



Huizhou Hadron Spectrometer: a proposed high-rate experimental setup at the high–intensity heavy-ion accelerator facility

Xu-Rong Chen^{1,2,3} · Yun-Yun Fan^{4,5} · Shuang-Shi Fang^{4,5,6} · Zhao-Qing Feng^{1,7} · Feng-Kun Guo^{3,5,8} · Wei-Jia Han¹ · Jun He⁹ · Qing-Hua He¹⁰ · Xiong-Hong He^{1,2} · Hong-Xia Huang⁹ · Xiao-Lin Kang¹¹ · Hong-Li Ma¹² · Wei-Hu Ma¹³ · Yong-Liang Ma¹⁴ · Norihito Muramatsu¹ · Zaiba Mushtaq^{1,2} · Xiao-Yang Niu^{1,2} · Jia-Lun Ping⁹ · Hao Qiu^{1,2} · Jun Shi^{15,16} · Ye Tian¹ · Qian Wang^{15,16} · Rong Wang^{1,2} · Shuai-Chun Wang¹³ · Xiao-Yun Wang¹⁷ · Jia-Jun Wu^{3,5} · Chu-Wen Xiao¹⁸ · Ju-Jun Xie^{1,2,5} · Hai-Bo Yang^{1,2} · Xie-Yang Yu^{1,2} · Hong-Lin Zhang¹ · Sheng-Hui Zhang¹² · Cheng-Xin Zhao¹⁹ · Kuang-Ta Chao²⁰ · Qiang Zhao⁴ · Bing-Song Zou²¹

Received: 11 November 2025 / Revised: 7 January 2026 / Accepted: 21 February 2026 / Published online: 29 May 2026

© The Author(s), under exclusive licence to China Science Publishing & Media Ltd. (Science Press), Shanghai Institute of Applied Physics, the Chinese Academy of Sciences, Chinese Nuclear Society 2026

Abstract

The high-intensity heavy-ion accelerator facility (HIAF), currently under construction in Huizhou, Guangdong Province, China, is expected to be completed by 2025. This facility will be capable of delivering proton and heavy-ion beams with energies of up to several GeV, thereby providing a versatile platform for advanced fundamental physics research. Key scientific objectives include exploring physics beyond the standard model through the search for new particles and interactions, testing fundamental symmetries, investigating exotic hadronic states such as dibaryons, pentaquark states, and multi-strange hypernuclei, conducting precise measurements of hadron and hypernucleus properties, and probing the phase boundary and the critical point of nuclear matter. To facilitate these investigations, we propose the construction of a dedicated experimental apparatus at HIAF—the Huizhou Hadron Spectrometer (HHaS). This paper presents the conceptual design of HHaS, which comprises a solenoid magnet, a five-dimensional silicon pixel tracker, a Low-Gain Avalanche Detector (LGAD) for time-of-flight measurements, and a Cherenkov–scintillation dual-readout electromagnetic calorimeter. The design targets an unprecedented event rate of 1–100 MHz, extensive particle acceptance, a track momentum resolution at the 1% level, an electromagnetic energy resolution of ~3% at 1 GeV, and broad particle-identification capability. Such capabilities position HHaS as a powerful instrument for high-precision experimental studies in particle and nuclear physics. The successful realization of HHaS is expected to strongly promote the development of medium- and high-energy physics research within China.

Keywords High-intensity heavy-ion accelerator facility · Physics beyond the standard model · η meson physics · Light hadron physics

1 Introduction

The high-intensity heavy-ion accelerator facility (HIAF) [1, 2], one of China’s major national scientific and technological facilities, is currently under construction in Huizhou, Guangdong Province, with completion expected by 2025. Designed

to deliver state-of-the-art beam performance, HIAF will provide intense proton (p) and heavy-ion (e.g., uranium) beams with energies up to 9.3 GeV and 2.45 GeV/u, respectively, at its high-energy terminal. Following a planned upgrade, the facility will further extend its capability, enabling the acceleration of uranium beams to energies as high as 9.1 GeV/u. Secondary π , K beams, as well as a polarized p beam can also be provided with future upgrades. This state-of-the-art facility, which will serve as a major nuclear-physics research center, offers exceptional opportunities to explore the fundamental properties of matter and the dynamics of strong interactions [3].

This work was supported by the CAS Project for Young Scientists in Basic Research (No. YSBR-088), the National Science Foundation of China (Nos. 12347103, 12435007, 12361141819, 12305145, 12375193, 12305210, 12405229 and 12222512), and Chongqing Natural Science Foundation (No. CSTB2025NSCQ-GPX0745).

Extended author information available on the last page of the article

The high-intensity p , π and K beams will produce vast quantities of light hadrons, composed of u , d , and s quarks, enabling detailed studies of their decay patterns, mass spectra, and internal structures, thereby shedding light on quark confinement, a defining feature of the strong interaction. It will also provide a powerful platform to search for new particles and interactions beyond the standard model (SM) [4–11], to test fundamental symmetries such as CP symmetry [12–15], as well as to search for new exotic hadron states [16–20] and dibaryons [21, 22]. On the other hand, heavy-ion beams at HIAF can be used to search for and locate the first-order phase boundary and the critical point, which are predicted to separate the hadron-gas and quark-gluon-plasma phases at high baryon density. Hypernuclei, a strongly interacting many-body system composed of nucleons and hyperons, can also be produced and studied in detail with the heavy-ion beams, shedding light on the hyperon-nucleon and hyperon–hyperon interactions, which are crucial for understanding the internal structure of neutron stars.

To explore these hadron-related physics topics with unparalleled precision, we propose a new experimental setup, Huizhou Hadron Spectrometer (HHaS), at the high-energy station of HIAF. Envisioned as a light hadron factory, HHaS aims to substantially improve the statistical reach of particle- and nuclear-physics measurements, potentially by about two orders of magnitude, compared to existing experimental setups (e.g., KLOE-2 [23], BESIII [24]). The successful construction and operation of HHaS will significantly promote a broad range of sub-atomic physics research and advance our understanding of the nature of matter.

The following sections of this paper describe the potential physics research directions, the performance requirements, the conceptual design, and the expected performance of HHaS.

2 Physics

While the SM has been extremely successful in the past several decades in describing the most basic building blocks in our Universe and the interactions among them, there are several phenomena that point to new physics beyond the SM [25, 26]. For example, the small but finite neutrino masses [27], the existence of dark matter [28, 29], and the matter–antimatter asymmetry in the Universe [27] all point to the need for new theories. Thus, the search for beyond-the-standard model (BSM) physics is one of the most exciting frontiers of particle physics [27]. The η meson, a pseudoscalar meson with all-zero discrete quantum numbers, i.e., $Q = I = J = S = B = L = 0$, is an excellent probe of BSM physics [30]. All of its possible strong decays are forbidden in the leading order by P , CP , charge, isospin, and G -parity conservation. Its electromagnetic decays are forbidden in the

leading order by C invariance and angular momentum conservation. As a result, BSM decay branching fractions of the η meson are enhanced, offering potential avenues to search for dark portal particles like dark photons, dark Higgs, and axion-like particles [4–11, 30–33]. Additionally, the detailed analysis of η meson decays can help test fundamental symmetries, such as C and CP symmetries [12–15] and lepton flavor conservation [34]. The decays of the η meson have been studied in various experiments in e^+e^- , e^-p , and pp collisions [12, 35–40]. The REDTOP collaboration [41] proposes an η factory experiment using pA or π^+A collisions with a fixed nuclear target to conduct the measurements of the η meson decays with a new level of precision. With the high-intensity proton and π^+ beams available at HIAF, HHaS can also function as an η factory. The large η production cross section in hadronic collisions, combined with the high luminosity easily obtained in fixed-target experiments, offers great potential for producing η samples with orders of magnitude higher statistics than the current data [42].

Due to the non-perturbative nature of quantum chromodynamics (QCD) at low energies, our quantitative understanding of the strong interaction is still limited. Understanding how quarks are confined in hadrons remains one of the central challenges in modern physics. Hadron spectroscopy, the study of hadronic excitation spectra, has become a focal point for shedding light on the interaction and dynamics between constituent quarks, spurring major experimental efforts at facilities such as ELSA, CEBAF, ESRF, SPring-8, BEPCII, SuperKEKB, J-PARC, GSI, COSY, SPS, and LHC [43–46]. The proton beam and the secondary π and K meson beams at HIAF are expected to provide a wealth of experimental data for studying light hadron spectroscopy and related dynamics. First, the high-luminosity proton beam can be used to study baryon excitations, hyperons, and dibaryon states [21, 22, 47] by bombarding proton or nuclear targets. In particular, as partner states of the P_c pentaquark states, the P_s states with a hidden-strangeness quark pair can also be searched for in the final state $p\phi$ in pp collisions [16, 17]. Additionally, the hyperon polarization in unpolarized hadronic collisions remains a long-standing question in hyperon production. The study of the $K\Lambda N$ final state offers a unique opportunity to investigate this issue and shed light on the internal structure of the Λ hyperon. Second, the secondary π beam can provide more precise πN scattering data, especially for final states such as $\pi N \rightarrow K\Lambda$, $K\Sigma$, and ωN [48–50]. The uncertainties in the differential cross sections of these two-body final states remain relatively large, and theoretical models have not yet reached a consensus [50, 51]. Consequently, the extracted parameters for N^* and Δ^* resonances vary significantly. Therefore, more precise experimental data are urgently needed. Exotic hadron states, like the pentaquark state mentioned above, may also be searched

for in πp scattering [16, 19, 20]. Finally, the K beam, which is expected to exceed the energy range and luminosity of the J-PARC [52] and JLab [53] experiments, will provide an important platform for studying hyperon excitations [54, 55]. Notably, the number of Ξ excitations listed by the PDG is currently below 10 [27], which is far fewer than the predictions of the quark model. At HIAF, more Ξ excitations can be discovered through the $KN \rightarrow \bar{K}\Xi^*$ reaction [56, 57]. For most of the above-mentioned studies, polarization observables measured with polarized targets and/or beams provide valuable constraints on partial wave analysis in disentangling overlapping baryon resonances [58, 59].

