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CBM performance for the measurement of (multi)strange hadrons' anisotropic flow in Au+Au collisions at FAIR

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Abstract

Performance studies for strange hadrons anisotropic flow measurement with the CBM experiment at FAIR are presented. Strange hadrons are reconstructed via their decay topology using the Particle-Finder Simple package, which provides an interface to the Kalman Filter Particle mathematics. Anisotropic flow of strange hadrons is studied as a function of rapidity, transverse momentum and collision centrality. The effects due to non-uniformity of the CBM detector response in the azimuthal angle, transverse momentum and rapidity are corrected using the QnTools analysis package.

1. Introduction

Strange quarks are produced at the early stage of a heavy-ion collision. At the mixed phase of the QCD matter (with temperature up to 120 MeV) the yield of strange quarks is expected to be comparable with that of light quarks and they are expected to provide information about the properties of the nuclear matter, its equation of state and compressibility. Anisotropic flow of produced particles, which is driven by the pressure gradients in the early dense phase of the collision evolution, is an important observable for understanding the dynamics and evolution of the QCD matter created in the collision. As such the collective flow of strange hadrons allows the study of the dynamics of the strange quark production. In particular, the slope of the directed flow is sensitive to the equation of state of created matter.

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2. CBM Experiment and Simulation Setup

The CBM is a multipurpose fixed-target experiment which is designed to measure charged hadrons, electrons and muons in proton-ion and heavy-ion collisions over the full FAIR energy range $\sqrt{s_{NN}} = 2.9 - 4.9\ GeV$ (see [1] and references therein). The main subsystems of the CBM experiment which are relevant to the measurement of strange hadrons' flow are listed below. They are the Silicon Tracking System (STS) and Micro-Vertex Detector (MVD), which are situated inside a dipole magnet and allow charged hadron tracking, the Time Of Flight (TOF) detector used for charged particle identification and the Projectile Spectator Detector (PSD), which is designed for centrality and reaction plane estimation.

A sample of 5 M Au+Au collisions at $\sqrt{s_{NN}} = 4.9\ GeV$ was used for the analysis. The sample was produced using the DCM-QGSM-SMM event generator [2, 3], which includes coalescence, fragmentation of nuclei recoil and hypernuclei production, and the GEANT4 [4, 5] package to transport particles through the CBM detector material. The simulated GEANT4 signals were used to reconstruct the collision and its products with algorithms implemented in the CBMROOT [6] software. Centrality was estimated using charged track multiplicity following the procedure described in [7, 8]. Particles were identified using TOF signals and the Bayesian approach [8, 9]. Short-lived strange particles were reconstructed via their weak decay products using PFSimple package [8, 10], which interfaces Kalman Filter Particle mathematics [11–13].

3. Anisotropic Flow Measurement Technique

In heavy ion collisions spatial asymmetry of initial energy density in the overlap region is converted due to interaction between produced particles to the asymmetry in final momentum distribution of collision products. It is quantified by the coefficients v_n in a Fourier decomposition of the azimuthal distribution $\rho(\varphi)$ of produced particles:

$$\rho(\varphi - \Psi_{\mathrm{RP}}) \sim 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_{\mathrm{RP}}))\ , \quad v_n = \langle \cos[n(\varphi - \Psi_{\mathrm{RP}})] \rangle, \tag{1}$$

where n is the harmonic number, φ is the azimuthal angle of the particle, Ψ_{RP} is the reaction (symmetry) plane angle, and angular brackets $< \dots >$ indicate the average over all particles in all collisions. Asymmetry of particle emission in a given collision can be quantified in terms of single particle unit vector $\mathbf{u}_n$ and a flow vector $\mathbf{q}_n$, which is a weighted sum of $\mathbf{u}_n$-vectors for a set of particles:

$$\mathbf{u}_n = \{\cos n\varphi, \sin n\varphi\}, \quad \mathbf{q}_n = \frac{1}{M}\sum_{i}^{N} w_i \mathbf{u}_{n,i}, \quad M = \sum_{i}^{N} w_i, \tag{2}$$

where w_i is a weight of i-th $\mathbf{u}_n$-vector and M is sum of weights. The reaction plane angle in Eq. (1) was estimated with the $\mathbf{Q}_n$-vector constructed from the transverse distribution of energy deposited in the PSD modules using equation similar to $\mathbf{q}_n$ in Eq. (2). Non-uniformity in azimuthal angle of the CBM acceptance and efficiency, which bias the measurement of the (directed) flow, was corrected for following the procedure [14], which was implemented in QnAnalysis/QnTools framework [8]. Additionally, the (p_T, y)-dependent inverse efficiency was used as a weight for individual tracks.

