DILEPTONS IN HEAVY ION COLLISIONS FROM DYNAMICAL MODELLING

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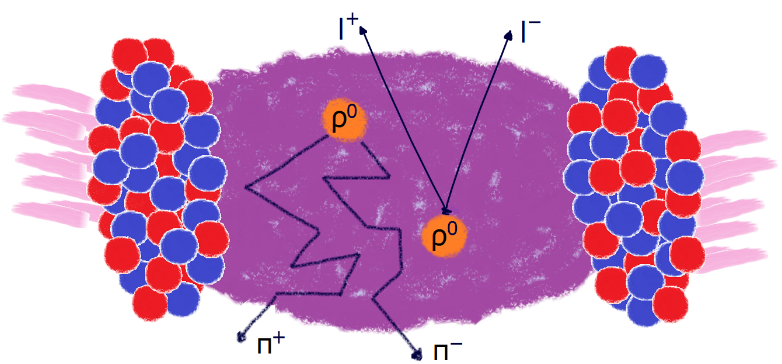
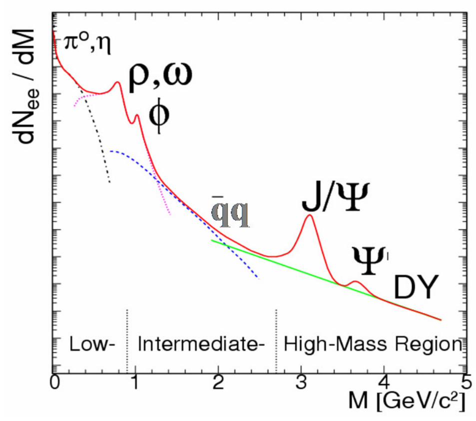
Exploration of hot and dense nuclear matter with low mass dileptons

- 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, signatures for onset of QGP formation
- Chiral symmetry restoration





Tool: transport/hydro simulations

- Here: UrQMD (Hadron/String transport approach)
  - based on relativistic dynamics
  - all (well) known resonances up to 3 GeV included
  - no phase transition (except in hybrid mode)
  - no explicit in-medium effects

- Of course we are not the first ones to do dileptons simulations
- Pioneering theory work done at Gießen for decades:
- → Mosel group
- → Cassing group
- → Continued by Bratkovskaya and Smekal

Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

Hadron/string transport approach

- Based on the propagation of hadrons
- Rescattering among hadrons is fully included
- String excitation/decay (LUND picture/PYTHIA) at higher energies
- Provides a solution for the time dependent n-body distribution (i.e. event-by-event simulations!) of hadrons

  The collision term C includes more than 100 hadrons
- **Soft/hard EoS can be switched on when needed**

M. Bleicher et al, J.Phys. G25 (1999) 1859-1896

List of included particles in the hadron cascade

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	2^{++}	$(1^{--})^*$	$(1^{--})^{**}$
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}

- Binary interactions between all implemented particles are treated
- Cross sections are taken from data or models
- Resonances are implemented in Breit-Wigner form
- No in-medium modifications

Channels for di-leptons

In UrQMD, dilepton pairs are generated from the mesonic Dalitz decays $\pi^0 \to \gamma e^+e^-$, $\eta \to \gamma e^+e^-$, $\eta' \to \gamma e^+e^-$ and $\omega \to \pi^0 e^+e^-$, the direct decay of the ρ, ω and ϕ vector mesons and the Dalitz decay of the Δ resonance.

Decays of the form, with P being a pseudoscalar meson and V a vector meson,

$$P \to \gamma e^+e^-, V \to P e^+e^- \tag{1}$$

can be decomposed into the corresponding decays into a virtual photon $\gamma^\star$, $P \to \gamma\gamma^\star$, $V \to P\gamma^\star$, and the subsequent decay of the photon via electromagnetic conversion, $\gamma^\star \to e^+e^-$ [43, 44, 45]:

$$\frac{d\Gamma_{P\to\gamma e^+e^-}}{dM^2} = \Gamma_{P\to\gamma\gamma^\star} \frac{1}{\pi M^4} M\Gamma_{\gamma^\star\to e^+e^-} \;, \tag{2}$$

$$\frac{d\Gamma_{V\to P e^+e^-}}{dM^2} = \Gamma_{V\to P\gamma^\star} \frac{1}{\pi M^4} M\Gamma_{\gamma^\star\to e^+e^-} \;, \tag{3}$$

Schmidt, Santini, Bleicher, Phys.Rev.C 79 (2009) 064908

where M is the mass of the virtual photon or, equivalently, the invariant mass of the lepton pair. The internal conversion probability of the photon is given by:

$$M\Gamma_{\gamma^\star\to e^+e^-} = \frac{\alpha}{3} M^2 \sqrt{1-\frac{4m_e^2}{M^2}} \left(1+\frac{2m_e^2}{M^2}\right) \tag{4}$$

with m_e being the electron mass. The widths $\Gamma_{P\to\gamma\gamma^\star}$ and $\Gamma_{V\to P\gamma^\star}$ can be related to the corresponding radiative widths $\Gamma_{P\to 2\gamma}$ and $\Gamma_{V\to P\gamma}$:

$$\Gamma_{P\to\gamma\gamma^\star} = 2\Gamma_{P\to 2\gamma}\left(1-\frac{M^2}{m_P^2}\right)^3 |F_{P\gamma\gamma^\star}(M^2)|^2, \tag{5}$$

$$\Gamma_{V\to P\gamma^\star} = \Gamma_{V\to P\gamma}\left[\left(1+\frac{M^2}{m_V^2-m_P^2}\right)^2 - \left(\frac{2m_V M}{m_V^2-m_P^2}\right)^2\right]^{3/2} |F_{VP\gamma^\star}(M^2)|^2, \tag{6}$$

where m_P and m_V are the masses of the pseudoscalar and vector meson respectively and $F_{P\gamma\gamma^\star}(M^2)$, $F_{VP\gamma^\star}(M^2)$ denote the form factors with $F_{P\gamma\gamma^\star}(0) = F_{VP\gamma^\star}(0) = 1$. The factor 2 in (5) occurs due to the identity of the two photons in the $P\to 2\gamma$ decay. The form factors can be obtained from the vector meson dominance model (VMD). In the present calculations the following parametrisations are employed [7, 43]:

$$\begin{aligned}
F_{\pi^0}(M^2) &= 1 + b_{\pi^0}M^2, \\
F_\eta(M^2) &= \left(1-\frac{M^2}{\Lambda_\eta^2}\right)^{-1}, \\
\left|F_\omega(M^2)\right|^2 &= \frac{\Lambda_\omega^2(\Lambda_\omega^2+\gamma_\omega^2)}{(\Lambda_\omega^2-M^2)^2+\Lambda_\omega^2\gamma_\omega^2}, \\
\left|F_{\eta'}(M^2)\right|^2 &= \frac{\Lambda_{\eta'}^2(\Lambda_{\eta'}^2+\gamma_{\eta'}^2)}{(\Lambda_{\eta'}^2-M^2)^2+\Lambda_{\eta'}^2\gamma_{\eta'}^2}
\end{aligned} \tag{7}$$

with $b_{\pi^0} = 5.5\,\mathrm{GeV}^{-2}$, $\Lambda_\eta = 0.72\,\mathrm{GeV}$, $\Lambda_\omega = 0.65\,\mathrm{GeV}$, $\gamma_\omega = 0.04\,\mathrm{GeV}$, $\Lambda_{\eta'} = 0.76\,\mathrm{GeV}$ and $\gamma_\eta' = 0.10\,\mathrm{GeV}$. In (7) the abbreviations F_P and F_V have been used to denote respectively $F_{P\gamma\gamma^\star}$ and $F_{VP\gamma^\star}$.

The width for the direct decay of a vector meson $V = \rho^0, \omega, \phi$ to a dilepton pair varies with the dilepton mass like M^{-3} according to [7]:

$$\Gamma_{V\to e^+e^-}(M) = \frac{\Gamma_{V\to e^+e^-}(m_V)}{m_V}\frac{m_V^4}{M^3}\sqrt{1-\frac{4m_e^2}{M^2}}\left(1+\frac{2m_e^2}{M^2}\right) \tag{8}$$

with $\Gamma_{V\to e^+e^-}(m_V)$ being the partial decay width at the meson pole mass.

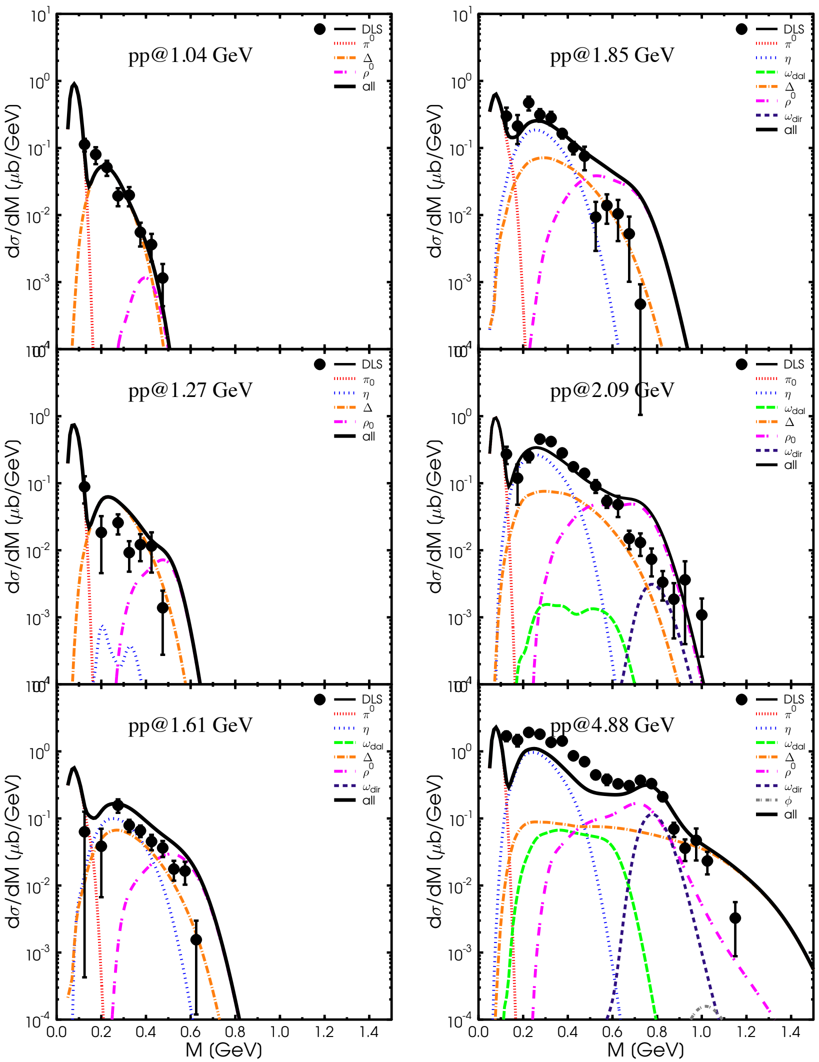
The decomposition of the $\Delta\to Ne^+e^-$ decay into the $\Delta\to N\gamma^\star$ decay and subsequent conversion of the photon leads to the following expression for the differential decay width:

