TECHNISCHE UNIVERSITÄT DARMSTADT

HADRONS IN MEDIUM

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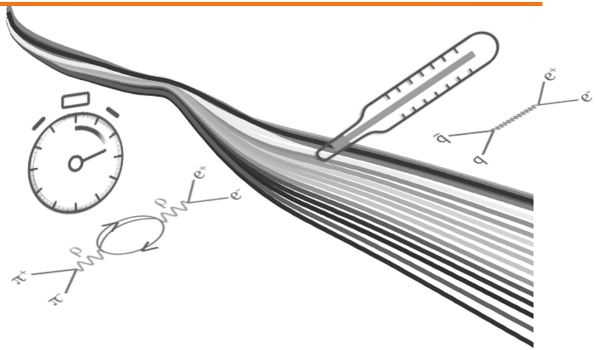
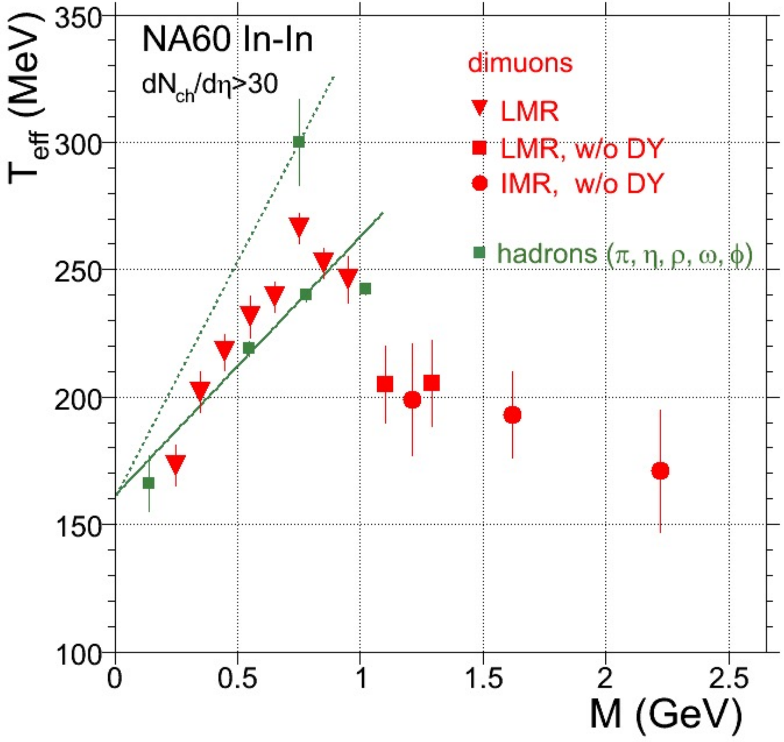
Technical University Darmstadt / GSI
06 July, 2022

Lecture 3



The rise and fall of T_{eff} of thermal dimuons



NA60, PRL 100 (2008) 022302

- $M < 1\ GeV$
  - strong, almost linear rise of T_{eff} with dimuon mass
  - follows trend set by hadrons
- $M > 1\ GeV$
  - drop of T_{eff} by ~$50\ MeV$
  - followed by an almost flat plateau

What can we learn from m_T spectra?
↝ radial flow
↝ origin of dileptons

Dileptons as

THERMOMETER

Emiting source temperature

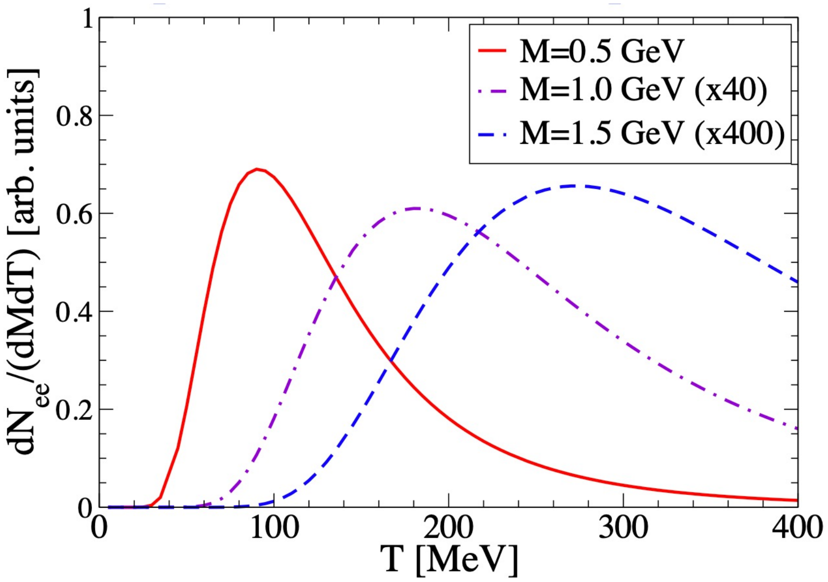
The time-differential invariant-mass spectrum, integrated over 3-momentum and 3-volume at each time snapshot:

$$\frac{dN_{ll}}{dMd\tau} = \frac{M}{q_0}\int d^3x\, d^3q\, \frac{dN_{ll}}{d^4x d^4q}$$

$$\simeq const\, V_{FB}(\tau)\frac{Im\Pi_{em}(M;T)}{M}\int \frac{d^3q}{q_0} e^{-\frac{q_0}{T}} \quad *$$

$$\simeq const\, V_{FB}(\tau)\frac{Im\Pi_{em}(M;T)}{M^2} e^{-\frac{M}{T}}(MT)^{3/2} \quad **$$

Temperature profile of dilepton yields

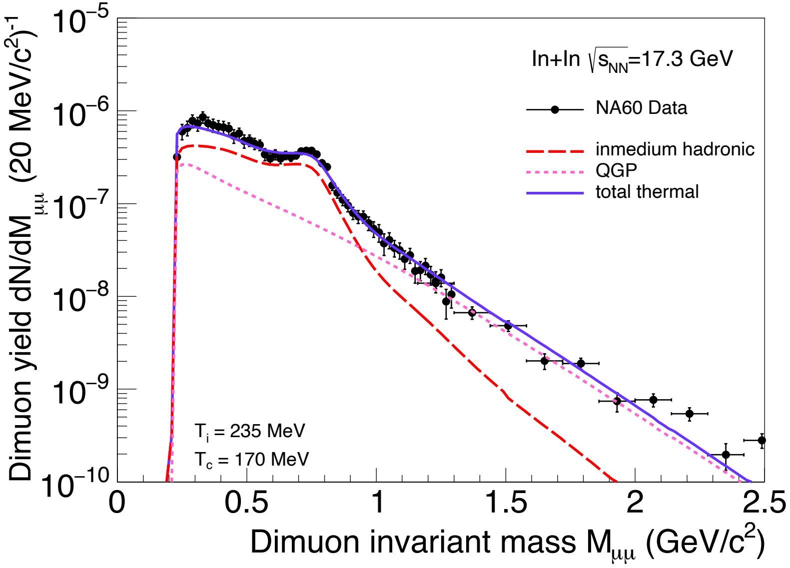


* assumed that the in-medium EM spectral function depends only weakly on 3-momentum

** invoke approximation $T/M \ll 1$

Dileptons as thermometer at SPS

Acceptance corrected $\mu^{+}\mu^{-}$excess yield



- IMR spectrum falls exponentially
- In the IMR the dilepton rate $\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}}\exp(-\frac{M}{T})$
- Independent of flow: no blue shift!

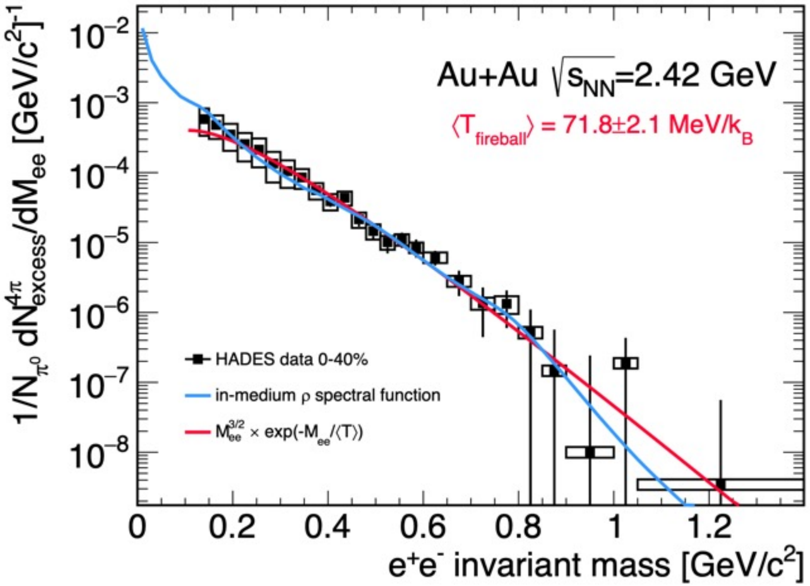
$M = 1.1 - 2\ GeV \quad : \langle T\rangle = 205\ \pm 12$ MeV
$M = 1.1 - 2.4\ GeV : \langle T\rangle = 230\ \pm 10$ MeV

↝ **the only explicit temperature measurement above T_{pc} in heavy-ion collisions!**

NA60, Arnaldi *et al.*, EPJC 61(2009) 711
NA60, Specht *et al.*, Chiral 2010, AIP Conf.Proc. 1322 (2010)

Dileptons as thermometer at SIS18

Acceptance corrected e^+e^- excess yield

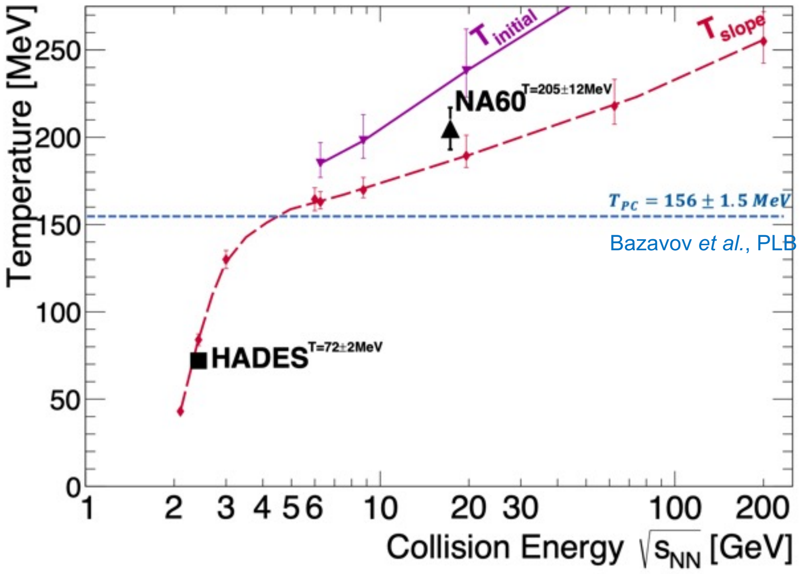


HADES, Nature Phys. 15(2019) 1040

- IMR spectrum falls exponentially
- In the IMR the dilepton rate $\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$
- Independent of flow: no blue shift!

