Longitudinal fluctuations of the medium created in heavy-ion collisions

Adam Bzdak

AGH University of Science and Technology, Kraków

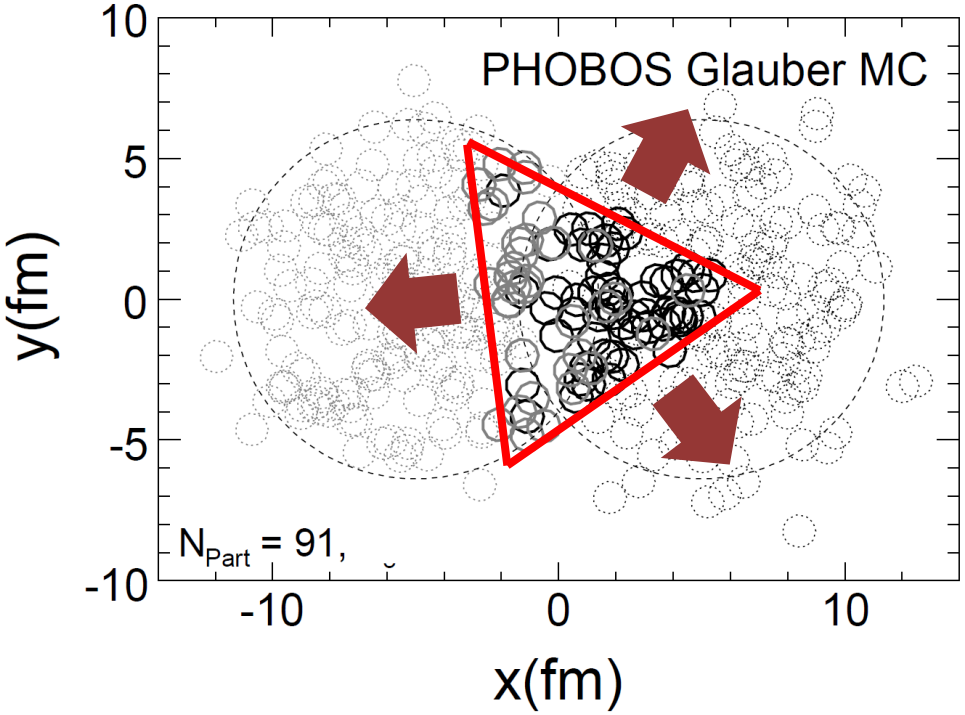
AB, D. Teaney, PRC 87 (2013) 2, 024906
AB, P. Bożek, arXiv:1509.02967
AB, K. Dusling, arXiv:1511.03620

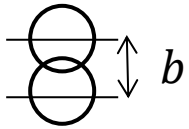
Outline

- transverse fluctuations
- longitudinal fluctuations
- multi-particle rapidity correlations
- CGC application
- conclusions

Transvers fluctuations and correlations
For example:

B. Alver, G. Roland,
PRC 81 (2010) 054905





$$\sigma_{in}(b) \sim e^{-b^2/\gamma}$$

inelastic cross-section

$$C_2(\Delta\varphi) \sim \cos(3\Delta\varphi)$$

$$\Delta\varphi = \varphi_1 - \varphi_2$$

φ — azimuthal angle

Fluctuation of ellipticity → $\cos(2\Delta\varphi)$

In general

$$C_2(\Delta\varphi) \sim \sum_{n=1} \langle v_n^2 \rangle \cos(n\Delta\varphi)$$

We also have multi-particle correlations

$$C_4 \sim \langle v_n^4 \rangle \cos(n[\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4])$$

$$C_6 \sim \langle v_n^6 \rangle \cos(n[\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4 - \varphi_5 - \varphi_6])$$

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

Longitudinal shape fluctuations

New source of rapidity correlations

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

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

single particle distribution in an event (neglecting statistical fluctuations)

