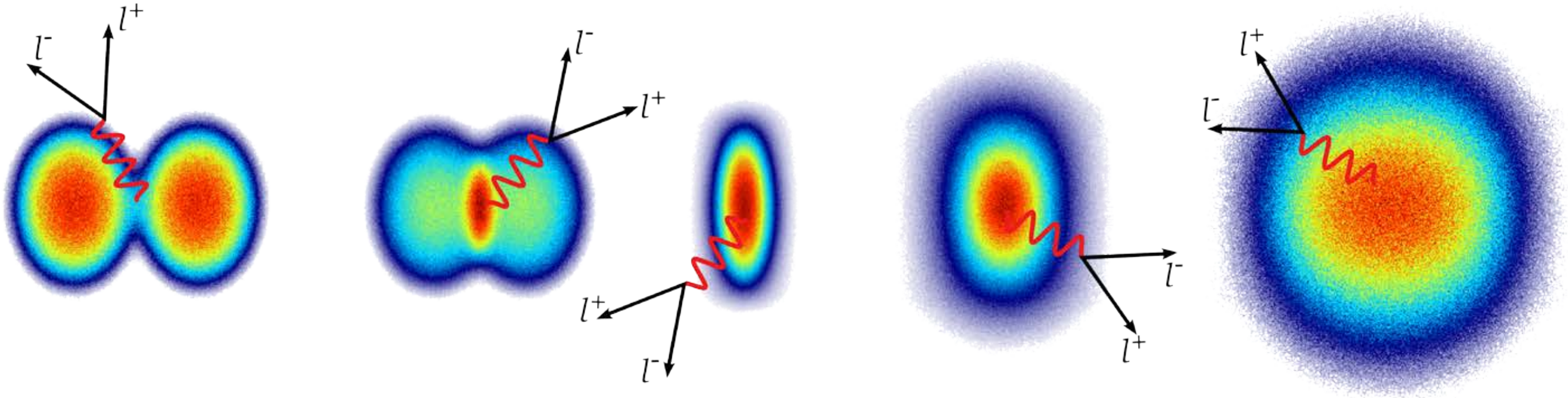
Modeling thermal dileptons at SIS energies

Thermal dileptons as fireball probes

XLVII. Arbeitstreffen Kernphysik in Schleching

Florian Seck – TU Darmstadt



Landmarks in the phase diagram of QCD matter

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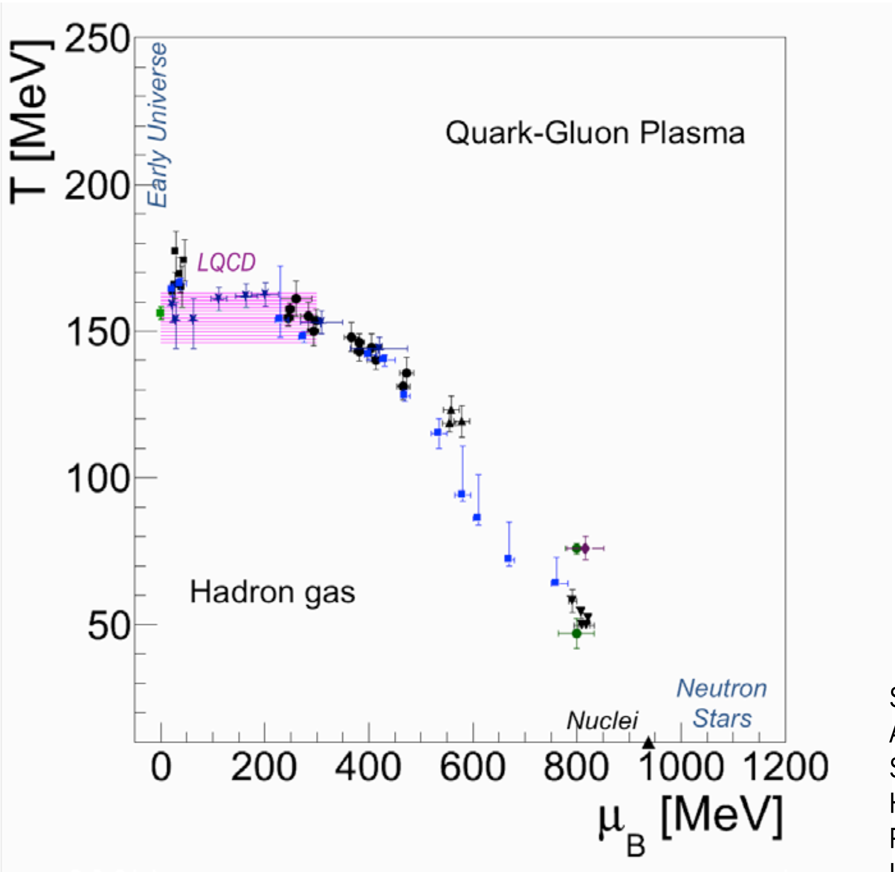

- What do we know?
  - chemical „freeze-out“ from measured particle yields analyzed with Statistical Hadronization Model
  - crossover transition at vanishing μ_B (lattice QCD)

SHM : J. Cleymans: PRC 73 (2006) 034905, A. Andronic PLB 673 (2009) 142
ALICE : J. Stachel, arXiv:1311.4662
STAR : PRC 79 (2009) 034909
HADES : NPA 931 (2014)
FOPI : PRC 76 (2007) 052203
Lattice : $T_c(\mu_B) = 154(9)\,[1-0.0006(7)\mu_B^2]$ MeV

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Landmarks in the phase diagram of QCD matter

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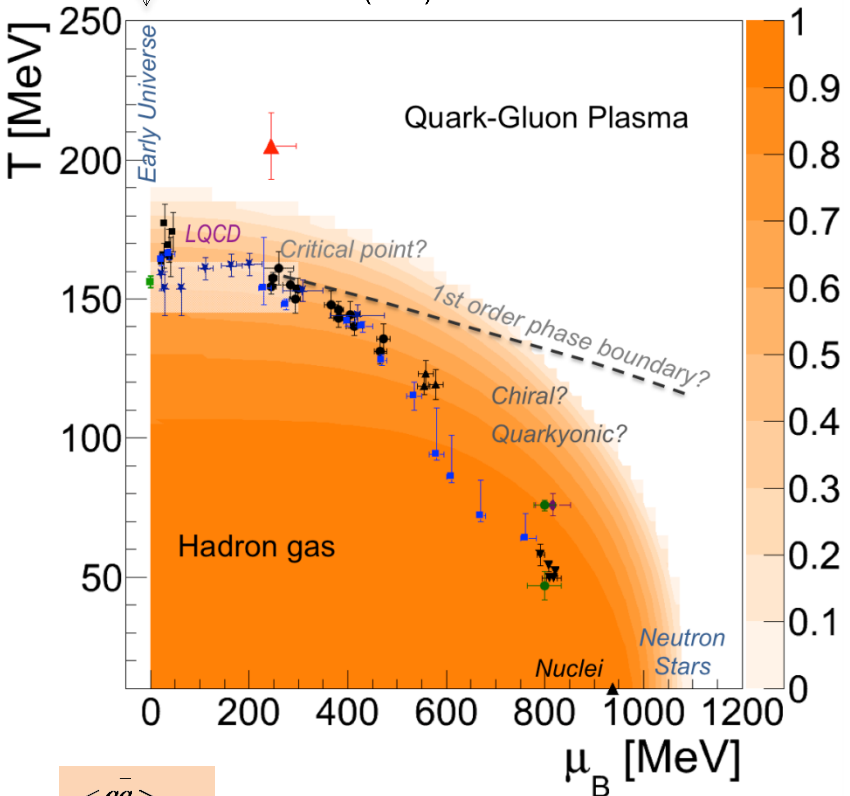
Direct γ
ALICE: JPCS 446 (2013) 012028
PHENIX: PRL 104 (2010) 132301



$\frac{\langle \bar{q}q \rangle_{T,\mu_B}}{\langle \bar{q}q \rangle_{T=0,\mu_B=0}}$

$\frac{\langle \bar{q}q \rangle_{T,\mu_B}}{\langle \bar{q}q \rangle_{T=0,\mu_B=0}}$: B.J. Schaefer and J. Wambach

▲ NA60 (μ+μ-) : H.J.Specht: AIP Conf.Proc. 1322 (2010)

- What do we know?
  - chemical „freeze-out“ from measured particle yields analyzed with Statistical Hadronization Model
  - crossover transition at vanishing μ_B (lattice QCD)
- What is predicted?
  - possible 1st order phase transition and critical point at large μ_B
  - QCD inspired effective models predict the melting of the condensate (order parameter) χ

