Saturation scale fluctuations and multi-particle rapidity correlations

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AB, K. Dusling, PRC 93 (2016) 031901; PRC 94 (2016) 044918
AB, P. Bożek, PRC 93 (2016) 024903
AB, D. Teaney, PRC 87 (2013) 024906

Outline

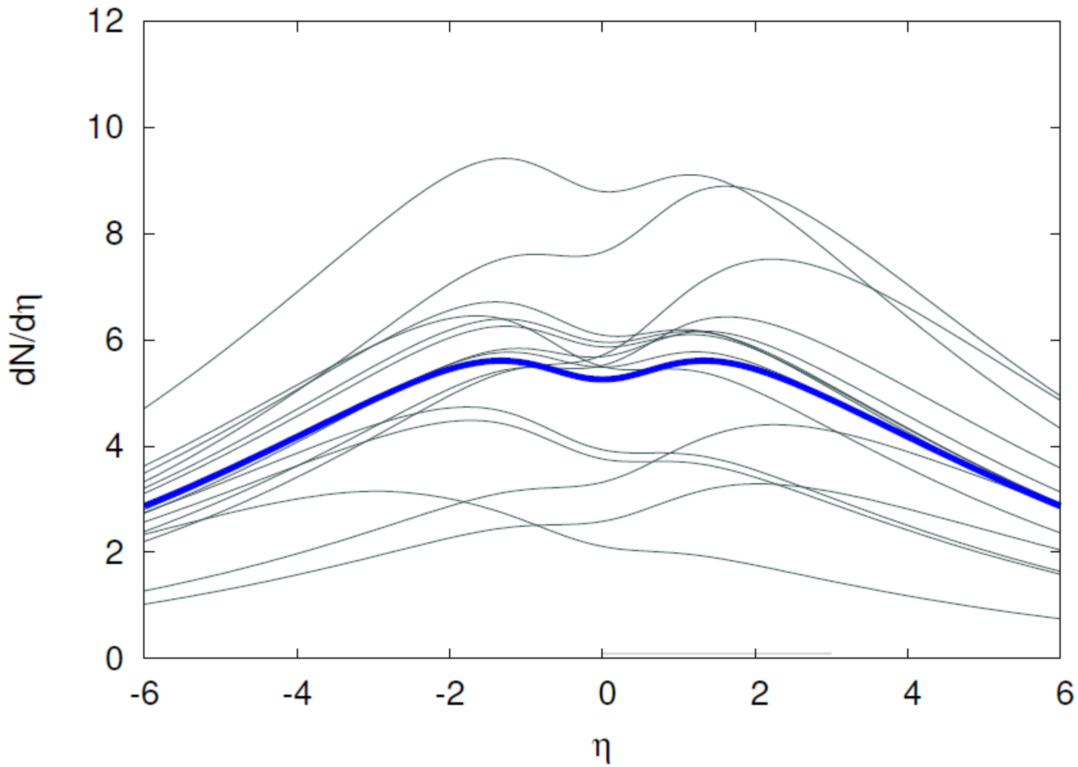
motivation

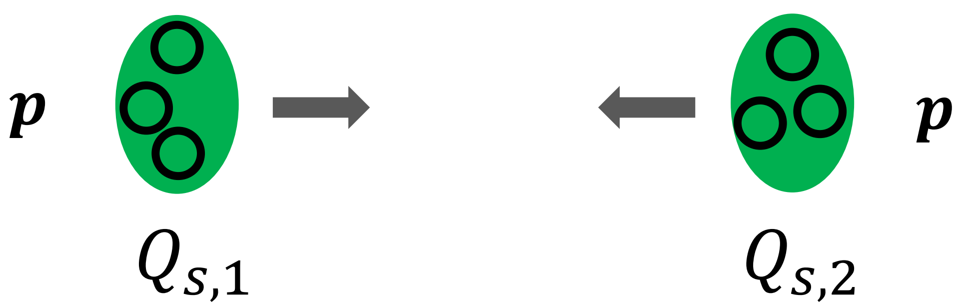
longitudinal fluctuations and correlations

CGC application

conclusions

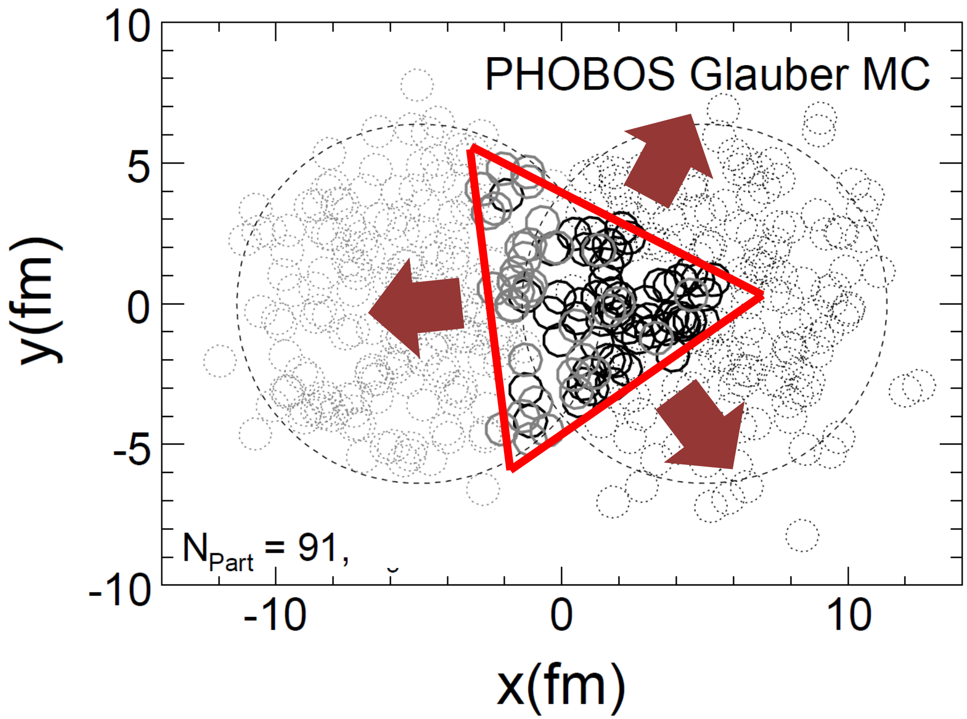
p+p is **not** symmetric in rapidity, it is more like p+A
The shape of the fireball fluctuates in rapidity





