

SELECTED RESULTS FROM HADES

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Physics at High Baryon Density – PHD2025

College of Physical Science and Technology CCNU, Wuhan, China

October 16 – 18, 2025



Status and future of the HADES experiment

Inclusive hadron emission, flow correlation and e-b-e proton number fluctuations

Excess radiation, flow and virtual photon polarisation

Establishing the “standard candle” for hadronic emissivity

Summary

The HADES spectrometer at GSI SIS-18

Geometry

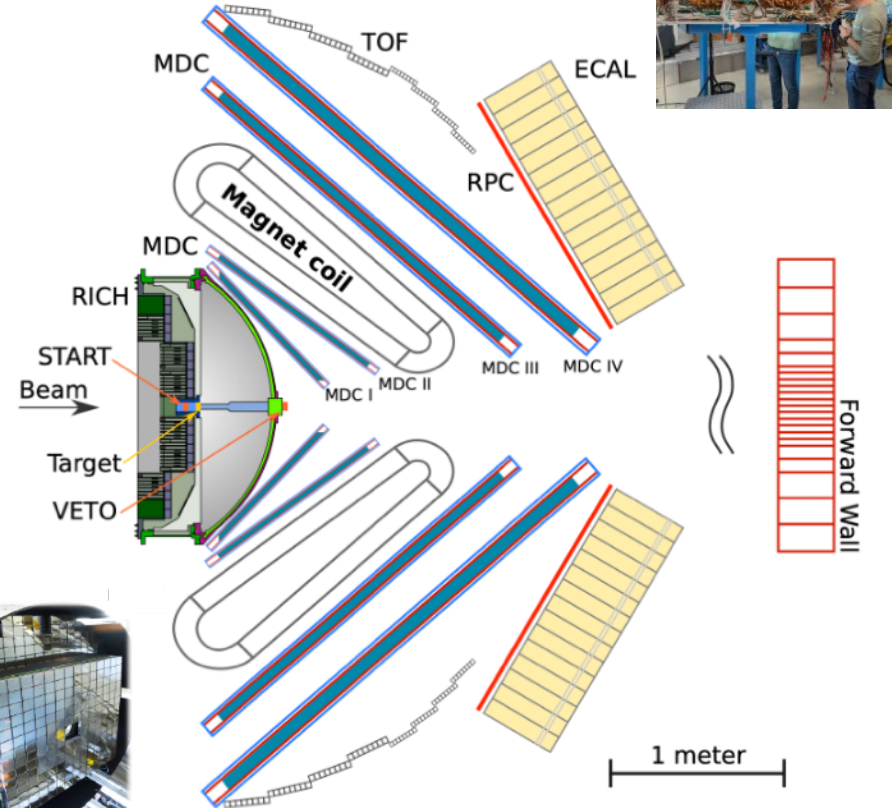
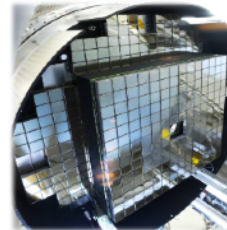
- Full azimuthal coverage with 6 identical sectors
- $18^\circ < \theta < 85^\circ$ (≈ 0.35 pair acceptance)

Particle Identification

- RICH – MAPMT based photo detection plane
- TOF – scintillator rods
- RPC – 2 layers of shielded cells ($\sigma_t \approx 70$ ps)
- ECAL – lead glas ($\sigma_t \approx 150$ ps)
- START – segmented LGAD or CVD ($\sigma_t \approx < 60$ ps)

Low-mass tracking

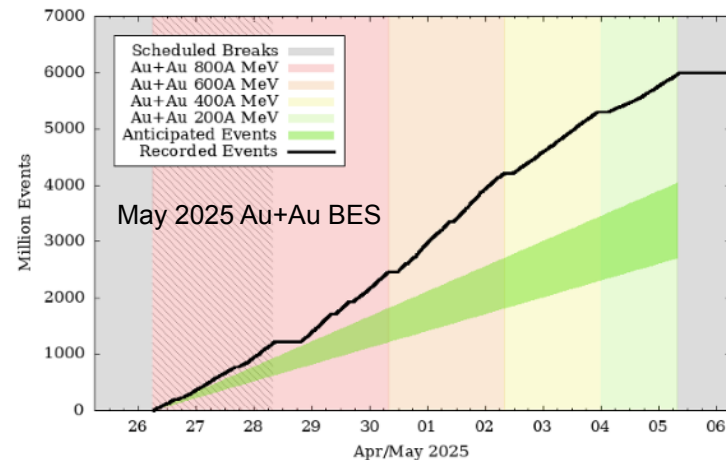
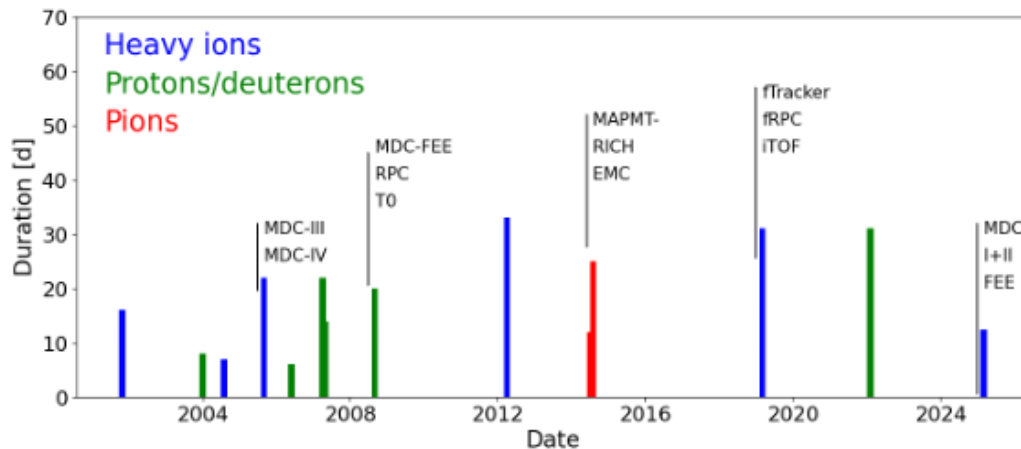
- Superconducting toroid ($B\rho \approx 0.36$ Tm)
- MDC – 4 planes of low-mass drift chambers
- Recent FEE upgrade with multi-hit capability



HADES physics runs

- Heavy-ion program at SIS18 concluded with Au+Au BES (800, 600, 400, 200 A MeV) in May 2025
- Significant **improvement of event rate** due to Spill Optimisation System (SOS) and MDC FEE upgrade
 - Knock-out extraction with feed back of interaction rate
- Six billion events** in nine days beam on target

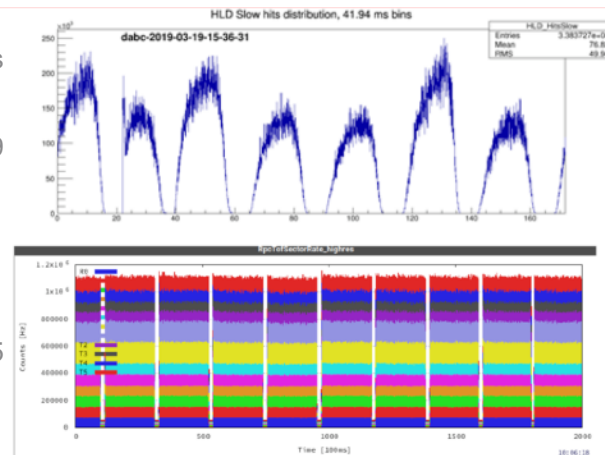
HADES collected data since 2002 (> 20 years of operation)



spill profiles

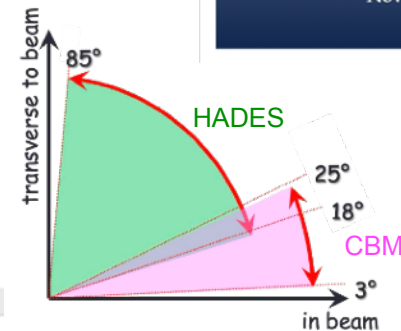
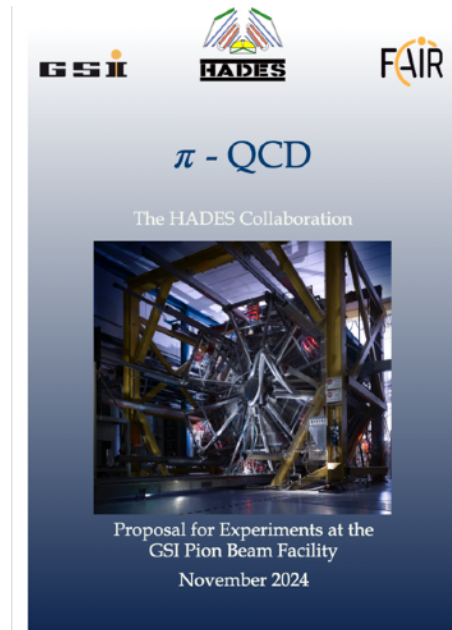
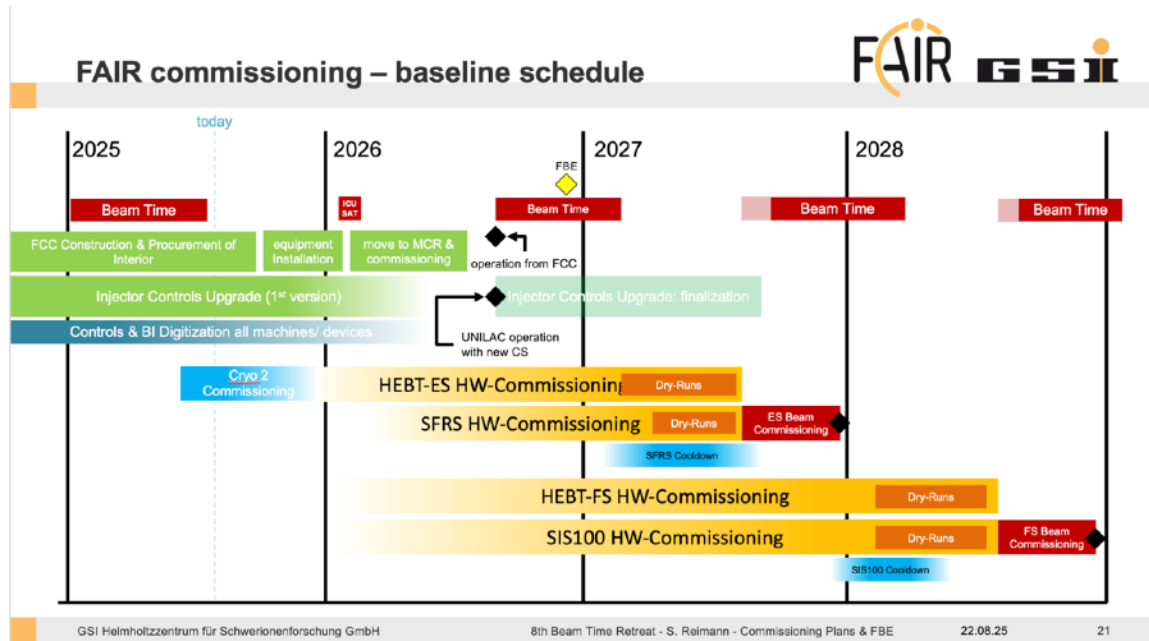
2019