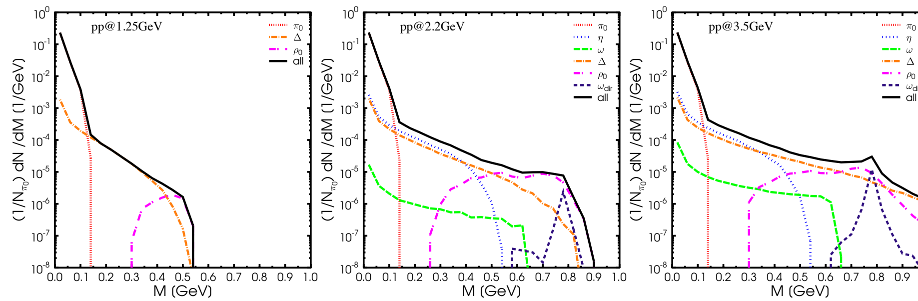
$$\frac{d\Gamma_{\Delta\to Ne^+e^-}}{dM^2} = \frac{\alpha}{3\pi M^2}\Gamma_{\Delta\to N\gamma^\star}\,. \tag{9}$$

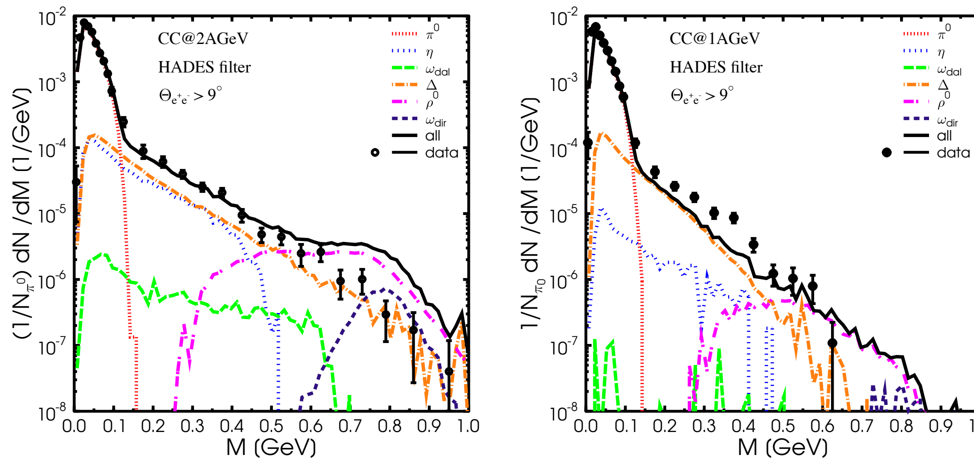
Summary

- Use standard rates (VMD)
- Use time integration (shining)
- Automatically includes collisional broadening

Comparison w/ DLS and HADES







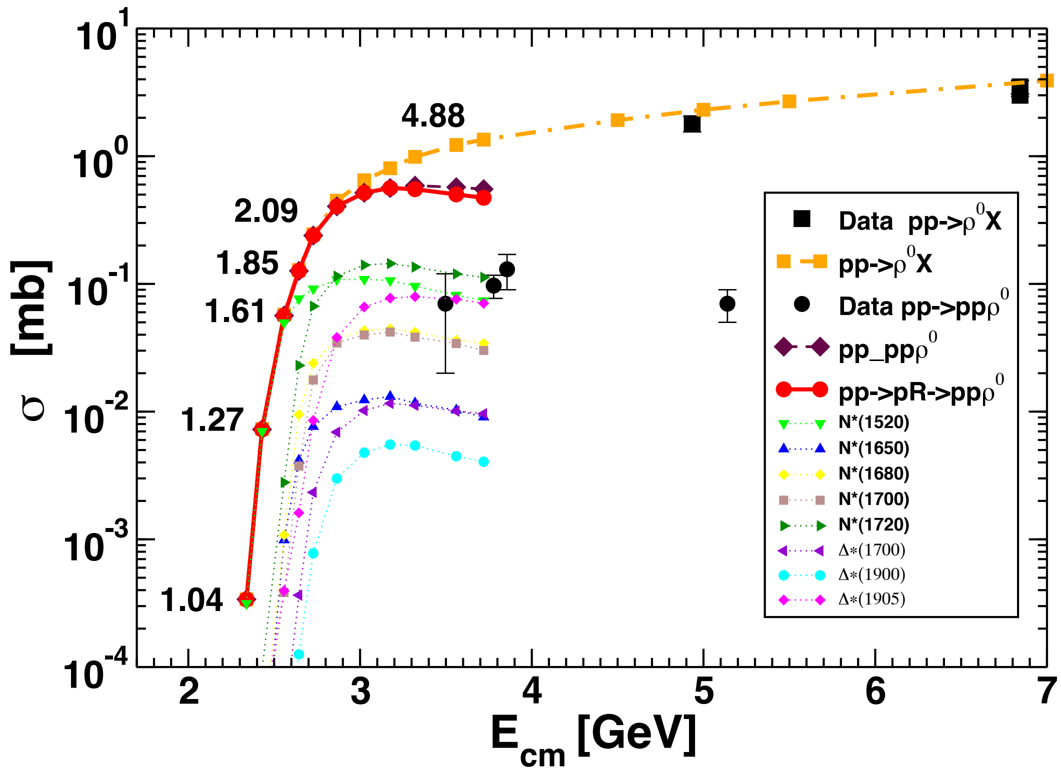
→ overestimation of the ρ, around 2 GeV

→ Descrepancy at 1GeV: Bremstrahlung

See GiBuu (Smekal/Larinov) 2021

Schmidt, Santini, Bleicher, Phys.Rev.C 79 (2009) 064908

pp→ppρ (excl. vs. incl.)



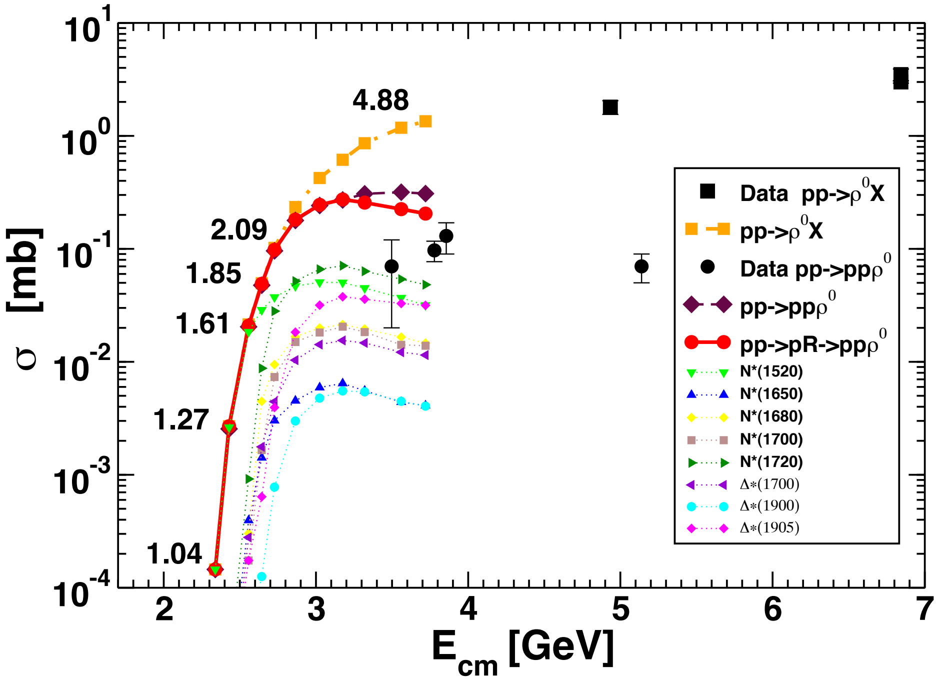
Resonance	$Br(N\rho)$	Resonance	$Br(N\rho)$
$N^*(1520)$	.15	$\Delta^*(1620)$	.05
$N^*(1650)$	.06	$\Delta^*(1700)$	.25
$N^*(1680)$	.10	$\Delta^*(1900)$	.25
$N^*(1700)$	.20	$\Delta^*(1905)$	.80
$N^*(1710)$	.05	$\Delta^*(1910)$	.10
$N^*(1720)$	.73	$\Delta^*(1930)$	.22
$N^*(1900)$	.15	$\Delta^*(1950)$	.08
$N^*(1990)$	.43		
$N^*(2080)$	.12		
$N^*(2190)$	.24		
$N^*(2220)$	.22		
$N^*(2250)$	.25		

