Torqued fireballs[1]

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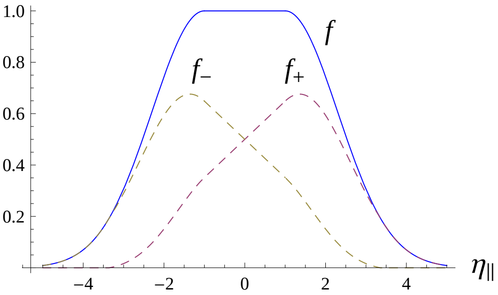
[1] arXiv:1011.3354 [nucl-th]

Emission profiles in rapidity

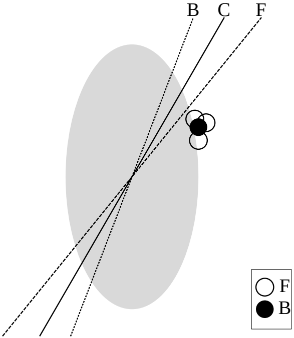


Emission profiles in space-time rapidity $\eta_{\parallel} = \frac{1}{2} \log{(t+z)/(t-z)}$ for the wounded nucleons (dashed lines) and the binary collisions (solid line). Profile $f_{\pm}$ correspond to the forward- and backward-moving wounded nucleons

Białas, Czyż, Fiałkowski, Wit, Adil, Guylassy, Hirano, Gaździcki, Gorenstein, Bzdak, Woźniak, Rybicki, Bożek, Wyskiel

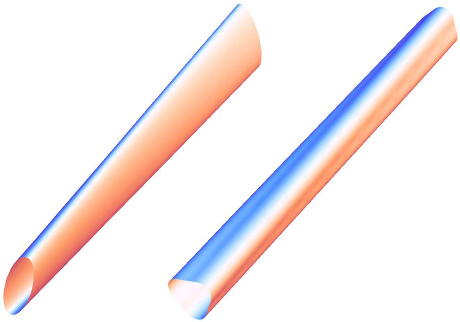
(*i.a.* explanation of v_1 (twist in $y - \eta$, FB multiplicity correlations)

Fluctuations



Generation of the torque effect. A random cluster of wounded nucleons, here with with 3 nucleons moving forward (open circles) and 1 moving backward (filled circle), causes a random torque of the principal axes. The angle of the torque is higher in F direction than in B direction

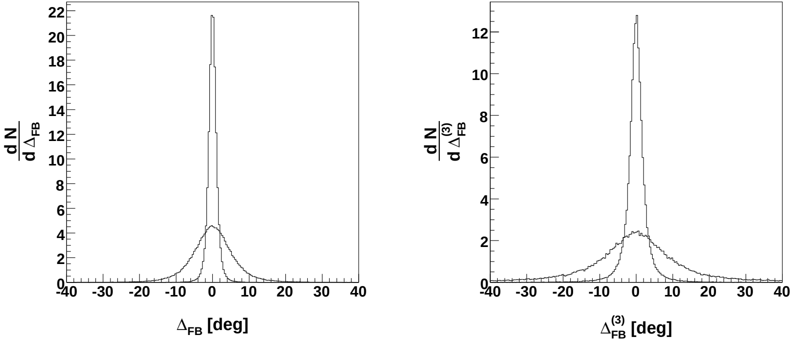
F:B:C = 3:1:4/2



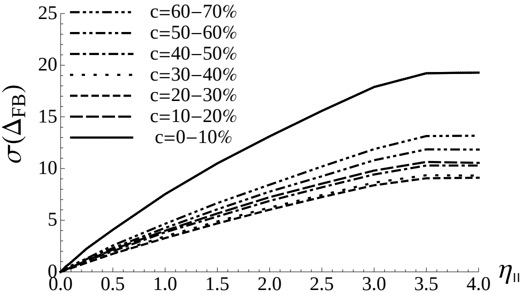
Schematic figure of the torqued fireball, elongated along the $\eta_{||}$ axis. The direction of the principal axes in the transverse plane rotates as $\eta_{||}$ increases. The left and right figures depict the rank-2 (elliptic) and rank-3 (triangular) cases. The effect occurs event-by-event

