In-medium spectral functions and dilepton production at HADES / CBM within a coarse-graining approach

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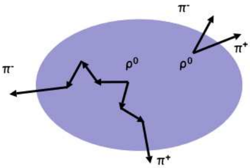
H-QM | Helmholtz Research School Quark Matter Studies

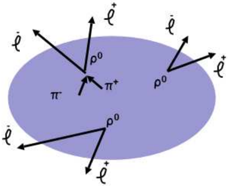
HGS-HIRe for FAIR

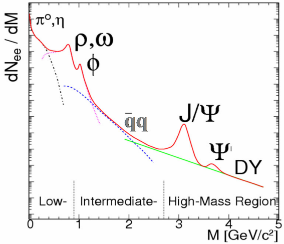
Overview

Why Dileptons (at CBM)...?

- 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**







Ultra-relativistic Quantum Molecular Dynamics

- Hadronic non-equilibrium transport approach
- Includes all baryons and mesons with masses up to 2.2 GeV
- Two processes for resonance production in UrQMD (at low energies)
  - **Collisions** (e.g. $\pi\pi \to \rho$)
  - **Higher resonance decays** (e.g. $\mathrm{N}^* \to N + \rho$)
- Resonances either decay after a certain time or are absorbed in another collision (e.g. $\rho + N \to N^*_{1520}$)
- String excitation possible above $\sqrt{s} =$ 3.2 GeV

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 Resonance "Mess"

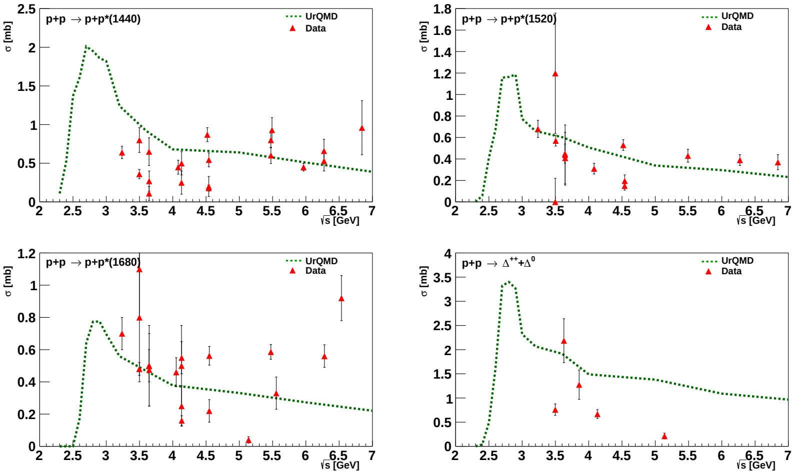
Resonance	Mass	Width	$N\pi$	$N\eta$	$N\omega$	$N\varrho$	$N\pi\pi$	$\Delta_{1232}\pi$	$N^*_{1440}\pi$	ΛK	ΣK	$f_0 N$	$a_0 N$
N^*_{1440}	1.440	350	0.65				0.10	0.25					
N^*_{1520}	1.515	120	0.60			0.15	0.05	0.20					
N^*_{1535}	1.550	140	0.60	0.30			0.05		0.05				
N^*_{1650}	1.645	160	0.60	0.06		0.06	0.04	0.10	0.05	0.07	0.02		
N^*_{1675}	1.675	140	0.40					0.55	0.05				
N^*_{1680}	1.680	140	0.60			0.10	0.10	0.15	0.05				
N^*_{1700}	1.730	150	0.05			0.20	0.30	0.40	0.05				
N^*_{1710}	1.710	500	0.16	0.15		0.05	0.21	0.20	0.10	0.10	0.03		
N^*_{1720}	1.720	550	0.10			0.73	0.05			0.10	0.02		
N^*_{1900}	1.850	350	0.30	0.14	0.39	0.15				0.02			
N^*_{1990}	1.950	500	0.12			0.43	0.19	0.14	0.05	0.03		0.04	
N^*_{2080}	2.000	550	0.42	0.04	0.15	0.12	0.05	0.10		0.12			
N^*_{2190}	2.150	470	0.29			0.24	0.10	0.15	0.05	0.12			
N^*_{2220}	2.220	550	0.29		0.05	0.22	0.17	0.20		0.12			
N^*_{2250}	2.250	470	0.18			0.25	0.20	0.20	0.05	0.12			
Δ_{1232}	1.232	115	1.00										
Δ^*_{1600}	1.700	350	0.10					0.65	0.25				
Δ^*_{1620}	1.675	160	0.15			0.05		0.65	0.15				
Δ^*_{1700}	1.750	350	0.20			0.25		0.55					
Δ^*_{1900}	1.840	260	0.25			0.25		0.25	0.25				
Δ^*_{1905}	1.880	350	0.18			0.80		0.02					
Δ^*_{1910}	1.900	250	0.30			0.10		0.35	0.25				
Δ^*_{1920}	1.920	200	0.27					0.40	0.30	0.03			
Δ^*_{1930}	1.970	350	0.15			0.22		0.20	0.28	0.15			
Δ^*_{1950}	1.990	350	0.38			0.08		0.20	0.18	0.12			0.04

