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Exploring Matter with Hadronic Beams at GSI and FAIR

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The Facility for Antiproton and Ion Research (FAIR) is the facility for hadron and nuclear physics in Europe, currently under construction at GSI, Germany, aimed at advancing fundamental research. FAIR offers opportunities for hadron physics research, enabling studies of quantum chromodynamics with hadron beams and providing insights into the formation of matter and the fundamental processes underlying dense matter phenomena. The hadron physics research program at FAIR spans a wide range of topics, from structure studies of hyperons and their interactions to the production of "exotic" hadrons containing strangeness and charm as well as measurements of the hadron structure. The integration of hadron physics into one facility together with heavy-ion and nuclear physics offers a unique opportunity for exploring matter from different angles. This proceeding outlines the capabilities of FAIR's facilities for fundamental hadron physics research, presenting both the infrastructure and key highlights of the hadron physics program.

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1. The Facility for Antiproton and Ion Research

The Facility for Antiproton and Ion Research (FAIR) is an upcoming accelerator facility located at the current research complex GSI, close to Darmstadt, Germany [1]. At FAIR, the heavy-ion facilities will, for example, enable the exploration of matter under extreme conditions, replicating the environments found in neutron stars and their mergers. The nuclear physics community aims to investigate the properties and limits of nuclei containing strangeness, *i.e.* hypernuclei. With a parallel operation of beamlines, illustrated in Figure 1, and experiments ranging from nuclear and medical physics, to exploring hadron physics and dense matter, it will be world leading in its field. At GSI, a linear accelerator (the UNILAC) provides a primary beam that is accelerated in the circular synchrotron ring SIS18, which allows for a beam of protons up to $T = 4.5$ GeV kinetic energy or a heavy-ion beam up to 1-2 GeV/u. At the heart of the future expansion is the SIS100 accelerator that will provide the FAIR experiments with a variety of ion beams, as well as protons with up to $T = 29$ GeV.

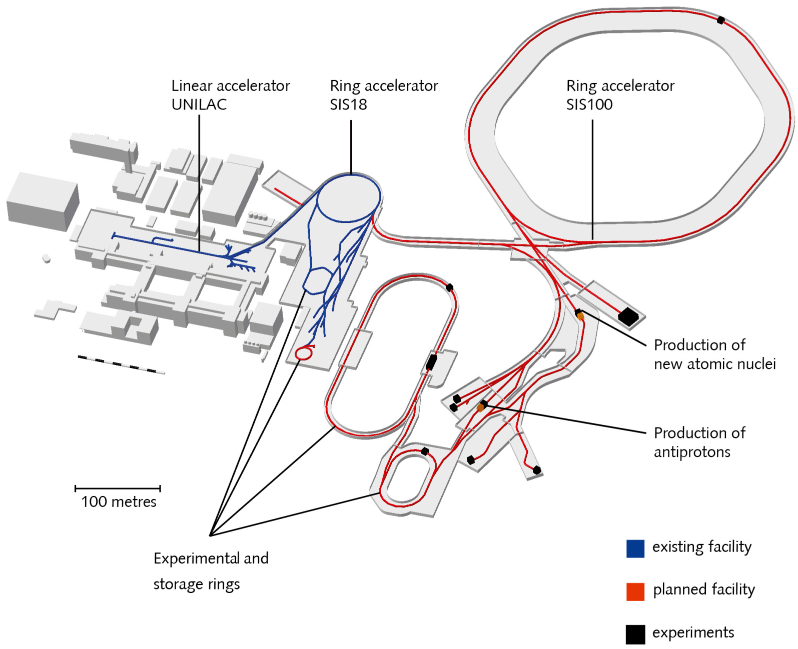

Figure 1: FAIR and GSI in Darmstadt, Germany. The blue lines indicate existing beamlines at GSI and the new beamlines and accelarators at FAIR are shown in red. Figure from ref [2].

