Present and future perspectives in hadron physics GSI/FAIR

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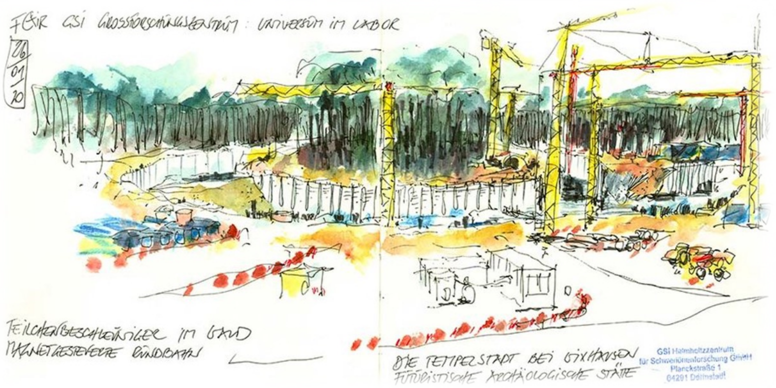
GSI / Technische Universität Darmstadt

STRONG-2020
Jun 17–19, 2024
Laboratori Nazionali di Frascati INFN, Italy



April 2024

FAIR GmbH – Facility for Antiproton and Ion Research

Emerging facility: FAIR
(Foundation: 2010)

GSI GmbH – Helmholtzzentrum für Schwerionenforschung

Existing facility: GSI Darmstadt
(Foundation: 1969)

Uniqueness

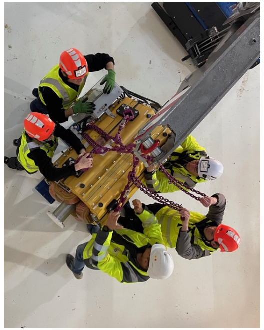
- Relativistic ion beams of highest intensities
- Storage rings for cooled (secondary) beams

FAIR project status

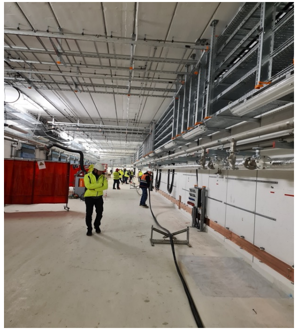
installation of SIS100 dipoles Apr’24

cryogenic bypass lines SIS100 placed in SIS100 tunnel, Apr‘24

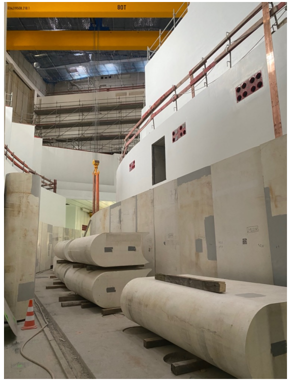
transport of the first quadrupole magnet in tunnel, Mar‘24

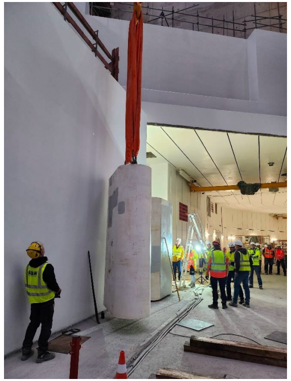


start of cable pulling work, Q3/23



6 He tanks of the cryo facility were installed, Apr’24





installation S-FRS lateral shielding blocks, May’24

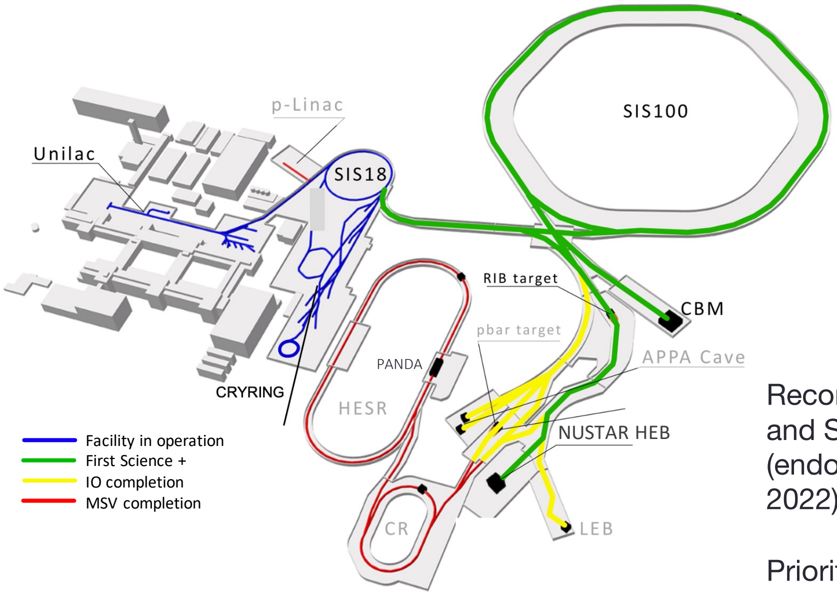
construction area south

CBM cave, Jun‘24

Facility for Antiproton and Ion Research: timeline

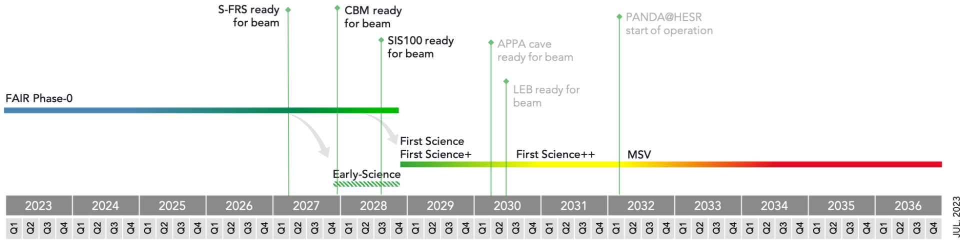
2018 start of **FAIR Phase-0**
~3 month beamtime/year

Intermediate forefront research program at GSI with improved beams and FAIR detectors



Recommendation of the "First Science and Staging Review of the FAIR Project" (endorsed by the FAIR Council in Oct. 2022):

Prioritize implementation of Scenario #3: **SIS100, Super-FRS-HEB, CBM (First Science+)** – the most appropriate start scenario to achieve world-leading science



GSI/FAIR multi-purpose (strong interaction) facilities

NUSTAR

Nuclear structure and reactions

Physics of explosive nucleosynthesis (*r*-process)

(rare-isotope beams: high energy, high Z, high intensity for fully stripped exotic nuclear beams)

APPA

Fundamental symmetries; ultra-high em fields

(anti-protons & highly stripped ions)

Dense bulk plasmas

(ion-beam bunch compression, petawatt-laser)

Materials research and radiation biology

(ion and anti-proton beams)

HADES CBM

QCD phase structure, properties of QCD matter, hadrons in-medium

(heavy-ion beams 2 – 10 GeV/u: highest interaction rate capability)

HADES CBM panda

Hadron structure and dynamics

(stored and cooled anti-protons, SIS18 secondary π beam, p beam 1.25 - 29 GeV)

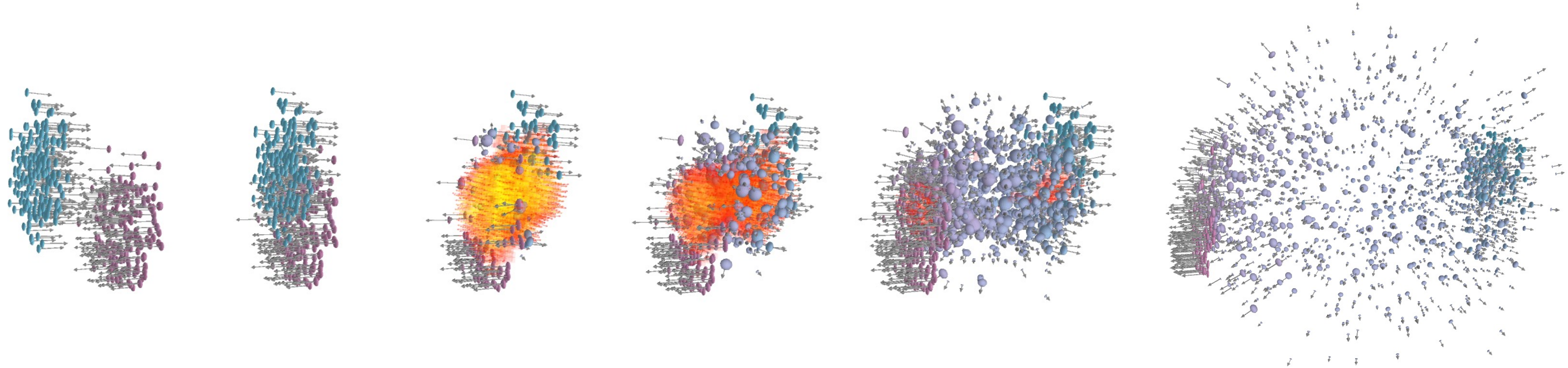
Decode the phases of nuclear matter
in the non-perturbative regime of QCD

OBJECTIVE

Method

Recreate various forms of cosmic matter in laboratory → high-energy heavy-ion collisions

Investigate transient states of QCD matter under extreme conditions



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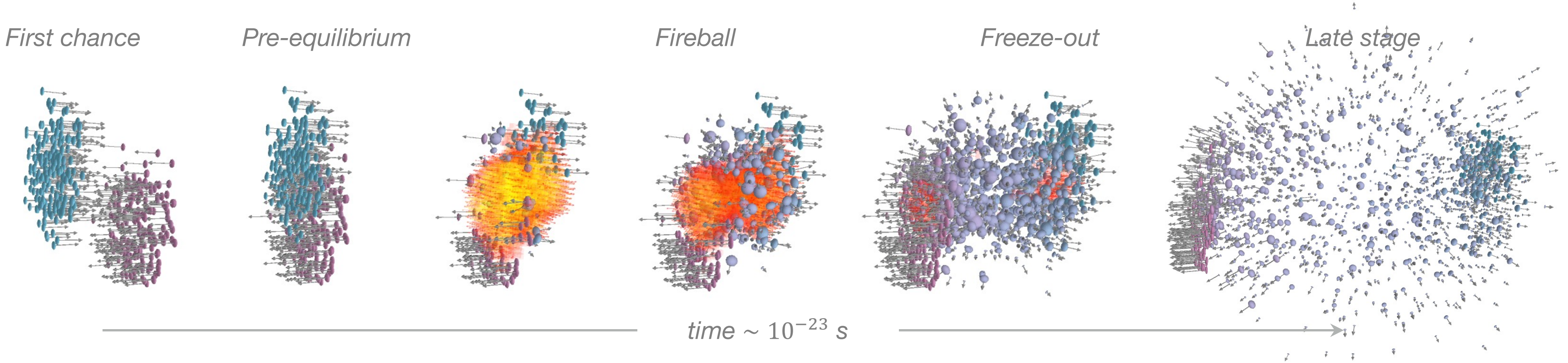
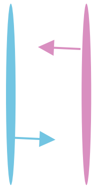




LHC energies $\sqrt{s_{NN}} = 2 - 5\ TeV$

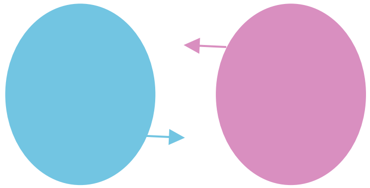
parton parton collisions

$N_{particles} = N_{anti-particles}$

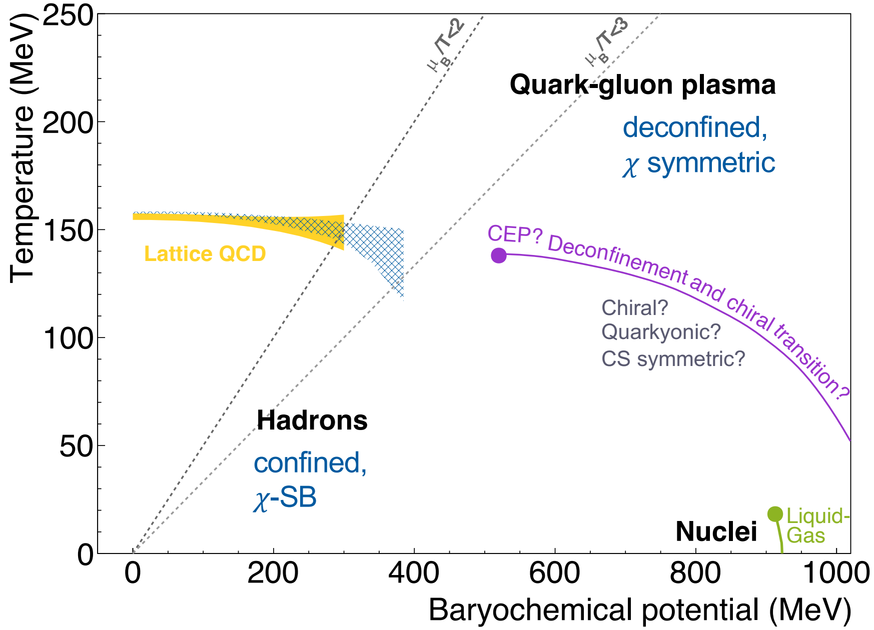
SIS energies $\sqrt{s_{NN}} = 2 - 5\ GeV$

