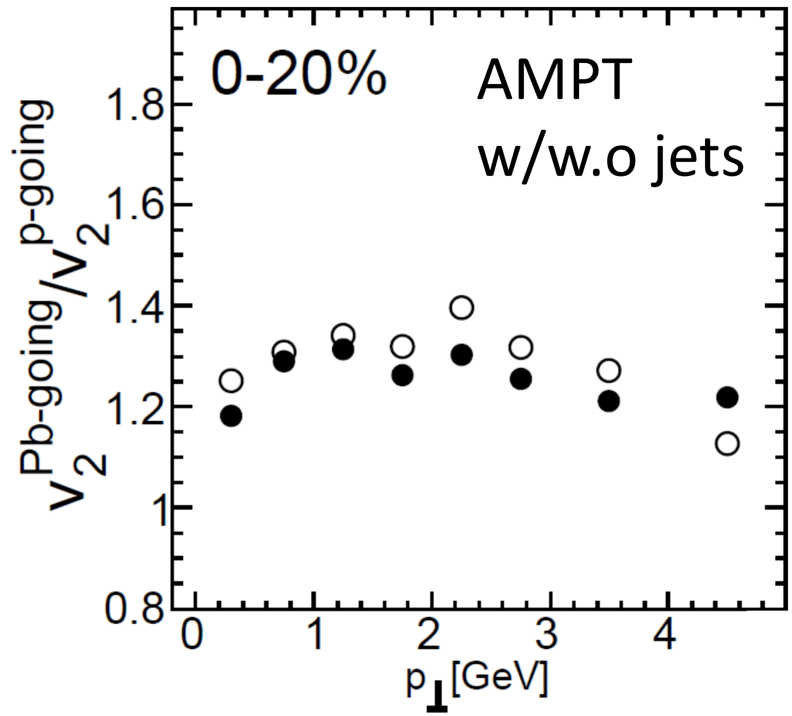


CGC predictions are not so clear, many uncertainties.

P.Bozek, AB, V.Skokov, PLB 728 (2014) 662

v_n on proton $(-4 < \eta < -2.5)$ and nucleus $(2.5 < \eta < 4)$ sides





for 40-60% the ratio is 1

CGC predictions are welcomed!

P.Bozek, AB, G.L. Ma, PLB 748 (2015) 301

Correlations:

N.Borghini, P.M.Dinh, J.-Y.Ollitrault,
PRC 63 (2001) 054906

$$(v_2\{2\})^2 = \left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle$$

$$= \left\langle v_2^2 \right\rangle + c_2$$

c_m is non-flow

$$(v_2\{4\})^4 = -\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle + 2\left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle^2$$

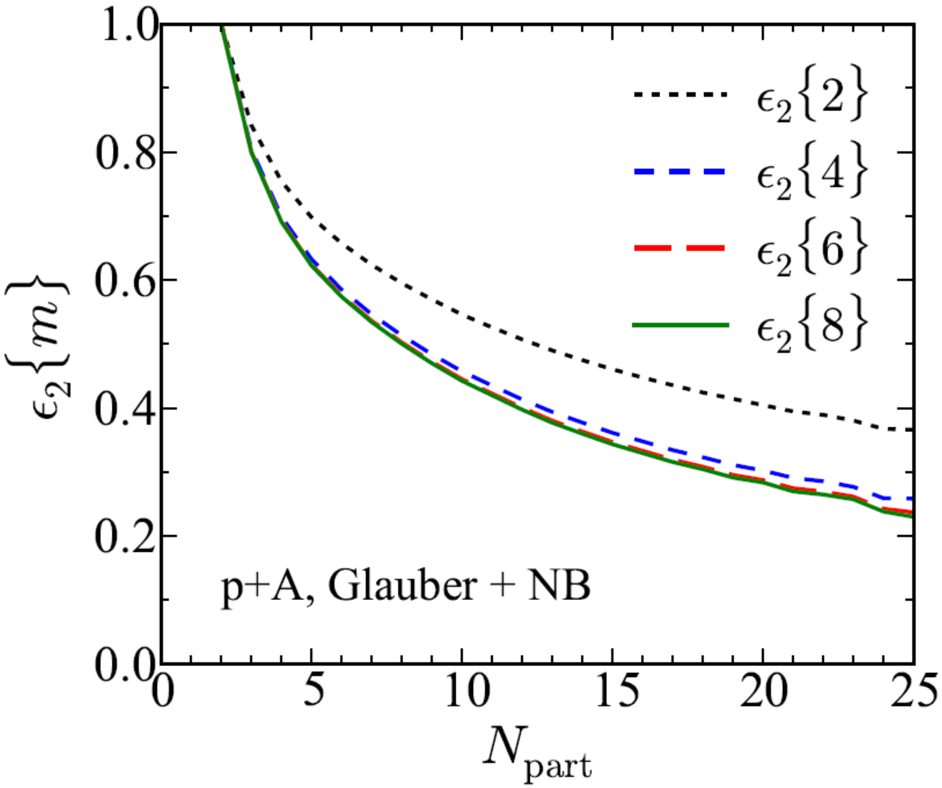
$$= -\langle v_2^4 \rangle + 2\left\langle v_2^2 \right\rangle^2 + c_4$$

