Software and Layout Optimization of HIRFL-CSR External-target Experiment

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Abstract

Heavy-ion collisions (HICs) is a unique experimental tool for investigating properties of nuclear matter under extreme conditions in the laboratory. At HIRFL-CSR energies, HICs can create nuclear matter with 2-3 times the saturation density (ρ_0). HIRFL-CSR External-target Experiment (CEE) is a large-acceptance spectrometer designed for exploring frontier topics of high-energy nuclear physics, such as QCD phase structure, nuclear matter equation of state and so on. In this letter, simulation and analysis software for the CEE experiment (CeeROOT) is introduced. Based on the CEE conceptual design and the CeeROOT software, configurations of its sub-detectors are optimized with considering foreseeable physical constrains. The final detector layout of the CEE spectrometer and its acceptances are validated through simulations of U+U collision at 500 MeV/u and pp collisions at 2.8 GeV, which demonstrates that the CEE experiment will serve as a detector with wide acceptance and multi-particle identification capabilities for studying high-energy nuclear physics topics at HIRFL-CSR energies with pp, pA and AA collisions.

Full Text

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Heavy-ion collisions (HICs) represent a unique experimental tool for investigating the properties of nuclear matter under extreme conditions in the laboratory. At HIRFL-CSR energies, HICs can create nuclear matter with densities 2–3 times the saturation density ($_0$). The HIRFL-CSR External-target Experiment (CEE) is a large-acceptance spectrometer designed to explore frontier topics in high-energy nuclear physics, such as QCD phase structure and the nuclear matter equation of state. In this paper, we introduce the simulation and analysis software for the CEE experiment (CeeROOT). Based on the CEE conceptual design and the CeeROOT software, we optimize the configurations of its sub-detectors while considering foreseeable physical constraints. The final detector layout of the CEE spectrometer and its acceptances are validated through simulations of U+U collisions at 500 MeV/u and pp collisions at 2.8 GeV, demonstrating that the CEE experiment will serve as a detector with wide acceptance and multi-particle identification capabilities for studying high-energy nuclear physics topics at HIRFL-CSR energies through pp, pA, and AA collisions.

Keywords: CEE Experiment, Simulation Software, Optimization, HIRFL-CSR

Introduction

Heavy-ion collisions (HICs) provide a unique tool to create hot and dense nuclear matter in the laboratory [1], enabling the study of bulk properties of nuclear matter under extreme conditions, such as Quantum Chromodynamics (QCD) phase structure [2-6] and the equation of state (EoS) [7-9]. The Heavy Ion Research Facility at Lanzhou-Cooling Storage Ring (HIRFL-CSR) can provide heavy-ion beams with kinetic energies up to 1.1 GeV/u for ^{12}C beams, while the maximum kinetic energy is 500 MeV/u for ^{238}U^{74+} beams and 2.8 GeV for proton beams [10].

In HICs at HIRFL-CSR energies, nuclear matter with densities of 2-3 $_0$ and temperatures of 40 MeV can be created [11, 12], forming what is known as a "fireball." The CSR External-target Experiment (CEE) is a large-acceptance spectrometer [13] designed to explore the properties of nuclear matter using heavy-ion and proton beams provided by the HIRFL-CSR accelerator [14].

Net-baryon high-order cumulants are predicted to be sensitive observables for probing QCD critical points [15, 16]. The CEE experiment will precisely measure proton high-order cumulants in 500 MeV/u U+U collisions corresponding to √s_{NN} = 2.14 GeV, which will provide strong constraints on fluctuation behavior in the pure hadronic phase. As indicated by recent STAR flow measurements, nuclear matter created at √s_{NN} ≤ 3 GeV is dominated by hadronic matter [17]. Currently, the lowest collision energy proton high-order cumulants at √s_{NN} = 2.4 GeV were provided by the HADES experiment in Au+Au collisions with relatively large uncertainties [18].

Properties of the EoS in the high-density region $> 2\ _0$, particularly the symmetry energy E_{sym} related to isospin asymmetry δ = (_n − _p)/(_n + _p) (where _p is proton density and _n is neutron density), are crucial for understanding QCD theory and other important phenomena such as the inner structure of neutron stars, neutron star mergers, HIC dynamics, and more [19-21]. Since ^{238}U is the naturally occurring nucleus with the largest isospin asymmetry, the fireball created in ^{238}U+^{238}U collisions at HIRFL-CSR energies is predicted to be an ideal environment for investigating the behavior of E_{sym} in the density region $> 2\ _0$ [20]. Other topics in the high-baryon density region, such as sub-threshold strangeness production [22], cluster formation mechanisms [23], short-range correlations [24], and hypernuclear physics [25], can also be investigated by the CEE experiment.