Nuclear stopping

$N_{particles} \gg N_{anti-particles}$



Searching for landmarks of the QCD matter phase diagram



[HotQCD], PLB 795 (2019) 15-21
[Wuppertal-Budapest], PRL 125 (2020)

Experimental challenges:

- isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- probe microscopic matter properties

→ **heavy-ion beams**

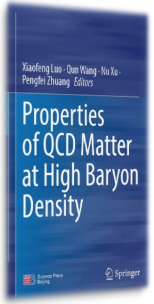
Study various aspects of meson/baryon physics:

- (*u, d, s, c*) production mechanism, spectra, correlations
- em transition form-factors

→ **secondary pion, p, d beams**

Worldwide experimental and theoretical efforts

Relevance for astrophysics



Chen, Dong, Fukushima, Galatyuk, *et al.*, doi:10.1007/978-981-19-4441-3_4 (2022)

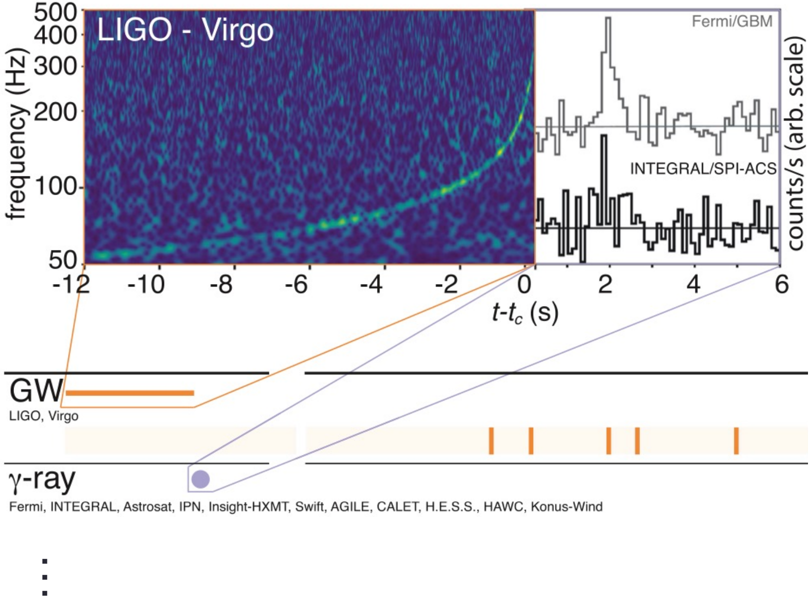
Multi-messenger signals from neutron star merger

- GW170817 17 Aug 2017 12:41:04 UTC
  First detection of a binary neutron star merger through gravitational waves

LIGO + VIRGO, PRL 119 (2017) 1611001

- GRB 170817A ~1,7 s later:
  Observation of the same event through electromagnetic waves (gamma-ray burst)

Fermi GBM + INTEGRAL + LIGO + Virgo, Astrophys.J.Lett. 848 (2017)



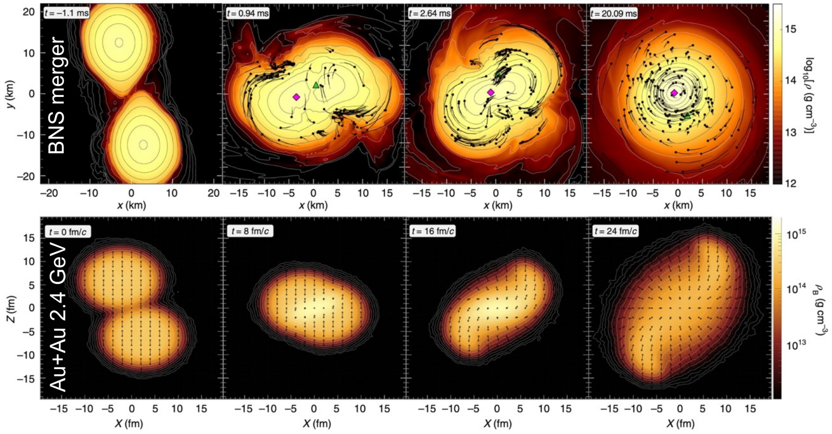
Laboratory studies of the matter properties in compact stellar objects

nature physics
ARTICLES
https://doi.org/10.1038/s41567-019-0583-8

Probing dense baryon-rich matter with virtual photons

The HADES Collaboration*

18 orders of magnitude in scales
still similar T < 70 MeV, $\rho < 3\rho_0$ for both



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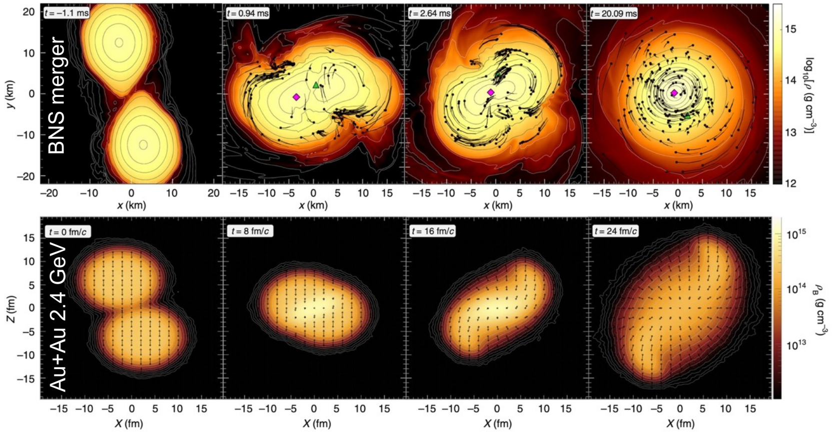

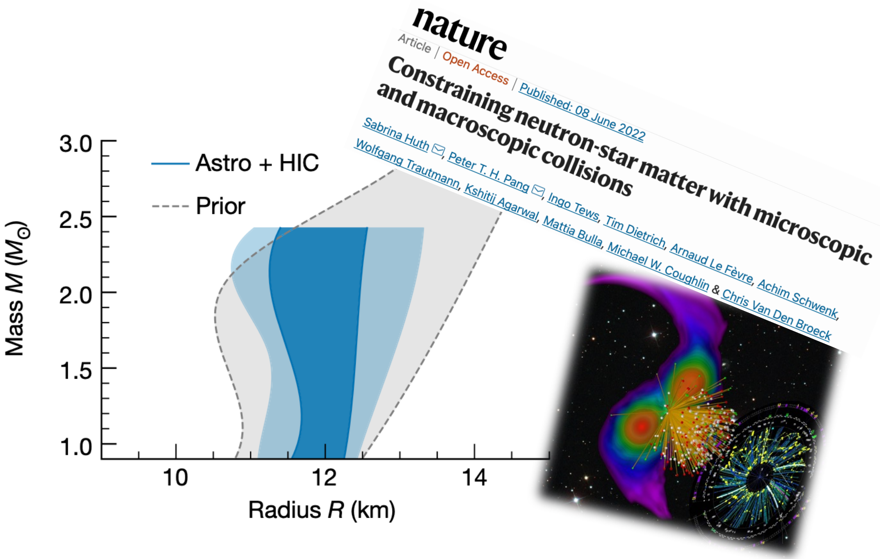

Remarkable consistency between multi-messenger observations and constraints from heavy-ion data

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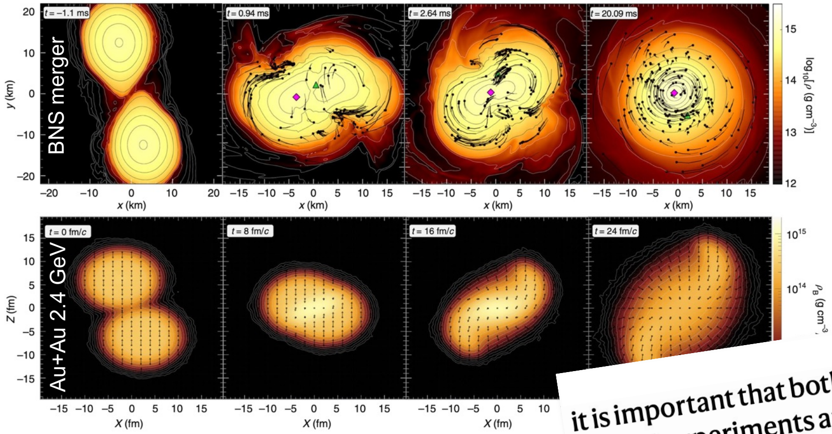
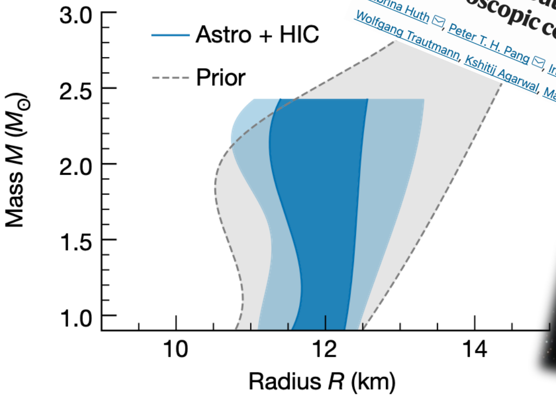


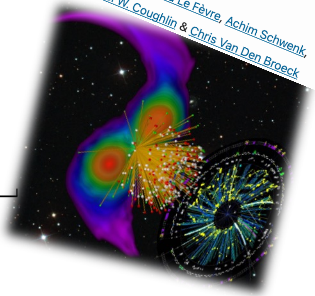
nature

Article | Open Access | Published: 08 June 2022

Constraining neutron-star matter with microscopic and macroscopic collisions

Sabrina Huth, Peter T. H. Pang, Ingo Tews, Tim Dietrich, Arnaud Le Fèvre, Achim Schwenk, Wolfgang Trautmann, Kshitij Agarwal, Mattia Bulla, Michael W. Coughlin & Chris Van Den Broeck



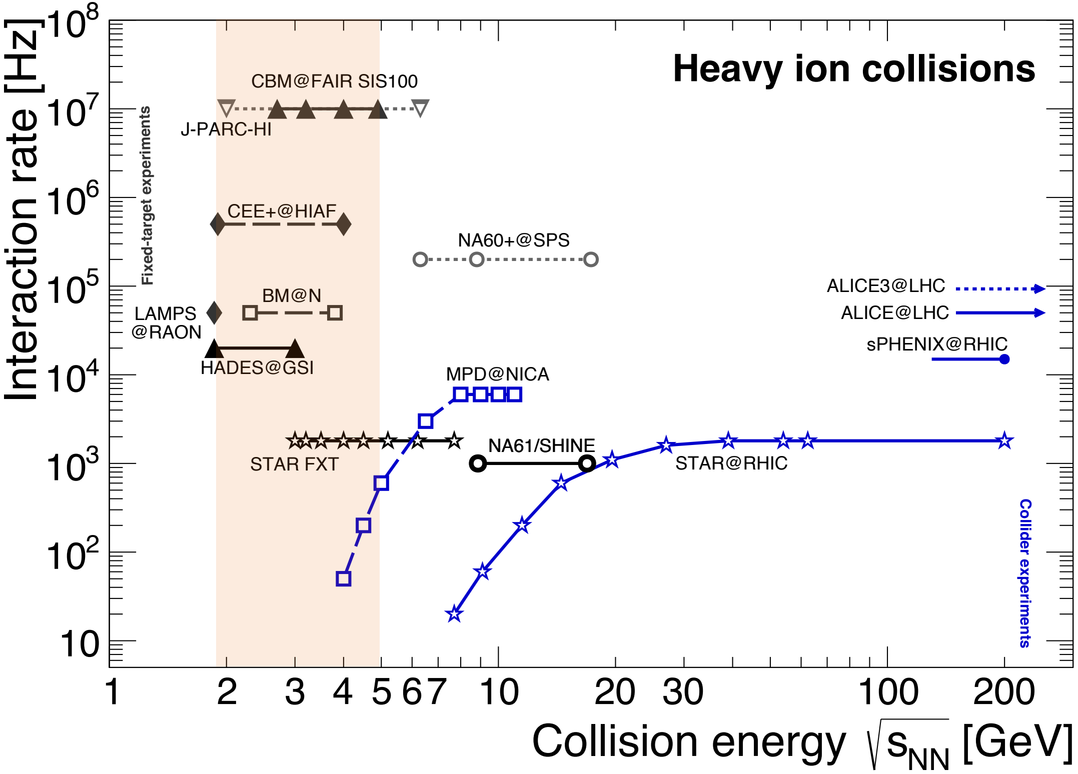


Remarkable consistency between multi-messenger observations and constraints from heavy-ion data

