Few-Body Syst (2026) 67:17
https://doi.org/10.1007/s00601-026-02035-w

Jenny Taylor

Hadron Physics Opportunities at FAIR with Proton and Pion Beams

Received: 14 January 2026 / Accepted: 2 March 2026

Abstract The Facility for Antiproton and Ion Research (FAIR) is a nuclear physics facility currently under construction at GSI in Germany, aimed at advancing fundamental research. FAIR will enable novel studies of matter under extreme conditions, replicating the environments found in neutron stars and their mergers. In addition, one of FAIR's scientific missions is to explore the exotic landscape and the properties of nuclei containing strangeness, *i.e.* hypernuclei. Connected to this, FAIR offers opportunities for hadron physics research, enabling the study of strongly interacting matter in the field of non-perturbative QCD using, in particular, high-intensity proton and pion beams. Integrating hadron, heavy-ion, and nuclear physics in one facility allows to probe matter from multiple angles with shared and versatile detector systems. This proceeding outlines the capabilities of FAIR for fundamental hadron physics research, presenting both the infrastructure and key highlights of the physics program. An overview of studies aimed at understanding *e.g.* baryon interactions is given and preliminary results from ongoing feasibility studies are presented.

1 Introduction

FAIR (Facility for Antiproton and Ion Research) is a next generation facility currently under construction at GSI in Germany [1]. With versatile detector systems and an advanced series of beamlines, FAIR will tackle challenging questions in the field of strong interactions, both within heavy-ion physics, hadron physics and nuclear physics. In the bigger picture, these fields aim to answer questions about matter in the universe, where the most extreme types of matter is formed. An overview of the accelerator complex can be seen in Fig. 1. The blue lines indicate the accelerators of the existing GSI facility, including the lower energy accelerator ring SIS18, and the red lines represent the new additions of FAIR, including the SIS100 accelerator, boosting up the energy and intensity of proton, deuteron, and heavy-ion beams. One unique feature of FAIR that sets it apart from other facilities is its ability to perform heavy-ion physics and hadron physics with the same detector setups. Recently, a new hadron physics program, "QCD at FAIR", has developed that puts a strong focus on the elementary reactions with more current and future detector systems than before to extract information about QCD in the non-pertutbative regime.

2 A Roadmap Towards Realizing "QCD at FAIR"

Like all major projects, FAIR and the "QCD at FAIR" program, will be realized in stages. The following section gives an overview of the current and upcoming stages of its realization.

J. Taylor (✉)
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany
E-mail: j.taylor@gsi.de

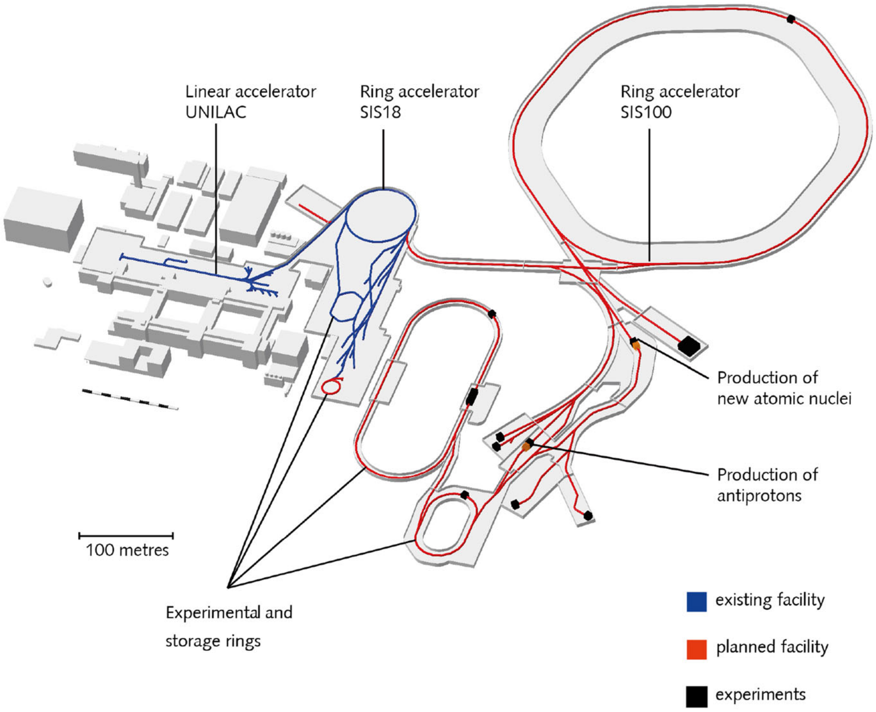

Fig. 1 Overview of GSI and FAIR. The blue lines represent the currently existing facility and the red lines mark the new additions. Figure taken from Ref [2]

