Electromagnetic probes from SIS18 to LHC energies in coarse-grained transport simulations

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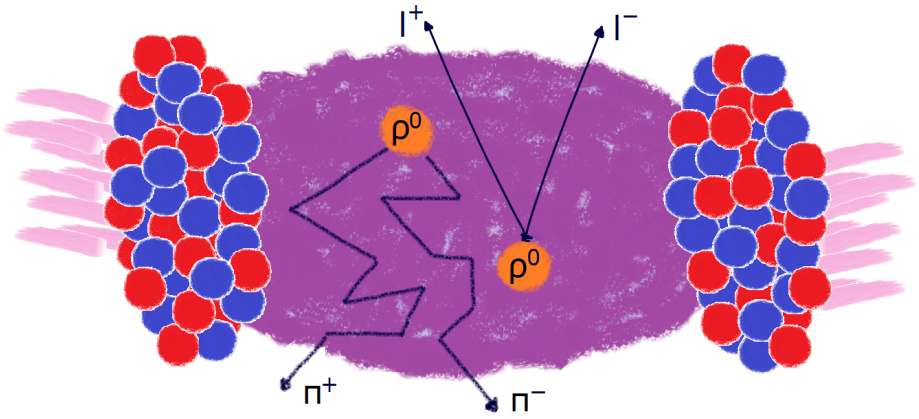
H-QM Helmholtz Research School Quark Matter Studies

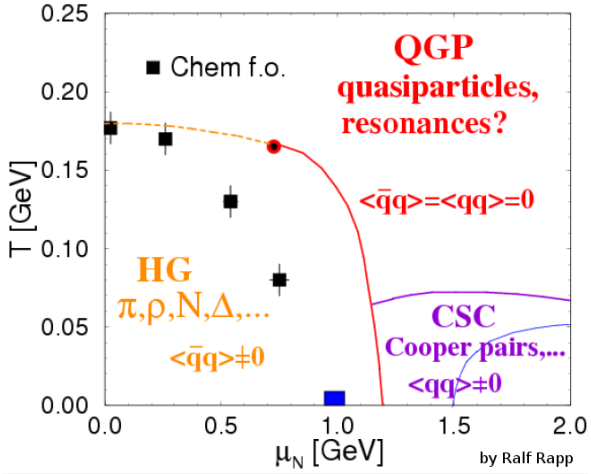
HIC for FAIR Helmholtz International Center

FIAS Frankfurt Institute for Advanced Studies

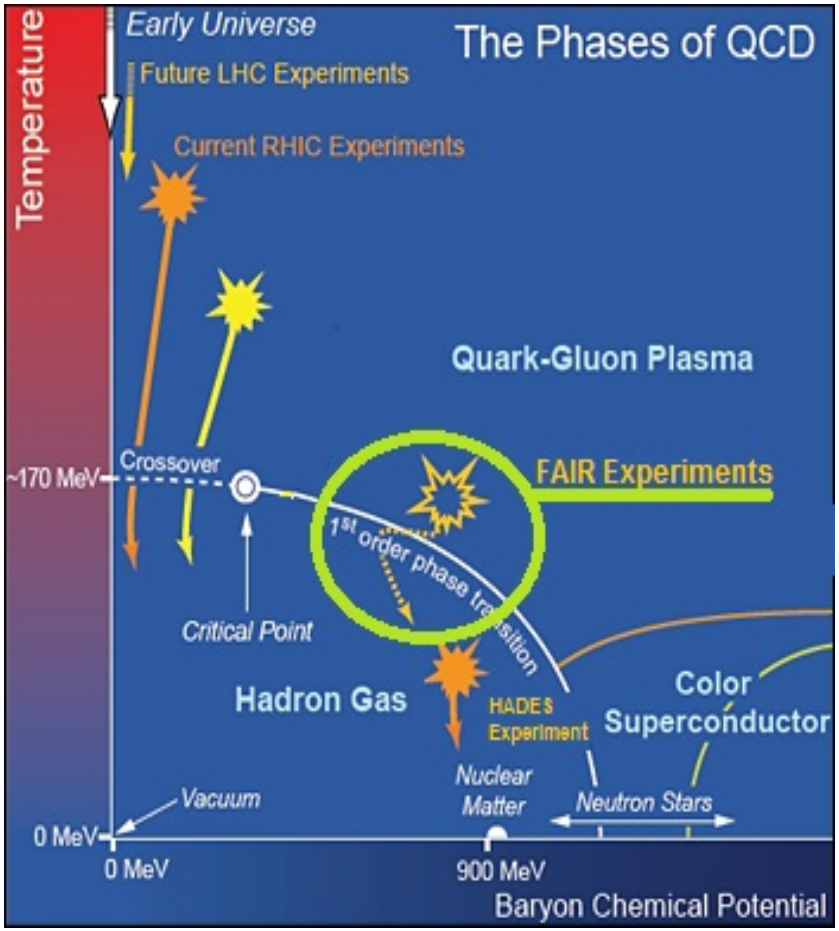
Why studying electomagnetic probes...?

- Clean and penetrating probe of hot and dense nuclear matter
- Reflect the **whole dynamics of a collision**
  - ↪ Allows to obtain information about the properties of <u>all</u> stages of the fireball
- Aim of studies: Properties of matter at finite T and μ_B
  - ↪ Hadrons in a dense and / or hot environment → More and more fundamental degrees of freedom dominate
  - ↪ Understanding the non-perturbative region of QCD
  - ↪ How are the "two faces" of QCD connected?





What can we learn from experiment and theory?

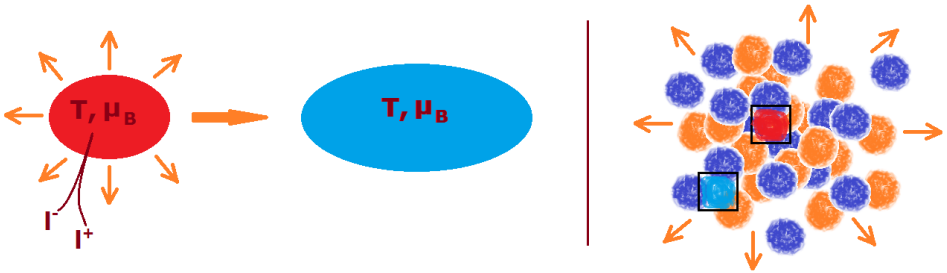


- **Dilepton spectra reflect trajectories of the system in QCD phase diagram**
- RHIC and LHC: High temperature, low baryochemical potential → What are the properties of the QGP?
- SIS 18: Moderate temperature and high baryochemical potential → What baryonic medium-modifications do appear?
- FAIR: Is there a 1st order phase transition / a critical point?

⇒ **Excitation function**: Equation of state of nuclear matter; test of spectral functions, chiral symmetry restoration?

Theoretical approaches: Microscopic ↔ Macroscopic

- Challenging for theoretical approaches...
  1. Hadronic low-energy domain of QCD → **No description from first principles!**
  2. **No fully self-consistent off-equilibrium scheme available!**
- **Models**: Simplification of the problem → Approximations
  ↪ Need depiction of space-time evolution, various sources and medium effects
- **Macroscopic models** → Bulk properties of the collision
  - **Fireball description** → Quite simplifying, global equilibrium
  - **Hydrodynamics** → Needs initial state & description of final state interactions - applicability at low energies?
- **Kinetic transport theory** → Describe all particle momenta and positions and all interactions individually



