Studying dilepton production in a coarse-graining approach - What we can learn about in-medium effects?

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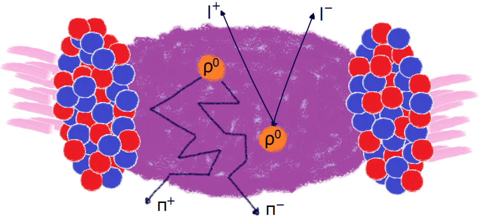
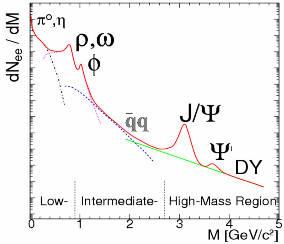
H-QM Helmholtz Research School Quark Matter Studies

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Why Dileptons...?

- Dileptons represent a clean and penetrating probe of hot and dense nuclear matter
- Reflect the **whole dynamics of a collision** → Correct description of dynamics essential!
- Aim of studies:
  - **In-medium modification of vector meson properties**
    Hadronic many-body effects
    Baryon vs. meson-driven modifications
    Vector Meson Dominance
  - **Chiral symmetry restoration**



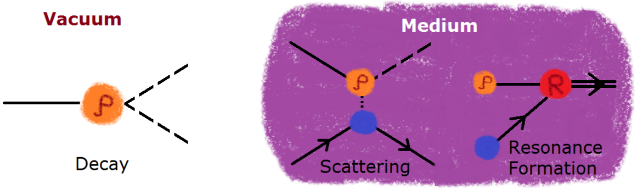


Medium-modifications of hadrons - why are they interesting?

- Basic theory of strong interactions is QCD → running coupling
  - Large coupling at small momenta → no description from first principles
- The relevant degrees at low energies are **hadrons**
- Hadron in a dense and / or hot environment → More and more fundamental degrees of freedom dominate
  - **How are the "two faces" of QCD connected?**
  - Important for understanding the non-perturbative region of QCD
- Role of **symmetries** is important
- Relevant quantity is the **hadron spectral function** → coupling to current $J(x)$ carrying the hadron's quantum numbers
- Vacuum spectral functions can be measured ($e^+e^- \rightarrow hadrons$) ⇒ **What for in-medium case?**

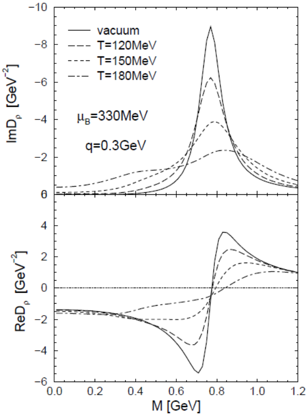
Vacuum vs. Medium

- What is different, when comparing vacuum processes with medium?
  - $\Rightarrow$ **Vacuum**: Probe can only decay, Lorentz invariance
  - $\Rightarrow$ **Medium**: Scattering with particles (mesons, baryons) which constitute the medium, explicit dependence on E and $\vec{q}$



- Unified language: Scattering is decay into particle and hole $\rightarrow$ Resonance-hole excitation
- Challenge is to determine the **self-energy** Π of a particle undergoing all those medium effects

Hadronic Many-Body Theory

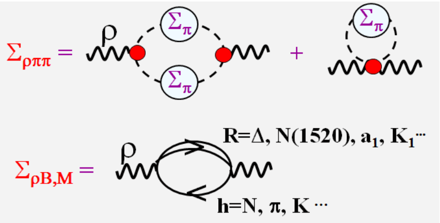


- Medium modifications of the ρ propegator

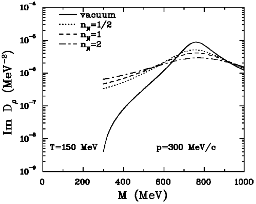
$$D_\rho \propto \frac{1}{M^2 - m_\rho^2 - \Sigma^{\rho\pi\pi} - \Sigma^{\rho M} - \Sigma^{\rho B}}$$

include interactions with pion cloud with hadrons ($\Sigma^{\rho\pi\pi}$) and direct scatterings off mesons and baryons ($\Sigma^{\rho M}$, $\Sigma^{\rho B}$)

