Rapidity Fluctuations in the Initial State of Ultra-Relativistic Heavy-Ion Collisions

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Opportunities for Exploring Longitudinal Dynamics
RIKEN BNL, 20-22 January 2016

Motivation/new data

- Old story ...
- New data from the LHC, new methodology (ATLAS notes 2015)
- Longitudinally-extended source model

Goal: understand key elements from an analytic model

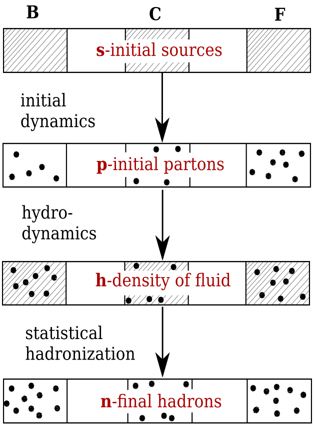
anatomy of the correlations

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

Based on [WB+ Piotr Bożek, arXiv:1512.01945]

3-stage approach

Generation and propagation of e-by-e fluctuations



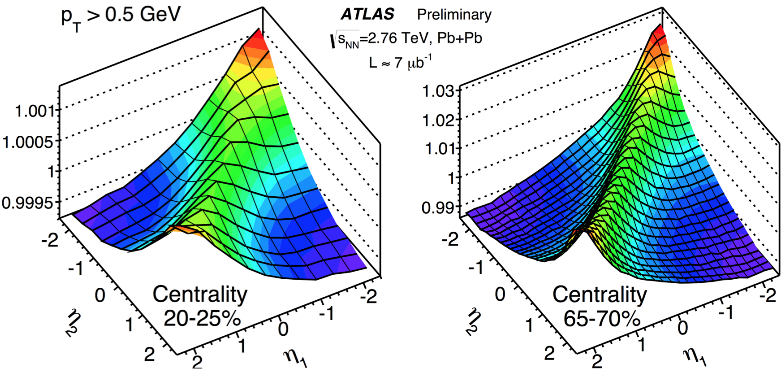
Concept of sources: wounded nucleons, quarks, flux tubes, ...
Hydro: provides mapping $\eta_S \to \eta$

New data

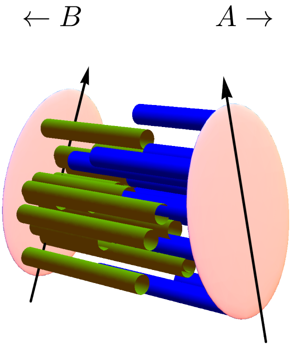
$$C(\eta_1,\eta_2) = \frac{\langle N(\eta_1,\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} = \frac{S(\eta_1,\eta_2)}{B(\eta_1,\eta_2)}$$

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

η_1 and η_2 – pseudorapidities of different hadrons



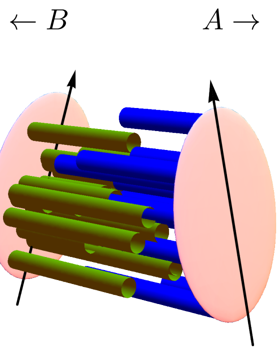
Rapidity-extended source model



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

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

Rapidity-extended source model



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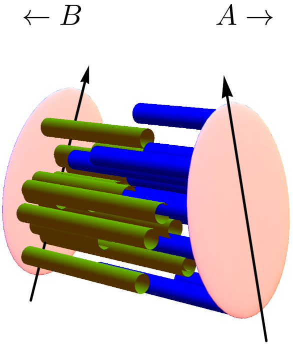
\end{aligned}
$$

Rapidity-extended source model



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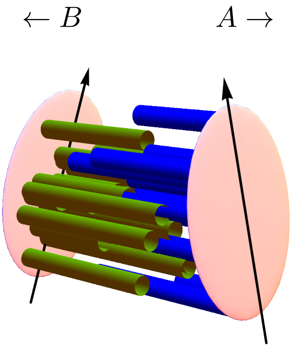

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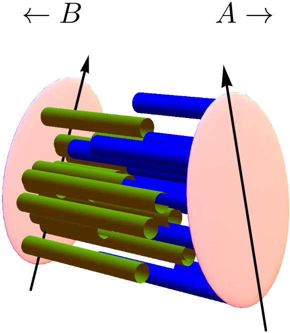
Rapidity-extended source model



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

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]

Rapidity-extended source model

Average number of particles:

$$\langle N(\eta)\rangle = \langle N_A\rangle\langle f_A(\eta)\rangle + \langle N_B\rangle\langle f_B(\eta)\rangle$$

Symmetric and antisymmetric parts (see next slide):