average single particle distribution

a_0 is rapidity independent fluctuation of fireball as a whole

multiplicity distribution

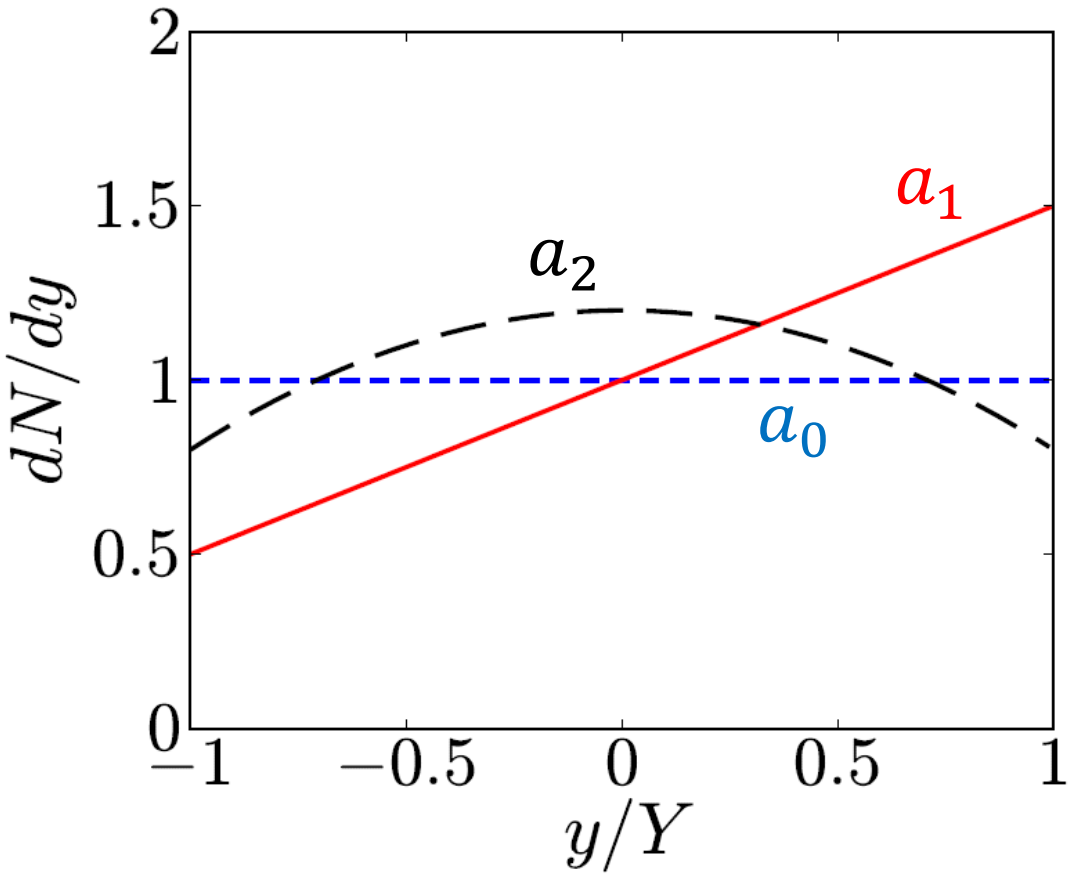
a_1 is an event-by-event rapidity asymmetry

e.g. asymmetry in the number of left- and right-going constituents (nucleons, quarks, diquarks, etc.) in p+p, p+A and A+A

Y - measurement is from $-Y$ to Y

A.Bialas, AB, K.Zalewski,
PLB 710 (2012) 332

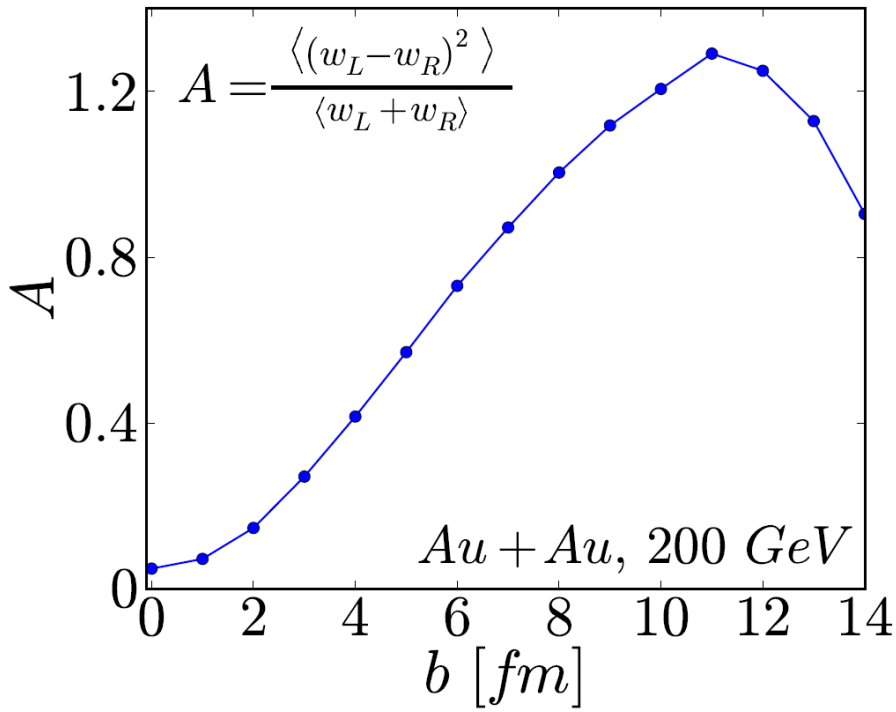
Fireball shape in rapidity can fluctuate



here $\mathrm{dN/dy} \equiv \rho_{\mathrm{event}}(y)$

a_1 could be driven by asymmetry in the number of left- and right-going constituents (nucleons, quarks, diquarks, etc.)

$$a_1 \sim w_L - w_R$$



$w_{L(R)}$ – left (right) moving wounded nucleons

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

In general

average single
particle distribution

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

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 (and short) range rapidity correlations

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

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

$$\Downarrow$$

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

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

Comments

new ATLAS results (ATLAS-CONF-2015-051)