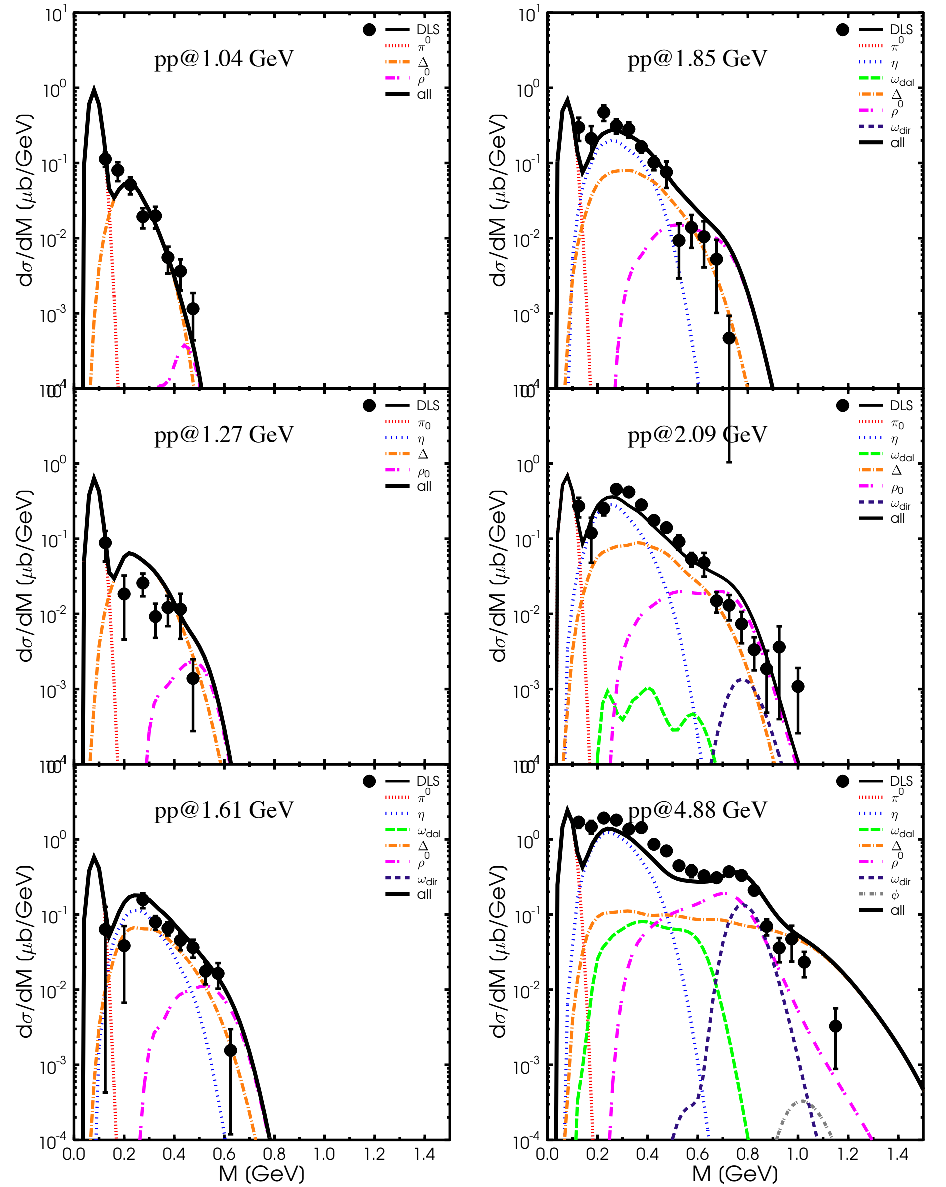
BR into ρ+x

However, branching ratios are not well measured, pp->pN* production cross sections also not well known

Schmidt, Santini, Bleicher, Phys.Rev.C 79 (2009) 064908

Test with reduced cross sections





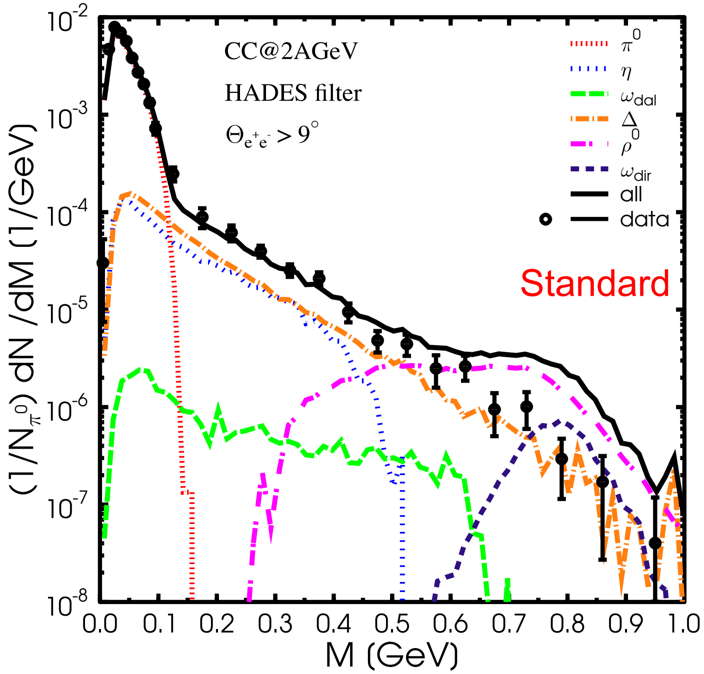
Divide all NN→NN*, ND cross section by 3

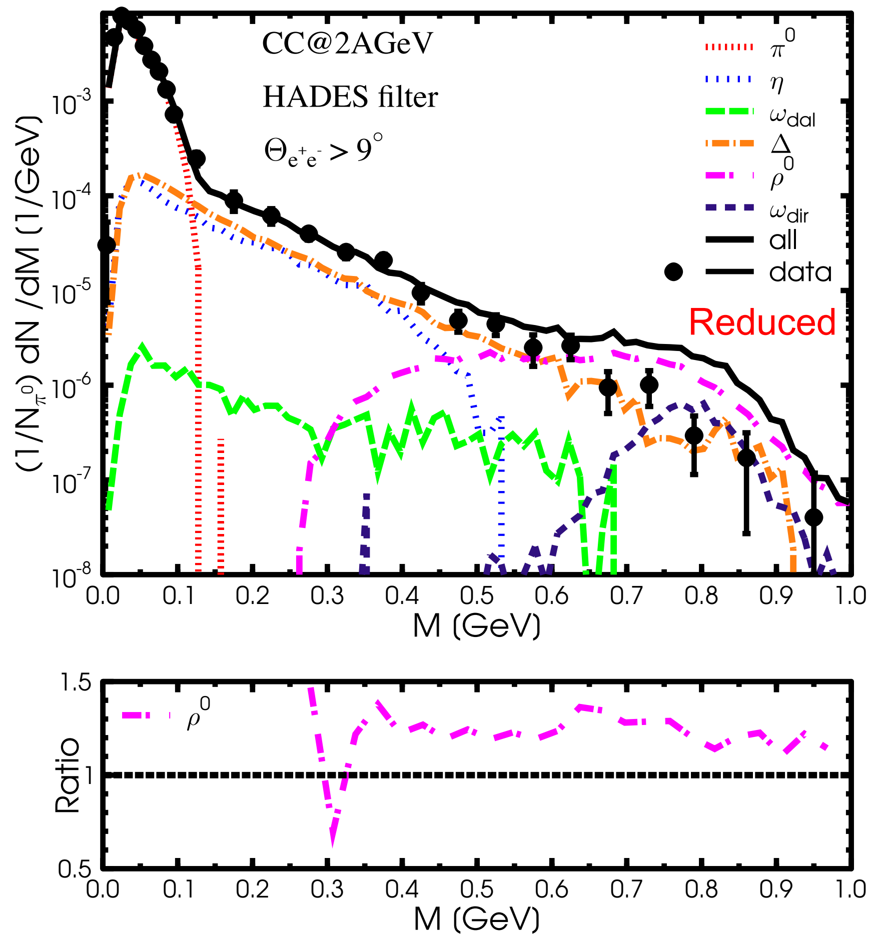
(except NN→NN(1535), constrained by eta production)

→ ρ contribution in pp is reduced
improved description of DLS pp data

Schmidt, Santini, Bleicher, Phys.Rev.C 79 (2009) 064908

Comparison with standard calculation





in CC only 20% reduction w/reduced cross sections → thermalization?!

ratio of the ρ contributions

Schmidt, Santini, Bleicher, Phys.Rev.C 79 (2009) 064908

Conclusions from this analysis

- Too much strength in ρ peak
- Resonance production not well enough constrained in pp
- Branching ratios not well enough constrained in pp

- Problems for CC remain, even if pp is fixed!

- Theory problems:
  - No proper finite temperature/density spectral function in the simulations (off-equilibrium effects)
  - No coherent addition of amplitudes

Possible solutions

- Use 1-fluid hydrodynamics at GSI energies
  - Problematic, because of instant thermalization
    → too high temperatures/densities → wrong dileptons (T^4 !)
    (but not too bad for hadrons)

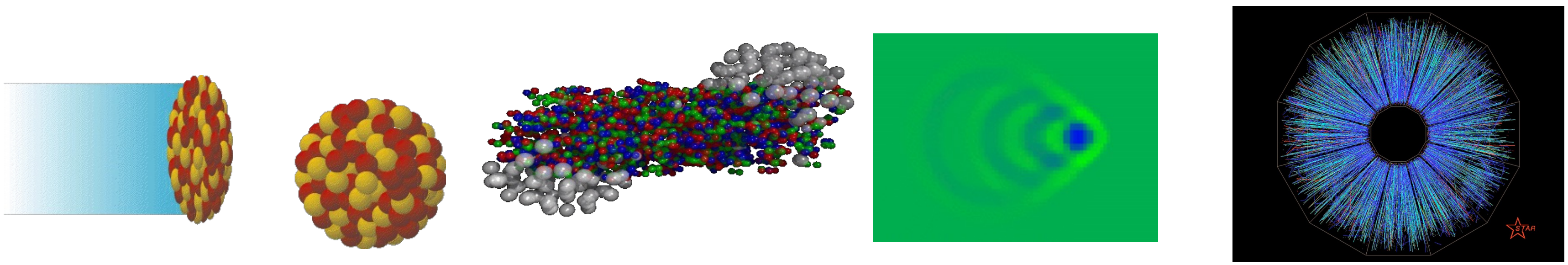
- Use hybrid model at GSI energies
  - Problematic because baryon currents separate only after the collision is over → not good

- Use coarse grained transport
  - Better, but wrong evolution when reaching mixed phase
    (no proper softening of the EoS → wrong life time*)
    * can be solved see (O. Savchuck, JS, TG, MB)

HYBDRID APPROACHES

Hybrid Approach

- Essential to draw conclusions from final state particle distributions about initially created medium
- Idea: Split reaction: initial state, dense phase, freeze-out
  → learn something about the EoS in dense stage



1) Non-equilibrium initial conditions via UrQMD

2) Hydrodynamic evolution **or** Transport calculation

3) Freeze-out via hadronic cascade (UrQMD)

(Dumitru, Bass, Bleicher et al, *Phys.Lett.B* 460 (1999) 411-416; Bass, Dumitru, Bleicher et al, *Phys.Rev.C* 60 (1999) 021902; *Petersen, Bleicher et al., PRC 78:044901, 2008*)

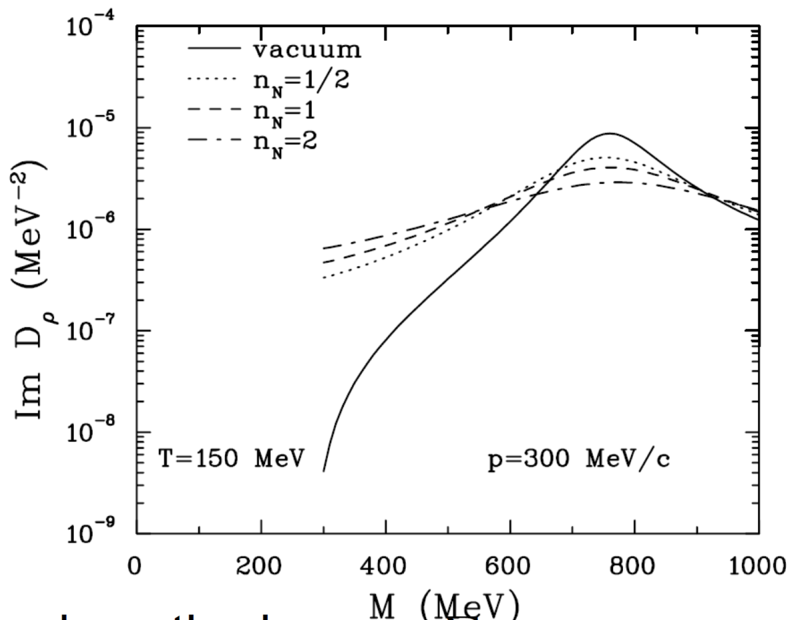
Di-Leptons from/in the medium

$\rho^* \rightarrow \mu\mu$ production In+In collisions at SPS energies

- Spectral density for the ρ meson in a heat bath of N and π re-derived and tabelled