2025



HADES in the years 2027 to 2032

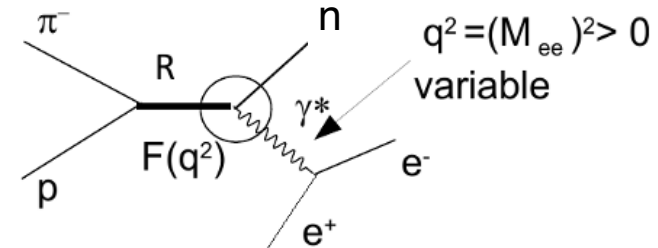
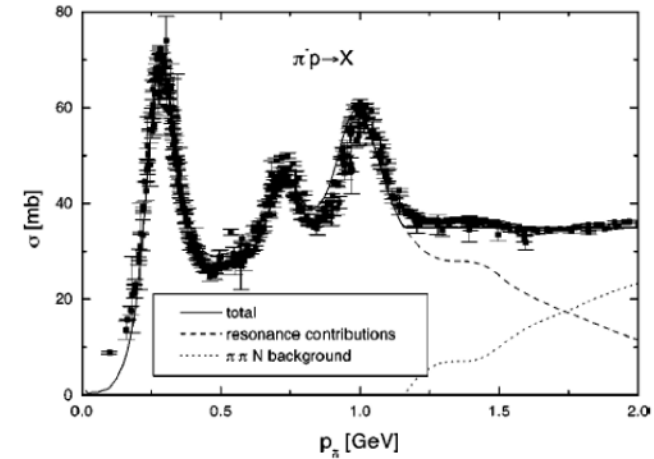
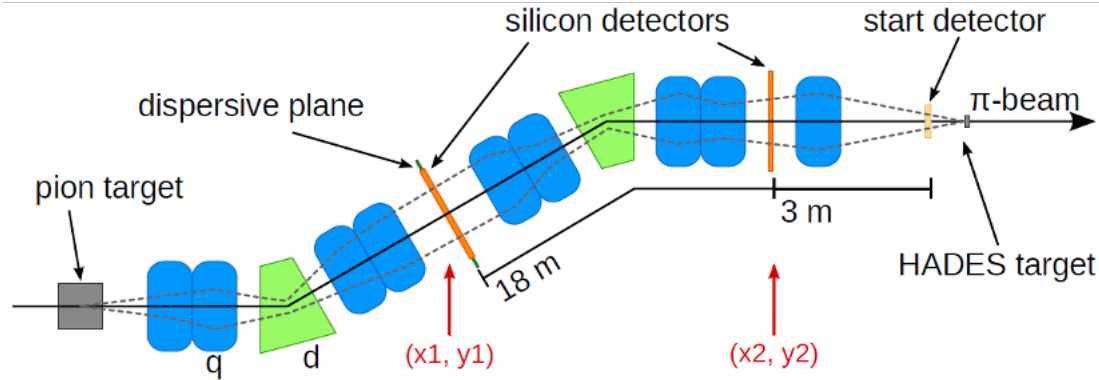
- Exploit opportunities of pion beam combined with dilepton spectrometer
- Proposal π - QCD contains ~ 100 days of beam on target
- Complement CBM program once CBM has finished day on experiments



CBM acceptance
optimised for
SIS300 beam

The HADES pion beam facility

- o Pion production target 40 m upstream the experiment target p
- o Direct **excitation of baryon resonance** and exclusive reconstruction
- o Combination with dilepton spectrometer **world-wide unique**

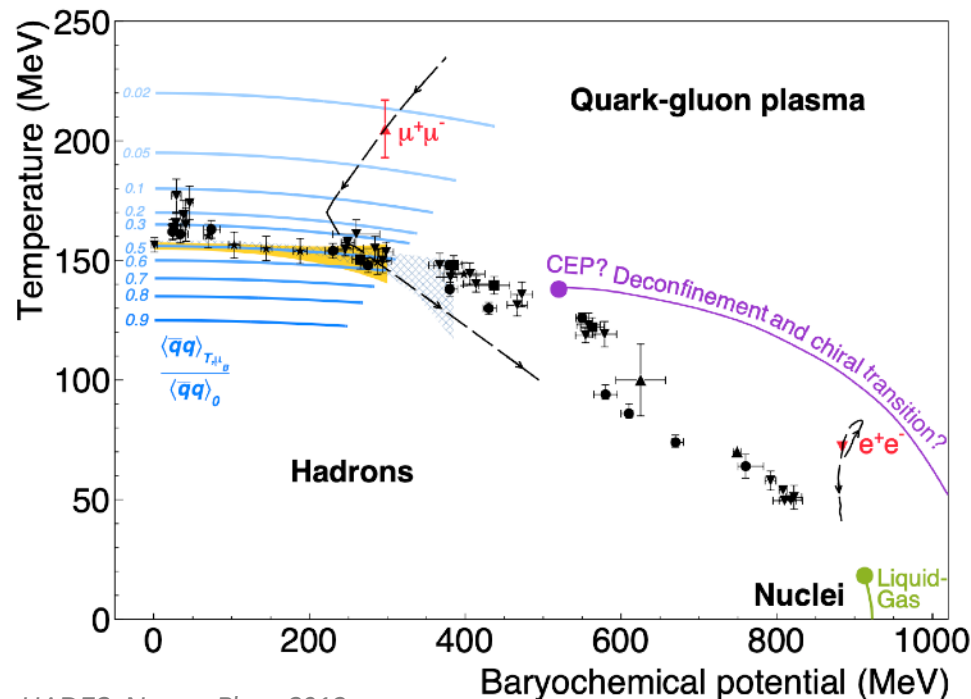


Exploration of the QCD Phase Diagram @ high- μ_B

From medium-effects to novel phases of QCD matter

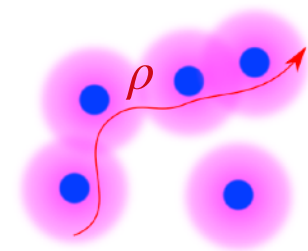
Conjectures for

$$T \gtrsim 25 \text{ MeV}, \mu_B \gtrsim 500 \text{ MeV:}$$



HADES, Nature Phys. 2019

- First order transition (CEP, mixed phase)?
 - Chiral
 - Deconfinement ?
- What phases?
 - Hadron resonance "gas"
 - Soft deconfinement
 - Quarkyonic
 - Moat regime
- Equilibration driven by entangled pion cloud?



c.f. K. Fukushima, T. Kojo, W. Weise; Phys. Rev. D 102 (2020)

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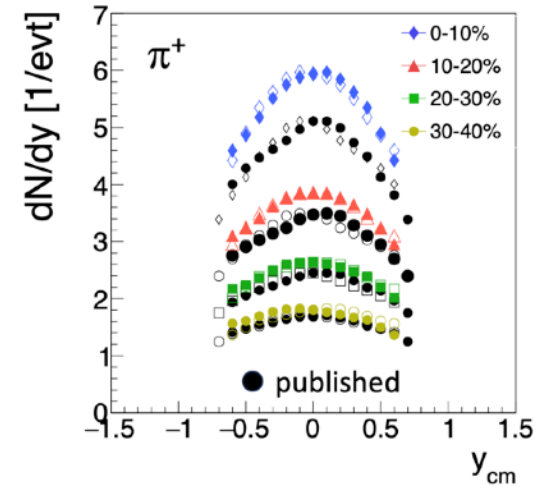
Excess radiation, flow and virtual photon polarisation

Establishing the “standard candle” for hadronic emissivity

Summary

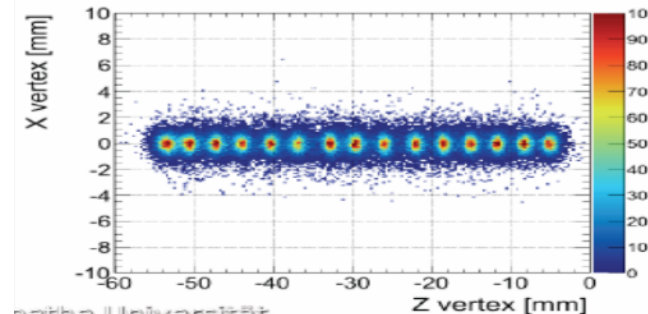
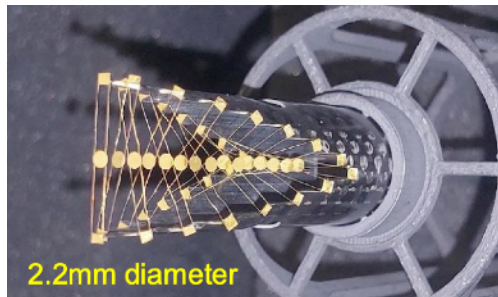
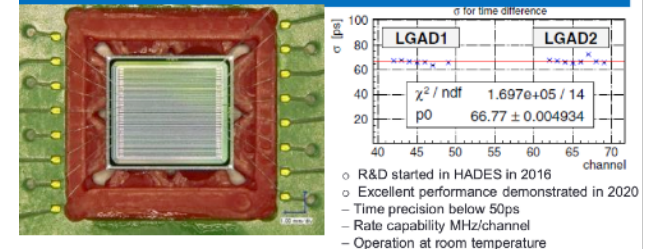
Event purity and efficiency – new method applied

- Event-pile-up mitigated by 15-fold, frame-less Au (Ag) target stack
- Instantaneous beam intensity monitoring using segmented LGAD T0 detector in beam
- Consistency between embedding in real data and full MC efficiency determination by e-b-e variation of beam background
 - Dead-time effects in MDC cells due to δ -electron production
- Au+Au pions effected up to ~20 % in 0-10% centrality



