Korelacje w pośpieszności na LHC

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Szczegóły: WB+Piotr Bożek, arXiv:1512.01945

Motivation/new data

- Old story . . . , investigated at RHIC
  Białas, Zalewski, Bzdak, . . .
  (not all understood at RHIC)
- New data from the LHC, new methodology (ATLAS notes 2015)
- Interplay of long- and short-range effects
- Longitudinally-extended source model

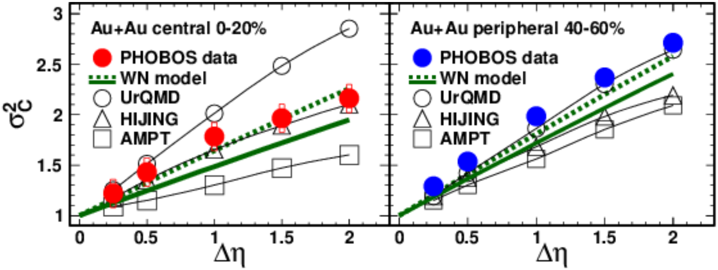
Goal: understand key elements from an analytic model

anatomy of the correlations

Physics issues: production mechanism in the early stage, degrees of freedom,. . .

Some years ago at RHIC . . .

PHOBOS: $\sigma_c^2 = \left\langle \frac{(n_F - n_B)^2}{n_F + n_B} \right\rangle$



[WNM: Bzdak, Woźniak 2010]

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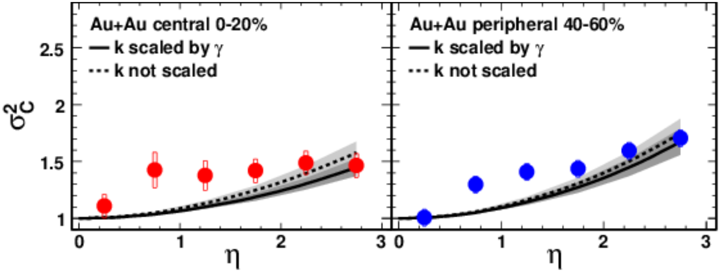
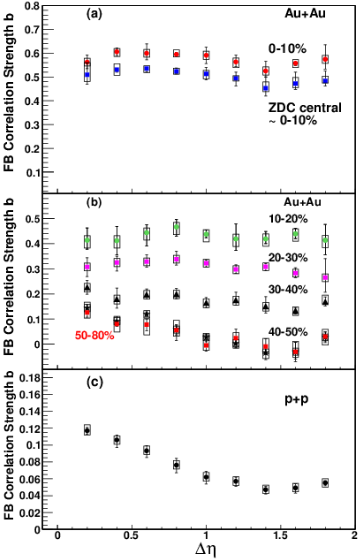


[WNM: Bzdak, Woźniak 2010]

Some years ago at RHIC ...

STAR (for symmetric): $b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle^2}{\langle n_F n_F \rangle - \langle n_F \rangle^2}$ (same as Pearson's ρ)

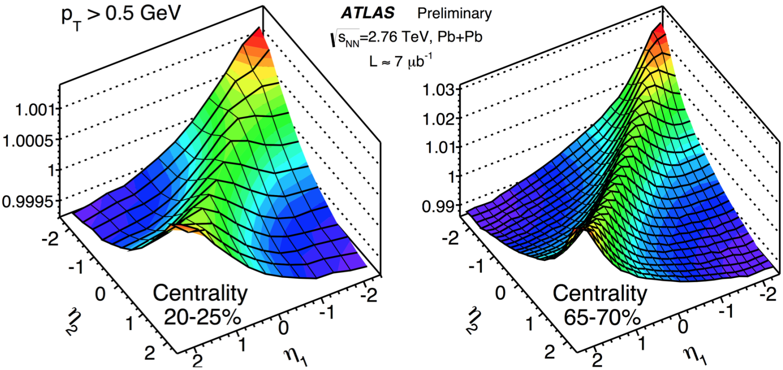


New data (ATLAS notes CONF-2015-020, -051)

$$C(\eta_1,\eta_2) = \frac{\langle N(\eta_1,\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} = \frac{S(\eta_1,\eta_2)}{B(\eta_1,\eta_2)}$$

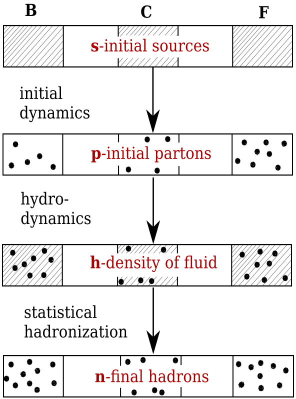
$$C_N(\eta_1,\eta_2) = \frac{C(\eta_1,\eta_2)}{C_p(\eta_1)C_p(\eta_2)}, \quad C_p(\eta_1) = \int d\eta_2 C(\eta_1,\eta_2), \; C_p(\eta_2) = \dots$$

η_1 and η_2 – pseudorapidities of different hadrons (no autocorrelations)



3-stage approach (superposition model)

Generation and propagation of e-by-e fluctuations



[Adam Olszewski+WB 2015]

Concept of sources: wounded nucleons, quarks, flux tubes, ...