[R. Rapp, J. Wambach, Eur.Phys.J. A6, 415-420 (1999)]



Alternative Approach: Spectral Function from Resonance Dominance



Resonance	Mass (GeV)	Width (GeV)	Branching ratio (ρN or $\rho\pi$)
$N(1700)$	1.737	0.249	0.13
$N(1720)$	1.717	0.383	0.87
$N(1900)$	1.879	0.498	0.44
$N(2000)$	1.903	0.494	0.60
$N(2080)$	1.804	0.447	0.26
$N(2090)$	1.928	0.414	0.49
$N(2100)$	1.885	0.113	0.27
$N(2190)$	2.127	0.547	0.29
$\Delta(1700)$	1.762	0.599	0.08
$\Delta(1900)$	1.920	0.263	0.38
$\Delta(1905)$	1.881	0.327	0.86
$\Delta(1940)$	2.057	0.460	0.35
$\Delta(2000)$	1.752	0.251	0.22
$\phi(1020)$	1.020	0.0045	0.13
$h_1(1170)$	1.170	0.36	1
$a_1(1260)$	1.230	0.40	0.68
$\pi(1300)$	1.300	0.40	0.32
$a_2(1320)$	1.318	0.107	0.70
$\omega(1420)$	1.419	0.174	1

- In-medium self energies of the ρ

$$\Sigma_\rho = \Sigma^0 + \Sigma^{\rho\pi} + \Sigma^{\rho N}$$

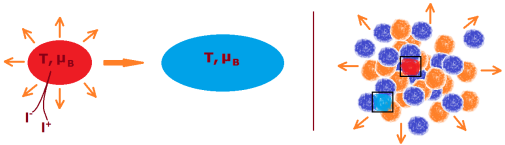
  were calculated using empirical scattering amplitudes from **resonance dominance**

  [V. L. Eletsky et al., Phys. Rev. C64, 035303 (2001)]

- For ρN scattering N^* and Δ^* resonances from Manley and Saleski
- Additional inclusion of the Δ_{1232} and the N_{1520} **subthreshold resonances**
  $\Rightarrow$ Important, as they significantly contribute!

Theoretical approaches

- General assumption when calculating spectral functions: **Equilibrated stage** (heat bath with fixed T,μ_B,...)
  $\rightarrow$ *<u>But</u>*: Situation in heavy-ion collision will be dominated by non-equilibrium evolution!



- Phenomenological approaches are necessary to model the heavy-ion reaction
  - **Transport approaches** $\rightarrow$ Treat the dynamics microscopically and account for non-equilibrium, but implementation of full medium-effects is difficult
  - **Fireball parametrizations** $\rightarrow$ Probably rather too simplifying...
  - **Hydrodynamics** Need initial state, description of final state interactions - applicability at low energies?

Fireball Parametrization

- Calculations with a **fireball model** achieved very good agreement with dilepton data from SPS and RHIC

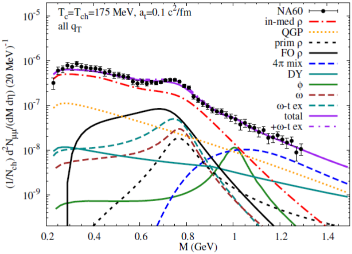
  [H. van Hees, R. Rapp, Nucl. Phys. A806, 339 (2008)]

- The zone of hot and dense matter is described by an isentropic expanding cylindrical volume

$$V_{\mathrm{FB}}(t) = \pi \left(r_{\perp,0} + \frac{1}{2} a_\perp t^2 \right)^2 \left(z_0 + v_{z,0} t + \frac{1}{2} a_z t^2 \right)$$

- *Problem*: How to choose parameters? Is it a plausible description or a too simple picture?

