Theoretical approaches to dilepton production: What can we learn about in-medium effects from model calculations?

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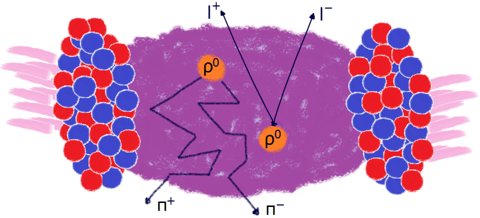
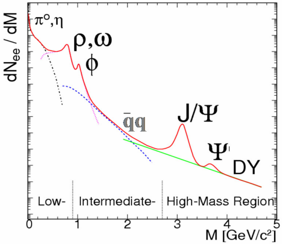
H-QM Helmholtz Research School Quark Matter Studies

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**



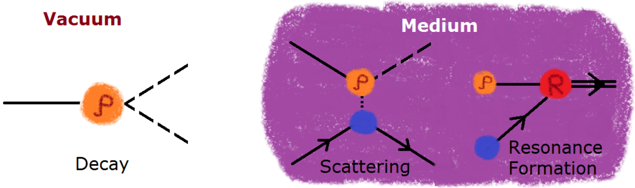


Medium-modifications of hadrons - why are they interesting?

- 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?
  - ⇒ **Vacuum**: Probe can only decay, Lorentz invariance
  - ⇒ **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 → Resonance-hole excitation
- Challenge is to determine the **self-energy** Π of a particle undergoing all those medium effects

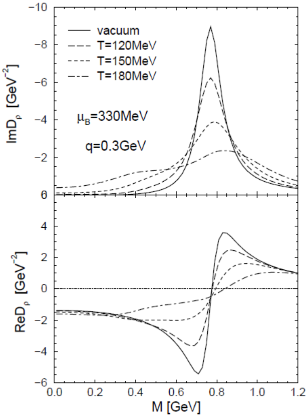
Hadronic Many-Body Theory

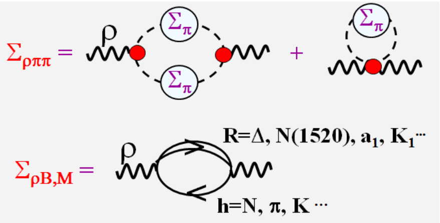
- Medium modifications of the ρ propegator

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

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

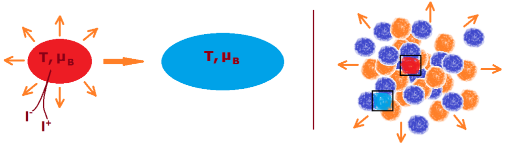
[R. Rapp, J. Wambach, Eur.Phys.J. A6, 415-420 (1999)]





Theoretical approaches

- General assumption when calculating spectral functions: **Equilibrated stage** (heat bath with fixed $T, \mu_B, \ldots$)
  $\rightarrow$ *But*: 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

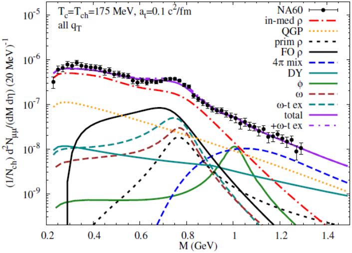
  [H. van Hees, R. Rapp, Nucl. Phys. A806, 339 (2008)]

- 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?

⇒ **Calculations with better constrained dynamics?**



Transport Models - GiBUU and UrQMD

- 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. $\pi\pi \rightarrow \rho$)
  - **Higher resonance decays** (e.g. $\mathrm{N}^* \rightarrow N + \rho$)
- String excitation possible above $\sqrt{s} \approx$ 3 GeV
- Resonances either decay after a certain time or are absorbed in another collision (e.g. $\rho + N \rightarrow N^*_{1520}$)