Hadronic Models

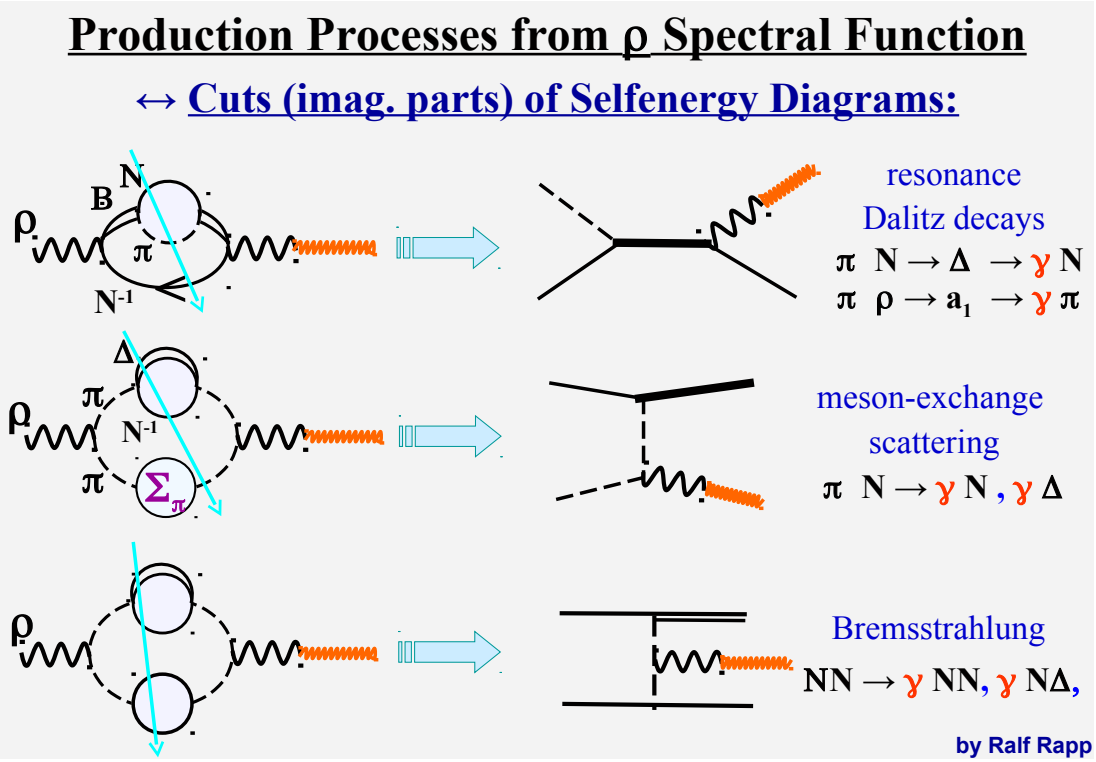
1. **Kinetic theory**
   - Realized in **transport models** (here UrQMD)
   - Effective solution of the **Boltzmann equation**
   - Physics input and parameters: cross-sections (total and partial), resonance parameters, string fragmentation scheme
   - **"On-shell" quasi-particles** on classical trajectories
   - Collision term includes **elastic & inelastic scatterings** (e.g. $\pi\pi \to \rho$) and **resonance decays** (e.g. $N^* \to N + \pi$)

   $\hookrightarrow$ But: Incoherent summation over processes, missing off-shell dynamics, restricted to lower densities (no multi-particle interactions) $\to$ **Medium effects only partially implemented**
2. **Hadronic many-body theory**
   - Calculate particle **self-energies** using **quantum field theory**
   - **Coherent summation**: Accounts for quantum interference

   $\hookrightarrow$ But: Restricted to equilibrated matter, assumes heat bath

$\to$ **Two sides of the same medal!**

Connection between HMBT and transport theory?



- Spectral function includes contributions explicitly treated in transport models (Bremsstrahlung, Δ Dalitz decays)
- **Coherent vs. incoherent summation** of processes – and different approximations...
- ...but nevertheless **same underlying microscopic physics**!

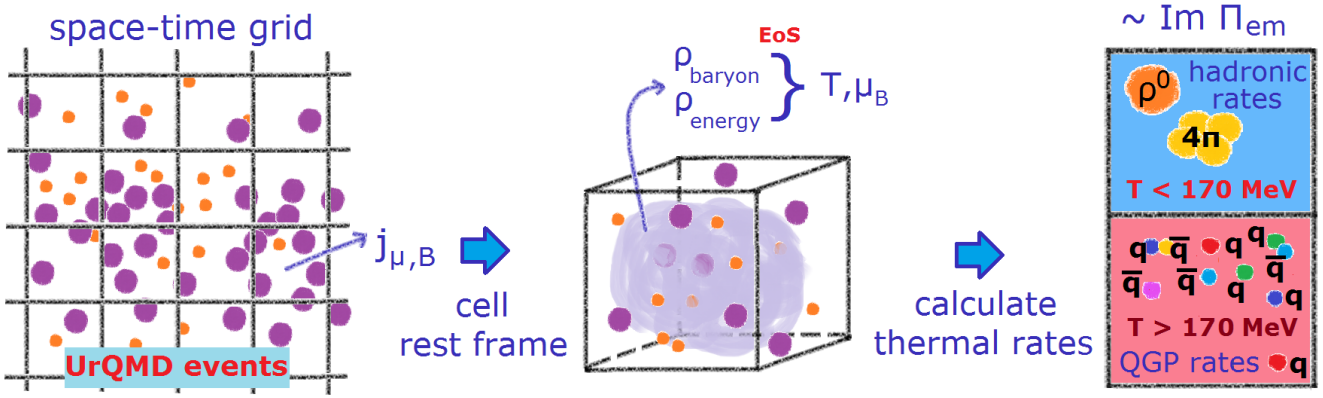
The Idea: Coarse-Graining

- Goal: One approach for all energies, realistic evolution of the reaction, but limited number of variables
  - ↪ Combining a realistic 3+1 dimensional microscopic expansion of the system with macroscopic description of the dilepton emission
- **Coarse-graining = Reduction of information** → System uniquely determined by (local) energy and particle densities
- Microscopic description → Necessary to average over many simulation 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
  - ↪ Equilibrium quantities have to be extracted locally at each space-time point

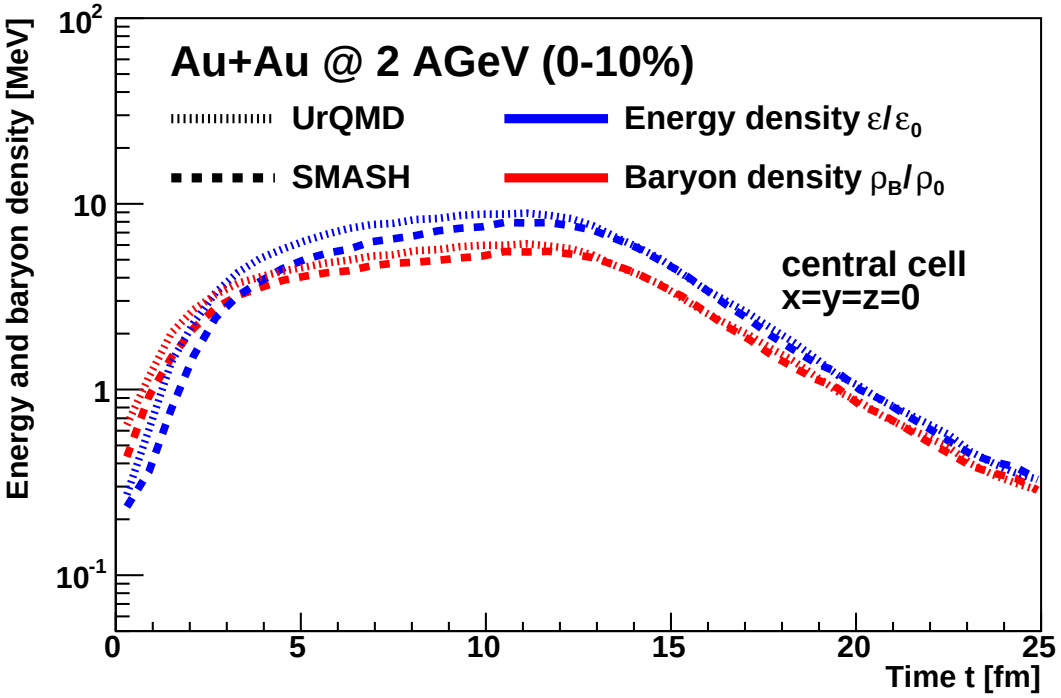
Coarse-Graining



- First proposed by Huovinen et al. [Phys. Rev. C66, 014903 (2002)]
- Put ensemble of UrQMD events on **grid of space-time cells**
- 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)]

Where is the advantage?



- **Robustness of the evolution** → Microscopic details differ, but evolution of energy and particle densities similar
- **Medium effects straightforward** in terms of T and μ_{B} ↔ *But*: Assumption of local equilibrium necessary

Accounting for Non-Equilibrium

→ To which extent is equilibrium obtained in the dynamics?

→ How can one deal with deviations from equilibrium?

