Harmonic decomposition of two particle angular correlations in Pb–Pb collisions at √sNN = 2.76 TeV

Andrew Adare Yale University for the ALICE Collaboration **October 20, 2011**

Based on arXiv:1109.2501 (Submitted 12 Sep 2011)

Harmonics of Big and Little Bangs

Temperature anisotropy from CMB radiation

Power spectra hold a wealth of info from early epochs

 ${y_1, y_2, \ldots, y_n}$ (250 yya similarly mal **Exam we similarly make 1.297 O.287 1.287 1.286 1.287 1.286 1.287 1.286** {yr6} – {y1, y2, y3, y4, y5, y7} 0.769 0.82 1.101 0.32 **Prover spectra"** ${y}$ ${f_{r\alpha}}$ ${A_{\perp}}$ α allieiane **From A+A collisions?**

 ${\bf W}$, was the set of **Example 1.500 What can be learned?** ${W}$, which is a set of ${W}$ or ${W}$

Thursday, October 20, 2011

Same and mixed event pair distributions

$$
\Delta \phi = \phi_A - \phi_B \qquad \Delta \eta = \eta_A - \eta_B
$$

-1

-1.5 -1

-0.5 0

1

 $\begin{bmatrix} 1 & 2 \end{bmatrix}$ **3 4** $\Delta\phi$

Azimuthal correlation function:

$$
C(\Delta \phi) \equiv \frac{N_{mixed}^{AB}}{N_{same}^{AB}} \cdot \frac{dN_{same}^{AB}/d\Delta \phi}{dN_{mixed}^{AB}/d\Delta \phi}
$$

Pb-Pb at 2.76 TeV

13.5 M events in 0-90% after event selection

Centrality VZERO detectors resolution < 1%

Tracking

TPC points + ITS vertex

optimum acceptance + precision for correlations

Event structure and shape evolution in the longitudinal (radial) direction. At least 70 TPC pad rows must be traversed by each track, out of which state 51 of χ²*/n*d*.*o*.*f*. <* 4 is imposed.

In central and low-p_T "bulk-dominated" **long-range correlations**

A near side ridge is observed A very broad away side is observed, even doublypeaked for 0-2% central vertices are determined using both the TPC and SPD. Collisions at a longitudinal position

In high-pt "jet-dominated" correlations distance between each track and the primary vertex is required to be with 3.2 (2.4) cm α in the longitudinal (radial) direction. At least 70 TPC pad rows must be traversed by each

The near-side ridge is not visible track, out of the $\frac{1}{2}$ TPC clusters must be assigned. In a track fit requirement of $\frac{1}{2}$

The away-side jet is very strong; sharp like proton-

proton case

intermediate transverse momentum (left) and at higher *p^T* (right).

 $\mathcal{P}(\mathcal{P})$ and $\mathcal{P}(\mathcal{P})$ and $\mathcal{P}(\mathcal{P})$ and $\mathcal{P}(\mathcal{P})$ and $\mathcal{P}(\mathcal{P})$ and $\mathcal{P}(\mathcal{P})$ and $\mathcal{P}(\mathcal{P})$

^T , and centrality interval, the correlation function is defined as

distance between each track and the primary vertex is required to be within 3.2 (2.4) α

Figure 1: Examples of two-particle correlation functions *C*(∆φ*,* ∆η) for central Pb–Pb collisions at low to

The two-particle correlation measure used here is the correlation function *C*(∆φ*,* ∆η),

 ω angles ω and ω are measured with respect to the trigger particle. The trigger p

correlations induced by imperfections in detector pair acceptance and efficiency are removed

via division by a mixed-event pair distribution, in which a trigger particle from a trigger particle from a par

procedure results in correlations due only to true physical effects (with some additional

residual pair inefficiency effects, which are negligible at long range in *|*∆η*|*.) Within a given