The CEE conceptual design was described in Ref. [13], including a superconducting dipole magnet, a time projection chamber (TPC) [26], an inner time-of-flight detector (iTOF) [27], a multi-wire drift chamber array (MWDC) [28-30], an external time-of-flight detector (eTOF) [31], a zero-degree calorimeter (ZDC) [32], and a beam monitoring detector [33]. The TPC and MWDC are tracking detectors covering the backward and forward regions, respectively, designed to measure trajectories and energy loss (dE/dx) of charged particles. By correlating reconstructed momentum and dE/dx, light charged particles such as $\pi\pm$, p, d, t, ^{3}He, and ^{4}He can be identified. The iTOF covers the left, right, and bottom sides of the TPC, while the eTOF can accept charged particles that pass through the MWDC. By combining momentum measured by the TPC (or MWDC) and time-of-flight measured by the iTOF (or eTOF), charged particles can be further identified, especially those with high momenta. The ZDC is designed to determine the reaction plane of heavy-ion collision events on an event-by-event basis [34].

In transitioning from conceptual design to technical design of the CEE spectrometer, foreseeable physical constraints existing in actual experiments must be addressed to ensure fair performance of the CEE detection system. For instance, background and side effects from the primary beam on the CEE sub-detectors require careful consideration. Reactions between the beam and detector frames should be avoided. The sub-detectors' acceptance should be optimized to its theoretical limit without increasing the budget. Such constraints need to be considered in the final design of the CEE spectrometer.

This paper is organized as follows: In Sec. II, we introduce a simulation and analysis software package for the CEE experiment called CeeROOT. In Sec. III, we describe the CEE layout optimization for each sub-detector and their acceptances after optimization. In Sec. IV, we discuss the acceptance for the reaction pp→pK$^+$+Λ at 2.8 GeV. The final part provides a summary including the current construction status and future physics program of the CEE experiment.

II. Simulation and Analysis Software of the CEE Experiment

Simulation software is an essential component of modern particle and nuclear physics experiments for detector configuration optimization, physics feasibility studies, efficiency evaluation, and more. The CeeROOT package is established based on the FairSoft package and the FairROOT platform [35]. FairSoft is a collection of open-source software with well-tested compatibility across various operating systems. FairROOT is a general simulation and analysis framework for nuclear and particle physics experiments, which defines general rules for detector geometry, particle definition, interfaces for various particle propagation engines, input/output (I/O) rules, event display interface, runtime database, and more. With the same detector configuration, detector responses can be simulated with Geant3 [36] or Geant4 [37], which are widely used Monte Carlo (MC) packages for simulating interactions between particles and materials.

The CeeROOT is a FairROOT realization for the CEE experiment. In general, CeeROOT includes detector geometry for all CEE sub-detectors, event generators, magnetic field, digitization, calibration software, tracking software, and event reconstruction software. In the simulation, interactions of particles generated by various event generators (see Section II A) and detectors are simulated by the Geant package. Information left by particles inside the sensitive volume of detectors is further digitized according to their specific detection mechanisms. After digitization, MC data are stored in a predefined format that is also used for experimental data. This enables the software to handle both MC data and experimental data in subsequent steps of calibration, reconstruction, and analysis. The flow chart of CEE simulation and data analysis is illustrated in Fig.

1 [Figure 1: see original paper]. In the CeeROOT package, a fast simulation is also developed for evaluating detector performance and physics feasibility studies by parameterizing the performance of all sub-detectors. In the following subsections, basic components of the CeeROOT package are introduced briefly.

A. Event Generator

The event generator, as illustrated in Fig. 1, is a basic component for defining input particle species and their initial coordinate and momentum distributions. Besides simple event generators like the box generator (flat phase space distribution), simulation data from several transport models such as UrQMD [38], GiBUU [39], PHSD [40], AMD [41], IQMD [42], JAM [43], LQMD [44], and PLUTO [45] are also supported. Table 1 shows the currently supported event generators in CeeROOT. Besides particles listed in the particle data book [46], ions with different charge states can also be defined, which allows one to simulate trajectories and responses of ions with different charge states in the CEE spectrometer.

