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Performance studies for collective flow measurements with CBM at FAIR

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Abstract. We present recent results from CBM performance studies for measurements of the directed (v_1) flow of π^+, Λ and K_s^0. For the performance studies we use the CBMROOT environment for Monte-Carlo simulations and event reconstruction. The Kalman Filter Particle Finder (KFParticleFinder) package is used for hyperon reconstruction via their weak decays, and the Projectile Spectator Detector (PSD) for event plane determination. A status of the fast simulator implementation for the PSD calorimeter response, which is required for high statistics simulation, is also presented.

1. Introduction

Compressed Baryonic Matter experiment [1] at the future FAIR facility is dedicated to studies of QCD phase diagram at high baryonic densities and moderate temperatures produced at heavy-ion collisions. Very high collision rate up to 10 MHz is expected at CBM and continuous streaming readout is proposed. CBM is expected to begin taking data at FAIR in 2025.

It was shown recently by studies from RHIC BES program that $dv_1/dy|_{y=0}$ and the difference between v_2 of particles and antiparticles in the $\sqrt{s_{NN}}$ region of a few GeV are of great interest for understanding a pattern of the phase transition between quark-gluon and hadronic matter [2]. Precision measurements of these observables in CBM experiment will be a significant step forward in exploration of the QCD phase diagram in the region of a $\sqrt{s_{NN}}$ = 2-5 GeV. Performance studies are crucial to understand detector capabilities in advance. Several related topics are important for flow measurements as well as other physical tasks: measurement of event plane, centrality and particle identification.

2. Simulation and reconstruction

Au-Au collisions are simulated with DCM-QGSM generator with Statistical Multifragmetation model (SMM) [3] and GEANT4 transport code. Performance studies with UrQMD model were reported previously [4]. Full simulation and reconstruction chain within CbmRoot is implemented. MDV, STS, RICH, TDR, TOF and PSD hits are simulated then reconstructed into tracks and clusters and processed into reduced analysis tree.

Two CBM detectors are of special importance for this performance study. STS [5] and MVD detectors located in the central rapidity region are used for track reconstruction and identification as well as for Event plane determination and centrality estimation.

PSD detector [6] located in the forward rapidity region is used for spectator detection, Event plane determination and centrality estimation. PSD geometry used in the simulations is: 44 modules 20 $\times$ 20 cm^2 covering full azimuthal angle with three groups of modules. The diamond-shaped beam pipe hole with side length 20 cm is in the center of PSD.

KF (Kalman Filter) Particle Finder algorithm [7] is used to identify V0 decays (Λ, $\bar{\Lambda}$, K_s^0) in the reconstruction.

3. Centrality determination in CBM

Centrality is needed to obtain event classes for different impact parameter b intervals. In CBM, centrality can be calculated with energy deposition in PSD, STS track multiplicity or combined 2D distribution [8]. For 1D distributions the fitting procedure with Negative Binomial Distribution is used [9]. N_{coll} and N_{part} parameters are obtained with Glauber Monte-Carlo model [9]. For 2D distributions an iterative procedure is used for profiling, fitting, perpendicular profiling. It was shown [8] that by using a combined 2D estimator one can improve impact parameter resolution for central collisions (0-30% centrality). In the studies reported here we have used STS tracks multiplicity and energy deposition in PSD as the estimator for event centrality.

4. v_n extraction procedure

Anisotropic transverse flow is the effect of azimuthal anisotropic particle production with respect to the reaction plane (1).

$$\frac{dN}{d(\phi - \Psi_{RP})} \sim 1 + 2\sum_{n=1} v_n(p_T, \eta) cos[n(\phi - \Psi_{RP})], \quad (1)$$

Scalar product (SP) method is used to extract flow coefficients v_n, eq. (2). In this method Q-vectors defined in (2) of subevents corresponding to 3 groups of PSD modules or STS subevents separated in rapidity are correlated with particle's unit vector. Correction on resolution factor R is used to obtain true v_n values.