The High Acceptance Di-Electron Spectrometer (HADES) detector [3] is an experimental setup operating at SIS18 at GSI. Its main physics topics consist of investigating the QCD phase diagram using dileptons for probing the dense matter as well as strangeness production, decays and interactions. It also takes data with a secondary π^- beam. A sucessor of the physics program, the high granularity Compressed Baryonic Matter (CBM) experiment [4] will operate at world leading heavy-ion collision rates of 10^7 beam particles and up to 400 fully reconstructed tracks per beam-target interaction. In the case of proton-proton collisions, with significantly smaller particle multiplicities, the interaction rates may even exceed 10^7 interactions/s. To facilitate the high interaction rates, a free-streaming data readout and triggering system is being developed [5]. In addition to the detectors and accelerators, GSI hosts the *Green IT Cube*, a high-performance computing center presently with 600 nodes consisting of 54 000 cores and 400 GPUs. The current online storage capacity is about 60 petabyte, which will be increased to 250 petabyte for FAIR operations.

The usage of proton beams is not unique, however, the energy range, intensity and the combination with versatile experimental setups at FAIR make the facility competitive. The current and future global landscape of hadron physics experiments consists of facilities utilizing various probes for investigating the properties of hadrons. At J-PARC [6], extracted proton beams are used for creating pion and kaon beams. Exploiting a beam with strangeness enables a very clean final state when producing strange baryons. JLab [7] as well as MAMI [8] and ELSA [9] extensively use photoproduction. Electron-positron annihilations are used as well for hadron physics purposes, *i.e.*, in the charmonium region with BESIII [10] at IHEP and at bottomonium energy regime at Belle II at KEK [11]. The usage of both proton and heavy-ion induced reactions at intermediate energies that can be measured with the same detector setups, *i.e.* HADES and CBM, at FAIR is a competative feature. In addition, the usage of the HADES experiment with excellent di-lepton measurement capabilities, particularly in combination with pion beams, is unique.

2. A Roadmap towards realizing "QCD at FAIR"

The hadron physics program at FAIR will be realized in different stages as illustrated in Figure 2. The first one consists of data taking with proton and π^- beams from SIS18. FAIR Phase-0 is part of this stage, with detectors developed for future FAIR experiments installed at running experiments. For example, HADES collected data with forward tracking planes based on the PANDA technology, which were crucial for extending the acceptance of the detector for the strangeness physics program [12]. This enables testing of existing subdetectors as well as a valuable contribution to current physics analyses. The data taking has been concluded and the data are currently being analyzed. The second phase, as described in this proceeding, focuses on the intermediate program where physics can be performed with accelerators and detectors available during the phase "First Science +". The proton beam from SIS100 in combination with CBM or part of it will serve as the primary driver for its hadron physics program. The full FAIR facility will be realized with the completion of the high-energy storage ring (HESR) providing an antiproton beam to the PANDA experiment.

The energy upgrade from SIS18 to SIS100 opens up a wide range of production channels including hyperon-antihyperon production, excited hyperon and charm production. In the following, selected examples of forseen physics topics will be discussed here.

3. Interaction Studies

How hadrons interact with each other is an important question to investigate for understanding the dynamics of QCD. Understanding final state interactions and interference effects are crucial aspects also for CP violation studies since CP violation would appear as interference. Hyperon-hyperon (YY), hyperon-nucleon (YN) as well as three-body interactions (YNN) are expected to be important for understanding the interior of neutron stars and will help to resolve the *Hyperon Puzzle of Neutron Stars* [13]. They can be investigated via *femtoscopy*, measuring correlation functions as is done

