SELECTED RESULTS FROM HADES

Joachim Stroth, Goethe University Frankfurt / GSI / HFHF

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 flucts

Excess radiation, flow and virtual photon polarisation

Establishing the “standard candle” for hadronic emissivity

Summary

The HADES spectrometer at GSI SIS-18

Geometry

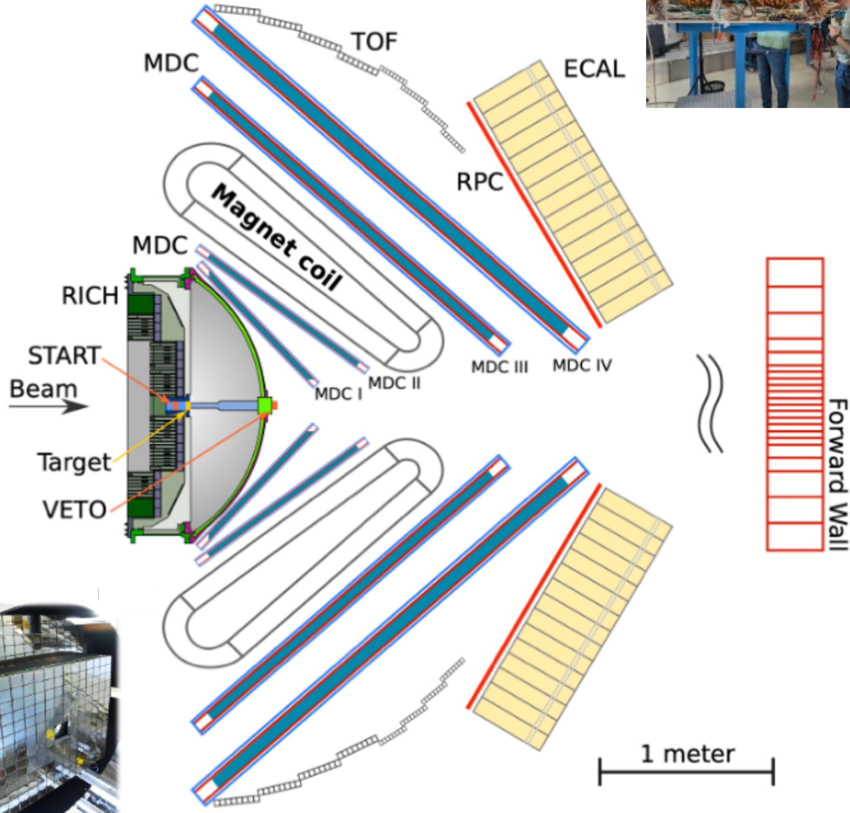
- Full azimuthal coverage with 6 identical sectors
- $18^o < \theta < 85^o$ ($\approx$ 0.35 pair acceptance)

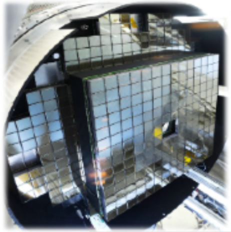
Particle Identification

- 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

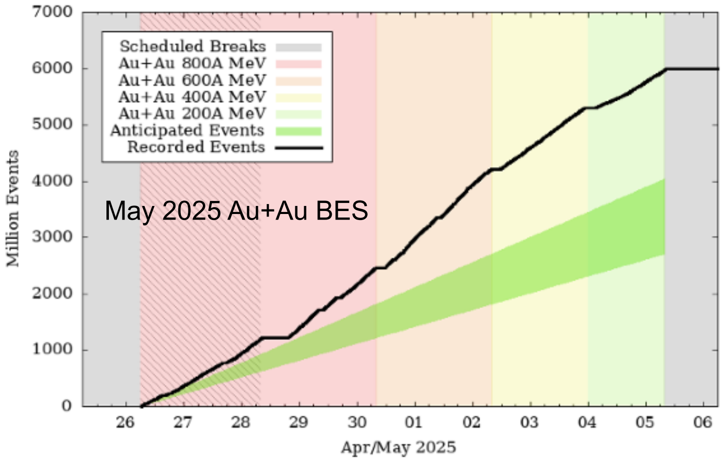
- Superconducting toroid ($B\rho \approx$ 0.36 Tm)
- MDC – 4 planes of low-mass drift chambers
- Recent FEE upgrade with multi-hit capability



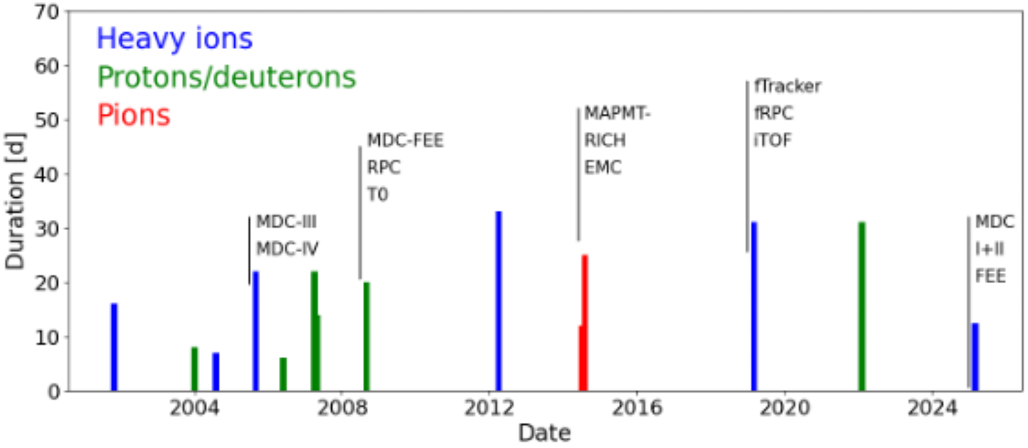


HADES physics runs

- 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

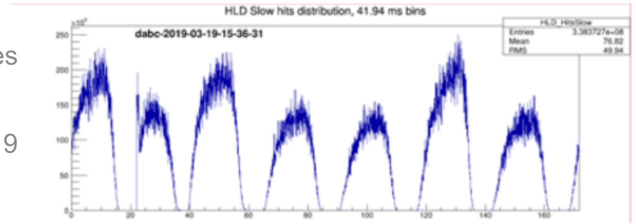


HADES collected data since 2002 (> 20 years of operation)