After the quark-gluon plasma (QGP) has been created and studied in relativistic heavy-ion collisions for two decades [60–63], a new frontier in high-energy nuclear physics is searching for the predicted first-order phase transition and the associated critical point between the QGP and hadronic phases in the high baryon density region of the QCD phase diagram [64]. Experimentally, this requires lower collision energies than the top RHIC and LHC energies [65]. A beam energy scan program has been carried out at RHIC, and new facilities like NICA [66], FAIR [67], and HIAF are being constructed to study heavy-ion collisions with center-of-mass energies of several GeV for this purpose. The CSR external-target experiment (CEE) is being constructed at the Cooling Storage Ring of the Heavy-Ion Research Facility in Lanzhou (HIRFL-CSR). Heavy-ion collisions can be conducted at CEE with a maximum beam kinetic energy around 1.1 GeV/u and a maximum event rate of around 10 kHz. The higher-order moments of net-proton multiplicity and the light nucleus production yield ratios are considered to be sensitive observables for locating the critical point [68, 69]. With the wide detector acceptance and strong particle-identification capability of charged particles and light nuclei, HHaS can contribute to the global effort of mapping out the QCD phase diagram.

Hypernuclei allow the study of hyperon-nucleon interactions, providing key insights into the strong interaction and strange quark behavior in nuclear environments, which is crucial for the understanding of neutron star interiors where hyperons may exist [70, 71]. Heavy-ion collisions at the HIAF energy can produce abundant hyperons, which may coalesce with nucleons in the collision system and form hypernuclei [72]. The exotic hypernuclei with multistrangeness might be produced in heavy-ion collisions at HIAF energies with the production cross sections above 1 μb [73]. With the intense heavy-ion beam at HIAF, various properties of hypernuclei can be measured with high precision and new (multi-strange) hypernuclei may be discovered at HHaS. The hyperon-nucleon interaction in dense matter can also be studied via the collective flow and phase-space

distribution of hyperons in heavy-ion collisions at HIAF energies [74, 75].

3 Requirements

To achieve the wide range of physics goals mentioned above, the following key requirements are imposed on the design of HHaS.

First, it is required to record the data of interaction events with a rate far beyond existing similar experiments. History has repeatedly demonstrated that new discoveries and understanding may be achieved with increased data statistics and improved precision. Taking advantage of the high beam intensity of HIAF, the capability to operate at an ultra-high event rate could be a key strong point of HHaS. HIAF can accelerate 2×10^{12} protons within 0.3 s, which can be slowly extracted to the experimental terminals. Assuming 1% of the beam particles interact with the target, a collision rate of ~ 10 GHz can be reached, which is far beyond the event rate of all the currently running experiments. The bottleneck for acquiring high-statistics data is not the beam intensity of HIAF, but the capability of the detector setup to record the events with a high collision rate. Even the secondary π (K) beam can reach the intensity of the order of 10^8 (10^6)/s, leading to the collision rate of ~ 1 MHz (~ 10 kHz) if the same thickness of a target is assumed. Unlike very high-energy experiments, the triggers using some specific characteristics (e.g., a pair of leptons, a high-energy gamma or jet), which can be easily picked up by a fast detector, cannot cover all the events that contain the broad interesting physics topics of HHaS described in Sect. 2. Thus, it is necessary as a good strategy to require all the detectors of HHaS to record signals from all collisions with a high event rate, and then reconstruct, select and analyze the events for interesting physics subjects afterward. For proton beam, HHaS targets at a maximum event rate of about 100 MHz. This is achievable with the state-of-the-art detector technologies, as described in Sect. 4 and 5. With beam intensity fluctuations and time structures, the average event rate will be slightly lower, by a factor of 3 as a conservative estimation.

Second, HHaS needs to have a large angular, momentum and energy acceptance because it attempts to cover a very wide range of physics studies. Many physics topics require the reconstruction of a particle with many daughters, or the exclusive measurement of a process with many final particles. Thus large acceptance is essential for HHaS, in order to carry out the targeted measurements efficiently.

Third, HHaS is required to have good momentum, energy and track-pointing resolutions. A percent-level track momentum resolution and several-percent-level electromagnetic energy resolution should be achieved, in order to obtain a good invariant mass resolution for decayed hadron states.

This is critical to distinguish signals from different light hadron states, which can be closely distributed in mass, and observe a weak exotic signal with a low production rate. A good track-pointing resolution enables HHaS to reconstruct secondary decay vertices precisely, for example, in order to distinguish strange particles and hypernuclei, which usually decay several centimeters away from the collision point, from backgrounds formed by the random combination of final-state particles.

Fourth, HHaS should be able to identify many types of final-state particles from the collisions, including $e^\pm$, γ , $\pi^\pm$, $K^\pm$, p , $\bar{p}$, deuteron (d), triton (t), ^3He , and ^4He . The $e^\pm$ and γ are important final particles for many physics studies. For example, they are among the daughter particles for almost all the η meson decay channels to be studied at HHaS. Yet, in the hadronic collision environment, their production yield is orders of magnitude lower than hadrons. Thus, very clean identification of $e^\pm$ and γ are critical for HHaS to work as an η factory experiment. The light nuclei, i.e., d , t , ^3He and ^4He , which play an important role in the study of nuclear matter phase transition and hypernuclei, also need to be identified clearly from other particles at HHaS.

Finally, as an advanced next-generation spectrometer, HHaS is required to have a high single-track efficiency. A minor efficiency loss for each particle could cause a large loss in efficiency for the final measurement which involves numerous particles. Furthermore, the systematic uncertainties associated with single-track efficiencies will also accumulate, leading to a large total systematic uncertainty on the physics measurement. This can be a critical challenge for HHaS, which targets a new level of precision for a wide range of physics measurements. Thus a high track efficiency at the 99% level is essential.

In general, HHaS aims to have a large acceptance, good momentum and energy resolutions, good particle-identification capabilities and a high tracking efficiency, which are at least comparable with current experiments. At the same time, HHaS is required to have an event recording rate that is orders of magnitude higher than current experiments, which will be its key advantage to achieve high-precision measurements and to make new discoveries.

4 Conceptual design

The detector system of HHaS comprises a solenoidal magnet, a pixel tracker, a time-of-flight (TOF) detector, and an electromagnetic calorimeter (EMC) that operate in concert to meet the above-mentioned requirements, as shown in Fig. 1.

A solenoidal magnet that provides a 1.5–4 T magnetic field forms the backbone of the spectrometer, enabling the precise momentum measurement of charged particles.

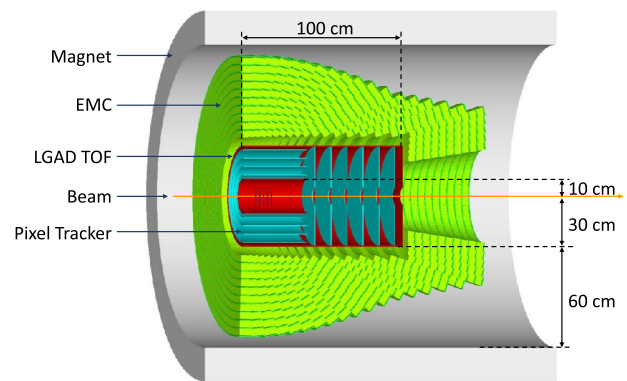


Fig. 1 (Color online) HHaS conceptual design

Depending on the physics requirements, the magnetic field can be lowered to detect particles with low transverse momentum (p_T), or increased to achieve better momentum resolutions.

The core tracking detector utilizes the advanced Monolithic Active Pixel Sensors (MAPS) technology [76–81], which provides excellent position resolution, fast readout, and a moderate material budget [82–84]. The pixel sensors are arranged in cylindrical barrel layers surrounding the target, together with disks covering the forward regions, enabling the detection of particles across a wide range of polar angle from 10 to 100 degrees with full azimuthal coverage. Unlike traditional MAPS sensors, which detect only whether a pixel is hit, the MAPS sensors developed for HHaS are designed to simultaneously measure both time information and the magnitude of ionization charge for each pixel. This design allows the HHaS pixel tracker to function as an innovative five-dimensional tracking device, capable of synchronously acquiring three-dimensional spatial coordinates, hit timings, and deposited ionization charge. The time measurement with a resolution of approximately 10 ns enables distinguishing hits from different collisions when HHaS operates at an ultra-high event rate. The ionization charge measurement helps distinguish different nuclei with identical charge-to-mass ratios (e.g., d , ^4He , and ^6Li) based on the differences in their energy deposition. This capability is crucial for studying hypernuclei and nuclear matter at high baryon densities. To accommodate the increased power consumption and technical challenges posed by time and ionization charge measurements, the MAPS sensors for HHaS have a moderate pixel pitch of approximately 100 μm , larger than the pixel pitches of MAPS sensors used in higher energy experiments focusing on heavy-flavor decay measurements [85, 86]. By using the ionization charge as a weight to calculate the charge-weighted centroid of each hit cluster, a hit position resolution of 30 μm or better can be achieved, which meets the requirements of HHaS, as

demonstrated in Sect. 5. With the excellent position resolution of the pixel tracker and the relatively strong magnet field, HHaS can reconstruct and measure charged particles with short track lengths. Thus, HHaS is designed as a very compact and cost-effective spectrometer, as presented in Fig. 1. Considering a typical sensor detection efficiency of 99% and a dead area of $\sim 1\%$ between neighboring sensors, the hit efficiency per layer should be about 98%. A track efficiency over 99% can be achieved by allowing at most one missed hit across all layers that a track penetrates. Thanks to the high granularity of the pixel detector, the hit and track efficiency losses due to the detector unit occupancy caused by a high particle multiplicity or a high event rate are limited, as discussed in Sect. 5. With a carbon-fiber support structure, flexible PCB cables and air cooling, the material budget can be constrained down to $X/X_0 \sim 0.3\%$ per layer, so that the multiple Coulomb scattering effect of particles is at an acceptable level.