$\Rightarrow$ **Calculations with better constrained dynamics?**



Transport Models

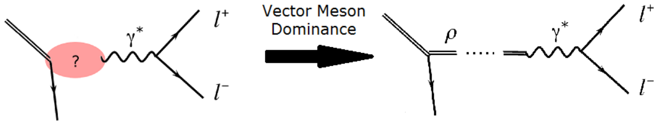
- Hadronic non-equilibrium approaches
- Include baryons and mesons with masses up to 2 GeV
- Hadrons are propagated on classical trajectories
- Two processes for resonance production (at low energies)
  - **Collisions** (e.g. $\pi\pi \to \rho$)
  - **Higher resonance decays** (e.g. $\mathrm{N}^* \to N + \rho$)
- String excitation possible above $\sqrt{s} \approx$ 3 GeV
- Resonances either decay after a certain time or are absorbed in another collision (e.g. $\rho + N \to N^*_{1520}$)

UrQMD resonances

Resonance	Mass	Width
N^*_{1440}	1.440	350
N^*_{1520}	1.515	120
N^*_{1535}	1.550	140
N^*_{1650}	1.645	160
N^*_{1675}	1.675	140
N^*_{1680}	1.680	140
N^*_{1700}	1.730	150
N^*_{1710}	1.710	500
N^*_{1720}	1.720	550
N^*_{1900}	1.850	350
N^*_{1990}	1.950	500
N^*_{2080}	2.000	550
N^*_{2190}	2.150	470
N^*_{2220}	2.220	550
N^*_{2250}	2.250	470
Δ_{1232}	1.232	115
Δ^*_{1600}	1.700	350
Δ^*_{1620}	1.675	160
Δ^*_{1700}	1.750	350
Δ^*_{1900}	1.840	260
Δ^*_{1905}	1.880	350
Δ^*_{1910}	1.900	250
Δ^*_{1920}	1.920	200
Δ^*_{1930}	1.970	350
Δ^*_{1950}	1.990	350

Dilepton Sources

- **Coupling to photon?**
  - Straightforward for direct decays (ρ, ω, ϕ)
  - What about the Dalitz decays? $(\pi^0, \eta, \eta', \omega)$
    P $\rightarrow \gamma + e^+e^-$
    V $\rightarrow$ P $+e^+e^-$
    $\Rightarrow$ Form factors necessary!
- Assumption: **Vector Meson Dominance** $\rightarrow$ Coupling between hadron and (virtual) photon via vector mesons



- Form factors for the Dalitz decays can be obtained from the **vector-meson dominance** model
- Baryon Resonances: $B^* \rightarrow B + \rho \rightarrow B + e^+e^-$, but Δ_{1232} traditionally treated explicitly

Challenges

- Large variety of parameters
- Many cross-sections and branchings are unmeasured or unmeasurable (especially for ρ and Δ lack of data)
- Consistency of description when going from resonances to strings?
- General difficulties of the transport approach at high density:
  - Off-shell effects
  - Multi-particle collisions

$\Rightarrow$ **How can we avoid (some of) these problems but still have a good description of the reaction dynamics?**

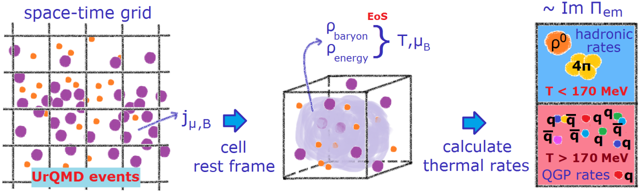
The Idea: Coarse-Graining

- Combining a realistic 3+1 dimensional expansion of the system with full in-medium spectral functions for the emission of dileptons
- **Idea: Microscopic description → Average over a many single events**
- Sufficiently large number of events → Distribution function $f(\vec{x}, \vec{p}, t)$ takes a smooth form

$$f(\vec{x}, \vec{p}, t) = \left\langle \sum_h \delta^3(\vec{x} - \vec{x}_h(t))\delta^3(\vec{p} - \vec{p}_h(t)) \right\rangle$$