Transvers fluctuations and correlations
For example:

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



$$C_2(\Delta\varphi) \sim \cos(3\Delta\varphi) \qquad \Delta\varphi = \varphi_1 - \varphi_2$$

φ – azimuthal angle

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

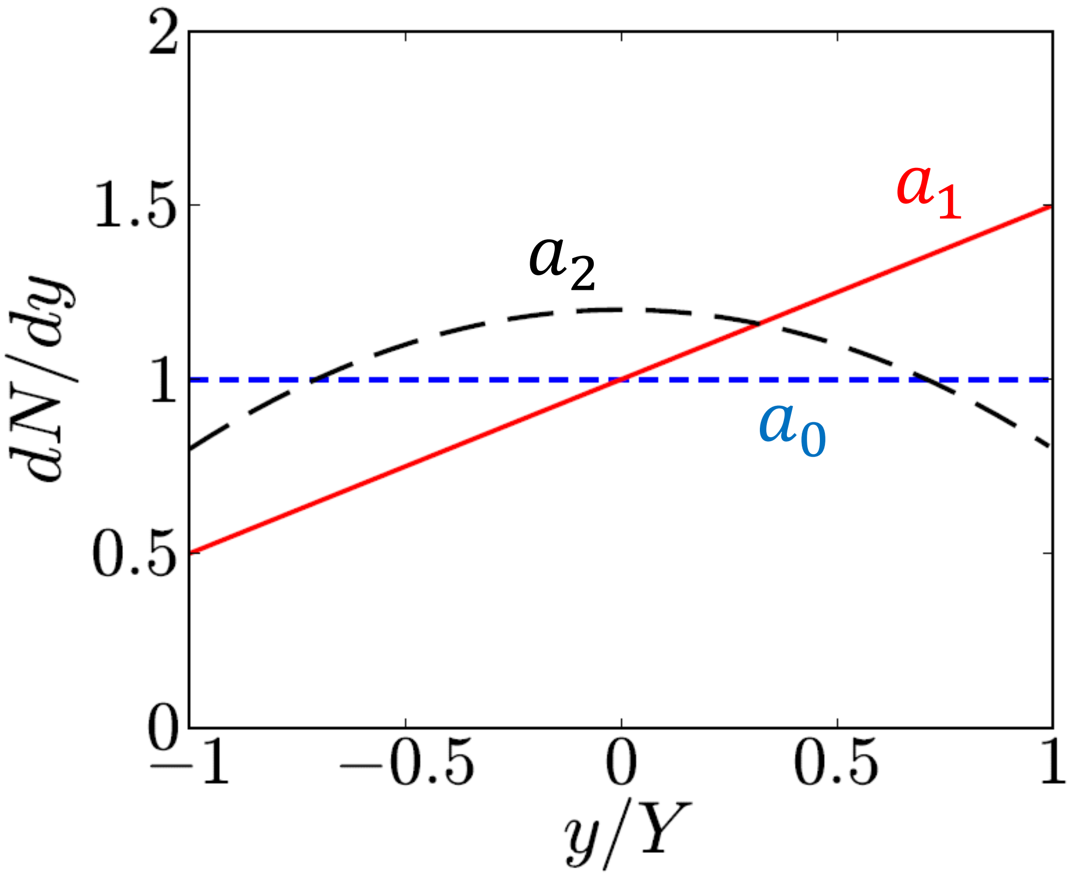
a_1 is an event-by-event rapidity asymmetry

