Theory overview on dileptons

Ralf-Arno Tripolt
(Justus-Liebig-University Giessen)

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JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

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CRC-TR 211

Outline

I) Introduction and motivation

II) Dileptons in heavy-ion collisions

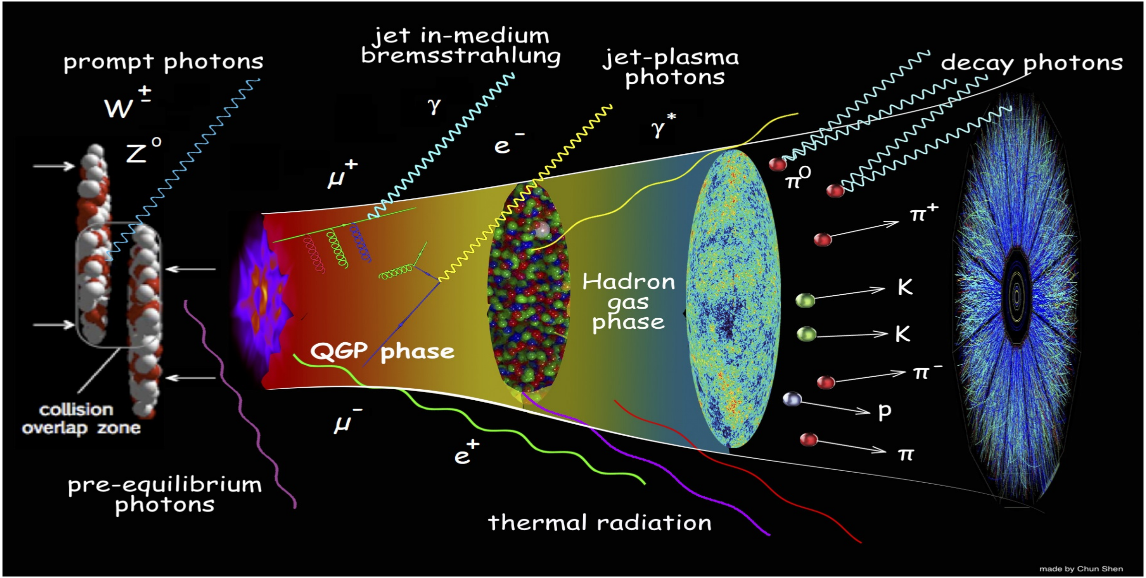
- Thermal dilepton rate and vector meson spectral function
- Connection to chiral symmetry and axial-vector spectral function
- Describing (axial-)vector mesons in nuclear matter (aFRG)

III) Applications

- Thermometer, chronometer, polarimeter
- Electrical conductivity
- Theory vs. experiment

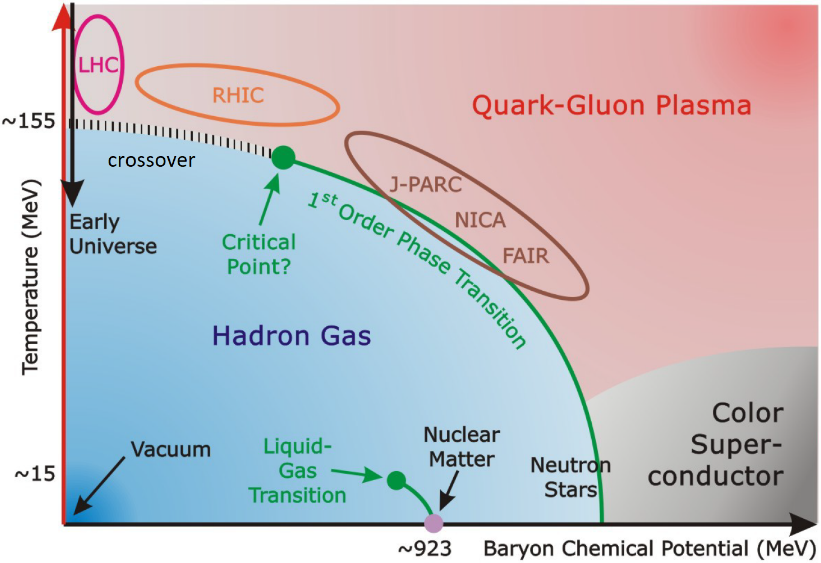
IV) Summary and outlook

Dileptons in heavy-ion collisions



[Figure by Chun Shen]

QCD phase diagram

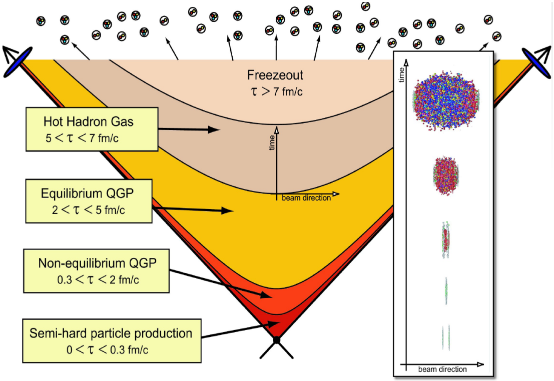


[Figure adapted from the CRC-TR 211]

Why dileptons?

- Electromagnetic (EM) probes, i.e. photons and dileptons, don't interact (directly) via the strong interaction (QCD) with the fireball
- they have a long mean free path and can therefore carry information from their production site to the detectors
- they are produced at all stages of the collision

→ **dileptons are uniquely well suited to study the properties of hot and dense matter in heavy-ion collisions!**



[M. Strickland, Acta Phys.Polon. B45 (2014) no.12, 2355-2394]

Dileptons in heavy-ion collisions

'Primordial' $q\bar{q}$ annihilation (Drell-Yan):

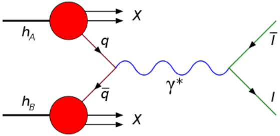
- $NN \to e^+e^-X$

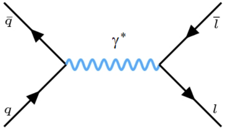
Thermal radiation from QGP and hadrons:

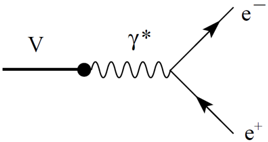
- $q\bar{q} \to e^+e^-$, ...
- $\pi^+\pi^- \to e^+e^-$, ...
- short-lived states: ρ, a_1, Δ, N^*, ...
- multi-meson reactions ('4π'):
  $\pi\rho$, $\pi\omega$, $\rho\rho$, πa_1, ...

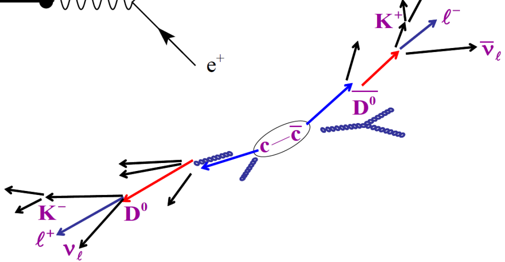
Decays of long-lived mesons and baryons:

- π^0, η, ϕ, J/Ψ, Ψ', correlated $D\bar{D}$ pairs, ...