$M = 0.2 - 1.2\ GeV \quad : \langle T \rangle = 71.8\ \pm 2.1$ MeV

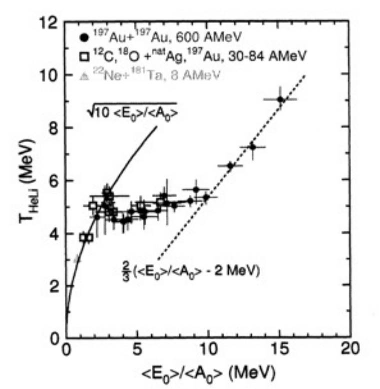
Mapping the QCD "caloric curve" (T vs ε)



Bazavov *et al.*, PLB 795 (2019) 15-21

Signature for phase transition?
↝ **phase transition may show up as a plateau!**
↝ **future high statistics experiments**

Nuclear liquid-gas phase transition

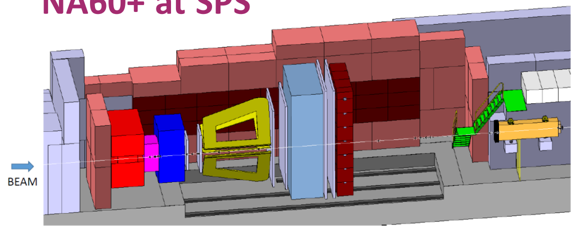


Pochodzalla *et al.*, PRL 75 (1995) 1040

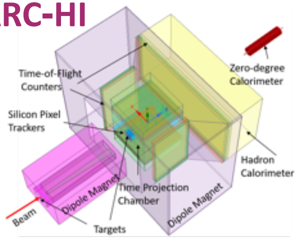
Rapp and v. Hess, PLB 753 (2016) 586
TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

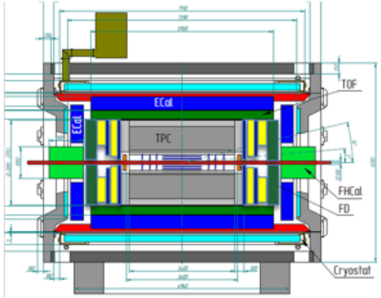
Mapping QCD “caloric curve”, > 2028

NA60+ at SPS



J-PARC-HI

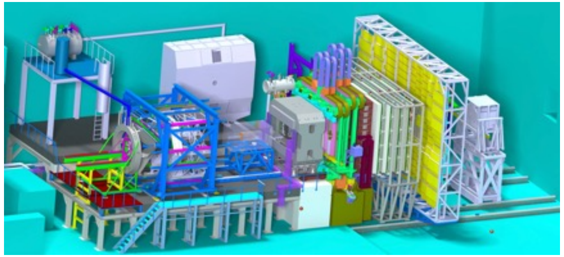


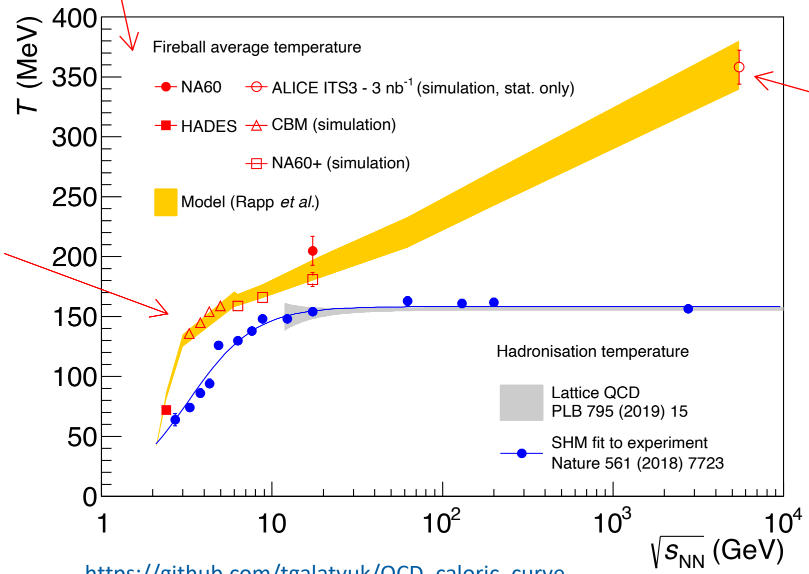


MPD at NICA

(Stage II: inner tracker, endcaps)

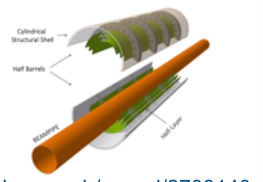
HADES$_{100kHz}$ / CBM at FAIR





https://github.com/tgalatyuk/QCD_caloric_curve

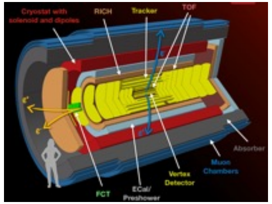
ALICE ITS3



https://cds.cern.ch/record/2703140

ALICE 3

(>2030)

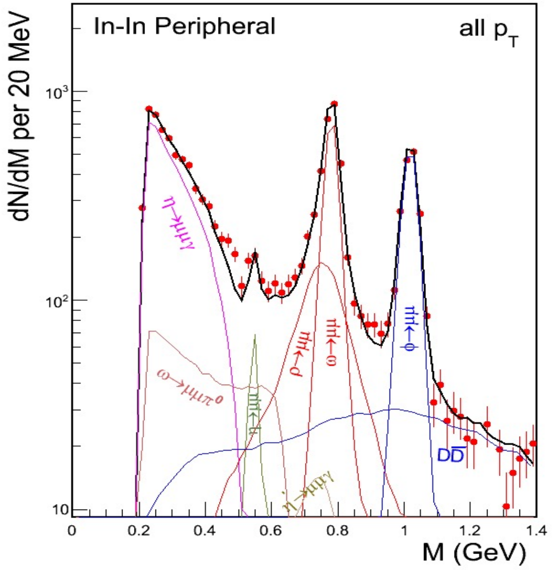


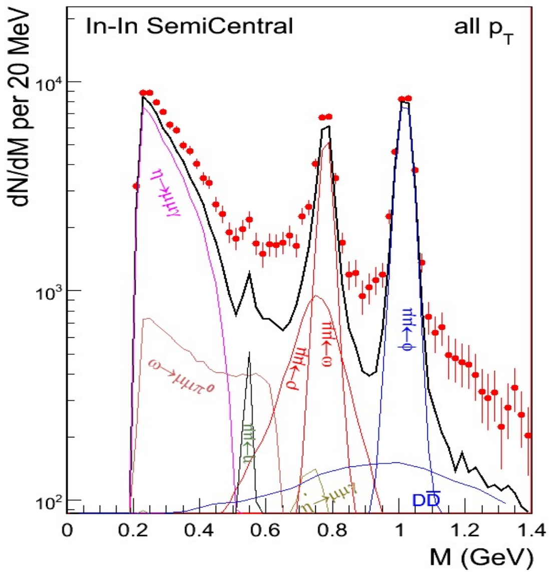
Dileptons as

CHRONOMETER

Dimuon invariant mass from NA60

NA60, Eur.Phys.J.C 49 (2007) 235

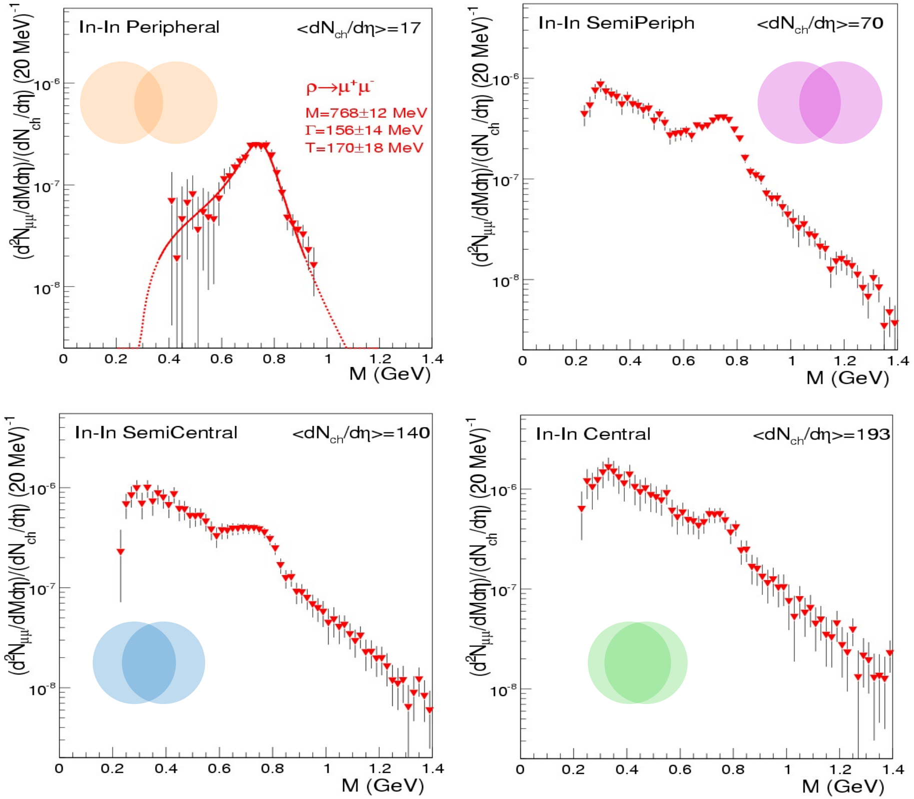




<u>Peripheral data</u>
well described by meson decay 'cocktail'
$(\eta, \eta', \rho, \omega, \phi)$ and $D\bar{D}$