B. Magnetic Field

The CEE spectrometer employs a superconducting dipole magnet for deflecting charged particles. By measuring trajectories of charged particles in a magnetic field, their momenta can be reconstructed. The height, width, and length of the available space inside the magnet are 1.6 m, 3.2 m, and 3.4 m, respectively. The coordinate origin of the CEE spectrometer is defined at the center of the magnet, with the TPC center placed at this location. The designed magnetic field strength is 0.5 T with uniformity better than $±$2.5% in the sensitive volume of the TPC. Since it is a dipole magnet, the magnetic field varies toward both entrances. The magnetic field of the CEE magnet is described by grid data including six variables: (x, y, z, Bx, By, Bz), where (x, y, z) are spatial coordinates and (Bx, By, Bz) is the corresponding magnetic field vector. The positive Z-axis direction represents the beam direction, while the X and Y axes complete a right-handed Cartesian coordinate system. The By field map at the y = 0 cm plane is shown in Fig. 2 Figure 2: see original paper. Fig. 2(b) shows the absolute value of By along the Z-axis; the shielding region indicates a magnetic field shield pipe, and the dip around z = -320 cm corresponds to a regulation dipole magnet. The reasons for needing these two additional components are discussed in Sec. III B. In Geant simulation, charged particles are propagated in fine steps, where magnetic field data is required for propagating the particle to the next spatial point. The magnetic field vector at any spatial point is obtained through linear extrapolation using the grid data.

In the simulation, magnetic field data were provided by magnet design software. The magnetic field of the CEE magnet will be measured when the magnet reaches its working condition, after which the measured grid data will be used for simulation as well as track reconstruction of experimental data.

III. Layout Optimization of the CEE Spectrometer

In the CEE detector layout optimization, the detector components and types adopted in the conceptual design are retained. Physical constraints for each subdetector are discussed. To avoid foreseeable drawbacks, the optimized detector configuration and optimization results are presented in the following subsections.

A. TPC Layout Optimization

The TPC of the CEE spectrometer is designed to measure energy loss and trajectories of light charged particles such as $\pi\pm$, K±, p, d, t, ^{3}He, and ^{4}He. In the conceptual design, heavy-ion beams such as ^{238}U were allowed to pass through the TPC drift volume. It was expected that tremendous ionization would be induced by the heavy-ion beam in the drift volume of the TPC, causing two major issues: (1) TPC electronics would be continuously saturated along the beam path, and (2) ionization left by the beam would cause huge space charge accumulation, which could distort the drifting electric field of the TPC. These effects not only create difficulties for tracking charged particles in the region along the beam path but could also potentially damage the TPC readout electronics. To avoid these effects, the TPC is divided into two parts, with a vertical gap left between them to exclude the spatial region where the beam passes through. Obviously, the width of the gap is related to the deflection distance of the beam in the x-direction, which depends on the ion type, energy, and charge state of the beam particle. The narrower the air gap, the greater the acceptance of the detector.

To reduce the deflection effect of the beam, a magnetic shielding pipe and a small regulation magnet are added in front of the TPC, as shown in Fig. 2. Eventually, it proves that a gap with a width of \$±\$7.5 cm is sufficient for all types of beams provided by HIRFL-CSR. The active volumes of the two TPCs cover the range 10 cm < |x| < 60 cm, height -40 cm < y < 40 cm, and length in the z direction -45 cm < z < 45 cm. Based on this TPC geometry configuration, TPC acceptances at different emission positions along the beam axis are evaluated using U+U collisions generated by the JAM model. It turns out that TPC acceptance for $\pi\pm$ reaches its maximum when the initial emission position is at (0, 0, -35) cm. Consequently, this position has been designated as the target position of the CEE experiment. Fig. 3 [Figure 3: see original paper] shows the transverse momentum (p_T) and rapidity (y) acceptance of the TPC for protons (left panel) and π^+ (right panel) in U+U collisions at 500 MeV/u simulated by the JAM model in most central collisions. The criterion for accepting a charged particle in the TPC is that its track length in the TPC active volume should exceed 15 cm. The TPC covers a polar angle range of 5° to 120° in the laboratory frame. However, the TPC has an acceptance deficiency in the azimuthal direction around 90° and 270° due to the existence of the vertical gap. For the future CEE experiment, this coverage loss needs to be corrected according to the TPC acceptance for each particle species.

Fig. 4 [Figure 4: see original paper] (a), (b), and (c) show simulated beam paths of $^{12}C^{6+}$ at 400 and 1000 MeV/u, and $^{238}U^{90+}$ at 500 MeV/u in the x-z plane, respectively. In each panel, the solid line with vertical bars presents the center of the simulated beam, vertical bars represent σ of the beam spatial spread in the x-axis, and dashed lines mark the 5σ position spread of the beam along the x-axis. The TPC detector frame and the target are also depicted in the figure. Under the current design, all these considered beams can pass through the gap without hitting the TPC detector frame. To accommodate different beams, downstream sub-detectors (i.e., eTOF, ZDC) are installed on rails parallel to the x-axis, respectively.