- 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)?

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

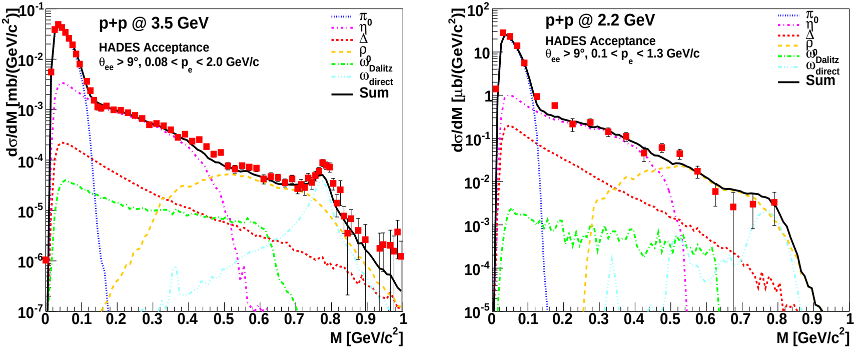
Example: Exclusive Resonance Cross-Sections

- SIS energies perfect to study baryon resonance effects



Transport Results

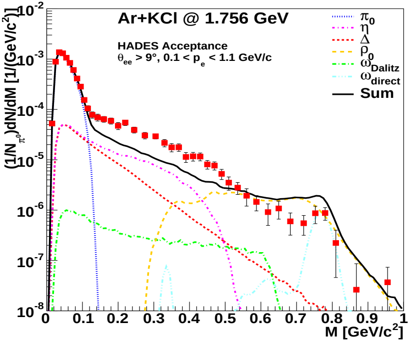
- There has been a lot of **improvement**, especially concerning the exact comparison and adjustment of the many parameters, cross-sections, branching ratios (→ GiBUU results by Janus)

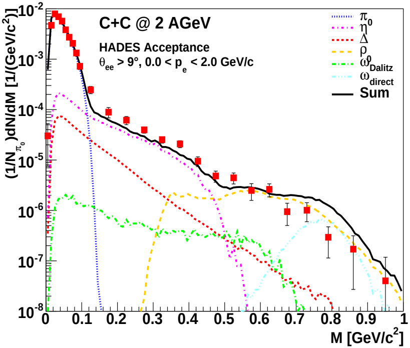


- However, this is difficult and one has to be careful...

Transport Results

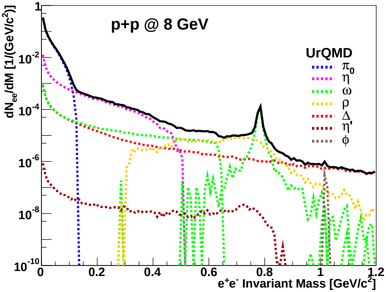
- We see an excess in heavy-ion collisions (e.g. Ar+KCl @ 1.76 AGeV) not yet described by the model
- Is NN and πN bremsstrahlung p+n interactions relevant? (How to avoid double counting?)
- Do we see in-medium effects?

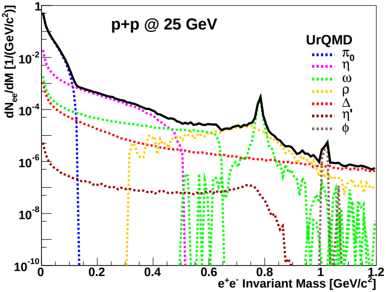




Transport Results for Elementary Reactions at CBM

- At CBM energies, the resonance model is complemented by string excitation
- ϕ produciton probably underestimated (known issue, due to production via strings)
- Δ Dalitz parametrization gives unphysically huge contribution at high masses $\rightarrow$ Mass distribution of Deltas crucial, high mass resonances dominate e^+e^- emission