Going forward, it is important that both statistic and systematic sources of uncertainty for HIC experiments are further improved.

advancing HIC experiments to probe higher densities, above 2–3n_{sat}, will be key

Some basic facts on high μ_B facilities



- **CBM** will play a unique role in the exploration of the QCD phase diagram in the region of high μ_B with rare and electromagnetic probes: high rate capability, energy range 3< $\sqrt{s_{NN}}$ <5 GeV
- **HADES**: established thermal radiation at high μ_B, limited to 20 kHz and $\sqrt{s_{NN}}$=2.4 GeV
- **STAR FXT@RHIC**: BES program completed; limited capabilities for rare probes
- **CEE+@HIAF construction**: multipurpose detector based on TPC, anticipated rate capability 500 kHz, anticipated start 2027
- **J-PARC-HI proposal:** addition of heavy-ion booster, state of the art detectors (e, μ, hadrons)

LHC ⟶ RHIC ⟶ SPS ⟶ SIS program needs ever more precise data and sensitivity for rare signals

TG, NPA 982 (2019), update 2024 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

Compressed Baryonic Matter experiment

Fixed target experiment
→ obtain highest luminosities

Versatile detector systems
→ optimal setup for given observable

Tracking based entirely on silicon
→ fast and precise track reconstruction

Free-streaming FEE
→ nearly dead-time free data taking

On-line event selection
→ highly selective data reduction

Measure with utmost precision:

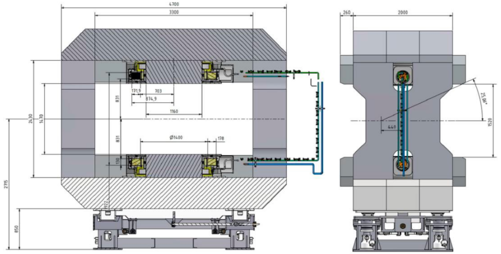
- light flavour (chemistry, vorticity, flow)
- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction)

Q4 2027 – installation and commissioning w/o beam
Q4 2028 – commissioning with SIS100 beam

CBM subsystems are on the verge of series production

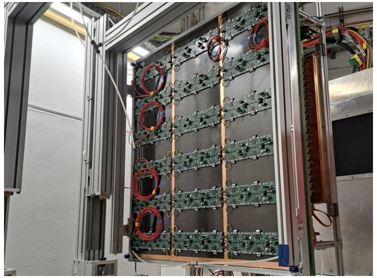
➡ pre-production is ongoing in all systems

Superconducting dipole magnet
award of contract to Bilfinger Noell GmbH 20.12.2023



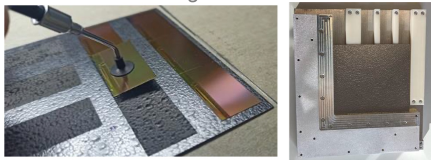
Beam monitoring system

Transition Radiation Detector

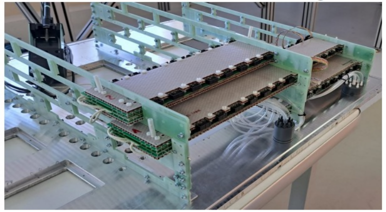


pre-production modules of 1D and 2D options ready

Micro Vertex Detector
sensor/module integration



Time of flight detector

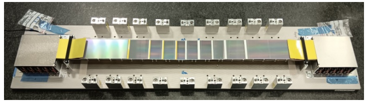


module pre-production concluded

MUon CHamber system

test of full-size GEM and RPC prototypes

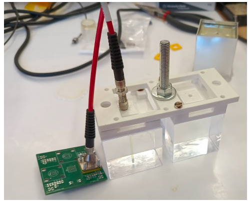
Silicon Tracking System



first STS series ladder

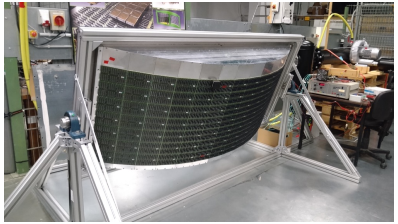
> 100 modules assembled

Forward Spectator Detector

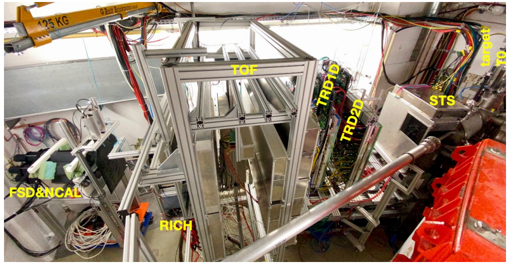


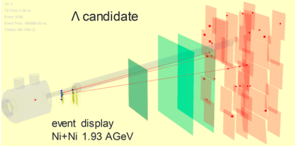
ZnS scintillators and LYSO crystals read-out via SiPM or/and PMT

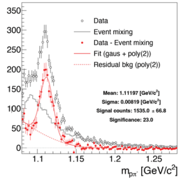
Ring Imaging Cherenkov detector
1 of 2 photo cameras ready
50% FEE produced



Prototype of CBM online data processing tests with mCBM



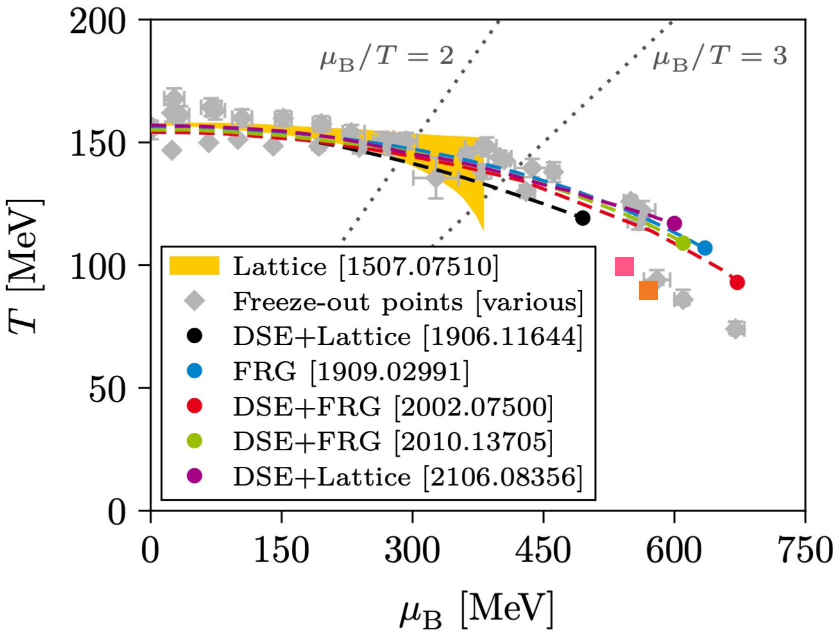




Quest for critical phenomenon connected to the 1st order phase transition

CRITICALITY

Critical point predictions from theory



Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Borsanyi *et al*. [Wuppertal-Budapest], PRL 125 (2020)

- Lattice QCD disfavours QCD critical point at $\mu_B/T < 3$
- Effective QCD theories[1-3] and lattice-Pade[5,6] predict QCD critical point in a similar ballpark $\boldsymbol{T \sim 90 - 120}$ **MeV**, $\boldsymbol{\mu_B \sim 500 - 650}$ **MeV**
- If true, reachable in heavy-ion collisions at $\sqrt{s_{NN}} \sim 3 - 5$ **GeV**
- Including possibility that the QCD critical point does not exist

Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
Vovchenko *et al.*, PRD 97, 114030 (2018)

DSE: Bernhardt, Fischer and Isserstedt, PLB 841 (2023)
FRG: Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)
BHE: Hippert et al., arXiv:2309.00579
lQCD-Pade: Basar, arXiv:2312.06952
lQCD-Pade: Clarke *et al.*, PoS LATTICE2023 (2024), 168

Event-by-event fluctuations and statistical mechanics

- In strong interactions, baryons, electrical charges and strangeness are conserved ($q \in \{B, Q, S\}$)
- Event-by-event fluctuations of q predicted within grand canonical ensemble

cf. Friman *et al.*, EPJC 71 (2011) 1694
Stephanov, RPL 107 (2011) 052301

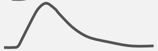
encodes the EoS

$$\frac{\kappa_n(N_q)}{VT^3} = \frac{1}{VT^3}\frac{\partial^n \ln Z(V,T,\vec{\mu})}{\partial(\mu_q/T)^n} = \frac{\partial^n \hat{P}}{\partial \hat{\mu}_q^n} \equiv \hat{\chi}_n^q$$

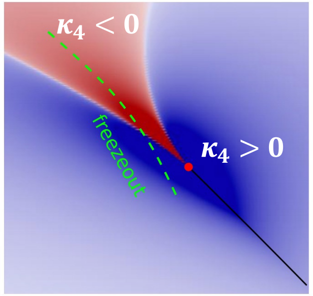
κ_n - cumulants (measurable in experiment)
$\hat{\chi}_n^q$ - susceptibilities (e.g. from lQCD)

Higher order cumulants describe the shape of measured distributions and quantify fluctuations

Variance $\kappa_2 = \langle(\delta N)^2\rangle = \sigma^2$ 

Skewness $\kappa_3 = \langle(\delta N)^3\rangle$ 

Kurtosis $\kappa_4 = \langle(\delta N)^4\rangle - 3\langle(\delta N^2)\rangle^2$ 



Stephanov, RPL 107 (2011) 052301

QCD critical point: large correlation length and fluctuations

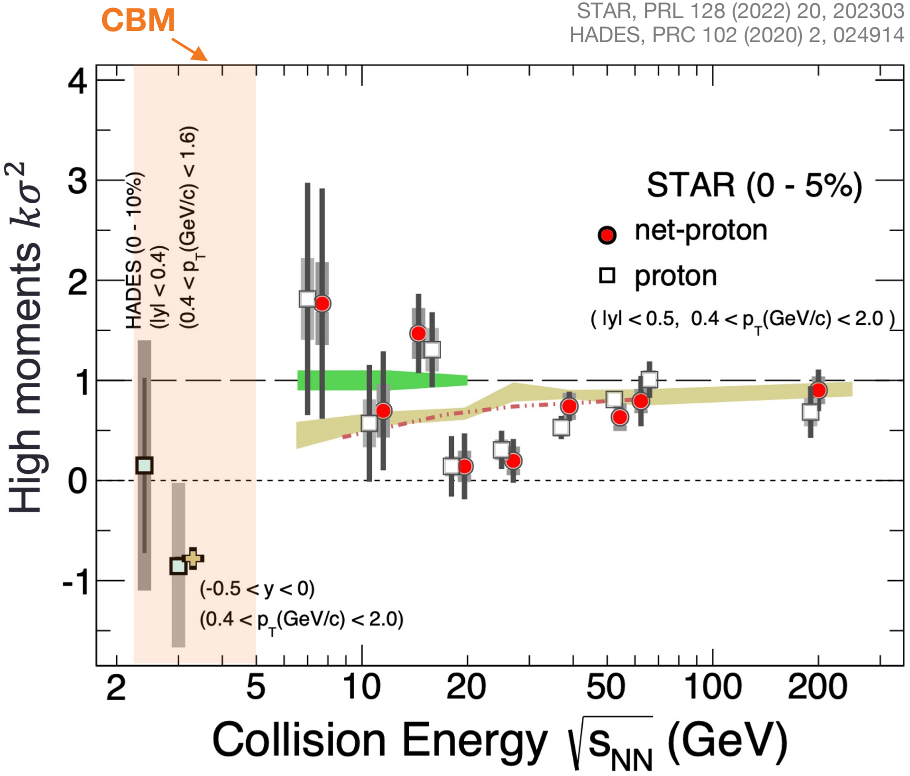
$\kappa_2 \sim \xi^2,\ \kappa_3 \sim \xi^{4.5},\ \kappa_4 \sim \xi^7$

$\xi \to \infty$ **diverges at critical point**

➡ Look for **enhanced fluctuations** and **non-monotonicity**

Critical point search

STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914



Braun-Munzinger, Friman, Redlich, Rustamov, Stachel, NPA 1008 (2021) 122141

- Current data consistent with non-critical physics?
  → **reduced errors from STAR BES-II indicate non-trivial physics!**