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

first hydro calculations

P.Bozek, W.Broniowski, A.Olszewski, PRC 92 (2015) 5, 054913
A.Monnai, B.Schenke, PLB 752 (2016) 317

sensitivity of a_1 to **saturation scale fluctuations**

AB, K.Dusling, arXiv:1511.03620

sensitivity of a_1 to string length fluctuations

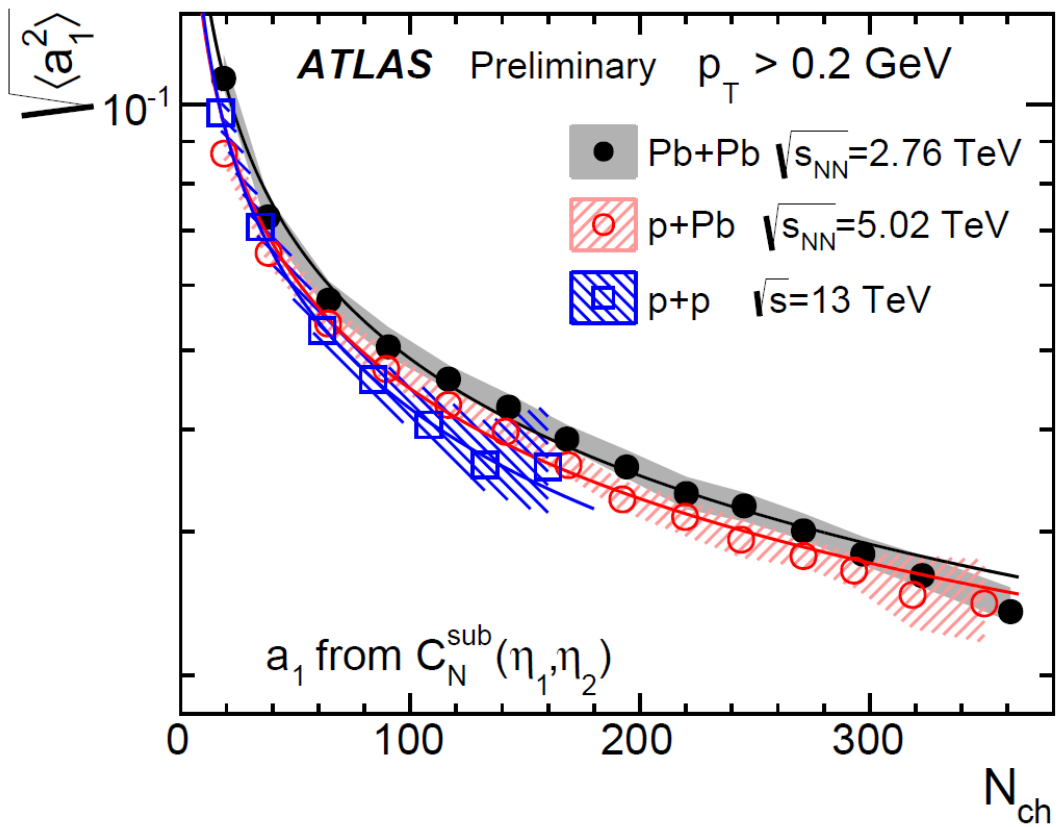
P.Bozek, W.Broniowski, arXiv:1512.01945

it is desired to remove short-range correlations related to resonances, jets, etc. → **multi-particle rapidity correlations**

AB, P.Bozek, arXiv:1509.02967

a_1 as a function of the number of produced particles in $|\eta| < 2.4$. Short-range correlations are removed (?)

ATLAS-CONF-2015-051



$$\sqrt{\langle a_1^2 \rangle} \sim \frac{1}{N_{\mathrm{ch}}^{0.47-0.49}}$$

Multi-particle rapidity correlations

For example the genuine 4 and 6-particle correlation functions

$$\frac{C_4(y_1, \dots, y_4)}{\langle \rho(y_1) \rangle \dots \langle \rho(y_4) \rangle} = \cdots + \left[\langle a_1^4 \rangle - 3 \langle a_1^2 \rangle^2 \right] \frac{y_1 y_2 y_3 y_4}{Y^4} + \cdots$$

$$\frac{C_6}{\langle \rho \rangle \dots \langle \rho \rangle} = \cdots + \left[\langle a_1^6 \rangle - 15 \langle a_1^2 \rangle \langle a_1^4 \rangle - 10 \langle a_1^3 \rangle^2 + 30 \langle a_1^2 \rangle^3 \right] \frac{y_1 y_2 y_3 y_4 y_5 y_6}{Y^6} + \cdots$$

AB, P. Bozek, arXiv:1509.02967

In general for 4 particles

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

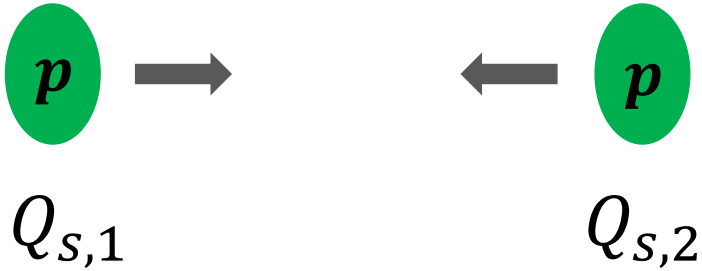
$$\begin{aligned} \langle a_i a_k a_m a_n \rangle_{[4]} \equiv & \langle a_i a_k a_m a_n \rangle - \langle a_i a_k \rangle \langle a_m a_n \rangle \\ & - \langle a_i a_m \rangle \langle a_k a_n \rangle - \langle a_i a_n \rangle \langle a_k a_m \rangle \end{aligned}$$