Eletsky,Belkacem,Ellis,Kapusta,

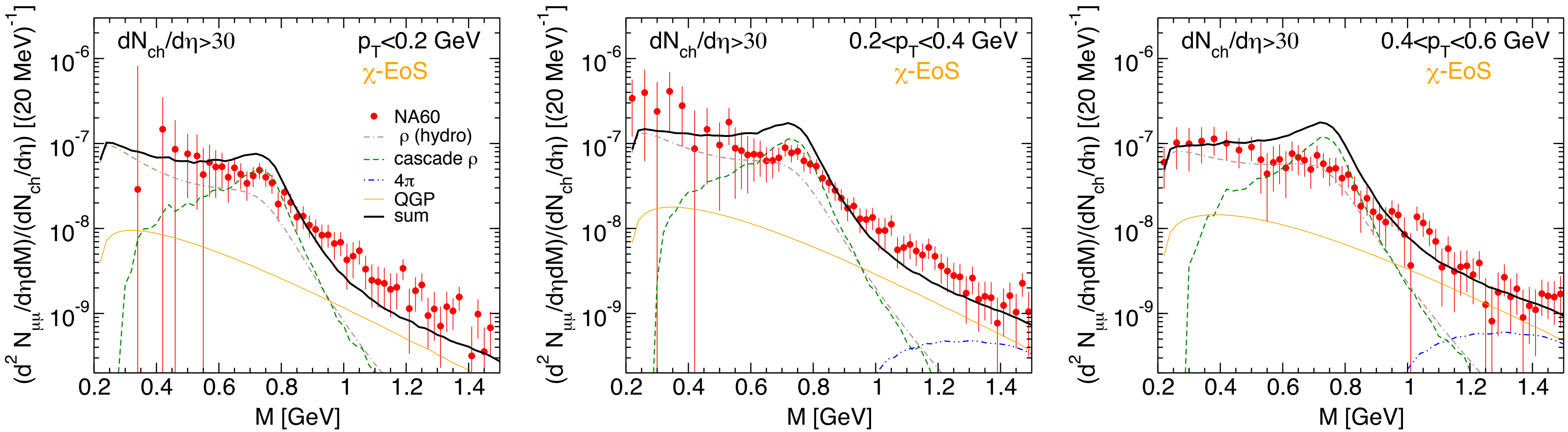
PRC64(2001),035202



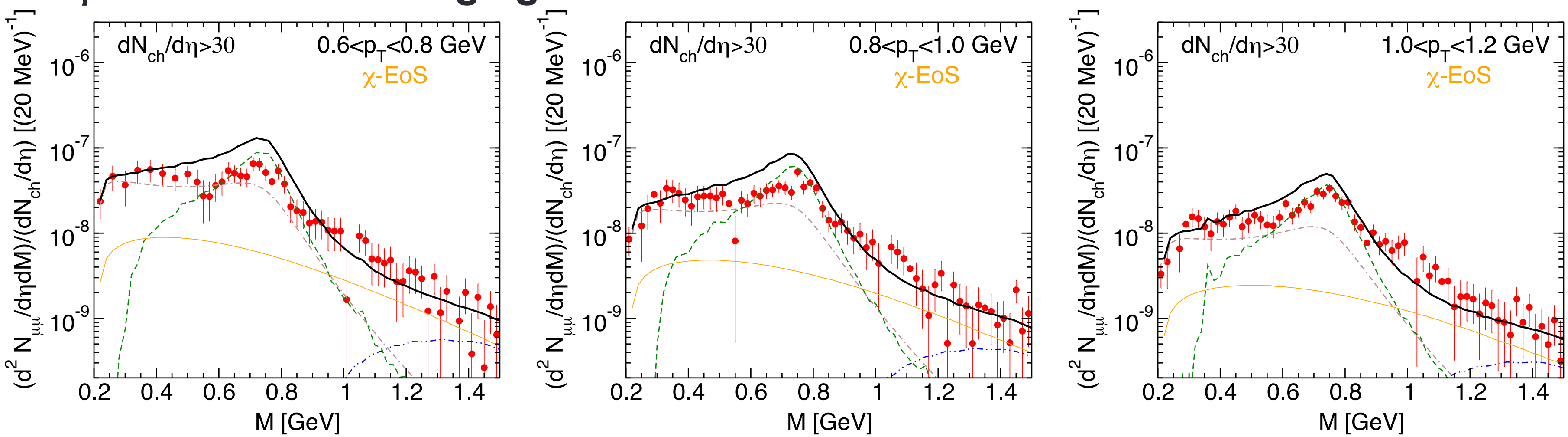
Authors give $f_{\rho a}$ as free to download; close the loop $\rightarrow \Sigma_\rho$

Santini, Bleicher, Steinheimer, Schramm, Phys.Rev.C 84 (2011) 014901

low pt (muon excess), In+In, 160 AGeV



→ **ρ from cascade stage gives additional contribution!**



Santini, Bleicher, Steinheimer, Schramm, Phys.Rev.C 84 (2011) 014901

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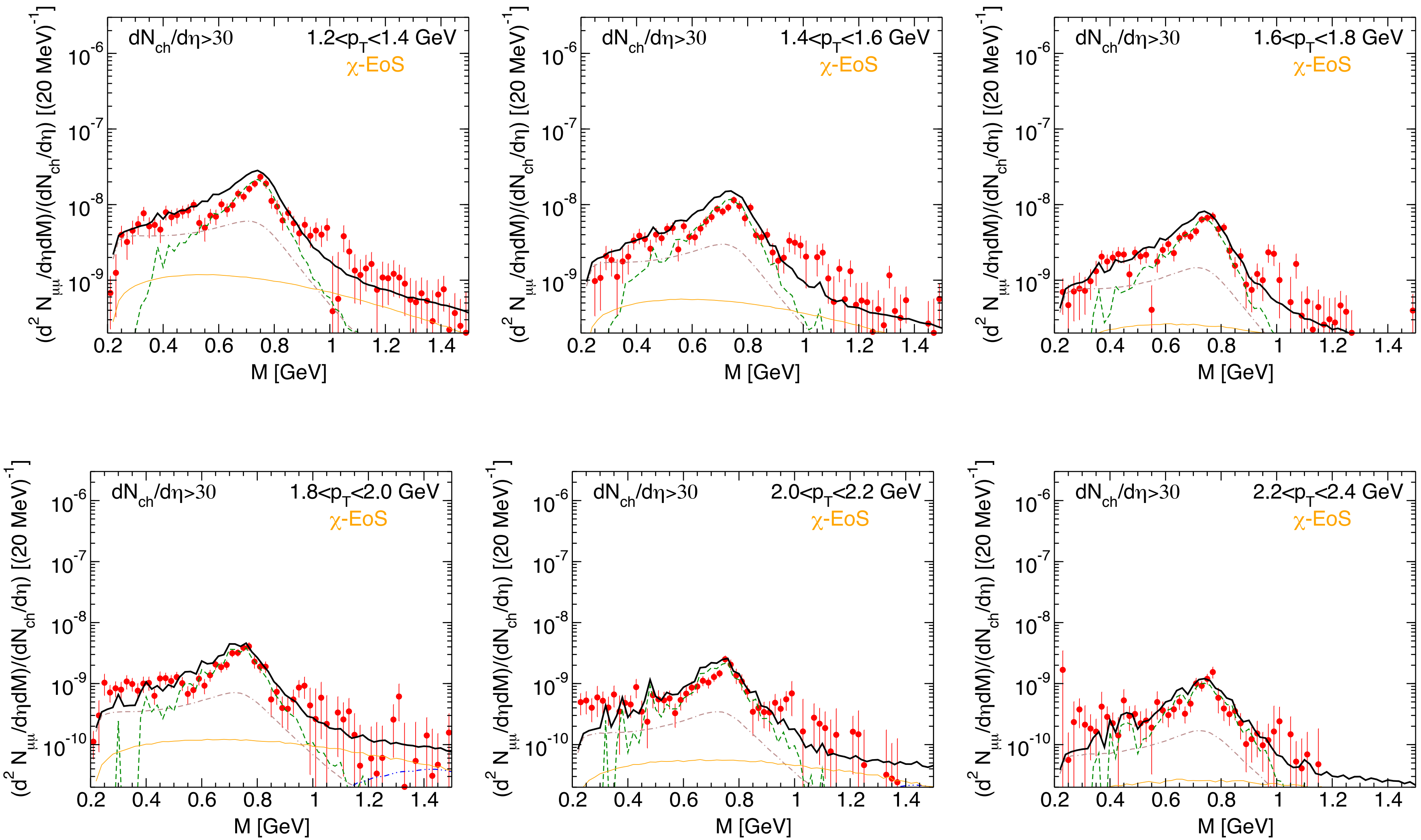
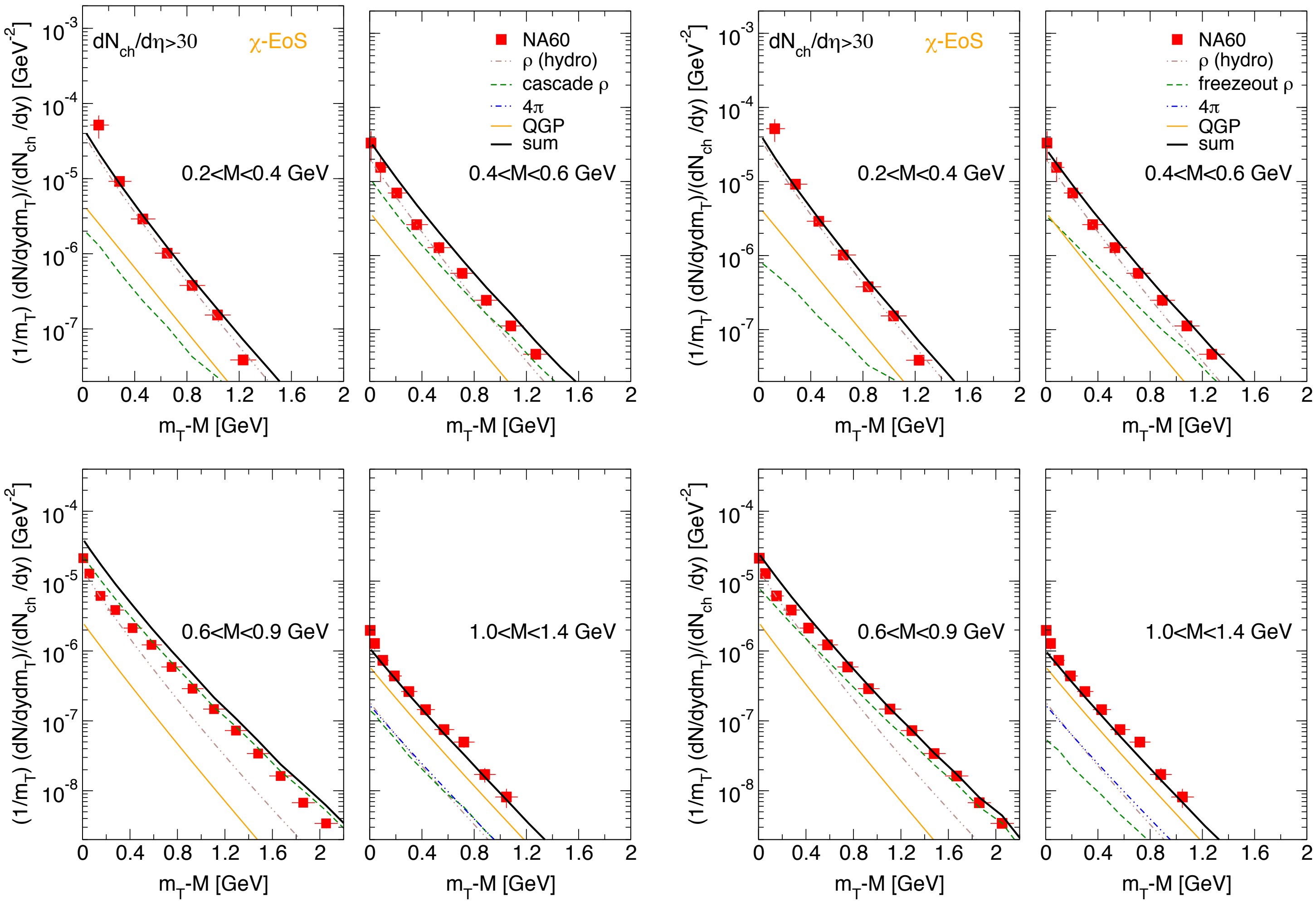
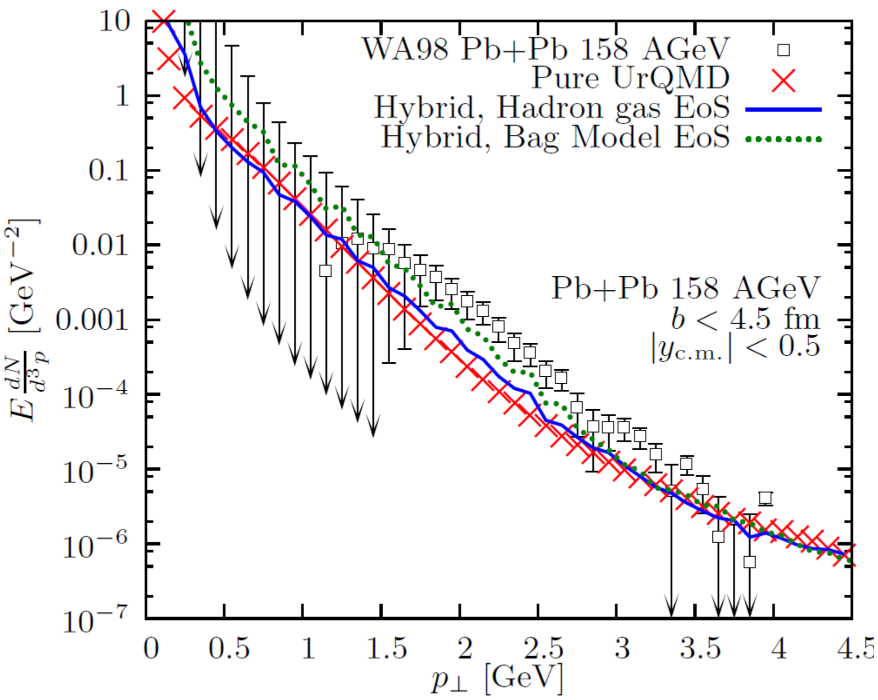