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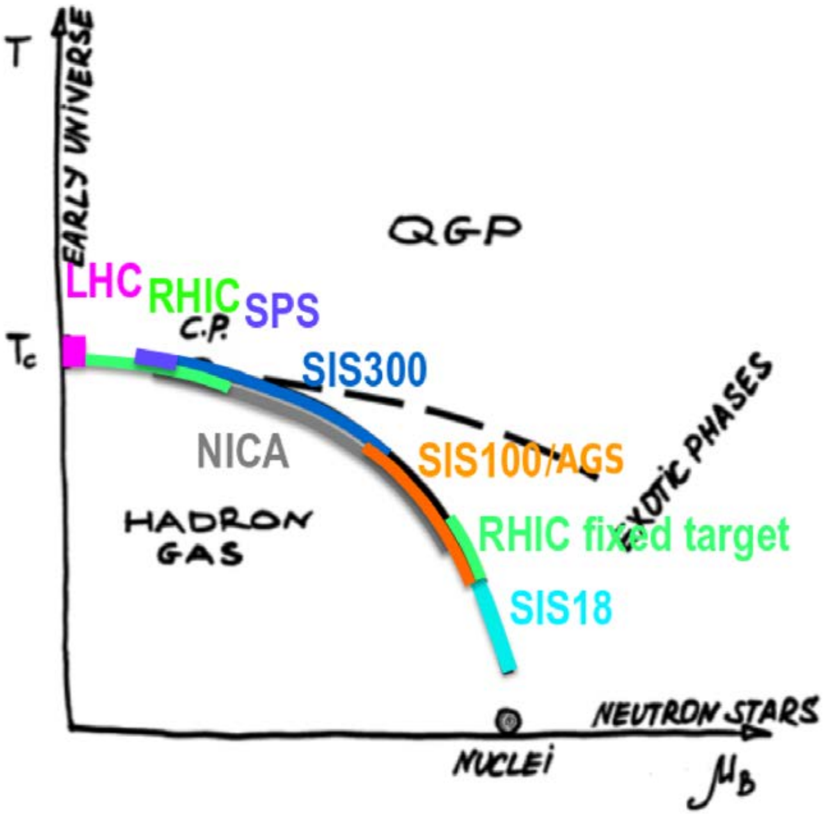
Exploring QCD phase structure with heavy-ion experiments using rare probes



- What could be done?
  - phase boundary(ies)
    - → fluctuations of conserved quantum numbers
    - → flavor production (multi-strange, charm)
  - change in microscopic degrees of freedom
  - restoration of chiral symmetry
  - emitting source temperature
    - → electromagnetic probes leave collision zone undistorted
    - → real photons only carry transverse momentum
    - → dileptons carry extra information: invariant mass

Electromagnetic probes in heavy-ion collisions

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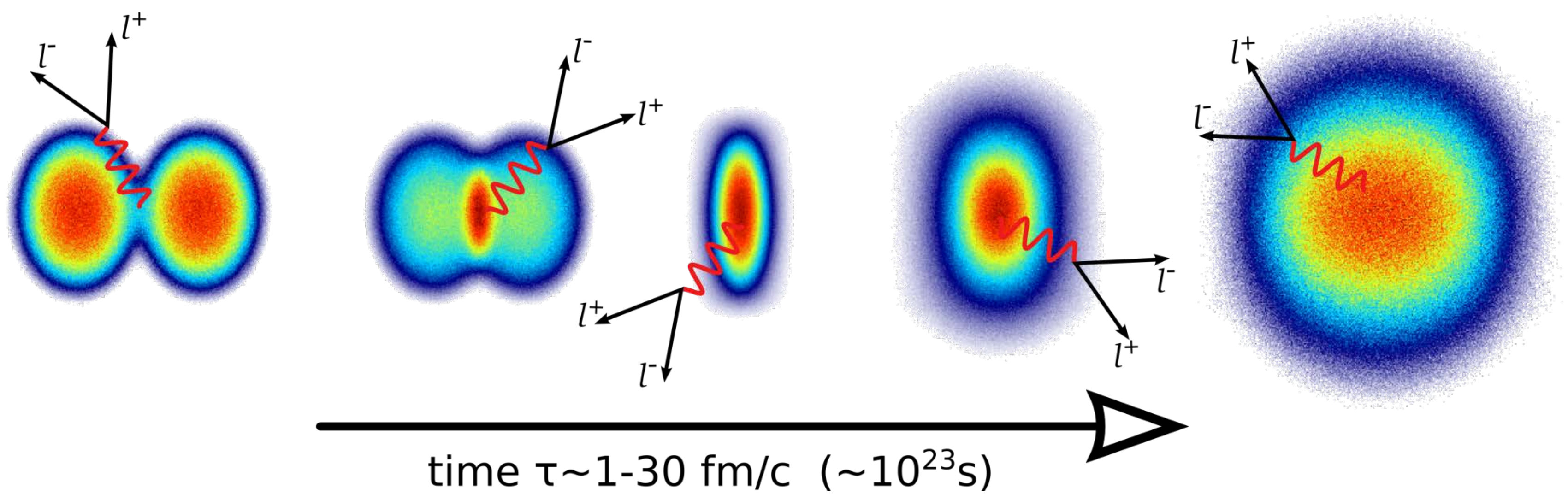
Dileptons are emitted during the whole history of a heavy-ion collision:

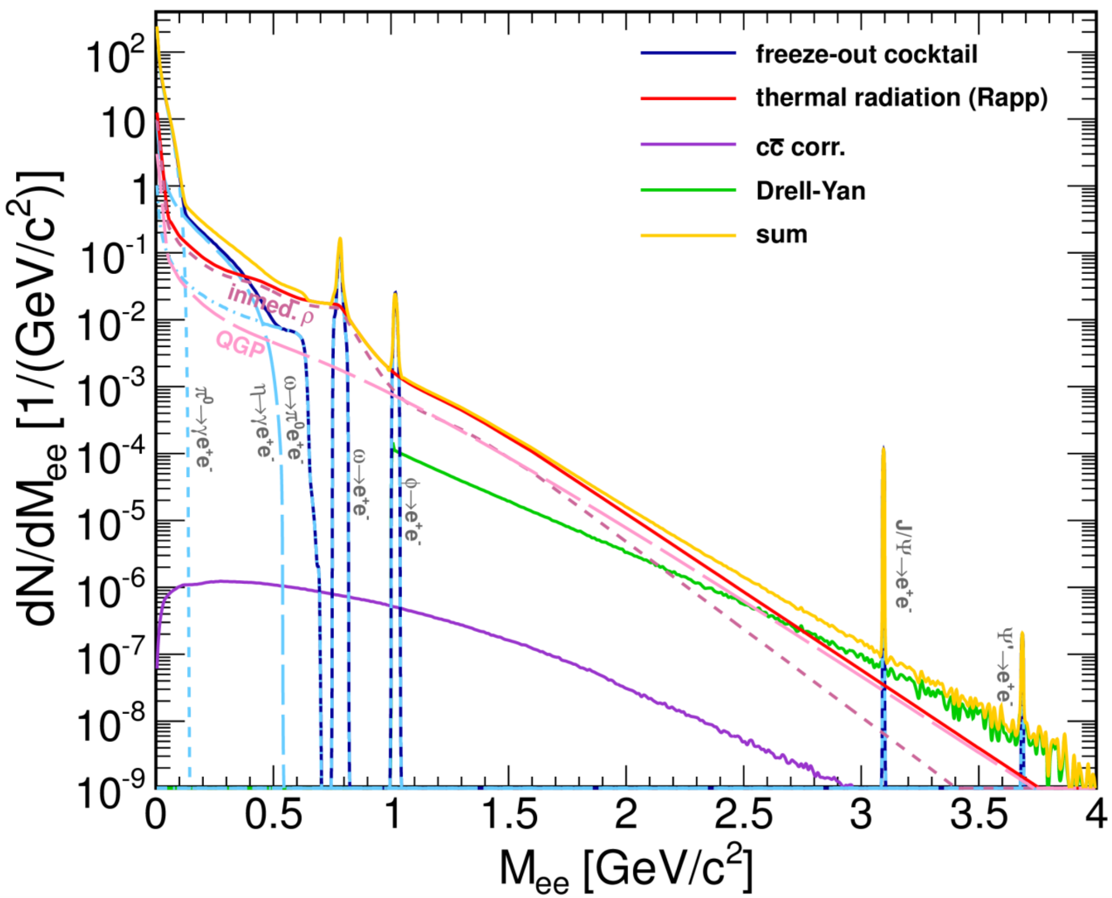
- from pre-equilibrium phase
- from thermalized medium: QGP and hot hadron gas
- from decays after thermal freeze-out