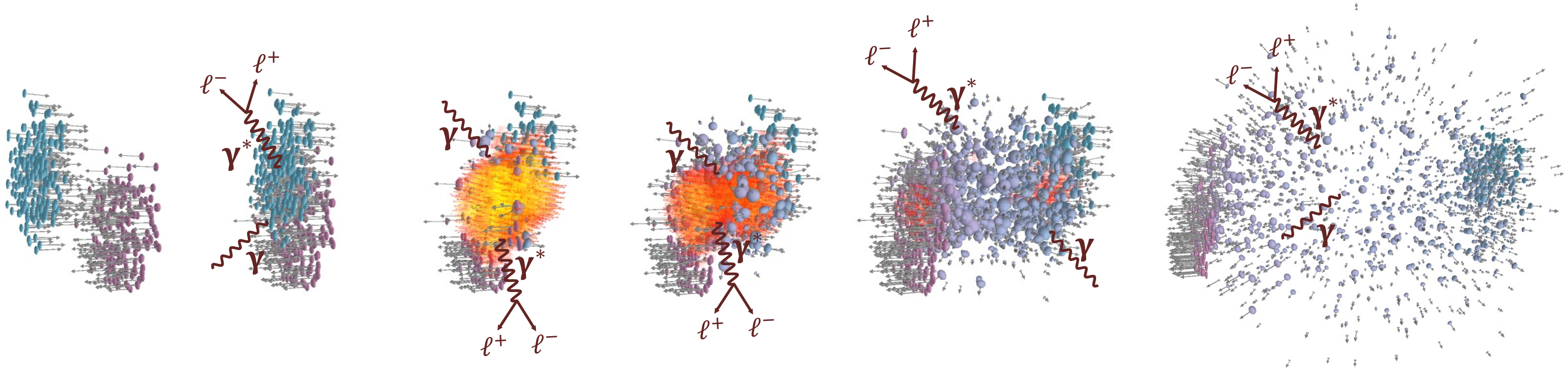
- Sensitivity to features of the QCD phase diagram grows with the order of the moment
- **Higher order moments probe the tails – statistics/artefacts!**
- Detailed **systematic** studies of experimental effects **is curtail**

Holzmann, Koch, Rustamov, Stroth, arXiv:2403.03598 [nucl-th]
Kitazawa’2012, Skokov’2013, Bzdak ‘2016, Kitazawa’2016, Braun-Munzinger’2017

Electromagnetic radiation

EMISSIVITY

Electromagnetic radiation as multi-messenger of fireball



Electromagnetic radiation (γ, γ^*)

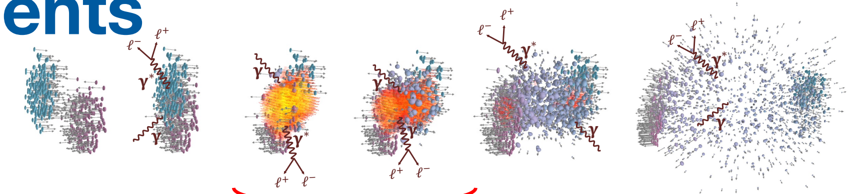
Reflect the whole history of a collision

No strong final state interaction
⇝ leave reaction volume undisturbed

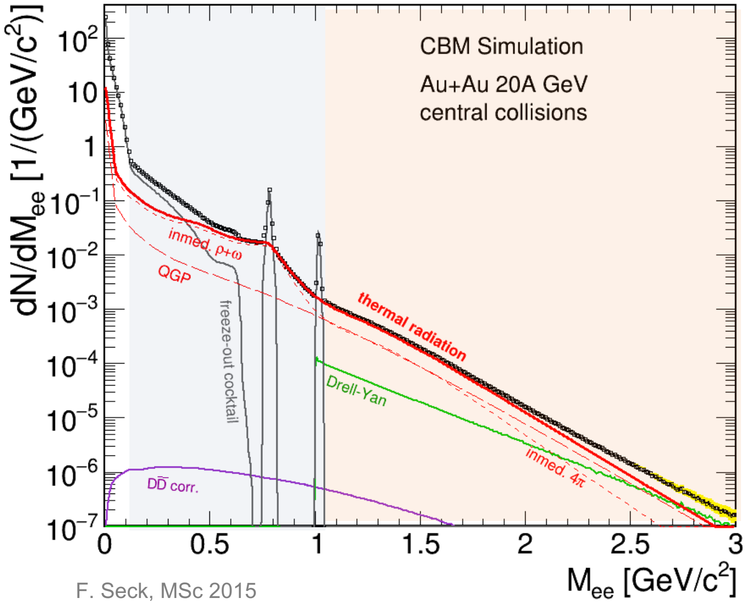
Encodes information on matter properties enabling unique measurements

- degrees of freedom of the medium
- fireball lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry

Thermal dilepton measurements



Low-mass regime Intermediate-mass regime



F. Seck, MSc 2015

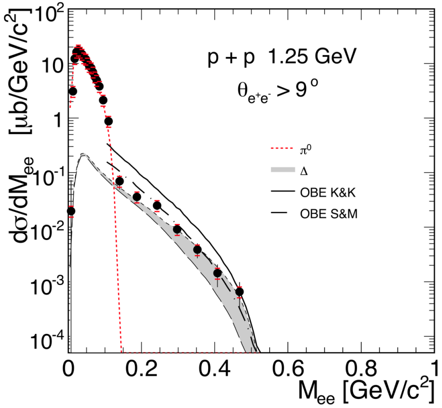
- Dileptons are rare probes!
- Decisive parameters for data quality:
  interaction rates (IR) and signal-to-combinatorial background ratio (S/CB): effective signal size: $S_{eff} \sim IR \times S/CB$
- Needs coverage of mid-rapidity, low-$M_{\ell\ell}$, and low-p
- Isolation of thermal radiation by subtraction of measured decay cocktail $(\pi^0, \eta, \omega, \varphi)$, Drell-Yan, $c\bar{c}$ $(b\bar{b})$

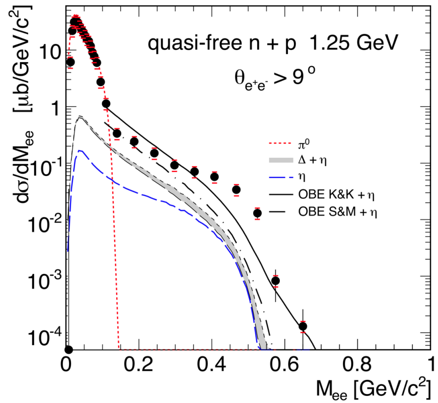
Measurement of NN reference in HADES

- p+p and d+p collisions at E_{kin} = 1.25 GeV
  - n+p reaction tagged by triggering on proton spectator

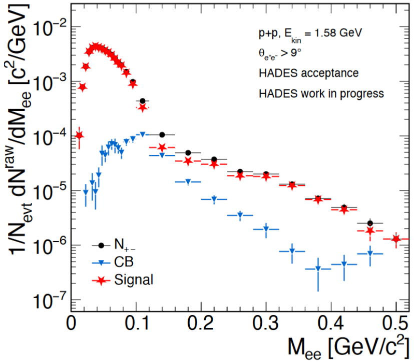
HADES, PLB 690 (2010) 118
Larionov *et al.*, PRC 102 (2021), 064913

NN ref. for $\sqrt{s_{NN}}$ = 2.42 GeV



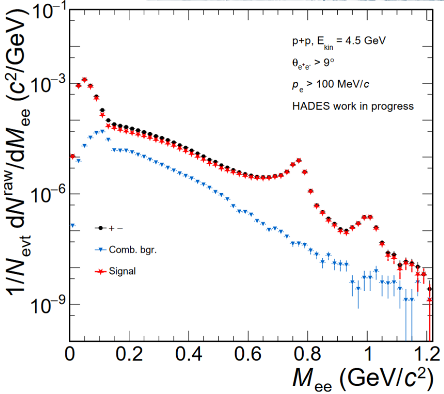


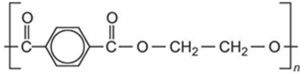
NN ref. for $\sqrt{s_{NN}}$ = 2.55 GeV



- ongoing analysis of p+p at E_{kin} = 1.58 GeV and 4.5 GeV
  - empty target run p+C/p/O as proxy for p+p/p+n

NN ref. for future FAIR

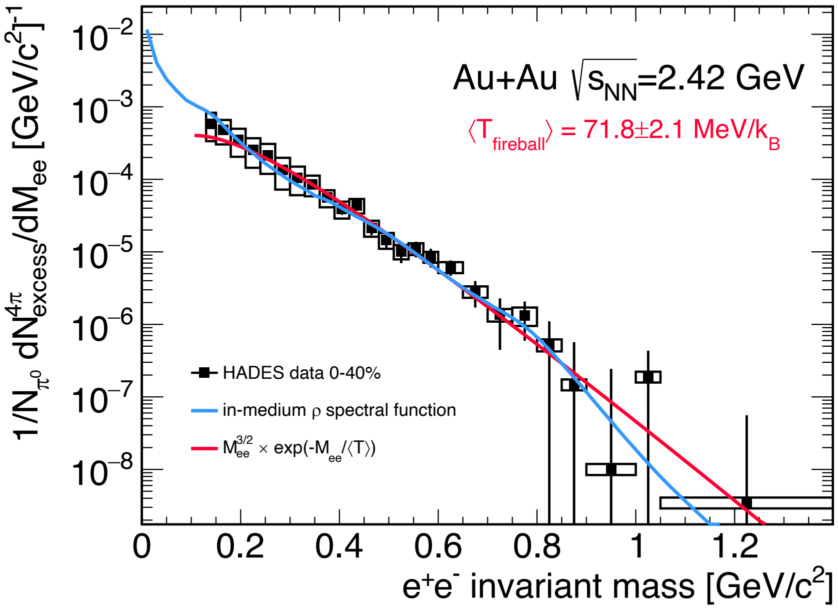




Mylar

Thermal dileptons from baryon rich matter

HADES, Nature Phys. 15 (2019) 1040



'Planck-like' **In-medium spectral function**

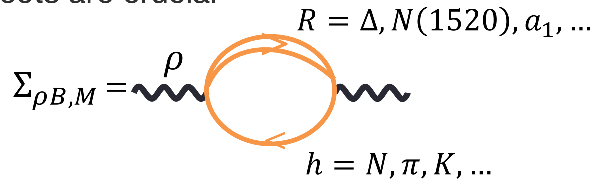
$$\frac{dN_{ll}}{d^4q\,d^4x} = -\frac{\alpha_{em}^2}{\pi^3}\frac{L(M^2)}{M^2} f^B(q_0,T)\, Im\Pi_{em}(M,q,T,\mu_B)$$

McLerran - Toimela formula, Phys. Rev. D 31 (1985) 545

- Thermal excess radiation established at HADES (Au+Au, Ag+Ag)
  - ρ-meson peak undergoes a strong broadening in medium
  - in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

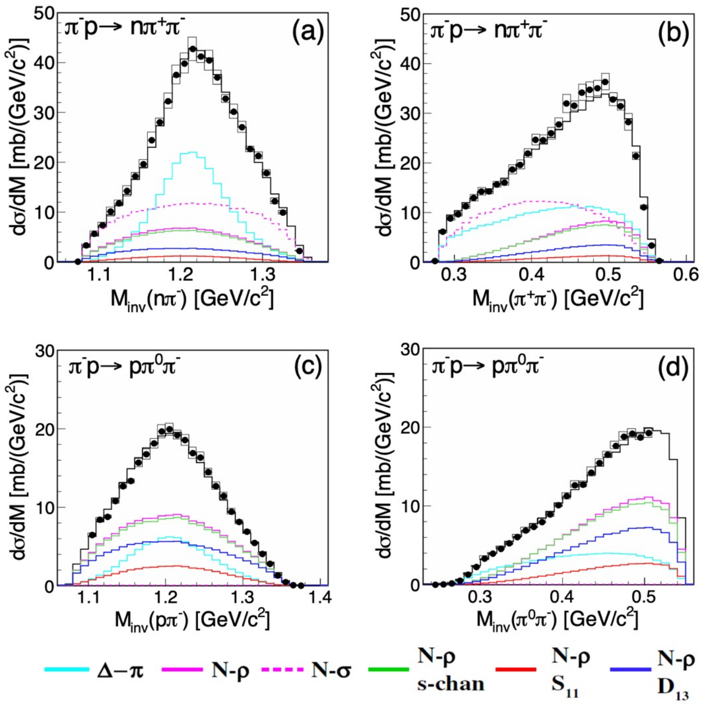
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

- Baryonic effects are crucial



The HADES pion beam facility

- Direct excitation of baryon resonance and exclusive reconstruction of final states
- Combination with dilepton spectrometer world-wide unique