2.1 From SIS18 to SIS100

SIS100 in addition to the already existing SIS18 will allow an increase in energy and thereby cross-sections of interesting processes of hadrons with strangeness contents such as double strangeness systems. With SIS18 energies, one is able to produce hadron with double strangeness close to its production threshold with a very limited yield in elementary proton-proton collisions. Increasing the maximum kinetic energy of the proton beam from T=4.5 GeV to T=29.0 GeV provides access to processes such as triple strangeness and hidden- and open-charm rich hadrons.

The first stage of realizing “QCD at FAIR", depicted by the three-color diagram on the left-bottom of Fig. 2, is already ongoing. This includes data-taking with FAIR/GSI experiments by providing a proton or pion beam from the SIS18 accelerator. At this stage, the primary physics topic being investigated concentrates on studying the many-body dynamics in baryon-rich matter. In the near future, the focus will be on studying the elementary meson-baryon system in SU(3) flavor exploiting secondary pion beams including electromagnetic transition form factor studies of light baryons. The second phase consists of performing physics with a higher energy proton beam as provided by SIS100. This enables precision studies of the production mechanisms of baryons and mesons including multi-strangeness and charm. The larger production cross-sections will also enable studies of electromagnetic form factors of excited hyperons. In addition, the composition of baryons will be investigated with a high-energy proton beam from SIS100, *e.g.* the pentaquark states as reported on by LHCb [3,4] will be investigated in the J/Ψ - p system. At a last stage, the composition of hadrons will also be studied with an antiproton beam from HESR (High Energy Storage Ring) which will provide access to *e.g.* gluonic degrees of freedom and exotic states.

To fully utilize the accelerator capabilities, advanced detector systems will be available such as HADES and CBM.

2.2 The HADES Spectrometer

The HADES (High-Acceptance Dielectron Spectrometer) is operating at GSI since 2001 with capabilities to perform physics with a heavy-ion beam as well as an elementary proton and pion beam provided by SIS18

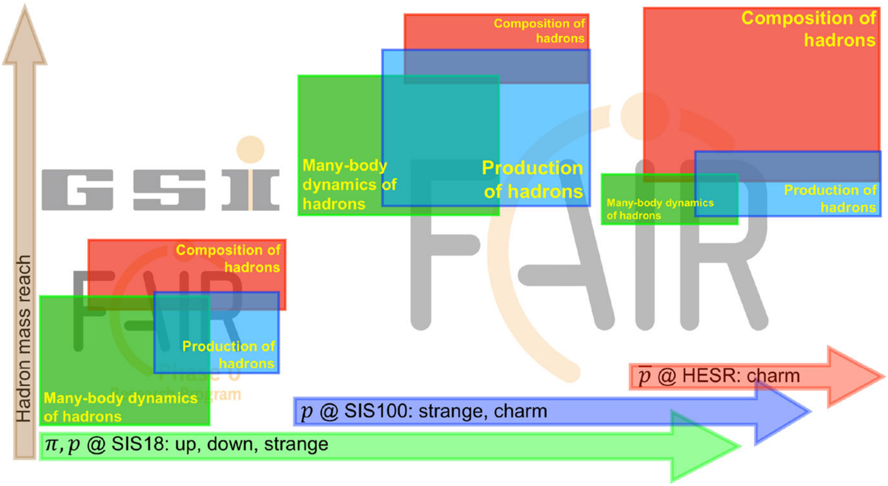

Fig. 2 A roadmap of “QCD at FAIR". The bottom left diagram indicates the current efforts of performing physics with a proton and pion beam delivered by SIS18. The next stage includes a high energy proton beam as provided by SIS100. In a final and future stage, also the composition of hadrons will be studied with antiproton induced reactions as indicated by the red line. The size of the boxes indicates the importance of each topic during the realization of FAIR

[5]. The detector itself excels in identifying di-lepton pairs. These are crucial tools for probing extreme matter since they are created in early stages in the fireball and carry information about the matter without final-state distortion. The detector itself is divided into six sectors. Each of these consist of a RICH detector for lepton identification followed by an advanced tracking system and finally a series of time-of-flight detectors for particle identification. All this is placed within a toroid magnetic field. In polar angle, the spectrometer covers 15°-85°. One important addition is a forward detector with tracking stations based on the PANDA [6] design that was added for a beamtime utilizing a proton beam impinging on a proton target within the FAIR Phase-0 program [7]. The detector covers the region below 7° which is crucial for the detection hyperon decay products.