Electromagnetic probes in heavy-ion collisions

Hadonic “cocktail” + thermal signal

Dilepton spectra reflect whole history of collision



➡ crucial to have:

- realistic emission rates
- accurate description of fireball evolution

Electromagnetic probes in heavy-ion collisions

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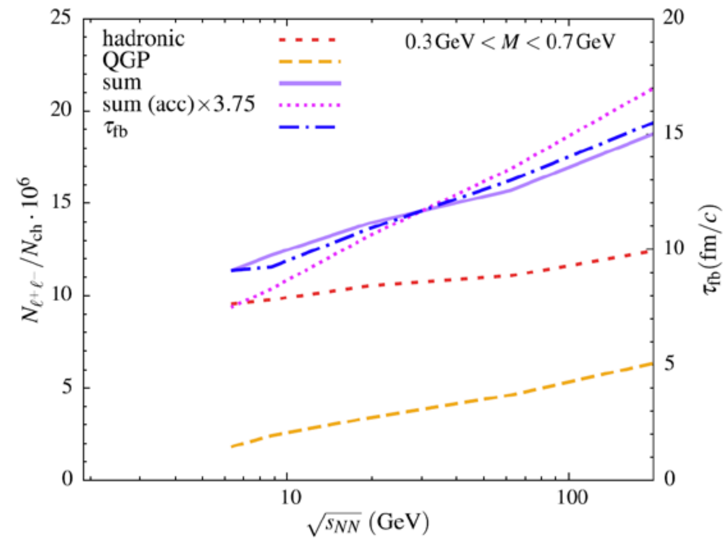
Insights from theory

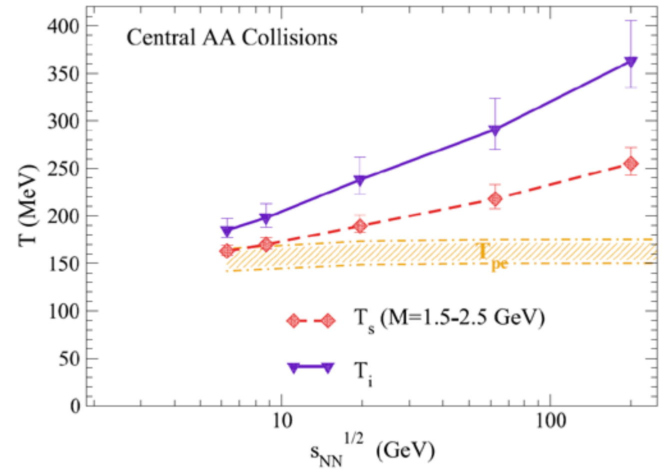
- integrated yield of thermal radiation in the mass range 0.3-0.7 GeV/c^2 is sensitive to the lifetime of the fireball

  R. Rapp, H. van Hees: PLB 753 (2016) 586–590

- dilepton yield determined by interplay between temperature and fireball volume

- slope of dileptons in the intermediate-mass range constitutes a blue-shift free fireball thermometer





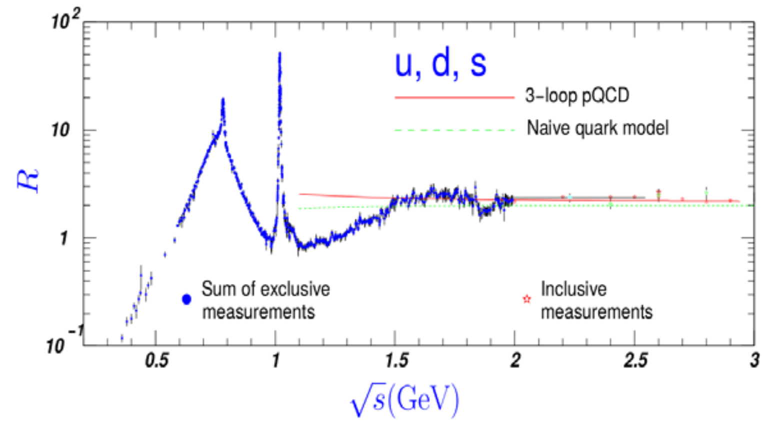
Realistic dilepton emission rates

8-differential thermal production rate

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{\mathrm{EM}}^2}{\pi^3 M^2} f^B(q\cdot u; T)\,\mathrm{Im}\Pi_{\mathrm{EM}}(M,q;\mu_B,T)$$ ⟸ dileptons

$$q_0 \frac{dN_\gamma}{d^4x d^3q} = -\frac{\alpha_{\mathrm{EM}}}{\pi^2} f^B(q\cdot u; T)\,\mathrm{Im}\Pi_{\mathrm{EM}}(q_0 = q;\mu_B,T)$$ ⟸ photons

$$R = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{\mathrm{Im}\Pi_{\mathrm{EM}}^{\mathrm{vac}}}{M^2}$$

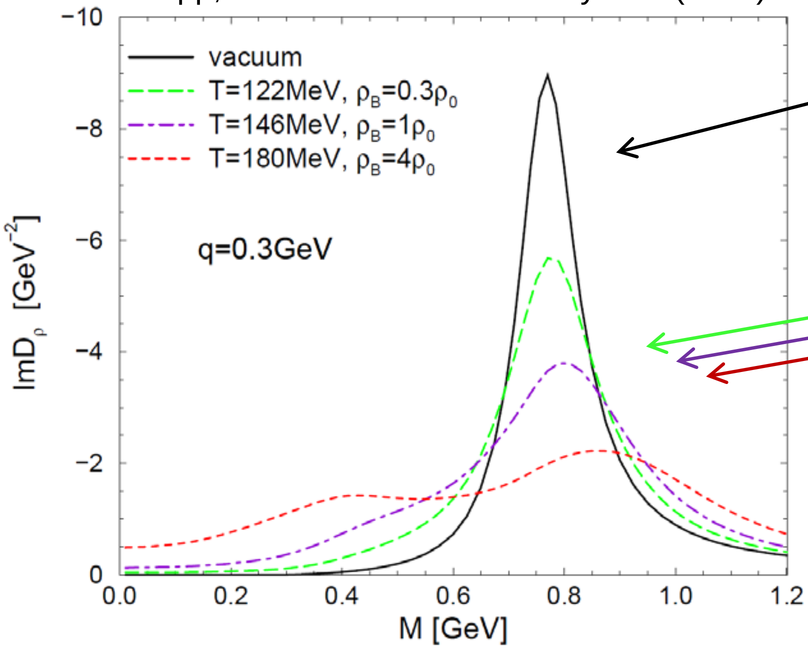


$$\mathrm{Im}\Pi_{\mathrm{EM}}^{\mathrm{vac}}(M) = \begin{cases} \sum\limits_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \mathrm{Im}D_v^{\mathrm{vac}}(M)\,, & M < M_{\mathrm{dual}}^{\mathrm{vac}} \simeq 1.5\,\mathrm{GeV/c}^2 \\ -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \dots\right) N_c \sum\limits_{q=u,d,s} (e_q)^2\,, & M > M_{\mathrm{dual}}^{\mathrm{vac}} \end{cases}$$

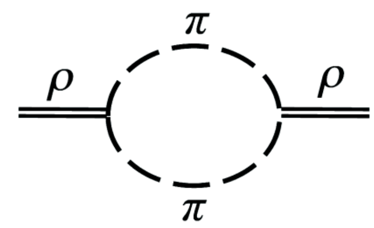
Realistic dilepton emission rates

The ρ meson in nuclear matter

Rapp, Wambach: Adv. Nucl. Phys. **25** (2000)

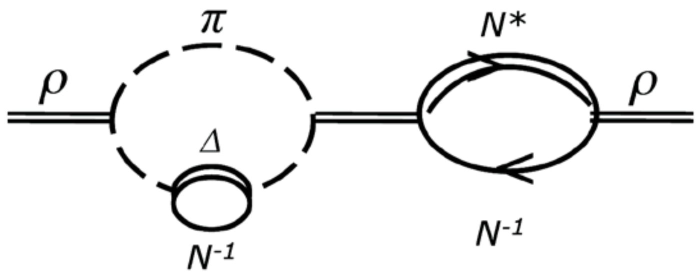


vacuum



medium

$$D_\rho\,(M,q;\mu_B,T) = [M^2 - m_\rho{}^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}\,]^{-1}$$



