A Theoretical View on Dilepton Production

Transport Calculations vs. Coarse-grained Dynamics

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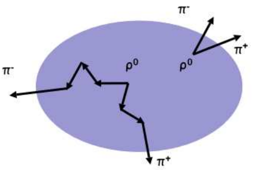
H-QM Helmholtz Research School Quark Matter Studies

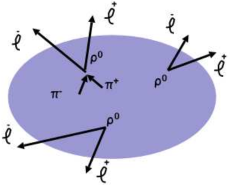
HGS-HIRe for FAIR

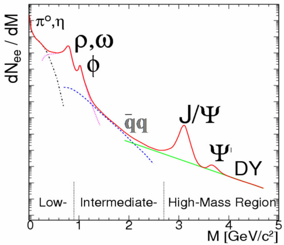
Overview

Why Dileptons...?

- Dileptons represent a clean and penetrating probe of hot and dense nuclear matter
- Reflect the whole dynamics of a collision
- Once produced they do not interact with the surrounding matter (no strong interactions)
- Aim of studies
  - In-medium modification of vector meson properties
  - Chiral symmetry restoration

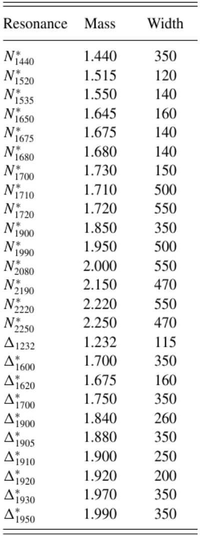






Ultra-relativistic Quantum Molecular Dynamics

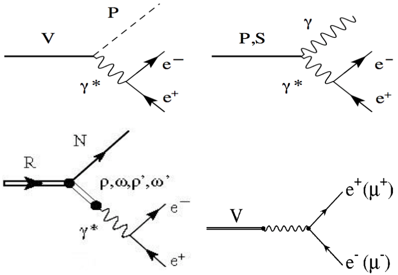
- Hadronic non-equilibrium transport approach
- Includes all baryons and mesons with masses up to 2.2 GeV
- Two processes for resonance production in UrQMD (at low energies)
  - **Collisions** (e.g. $\pi\pi \rightarrow \rho$)
  - **Higher resonance decays** (e.g. $\mathrm{N}^* \rightarrow N + \rho$)
- Resonances either decay after a certain time or are absorbed in another collision (e.g. $\rho + N \rightarrow N^*_{1520}$)
- **No explicit in-medium modifications!**



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

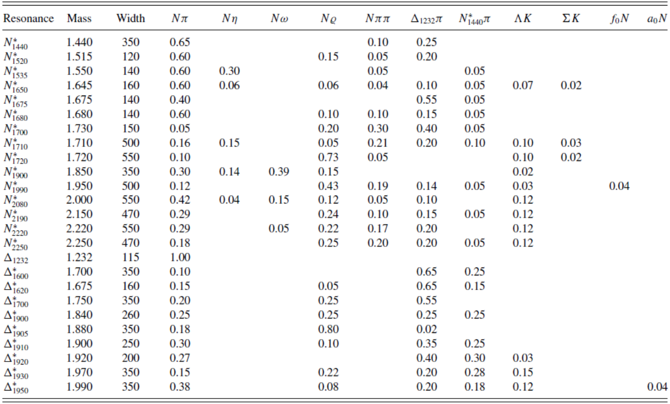
Dilepton sources in UrQMD

- **Dalitz Decays**
  $\Rightarrow \pi^0, \eta, \eta', \omega, \Delta$
  $\mathrm{P} \rightarrow \gamma + e^+e^-$
  $\mathrm{V} \rightarrow \mathrm{P} + e^+e^-$
- **Direct Decays**
  $\Rightarrow \rho^0, \omega, \phi$



- Dalitz decays are decomposed into the corresponding decays into a virtual photon and the subsequent decay of the photon via electromagnetic conversion
- Form factors for the Dalitz decays are obtained from the **vector-meson dominance** model
- Assumption: Resonance can continuously emit dileptons over its whole lifetime (Time Integration Method / "Shining")