- UrQMD model constitutes a non-equilibrium approach → the equilibrium quantities have to be extracted locally at each space-time point

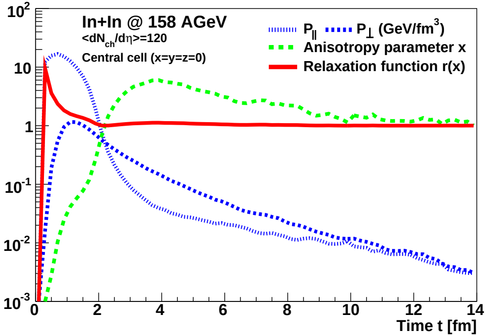
Coarse Graining



- Take an ensemble of UrQMD events and span a **grid of small space time cells**.
- For those cells we determine baryon and energy density and use Eckart's definition to determine the **rest frame** properties $\rightarrow$ use equation of state to calculate T and μ_B
- Two EoS: **Free hadron gas** with UrQMD-like degrees of freedom + **Lattice EoS** for $T > 170$ MeV

  [D. Zschiesche et al., Phys. Lett. B547, 7 (2002); M. He et al., Phys. Rev. C 85 (2012)]
- Extract μ_π via simple Boltzmann approximation

Anisotropy



- Large pressure anisotropy in the early stages of the reaction
- Description developed for anisotropic hydrodynamics

  [W. Florkowski and R. Ryblewski, Phys.Rev. C83 (2011)]

- Energy-momentum tensor takes the form

$$T^{\mu\nu} = (\varepsilon + P_\perp)\, u^\mu u^\nu - P_\perp\, g^{\mu\nu} - (P_\perp - P_\parallel) v^\mu v^\nu$$

Dilepton Rates

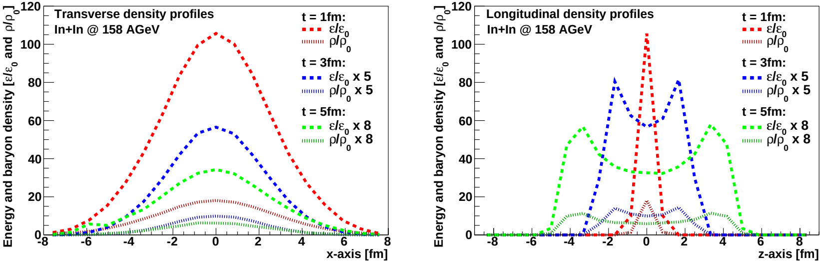
- Lepton pair emission is calculated for each cell of 4-dim. grid, using thermal equilibrium rates per four-volume and four-momentum from a bath at T and μ_B
- The ρ dilepton emission (similar for ω, ϕ) of each cell is accordingly calculated using the expression

[R. Rapp, J. Wambach, Adv. Nucl. Phys. 25, 1 (2000)]

$$\frac{\mathrm{d}^8 \mathrm{N}_{\rho\to \mathrm{ll}}}{\mathrm{d}^4\mathrm{x}\mathrm{d}^4\mathrm{q}} = -\frac{\alpha^2 \mathrm{m}_\rho^4}{\pi^3 \mathrm{g}_\rho^2}\frac{\mathrm{L}(\mathrm{M}^2)}{\mathrm{M}^2}\mathrm{z}_\pi^2 \mathrm{f}_\mathrm{B}(\mathrm{q}_0;\mathrm{T})\mathrm{Im}\mathrm{D}_\rho(\mathrm{M},\mathrm{q};\mathrm{T},\mu_\mathrm{B})$$

- Multi-pion lepton pair production and QGP emission are also included in the calculations
- For cells with $\mathrm{T} < 50$ MeV (mainly late stage) $\rightarrow$ Directly take the ρ contribution from transport