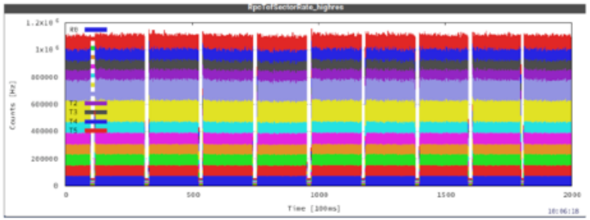


spill profiles

2019

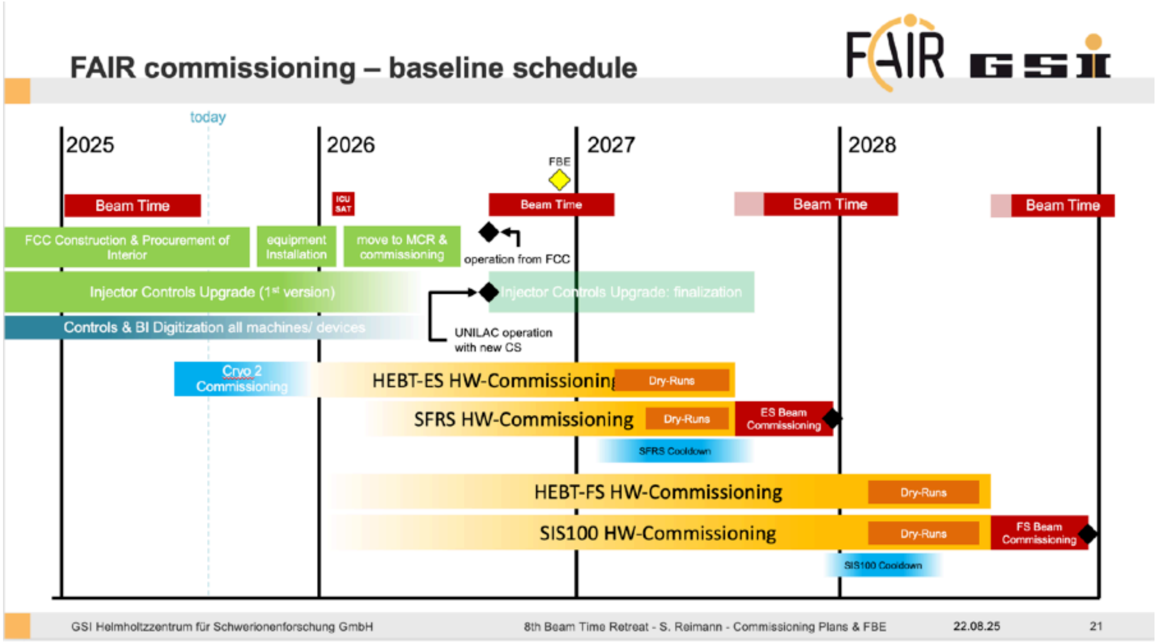


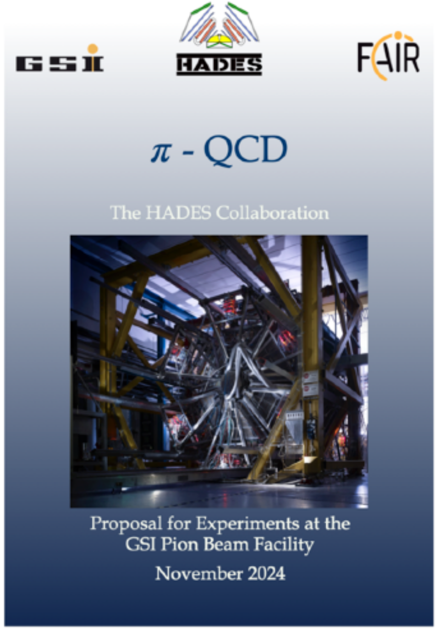
2025

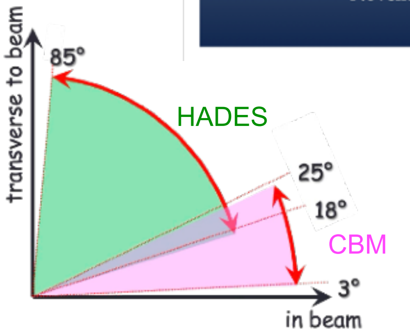


HADES in the years 2027 to 2032

- 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



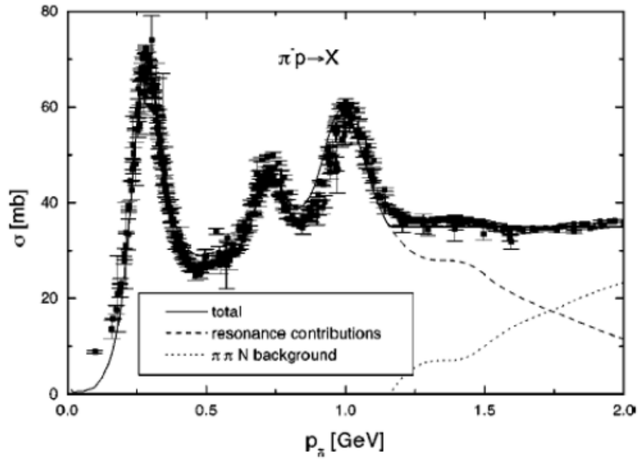


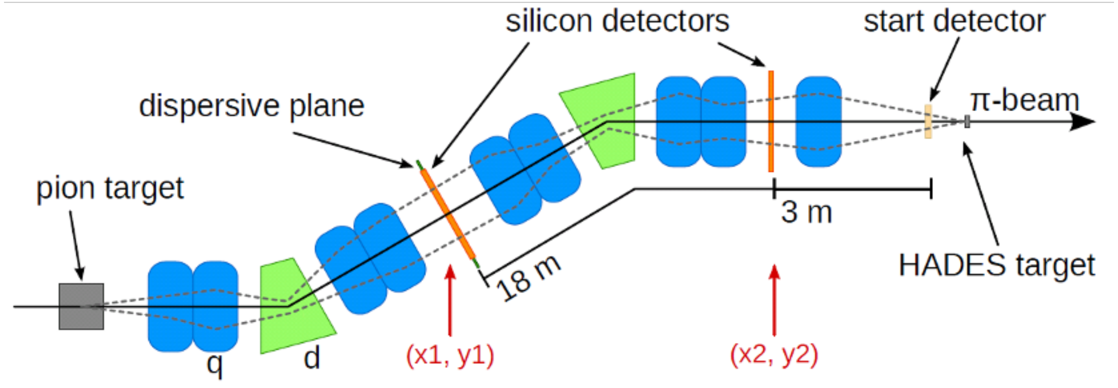


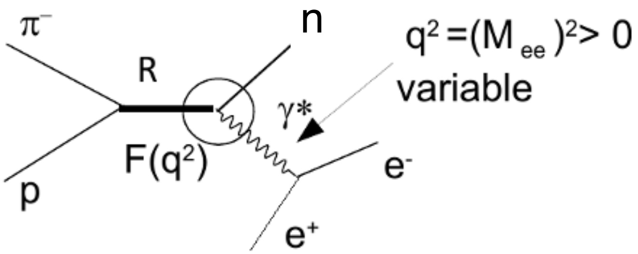
CBM acceptance optimised for SIS300 beam

The HADES pion beam facility

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

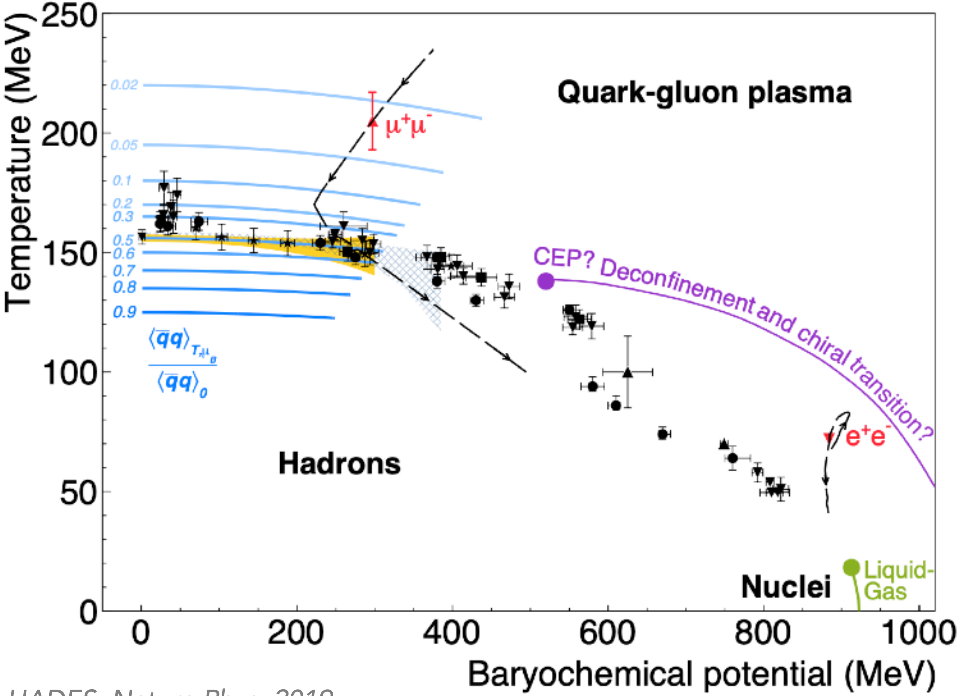






Exploration of the QCD Phase Diagram @ high-μ_B

From medium-effects to novel phases of QCD matter

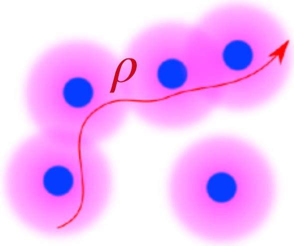


HADES, Nature Phys. 2019

Conjectures for

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

- 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)

Status and future of the HADES experiment

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

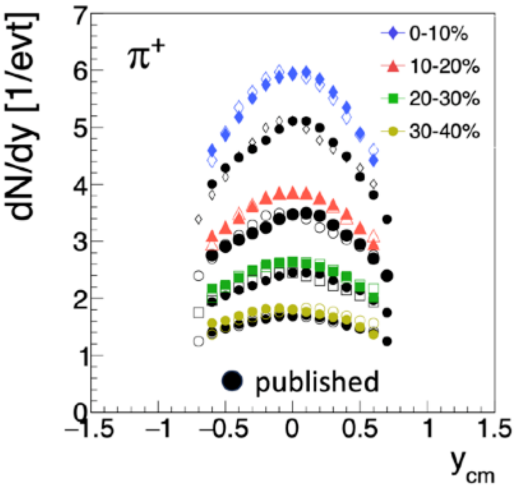
Excess radiation, flow and virtual photon polarisation

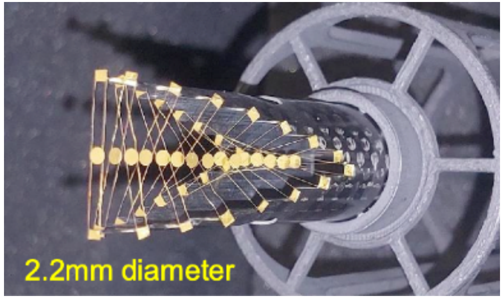
Establishing the “standard candle” for hadronic emissivity

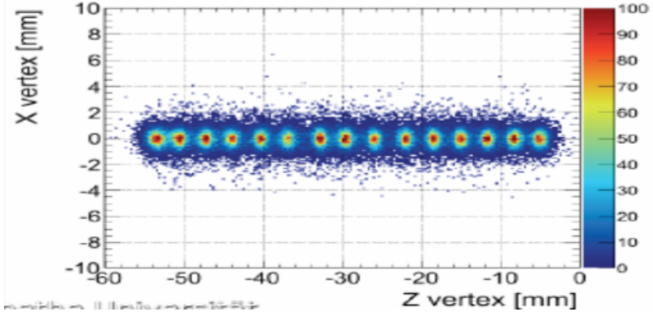
Summarys

Event purity and efficiency – new method applied

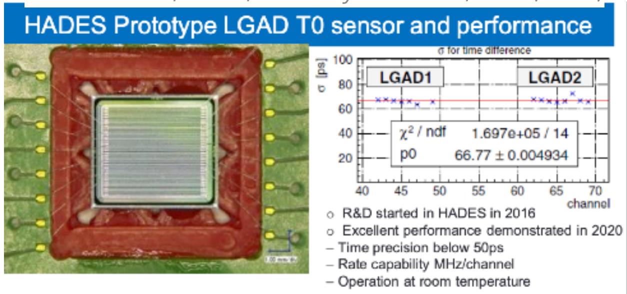
- Event-pile-up mitigated by 15-fold, frame-less Au (Ag) target stack
- Instantaneous beam intensity monitoring using segmented LGAD T0 detector in beam
- Consistency between embedding in real data and full MC efficiency determination by e-b-e variation of beam background
  - → Dead-time effects in MDC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