Challenges

- Cross-sections not implemented explicitly but intermediate baryonic resonances are used
- Some cross-sections are even unmeasured or unmeasurable (especially for ρ and Δ lack of data)
- Consistency of description when going from resonances to strings?
- "Δ crisis" $\rightarrow$ How to describe e^+e^- emission? Dalitz decay? VMD via ρ? What about the form factor? Which / how to dertermine?
- General difficulties of the transport approach at high density:
  - Off-shell effects
  - Multi-particle collisions

$\Rightarrow$ **How can we avoid these problems?**

Coarse Graining

- We 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 EoS to calculate T and μ_B
- For the Rapp Spectral function, we also extract pion and kaon chemical potential via simple Boltzmann approximation
- An equation of state for a **free hadron gas** without any phase transition is used [D. Zschiesche et al., Phys. Lett. B547, 7 (2002)]
- To account for **QGP emission**, we make the simplifying assumption that cells with T above 175 MeV contribute only to the Quark-Gluon emission

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)]

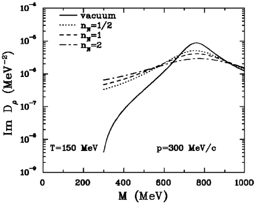
$$\frac{\mathrm{d}^8 N_{\rho \to ll}}{\mathrm{d}^4 x \mathrm{d}^4 q} = -\frac{\alpha^2 m_\rho^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} f_B(q_0; T) \mathrm{Im} D_\rho(M, q; T, \mu_B)$$

- The 4π lepton pair production can be determined from the electromagnetic spectral function extracted in e^+e^- annihilation [Z. Huang, Phys. Lett. B361, 131 (1995)]

$$\frac{\mathrm{d}^8 N_{4\pi \to ll}}{\mathrm{d}^4 x \mathrm{d}^4 q} = \frac{4\alpha^2}{(2\pi)^2} e^{-q_0/T} \frac{M^2}{16\pi^3 \alpha^2} \sigma(e^+e^- \to 4\pi)$$

- QGP contribution is evaluated as $q\bar{q}$ annihilation with HTL improvement [J. Cleymans et al., Phys. Rev. D35, 2153 (1987)]

Eletsky Spectral Function



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

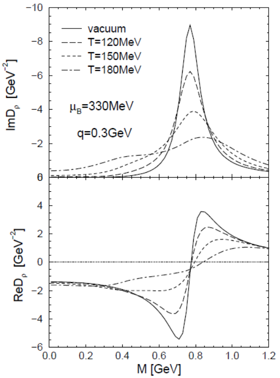
$$\Sigma_\rho = \Sigma^0 + \Sigma^{\rho\pi} + \Sigma^{\rho N}$$

  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!

Rapp Spectral Function



- Includes finite temperature propagators of ω, ρ and ϕ meson

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

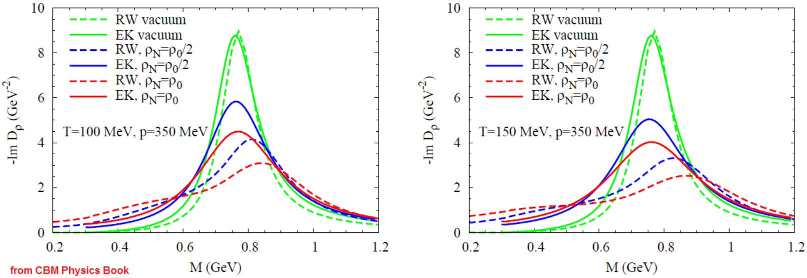
- Medium modifications of the ρ propegator

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

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

- Pion cloud modification approximated by using effective nucleon density $\rho_{eff} = \rho_N + \rho_{\bar{N}} + 0.5(\rho_{B^* + \bar{B}^*})$

Comparison of Rapp & Eletsky SFs



from CBM Physics Book

- Qualitative agreement between Rapp and Eletsky approach in spite of different ansatz (many-body calculation vs. empirical approach)
- However, significant difference is the **stronger broadening** and **additional low-mass strength** of the Rapp approach

Previous Calculations

- Previous calculations were done with a **fireball model**

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

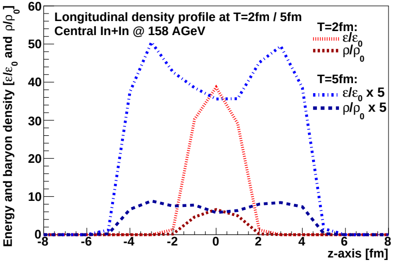
- The zone of hot and dense matter is described by an isentropic expanding cylindrical volume

