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Contents

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1. WP2.1 final delivery D2.6: Physics performance for major observables

In this report we summarize the final delivery D2.6 of Work Package 2.3, revised for the second part of the project. The works address the preparation for the data taking and physics performance studies for the Compressed Baryonic Matter (CBM) experiment, which is currently entering its final planning stage to be based at its already constructed CBM cave at the under-construction FAIR facility near Darmstadt, Germany.

In the first part of the EURIZON project (former CREMLINplus), the common frameworks for centrality determination and anisotropic flow measurements for the CBM experiment at FAIR and MPD experiments at NICA were developed and tested. The performance for the flow measurement of protons, charged-pions and kaons were investigated with the existing heavy-ion event generators. Based on the comparison of the results obtained for the reconstructed and generated signals, it was concluded that the CBM and MPD setups will be capable of the precise differential measurements of directed and elliptic flow of charged hadrons. Results were presented at major international conferences and workshops as well as semi-internally during the CBM/FAIR and NICA collaboration meetings. A series of international workshops aimed at promoting scientific exchange and development of novel ideas in the area of common software packages for simulation, data analysis, and physics performance studies at future FAIR and NICA facilities have been organized.

After a significant reformulation of the project, which led to the project renaming to EURIZON in 2022, physics performance studies were continued with the singular focus on CBM and preparation of software for real-time selection of rare physics signals during the 2022-2024 data taking for the mCBM demonstrator experiment.

The progress includes new physics performance study for directed flow measurement at CBM of strange hyperons for different SIS100 beam momenta. The mCBM implementation of unpackers to translate messages into a universal format and their treatment per timeslice for the STS, MUCH, RICH, TOF, BMON, and TRD subsystems. The time-cluster trigger and the time-window event-builder algorithms were finalized. The work to maintain the geometry implementation in GEANT in line with the evolving technical design of CBM experiment in its various configurations, which required physics performance studies, has been completed. Updated CBM setup, including frequently changing mCBM material maps, are deployed via CBMROOT software releases. As a joint activity together with WP2.5, a Monte-Carlo performance study with the new CBM Forward Spectator Detector (FSD), which will detect projectile spectator fragments for the determination of the collision centrality and the reaction plane, has been continued. The full FSD simulation chain, including GEANT geometry and digitizers, were implemented in the CBMROOT software release. Predictions for the single and double-strange hypernuclei production in heavy-ion collisions at the CBM collision energies using Boltzmann-Uehling-Uhlenbeck (BUU) model with off-shell transport and coalescence at the final stage are made available and integrated into the CBM framework for physics performance studies. The BUU model calculations include many resonances, momentum dependent mean field, Coulomb effects on charged particle production, Pauli exclusion and off-shell propagation.

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2. Performance studies for the CBM experiment at FAIR

2.1 Online software for the mCBM experiment

The development of online software to select rare physics signals in real-time from the raw data stream was prompted by the data taking campaign of the mCBM demonstrator experiment (see Fig. 2.1a) in 2022-2024.