<u>More central data</u>
clear excess of data above decay 'cocktail'

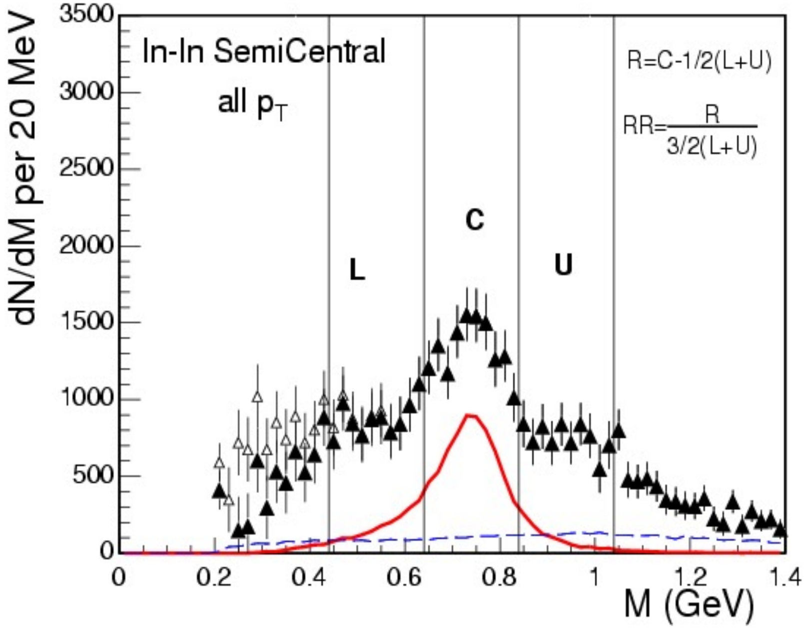
Excess as a function of centrality

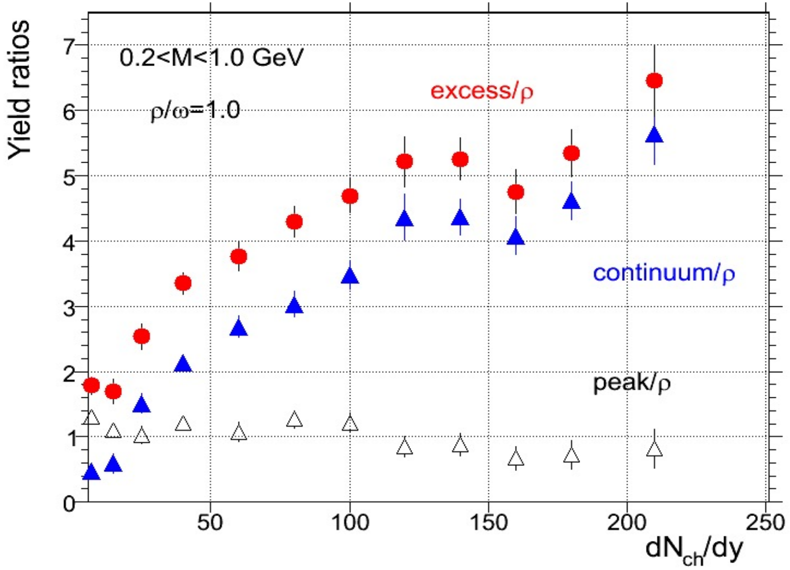


Excess radiation is rising with centrality

The dilepton clock

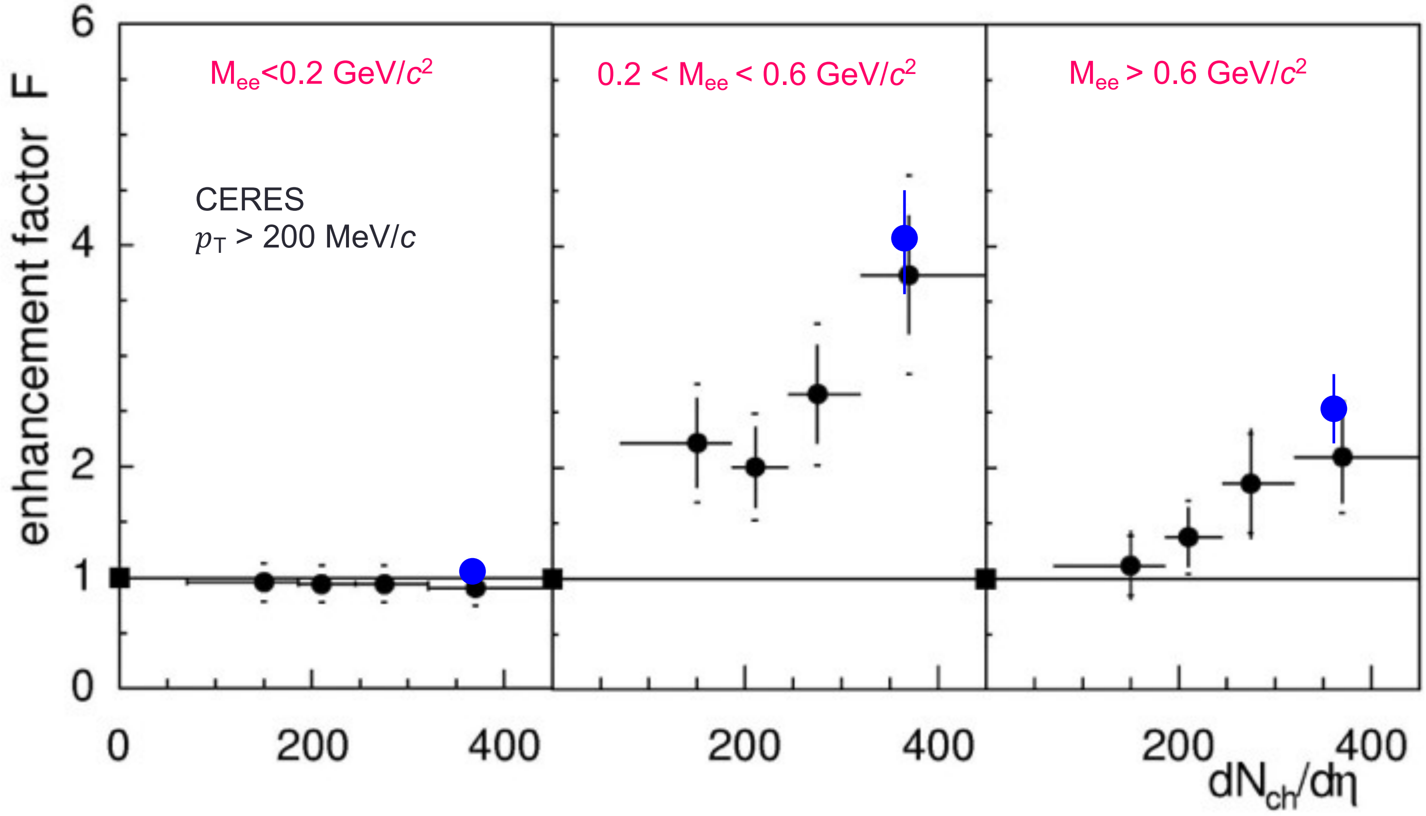
Centrality dependence of spectral shape





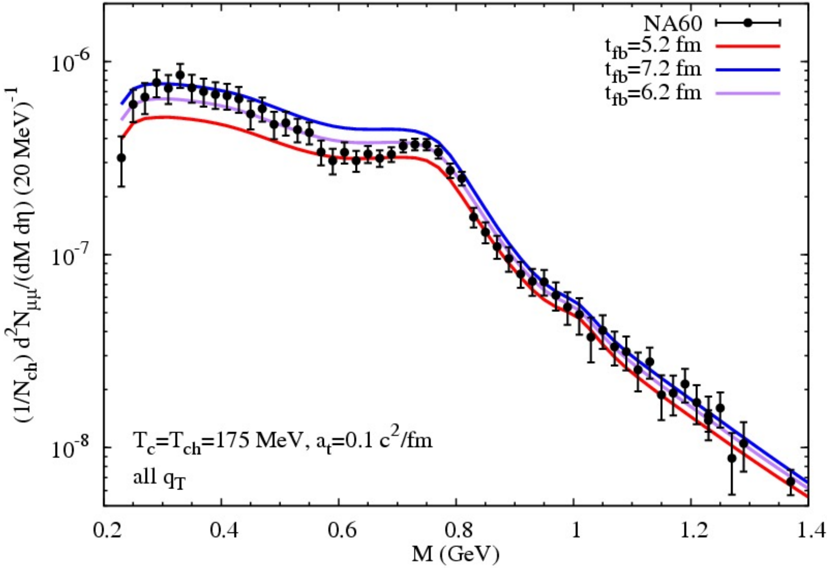
Rapid increase of relative yield reflect the number of ρ's regenerated in fireball