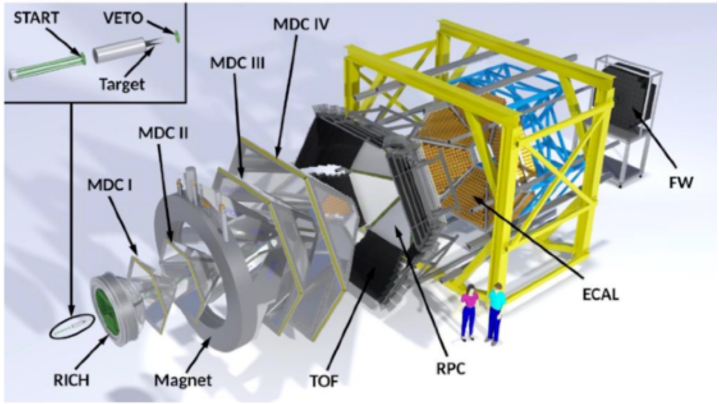


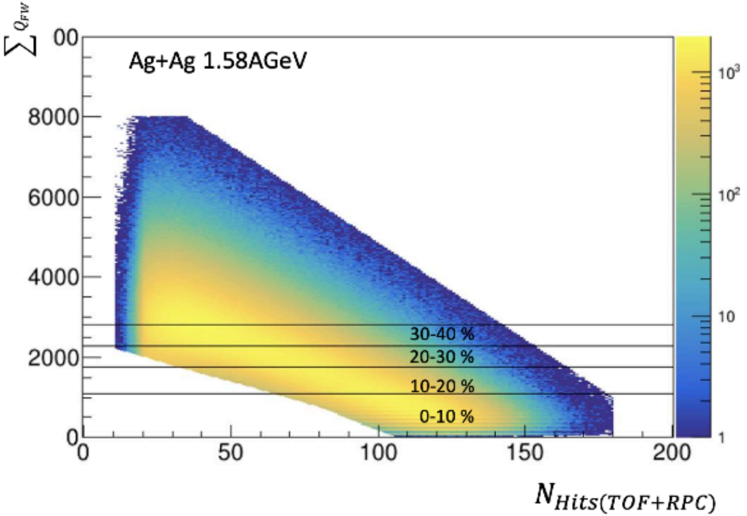
J. Pietraszko, et al., Eur. Phys. J. A 56, 183 (2020)

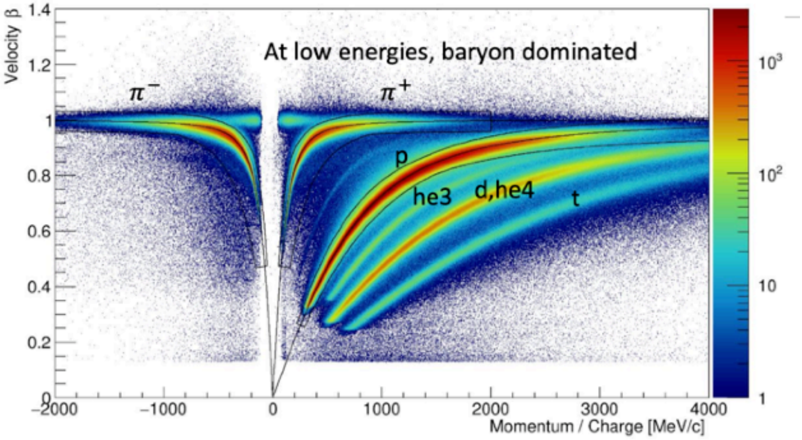


E.b.e proton number fluctuations

- 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 $\sum Q_{\mathrm{FW}}$ (spectator nucleons)
- Large acceptance for protons around mid-rapidity







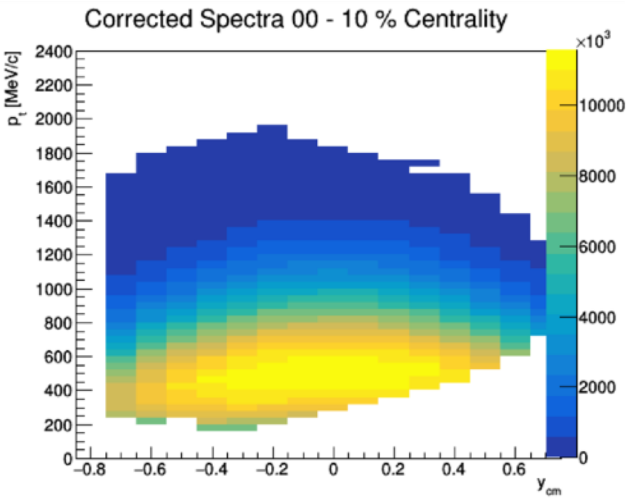
Corrections applied to data

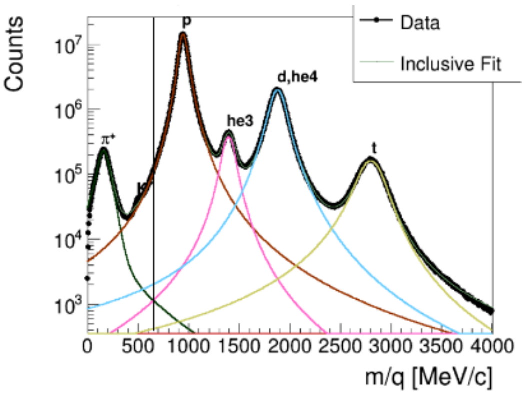
- Detector efficiency via unfolding and moment expansion
- PID (incl. purity from decor relation) using “Fuzzy Logic”. Fits for every $p_t - y$ bin A. Rustamov, J. S., M. Nabroth QM2025
  A. Rustamov; *Phys.Rev.C 110 (2024) 6, 064910*
- Volume fluctuations mitigated by event-mixing method

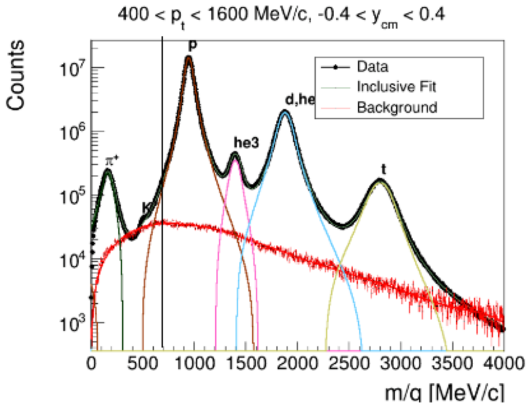
A.R., R. Holzmann, J. S., NPA 1034 (2023) 122641
V. Koch, R. Holzmann, A.Rustamov, J. S., Nucl. Phys. A 1050 (2024) 122924

	MC Test	Applied on Data
MC Truth		
Tikhonov Unfolding (Hard cut based) [S. Schmitt, J. Instrum. 7, T10003 (2012)]	✓	—
SVD Unfolding (Hard cut based) [A. Höcker and V. Kartvelishvili, Nucl. Instrum. Methods Phys. Res. A 372, 469 (1996)]	✓	—
Bayesian Unfolding (Hard cut based) [G. D'Agostini, Nucl. Instrum. Methods Phys. Res. A A362, 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) + Baysesian Unf.	✓	✓
Iterative Gen. Neueral Network Unfolding [M. Backes, A. Butter, M. Dunford and B. Malaescu, SciPost Phys.Core 7 (2024) 1, 007]	✓	(✓)

T. Nonaka et. al. Nucl. Instrum. Meth. A906 (2018) 10-17

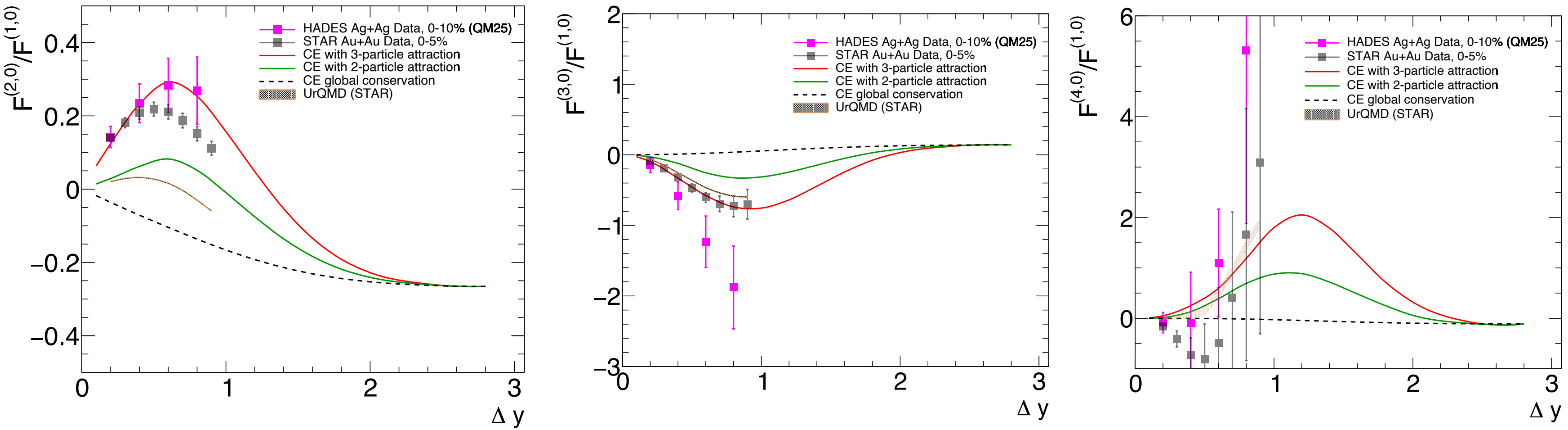






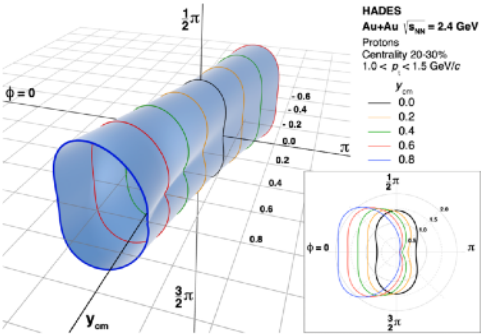
Factorial cumulants: comparison to STAR FXT data