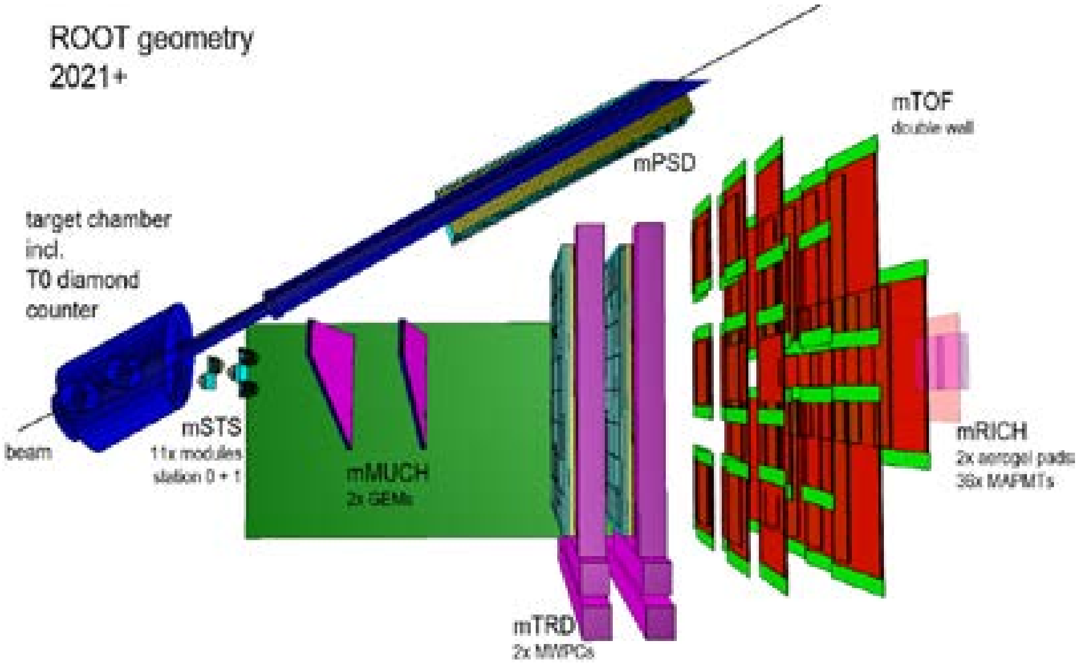

Fig. 2.1a Geometry of the mCBM experiment as implemented in the GEANT simulations.

The progress includes implementation of an online-capable trigger algorithm, event builder and selector, new unpackers for different detector subsystems, an optimized TOF hits reconstruction algorithm, and integration of a multicore parallelization scheme. The TOF hit reconstruction algorithm is production ready with calculation speed improved from $O(N^3)$ to $O(N^{1.2})$ (see Fig. 2.1b).

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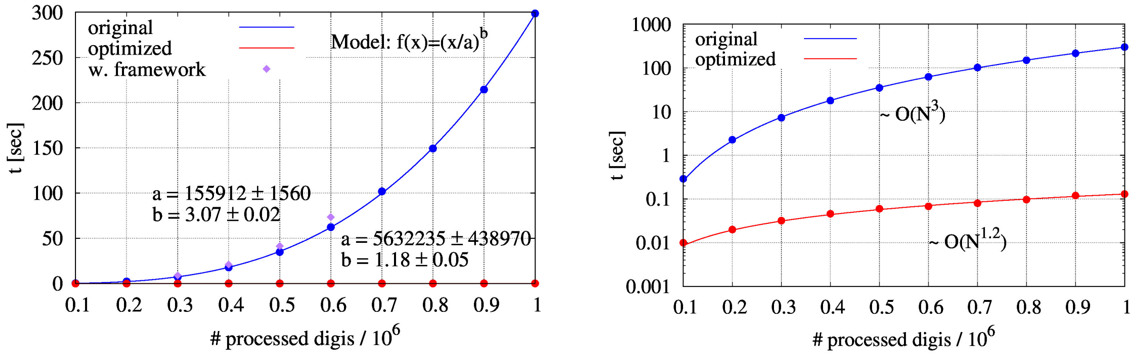

Fig. 2.1b Online performance of the TOF hit reconstruction algorithm.

2.2 Development of the GEANT4 geometry for studies of major physics observables

The CBM geometry implementation in GEANT4 was put in line with the engineering CAD design (see Fig. 2.2a), which improved accuracy of the Monte-Carlo simulations for physics performance studies.