The five-dimensional pixel tracker is the most challenging detector of HHaS. Currently, several types of four-dimensional (three-dimensional position + time) and five-dimensional pixel sensors are being developed worldwide for various experiments. For example, the MIMOSIS sensor has been developed for the CBM experiment [87, 88]. HV-MAPS have been prototyped for experiments such as Mu3e [89], ATLAS [90, 91], and CLIC [92]. They provide fast time stamping, and the ionization charge information is derived from the time-over-threshold measurement [93]. These representative chips are each continuously optimized for their specific physics objectives, pushing against technical limits. Similarly, significant R&D efforts are focused on developing the Nupix-H [94], a series of MAPS chips tailored for HHaS applications. Currently, the small-array prototype MAPS chips under development integrate fully digital circuitry to enhance data transmission rates. A global timestamp distribution mechanism achieves a time resolution of 10 ns. Time-over-threshold measurements are used to derive energy information. An event-driven readout architecture implements zero suppression, and a dual-column readout structure coupled with multi-layer arbitration integrates and transfers data. This readout architecture enables a readout dead time of approximately 10 μs , supporting an event rate of 100 MHz while maintaining acceptable occupancy. A 5 Gbps serializer transforms parallel data into a stable serial stream and drives it off-chip.

Inside and outside the pixel tracking detector, the capacitively-coupled (AC) low-gain avalanche detectors (LGAD) [95, 96] are placed for TOF measurements. The average radii for the inner and outer barrel layers are 10 and 30 cm, respectively. A disk layer is placed to cover the forward direction. The outer layers measure the flight end time of each charged particle, while the collision time, i.e., the common start time of all primary particles, is measured

by the inner LGAD layer using all charged particles that are detected there. A time resolution of about 30 ps can be achieved with the state-of-the-art LGAD technology, which helps both the identification of various charged particles and the separation of tracks from different collisions. The AC-LGAD strips are read out by fast front-end amplifiers and time-to-digital converters (TDCs) with a shaping time of 1 ns and per hit dead time of about 2 μs . Thanks to the strip pitch of $\sim 100 \mu\text{m}$ in the $r \times \phi$ direction, a charge-weighted hit position resolution below 30 μm can be obtained in the $r \times \phi$ direction, so that the LGAD TOF provides another 1 or 2 precise hits in addition to the pixel tracker and a longer track length for momentum reconstruction. The z strip pitch is much larger at cm scale in order to have acceptable channel density, total layer material thickness and power consumption. With this design, a material budget of $X/X_0 \sim 3\%$ per layer is expected. Unlike Direct-coupled (DC) LGAD, the AC-LGAD has no dead area surrounding each pixel or strip, thus achieving a high hit efficiency above 98%. The efficiency loss induced by the detector unit occupancy is also very small as described in Sect. 5. Currently, AC-LGAD chips with 7-mm-long strips have been made, with a time and position resolution close to the requirements of HHaS [96]. AC-LGAD with longer strips will be developed in order to decrease the overall material budget and power consumption of the detector. The readout ASIC is also being developed in parallel. Full-size LGAD sensor chips and prototype detectors will be manufactured in the future.

The dual-readout EMC will be installed outside the LGAD TOF detector. As shown in Fig. 1, layers of lead glass and plastic scintillator are assembled in an alternating sequence, forming towers pointing to the target area, with a total thickness of $X/X_0 \sim 14$. Silicon photomultipliers (SiPMs) are coupled directly to the lead glass and plastic scintillator tiles to readout Cherenkov and scintillation light, respectively, thereby enabling effective separation between electromagnetic and hadronic showers. This separation is possible because (1) most particles in a hadronic shower with an energy around 1 GeV lack sufficient velocity to produce Cherenkov radiation and (2) electrons in an electromagnetic shower can easily produce Cherenkov light due to their sub-MeV/ c^2 mass [97, 98]. This type of dual-readout EMC, which is named ADRIANO-II, has also been adopted by the REDTOP collaboration [41, 99]. Tests by the REDTOP collaboration show that ADRIANO-II can achieve an energy resolution of approximately 3% at 1 GeV. Our simulations indicate performance comparable to those test results (see Sect. 5). A time resolution of approximately 200 ps facilitates the separation of signals from different events. The module dead time must be at the microsecond level so that the data acquisition efficiency should be reasonably high when HHaS operates at high event rates. In the current design, the SiPM signals are shaped and integrated

over windows of 100 ns and then digitized with a per-tower dead time of about 1 μ s. The combination of a short tower dead time and streaming readout allows the EMC to operate at a high event rate without introducing significant efficiency loss due to occupancy.

Depending on the physics topics to be studied, a multi-layer solid nuclear target, a liquid hydrogen target, or a polarized ^3He target may be placed in the center of HHaS along the beamline. The polarized ^3He target can effectively serve as a polarized neutron target after subtracting the contribution from the beam colliding with the protons in it. With the innermost LGAD layer 10 cm from the beamline, enough space is left to accommodate the usage of all these types of targets, especially the liquid hydrogen and polarized ^3He targets, which have a dewar to work at a low temperature.

To cope with the targeted interaction rate of up to 100 MHz in proton beam operation, all detector subsystems are designed to operate in a triggerless, streaming readout mode. The front-end ASICs provide local buffering and zero-suppressed transmission of the hit information, such that only time-stamped signals above the thresholds are sent off-detector. Together with the fine segmentation of the pixel, LGAD, and EMC systems, which keeps the average hit rate per channel sufficiently low, the system with this design can handle the ultra-high event rate without much efficiency loss due to the channel digitization time per hit.

Table 1 summarizes the key parameters of the design and requirements of the detectors described above.

5 Expected performance

The capability to sustain an ultra-high event rate is an advantage that sets HHaS apart from many existing experimental setups. For low-multiplicity collisions with a proton beam, HHaS can operate at an interaction rate of 100 MHz. Due to the choice of fast detector technologies for all the three detectors, HHaS runs without triggers and reads out all signals that the detectors receive. Then, using the measured time information, signals can be assigned to different interactions. With an event rate of 100 MHz, there are only 10 collision events on average in a $\pm 5\sigma$ (~ 100 ns) time window of the pixel tracker. The total number of charged tracks is less than 100 from these ~ 10 events when using a proton beam, which can be well handled by the track-finding algorithm. After that, tracks from the ~ 10 different collisions are further separated using the time information of the 1 or 2 LGAD hits in each track. As the 30-ps time resolution of LGAD is much more precise compared to the average collision time interval of 10 ns, tracks from different collisions can be separated unambiguously. The EMC time resolution of about 200 ps also allows clear separation of signals from different collisions.

Table 1 Key parameters of the design and requirements of the detectors

Parameters	Value
<i>B</i> field strength (T)	1.5–4
Pixel tracker	
Number of barrel layers	~ 4
Number of forward disks	~ 6
Pixel pitch (μm)	~ 100
Position resolution (μm)	~ 30
Time resolution (ns)	~ 10
Pixel dead time (μs)	~ 10
Sensor hit efficiency	$\sim 99\%$
X/X_0	$\sim 0.3\%$
LGAD TOF	
Inner barrel radius (cm)	~ 10
Outer barrel radius (cm)	~ 30
Inner barrel length (cm)	~ 40
Outer barrel length (cm)	~ 100
Strip pitch in $r \times \phi$ (μm)	~ 100
Strip pitch in z (cm)	1–2
Position resolution in $r \times \phi$ (μm)	~ 30
Position resolution in z (mm)	3–6
Time resolution (ps)	~ 30
Strip dead time (μs)	~ 2
Hit efficiency	$\sim 98\%$
X/X_0	$\sim 3\%$
EMC	
Number of modules	~ 2000
Number of layers	4–10
X/X_0	~ 14
Energy resolution	$\sim 3\%$ @ 1 GeV
Time resolution (ps)	~ 200
Module dead time (μs)	~ 1

Another challenge associated with the ultra-high event rate is the occupancy of detector units. In the triggerless streaming scheme, each pixel, strip, or tower behaves as an independent channel with local buffering, so that dead time losses are driven by the local hit rate rather than by the global interaction rate. For example, when one pixel is hit, it takes about 10 μs to readout the time and charge of this hit. This pixel is dead during this time, but other pixels remain ready to detect signals from other particles. The detector occupancy, i.e., the fraction of inactive channels during data taking, is proportional to the unit dead time, particle multiplicity of a collision event and event rate, and is inversely proportional to the granularity of the detector. Considering that a typical $p + ^7\text{Li}$ collision at 1.8 GeV generates 4 charged particles and 0.4 γ , with the pixel, LGAD strip, and EMC tower front-end readout dead time of 10, 2 and 1 μs , respectively, the average occupancies of the innermost pixel

layer, the outer LGAD layer and the EMC are estimated to be 0.02%, 0.1% and 7%, respectively, with an event rate of 100 MHz. Together with precise time stamping, this strategy provides a robust way of handling ~ 100 MHz interaction rates while keeping inefficiencies from the electronics at an acceptable level. For collisions with heavy-ion beams, hundreds of particles per event can be generated, thus HHaS runs at a lower event rate around 1 MHz in order to avoid a high detector occupancy and a large efficiency loss.

The total data rate of HHaS is estimated to be about 40 GB/s with an event rate of 100 MHz using proton beam. This will impose some challenges on the data acquisition system, storage system as well as data processing, but should still be manageable. A parallelized four-dimensional track-reconstruction algorithm based on GPUs needs to be developed, in order to conduct the data processing with an acceptable cost.

The radiation dose and 1 MeV neutron equivalent fluence for various materials and components of HHaS have been simulated with the FLUKA software [100]. The results show that most detector components can sustain the radiation for 1 year of accumulated running time. However, the innermost lead glass tiles of the EMC will receive a radiation dose up to 500 Gy. There are only a limited number of references about radiation hardness for the broad range of existing lead glass types. Thus, detailed measurements need to be carried out to select a lead glass type that can sustain such a high radiation dose.

With the 1–100 MHz event rate, HHaS is several orders of magnitude faster than most of the existing high-energy particle and nuclear-physics experiments, granting HHaS a great potential for discoveries and precision measurements. The event rates with secondary π and K beams are at 1 MHz and 10 kHz levels, respectively, which are limited by the beam intensities as mentioned in Sect. 3.

HHaS accepts charged particles with the p_T above 50 MeV/c (in case of the magnetic field of 1.5 T) and γ with the energy above 50 MeV across a wide angular range from 10 to 100 degrees in the polar angle (θ) with the full azimuthal coverage. Some low- p_T tracks may not be able to reach the outer barrel LGAD layer, but can swirl in-and-out several loops until hitting the endcap LGAD disk. A successful momentum reconstruction and TOF measurement can still be achieved for these low- p_T tracks, at least in low-multiplicity events using p , π and K beams. This p_T , energy and angle acceptance is very large for particles produced by a multi-GeV beam bombarding a fixed target, making HHaS a very efficient experiment for exclusive reaction-channel measurements and for the reconstruction of particles that decay into multiple daughters.