B. Beam Path Simulation and Magnetic Shield Pipe

To prevent the beam from hitting the detector frame, the beam path serves as a major geometrical reference for optimizing the air gap of the TPC and placing downstream detectors such as the third MWDC, eTOF, and ZDC. The typical beams to be used in the CEE experiment are $^{12}C^{6+}$ at 400/1000 MeV/u and $^{238}U^{74+}$ at 500 MeV/u. Before the heavy-ion beam reaches the target, it passes through a Ti foil with a thickness of 30 µm for sealing the vacuum pipe and then propagates through air for more than 1 m. The charge state of light ion beams such as $^{12}C^{6+}$ would not change, but the heavy-ion beam $^{238}U^{74+}$ would transform to uranium ions with charge states around 90, i.e., $^{238}U^{90+}$, according to calculations using the ETACHA4 code [47]. Thus, $^{238}U^{90+}$ ions are used for beam path simulation instead of the original $^{238}U^{74+}$ beam ions.

As discussed in the previous subsection, minimizing the deflection effect for beams is crucial for narrowing the gap width of the TPC, thereby increasing its geometrical acceptance. To achieve this goal, a small dipole magnet and a magnetic shield pipe have been added upstream. The polarity of the small dipole magnet is opposite to that of the CEE magnet, as illustrated in Fig. 2. This configuration induces a position offset for the beam, which partially counteracts the deflection effect caused by the CEE magnet. The shielding pipe spans from -290 cm to -80 cm, as illustrated in Fig. 2. Beam paths for $^{12}C^{6+}$ at 400 and 1000 MeV, and $^{238}U^{90+}$ at 500 MeV/u are simulated including the regulation magnet, shield pipe, and CEE magnet. To account for energy loss of the beam in air, the medium in the simulation is set to air. Initial spatial and momentum distributions at the plane z = -400 cm are set to Gaussian distributions with position divergence σ__x = σ__y = 0.15 cm and relative momentum divergence ΔP__x/y/P = 0.1%, respectively, which are typical spatial and momentum spreads of heavy beams at the CEE experimental hall.

C. MWDC and eTOF Layout Optimization

In the conceptual design, MWDC and eTOF are placed outside the magnet in a two-arm detector configuration, meaning that charged particles emitted in the forward region cannot be fully covered by the MWDC-eTOF sub-detectors. To increase forward angle acceptance, two MWDCs are placed inside the magnet after the TPC, while the third MWDC is placed outside the magnet, covering the downstream entrance of the magnet almost fully. The eTOF is placed after the third MWDC. The active area of eTOF is designed to contain all charged particles that pass through all three MWDCs. To prevent the beam from hitting the detector frames of MWDC and eTOF, both have inactive regions in the middle. Fig. 5 [Figure 5: see original paper] shows the acceptance of MWDC and eTOF in polar angle ( ) and azimuthal angle ( ) for protons in U+U collisions at 500 MeV/u simulated by the JAM model. The MWDC-eTOF system covers a polar angle range of 5° < < 15° and azimuthal angle of 0° < < 360°. Due to the rectangular shape of the MWDCs and eTOF detectors, particles emitted at large polar angles can also be contained. The TPC acceptance for protons in the same collision system is also shown in Fig. 5, depicted by contour lines. One can see that there are overlapping acceptance regions between TPC and MWDC, which can be used for cross-calibration of the tracking detectors.

D. ZDC Detector Optimization

The ZDC is primarily designed to measure the event plane of HICs, and its hit multiplicity also helps determine the collision centrality [34, 48]. In the conceptual design, the ZDC was designed as a calorimetric-type detector placed downstream for measuring the energy and position of heavy fragments emitted at small polar angles. Considering that the energy resolution of hadronic calorimeters at HIRFL-CSR energies is difficult to achieve with high precision, the ZDC has been redesigned to measure energy loss and hit position of particles emitted in the forward region. This design has been successfully used by other experiments such as the FOPI experiment [49] and the STAR experiment [50].

In the new design, the ZDC is a plastic scintillator disc with inner and outer radii of 5 cm and 100 cm, respectively. The ZDC is divided into 8 rings, with each ring containing 24 sectors, for a total of 192 plastic scintillator modules. The ZDC is placed just after the eTOF. As mentioned above, to accommodate different beams, the ZDC is installed on a horizontal rail, and its position along the x-axis can be adjusted. An event plane reconstruction algorithm based on the ZDC has been developed, and it shows excellent reaction plane resolution based on simulated data [34].