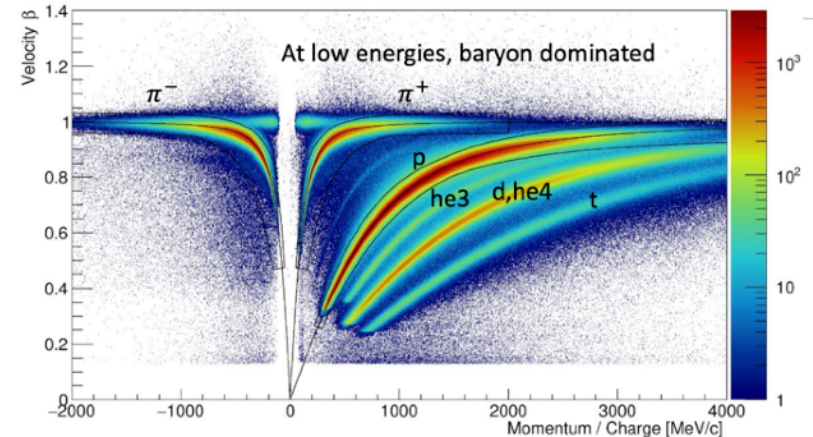
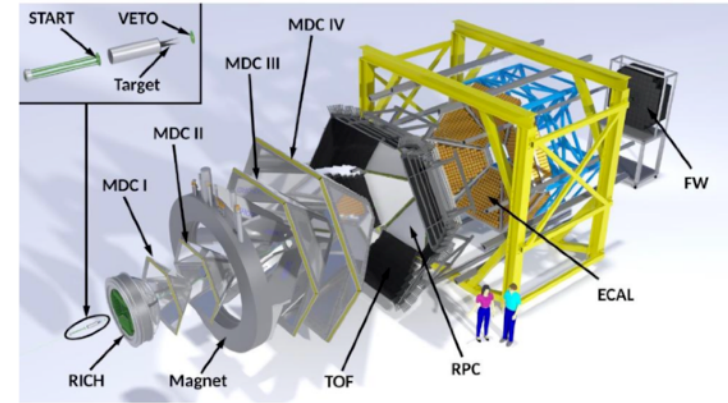
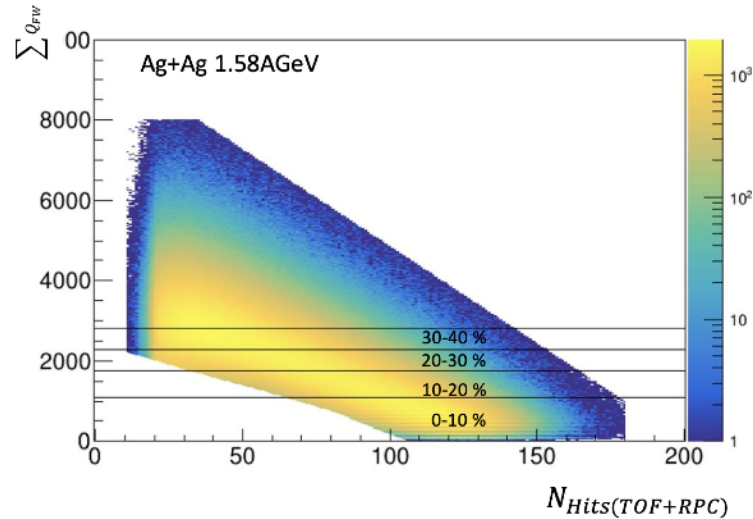
J. Pietraszko, et al., Eur. Phys. J. A 56, 183 (2020)

HADES Prototype LGAD T0 sensor and performance



E.b.e proton number fluctuations

- Event activity (N_{Hits}) from wounded nucleons via Glauber MC plus independent (binomial) particle emission to detector hits
- Centrality for fluctuation analysis using selection on forward going particles $\sum Q_{\text{FW}}$ (spectator nucleons)
- Large acceptance for protons around mid-rapidity



Corrections applied to data

- Detector efficiency via unfolding and moment expansion
- PID (incl. purity from decor relation) using "Fuzzy Logic". Fits for every $p_t - y$ bin
- Volume fluctuations mitigated by event-mixing method

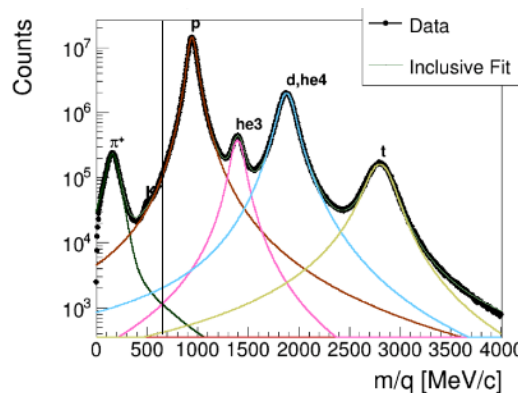
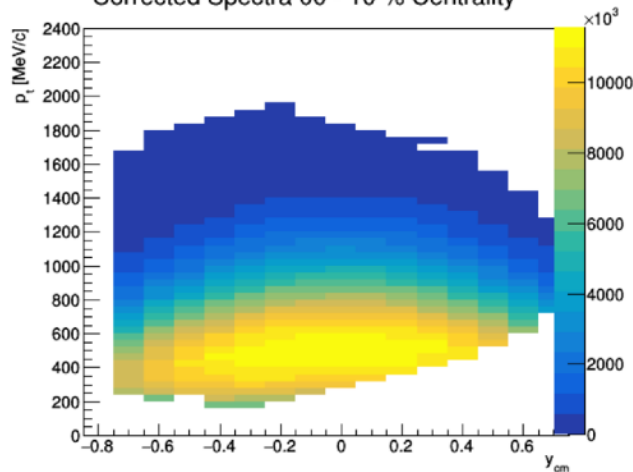
A. Rustamov, J. S., M. Nabroth QM2025

A. Rustamov; *Phys.Rev.C* 110 (2024) 6, 064910

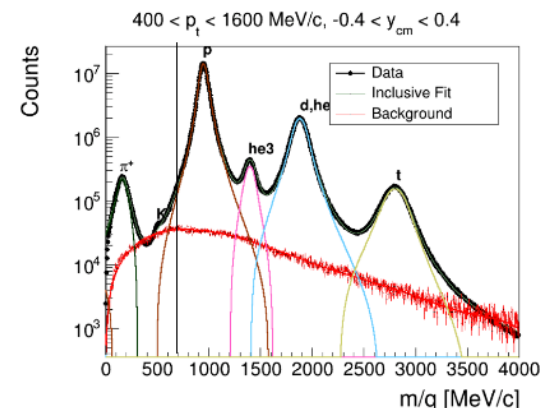
V. Koch, R. Holzmann, A. Rustamov, J. S., *Nucl. Phys. A* 1050 (2024) 122924

	MC Truth	MC Test	Applied on Data
●	Tikhonov Unfolding (Hard cut based) [S. Schnitt, J. Instrum. 7, T10003 (2012)]	✓	✓
✕	SVD Unfolding (Hard cut based) [A. Höcker and V. Karvelashvili, Nucl. Instrum. Methods Phys. Res. A 372, 469 (1996)]	✓	✓
✕	Bayesian Unfolding (Hard cut based) [G. D'Agostini, Nucl. Instrum. Methods Phys. Res. A 3362, 487 (1995)]	✓	✓
✕	Moment Expansion (Hard cut based) [T. Nonaka et. al. Nucl. Instrum. Meth. A 906 (2018) 10-17]	✓	✓
✕	E-by-E Binomial (Hard cut based) [Toshihiro Nonaka, Masakiyo Kitazawa, and Shinichi Esumi Phys. Rev. C 95, 064912]	✓	✓
✕	Fuzzy Logic Corr. + Moment Expansion	✓	✓
✕	Fuzzy Logic Corr. (Cornish-Fisher Expansion) + Bayesies Unf.	✓	✓
✕	Iterative Gen. Neural Network Unfolding [M. Backes, A. Butter, M. Dunford and B. Malaescu, SciPost Phys. Core 7 (2024) 1, 007]	✓	✓ (✓)

Corrected Spectra 00 - 10 % Centrality



T. Nonaka et. al. *Nucl. Instrum. Meth. A* 906 (2018) 10-17

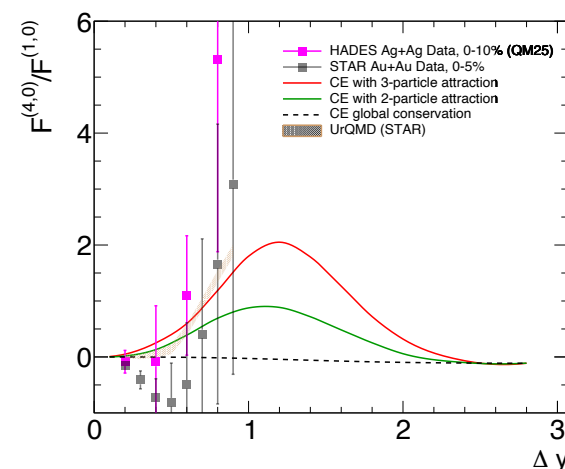
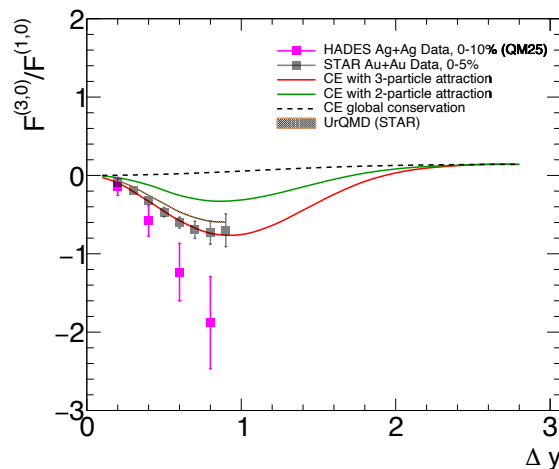
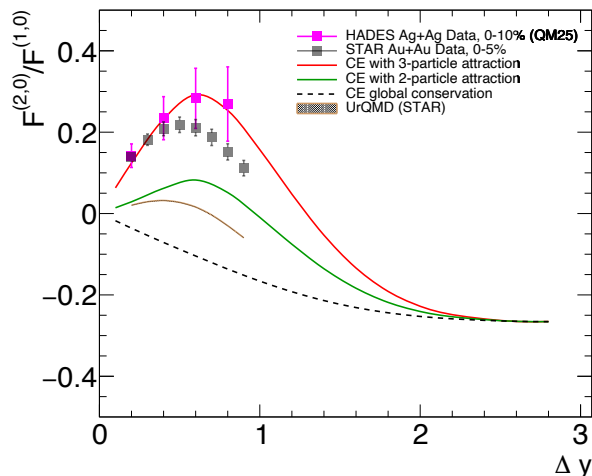


Factorial cumulants: comparison to STAR FXT data

- Canonical baselines from HRG with interactions
- UrQMD calculation taken from STAR
- Comparison to baseline suggests importance of three-body attractive interactions

