PROCEEDINGS OF SCIENCE

Dilepton anisotropy at low beam energies in a transport approach

Renan Hirayama[a,b,c,*] **and Hannah Elfner**[d,a,b,c]

[a] *Helmholtz Research Academy Hesse (HFHF)*
GSI Helmholtz Center, Campus Frankfurt, Max-von-Laue-Str. 12, 60438 Frankfurt am Main, Germany
[b] *Institute for Theoretical Physics*
Goethe University, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany
[c] *Frankfurt Institute for Advanced Studies*
Ruth-Moufang-Strasse 1, 60438 Frankfurt am Main, Germany
[d] *GSI Helmholtzzentrum für Schwerionenforschung*
Planckstraße 1, 64291 Darmstadt, Germany

E-mail: hirayama@fias.uni-frankfurt.de

We present calculations of dielectron anisotropic flow in heavy-ion collisions at HADES beam energies from a hadronic transport approach. The collectivity of the electromagnetic radiation produced during the evolution of these collisions has recently been dubbed as a barometer, serving as a probe for the flow velocity of the underlying hadronic matter. In particular, we study the elliptic flow coefficient v_2 of dileptons in different collisions systems, and its relation to the flow of hadrons.

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*Speaker

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1. Introduction

Dileptons are regarded as powerful probes and multi-messengers for the physics of a heavy-ion collision (HIC), because the small ratio between the electromagnetic and strong couplings allows them to leave the hot and dense medium mostly undisturbed. The detected leptons carry information about the whole evolution, unlike hadrons, which are only measured in their final state. Despite being very versatile probes, the small electroweak coupling also makes dileptons rare and difficult to measure; and there is an inherent combinatorial uncertainty from matching a lepton with the antilepton originating from the same process.

An observable of current interest is the anisotropic flow of dileptons, in all beam energy ranges of HICs [1–4], as it is sensitive to shear and bulk viscosities [5], as well as the equation of state at early times [6]. On top of the aforementioned experimental complications, the specific method used to compute the flow coefficient may carry systematic uncertainties, such as the determination of the reaction plane and its resolution. The HADES collaboration is currently analysing dilepton anisotropy in Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV using the reaction plane method [1]. In this work, we propose the *scalar product* method, which correlates the differential dilepton event flow vector with the global hadron flow in an event-by-event basis, and which may help decrease the large error bars associated with this measurement.

2. SMASH

We simulate heavy-ion collisions using the cascade mode of SMASH (*Simulating Many Accelerated Strongly-interacting Hadrons*), a general purpose transport approach which evolves hadrons according to the relativistic Boltzmann equation [7]. We use a geometric criterion to determine binary scatterings, and *hadronic* decays are selected randomly with a rate equal to the inverse of a mass-dependent parametrization of the width in the hadron rest frame, fixed to the vacuum value Γ_0 given by the Particle Data Group [8] at the pole mass. Hadrons with $\Gamma_0 < 15$ keV (such as π^0 and η mesons) are taken as stable and do not decay, the rest are treated as resonances with finite lifetimes.

Since the electromagnetic branching ratio of resonances is very small, e.g. $\mathrm{BR}_{\rho\to e^+e^-} \approx 10^{-5}$, an unfeasible number of events would be needed to accumulate statistics if we treated dilepton emission in the same way as the hadronic decays. Instead, we use the perturbative *shining method* [9, 10], where at every time step with duration $\Delta\tau$ the resonance radiates its electromagnetic channels, but the emission carries the weight

$$w_{R\to\text{e.m.}}(\Delta\tau) = \int_0^{\Delta\tau} \frac{\mathrm{d}t}{\gamma_R}\Gamma_{R\to\text{e.m.}}(M_{ll}), \tag{1}$$

which is taken into account later when computing multiplicities. Here, γ_R is the resonance's Lorentz factor, and $M_{l^+l^-}$ is the dilepton invariant mass. When the emission is direct ($R \to l^+l^-$), the latter is equal to the resonance mass, but in a Dalitz process ($R \to Xl^+l^-$) it is sampled uniformly from the available phase space. For hadrons considered stable, the dilepton decay is performed at the end of the event.

