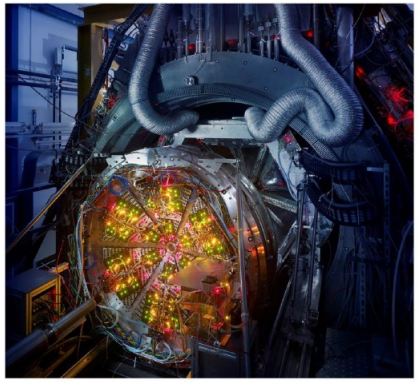
Exploring dense matter with dielectron probes at HADES

Jornadas LIP – Évora, 16 February 2018

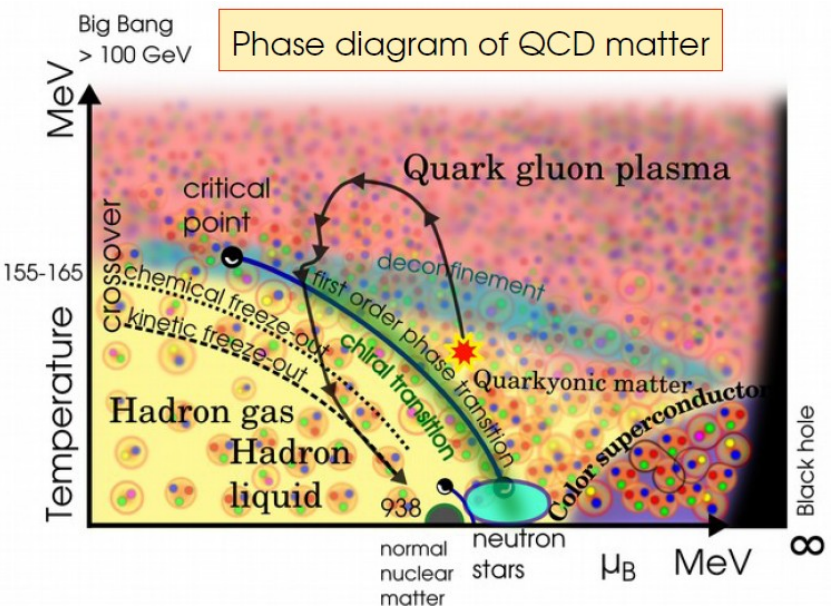


Celso Franco

on behalf of the HADES group

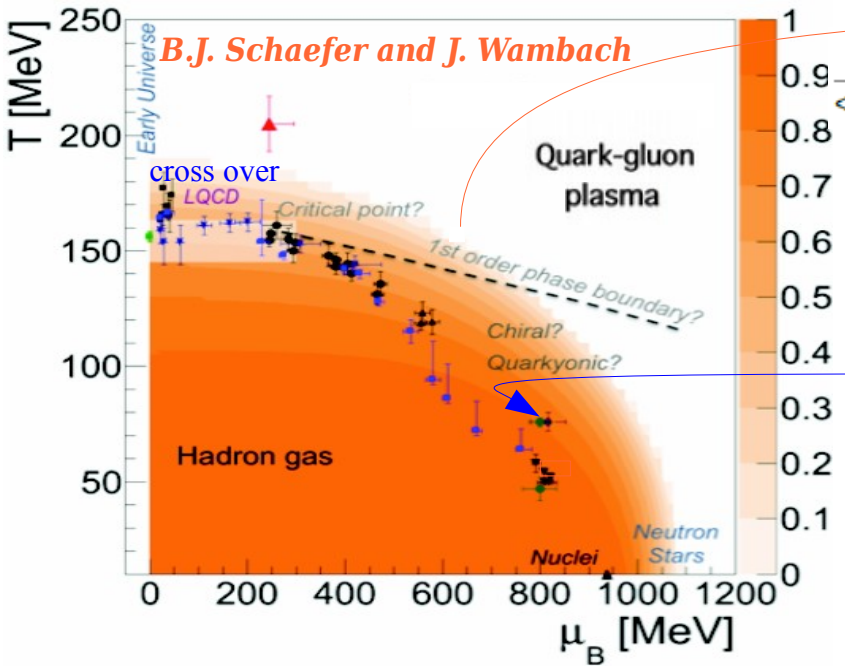



Phase diagram of QCD matter: From Big-Bang to Neutron Stars

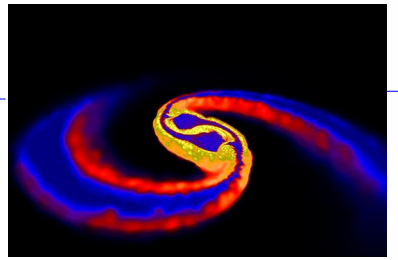


- Heavy-Ion collisions permit a dynamic access to some regions of the diagram → Study the nature of phase transitions in QCD matter: chiral symmetry restoration, deconfinement, etc.

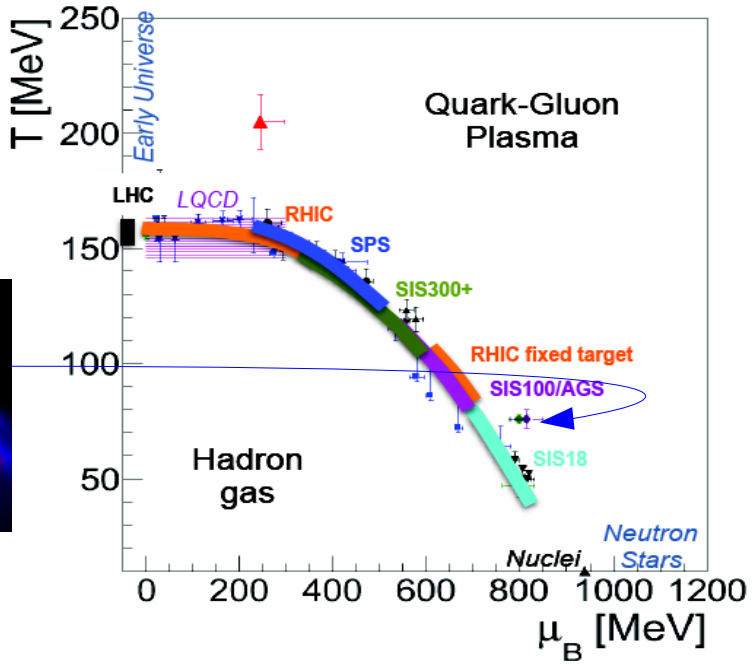
By investigating the limits of hadronic existence one can gain a deeper understanding about the mass generation mechanism in hadrons