In particular

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

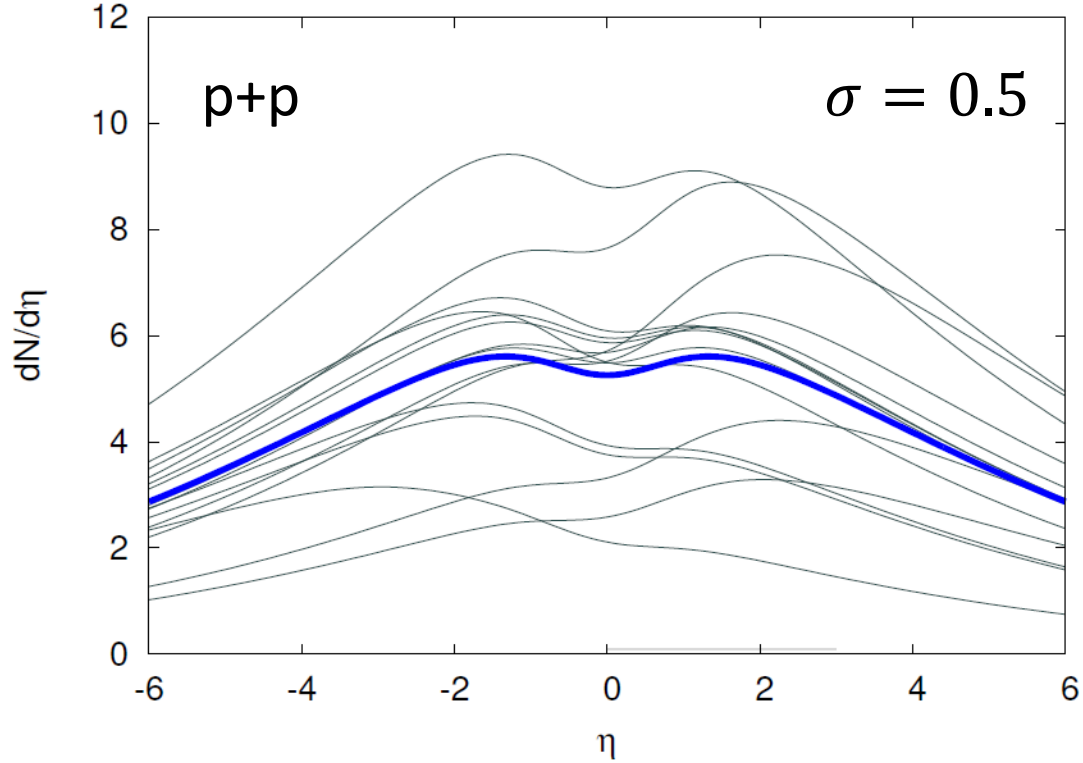
AB, P. Bozek, arXiv:1509.02967

CGC application



CGC application

AB, K. Dusling, arXiv:1511.03620

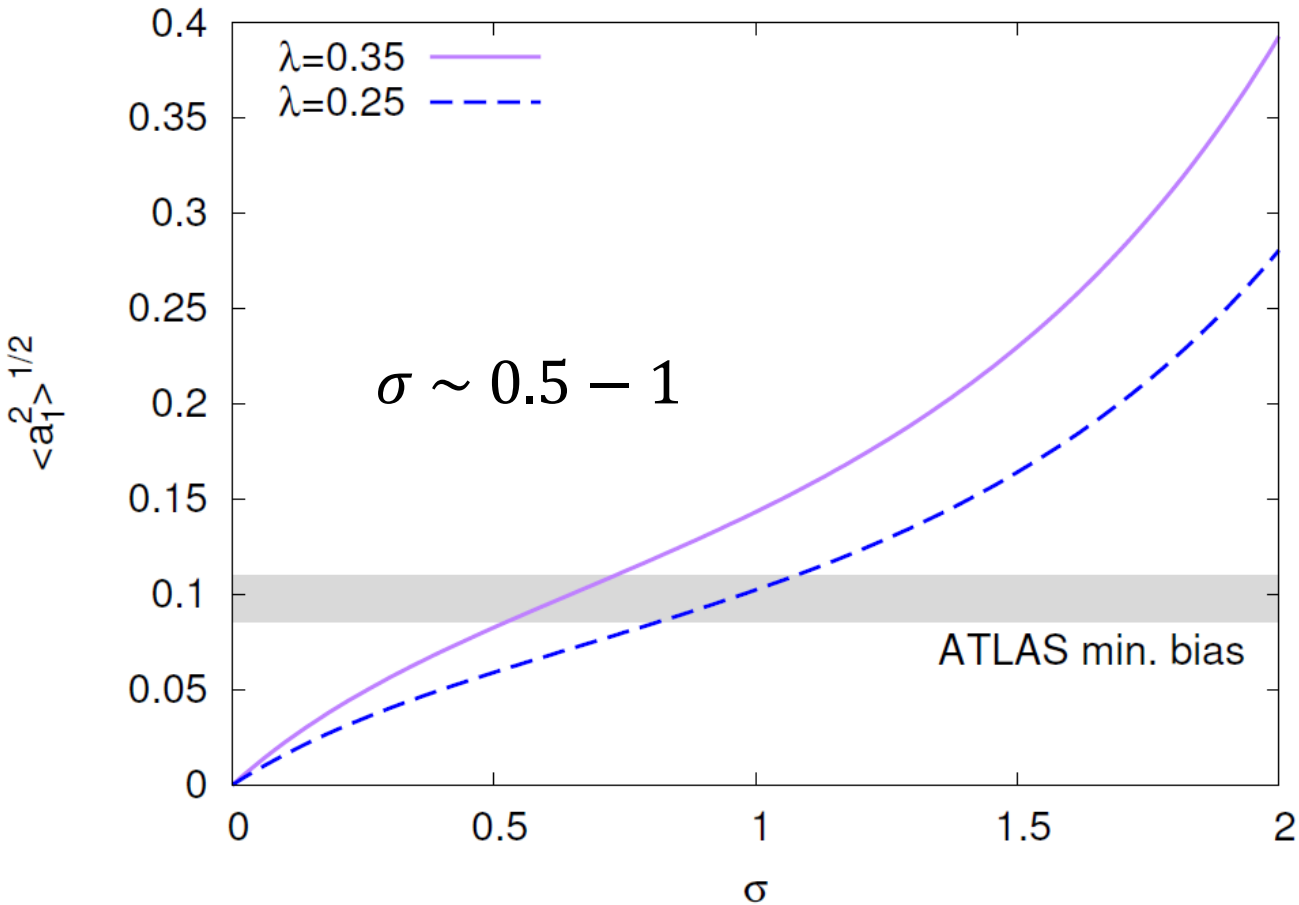


$$Q_1^2 = Q_{o,1}^2 e^{+\lambda y}$$

$$Q_2^2 = Q_{o,2}^2 e^{-\lambda y}$$

$$\frac{dN}{dy} \propto S_\perp \mathrm{Min}[Q_1^2, Q_2^2] \left(2 + \ln \frac{\mathrm{Max}[Q_1^2, Q_2^2]}{\mathrm{Min}[Q_1^2, Q_2^2]}\right)$$