FB torque angle

$$\Psi^{(k)} = \frac{1}{k}\arctan\left(\sum_{i=1}^{n} w_i r_i^2 \sin(k\phi_i) / \sum_{i=1}^{n} w_i r_i^2 \cos(k\phi_i)\right)$$

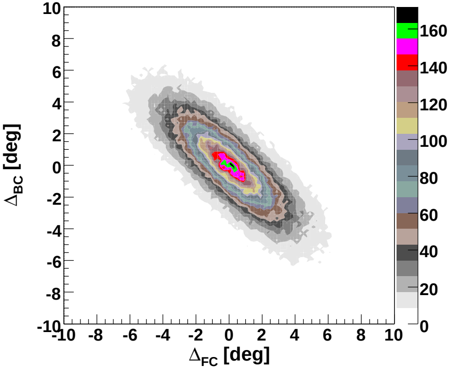


Distribution of $\Delta_{FB} = \Psi^{(k)}(\eta_{||}) - \Psi^{(k)}(-\eta_{||})$ for $k = 2$ and 3. The narrower and wider distributions correspond to $\eta_{||} = 0.5$ and 2.5. GLISSANDO, $c = 20 - 30\%$, Au+Au@200GeV, mixed model, $\alpha = 0.145$ $(n \sim (1-\alpha)N_w/2 + \alpha N_{bin})$

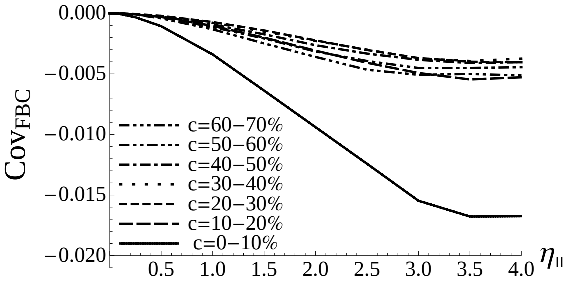


rms width of the Δ_{FB} distribution

FBC measure

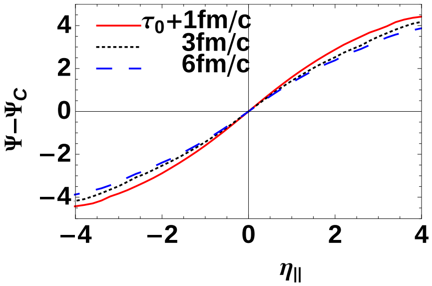


2-dim. distribution of the relative torque angles Δ_{FC} and Δ_{BC}, for centrality $50-60\%$, space-time rapidity $\eta_{||} = 2.5$. The correlation coefficient is $\rho_{FCB} = -0.61$



Covariance of Δ_{FC} and Δ_{BC} as a function of $\eta_{\|}$ for various centralities

Hydro evolution

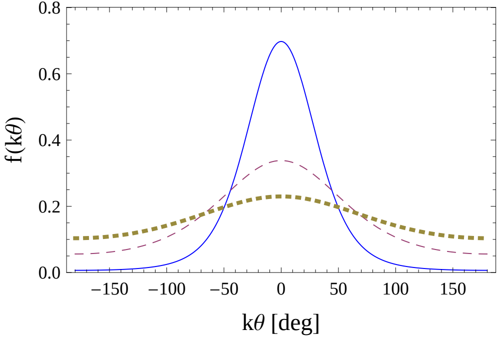


Dependence of the torque angle of the *fluid velocity field* on space-time rapidity after the 3+1-dimensional hydro evolution. Subsequent curves are for different evolution times