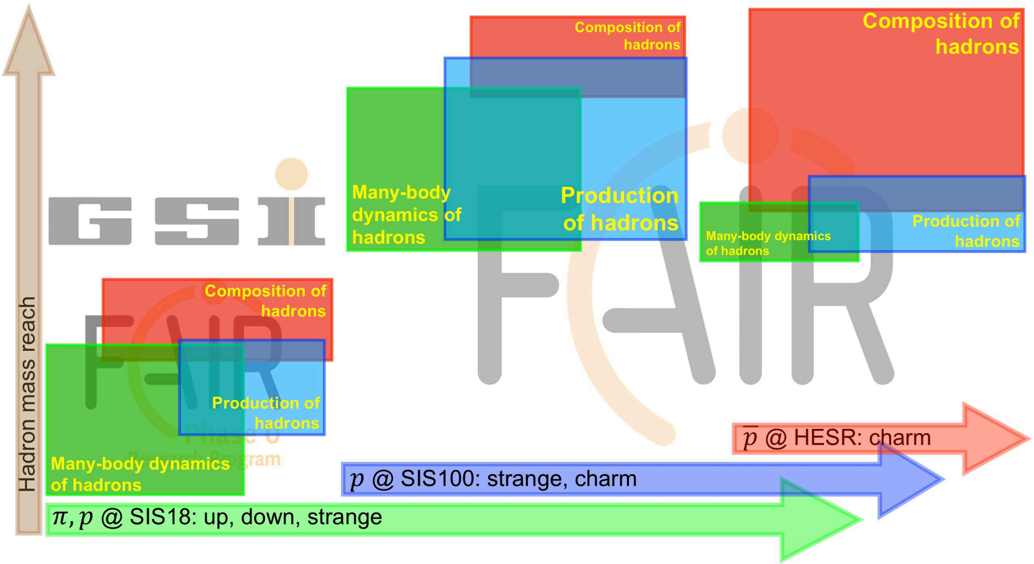

Figure 2: Conceptual map of the physics topics addressed at GSI and FAIR. The QCD@FAIR program constitutes the central part of the timeline.

by ALICE [14, 15] and STAR [16] at higher and HADES at lower energies. One limitation of the femtoscopic method is an assumption on the source, from which the particles are emitted and which enters the formalism. This introduces uncertainties that are difficult to control.

An alternative to femtoscopy that eliminates assumptions on the source function is the Dalitz plot analysis and using dispersion relations to extract the interactions. This is a method that is suitable at large momentum transfers where the scattering length can be extracted from the final state interactions [17, 18]. The method is based on the assumption that there is enough separation between the short range production processes and the long range final state interactions. If the scattering length is large enough so that the data are sensitive to it and the resolution is good enough, then this method is valid. A benefit of this method is that it allows for a systematic determination of the uncertainties through the fit of the theoretical model to data. Here, one interesting channel for CBM is $pp \to \Sigma^+\Sigma^+K^0_SK^0_S$ with a missing mass analysis. The correlation in the $\Sigma^+\Sigma^+$ system is expected to be large [19] and will show up as a distortion of the low mass spectrum with respect to pure phase space distribution.

SIS100 energies allow for the production of charmed mesons such as excited D-mesons and hyperons, *e.g.* Λ_c. The channel $pp \to \bar{D}^0\Lambda_c p$ has a relatively high expected cross section at SIS100 energies [20] and is thus suitable for investigating the $\Lambda_c p$ and $\bar{D}^0 p$ interactions. Monte Carlo simulations of this reaction in the decay channels $\Lambda_c \to K^-\pi^+$ and $\bar{D}_0 \to K^+\pi^-$ have been performed accounting for the acceptance of CBM and considering the case in which all the final-state particles are registered. The resulting Dalitz plot, as shown in Figure 3, has a uniform distribution over the complete phase space, thereby demonstrating that CBM has a nearly uniform coverage with an excellent potential to identify final state interactions in the reaction of interest.

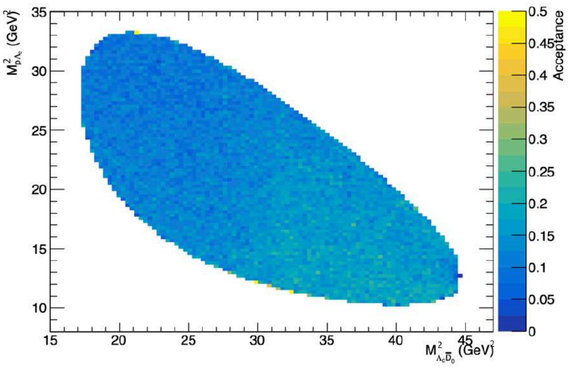

Figure 3: Dalitz plot $M^2(p\Lambda_c)$ vs $M^2(\Lambda_c\bar{D}_0)$ from the reaction $pp \to \Lambda_c p\bar{D}_0$ at p_{beam} = 30 GeV/c in the decay channels $\Lambda_c \to K^-\pi^+$ and $\bar{D}_0 \to K^+\pi^-$. The color code indicates the acceptance of CBM, whereby all the final-state particles are reconstructed.