Centrality dependence of excess



The dilepton clock

NA60: AIP Conf.Proc. 1322 (2010) 1

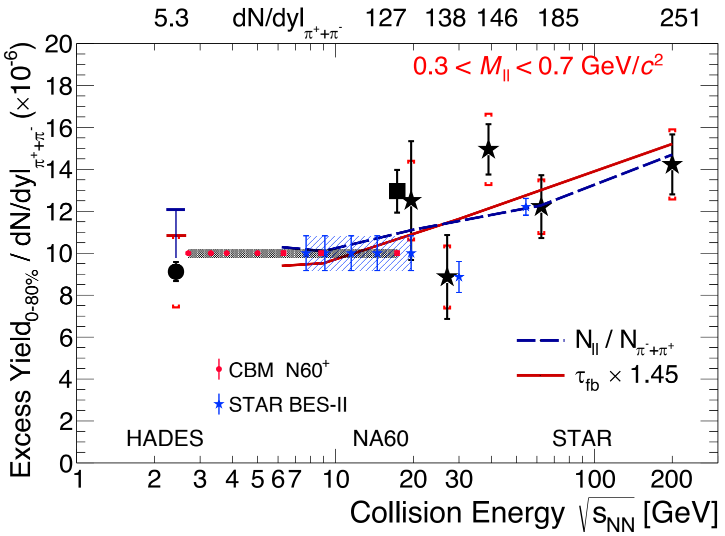


"explicit" measurement of interacting-fireball lifetime: $\tau_{FB} \approx (7 \pm 1)\ fm/c$

The dilepton clock

Integrated low-mass radiation
$0.3 < M < 0.7$ GeV/c^2 tracks the fireball lifetime

U. W. Heinz and K. S. Lee, PLB 259, 162 (1991)
H. W. Barz, B. L. Friman, J. Knoll and H. Schulz, PLB 254, 315 (1991)



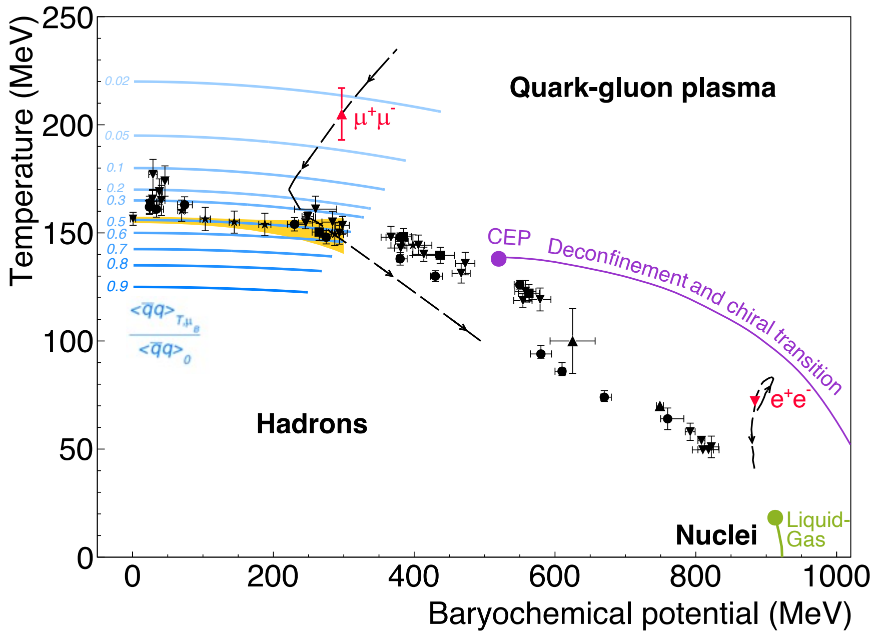
TG., JPS Conf.Proc. 32 (2020) 010079

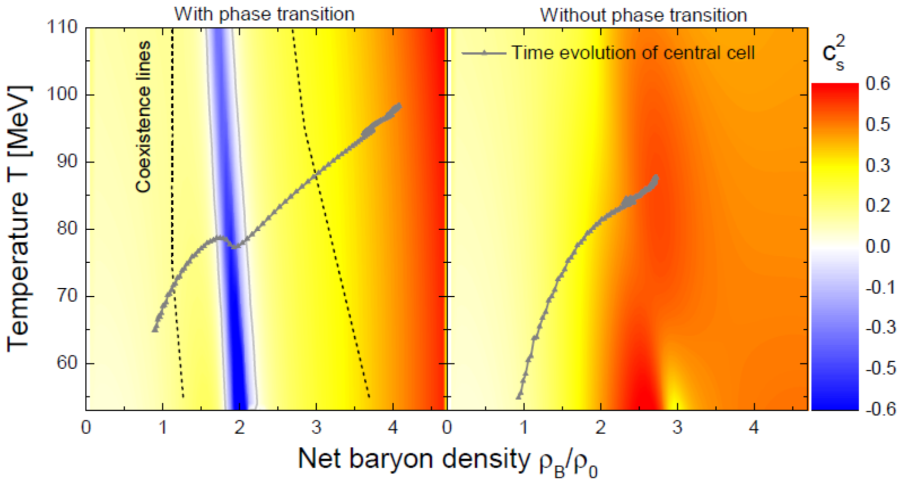
The amount of radiation depends on both the volume V_{FB} and the lifetime of the fireball τ_{FB}

V_{FB}, at a given collision energy and centrality class, is proportional to the number of charged particles → accessible through hadronic final-state observables

→ Normalize the low-mass dilepton yields to the number of charged particles or the number of pions
→ obtain a measure of the τ_{FB}

Dilepton signature of a 1st order phase transition





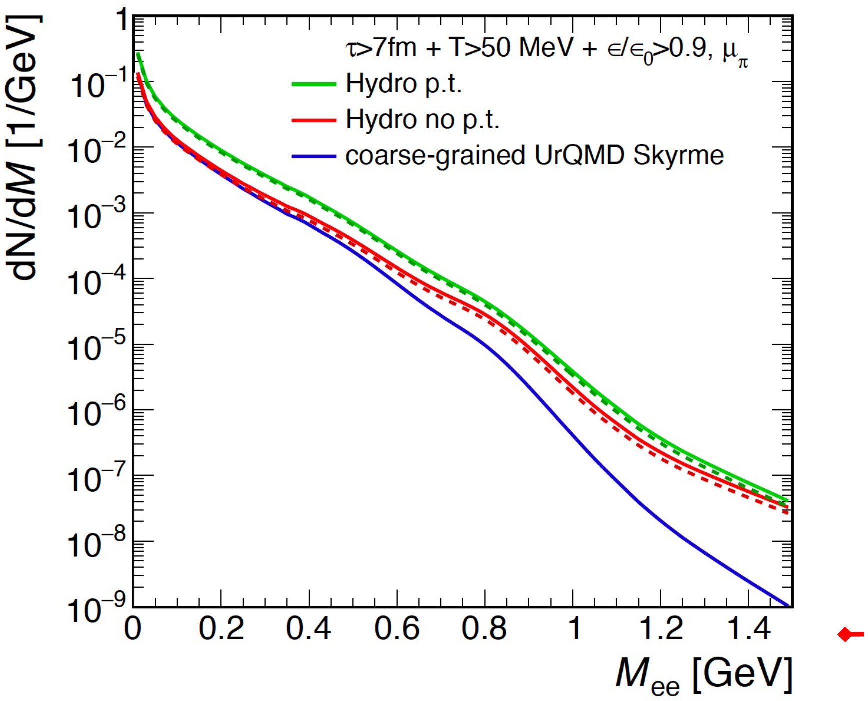
Dilepton radiation in hydrodynamics

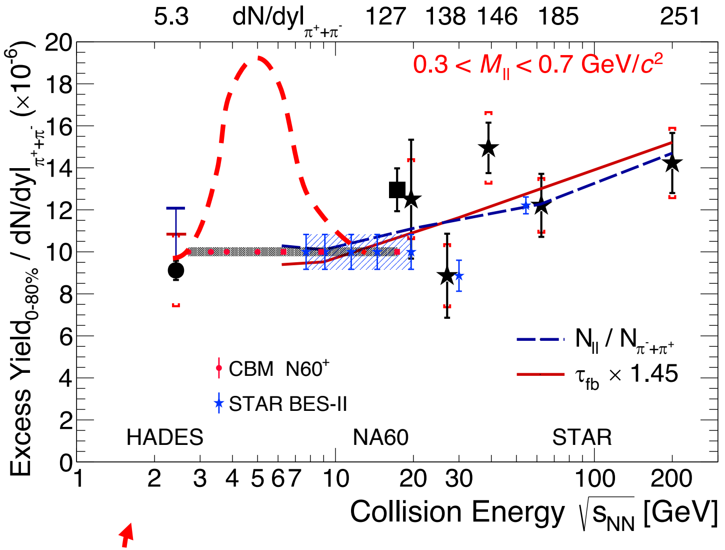
- implement 1st-order transition into CMF/PNJL model by increasing scalar quark couplings

Seck, TG, et al., arXiv:2010.04614 [nucl-th]

Dilepton signature of a 1st order phase transition

Factor of ~2 extra radiation in case of hydro with phase transition

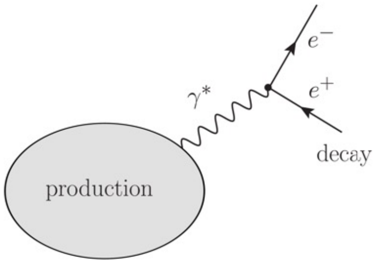




Dileptons as

POLARIMETER

Virtual photon polarization and dilepton anisotropy



The spin-1 structure of the EM correlator carries valuable information on the production process of lepton pairs:

- Angular distribution of dilepton pairs
- Polarization states of the γ^*
- Information on the production mechanism

Speranza, Jaiswal, Friman, PLB782 (2018) 395
Speranza, PhD thesis, TUDa 2017

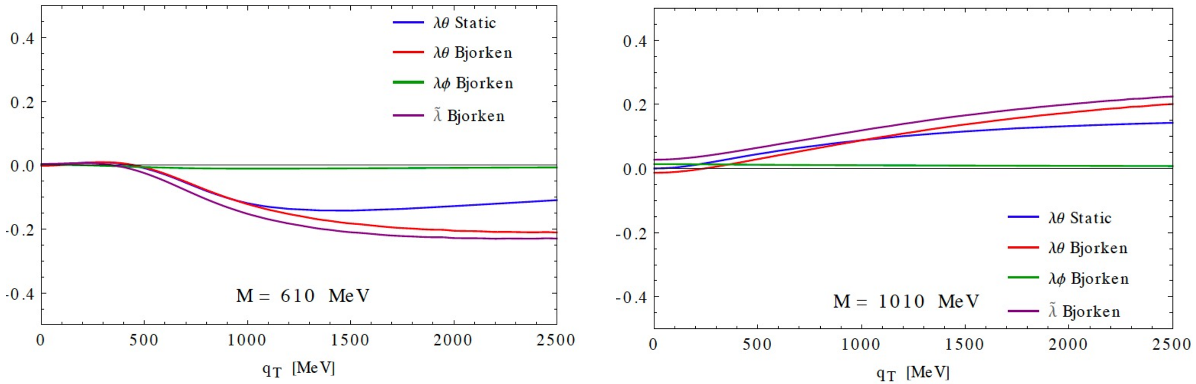
$$\frac{d\Gamma}{d^4q d\Omega_l} = \mathcal{N}\left(1 + \lambda_\theta cos^2\theta_l + \lambda_\phi sin^2\theta_l cos2\phi_l + \cdots\right)$$

$$\Gamma \equiv \frac{dN}{d^4x}$$ dilepton production rate

$$\lambda_\theta = \frac{\rho_T - \rho_L}{\rho_T + \rho_L}$$ anisotropy coefficient

$$\tilde{\lambda} = \frac{\lambda_\theta - 3\lambda_\phi}{1 - \lambda_\phi}$$

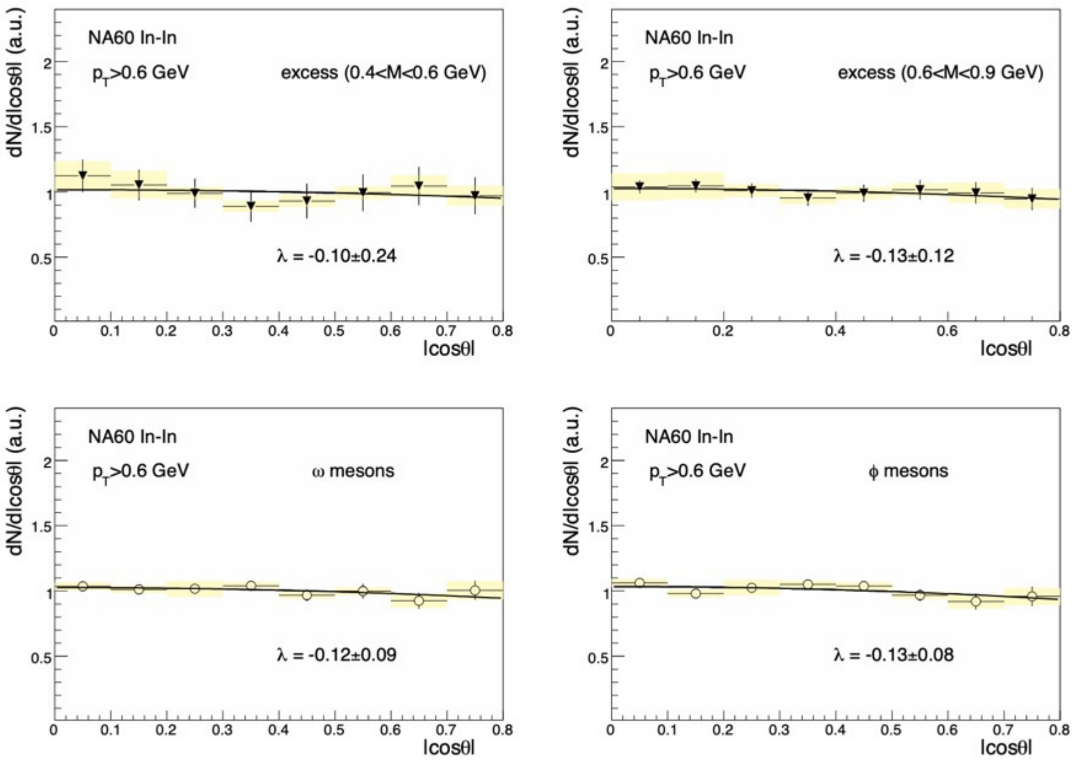
ρ_T, ρ_L from realistic EM spectral functions



Speranza, Friman, Galatyuk, v. Hees, Rapp, Wambach, in preparation

Virtual photons from (unpolarized) thermal sources are polarized!

Polarization measurements NA60



- NA60: no evidence for polarization at least not at the level of statistical and systematic uncertainties

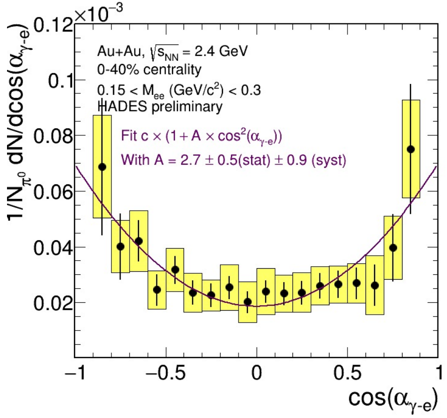
NA60: PRL 96 (2009) 222301

HADES n+p $\sqrt{s_{NN}}$=2.4 GeV

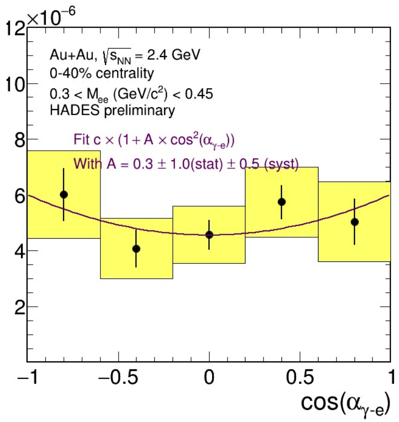
Helicity angle (in the γ^* rest frame)…

- … measures the photon polarization HADES: PRC 84 (2011) 014902

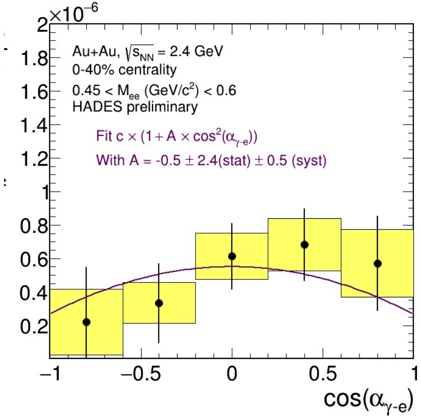
0.15 < M_{ee} (GeV/c^2) < 0.3



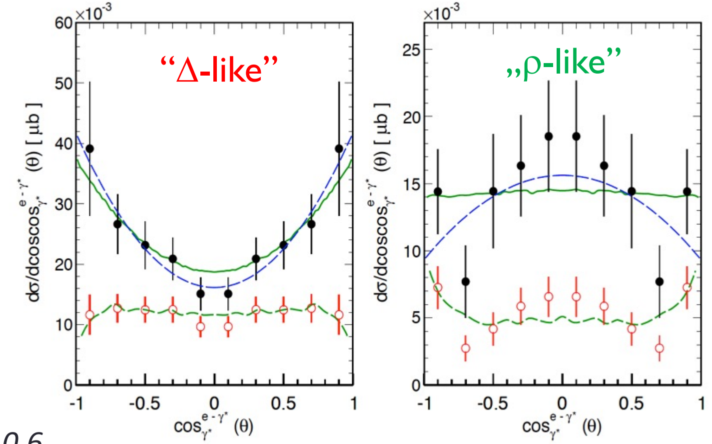
0.3 < M_{ee} (GeV/c^2) < 0.45



0.45 < M_{ee} (GeV/c^2) < 0.6



0.15 < M_{ee} (GeV/c^2) < 0.3 *M_{ee} > 0.3 GeV/c^2*



For $\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$ expected B=-1 → hint for vector meson contribution

Bratkovskaya *et al.*, PLB 348 (1995) 325

Dileptons as

AMPEREMETER

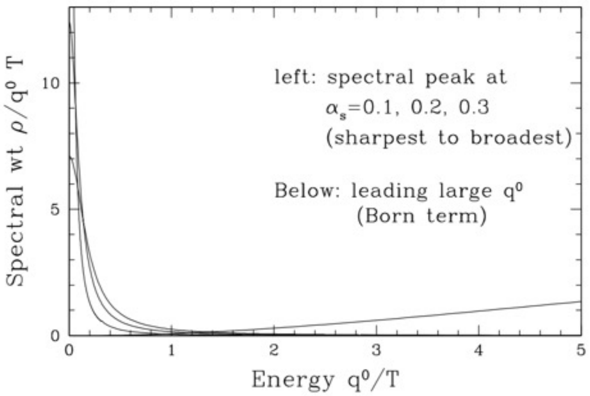
Transport properties of the medium

Electrical conductivity

can be directly obtained from the low-energy limit of the EM spectral function (at vanishing momentum)