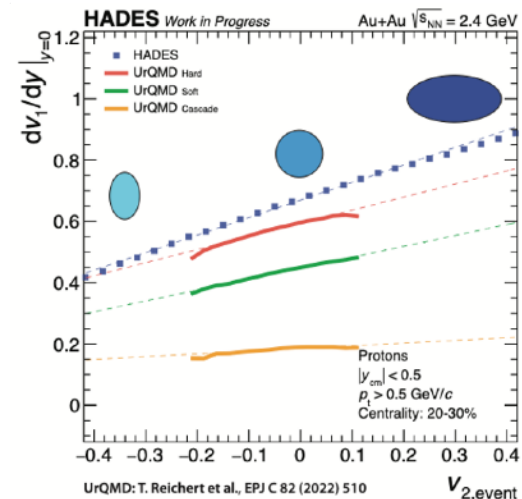
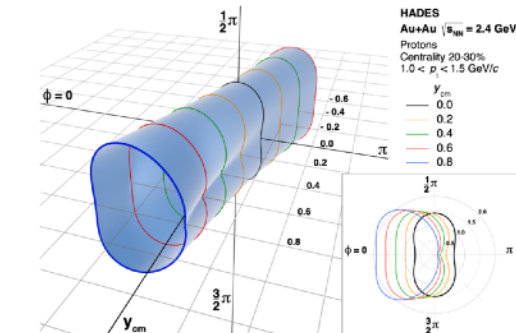
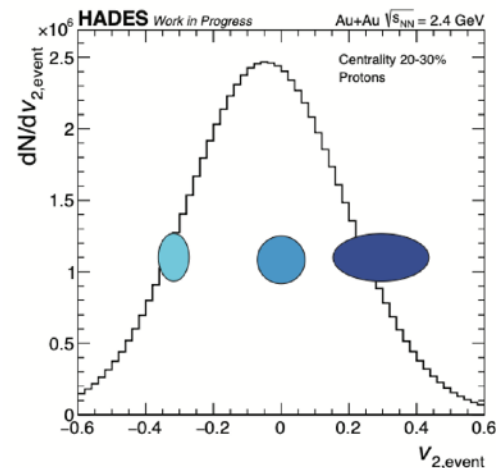
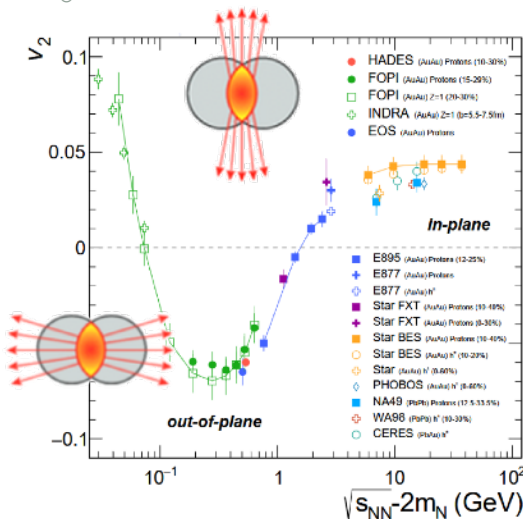
B. Friman, A. Rustamov, K. Redlich, e-Print: 2508.18879 [nucl-th]

*P. Braun-Munzinger, K. Redlich, A. Rustamov,
J. Stachel, JHEP 08 (2024) 113*



Flow correlations

- High statistics enable to characterise the particle production in heavy-ion collisions as a full 3D-picture in momentum space.
- Events are sorted into ellipticity-classes according their event-wise magnitude of the elliptic flow $v_{2,\text{event}}$ as proposed in T. Reichert et al.
- Correlations between the flow coefficients v_1 , v_2 and v_4 and the event-wise $v_{2,\text{event}}$
- Enhanced sensitivity to EOS in $dv_3/dy|_{y=0}$ vs $v_{2,\text{event}}$

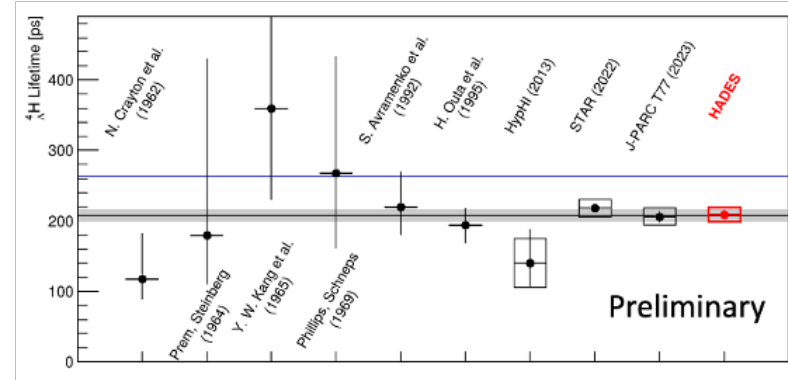


Hypernuclei lifetimes from two-body decays

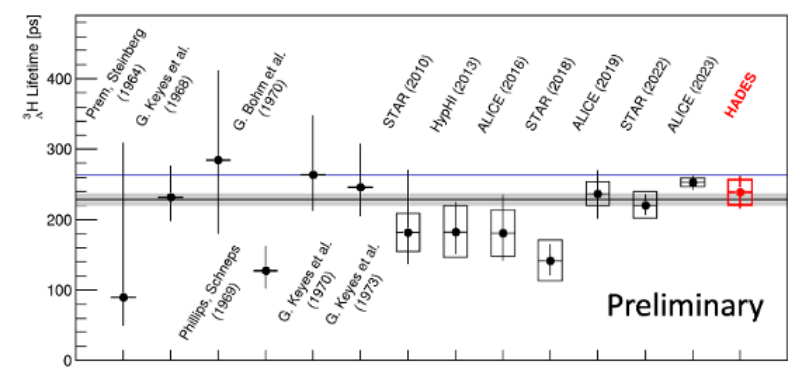
Simon Spies (HADES)



- $\tau = (239 \pm 23 \pm 18) \text{ ps}$
- Decays observed: $(4.8 \pm 0.5 \pm 0.5 \pm 0.2) \times 10^4$



- $\tau = (209 \pm 7 \pm 10) \text{ ps}$
- Decays observed: $(46.1 \pm 0.2 \pm 0.6 \pm 0.3) \times 10^4$



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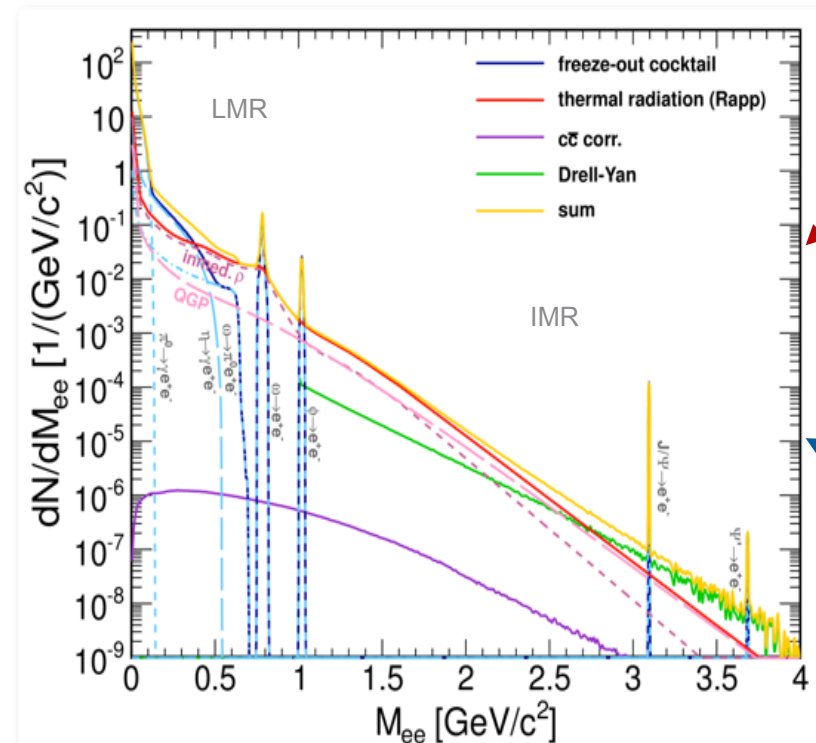
Summary

Excess Radiation as “Standard Candle” for (U)RHIC

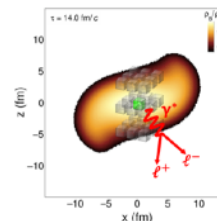
Medium radiation from *Thermal Emission Rates* (ϵ):

$$\frac{dR_{ee}}{dM dy dp_T d\alpha} = \int -\frac{\alpha^2}{\pi^3} \frac{L(M)}{M^2} f^B(q_0; T) \text{Im}\Pi_{em\mu}^\mu(q_0, \vec{q}, \mu_i, T) dV dt$$

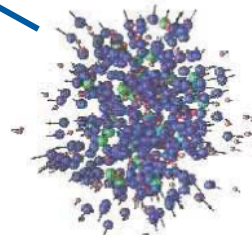
$$\equiv \int \frac{d^4\epsilon}{dq} \left[T(x), \mu_B(x), \vec{v}(x) \right] dx$$



shining



UrQMD

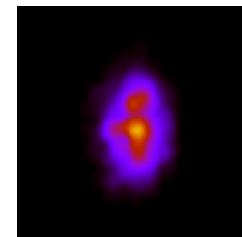


or

coarse graining

*T: Galatyuk, JS, et al.,
EPJA 52 (2016) 5*

hydro



Dilepton emission from
Microscopic Transport.