4. Spectroscopy

The strange sector offers a wide range of opportunities to investigate QCD and the intermediate energy scale in terms of production, interactions and spectroscopy. The excited strange baryon spectrum needs to be further explored as there are many baryon-like states expected but only a limited fraction experimentally observed [21]. This is especially true for the strangeness −2 and −3 sectors. At SIS100 energies, the production cross sections for multi strange hyperons are expected to be very large as estimated from the known $S = -1$ cross sections and assuming a constant ratio between the cross secion of $S = -1$ and $S = -2$ and −3 particles. The high energies and acceptances (see Figure 4) will also provide access to the majority of predicted states in the $S = -2$ and $S = -3$ sectors. With the excellent mass resolution of CBM for hyperons (around σ_M = 2 MeV/c^2 for Ξ^- and Ω^-), line-shape studies will also be possible, thereby providing valuable information on the internal structure of the excited states.

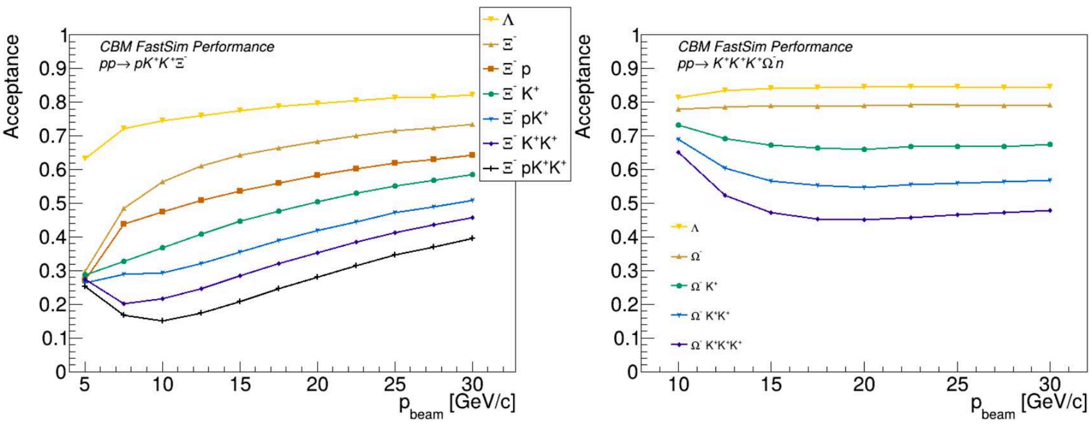

Figure 4: Acceptance of CBM for observing the reactions $pp \to \Xi^- pK^+K^+$ in the decay channel $\Xi^- \to \Lambda\pi^-$ (left panel) and the $pp \to \Omega^- K^+K^+K^+n$ in the decay channel $\Omega^- \to \Lambda K^-$ (right panel). In both cases the Λ decays via $\Lambda \to p\pi^-$. The various lines present the expected acceptances in case of reconstructing different set of final-state charged particles as indicated in the legend.

5. Electromagnetic Structure of Hadrons

The structure of baryons is parametrized in terms of electric and magnetic form factors. These form factors can be studied in two kinematic regions, the space-like (accessible in elastic scattering events, $q^2 < 0$) and the time-like region (accessible in annihilation experiments, $q^2 > 0$). The electromagnetic structure of short-lived hyperons can be studied in the time-like region. This can be done at low momentum transfer *e.g.* with Dalitz decays when a hyperon Y decays into a baryon B and an e^+e^- pair via the reaction $Y \to Be^+e^-$.

The role of meson clouds and the validity of vector-meson dominance can be investigated by a study of the q^2 dependence of form factors. This has been successfully demonstrated by a study of the decay $N^*(1520) \to ne^+e^-$ at HADES using pion-induced reactions [22]. The data revealed the importance of pion-cloud effects as predicted in [23]. The exploration of form factors via dilepton studies is one of the key aspects of current and future FAIR experiments.