Neutron star merger

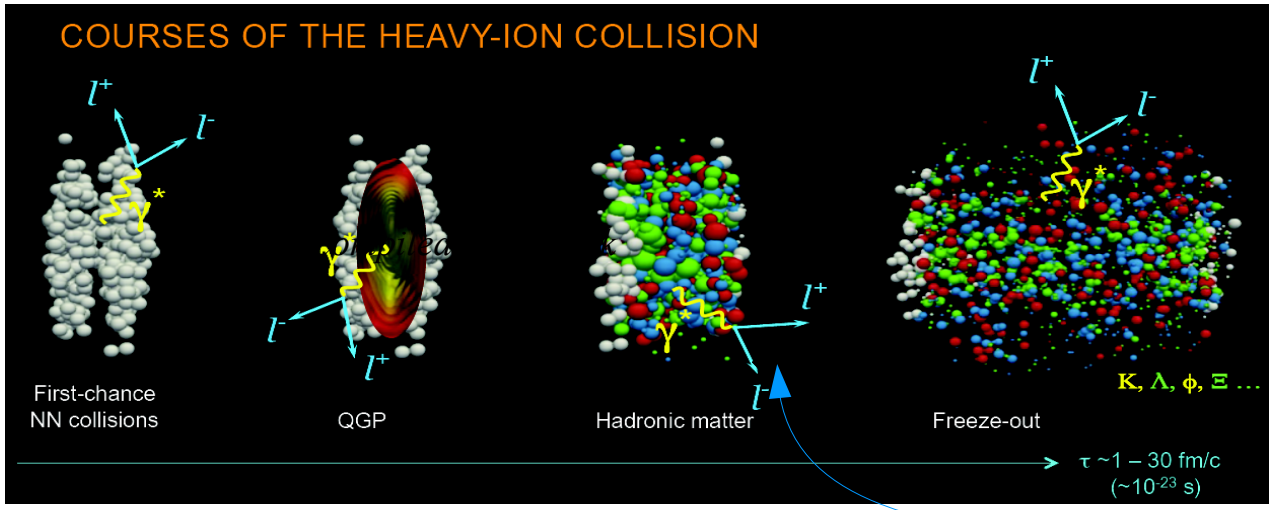


Rosswog

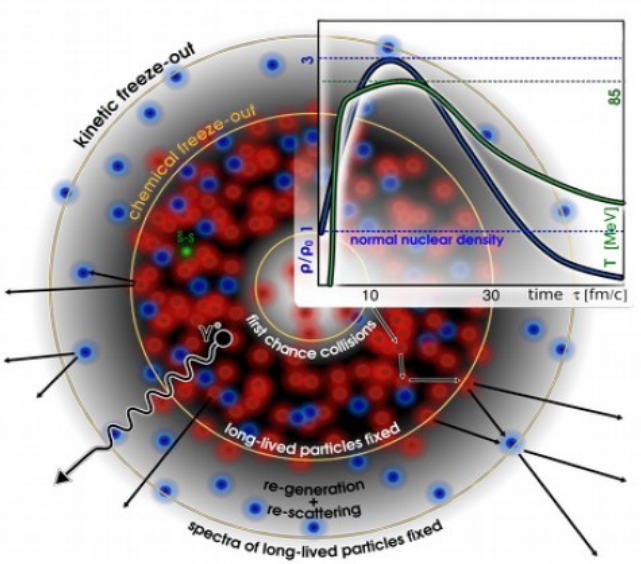


Dilepton probes in Heavy-Ion collisions *(HIC)*

- The different phases of QCD matter are best investigated by analyzing the hadron properties within the fireball *(hot/dense medium)* created by a **Heavy-Ion collision**:



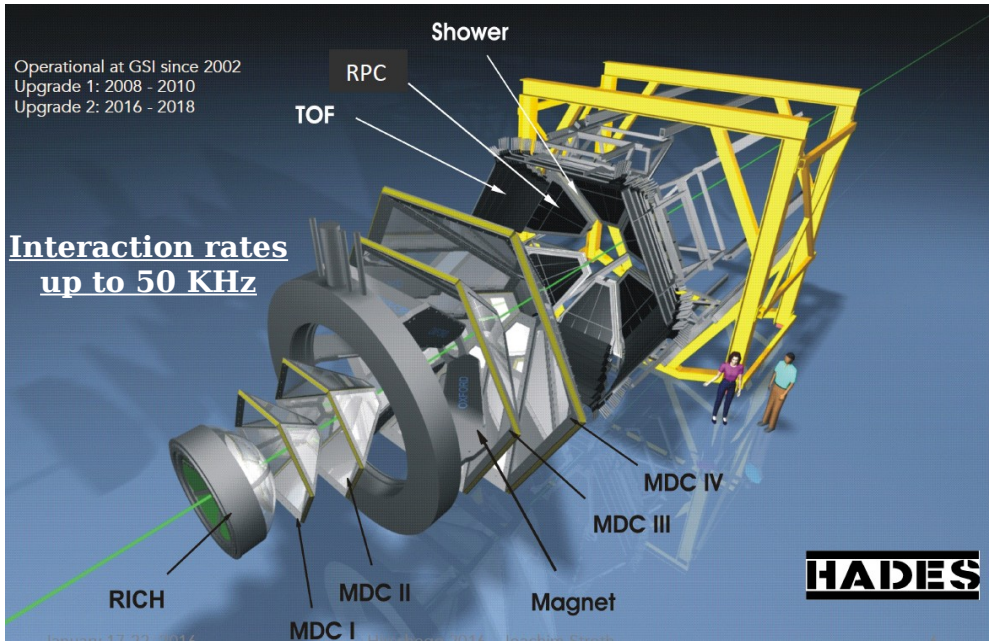
Time evolution of a low energy HIC



- **Why dileptons?**
  - They are emitted during the whole history of a HIC
  - They leave the fireball undisturbed *(no strong interaction in the dense medium)*

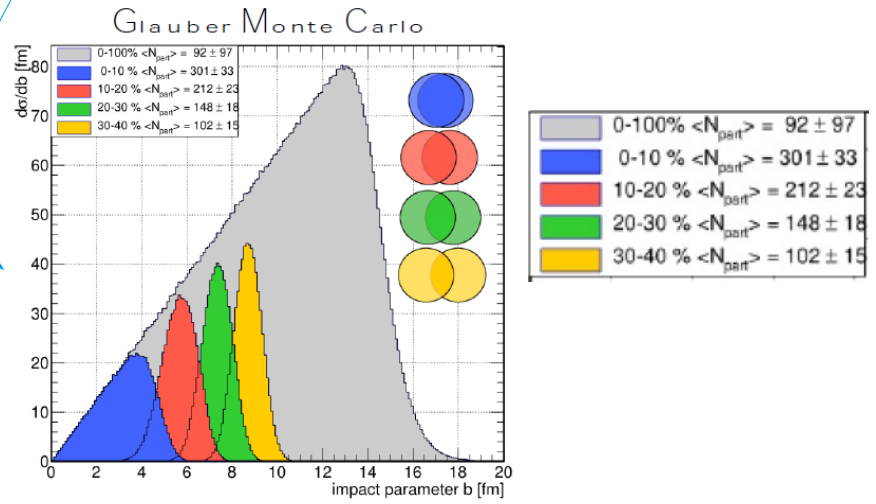
The HADES experiment: Fixed target setup using proton *(1-4 GeV)*, pion *(0.4-2 GeV)* and nuclei *(1-2 AGeV)* beams from SIS18 at GSI