The hit position resolution of the pixel tracker and the LGAD TOF (in the $r \times \phi$ direction) is around or below 30 μm . Thanks to the good hit precision, HHaS can reconstruct charged-particle tracks with good momentum resolutions,

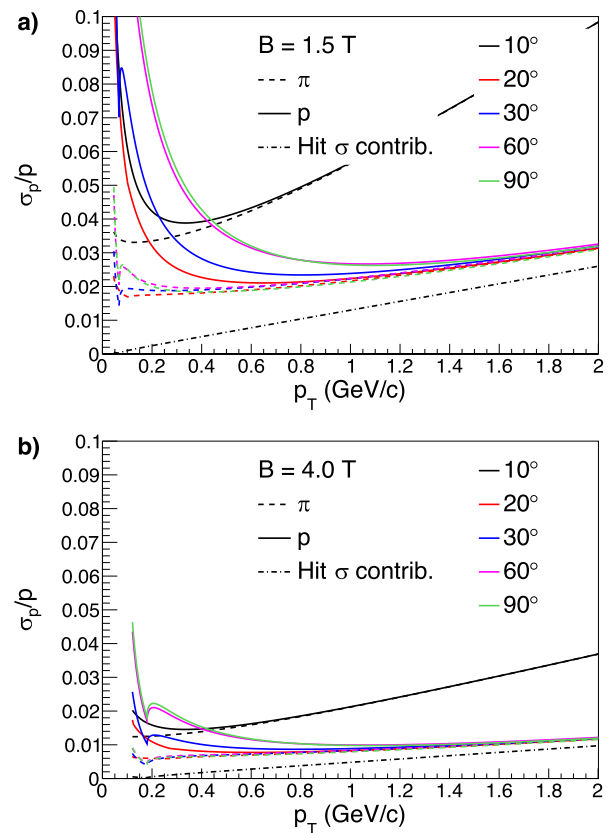


Fig. 2 (Color online) Estimated momentum resolution as a function of transverse momentum for $\pi^\pm$ and protons at different polar angles, with 1.5 T (a) and 4 T (b) magnetic fields. The momentum resolution from hit position resolution alone is shown by the dashdotted line

even though the radius of the outer LGAD TOF layer is only 30 cm. Figure 2 shows the estimated momentum resolution as a function of p_T for $\pi^\pm$ and protons at different polar angles, assuming a 30- μm hit position resolution and a pixel detector thickness of $X/X_0 = 0.3\%$ per layer.

For particles with the p_T below 1 GeV/c, the dominant contribution of the momentum resolution is the multiple Coulomb scattering effect, which decreases with increasing p_T . The hit resolution contribution, shown by the dash dotted line, increases linearly with p_T and becomes important only at a very large p_T , where the particle production yield is very low. There is a kink structure with $p_T = 68$ (180) MeV for the $B = 1.5$ (4) T case, because that's the point where the tracks are barely able to reach the outer barrel LGAD layer. Below this p_T , as the transverse track length increases with increasing p_T , the momentum resolution also improves rapidly. Above this p_T , the track becomes straighter and shorter as p_T increases, and the momentum resolution degrades slightly with increasing p_T , until the decrease in the multiple Coulomb scattering effect becomes dominant.

For most charged particles, a momentum resolution of around 1% can be achieved with a magnetic field of 4 T,

except for very forward particles (e.g., $\theta = 10^\circ$) with a limited transverse track length or very low momentum particles which suffer from a large multiple Coulomb scattering effect. The use of a lower magnetic field strength of 1.5 T degrades the momentum resolution to a level of 3% but improves the acceptance for low p_T particles.

Once the momenta are measured, charged particles are mainly identified by the measured TOF. Assuming an LGAD TOF time resolution of $\delta_t = 30$ ps, the separation ability for various charged particles at different polar angles (θ) is shown in Fig. 3. It can be seen that the $e-\pi$ separation is the most difficult with TOF. Due to their small masses, $e^\pm$ with p_T above ~ 200 MeV cannot be identified clearly from $\pi^\pm$ with TOF measurements. Their identification must be achieved using the dual-readout EMC, which will be discussed later.

In Fig. 4, the p_T for 4- σ and 6- σ π - K and K - p separation is plotted as a function of θ on top of the produced $\pi^\pm$, $K^\pm$ and (anti-)proton distributions for the cases of top-energy proton (9.3 GeV) and uranium (2.45 GeV/u) beams at HIAF from GiBUU [101] simulation. It can be seen that the majority of the produced charged particles lie below the π - K and K - p separation lines, meaning that they can be well separated with the TOF measurements. It should also be noted that the top-energy collisions are the most difficult cases for charged-particle identification. With lower beam energies, the produced particles will be distributed at larger θ , and the mean p_T will decrease slightly, making the particle identification easier.

For the search and measurement of decayed particles, the daughter particles tend to have lower p_T 's than primary particles, which dominate the distributions in Fig. 4. Figure 5 shows the p_T vs. θ for the $\pi^\pm$ mesons from the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay in the case that the η meson is produced by a proton beam with a kinetic energy of 1.8 GeV bombarding a ^7Li

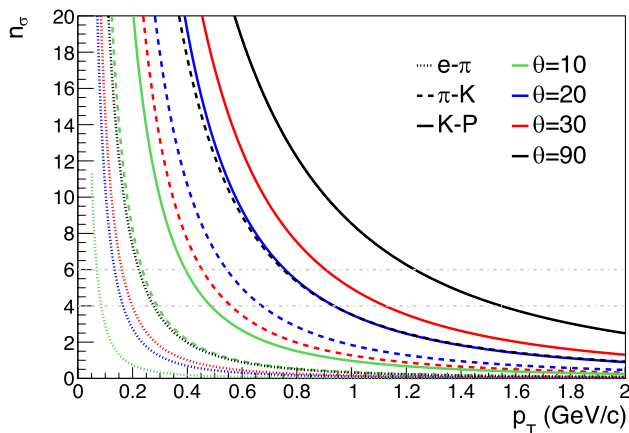


Fig. 3 (Color online) n_σ separation as a function of transverse momentum for various charged particles at different polar angles using TOF measurements

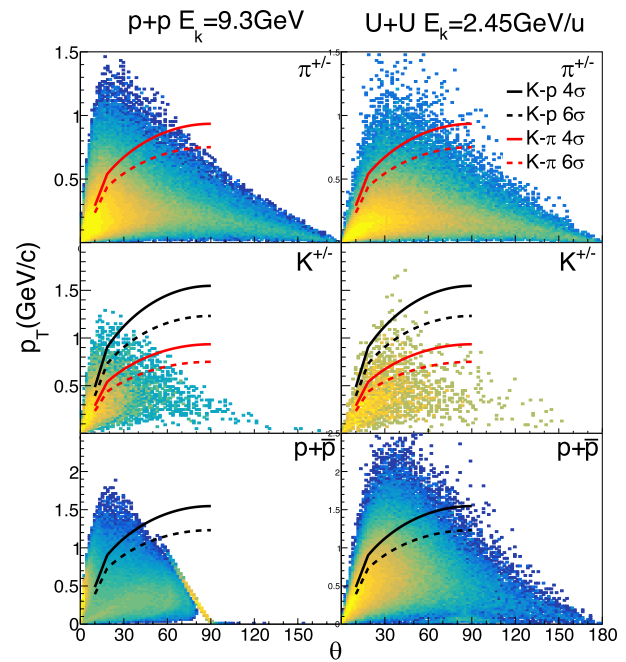


Fig. 4 (Color online) p_T vs. θ distributions for $\pi^\pm$, $K^\pm$ and protons produced with top-energy proton and uranium beams at HIAF from GiBUU [101] simulation, comparing with the p_T for 4- σ and 6- σ π - K and K - p separation

target. As shown in the plot, the 4- σ and 6- σ π - K separation curves are well above the $\pi^\pm$ distribution, meaning that all the $\pi^\pm$ from the η decay can be well identified.

The response of the dual-readout EMC to electrons and γ is simulated using the Geant4 package [102–104]. The resulting electromagnetic energy (E_{EM}) resolution is shown in Fig. 6. An energy resolution of $\sim 3\%$ @ 1 GeV can

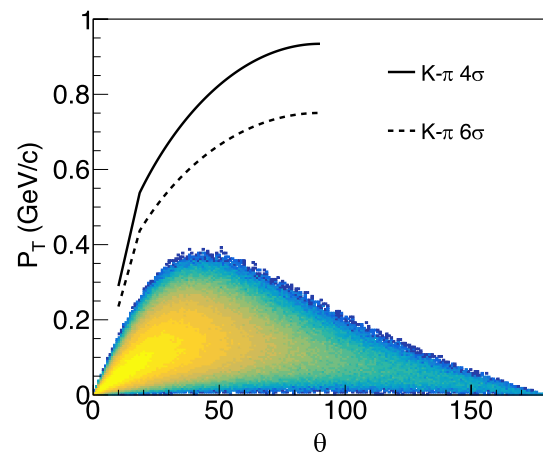


Fig. 5 (Color online) p_T vs. θ distribution for $\pi^\pm$ from $\eta \rightarrow \pi^+\pi^-\pi^0$ decay, for the η meson produced by a proton beam with a kinetic energy of 1.8 GeV bombarding a ^7Li target, comparing with the p_T for 4- σ and 6- σ π - K separation