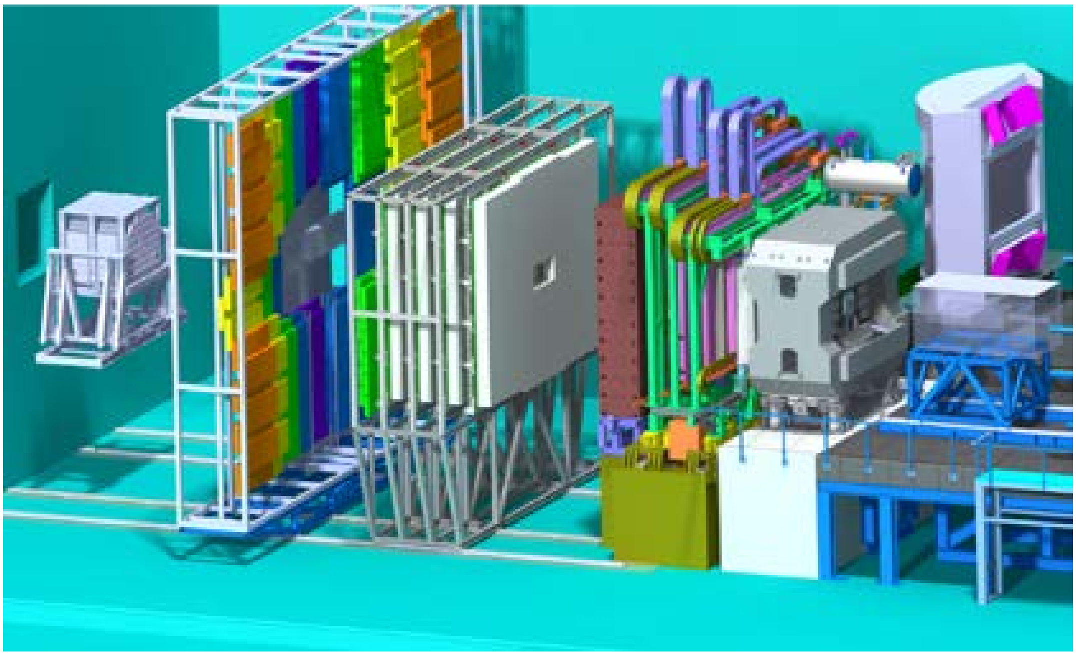

Fig. 2.2a Engineering (CAD) drawing of the CBM experiment.

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The consistent integration of the geometries was achieved by coordinated work between CBM detector subsystems and Software and Simulation development teams. Many improvements were made in GEANT to describe CBM subsystem geometries and passive materials (see. Fig. 2.3a, left). Different CBM setup configurations are deployed and made centrally available to the CBM Collaboration via CBMROOT software release. The newly developed ROOT macros were used to extract from GEANT the three dimensional maps of the CBM detector material budget and made them available to the Cellular Automaton tracking algorithm in CBM. Several automated validation procedures (Continuous Integration in Gitlab) of the new geometries, including frequently updated mCBM material budget maps, has been established. A set of new CBM magnet geometries and corresponding magnetic field maps (see Fig. 2.2b, right) which corresponds to the new design of the CBM magnet and modular STS geometry developed within WP2.1, and optionally includes the magnet clamps, RICH shielding box, or iron absorbers of MUCH subsystem, is made available via CBMROOT software release.