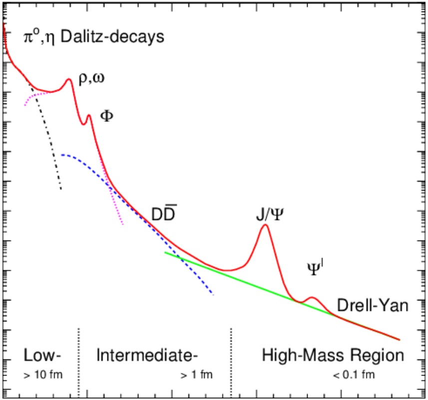


What can we learn from dileptons?

Sketch of a dilepton invariant-mass spectrum:

contains information on:

- temperature
- fireball lifetime
- degree of collectivity
- in-medium spectral functions and connection to chiral symmetry
- changes in degrees of freedom
- production mechanism, polarization
- transport coefficients (electrical conductivity)



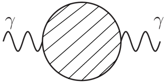
[A. Drees]

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

Dilepton production rates

Thermal field theory: Electromagnetic correlation function

$$\Pi^{\mu\nu}_{\mathrm{EM}}(M,p;\mu_B,T) = -\mathrm{i}\int d^4x\ e^{ip\cdot x}\ \Theta(x_0)\ \langle\!\langle [j^\mu_{\mathrm{EM}}(x), j^\nu_{\mathrm{EM}}(0)]\rangle\!\rangle$$



determines both photon and dilepton rates:

- photons: $$p_0\frac{dR_\gamma}{d^3p} = -\frac{\alpha_{\mathrm{EM}}}{\pi^2}\ f^B(p_0;T)\ \ g_{\mu\nu}\ \ \mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{EM}}(M=0,p;\mu_B,T)$$
- dileptons: $$\frac{dR_{ll}}{d^3p} = -\frac{\alpha^2_{\mathrm{EM}}}{\pi^3M^2}\ f^B(p_0;T)\ \frac{1}{3}\ g_{\mu\nu}\ \ \mathrm{Im}\,\Pi^{\mu\nu}_{\mathrm{EM}}(M,p;\mu_B,T)$$

Relativistic kinetic theory:

$$p_0\frac{dR}{d^3p} = \int \frac{d^3q_1}{2(2\pi)^3E_1}\frac{d^3q_2}{2(2\pi)^3E_2}\frac{d^3q_3}{2(2\pi)^3E_3}(2\pi)^4\delta^{(4)}(q_1+q_2\to q_3+p)\,|\mathcal{M}|^2\,\frac{f(E_1)f(E_2)[1\pm f(E_3)]}{2(2\pi)^3}$$

[E.L. Feinberg, Nuovo Cim. A34, 391 (1976)], [L.D. McLerran, T. Toimela, Phys.Rev. D31, 545 (1985)]
[H.A. Weldon, Phys.Rev. D42, 2384-2387 (1990)], [C. Gale, J. Kapusta, Phys.Rev. C35, 2107 (1987) & Nucl.Phys. B357, 65-89 (1991)]

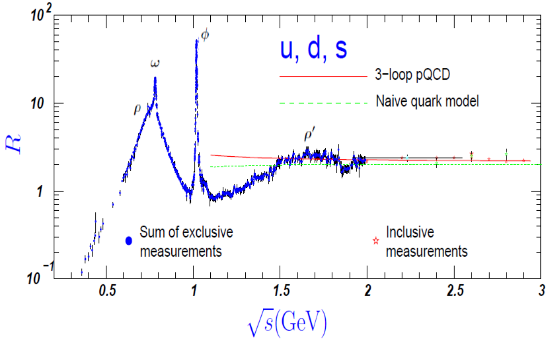
EM spectral function in the vacuum

In the vacuum, $\mathrm{Im}\,\Pi_{\mathrm{em}}^{\mathrm{vac}}$ is accurately known from e^+e^- annihilation:

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

In the low-mass regime (LMR: $M \leq 1$ GeV) the EM spectral function is saturated by the spectral functions of the light vector mesons (VDM):

$$\mathrm{Im}\Pi_{\mathrm{EM}}^{\mathrm{vac}}(M) = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \mathrm{Im}D_v^{\mathrm{vac}}(M)$$



[Particle Data Group]

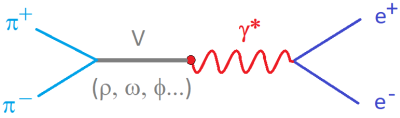
For higher energies, quark degrees of freedom:

$$\mathrm{Im}\Pi_{\mathrm{EM}}^{\mathrm{vac}}(M) = -\frac{M^2}{12\pi}\left[1 + \frac{\alpha_s(M)}{\pi} + \ldots\right] N_c \sum_{q=u,d,s} (e_q)^2$$

[J.J. Sakurai, Ann.Phys. 11 (1960) & Currents and Mesons, Chicago Lectures]
[R. Rapp, J. Wambach, Adv.Nucl.Phys. 25, 1 (2000)]
[R. Rapp, Acta Phys.Polon. B42, 2823-2852 (2011)]

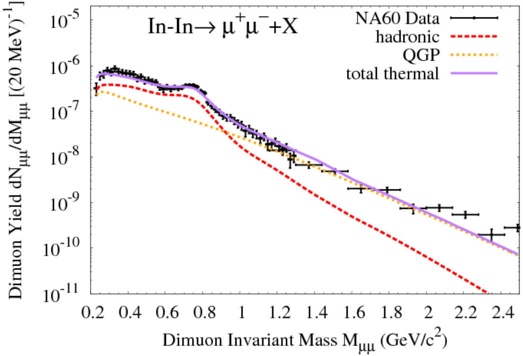
Connection between dileptons and vector mesons

Vector mesons have the same quantum numbers as photons and can decay directly into dileptons:



Excess dimuon invariant-mass spectrum as measured in In-In collisions at $\sqrt{s_{NN}} = 17.3$ GeV by the NA60 collaboration at the SPS is well described by using vector meson dominance:

$$\mathrm{Im}\Pi^{\mu\nu}_{\mathrm{EM}}(M) \sim \mathrm{Im}D^{\mu\nu}_{\rho} + \frac{1}{9}D^{\mu\nu}_{\omega} + \frac{2}{9}D^{\mu\nu}_{\phi}$$



[R. Rapp, H. van Hees, Phys. Lett. B 753 (2016) 586-590]

Connection to chiral symmetry

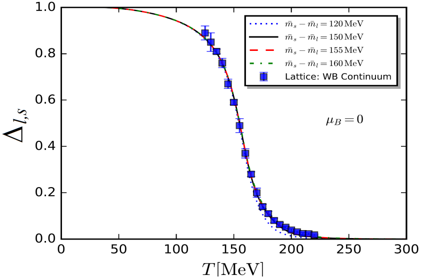
Chiral symmetry:

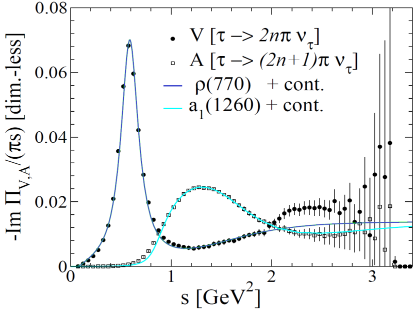
- QCD Lagrangian has chiral symmetry $\mathrm{SU}(N_f)_L \times \mathrm{SU}(N_f)_R$ in the limit of vanishing quark masses
- chiral symmetry is broken spontaneously by dynamical formation of a quark condensate $\langle \bar{q}q \rangle \sim \Delta_{l,s}$

QCD and chiral sum rules:

$$\int_0^\infty \frac{ds}{\pi}(\Pi_V(s) - \Pi_A(s)) = m_\pi^2 f_\pi^2 = -2m_q \langle \bar{q}q \rangle$$

- sum rules connect spectral functions and condensates
- chiral restoration manifests itself through mixing of vector and axial-vector correlators!





[W.-j. Fu, J.M. Pawlowski, F. Rennecke, arXiv:1909.02991]
[S. Borsanyi et al. (Wuppertal-Budapest), JHEP 09, 073 (2010)]
[R. Barate, et al., (ALEPH), EPJC 4 (1998) 409-431]
[R. Rapp, J. Wambach, H. v. Hees, Landolt-Bornstein 23, 134]

Chiral Mixing

At low temperatures and densities, i.e. for a dilute pion gas, one can apply chiral reduction and current algebra to find the following 'mixing theorem' for the vector and axial-vector correlation functions:

$$\Pi_V(q) = (1-\varepsilon)\,\Pi_V^0(q) + \varepsilon\,\Pi_A^0(q)$$

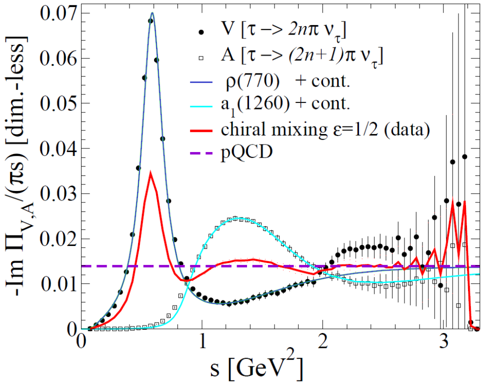
with mixing parameter $\varepsilon = T^2/6f_\pi^2$.

Chiral mixing has direct consequences on the thermal dilepton rate:

$$\frac{dN_{ll}}{d^4x d^4q} = \frac{4\alpha_{\mathsf{EM}}^2 f^B}{(2\pi)^2}\left\{\rho_{\mathsf{EM}} - (\varepsilon - \frac{\varepsilon^2}{2})(\rho_V - \rho_A)\right)\right\}$$

[M. Dey et al., Phys. Lett. B 252 (1990), 620-624]

[Z. Huang, Phys. Lett. B 361 (1995) 131-136]



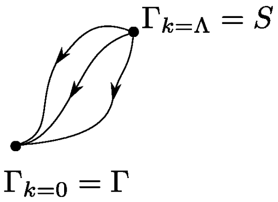
[R. Rapp, Acta Phys. Polon. B 42 (2011) 2823-2852]

In-medium spectral functions with the FRG

Functional Renormalization Group (FRG):

$$\partial_k \Gamma_k = \frac{1}{2} \mathrm{STr} \left(\partial_k R_k \left[\Gamma_k^{(2)} + R_k \right]^{-1} \right)$$

[C. Wetterich, Phys.Lett. B301, 90 (1993)]



[wikipedia.org]

- non-perturbative framework used in quantum field theory and statistical physics
- implements Wilson's coarse-graining idea: fluctuations are successively integrated out
- properly deals with phase transitions at finite temperature and density
- **analytically-continued FRG (aFRG) method allows to calculate spectral functions!**

Vector mesons in nuclear matter

Parity-Doublet Model with the FRG:

$$\Gamma_k = \int d^4x \Big\{ \bar{N}_1 \left(\not{\partial} - \mu_B \gamma_0 + h_{s,1}(\sigma + i\vec{\tau}\cdot\vec{\pi}\gamma^5) + h_{v,1}(\gamma_\mu \vec{\tau}\cdot\vec{\rho}_\mu + \gamma_\mu\gamma^5\vec{\tau}\cdot\vec{a}_{1,\mu}) \right) N_1$$
$$+ \bar{N}_2 \left(\not{\partial} - \mu_B \gamma_0 + h_{s,2}(\sigma - i\vec{\tau}\cdot\vec{\pi}\gamma^5) + h_{v,2}(\gamma_\mu \vec{\tau}\cdot\vec{\rho}_\mu - \gamma_\mu\gamma^5\vec{\tau}\cdot\vec{a}_{1,\mu}) \right) N_2$$
$$+ m_{0,N} \left(\bar{N}_1 \gamma^5 N_2 - \bar{N}_2 \gamma^5 N_1 \right) + U_k(\phi^2) - c\sigma + \frac{1}{2}(D_\mu\phi)^\dagger D_\mu\phi$$
$$- \frac{1}{4}\,\mathrm{tr}\; \partial_\mu\rho_{\mu\nu}\partial_\sigma\rho_{\sigma\nu} + \frac{m_v^2}{8}\,\mathrm{tr}\;\rho_{\mu\nu}\rho_{\mu\nu} \Big\} .$$

- effective theory to describe a chiral phase transition inside nuclear matter entirely in terms of hadronic degrees of freedom
- nucleon $N_1 = N(938)$ is described together with its parity partner $N_2 = N^*(1535)$
- can account for a finite nucleon mass in a chirally-invariant way!
- (axial-)vector mesons are included using new field-strength formulation!

[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]
[C. Jung, L. von Smekal, Phys. Rev. D 100, 116009 (2019)]

Parity doubling also observed in lattice QCD

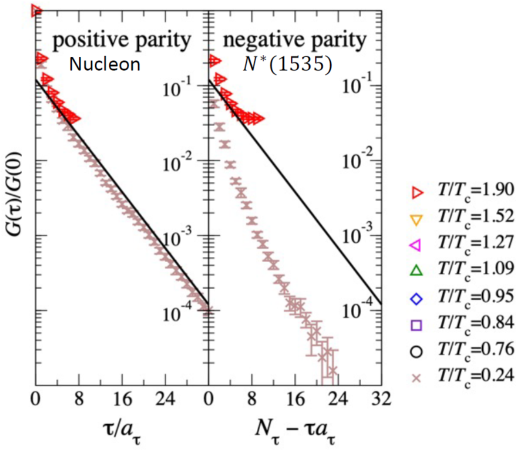
Results from FASTSUM 2+1 flavour ensembles:

- steeper slope corresponds to larger mass $G(\tau) \sim \exp(-m\tau)$
- nucleon ground state m_N is largely independent of T
- mass of negative-parity partner decreases substantially and approaches m_N

$\rightarrow$ **indicates parity doubling above T_c due to restoration of chiral symmetry!**

$\rightarrow$ **mass splitting burns off but ground state mass remains!**

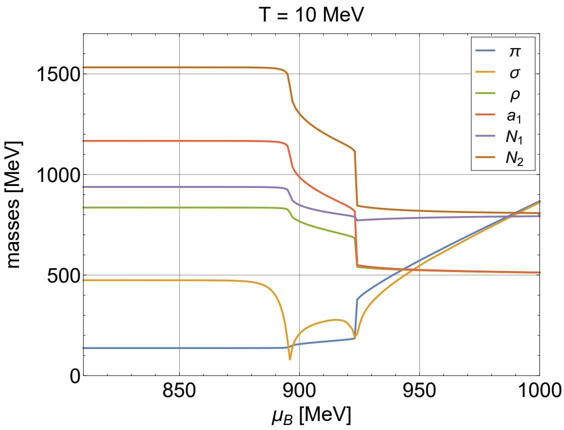
Euclidean correlator ratios

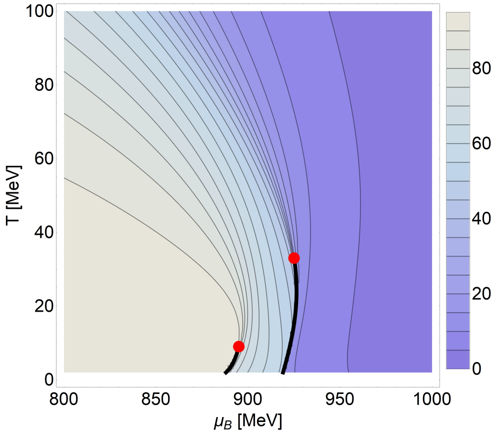


[Aarts et al., Phys. Rev. D 92 (2015) no.1, 014503]
[Allton et al., PoS LATTICE (2016) 183]

Masses and phase diagram of the parity-doublet model (FRG)

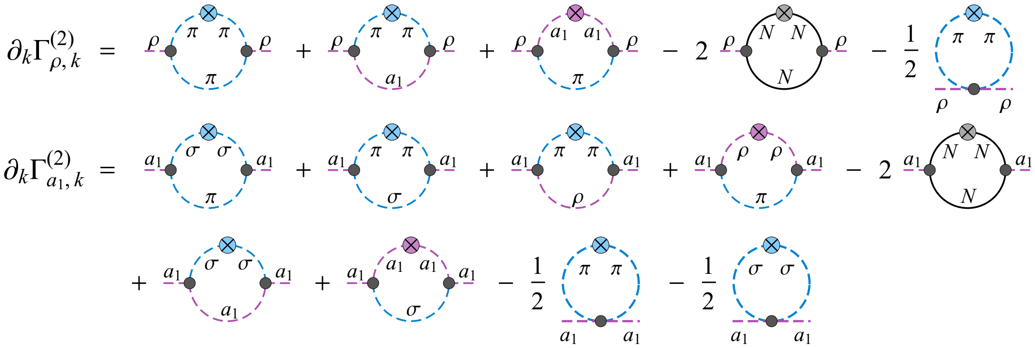
Phase diagram exhibits nuclear liquid-gas transition and chiral phase transition:





[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]

Flow equations for ρ and a_1 2-point functions



- dynamical vector mesons included using formulation in terms of field strengths!
- vertices extracted from ansatz for the effective average action Γ_k
- analytic continuation of flow equations is possible with the aFRG method!

[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]
[C. Jung, L. von Smekal, Phys. Rev. D 100, 116009 (2019)]

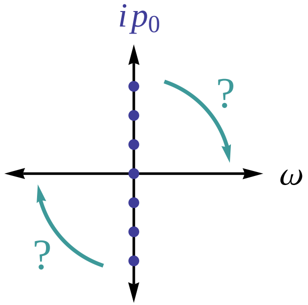
Two-step analytic continuation procedure

1) Use periodicity w.r.t. imaginary energy $ip_0 = i2n\pi T$:

$$n_{B,F}(E + ip_0) \to n_{B,F}(E)$$

2) Substitute p_0 by continuous real frequency ω:

$$\Gamma^{(2),R}(\omega, \vec{p}) = - \lim_{\epsilon \to 0} \Gamma^{(2),E}(ip_0 \to -\omega - i\epsilon, \vec{p})$$



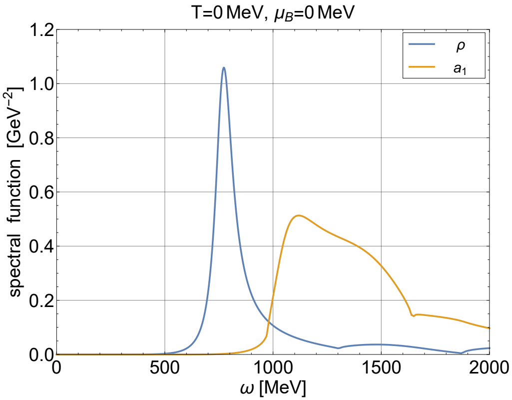
Spectral function is then given by

$$\rho(\omega, \vec{p}) = -\frac{1}{\pi} \mathrm{Im} \frac{1}{\Gamma^{(2),R}(\omega, \vec{p})}$$

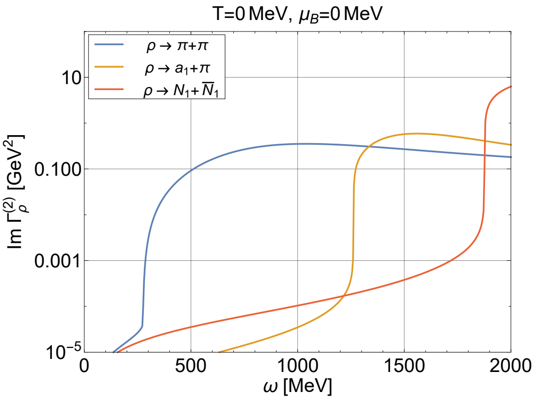
[K. Kamikado, N. Strodthoff, L. von Smekal, J. Wambach, Eur.Phys.J. C74 (2014) 2806]
[R.-A. T., N. Strodthoff, L. v. Smekal, and J. Wambach, Phys. Rev. **D 89**, 034010 (2014)]
[J. M. Pawlowski, N. Strodthoff, Phys. Rev. **D 92**, 094009 (2015)]
[N. Landsman and C. v. Weert, Physics Reports 145, 3&4 (1987) 141]

ρ and a_1 spectral functions in the vacuum (aFRG)

spectral functions:



imaginary part of ρ 2-point function:



[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]