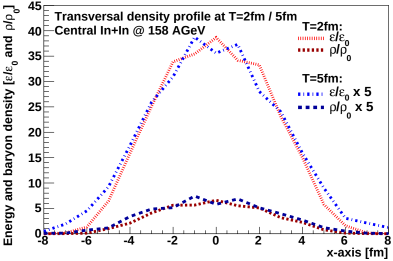
$$V_{\mathrm{FB}}(t) = \pi \left(r_{\perp,0} + \frac{1}{2} a_\perp t^2 \right)^2 \left(z_0 + v_{z,0} t + \frac{1}{2} a_z t^2 \right)$$

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

$\Rightarrow$ **Make calculations with better constrained input...**

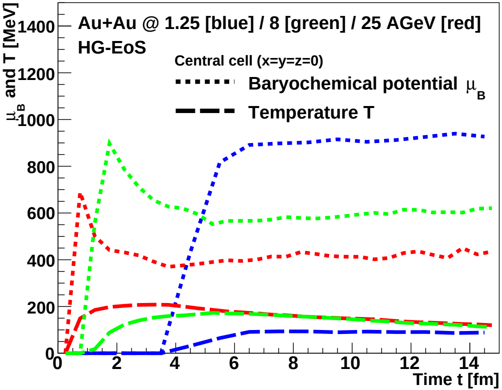
UrQMD Energy and Baryon Density as Input...





- The UrQMD input we use gives a **more realistic and nuanced picture** of the collision evolution (here e.g. for In+In @ 158 AGeV)
- Energy and baryon density are by no means homogeneous in the whole fireball ⇒ Different **expansion dynamics** might lead to significantly differing dilepton spectra

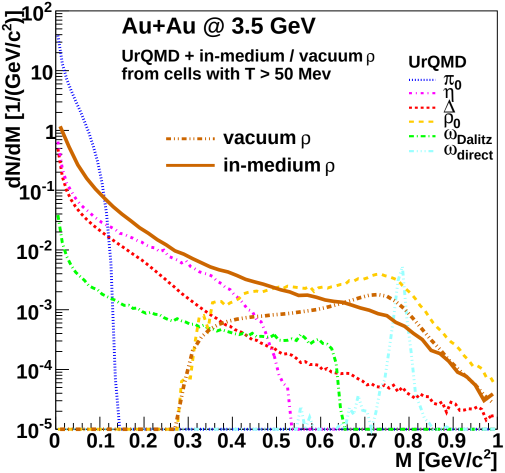
Temperature and Chemical Potential from Coarse Graining



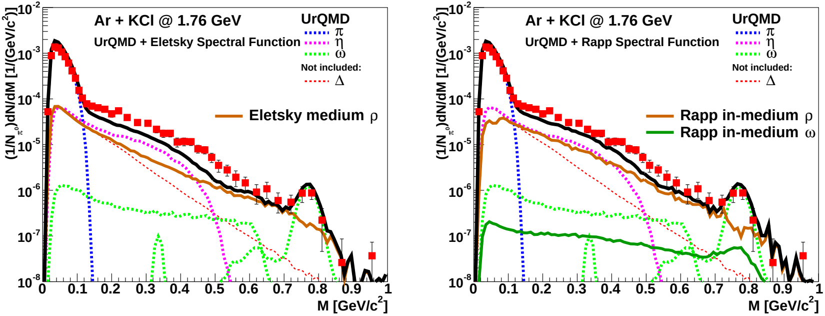
- For a central cell in an Au+Au collision @ 1.25 AGeV we get a high μ_B up to 1000 MeV and a maximum temperature of $\approx$ 100 MeV.
- With increasing beam energy, **temperature rises** and baryon **chemical potential decreases** $\rightarrow$ Less baryon dominated at higher energies

Au+Au @ 3.5 AGeV

- The UrQMD ρ contribution as well as the coarse-graining results for the vacuum and in-medium spectral functions are shown
- In-medium ρ "melts" away at the pole mass while it becomes dominant at lower masses