Washing-out by statistical hadronization

$$f(k\theta) = \frac{e^{-nv_k^2/w^2}}{2\pi s^3}\left\{\sqrt{\pi n}v_k \cos(k\theta) e^{nv_k^2\cos^2(k\theta)/(s^2w^2)}\left[\mathrm{sgn}[\cos(k\theta)]\mathrm{erf}\left(\frac{\sqrt{n}v_k|\cos(k\theta)|}{sw}\right)+1\right]+sw\right\}$$

$$w=\sqrt{1-2v_k^2},\quad s=\sqrt{1-2v_k^2\sin^2(k\theta)}$$



E-by-e distribution of $k\theta$ for $v_k = 5\%$, $k = 2, 3, \ldots$, for several values of the multiplicity n: 600 (solid), 100 (dashed), and 20 (dotted)

Cumulants

Consider [similarly to Borghini, Ollitrault, ...]

$$\left\langle e^{2i(\phi_F-\phi_B)}\right\rangle = \frac{1}{N_{\rm events}}\sum_{\rm events}\frac{1}{n_F n_B}\sum_{i=1}^{n_F}\sum_{j=1}^{n_B} e^{2i(\phi_i-\phi_j)}$$

ϕ_i, ϕ_j - angles of the F and B particles, n_F, n_B - multiplicities
If no correlations, $f(\phi) = v_0 + 2\sum_{k=1} v_k \cos[k(\phi - \Psi^{(k)})]$, and

$$\left\langle e^{2i(\phi_F-\phi_B)}\right\rangle = \langle v_{2,F} v_{2,B} \cos(2\Delta_{FB})\rangle_{\rm events}$$

Non-flow contributions $\sim 1/n$: *resonance decays*, conservation laws, BE correlations, short-range correlations, etc.
Divide the cumulant by $v_{2,F} v_{2,B}$, *e.g.*:

$$\cos(2\Delta_{FB})\{2\} \equiv \frac{\left\langle e^{2i(\phi_F-\phi_B)}\right\rangle}{\sqrt{\left\langle e^{2i(\phi_{F,1}-\phi_{F,2})}\right\rangle \left\langle e^{2i(\phi_{B,1}-\phi_{B,2})}\right\rangle}} = \langle\cos(2\Delta_{FB})\rangle_{\rm events} + {\rm nf}$$

One may also use higher-order cumulants, *e.g.*:

$$\cos(4\Delta_{FB})\,\{4\} \equiv \frac{\left\langle e^{2i[(\phi_{F,1}+\phi_{F,2})-(\phi_{B,1}+\phi_{B,2})]}\right\rangle}{\left\langle e^{2i[(\phi_{F,1}-\phi_{F,2})-(\phi_{B,1}-\phi_{B,2})]}\right\rangle} = \langle\cos(4\Delta_{FB})\rangle_{\rm events} + {\rm nf}$$

FBC case:

$$A_{FBC}\{4\} = \frac{\left\langle e^{i2[(\phi_F-\phi_{C,1})-(\phi_B-\phi_{C,2})]}\right\rangle - \left\langle e^{i2[(\phi_F-\phi_{C,1})+(\phi_B-\phi_{C,2})]}\right\rangle}{v_{2,F}v_{2,B}v_{2,C}^2} =$$

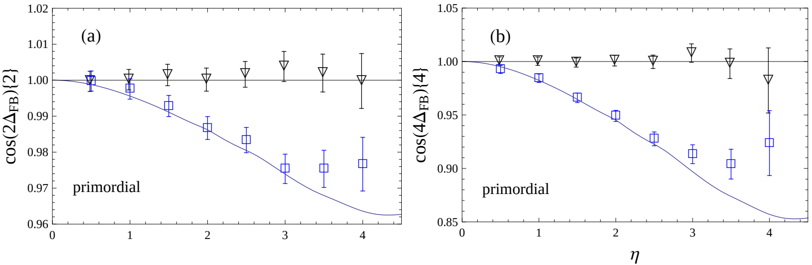
$$= \langle 2\sin(2\Delta_{FC})\sin(2\Delta_{BC})\rangle_{\rm events} + {\rm nf}$$