- **Macroscopic descriptions** → *Equilibrium* usually introduced as ad-hoc assumption
- **Transport models** → *Non-equilibrium* normal case at any stage
- Two aspects have to be taken into account:
  1. Kinetic non-equilibrium → momentum-space anisotropies
  2. Chemical non-equilibrium → overdense pionic system
     → finite pion chemical potential μ_π

⇒ Calculate "effective" energy density and determine μ_π in Boltzmann approximation

Dilepton & Photon Rates

- Emission is calculated for each cell of 4-dim. grid
- Electromagnetic emission is **related to the imaginary part of the retarded current-current correlator** $\Pi_{\mathrm{em}}^{(\mathrm{ret})}$ as

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

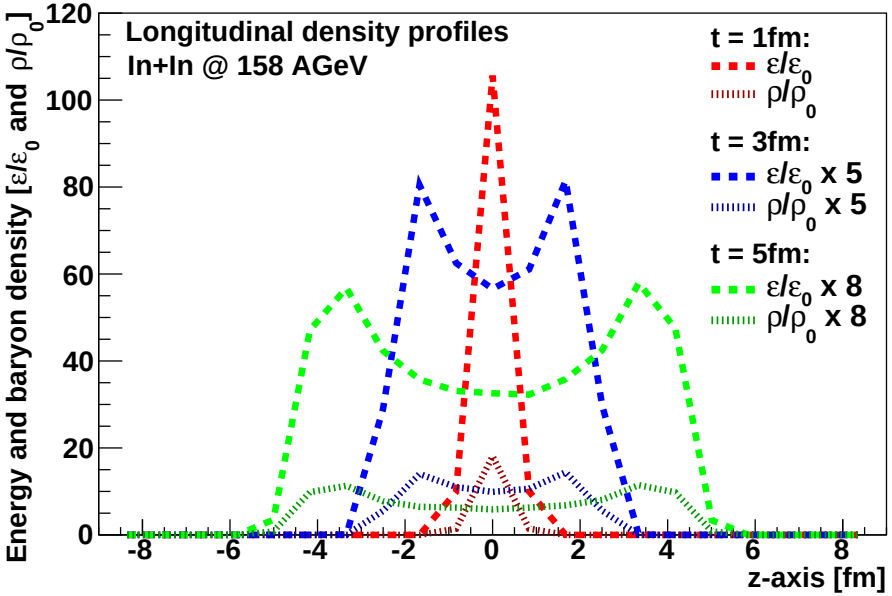
$$\frac{\mathrm{d}N_{ll}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha_{\mathrm{em}}^2 L(M)}{\pi^3 M^2}\, f_{\mathrm{B}}(q;T) \times \mathrm{Im}\ \Pi_{\mathrm{em}}^{(\mathrm{ret})}(M,\vec{q};\mu_{\mathrm{B}},T),$$

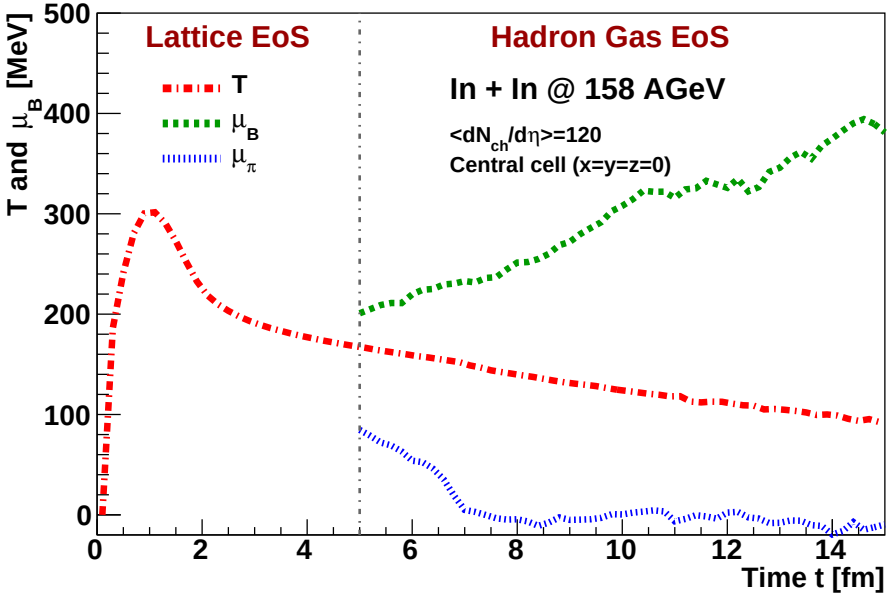
$$q_0\frac{\mathrm{d}N_{\gamma}}{\mathrm{d}^4x\mathrm{d}^3q} = -\frac{\alpha_{\mathrm{em}}}{\pi^2}\, f_{\mathrm{B}}(q;T) \times \mathrm{Im}\ \Pi_{\mathrm{em}}^{T,(\mathrm{ret})}(q_0=|\vec{q}|;\mu_{\mathrm{B}},T).$$

- Include ρ and ω spectral functions from HMBT (Rapp et al.), meson gas contributions and lattice rates for the QGP
- Non-thermal dilepton contributions (π, η, ϕ) directly from UrQMD + freeze-out ρ and ω (if $T < 50\,\mathrm{MeV}$)

$\hookrightarrow$ For more details about the CG-approach see PRC 91, 054911 (2015); PRC 92, 014911 (2015) and PRC 93, 054901 (2016)

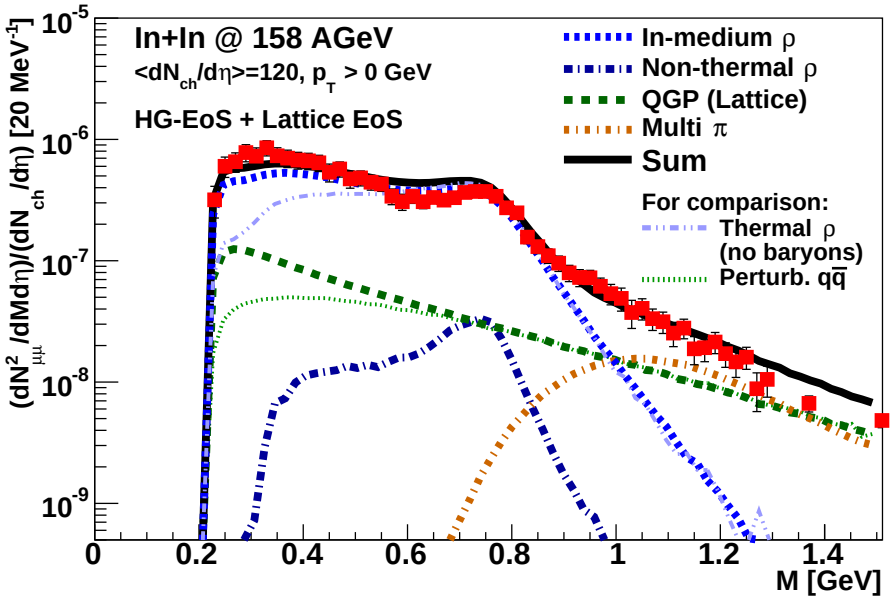
Baseline comparison for SPS / NA60 [S.E. et al., Phys. Rev. C 91, 054911 (2015)]

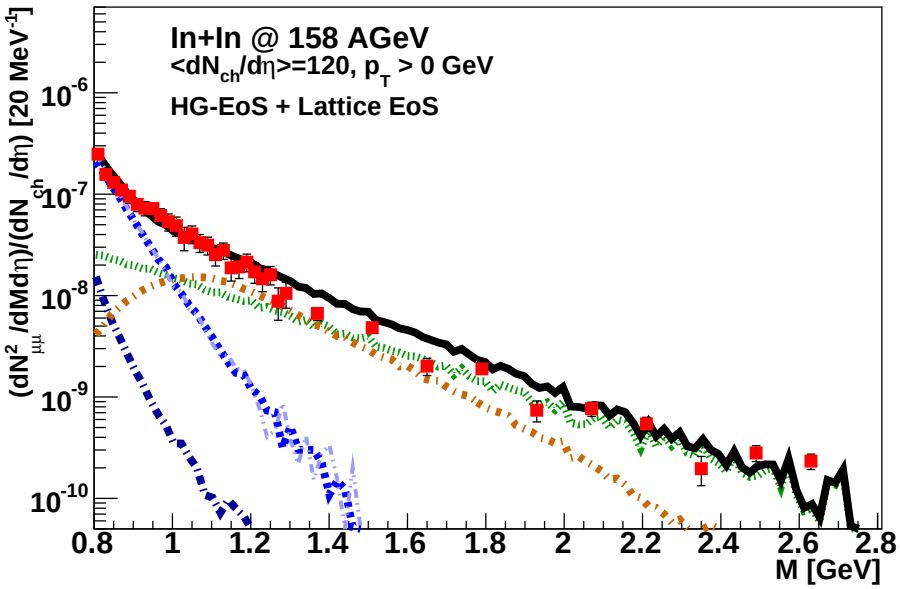




- The coarse-graining of UrQMD input gives **realistic and nuanced picture** of the collision evolution → Detailed space-time description of temperature and chemical potential
- At SPS one reaches temperatures significantly above T_c in combination with moderate values of μ_B
- Note: Right plot shows maxima of T and μ (central cell), not average → Different values for each space-time cell!