E. Final Detector Configuration and Technical Design

Finally, the optimized detector configuration of the CEE experiment is accomplished, as shown in Fig. 6 [Figure 6: see original paper]. Based on this optimized configuration, the technical design of the CEE spectrometer is achieved, considering realistic detector frames and their geometry compatibilities, as shown in Fig. 7 [Figure 7: see original paper]. As mentioned above, (0, 0, -35) cm is the nominal target position of the CEE experiment, located in the TPC air gap. The designed reaction rate of the CEE experiment reaches up to 10 kHz for heavy-ion collisions such as U+U collisions.

Typical momentum resolution and TOF time resolution of the CEE experiment are 5% and < 80 ps, respectively. According to fast simulation [14], charged particles such as $\pi\pm$, p, d, t, ^{3}He, and ^{4}He can be well identified. By combining TPC and MWDC, the CEE spectrometer can cover >80% of produced protons in 500 MeV/u U+U collisions simulated by the JAM model. These features make the CEE an ideal spectrometer for studying frontier topics discussed in Sec. I in the high-baryon density region. More detailed performance characteristics are described in Ref. [14].

IV. Acceptance for pp→pK$^+$+Λ Reaction

HIRFL-CSR can provide proton beams with a maximum energy of 2.8 GeV according to its design, enabling us to perform pp and pA reactions to investigate topics related to hadron physics [51], hypernuclei [25, 52], and more. Studying the feasibility of conducting hadron physics studies through pp and pA reactions using the CEE spectrometer is crucial for expanding the physics scope of the CEE spectrometer and maximizing its scientific value.

The reaction pp→pK$^+$+Λ is a typical channel for verifying detector performance. The Λ hyperon is a short-lived particle with a lifetime of about 263 ps and has a charged decay channel $\Lambda \to p + \pi^-$ with a branching ratio of about 64% [46]. If the four-momenta of its two daughter particles can be measured, the Λ hyperon can be identified by reconstructing its invariant mass.

The phase space of pp→pK$^+$+Λ at 2.8 GeV is simulated with the PLUTO generator. The polar angle ( ) distributions of final products—p, K$^+$, Λ, as well as p and π^- from Λ hyperon decay—are shown by solid lines in Fig. 8 [Figure 8: see original paper] (a)-(e), respectively. In this simulation, a charged particle is considered measurable if its track length in the TPC exceeds 15 cm or if it can pass through all three MWDCs. The fraction detectable by the CEE spectrometer is shown by the shaded distribution in each panel. A Λ hyperon with two detectable daughter particles is treated as a detectable candidate, and it turns out that about 37% of Λ hyperons are within the acceptance of the CEE spectrometer. Since the designed performance of the CEE spectrometer for charged particles is comparable to that of existing experiments such as FOPI, HADES, and STAR, it is expected that the CEE spectrometer will play a crucial role in experimentally investigating the aforementioned topics within pp, pA, and AA reactions at HIRFL-CSR energies.

V. Summary

In this paper, we introduced the analysis and simulation software package (CeeROOT) for the CEE experiment. Based on the CEE conceptual design and the CeeROOT package, we presented optimization procedures, physical considerations, and optimization results for the CEE detector configuration. The final optimized detector configuration serves as a blueprint for the final technical design of the CEE experiment. The acceptance of the CEE spectrometer for charged particles in U+U collisions at 500 MeV/u and for pp→pK$^+$+Λ at 2.8 GeV demonstrates that the CEE experiment is an ideal spectrometer for studying frontier physics topics at HIRFL-CSR energies through pp, pA, and AA collisions. Currently, components of the CEE experiment are in the mass production stage, and the CEE spectrometer is expected to be commissioned in 2025.

References

[1] L. P. Csernai, Introduction to relativistic heavy ion collisions

[2] W. Busza, K. Rajagopal and W. van der Schee, Ann. Rev. Nucl. Part. Sci. 68, 339-376 (2018) doi:10.1146/annurev-nucl-101917-020852 [arXiv:1802.04801 [hep-ph]].

[3] X. Luo and N. Xu, Nucl. Sci. Tech. 28, no.8, 112 (2017) doi:10.1007/s41365-017-0257-0 [arXiv:1701.02105 [nucl-ex]].