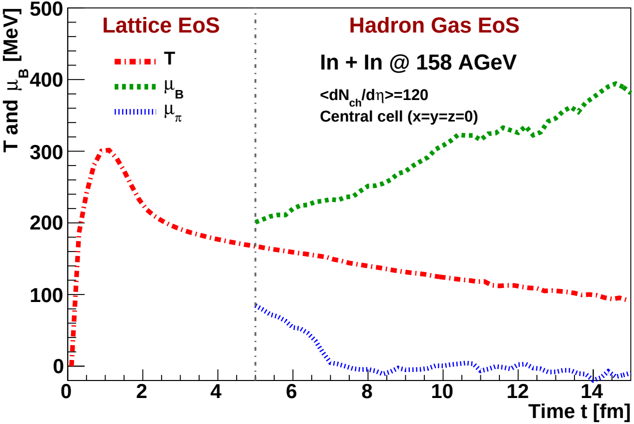
UrQMD Energy and Baryon Density as Input...



- The UrQMD input we use gives a **more realistic and nuanced picture** of the collision evolution than e.g. the fireball approach

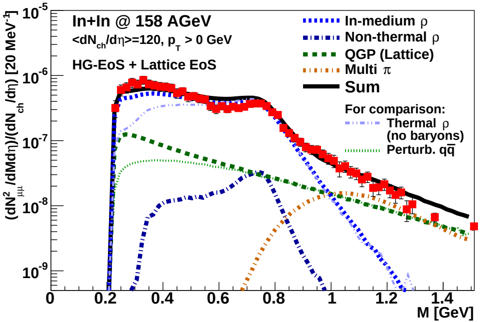
$\rightarrow$ Energy and baryon density are by no means homogeneous in the whole fireball!

Temperature and Chemical Potential from Coarse Graining



- Note: Maximum values (central cell), not average → Different T and μ obtained for each space-time cell

NA60 Excess Invariant Mass Spectra

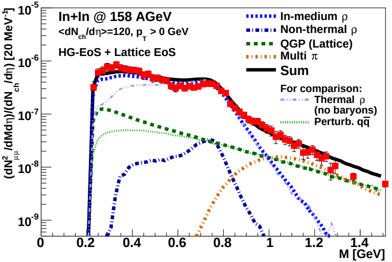


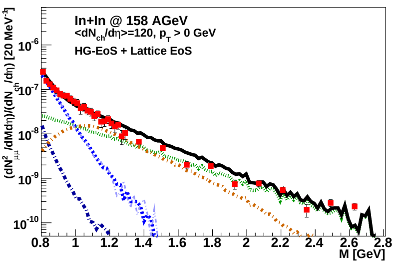
- In-medium ρ shows broadening compared to case without baryons
- 4π and QGP contribution dominate especially above 1 GeV
- Significant part of the excess at low masses also stems from the QGP

$\Rightarrow$ Good overall agreement between coarse-graining result and NA60 data

$\Rightarrow$ Results similar to fireball approach in spite of different dynamics

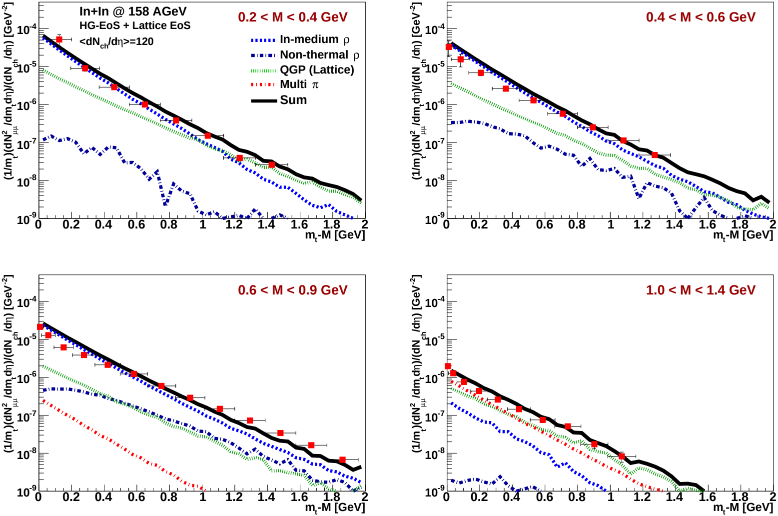
Intermediate Mass Region (M > 1 GeV)