Hydro: provides mapping $\eta_s = \frac{1}{2}\log\frac{t+z}{t-z} \to \eta$

Not much mixing between the bins

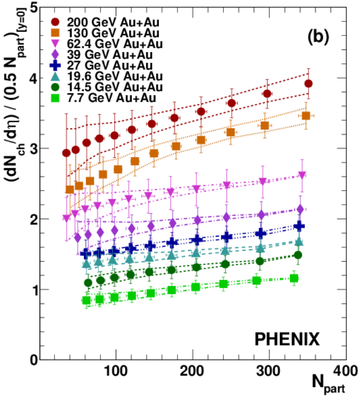
For long-range separations:

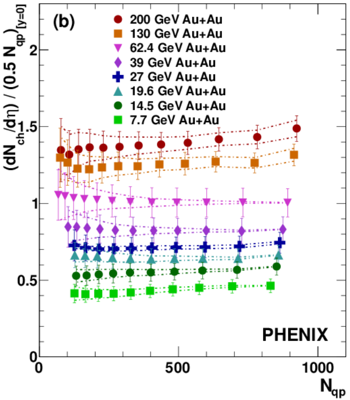
$$C^s(\eta_{s,1}, \eta_{s,2}) \simeq C^n(\eta_1, \eta_2)$$

Wounded quarks as sources

Also needed linearly of produced number of particles on the number of sources, $n \sim s$. This is accomplished in the wounded quark model (and not in the wounded nucleon model, which requires an admixture of a (nonlinear) binary component

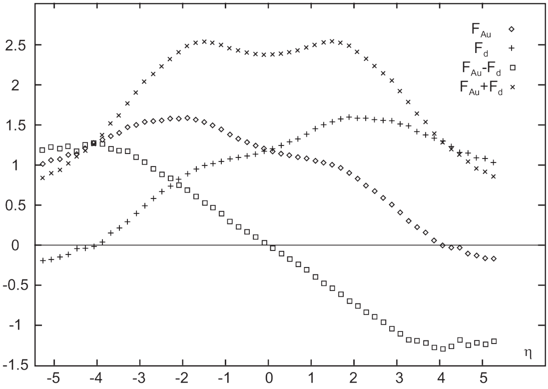
[PHENIX 2016]





Białas-Czyż triangles in rapidity profiles

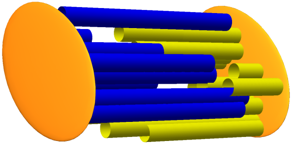
Charged hadron spectra in d+Au @ RHIC [Białas+Czyż 2004]



Asymmetric profiles used ever since . . . [Bożek+Wyskiel, Bzdak]

$$\langle f_A(\eta) \rangle = h(\eta) \frac{y_b + \eta}{2y_b}, \quad \langle f_B(\eta) \rangle = h(\eta) \frac{y_b - \eta}{2y_b}$$

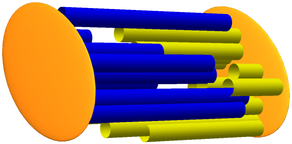
Rapidity-extended source model



$$\begin{aligned}\langle N(\eta_1)N(\eta_2)\rangle &= \langle N_A\rangle\langle f_A(\eta_1,\eta_2)\rangle + \langle N_A(N_A-1)\rangle\langle f_A(\eta_1)\rangle\langle f_A(\eta_2)\rangle \\ &+ \langle N_B\rangle\langle f_B(\eta_1,\eta_2)\rangle + \langle N_B(N_B-1)\rangle\langle f_B(\eta_1)\rangle\langle f_B(\eta_2)\rangle \\ &+ \langle N_A N_B\rangle\left[\langle f_A(\eta_1)\rangle\langle f_B(\eta_2)\rangle + \langle f_B(\eta_1)\rangle\langle f_A(\eta_2)\rangle\right]\end{aligned}$$

$f_{A,B}(\eta_i)$ and $f_{A,B}(\eta_1,\eta_2)$ – probabilities of emission from a single source

Rapidity-extended source model



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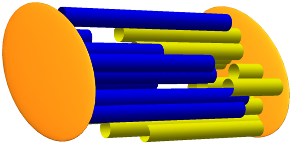