$$P[\rho] = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\rho^2}{2\sigma^2}\right] \quad \text{where} \quad \rho \equiv \log\left(\frac{Q^2}{\bar{Q}^2}\right)$$



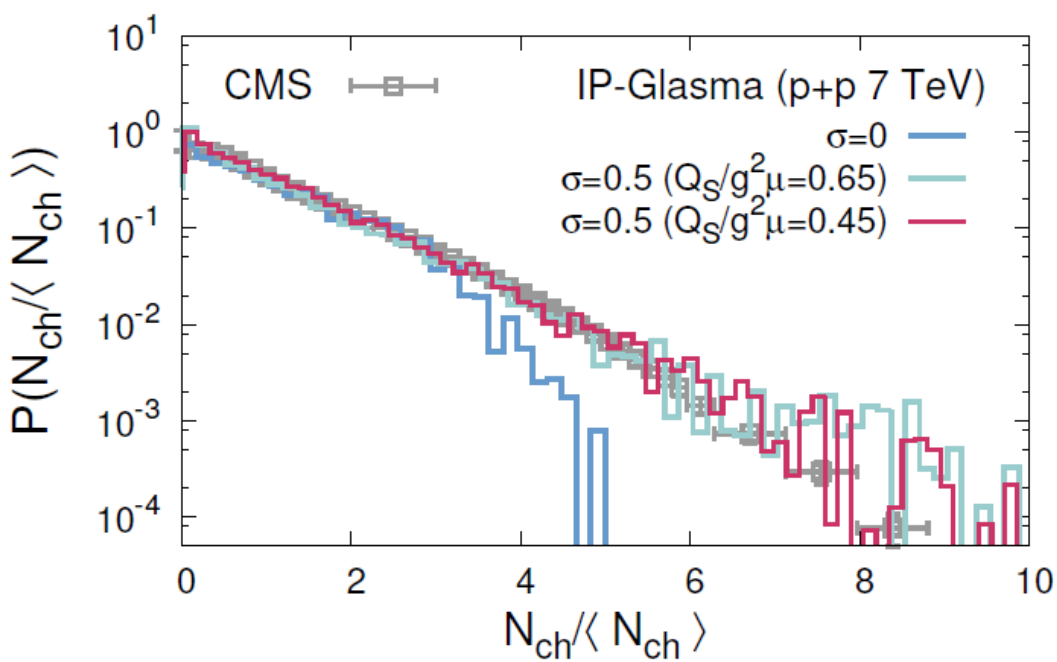
$$\langle a_1^2 \rangle \simeq \frac{\lambda^2 \sigma^2}{2} \frac{4\pi\left(1+2\sigma^2\right)\exp\left[\sigma^2\right]\mathrm{Erfc}\left[\sigma\right] - 8\sqrt{\pi}\sigma}{\left(\sqrt{\pi}\left(\sigma^2-2\right)\mathrm{Erfc}\left[\frac{\sigma}{2}\right] - 2\sigma\exp\left[-\frac{\sigma^2}{4}\right]\right)^2}$$