3 Pion Beams at HADES

The pion beam facility at FAIR is described in detail in Ref. [8]. The beam is created from a primary ion beam from SIS18 impinging on a production target consisting of Be. Next, the beam is transported through a 33.5 m beamline through a series of two de-focusing dipole and nine focusing quadrupole magnets. Throughout the beamline, the beam is tracked using position sensitive pixel detectors. This setup has the potential to create a pion beam with momentum of 0.5-2.5 GeV/c . Finally, the pion beam interacts with a target and the HADES detector detects the scattered particles. HADES has previously taken pion beam data in 2014 with an achieved intensity of 2.2×10^5. Here, an extracted ^{14}N beam and a 10 cm Be target was used for producing the pion beam. An upcoming beamtime is expected to increase the intensity to 10^6 pions/s [9]. Two different reaction targets, a CH_2 and C target, are planned for optimizing the interaction rates at different energies. The physics focus is hyperon production, self-polarisation and electromagnetic transition form factors in the third resonance region.

4 Hypernuclei at HADES

In 2014, a signal sample of about 120 hypertriton events were observed in pion induced reactions. This is expected to increase to around 10000 events in a planned beamtime. HADES also expect to be able to extract the lifetimes and branching ratios which in turn gives access to the formation dynamics of $Y\ N$ states and the interaction [9].

5 Hyperon Physics at HADES

Double-strange systems are being investigated at HADES, such as the $\Lambda\Lambda$ and Ξ^- production. In the case of $\Lambda\Lambda$, extracting the correlation function is of interest which would shed light on the interactions. A commonly used method for extracting 2- or 3-body correlations is femtoscopy, for example as used in Refs. [10,11]. Here, a correlation function is constructed from a source function and the correlated wave function. This method is used for extracting correlations at HADES for particles created in heavy-ion reactions such as the $p\ \Lambda$ interaction. One would also like to apply it for extracting low-energy parameters of $\Lambda\Lambda$ created in proton-proton collisions.

The Ξ^- production is being investigated to explain an enhancement that was observed in sub-threshold heavy ion-collisions, Ar+KCl [12] and in p+Nb [13], as compared to the expectation from transport models. One explanation that was proposed is the presence of higher lying resonances with a significant branching ratio into the Ξ^- decay mode [14]. By observing the Ξ^- created in elementary reactions, it can be concluded if the observed enhancement is due to material effects or due to elementary processes.

Due to the quark content, the cross-sections for the two channels are expected to be the same and a range of predictions currently exists [7]. No signal is observed for the channels so upper limits for the cross-sections are provided. Preliminary upper limits have been set for the cross-sections for $\Lambda\Lambda$ and Ξ^- production. The aim is to perform precision measurements with the high-acceptance future CBM setup in combination with intense proton beams from SIS100 as discussed next.

6 The CBM Spectrometer

The CBM (Compressed Baryonic Matter) spectrometer [15] is a new generation detector that is currently being commissioned. Similar to HADES, it will be performing physics with a heavy-ion beam and proton beam to investigate extreme matter and QCD. However, it has the capabilities to run with much higher interaction rates, 10^7 Hz for Au Au collisions, and higher energies since the beam will be provided by SIS100. To facilitate the reconstruction at such high rates, a free-streaming DAQ will be utilized. For the detector setup itself, a superconducting dipole magnet will be placed around the target region. Particles will be identified by a RICH detector and a time-of-flight detector. Tracking and vertexing will be performed by a silicon tracking system and a micro vertex detector. CBM will cover polar angles 2.5°-25.0°.

7 Hyperon Interaction Studies at CBM

CBM is well suited for studying various aspects of hyperon physics, from production and decay of hyperons to interaction studies. Interaction studies are crucial since information about hadronic interactions are needed for various reasons. In particular, they are crucial for understanding matter effects, not the least the *Hyperon Puzzle of Neutron Stars* [16,17]. Preliminary studies show a high acceptance (as shown in Fig. 3) for many hyperon channels as well as large count rates. CBM is therefore expected to take the interaction studies at FAIR to the next level with higher rates, higher cross-sections and advanced readout system with high-resolution tracking. As is shown in Ref. [7], close to threshold, the cross-sections for single-strangeness production are rapidly increasing. The same behavior is expected for double strange channels.