*N*mixed

*N*same

 95 event is paired with associated particles from separate events. This acceptance correction acceptance corrections from separate events. This acceptance correction acceptance correction acceptance correction acceptanc

Event structure and signal property and structure

In central and low-p_T "bulk-dominated" long-range correlations

A near side ridge is observed and all \overline{a} all \overline{a} all \overline{a} all \overline{a} all \overline{a} and \overline{a} A very broad away side is observed, ev peaked for 0-2% central **ratio**

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The near-side ridge is not visible The away-side jet is very strong; sharp like protontrack, out of the $\frac{1}{2}$ TPC clusters must be assigned. In a track fit requirement of $\frac{1}{2}$

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Single vs. pair Fourier decomposition ously at RHIC μ at RHIC μ at RHIC μ and μ after subtraction of a correlated component whose shape was shape was μ l Single I Sinale ve nair Fourier decomposition 6 equal to value provide provide the significant larger

Single-particle anisotropy and the emitted of the emitted **(the familiar v_n coefficients)** da
N *n*=1

∞

$$
\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos(n(\phi - \Psi_n))
$$

⁵⁰ also extends over a large range in *|*∆η*|* [17, 18]. The latter feature has been observed previ-

higher-order flow components $\tilde{3}$ –38. The azimuthal momentum distribution of the emitted of the

Similar form, but indep. of Ψⁿ

$$
\frac{dN^{pairs}}{d\Delta\phi} \propto 1 + \sum_{n=1}^{\infty} 2V_{n\Delta}(p_T^t, p_T^a) \cos(n\Delta\phi)
$$

Extract directly from 2-particle azimuthal d correlations! t root d **Extract directly from 2-particle azimuthal**

■ **This is a measurement of the** *Theorie* **from the azimuthal** separated (*|*∆η*| >* 0*.*8) pair azimuthal correlations in Pb–Pb collisions in different centrality **the convention of the convention of the two-particle fourier coefficients as** *Fourier coefficients* **as** *Pourier coefficients* **as** *Pourier coefficients* **as** *Vn*

$$
V_{n\Delta} \equiv \langle \cos(n\Delta\phi) \rangle = \sum_i C_i \cos(n\Delta\phi_i) / \sum_i C_i.
$$

A. Adare (ALICE) classes and in several transverse momentum intervals. Details of the experimental setup and $A \quad A \quad A$ and C F $A.$ *Adare (ALICE)*

 $\mathcal{L}^{\mathcal{L}}(\mathcal{L}^{\mathcal{L}})$ becomes equal to v2 and at pt pt $\mathcal{L}^{\mathcal{L}}(\mathcal{L}^{\mathcal{L}})$

0.05

032301-4

 \sim 3 GeV \sim

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$$
V_{n\Delta}\equiv\left\langle \cos\left(n\Delta\phi\right)\right\rangle =\sum_{i}C_{i}\cos(n\Delta\phi_{i})\left/\sum_{i}C_{i}. \hspace{1cm} \underbrace{\sum_{i}C_{i}}_{0.998+} \underbrace{1.002}_{1+\frac{1}{2}+\frac{1}{4}
$$

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]

-2 [10

V

Decomposition in bulk region

"Power spectrum" of pair Fourier components Vn^Δ

For ultra-central collisions, n = 3 dominates. In bulk-dominated correlations, the n > 5 harmonics are weak. In buik-dominated correlations, the n $>$ 5 narmonics are weak.

(But not necessarily zero...work in progress.)

\vert V_{2∆} dominates as collisions become less central. are superimposed in columnications in color. The curve in curve. The ratio of data to the curve in color. The color of data to collision geometry, rather than fluctuations, becomes primary effect and σ 5 sum is σ 5 shown in the lower panel. Center: Amplitude of *Vn*[∆] harmonics vs. *n* for the same *pt*

A. Adare (ALICE) class. Right: *Vn*∆ spectra for a variety of centrality classes. A variety classes are represented with a variety contract with α variety $\$

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Decomposition in jet region

Di-jet Fourier components Vn^Δ

Very different spectral signature than bulk correlations!