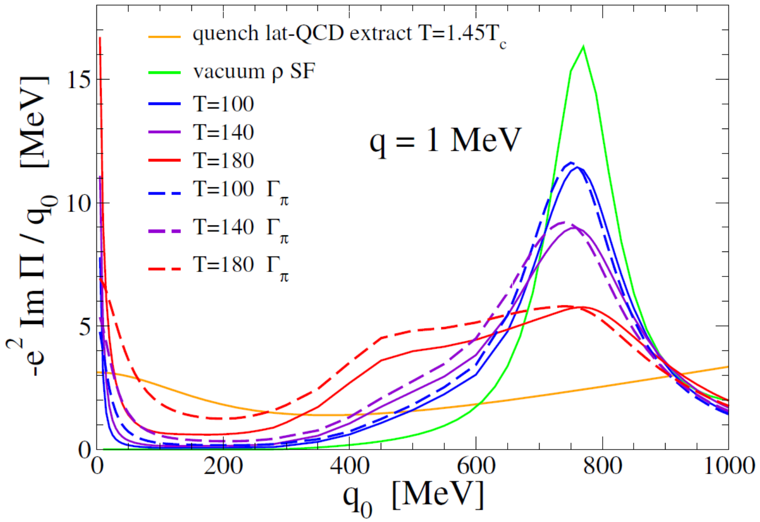
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Transport peak in the limit of very low mass and p_T



Moore and Robert, arXiv:hep-ph/0607172

Rapp, EMMI RRTF 2021

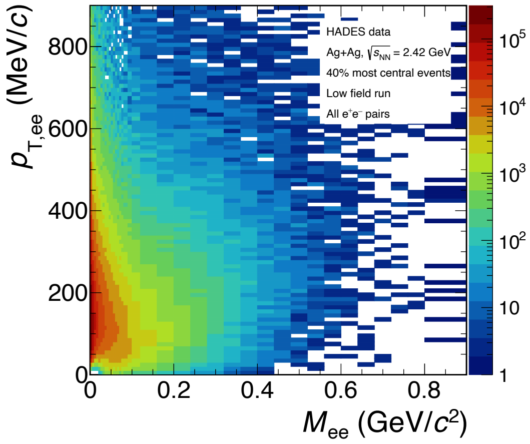


- Conductivity is reduced when thermal-pion interactions included
- Transport peak broadens

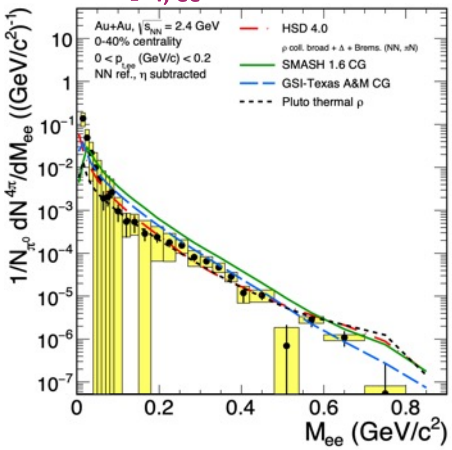
Experimental challenge

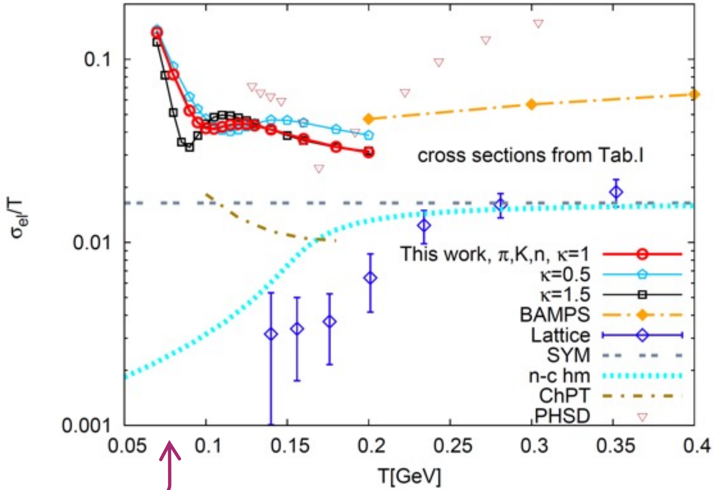
Measure accurately low mass – low p_T thermal excess yiled

HADES, data

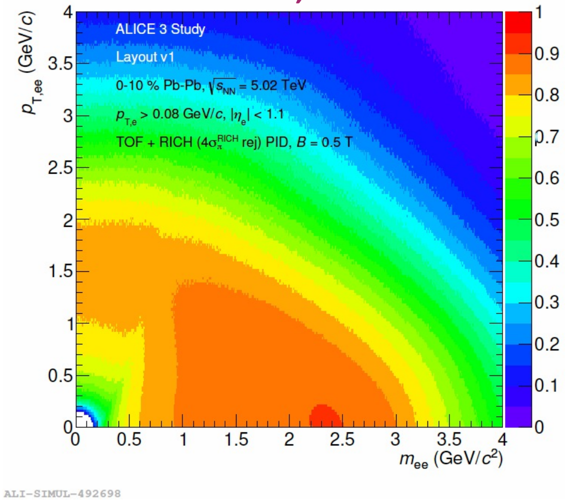


$p_{T,\,ee}$ < 200 MeV/c





ALICE 3, simulations



large spread in literature

Greif, Greiner, Denicol, Phys.Rev. D93 (2016) 096012
Atchison, Rapp, Phys. Conf.Ser. 832 (2017) 012057 (2017)

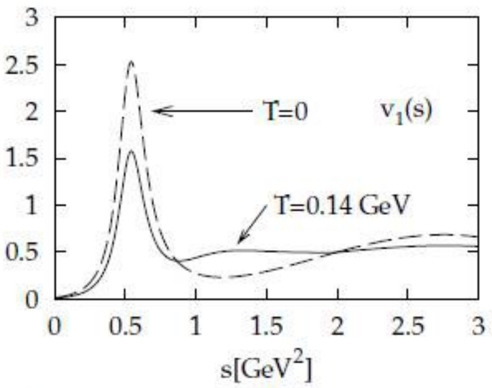
Dileptons and

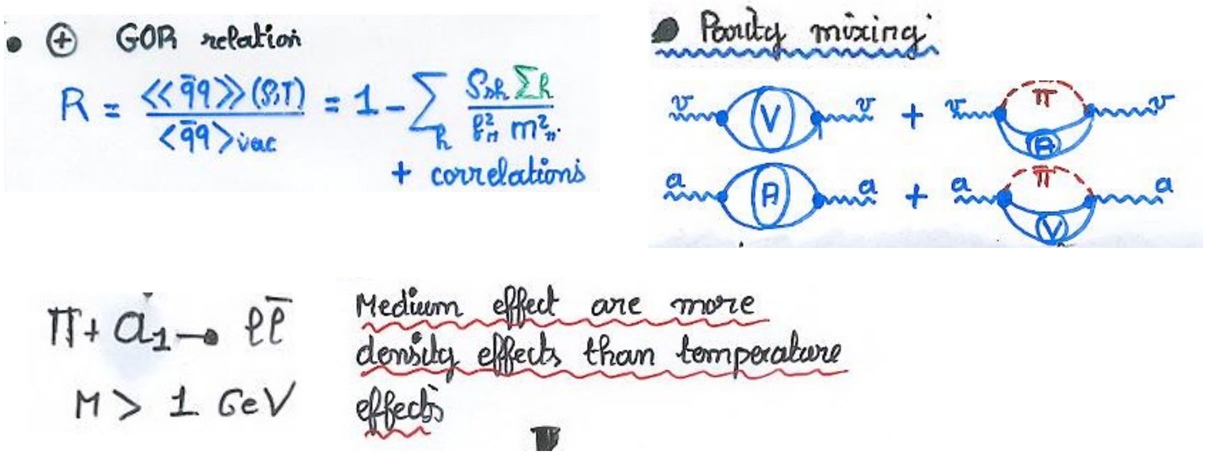
CHIRAL SYMMETRY

(additional) Signature for chiral symmetry restoration

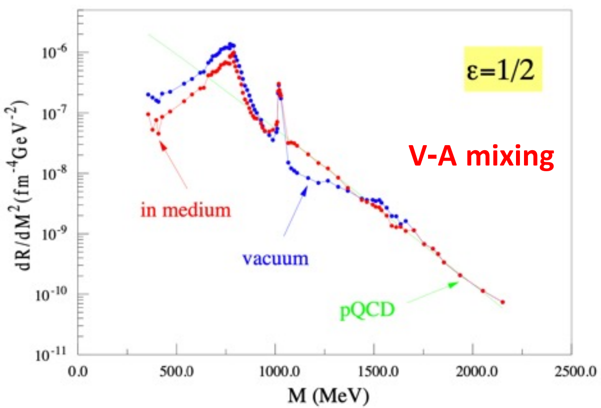
- Changes in yield and shape at $M_{ee} > 1.1$ GeV/c^2 due to $\rho - a_1$ **chiral mixing**
- $\pi a_1 \to \gamma^* \to \ell^+\ell^-$ (chiral mixing) is a dominant hadronic source in IMR

Dey, Eletsky and Ioffe, Phys.Lett. B252 (1990)