The Resonance "Mess"

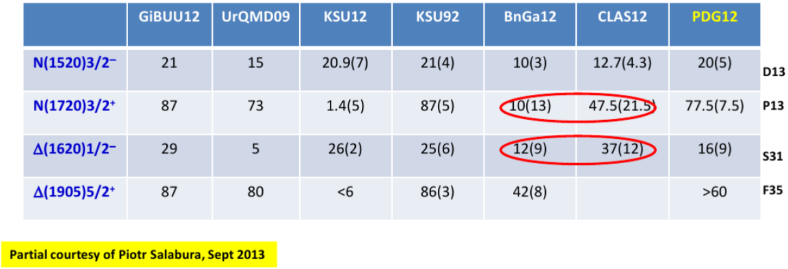


Resonance	Mass	Width	$N\pi$	$N\eta$	$N\omega$	$N\varrho$	$N\pi\pi$	$\Delta_{1232}\pi$	$N^*_{1440}\pi$	ΛK	ΣK	$f_0 N$	$a_0 N$
N^*_{1440}	1.440	350	0.65				0.10	0.25					
N^*_{1520}	1.515	120	0.60			0.15	0.05	0.20					
N^*_{1535}	1.550	140	0.60	0.30			0.05		0.05				
N^*_{1650}	1.645	160	0.60	0.06		0.06	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...

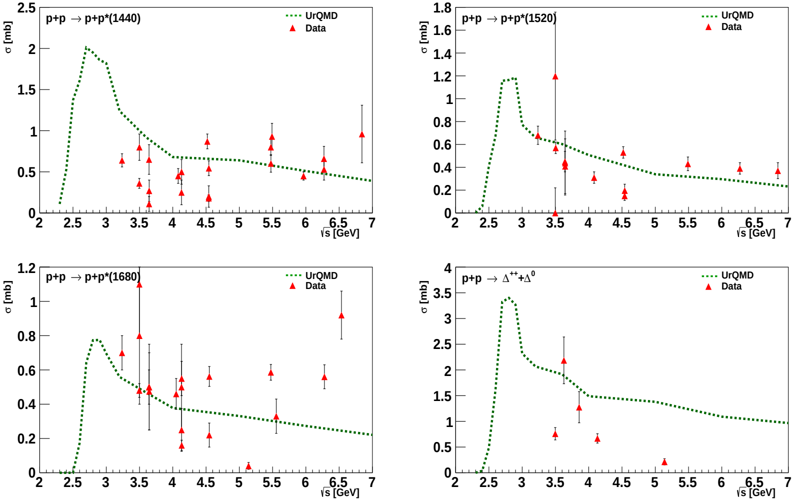
$N^*/\Delta^* \rightarrow N\rho$ Branching Ratios



	GiBUU12	UrQMD09	KSU12	KSU92	BnGa12	CLAS12	PDG12	
N(1520)3/2⁻	21	15	20.9(7)	21(4)	10(3)	12.7(4.3)	20(5)	**D13**
N(1720)3/2⁺	87	73	1.4(5)	87(5)	10(13)	47.5(21.5)	77.5(7.5)	**P13**
Δ(1620)1/2⁻	29	5	26(2)	25(6)	12(9)	37(12)	16(9)	**S31**
Δ(1905)5/2⁺	87	80	<6	86(3)	42(8)		>60	**F35**

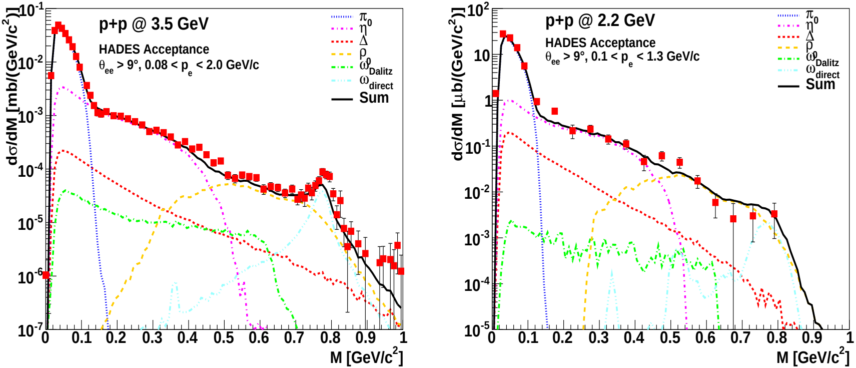
Partial courtesy of Piotr Salabura, Sept 2013

