Exploring the QCD phase diagram in the region of highest $\mu_{\rm B}$ with HADES



Manuel Lorenz for the collaboration

Goethe-University Frankfurt

The high $\mu_{\rm B}$ Side of the Phase Diagram

Central Au+Au √s_{NN}=2.4 GeV



M. Hanauske, J.Phys.: Conf. Series878 012031 (2017) L. Rezzolla et. al. PRL 122, n0.6, 061101 (2019)



Hierarchy in hadron yields: $p \approx 100$, $p_{bound} \approx 50$, $\pi \approx 10$, $K^+ \approx 10^{-2}$, $K^- \approx 10^{-4}$



emission Aspects of medium

Outline of this Talk

Au+Au $\sqrt{s_{NN}}$ =2.4 GeV, 2.2x10⁹ events analyzed

1. Virtual Photons:

Vector meson spectral functions modified by coupling to baryons

2. Subthreshold Strangeness Production:

NN→NYK⁺ √s_{NN}= 2.55 GeV $NN \rightarrow NNK^+K^ \sqrt{s_{NN}} = 2.86 \text{ GeV}$ (Kinematical suppression of direct K-)

Coupling of K⁻ to baryons via strangeness exchange reactions e.g $\pi Y \rightarrow NK^-$



4. FAIR-Phase 0: new Ag+Ag data and the future





h

K⁻

HADES at GSI/FAIR in Darmstadt, Germany







Virtual Photons

<u>Virtual Photon Radiation from</u> <u>Dense Baryon Matter</u>



- First measurement for a heavy system at low $\sqrt{s_{NN}}$.
- Strong excess (0.15<M<0.7 GeV/c²) above components of meson decays at freeze-out and NN-reference.
- Isolation of excess by subtracting the NN-reference.

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- Medium radiation: Strong broadening of the ρ due to direct ρ -baryon scattering
- Exponentially falling spectrum,
 - \rightarrow extraction of temperature $\langle T_{ee} \rangle$ = 72 MeV

<u>Virtual Photon Radiation from</u> <u>Dense Baryon Matter</u>



Onset of medium radiation in Ar+KCl collisions

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- Strong excess (0.15<M<0.7 GeV/c²) above components of meson decays at freeze-out and NN-reference.
 - Isolation of excess by subtracting the NN-reference.
 - Medium radiation: Strong broadening of the ρ due to direct ρ -baryon scattering
 - Exponentially falling spectrum, \rightarrow extraction of temperature $\langle T_{ee} \rangle = 72 \text{ MeV}$
 - Thermal rates folded over coarse-grained transport medium evolution works at low energies
 - Supports baryon-driven medium effects at SPS, RHIC (LHC)!



<u>Strangeness</u>

φ-AntiKaon Interplay in HIC



Increased in HIC at low $\sqrt{s_{NN}}$: \rightarrow 25% of K⁻ result from Φ decays!



→ No indication from K⁻ spectrum for sequential K⁺K⁻ freeze-out if corrected for feed-down.

Sub-threshold Strangeness Production in Au+Au @ $\sqrt{s_{NN}}$ = 2.4 GeV

Complete set of strange hadrons produced below NN-threshold: $NN \rightarrow NYK^+$: $\sqrt{s_{NN}} = 2.55 \text{ GeV}$ $NN \rightarrow NNK^+K^-$: $\sqrt{s_{NN}} = 2.86 \text{ GeV}$

(A_{Part}) $\alpha = 1.45 \pm 0.06$ χ^2 /NDF = 5.90/10 = 0.59 Mult / 10-4 K x 40 φx40 10-5 200 300 10080

 \rightarrow unique observable:

Energy must be provided from the system.

Strange particle yields rise stronger than linear with

$$(M \sim ^{\alpha})$$

Universal <A_{part}> dependence of strangeness production

→ Hierarchy in production threshold not reflected. Scaling with absolute amount of strangeness, not with individual hadron states.