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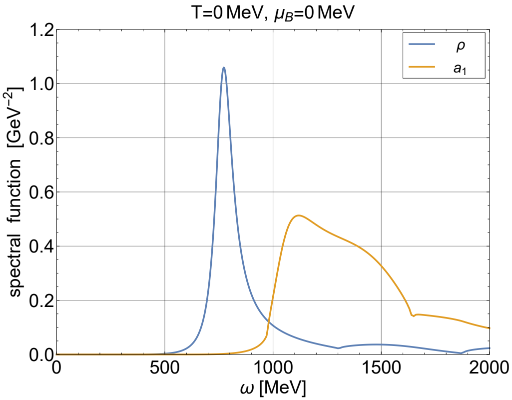
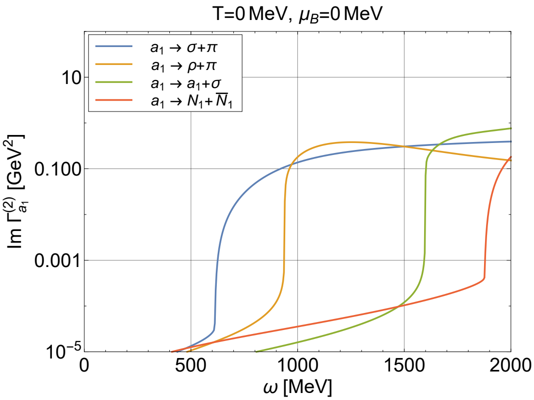


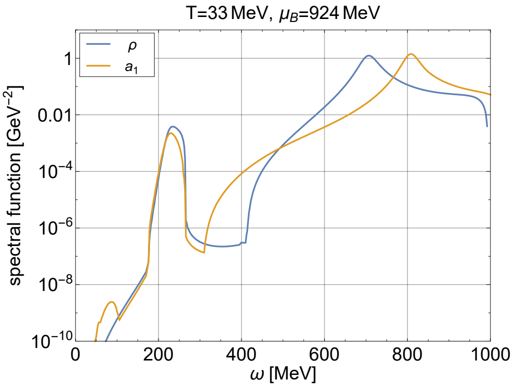
imaginary part of a_1 2-point function:



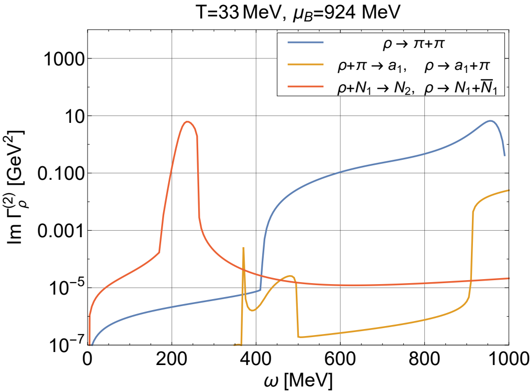
[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]

ρ and a_1 spectral functions near chiral CEP (aFRG)

spectral functions:



imaginary part of ρ 2-point function:



- a pronounced peak at lower energies due to the process $\rho + N_1 \to N_2$ is observed!

[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]

ρ and a_1 spectral functions near chiral CEP (aFRG)

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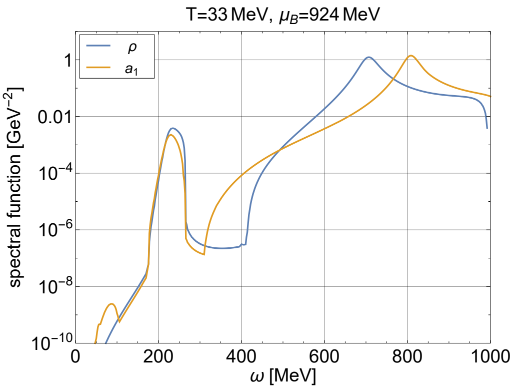
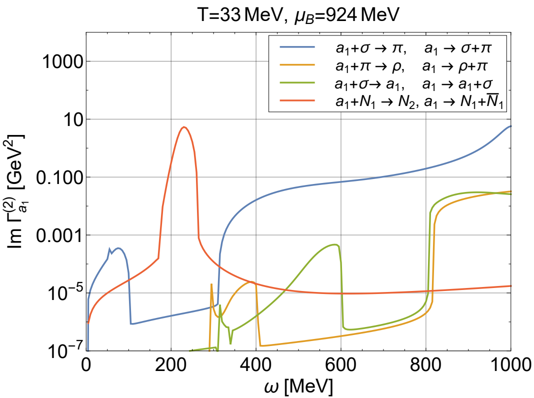


imaginary part of a_1 2-point function:



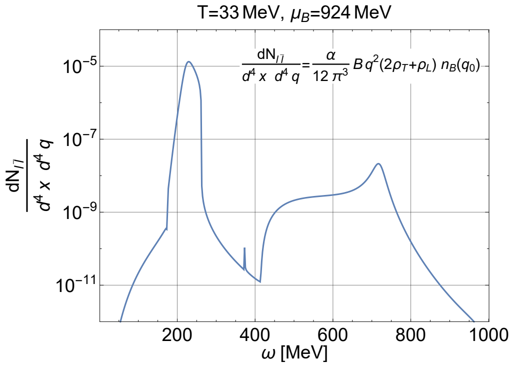
- a pronounced peak at lower energies due to the process $a_1 + N_1 \to N_2$ is observed!

[R.-A. T., C. Jung, L. von Smekal, J. Wambach, Phys. Rev. D 104, 054005 (2021)]

Preliminary results on dilepton rate near chiral CEP (aFRG)

The resonance-production peak in the ρ spectral function due to the process $\rho + N_1 \to N_2$ directly translates into a peak in the thermal dilepton rate!

- unique prediction of the parity-doublet model!
- detection would yield strong evidence in support of the parity-doubling scenario as providing the mechanism for chiral symmetry restoration in dense nuclear matter!



An overpopulation of $N(1535)$ states could also be measured by an increased η yield:

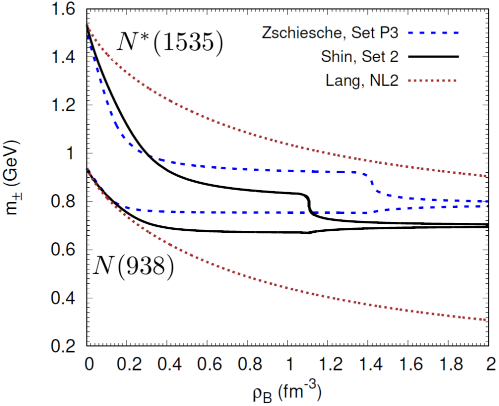
N(1535) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	32–52 %	464
$N\eta$	30–55 %	176

Transport simulation with parity doubling

Parity-doublet model (PDM) mean fields for the nucleon, $N(938)$, and its parity partner, $N^*(1535)$, were included in the GiBUU microscopic transport model:

- red-dotted line: Walecka mean fields (NL2)
- blue-dashed line: PDM mean fields (P3)
- mass of the $N^*(1535)$ resonance decreases quickly with increasing baryon density ρ_B for the PDM fields