SMASH relies solely on vacuum properties, and the resulting dilepton yield for $p+p$ collisions matches experimental data [10]. However, the modifications caused by medium interactions in larger systems cannot be fully explained by the collisional broadening that arises in vacuum-based hadronic scatterings [11], as is especially noticeable around the ρ meson pole mass. Therefore, we make a caveat that the *number* of dileptons in a given invariant mass is not consistent with HIC experiments, but assume that the anisotropic flow is insensitive to this problem.

3. Anisotropic flow

In order to describe anisotropic flow, particle yields are written as a Fourier series over the azimuthal momentum, and the coefficient of order n is named v_n. In the traditional Reaction Plane (RP) method, the reaction plane Ψ_{RP} is defined as the angle between the impact parameter and the beam direction. Then, the flow coefficient is computed with respect to this plane as $v_n\{\mathrm{RP}\} \equiv \langle\cos[n(\phi - \Psi_{\mathrm{RP}})]\rangle$. This definition carries the nice geometric interpretation where particles tend to flow in or out of the reaction plane, depending on the beam energy.

In HADES, the reconstruction of Ψ_{RP} is done with the Forward Wall detector, which measures spectator protons [12]. This brings about a systematic uncertainty, on top of the difficulty of reconstructing the dileptons. We propose a different definition:

$$v_n^{ll}(X) = \frac{\left\langle |\mathbf{q}_n^h||\mathbf{q}_n^{ll}(X)| \cos[n(\Psi_n^h - \Psi_n^{ll})] \right\rangle_{\mathrm{ev}}}{\sqrt{\left\langle |\mathbf{q}_n^h|^2 \right\rangle_{\mathrm{ev}}}}, \qquad (2)$$

where the *event flow vector* is

$$\mathbf{q}_n^k(X) \overset{\mathrm{SMASH}}{\longrightarrow} \frac{1}{N^k} \sum_{j\in X}^{N^k} \begin{pmatrix} \cos n\phi_j \\ \sin n\phi_j \end{pmatrix} \qquad (3)$$

for dileptons $k = ll$ or hadrons $k = h$.

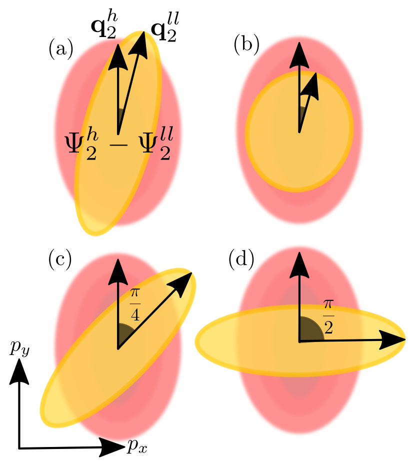

Figure 1: Sketch of the scalar product method 2, with the dilepton (hadron) event vector in yellow (red). See text for interpretation.

We evaluate the dilepton event flow vector differentially in phase space bins X, but $\mathbf{q}^h$ is integrated over all hadrons with $p_T > 0.1$ GeV.

Definition (2) was originally proposed by [5] for dilepton flow at RHIC and LHC energies, where the spectators are not readily available. To do so, it skips the reconstruction of the reaction plane, and uses the flow of hadrons as a reference instead, which is anyway measured. With it, the geometric interpretation is lost, but can be understood with the assistance of Fig. 1, where $v_2(a) > v_2(b) > v_2(c) = 0 > v_2(d)$:

- If both $\mathbf{q}^h$ and $\mathbf{q}^{ll}$ are aligned with a non-zero absolute value, $v_n^{ll} > 0$;
- If they are misaligned by $\pi/2n$ or one is 0, $v_n^{ll} = 0$;
- If $\pi/2n < \Psi_n^h - \Psi_n^{ll} < \pi/n$, they are anti-correlated and $v_n^{ll} < 0$.