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

So let’s expand in the orthogonal polynomials

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

Long (and short) range rapidity correlations

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

orthogonal polynomials

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

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

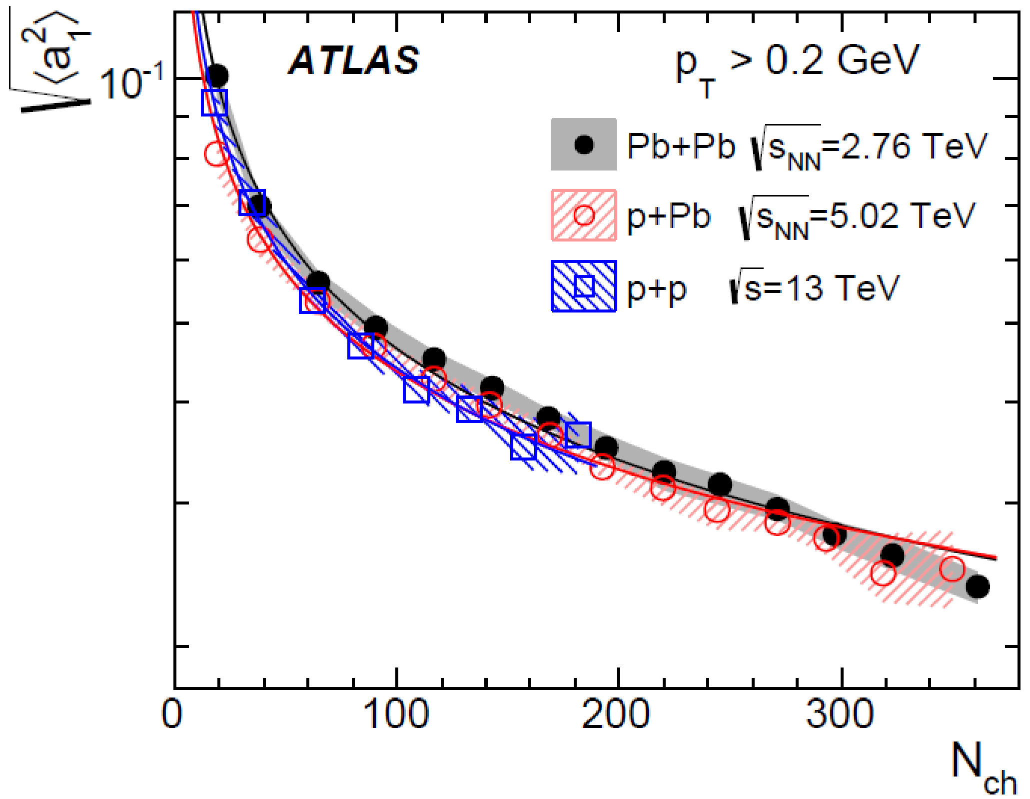
arXiv:1606.08170

The ATLAS Collaboration

Abstract

Two-particle pseudorapidity correlations are measured in $\sqrt{s_{\rm NN}}$ = 2.76 TeV Pb+Pb, $\sqrt{s_{\rm NN}}$ = 5.02 TeV p+Pb, and $\sqrt{s}$ = 13 TeV pp collisions at the LHC, with total integrated luminosities of approximately 7 μb^{-1}, 28 nb^{-1}, and 65 nb^{-1}, respectively. The correlation function $C_{\rm N}(\eta_1, \eta_2)$ is measured as a function of event multiplicity using charged particles in the pseudorapidity range $|\eta| < 2.4$. The correlation function contains a significant short-range component, which is estimated and subtracted. After removal of the short-range component, the shape of the correlation function is described approximately by $1 + \langle a_1^2 \rangle \eta_1 \eta_2$ in all collision systems over the full multiplicity range. The values of $\sqrt{\langle a_1^2 \rangle}$ are consistent between the opposite-charge pairs and same-charge pairs, and for the three collision systems at similar multiplicity. The values of $\sqrt{\langle a_1^2 \rangle}$ and the magnitude of the short-range component both follow a power-law dependence on the event multiplicity. The η distribution of the short-range component, after symmetrizing the proton and lead directions in p+Pb collisions, is found to be smaller than that in pp collisions with comparable multiplicity.

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



surprising scaling

$$\sqrt{\langle a_1^2 \rangle} \sim \frac{1}{N_{\text{ch}}^{0.43-0.47}}$$

new ATLAS results, arXiv:1606.08170

see also J.Jia, S.Radhakrishnan and M.Zhou, PRC 93, 044905 (2016)
for more practical discussion

hydro calculations

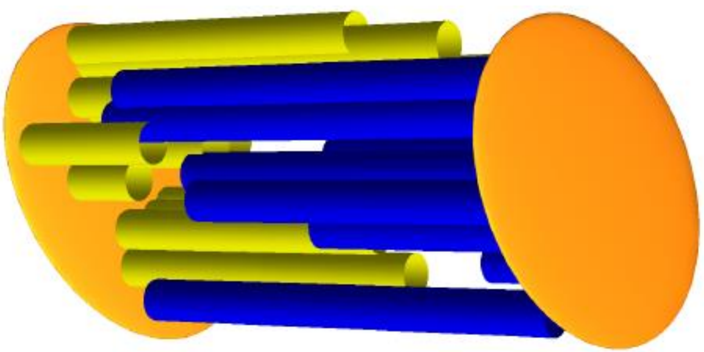
P.Bożek, W.Broniowski, A.Olszewski, PRC 92 (2015) 5, 054913
A.Monnai, B.Schenke, PLB 752 (2016) 317

3-D Glasma calculation

B.Schenke, S.Schlichting, PRC 94, 044907 (2016)

sensitivity of $\langle a_1^2 \rangle$ to string length fluctuations

P.Bożek, W.Broniowski, PRC 93, 064910 (2016)



Multi-particle rapidity correlations

AB, P. Bożek, PRC 93, 024903 (2016)

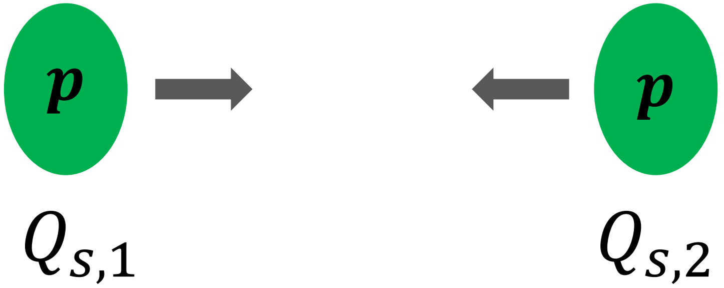
For example the genuine 4 and 6-particle correlation functions

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

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

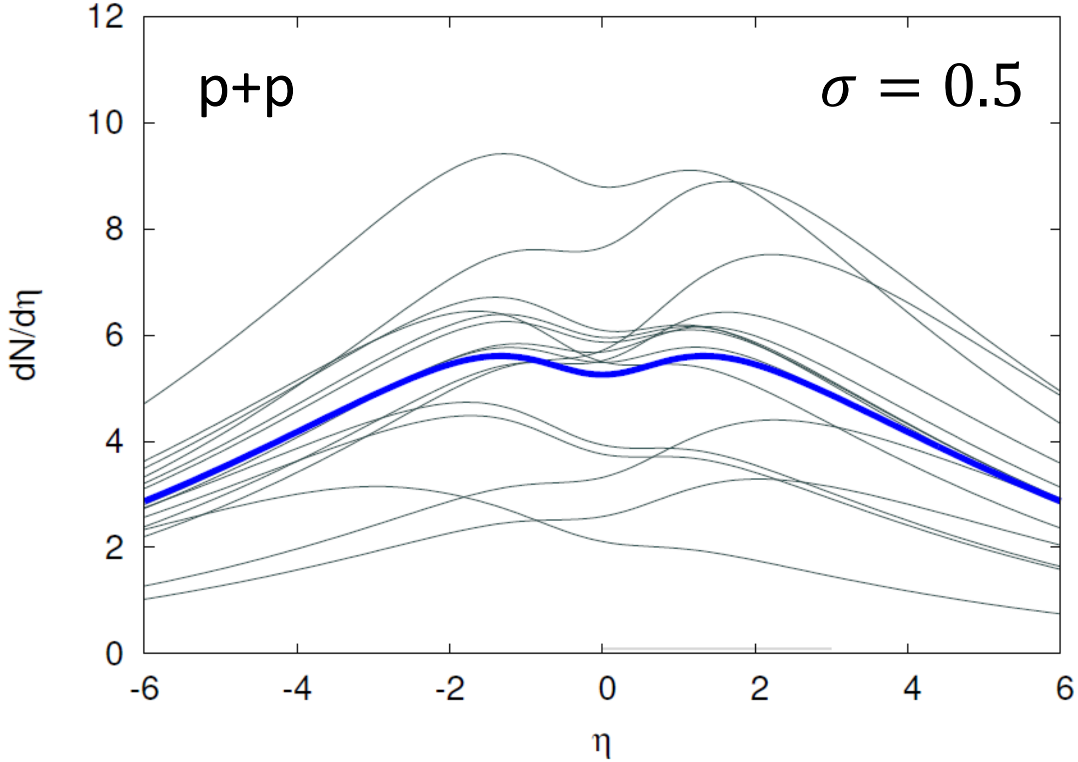
I denote these coefficients by $\langle a_1^4\rangle_{[4]}$ and $\langle a_1^6\rangle_{[6]}$