[4] A. Bzdak, S. Esumi, V. Koch, J. Liao, M. Stephanov and N. Xu, Rept. Phys. (2020) [arXiv:1906.00936 doi:10.1016/j.physrep.2020.01.005 [nucl-th]].

[5] X. Luo, S. Shi, N. Xu and Y. Zhang, Particles 3, no.2, 278-307 (2020) doi:10.3390/particles3020022 [arXiv:2004.00789 [nucl-ex]].

[6] J. Chen, J. H. Chen, X. Dong, X. He, X. H. He, H. Huang, H. Z. Huang, F. Liu, X. Luo and X. F. Luo, et al. Nucl. Sci. Tech. 35, no.12, 214 (2024) doi:10.1007/s41365-024-01591-2 [arXiv:2407.02935 [nucl-ex]].

[7] J. M. Lattimer, Ann. Rev. Nucl. Part. Sci. 71, 433-464 (2021) doi:10.1146/annurev-nucl-102419-124827

[8] Y. P. ZHANG, Z. Y. SUN, G. C. YONG, Z. Q. FENG, Acta Phys. Sin., 74, 112101 (2025) doi: 10.7498/aps.74.20241650

[9] J. Steinheimer, A. Motornenko, A. Sorensen, Y. Nara, V. Koch and M. Bleicher, Eur. Phys. J. C 82, no.10, 911 (2022) [arXiv:2208.12091 doi:10.1140/epjc/s10052-022-10894-w [nucl-th]].

[10] J. W. Xia, W. L. Zhan, B. W. Wei, Y. J. Yuan, M. T. Song, W. Z. Zhang, X. D. Yang, P. Yuan, D. Q. Gao and H. W. Zhao, et al. The heavy ion cooler-storage-ring project (HIRFL-CSR) at Lanzhou, Nucl. Instrum. Meth. A 488, no.1-2, 11-25 (2002) doi:10.1016/s0168-9002(02)00475-8

[11] M. Zhang, Z. G. Xiao, B. A. Li, L. W. Chen, G. C. Yong and S. J. Zhu, Phys. Rev. C 80, 034616 (2009) doi:10.1103/PhysRevC.80.034616 [arXiv:0904.0447 [nucl-th]].

[12] F. Fu, Z. G. Xiao, Y. P. Zhang, Z. Q. Feng, G. M. Jin, H. S. Xu, N. Yao, X. H. Yuan, X. Y. Zhang and M. Zhang, Phys. Lett. B 666, 359-363 (2008) doi:10.1016/j.physletb.2008.07.063

[13] L. Lü, H. Yi, Z. Xiao, M. Shao, S. Zhang, G. Xiao and N. Xu, Conceptual design of the HIRFL-CSR external-target experiment, Sci. China Phys. Mech. Astron. 60, no.1, 012021 (2017) doi:10.1007/s11433-016-0342-x

[14] D. Guo, X. He, P. Li, Z. Qin, C. Hu, B. Wang, Y. Zhou, K. Zheng, Y. Zhang and X. Wei, et al. Eur. Phys. J. A 60, no.2, 36 (2024) doi:10.1140/epja/s10050-024-01245-2

[15] M. A. Stephanov, Phys. Rev. Lett. 107 (2011), 052301 doi:10.1103/PhysRevLett.107.052301