Vector-meson dominance in hot & dense matter

Generalized „Bremsstrahlung“ – Fourier transform of current-current correlation function $\langle j(x), j(0) \rangle$:

$$\Pi_{EM}^{\mu\nu}(q) = \int d^4x e^{iqx} \Theta(x_0) \langle [j_{EM}^\mu(x), j_{EM}^\nu(0)] \rangle_T$$

L. McLerran, K. Toimela, *Phys. Rev. D* 31 (1985)

See also: Ralf Rapp *arXiv-1110-4345*

Extension of the Gounaris-Sakurai formula to a thermal pion gas: C. Gale, J. Kapusta: *Nucl. Phys. B* 357 (1991) 65

$$j_{EM}^\mu = \frac{1}{2}(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d) + \frac{1}{6}(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d) - \frac{1}{3}\bar{s}\gamma^\mu s \Rightarrow \text{Im}\Pi_{EM} \sim \text{Im}D_\rho + \frac{1}{9}\text{Im}D_\omega + \frac{2}{9}\text{Im}D_\phi$$

Hadronic current can be approximated by the imaginary part of the in-medium ρ propagator.
Inclusion of meson-baryon coupling, ρ only:

$$\text{Im}\Pi_{EM}(M) = \left(\frac{m_\rho^2}{g_\rho}\right)^2 \text{Im}D_\rho(M)$$

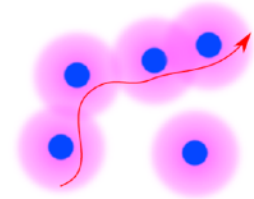
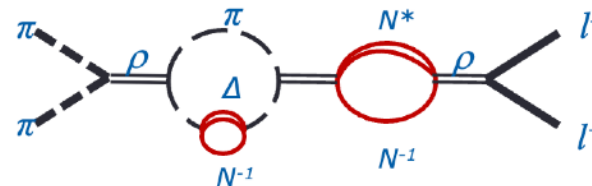
$$D_\rho(M, q; \mu_B, T) = \frac{1}{(M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B})}$$

R. Rapp, J. Wambach: *Adv.Nucl.Phys.* 25 (2000) 1

B. Friman, *Nucl. Phys. A* 610 (1996) 358c;

B. Friman and H.J. Pirner, *Nucl. Phys. A* 617 (1997) 496

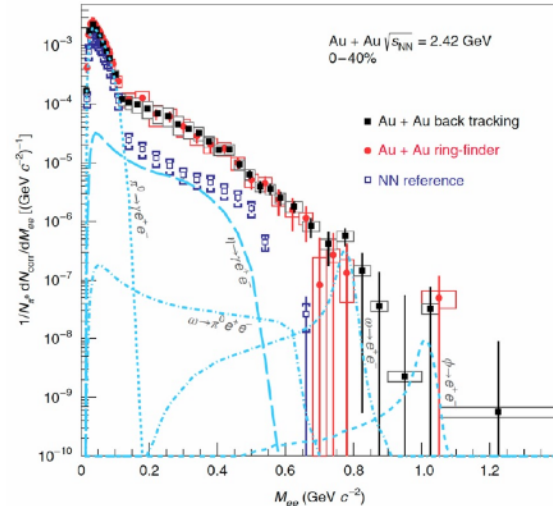
M. Asakawa, C-M. Ko et al., *PRC* 46 (1992) R1159



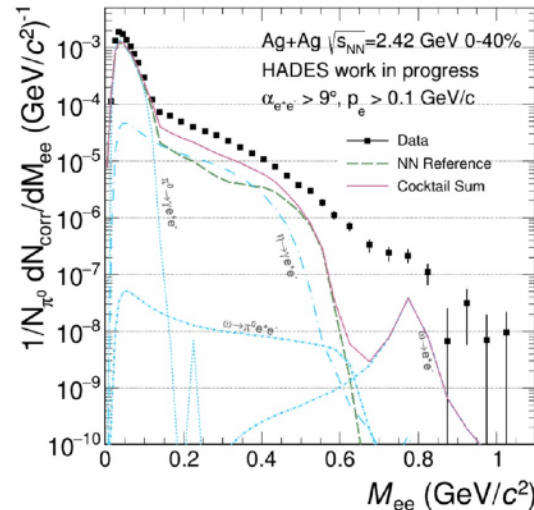
Dilepton spectra measured by HADES

- **Significant excess radiation** above contributions from initial state (from NN reference) and freeze-out (meson cocktail) visible
- Excess radiation drops by four orders of magnitude for inv. mass of 0.2 down to 1 GeV

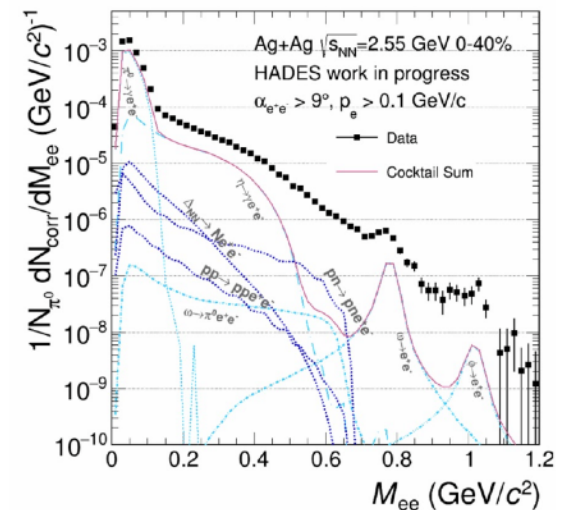
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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



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

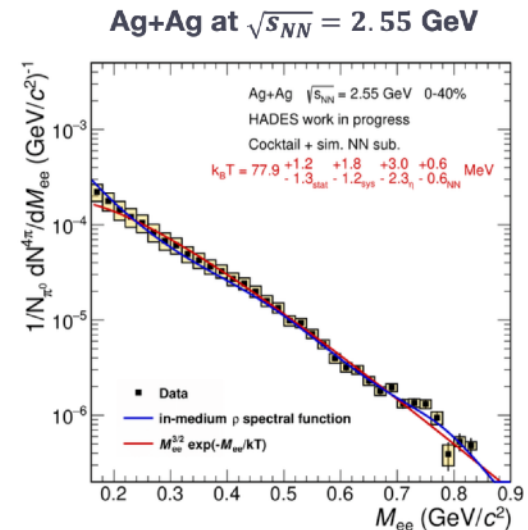
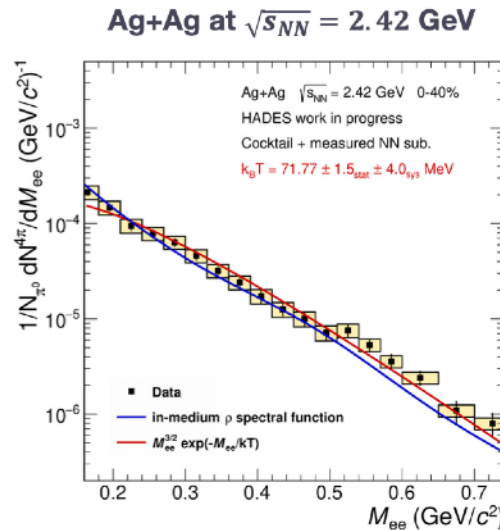
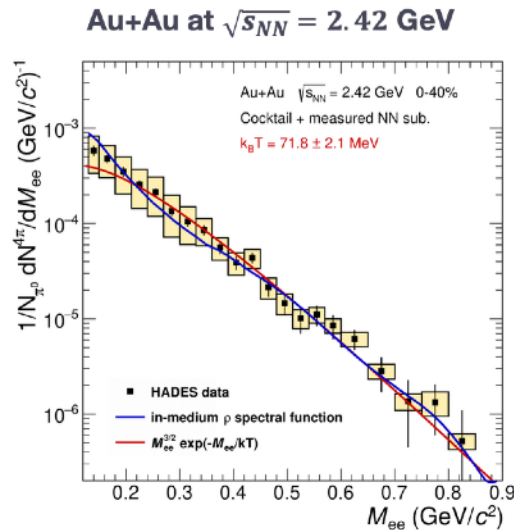


Excess radiation measured by HADES

- o Spectral distribution reproduced by a fit assuming thermal radiation
- o Significantly higher temperature at higher collision energy
- o No indication of a ρ bump at the lower beam energy energy $\rightarrow$ strong melting

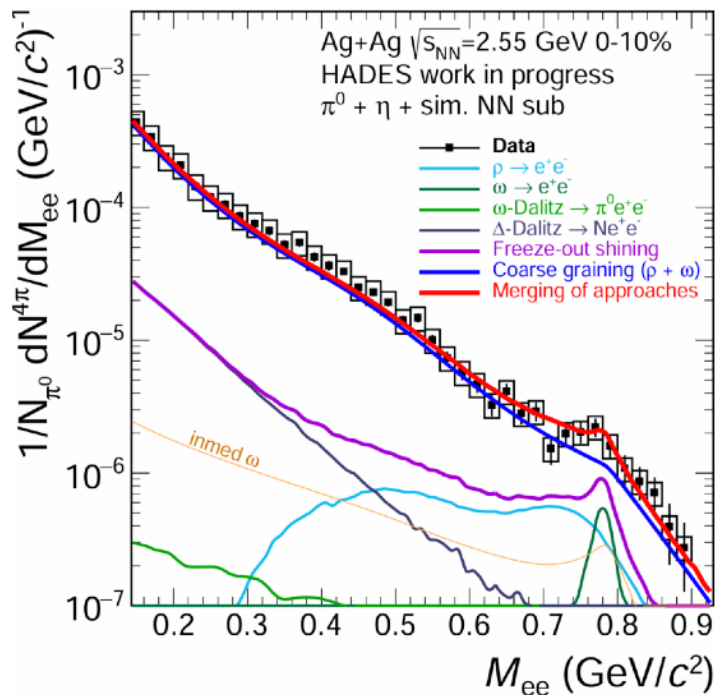
N. Holt, R. Rapp: Eur. Phys. J. A 56 (2020) 11, 292

P. Hohler, R. Rapp: Phys.Lett.B 731 (2014) 103-109



Refined coarse-graining for HADES

- Treat the “corona” of the dense phase separately
- Explains bump around vector mesons ρ , ω mass



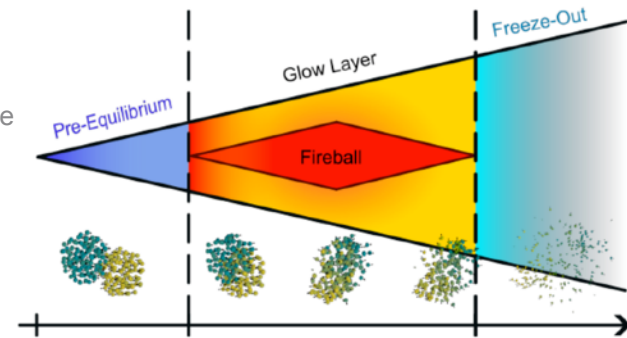
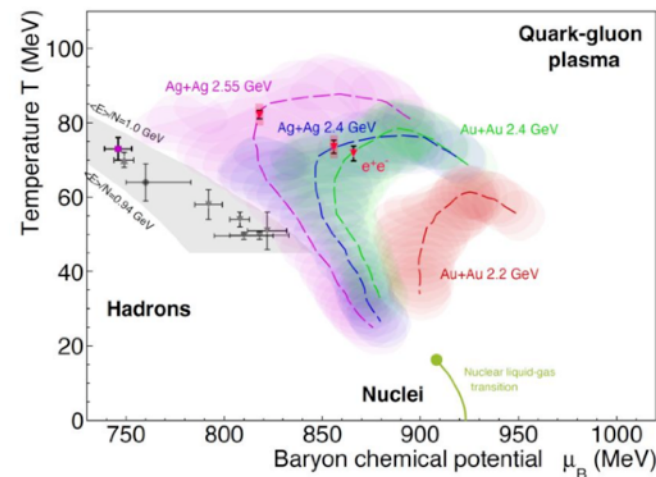
“Cloud reflects the conditions in the coarse-grained UrQMD evolution