- All odd harmonics < 0, and finite to large n

Aside: Gaussian Fourier transform

Away-side peak is (sort of) Gaussian:

The F.T. of a Gaussian($\mu = \pi$, $\sigma_{\Delta\varphi}$) is \pm Gaussian($\mu = 0$, $\sigma_n = 1/\sigma_{\Delta\varphi}$).

Fit demonstration: when μ=π, odd VnΔ coefficients are negative.

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Trigger pτ^t dependence of V_nΔ

Similar trends as for v_n

Rises with p_T ^t to maximum near 3-4 GeV, then declines

Centrality dependence:

V2Δ dominates as collisions become less central

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The factorization hypothesis state particles at large *|*∆η*|* is induced by a collective response to initial-state coordinate-space anis from collision and fluctuation and fluctuations in such a case, *C*(\sim

Factorization of two-particle anisotropy mechanism that affects all particles in the event, and *Vn*[∆] depends only on the single-particle

For pairs correlated to one another through a common symmetry plane Ψn, r or pairs correlated to one another unbugh a d
| their correlation is dictated by bulk anisotropy: azimuthal distribution with respect to the *n*-th order symmetry plane Ψ*n*. Under these circum-

¹⁷⁵ anisotropic flow analyses [17, 30, 39]. This is expected if the azimuthal anisotropy of final

$$
V_{n\Delta}(p_T^t, p_T^a) = \langle \langle e^{in(\phi_a - \phi_t)} \rangle \rangle
$$

= $\langle \langle e^{in(\phi_a - \Psi_n)} \rangle \rangle \langle \langle e^{-in(\phi_t - \Psi_n)} \rangle \rangle$
= $\langle v_n \{2\} (p_T^t) v_n \{2\} (p_T^a) \rangle$.

the flow-dominated mechanism, dijet-related processes do not directly influence every particle;

V_n Δ would be generated from one v_n(p_T) curve, $\mathbf{v}_{\mathsf{n}\Delta}$ would be generated from one $\mathbf{v}_{\mathsf{n}}(\mathsf{p}_{\mathsf{T}})$ curve,
evaluated at $\mathsf{p}_{\mathsf{T}}^t$ and $\mathsf{p}_{\mathsf{T}}^a$. events, and **v**_{*2*} seems the use of a two-particle measurement to obtain $\frac{1}{2}$ such that $\frac{1}{2$

Factorization expected: Factorization expected:

✔ For correlations from collective flow. **is Flow is global and affects all particles in the event.** The *azimuthal shapes* $\frac{1}{2}$

✘ **Not for pairs from fragmenting di-jets.** of these peaks are similar to those from pp or d–Au collisions (albeit suppressed), reflecting *K* Not for pairs from fragmenting di-jets.

A. Adare (ALICE) Di-jet shapes are "local", not strongly connected to Ψn. correlations between high-produced between high-produced fractions are not expected to formulations are factori
A. Adare (ALICE)

Thursday, October 20, 2011 **and resonances in a set of pairs.** Similarly, a small number of particles with a small number of particles with $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ an Thursday, October 20, 2011

^T , high-*p^a*

The factorization hypothesis state particles at large *|*∆η*|* is induced by a collective response to initial-state coordinate-space anis from collision and fluctuation and fluctuations in such a case, *C*(\sim reduce the rate of random associations and preserve a #⁰ identification signal-to-background ratio (S/B) larger than 4:1 for central Au þ Au and 20:1 in p þ p. A systematic $u_{\rm eff} = 1.6$ –6%, depending on S/B, is included for ~ 1.6 , included for ~ 1.6 between previously reported in much broader points for the pT ranges for the pT ranges for the pT ranges for the p unidentified charged hadron triggers [4,5]). Here we quantify the trends in the shape and yield between these two extremes.