CGC application



CGC application

AB, K. Dusling,
PRC 93, 031901 (2016)



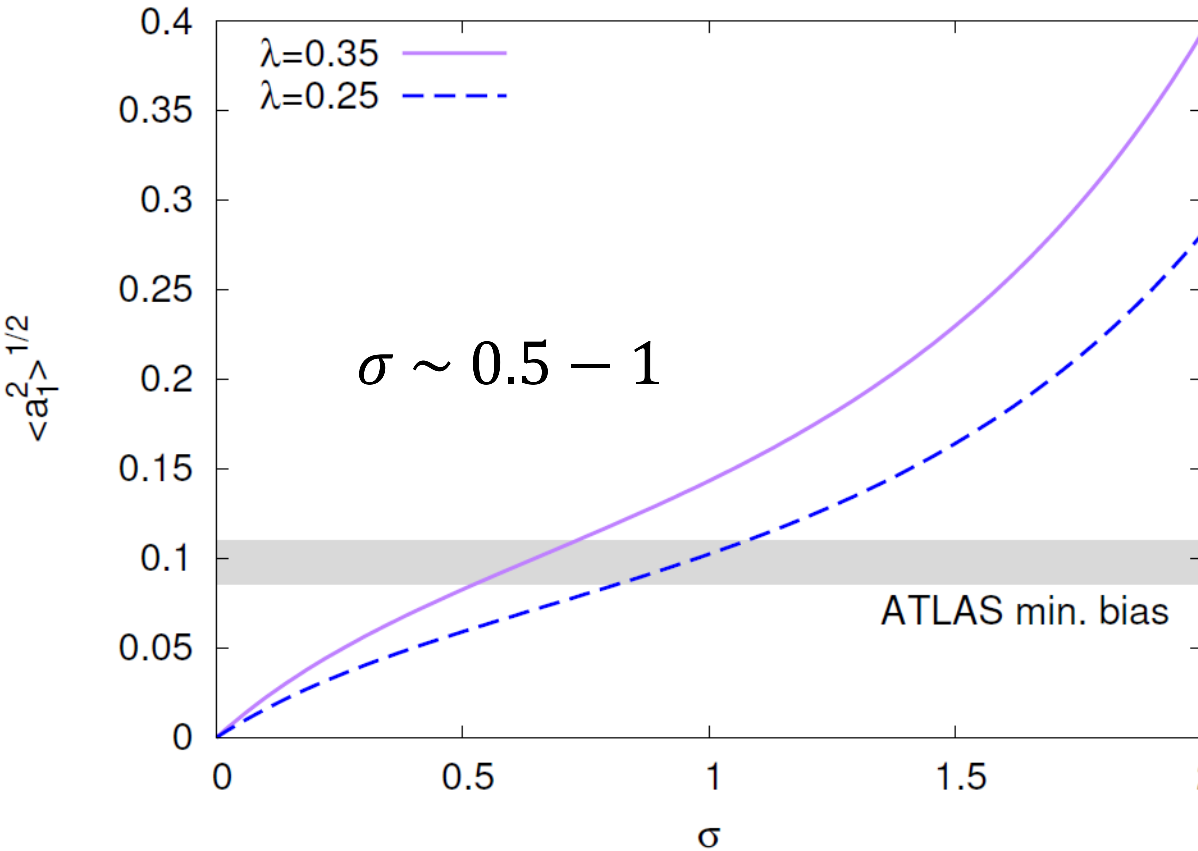
$$Q_1^2 = Q_{o,1}^2 e^{+\lambda y}$$

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

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

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

AB, K. Dusling, PRC 93 (2016) 031901



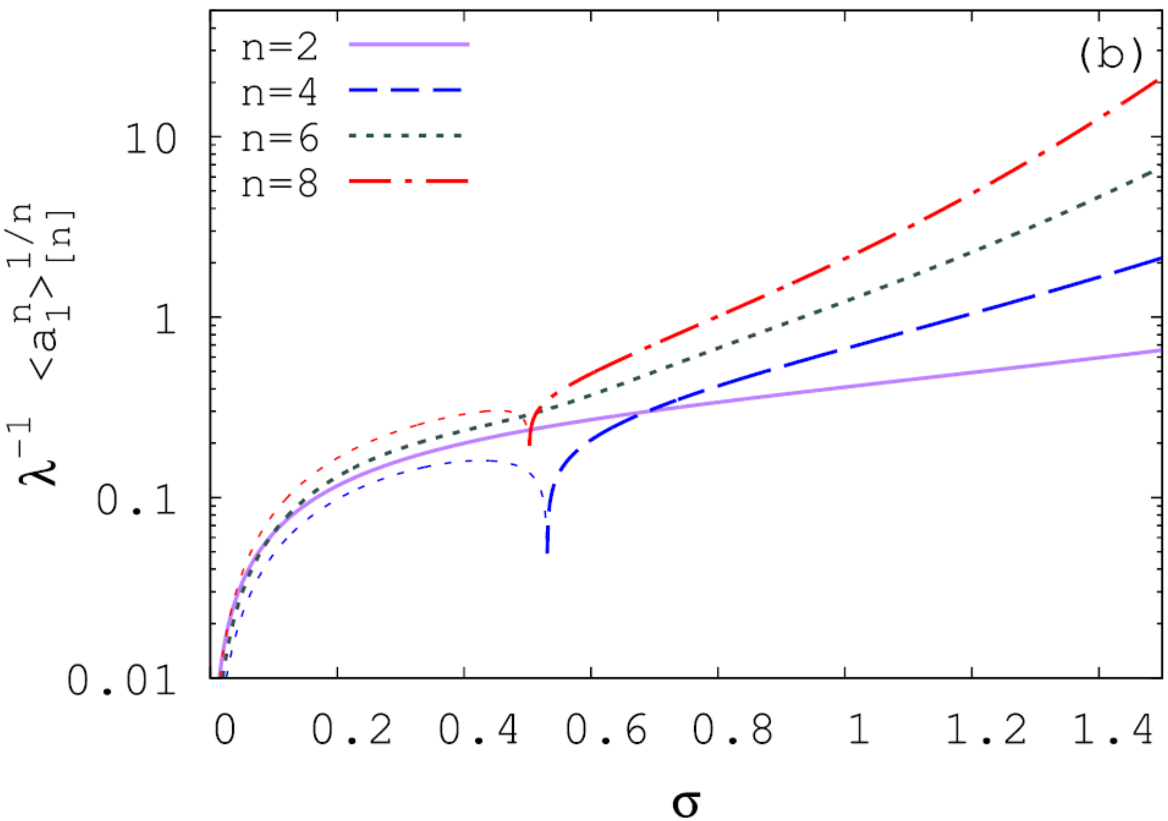
$$\langle a_1^2 \rangle \simeq \frac{\lambda^2 \sigma^2}{2} \frac{4\pi \left(1 + 2\sigma^2\right) \exp\left[\sigma^2\right] \mathrm{Erfc}\left[\sigma\right] - 8\sqrt{\pi}\sigma}{\left(\sqrt{\pi}\left(\sigma^2 - 2\right) \mathrm{Erfc}\left[\frac{\sigma}{2}\right] - 2\sigma \exp\left[-\frac{\sigma^2}{4}\right]\right)^2}$$