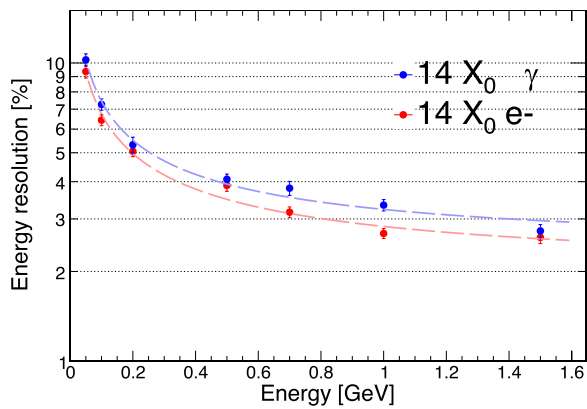
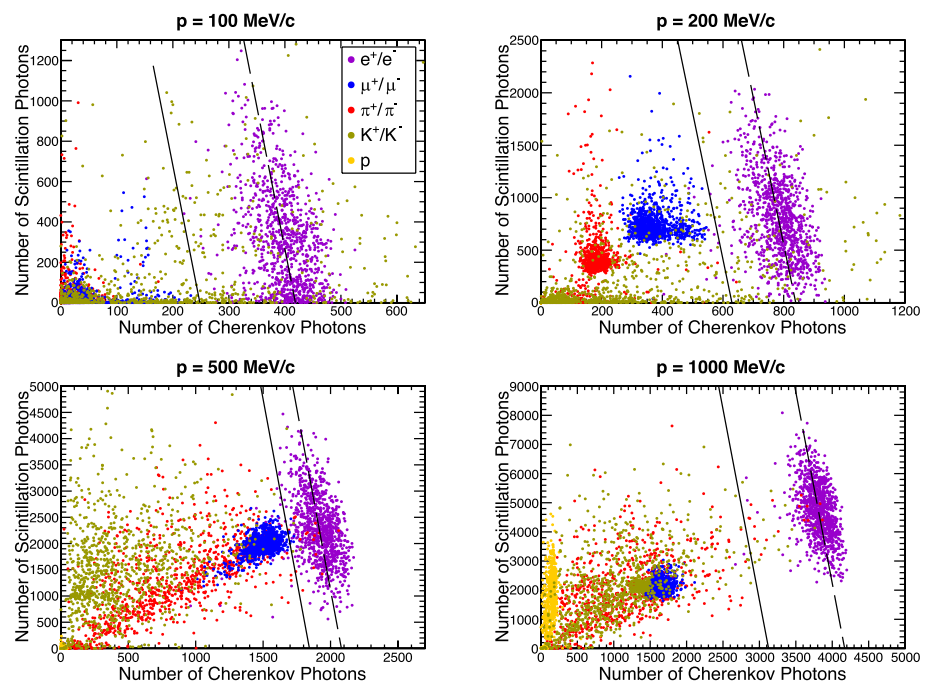


Fig. 6 (Color online) Energy resolution as a function of energy for electrons and γ from MC simulations

be obtained. For the ADRIANO-II type calorimeter, most of the energy loss happens in the denser and thicker lead glass, where only Cherenkov light is generated. The number of Cherenkov photons generated per unit energy loss is orders of magnitude lower than that of scintillation photons. Thus, the total number of generated Cherenkov plus scintillation photons in the ADRIANO-II EMC is much less than that in a traditional EMC by inorganic scintillators [105]. However, due to small tile sizes, the photons can hit the SiPMs before traveling a very large distance. This helps the ADRIANO-II EMC to gain a better photon collection efficiency and obtain an energy resolution close to the expensive scintillating crystal calorimeters.

The Cherenkov-scintillation dual-readout EMC has a very good ability to separate electromagnetic shower signals from the backgrounds generated by hadrons. Figure 7 illustrates how electrons with selected momenta can be identified clearly from other charged particles using the number of scintillation photons vs. Cherenkov photons measured by the EMC. A linear cut, shown by the solid line in each panel, is applied to separate electrons from other charged particles. With this selection, the electron identification efficiency remains above 99% across all four momenta, while the pion rejection efficiency stays above 98%. Other charged hadrons, such as kaons and protons, can be identified from electrons clearly with the TOF measurements thanks to their larger masses, as discussed before. In contrast to the identification of electrons from charged hadrons, the separation of neutral γ rays and neutrons is more challenging, because without the particle momentum measurement from the tracker, a γ with a certain energy can be contaminated by a higher energy neutron, which leaves a part of its energy in the calorimeter [106–108]. Figure 8 shows the numbers of scintillation vs. Cherenkov photons detected by the SiPMs in the dual-readout EMC for γ 's and neutrons from MC simulations. The γ sample used here comes from the $\eta \rightarrow \pi^+ \pi^- \pi^0 \rightarrow \pi^+ \pi^- \gamma \gamma$ decay with a 1.8 GeV proton beam bombarding a ^7Li target, simulated with the GiBUU model [101]. The background neutron sample is generated for the same collision system using GiBUU simulation. Good γ -n separation is achieved except for very low-energy γ 's distributed at the bottom-left corner of the plot. Using a boosted decision tree algorithm, a 98% γ identification efficiency can be achieved while the

Fig. 7 (Color online) Numbers of scintillation vs. Cherenkov photons detected by the SiPMs in the dual-readout EMC for various charged particles with certain momenta from Geant4 simulations. The dashed and solid lines show the center of electron distributions and selection cuts for electrons, respectively



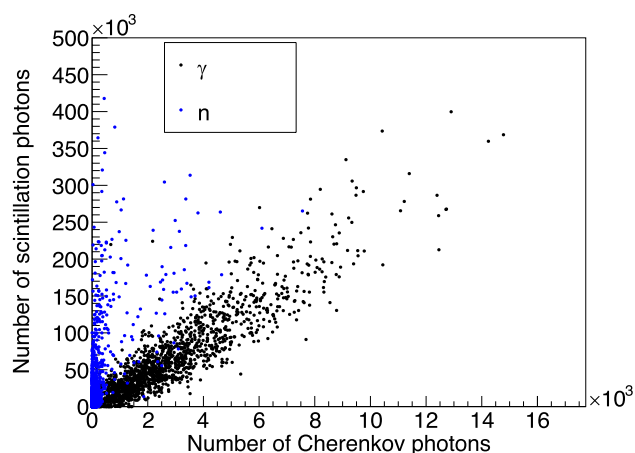


Fig. 8 (Color online) Numbers of scintillation vs. Cherenkov photons detected by the SiPMs in the dual-readout EMC for γ and neutrons from Geant4 simulations

neutrons are rejected with 98% efficiency. Considering the relatively good energy resolution, the excellent electromagnetic-hadronic shower separation ability and the very low cost of lead glass and plastic scintillator, ADRIANO-II is a very suitable and cost-effective EMC for HHaS.

With the advantage of the good hit resolution of the pixel tracker, HHaS is expected to have a good track-pointing resolution around the collision point. The dominant contribution to the track-pointing resolution is the multiple Coulomb scattering effect. Figure 9 shows the estimated track-pointing resolution as a function of p_T for $\pi^\pm$ and protons at different polar angles. The pointing resolution for tracks with a polar angle of 10 degrees is better than others because they do not penetrate the inner LGAD barrel, which is much thicker than the pixel layers. For protons with a typical p_T of 500 MeV/c,

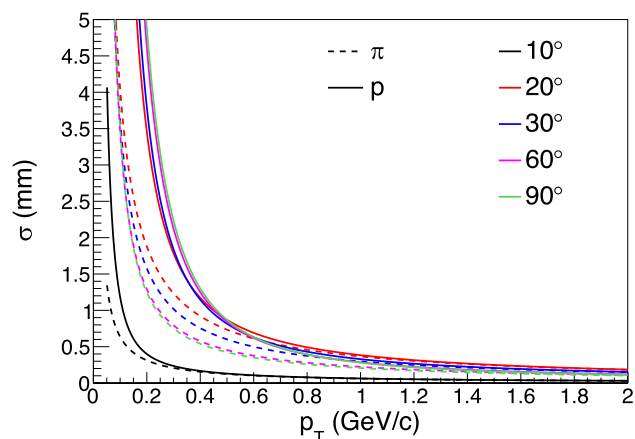


Fig. 9 (Color online) Estimated track-pointing resolution around the collision point as a function of p_T for $\pi^\pm$ and protons at different polar angles

the pointing resolution is around 0.9 mm. For $\pi^\pm$ with a p_T of 200 MeV/c, the pointing resolution is about 1.5 mm. These mm level pointing resolutions allow HHaS to reconstruct secondary decay vertices precisely, so that particles with strangeness and hypernuclei, which have a typical decay $c\tau$ of several cm, can be clearly identified from combinatorial backgrounds.

Table 2 summarizes the expected performance of HHaS, which is described above.

Preliminary simulations for the η meson physics to be conducted at HHaS are given in Ref. [42]. With a running time of only one month, HHaS is capable of taking a sample of 5.9×10^{11} η mesons, which is three orders of magnitude larger than the total η samples recorded globally to date. One to two orders of magnitude higher sensitivities than the current results can be achieved in the search for dark photon and dark Higgs, and the tests of C and CP symmetries. This demonstrates the great advantage from the outstanding event rate and the comprehensive capabilities of HHaS. Detailed simulation studies will be carried out for more potential physics measurements at HHaS.

6 Summary

In summary, we propose a new experimental setup, named HHaS, at the HIAF high-energy station. This setup consists of a solenoidal magnet, a 5-dimensional pixel tracking detector employing MAPS technology, a LGAD TOF detector and a Cherenkov--scintillation dual-readout EMC. HHaS has a large particle acceptance, a typical momentum resolution of

Table 2 Summary of the performance expected for HHaS

Event rate	~ 100 MHz (p beam) ~ 1 MHz (heavy-ion beam) ~ 1 MHz (π beam) ~ 10 kHz (K beam)
Angular acceptance	$10^\circ < \theta < 100^\circ$ $0 < \phi < 2\pi$
p_T range	> 50 MeV/c ($B = 1.5$ T) > 130 MeV/c ($B = 4$ T)
E_{EM} range	> 50 MeV
Track efficiency	$\sim 99\%$
TOF efficiency	$\sim 98\%$
Typical momentum resolution	$\sim 3\%$ ($B = 1.5$ T) $\sim 1\%$ ($B = 4$ T)
E_{EM} resolution	$\sim 3\%$ @ 1 GeV
Track-pointing resolution	~ 0.9 mm (p @ 500 MeV/c) ~ 1.5 mm ($\pi^\pm$ @ 200 MeV/c)
Identified particles	$e^\pm, \gamma, \pi^\pm, K^\pm, p, \bar{p},$ $d, t, {}^3\text{He}, {}^4\text{He}$