- $p_\pi = [0.66, 0.69, 0.75, 0.8]\ \mathrm{GeV}/c$

- $\pi^- + p \to \pi^- + \pi^+ + n$
  - hadronic final states used in PWA (Bonn/Gatchina code)
  - use invariant masses, and angular distribution

- $\pi^- + p \to e^- + e^+ + n$
  - prediction for dilepton invariant mass assuming strict VMD
  - comparison to two-component model by Pena & Ramalho

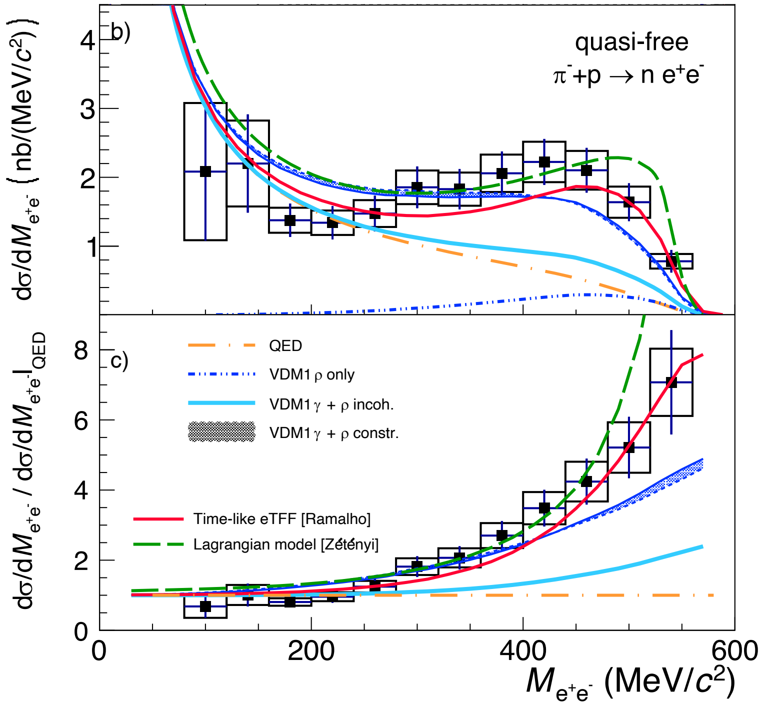
HADES, PRC 102 (2020) 2, 024001
HADES, PRC 95 (2017) 065205

PDG particle data group

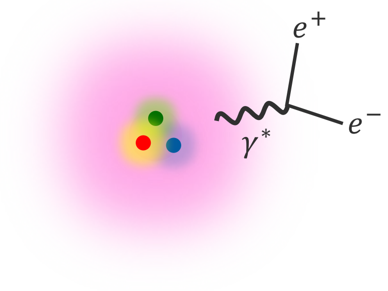
4 first entries ($N\rho$)
4 additional entries
first entry BR $\Delta \to pe^+e^-$

First measurement of massive γ^* emission from N^* baryon resonances (exclusive analysis $\pi^- p \to e^+ e^- n$)

HADES, arXiv:2205.15914 [nucl-ex], with PRL
HADES, arXiv:2309.13357 [nucl-ex], accepted PRC

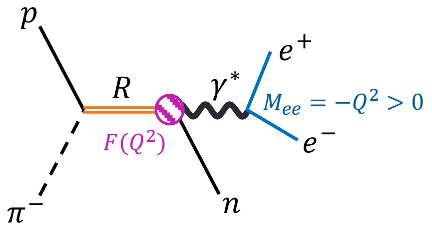


Ramalho, Pena, PRD95 (2017) 014003
Zetenyi, Nitt, Buballa, TG, PRC 104 (2021) 1, 015201
Speranza *et al.*, PLB764 (2017) 282



- Study the structure of the nucleon as an extended object (quark core and meson cloud)

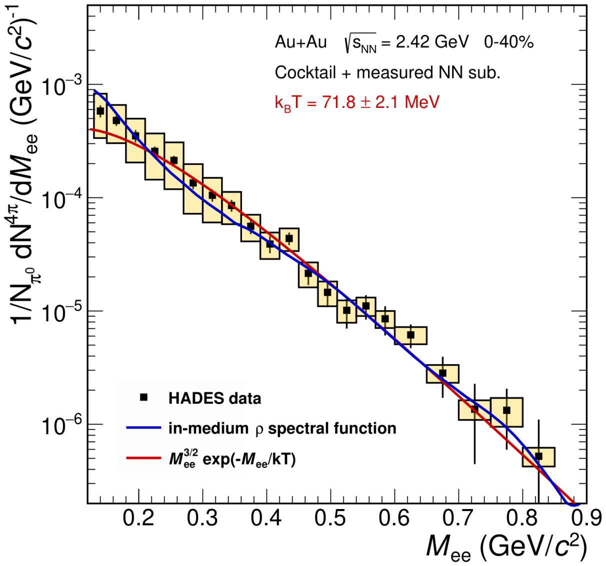
- Dominance of the $N^*(1520)$ resonance at $\sqrt{s_{NN}} = 1.49$ GeV
  - ρ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**



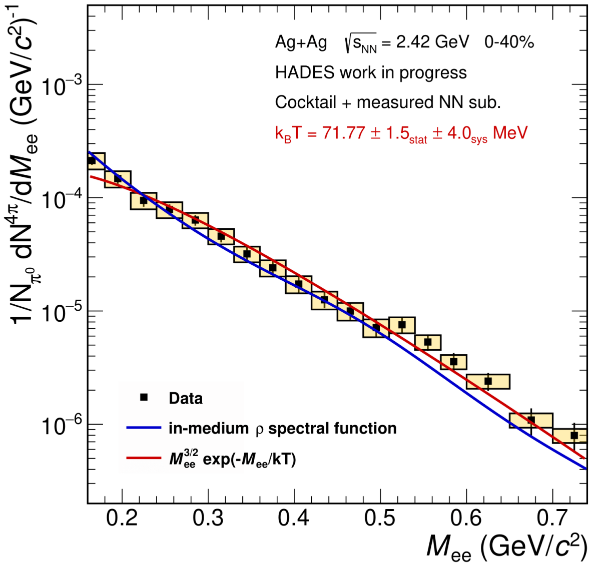
Thermal dileptons HADES systematics

Excellent agreement between experiment and theory for excess radiation

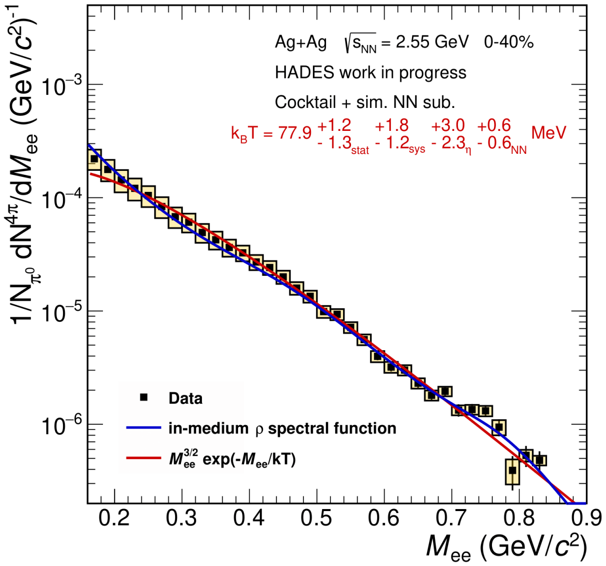
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag at $\sqrt{s_{NN}} = 2.42$ GeV



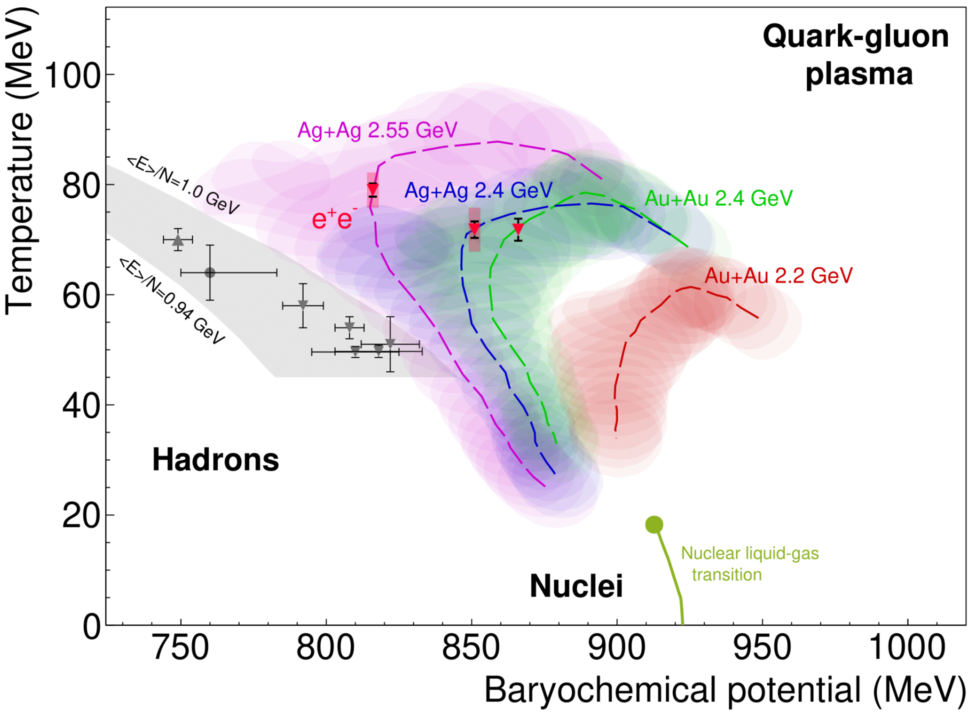
Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



Mapping QCD phase diagram with dileptons

- Trajectories from coarse-grained UrQMD
- Measured average temperatures from HADES well above universal freeze-out region

FO curve: J. Cleymans, K. Redlich, Nucl. Phys. A 661 (1999) 379
Au+Au 2.4 GeV data: HADES, Nature Phys. 15(2019) 1040
Ag+Ag data: HADES preliminary
figure: Seck, TG

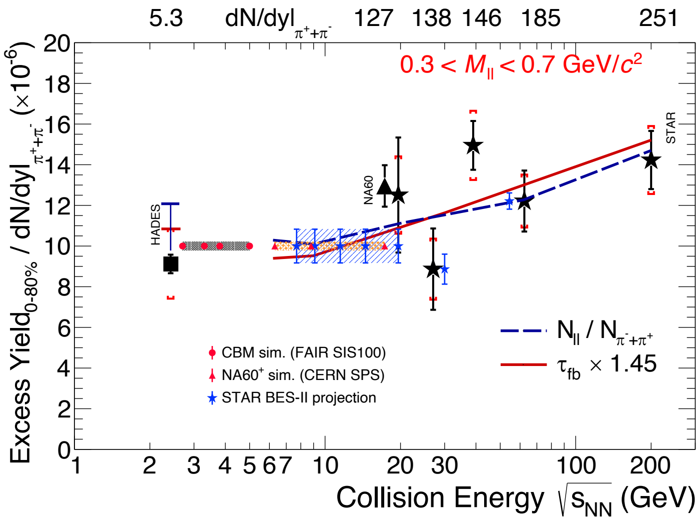


Thermal dileptons excitation functions

Excess yield in LMR tracks fireball lifetime

- Search for "**extra radiation**" due to latent heat around **phase transition** (& critical point?)