are used in more central events and for lower-pT α in more central events and for lower-pT α

Factorization of two-particle anisotropy mechanism that affects all particles in the event, and *Vn*[∆] depends only on the single-particle arms using the drift chambers α with α

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For pairs correlated to one another through a common symmetry plane Ψ_{n-} ion is dictated by buik anisotropy distribution. Figure 2 shows the results. In p $\mathcal{L}_{\mathcal{L}}$ mmon symmetry plane Ψ_{n} $\sum_{i=1}^{n}$ as expected from the angular ordering from the angular ordering $\sum_{i=1}^{n}$

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V_nΔ</sub> would be generated from one v_n(p_T) curve, evaluated at p_T^t and p_T^a. The village over the controlles and p_{articl}es are averaging over the controlles and p_{articl}es and p_{articl}es and p_{articl}es and p_{articl}es and p_{articl}es and p_{articl}es and p_a dNpair ^d!% ^¼ ^N^a

185 for correlations from collective flow. The state distribution of the state of the stat Flow is global and affects all particles in the event. and affects all particles in the event. $\;$

A. Adare (ALICE) ✘ **Not for pairs from fragmenting di-jets. Di-jet shapes are "local", not strongly connected to Ψn. K** Not for pairs from fragmenting di-jets.
Pions and charged hadrons in Weak shape departments on Participal and Charged Reserves to the background of the **Di-jet shapes are "local", not strongly connected to** Ψ_n **.** $\qquad \qquad 0 \qquad 2 \qquad 4 \qquad 0 \qquad 2 \qquad 4$
A. Adare (ALICE) level, 'n Autonomiese is determined in Australia
The Au collisions using the Au collisions using the Au collisions using the Au collisions using the Au collisio

(ZYAM) method is used in p p. In certain cases, e.g., e.
, e.g., e.g.,

consistent with the measurement in the measurement in the p μ μ

Improving on $V_{n\Delta} = v_n(p_T)^2$ **with triggered correlations...**

12 p_T ^t bins, 12 p_T ^a bins; p_T ^t $\geq p_T$ ^a \Rightarrow 78 $V_{n\Delta}$ points.

Fit all simultaneously to find $v_n(p_T)$ curve with best-fit $v_n(p_T t)$ x $v_n(p_T t)$ product.

- Fit supports factorization at low p_T^a
- 㱺 **suggests flow correlations.**
- **Fit deviates from data in jet-dominated high p_T^a region**
- ⇒ collective description less appropriate._{A. Adare} (ALICE)

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Global fit parameters are v_n coefficients

Best-fit vn{GF}(pT) ¹³

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Global fit parameters are v_n coefficients **2 ≤ n ≤ 5 shown here (n=1 later)**

High-precision measure of vn from 2-particle correlations! Agreement with other methods?

Comparison with ALICE v_n{2} 14 \blacksquare central collisions \blacksquare equal to v2 at lower points and reaches significantly larger parties of the significantly larger \sim

Published ALICE vn{2}

PRL 107 032301 (2011) Scalar-product (SP) method |Δη| > 1.0

 2π GeV \sim 2π becomes equal to v2 and at pt \sim 2π

 $\mathcal{S} = \{ \mathcal{S} \mid \mathcal{S} \in \mathcal{S} \mid \mathcal{S} \neq \emptyset \}$