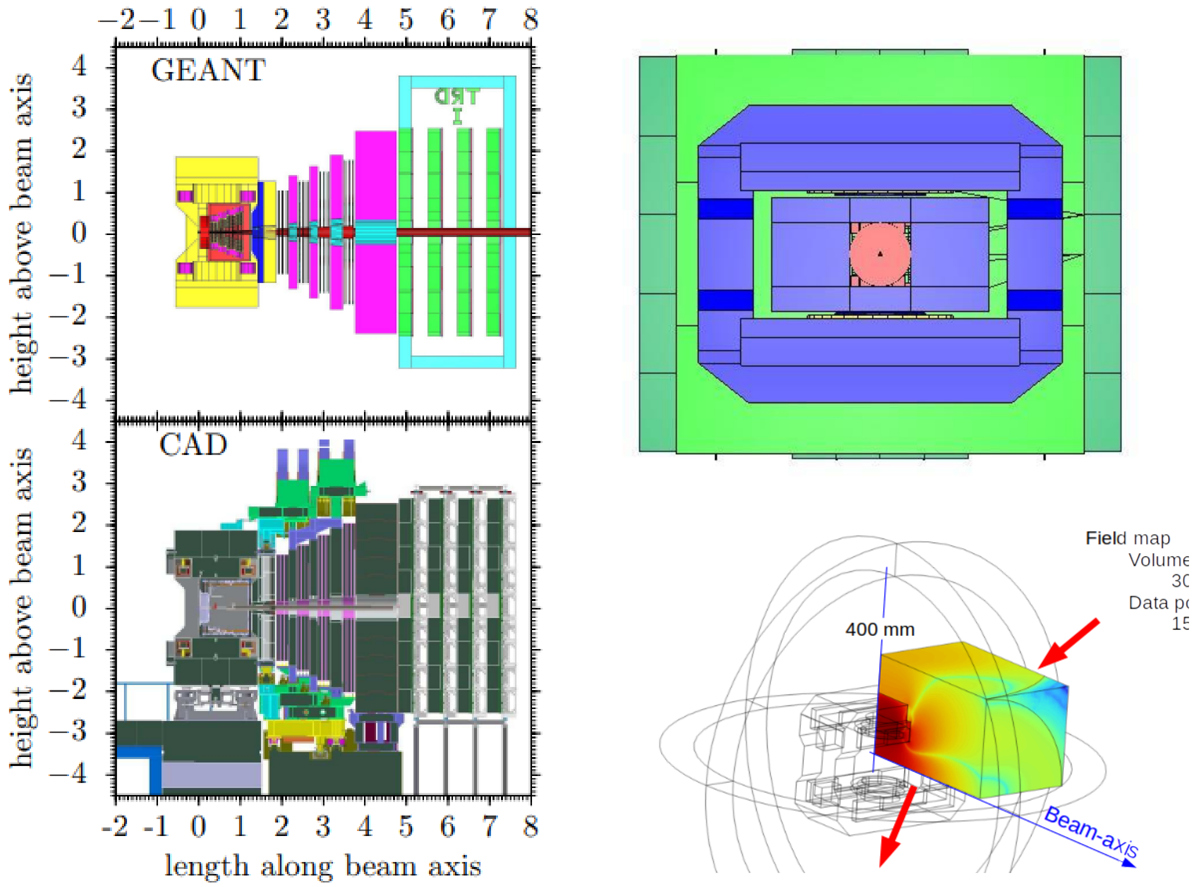

Fig. 2.2b: CBM geometry as implemented in the (upper left) the GEANT framework used for physics performance studies with Monte-Carlo simulations and (lower left) engineering CAD model (upper left). New (upper right) magnet geometry and (lower right) magnetic field map.

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Using the GEANT4 simulation of the CBM detector response, the CBM acceptance and reconstruction efficiency for Λ, K_S^0 and Ξ^- as a function of transverse momentum and rapidity were obtained different collision energies achievable with the SIS-100 accelerator (see Fig. 2.2c and Fig. 2.2d).

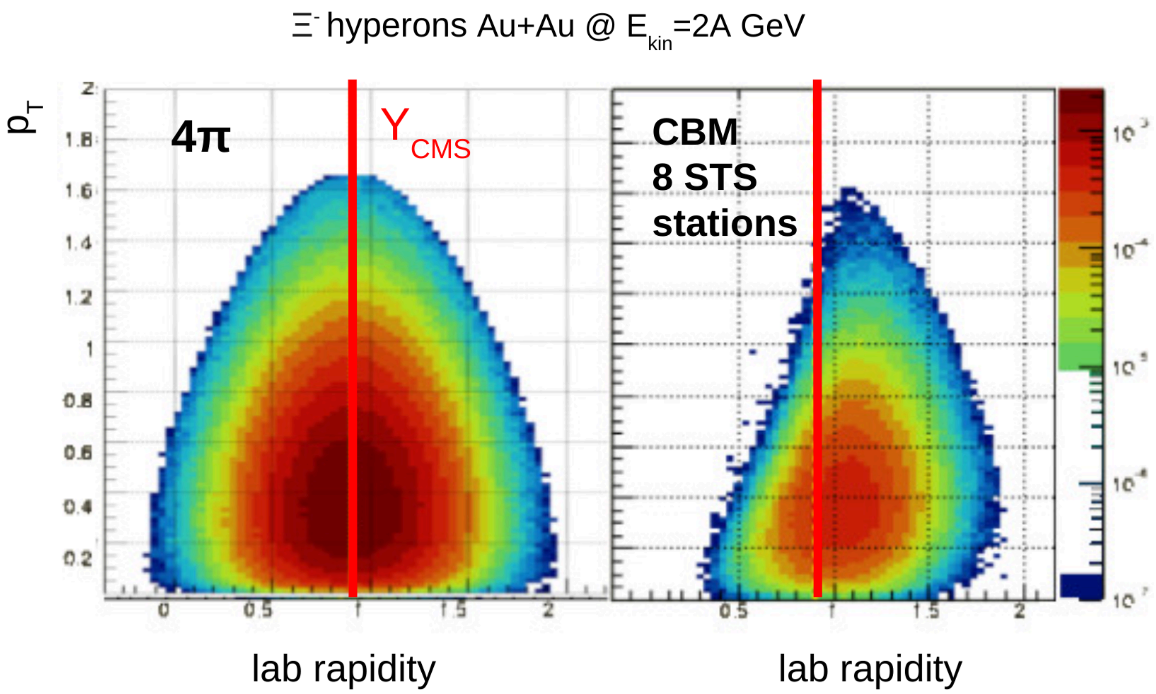

Fig. 2.2c: Full kinematic phase space (left) and CBM acceptance (right) for Ξ^- baryons using the new STS geometry design developed in WP2.1.