- **HADES program** *(spectrometer optimized for rare probes → ex. BR(e^+e^-) ~ 10^{-5})*:
  - Excitation function for low mass e^+e^- and strange baryons and mesons
  - Various aspects of baryon-resonance physics



- Full ϕ coverage, 18° to 85° in θ
- π/p/K PID: dE/dx in MDC + TOF/RPC
- e^+/e^- PID: RICH+TOF or RICH+RPC+Shower
- Mass resolution → 2% of M(ρ, ω)

- 2002–2009: light A+A, p+p, n+p, p+A
- 2011–2014: Au+Au, π–induced reactions
- 2018–2020 (FAIR Phase–0):
- → high stat. A+A, π+p/π+A, p+A



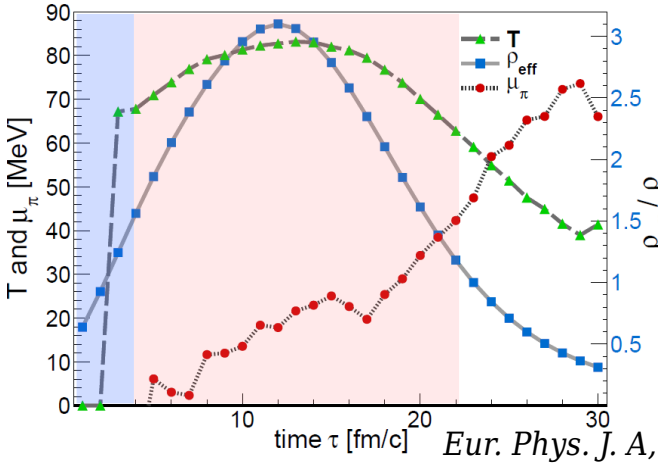
4.3×10^9 of 40% most central Au+Au events recorded

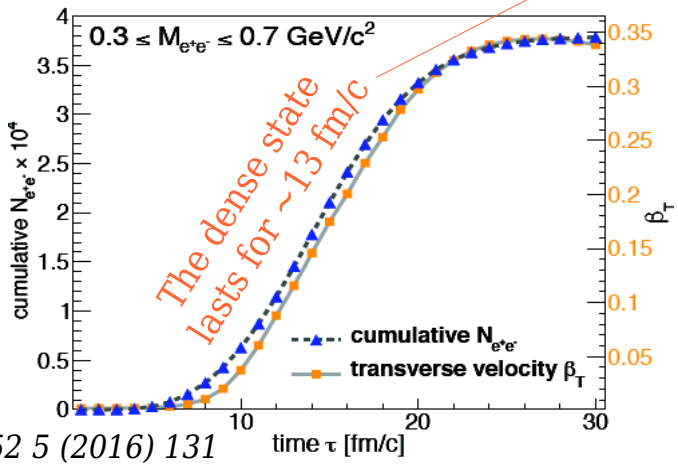
Relevance of the Au+Au program: $\sqrt{s_{NN}}=2.42\,\mathbf{GeV}$ $(E_{Au}=1.23\ AGeV)$

- Great conditions to study the properties of hadrons within a dense baryon-rich medium:

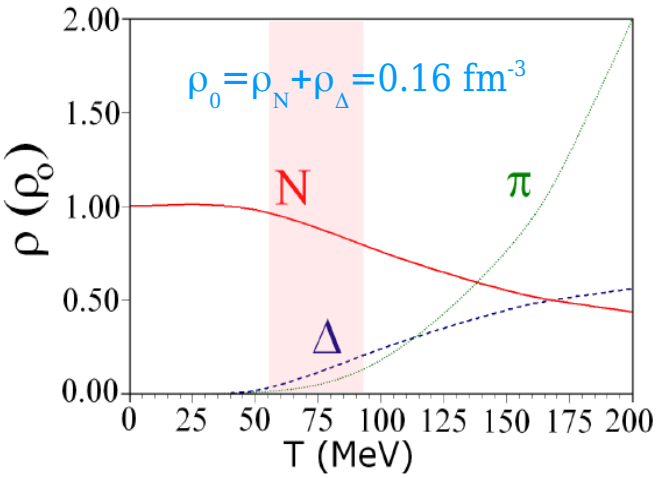
Thermodynamic properties from coarse graining UrQMD

a factor 1.5–3 longer than the π-rich fireballs at higher HIC energies

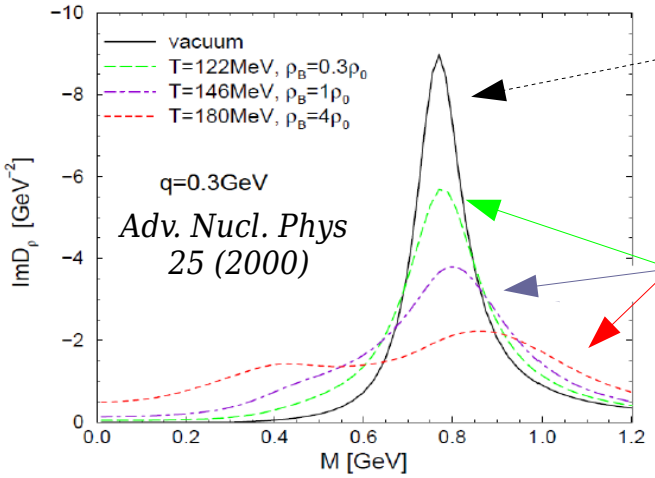




Eur. Phys. J. A, 52 5 (2016) 131

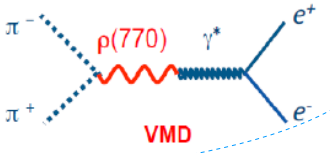


ρ ($\tau \approx 1.5$ fm/c) spectral function

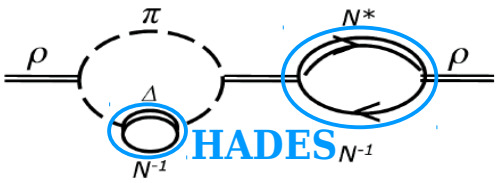


Vacuum

ρ and γ* have $J^P = 1^-$



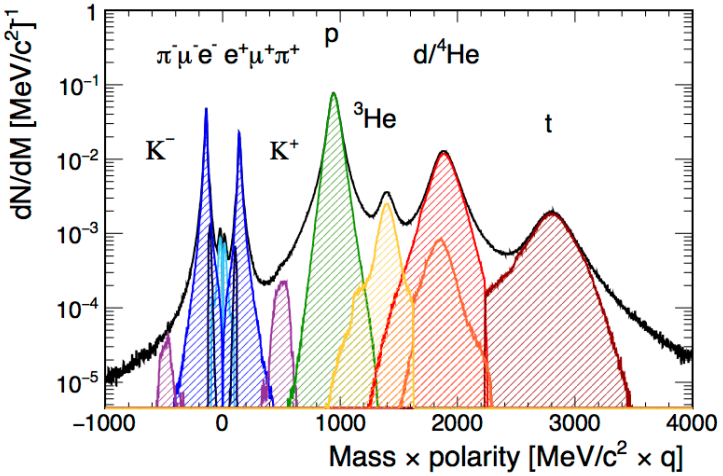
Additional contributions of the ρ self-energy in the medium