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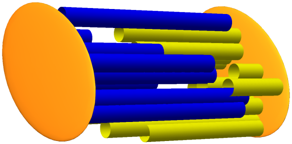

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&+ \langle N_B\rangle\langle f_B(\eta_1,\eta_2)\rangle + \langle N_B(N_B-1)\rangle\langle f_B(\eta_1)\rangle\langle f_B(\eta_2)\rangle \\
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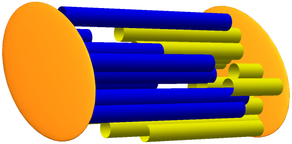


$$\begin{aligned}\langle N(\eta_1)N(\eta_2)\rangle &= \langle N_A\rangle \mathrm{cov}_A(\eta_1,\eta_2) + \langle N_A^2\rangle\langle f_A(\eta_1)\rangle\langle f_A(\eta_2)\rangle \\ &+ \langle N_B\rangle \mathrm{cov}_B(\eta_1,\eta_2) + \langle N_B^2\rangle\langle f_B(\eta_1)\rangle\langle f_B(\eta_2)\rangle \\ &+ \langle N_A N_B\rangle \left[\langle f_A(\eta_1)\rangle\langle f_B(\eta_2)\rangle + \langle f_B(\eta_1)\rangle\langle f_A(\eta_2)\rangle\right]\end{aligned}$$

Production is independent/uncorrelated, unless from the same source. However, even if $\mathrm{cov}_{A,B}(\eta_1,\eta_2)=0$ we have nontrivial $C(\eta_1,\eta_2)$ from the fluctuation of N_A and N_B [Bzdak+Teaney 2013]

Correlations in rapidity-extended source model

Average number of particles: $\langle N(\eta)\rangle = \langle N_A\rangle\langle f_A(\eta)\rangle + \langle N_B\rangle\langle f_B(\eta)\rangle$ with symmetric and antisymmetric parts

$$\langle f_{A,B}(\eta)\rangle = f_s(\eta) \pm f_a(\eta)$$

After elementary transformations ($N_+ = N_A + N_B,\ \ N_- = N_A - N_B$)

$$\begin{aligned} C(\eta_1,\eta_2) &= 1 + \frac{1}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} \times \\ & \Big\{ \langle N_A\rangle \mathrm{cov}_A(\eta_1,\eta_2) + \langle N_B\rangle \mathrm{cov}_B(\eta_1,\eta_2) \\ &+ \mathrm{var}(N_+) f_s(\eta_1) f_s(\eta_2) + \mathrm{var}(N_-) f_a(\eta_1) f_a(\eta_2) \\ &+ \left[\mathrm{var}(N_A) - \mathrm{var}(N_B)\right]\left[f_s(\eta_1) f_a(\eta_2) + f_a(\eta_1) f_s(\eta_2)\right] \Big\} \end{aligned}$$

Correlations in elem. production + fluctuation of the number of sources

Observation by Bzdak and Teaney

Vanishing covariance, symmetric system, profiles from the previous slides:

$$\langle N_A \rangle = \langle N_B \rangle, \quad \mathrm{var}(N_A) = \mathrm{var}(N_B)$$

Then

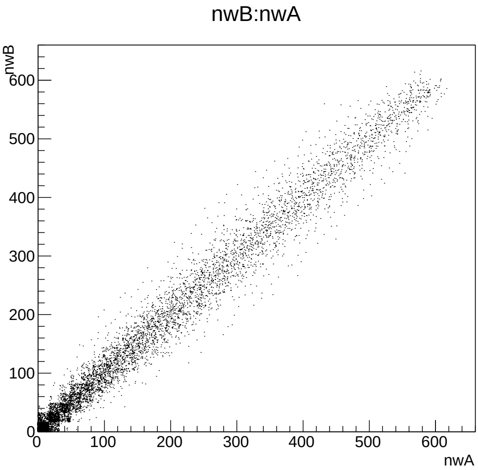
$$C(\eta_1, \eta_2) = 1 + \frac{1}{\langle N_+ \rangle^2} \left[\mathrm{var}(N_+) + \mathrm{var}(N_-) \frac{\eta_1}{y_b} \frac{\eta_2}{y_b} \right]$$

[Bzdak+Teaney 2013]

Fluctuations of N_A vs N_B yield the $\eta_1 \eta_2$ structure in $C(\eta_1, \eta_2)$