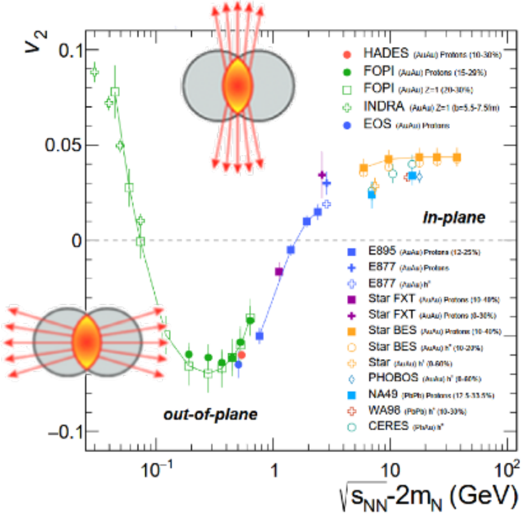
- Canonical baselines from HRG with interactions — *B. Friman, A. Rustamov, K. Redlich, e-Print: 2508.18879 [nucl-th]*
- UrQMD calculation taken from STAR
- Comparison to baseline suggests importance of three-body attractive interactions — *P. Braun-Munzinger, K. Redlich, A. Rustamov, J. Stachel, JHEP 08 (2024) 113*

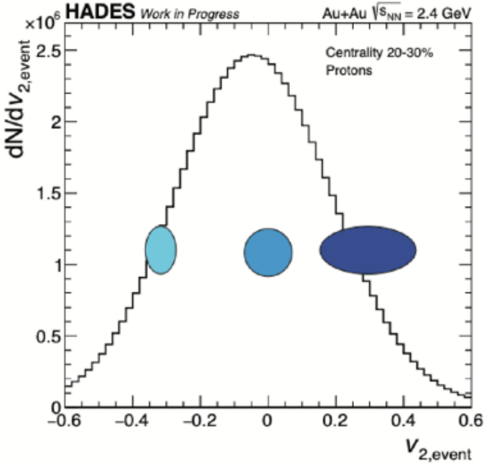


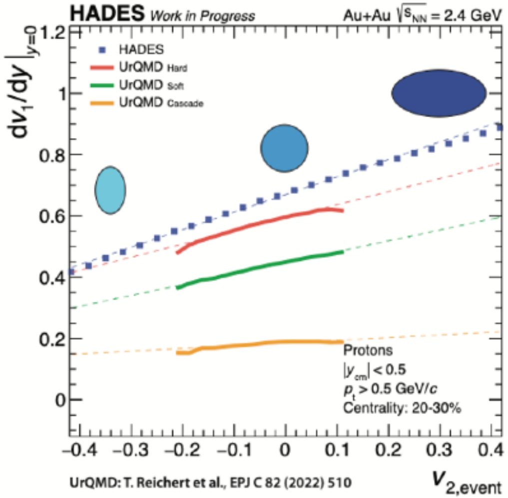
Flow correlations

- 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 $v_{2,\mathrm{event}}$ as proposed in T. Reichert et al.
- Correlations between the flow coefficients v_1, v_2 and v_4 and the event-wise $v_{2,\mathrm{event}}$ Enhanced sensitivity to EOS in $dv_3/dy|_{y=0}$ vs $v_{2,\mathrm{event}}$
-









T. Reichert et al. (UrQMD), EPJ C 82 (2022) 510

Hypernuclei lifetimes from two-body decays

Simon Spies (HADES)

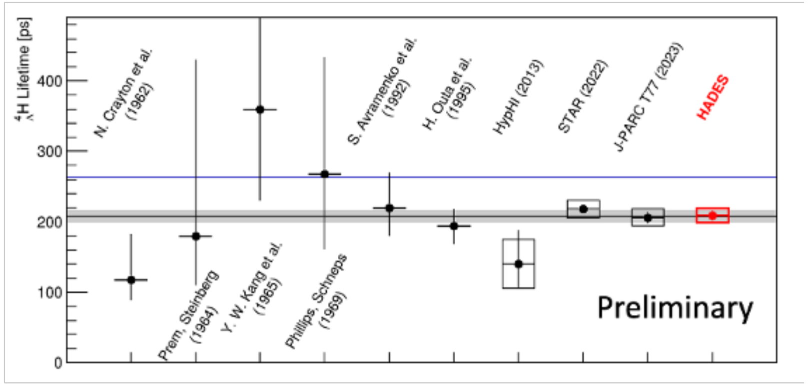
HYP2025 TOKYO

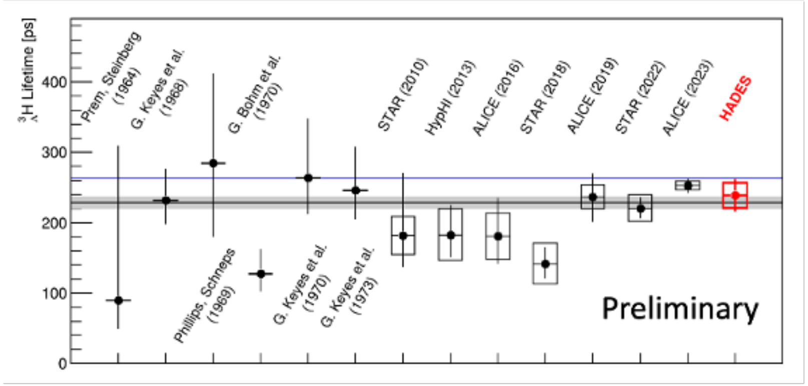
$${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$

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

$${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$

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





Status and future of the HADES experiment

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

Excess radiation, flow and virtual photon polarisation

Establishing the “standard candle” for hadronic emissivity

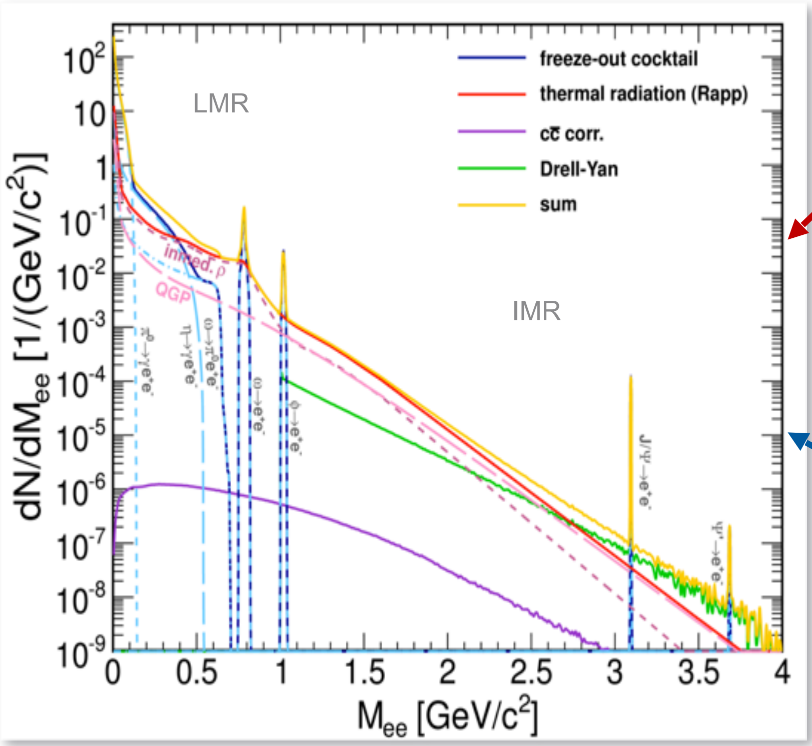
Summary

Excess Radiation as "Standard Candle" for (U)RHIC

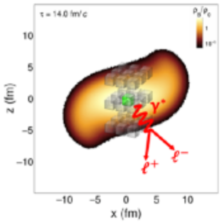
Medium radiation from ***Thermal Emission Rates*** (ϵ):

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

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



shining

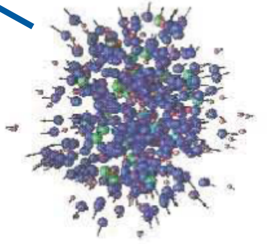


or

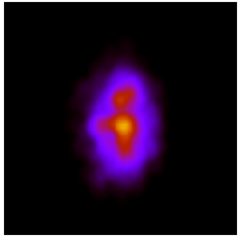
coarse graining

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

UrQMD



hydro



Dilepton emission from
Microscopic Transport.