$$Q_{n,j} = \sum_{i=1}^{M} e^{nj\phi_i}; v_n^{obs} = \langle\langle u_{ij} Q_j \rangle\rangle; v_n^{true} = v_n^{obs}/R; j \in \{x, y\}. \quad (2)$$

Invariant mass method to separate flow contribution of decaying particles from flow of combinatorial background is implemented. In this method v_n is calculated for each bin in invariant mass as well as signal to background ratio. v_n of combinatorial background is estimated in the regions outside mass peak and v_n of signal is obtained with formula (3).

$$v_n^S = v_n^{meas} + \frac{Bg}{S}(v_n^{meas} - v_n^{Bg}), \quad (3)$$

where Bg and S are Background and Signal values in the invariant mass distributions.

In experiment non-uniformity of detectors' acceptance lead to distortions of the Q-vector distributions. Several methods were developed in order to correct for these effects. We utilize Q-vector Corrections framework based on [10]. Several corrections, such as gain equalization, recentering, alignment are possible within this framework. In this study recentering correction is applied to the Q-vectors of each subevent.

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5. Results of performance studies for charged hadrons flow measurements

Positively charged pions directed flow v_1 is shown in the figure 5 vs. transverse momentum (left) and rapidity (right). Results are obtained using central (PSD1) and outer (PSD3) modules for projectile spectator plane ($\Psi_{\rm proj}$) estimation. Centrality is determined using PSD energy.

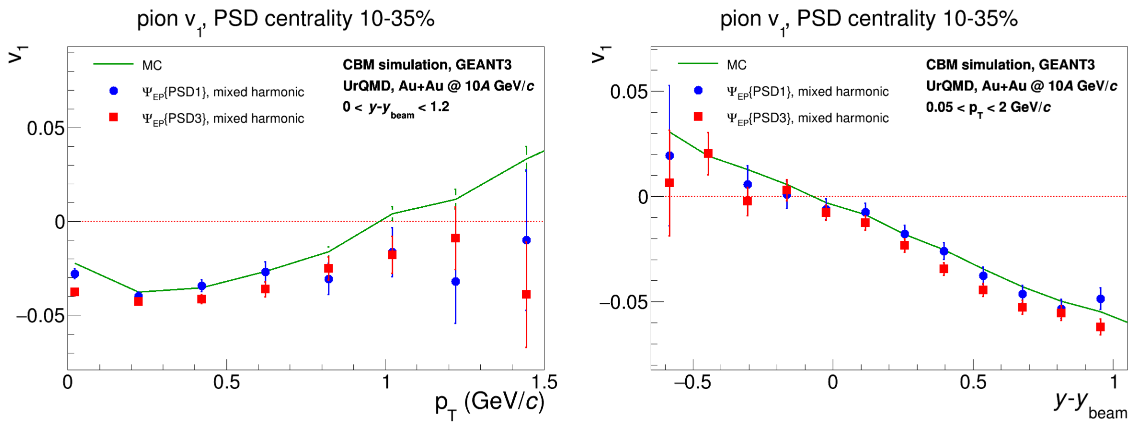

Figure 1. Left: $v_1(p_T)$ for π^+ for centrality 10-35% for $p_{Beam} = 10$A GeV/c. Right: $v_1(y)$ for π^+ for the same centrality class and beam momentum

6. Results of performance studies for strange hadrons flow measurements

Directed flow (v_1) of Λ and K_s^0 extracted for MC and reconstructed particles is shown in figure 2 for mid-central collisions (centrality class 20-30%). Flow dependence obtained with SP method is compared to model distribution.