particles in 1 < pt < 2 GeV=c for pairs in j!!j > 1. We

particle azimuthal correlations are measured by calculating

observe a clear double a clear double $\mathcal{O}(\mathcal{C})$

 $\mathcal{S}_{\mathcal{S}}$, but only after subtraction of the elliptic flow

component. This two-peak structure has been interpreted

as an indication for various jet-medium modifications

where $\mathcal{M} = \mathcal{M} \times \mathcal{M}$

 $\mathcal{O}(\mathcal{S}_1)$ and more recently as a manifestor \mathcal{S}_2

is the number of associated particles as function of $\mathcal{O}(n)$

tation of triangular flow $\mathcal{O}(10^4)$

with the same (different) event, and N

azimuthal correlation shape expected from v2, v3, v3, v3, v4, and v3, v4, and

 τ

v⁵ evaluated at corresponding transverse momenta with the

 \mathcal{A}^{max}

measured two-particle azimuthal triggered correlation and

observed in very central collisions \mathcal{C}

find that the combination of these harmonics gives a natu-

 $p_{\rm eff}$ as 2×3 GeV ~ 3

ral description of the observed correlation structure on the

 $p_{\rm c}$ in 2π and 2π for pairs in \mathcal{L}

observe a clear doubly peaked correlation structure cen-

tered opposite to the trigger particle. This feature has been

observed at lower energies in broader centrality bins in broader centrality bins in broader centrality bins in
The centrality bins in broader centrality bins in broader centrality bins in broader centrality bins in broad

 $\begin{bmatrix} 3 & 3 & 3 \ 2 & 3 & 3 \end{bmatrix}$

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 $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 &$

tation of triangular flow $\mathbf{1}_{\mathbf{1}_{\mathbf{1}}}$

azimuthal correlation shape expected from v2, v3, v3, v3, v4, and v3, v4, and

 $\frac{1}{2}$ evaluated at corresponding transverse momenta with the set of $\frac{1}{2}$

measured two-particle azimuthal triggered correlation and

find that the combination of the combination of the combination of the combination of these harmonics gives a natural \mathbf{f}_i

ral description of the observed correlation structure on the

FIG. 4 (color online). The two-particle azimuthal correlation,

measured in 0 < !" < # and shown symmetrized over 2#,

between a trigger particle with 2 < pt < 3 GeV=c and an asso-

V1Δ behaves exceptionally... to symmetry planes existing at the scale of the entire event. \blacksquare Denaves exceptionally... ²⁷⁵ which can be interpreted as the coefficients of Eq. 1. The results of the global fit for

The n=1 harmonic doesn't factorize Including the near-side peak enhances **and** *v***2 reaches a maximum value below** 3 Central and 3 GeV/^c 2 ≤ *n* ≤ 5, denoted *vn{GF}*, are shown in Fig. 6 for several centrality selections. For the 0– e n=1 harmonic doesn't factorize **or even show than the higher-order** than the higher-order than the higher-order

disagreement. higher harmonics peak at a higher *p^T* . These results are in very close agreement with recent ²⁸⁰ measurements of *vⁿ* at the same collision energy [32].

even non-hydrodynamic correlations can factorize if particles exhibit anisotropy with respect

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The n=1 harmonic doesn't factorize Including the near-side peak enhances **and a maximum value below** 3.8 km¹ < 1.8 **disagreement.** 2 ≤ *n* ≤ 5, denoted *vn{GF}*, are shown in Fig. 6 for several centrality selections. For the 0– e $n=1$ harmonic doesn't factorize e $e^{(a)}$ $e^{(a)}$ $e^{(a)}$ $e^{(a)}$ $e^{(a)}$ $e^{(a)}$ p_1 ²⁸⁰ measurements of *vⁿ* at the same collision energy [32].

No good global fit over all momenta The global fit was performed not only over the full momentum range (as shown in Fig. 6), However, v₁{GF} is qualitatively similar to **viscous hydro predictions...under investigation.** $i \in \{1, \ldots, T\}$ 285 steep in the particle momentum distribution, indicating that a relatively small number of $\frac{1}{200}$ $\text{resugauon.} \hspace{2em} \begin{array}{c} \text{1.63} \\ \text{1.61} \end{array}$

even non-hydrodynamic correlations can factorize if particles exhibit anisotropy with respect

Summary

Factorization hypothesis and global fit:

Collective behavior (flow) describes bulk anisotropy (ridge, double-hump)

 - No need to invoke Mach cone explanations.