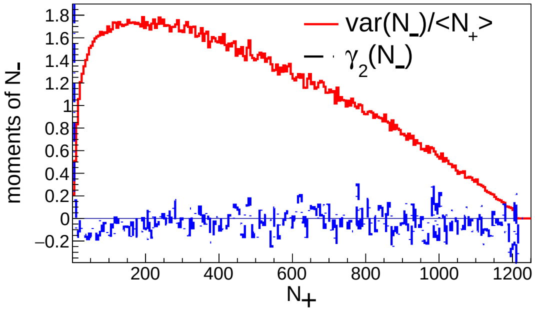
Fluctuations of N_A vs N_B in the wounded quark model

Pb+Pb @ 2.76 TeV



Fluctuations of N_A vs N_B in the wounded quark model

(fixed N_+)

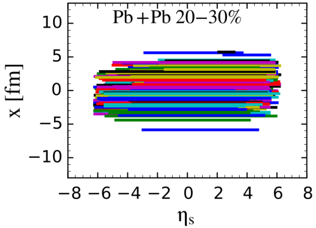


May obtain the moments of fluctuation of sources from Monte Carlo

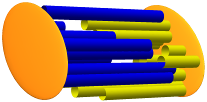
Fluctuating length

- Idea: entropy deposition from wounded nucleons originates from string-like objects whose other end-point is randomly distributed in η (related to [Brodsky+Gunion+Kuhn 1977])
- *"Soft particle production ... is dominated by multiple gluon exchanges between partons from the colliding hadrons, followed by radiation of ... partons distributed uniformly in rapidity"* [Białas+Jeżabek 2004]
- Torque in p-A collisions [Bożek+WB+Moreira 2011, Bożek+WB 2015]
- Similar ideas in [Monnai+Schenke 215]
- Built-in into existing models/codes

e.g., HIJING [L.-G. Pang, QM2015]:



What it yields?



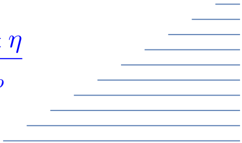
$$f_A(\eta;y)=\theta(y<\eta<y_b),\quad f_B(\eta;y)=\theta(-y_b<\eta<-y)$$

(uniform string fragmentation function)

Random end y is uniformly selected from $[-y_b,y_b]$, where y_b is the beam rapidity

Averaging over $y \to$ "triangles":

$$\langle f_{A,B}(\eta)\rangle = \int_{-y_b}^{y_b}\frac{dy}{2y_b} f_{A,B}(\eta;y) = \frac{y_b \pm \eta}{2y_b}$$



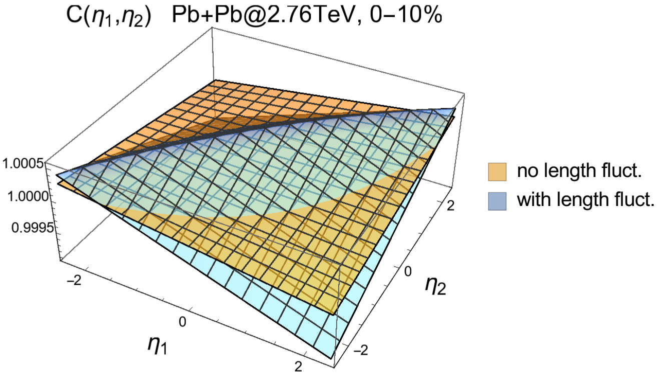
Correlations just from length fluctuations:

$$\langle f_{A,B}(\eta_1,\eta_2)\rangle = \int_{-y_b}^{y_b} dy f_{A,B}(\eta_1;y) f_{A,B}(\eta_2;y) = \frac{y_b \pm \min(\eta_1,\eta_2)}{2y_b}$$

$$\mathrm{cov}_{A,B}(\eta_1,\eta_2) = \frac{y_b^2-\eta_1\eta_2-y_b|\eta_1-\eta_2|}{4y_b^2}$$

Results for C

$$\bar{C}(\eta_1,\eta_2) = \frac{C(\eta_1,\eta_2)}{\int_{-Y}^{Y}\frac{d\eta_1}{2Y}\int_{-Y}^{Y}\frac{d\eta_2}{2Y}C(\eta_1,\eta_2)} \quad \text{(normalization to 1)}$$



Generation of the ridge (structure from $-|\eta_1 - \eta_2|$)
Fluctuating length affects both short- and long-range components

Results for C

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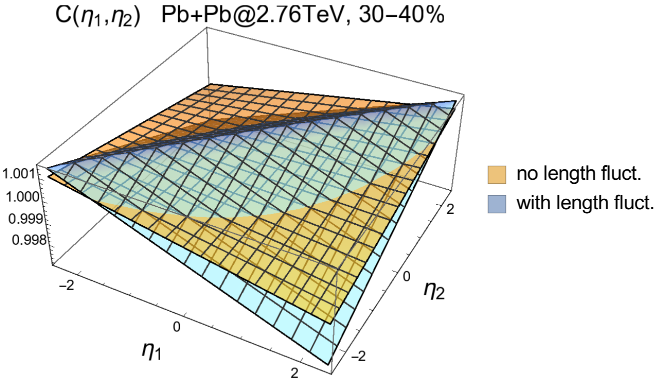