$\sim 1\%$ for charged particles, an electromagnetic energy resolution of $\sim 3\%$ @ 1 GeV and a track-pointing resolution at the millimeter level. It can clearly identify and measure $e^\pm$, γ , $\pi^\pm$, $K^\pm$, p , $\bar{p}$, d , t , ^3He and ^4He . Most impressively, the system can sustain interaction rates of ~ 100 MHz and ~ 1 MHz for proton and heavy-ion beam experiments, respectively. This capability sets HHaS apart from many existing experimental setups, making it a very versatile and competitive spectrometer to search for BSM physics, to test fundamental symmetries, to study light hadron spectroscopy and related dynamics, to measure the properties of hypernuclei and probe hyperon–nucleon interactions, to discover exotic hadron states and multi-strange hypernuclei, as well as to map the QCD phase diagram.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Xiong-Hong He, Hao Qiu, Ye Tian, Rong Wang, Shuai-Chun Wang, and Xie-Yang Yu. The first draft of the manuscript was written by Xu-Rong Chen, Yun-Yun Fan, Shuang-Shi Fang, Zhao-Qing Feng, Jun He, Qing-Hua He, Xiao-Lin Kang, Zaiba Mushtaq, Xiao-Yang Niu, Hao Qiu, Rong Wang, Xiao-Yun Wang, Jia-Jun Wu, and Xie-Yang Yu, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are openly available in Science Data Bank at <https://cstr.cn/31253.11.science/cdb.32806> and <https://doi.org/10.57760/sciencedb.32806>.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Declaration of generative AI use During the preparation of this work, the author Hao Qiu used DeepSeek for the purpose of language editing and grammar checking only. The tool was used to improve the readability and clarity of the text. After using this service/tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article. No AI tool was used to generate scientific data, perform analysis, or formulate conclusions.

References

- J.C. Yang, J. Xia, G. Xiao et al., High intensity heavy ion accelerator facility (HIAF) in China. Nucl. Instrum. Meth. B **317**, 263–265 (2013). <https://doi.org/10.1016/j.nimb.2013.08.046>
- X. Zhou, J. Yang, Status of the high-intensity heavy-ion accelerator facility in China. AAPPS Bull. **32**, 35 (2022). <https://doi.org/10.1007/s43673-022-00064-1>
- F. An, D. Bai, H. Cai et al., High-precision physics experiments at huizhou large-scale scientific facilities. Chin. Phys. Lett. **42**, 110102 (2025). <https://doi.org/10.1088/0256-307X/42/11/110102>
- B. Holdom, Two $U(1)$'s and e charge shifts. Phys. Lett. B **166**, 196–198 (1986). [https://doi.org/10.1016/0370-2693\(86\)91377-8](https://doi.org/10.1016/0370-2693(86)91377-8)
- P. Galison, A. Manohar, Two Z 's or not two Z 's? Phys. Lett. B **136**, 279–283 (1984). [https://doi.org/10.1016/0370-2693\(84\)91161-4](https://doi.org/10.1016/0370-2693(84)91161-4)
- P. Fayet, Extra $U(1)$'s and new forces. Nucl. Phys. B **347**, 743–768 (1990). [https://doi.org/10.1016/0550-3213\(90\)90381-M](https://doi.org/10.1016/0550-3213(90)90381-M)
- C.P. Burgess, M. Pospelov, T. ter Veldhuis, The minimal model of nonbaryonic dark matter: a singlet scalar. Nucl. Phys. B **619**, 709–728 (2001). [https://doi.org/10.1016/S0550-3213\(01\)00513-2](https://doi.org/10.1016/S0550-3213(01)00513-2)
- D. O'Connell, M.J. Ramsey-Musolf, M.B. Wise, Minimal extension of the standard model scalar sector. Phys. Rev. D **75**, 037701 (2007). <https://doi.org/10.1103/PhysRevD.75.037701>
- H. Georgi, D.B. Kaplan, L. Randall, Manifesting the invisible axion at low-energies. Phys. Lett. B **169**, 73–78 (1986). [https://doi.org/10.1016/0370-2693\(86\)90688-X](https://doi.org/10.1016/0370-2693(86)90688-X)
- D. Aloni, Y. Soreq, M. Williams, Coupling QCD-scale axion-like particles to gluons. Phys. Rev. Lett. **123**, 031803 (2019). <https://doi.org/10.1103/PhysRevLett.123.031803>
- G. Landini, E. Meggiolaro, Study of the interactions of the axion with mesons and photons using a chiral effective Lagrangian model. Eur. Phys. J. C **80**, 302 (2020). <https://doi.org/10.1140/epjc/s10052-020-7849-2>
- F. Ambrosino, A. Antonelli, M. Antonelli et al., Measurement of the branching ratio and search for a CP violating asymmetry in the $\eta \rightarrow \pi^+ \pi^- e^+ e^- (\gamma)$ decay at KLOE. Phys. Lett. B **675**, 283–288 (2009). <https://doi.org/10.1016/j.physletb.2009.04.013>
- S. Gardner, J. Shi, Patterns of CP violation from mirror symmetry breaking in the $\eta \rightarrow \pi^+ \pi^- \pi^0$ Dalitz plot. Phys. Rev. D **101**, 115038 (2020). <https://doi.org/10.1103/PhysRevD.101.115038>
- J. Shi, J. Liang, S. Gardner, Revisiting C and CP violation in $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay. Phys. Rev. D **110**, 055039 (2024). <https://doi.org/10.1103/PhysRevD.110.055039>
- P. Sanchez-Puertas, CP violation in η muonic decays. JHEP **01**, 031 (2019). [https://doi.org/10.1007/JHEP01\(2019\)031](https://doi.org/10.1007/JHEP01(2019)031)
- B.C. Liu, B.S. Zou, Mass and $K\Lambda$ coupling of the $N^*(1535)$. Phys. Rev. Lett. **96**, 042002 (2006). <https://doi.org/10.1103/PhysRevLett.96.042002>
- S.M. Wu, F. Wang, B.S. Zou, Strange molecular partners of P_c states in the $\gamma p \rightarrow \phi p$ reaction. Phys. Rev. C **108**, 045201 (2023). <https://doi.org/10.1103/PhysRevC.108.045201>
- J. He, Nucleon resonances $N(1875)$ and $N(2100)$ as strange partners of LHCb pentaquarks. Phys. Rev. D **95**, 074031 (2017). <https://doi.org/10.1103/PhysRevD.95.074031>
- X.Y. Wang, H.F. Zhou, X. Liu, Prospects for detecting the hidden-strange pentaquarklike state $N^*(2080)$ in the $\pi^- p \rightarrow \phi n$ reaction. Phys. Rev. D **110**, 014026 (2024). <https://doi.org/10.1103/PhysRevD.110.014026>
- X.Y. Wang, Y. Gao, X. Liu, Production potential of hidden-strange molecular pentaquarks through the $\pi^- p \rightarrow K^* \Sigma$ process. Phys. Rev. D **111**, 034021 (2025). <https://doi.org/10.1103/PhysRevD.111.034021>
- H. Clement, On the history of dibaryons and their final observation. Prog. Part. Nucl. Phys. **93**, 195 (2017). <https://doi.org/10.1016/j.ppnp.2016.12.004>
- Y. Dong, F. Huang, P. Shen et al., On the decays of d (2380) in a constituent chiral quark model. Chin. Phys. C **41**, 101001 (2017). <https://doi.org/10.1088/1674-1137/41/10/101001>
- A. Aloisio et al., The KLOE detector: technical proposal. Technical proposal. LNF-93/002 (1993)
- M. Ablikim, Z.H. An, J.Z. Bai et al., Design and construction of the BESIII detector. Nucl. Instrum. Meth. A **614**, 345–399 (2010). <https://doi.org/10.1016/j.nima.2009.12.050>
- R. Essig, J.A. Jaros, W. Wester et al., Dark sectors and new, light, weakly-coupled particles. 2013. arXiv:1311.0029