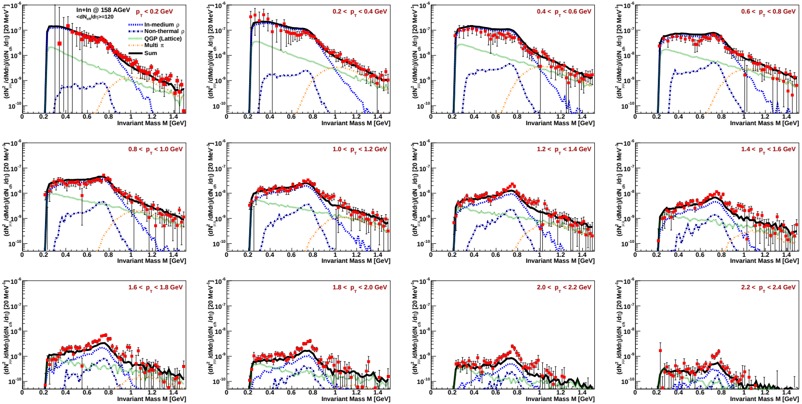


- QGP and multi-pion annihilation are the relevant sources in the intermediate mass region
- For M > 1.5 Gev QGP contribution clearly dominates
- Duality between hadronic and partonic emission rates?

m_t Spectra

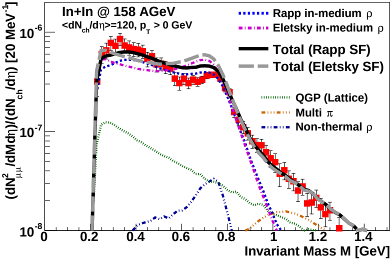

In+In @ 158 AGeV
HG-EoS + Lattice EoS
<dN_ch/dη>=120
0.2 < M < 0.4 GeV
0.4 < M < 0.6 GeV
0.6 < M < 0.9 GeV
1.0 < M < 1.4 GeV
In-medium ρ
Non-thermal ρ
QGP (Lattice)
Multi π
Sum
(1/m_t)(dN²_μμ/dm_t dη)/(dN_ch/dη) [GeV⁻²]
m_t-M [GeV]

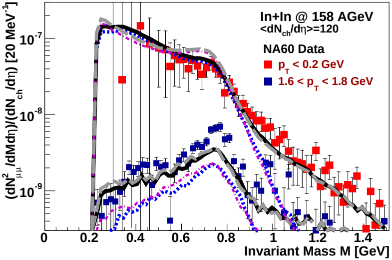
Spectra in p_t Slices



- Strongest broadening at low p_t
- Note the momentum dependence of and thermal and non-thermal ρ contribution

Comparison of Spectral Functions

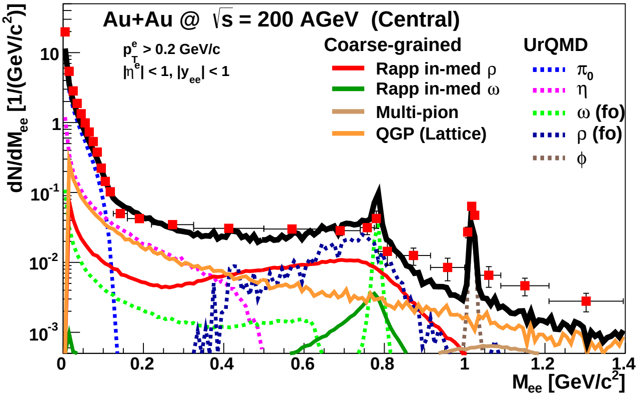




- In-medium self energies of the ρ were calculated using empirical scattering amplitudes from **resonance dominance**