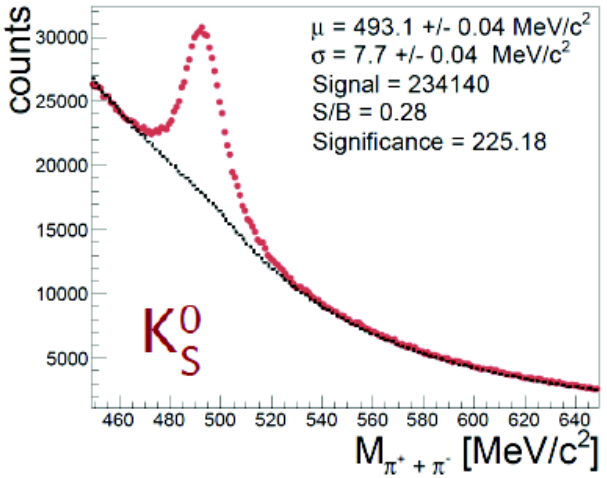


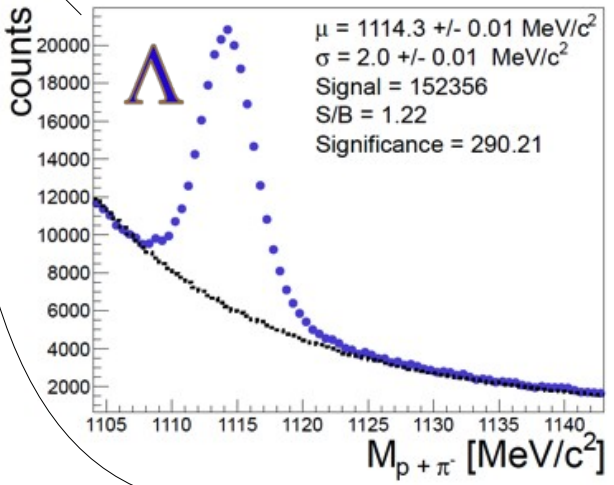
A strong modification of the ρ spectral function is expected at high ρ_B