Using PFSimple decay reconstruction package, configured for selection of decay candidates with high signal-to-background ratio (5 for Λ, 2 for K_S^0 , 15 for Ξ^-), it was demonstrated that the CBM acceptance covers both midrapidity and forward rapidity $0 < y < 1$ regions in transverse momentum range $0 < p_T < 1.5$ GeV/*c* (see Fig. 2.3d). The acceptance coverage for backward rapidity depends on the collision energy and is the largest at $\sqrt{s_{NN}} = 4.9$ GeV. Coverage of mid- and forward-rapidity is necessary for collective flow measurements, in particular for extraction of the slope dv_1/dy and offset v_1 at $y = 0$. Coverage of the backward-rapidity region allows to reduce systematic uncertainties in directed flow measurement caused by correlations due to global momentum conservation, using the anti-symmetry of v_1 as a function of rapidity. Reconstruction efficiency reaches values up to 50% for Λ and K_S^0 , and up to 20% for Ξ^- in the whole range of SIS-100 collision energy range. At $\sqrt{s_{NN}} = 4.9$ GeV the maximum of reconstruction efficiency is located near midrapidity, while at $\sqrt{s_{NN}} = 2.9$ GeV the maximum is shifted to forward rapidities ($y \approx 1$). At $\sqrt{s_{NN}} = 2.9$ GeV the reconstruction efficiency at midrapidity and backward rapidity is low ($\lesssim 10\%$), especially for $p_T > 0.5$ GeV/*c*.

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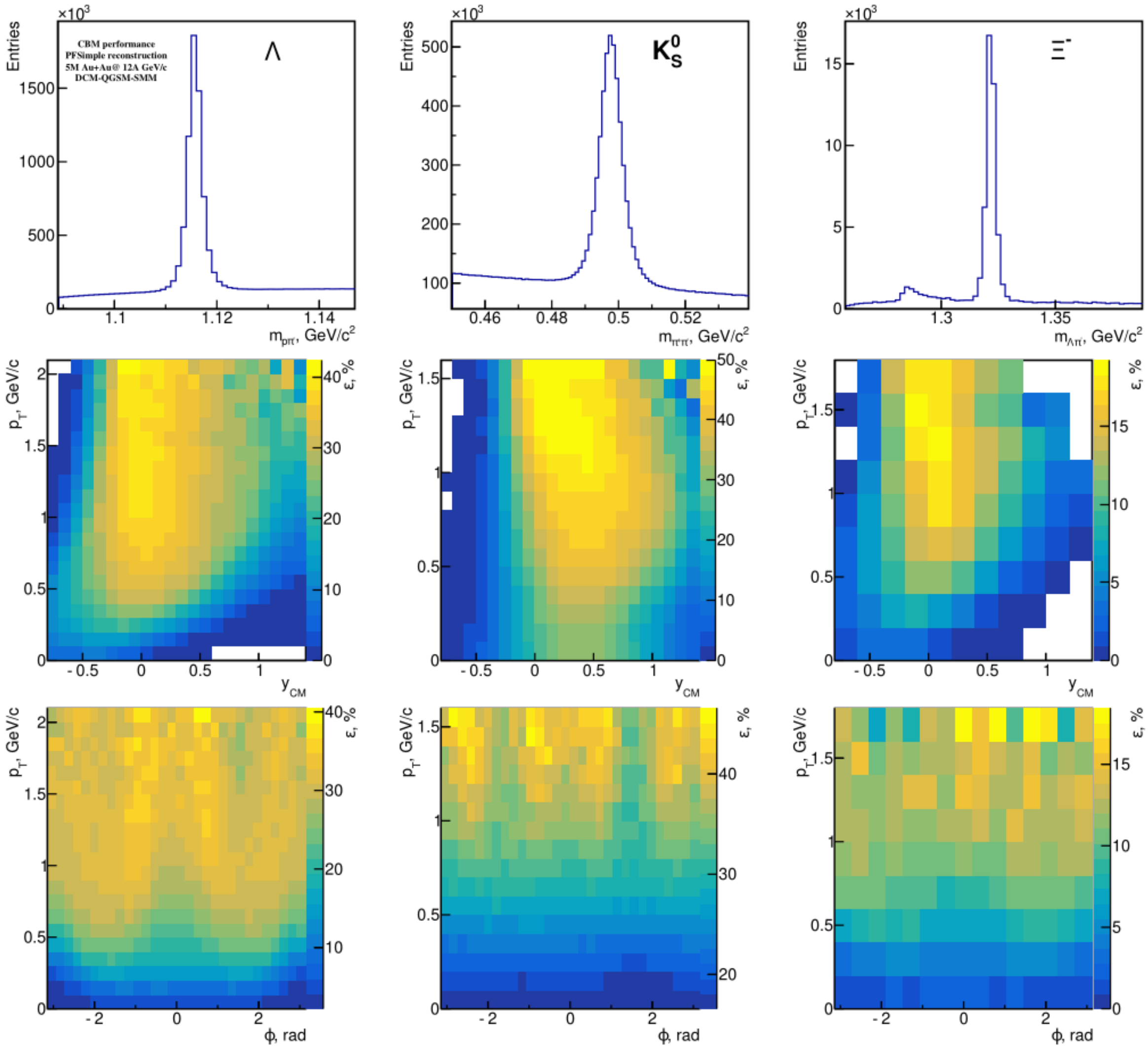

Fig. 2.2d: Performance of the Λ, K_S^0 and Ξ⁻ reconstruction (upper panels) and multi-differential acceptance (middle and bottom panels) of the CBM for top SIS100 beam momentum.