Vector-meson dominance in hot & dense matter

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

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

L. McLerran, K. Toimela, Phys. Rev. D31 (1985)

See also: Ralf Rapp arXiv-1110-4345

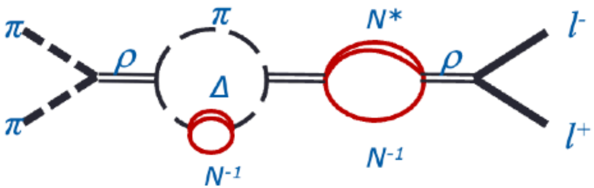
Extension of the Gounaris-Sakurai formula to a thermal pion gas: *C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65*

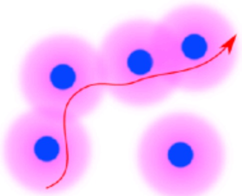
$$j^{\mu}_{EM} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \frac{1}{3}\bar{s}\gamma^{\mu}s \;\Rightarrow\; \mathrm{Im}\Pi_{EM} \sim \mathrm{Im}\,\mathrm{D}_{\rho} + \frac{1}{9}\mathrm{Im}\,\mathrm{D}_{\omega} + \frac{2}{9}\mathrm{Im}\,\mathrm{D}_{\phi}$$

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

$$\mathrm{Im}\Pi_{EM}(M) = \left(\frac{m_{\rho}^2}{g_{\rho}}\right)^2 \mathrm{Im}D_{\rho}(M) \qquad D_{\rho}(M, q; \mu_B, T) = \frac{1}{(M^2 - m_{\rho}^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B})}$$

R. Rapp, J. Wambach: Adv.Nucl.Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496
M. Asakawa, C-M. Ko et al., PRC 46 (1992) R1159

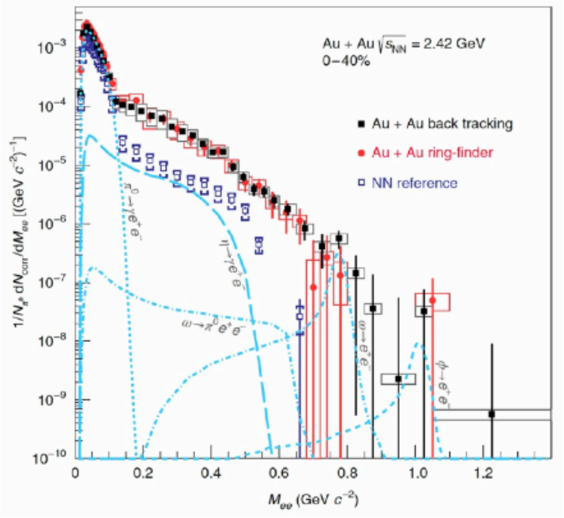




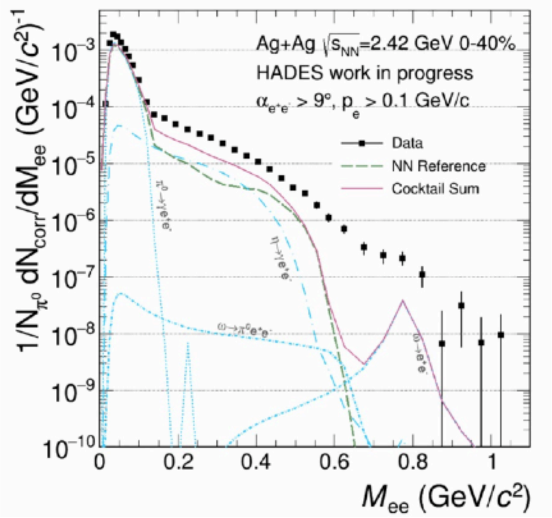
Dilepton spectra measured by HADES

- **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

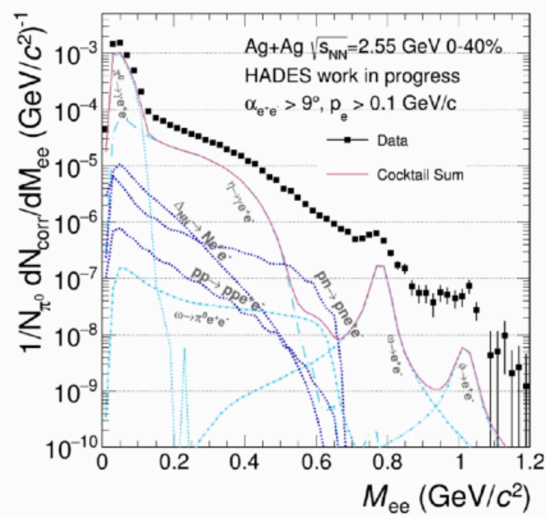
Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



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



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

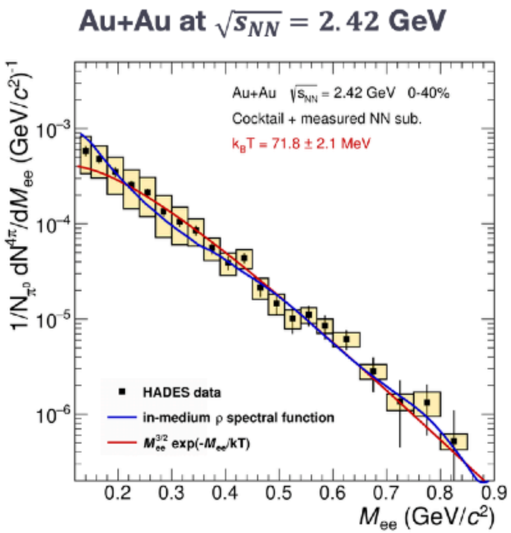


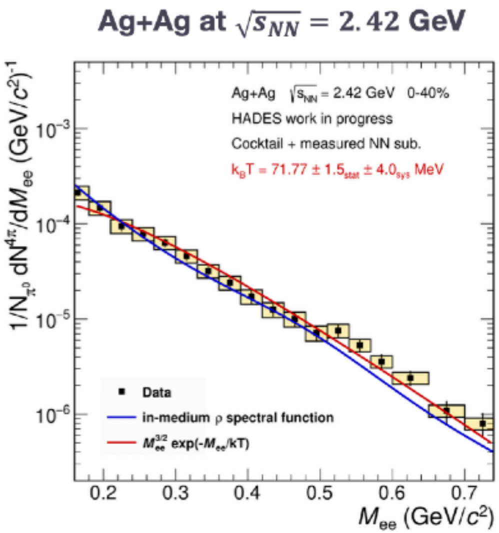
HADES, Nature Phys. 2019

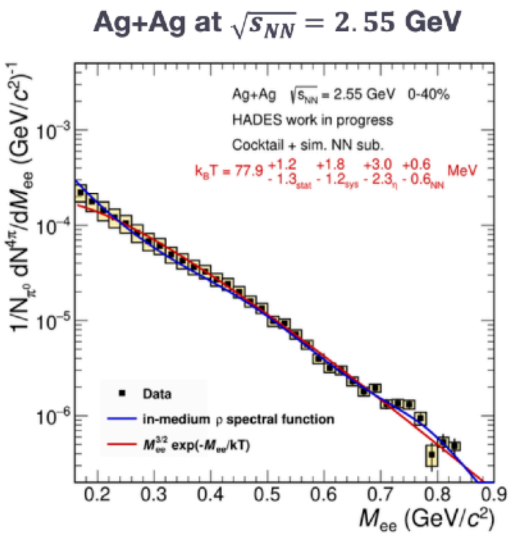
Excess radiation measured by HADES

- Spectral distribution reproduced by a fit assuming thermal radiation
- Significantly higher temperature at higher collision energy
- No indication of a ρ bump at the lower beam energy energy → 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



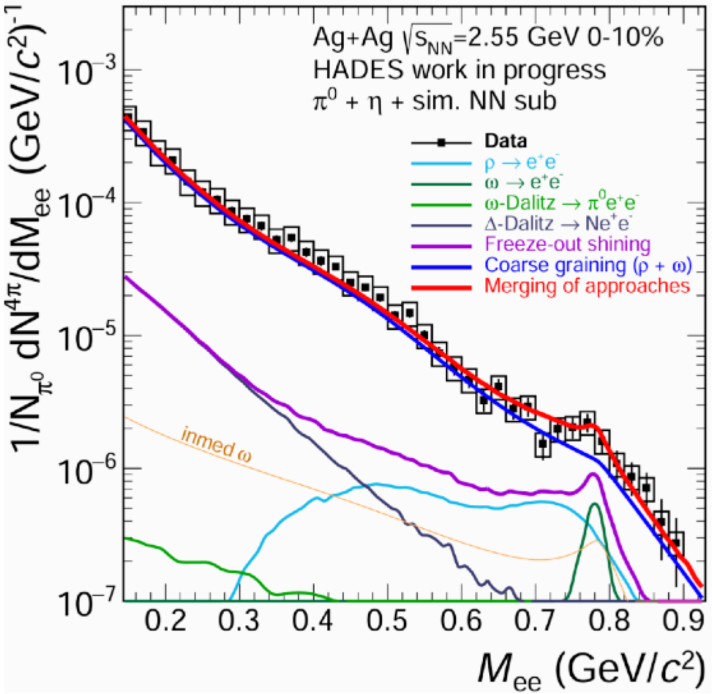




cf Niklas Schild, this school

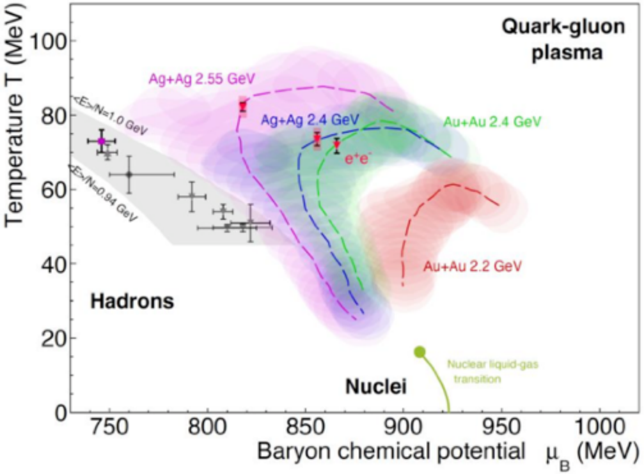
Refined coarse-graining for HADES

- 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

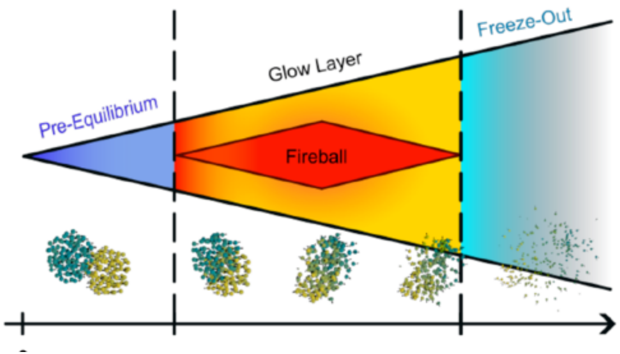
Dashed line is mean



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

Pre-eqilibrium treated by reference spectrum

Freeze-out via hadronic cocktail



pictures from Jessica Vogel and Florian Seck (HADES)