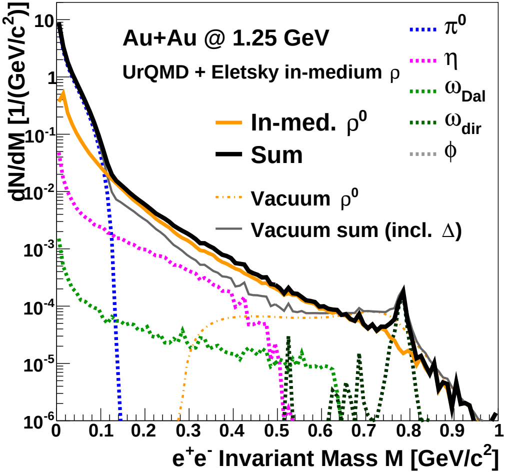


Ar + KCl @ 1.76 AGeV



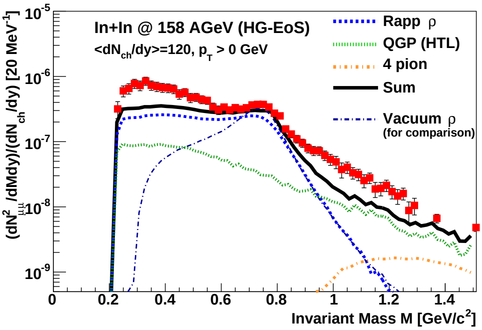
- Comparison of spectral functiosn to HADES data shows that the in-medium ρ is dominated by the Δ_{1232} contribution, as shapes agree at lowest masses
- Still below the data for intermediate mass region, Rapp spectral function gives a little more contribution

Au + Au @ 1.25 AGeV



- Expect an even more significant excess due to baryon driven medium effects compared to Ar+KCl @ 1.76 AGeV
- HADES data hopefully help constraining effects...

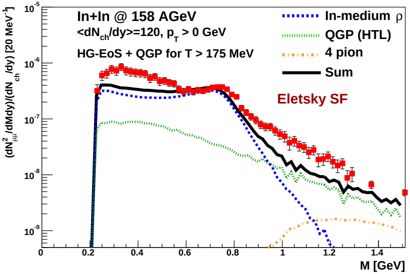
Looking at NA60 - Rapp Spectral Function

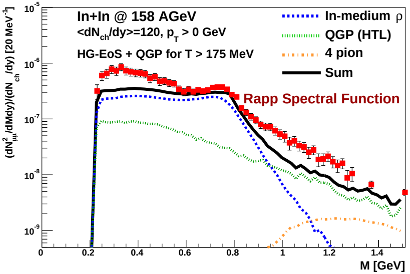


- In-medium ρ contribution to dimuon excess was calculated with the Rapp spectral function for the Hadron Gas EoS
- 4π and QGP contribution dominate especially above 1 GeV, however, a significant part of the excess at low masses also stems from the QGP

$\Rightarrow$ Good overall agreement, but **underestimation of the low-mass tail** of the excess dimuons

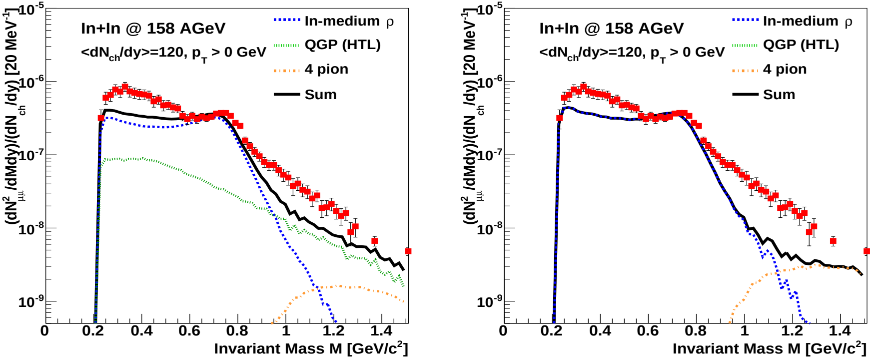
Comparison of Spectral Functions





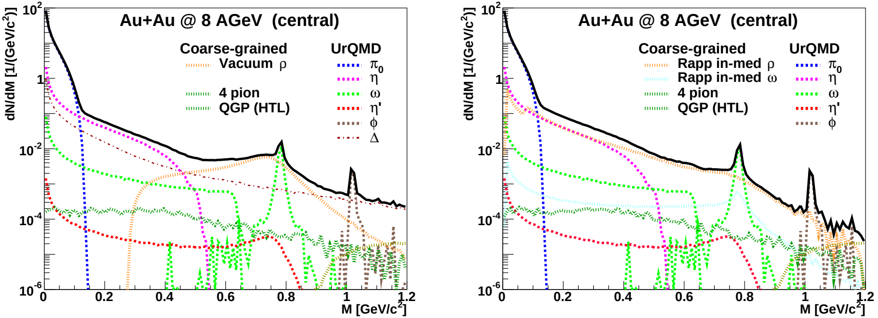
- No big differences between the approaches visible, with none of the spectral functions the yield is completely described
- *Caveat:* The parameters which go into the spectral funtion are different (chemical potential vs. effective baryon density)

Quark Hadron Duality?