Given the low production cross-sections of charmed states, the high intensities of SIS100 and high-rate capabilities of CBM are crucial for the measurements of these states. At CBM, the acceptance of the channel $pp \rightarrow \bar{D}^0 \Lambda_c p$ is found to be high and covering a large part of the phase space. This enables studies of the interactions between $\Lambda_c p$ and $\bar{D}^0 p$ among many other topics.

7.1 Interaction Studies with Final State Interactions

An alternative approach to femtoscopy, is utilizing FSI (Final State Interactions), to extract the scattering length, a_0 and effective range r_0 [19] of the baryon-baryon interaction produced in exclusive proton-proton scattering. Compared to femtoscopy, one benefit is that the uncertainty of the source term is eliminated. In addition, uncertainties are straight forward to parametrize and use in a mathematical procedure constrained by unitarity and analyticity. In this approach, dispersion relations can be used that link the real and imaginary part of the amplitude. These relations provide controlled access to the scattering length. The presence of interactions will affect the shape of the invariant mass histogram close to threshold. Therefore, to extract scattering lengths from the models, a framework describing the interactions close to threshold is used that contains the low energy parameters. The larger the scattering length, the greater the impact on the shape of the histogram. This

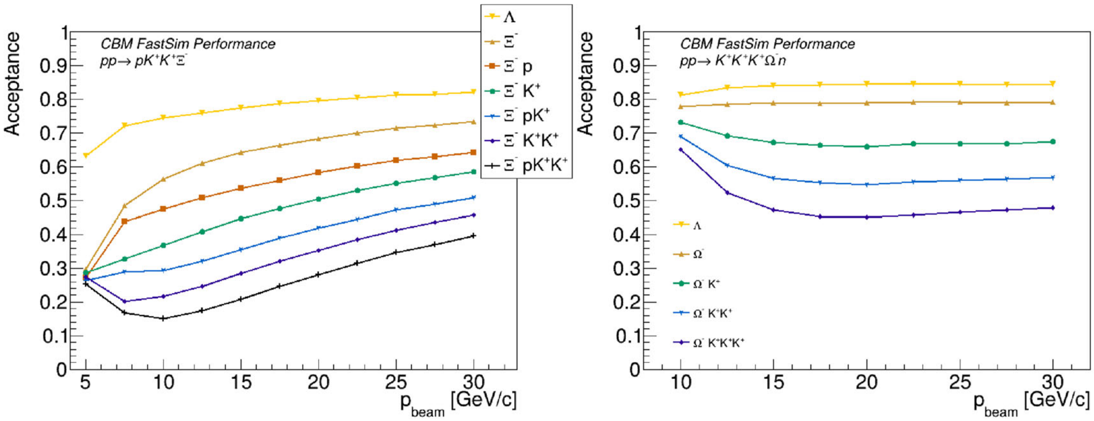

Fig. 3 Acceptances of the simplest double strangeness and tripple strangeness channels at CBM energies as a function of the beam momentum with the Ξ^- production to the left and the s^- production to the right. Different lines correspond to the acceptance of different final-state particles of the reaction with CBM

method can only be used for systems with large enough expected scattering amplitudes given the smearing of the histogram from detector resolution effects. Experimentally, an invariant mass resolution of at least 1/a^2 is needed to reach sufficient sensitivity to extract low-energy parameters. One system with a large enough expected scattering length is $\Sigma^+\Sigma^+$ created in the reaction $pp \to \Sigma^+\Sigma^+K^0K^0$. Here, calculations in chiral effective field theory predicts a_0 = -1.8 fm [18]. The presence of a Coulomb repulsion between the hyperons will distort the signal but a theoretical framework exists for this situation [20]. At CBM it would therefore be interesting to apply the dispersion relation method to this system and extract the scattering length. A missing mass analysis needs to be performed on the system $2\pi^+2\pi^-$, *i.e.* the decay products of the kaons since the Σ^+ mainly decays into the neutral decay mode.

