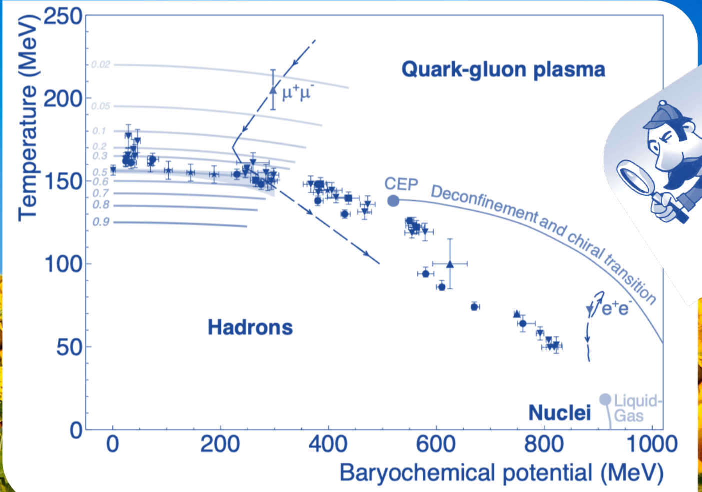
Mini Workshop “Phase transitions in particle physics” | Galileo Galilei Institute For Theoretical Physics | Arcetri, Firenze | 28 Mar – 1 Apr 2022

Decoding the phase structure of QCD at high μ_B



Tetyana Galatyuk
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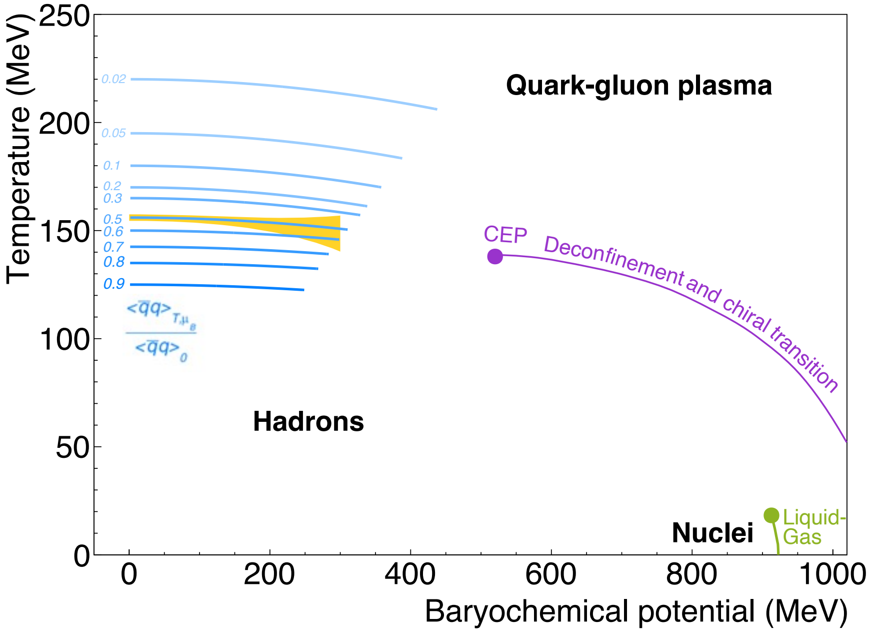
GSI · FAIR · TECHNISCHE UNIVERSITÄT DARMSTADT · Bundesministerium für Bildung und Forschung · HFHF Helmholtz Forschungsakademie Hessen für FAIR · EL EM EN TS · CRC-TR 211

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM

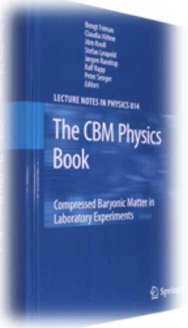


Borsanyi *et al*. [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141

- **vanishing μ_B, high T (lattice QCD)**
  - crossover
    - $T_{pc} = 156.5 \pm 1.5$ MeV (physical quark masses)
    - $T_c = 132^{+3}_{-6}$ MeV (chiral limit)
  - no critical point indicated by lattice QCD at $\mu_B^{CEP}/T_c < 3$

Bazavov *et al.* [HotQCD], PLB 795 (2019) 15-21
Ding *et al.*, [HotQCD], PRL 123 (2019) 6, 062002
Dini *et al.*, Phys.Rev.D 105 (2022) 3, 034510