Dashed line is mean

Suppress “shining” only for hadrons propagating in the “thermalised” space-time

Pre-equilibrium treated by reference spectrum

Freeze-out via hadronic cocktail



pictures from Jessica Vogel and Florian Seck (HADES)

Polarisation & electrical conductivity

- **Polarisation** sensitive to the difference of longitudinal and transverse components of the spectral function
- **Conductivity** accessible via the zero-energy limit of the spectral function

R. Rapp, H. van Hees, *Phys. Lett. B* 753, 586 (2016)

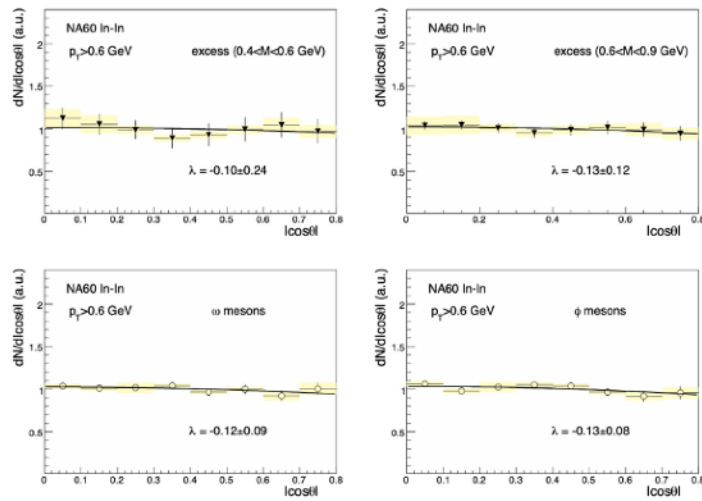
G. Baym et al., *Phys. Rev. C* 95, 044907 (2017)

E. Speranza et al., *Phys. Lett. B* 782, 395 (2018)

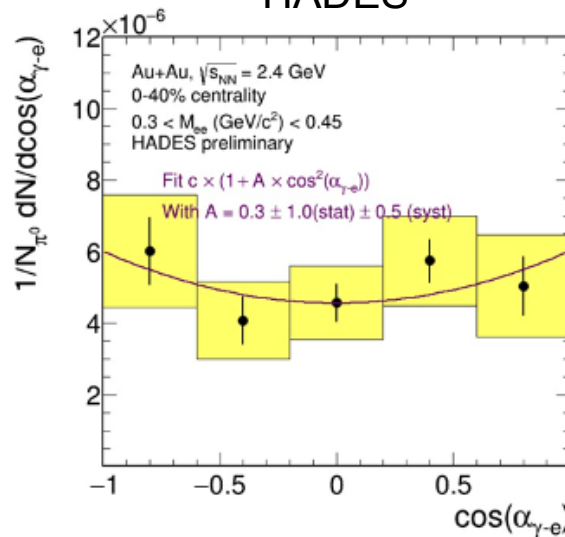
R. Rapp; *Phys. Rev. C* 110 (2024) 5, 054909

J. Atchison et al.; *Phys. Lett. B* 858 (2024) 139024

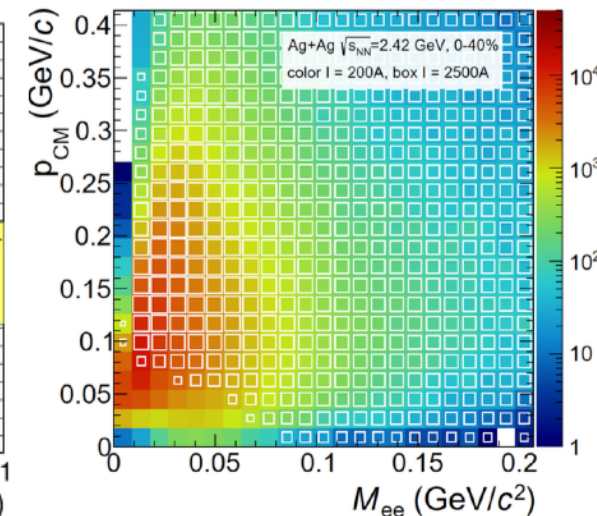
NA60



HADES

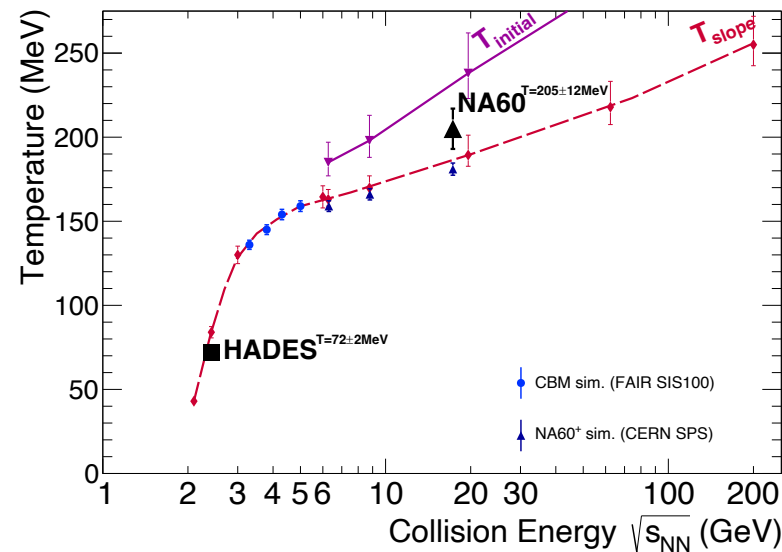
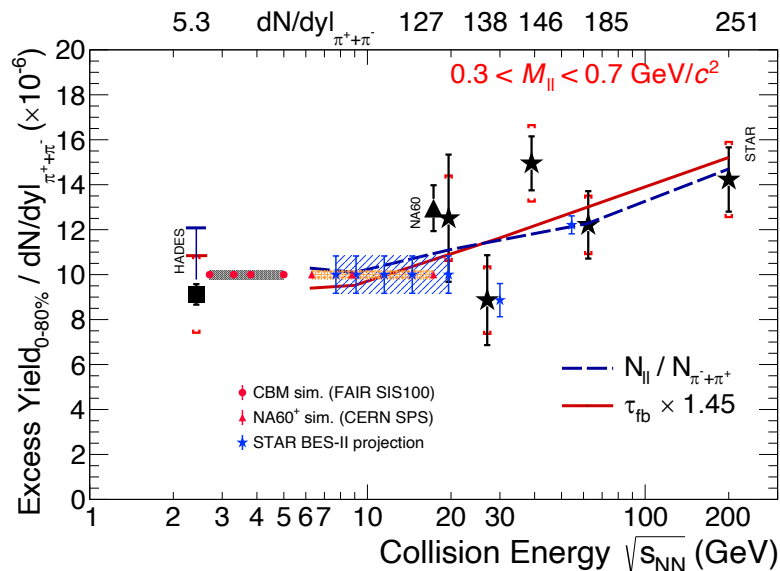


Low-field measurement by
HADES to study sensitivity



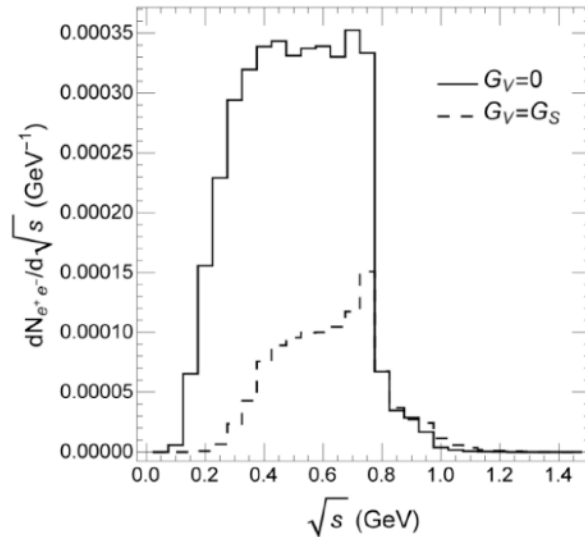
The quest for the full excitation energy

- The challenge and mission for CBM

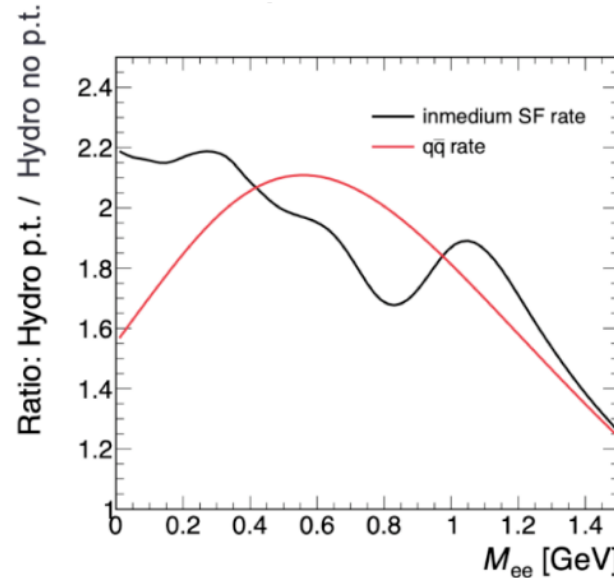


Possible dilepton signal of a first-order phase transition

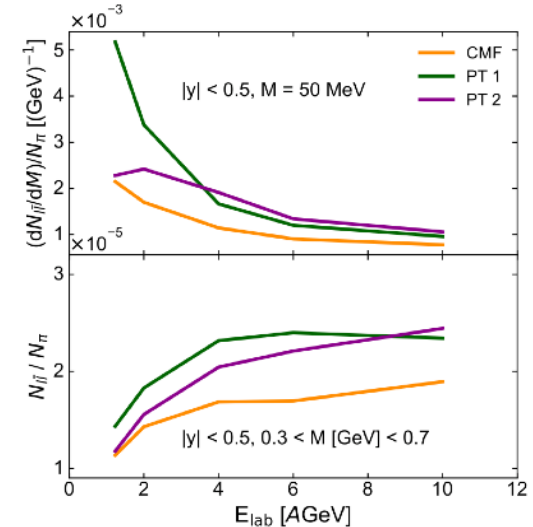
- Modification of the expansion trajectory in the phase diagram
- Changes of the in-medium photon propagator