Example: Exclusive Resonance Cross-Sections



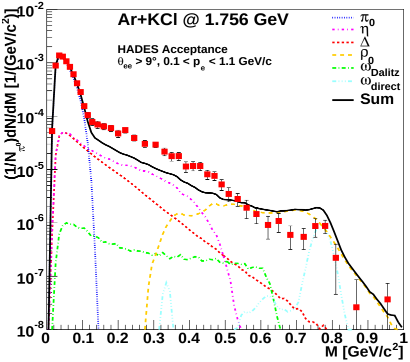
Transport Results

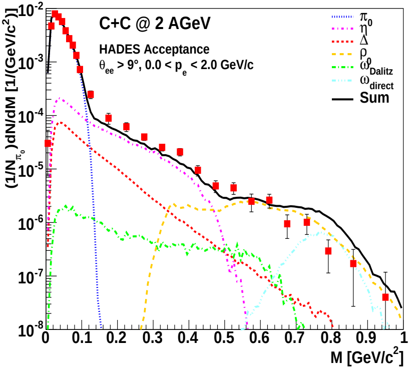
- p+p Results look quite nice after adjusting resonance production and branching ratio



Transport Results

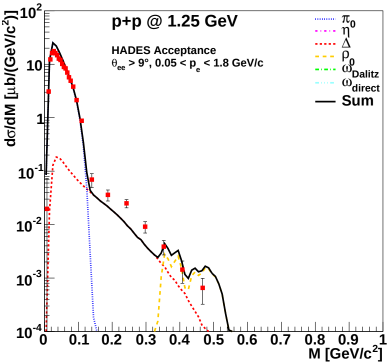
- We see an excess in heavy-ion collisions (e.g. Ar+KCl @ 1.76 AGeV) not yet described by the model

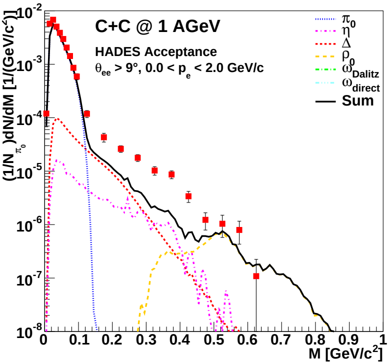




Transport Results

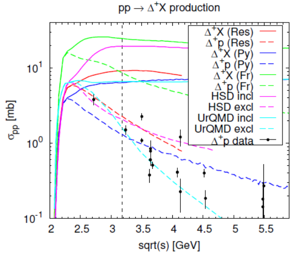
- At low energies around $E_{kin} = 1$ GeV, a pure transport description becomes difficult as well
- Processes like NN and πN bremsstrahlung become dominant, especially for p+n interactions (How avoid double counting?)
- Δ form factor? Which / how to dertermine?

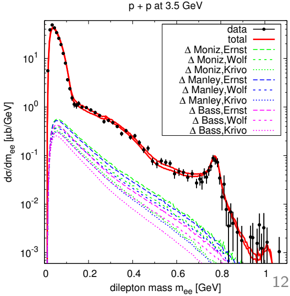




The Transport Status Quo

- There has been a lot of **improvement**, especially concerning the exact comparison and adjustment of the many parameters, cross-sections, branching ratios (compare GiBUU results by Janus)
- However, this is a **hard job** and one has to be careful
- Still the models show big differences in some details