See also:

L.McLerran, M.Praszalowicz, Annals Phys. 372 (2016) 215

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

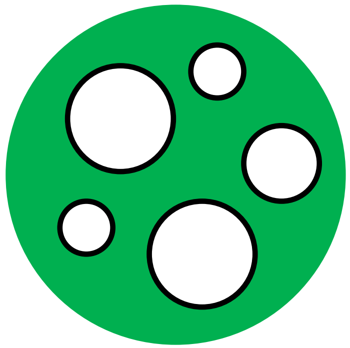
AB, K. Dusling, PRC 94, 044918 (2016)



$$\left\langle a_1^n \right\rangle = \frac{\left[\lambda \sigma \sqrt{\pi} \exp\left(\frac{\sigma^2 (n-2)}{4}\right)\right]^n}{\sqrt{\pi}} \frac{n! U\left(\frac{1+n}{2}; \frac{1}{2}; \frac{n^2 \sigma^2}{4}\right)}{\left[\sqrt{\pi}(\sigma^2 - 2)\,\mathrm{Erfc}\left(\frac{\sigma}{2}\right) - 2\sigma \exp\left(-\frac{\sigma^2}{4}\right)\right]^n}$$

U – confluent hypergeometric function

Erfc – complementary error function



Proton as a set of domains in which Q_s fluctuate independently

Superposition of independent log-normal distributions can be approximated by log-normal

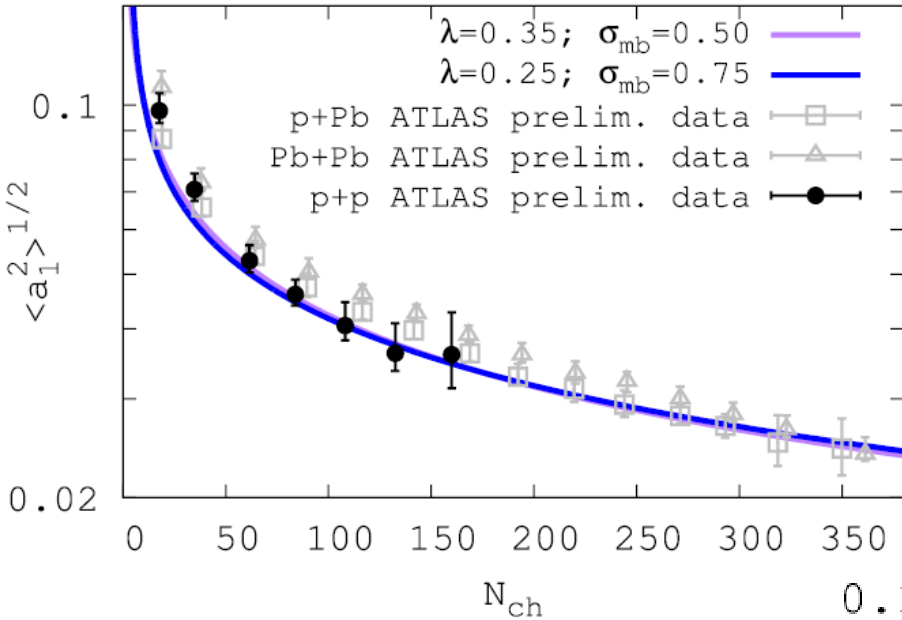
$$\sigma^2 = \ln\left[\frac{1}{N_\mathrm{d}}\left(e^{\sigma_\mathrm{d}^2} - 1\right) + 1\right]$$

N_d - number of domains

$$\sigma^2 \approx \frac{\sigma_\mathrm{d}^2}{N_\mathrm{d}}$$

$$\sigma^2 = \frac{N_\mathrm{ch}^\mathrm{mb}}{N_\mathrm{ch}}\sigma_\mathrm{mb}^2$$