[arXiv:1104.1627 [hep-ph]].
[16] S. Wu, Nucl. Sci. Tech. no.8, (2025) doi:10.1007/s41365-025-01721-4
[17] M. S. Abdallah et al. [STAR], Phys. Lett. B 827 (2022), 137003 doi:10.1016/j.physletb.2022.137003 [arXiv:2108.00908 [nucl-ex]].
[18] J. Adamczewski-Musch et al. [HADES], Phys. Rev. C 102 (2020) no.2, 024914 doi:10.1103/PhysRevC.102.024914 [arXiv:2002.08701 [nucl-ex]].
[19] S. Huth, P. T. H. Pang, I. Tews, T. Dietrich, A. L. Fèvre, A. Schwenk, W. Trautmann, K. Agarwal, M. Bulla and M. W. Coughlin, et al. Nature 606 (2022), 276-280 doi:10.1038/s41586-022-04750-w [arXiv:2107.06229 [nucl-th]].
[20] B. A. Li, B. J. Cai, L. W. Chen, W. J. Xie, J. Xu and N. B. Zhang, Nuovo Cim. C 45 (2022) no.3, 54 doi:10.1393/ncc/i2022-22054-3 [arXiv:2201.09133 [nucl-th]].
[21] L. W. Chen, Sci. China Phys. Mech. Astron. 54 (2011), 124-129 doi:10.1007/s11433-011-4415-9 [arXiv:1101.2384 [nucl-th]].
[22] T. Song, L. Tolos, E. Bratkovskaya, J. Aichelin and J. Wirth, Phys. Rev. C 103, no.4, 044901 (2021) doi:10.1103/PhysRevC.103.044901 [arXiv:2012.05589 [nucl-th]].
[23] R. Wang, Y. G. Ma, L. W. Chen, C. M. Ko, K. J. Sun and Z. Zhang, Phys. Rev. C 108, no.3, L031601 (2023) doi:10.1103/PhysRevC.108.L031601 [arXiv:2305.02988 [nucl-th]].
[24] B. A. Li, W. J. Guo and Z. Shi, Phys. Rev. C 91, no.4, 044601 (2015) doi:10.1103/PhysRevC.91.044601 [arXiv:1408.6415 [nucl-th]].
[25] S. Zhang, J. H. Chen, Y. G. Ma, Z. B. Tang and Z. B. Xu, Int. J. Mod. Phys. E 19, no.08n09, 1829 (2010) doi:10.1142/S0218301310016260
[26] W. Huang, F. Lu, H. Li, H. Dong, Y. j. Ye, C. S. Zhou, L. X. Liu, L. Du, X. H. Jin and Peng-Liu, et al. Nucl. Sci. Tech. 29, no.3, 41 (2018) doi:10.1007/s41365-018-0382-4
[27] X. Wang, D. Hu, M. Shao, L. Zhao, Y. Sun, J. Lu, H. Xu and Y. Zhou, JINST 17, no.09, P09023 (2022) doi:10.1088/1748-0221/17/09/P09023 [arXiv:2203.15900 [physics.ins-det]].
[28] L. M. Lyu, H. Yi, L. M. Duan, Z. Zhang and Z. G. Xiao, Nucl. Sci. Tech. 31, no.1, 11 (2020) doi:10.1007/s41365-019-0716-x
[29] Z. B. He, Z. Qin, P. Ma, H. R. Yang, X. L. Wei, C. G. Lu, X. J. Wen, X. L. Zhang, T. Chen and Z. J. Li, et al. Nucl. Sci. Tech. 35, no.10, 174 (2024) doi:10.1007/s41365-024-01515-0
[30] Z. Qin, Z. He, Z. Cao, T. Chen, Z. Deng, L. Duan, D. Guo, R. Hu, J. Kong and C. Liu, et al. Nucl. Sci. Tech. 36, no.4, 67 (2025) doi:10.1007/s41365-024-01628-6 [arXiv:2406.12878 [physics.ins-det]].
[31] B. Wang, D. Han, Y. Wang, X. L. Chen and Y. Li, JINST 15, no.08, C08022 (2020) doi:10.1088/1748-0221/15/08/C08022
[32] S. H. Zhu, H. B. Yang, H. Pei, C. X. Zhao, X. Q. Li and G. M. Huang, JINST 16, no.08, P08014 (2021) doi:10.1088/1748-0221/16/08/P08014
[33] J. Liu, C. S. Gao, H. L. Wang, Z. Wang, X. M. Sun, R. Chen, F. Yan, B. H. You, Z. X. Song and C. X. Zhao, et al. Nucl. Sci. Tech. 36, no.5, 87 (2025) doi:10.1007/s41365-025-01652-0
[34] L. K. Liu, H. Pei, Y. P. Wang, Y. Wang, B. Zhang, N. Xu, S. S. Shi and S.

Shi, Event plane determination from the zero degree calorimeter at the cooling storage ring external-target experiment, Nucl. Sci. Tech. 34, no.7, 100 (2023) doi:10.1007/s41365-023-01262-8 [arXiv:2302.11759 [nucl-ex]].

[35] M. Al-Turany, D. Bertini, R. Karabowicz, D. Kresan, P. Malzacher, T. Stockmanns and F. Uhlig, The FairRoot framework, J. Phys. Conf. Ser. 396, 022001 (2012) doi:10.1088/1742-6596/396/2/022001

[36] R. Brun, F. Bruyant, M. Maire, A. C. McPherson and P. Zanarini, GEANT3, CERN-DD-EE-84-1.

[37] S. Agostinelli et al. [GEANT4], GEANT4–a simulation toolkit, Nucl. Instrum. Meth. A 506, 250-303 (2003) doi:10.1016/S0168-9002(03)01368-8

[38] M. Bleicher, E. Zabrodin, C. Spieles, S. A. Bass, C. Ernst, S. Soff, L. Bravina, M. Belkacem, H. Weber and H. Stoecker, et al. Relativistic hadron hadron collisions in the ultra-relativistic quantum molecular dynamics model, J. Phys. G 25 (1999), 1859-1896 doi:10.1088/0954-3899/25/9/308 [arXiv:hep-ph/9909407 [hep-ph]].