F. Li and C.M. Ko PRC 95 (2017) 5, 055203



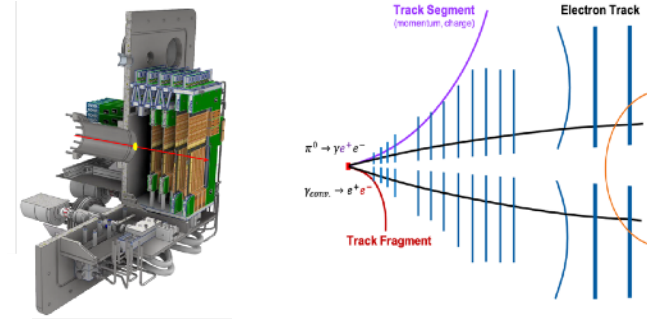
F. Seck, JS, et al., PRC 106, 014904 (2022)



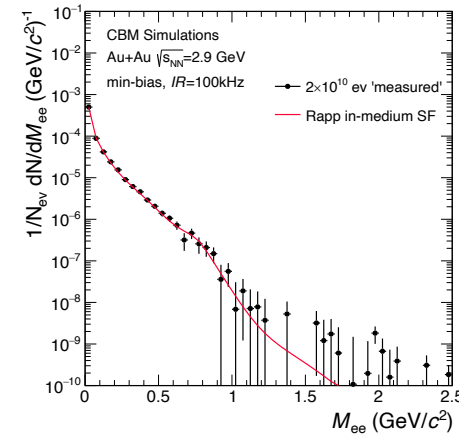
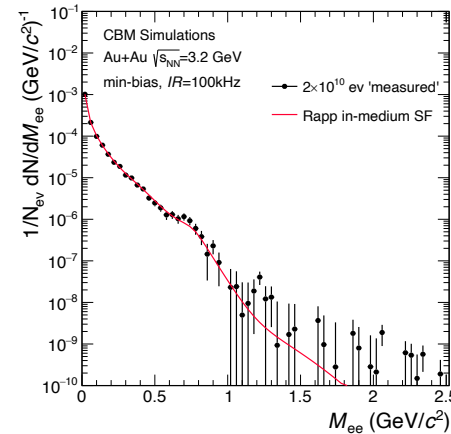
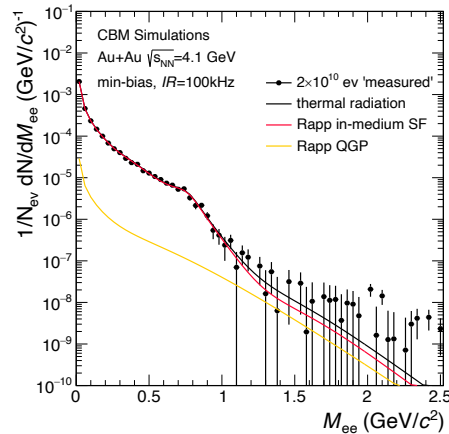
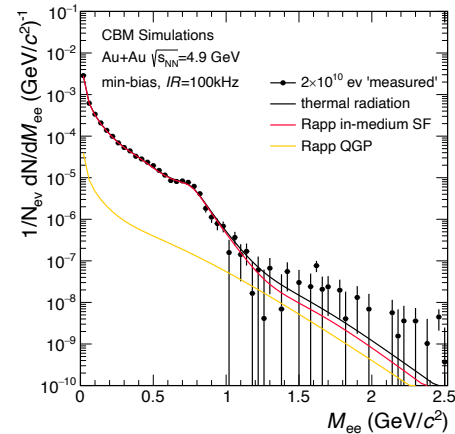
O. Savchuk et al. J.Phys.G 50 (2023) 12, 125104

CBM dielectron performance (first year, 5 days/energy)

- Background rejection using topological cuts (*T. Galatyuk, PhD thesis GU Frankfurt 2009*)
- Micro vertex tracker augments low-momentum tracking
- Identify background pairs (small opening angle) by combining identified electron/positrons with track segments/fragments



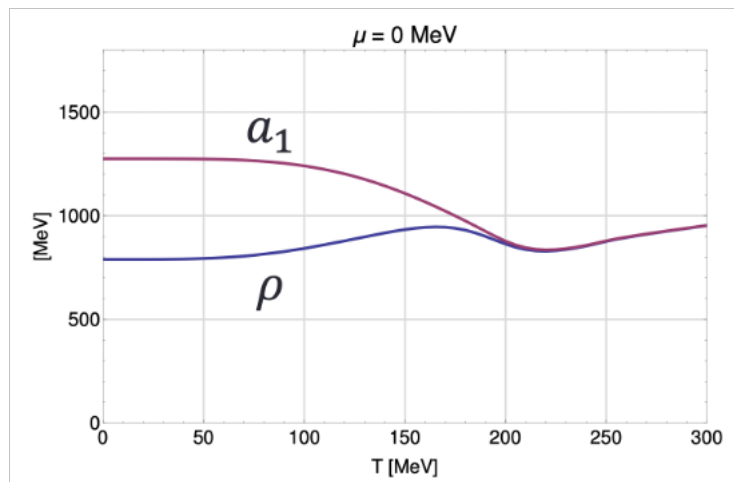
see also CBM: PhD thesis A. Meyer-Ahrens, Münster



CBM dilepton performance

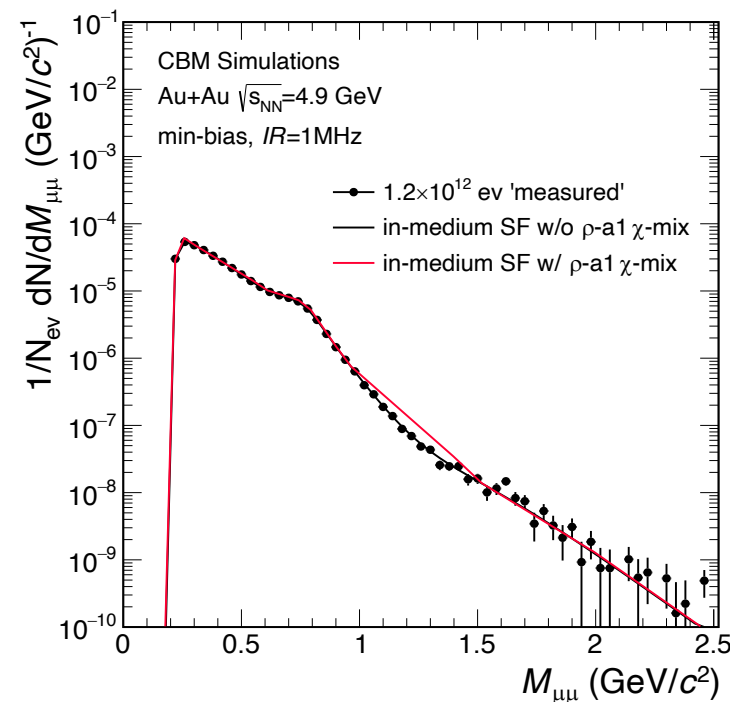
- Search for signs of (partial) χ -symmetry restoration ($\langle \bar{q}q \rangle \rightarrow 0$)
- Degeneracy of chiral partners:

$$\int_0^\infty \frac{ds}{\pi} [\text{Im}\Pi_V(s) - \text{Im}\Pi_A(s)] = -2m\langle \bar{q}q \rangle$$



Jung et al., PRD 95, 036020 (2017)

Hohler and Rapp, PLB 731 (2014)



Status and future of the HADES experiment

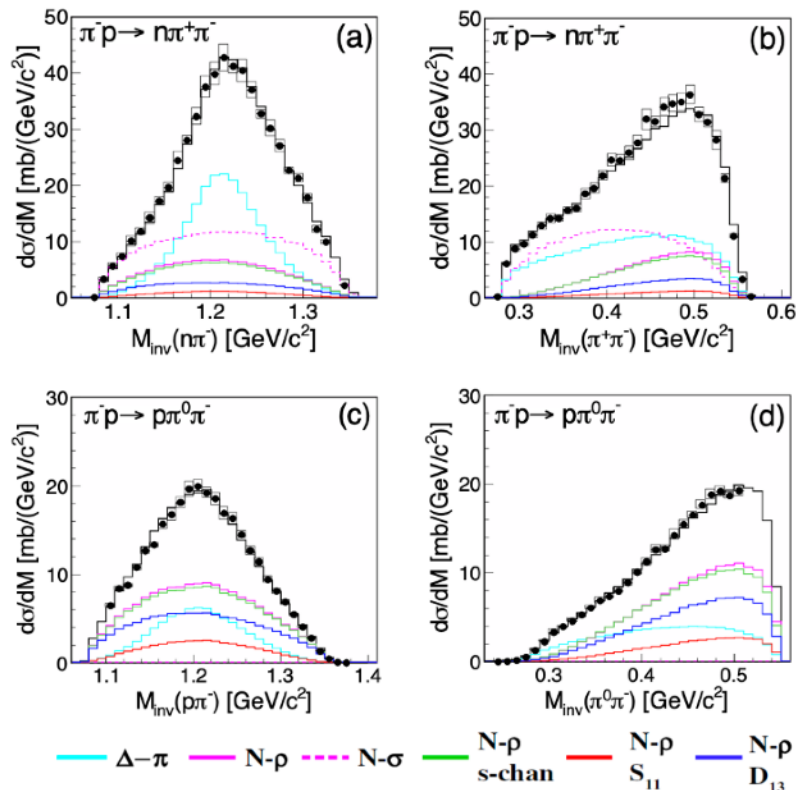
Inclusive hadron emission, flow correlation and e-b-e proton number fluctuations

Excess radiation, flow and virtual photon polarisation

Establishing the “standard candle” for hadronic emissivity

Summary

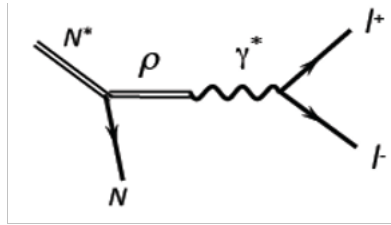
Extraction of partial waves from two-pion channel