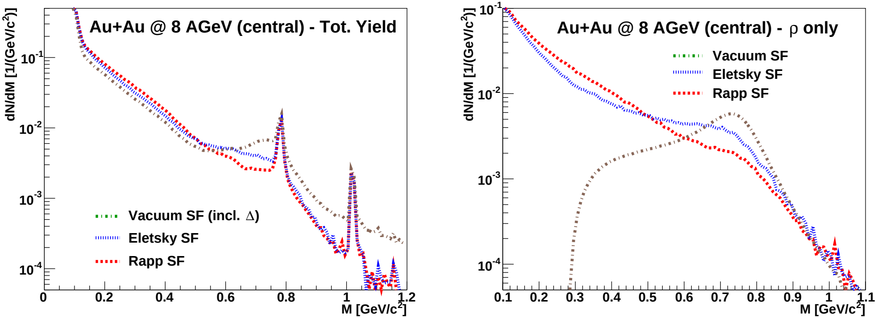
- Compare dilepton yields for **pure Hadron Gas** (left) and **HG with QGP emission** (right) for temperatures above 175 MeV
- Below 1 GeV, the QGP and ρ contributions are completely complementary, at higher masses a QGP contribution is clearly necessary

Au+Au @ 8 AGeV



- Also for Au+Au @ 8 AGeV a **significant in-medium modification** of the ρ spectral fuction appears
- Dilepton yield is enhanced at low masses
- Temperature in hottest cells around 175 MeV, causing already a **small QGP emission**

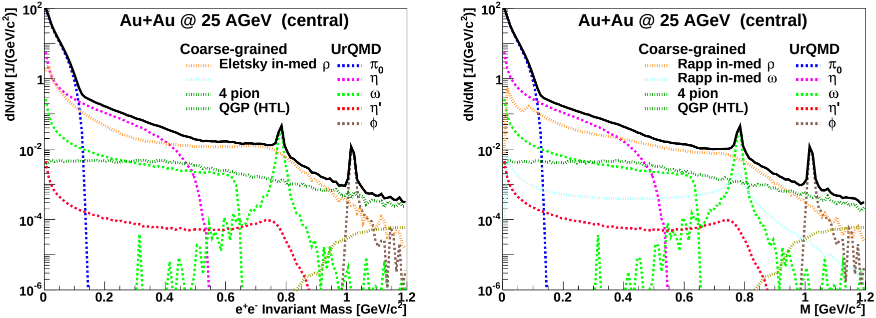
Au+Au @ 8 AGeV - Comparison of Spectral Functions



- Significant difference between the spectal shapes of the different approaches
- However, effects might be less obvious when looking at the total dilepton yield

⇒ **High-precision measurement** will be crucial to learn about the spectral functions!

Au+Au @ 25 AGeV



- At 25 AGeV the invariant mass spectrum does not differ qualtitatively from the 8 AGeV result
- However, at large masses we get now a significant contribution from QGP emission
- It might be very interesting at CBM to look especially at the region for M $>$ 1 GeV (detailed study necessary)

Outlook

- Role of **equation of state** on dielepton spectra?
- Continue work on dilepton calculations with **hybrid model** (transport + hydro)
- Using **different input** from transport (e.g. from GiBUU)

Summary

- New approach to combine realistic transport caluclations with in-medium modified spectral functions for vector mesons
- Non-equilibrium treatment highly non-trivial $\Rightarrow$ Use **equilibrium** rates for a **coarse-grained transport dynamics**
- Explanation of dilepton measurements is still a challenge for theory $\Rightarrow$ Need for **more experimental input**!
- CBM will be possible to explore physics in an up-to-now mostly **uninvestigated energy range** $\rightarrow$ Test and constrain models
- Not only low-mass regime but also $\mathbf{M > 1}$ **GeV** might be worth being intensively studied
- High **precision data necessary** to constrain model calculations, that still have large uncertainties
- **Further work in progress...!**