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)
- 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 → 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
- At SIS, an equation of state for a **free hadron gas** without any phase transition is used [D. Zschiesche et al., Phys. Lett. B547, 7 (2002)]
- A **Chiral EoS** is used for the NA60 calculation (including chiral symmetry restoration and phase transition)

  [J. Steinheimer et al., J. Phys. G38 (2011)]

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)]

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

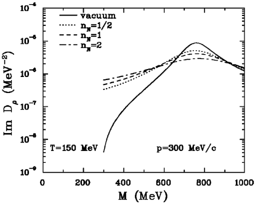
- The 4π lepton pair production can be determined from the electromagnetic spectral function extracted in e^+e^- annihilation [Z. Huang, Phys. Lett. B361, 131 (1995)]

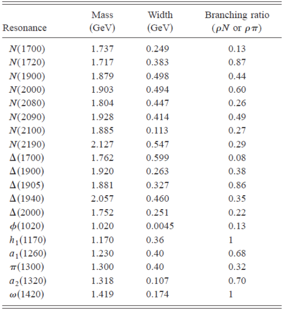
$$\frac{\mathrm{d}^8N_{4\pi\to ll}}{\mathrm{d}^4x\mathrm{d}^4q} = \frac{4\alpha^2}{(2\pi)^2} e^{-q_0/T}\frac{M^2}{16\pi^3\alpha^2}\sigma(e^+e^- \to 4\pi)$$

- QGP contribution is evaluated according to Cleymans et al.

  [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

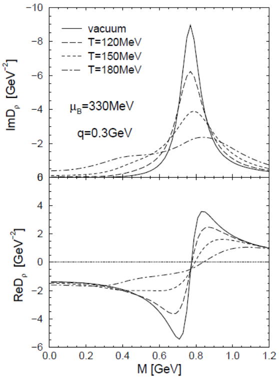
- In-medium self energies of the ρ

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

  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 $\rho_{eff} = \rho_N + \rho_{\bar{N}} + 0.5(\rho_{B^*+\bar{B}^*})$

Previous Calculations

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

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

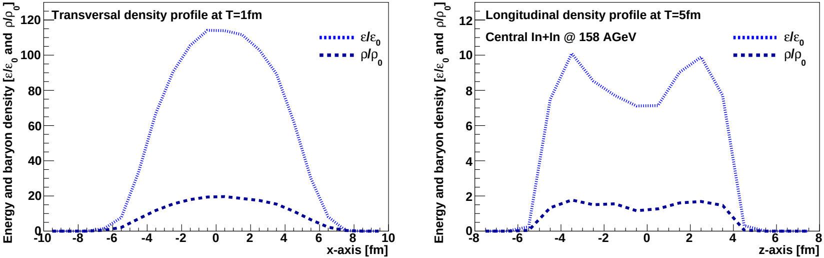
- The zone of hot and dense matter is described by an isentropic expanding cylindrical volume

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

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

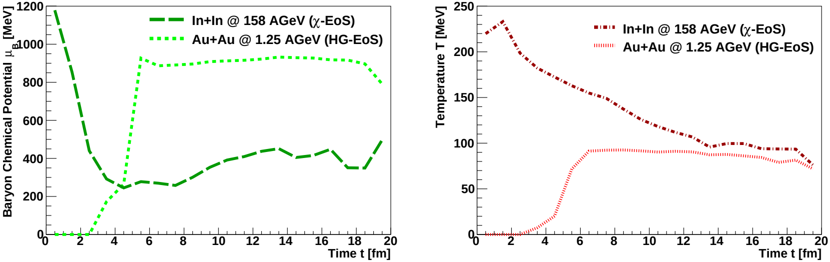
⇒ **Make calculations with better constrained input...**

UrQMD Energy and Baryon Density as Input...