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

The Input Problem

GiBUU Resonances

		M_0	Γ_0	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2]		branching ratio in %						
	rating	[MeV]	[MeV]	NR	ΔR	πN	ηN	$\pi\Delta$	ρN	σN	$\pi N^*(1440)$	$\sigma\Delta$
$P_{11}(1440)$	****	1462	391	70	—	69	—	22_P	—	9	—	—
$S_{11}(1535)$	***	1534	151	8	60	51	43	—	$2_S + 1_D$	1	2	—
$S_{11}(1650)$	****	1659	173	4	12	89	3	2_D	3_D	2	1	—
$D_{13}(1520)$	****	1524	124	4	12	59	—	$5_S + 15_D$	21_S	—	—	—
$D_{15}(1675)$	****	1676	159	17	—	47	—	53_D	—	—	—	—
$P_{13}(1720)$	*	1717	383	4	12	13	—	—	87_P	—	—	—
$F_{15}(1680)$	****	1684	139	4	12	70	—	$10_P + 1_F$	$5_P + 2_F$	12	—	—
$P_{33}(1232)$	****	1232	118	OBE	210	100	—	—	—	—	—	—
$S_{31}(1620)$	**	1672	154	7	21	9	—	62_D	$25_S + 4_D$	—	—	—
$D_{33}(1700)$	*	1762	599	7	21	14	—	$74_S + 4_D$	8_S	—	—	—
$P_{31}(1910)$	****	1882	239	14	—	23	—	—	—	—	67	10_P
$P_{33}(1600)$	***	1706	430	14	—	12	—	68_P	—	—	20	—
$F_{35}(1905)$	***	1881	327	7	21	12	—	1_P	87_P	—	—	—
$F_{37}(1950)$	****	1945	300	14	—	38	—	18_F	—	—	—	44_F

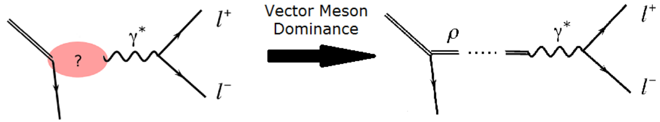
- Which **resonances** do I have to include?
- Which resonance is produced with which probability?
- What is the actual **branching ratio** (e.g. to the ρ)?

→ Poor experimental input

→ Many parameters one can "play" with, as they are not fixed...

Dilepton Sources

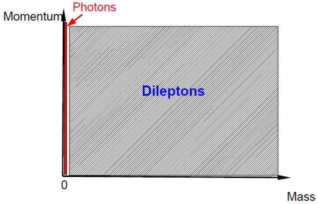
- **Coupling to photon?**
  - Straightforward for direct decays (ρ, ω, ϕ)
  - What about the Dalitz decays? $(\pi^0, \eta, \eta', \omega)$
    $\mathrm{P} \to \gamma + e^+e^-$
    $\mathrm{V} \to \mathrm{P} + e^+e^-$
    $\Rightarrow$ Form factors necessary!
- Assumption: **Vector Meson Dominance** $\to$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



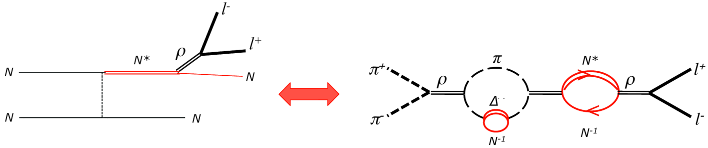
- Form factors for the Dalitz decays can be obtained from the **vector-meson dominance** model
- Baryon Resonances: $B^* \to B + \rho \to B + e^+e^-$, but Δ_{1232} traditionally treated explicitly

$\Delta \to N + e^+ e^-$

- Photon couplings ($R \to \gamma N$) known from photoprduction experiments ($\gamma N \to X$)
- But: Only determined for photon point $\to$ What for time-like region?

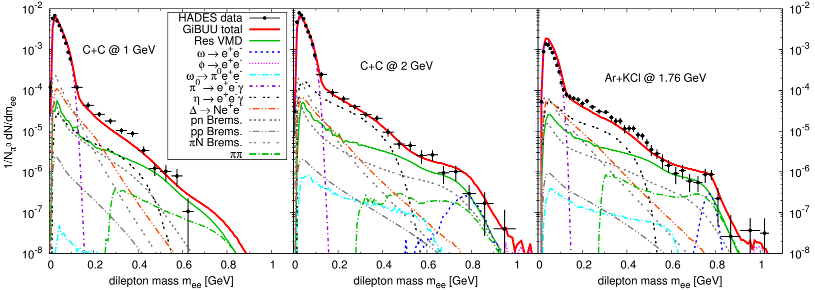


- Need models for the form-factor, but basically no constraints
- Assumption (J. Weil): Use VMD also for Δ_{1232} decay and implement it as a two step process into the transport model
- Note: Same physics that goes into calculation of spectral functions