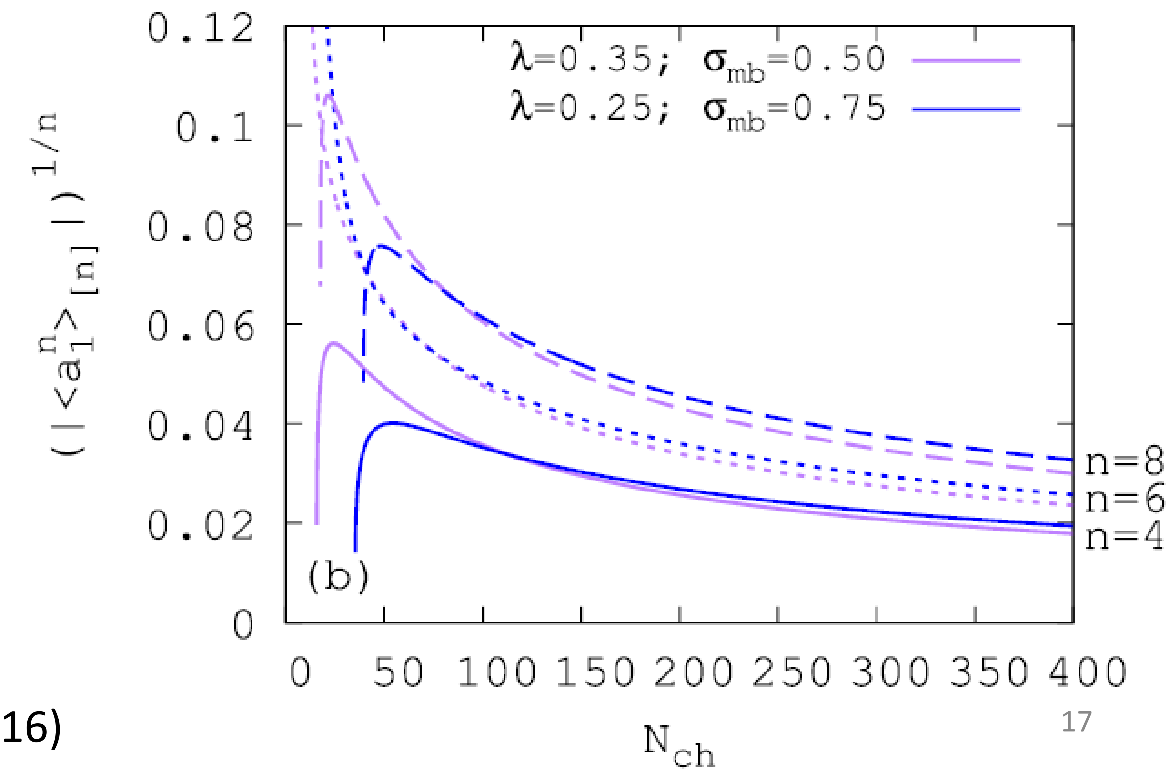
mb – minimum bias



postdiction

p+Pb and Pb+Pb is a puzzle

prediction



AB, K. Dusling, PRC 94, 044918 (2016)

Conclusions

Systematic approach to longitudinal dynamics

Decomposition of multi-particle correlations into orthogonal polynomials

New source of long-range rapidity correlations

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

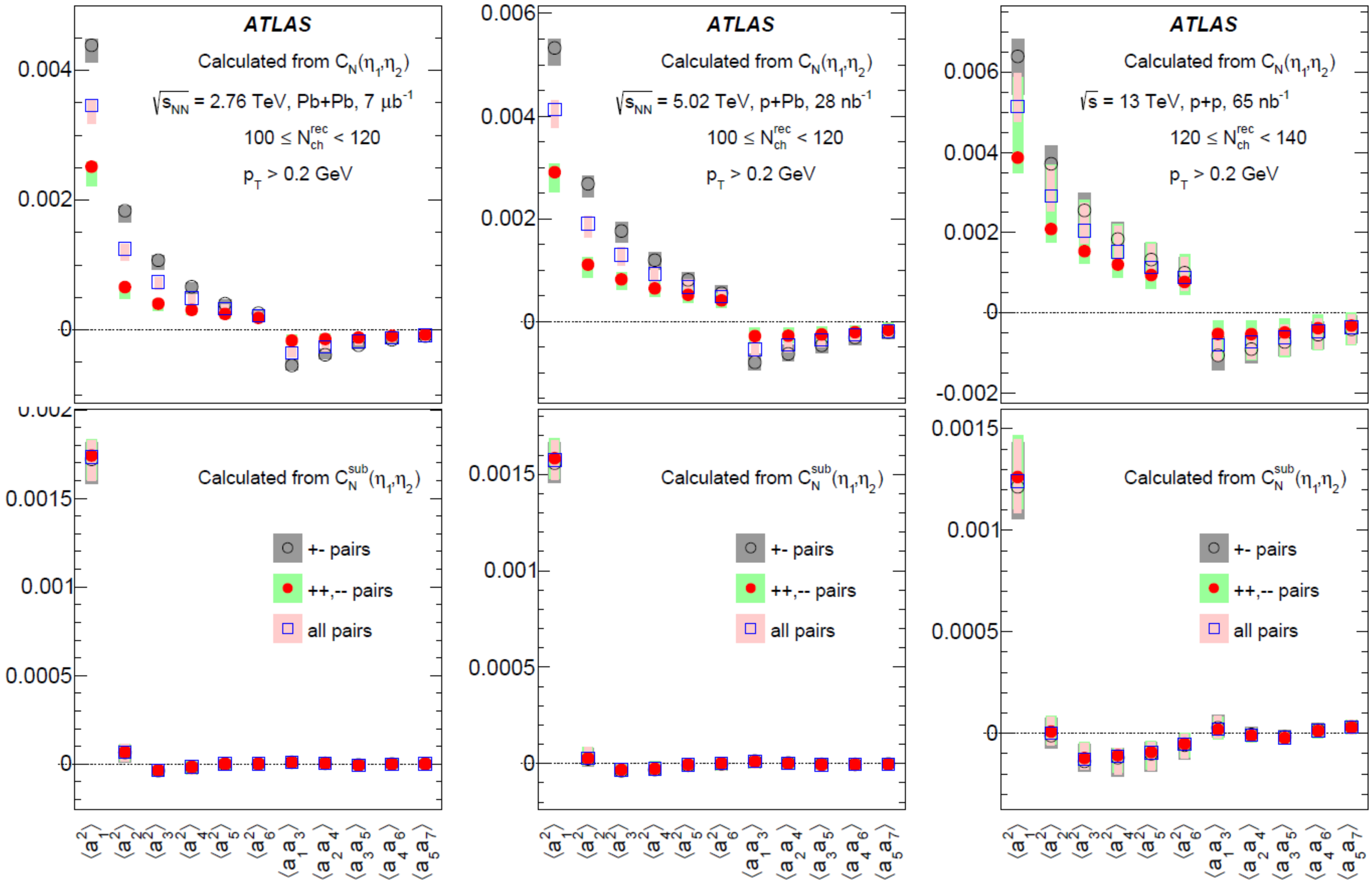
It helps to pin-down the width of Gaussian fluctuations of the logarithm of the saturation scale

Predictions for multi-particle correlations

Backup

ATLAS results for $\langle a_n a_m \rangle$

arXiv:1606.08170



Multi-particle correlation functions

AB, P. Bożek, PRC 93, 024903 (2016)