Global fit coefficients (vn{GF}) consistent with other measurements.

- Another method to measure flow coefficients

Bulk anisotropy factorizes, jet anisotropy does not.

- **Bulk correlations related to global symmetries...**
- **But no such indication for shape of di-jet correlations.**

Outlook:

Tackling open questions:

- **Higher harmonics?**
- **Origin of V₁∆? Relation to v₁?**

Second-year Pb-Pb data taking is just around the corner!

Sound perturbation animation

Hot spot / density perturbation produces coherent sound waves in hubbleexpanding medium.

2D Sound perturbation simulation

Thursday, October 20, 2011

Top

single particle distribution of particles having crossed freezout circle. Baseline was set at solid line to enhance effect (simulates combinatoric pedestal from averaging many events).

Bottom

Pair distribution showing 2 peak away side structure.

Cross-correlations and autocorrelations 20

For single-particle distributions x^a , x^b with length and period N **Pair cross-correlation*:**

$$
x_i^{ab} = \sum_{j=0}^{N-1} x_j^a x_{((i+j))_N}^b
$$

 $0 \leq i \leq N-1$ $((i))_N \equiv i \mod N$

Three-particle cross-correlation:

$$
x_{ij}^{ab} = \sum_{k=0}^{N-1} x_k^a \left(x_{((i+k))_N}^b + x_{((j+k))_N}^b \right)
$$

Somewhat like a "really fast" MC technique for calculating difference between two periodic, random variables.

Linear cross correlations for nonperiodic variables (e.g. Δη correlations) are even simpler.

*Similar to convolution (x^a o x^b). (Cross-correlation uses i+j, while convolution sum uses i-j).

Two peaks at +/- 1 rad

Top

Single-particle φ distribution with two Gaussian peaks. σ = π/3 and μ = ± 1.

Bottom

Autocorrelation representing pair distribution

Observation

S.P. dists. with 120° peak separation lead to strong v3 correlated component, even if the event is not triangular.

A. Adare (ALICE)

xa

 ϕ (rad)

Different inputs, similar results

Right:

v1-v4 sum {-0.05, 0.1, 0.1, 0.02}

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Pair distribution qualitatively similar

Triangular-shaped events ²³

Top

Pure v3 single-particle φ distribution.

Bottom

Again, autocorrelation (= pair distribution)

2.2 arb. units arb. units 2 1.8 1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 $_0$ -2 -1 0 1 2 3 4 5 ϕ (rad) Pair $\Delta\phi$ distribution 1.6 arb. units arb. units 1.4 1.2 1 0.8 0.6 0.4 -2 -1 0 1 2 3 4 5 $\Delta \phi$ (rad)

Triangular event

Observations

Pair distribution has same shape as S.P. distribution (true for all n)

Away-side correlation strength equal to near side Allows distinction from flux-tube/ perturbation vs. triangular flow pictures?

Three-particle correlations

Three-particle shapes are very different between the two cases… Even if reality is some admixture between these, experimental sensitivity may be sufficient.

But we should examine the unsubtracted, central data! No ZYAM!!

Double Gaussian autocorrelation

Triangular flow autocorrelation

High trigger, low associated pT

High-p_T triggers from jet **fragmentation**

Expect anisotropy from pathlength-dependent quenching (PLDQ).

Low-p_T partners from **bulk Expect anisotropy from flow**

Do correlations factorize for this case? Yes, but not as cleanly as for low p_T^t , low p_T^a **correlations.**

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Hot-spot / flux-tube / sound models

Similar qualitative features

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Figure 3. Single- (left) and two- (right) particle angular distributions in the simplified model.

Figure 4. Temporal evolution of energy density for the simplified model (left). Trajectories of the fluid cells around the tube (right).

A. Adare (ALICE) subtracted from the raw correlation. By doing the effects of \mathbf{A} **and flow shape and flow sha**