Transport Results

- The transport calculations can describe dilepton production in heavy-ion collisions at low energies with good accuracy (here GiBUU results by Janus Weil)



- However, the SIS energy regime remains an interesting field with many open questions regarding elementary and heavy-ion collisions (bremsstrahlung, *pd* reactions, ...)

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?**

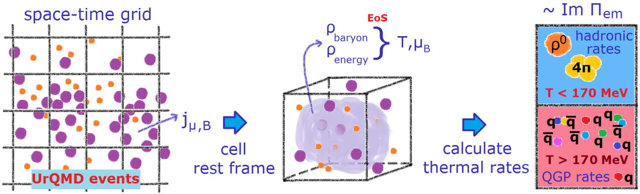
The Idea: Coarse-Graining

- 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

Dilepton Rates

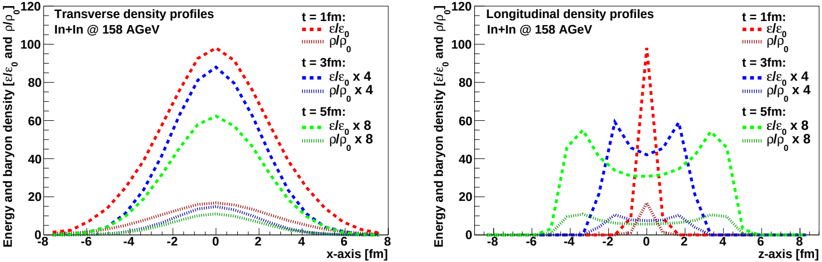
- Lepton pair emission is calculated for each cell of 4-dim. grid, using thermal equilibrium rates per four-volume and four-momentum from a bath at T and μ_B
- The ρ dilepton emission (similar for ω, ϕ) of each cell is accordingly calculated using the expression

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

$$\frac{d^8 N_{\rho \rightarrow ll}}{d^4x d^4q} = -\frac{\alpha^2 m_\rho^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} z_\pi^2 f_B(q_0; T) \mathrm{Im} D_\rho(M, q; T, \mu_B)$$

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

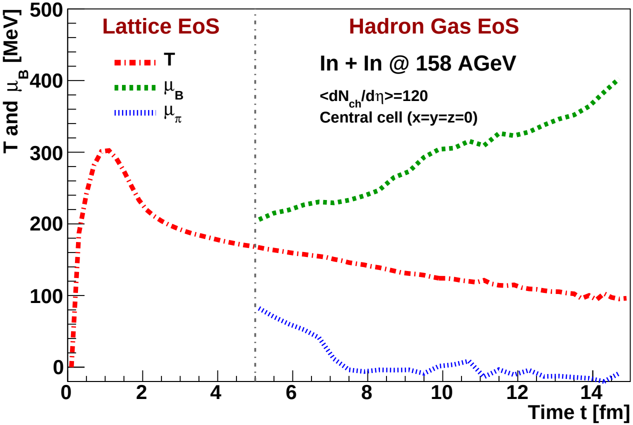
UrQMD Energy and Baryon Density as Input...



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

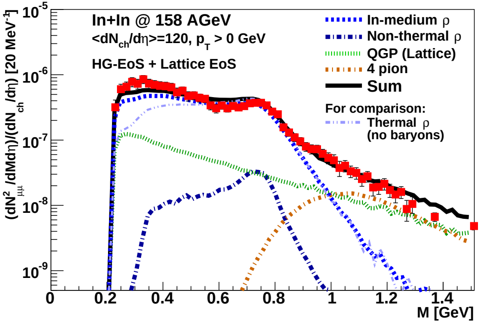
$\rightarrow$ Energy and baryon density are by no means homogeneous in the whole fireball!