Examples of hadronic reconstruction at HADES: Au+Au data

Used to study the strangeness production *(not covered by this talk)*

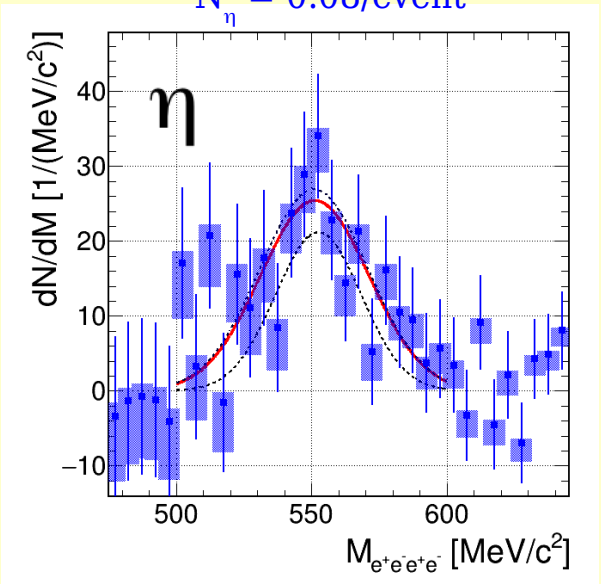




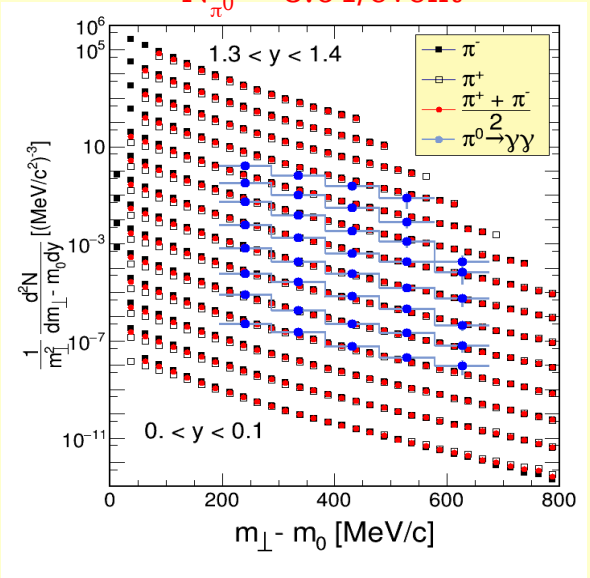


Relevant contributions of the Hadronic cocktail to the e^+e^- mass spectrum

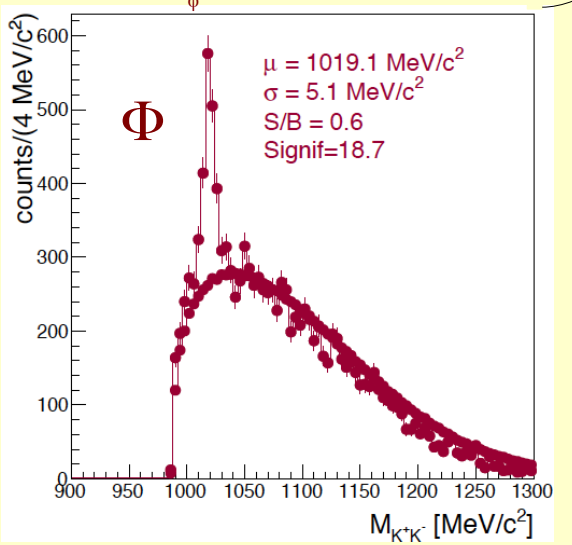
N_η = 0.08/event



N_{π^0} = 8.64/event

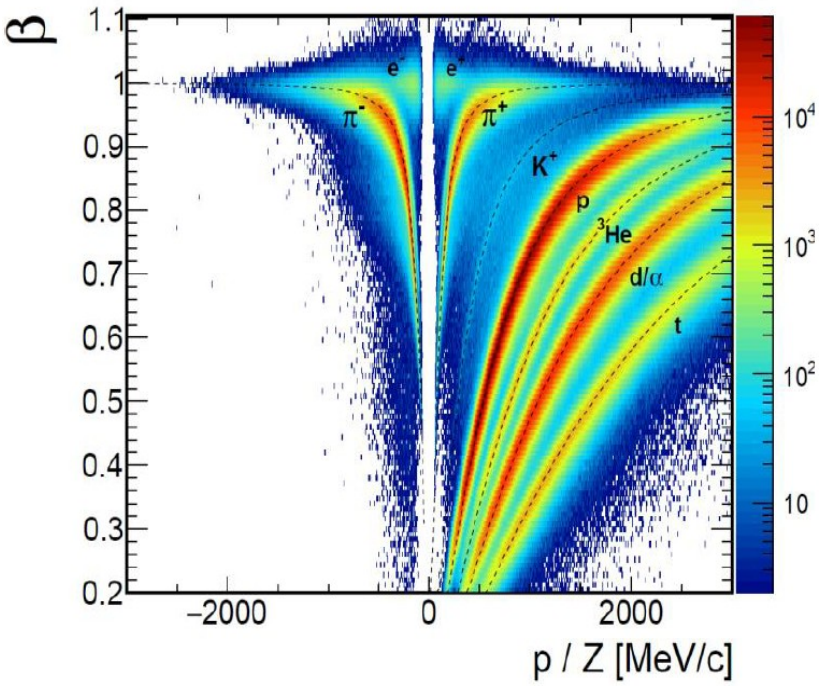


$N_\phi = 2\times10^{-4}$/event



Identification of Positrons and Electrons

- **Relevant information for the PID of $e^{+/-}$:**
  - Particle velocity **β**
  - Particle momentum **p**
  - Energy Loss in tracking detectors
  - Charge deposited in Shower detector
  - Track quality
  - Cherenkov radiation *(generated when $e^{+/-}$ traverse the RICH detector)*



- All variables are combined in a multivariate analysis by a **Neural Network** *(NN)*

- The NN improves the efficiency of the lepton selection up to a maximum of 10%, specially at high-momentum, due to the consideration of multidimensional correlations

Flowchart of the method used for the PID of leptons

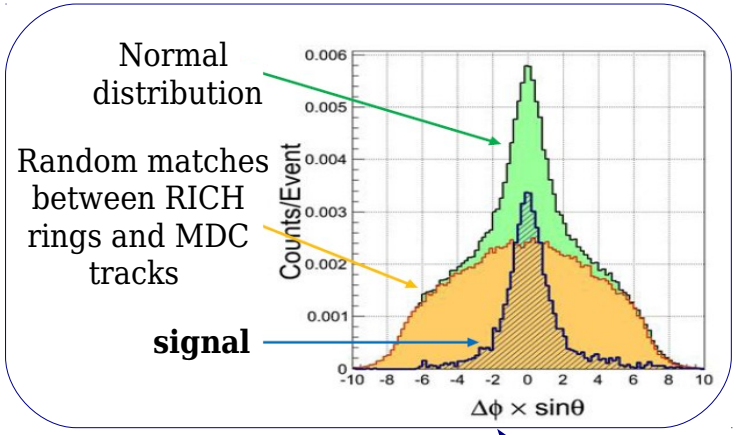
PID variables

PID variables

Signal Sample *(lepton tracks)*

multivariate input

Background Sample *(hadron tracks)*



Dynamic Neural Network

Trained in simulation

single network output for each data track

Network Cut

Lepton Purity ~ 99% (using data)

Accepted Tracks

Rejected Tracks

Dilepton reconstruction

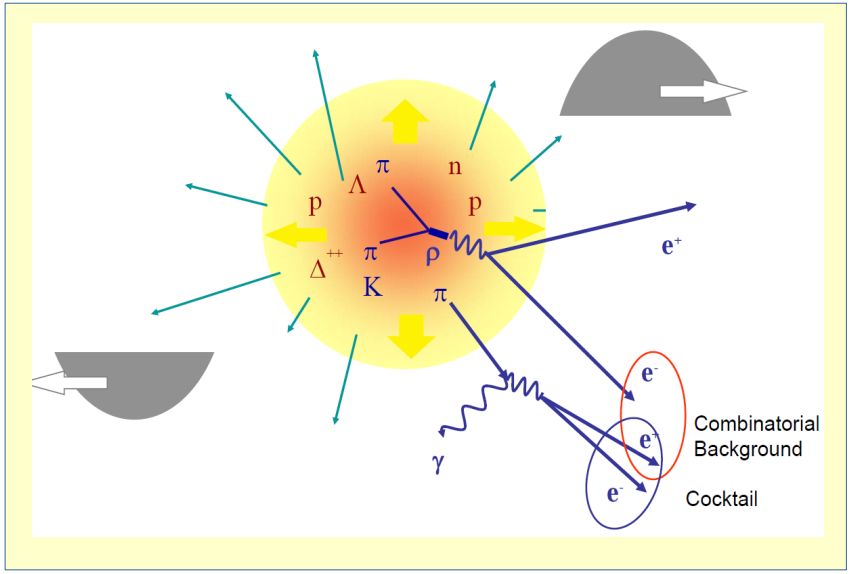
- **Definitions** *(combinatorial background & signal)*:

$$CB = k\left(2\sqrt{N_{e+e+} \times N_{e-e-}}\right)$$

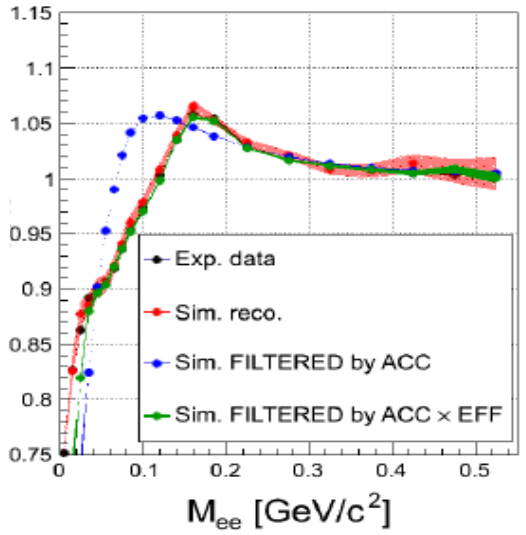
estimated from like−sign pairs

$$Signal = N_{e+e-} - CB$$

contribution from $\gamma \rightarrow e^+e^-$ *(conversion in the spectrometer)* is subtracted: $\theta(e^+,e^-) > 9$ deg