The ρ spectral function strongly broadens in the medium as the ρ meson couples to baryons !

additional contributions to the ρ meson self-energy in the medium

Realistic dilepton emission rates

Hadronic matter

- parameterization of Rapp-Wambach

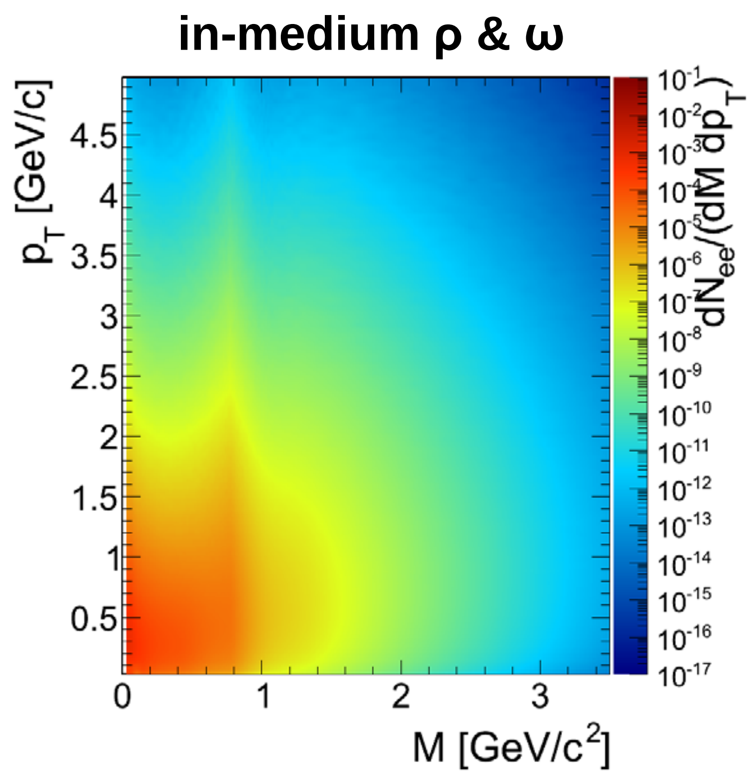
  in-medium ρ spectral function

  Rapp, Wambach: Eur. Phys. J. A **6** (1999) 415-420

- reproduces excess

  for available experimental data well

  - CERES
  - NA60
  - STAR (including BES)
  - PHENIX with HBD

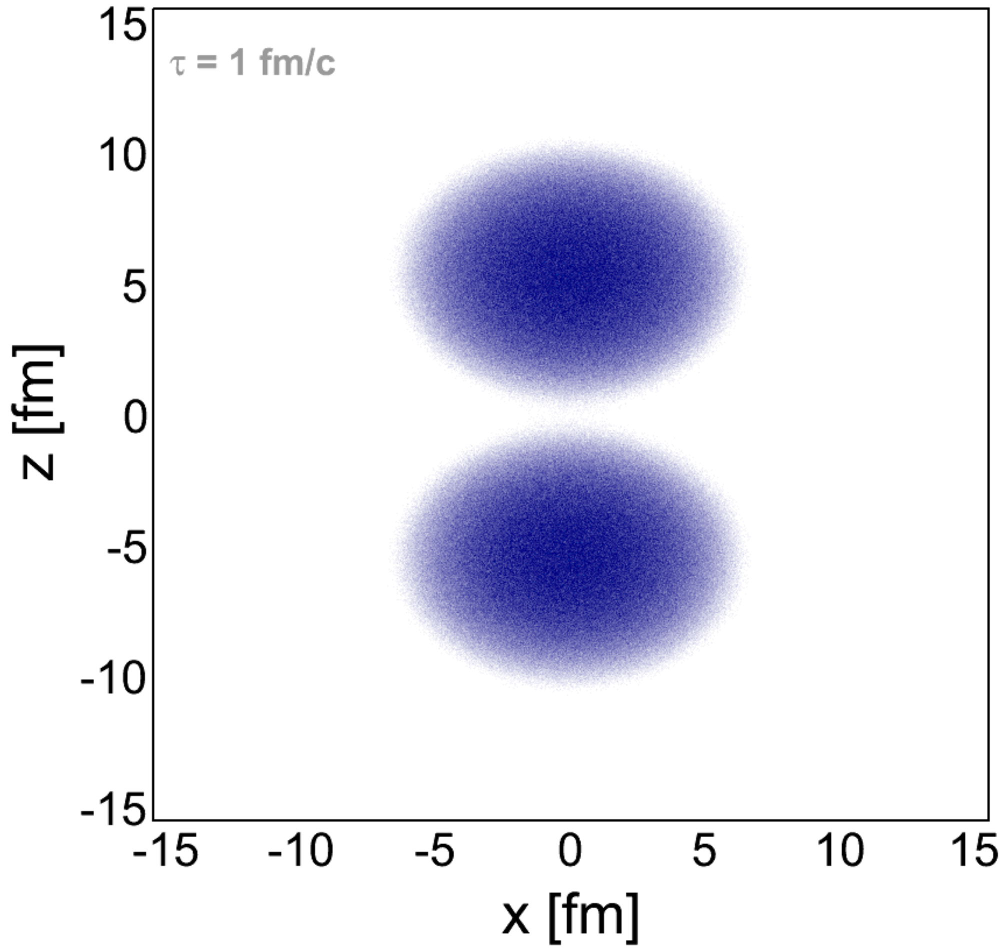


- at higher masses: include hadronic continuum radiation

  Hohler, Rapp: Phys. Lett. B **731** (2014) 103-109

Space-time evolution of a heavy-ion collision

Au+Au at 1.23 AGeV ($\sqrt{s_{NN}}$ = 2.4 GeV) ⇨ HADES energy regime



Space-time evolution of a heavy-ion collision

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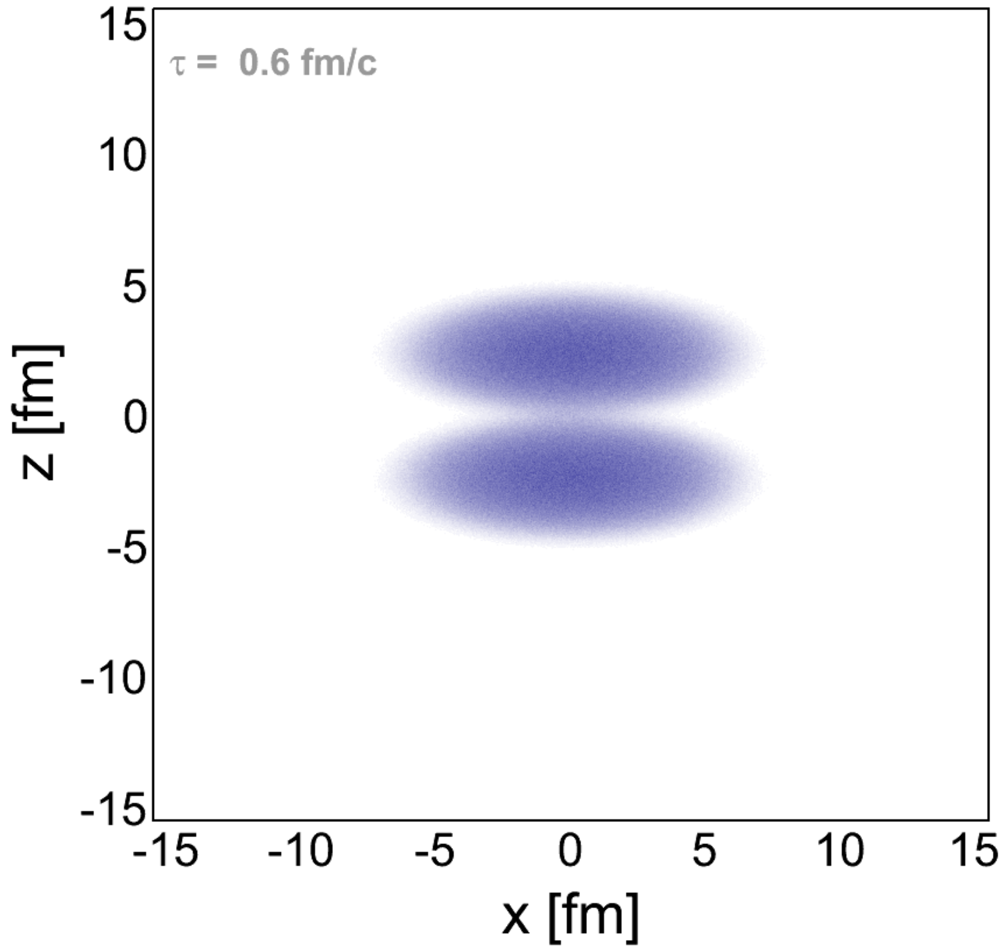
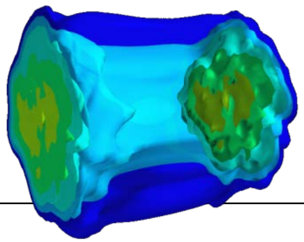
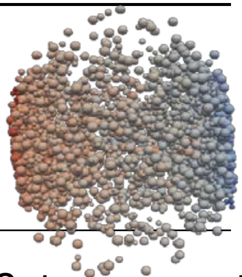
Au+Au at 11 AGeV ($\sqrt{s_{NN}}$ = 4.9 GeV) ⇨ CBM energy regime