Bulk Properties

Proton Number Fluctuations

Proton number fluctuations in $\sqrt{s_{NN}}=2.4~{\rm GeV}$ Au+Au collisions studied with HADES

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deo al Diportimendo di Ficio and INFN, Invirentà di Terrino, Italy "e-mail: hades-nfr@gride (1. Stroth)
dermail: Adaranet

(Dated: February 21, 2020

We present as analysis of proton muther fluctuations in $\sqrt{m_{\pi}} - 2.4 \, {\rm cm}^{10}$ Ba sl¹¹A to only links measured with the High-Acopyane Diffactors Representations (HANES) as (4.2. We is the halp of extensive discord simulations dow with RQMD transport model events including models indexes, whole subscard discuss influences the discord simulation areas board in the standard simulation of the standard intervents momentum bins, we will a contributing backchine have been considered and system latentity order corrections have been applied to the data. The difference considered and spectrality and moments and domains $d_{\pi_{1}}$ of order $m_{\pi_{1}}$, $d_{\pi_{2}}$ shows been distribute as a function of constraining shows a prover-law scaling with the mass number of protons, $L_{\pi_{1}} C_{\pi_{2}} N(m_{\pi_{1}})^{2}$, indicative of meanty for strengths of the strengt correction of the strengths of the strength of the strengths of the strengths of the strength of the strength of the strengths of the strength of the strength of the strengths of the strengths of the strengths of the strengths of the st





First analysis at Au+Au @ $\sqrt{s_{NN}}$ = 2.4 GeV. Detailed study of experimental effects.

Comparison to data from STAR for different rapidity bins.

$\langle N_p \rangle$ scaling of Correlators C_n

Cumulants K_n hold information on multi-particle correlators C_n Ling & Stephanov, PRC 93, 034915 (2016)

Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics Bzdak, Koch & Strodthoff, PRC 95, 054906 (2017)



Flow Anisotropies

 ${\sf Out-of-plane}\;v_2$

- Long spectator passing time $\tau_{passing} \approx \tau_{expansion}$
- Squeeze-out







Event plane reconstruction Based on hits of charged projectile spectators in the FW

First analysis up to v_6 in this energy regime

Parameterization of y dependence:

 $v_{1,3,5}(y_{cm}) = ay_{cm} + by_{cm}^3$ $v_{2,4,6}(y_{cm}) = c + dy_{cm}^2$



arxiv.org/abs/2005.12217

3D Visualization of Particle Flow



Mid-rapidity: Almost elliptical shape odd coefficients consistent with zero

Forward/backward rapidities: Triangular shape Interplay: central fireball pressure and interaction with spectator matter?

With rapidity depend parameterization n = 1 - 6 (see previous slide)

 $1 + 2\sum_{n=1}^{\infty} v_n \left(y_{cm} \right) \cos n \left(\phi - \psi_{RP} \right)$

<u>p, d, t : Scaling Behavior</u>

• Ideal fluid dynamics prediction: 0.5

N. Borghini and J.-Y. Ollitrault, Phys. Lett. B642, 227 (2006).

• At mid-rapidity p, d, t data are remarkably close.



Identical π Intensity Interferometry



Identical π Intensity Interferometry



Identical pion correlations as function of the eventplane angle Φ and pair momentum (5 bins)

Initial (nuclear overlap) eccentricity is relaxed at freeze-out $\epsilon_{\text{initial}} > \epsilon_{\text{final}}$.



 $\begin{pmatrix} R_{\rm o}^2 & R_{\rm os}^2 & R_{\rm ol}^2 \\ R_{\rm os}^2 & R_{\rm s}^2 & R_{\rm sl}^2 \\ R_{\rm ol}^2 & R_{\rm sl}^2 & R_{\rm l}^2 \end{pmatrix}$ $R_{ij}^2 =$



FAIR-Phase 0

$Ag+Ag\sqrt{s_{NN}} = 2.6 \text{ GeV: Virtual Photons}$





Supplemented

by new ECAL

detector

1/2 of the CBM RICH photon detector Stable operation during 4 weeks of beamtime





16000

<u>Ag+Ag √s_{NN}= 2.6 GeV: Strangeness</u>





 K_{s}^{0} and Λ production at the NN-threshold

Proposals for beam time at SIS18: 2021 - 2025

Pion induced reactions on CH_2 and C, Ag targets The HADES Collaboration

HADES Spokespersons: J. Stroth (Lstroth@gi.de), P. Thusty (th

GSI contact: J. Pietraszko ()-pietraszko@g

Infrastructure: SIS18, pion production target and H

Beam: Nitrogen at 2.4 GeV, maximum intensity, slow

be electromagnetic structure of baryons and the rule of intermediat

by states in the decay process. The measurement of e^+e^- product

makine to the electromagnetic transition form factors of baryons is indive to the electromognetic transition form between or any spin-der pulses the relie of vector mesons (ρ, ω) . Differential errors one that will be included in Partial Wave Analyses to extract various has

norm which are ρN and $\omega N,$ with unprecedented precision. From Θ

prestigate medium effects in cold nuclear matter. The whole data a

orbat input to calculations of the emissivity of dense and hot had

blow is an encourier summary of the proposed study with π^- be

pectrometer

Abstract Te will study baryon excitation and decay in the third resonance

This is a new experiment proposal.