Time-like form factors are very challenging to study because of the small branching ratios of the decaying baryons into the e^+e^- final state as well as the small invariant mass region of the pair that needs to be populated. Thus, the high intensity of SIS100 beams provides a clear advantage, opening excellent prospects for precise form-factor measurements. In the future, it will be interesting for CBM to extend previous studies of electromagnetic form factors of light (u,d) baryons to $\Lambda(1520)$, $\Sigma^*(1385)$, Ξ^* and Ω^* which could test predictions of kaon cloud effects.

6. Exotic Hadrons

The hidden-charm sector offers many possibilities for interesting physics. Particularly, the lowest hidden-charm vector state, the J/ψ with its prominent decay into dilepton pairs can be exploited for various physics topics with a detector such as CBM. With the proton beam energy range available at SIS100, the J/ψ can be produced close to its threshold.

One intriguing aspect of the J/ψ is the hypothesized pentaquark states found by LHCb in the $J/\psi p$ invariant mass system [24]. Three narrow states were observed with two largely overlapping each other [25]. This discovery has yet to be confirmed.

Detailed simulation studies have been performed with CbmRoot [26] to demonstrate the feasibility to resolve these pentaquark states with CBM. The momentum of the J/ψ is reconstructed in both the e^+e^- and $\mu^+\mu^-$ decay channels. In both decay channels, a $J/\psi p$ invariant mass resolution of about 6 MeV/c^2 (Figure 5, left panel) is achieved after a kinematic fit using the KinFit package [27] is applied. In addition, a fit is performed to a set of simulations of a reaction model containing phase space as well as three resonances [28] based on the LHCb results to resolve the pentaquark states. The results are shown in the right panel of Figure 5. The fit results showcase the CBM capabilities for exclusive channels.

7. Conclusions and Outlook

This proceeding outlines FAIR and the physics topics addressed with hadronic beams within the "QCD at FAIR" program. A white paper is under way describing the various hadron physics aspects that can be addressed at FAIR including the results of feasibility studies based on Monte Carlo

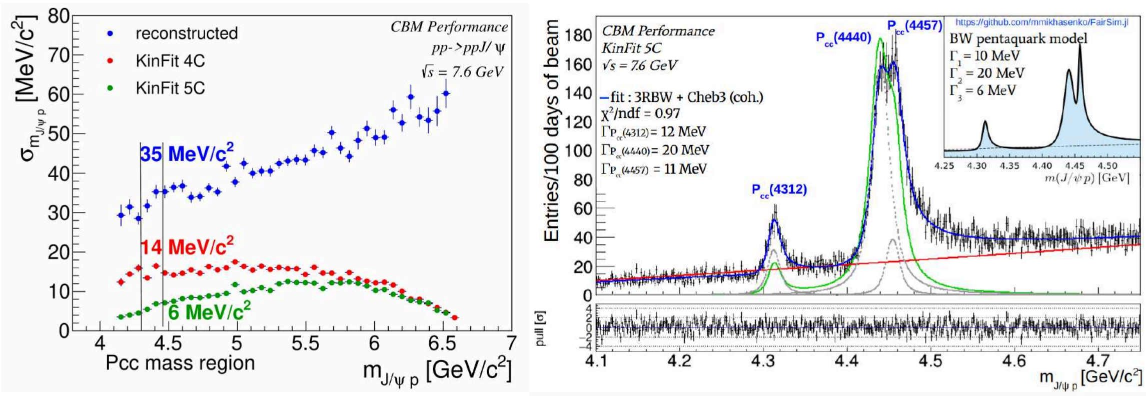

Figure 5: J/ψ mass resolution (left panel) obatined with the analysis procedure (blue points), when constraining the system to the beam-target with a 4C fit (red points) and with an additional mass constraint of the reconstructed dilepton pair to the J/ψ mass (green points). The right panel shows a fit performed to a pentaquark model and a phase space background in the reconstructed $J/\psi p$ system.

simulations. Interaction studies in the strange and charm sector as well as spectroscopy, structure studies and investigations of exotic hadrons are some of the pillars in this versatile program. This constitutes the starting point of a cross-community based physics program at FAIR.

8. Acknowledgements

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