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203

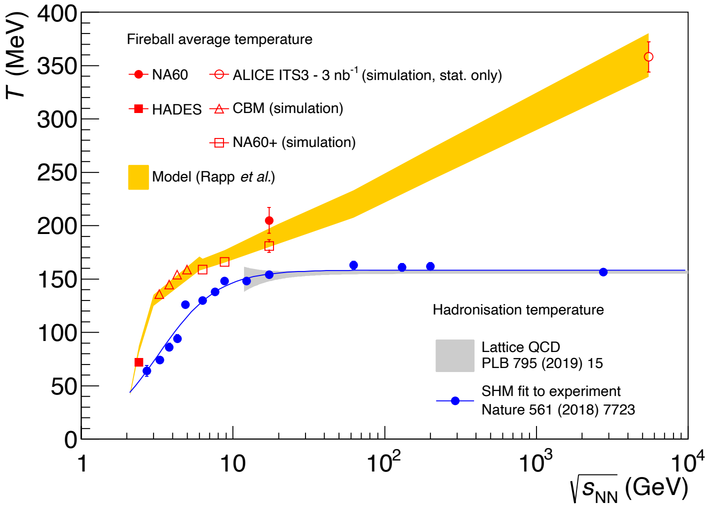


TG, JPS Conf.Proc. 32 (2020) 010079

Invariant mass slope measures radiating source T

- **Flattening** of caloric curve (T vs ε) → evidence for a **phase transition**
- Probe time dependence of fireball temperature: *$M_{\ell\ell}$ versus v_2, photon polarization*

Seck, Friman, TG, van Hees, Speranza, Rapp, Wambach, [arXiv:2309.03189 [nucl-th]]



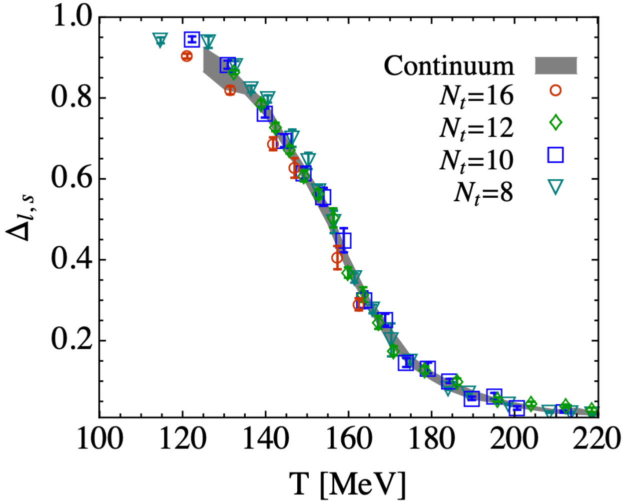
https://github.com/tgalatyuk/QCD_caloric_curve

Dileptons and chiral symmetry of QCD

Spontaneously broken in the vacuum

$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$

Condensates $\langle\bar{q}q\rangle$ calculated by lattice QCD

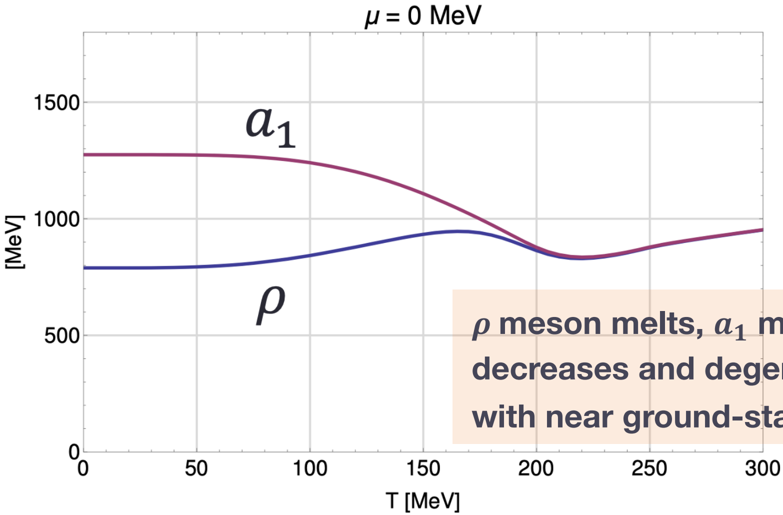


Bazavov *et al.* [Hot QCD Coll.], PRD90 (2014) 094503

S. Weinberg, PRL 18 (1967) 507

$$\int_0^\infty \frac{ds}{\pi}[\Pi_V(s) - \Pi_{AV}(s)] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

Restoration at finite T and μ_B manifests itself through mixing of vector and axial-vector correlators



ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

Hadronic many-body theory Hohler and Rapp, PLB 731 (2014)
FRG Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
Light mesons and baryons from lattice QCD, Aartz, QM2022, April 2022

Additional signature for chiral symmetry restoration: chiral $\rho - a_1$ mixing

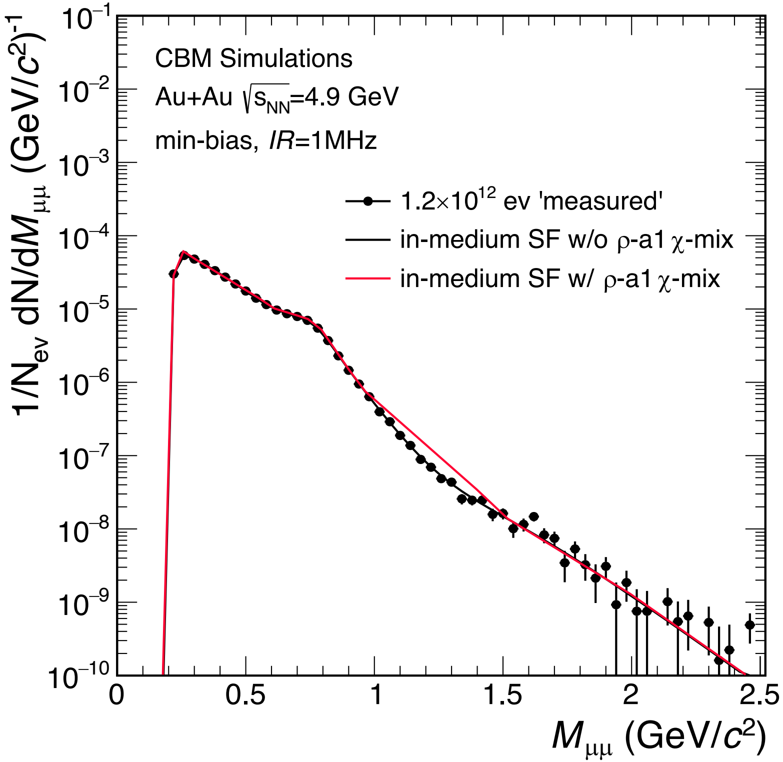
Experimental challenge: physics background ($M_{\ell\ell}$ > 1 GeV)

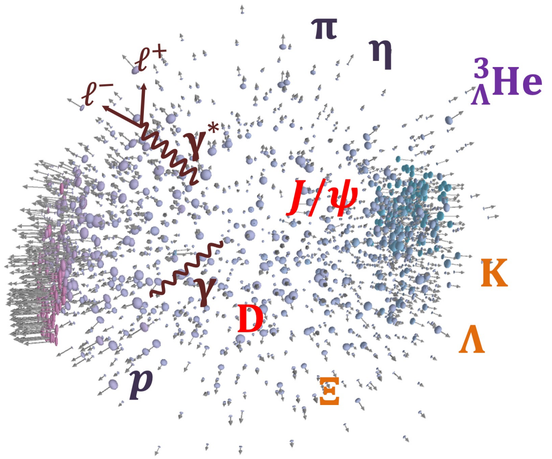
- correlated charm: excellent vertex resolution → topological separation of prompt and non-prompt source employing DCA cut
- QGP: decrease towards lower energy
- $\mathcal{D}$rell-Υan: pp, pA measurements

- **20-30% enhancement** w.r.t. no chiral mixing is **predicted** in the region 0.8<M<1.5 MeV/c^2

Dey, Eletsky, Ioffe, PLB252 (1990)
Rapp, Wambach, ANP 25 (2000)
Sakai *et al.*, arXiv:2308.03305 [nucl-th]

- **CBM, NA60+, ALICE3 sensitivity** (statictical and systematic) to detect a signal is **demonstrated**





Final state "hadron-chemistry"

HADRON PRODUCTION

MATTER EFFECTS ON STRANGENESS PRODUCTION

VOLUME 55, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1985

Subthreshold Kaon Production as a Probe of the Nuclear Equation of State

J. Aichelin and Che Ming Ko[a]
Joint Institute for Heavy Ion Research, Holifield Heavy Ion Research Facility, Oak Ridge, Tennessee 37831
(Received 11 June 1985; revised manuscript received 23 September 1985)

The production of kaons at subthreshold energies from heavy-ion collisions is sensitive to the nuclear equation of state. In the Boltzmann-Uehling-Uhlenbeck model, the number of produced kaons from central collisions between heavy nuclei at incident energies around 700 MeV/nucleon can vary by a factor of ~3, depending on the equation of state.

In a nutshell:

- softer EoS leads to higher compression
  leads to more secondary interaction
- thus the larger probability to produce particles
  below free nucleon-nucleon production threshold

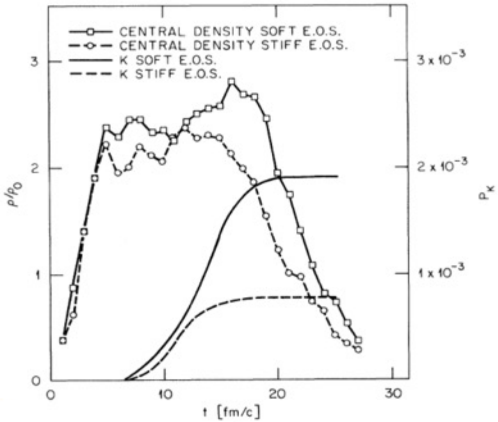
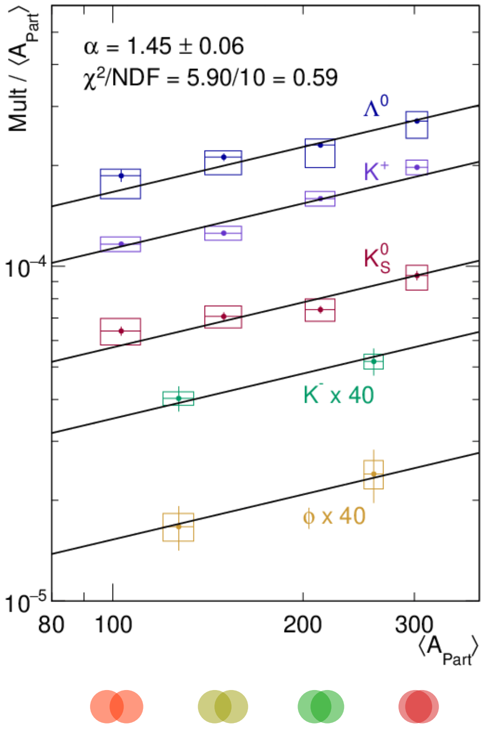


FIG. 1. Central density ρ/ρ_0 and total kaon-production probability P_K as functions of the collision time for reactions between Nb nuclei at an incident energy 700*A* MeV and at an impact parameter $b = 0.5$ fm.

Rare sub-threshold strangeness production

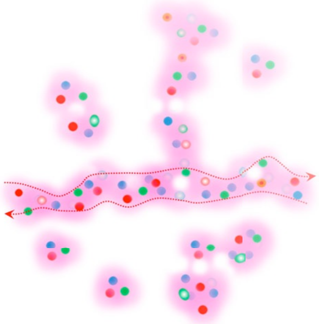
HADES, PLB 793 (2019) 457



- Different particles
- Different production mechanisms
- Different production thresholds in NN

but

- Universal scaling with participant number $M\sim\langle A_{part}\rangle^{\alpha}$
  - **not expected if strangeness produced in isolated NN collisions**
  - **quarks are easily reshuffled between hadron states?**



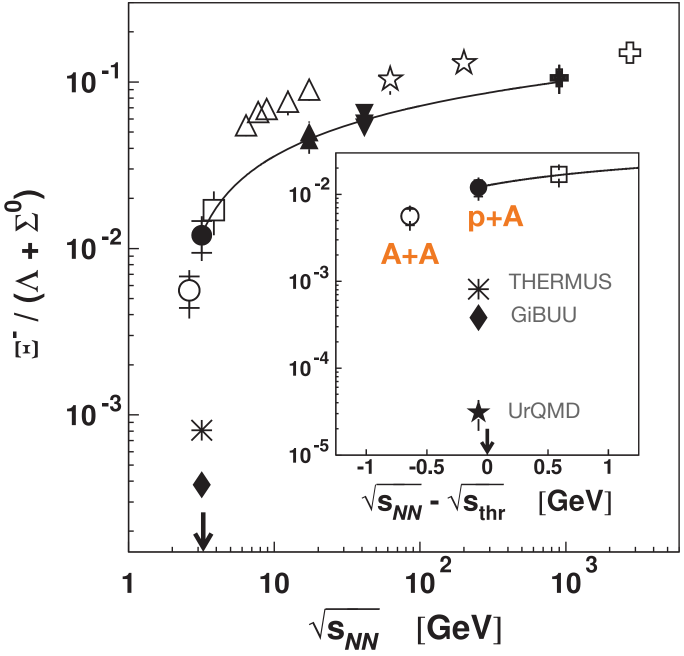
Connection to “soft deconfinement”?