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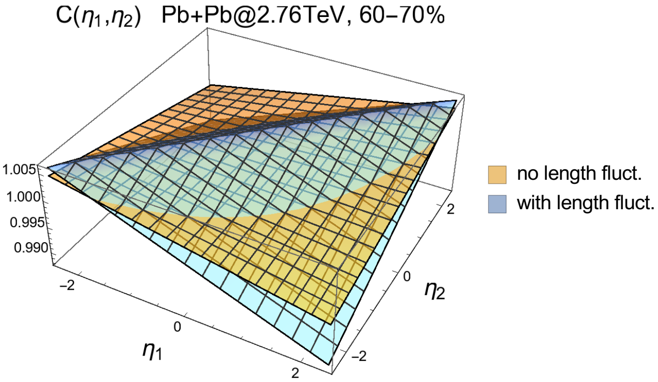
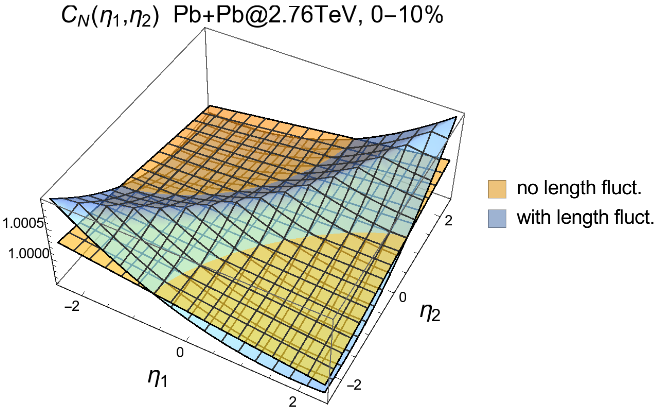


Generation of the ridge (structure from $-|\eta_1 - \eta_2|$)

Fluctuating length affects both short- and long-range components

Results for C_N

$$\bar{C}_N(\eta_1,\eta_2) = \frac{C_N(\eta_1,\eta_2)}{\int_{-Y}^{Y}\frac{d\eta_1}{2Y}\int_{-Y}^{Y}\frac{d\eta_2}{2Y} C_N(\eta_1,\eta_2)} \quad \text{(normalization to 1)}$$



Generation of the saddle in the ridge (seen in experiment) is trivial
Fluctuating length essential

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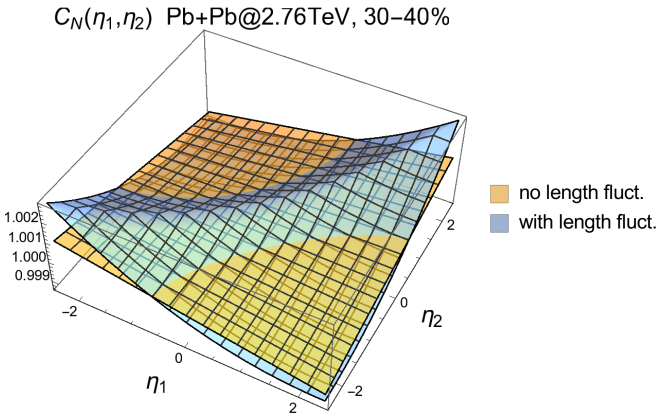

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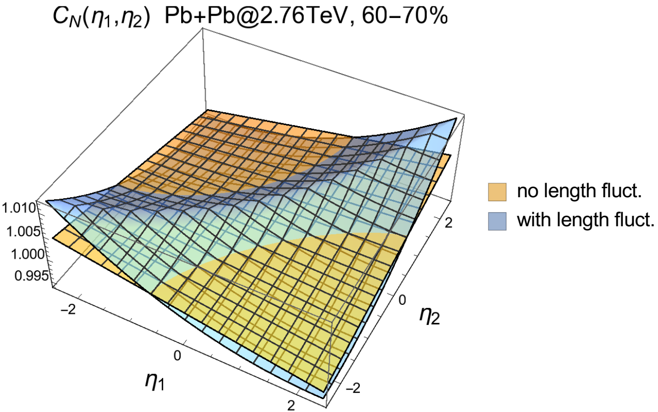