[39] O. Buss, T. Gaitanos, K. Gallmeister, H. van Hees, M. Kaskulov, O. Lalakulich, A. B. Larionov, T. Leitner, J. Weil and U. Mosel, Transport-theoretical Description of Nuclear Reactions, Phys. Rept. 512 (2012), 1-124 doi:10.1016/j.physrep.2011.12.001 [arXiv:1106.1344 [hep-ph]].

[40] W. Cassing and E. L. Bratkovskaya, Parton-Hadron-String Dynamics: an off-shell transport approach for relativistic energies, Nucl. Phys. A 831 (2009), 215-242 doi:10.1016/j.nuclphysa.2009.09.007 [arXiv:0907.5331 [nucl-th]].

[41] N. Ikeno, A. Ono, Y. Nara and A. Ohnishi, Phys. Rev. C 93, no.4, 044612 (2016) [erratum: Phys. Rev. C 97, no.6, 069902 (2018)] doi:10.1103/PhysRevC.93.044612 [arXiv:1601.07636 [nucl-th]].

[42] C. Hartnack, R. K. Puri, J. Aichelin, J. Konopka, S. A. Bass, H. Stoecker and W. Greiner, Modeling the many body dynamics of heavy ion collisions: Present status and future perspective, Eur. Phys. J. A 1 (1998), 151-169 doi:10.1007/s100500050045 [arXiv:nucl-th/9811015 [nucl-th]].

[43] Y. Nara and A. Ohnishi, Phys. Rev. C 105, no.1, 014911 (2022) doi:10.1103/PhysRevC.105.014911 [arXiv:2109.07594 [nucl-th]].

[44] Z. Q. Feng, Phys. Rev. C 84, (2011) doi:10.1103/PhysRevC.84.024610 [arXiv:1106.3797 [nucl-th]].

[45] I. Fröhlich, L. Cazon, T. Galatyuk, V. Hejny, R. Holzmann, M. Kagarlis, W. Kuhn, J. G. Messchendorp, V. Metag and M. A. Pleier, et al. PoS ACAT, 076 (2007) doi:10.22323/1.050.0076 [arXiv:0708.2382 [nucl-ex]].

[46] S. Navas et al. [Particle Data Group], Phys. Rev. D 110, no.3, 030001 (2024) doi:10.1103/PhysRevD.110.030001

[47] Lamour, E. and Fainstein, P. D. and Galassi, M. and Prigent, C. and Ramirez, C. A. and Rivarola, R. D. and Rozet, J.-P. and Trassinelli, M. and Vernhet, D., Phys. Rev. A 92, 042703 (2015) doi:10.1103/PhysRevA.92.042703

[48] B. Zhang, L. K. Liu, H. Pei, S. S. Shi, S. Shi, N. Xu, Y. P. Wang and Y. Wang, Nucl. Sci. Tech. 34, no.11, 176 (2023) doi:10.1007/s41365-023-01338-5 [arXiv:2304.14411 [physics.ins-det]].

[49] A. Gobbi et al. [FOPI], A Highly segmented Delta E time-of-flight wall as forward detector of the 4 pi system for charged particles at the SIS / ESR

accelerator, Nucl. Instrum. Meth. A 324 (1993), 156-176 doi:10.1016/0168-9002(93)90974-M

[50] J. Adams, A. Ewigleben, S. Garrett, W. He, T. C. Huang, P. M. Jacobs, X. Ju, M. A. Lisa, M. Lomnitz and R. Pak, et al. The STAR Event Plane Detector, Nucl. Instrum. Meth. A 968 (2020), 163970 doi:10.1016/j.nima.2020.163970 [arXiv:1912.05243 [physics.ins-det]].

[51] C. Zheng et al., Hadron Physics Programs at HIRFL-CSRm: Plan and Status. Chinese Physics C, 2007, 31(12): 1177-1180.

[52] J. T. Balewski, A. Budzanowski, H. Dombrowski, W. Eyrich, C. Goodman, D. Grzonka, J. Haidenbauer, C. Hanhart, J. Hauffe and L. Jarczyk, et al. Phys. Lett. B 420, 211-216 (1998) doi:10.1016/S0370-2693(97)01527-X [arXiv:nucl-ex/9803003 [nucl-ex]].

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