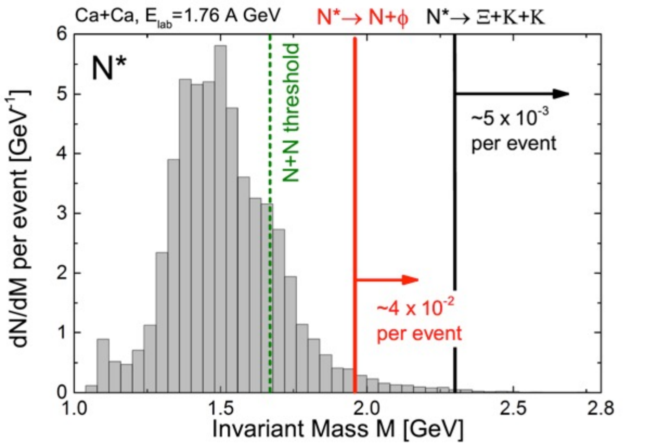
Fukushima, Kojo, Weise, Phys.Rev.D 102 (2020) 9, 096017

Quantum percolation at $\rho\sim1.8\rho_0$ of the interaction meson clouds

What is so strange about Ξ⁻?

HADES, PRL 103 (2009) 132310
HADES, PRL 114 (2015) 212301



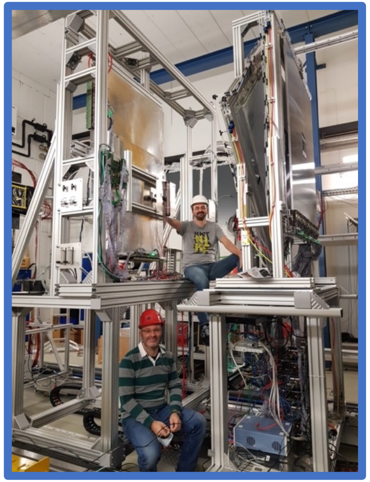


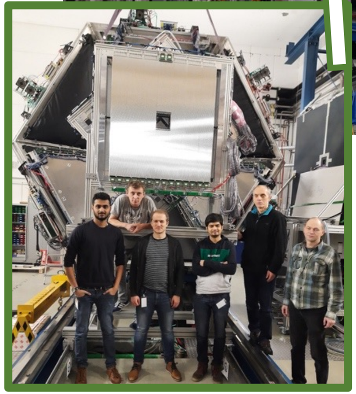
Steinheimer *et al.*, J.Phys. G43 (2016) no.1, 015104

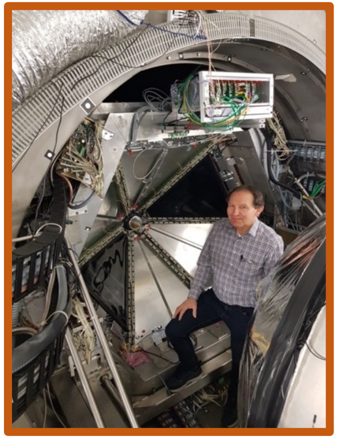
- Multi-strange baryons (Ξ, Ω) are expected to be a sensitive probe for compressed baryonic matter
- HADES observes unexpectedly large production cross sections in Ar+KCl and p+Nb collisions
- UrQMD microscopic transport models → dominant role of high mass baryonic resonances?
  - $N^* \rightarrow N + \phi$ is fixed by ANKE data
    Maeda *et al.* [ANKE], PRC 77, 015204 (2008)
  - spectroscopy of $N^* \rightarrow \Xi + K + K$
  - branching ratios

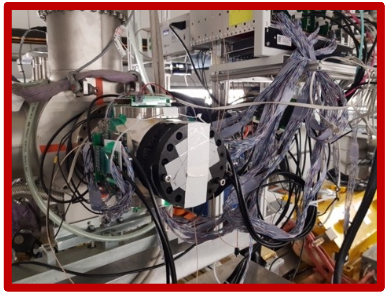
The upgraded HADES detector 2022

- Improved physics performance through instrumentation of the very forward hemisphere using FAIR technology
- In particular important for the Hyperon Program









Forward RPC

LIP Coimbra

- Based on R&D for neuLAND
- TRB3 read-out

STS2

Jagiellonian Univ.

- PANDA straw technology
- PANDA PASTTREC FEE chip

STS1

TransFAIR, Jülich

- PANDA straw technology
- PANDA PASTTREC FEE chip

iTOF

TransFAIR, Jülich

- APD read-out
- Enhances trigger purity

T0

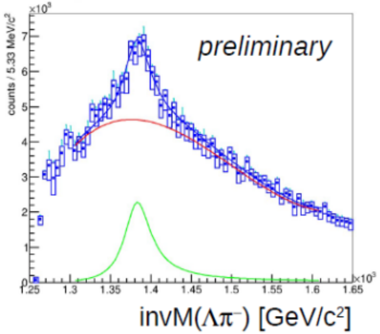
GSI, TU Darmstadt

- LGAD technology
- In-beam detector

HADES – PANDA Phase-0

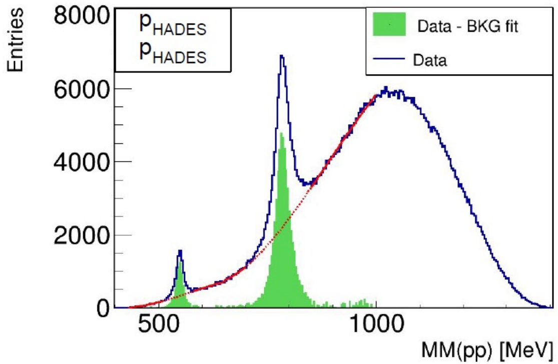
FAIR Phase 0 Research Program

$\Sigma^{*-}(1385) \rightarrow \Lambda\pi^-$



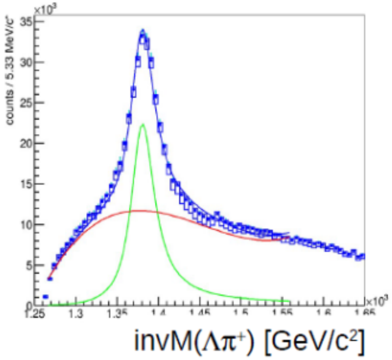
- Hyperon radiative decays
- Hyperon Dalitz-decays
- Doubly strange baryons
- Double Λ correlations (femtoscopy)
- Inclusive hadrons and dileptons

exclusive $pp \rightarrow pp\eta/\omega$

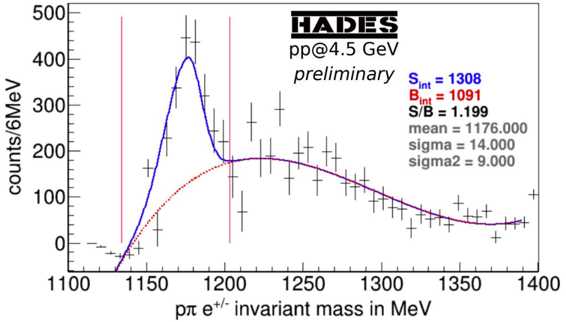


- production cross section, decay dynamics
- CP violation in $\eta \rightarrow \pi^+\pi^-e^+e^-$, search for $X17$ axion like particle
- production mechanism of $a1(1260), f1(1285)$

$\Sigma^{*+}(1385) \rightarrow \Lambda\pi^+$



$\Sigma^0 \rightarrow \Lambda e^+e^-$ Dalitz decay in $pp \rightarrow pK + \Sigma^0$



HADES towards FAIR

Conclusion of Phase-0 (now – 2026)

Strong interest from high-μ_B HIC community, relevance for astrophysics

- **Au+Au beam energy scan (0.8 – 0.6 – 0.4 – 0.2 *A*GeV)**

Strong interest from hadron structure community, crucial input to PWA

- **π+CH2,C beam** energy scan of baryon excitation functions and decay modes; high-intensity **pion beam** running demonstrated (up to **8 x10^{10}/s** ^{14}Nitrogen ions), high duty cycle CH2 and C target and π beam at $\sqrt{s}$=1.67-1.70-1.73-1.79 GeV
  - hadronic channels: new data from HADES will dramatically improve the world data base for PWA!
  - electromagnetic channels: explore baryon electromagnetic structure in time like ($q^2 > 0$) region

Intermediate program during commissioning of ES, FS, FS+ (2027 – ~2030)

- imperative to follow-up and solidify the discussions regarding the operation of and the physics perspectives of HADES during these phases

Operation with SIS100 beam (beyond ~2030)

- will go inline with preparation of a new MoU (FAIR M&O MoU)

Physics perspectives with hadron beams at GSI/FAIR

- Initiative (2022) from FAIR-motivated group from within CBM, HADES, PANDA (building up on success of PANDA Phase-0 at HADES)

- Promote the realisation of FS+ at FAIR
- Identify a QCD-inspired physics program with SIS100 proton beams
- Evaluate its complementarity with programs at other facilities
- Strengthen collaborations among hadron-, nuclear- and heavy-ion communities
- Reach out for new collaborators from both experiment and theory!

- Kick-off satellite event at MESON2023 in June 2023
- Feasibility studies using Monte Carlo simulations
- Workshop “physics opportunities with proton beams at SIS100” in Wuppertal, February 2024

https://indico.gsi.de/event/18475/overview

87 participants

From SIS18 to SIS100

…what could that add in strong-QCD physics?

Energy upgrade:

- from max 4.7 GeV (SIS18) to 29 GeV (SIS100) proton energy
- opening new realm:
  - production, spectroscopy and interactions of double and triple strangeness
  - charm production and interactions close to production threshold
- significant increase in production yield of hyperons

Intensity upgrade:

- from max 10^{12} (SIS18) to 2×10^{13} (SIS100) protons/cycle
- even with 10^{10} p/cycle and 1% LH2 target: ~10 pb^{-1} / day

Detector enrichment:

- towards high-rate capabilities and free-streaming DAQ's
- excellent mass resolution (~2%)
- excellent coverage for exclusive channels

Theory enrichment:

- terra incognita: theoretically complicated region to describe, transition from resonance to string production
- important new insight into hadron structure (hyperon spectrum, charm content of nucleon)

Competitive and complementary program to other facilities world-wide

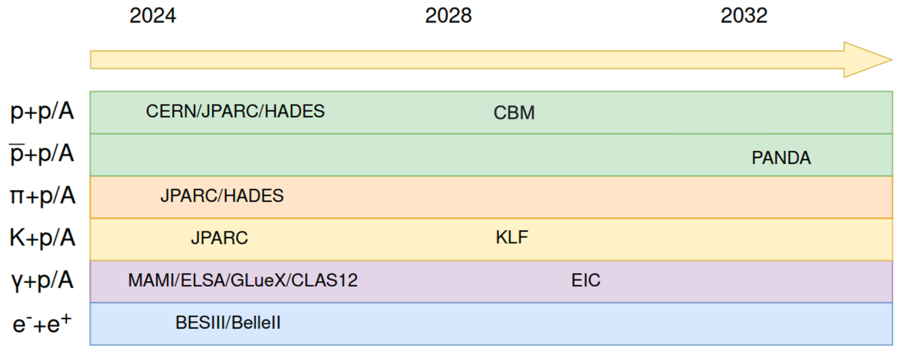
Numerous γ, π, K facilites now and upcoming

CERN primarily serves higher energy domain,
→ different production mechanism

JPARC uses dedicated experiments,
→ complementary to CBM

CBM can measure p- and A-induced reactions
→ backgrounds, systematics *etc.*

Hyperon Physics Facilities/Experiments

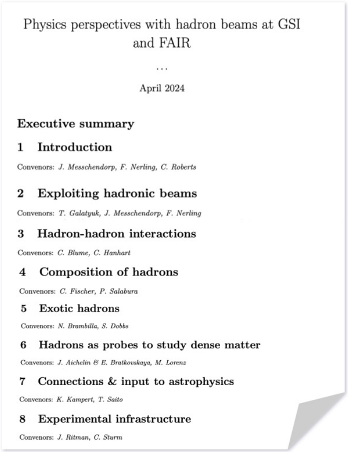


Compilation J. Taylor

A comprehensive QCD program

pic. adopted from J. Messchendorp

- Tremendous physics potential with proton beam from SIS100
- **Substantial extension of QCD program at FAIR and its impact on increased attractivity/visibility for international community**
- Preparations for a “white-paper” beginning



Physics perspectives with hadron beams at GSI and FAIR

…

April 2024

Executive summary

1 Introduction

Convenors: *J. Messchendorp, F. Nerling, C. Roberts*

2 Exploiting hadronic beams

Convenors: *T. Galatyuk, J. Messchendorp, F. Nerling*

3 Hadron-hadron interactions

Convenors: *C. Blume, C. Hanhart*

4 Composition of hadrons

Convenors: *C. Fischer, P. Salabura*

5 Exotic hadrons

Convenors: *N. Brambilla, S. Dobbs*

6 Hadrons as probes to study dense matter

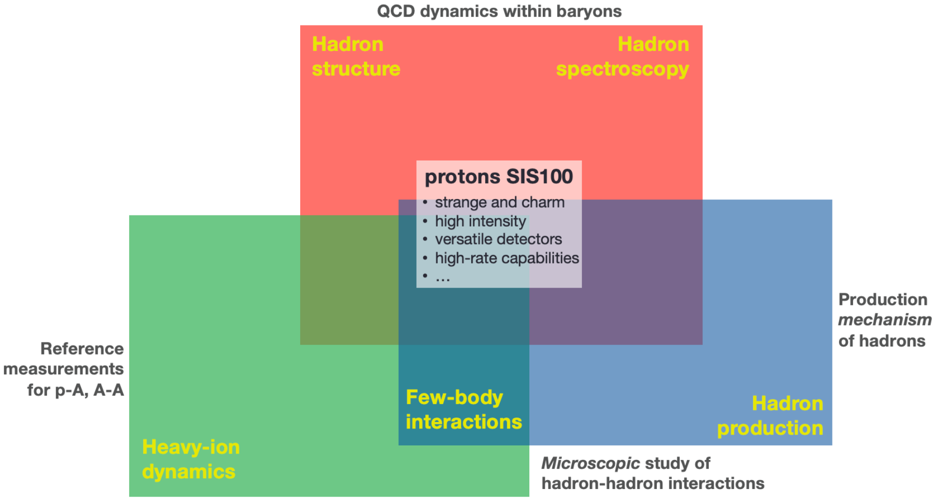
Convenors: *J. Aichelin & E. Bratkovskaya, M. Lorenz*

7 Connections & input to astrophysics

Convenors: *K. Kampert, T. Saito*

8 Experimental infrastructure

Convenors: *J. Ritman, C. Sturm*



Strong support by community of physics program employing world-unique combination of GSI secondary pion beam + HADES

Summary: The future is bright!