pt distribution, In+In, 160 AGeV

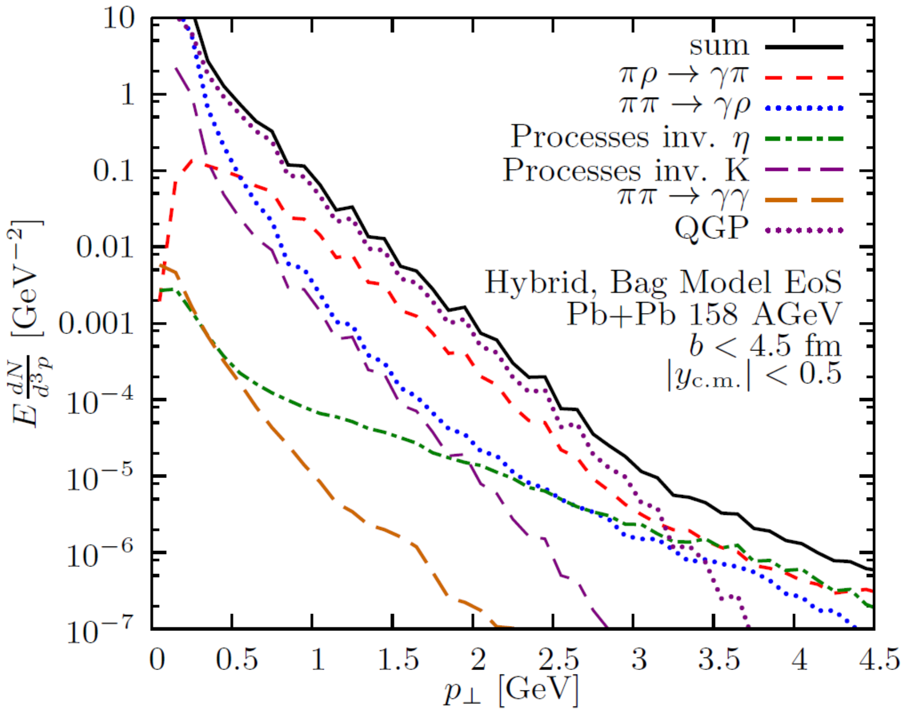


- High mass dileptons sensitive to QGP (yellow line)

Hybrid also works for photons



Comparisons



Hybrid, QGP: Channels

- Main effect is due to increase in lifetime due to softer expansion with Bag Model EoS

Bauechle, Bleicher, Phys.Rev. C81 (2010) 044904

Conclusion from hybrid approach

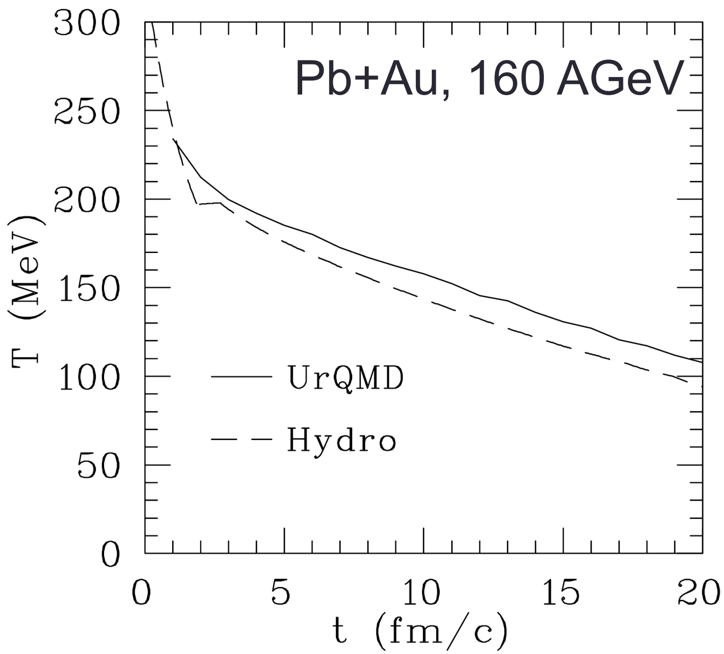
- Works very well at high energies (also for hadron yields)
- Allows to include in-medium spectral function
- Allows to use HG or QGP EoS
- Shows window to access QGP properties at high muon masses (M>1 GeV)

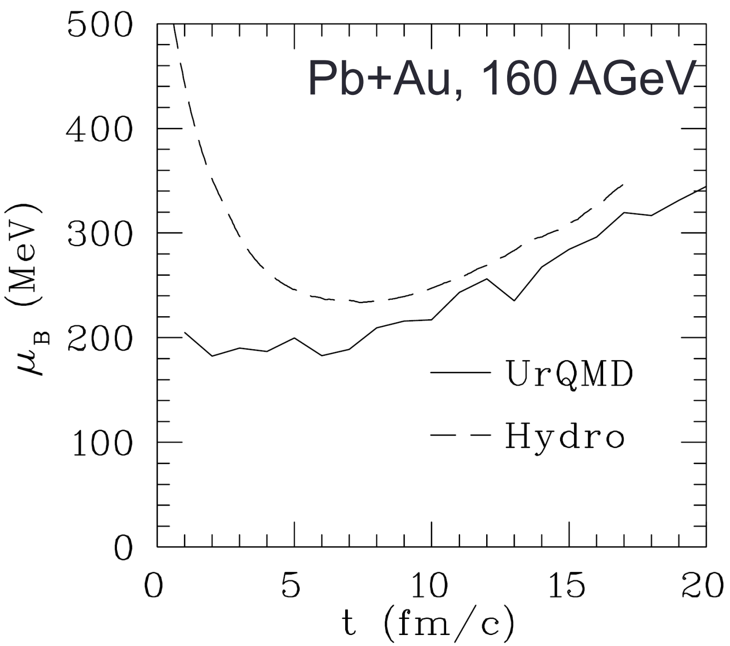
- Relies on separation of baryon currents
  - → not applicable at FAIR energies