The directed flow v_1 was calculated using the scalar product method:

$$v_{1,\alpha}\{A\} = \frac{2\langle q_{1,\alpha} Q^A_{1,\alpha}\rangle}{R^A_{1,\alpha}}. \tag{3}$$

Here $\alpha = (x, y)$ are components of the $\mathbf{q}_1$ or $\mathbf{Q}_1$ vectors, while $A = 1, 2, 3$ of the PSD modules grouped in three subevents [15]. The $R^A_{1,\alpha}$ accounts for the reaction plane resolution of the PSD and is determined using correlations between components of the $\mathbf{Q}_{1,\alpha}$ vectors as described in [15].

Equation (3) was used to calculate directed flow of all reconstructed candidates for strange hadron decays ($v_{1,\mathrm{ALL}}$). The directed flow of the real strange hadrons ($v_{1,s}$) decays was separated from the contribution of the combinatorial background ($v_{1,\mathrm{BG}}$) using the invariant mass fit method:

$$v_{1,\mathrm{ALL}}(m_{\mathrm{inv}}) = \frac{v_{1,s} N_s(m_{\mathrm{inv}}) + v_{1,\mathrm{BG}}(m_{\mathrm{inv}}) N_{\mathrm{BG}}(m_{\mathrm{inv}})}{N_s(m_{\mathrm{inv}}) + N_{\mathrm{BG}}(m_{\mathrm{inv}})}\ . \tag{4}$$

Here $N_s(m_{\mathrm{inv}})$ and $N_{\mathrm{BG}}(m_{\mathrm{inv}})$ are yields vs. the invariant mass for the signal and background candidates extracted using the fit to the invariant mass distribution, $v_{1,s}$ is assumed constant and $v_{1,\mathrm{BG}}(m_{\mathrm{inv}})$ is assumed as a linear function of invariant mass.

An illustration of the invariant mass fit procedure is given in Fig. 1. In the fit of the invariant mass distribution of all reconstructed decay candidates (top panels in Fig. 1) a double-sided crystal ball function was used for the signal, while a third order polynomial function was used for combinatorial background. The dependence of $v_{1,\mathrm{ALL}}$ on the invariant mass and corresponding fits with Eq. 4 are shown in the bottom panels of Fig. 1.

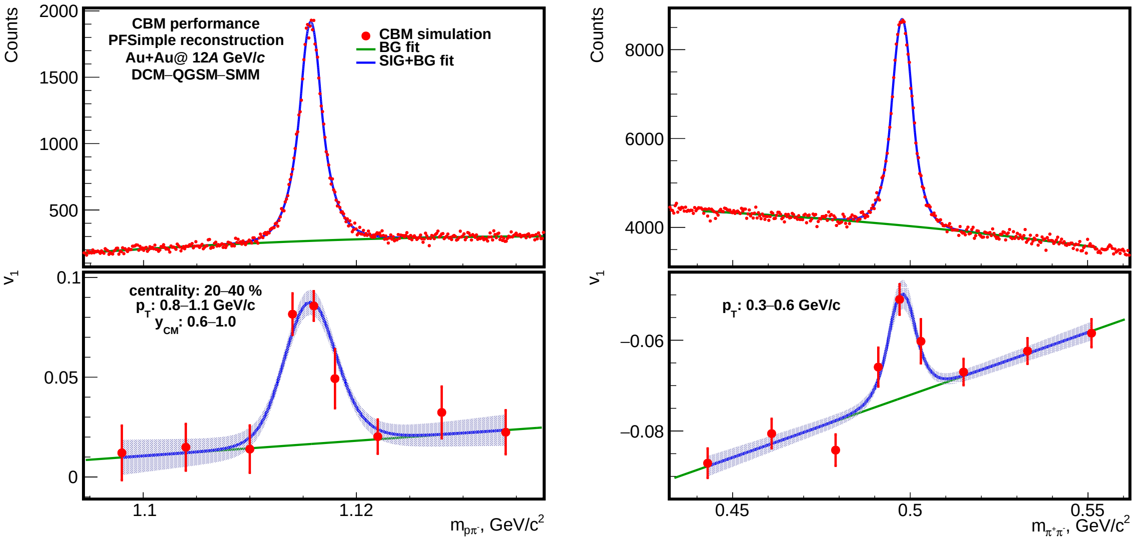

Figure 1: (upper panels) Invariant mass distribution of $\Lambda \to p\pi^-$ (left) and $K^0_S \to \pi^+\pi^-$ (right), fitted with a combination of the double-sided crystal ball function (SIG) and 3-d order polynomial (BG). (bottom panels) Directed flow of Λ (left) and K^0_S (right) vs. invariant mass, fitted using Eq. (4).