NA60 - Dilepton Spectra

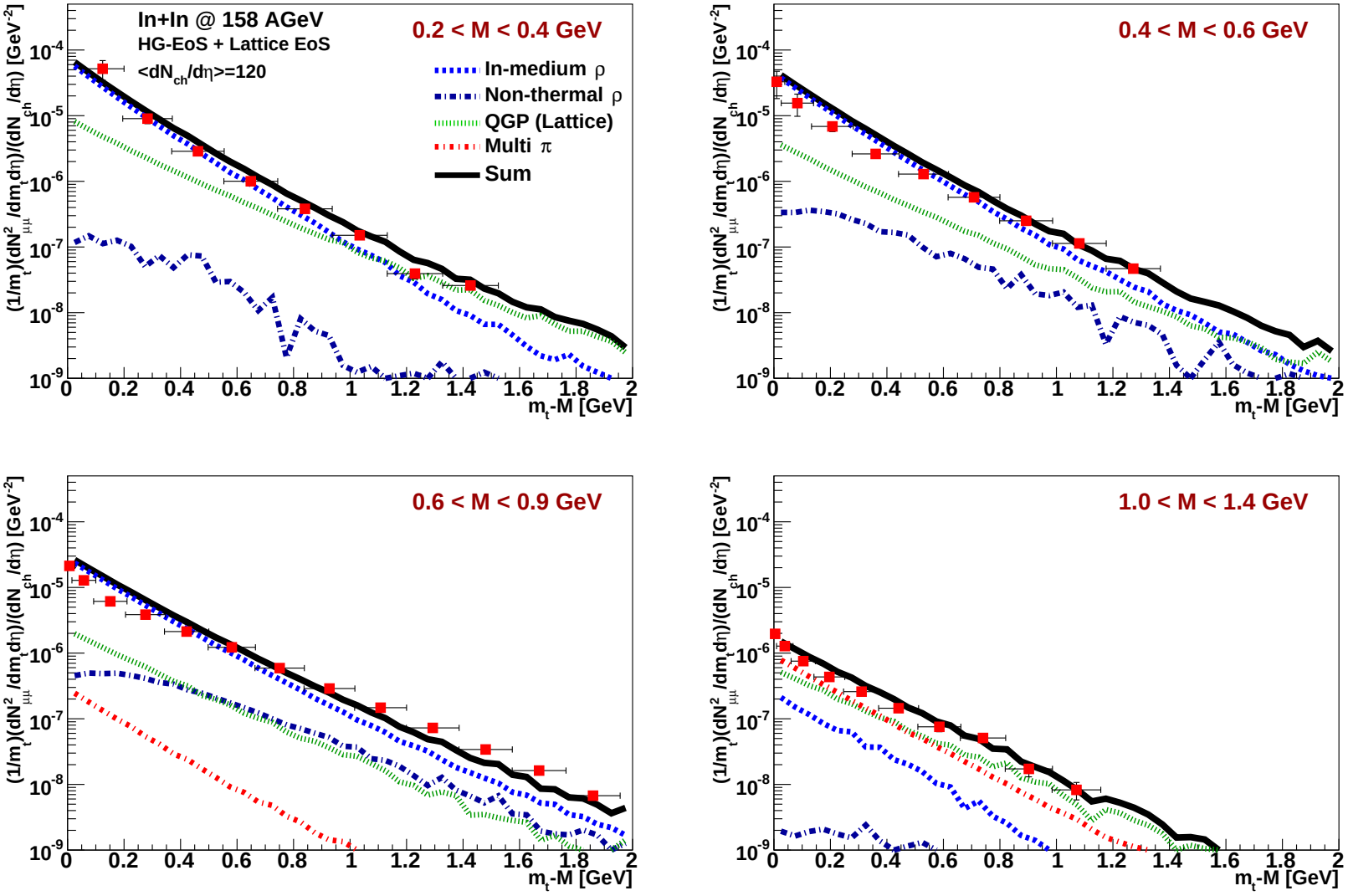




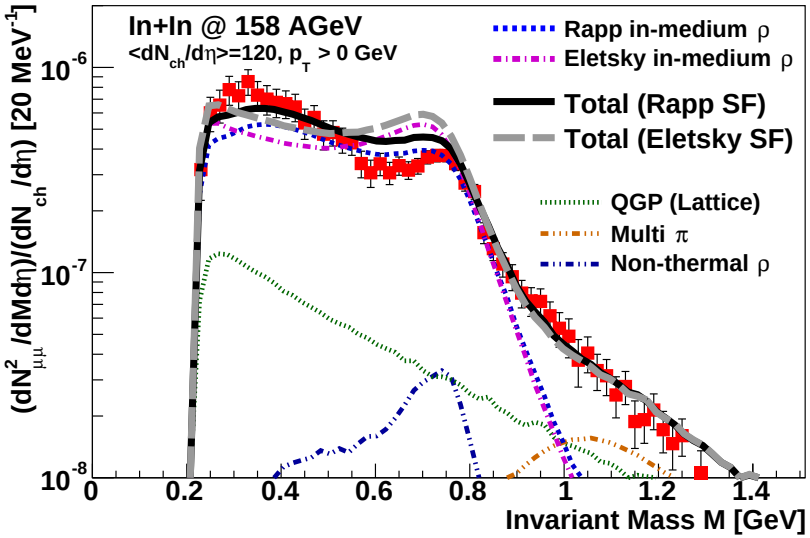
- ρ shows **broadening compared to case without baryons**
- QGP and multi-pion annihilation are the relevant sources in the intermediate mass region
- For M $>$ 1.5 GeV/c^2 QGP contribution clearly dominates
- **Duality** between hadronic and partonic emission rates?

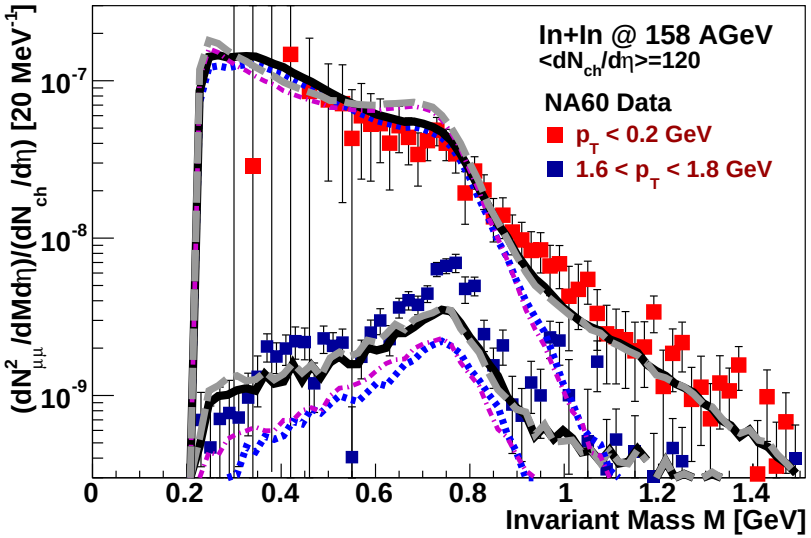
$\hookrightarrow$ Results agree with fireball + hydro calculations; differences in dynamics