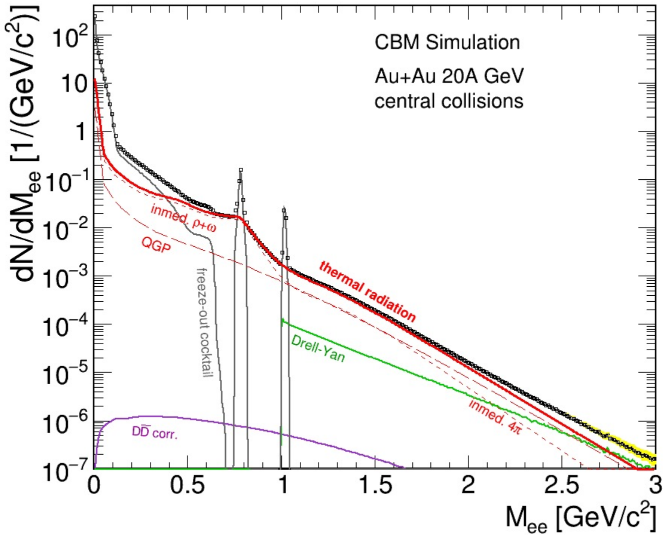
R.Rapp, J. Wambach, Adv.Nucl.Phys. 25 (2000)



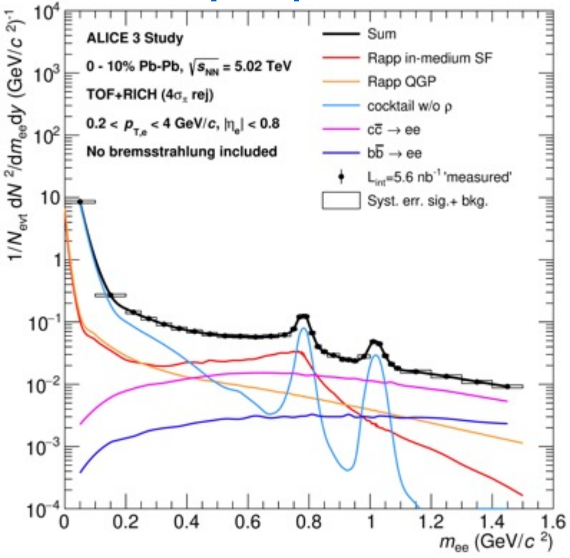
Guy Chanfray, 1999 Lecture Notes

Experimental challenge: physics background ($M_{ll} > 1$ GeV/c^2)

F. Seck [CBM], 2015



F. Eisenhut [ALICE], DPG 2021

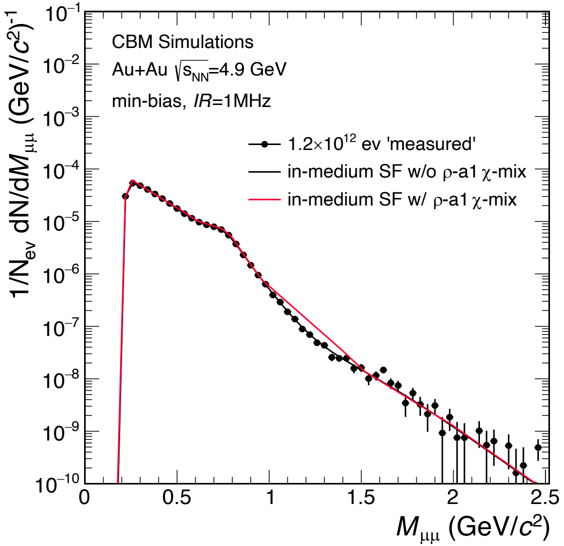


- Towards lower energy
  - negligible correlated charm contribution
  - decrease of QGP
  - Drell-Yan contribution

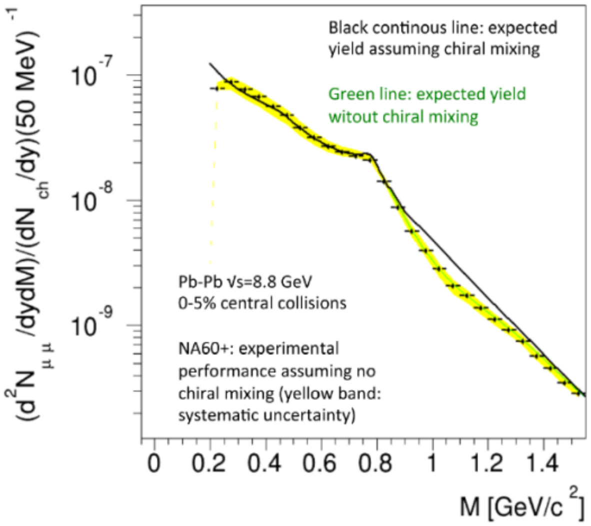
- LHC energies
  - large contribution from $c\bar{c}, b\bar{b}$ and QGP
  - negligible Drell-Yan

Feasibility studies

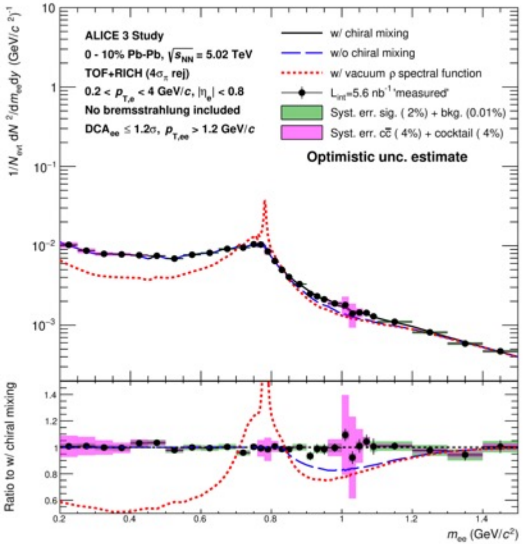
TG [CBM], 2022



Usai [NA60+], 2020



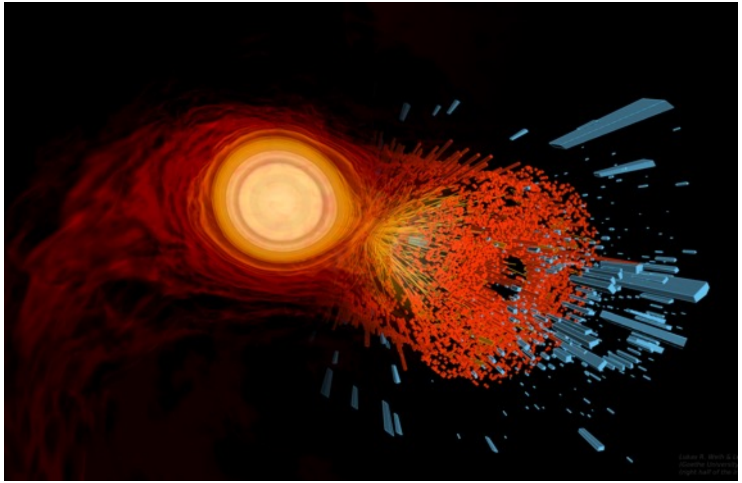
F. Eisenhut [ALICE], DPG 2021



- Towards lower energy
  - 𝒟rell-𝒴an contribution → pp, pA measurements

- LHC energies
  - excellent vertex resolution → topological separation of prompt and non-prompt source employing DCA cut
  - choice of the p_T cut

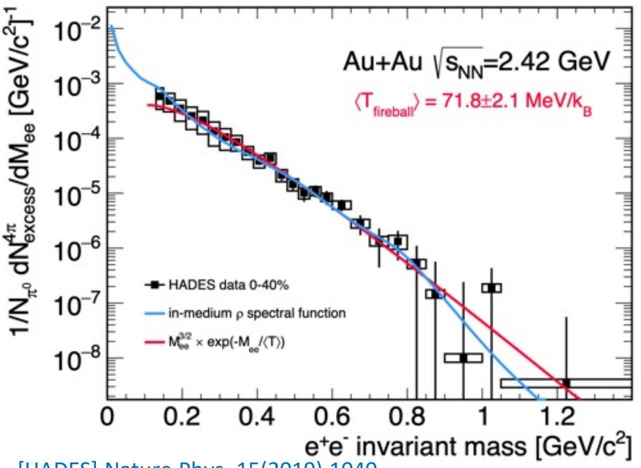
How can heavy-ion experiments help us understand binary neutron star mergers?



How can binary neutron star mergers help us understand heavy-ion experiments?

HIC and BNSM

invariant mass



[HADES] Nature Phys. 15(2019) 1040

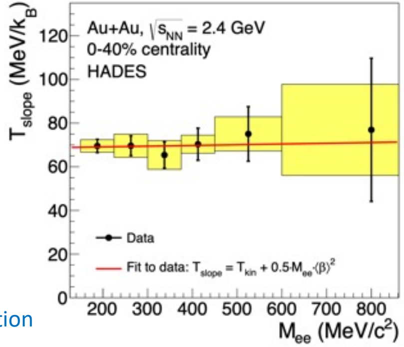
Extreme and shiny

What have we learnt from excess radiation Au+Au $\sqrt{s_{NN}}$=2.4 GeV?

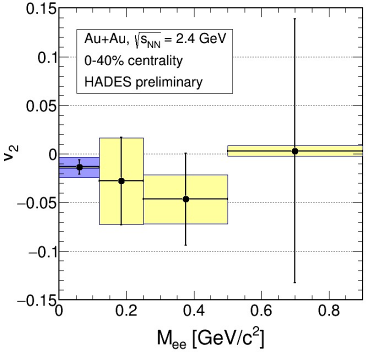
Radiation from a source

- long-lived (τ≈13 fm)
- in local thermal equilibrium
- $\langle T\rangle \approx$ 72 MeV
- $\rho = 2 - 3\ \rho_0$

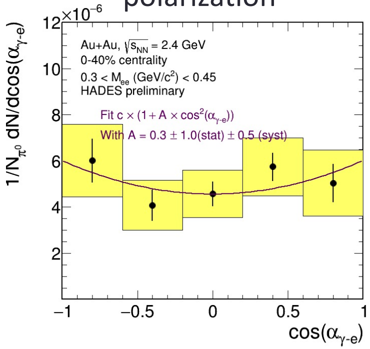
inverse slope (p_t)



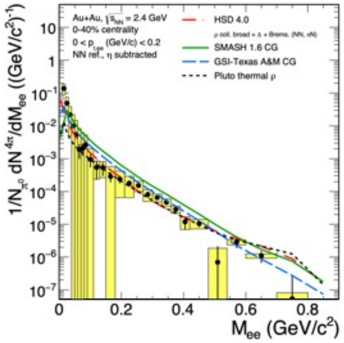
elliptic flow (v_2)



polarization



electric conductivity?