etc.

if in each event $v_2 = \overline{v_2}$
and no non-flow → $v_2\{2\} = \overline{v_2}$, $v_2\{m\} = \overline{v_2}$

p+A with negative binomial distribution

for many other implementations it looks similar



$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

AB, P. Bozek, L. McLerran, NPA 927 (2014) 15
L. Yan, J.-Y. Ollitrault, PRL 112 (2014) 082301
AB, V. Skokov, NPA 943 (2015) 1

$$\left\langle \epsilon_2^{2n} \right\rangle = \frac{n! \lim\limits_{z\to 0} \frac{d^n}{dz^n} \left\langle I_0\left(2\sqrt{z} r^2\right)\right\rangle^N}{\lim\limits_{z\to 0} \frac{d^{2n}}{dz^{2n}} \left\langle e^{-r^2 z}\right\rangle^N}$$

Long-range (pseudo)rapidity correlations

AB, D. Teaney,
PRC 87 (2013) 024906

average single particle distribution

$$\rho_{\text{event}}(y) = \langle \rho(y) \rangle \left[1 + \sum_{i=0} a_i T_i(y/Y) \right]$$

single particle distribution in an event

orthogonal polynomial Chebyshev, Legendre, etc. ?

a_i - coefficients analogous to elliptic, triangular etc. flow

y - rapidity or pseudorapidity

Y - measurement is from $-Y$ to Y

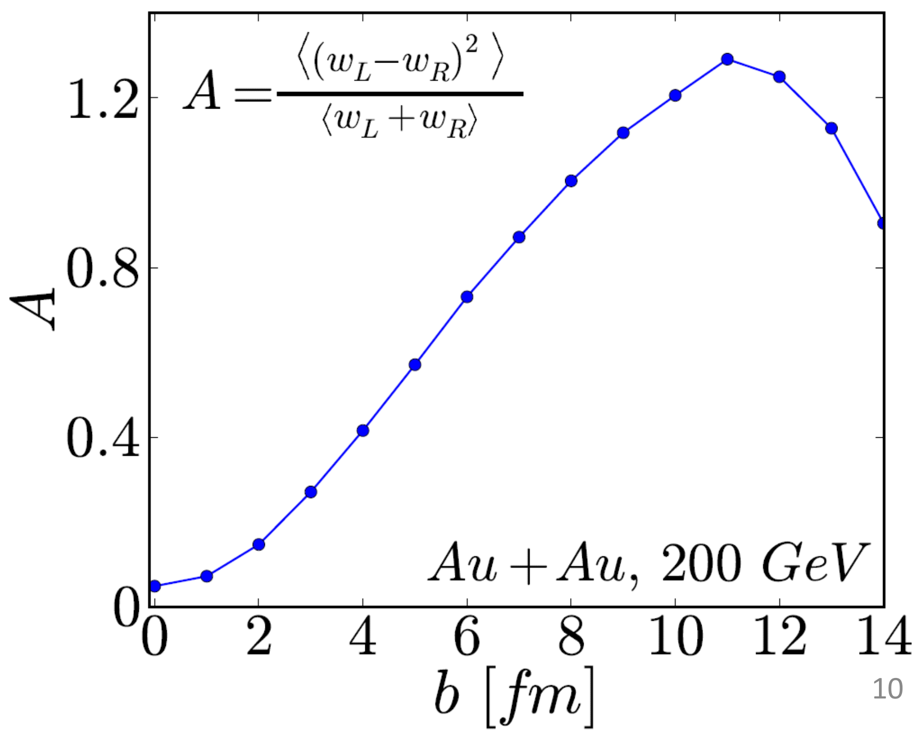
Long-range (pseudo)rapidity correlations