AB, K. Dusling, arXiv:1511.03620

We conclude that $\sigma \sim 0.5 - 1$

$$P[\rho] = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\rho^2}{2\sigma^2}\right] \quad \text{where} \quad \rho \equiv \log\left(\frac{Q^2}{\bar{Q}^2}\right)$$

Tails of multiplicity distributions are effected



L. McLerran, P. Tribedy, NPA 945 (2016) 216

Conclusions

Systematic approach to longitudinal dynamics

New source of long-range rapidity correlations

Decomposition of multi-particle correlations into orthogonal polynomials

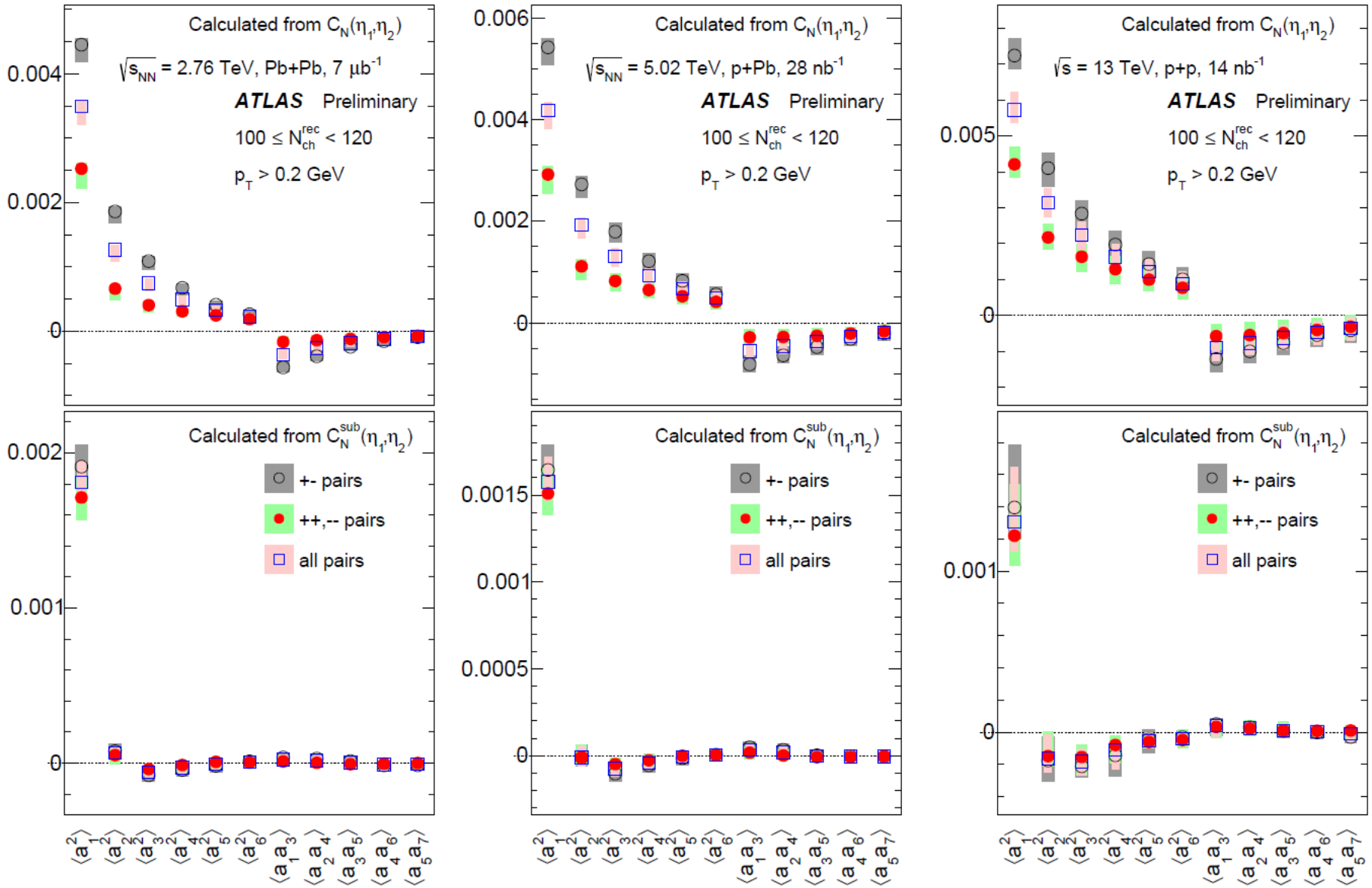
ATLAS sees asymmetric term, interesting scaling for p+p, p+Pb and Pb+Pb