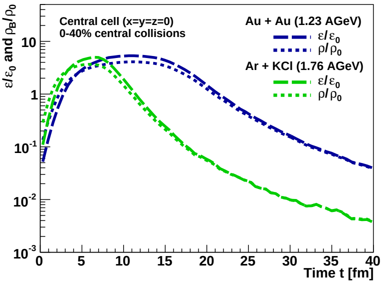
  [V. L. Eletsky et al., Phys. Rev. C64, 035303 (2001)]
- Not enough broadening due to low-density expansion of the self energies $\rightarrow$ Overshoots data at peak
- Note: Different quantities spectral function (μ_B vs. ρ_{eff})

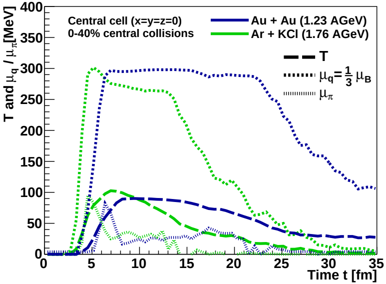
Comparison to STAR results



- QGP dominates thermal emission at low and high masses
- Also significant non-thermal ρ
- Missing contribution from charm at higher masses

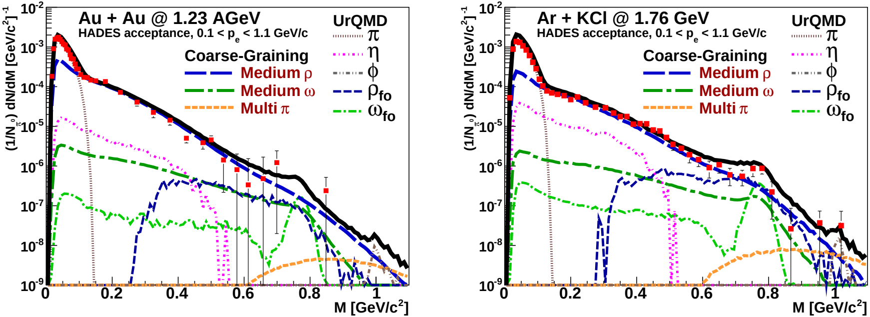
Reaction Dynamics SIS Energies





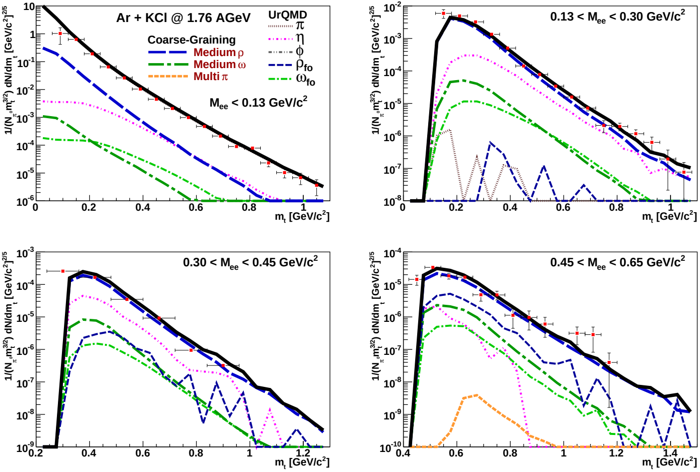
- Huge lifetimes of the hot and dense fireball (for Au+Au more than 20 fm/c!)
- Moderate temperatures and very **high baryon density** respectively baryochemical potential $\rightarrow$ Ideal situation to study in-medium modifications