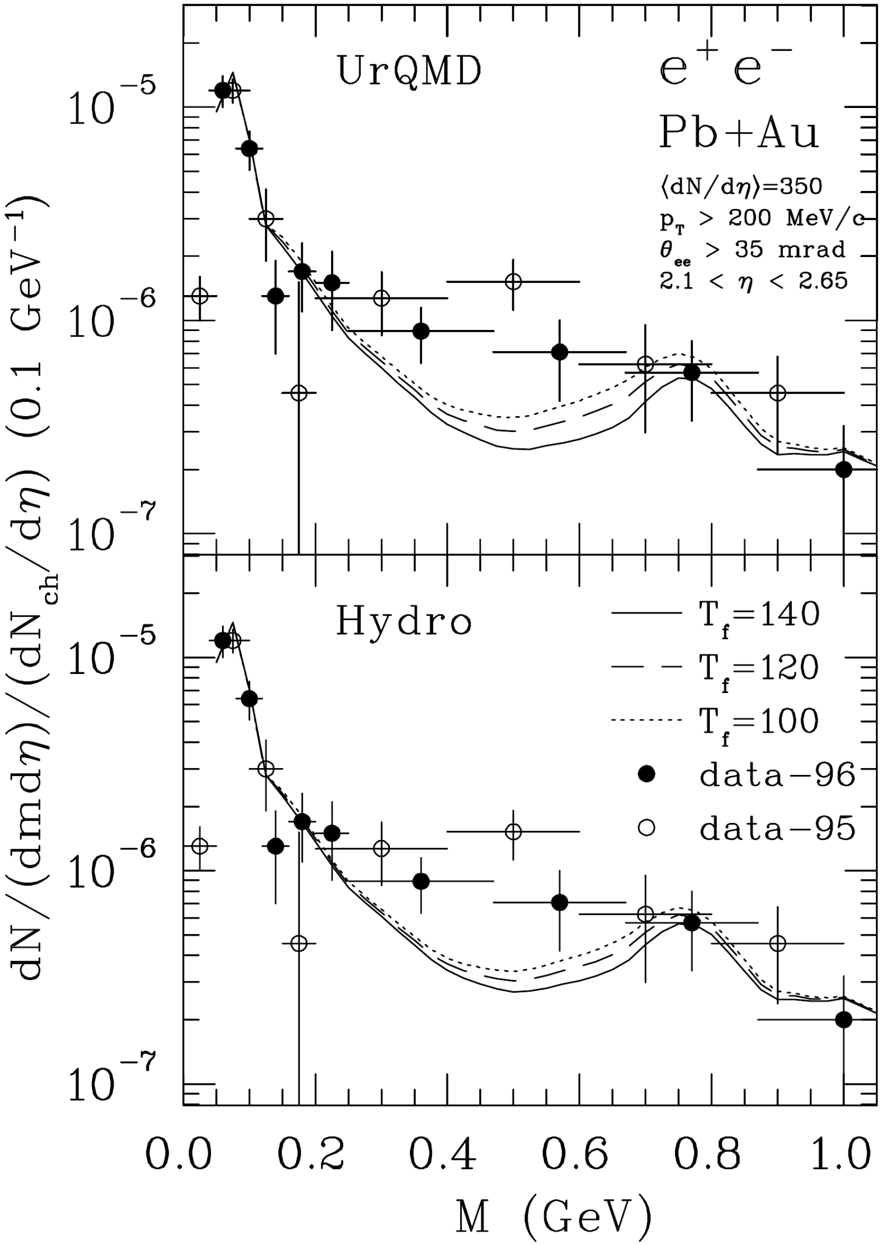
COARSE GRAINING APPROACHES

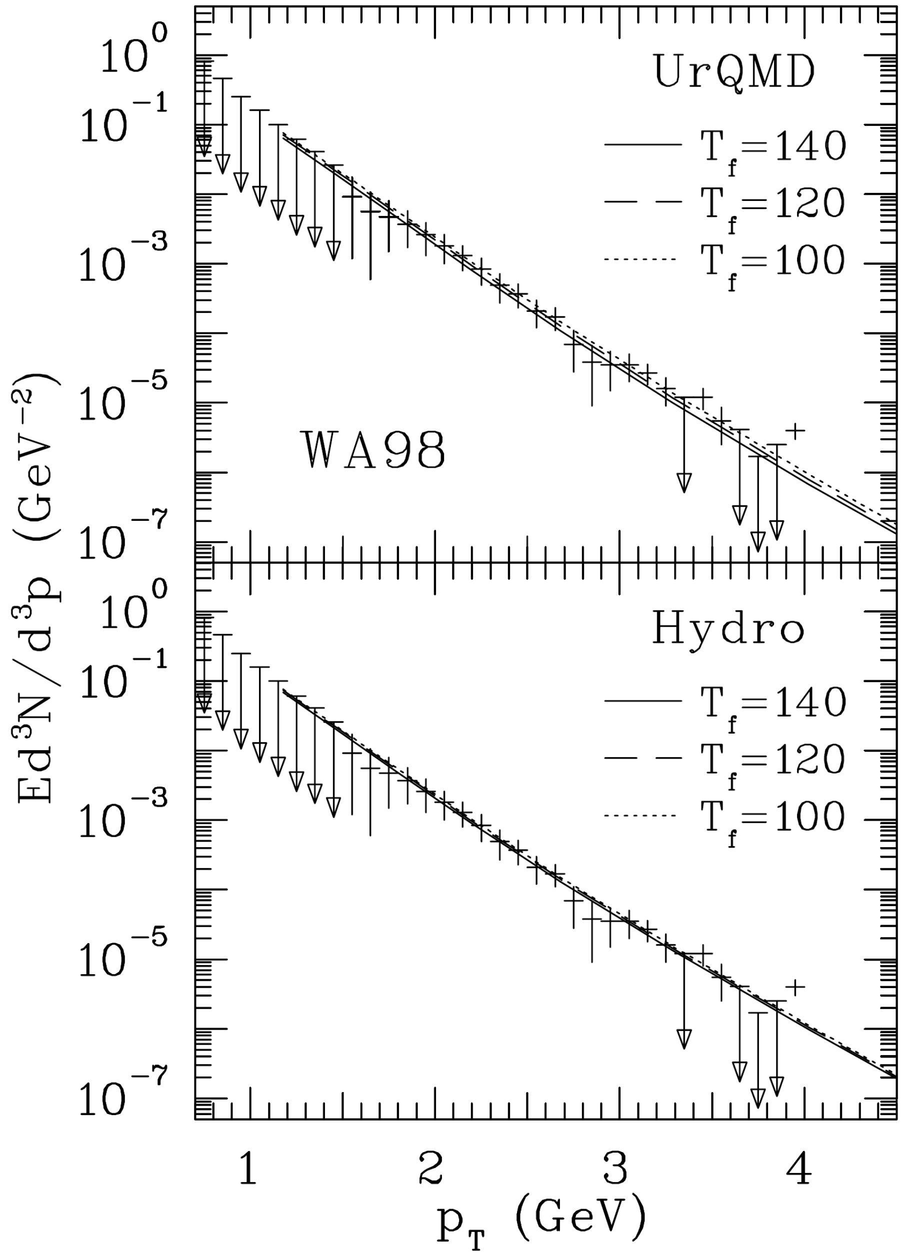
An alternative to hybrid models

- coarse grained transport simulations for leptons/photons
- First explored with UrQMD by Huovinen et al. *Phys.Rev.C* 66 (2002) 014903









Huovinen et al. Phys.Rev.C 66 (2002) 014903

A first conclusion

- Both hydro and coarse grained UrQMD provide a similarly good description of the data

GeV mass range. Further the results obtained by Rapp *et al.* [29,32] were obtained with a less sophisticated approach than employed here. They used a very simple parametrizations of the space-time evolution of the temperature and flow velocity, essentially spherical fireballs or cylindrical firetubes. They did not compare with the hadronic data, which we view as an

from *Huovinen et al. Phys.Rev.C 66 (2002) 014903*

- Lets see, if we can merge “Rapp" and coarse graining

Coarse graining: Idea

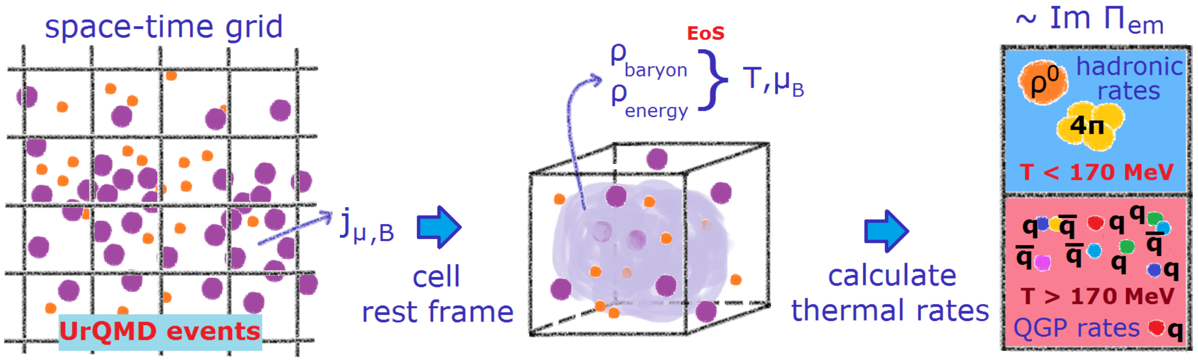
- Combining a realistic 3+1 dimensional expansion of the system with full in-medium spectral functions for the emission of dileptons
- Idea: Microscopic description
  $\longrightarrow$ Average over a many single events
- Sufficiently large number of events
  $\longrightarrow$ Distribution function f(x,p,t) 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 $\longrightarrow$ the equilibrium quantities have to be extracted locally at each space-time point

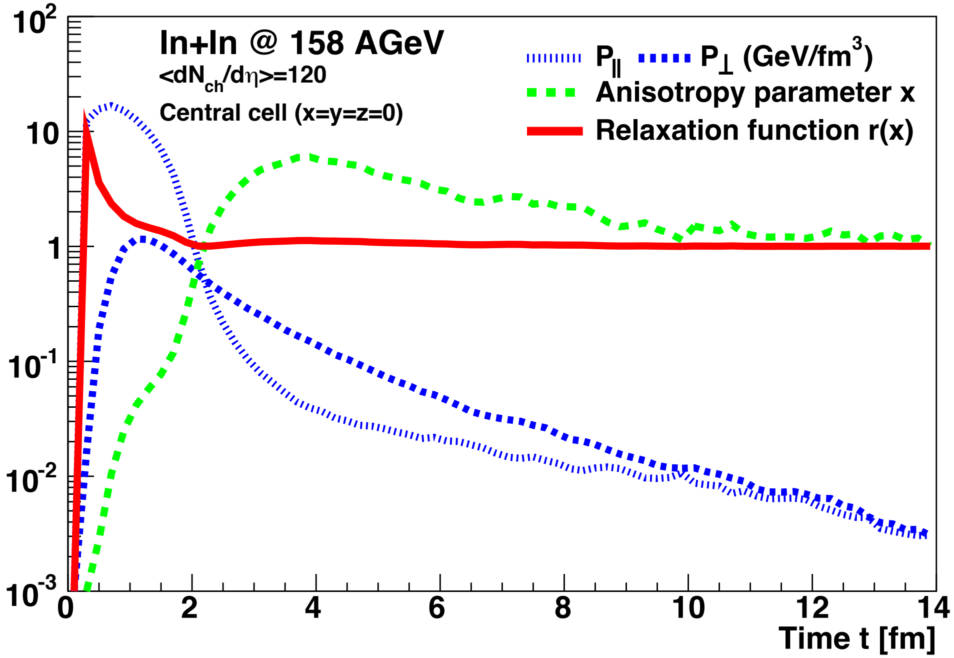
Endres, Hees, Bleicher, PoS CPOD2013 (2013) 052