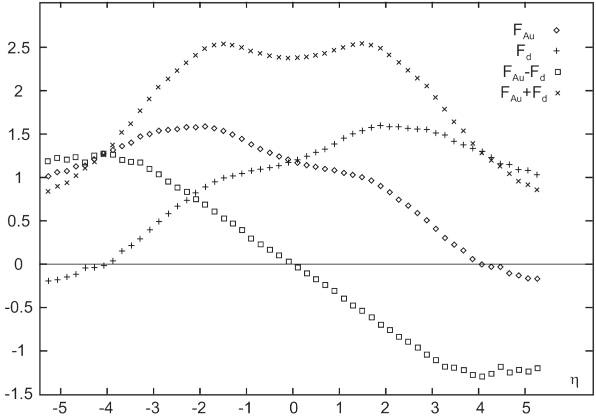
$$\langle f_A(\eta)\rangle = f_s(\eta) + f_a(\eta), \quad \langle f_B(\eta)\rangle = f_s(\eta) - f_a(\eta)$$

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

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

Białas-Czyż triangles

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



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

Asymmetric profiles used ever since ...

Observation by Bzdak and Teaney

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

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

Then

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

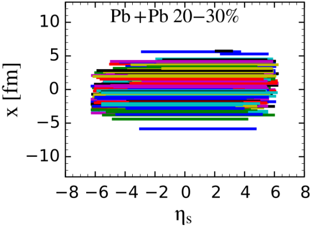
[Bzdak+Teaney 2013]

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

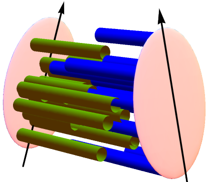
Fluctuating length

- 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 in hadronic collisions 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 (see talk by PB) [PB+WB+Moreira 2011, PB+WB, arXiv:1506.02817]
- Similar ideas in [Monnai+Schenke, arXiv:1509.04103]
- Built-in into existing models/codes

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



What it yields?



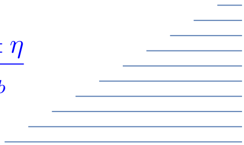
$$f_A(\eta;y)=\theta(y<\eta<y_b),\quad f_B(\eta;y)=\theta(-y_b<\eta<-y)$$

(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":

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



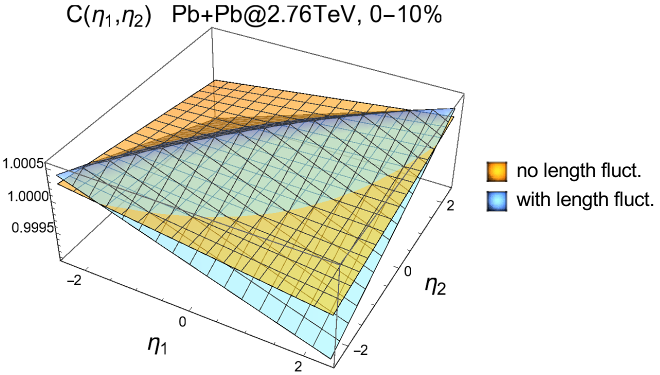
Correlations from length fluctuations:

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

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

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

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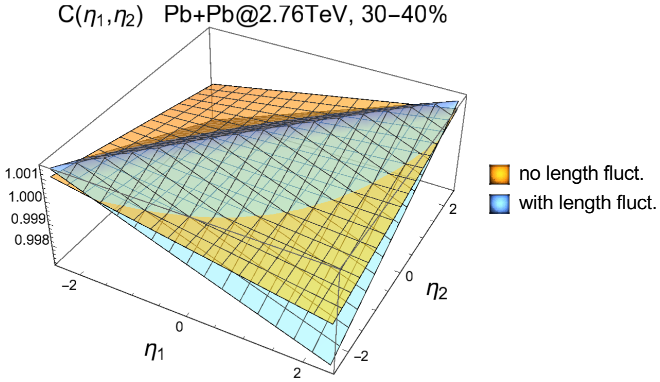

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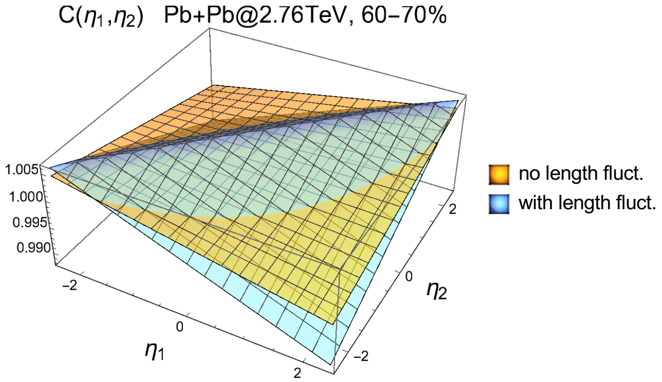