NA60 - m_t Spectra



NA60 - Comparison of Spectral Functions



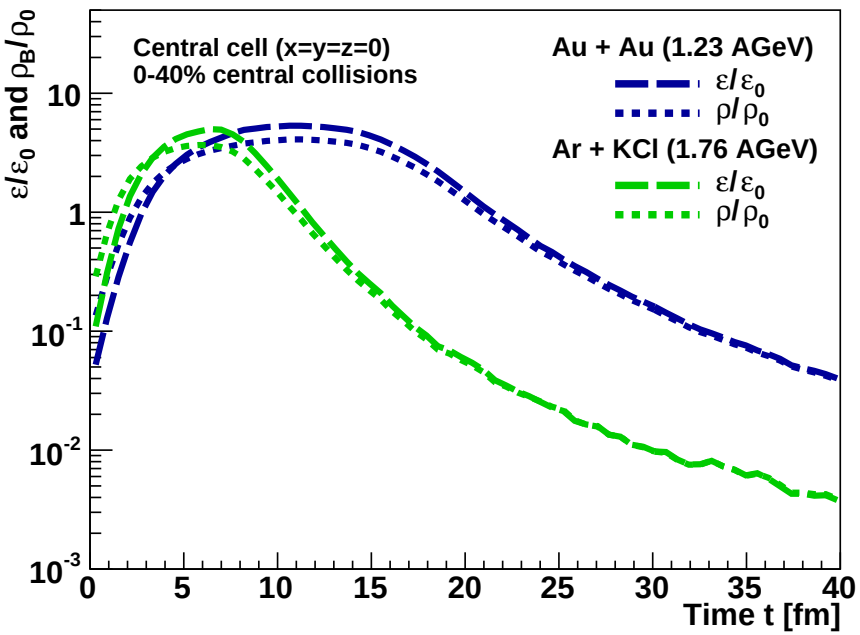


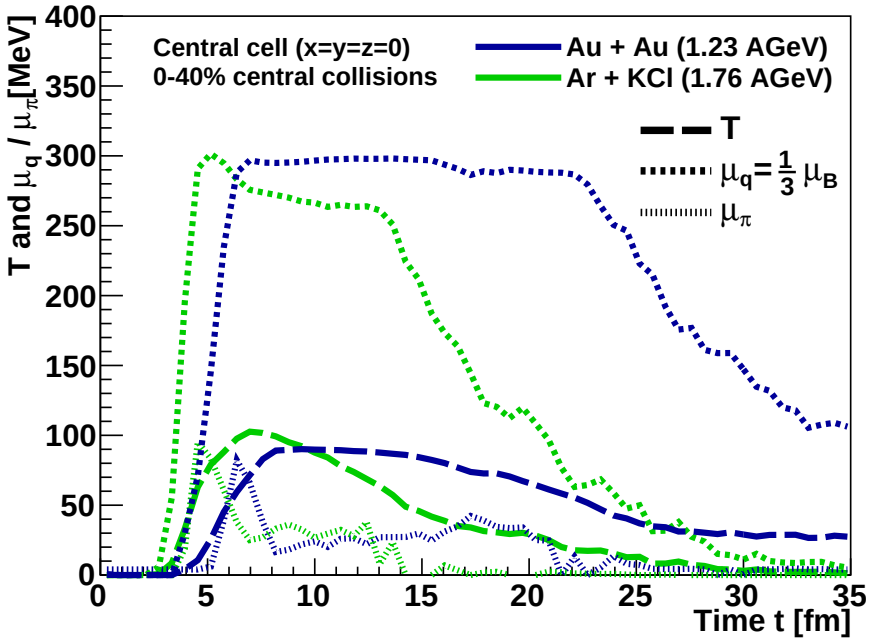
- HMBT results $\leftrightarrow$ ρ spectral function obtained using **empirical scattering amplitudes from resonance dominance**

  [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, underestimates for lower masses

SIS 18 - Low T, highest μ_B

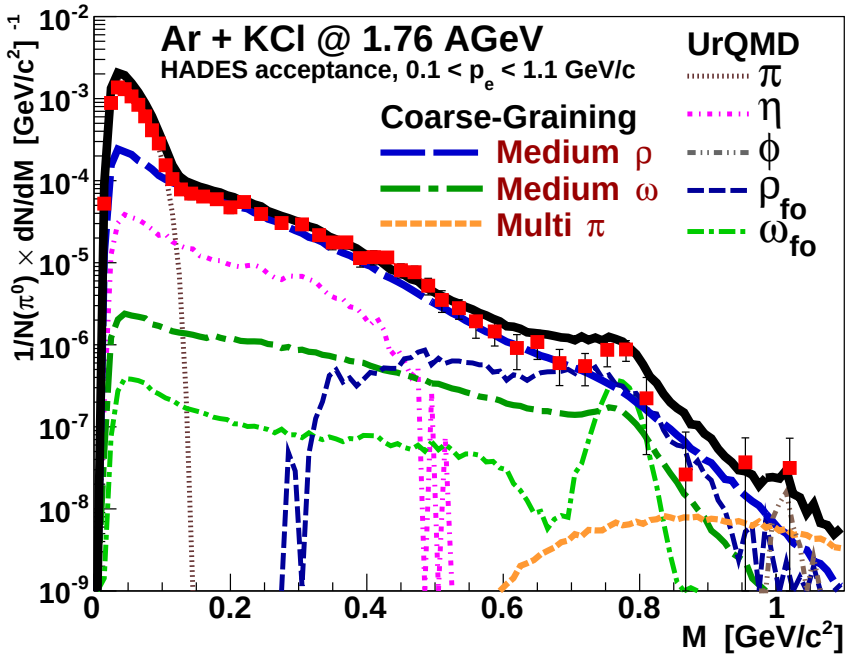
[S.E. et al., Phys. Rev. C 92, 014911 (2015)]

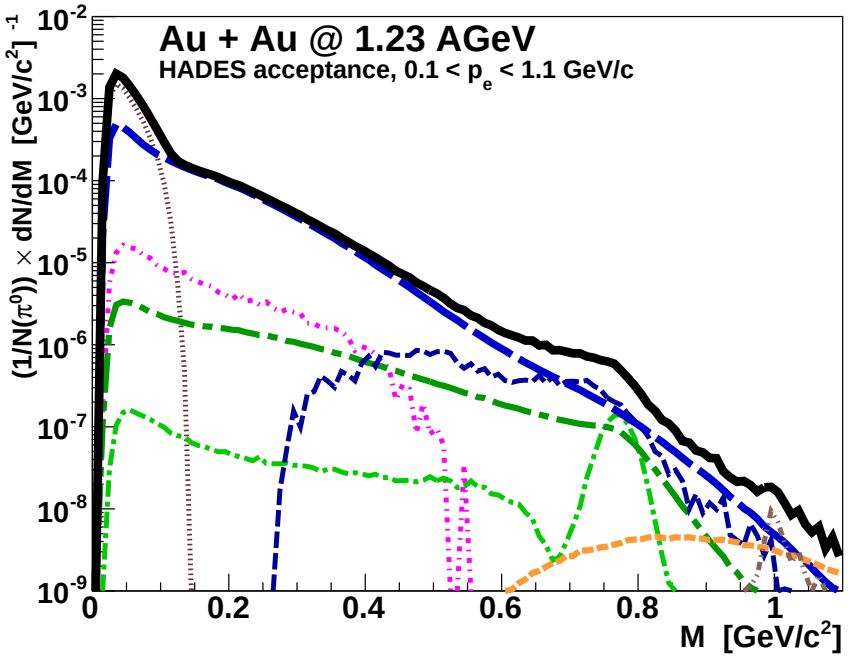




- **Very slow evolution** of the fireball
  - $\hookrightarrow$ T and μ_B remain roughly constant for up to 20 fm/c!
- Moderate temperatures and very **high baryon density** respectively baryochemical potential $\rightarrow$ Ideal situation to study in-medium modifications