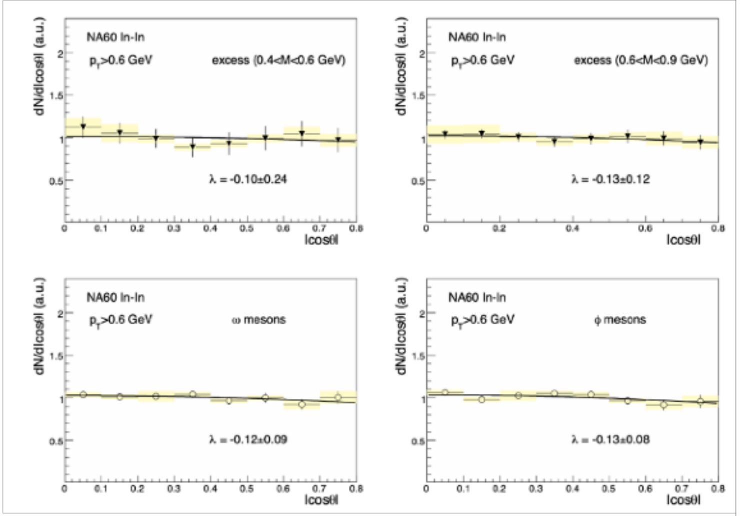
Polarisation & electrical conductivity

- 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

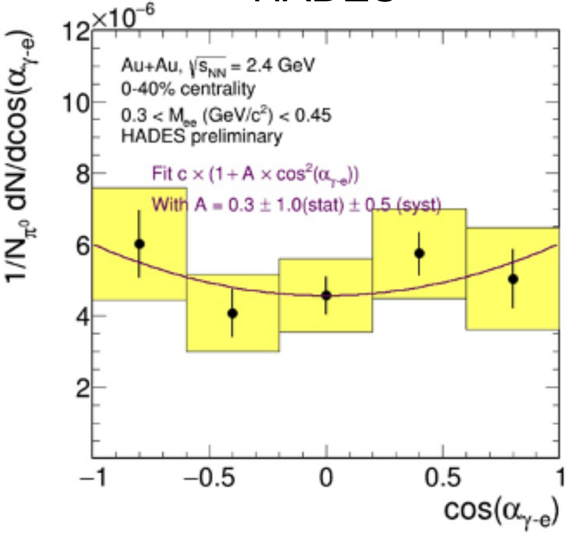
R. Rapp, H. van Hees, Phys. Lett. B 753, 586 (2016)
G. Baym et al., Phys. Rev. C 95, 044907 (2017)
E. Speranza et al., Phys. Lett. B 782, 395 (2018)

R. Rapp; Phys. Rev. C 110 (2024) 5, 054909
J. Atchison et al.; Phys. Lett. B 858 (2024) 139024

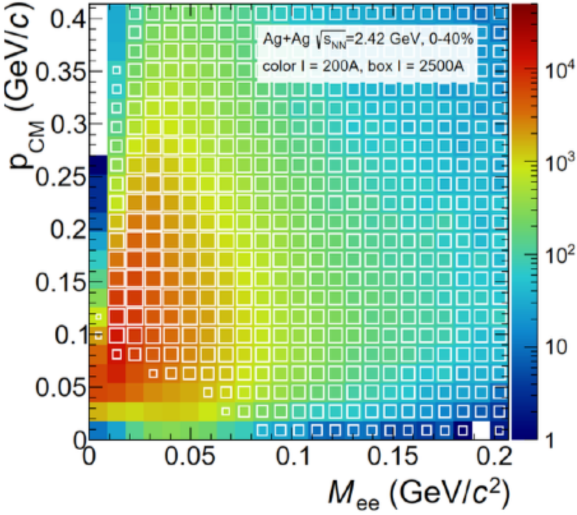
NA60



HADES

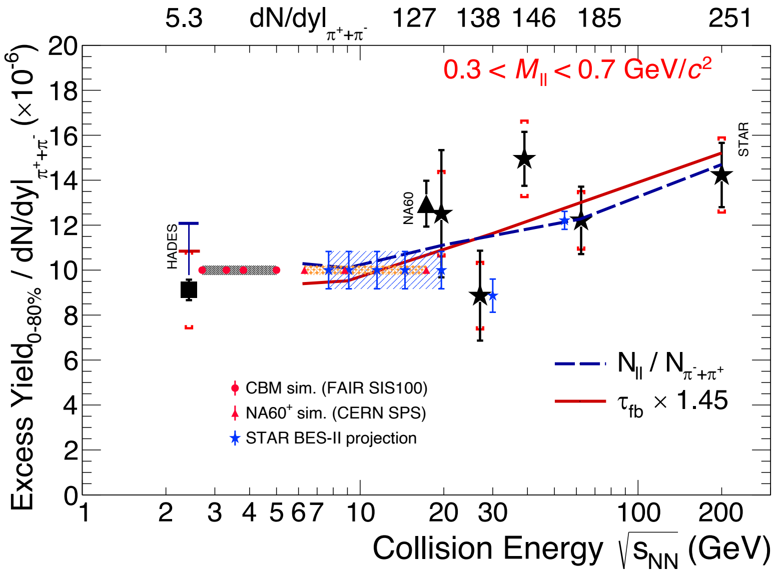


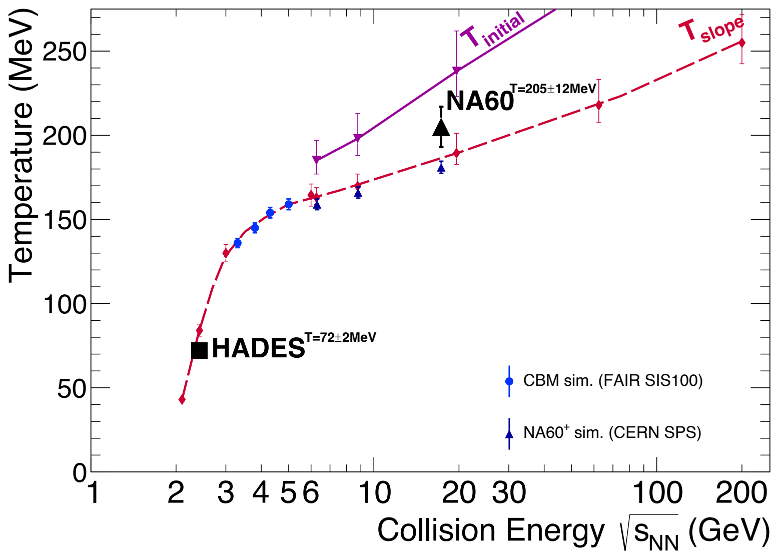
Low-field measurement by HADES to study sensitivity



The quest for the full excitation energy

- The challenge and mission for CBM

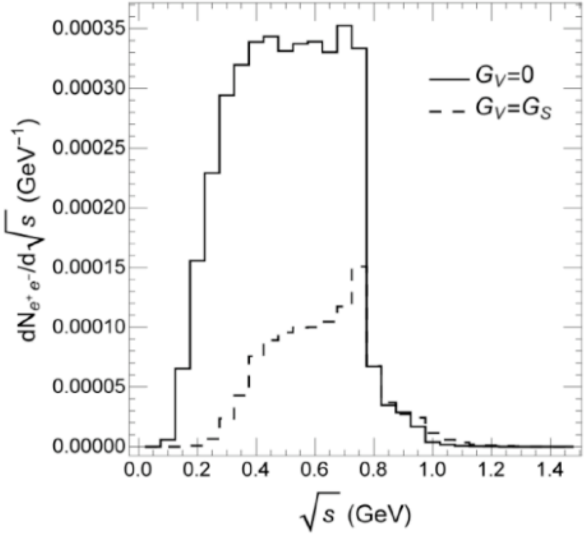




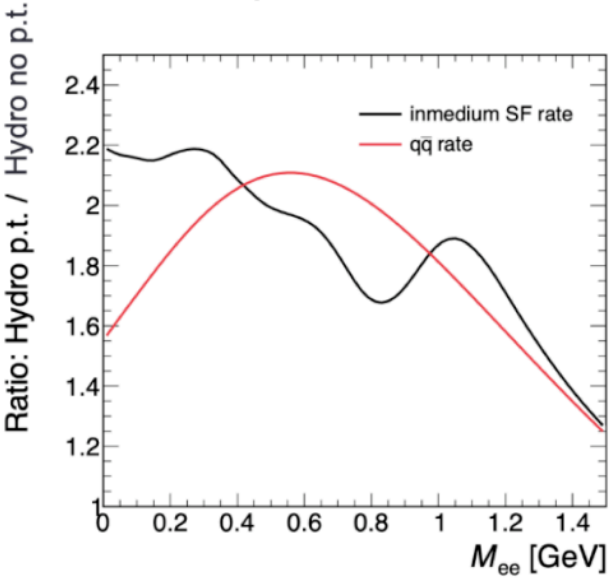
T. Galatyuk, JPS Conf.Proc. 32 (2020) 010079 and https://github.com/tgalatyuk/QCD_caloric_curve