2.3 New FSD detector for reaction plane determination in collective flow measurements

As a joint activity together with the redefined scope of WP2.5, a Monte-Carlo performance study for the design of a new CBM Forward Spectator Detector (FSD) has been performed. The new FSD detector will allow detection of the projectile spectator fragments in the beam momentum range of 3.3−12 *A*GeV/*c*, which is required for the determination of the collision reaction plane with an accuracy better than 40 degrees and the collision centrality with an accuracy better than 10%. A software implementation of the FSD within the CBMROOT software (see Fig. 2.3a(left)) and a test sample of Monte-Carlo simulations using the DCM-QGSM-SMM model with spectator fragments and GEANT4 transport are prepared.

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In order to measure anisotropic flow coefficients one needs to estimate the reaction plane of the collision, which is spanned by beam axis and impact parameter vector. It is done using nucleons not participating in the collision (spectators), registered with the Projectile Spectators Detector (PSD), which will be replaced after the FSD design studies are complete. Imperfections in the reaction plane estimation are taken into account by the resolution correction factor Figure 2.3a(right) shows the R_1 for the case of the PSD submodules calculated as a function of centrality for top SIS100 beam momentum (see), evaluated using three- and four-subevents methods. These results serve as a benchmark for the new studies of the FSD detector.

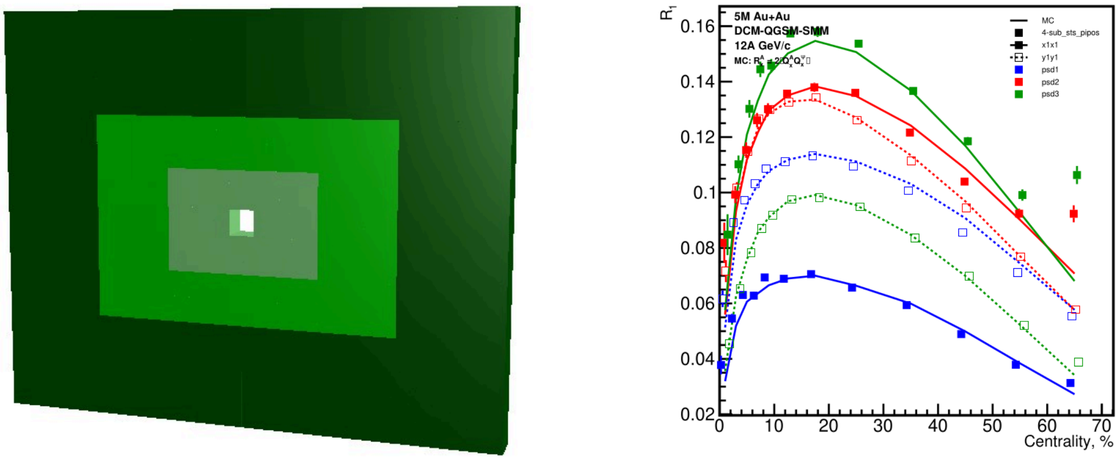

Fig. 2.3a: (left) GEANT implementation of the FSD geometry inspired by the design of the HADES Forward Wall detector. (right) Resolution correction factor of the PSD, which serves as a benchmark for the new studies of the FSD detector, calculated as a function of centrality for top SIS100 beam momentum.

Produced particles and their decay products entering the acceptance of the PSD or FSD bias the measured value of flow. Spread of hadronic shower in the PSD calorimeter in transverse to the beam direction results in spurious correlations between particles used in the subevents methods. Azimuthal non-uniformity of the reconstruction efficiency and effects of magnetic field have to be corrected for. Magnitudes of corrections for azimuthal non-uniformity in decay reconstruction are of the order of a few percent. The corrections for the PSD/FSD non-uniformities are of the order of several percents in the direction perpendicular to the CBM magnetic field and one order of magnitude less for the direction along it. Combinatorial background contribution to collective flow of Λ, K_S^0 and Ξ^- is subtracted with invariant mass fit method, which is implemented within the QnTools software package.