- The UrQMD input we use gives a more and realistic and nuanced picture of the collision evolution
- Energy and baryon density are by no means homogeneous in the whole fireball ⇒ Different expansion dynamics might lead to significantly differing dilepton spectra

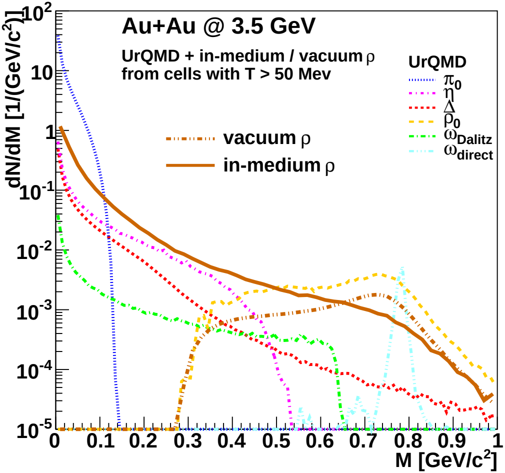
Temperature and Chemical Potential from Coarse Graining



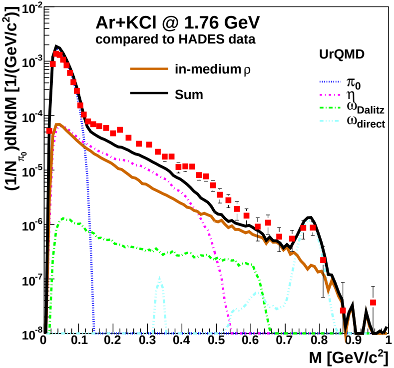
- For a central cell in an Au+Au collision @ 1.25 AGeV we get very high μ_B up to 1000 MeV and a maximum temperature of $\approx$ 100 MeV
- For In+In at NA60 energy, the baryon density decreases very fast after the start of the collision, the temperature reaches a maximum of 230 MeV

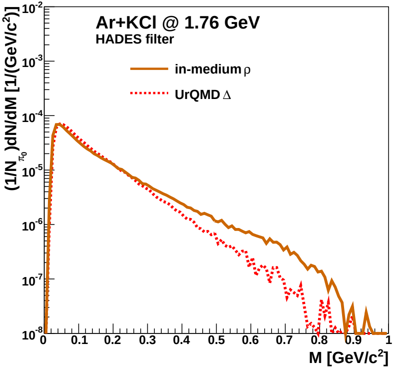
Au+Au @ 3.5 AGeV

- 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



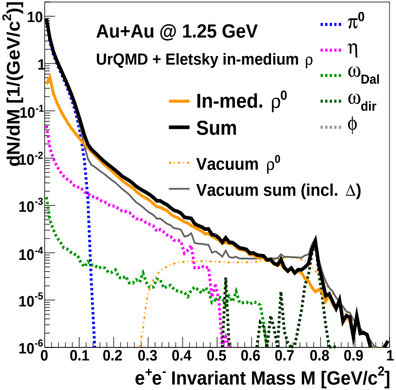
Ar + KCl @ 1.76 AGeV

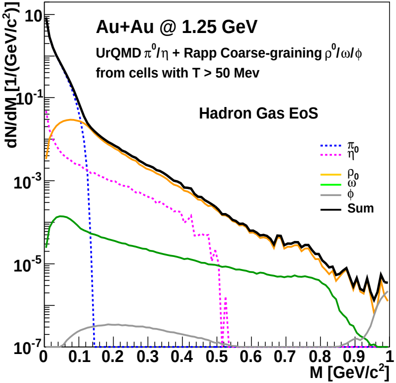




- Comparison of Eletsky spectral funktion to existing HADES data shows that the in-medium ρ is dominated by the Δ_{1232} contribution
- Still below the data for intermediate mass region

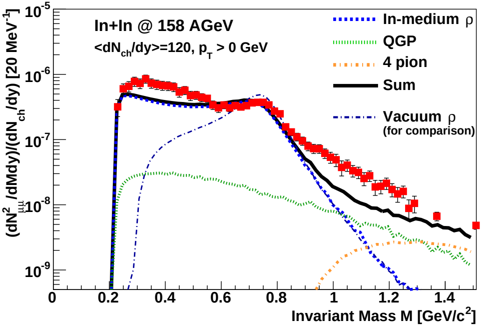
Au + Au @ 1.25 AGeV





- Eletsky and Rapp spectral function agree quite well here
- The Dalitz-ω from the Rapp spectral function lies on the UrQMD result, while we don't see a significant (direct-)ω peak in the coarse-grained result