Generation of the ridge (structure from $-|\eta_1 - \eta_2|$)

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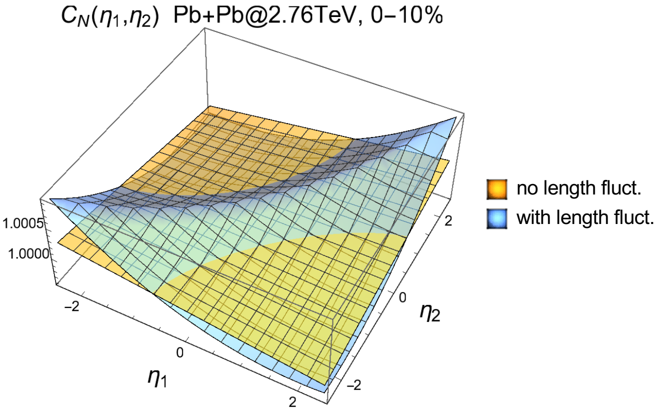
Results for C_N

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



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

Fluctuating length essential

Results for C_N

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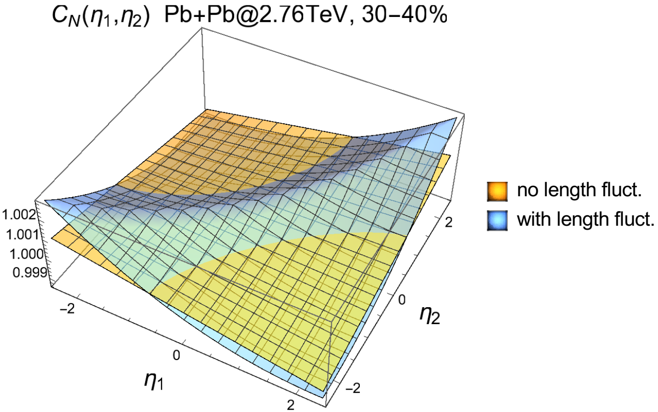

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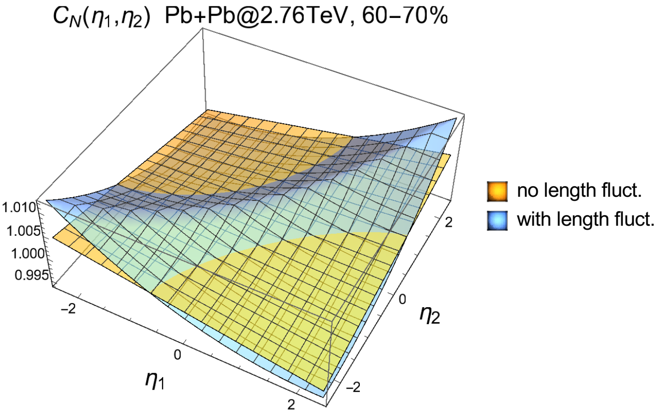

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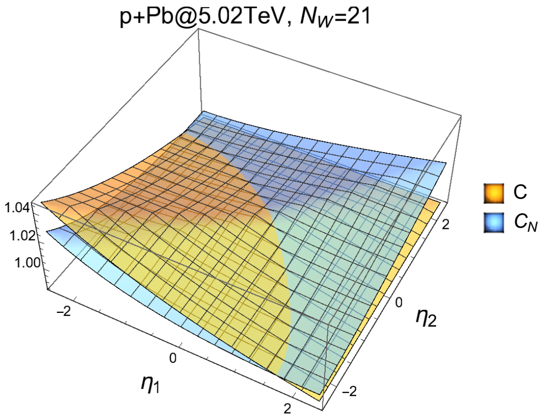
C and C_N for p-Pb collisions



a_{nm} coefficients

$$
\begin{aligned}
a_{nm} &= \int_{-Y}^{Y} \frac{d\eta_1}{Y} \int_{-Y}^{Y} \frac{d\eta_2}{Y} C(\eta_1, \eta_2) T_n\left(\frac{\eta_1}{Y}\right) T_m\left(\frac{\eta_1}{Y}\right) \\
T_n(x) &= \sqrt{2+1/2}P_n(x)
\end{aligned}
$$

[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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ω – overlaid strength

a_{nm} coefficients

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

a_{nm} coefficients

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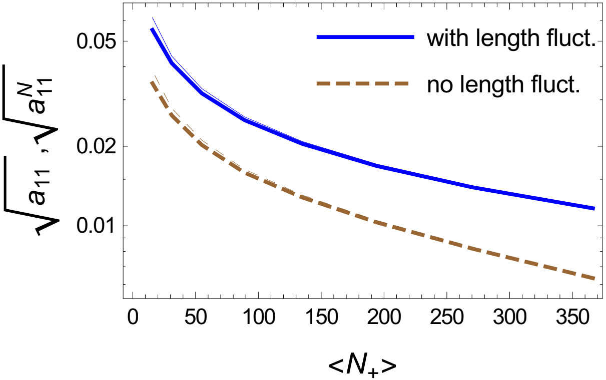
Results for a_{nm}