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

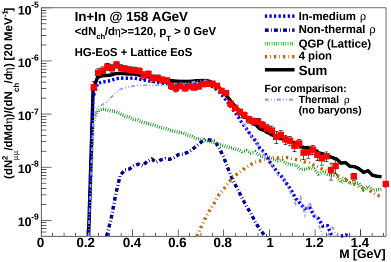


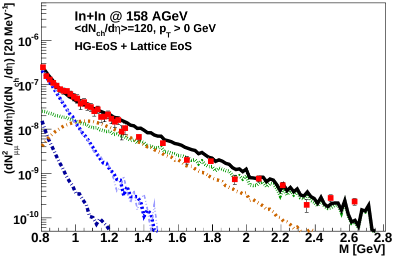
- In-medium ρ shows broadening compared to case without baryons
- 4π and QGP contribution dominate especially above 1 GeV
- Significant part of the excess at low masses also stems from the QGP

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

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

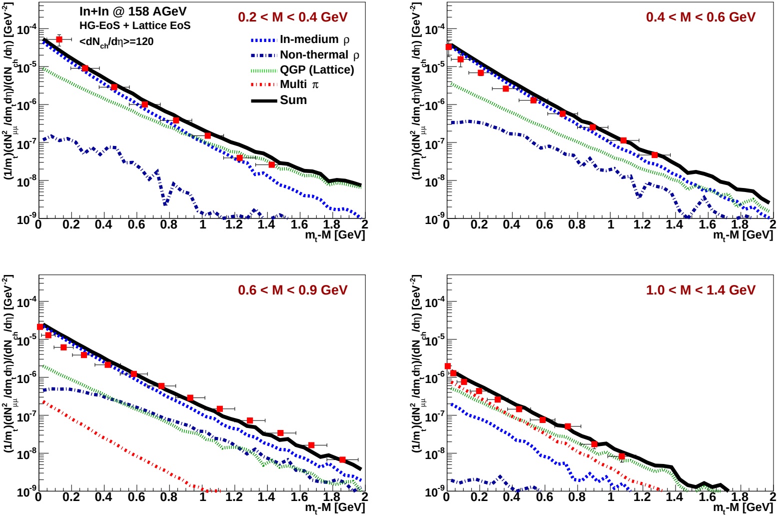
Intermediate Mass Region (M > 1 GeV)



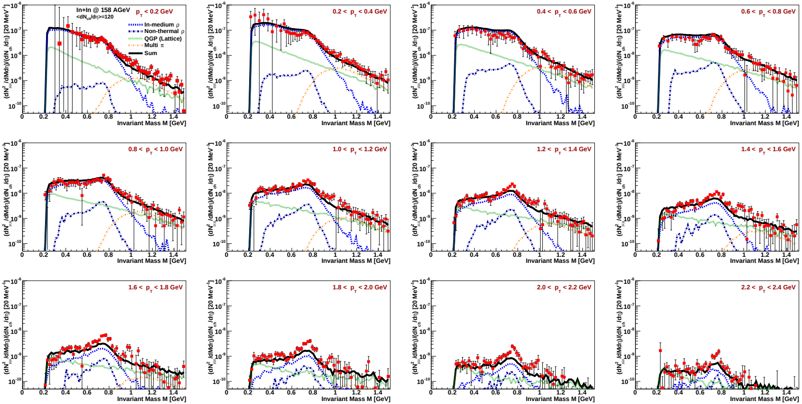


- QGP and multi-pion annihilation are the relevant sources in the intermediate mass region
- For M > 1.5 Gev QGP contribution clearly dominates
- Duality between hadronic and partonic emission rates?