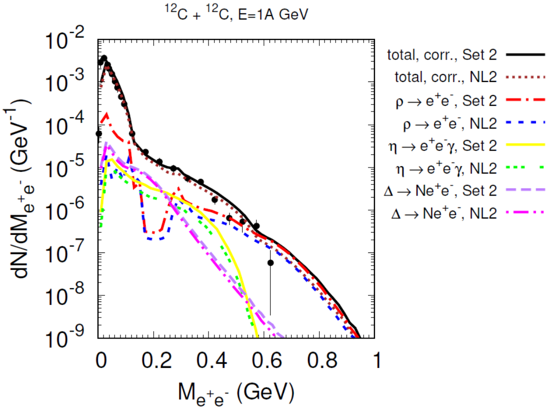
$\rightarrow$ **leads to enhancement of $N^*(1535)$ production in the intermediate stages of central heavy-ion collisions at 1 AGeV!**

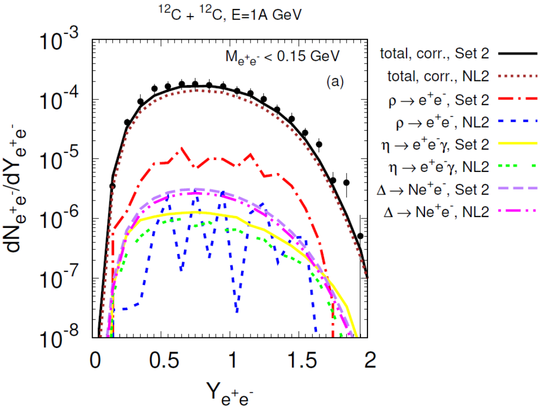


[A. B. Larionov, L. von Smekal, arXiv: 2109.03556]

Transport simulation with parity doubling

Invariant-mass and rapidity distributions of dileptons in C+C collisions at 1 AGeV with GiBUU:





$\rightarrow$ **PDM mean fields lead to enhanced $\rho \rightarrow e^+e^-$ and $\eta \rightarrow e^+e^-\gamma$ signals!**

[A. B. Larionov, L. von Smekal, arXiv: 2109.03556]

In-medium spectral functions from HMBT

Hadronic Many-Body Theory (HMBT):

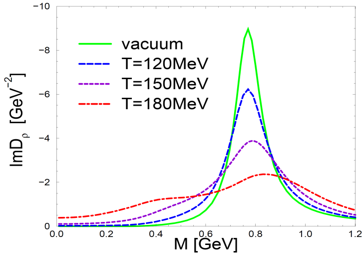
- based on effective hadronic Lagrangians
- parameters are kept constant and constrained by empirical information

Medium modifications of the ρ propagator:

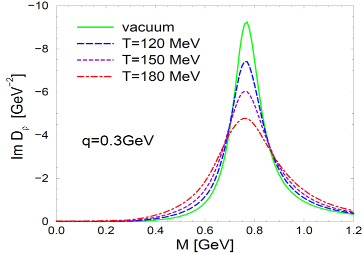
$$D_\rho = \frac{1}{M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B}}$$

- ρ-peak undergoes a strong broadening!
- baryonic effects are crucial!

mesons and baryons, $\mu_B = 330$ MeV:



without baryons:



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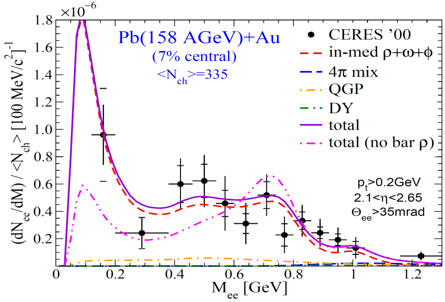
Comparison to data: CERES and NA60

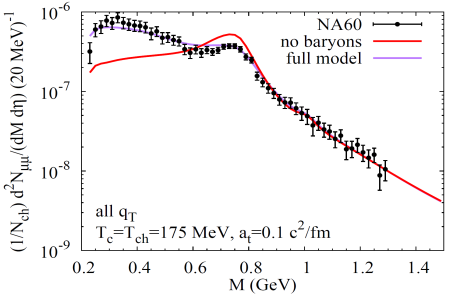
Low-mass dileptons at CERES:

- excess dielectron spectrum in central Pb-Au show an enhancement at low energies
- in-medium ρ spectral function with baryonic effects in quantitative agreement!

High-precision N60 data:

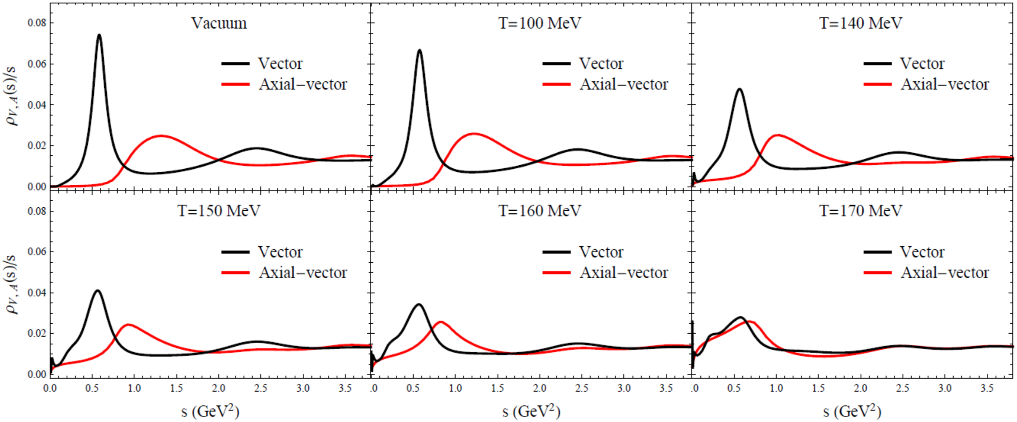
- excess dimuon invariant-mass spectrum in In-In confirms melting of ρ, in particular due to baryon-induced effects
- realizes the long-sought thermometer at masses $M > 1$ GeV!





[R. Rapp, J. Wambach, Eur.Phys.J. A6, 415-420 (1999)]
[R. Rapp, J. Wambach, H. van Hees, Landolt-Bornstein 23, 134 (2010)]
[G. Agakichiev et al. (CERES/NA45), Eur.Phys.J. C41, 475 (2005)]
[D. Adamova et al. (CERES/NA45), Phys.Lett.B 666, 425 (2008)]
[R. Rapp, H. van Hees, Phys.Lett. B753, 586-590 (2016)]
[R. Arnaldi et al. (NA60), Eur.Phys.J. C59, 607; ibid. 61, 711 (2009)]
[S. Damjanovic, R. Shahoyan, H.J. Specht (NA60), CERNCour.49N9, 31 (2009)]

In-medium spectral functions from HMBT and sum rules



- QCD and Weinberg sum rules can be used to constrain spectral function of a_1 meson
- chiral mass splitting 'burns off', degeneration near ground-state mass!