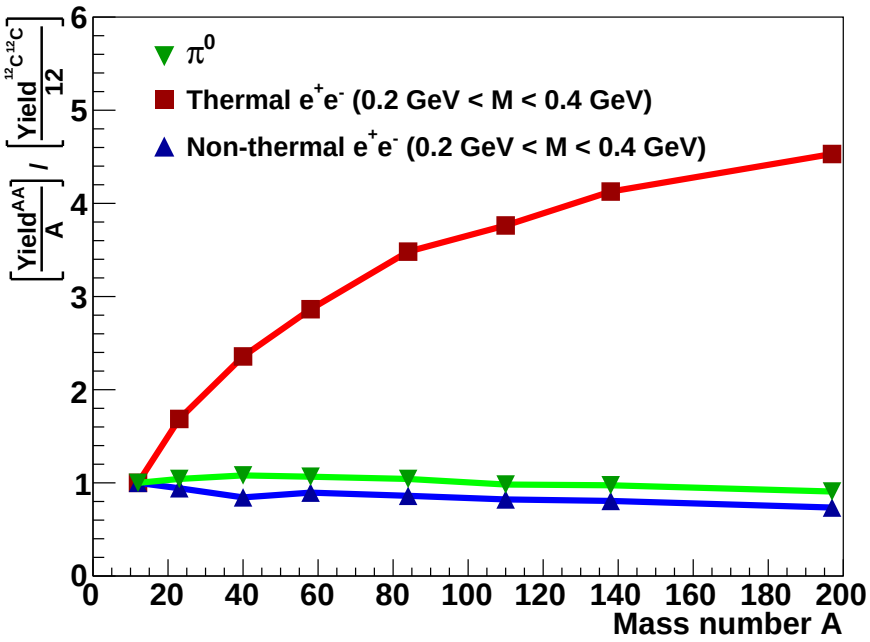
SIS 18 - Dilepton Spectra from HADES

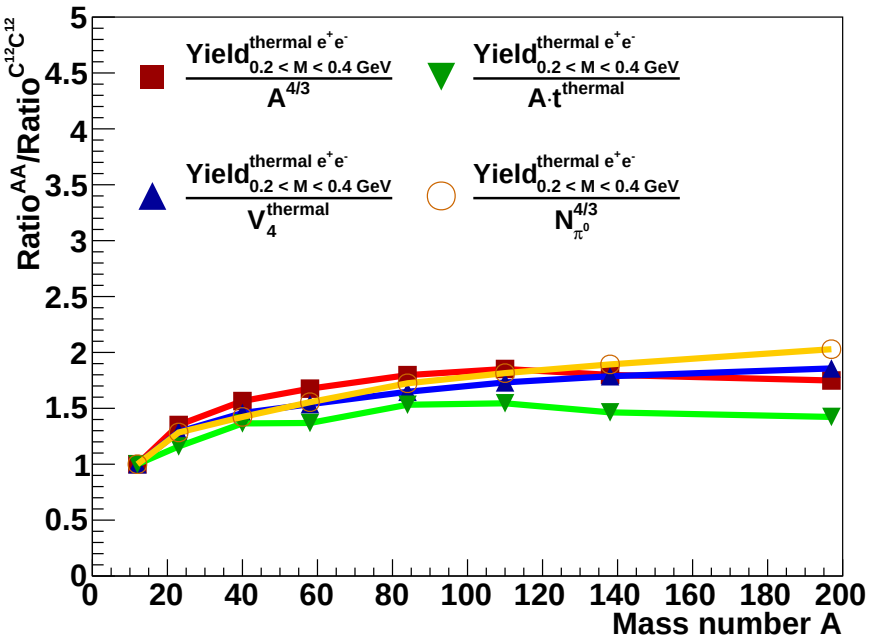




- **Significant in-medium broadening** of the ρ spectral function, causing a strong increase of the dilepton yield below the pole mass
- Low-mass enhancement **increases with system size**
- Low temperatures $\rightarrow$ Higher masses and pole mass peak suppressed

SIS 18 - System size & lifetime effects ($E_{lab} = 1.76 AGeV$)

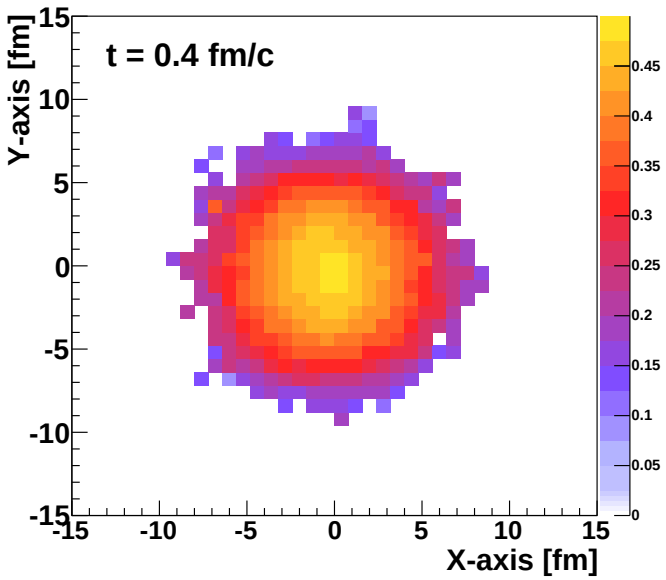


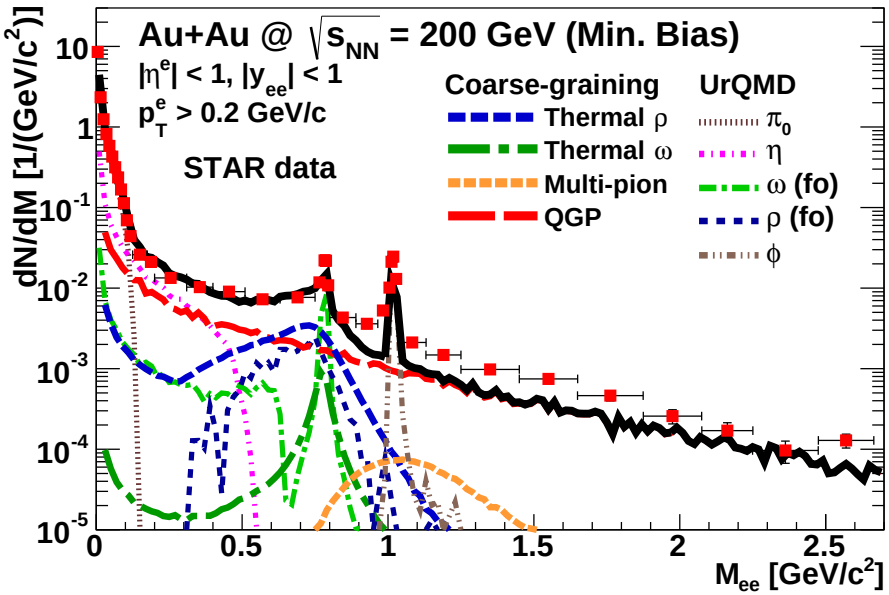


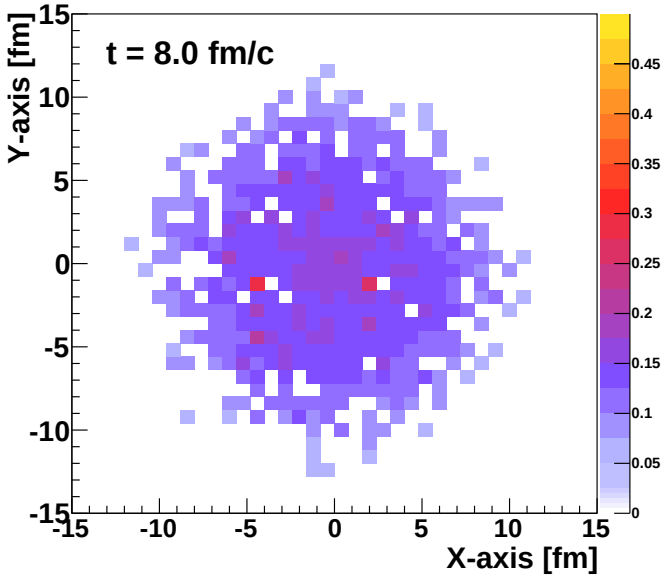
- *Non-thermal dileptons* represent **final hadronic state** (freeze-out volume) $\rightarrow$ Result scales with A
- *Thermal dileptons* depend on **volume and lifetime** $\rightarrow$ Show increase with $A^{4/3} \approx A \cdot t \approx V_4^{thermal}$
- Waiting for HADES Au+Au data...would be great to have more systematic studies in future experiments!

RHIC - Highest T, low μ_B

[S.E. et al., arXiv:1604.06415 [nucl-th]]