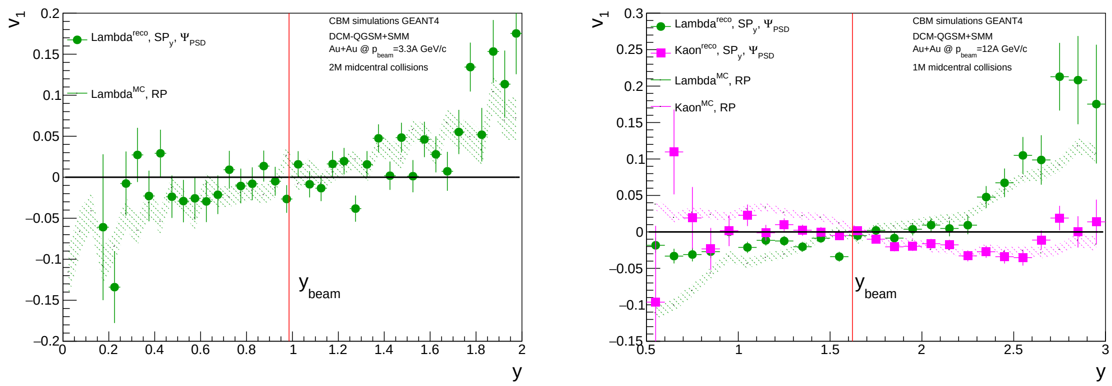

Figure 2. Left: $v_1(y)$ for Λ for centrality 20-30% for $p_{Beam} = 3.3$A GeV/c. Right: $v_1(y)$ for Λ and K_s^0 for centrality 20-30% for $p_{Beam} = 12$A GeV/c. Comparison of model distributions with data-driven calculations using Scalar product method with Event plane from PSD1 subevent is shown.

7. Fast Monte-Carlo simulations with PSD

Simulation of A-A collisions at SIS100 beam momenta with PSD requires large CPU and disk space utilization (GEANT4 event – 90 seconds of CPU time and 5Mb space at GSI farm). Fast

Monte-Carlo Simulator (FastMC) is proposed to perform high-statistic productions of simulated A-A collisions with PSD and GEANT4. FastMC is based on assumption of linear response to the particles entering PSD. The energy deposition in PSD modules should be parameterized as a function of particle's type, position on PSD surface, momentum etc. Good reproducibility of energy profile shape and transverse energy distribution is required.

The Simplest realization of FastMC is to use the full energy of incident particles as the energy deposition to the corresponding PSD module. This approximation does not consider shower leakage between modules and to the surrounding space, energy resolution of the detector, dependence on the incident angle. Figure 3 shows total energy deposition in PSD versus impact parameter in GEANT4 simulations within CBMROOT (left) and within The Simplest FastMC approach (right) for p_{Beam} = 10A GeV/c. As one can see, the Simplest FastMC manages to reproduce the shape of this dependence.

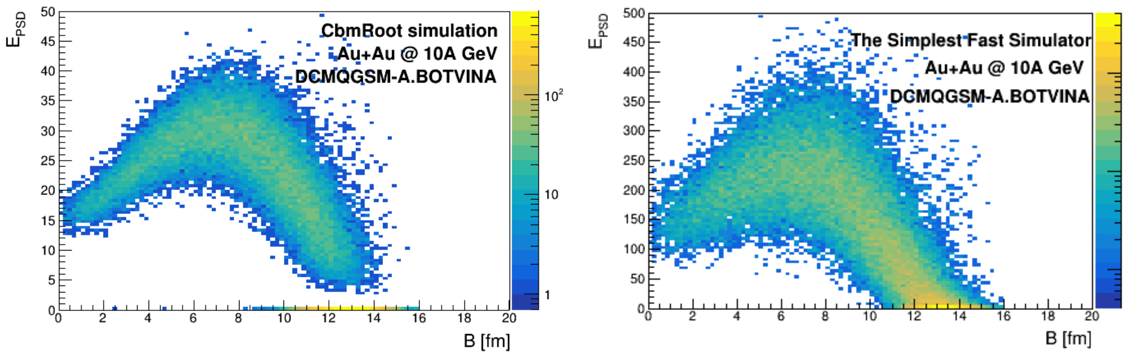

Figure 3. Left: Energy in PSD (E_{PSD}) vs impact parameter (b) simulated using GEANT4. Right: E_{PSD} vs b obtained using The Simplest FastMC.

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