HADES Results



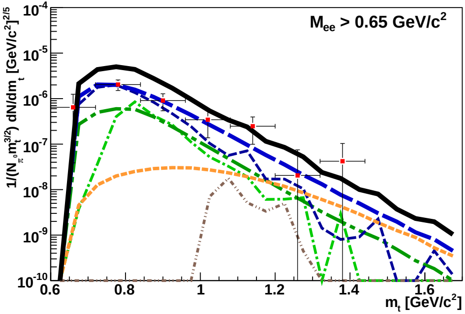
- At those low collision energies a **significant in-medium broadening** of the ρ spectral function appears
- High baryon chemical potential $\rightarrow$ Good check for baryonic effects in spectral functions
- Note the strong broadening of the ω as well!

Ar+KCl @ 1.76 AGeV - m_t-Spectra



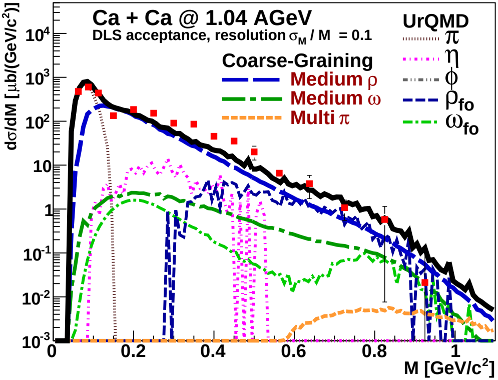
- Good agreement here with data up to $M_{ee} = 0.65\ \text{GeV}/c^2$
- Note: Model completely the same as for NA60 and STAR

Ar+KCl @ 1.76 AGeV - m_t-Spectra



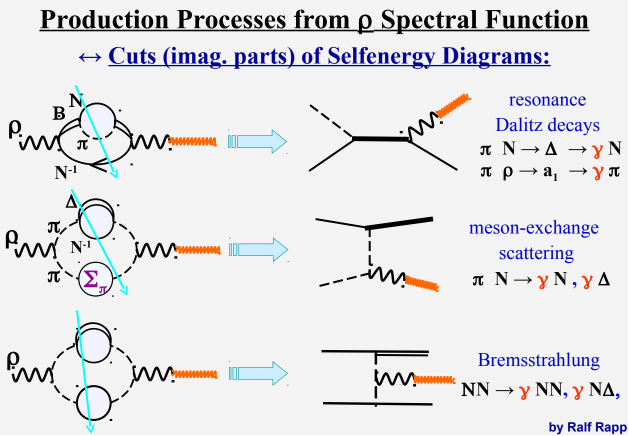
- Overshoot data at low m_t around the ρ pole mass for $M > 0.65$ GeV/c^2
- Probably due to "freeze-out" ρ from UrQMD $\rightarrow$ Known fact that implemented cross-sections are too high at threshold
- *However*: Coarse-graining works also for SIS 18 energies $\rightarrow$ Same physical description as for NA60

What about the old DLS data...?



- Experimental excess in mass range 0.2 to 0.6 GeV/c^2
- Possible reasons: Bremsstrahlung (low energy!), limits of thermal description, quality of filter and data, . . .

Connection to microscopic / transport description?



- Spectral function includes contributions (Bremsstrahlung, Δ Dalitz decays) that are usually explicitly treated in transport models → To which extend comparable?

Outlook

- Explanation of dilepton measurements is still a challenge for theory $\Rightarrow$ Need for more experimental input!
- High precision data necessary to constrain model calculations which still have large uncertainties
  - $\rightarrow$ Study of pion-induced reactions (at SIS / HADES) will be essential for better determination of baryonic resonance properties
- CBM will enable to explore physics in an up-to-now uninvestigated energy range
  - Very high baryonic densities $\rightarrow$ Better constraints for spectral functions?
  - Not only low-mass regime but also $M > 1$ GeV might be worth being intensively studied $\rightarrow$ deconfinement / phase-transition?
- Improve Coarse-Graining approach $\rightarrow$ Hydro + coarse-grained transport (for better consistency when using QGP rates)