It helps to pin-down the width of Gaussian fluctuations of the logarithm of the saturation scale

Backup

ATLAS (preliminary)

ATLAS-CONF-2015-051



Multi-particle correlation functions

$$C_2(y_1, y_2) = \rho_2(y_1, y_2) - \rho(y_1)\rho(y_2)$$

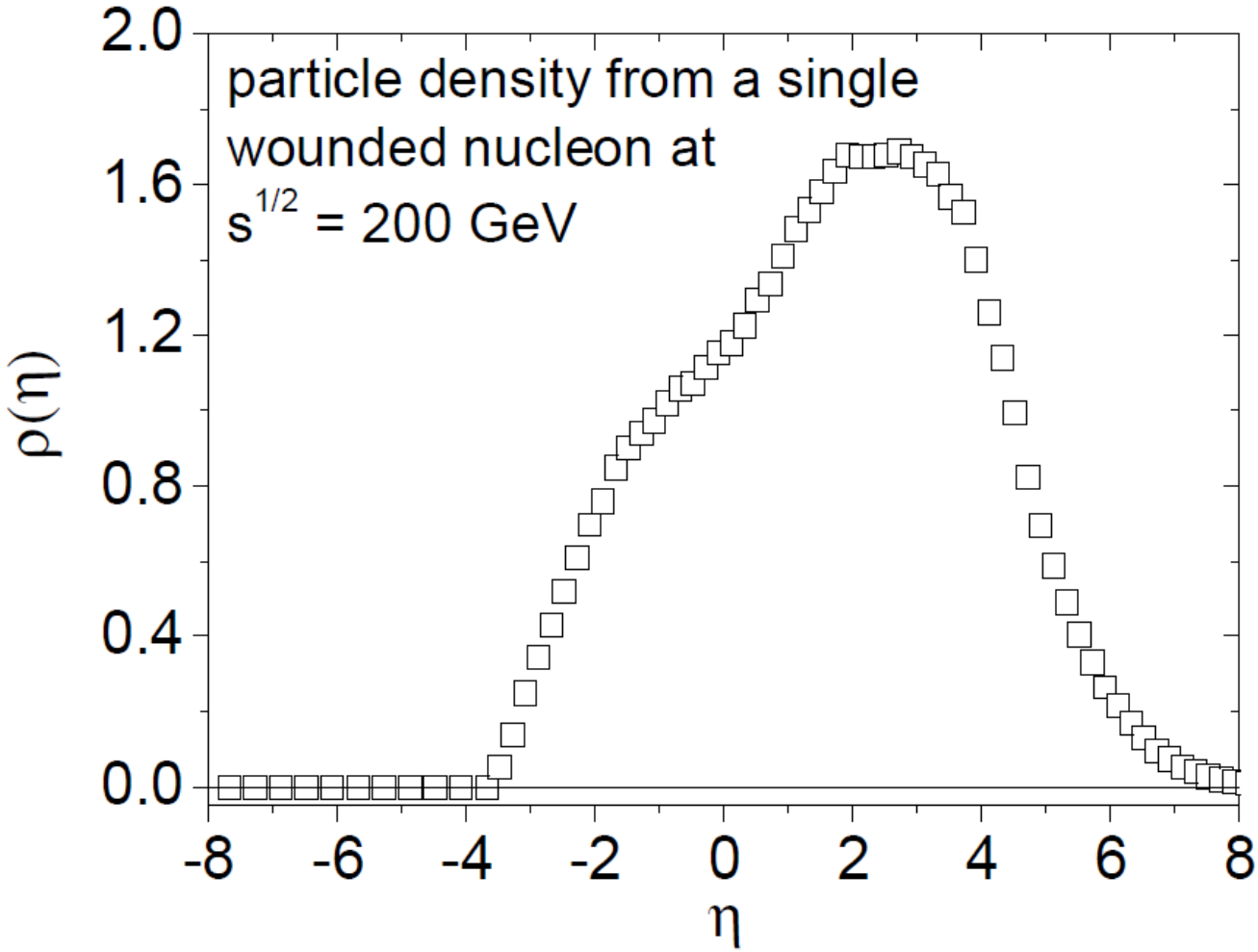
$$\begin{aligned}\rho_3(y_1, y_2, y_3) = {} & \rho(y_1)\rho(y_2)\rho(y_3) + \rho(y_1)C_2(y_2, y_3) + \rho(y_2)C_2(y_1, y_3) + \\ & \rho(y_3)C_2(y_1, y_2) + C_3(y_1, y_2, y_3),\end{aligned}$$