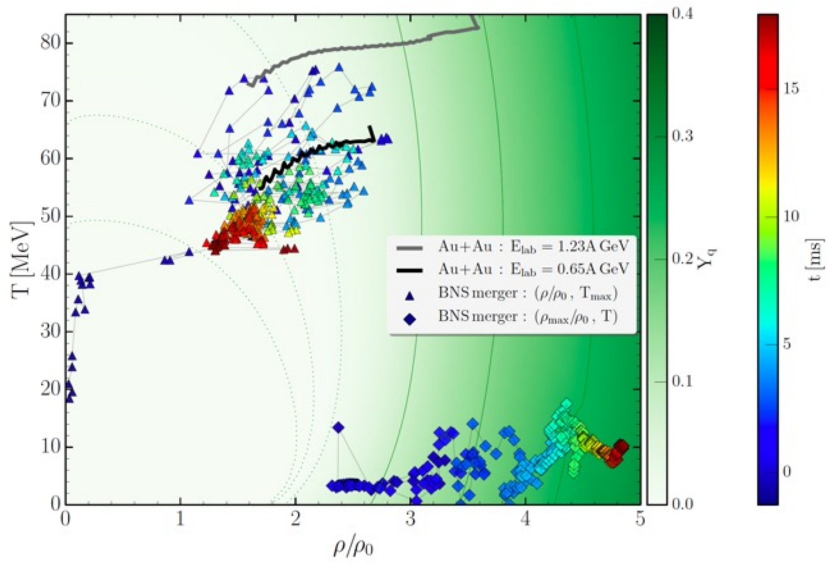


[HADES] in preparation

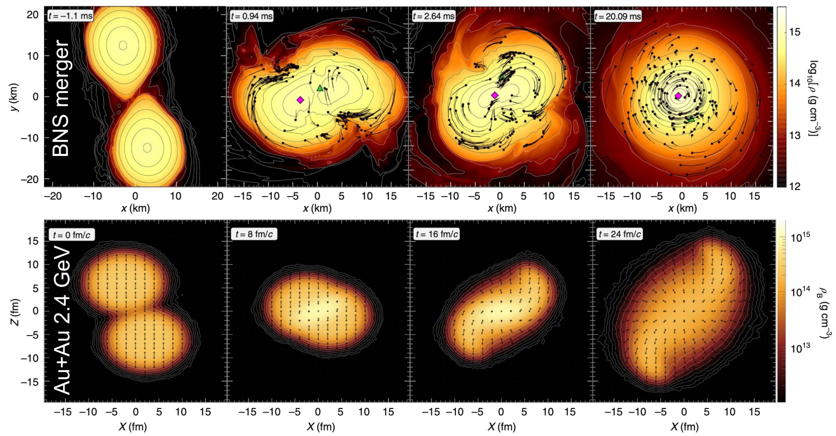
The QCD phase structure at highest μ_B

Hanauske *et al.*, Particles 2 (2019) no.1
Rezzolla *et al.*, Phys. Rev. Lett. 122 (2019) no. 6, 061101

18 orders of magnitude in scales
still similar T < 70 MeV, $\rho < 3\rho_0$ for both



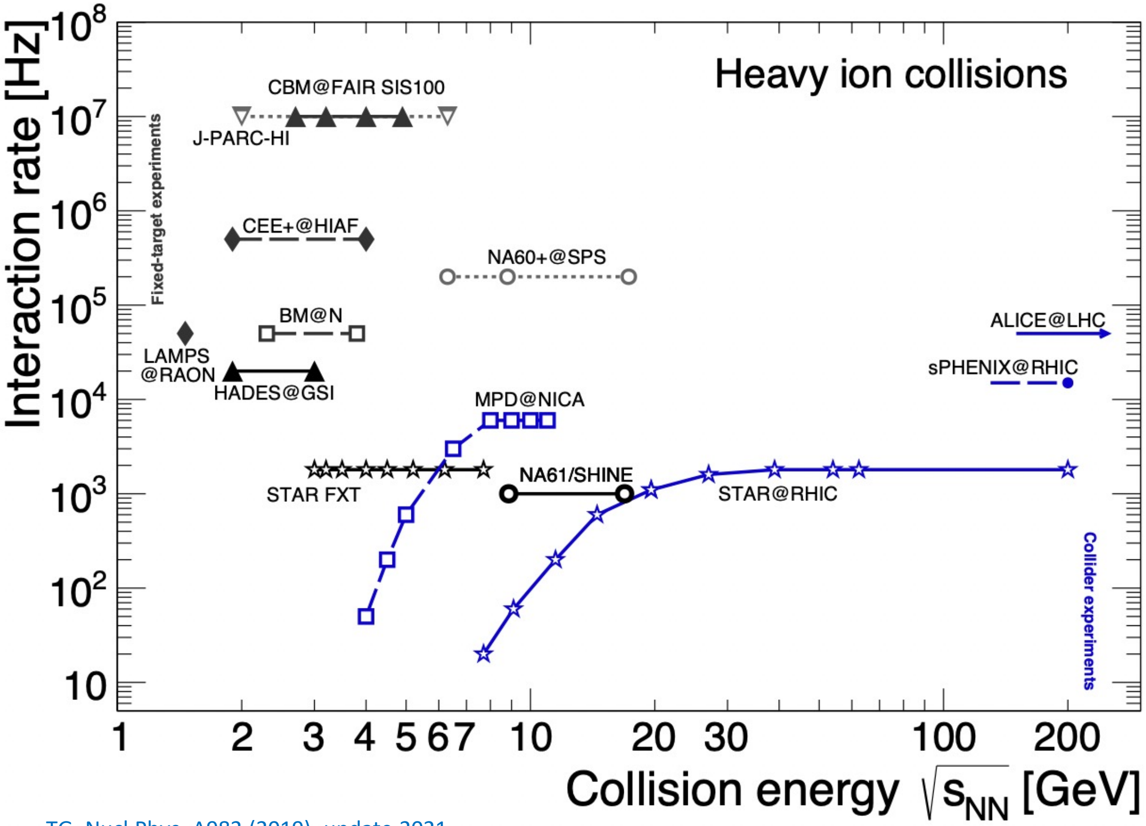
Possible HIC trajectories and NS merger simulations within an effective hadronic model



- ☐ Dileptons sensitive to dense phase
- ☐ Important input to constrain the EoS of dense matter

⤳ strong connections between the fields

The future is bright



- Future experiments aim at utmost precision measurements for rare probes (dileptons and photons)
- New theoretical developments are expected to provide chirally and thermodynamically consistent in-medium vector-meson spectral functions (e.g. FRG, lattice QCD)

TG, Nucl.Phys. A982 (2019), update 2021
CBM, EPJA 53 3 (2017) 60

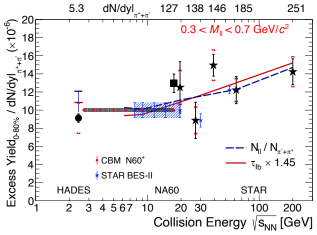
Detectors are high-tech prototypes

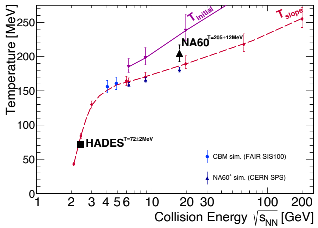
Success through perfect teamwork of experts in many fields

Résumé and take home message

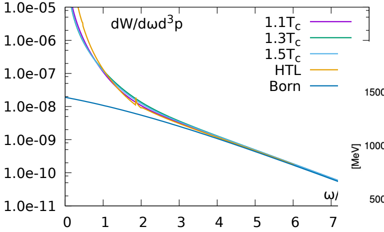
- Unique possibility of characterizing properties of hot and dense QCD matter with dileptons
- Robust understanding of low-mass dilepton excess radiation through ρ-baryon coupling (at LHC, RHIC, SPS and SIS18 energies)
- Complementary program on exclusive measurements in π, p induced reactions with HADES
- Enable unique measurements:

Fireball lifetime, temperature

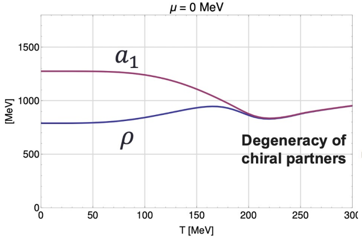




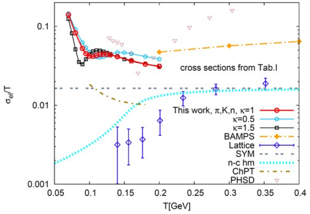
Degrees of freedom of the medium



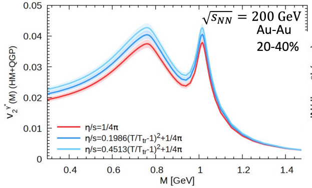
Restoration of chiral symmetry



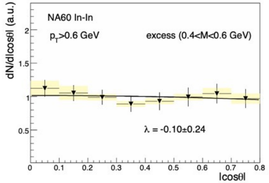
Transport properties



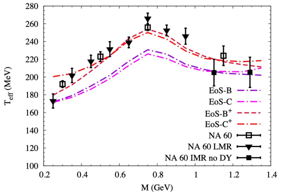
Viscosity



Polarization



Acceleration



Thank you for your attention!