Description of the fireball evolution





Coarse-graining of hadronic transport

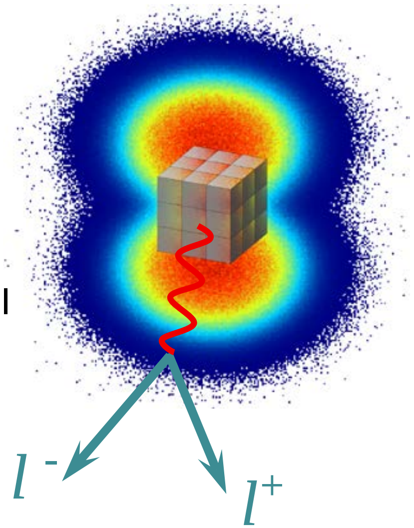
- “combine” the advantages of both descriptions: hydrodynamics & transport
- simulate events with a transport model

  ⟶ ensemble average to obtain smooth space-time distributions

- divide space-time evolution into 4-dimesional cells

  21 x 21 x 21 space cells (1fm^3), 30 time steps ⟶ ~ 280 k cells

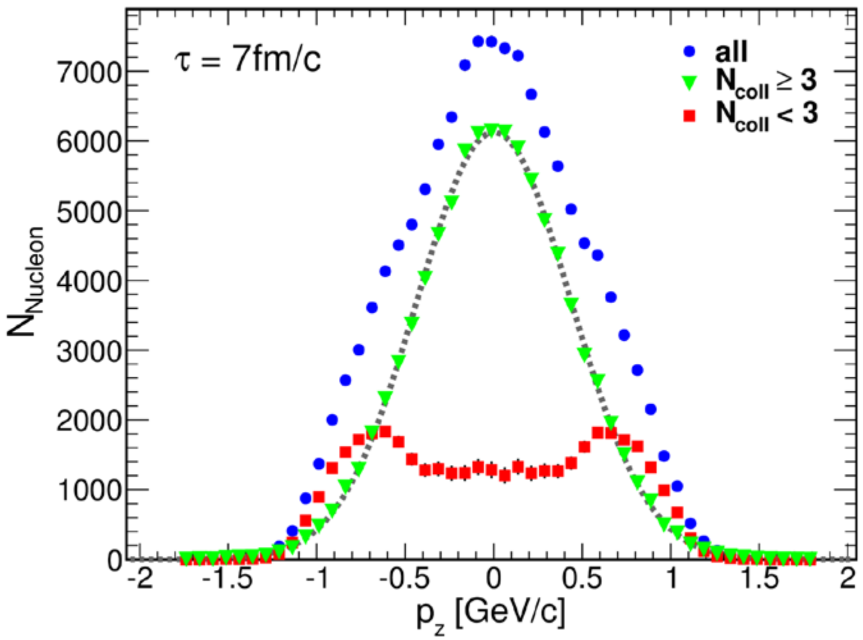
- determine for each cell the bulk properties like T, ρ_B & v_{coll}

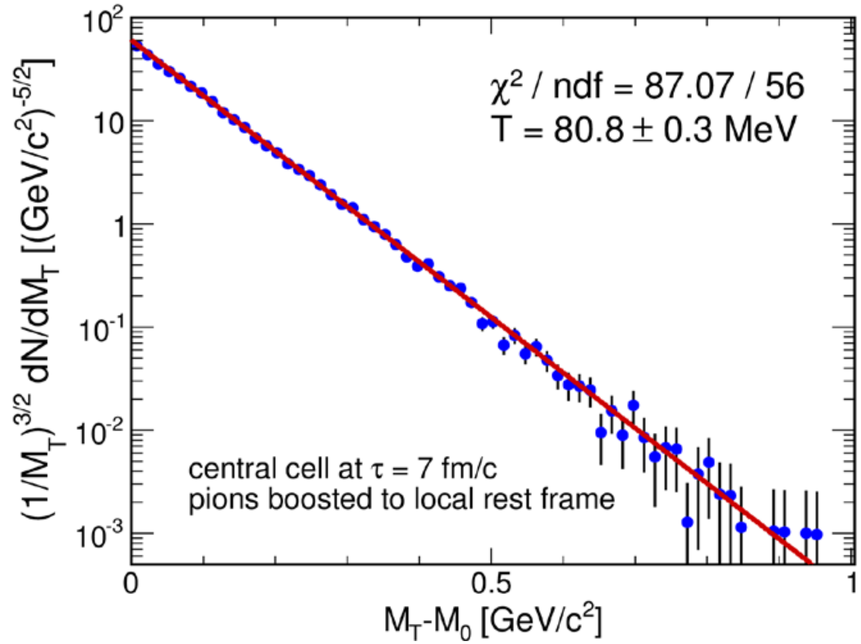


- calculate dilepton rates based on these inputs
- sum up the contributions of all cells
- similar approaches by
  - Huovinen *et al.*: Phys. Rev. C **66** (2002) 014903
  - Endres *et al.*: Phys. Rev. C **91** (2015) 054911, Phys. Rev. C **92** (2015) 014911

Local thermalization?

Momentum distributions of nucleons ($N_{coll} \geq 3$) & pion m_t spectra

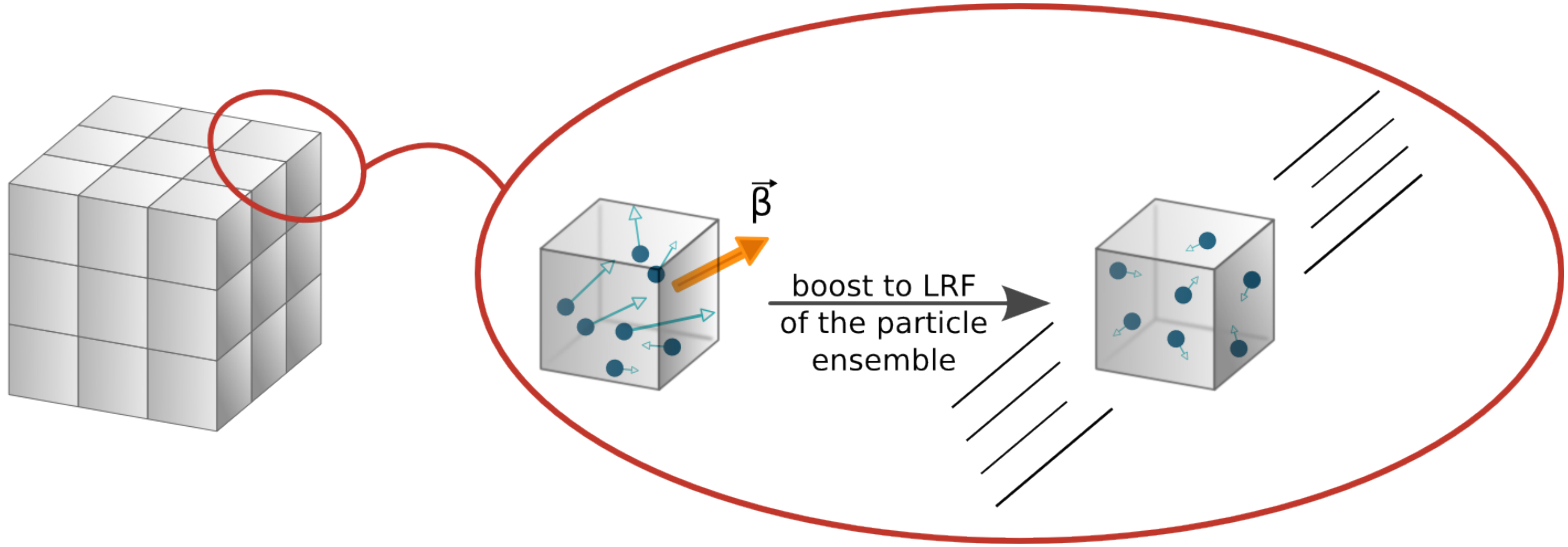




- Gaussian shaped p_z distribution builds up for nucleons with $N_{coll} \geq 3$
- m_t spectra show exponential shape