7.2 Cusp Analysis

One promising way of constraining FSI is with the Jost function method. For the production of hidden strangeness such as in proton-proton interactions, the production operator can be viewed as point-like for sufficient energy and momentum transfer. Then, the FSI are described by a Jost function instead of the scattering amplitude. In the vicinity of a two body threshold in another coupled channel, cusp structures are expected to appear. This appears in s-wave coupled channels due to a non-analytic behavior of the S-matrix. Since the cusp is present at the threshold, it is sensitive to the transition strength as well as the coupled scattering lengths between the channel studied and the threshold channel. The system can be described with an effective range expansion that includes the scattering length a_0 and the effective range r_0, which in turn affects the scattering amplitude. By fitting low-energy parameters to the production data from CBM, one would be able to systematically extract the parameters of interest.

This method has previously, for example, been used to determine the $\pi\pi$ [21,22] scattering lengths and the coupeled $N\ D$ [23] scattering length.

In the $pp \to \Lambda\Lambda K^+K^+$ channel, two cusps are expected in the invariant mass histogram, $M(\Lambda\Lambda)$, at the threshold of the $\Xi^0 n$ and $\Xi^- p$ channels at 2.254 GeV/c^2 and 2.260 GeV/c^2 respectively. Chiral effective field theory predicts a_0 = 0.8 fm for $\Lambda\Lambda$ [18]. Simulation studies have been performed to investigate the feasibility of performing a cusp analysis measurement at CBM for this coupled channel, *i.e.* $\Lambda\Lambda$ and ΞN. In the lower mass regions where the cusps are expected, a $\Lambda\Lambda$ invariant mass resolution of 6 MeV/c^2 is reachable as demonstrated by Monte Carlo simulations when using the KinFit software [24] for constraining the system first to the beam-target system (4C) and then performing two additional mass fits for both Λ hyperons. A high 20% efficiency is obtained for the exclusive system. As shown in Fig. 4, the amplitude including the coupling can be distinguished from phase-space even when including the preliminary CBM response.

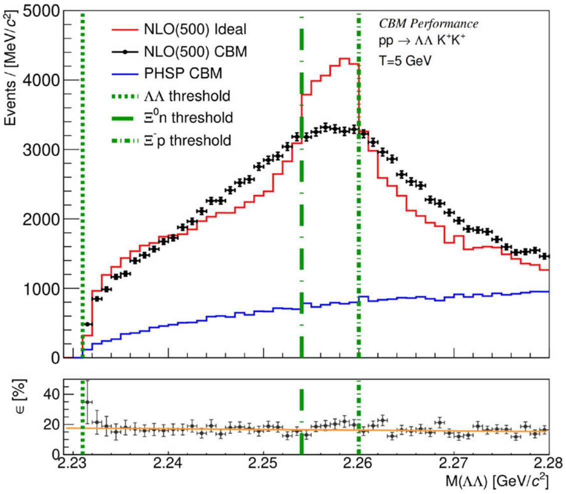

Fig. 4 $\Lambda\Lambda$ invariant mass spectrum (top panel) for three cases, phase space distribution (blue curve), interaction amplitude in NLO calculations (red curve) and the same interaction amplitude smeared with the CBM resolution. The bottom panel shows the acceptance*reconstruction efficiency (ϵ) as a function of the invariant $\Lambda\Lambda$ mass. Three thresholds are marked with green lines, the $\Lambda\Lambda$, the $\Xi^- p$ and $\Xi^0 n$

8 Study of Mesonic Nuclei with WASA at FRS

In addition to the previously mentioned systems, the FRS (FRagment Separator) at FAIR will be used to separate heavy fragments for further analysis [25]. This setup can also be used to identify products from a reaction. The high acceptance spectrometer WASA (Wide Angle Shower Apparatus) [26] is then used for detecting the decay products emitted into a different direction. WASA consists of a 1T superconducting solenoid magnet [27], tracking detectors and scintillator detectors as well as a scintillator electromagnetic calorimeter.

This setup has been used to study mesic nuclei, such as the η'-mesic ^{11}C nuclei [28]. The nuclei are populated by the reaction $^{12}C(p, d)$ where a ^{12}C atom is excited by a proton and emits a deuetron. In this reaction there is a possibility that η'-mesic ^{11}C nuclei are created. Deuterons in the forward direction are analyzed by the FRS and protons in the backward direction measured with the WASA detector. By fitting calculated spectra with varying optical-potential parameters of the interaction, η'-mesic ^{11}C nuclei are observed with a 3.5σ significance [29]. A similar setup, with the inclusion of fiber detector stations, was used to search for hypernuclei, such as the hypertriton. In the future, the Super-FRS [30] will be completed as a larger, superconducting version of the original FRS and with a larger acceptance and transmission rate. It will therefore be able to cope with the higher intensity beams of FAIR. There are currently plans for using WASA there also in the future [28].