Possible dilepton signal of a first-order phase transition

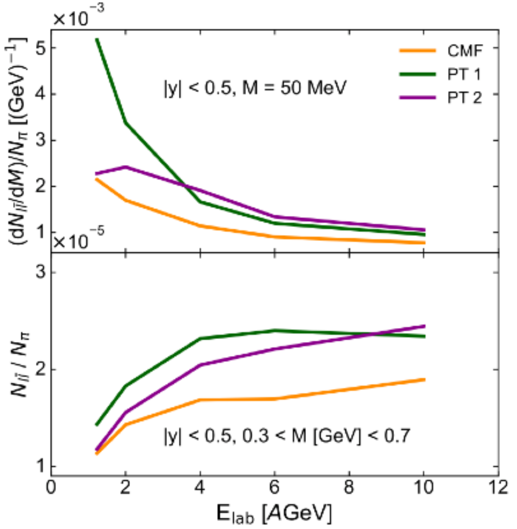
- Modification of the expansion trajectory in the phase diagram
- Changes of the in-medium photon propagator



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



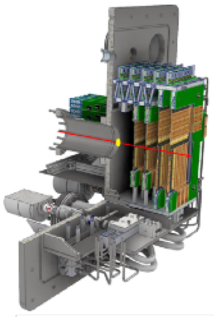
F. Seck, JS, et al., PRC 106, 014904 (2022)

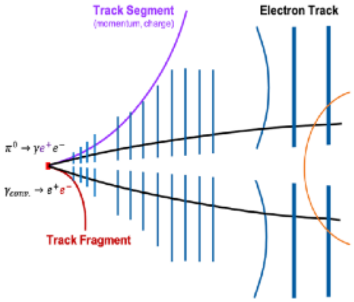


O. Savchuk et al. J.Phys.G 50 (2023) 12, 125104

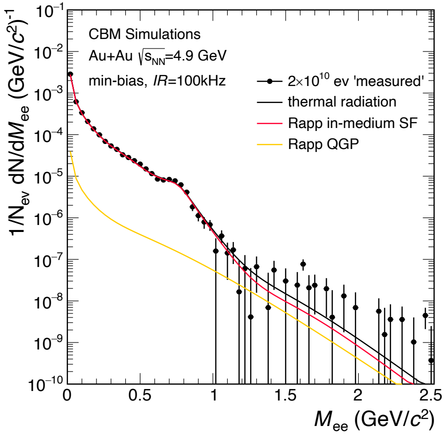
CBM dielectron performance (first year, 5 days/energy)

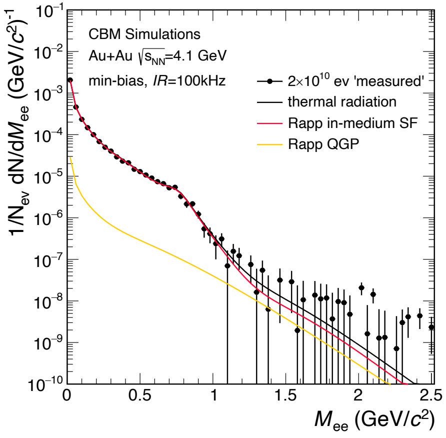
- Background rejection using topological cuts *(T. Galatyuk, PhD thesis GU Frankfurt 2009)*
- Micro vertex tracker augments low-momentum tracking
- Identify background pairs (small opening angle) by combining identified electron/positrons with track segments/fragments

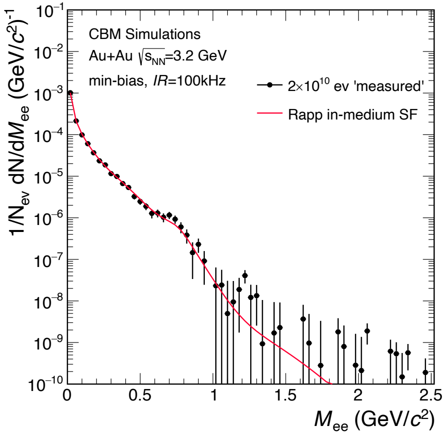


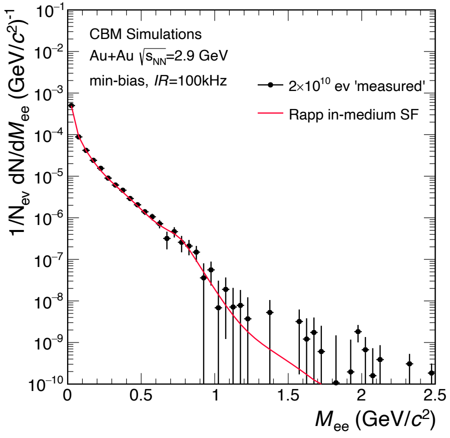


see also CBM: PhD thesis A. Meyer-Ahrens, Münster





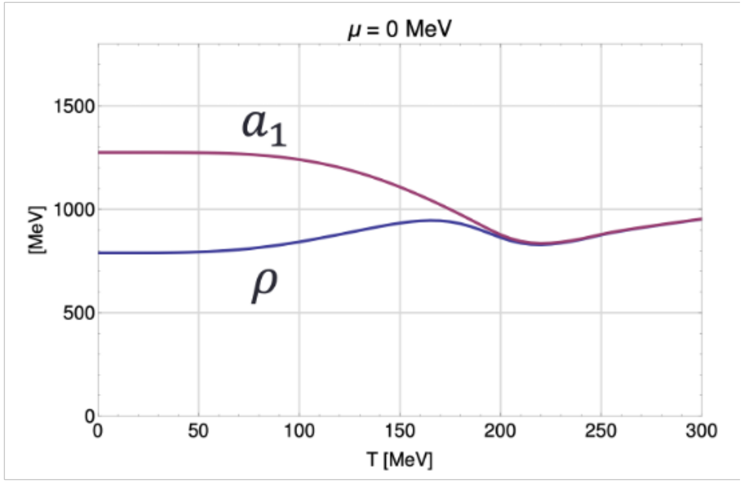




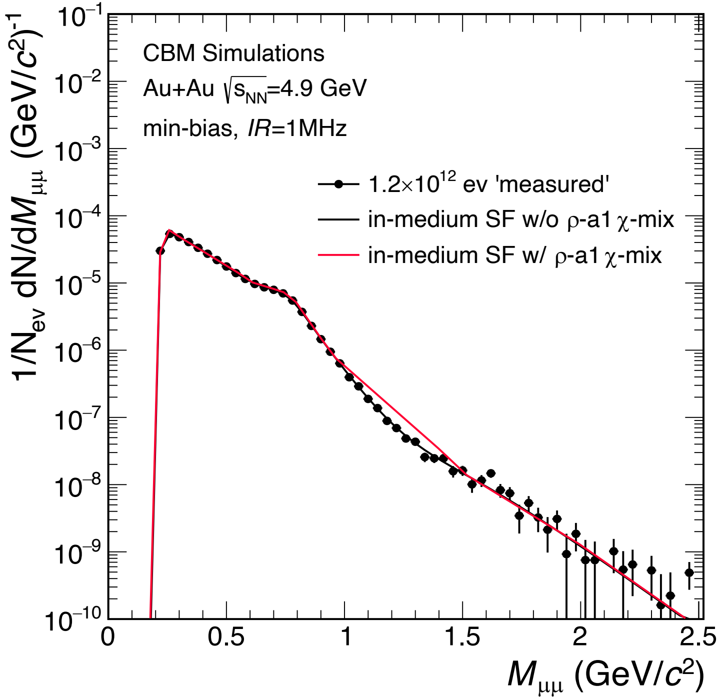
CBM dilepton performance

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

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

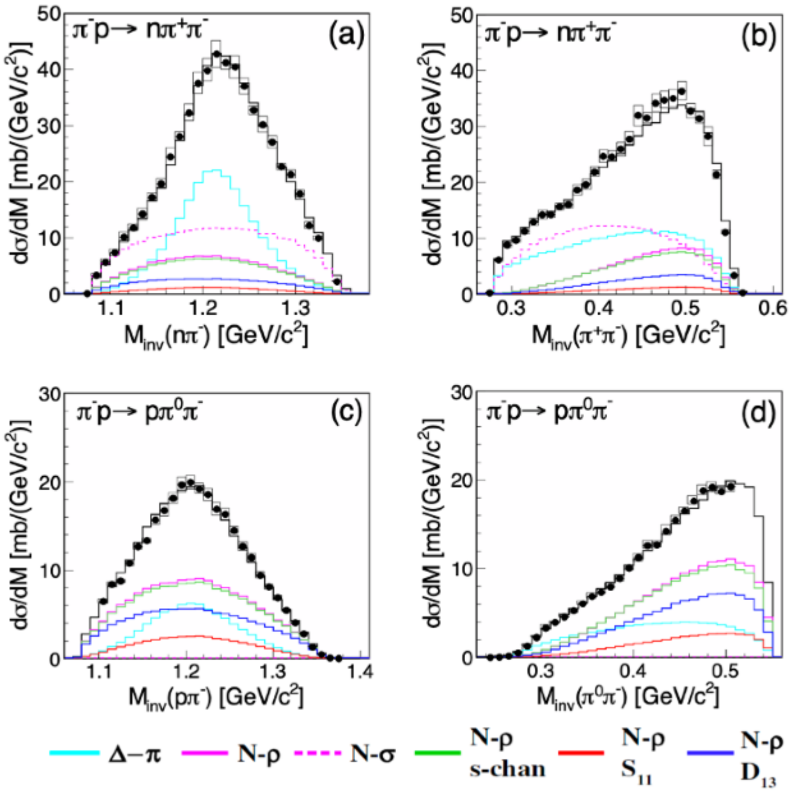


Jung et al., PRD 95, 036020 (2017)
Hohler and Rapp, PLB 731 (2014)