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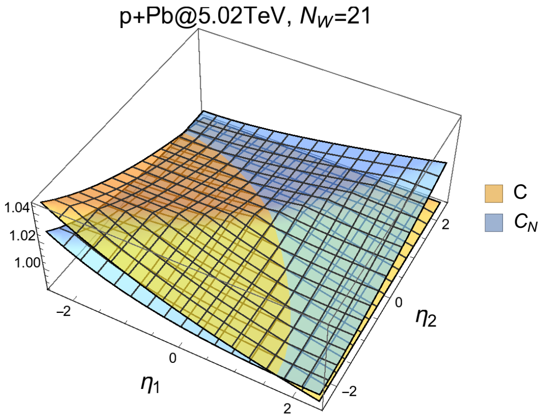
C and C_N for p-Pb collisions



a_{nm} coefficients

$$a_{nm} = \int_{-Y}^{Y} \frac{d\eta_1}{Y} \int_{-Y}^{Y} \frac{d\eta_2}{Y} C(\eta_1,\eta_2) T_n\left(\frac{\eta_1}{Y}\right) T_m\left(\frac{\eta_1}{Y}\right)$$

$$T_n(x) = \sqrt{2+1/2}P_n(x)$$

[Bzdak+Teaney 2013, Jia 2015]

(play analogous role to flow coefficients in harmonic flow)

$$a_{nn} = \frac{\frac{\mathrm{var}(N_-)}{\langle N_+\rangle} + \frac{\mathrm{var}(\omega)}{\langle\omega\rangle^2}}{6\langle N_+\rangle} \frac{Y^2}{y_p^2}\delta_{n1} - \frac{\frac{\mathrm{var}(\omega)}{\langle\omega\rangle^2}+1}{6\langle N_+\rangle}\frac{Y^2}{y_p^2}\delta_{n1} + \frac{\frac{\mathrm{var}(\omega)}{\langle\omega\rangle^2}+1}{(2n-1)(2n+3)\langle N_+\rangle}\frac{Y}{y_p}$$

$$a_{n,n+2} = -\frac{\frac{\mathrm{var}(\omega)}{\langle\omega\rangle^2}+1}{2(2n+3)\sqrt{(2n+1)(2n+5)}\langle N_+\rangle}\frac{Y}{y_p} \quad \text{(length fluct.)}$$

other $=0$

a_{nm} coefficients

$$
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$$

$$
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ω – overlaid strength

a_{nm} coefficients

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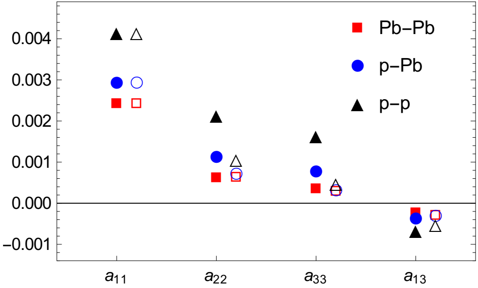
$$a_{nn} = \frac{\frac{\mathrm{var}(N_-)}{\langle N_+ \rangle} + \frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2}}{6\langle N_+ \rangle} \frac{Y^2}{y_p^2} \delta_{n1} - \frac{\frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2} + 1}{6\langle N_+ \rangle} \frac{Y^2}{y_p^2} \delta_{n1} + \frac{\frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2} + 1}{(2n-1)(2n+3)\langle N_+ \rangle} \frac{Y}{y_p}$$

$$a_{n,n+2} = -\frac{\frac{\mathrm{var}(\omega)}{\langle \omega \rangle^2} + 1}{2(2n+3)\sqrt{(2n+1)(2n+5)}\langle N_+ \rangle} \frac{Y}{y_p} \quad \text{(length fluct.)}$$

$a_{nm} \sim 1/\langle N_+ \rangle$– fall-off similarly as in experiment if $N_+ \sim N_{\rm ch}$

Results for a_{nm}

Pb-Pb@2.76TeV



(filled – from Fig. 7 of ATLAS-CONF-2015-020, open – model)

N_{ch}/N_+ fitted by adjusting $a_{11}^{exp} = c^{exp}/N_{ch} = a_{11}^{mod} = c^{mod}/N_+$

$N_{ch} = 4.7N_+$, acceptance $\Delta\eta = 4.8 \longrightarrow dN_{ch}/d\eta \simeq 1 \times N_+$
(exp: $dN_{ch}/d\eta \simeq (3-4) \times N_W$ and $dN_{ch}/d\eta \simeq 1.4 \times Q_W \to$ wounded quarks, partons)
$N_{ch} = 5.1N_A$ for p-Pb@5.02TeV
$N_{ch} = 8.1N_+$ for p-p@13TeV – requires sources at partonic level