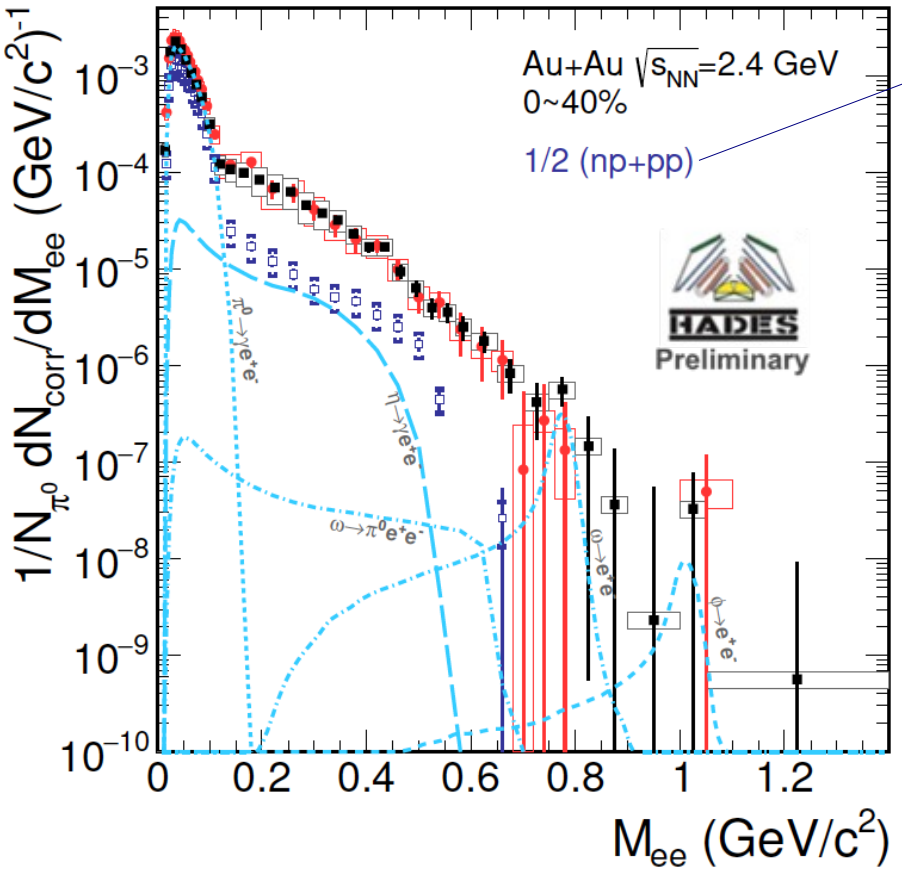
$$k = \frac{N_{e+e-}}{\sqrt{N_{e+e+} \times N_{e-e-}}}$$



estimated using leptons from different events of similar multiplicities, with the leptons originating from similar target positions

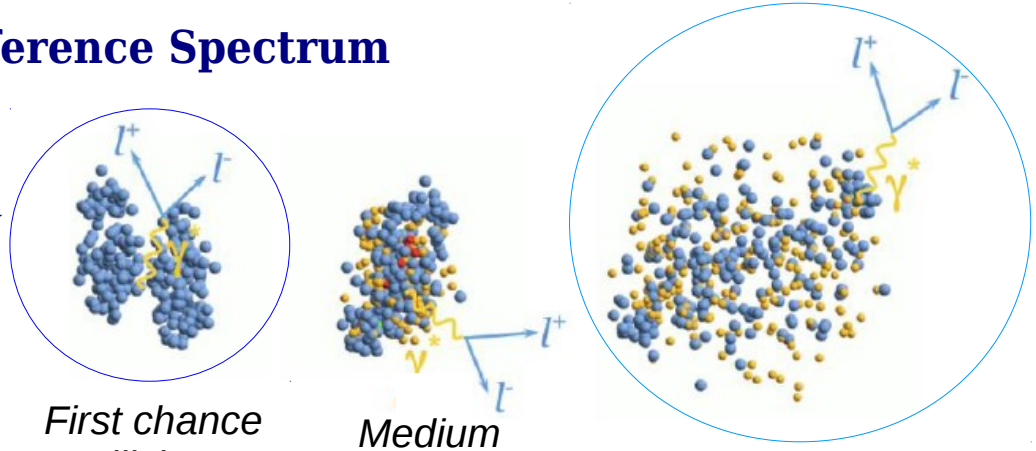
Invariant mass spectra of e^+e^-: Au+Au data