[P.M. Hohler, R. Rapp, Annals Phys. 368, 70-109 (2016)]
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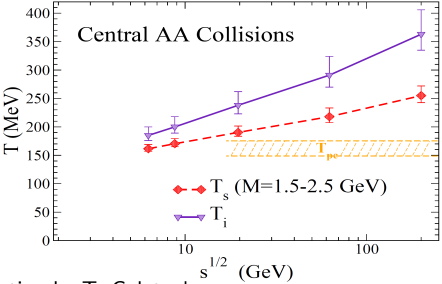
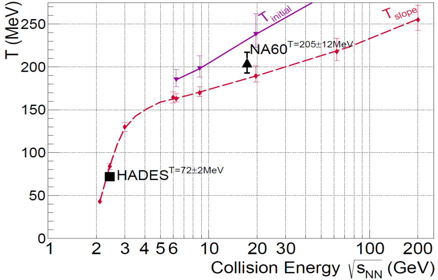
Dileptons as a thermometer

Thermometer:

- in the intermediate-mass regime, $1.5 < M < 2.5$ GeV, the dilepton rate is $dR_{ll}/dM \propto (MT)^{3/2} \exp(-M/T)$
- independent of flow: no blue-shift effects!
- NA60: $T = 205 \pm 12$ MeV (the only explicit temperature measurement above T_c in heavy-ion collisions!)
- represents an average over the fireball evolution



compilation by T. Galatyuk:



Signatures for phase transitions?

- phase transition may show up as a plateau!

[R. Rapp, H. van Hees, Phys.Lett. B753, 586-590 (2016)]
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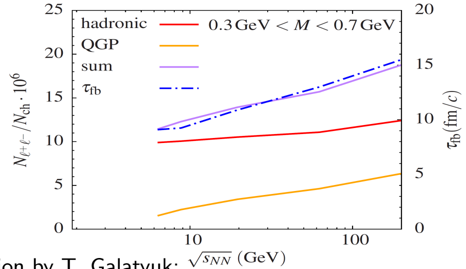
[HADES, Nature Physics 15, 1040-1045 (2019)]
[NA60, Chiral 2010, AIP Conf.Proc. 1322 (2010)]

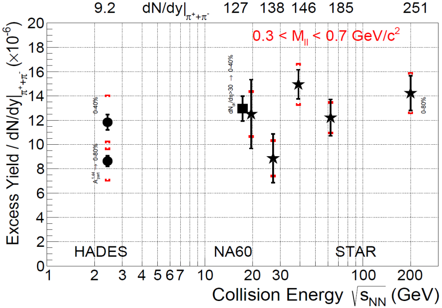
Dileptons as a chronometer

Chronometer:

- in the low-mass regime, $0.3 < M < 0.7$ GeV, hadronic and QGP radiation are both relevant
- integrated low-mass radiation tracks the fireball lifetime!
- low-mass dileptons are an excellent tool to detect ‘anomalous’ variations



compilation by T. Galatyuk:



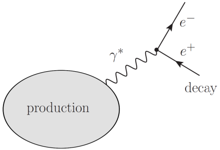
Signatures for phase transitions?

- extra radiation when system lives longer around the critical point!

[R. Rapp, H. van Hees, Phys.Lett. B753, 586-590 (2016)]
[T. Galatyuk, QM2018]
[U.W. Heinz, K.S. Lee, Phys.Lett. B259, 162 (1991)]
[H.W. Barz, B.L. Friman, J. Knoll and H. Schulz, Phys.Lett. B254, 315 (1991)]
[R. Rapp, H. van Hees, Phys.Lett. B753, 586 (2016)]

Dileptons as a polarimeter

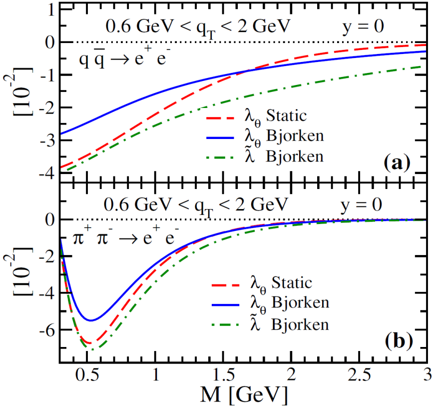
Angular distribution of dilepton rate in the photon rest frame:



$$\frac{dR}{d^4q d\Omega_\ell} = \mathcal{N}\Big(1 + \lambda_\theta \cos^2\theta_\ell + \lambda_\phi \sin^2\theta_\ell \cos 2\phi_\ell + \dots\Big)$$

with anisotropy coefficients λ, e.g. $\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$

- angular distribution of dileptons gives information on polarization of γ^* and thus on production mechanism
- virtual photons from (unpolarized) thermal sources are polarized!
- systematic study of all relevant processes needed!



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[E.L. Bratkovskaya, O.V. Teryaev V.D. Toneev, Phys.Lett. B348, 283 (1995)]
[E. Speranza, M. Zétényi, B. Friman, Phys.Lett. B764, 282 (2017)]

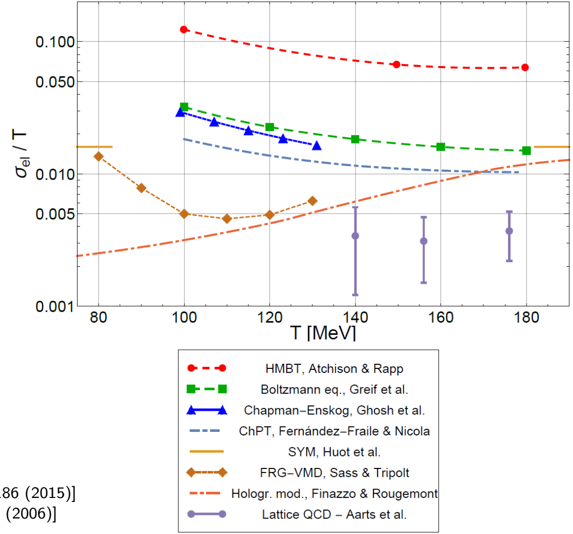
Dileptons as an amperemeter?

Electrical Conductivity:

- defined as the low-energy limit of the EM spectral function:

$$\sigma_{el} = -e^2 \lim_{p_0 \to 0} \frac{\partial}{\partial p_0} \mathrm{Im}\Pi_{\mathrm{EM}}(p_0, |\vec{p}| = 0)$$

- large spread in literature
- interesting possibility: extract conductivity peak from dilepton spectra at low energies!?