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

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

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

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

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

In general

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

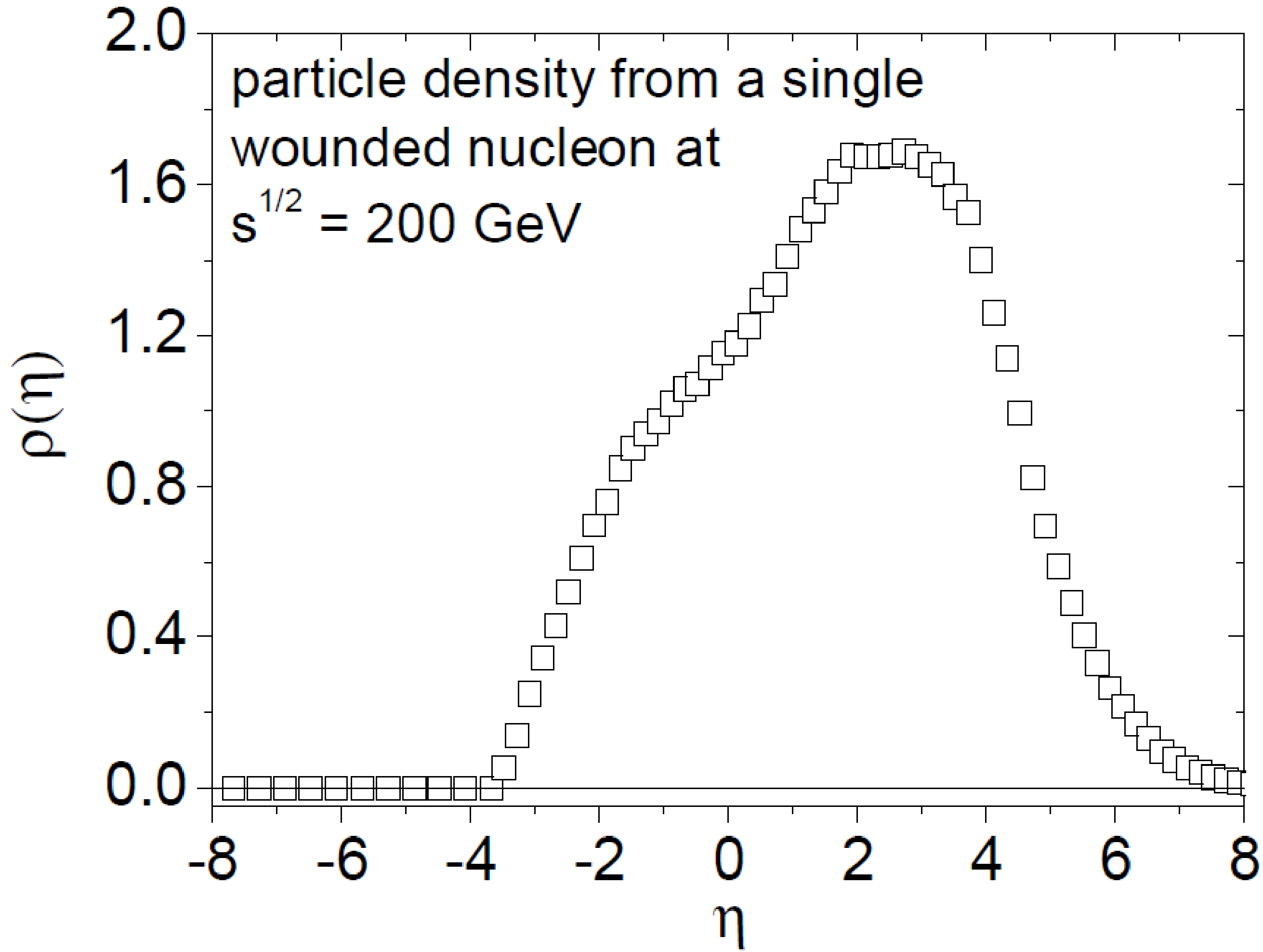
We also have multi-particle correlations