Status and future of the HADES experiment
Inclusive hadron emission, flow correlation and e-b-e proton number flucts
Excess radiation, flow and virtual photon polarisation
Establishing the “standard candle” for hadronic emissivity
Summary

Extraction of partial waves from two-pion channel

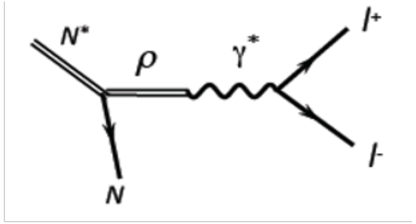


- $p_\pi = [0.66, 0.69, 0.75, 0.8]$ GeV
- $\pi^- + p \to \pi^- + \pi^+ + n$
  - Hadronic final states used in PWA (Bonn/ Gatchina code)
  - Use invariant masses, and angular distribution (not shown here)
- $\pi^- + p \to e^- + e^+ + n$
  - Prediction for dilepton invariant mass assuming strict VMD
 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

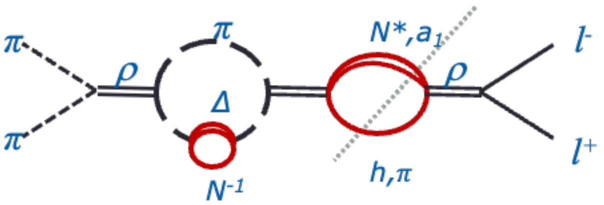
HADES arXiv:2309.13357; arXiv:2205.15914; Phys. Rev. C 102 (2020) 2, 024001

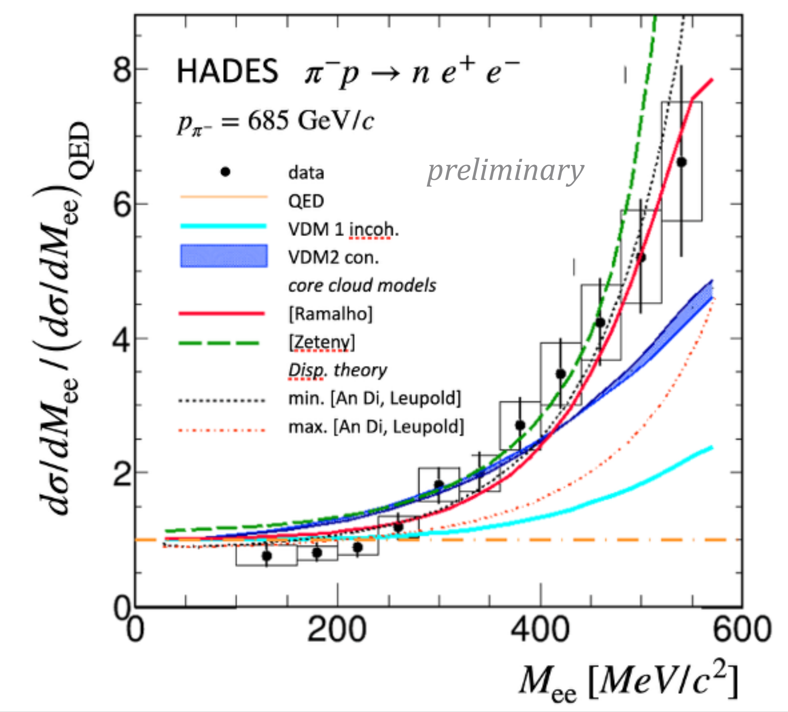
$\pi^- + p \rightarrow e^- + e^+ + n$

Resonance-Dalitz decay (a la VMD) …



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



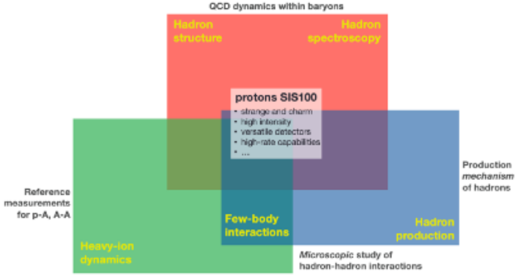


Transition form factor (time-like) extracted by subtracting QED expectation from exclusive invariant mass distribution.

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
-

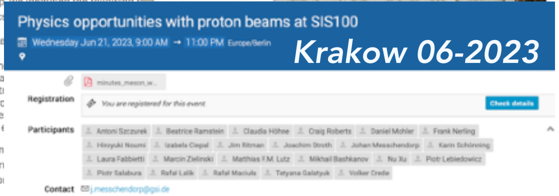


Hadron Physics at GSI and FAIR: Prospects for the Next Decade

...

December 5, 2024

Contents



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

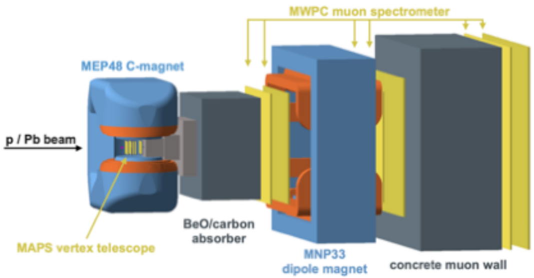
Inclusive hadron emission, flow correlation and e-b-e proton number flucts

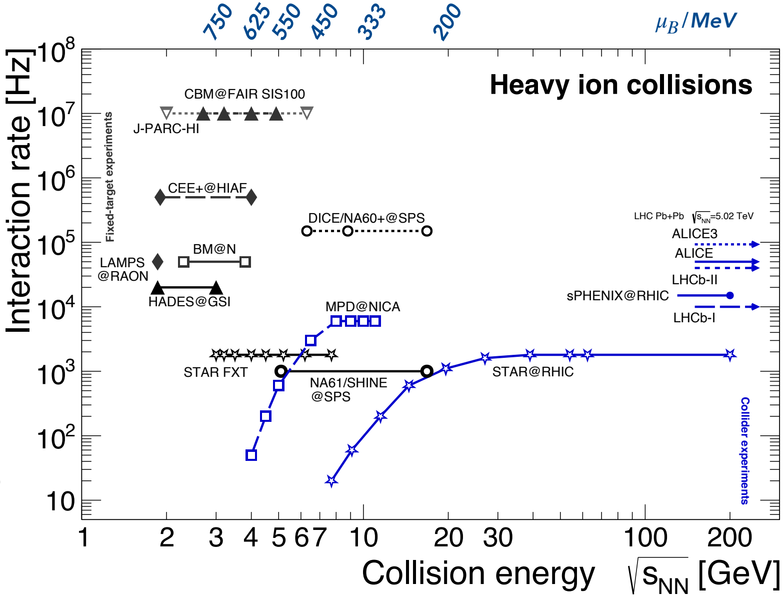
Excess radiation, flow and virtual photon polarisation

Establishing the “standard candle” for hadronic emissivity

Summary

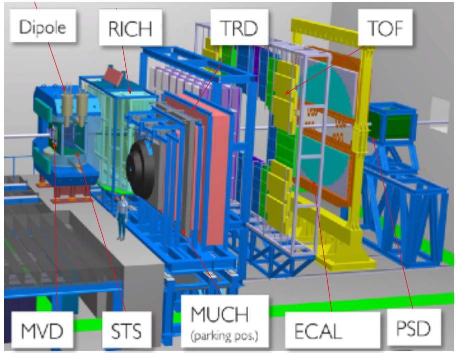
Future facilities for high μ_B physics



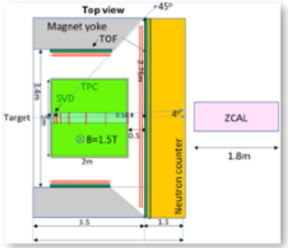


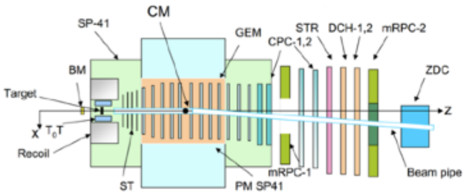
T. Galatyuk, Nucl. Phys. A982 (2019), https://github.com/tgalatyuk/QCD_caloric_curve

CBM– FAIR

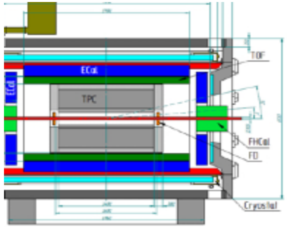


DHS – JPARC-HI



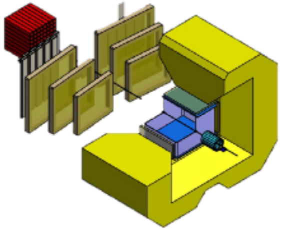


BM@N – NICA



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