We request 89 shifts.

p+p reactions at 4.5 GeV on CH_2 The HADES and HADES-PANDA Collaborations p+Ag reactions at 4.5 GeV The HADES Collaboration Beam Energy Scan for proton and HADES neutron induced reactions on Spokespersons: J. Stroth (j.stroth@gsi.de), P. Thusty (thus protons. GSI contact: J. Pietraszko (j. pietraszko/0 gsi.) HADES The HADES Collaboration Infrastructure: SIS18, CH₂ (LH₂) target, HADES Studies of QCD matter with Spokespersons: J. Stroth (j.stroth/0gsi.de), P. Thusty (thus Beam: p at 4.5 GeV, beam intensity 2×10^6 protons/s, sk GSI contact: J. Pietraszko (j.pietraszko@gsi.de) Au+Au collisions at 0.8A-0.6A-0.4A-0.2A GeV Abstract Infrastructure: SIS18, HADES cave and We propose to incentigate p+p reactions with an improved experin part of the NeuLAND detector to measure the record suscenses of charged particles emitted into the very forward HADES achieved by additional tracking stations compared of straw modules but Beam: p at 3.5–4.5 GeV, beam intensity $4\times10^6~{\rm protons/s},$ s forward Tracker. This solid angle is not equipped with a magnetic t The HADES Collaboration icensis account. This soul angle is not equipped with a magnetic identification is provided by an excellent time-of-flight measurement with Spokespersons: J. Stroth (j.stroth@gsi.de), P. Thisty (thisty tor placed about 6 in downstream of the target. Two main physics topic GSI contact: J. Pietraszko (j.pietraszko@pi.de) exclusive reconstruction of strangeness production; (2) inclusive mean Abstract particle and delectron production as reference for $p \circ A$ and heavy-in We propose to investigate p+Ag reactions with an improved experi-Infrastructure: SIS18, HADES care and part of the NeuLANE scattering parameters and phase shifts. The former will allow for stormaking measurements of charged particles emitted into the very forward b reasons measurements or charged particles reacted into the very newsrat physics topics are addressed: (i) disloction production in the low and i duction and for first pioneering measurements of the electromagnetic tr (a)cars topics are addressed: (i) distortion production in the law and region; (ii) ω disappearance in "cold" nuclear matter; (iii) strangene of hyperon. These measurements are complementary to the planned of hyperons. These measurements are complementary to the planned production in proton-antiproton collisions with PANDA. The results propagation in "cold" underst matter (comparison and constraints for the Beam: d with kinetic energy of $T_4 = 1.0, 1.13, 1.25, 1.75 \ A$ HADES models) (iv) $\Lambda - p$ scattering parameters and phase shifts; (v) under intensity 2×10^2 deuterons/s, slow extraction important reference for the future program at FAIR. responses rememe as the many program as FAR. Below is an encurive managing of the proposed study with poston bear with $(rr) \propto -p$ scattering parameters are passe much N_1 would chained in market; (vi) search for a dark photon in the dielectron d Spokespersons: J. Stroth (j.stroth@gsi.de), P. Tiusty (tlusty@ujf.cas.cz) will also provide an important reference for the farmer program at FAIRspectrometer combined with the new forward detection system. with also provide an expectant reverence for the networ program at FAR. Below is an encourier summary of the proposed study with proton beam We propose to investigate p+p and quasi-free n+p reactions with deep Abstract GSI contact: J. Pietraszko (j.pietraszko@gii.de) performer combined with the new forward detection system. LR2 target with an improved experimental set-up which enables means where emitted into the very forward beniephere. Quasi-free $p \circ p$ and $n \circ$ where particles emitters into one very neware newarphere. Quast-new p- p and w-be dimensionally by tagging the proton spectator from destorium break-op Infrastructure: SIS18 and HADES cave This is a new experiment proposal. for encodangiest by targging the proton spectator from description needs of detector which severes abuset complete (~ 5955) plane space for the spectal extertor which every assist complete (~ 90x) phase space for the operation main goals of proposal are: (1) measurement of NN reference spectra for (the anc slow extraction Au at 0.8.4–0.6.4–0.2.4 GeV, beam intensity 1.2×10^6 ions/s (flat top) This is a new experiment proposal. taxin goats of proposal are: (1) measurement of NN reterence spectra for usediant effects in heavy-ion collisions at 1-2 AGeV; (2) characterisation of We request 88 shifts. 0.04 °0.04 °0.04 °0.04 °0.04 °0.05 We request 88 shifts. We will study baryonic matter in the proximity of the nuclear logisly gas phase transition future heavy-ion program at FAIR. We will study baryonic matter in the postibility of the moderal fuplicity gap blass transition. The larger Au-Au comparison (2) which for SAA GAV and 20 shifts for SAA GAV are op-timated on a study of the study Below is an ensemitive summary of the proposed study with poston beam spectrum in an entrustric entrusion) is the property detection system. timized for abundant how-mass dielectron and strangeness production; the shorter Asi-Asi composigns (9 shifts for 0.4.4 GeV and 9 shifts for 0.2.4 GeV) will allow to collect most composigne (9 skilles for 0.4.4 GeV and 9 skilles for 0.2.4 GeV) with addre to concert most absoluted particles (r, p, d, 1, Be, Li) in large quantilities. e.g. witholds for event-hypercent atomisat particles (r, (r, d, t, Be, G) in large quantities, r,d: autibable for event-by-event analysis of particle correlations and fluctuations as well as to extract transpratator of the This is a new experiment proposal. and yies of particle correlations and fluctuations as well as to extract temperature of the system at brease-out. We aim at a high statistics beam energy scan to enable (i) how any product of the statistics of the statistics beam energy scan to enable (i) how any product of the statistics of the statistics beam energy scan to enable (i) how any product of the statistics of the statistics beam energy scan to example the statistics of the statistics of the statistics of the statistics beam energy scan to example (i) how any product of the statistics of the system at mean-out. We am at a high statistics beam everys scan to enable (i) laboratory studies of the matter properties (Equation of State) in compact studies objects; (ii) detec-We request 104 shifts. studies of the matter properties (Dipartion-of-State) in compact studies objects (ii) detec-tion of measurable consequences of phase transition and critical point in the QCD phase tion of measurable consequences of phase transition and critical point in the QCD phase diagram. Messawer, C+C collisions (6 shifts for 0.8.4 GeV and 6 shifts for 0.6.4 GeV) will serve as a reference system. In the following we clusidate the proposed studies using the RADES spectrometer This is a proposal for a new experiment