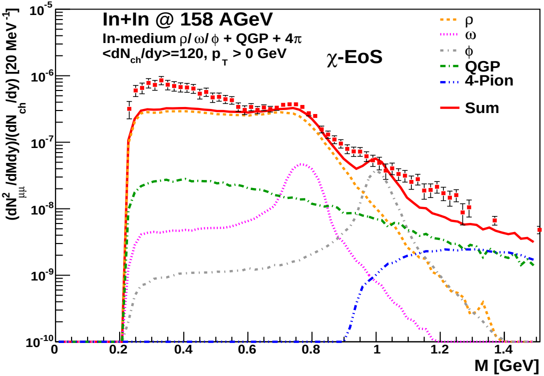
Looking at NA60 - Eletsky Spectral Function



- In-medium ρ contribution (*blue*) to dimuon excess was calculated with the Eletsky spectral function for a **chiral EoS**
- 4π (*orange*) and QGP (*green*) contribution are included as well, they are negligible mostly at low masses, but dominate above 1 GeV

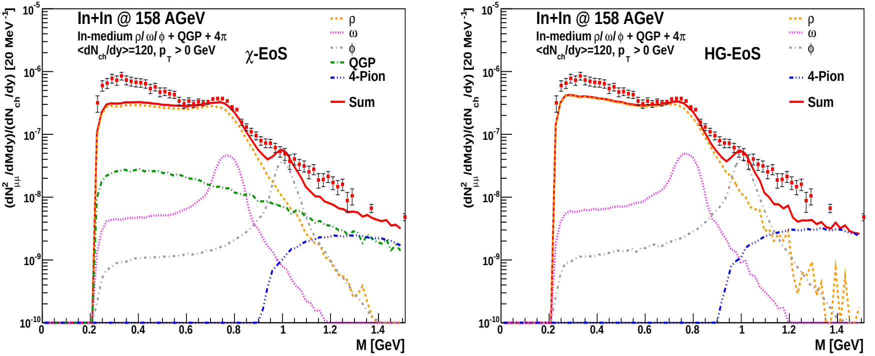
⇒ Eletsky spectral function gives a good overall agreement, but can not describe the low-mass tail of the excess dimuons completely

Rapp Spectral Function for NA60



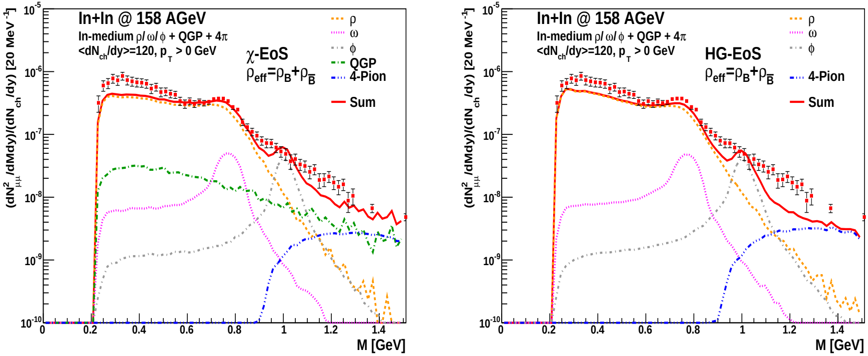
- Calcuation for Rapp spectral function (with ρ, ω and ϕ included) and additional QGP and 4π contribution
- Fits the data quite well at the ρ pole mass, but is too low in the low mass tail