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
  → 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

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 (v^μ = (0, 0, 0, 1))

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

Endres, Hees, Bleicher, Phys.Rev.C 91 (2015) 5, 054911

Dilepton rates

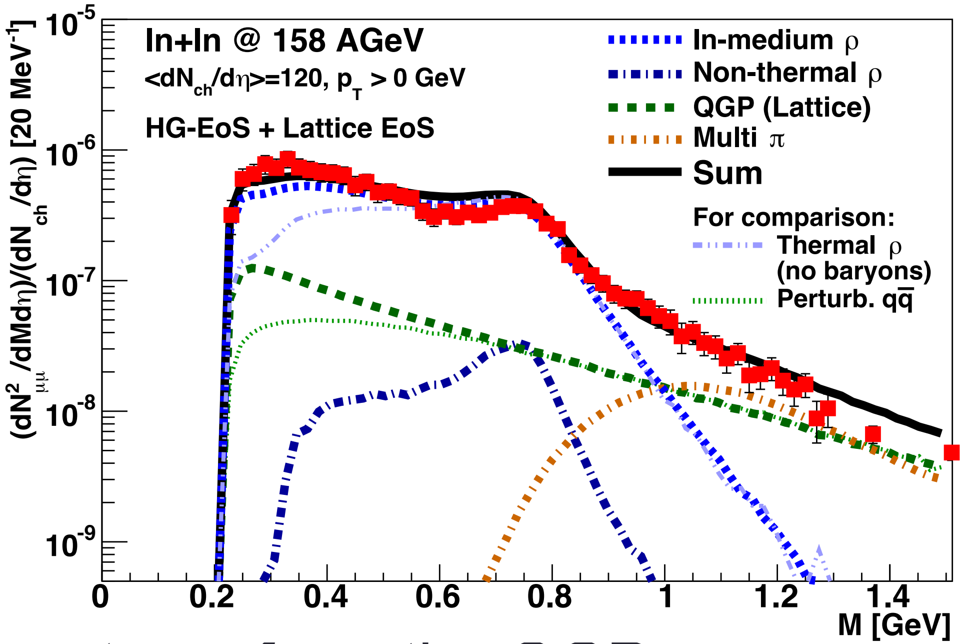
- Lepton pair emission is calculated for each cell of 4-dim. grid, using thermal equilibrium rates per four-volume and four-momentum from a bath at T and μB
- The ρ dilepton emission (similar for ω, φ) of each cell is accordingly calculated using the expression *[R. Rapp, J. Wambach, Adv. Nucl. Phys. 25, 1 (2000)]*

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

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

NA60 di-muon excess (now with cg)

- In-medium ρ shows broadening compared to case without baryons
- 4π and QGP contribution dominate especially above 1 GeV



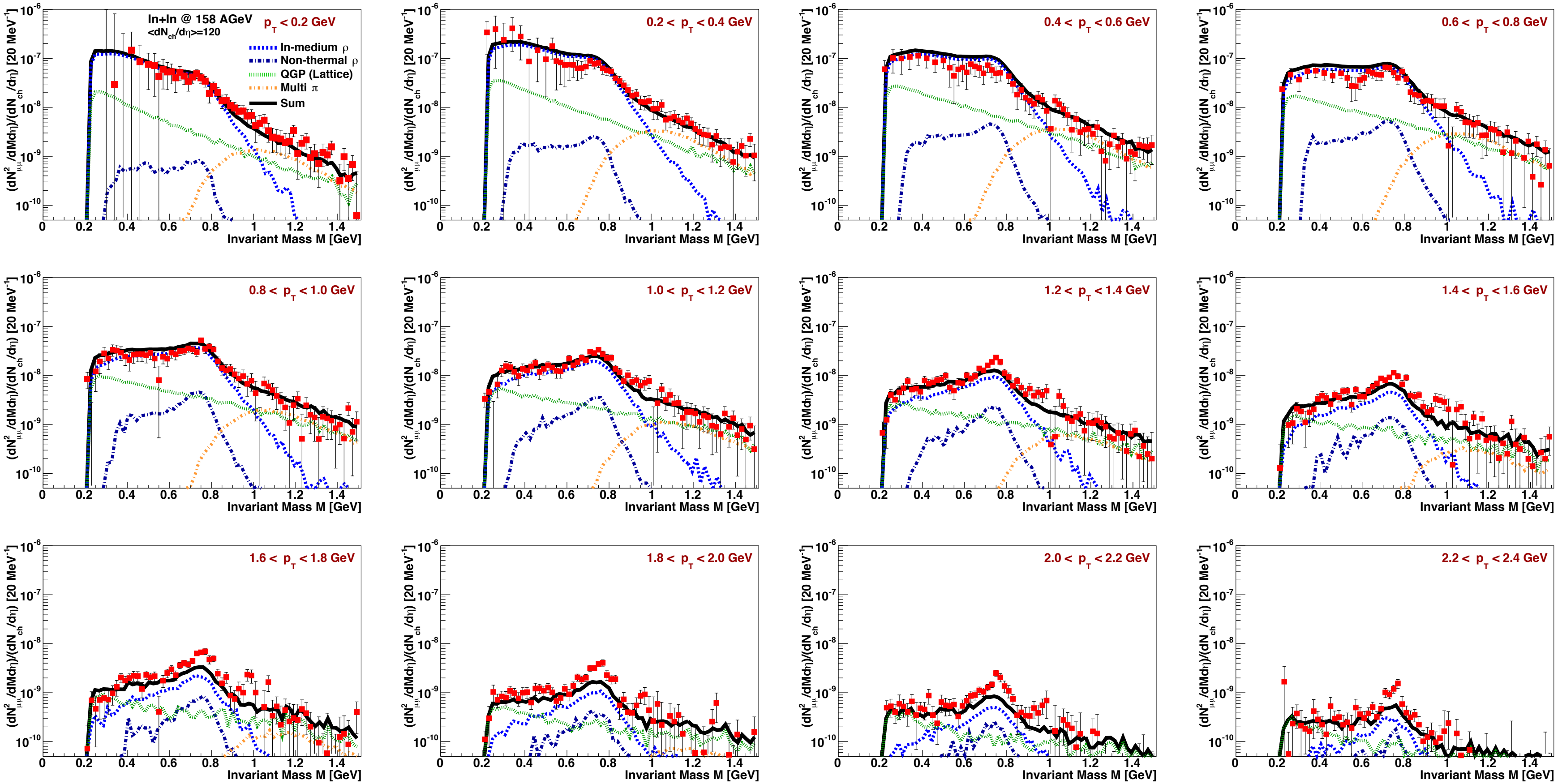
- Significant part of the excess at low masses also stems from the QGP

⇒ Good overall agreement between coarse-graining result and NA60 data

⇒ Results similar to fireball approach in spite of different dynamics

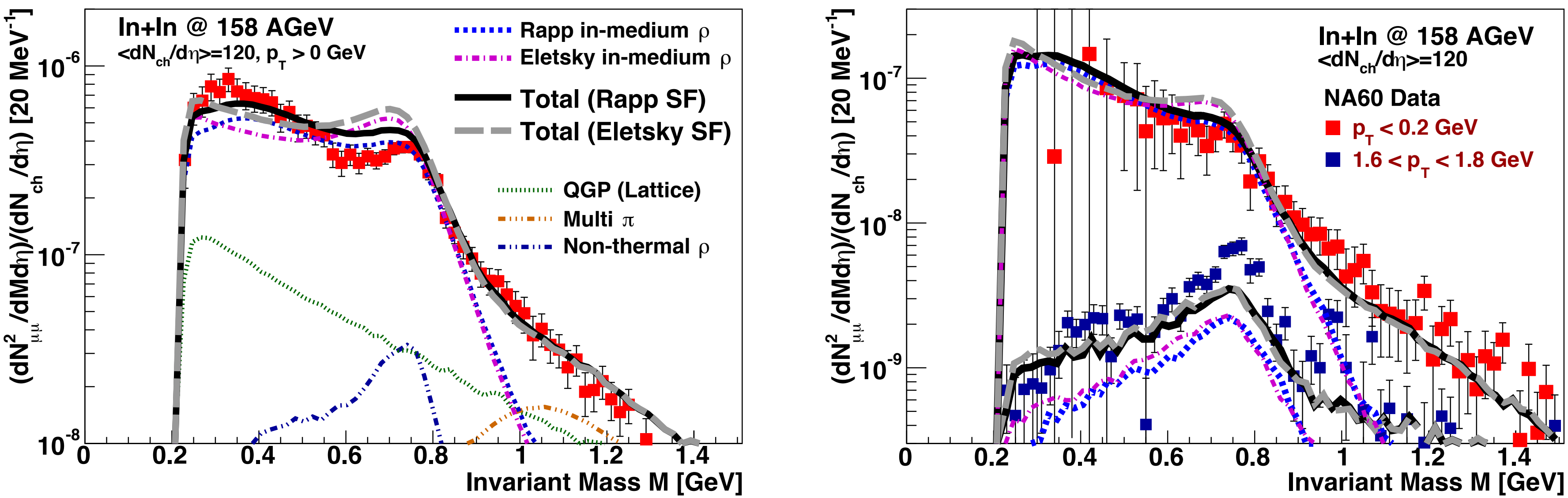
Endres, Hees, Bleicher, Phys.Rev.C 91 (2015) 5, 054911

pt spectra in In+In at 160 AGeV



Endres, Hees, Bleicher, Phys.Rev.C 91 (2015) 5, 054911

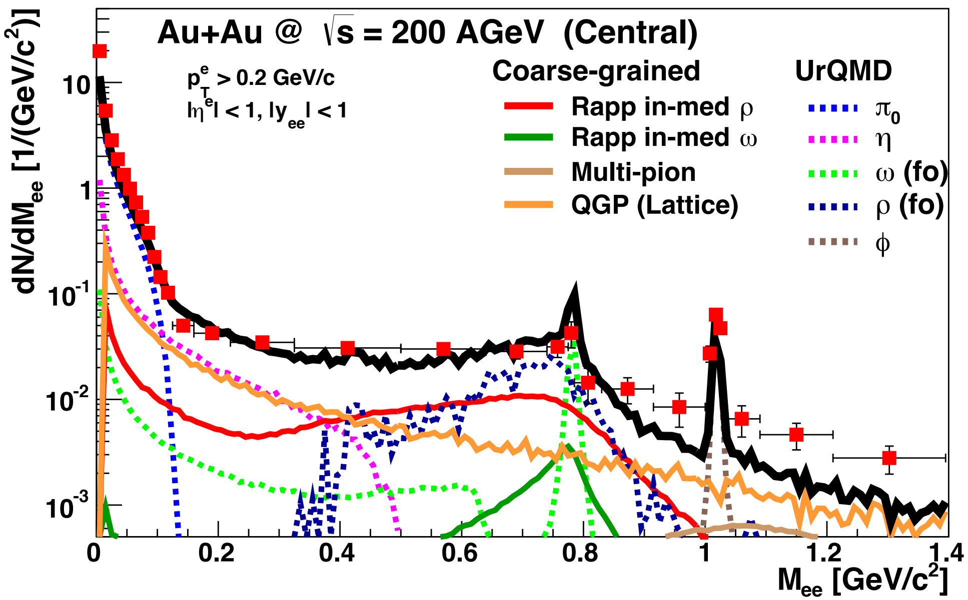
Comparison of the spectral functions



- In *[V. L. Eletsky et al., Phys. Rev. C64, 035303 (2001)]* not enough broadening due to low-density expansion of the self energies
  → Overshoots data at peak as observed before