9 Summary and Outlook

The physics program of “QCD at FAIR" offers a rich hadron physics program. Interaction studies, especially involving strangeness is one of the main topics. Preliminary studies shows that CBM will be able to measure the cusp effect in the coupled channel $\Lambda\Lambda$ and ΞN. In addition, interactions are studied from different angles such as hypernuclei or mesic nuclei production. A White Paper [31] about the efforts has been prepared and submitted to Progress in Particle and Nuclear Physics. The longer term plans of FAIR also includes physics with an antiproton beam. This will enable the production of double strange hypernuclei using re-scattering for producing low-energy hyperons and absorption in a secondary target [6].

Author Contribution J.T. wrote the manuscript text, prepared Figure 3, and reviewed the manuscript.

DataAvailability Experimental data from the HADES experiment and simulated data from the CBM experiment are used for the analyses reported on in this proceeding. Restrictions on the data availability apply but the data is available upon request and with the permission of the experiment and GSI GmbH and FAIR.

Funding Open Access funding enabled and organized by Projekt DEAL. The publication is funded by the Open Access Publishing Fund of GSI Helmholtzzentrum for heavy ion research.

Declarations

Competing interests The authors declare no competing interests.

References

1. FAIR website: https://fair-center.eu/overview [accessed Nov 11, 2025]
2. FAIR website: https://fair-center.eu/overview/accelerator [accessed Nov 11, 2025]
3. The LHCb Collaboration, Phys. Rev. Lett. **115**, 072001 (2015)
4. The LHCb Collaboration, Phys. Rev. Lett. **122**, 222001 (2019)
5. The HADES Collaboration, Eur. Phys. J. A **41**, 243–277 (2009)
6. The PANDA Collaboration, Eur. Phys. J. A **57**, 44 (2021)
7. The HADES and PANDA@HADES Collaborations, Eur. Phys. J. A **57**, 138 (2021)
8. The HADES Collaboration, Eur. Phys. J. A **53**, 188 (2017)
9. Proposal for Experiments at the GSI Pion Beam Facility, December 2024, Version 0.1, URL: https://hades.gsi.de/node/139
10. The ALICE Collaboration, Phys. Rev. C **99**(2), 024001 (2019)
11. The STAR Collaboration, Phys. Rev. Lett. **114**(2), 022301 (2015)
12. The HADES Collaboration, Phys. Rev. Lett. **103**, 132301 (2009)
13. The HADES Collaboration, Phys. Rev. Lett. **114**, 212301 (2015)
14. J. Steinheimer et al., J. Phys. **G43**, 015104 (2016)
15. The CBM Collaboration, Eur. Phys. J. A **53**, 60 (2017)
16. D. Lonardoni et al., Phys. Rev. Lett. **114**, 092301 (2015)
17. L. Tolos et al., Prog. Part. Nucl. Phys. **112**, 103770 (2020)
18. J. Haidenbauer et al., Nucl. Phys. A **954**, 273–293 (2016)
19. C. Hanhart et al., Phys. Rev. C **69**, 034006 (2004)
20. J. Haidenbauer et al., Phys. Rev. C **72**, 034006 (2005)
21. J.R. Batley et al., Phys. Lett. B **633**, 173–182 (2006)
22. J.R. Batley et al., Eur. Phys. J. C **64**, 589–608 (2009)
23. S. Sakai et al., Phys. Lett. B **808**, 135623 (2020)
24. KinFit Development Group, Comput. Softw. Big. Sci. **8**, 3 (2024)
25. H. Geissel et al., Nucl. Instrum. Methods Phys. Res. B **70**, 286 (1992)
26. C. Bargholtz et al., Nucl. Instrum. Methods Phys. Res. A **594**, 339 (2008)
27. R.J.M.Y. Ruber et al., Nucl. Instrum. Methods Phys. Res. A **503**, 431 (2003)
28. T.R. Saito et al., Nucl. Instrum. Methods Phys. Res. B **542**, 22–25 (2023)
29. Preprint: K. Itahashi *et. al.*, arXiv:2509.07824 [nucl-ex], 9 Sep 2025
30. H. Geissel et al., Nucl. Instrum. Meth. B **204**, 71–85 (2003)
31. Preprint: J. Messchendorp and F. Nerling *et al.* , arXiv:2512.15986 [hep-ex], 17 Nov 2025