Pb-Pb@2.76TeV



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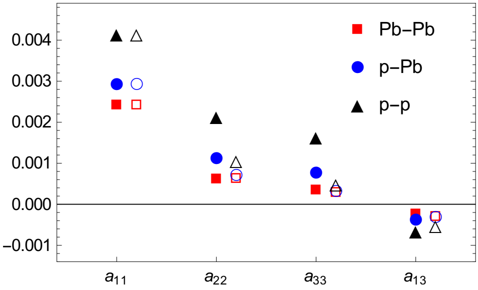


(filled – from Fig. 7 of ATLAS-CONF-2015-020, open – model)

a_{11} fitted by adjusting:

$N_{\rm ch} = 4.7 N_+$ for Pb-Pb@2.76TeV $\longrightarrow dN_{\rm ch}/d\eta \simeq 1 \times N_+$

(exp: $dN_{\rm ch}/d\eta \simeq (3-4) \times N_W$ with wounded nucleons $\to$ need more participants, wounded constituents? – used in [Monnai+Schenke 2015])

$N_{\rm ch} = 5.1 N_A$ for p-Pb@5.02TeV

$N_{\rm ch} = 8.1 N_+$ for p-p@13TeV – requires sources at partonic level

Smearing of η

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

Gaussian smearing:

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

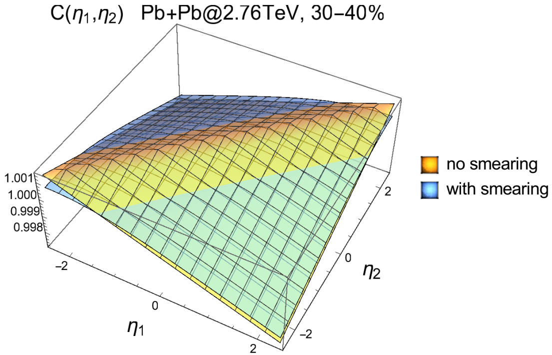
$$|\eta_1-\eta_2| \to \frac{2\sigma_\eta e^{-\frac{(\eta_1-\eta_2)^2}{4\sigma_\eta^2}}}{\sqrt{\pi}} + (\eta_1-\eta_2)\,{\rm erf}\left(\frac{\eta_1-\eta_2}{2\sigma_\eta}\right)$$

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

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

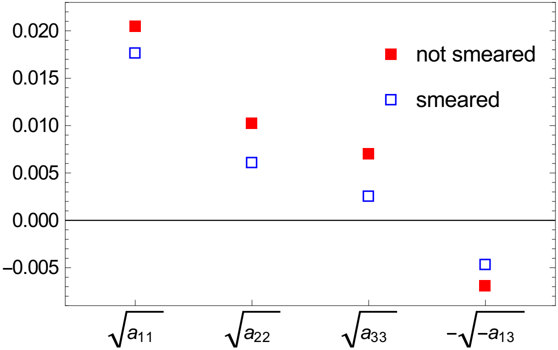
Smearing of η

(→ 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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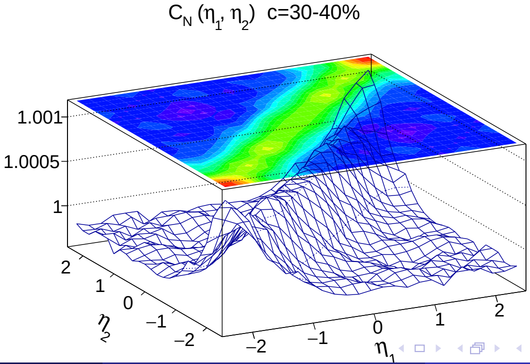
Hydro (no length fluctuations included here):



Conclusions

- Data: need for extra longitudinal fluctuations in the initial state (see also the talk by Piotr Bożek: torque in p+Pb)
- Analytic expressions in the simple model, grasping features of more involved approaches
- The correlations from the early production mechanism contribute to short- and long-range components in η, no flow needed – robust effect
- Anatomy:
    - Early stage: N_A vs N_B fluctuations, length fluctuations
    - Late stage: resonance decays (significant effect), conservation laws
- $1/\sqrt{N_{ch}}$ scaling of $\sqrt{a_{11}} \to$ 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 can be understood if sources are partons (e.g., wounded quarks)
- Intricate procedures: $C \to C_N$, normalization, removing short-range correlations – necessary in modeling for 1-1 comparisons
- To eliminate short-range component use the cumulant method [Bzdak+Bożek 2015]