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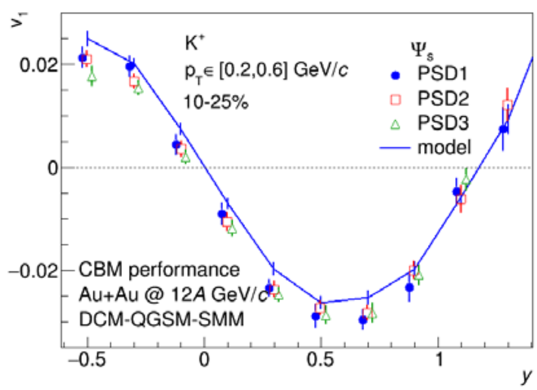
2.4 Performance for anisotropic flow measurement in the CBM experiment

The Compressed Baryonic Matter (CBM) experiment at the Facility of Antiproton and Ion Research (FAIR) will perform heavy-ion collisions at $\sqrt{s_{NN}}$ =2.9−4.9 GeV. Multi-differential measurements of yields and collective flow of rarely produced multi-strange hadrons will become available with CBM thanks to its operation at the peak interaction rate of 10^7 Hz.

Anisotropic flow coefficients are calculated by correlating azimuthal angles of particles whose flow is measured and particles in the PSD or FSD acceptance used for reaction plane estimation, which are reconstructed in different kinematic regions. Azimuthal correlations can originate not only due to common anisotropy with respect to the reaction plane but also due to other physics phenomena and detector effects such as: (a) short-range correlations and resonance decays (non-flow); (b) global transverse momentum conservation; (c) event-by-event fluctuations in nucleon positions (flow fluctuations); (d) Auto-correlations imposed by the same particle (or particle and its decay product) traversing acceptance of multiple CBM subsystems; (e) Transverse spread of hadronic showers across multiple modules of the PSD calorimeter or FSD scintillator tiles.

Figure 2.4a(left) shows the rapidity dependence of directed flow for positively charged kaons. Results are shown for the flow of generator-level particles calculated relative to the true reaction plane (blue line) and wrt. spectator symmetry plane estimated from different PSD subevents. It can be seen that additional correlations arise if the spectator plane is estimated using signals from outer PSD modules (PSD2 and PSD3 subevents) which are contaminated by the signal from produced particles. Figure 2.4a(right) presents the rapidity dependence of directed flow calculated relative to the true reaction plane for the tracks matched to generator-level positively charged kaons and tracks identified as kaons using CBM time-of-flight detector.



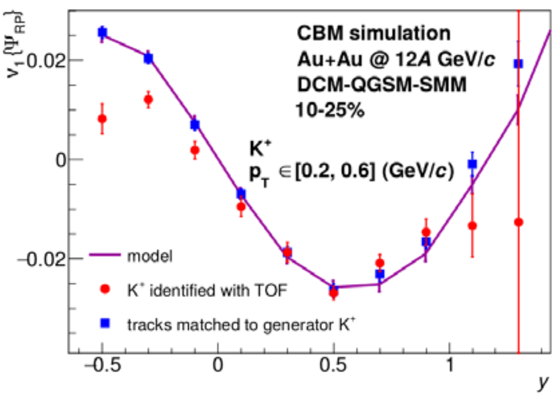


Fig. 2.4a CBM performance for directed flow measurement of positively charged kaons as a function of centrality for top beam momentum of SIS-100 accelerator at FAIR.

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Using the GEANT4 simulation of the CBM detector response, the directed flow slope at midrapidity (dv_1/dy) for Λ, K_S^0 and Ξ^- was studies as a function of transverse momentum and rapidity at the highest (4.9 GeV) and lowest (2.9 GeV) collision energies achievable with the SIS-100 accelerator (see Fig. *Fig. 2.4b*).