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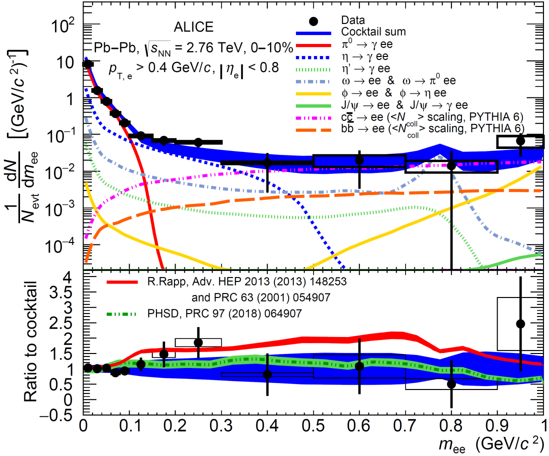
[M. Greif, C. Greiner, G.S. Denicol, Phys.Rev. D93, 096012 (2016)]
[D. Fernandez-Fraile, A. Gomez Nicola, Phys.Rev. D73, 045025 (2006)]
[G. Aarts, C. Allton, A. Amato, P. Giudice, S. Hands, J.I. Skullerud, JHEP 1502, 186 (2015)]
[S. Caron-Huot, P. Kovtun, G.D. Moore, A. Starinets, L.G. Yaffe, JHEP 0612, 015 (2006)]
[S.I. Finazzo, R. Rougemont, Phys.Rev. D93, 034017 (2016)]
[J. Atchison, R. Rapp, J.Phys. Conf.Ser. 832, 012057 (2017)]

Dileptons at high collision energies

Dielectron invariant-mass spectrum measured by ALICE compared to two model calculations which use a broad in-medium ρ spectral function:

- Hadronic Many-Body Theory (HMBT)
- Parton Hadron String Dynamics (PHSD)



Results:

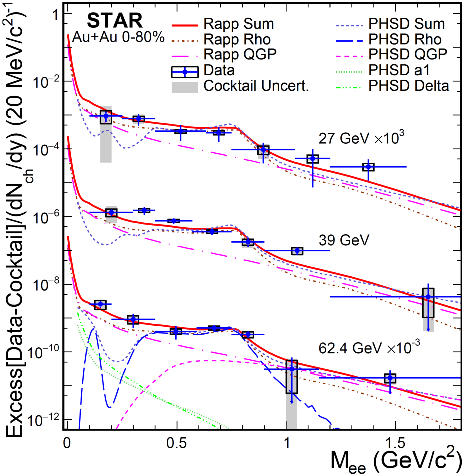
- both model calculations are consistent with the data within uncertainties
- precision measurements are needed to distinguish between the models and to constrain the in-medium properties of the ρ-meson!

[ALICE Collaboration, Phys.Rev. C99, 024002 (2019)]

Dileptons at intermediate energies

STAR Beam Energy Scan:

- acceptance-corrected dielectron excess mass spectrum in good agreement with model calculations for all collision energies
- each model includes thermal contributions from the in-medium ρ and the QGP
- high-precision measurements needed: BES phase II is focusing on regime with high baryon density: 7.7 to 19.6 GeV



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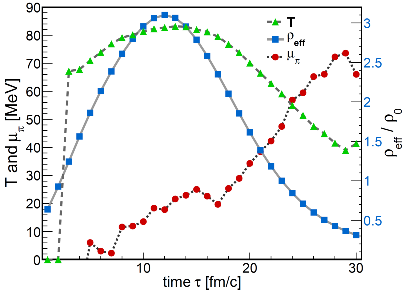
Towards lower energies: Coarse graining

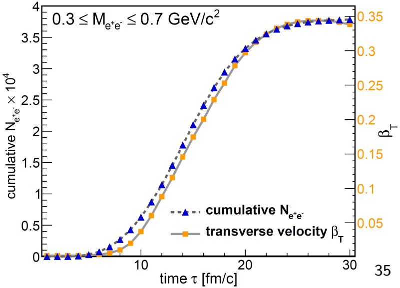
Challenges at low collision energies:

- justification for thermalization in hydro?
- implementation of in-medium effects in transport?

Coarse-graining idea:

- average hadron distributions from transport calculations in suitable space-time cells over many events
- extract smooth space-time evolutions of temperature, density and chemical potential
- use thermal dilepton rates and convolute them with space-time evolution to obtain dilepton spectra
- interesting observation: time evolution of the cumulative low-mass radiation tracks transverse velocity → life time!





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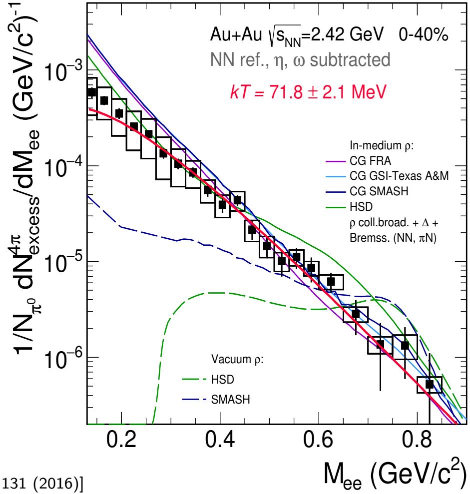
[J. Staudenmaier, J. Weil, V. Steinberg, S. Endres, H. Petersen, Phys.Rev. C98, 054908 (2018)]

Dileptons at HADES

Strong excess of dileptons observed:

- transport calculations with vacuum-ρ cannot reproduce data
- coarse-graining approaches with in-medium-ρ in better agreement
- structureless excess yield indicates strong medium modifications of the ρ, probably due to high baryon density $(n_B + n_{\bar{B}})$!
- strong broadening can be connected to partial restoration of chiral symmetry!

acceptance-corrected excess radiation:



[HADES Collaboration, Nature Physics 15, 1040-1045 (2019)]
CG FRA: [S. Endres, H. van Hees, J. Weil, M. Bleicher, Phys.Rev. C92, 014911 (2015)]
CG GSI-Texas A&M: [T. Galatyuk, P.M. Hohler, R. Rapp, F. Seck, J. Stroth, Eur.Phys.J. A52, 131 (2016)]
CG SMASH: [J. Staudenmaier, J. Weil, V. Steinberg, S. Endres, H. Petersen, Phys.Rev. C98, 054908 (2018)]
HSD: [E.L. Bratkovskaya, J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, Phys.Rev. C87, 064907 (2013)]

Summary and Outlook

Dileptons provide a wide range of insights on the created medium:

- basic kinematic information: fireball temperature, degree of collectivity, lifetime
- dynamical information: in-medium spectral functions encoding changes in the degrees of freedom and chiral symmetry restoration, transport coefficients like electrical conductivity
- melting of the ρ-meson in a strongly-interacting hadronic medium, indicating a transition in degrees of freedom ($q\bar{q}$ continuum) and compatible with chiral restoration
- emerging consensus that chiral partners degenerate at the ground state mass, i.e. chiral splitting burns off but ground-state mass remains (e.g. generated by gluon condensate)

Outlook:

- new theoretical developments will provide realistic chirally and thermodynamically consistent in-medium vector-meson spectral functions (e.g. aFRG, lattice QCD)
- dileptons measured in running and upcoming experiments (STAR BES-II, NA60+, FAIR, NICA, J-PARC, ...) can help to identify QCD phase transitions and the critical point!