For small torque angles

$$A_{FBC}\{4\} \sim 8\,{\rm cov}(\Delta_{FC},\Delta_{BC}) + {\rm nf}$$

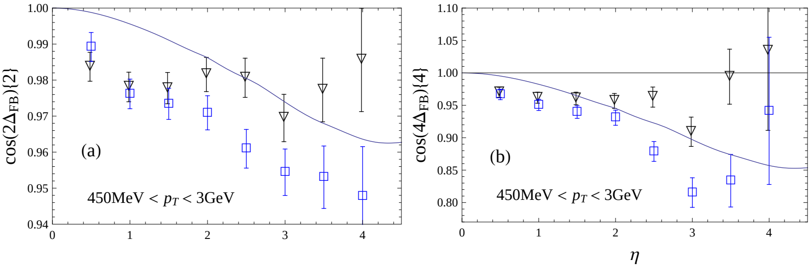
THERMINATOR - primordial

(100k events at a fixed torque corresponding to the rms value of the angle)



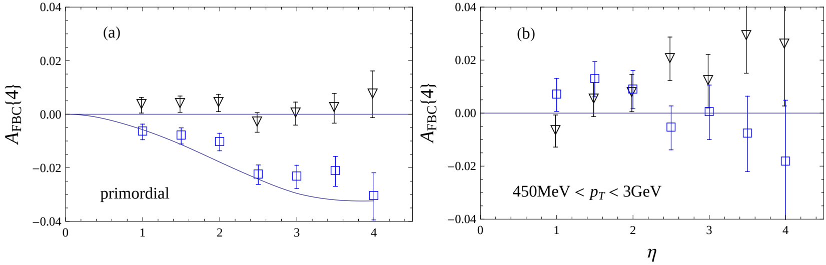
Cumulant measures of the torque obtained for $c = 20 - 25\%$ with the primordial particles only (*i.e.*, with no resonance decays), plotted as functions of pseudorapidity. Triangles correspond to no torque, squares to included torque. The solid line represents evaluation directly from the fireball torque of the fluid velocity. The η windows have the width of one unit. The error bars indicate the statistical errors of the THERMINATOR simulation

THERMINATOR - all charged



Same with all charged pions, kaons, protons, and antiprotons, $450 \text{ MeV} < p_T < 3 \text{ GeV}$. The departure of the triangles (no torque) from unity displays the non-flow contribution due to resonance decays. The squares (torque) are shifted away from the case without the torque

THERMINATOR - FBC



A_{FBC} obtained from for the primordial particles (left) and all charged pions, kaons, protons, and antiprotons (right). Triangles correspond to no torque, squares to included torque. The solid line shows $8\mathrm{cov}_{FBC}$.

Summary

1. Asymmetric emission profiles, where the wounded nucleons emit predominantly in the direction of their motion, + statistical fluctuations of the source density, lead to e-by-e torqued fireballs
2. The rms width of the torque angle between the forward ($\eta_{||} \sim 3$) and backward ($\eta_{||} \sim -3$) regions varies from 20° for the most central collisions to 10° for the mid-central and mid-peripheral Au+Au collisions at the highest RHIC energies
3. The initial torque is transformed, via hydro, into the torque of the flow velocity of the fluid, and subsequently into the torque of the p_T distributions of the detected particles
4. Statistical measures based on cumulants containing particles in separated η bins useful experimentally
5. Non-flow corrections sizable, but do not overshadow the effect (THERMINATOR). Possibility for PHOBOS and STAR
6. Since the statistical noise increases as the product of the multiplicity and v_2, optimum choice is $c \sim 20 - 30\%$ and higher p_T
7. Similar torque size for the elliptic and triangular flows (and higher k)