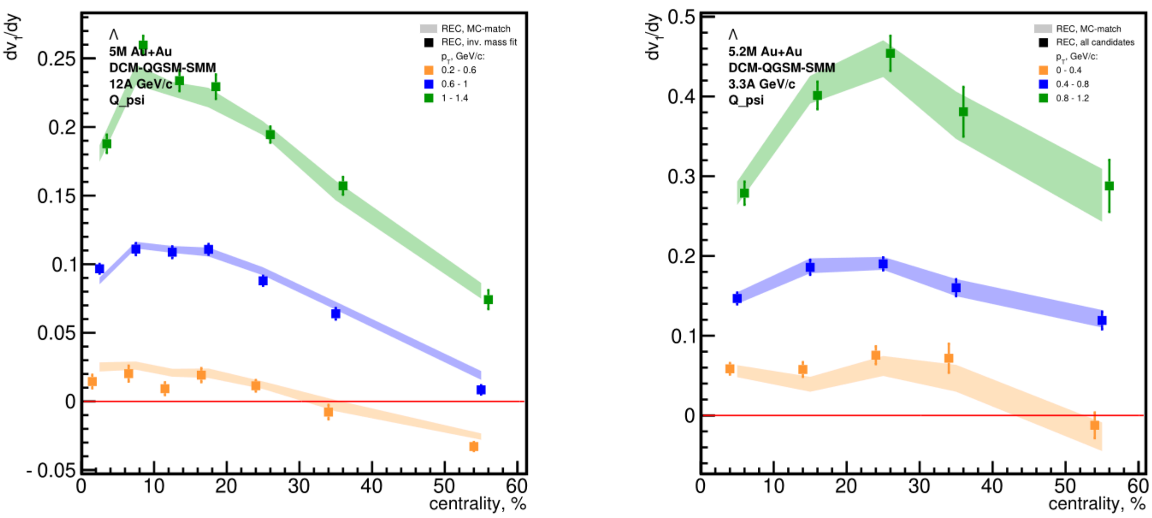

Fig. 2.4b CBM performance for directed flow measurement of Λ hyperons as a function of centrality highest (4.9 GeV) and lowest (2.9 GeV) collision energies of SIS-100 accelerator at FAIR.

Statistical uncertainties of (multi-)strange hadrons directed flow slope dv_1/dy are estimated for the expected first CBM data taking period (2×10^{10} events) both for the lowest and the highest SIS-100 collision energies. The measurement of dv_1/dy of Λ at $\sqrt{s_{NN}} = 2.9$ GeV requires 10^{12} collisions. The relative error will be of order 25% that will allow CBM to perform an energy scan of dv_1/dy of (multi-)strange hadrons, and provide experimental data to discriminate between models implementing EoS with and without first order phase transition. The measurements of the particle-antiparticle difference of directed flow will be possible, which are needed to quantify the magnitude and evolution of the magnetic field in a heavy-ion collision.

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2.4 New approach for single and double-strange hypernuclei production in heavy-ion collisions

A new approach for coalescence, in which the elastic hadronic cross sections determine the interaction among participants and the coalescence time (the only free parameter) is fixed by FOPI data for charged fragments, was developed. Predictions for the single and double-strange hypernuclei production in heavy-ion collisions at the CBM collision energies of few AGeV using Boltzmann-Uehling-Uhlenbeck (BUU) model with off-shell transport and coalescence at the final stage are made available (see Fig. 2.4a) and integrated with the CBMROOT simulations.

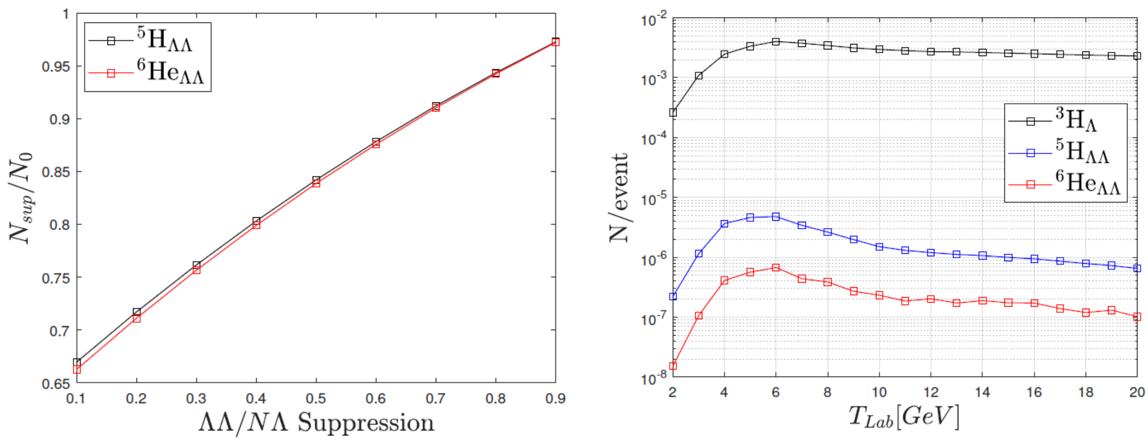

Fig. 2.4a: Predictions for the Hypernuclei production in 0-10% central Au+Au collisions vs. (left) ΛΛ interaction strength and (right) kinetic mean energy. Calculations are from the Boltzmann-Uehling-Uhlenbeck (BUU) model with off-shell transport and coalescence at the final stage.

The BUU model calculations include hadronic degrees of freedom with many resonances, momentum dependent mean field for baryons, Coulomb effects on charged particle production, effects due to Pauli exclusion and off-shell propagation.

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