26. G. Bertone, D. Hooper, J. Silk, Particle dark matter: evidence, candidates and constraints. *Phys. Rept.* **405**, 279–390 (2005). <https://doi.org/10.1016/j.physrep.2004.08.031>
27. S. Navas, C. Amsler, T. Gutsche et al., Review of particle physics. *Phys. Rev. D* **110**, 030001 (2024). <https://doi.org/10.1103/PhysRevD.110.030001>
28. M. Drees, F.A. Gomes Ferreira, A very heavy sneutrino as viable thermal dark matter candidate in $U(1)'$ extensions of the MSSM. *M. J. High Energ. Phys.* **2019**, 167 (2019). [https://doi.org/10.1007/JHEP04\(2019\)167](https://doi.org/10.1007/JHEP04(2019)167)
29. A. Banik, M. Drees, Non-thermal WIMP production from higher order moduli decay. *JCAP* **12**, 032 (2023). <https://doi.org/10.1088/1475-7516/2023/12/032>
30. L. Gan, B. Kubis, E. Passemar et al., Precision tests of fundamental physics with η and η' mesons. *Phys. Rept.* **945**, 1–105 (2022). <https://doi.org/10.1016/j.physrep.2021.11.001>
31. Q. Gao, D. Lin, H. Liu et al., Dark photons and axion-like particles at the electron-ion collider in China. *J. High Energ. Phys.* **2025**, 070 (2025). [https://doi.org/10.1007/JHEP06\(2025\)070](https://doi.org/10.1007/JHEP06(2025)070)
32. X. Ding, Dark photon and Axion-like particle search at BESIII. *EPI Web Conf.* **303**, 05002 (2024). <https://doi.org/10.1051/epjconf/202430305002>
33. G. Alonso-Álvarez, J. Jaeckel, D.D. Lopes, Tracking axion-like particles at the LHC [arXiv:2302.12262](https://arxiv.org/abs/2302.12262)
34. D.B. White, W.B. Tipples, R. Abegg et al., Search for the decays $\eta \rightarrow \mu e$ and $\eta \rightarrow e^+ e^-$. *Phys. Rev. D* **53**, 6658–6661 (1996). <https://doi.org/10.1103/PhysRevD.53.6658>
35. P. Adlarson et al., Search for C violation in the decay $\eta \rightarrow \pi^0 + e^+ + e^-$ with WASA-at-COSY. *Phys. Lett. B* **784**, 378–384 (2018). <https://doi.org/10.1016/j.physletb.2018.07.017>
36. R. Aaij, A.S.W. Abdelmotteleb, C.o. Abellan Beteta, Production of η and η' mesons in pp and pPb collisions. *Phys. Rev. C* **109**, 024907 (2024). <https://doi.org/10.1103/PhysRevC.109.024907>
37. R. Aaij et al., Search for the CP -violating strong decays $\eta \rightarrow \pi^+ \pi^-$ and $\eta'(958) \rightarrow \pi^+ \pi^-$. *Phys. Lett. B* **764**, 233–240 (2017). <https://doi.org/10.1016/j.physletb.2016.11.032>
38. M. Ablikim, M.N. Achasov, P. Adlarson et al., Measurement of the absolute branching fractions of $J/\psi \rightarrow \gamma \eta$ and η decay modes. *Phys. Rev. D* **104**, 092004 (2021). <https://doi.org/10.1103/PhysRevD.104.092004>
39. M. Ablikim, M.N. Achasov, X.C. Ai et al., Measurement of the matrix elements for the decays $\eta \rightarrow \pi^+ \pi^- \pi^0$ and $\eta/\eta' \rightarrow \pi^0 \pi^0 \pi^0$. *Phys. Rev. D* **92**, 012014 (2015). <https://doi.org/10.1103/PhysRevD.92.012014>
40. V.L. Kashevarov, P. Ott, S. Prakhov et al., Study of η and η' photoproduction at MAMI. *Phys. Rev. Lett.* **118**, 212001 (2017). <https://doi.org/10.1103/PhysRevLett.118.212001>
41. J. Elam, et al., The REDTOP experiment: Rare η/η' Decays To Probe New Physics. [arXiv:2203.07651](https://arxiv.org/abs/2203.07651)
42. X. Chen, X. He, Q. Hu et al., Plan for a super η factory at Huizhou accelerator complex. *Nucl. Sci. Tech.* **36**, 137 (2025). <https://doi.org/10.1007/s41365-025-01708-1>
43. S. Godfrey, J. Napolitano, Light meson spectroscopy. *Rev. Mod. Phys.* **71**, 1411 (1999). <https://doi.org/10.1103/PhysRevD.110.030001>
44. A. Thiel, F. Afzal, Y. Wunderlich, Light baryon spectroscopy. *Prog. Part. Nucl. Phys.* **125**, 103949 (2022). <https://doi.org/10.1016/j.pnpnp.2022.103949>
45. X. Wang, X. Liu, Development status and future plan of meson beam experiments at home and abroad. *Nucl. Phys. Rev.* **42**, 10–24 (2025). <https://doi.org/10.11804/NuclPhysRev.42.202408>
46. N. Muramatsu, S.K. Wang, Q.H. He, et al., First measurement of differential cross sections and photon beam asymmetries for photoproduction of the $f_0(980)$ meson decaying into $\pi^0 \pi^0$ at $E_{\gamma}/t; 2.4$ gev. *Phys. Rev. C* **107**, L042201 (2023). <https://doi.org/10.1103/PhysRevC.107.L042201>
47. B.S. Zou, Complementary studies on N^* from $e^+ e^-$, pp and p anti- p collisions. *Chin. Phys. C* **33**, 1113–1119 (2009). <https://doi.org/10.1088/1674-1137/33/12/011>
48. D. Ronchen, M. Doring, F. Huang et al., Coupled-channel dynamics in the reactions $\pi N \rightarrow \pi N$, ηN , $K\Lambda$, $K\Sigma$. *Eur. Phys. J. A* **49**, 44 (2013). <https://doi.org/10.1140/epja/i2013-13044-5>
49. H. Kamano, S.X. Nakamura, T.S.H. Lee et al., Nucleon resonances within a dynamical coupled-channels model of πN and γN reactions. *Phys. Rev. C* **88**, 035209 (2013). <https://doi.org/10.1103/PhysRevC.88.035209>
50. Y.F. Wang, D. Rönchen, U.G. Meißner, et al., Reaction $\pi N \rightarrow \omega N$ in a dynamical coupled-channel approach. *Phys. Rev. D* **106**, 094031 (2022). <https://doi.org/10.1103/PhysRevD.106.094031>
51. A. Matsuyama, T. Sato, T.S.H. Lee, Dynamical coupled-channel model of meson production reactions in the nucleon resonance region. *Phys. Rept.* **439**, 193–253 (2007). <https://doi.org/10.1016/j.physrep.2006.12.003>
52. K. Aoki, et al., Extension of the J-PARC hadron experimental facility: Third White Paper. [arXiv:2110.04462](https://arxiv.org/abs/2110.04462)
53. M. Amarian, et al., Strange hadron spectroscopy with secondary KL beam in hall D. [arXiv:2008.08215](https://arxiv.org/abs/2008.08215)
54. H. Kamano, S.X. Nakamura, T.S.H. Lee, et al., Dynamical coupled-channels model of $K^- p$ reactions. II. Extraction of Λ^* and Σ^* hyperon resonances. *Phys. Rev. C* **92**, 025205 (2015). [Erratum: *Phys. Rev. C* **95**, 049903 (2017)]. <https://doi.org/10.1103/PhysRevC.92.025205>
55. J.J. Wu, S. Dulat, B.S. Zou, Evidence for a new Sigma* resonance with $J^{*}P = 1/2^-$ in the old data of $K^- p \rightarrow \Lambda \pi^+ \pi^-$ reaction. *Phys. Rev. D* **80**, 017503 (2009). <https://doi.org/10.1103/PhysRevD.80.017503>
56. Q.Y. Guo, J. Liu, P.w. Wu, et al., $\Xi(1530)$ production in $K^- p$ scattering process. <http://arxiv.org/abs/2507.02232> [arXiv:2507.02232](https://arxiv.org/abs/2507.02232)
57. Q.Y. Guo, Z.L. Yue, D.Y. Chen, $\Xi(1620)^-$ production in $K^- p$ scattering process. *Eur. Phys. J. C* **84**, 380 (2024). <https://doi.org/10.1140/epjc/s10052-024-12754-1>
58. P. Gao, J. Shi, B.S. Zou, Σ resonances from $K^- N \rightarrow \pi \Lambda$ reactions with the center of mass energy from 1550 to 1676 MeV. *Phys. Rev. C* **86**, 025201 (2012). <https://doi.org/10.1103/PhysRevC.86.025201>
59. J. Shi, B.S. Zou, Theoretical study of Λ resonances from an analysis of Crystal Ball $K^- p \rightarrow \pi^0 \Sigma^0$ reaction data with center-of-mass energies of 1536–1676 MeV. *Phys. Rev. C* **91**, 035202 (2015). <https://doi.org/10.1103/PhysRevC.91.035202>
60. J. Adams, M. Aggarwal, Z. Ahammed et al., Experimental and theoretical challenges in the search for the quark gluon plasma: the STAR collaboration's critical assessment of the evidence from RHIC collisions. *Nucl. Phys. A* **757**, 102–183 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.03.085>
61. K. Adcox, S.S. Adler, S. Afanasiev et al., Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX collaboration. *Nucl. Phys. A* **757**, 184–283 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.03.086>
62. B.B. Back, M. Baker, M. Ballintijn et al., The PHOBOS perspective on discoveries at RHIC. *Nucl. Phys. A* **757**, 28–101 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.03.084>
63. I. Arsene, I. Bearden, D. Beavis et al., Quark gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment. *Nucl. Phys. A* **757**, 1–27 (2005). <https://doi.org/10.1016/j.nuclphysa.2005.02.130>