Comparison of EoS



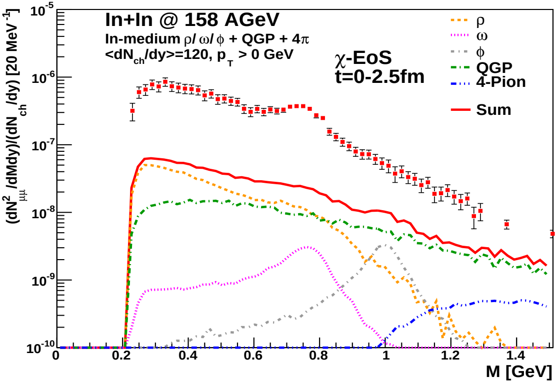
- With the **Hadron Gas EoS** we get a better agreement at low masses
- The lack of QGP lowers the result at high masses

Dependence on Baryon Density



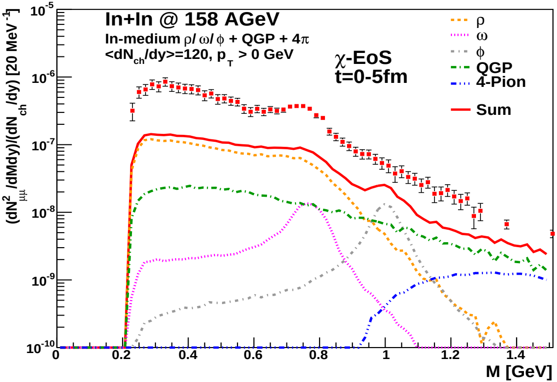
- An **increase in baryon density** (take $\rho_{eff} = \rho_B + \rho_{\bar{B}}$) leads to a better description
  $\rightarrow$ Baryons crucial for description of low mass tail

Time evolution (t<2.5fm)



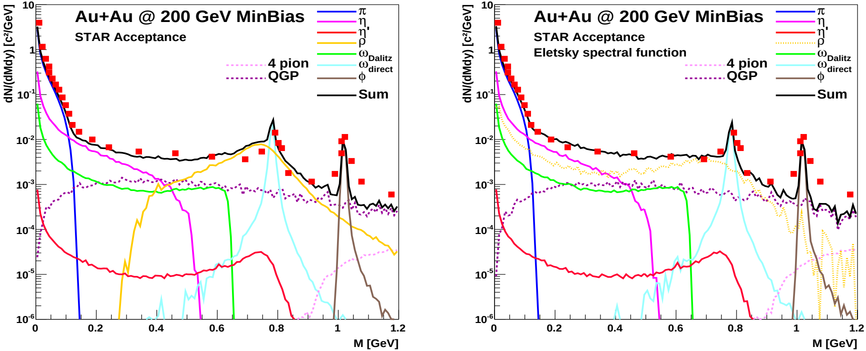
- The broadening is large at the beginning of the evolution, no peak at the ρ pole mass
- Same order of magnitude for QGP and in-medium ρ

Time evolution (t<5fm)



- Later the ρ dominates, shape of the spectrum is flatter, peak at pole mass evolves

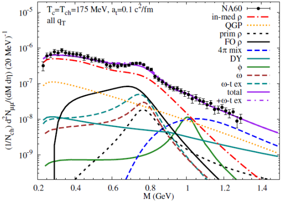
Dileptons at RHIC



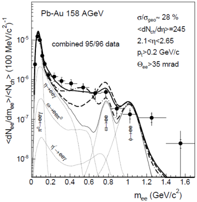
- Comparison between pure transport and transport + in-medium ρ from coarse-graining

Outlook

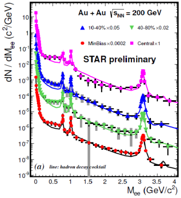
- Coarse-graining to be done at other energies and compared to further NA60, CERES, RHIC, LHC data



[Rapp, Hees]



[CERES Collab.]



[STAR Collab.]

- Investigation of diffent equations of state
- Further 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 ⇒ Use **equilibrium** rates for a **coarse-grained transport dynamics**
- First calculations show that we get a good description of the invariant mass spectrum, the coarse-graining is applicable for all energy regimes
- Explanation of dilepton measurements is still a challenge for theory ⇒ Need for more experimental input!
- Waiting for HADES Au+Au data and for the pion beam!
- **Further work in progress...!**