$$\rho_{\text{event}}(y) = \langle \rho(y) \rangle \left[1 + a_0 + a_1 \frac{y}{Y} + \cdots \right]$$

a_1 could be driven by asymmetry in the number of left- and right-going wounded nucleons, w_L and w_R

a_0 is rapidity independent fluctuation of fireball as a whole

see also
J.Jia, S.Radhakrishnan, M.Zhou
arXiv:1506.03496 (2015)
for more practical discussion



Long-range (pseudo)rapidity correlations

AB, D. Teaney,
PRC 87 (2013) 024906

$$\rho_{\text{event}}(y) = \langle \rho(y) \rangle \left[1 + \sum_{i=0} a_i T_i(y/Y)\right]$$

$$\downarrow$$

$$\frac{C_2(y_1, y_2)}{\langle \rho(y_1) \rangle \langle \rho(y_2) \rangle} = \sum_{i,k} \langle a_i a_k \rangle T_i(y_1/Y) T_k(y_2/Y)$$

Long-range two-particle correlation function

$$\frac{C_2(y_1, y_2)}{\langle \rho(y_1) \rangle \langle \rho(y_2) \rangle} \sim \langle a_0^2 \rangle + \langle a_1^2 \rangle \frac{y_1 y_2}{Y^2} + \cdots$$

First hydro calculations reported recently

P.Bozek, W.Broniowski, A.Olszewski, arXiv:1509.04124

A.Monnai, B.Schenke, arXiv:1509.04103

New ATLAS results reported at this QM → J. Jia

It would be interesting to calculate $\langle a_i a_k \rangle$ in CGC related models.

New nontrivial tests for all models in p+p, p+A, A+A collisions

It is important to remove the short-range correlations related to resonances, jets, etc. → **multi-particle rapidity correlations**

$$\frac{C_n(y_1, \ldots, y_n)}{\langle \rho(y_1) \rangle \ldots \langle \rho(y_n) \rangle}$$

AB, P. Bozek,
arXiv:1509.02967

AB, D. Teaney,
PRC 87 (2013) 024906

For example the genuine 4-particle correlation function

$$\frac{C_4(y_1,y_2,y_3,y_4)}{\langle\rho(y_1)\rangle\ldots\langle\rho(y_4)\rangle} = \sum_{i,k,m,n=0} \langle a_i a_k a_m a_n\rangle_{[4]} T_i\left(y_1\right) T_k\left(y_2\right) T_m\left(y_3\right) T_n\left(y_4\right)$$

$$\begin{aligned}\langle a_i a_k a_m a_n\rangle_{[4]} \equiv\ & \langle a_i a_k a_m a_n\rangle - \langle a_i a_k\rangle\langle a_m a_n\rangle \\ & - \langle a_i a_m\rangle\langle a_k a_n\rangle - \langle a_i a_n\rangle\langle a_k a_m\rangle\end{aligned}$$

In particular

$$\langle a_i^4\rangle_{[4]} \equiv \langle a_i^4\rangle - 3\langle a_i^2\rangle^2$$

For more details see: AB, P. Bozek, arXiv:1509.02967

Conclusions

Hydro can fit all data in p+Pb, d+Au and He3+Au

CGC less successful

New tests: $\langle p_t \rangle, v_2, v_3$ vs. (pseudo)rapidity

$\langle N_{ch} \rangle$ vs. N_{part}

Multi-particle long-range rapidity correlations could shed more light on physics in small systems