In total we request 94 shifts.

Summary

Virtual Photons:

Strong broadening of the ρ , exponentially falling spectrum, \rightarrow extraction of temperature $< T_{ee} > = 72$ MeV Onset of medium radiation in Ar+KCl collisions.

Strangeness:

No indication for sequential K^+K^- freeze-out if p_t spectra corrected for feed-down. Universal $\langle A_{part} \rangle$ dependence of strangeness production.

The Bulk:

First data on: proton number fluctuations. flow anisotropies up to v_6 . identical pion HBT as function Φ and k_t .

FAIR-Phase0:

High quality data to come are here A lot to come in the next years.









Back Up

EM Formfactors of Baryonic Resonances



φ-AntiKaon Interplay in Cold Nuclear Matter











<u>Light Nuclei</u>

Data collection: https://arxiv.org/abs/2004.0441



Hierarchy in hadron yields: $p \approx 100$, $p_{bound} \approx 50$, $\pi \approx 10$,



High statistic multi-differential data

p, d, t V_1, V_2, V_3, V_4



High statistic multi-differential data

Comparison p,d,t at mid-rapidity

Sensitivity to EOS

UrQMD prediction: P. Hillmann et al. J.Phys. G45 (2018) no.8, 085101

Consequences for the created system?



Can we connect this to an observable?

Figures from W. Weise

Volume-corrected proton cumulants vs Δy





Ling & Stephanov, PRC 93, 034915 (2016)

Bzdak, Koch & Strodthoff, PRC 95, 054906 (2017

Cumulants K_n hold information on multi-particle correlators C_n

Investigate C_n vs. $\langle N_p \rangle$ to isolate relevant physics

Protons and light nuclei at Au+Au √s_{NN}= 2.4 GeV



Careful analysis of protons:

Extension to high lab. momenta in order to cover forward hemisphere (no acceptance at low p_t)

- Estimate spectator contamination by symmetry of the distribution
- Minimize uncertainty due to extrapolation in y \rightarrow Similar investigations for d and t are ongoing.