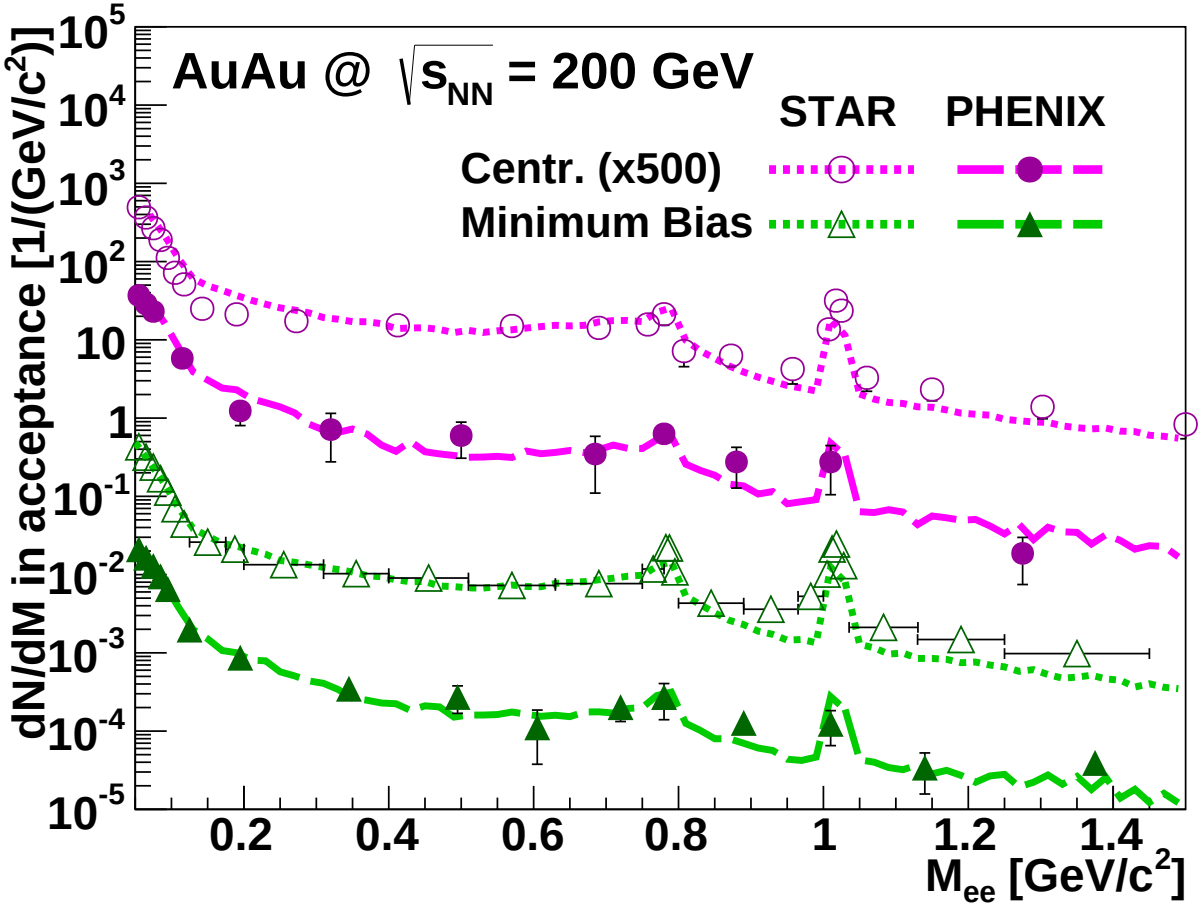






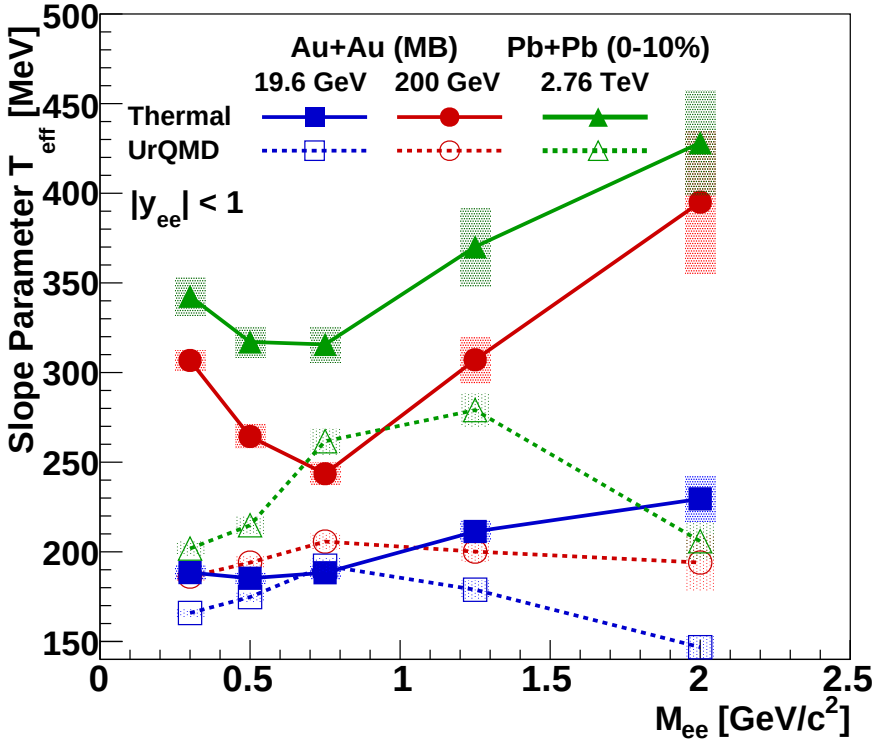
- At collider energies **high initial temperatures** ($T > 450$ MeV)
- Strong QGP contribution
- Medium-modified open charm not yet included
- **Low baryochemical potential**
  $\hookrightarrow$ Vacuum-like ρ and ω shape

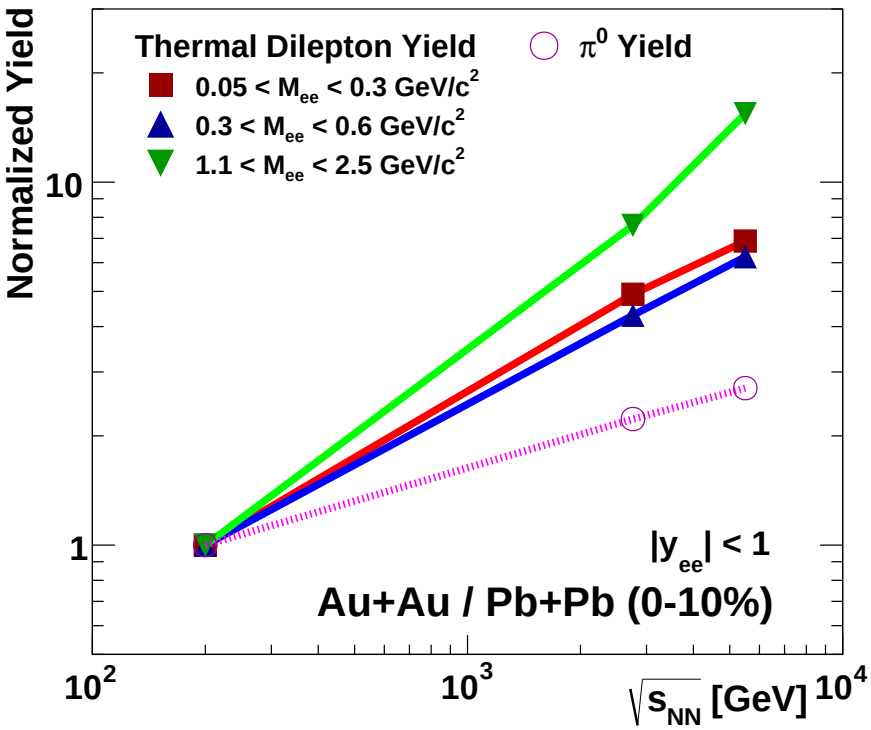
RHIC - Consistency between STAR and PHENIX results?



- Recent PHENIX measurement and STAR results compatible
- Low-mass region well described by theory