4. Results

Figure 2 (left) shows the CBM performance for Λ, K^0_S and Ξ^- measurement of directed flow as a function of rapidity. Solid lines represent MC-true input, empty circles stand for measured directed

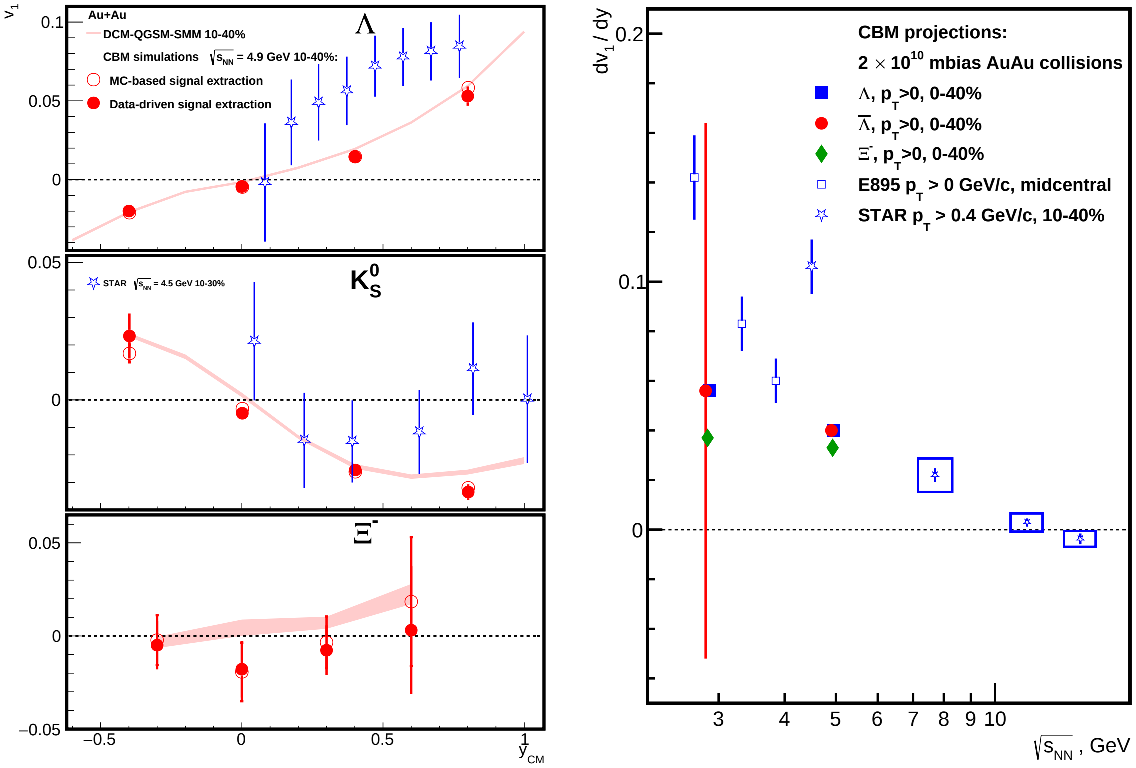

Figure 2: Directed flow of Λ (**left top**), K^0_S (**left middle**) and Ξ^- (**left bottom**) as a function of rapidity: comparison of MC input with reconstructed values; comparison of expected CBM performance (1.5M events, stat. errors only) and STAR FXT data (0.65M events, stat. and syst. errors) (for Λ and K^0_S); dv_1/dy as a function of collision energy - performances comparison (**right**).

flow of particles identified as signal according to MC-matching and full circles represent measured flow of signal extracted using invariant mass fitting procedure (for Λ-hyperons and K^0_S-mesons) and directed flow of all reconstructed candidates for Ξ^--baryons. Due to limited statistics the results from the invariant mass fitting procedure for Ξ^- are not shown. The directed flow calculated using both MC-based signal extraction and invariant mass fit method reproduces the MC-true values within statistical uncertainties. For comparison, the experimental data by the STAR collaboration [16] for Λ and K^0_S are shown in left panels of Fig. 2. The magnitudes of v_1 for Λ and K^0_S measured by STAR and predictions from the DCM-QGSM-SMM model have comparable magnitudes and the same sign of the slopes as a function of rapidity. Figure 2 (right) shows CBM projections for the statistical errors on the slope of the directed flow, dv_1/dy, for (multi)strange hadrons in comparison with existing world data as a function of collision energy. Projections for $\bar{\Lambda}$ was calculated assuming the same magntidue of dv_1/dy as for Λ's and the ratio of the $\bar{\Lambda}/\Lambda$ yield predicted by the thermal model [17].

5. Conclusions

Performance of the CBM experiment for measurements of the directed flow of strange hadrons is presented. The data-driven approach to calculate the directed flow in Monte-Carlo simulations is shown to reproduce within the statistical uncertainties the input Monte Carlo values. The CBM performance is compared with that of STAR experiment and projections for statistical uncertainties with high statistic data at CBM are presented.

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