Determination of bulk properties

(Baryon) density & collective flow velocity



- baryon density via 4-current $j^{\mu}_{\mathrm{CF}} = \begin{pmatrix} \varrho_{\mathrm{CF}} \\ \varrho_{\mathrm{CF}}\, \vec{\beta}_{\mathrm{cell}} \end{pmatrix}$
- particles described by normalized 3D Gaussians
- perform Lorentz-boost into the local rest frame, where the baryon current vanishes (Eckart frame) $j^{\mu}_{\mathrm{LRF}} = \begin{pmatrix} \varrho_{\mathrm{LRF}} \\ \vec{0} \end{pmatrix} = j_{\mathrm{CF},\,\nu}\, \Lambda^{\mu\nu}(\vec{\beta}_{\mathrm{cell}})$

Determination of bulk properties

Temperature

- in Boltzmann approximation

$$\frac{d^3N}{d\vec{p}} = \frac{d^3N}{dp_z\, p_t\, dp_t\, d\theta} \propto \exp(-E/T)$$

- integration over rapidity and azimuthal angle

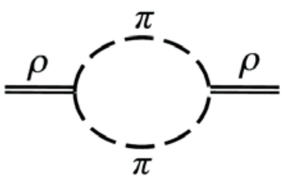
$$\Rightarrow \boxed{\frac{1}{m_t^{3/2}} \frac{dN}{dm_t} \propto \exp(-m_t/T)}$$

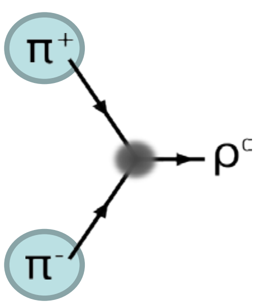
- subtract mean flow v_{coll} of the cells from particle motion
- fill m_t spectra & fit exponential function to extract T
- use different fit ranges / particle species to get the systematics

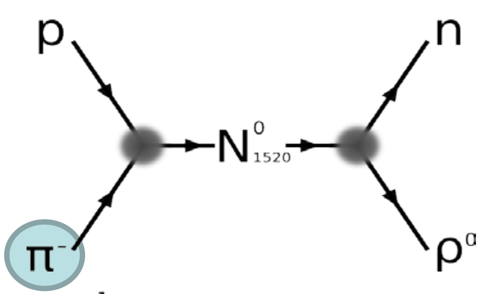
Out of chemical equilibrium ?

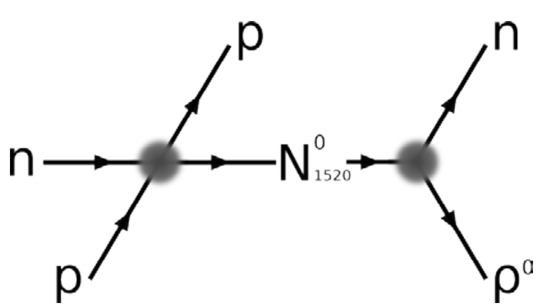
Build-up of effective chemical potentials

- thermal emission rates assume chemical equilibrium
- chemical non-equilibrium possible, e.g. after chemical freeze-out
  - no more inelastic interactions → pion number conserved
  - system in thermal equilibrium cools down further → too many pions
  - cured by build-up of an effective chemical potential μ_π
- pions determine the ρ self-energy









- include a factor $(z_\pi)^k$ into the dilepton rates with the fugacity $z = \exp\left(\frac{\mu_\pi}{T}\right)$
  - exponent *k* reflects the main production mechanism of ρ mesons

Out of chemical equilibrium ?

Derivation of the effective chemical potentials

- particle density in Boltzmann approximation

$$n = \frac{g}{(2\pi)^3} \int_{\mathbb{R}^3} d^3\vec{p}\ \exp(-\beta\ (E-\mu))$$

- carrying out the momentum integral yields $n = \frac{4\pi\ g\ m^3}{(2\pi)^3}\ z\ \frac{1}{\beta\ m} K_2(\beta m)$

- solving for the chemical potential results in

$$\mu = T\ \ln\left(\frac{2\pi^2\ n\ (\hbar c)^3}{g\ T\ m^2\ K_2\left(\frac{m}{T}\right)} \right)$$

Results

Au+Au at 1.23 AGeV

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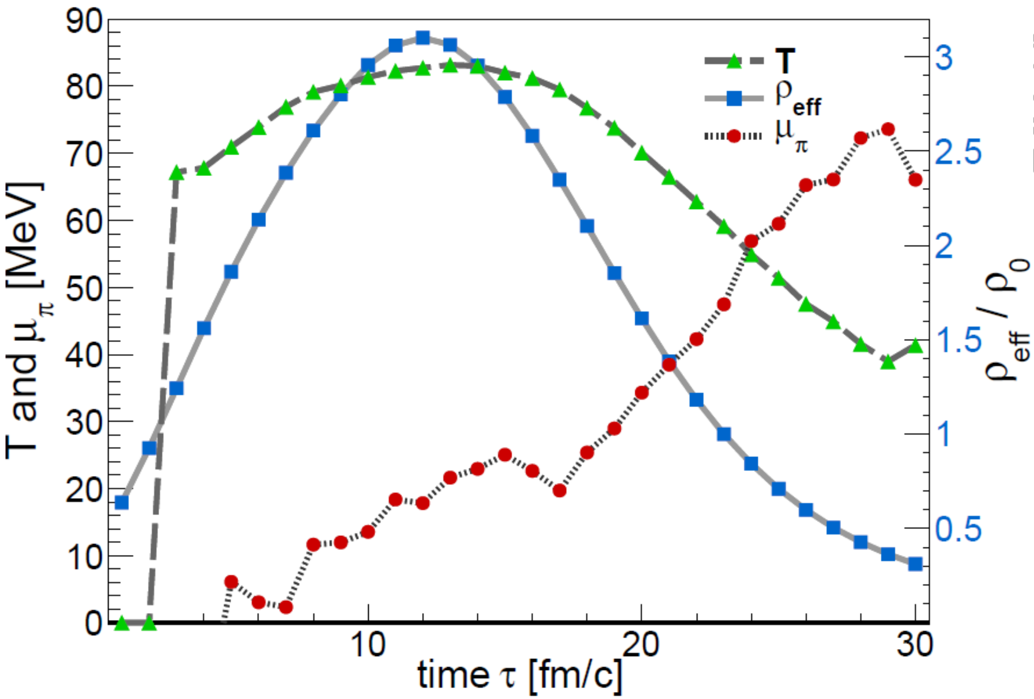
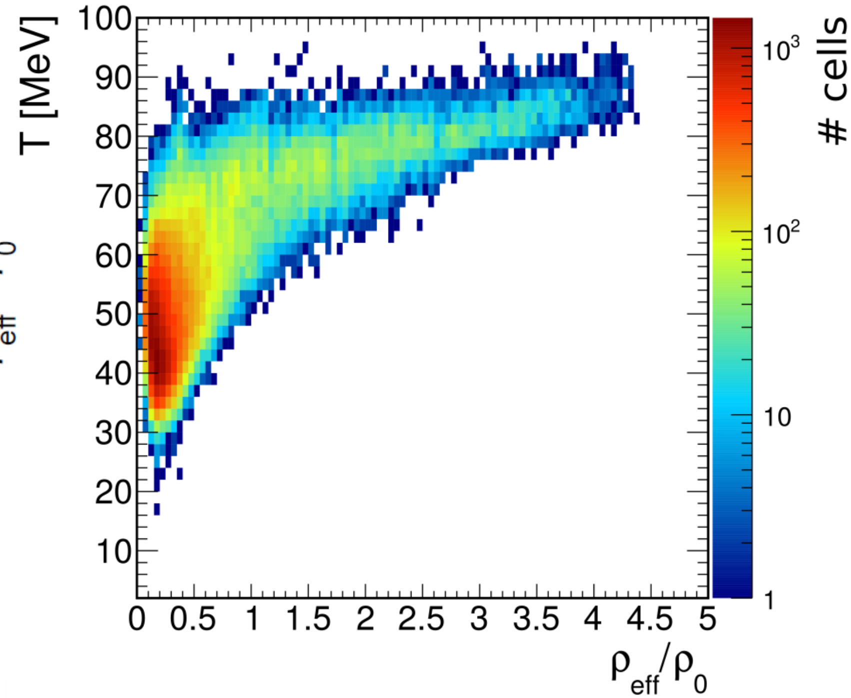
- evolution of T, ρ_{eff} and μ_π in the central cube of 7x7x7 cells
- location of cells in the temperature-density plane