Conclusions

- New data coming!
- Derived analytic expressions in the simple superposition model, grasping features of more involved approaches (MC codes). Anatomy: fluctuation of sources + *intrinsic* correlations from string breakup
- The correlations from the early production mechanism contribute to both short- and long-range components in η
- $1/N_{ch}$ scaling of a_{11} $\rightarrow$ linear relation $N_{\rm ch} = \kappa N_{\rm sources}$, with the value of κ suggesting wounded constituents as degrees of freedom
- Universality of Pb-Pb, p-Pb, and (possibly) p-p should be understood if sources are partons (e.g., wounded quarks)
- Intricate procedures: $C \rightarrow C_N$, normalization, *removing short-range correlations* – necessary in modeling for 1-1 comparisons
- To eliminate short-range component use the multiparticle cumulant method [Bzdak+Bożek 2015]
- Extension to azimuthal moments (”torque” effect of event-plane decorrelation, [Bożek+WB+Moreira 2011]), CMS data
- Wounded quarks!

BACKUP

Fluctuating strength

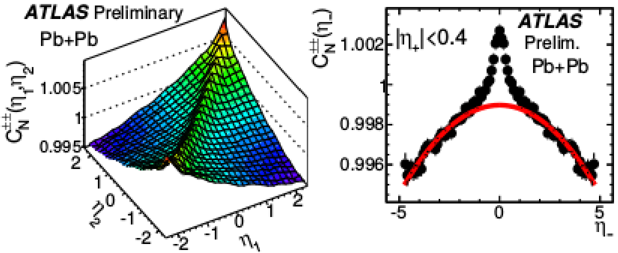
Additional ingredient:

$$f_A(\eta; y) = \omega\theta(y < \eta < y_b), \quad f_B(\eta; y) = \omega\theta(-y_b < \eta < -y)$$

ω – random strength of the source, included in models to increase multiplicity fluctuations, a.k.a. overlaid distribution

Removing the short-range effects

Rather involved experimental procedure, which gets rid of correlations shorter that ~ 1 unit in $\eta_1 - \eta_2$



Removes resonances, jets, ..., some of the source fluctuations
After the procedure only a_{11} survives in exp., other =0 (do not throw out the baby with the bath water!)

It should be carried out in a model simulation

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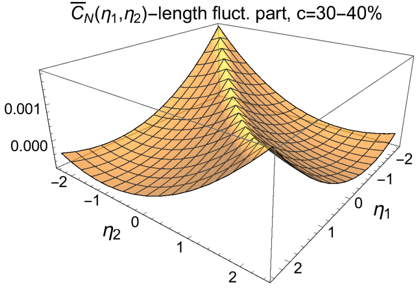

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After the procedure only a_{11} survives in exp., other =0 (do not throw out the baby with the bath water!)

It should be carried out in a model simulation

Smearing of η

There is some "communication" between adjacent bins in η, so the mapping $\eta_S \to \eta$ should be smeared

Gaussian smearing:

$$S_{\rm sm}(\eta_1,\eta_2) = \int d\eta_1' \int d\eta_2' g(\eta_1,\eta_1') g(\eta_2,\eta_2') S(\eta_1',\eta_2')$$

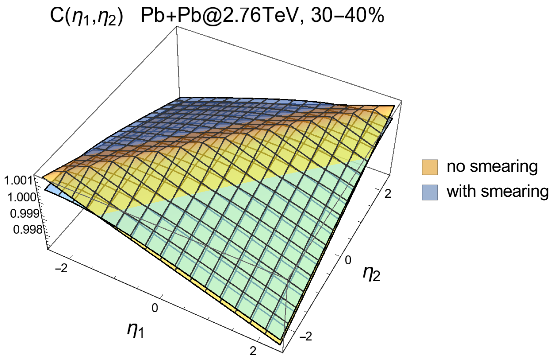
$$|\eta_1-\eta_2| \to \frac{2\sigma_\eta e^{-\frac{(\eta_1-\eta_2)^2}{4\sigma_\eta^2}}}{\sqrt{\pi}} + (\eta_1-\eta_2)\,{\rm erf}\left(\frac{\eta_1-\eta_2}{2\sigma_\eta}\right)$$

with the other terms (η_1, η_2, $\eta_1\eta_2$) unchanged

($\to$ Bzdak-Teaney term not modified)

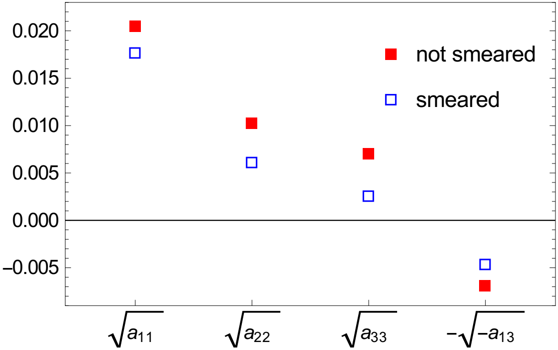
Smearing of η

($\rightarrow$ Bzdak-Teaney term not modified)