Two independent methods *(red, black)*



Hadronic cocktail

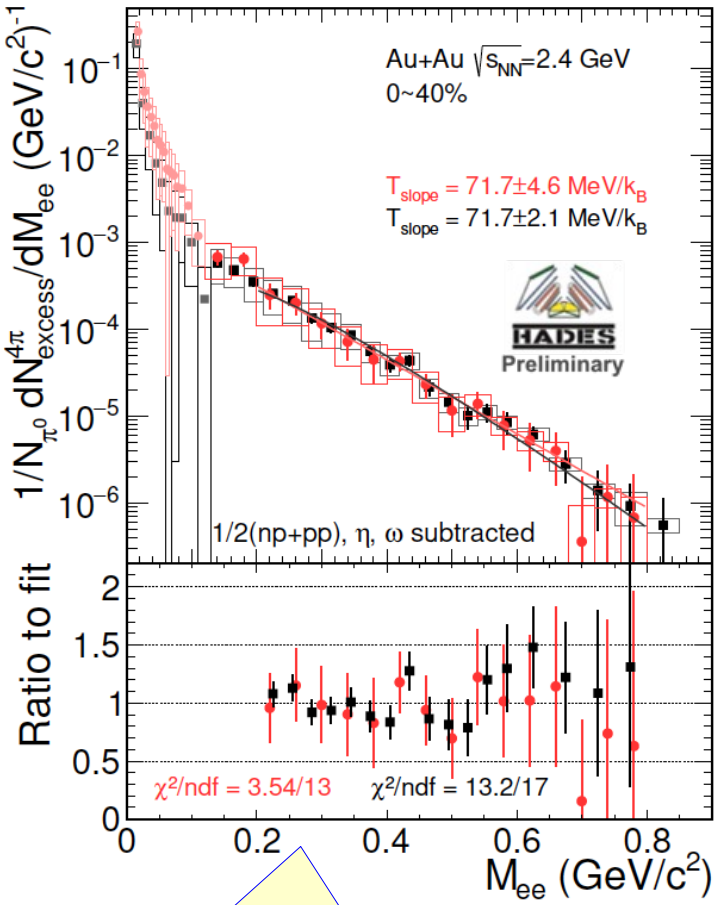
Reference Spectrum

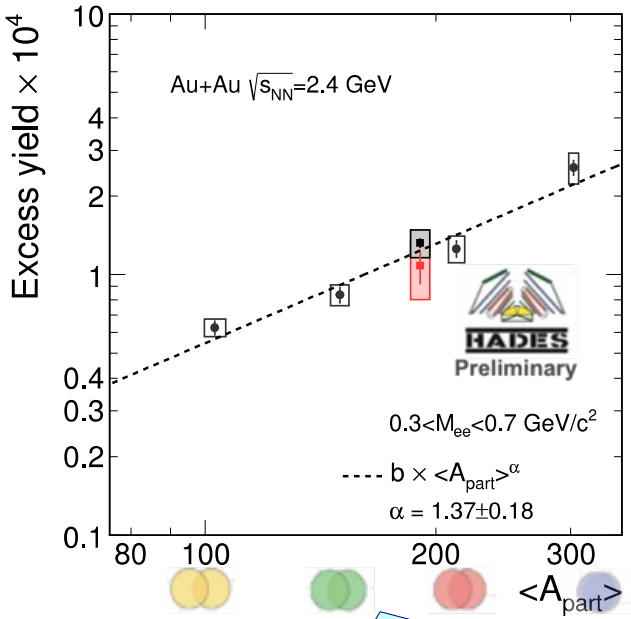


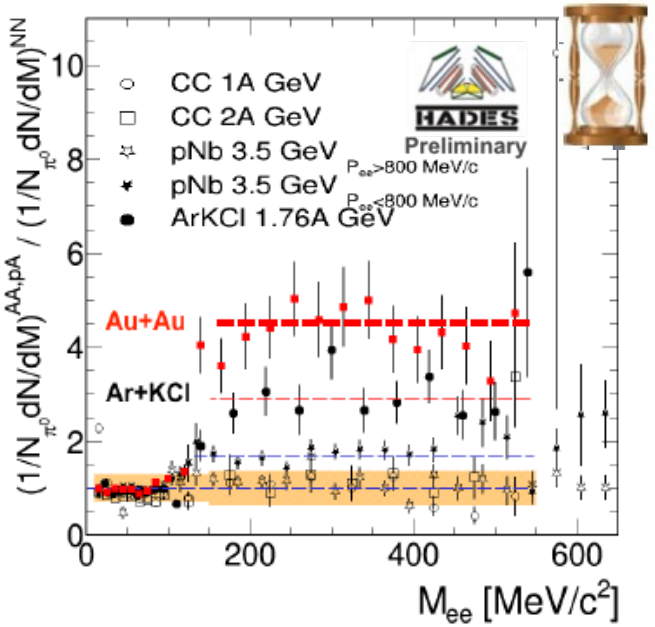
Strong excess of medium radiation above 150 MeV/c²

- π^0 from charged pions multiplicity
- η from γ conversion
- ϕ from K^+K^- channel
- ω from the statistical Hadronization Model

Temperature & lifetime of the fireball: using the acceptance corrected mass spectrum subtracted from the first chance collisions and the cocktail







Strong excess yield dependence with $A^{1.3}_{part}$:

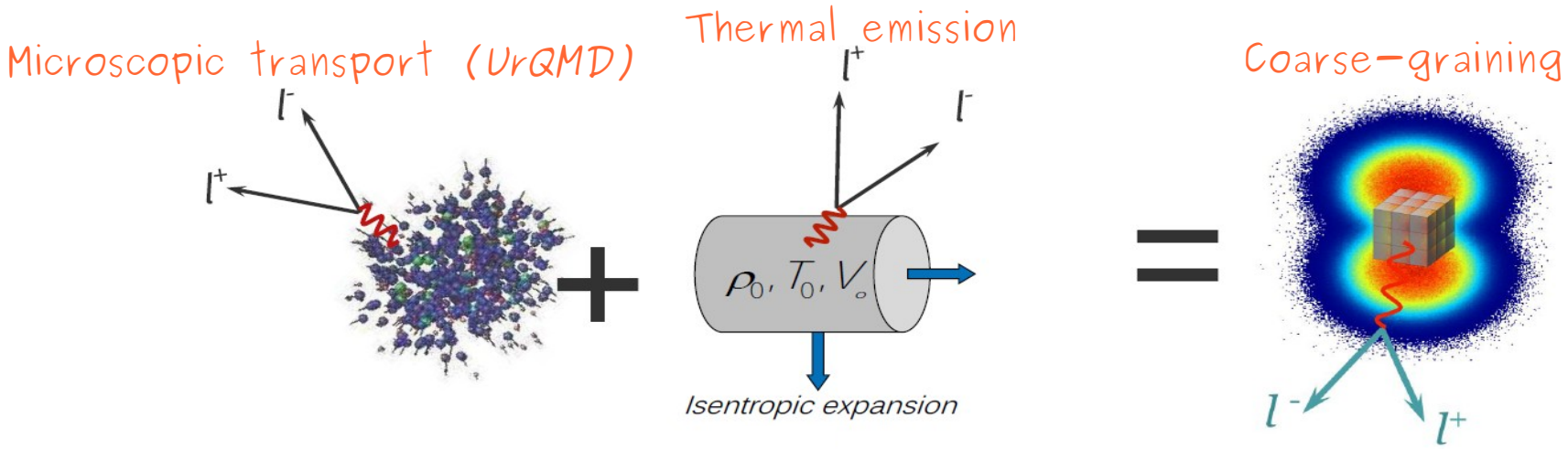
- Implies the existence of a regeneration of baryonic resonances (chronometer of the collision)

Almost exponential shape allows for the extraction of the temperature: the medium is radiating as a black body with a temperature of 72 MeV

Consistent with a significant drop of the $q\bar{q}$ condensate
(order parameter of chiral symmetry restoration)

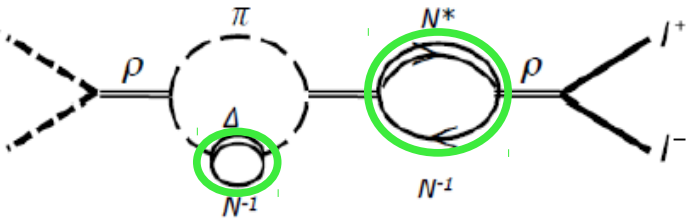
Description of the fireball evolution: Coarse-Graining hadron transport

(Eur. Phys. J. A, 52 5 (2016) 131)



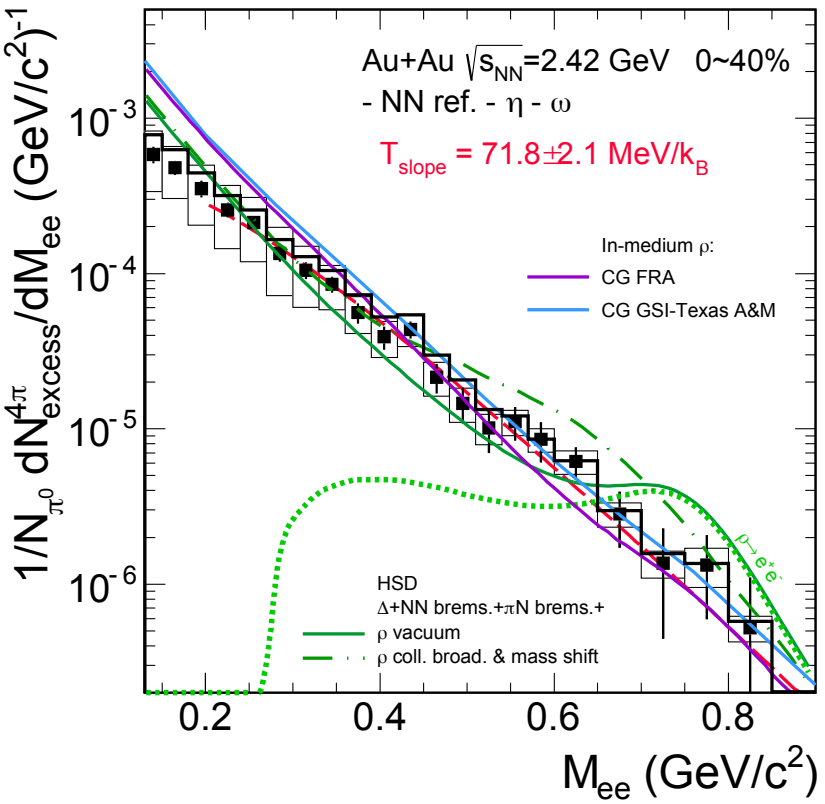
- **Theoretical description of the dilepton emission rates in HADES:**
  - Au+Au is simulated with UrQMD (Ultra Relativistic Quantum Molecular Dynamics)
  - The volume of the fireball is discretized in 21x21x21 space cells of 1 fm^3 and their evolution is analyzed in 30 time steps of Δt = 1 fm/c (~ 280 k cells)
  - For each cell the bulk properties are extracted: T, μ_B and $\vec{v}_{coll}$. The dilepton rates are calculated from these inputs and summed up for all cells