64. W.j. Fu, J.M. Pawlowski, F. Rennecke, QCD phase structure at finite temperature and density. *Phys. Rev. D* **101**, 054032 (2020). <https://doi.org/10.1103/PhysRevD.101.054032>
65. STAR collaboration, Precision measurement of (net-)proton number fluctuations in Au+Au collisions at RHIC. (2025). [arXiv:2504.00817](https://arxiv.org/abs/2504.00817)
66. V. Golovatyuk, V. Kekelidze, V. Kolesnikov et al., The multi-purpose detector (MPD) of the collider experiment. *Eur. Phys. J. A* **52**, 212 (2016). <https://doi.org/10.1140/epja/i2016-16212-1>
67. T. Ablyazimov, A. Abuhoza, R. Adak et al., Challenges in QCD matter physics -The scientific programme of the compressed baryonic matter experiment at FAIR. *Eur. Phys. J. A* **53**, 60 (2017). <https://doi.org/10.1140/epja/i2017-12248-y>
68. M.A. Stephanov, QCD critical point and event-by-event fluctuations. *J. Phys. G Nucl. Part. Phys.* **38**, 124147 (2011). <https://doi.org/10.1088/0954-3899/38/12/124147>
69. M. Hippert, J. Grefa, T.A. Manning et al., Bayesian location of the QCD critical point from a holographic perspective. *Phys. Rev. D* **110**, 094006 (2024). <https://doi.org/10.1103/PhysRevD.110.094006>
70. D. Lonardonì, A. Lovato, S. Gandolfi et al., Hyperon puzzle: hints from quantum monte carlo calculations. *Phys. Rev. Lett.* **114**, 092301 (2015). <https://doi.org/10.1103/PhysRevLett.114.092301>
71. E. Annala, T. Gorda, J. Hirvonen et al., Strongly interacting matter exhibits deconfined behavior in massive neutron stars. *Nat. Commun.* **14**, 8451 (2023). <https://doi.org/10.1038/s41467-023-44051-y>
72. A. Andronic, P. Braun-Munzinger, J. Stachel et al., Production of light nuclei, hypernuclei and their antiparticles in relativistic nuclear collisions. *Phys. Lett. B* **697**, 203 (2011). <https://doi.org/10.1016/j.physletb.2011.01.053>
73. Z.Q. Feng, Formation and dynamics of exotic hypernuclei in heavy-ion collisions. *Phys. Rev. C* **102**, 044604 (2020). <https://doi.org/10.1103/PhysRevC.102.044604>
74. Z.Q. Feng, Extracting the hyperon-nucleon interaction via collective flows in heavy-ion collisions. *Phys. Lett. B* **851**, 138580 (2024). <https://doi.org/10.1016/j.physletb.2024.138580>
75. S.N. Wei, Z.Q. Feng, W.Z. Jiang, Correlation of the hyperon potential stiffness with hyperon constituents in neutron stars and heavy-ion collisions. *Phys. Lett. B* **853**, 138658 (2024). <https://doi.org/10.1016/j.physletb.2024.138658>
76. I. Valin, C. Hu-Guo, J. Baudot et al., A reticle size CMOS pixel sensor dedicated to the STAR HFT. *J. Instrum.* **7**, C01102 (2012). <https://doi.org/10.1088/1748-0221/7/01/C01102>
77. M. Mager, ALPIDE, the monolithic active pixel sensor for the ALICE ITS upgrade. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **824**, 434–438 (2016). <https://doi.org/10.1016/j.nima.2015.09.057>
78. W. Snoeys, CMOS monolithic active pixel sensors for high-energy physics. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **765**, 167–171 (2014). <https://doi.org/10.1016/j.nima.2014.07.017>
79. G. Contin, E. Anderssen, L. Greiner et al., The STAR Heavy Flavor Tracker (HFT): focus on the MAPS based PXL detector. *Nucl. Part. Phys. Proc.* **273–275**, 1155–1159 (2016). <https://doi.org/10.1016/j.nuclphysbps.2015.09.181>
80. T. Kugathasan, Review on depleted CMOS. *PoS* 2018, 042 (2019). <https://doi.org/10.22323/1.348.0042>
81. G. Aglieri Rinella, G. Alocco, M. Antonelli et al., Characterization of analogue Monolithic Active Pixel Sensor test structures implemented in a 65 nm CMOS imaging process. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **1069**, 169896 (2024). <https://doi.org/10.1016/j.nima.2024.169896>
82. R. Turchetta, J.D. Berst, B. Casadei et al., A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **458**, 677–689 (2001). [https://doi.org/10.1016/S0168-9002\(00\)00893-7](https://doi.org/10.1016/S0168-9002(00)00893-7)
83. R. Turchetta, P. Allport, G. Casse et al., CMOS Monolithic Active Pixel Sensors (MAPS): New 'eyes' for science. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **560**, 139–142 (2006). <https://doi.org/10.1016/j.nima.2005.11.241>
84. G. Contin, L. Greiner, J. Schambach et al., The STAR MAPS-based pixel detector. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **907**, 60–80 (2018). <https://doi.org/10.1016/j.nima.2018.03.003>
85. L. Greiner, E. Anderssen, H. Matis et al., A maps based vertex detector for the star experiment at RHIC. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **650**, 68–72 (2011). <https://doi.org/10.1016/j.nima.2010.12.006>
86. D. Colella, Applications of CMOS Technology at the ALICE Experiment. *PoS* 2023, 120 (2025). <https://doi.org/10.22323/1.468.0120>
87. M. Deveaux, B. Arnoldi-Meadows, G. Bertolone et al., Observations on mimosi-0, the first dedicated CPS prototype for the CBM MVD. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **958**, 162653 (2020). <https://doi.org/10.1016/j.nima.2019.162653>
88. M. Deveaux, A.M. Altingun, J. Andary et al., In beam performances of the mimosi-2.1 CMOS monolithic active pixel sensor. (2025). <http://arxiv.org/abs/2502.05303>
89. K. Arndt, H. Augustin, P. Baesso et al., Technical design of the phase I Mu3e experiment. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **1014**, 165679 (2021). <https://doi.org/10.1016/j.nima.2021.165679>
90. I. Peric, M. Prathapan, H. Augustin et al., A high-voltage pixel sensor for the atlas upgrade. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **924**, 99–103 (2019). <https://doi.org/10.1016/j.nima.2018.06.060>
91. M. Prathapan, R. Schimassek, M. Benoit et al., ATLASpix3 : A high voltage CMOS sensor chip designed for ATLAS Inner Tracker. in *Topical Workshop on Electronics for Particle Physics*, 2019, p. 10. <https://doi.org/10.22323/1.370.0010>
92. J. Kröger, Silicon pixel sensor ramp; d for the clic tracking detector. *J. Instrum.* **15**, C08005 (2020). <https://doi.org/10.1088/1748-0221/15/08/C08005>
93. A. Schöning, J. Anders, H. Augustin et al., Mupix and atlaspix – architectures and results. (2020). [arXiv:2002.07253](https://arxiv.org/abs/2002.07253)
94. R. He, X.Y. Niu, R. Yin et al., Nupix-H2: A MAPS with multidimensional measurements for the china hyper-nuclear spectrometer. *IEEE T. Nucl. Sci.* **72**, 584–590 (2025). <https://doi.org/10.1109/TNS.2024.3467067>
95. M. Tornago, R. Arcidiacono, N. Cartiglia et al., Resistive AC-coupled silicon detectors: Principles of operation and first results from a combined analysis of beam test and laser data. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **1003**, 165319 (2021). <https://doi.org/10.1016/j.nima.2021.165319>
96. W. Sun, M. Li, Z. Liang et al., The performance of AC-coupled strip LGAD developed by IHEP. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **1062**, 169203 (2024). <https://doi.org/10.1016/j.nima.2024.169203>
97. C. Gatto, G.C. Blazey, A. Dychkant et al., Preliminary results from ADRIANO2 test beams. *Instruments* **6**, 49 (2022). <https://doi.org/10.3390/instruments6040049>
98. N. Akchurin, F. Bedeschi, A. Cardini et al., Particle identification in the longitudinally unsegmented RD52 calorimeter. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **735**, 120–129 (2014). <https://doi.org/10.1016/j.nima.2013.09.024>
99. Z. Sheemanto, C. Gatto, ADRIANO2 Calorimeter performance from 2022 Prototypes
100. A. Ferrari, P.R. Sala, A. Fasso et al., FLUKA: A multi-particle transport code (Program version 2005). <https://doi.org/10.2172/877507>

101. O. Buss, T. Gaitanos, K. Gallmeister et al., Transport-theoretical description of nuclear reactions. *Phys. Rept.* **512**, 1–124 (2012). <https://doi.org/10.1016/j.physrep.2011.12.001>
102. J. Allison, K. Amako, J. Apostolakis et al., Recent developments in geant4. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **835**, 186–225 (2016). <https://doi.org/10.1016/j.nima.2016.06.125>
103. J. Allison, K. Amako, J. Apostolakis et al., Geant4 developments and applications. *IEEE Trans. Nucl. Sci.* **53**, 270–278 (2006). <https://doi.org/10.1109/TNS.2006.869826>
104. S. Agostinelli, J. Allison, K. Amako et al., Geant4—a simulation toolkit. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **506**, 250–303 (2003) [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
105. M. Antonello, M. Caccia, R. Ferrari et al., Dual-readout calorimetry, an integrated high-resolution solution for energy measurements at future electron–positron colliders. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **958**, 162063 (2020). <https://doi.org/10.1016/j.nima.2019.04.017>
106. I. Pezzotti, H. Newman, J. Freeman et al., Dual-readout calorimetry for future experiments probing fundamental physics. <http://arxiv.org/abs/2203.04312>
107. C. Gatto, V. Di Benedetto, A. Mazzacane, A review of the multiple-readout concept and its application in an integrally active calorimeter. *Instruments* **8**, 49 (2024). <https://doi.org/10.3390/instruments8040049>
108. N. Akchurin, M. Alwarawrah, A. Cardini et al., Neutron signals for dual-readout calorimetry. *Nucl. Instrum. Meth. Phys. Res. Sect. A* **598**, 422–431 (2009). <https://doi.org/10.1016/j.nima.2008.09.045>

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Xu-Rong Chen^{1,2,3} · Yun-Yun Fan^{4,5} · Shuang-Shi Fang^{4,5,6} · Zhao-Qing Feng^{1,7}  · Feng-Kun Guo^{3,5,8}  · Wei-Jia Han¹ · Jun He⁹ · Qing-Hua He¹⁰ · Xiong-Hong He^{1,2}  · Hong-Xia Huang⁹  · Xiao-Lin Kang¹¹ · Hong-Li Ma¹² · Wei-Hu Ma¹³ · Yong-Liang Ma¹⁴ · Norihito Muramatsu¹ · Zaiba Mushtaq^{1,2} · Xiao-Yang Niu^{1,2}  · Jia-Lun Ping⁹ · Hao Qiu^{1,2}  · Jun Shi^{15,16}  · Ye Tian¹ · Qian Wang^{15,16} · Rong Wang^{1,2}  · Shuai-Chun Wang¹³ · Xiao-Yun Wang¹⁷ · Jia-Jun Wu^{3,5} · Chu-Wen Xiao¹⁸ · Ju-Jun Xie^{1,2,5} · Hai-Bo Yang^{1,2}  · Xie-Yang Yu^{1,2} · Hong-Lin Zhang¹  · Sheng-Hui Zhang¹²  · Cheng-Xin Zhao¹⁹  · Kuang-Ta Chao²⁰ · Qiang Zhao⁴ · Bing-Song Zou²¹

✉ Hao Qiu
qiu@impcas.ac.cn

¹ State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

² School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China

³ Southern Center for Nuclear Science Theory (SCNT), Institute of Modern Physics, Chinese Academy of Sciences, Huizhou 516000, China

⁴ Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

⁵ School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

⁶ Center for High Energy Physics, Henan Academy of Sciences, Zhengzhou 450046, China

⁷ School of Physics and Optoelectronics, South China University of Technology, Guangzhou 510640, China

⁸ Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China

⁹ Department of Physics, Nanjing Normal University, Nanjing 210023, China

¹⁰ Department of Nuclear Science and Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

¹¹ School of Mathematics and Physics, China University of Geosciences, Wuhan 430074, China

¹² Chongqing Key Laboratory for Strongly Coupled Physics, Department of Physics, Chongqing University, Chongqing 401331, China

¹³ Institute of Modern Physics, Fudan University, Shanghai 200433, China

¹⁴ School of Frontier Sciences, Nanjing University, Suzhou 215163, China

¹⁵ State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China

¹⁶ Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong Basic Research Center of Excellence for Structure and Fundamental Interactions of Matter, Guangzhou 510006, China

¹⁷ Department of Physics, Lanzhou University of Technology, Lanzhou 730050, China

¹⁸ Department of Physics, Guangxi Normal University, Guilin 541004, China

¹⁹ School of Integrated Circuits, Jiangnan University, Wuxi 214401, China

²⁰ School of Physics and Center for High Energy Physics, Peking University, Beijing 100871, China

²¹ Department of Physics and Center for High Energy Physics, Tsinghua University, Beijing 100084, China