Endres, Hees, Bleicher, Phys.Rev.C 91 (2015) 5, 054911

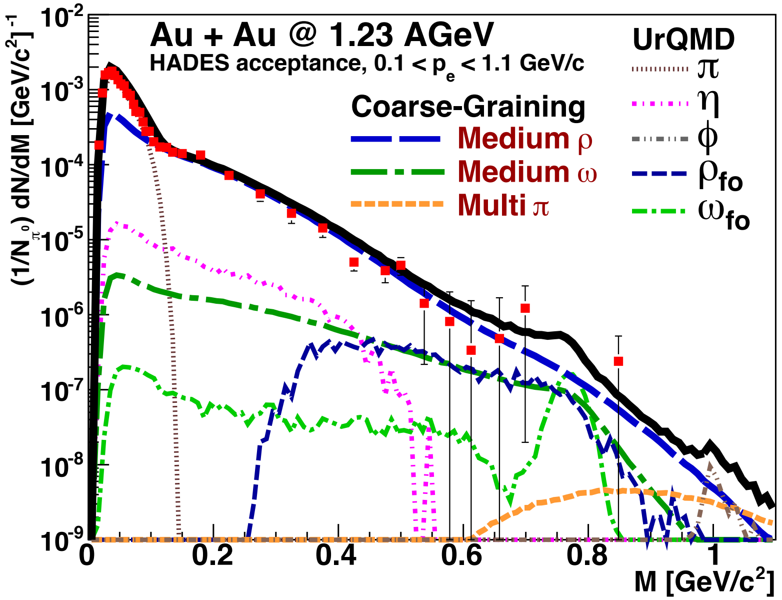
Cross check with RHIC

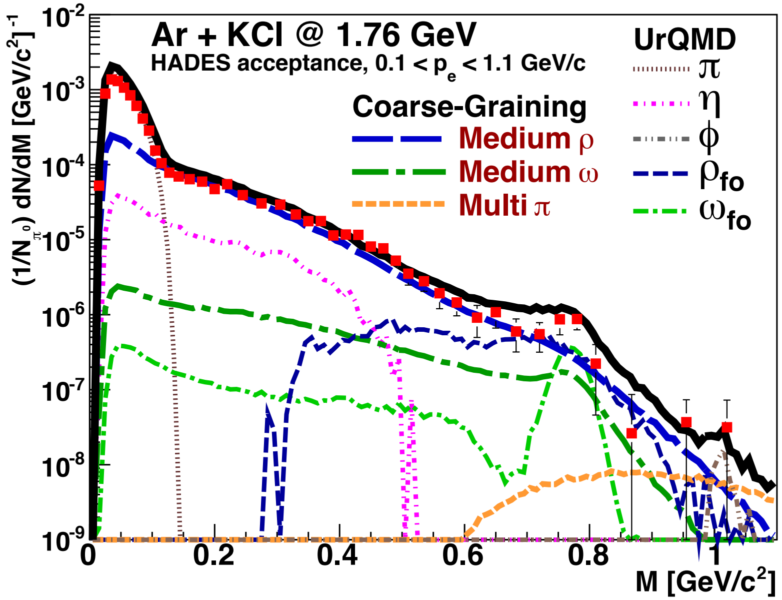


- QGP dominates thermal emission at low and high masses
- Also significant non-thermal ρ
- Missing contribution from charm at higher masses

Endres, Hees, Bleicher, Phys.Rev.C 94 (2016) 2, 024912

HADES results

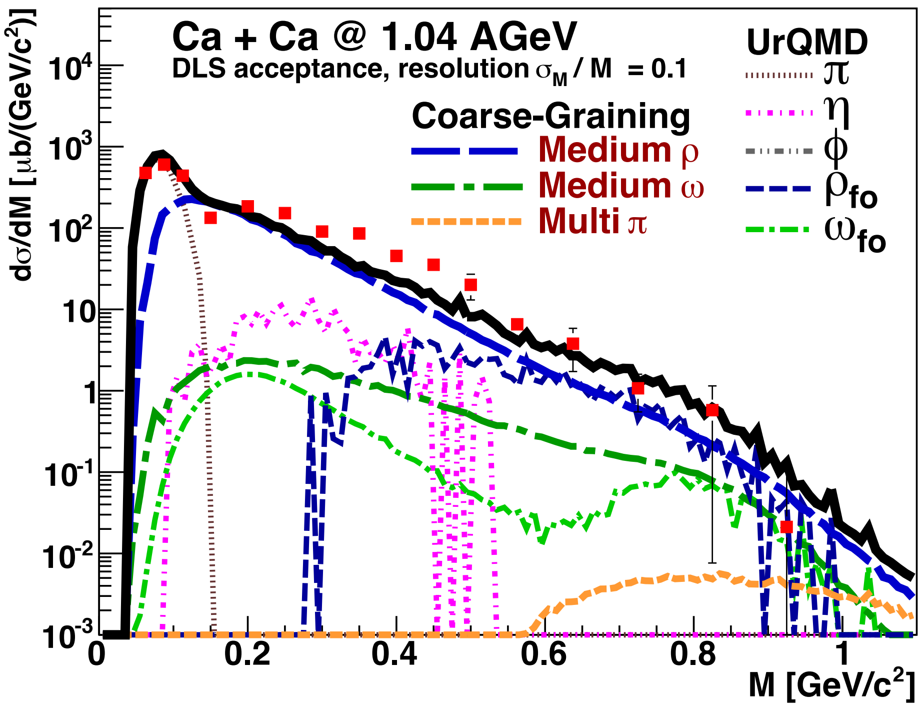




- At those low collision energies a significant in-medium broadening of the ρ spectral function appears
- High baryon chemical potential
  → Good check for baryonic effects in spectral functions

Endres, Hees, Bleicher, Phys.Rev.C 92 (2015) 1, 014911

What about DLS data?!



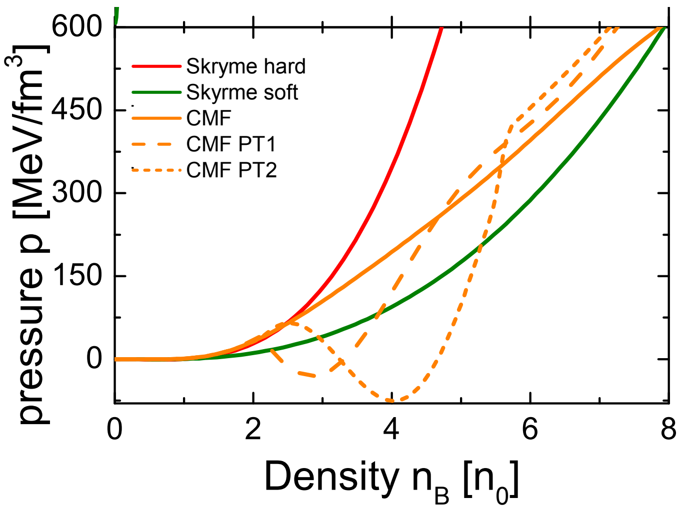
- Experimental excess in mass range 0.2 to 0.6 GeV
- Possible reasons: Bremsstrahlung (low energy!), limits of thermal description, quality of filter and data, . . .

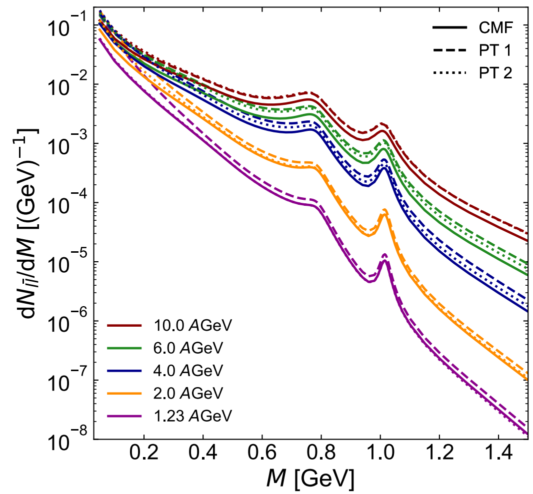
Endres, Hees, Bleicher, Phys.Rev.C 92 (2015) 1, 014911

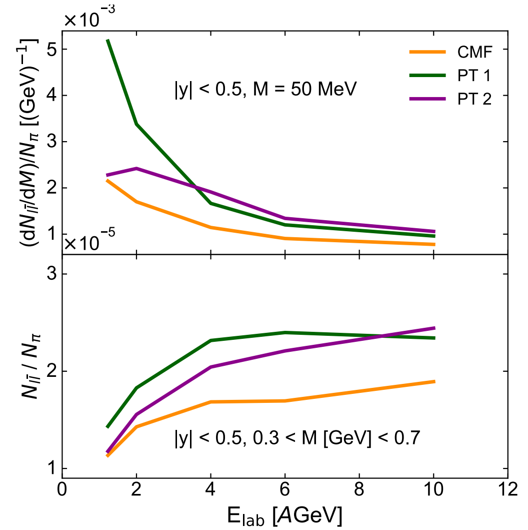
Conclusion of coarse graining

- Looks good at first glance
  - Our c/g code is also used for SMASH
  - Simplified reimplementation used by GSI group w/UrQMD
- Why does it look good?
  - at SPS above phase transition
  - At SIS below the phase transition
  - → No problem with mixed phase expected at FAIR
- For FAIR:
  Need model that includes phase transition in initial stage and delayed expansion when entering mixed phase

UrQMD with phase transition







Steinheimer, Sorensen, Nara, Motornenko, Koch, MB 2208.12091

Savchuk, Motornenko, Steinheimer, Galatyuk, MB, arxiv:2209.05267

- Effects of a phase transition are visible in de-leptons!
- Enhancement on the order of factor 2-5

Summary

- Dileptons have the potential to map out in-medium spectral functions
- Dileptons allow to see the onset of QGP formation

- But: 1f hydro, hybrid models and coarse graining are **not** enough to capture all physics that we expect (work underway to fix coarse graining!)

- Possible solution: multi-fluid hydrodynamics