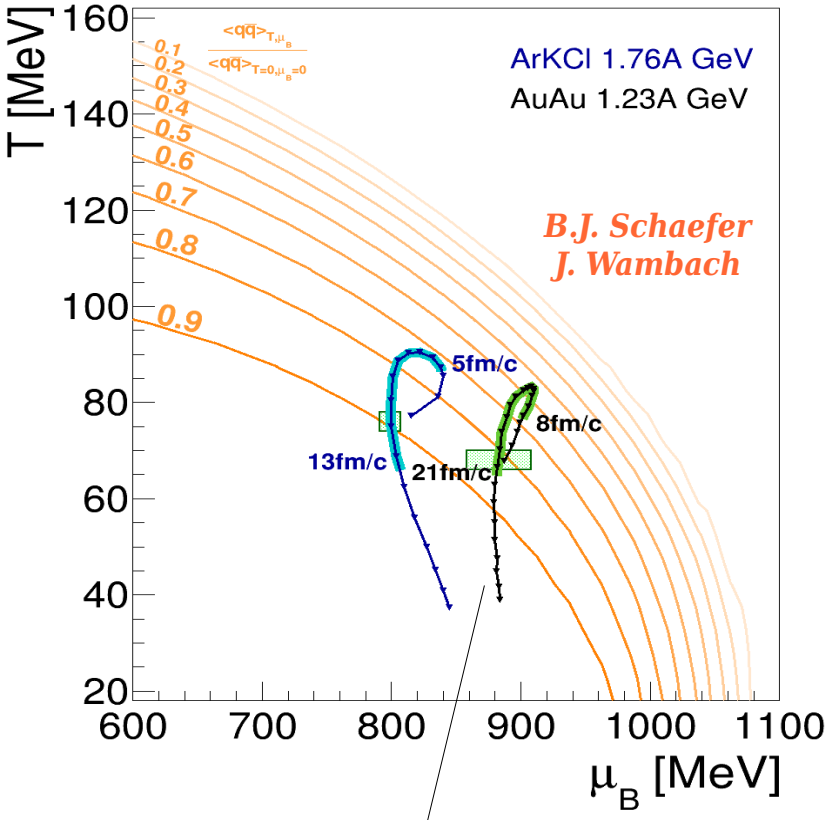
$$\frac{d^3N}{dMdydp_t} \equiv \int_{t=0}^{\infty} \frac{d^4\varepsilon}{d\mathbf{p}} \left[T(\mathbf{x}), \mu_B(\mathbf{x}), \vec{v}_{coll}(\mathbf{x}), ..\right] d\mathbf{x}$$



Results from the Coarse-Graining *(CG)* simulation

The CG models are embedded with a strongly broadened ρ meson in order to account for the direct ρ–baryon scattering inside the dense medium (*Adv. Nucl. Phys. 25 (2000)*)





The melting of the $q\bar{q}$ condensate matches spectral medium effects: $\frac{\langle\langle \bar{q}q \rangle\rangle(T,\mu_B)}{\langle \bar{q}q \rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$

Summary

- HADES explores baryon-rich matter at SIS18 *(energies < 2 AGeV)* using several collision systems of different sizes. **The excitation function of e^+e^- from the heaviest system explored so far, Au+Au collisions at 1.23 AGeV, is now completed**:

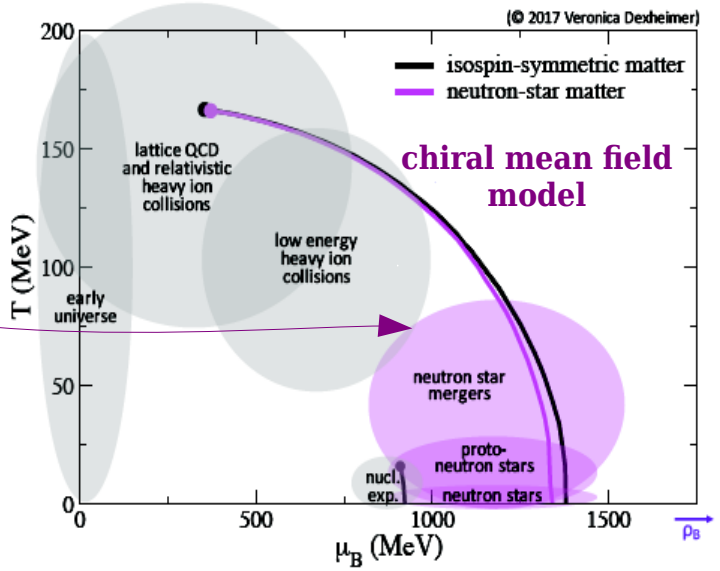
  - The medium radiates in a "Planck-like" way with T ≈72 MeV *(hotter than at freeze-out)*

  - The fireball lifetime is easily accessed due to the non-linear dependence of dilepton emission with the system size. The lifetime was found to be quite long: τ ≈13 fm/c

  - The dilepton emission by the baryon-rich medium ($\rho_{max} \approx 3\rho_0$) can be explained by a strong in-medium broadening of the ρ meson

  - The medium investigated by HADES can provide new insights about poorly known Astrophysical processes

First measurment of radiation from matter in the same conditions as neutron star mergers!



Outlook

- **FAIR phase 0** *(2018-2020)*:

  - Ag + Ag at 1.65 AGeV → access for the first time at these collision energies the intermediate mass dileptons *(above 1 GeV)*, in order to study the chiral ρ–a1 mixing and also to quantify the lifetime and baryon density dependence of the ρ spectral function

  - π + p/A at √s = 1.7 – 1.9 GeV → unique study of the electromagnetic structure of baryonic resonances

  - p + p/A at 4.5 GeV → measure, for the first time, the EM transition form factor of hyperon Dalitz decay ($Y \to \Lambda e^+e^-$)