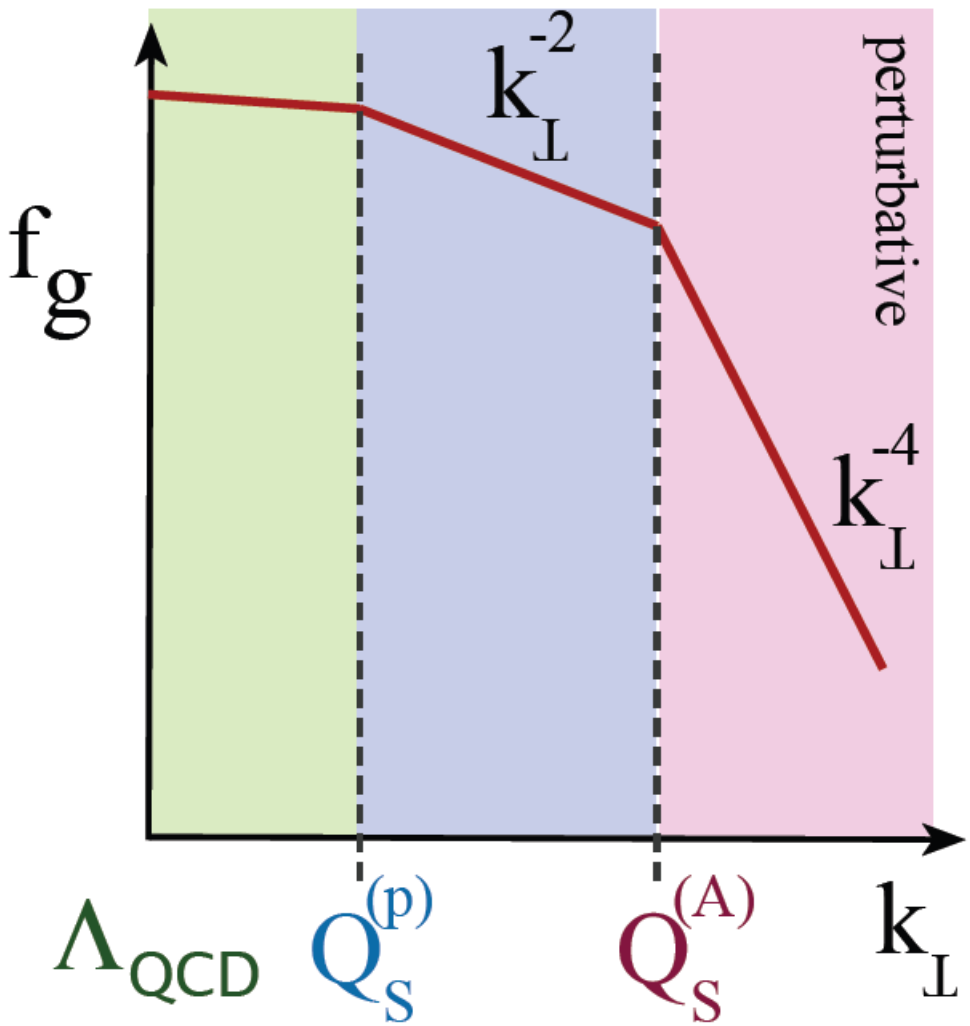
$$\begin{aligned}\rho_4(y_1, y_2, y_3, y_4) = {} & \rho(y_1)\rho(y_2)\rho(y_3)\rho(y_4) + \rho(y_1)\rho(y_2)C_2(y_3, y_4) + \rho(y_1)\rho(y_3)C_2(y_2, y_4) + \\ & \rho(y_1)\rho(y_4)C_2(y_2, y_3) + \rho(y_2)\rho(y_3)C_2(y_1, y_4) + \rho(y_2)\rho(y_4)C_2(y_1, y_3) + \\ & \rho(y_3)\rho(y_4)C_2(y_1, y_2) + \rho(y_1)C_3(y_2, y_3, y_4) + \rho(y_2)C_3(y_1, y_3, y_4) + \\ & \rho(y_3)C_3(y_1, y_2, y_4) + \rho(y_4)C_3(y_1, y_2, y_3) + C_2(y_1, y_2)C_2(y_3, y_4) + \\ & C_2(y_1, y_3)C_2(y_2, y_4) + C_2(y_1, y_4)C_2(y_2, y_3) + C_4(y_1, y_2, y_3, y_4).\end{aligned}$$

$$\rho_5 = \rho\rho\rho\rho\rho + \underbrace{\rho C_4}_{5} + \underbrace{\rho\rho C_3}_{10} + \underbrace{\rho\rho\rho C_2}_{10} + \underbrace{\rho C_2 C_2}_{15} + \underbrace{C_2 C_3}_{10} + C_5$$

$$\begin{aligned}\rho_6 = {} & \rho\rho\rho\rho\rho\rho + \underbrace{\rho C_5}_{6} + \underbrace{\rho\rho C_4}_{15} + \underbrace{\rho\rho\rho C_3}_{20} + \underbrace{\rho\rho\rho\rho C_2}_{15} + \underbrace{\rho C_2 C_3}_{60} + \underbrace{\rho\rho C_2 C_2}_{45} + \underbrace{C_2 C_4}_{15} + \\ & \underbrace{C_3 C_3}_{10} + \underbrace{C_2 C_2 C_2}_{15} + C_6,\end{aligned}$$

Two-source model



A.Bialas, AB, PRC 77 (2008) 034908

CGC in asymmetric systems, two scales