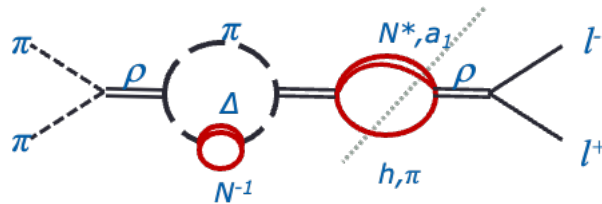
- $p_\pi = [0.66, 0.69, 0.75, 0.8] \text{ GeV}$
- $\pi^- + p \rightarrow \pi^- + \pi^+ + n$
 - Hadronic final states used in PWA (Bonn/Gatchina code)
 - Use invariant masses, and angular distribution (not shown here)
- $\pi^- + p \rightarrow e^- + e^+ + n$
 - Prediction for dilepton invariant mass assuming strict VMD
 - Comparison to two-component model by Pena & Ramalho

$$\pi^- + p \rightarrow e^- + e^+ + n$$

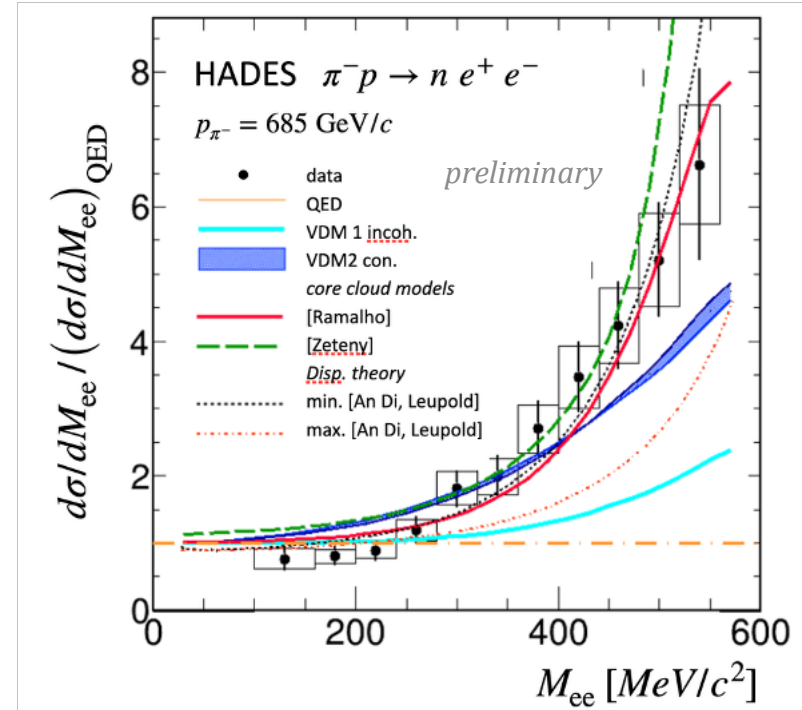
Resonance-Dalitz decay (a la VMD) ...



... is analogous to baryonic contribution to in-medium ρ self-energy (emissivity)



Transition form factor (time-like) extracted by subtracting QED expectation from exclusive invariant mass distribution.

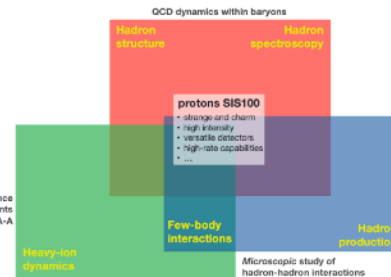


Initiative for Hadron Physics at GSI and FAIR in next decade

Four dedicated workshops with the goal publish a **White**

- ▶ **Editors:** J. Messchendorp, F. Nerling, 14 Convenors, > 40 Contributors

▶



Hadron Physics at GSI and FAIR: Prospects for the Next Decade

December 3, 2024

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QCD at FAIR Workshop 2024

Wuppertal University

GSI 11-2024

11-16 November 2024
GSI Helmholtz Center for Schwerionenforschung GmbH

QCD at FAIR – Physics perspectives with hadron beams for the next decade (first edition)

This workshop brings together experts from theory and experiment in the field of strong QCD. The objective is to discuss the contents and status of a white paper addressing a new and inspiring physics program using proton beams expected at FAIR with the SIS100 accelerator. It is a follow-up of earlier events that were held in June 2023 and February 2024. For further details including an executive summary and slides that were presented in these events, we refer to <https://indico.gsi.de/event/17693> and <https://indico.gsi.de/event/18475>.

The purpose of this workshop is to review the progress and activities of the white paper among its contributors. A portion of the workshop, as specified in the agenda, will be open to the public for those who are interested.

Workshop agenda

- Overview
- Timeline
- Registration
- Participant List
- Venue details
- Accommodation
- Workshop fee
- Payment details
- Contact

Contact

- J. Messchendorp @gsi.de
- paul@physik.uni-wuppertal.de

Wuppertal 02-2024

Purpose of this workshop is to bring together experts working in the field of proton induced interactions, and to explore possibilities for exciting physics at the SIS100 accelerator at FAIR.

This workshop is a follow-up of a kick-off event that was held in June 2023 connected to the MESON2023 conference. For further details including an executive summary that were presented, we refer to <https://indico.gsi.de/event/17693>.

Based on the outcome of the kick-off workshop further explore to formulate an inspiring physics

- Open- and hidden-charm production in e⁺e⁻
- Charm content of the proton
- Emergent hadron mass and QCD trace an
- Gravitational form factors and gluonic ma
- Hyperon production, spectroscopy and st
- Hyperon-baryon interactions via femtosco
- Hadronic production mechanisms as re
- Search and line-shape measurements of f

The overarching aim of this workshop is to open experimental endeavors that leverage complex aspiration to nurture a thriving, collaborative co



Physics opportunities with proton beams at SIS100

Wednesday Jun 21, 2023, 9:00 AM → 11:00 PM, Europe/Berlin

Krakow 06-2023

Registration

You are registered for this event

Participants

- Anton Szczepanik
- Beatrice Kampen
- Christina Höhne
- Craig Roberts
- Daniel Müller
- Frank Nerling
- Hongyi Niu
- Isabella Cepal
- Jim Krieger
- Joachim Stroth
- John Messchendorp
- Karin Schöningh
- Laura Fabbietti
- Marion Ziehl
- Matthias T.M. Lutz
- Mikhail Bashkanov
- Nu Xu
- Piotr Lebedev
- Peter Salabura
- Rafal Lefkiewicz
- Rafal Mankus
- Tatyana Gaitanyuk
- Yoshiko Oishi

Contact

J. Messchendorp@gsi.de

<https://indico.gsi.de/event/20301/>

<https://indico.gsi.de/event/18475>

<https://indico.gsi.de/event/17693>

Status and future of the HADES experiment

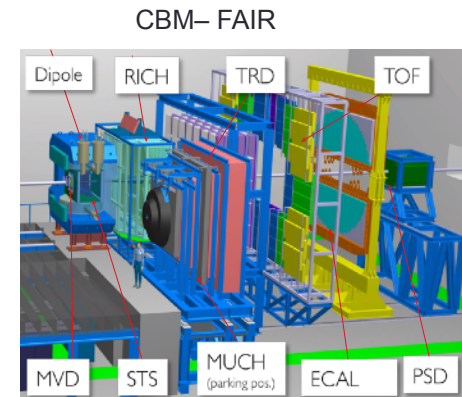
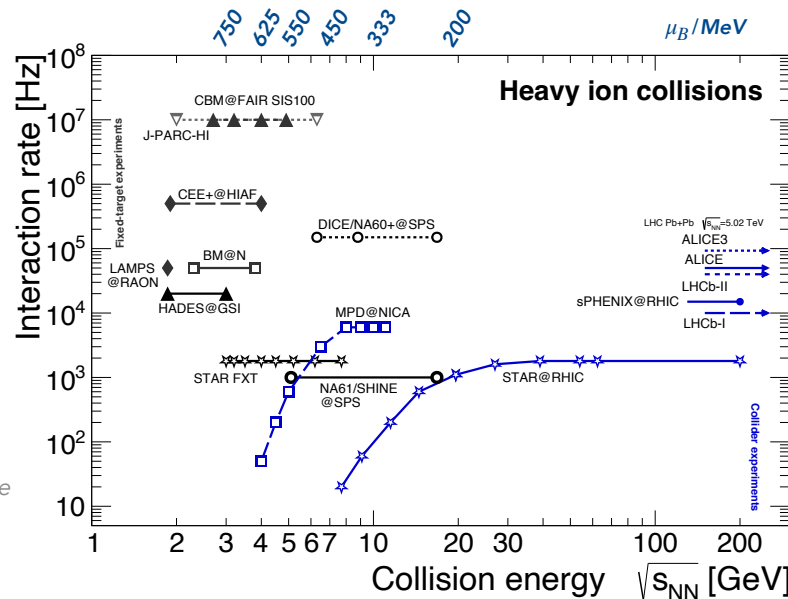
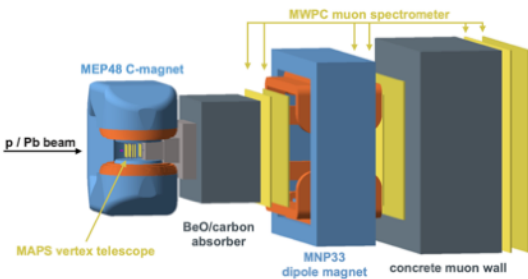
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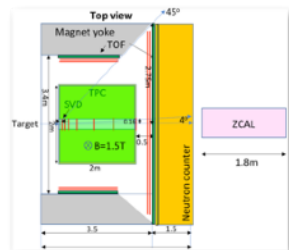
Summary

Future facilities for high μ_B physics

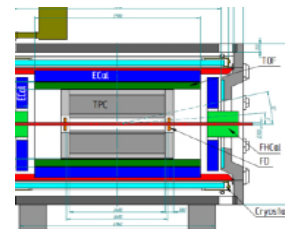
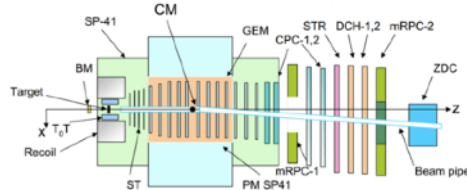


T. Galatyuk, Nucl. Phys. A982 (2019),
https://github.com/tgalatyuk/QCD_caloric_curve

DHS – JPARC-HI

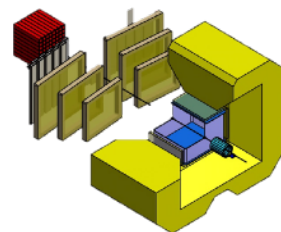


BM@N – NICA



MPD – NICA

CEE– HIAF



FAIR – Cosmic Matter in the Laboratory



APPA

- Atomic processes in highly ionised isotopes

NUSTAR

- Experiments with rare (neutron-rich) isotopes

CBM

- Investigation of compressed baryonic matter

Compressed Baryonic Matter at FAIR



Summary (and home work)

- Multi-differential comparison of data to transport models ahead
- E-b-e observable approaching “stability” and suggest canonical baseline
- Dileptons are an excellent tool to explore the QCD phase diagram in the region of high μ_B
- Excess radiation is well described by thermal emission rates – standard candle established?!
- To fully exploit this observable, measurement at unprecedented precision and statistics are needed
- Additional insight from polarisation measurements and from very-low mass (momentum) dilepton (electrical conductivity)
- Promising perspectives to establish the full excitation function up to the exclusion region for CEP

Thank you for your attention