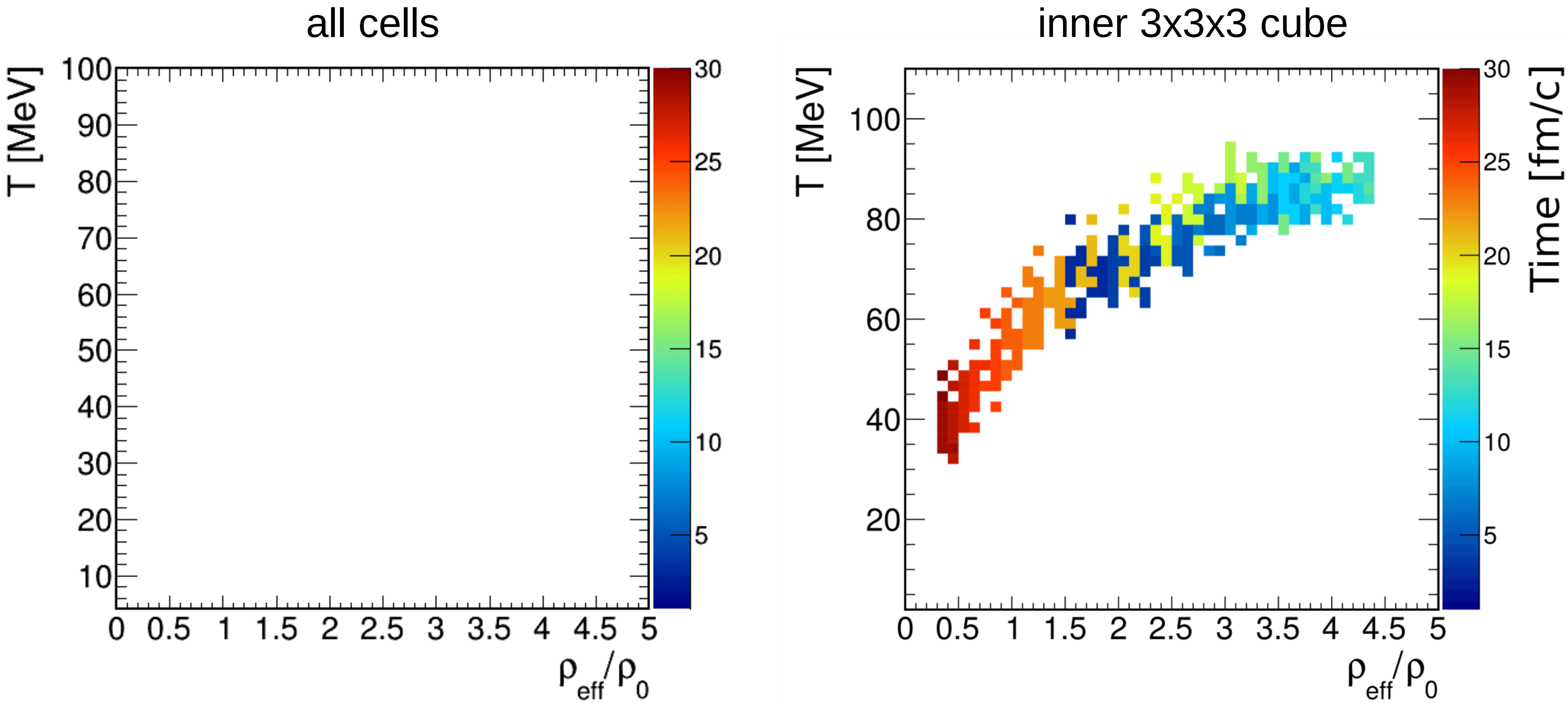




Results

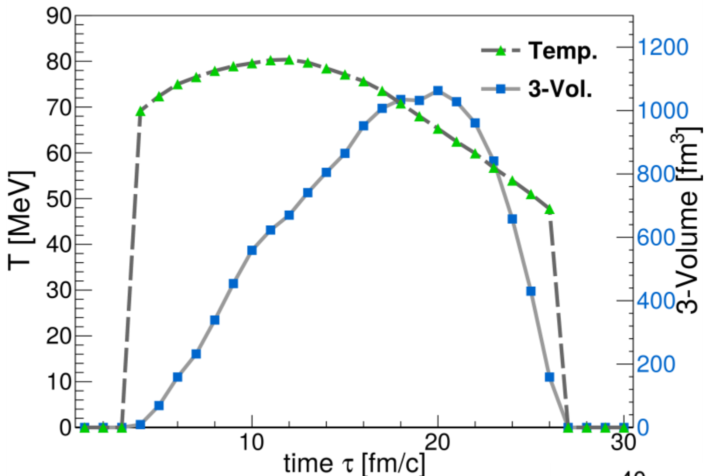
Au+Au at 1.23 AGeV

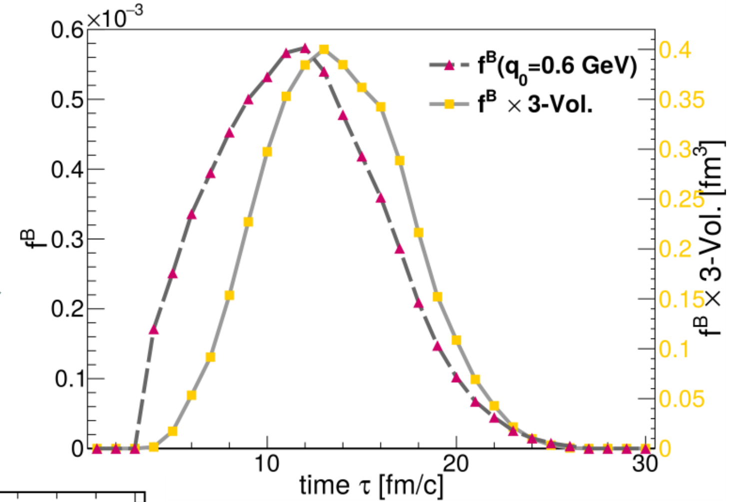
- trajectories of the cells in the temperature-density plane