We note that hadrons are only detected in their final state, while dileptons correspond to the time-integrated emission throughout the whole evolution. Then, a larger v_2^{ll} means that the dilepton flow is more *correlated* to the final (measured) flow of hadrons, not necessarily that the dilepton anisotropy is itself stronger.

4. Results

We apply the scalar product method (2) to dielectrons from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV simulated with SMASH. Figure 2 shows v_2 as a function of invariant mass. The only cut is on small transverse momenta p_T, which are excluded due to detector limitations.

The flow can be divided into two regions in invariant mass. The region below the pion mass is dominated to the Dalitz decay of neutral pions ($\pi^0 \to \gamma e^+ e^-$) with an absolute value between 2% and 4%, consistent to the preliminary results shown in [1] but with the opposite sign. Moreover, the centrality dependence is reverse from the geometric interpretation, with v_2 *decreasing* with the impact parameter. Pions are stable and only decay at the end of the collision, as such dileptons that come from them are highly correlated to the final state. Since central collisions produce more pions than non-central ones, they result in a larger v_2. Dielectrons with invariant mass $M_{ee} > m_\pi$ have a very small but non-zero flow, also consistent with HADES preliminary results. This may be because these dielectrons (or their sources) really have no preferred direction, or perhaps some sources flow in the opposite direction of others, such that the average flow is small. We are currently investigating this possibility.

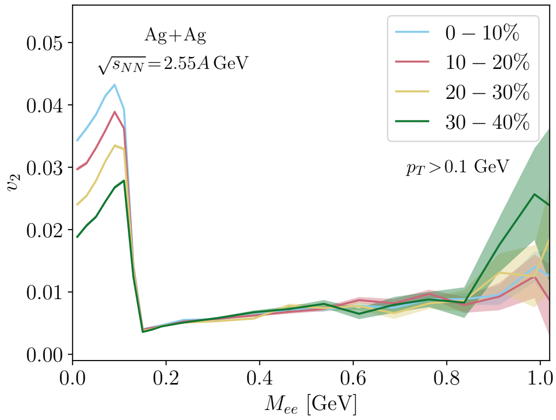

Figure 2: Dielectron v_2 as a function of invariant mass M_{ee} for Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ in different centrality classes.

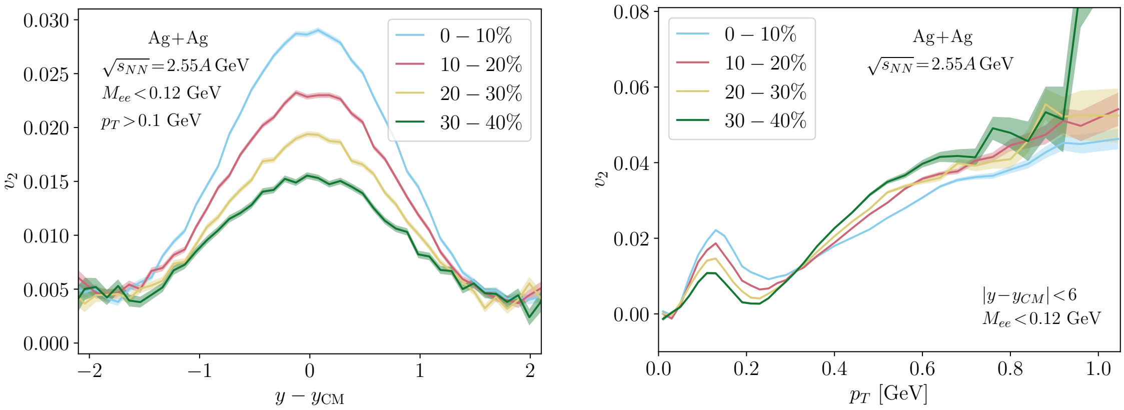

Figure 3: Same as Fig. 2, as a function of (left) rapidity $y - y_{\rm CM}$ and (right) transverse momentum p_T.