From NuPECC LRP2024 Executive Summary (draft as of April 2024)

- To investigate nuclear matter at high baryonic density, the timely completion of **SIS-100** at **FAIR** and the realization of the **CBM** experiment are of utmost importance. Efforts should continue to support R&D activities related to advanced **CBM** silicon vertexing and tracking devices.

- The full exploitation of the existing detectors and facilities, in particular **HADES** and **R3B** at **SIS-18/SIS-100**, should receive full support.

- Full exploitation of the novel research opportunities as provided by the FAIR facility for the **APPA**, **CBM**, **NUSTAR** and **PANDA** collaborations.
- Realization of First Science+ until 2028 followed by the expedited completion of the **APPA** cave and the **Super-FRS** low-energy branch.

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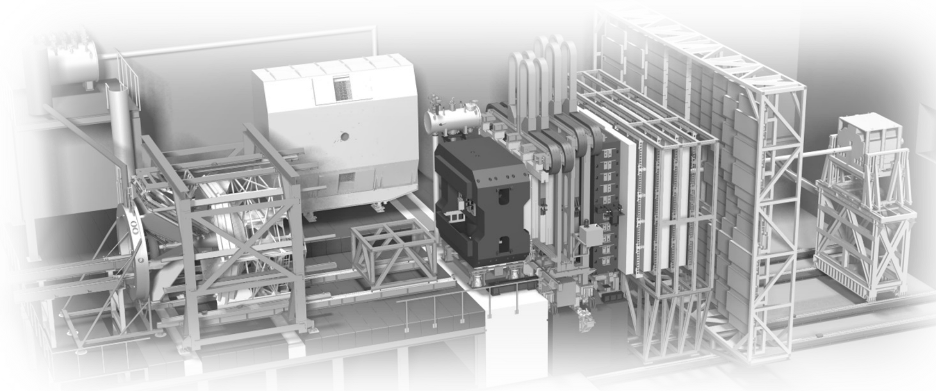
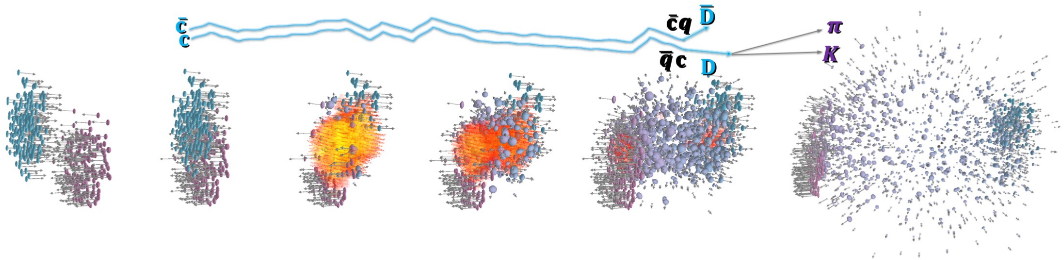
Bonus slides



Charm $(c, \bar{c})$ of the baryon-rich matter

IN-MEDIUM QCD FORCE

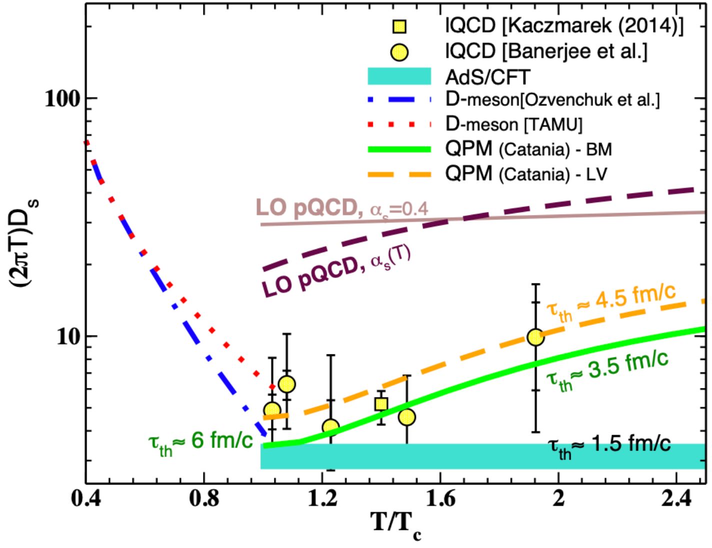
What is so “charming” about charm?



Heavy quarks

- produced in initial hard scattering processes
- experience the full evolution of the QCD medium

→ probe in-medium QCD force!



Scardina *et al.*, PRC96, 044905 (2017)
HotQCD, PRL 132 (2024) 5, 051902

- heavy-quark potential accurately known in the vacuum (Ψ , Υ spectroscopy)
- $\mu_B = 0$, finite T – heavy-quark potential is modified (screened), guidance from LQCD

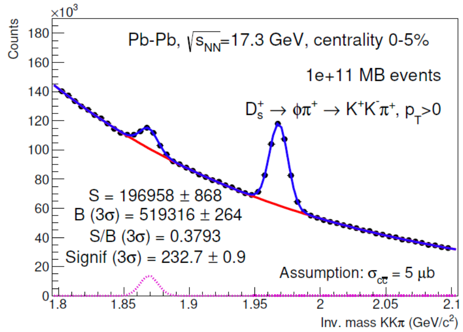
How is the fundamental QCD force screened at $\mu_B > 0$?

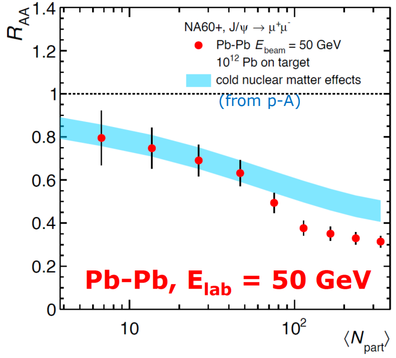
Consequences for heavy-quark transport

$\sqrt{s_{NN}}$~6 GeV (and below) increased sensitivity to hadronic medium effects – important input for precision measurements at LHC

Charm performance studies

Larsen *et al.*, NA61/SHINE, EPJ Web Conf. 191 (2018) 05003





NA60++ / CBM (cross-sections unknown!)

Open charm

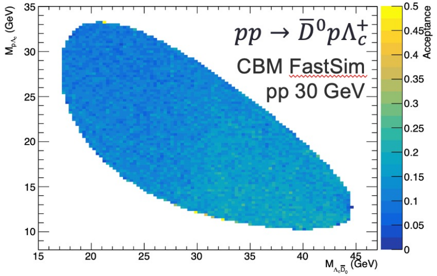
- accessible down at lowest $\sqrt{s_{NN}}$ with 1% statistical precision
  ↝ R_{AA} and v_2 vs p_T, y and centrality
  → **charm diffusion coefficient and thermalization**
- **D_s** and **Λ_c** yield feasible with statistical precision of few percent
  → **insight on hadronization mechanism**

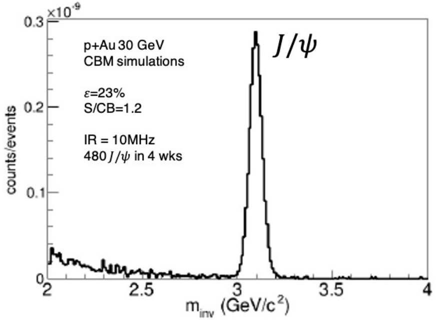
J/ψ

- detection of **onset of anomalous suppression** effects down to low SPS energy ($\psi(2S)$ also within reach for E~100 *A*GeV)
- pp/pA collisions to establish cold nuclear matter effects
- study intrinsic charm component of the hadron wave function

Vogt, PRC 106 (2022) 2, 025201
NNPDF, Nature 608 (2022) 7923, 483-487

Charm-N interaction





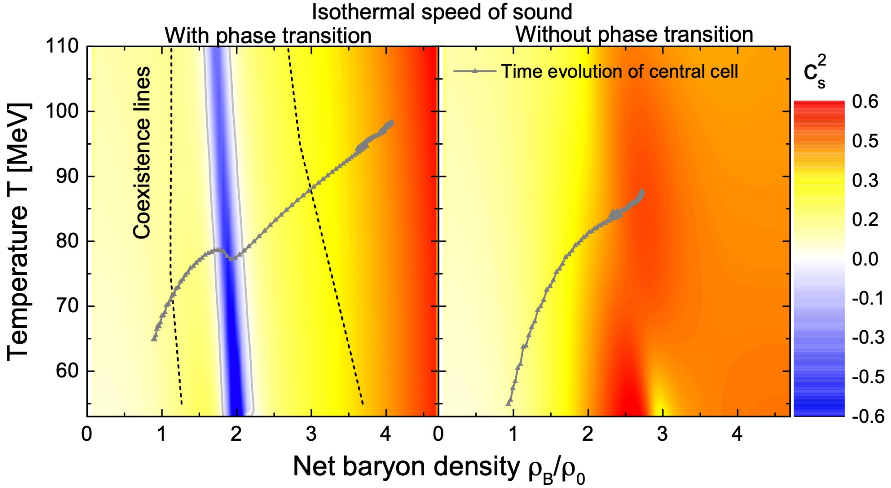
Tremendous physics potential with proton beam from SIS100

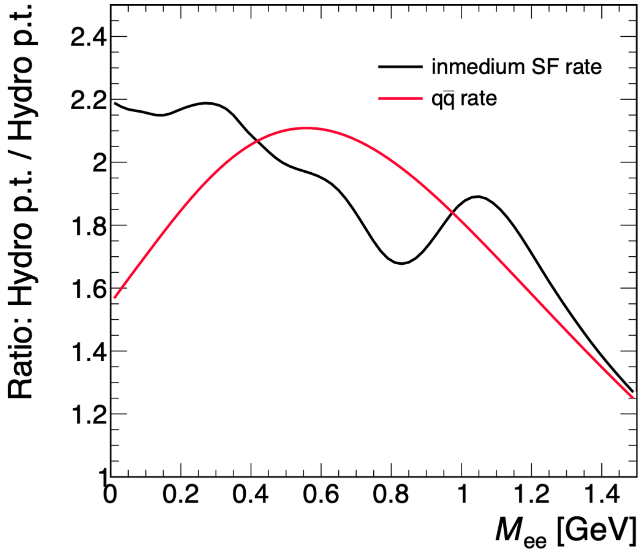
Workshop "physics opportunities with proton beams at SIS100" in Wuppertal, February 2024
https://indico.gsi.de/event/18475/overview

Dilepton signature of a 1st order phase transition

See also:
Savchuk, TG, *et al.*, J.Phys.G 50 (2023) 12, 125104
Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203

Seck, TG, *et al.*, PRC 106 (2022) 1, 014904





- Ideal hydro simulations with and w/o first order nuclear matter – quark matter phase transition
- Chiral Mean Field model that matches lattice QCD at low μ_B and neutron-star constraints at high density

Most et al., PRD 107 (2023) 4, 043034

Dilepton emission shows a significant effect: factor 2 enhancement of dilepton emission due to extended "cooking"