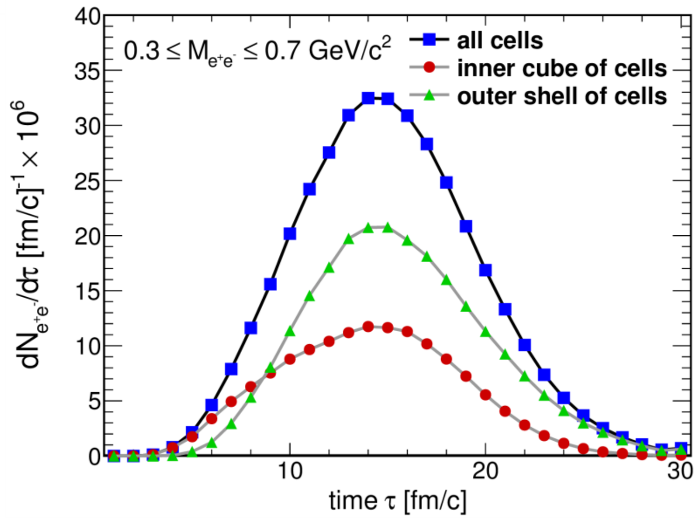


Results

Interplay temperature – fireball volume







Results

T. Galatyuk, P. M. Hohler, R. Rapp, F. Seck, J. Stroth
arXiv:1512.08688 [nucl-th]

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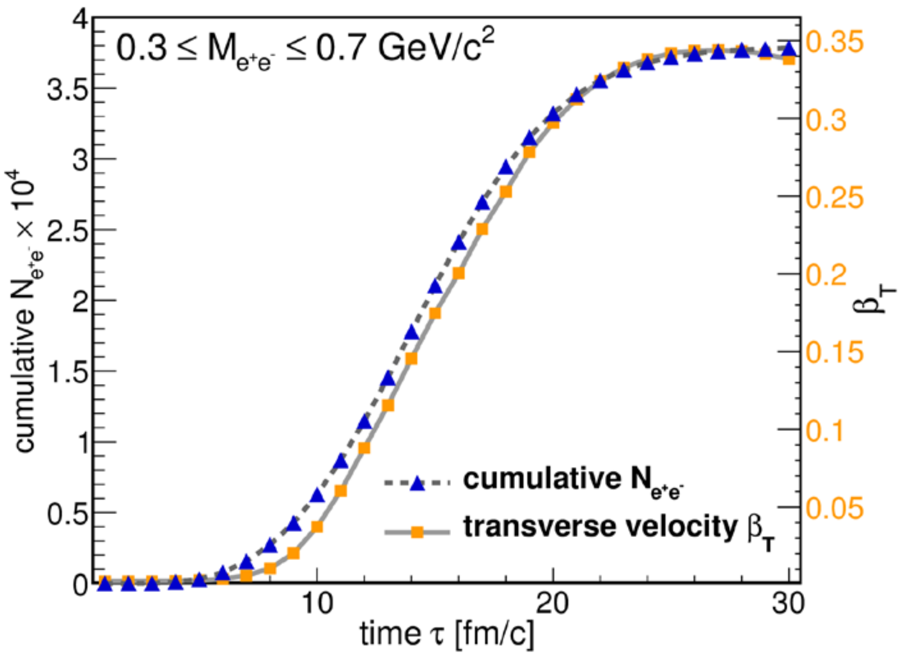
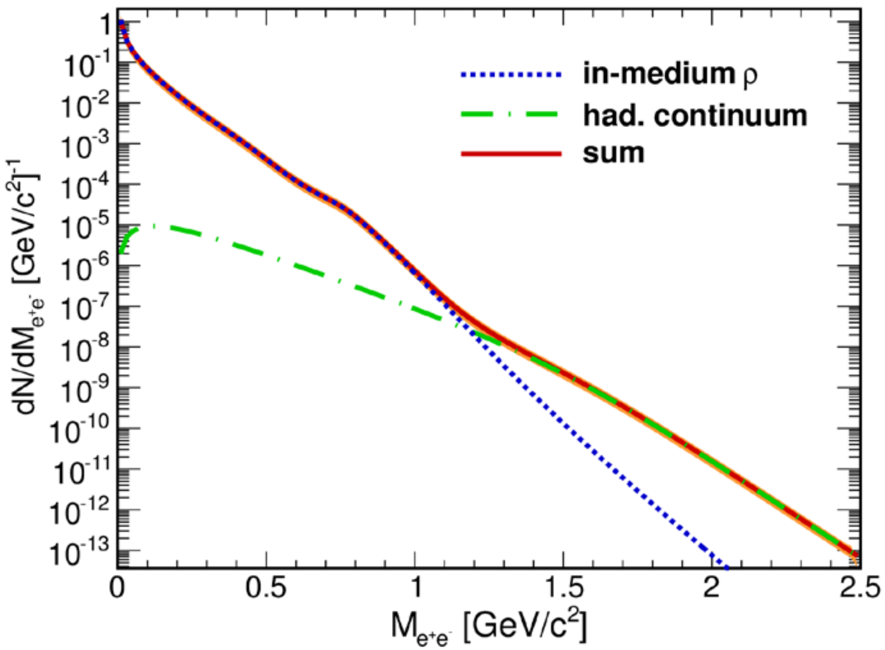
- time evolution of cumulative dilepton yield in mass window M = 0.3-0.7 GeV/c^2
- active radiation window ~13 fm/c follows build-up of collective medium flow
- strong medium effects on ρ-meson ⇨ remarkably structureless low-mass spectrum





Results

T. Galatyuk, P. M. Hohler, R. Rapp, F. Seck, J. Stroth
arXiv:1512.08688 [nucl-th]

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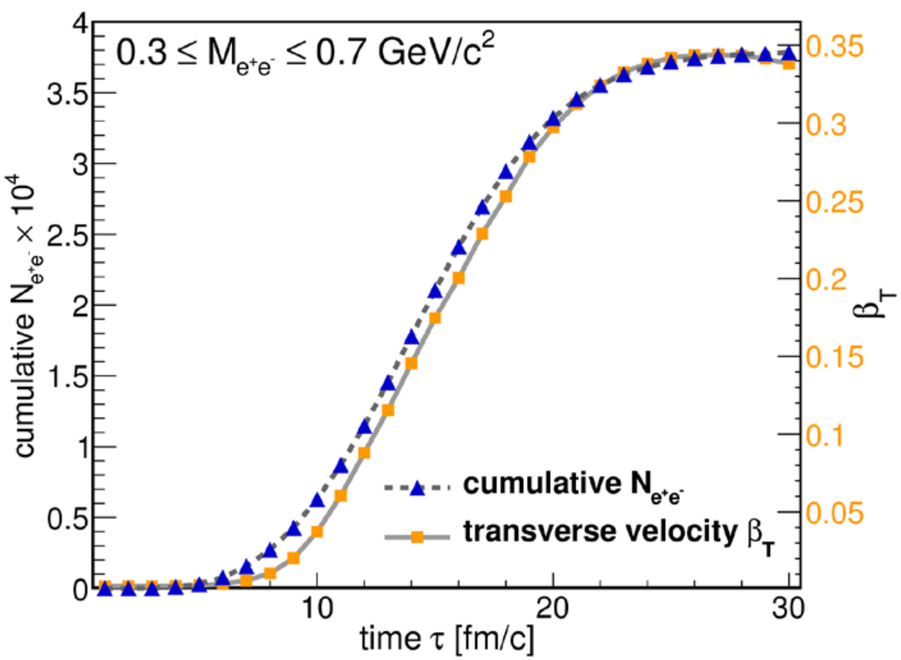
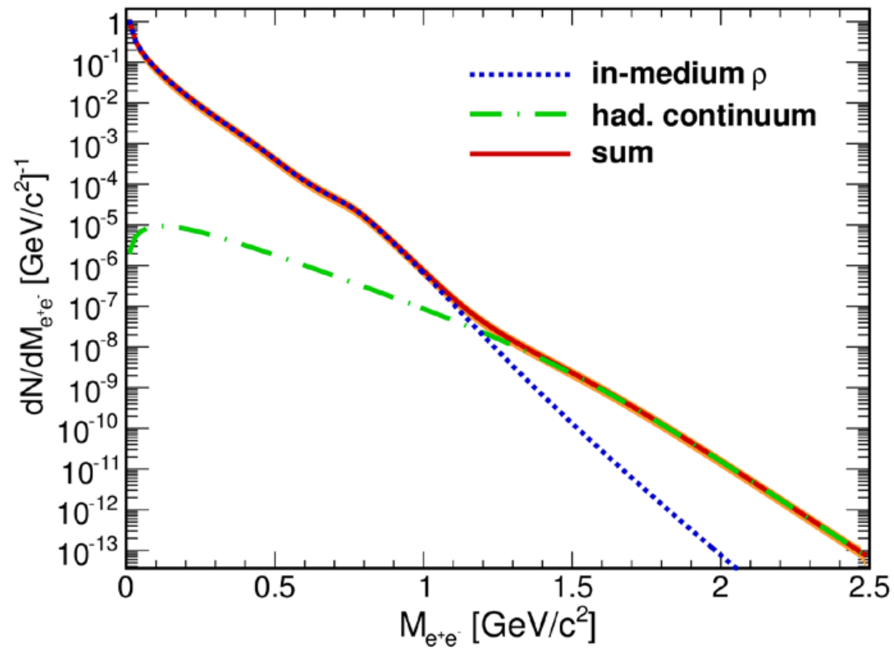
- radiation stems from time interval with highest densities, different at higher energies
- $\mathrm{d}R_{ll}/\mathrm{d}M \propto (MT)^{3/2}\exp(-M/T)$
- inverse slope parameter: $T_S = 88 \pm 5$ MeV in IMR, $T_S = 64 \pm 5$ MeV in LMR





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Summary & Outlook

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- dileptons are excellent fireball probes
  - thermometer & chronometer
- thermal dilepton spectra from highest to lowest energies
  - realistic thermal dilepton emission rates
  - accurate description of fireball evolution in terms of T, ρ_{eff}, v_{coll} and μ_{π}
  - coarse-graining of hadronic transport at SIS energies
- baseline for future explorations
  - any significant deviation can indicate new physics!

THANK YOU FOR YOUR ATTENTION !