Next, we restrict the analysis for the small mass region. The rapidity dependence of v_2 is shown to the left of Fig. 3 and can be understood from the discussion above. It peaks around midrapidity and drops between $1 < |y - y_{\rm CM}| < 2$, similar to the rapidity spectra of pions in SMASH [13]. The transverse momentum dependence is shown to the right and reveals a more interesting structure. We see a *bump* at low-p_T following the previously explained centrality ordering, but this flips above $p_T > 0.3$ GeV, where we find the traditional behavior of v_2 *increasing* with impact parameter. We can understand this by analysing the flow at different stages of the evolution, as shown in Fig. 4.

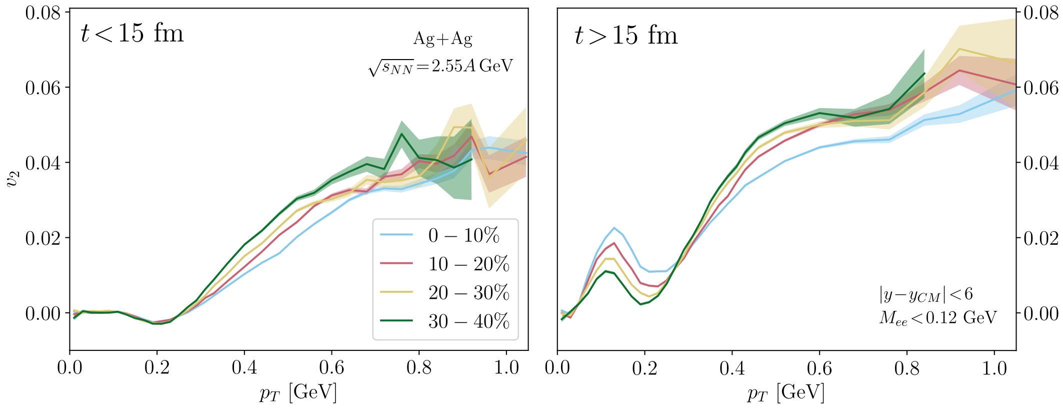

Figure 4: Dielectron v_2 as a function of p_T, for dileptons emitted (left) before and (right) after t = 15 fm.

In a previous publication [11], we determined that the medium created in this collision system becomes effectively dilute with respect to collisional broadening at around $t \approx 15$ fm. Before that the system is dense; as we see in the left of Fig. 4, the bump is not present. Since pions only decay at the end of the event, the flow of high-p_T dileptons follows the flow of resonances, most likely Δ baryons. As seen to the right, the bump only arises for dileptons emitted in the dilute stage, pointing to a non-flow contribution. We believe that these low-p_T dileptons come from chains of decays such as $N^* \to (\rho^0, \pi^0)N \to e^+e^-N$, as intermediate hadrons have a smaller transverse momentum than the original resonance.

5. Discussion and outlook

In this work, we calculated the anisotropic flow of dileptons directly from the hadronic transport approach SMASH, proposing the usage of the scalar product method 2. We found that the elliptic flow coefficient is consistent to HADES preliminary results, albeit with a different sign, since the geometric interpretation is not appropriate. We also found an interesting structure in the transverse momentum dependency of v_2, which we understand to be a non-flow contribution.

The setup we used for this analysis is simplified, as we did not include nuclear potentials in the calculations, nor studied the effect of different choices for the reference hadronic flow. It is possible that considering e.g. only charged pions will lead to different results, and the robustness of the method will be assessed in a future publication, along with a faithful comparison to the reaction plane method, and to experimental data, when it becomes publicly available.

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