m_t Spectra

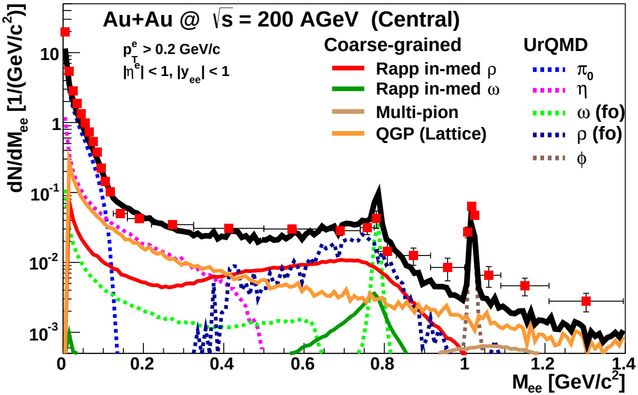

In+In @ 158 AGeV
HG-EoS + Lattice EoS
<dN_ch/dη>=120
0.2 < M < 0.4 GeV
0.4 < M < 0.6 GeV
0.6 < M < 0.9 GeV
1.0 < M < 1.4 GeV
In-medium ρ
Non-thermal ρ
QGP (Lattice)
Multi π
Sum
(1/m_t)(dN²_μμ/dm_t dη)/(dN_ch/dη) [GeV⁻²]
m_t-M [GeV]

Spectra in p_t Slices



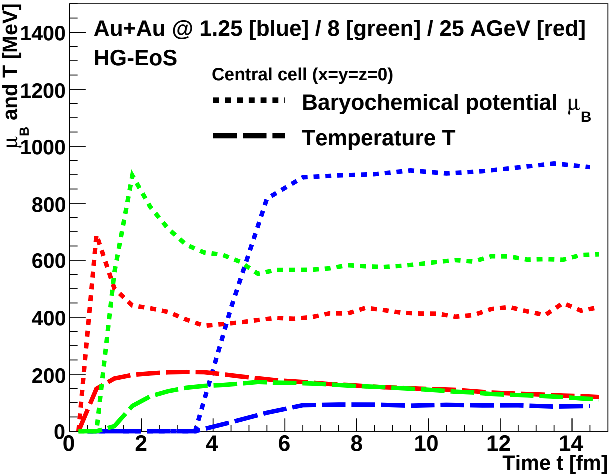
- Strongest broadening at low p_t
- Note the momentum dependence of and thermal and non-thermal ρ contribution

Comparison to STAR results

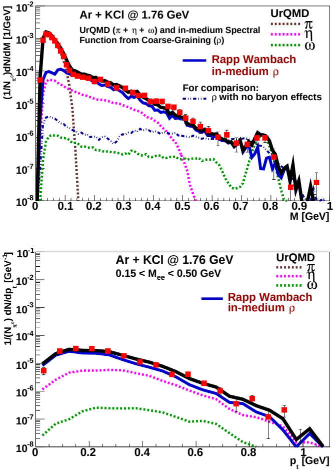


- QGP dominates thermal emission at low and high masses
- Also significant non-thermal ρ
- Missing contribution from charm at higher masses

HADES and CBM

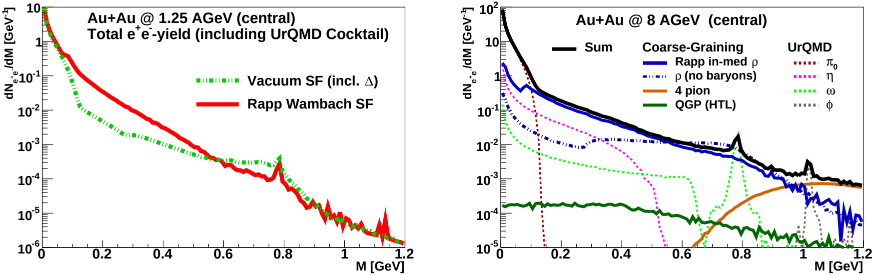


Ar+KCl @ 1.76 AGeV



- Coarse-graining works also for SIS 18 energies
  $\rightarrow$ Hydro or fireball descriptions not reasonably applicable

Au+Au @ 1.25 and 8 AGeV



- 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
- At CBM we scratch temperatures around T_C $\rightarrow$ Can we learn something about the deconfinement?

Outlook

- Explanation of dilepton measurements is still a challenge for theory ⇒ Need for more e experimental input!
- High precision data necessary to constrain model calculations which still have large uncertainties
  - → 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 → Better constraints for spectral functions?
  - Not only low-mass regime but also $M > 1$ GeV might be worth being intensively studied → deconfinement / phase-transition?
- Improve Coarse-Graining approach → Hydro + coarse-grained transport (for better consistency when using QGP rates)