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

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

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

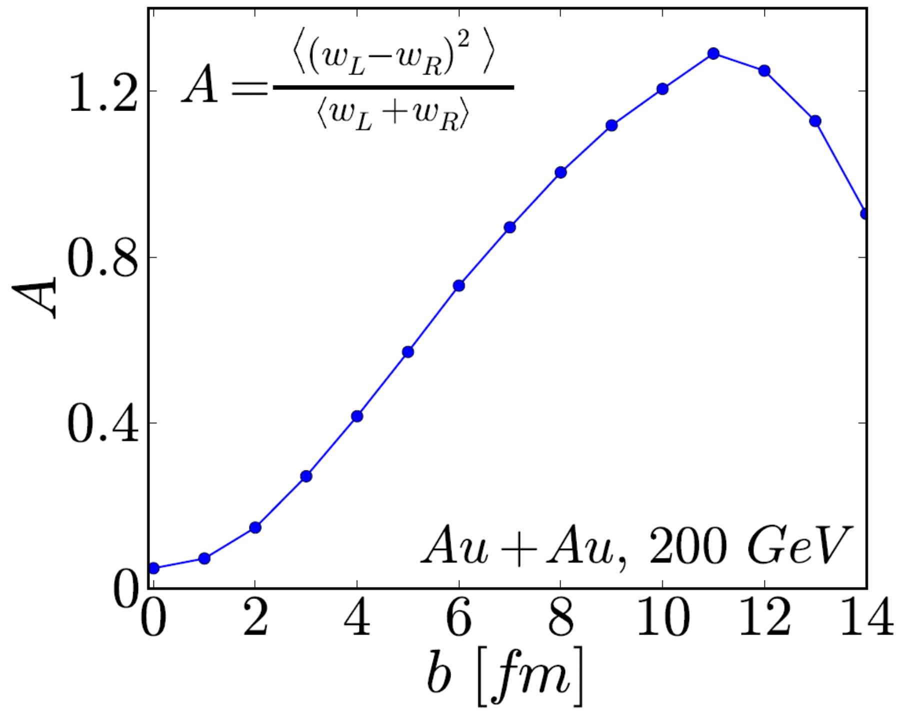
Two-source model



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

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

$$a_1 \sim w_L - w_R$$



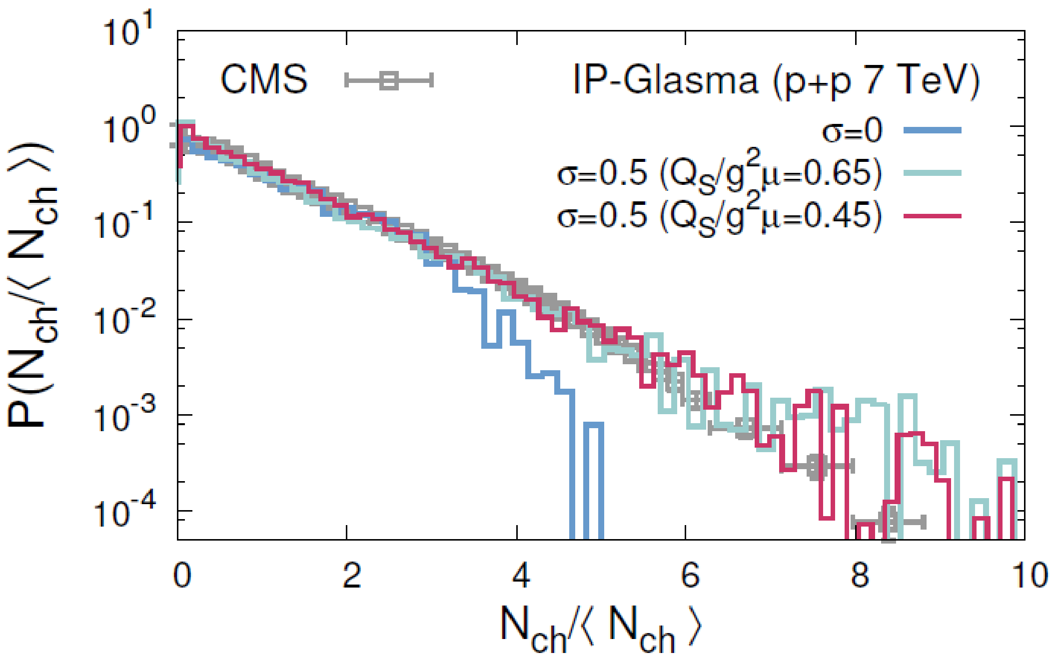
AB, D. Teaney,
PRC 87 (2013) 024906

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

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

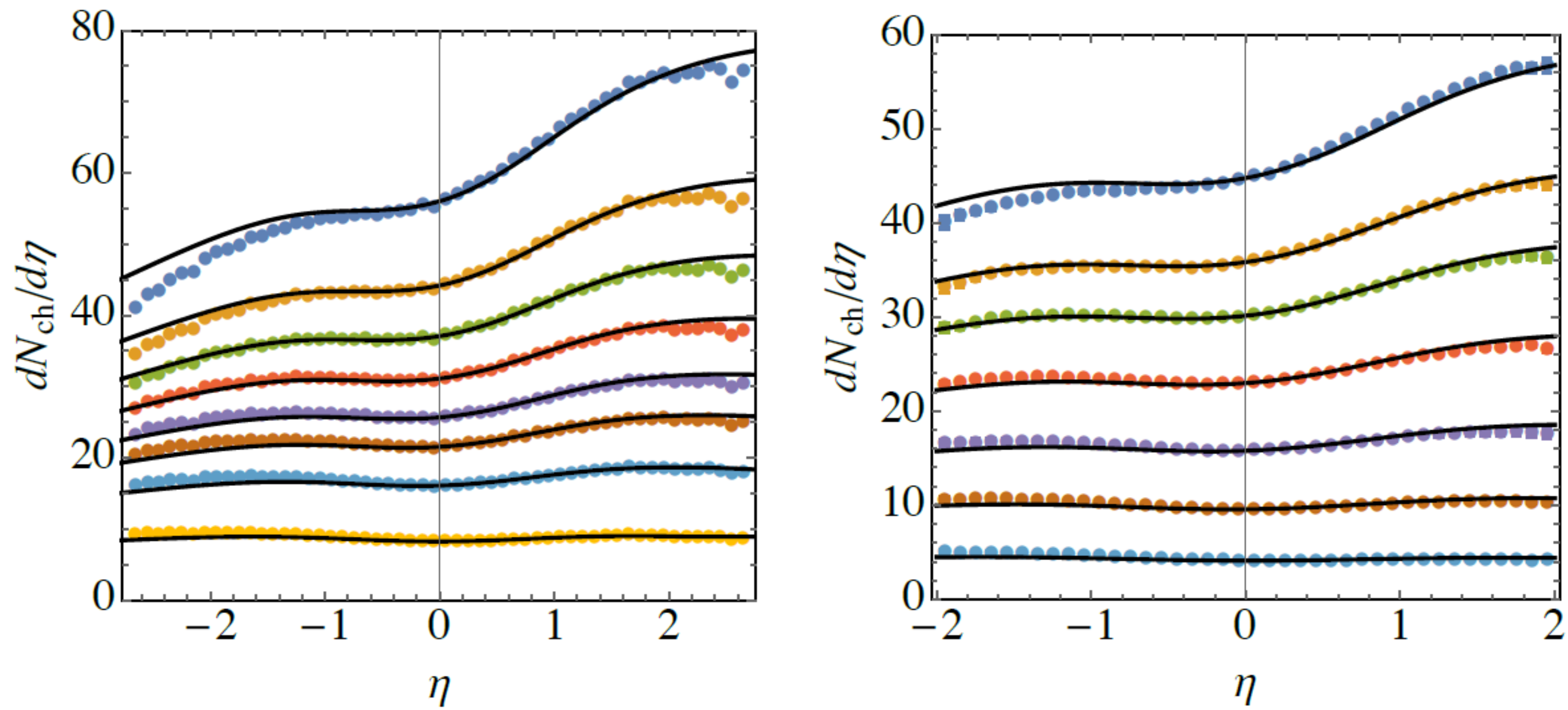


Figure 6: Multiplicity dependence on pseudo-rapidity η for the fluctuating case with $\sigma = 1.55$. Left plot corresponds to ATLAS whereas the right one to ALICE. Different curves correspond to the centrality classes defined in Tables 1 and 2.

L.McLerran, M.Praszalowicz, Annals Phys. 372 (2016) 215

CGC in asymmetric systems, two scales