Smearing of η

($\rightarrow$ Bzdak-Teaney term not modified)



From initial state to final hadrons

- $\eta_S \to \eta$, some extra hydro push $\to$ reduction of a_{nm}
- resonance decays – relevant effect [PB+WB+Adam Olszewski 2015] $\to$ increase
- charge conservation, other correlations – not included
- removal of the short-range effects (not simple in a model)

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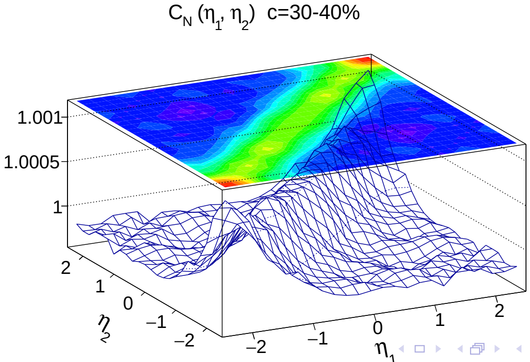
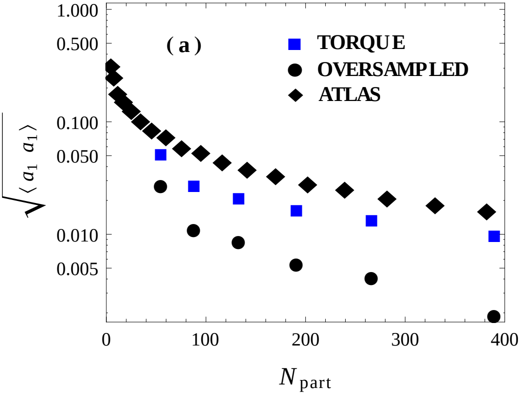
Hydro (no length fluctuations included here):



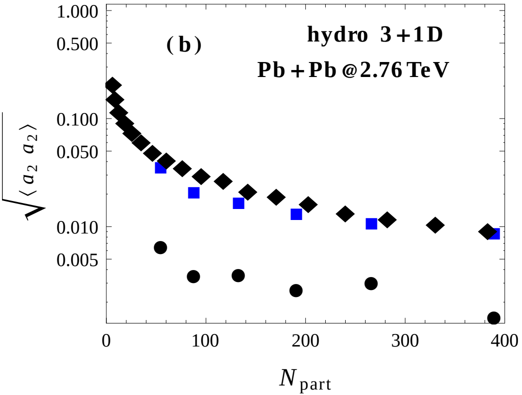
a_{nm} from hydro



$\langle a_n a_m\rangle = a_{nm}$, "torque"=our model without length fluct.,
"oversampled"=no resonance decays

About 50% of $\sqrt{a_{11}}$ from resonances!

a_{nm} from hydro



$\langle a_n a_m \rangle = a_{nm}$, "torque"=our model without length fluct., "oversampled"=no resonance decays

b coefficient from C

The b correlation coefficient is defined for the symmetric system as follows:

$$b = \frac{\langle n_F n_B \rangle - \langle n_F \rangle \langle n_F \rangle}{\langle n_F n_F \rangle - \langle n_F \rangle \langle n_F \rangle}$$

With fixed N_+ and for $\mathrm{cov}_{A,B}(\eta_1, \eta_2) = 0$ the one- and two-particle densities are

$$N(\eta) = N_+ f_s(\eta)$$
$$N(\eta_1, \eta_2) = N_+(N_+ - 1) f_s(\eta_1) f_s(\eta_2) + \mathrm{var}(N_-) f_a(\eta_1) f_a(\eta_2) + \delta(\eta_1 - \eta_2) N_+ f_s(\eta_1)$$

Then for $F = [0, \infty)$ and $B = (-\infty, 0]$

$$\langle n_F n_B \rangle - \langle n_F \rangle \langle n_F \rangle = -N_+/4 + \mathrm{var}(N_-) \int_0^y d\eta_1 \int_{-y}^0 d\eta_2 f_a(\eta_1) f_a(\eta_2)$$
$$= -N_+/4 - \mathrm{var}(N_-) \int_0^y d\eta_1 \int_0^y d\eta_2 f_a(\eta_1) f_a(\eta_2) = -\langle n_F n_F \rangle + \langle n_F \rangle \langle n_F \rangle$$

hence $b = -1$, which is obvious from $n_B = N_+ - n_F$, $\langle n_F \rangle = \langle n_B \rangle = N_+/2$