RHIC & LHC - Energy dependence of dilepton production

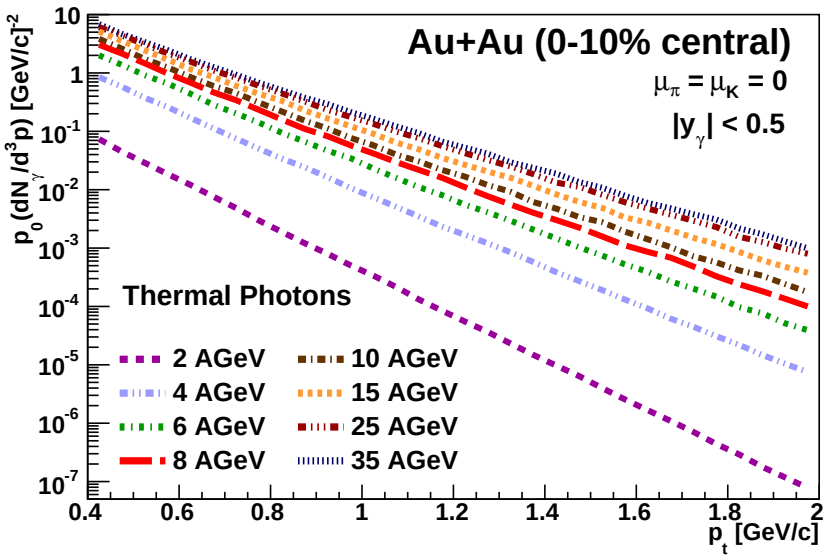


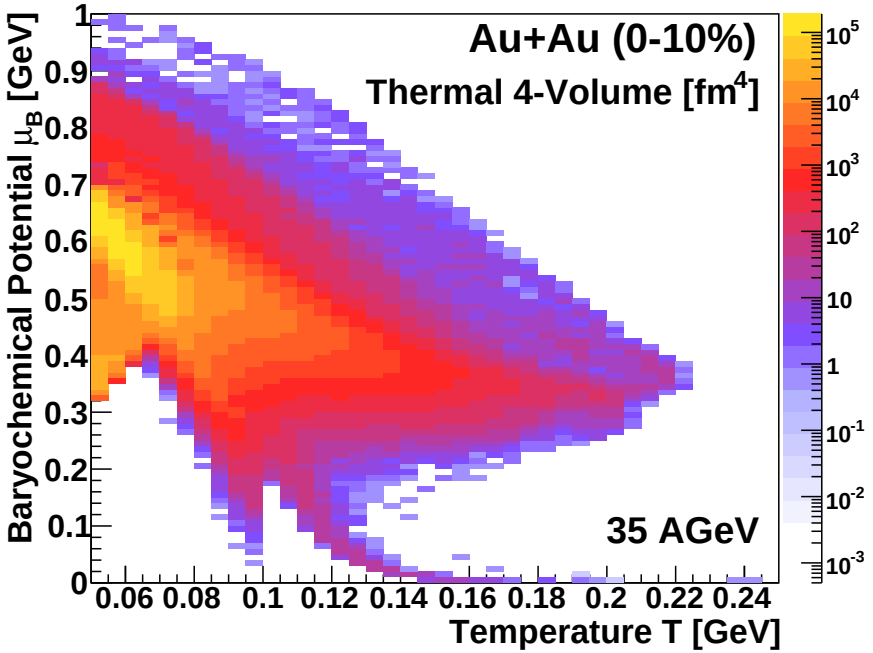


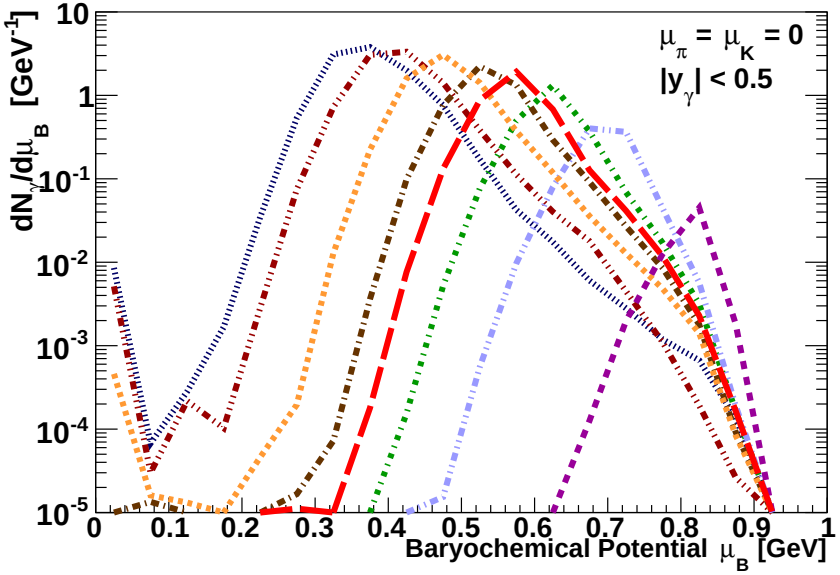
- **No qualitative difference** between RHIC and LHC results
  - ↪ μ_B already close to zero, only higher T
  - ↪ More QGP and harder slopes
- High-mass radiation shows strongest increase when going from RHIC to LHC
- Different mass dependence for thermal and non-thermal slopes

FAIR - What are the perspectives?

[S.E. et al., Phys. Rev. C 93, 054901 (2016)]

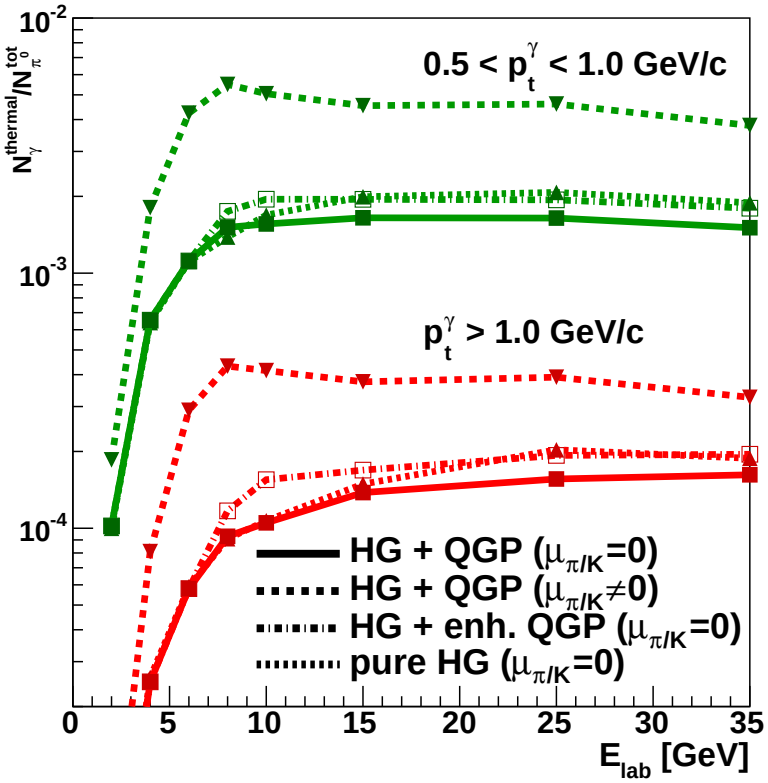


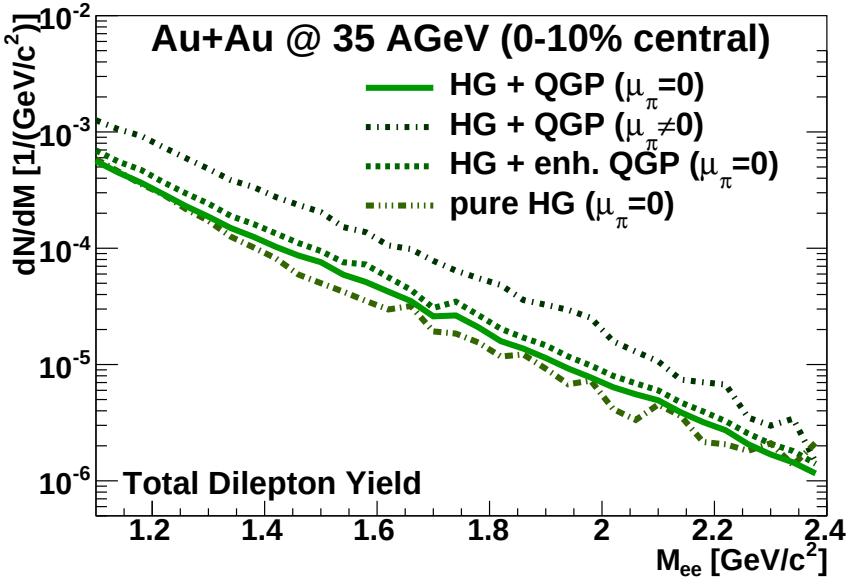




- Unexplored **transition region**
  - ↪ Hadron gas ↔ QGP
  - ↪ high μ_B ↔ moderate μ_B
- High luminosities enable **systematic studies**
  - ↪ Energy, momentum, centrality, system size, ...

FAIR - Signals for a phase transition?





- **Phase transition effects not very strong** $\leftrightarrow$ Duality of rates
- Several (more prominent) effects make it **difficult to find clear signals** for a phase transition
  - $\hookrightarrow$ Non-equilibrium (pion chemical potential)
  - $\hookrightarrow$ Finite baryon density

What did we learn - what can we learn?

- Dilepton spectra from SIS 18 to RHIC and LHC energies can be consistently described as a combination of
  1. a **cocktail** of hadronic decay contributions,
  2. thermal emission from **medium-modified vector-meson spectral functions**,
  3. and radiation from the **Quark-Gluon Plasma** phase
- Spectra fully determined by trajectory in $T - \mu_B$ plane
- Aspects which still have to be studied:
  - Open charm contribution due to correlated D and $\bar{D}$ mesons
  - Influence of the EoS $\leftrightarrow$ Consistency with underlying dynamics?
  - More detailed investigation of the non-equilibrium effects
  - How do the results compare to purely microscopic calculation?
- **Wishlist for experimentalists**: Systematic studies (of energy dependence, system size, ...), good statistics, better constraints for resonance parameters for hadronic models (pion beam @ HADES)