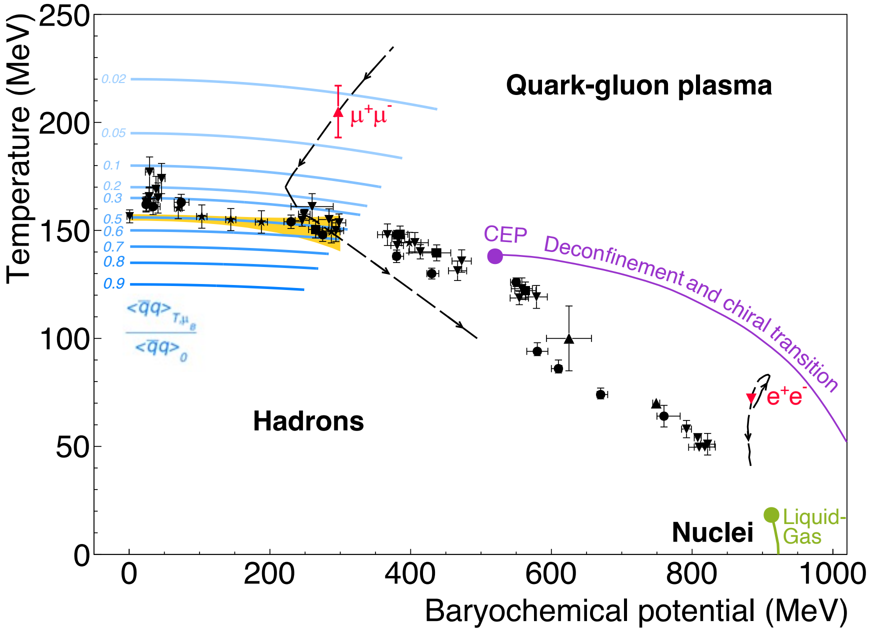
- **large μ_B moderate T (lQCD inspired theories)**
  - limits of hadronic existence?
  - 1st order transition?
  - QCD critical point?
  - equation-of-state of dense matter?



high μ_B region – large discovery potential!

Friman *et al.*,
Lect. Notes Phys. 814 (2011) 1

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM



[HADES], Nature Phys. 15 (2019) 10, 1040-1045
Andronic *et al.*, Nature 561 (2018) no.7723

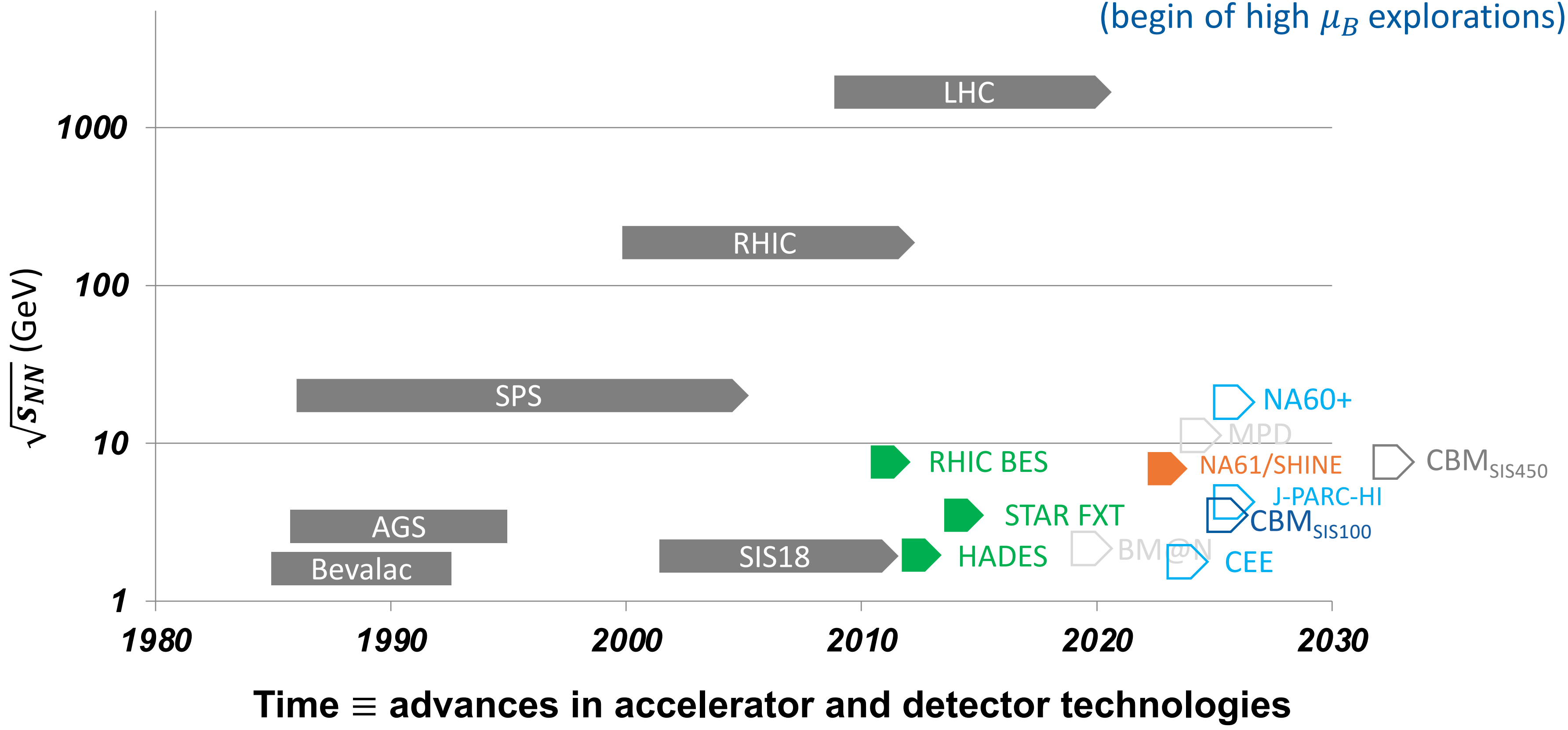
- **experimental challenge:**
  - locate the onset of QGP
  - detect the conjectured QCD critical point
  - probe microscopic matter properties

- **measure with utmost precision:**
  - strangeness (chemistry)
  - charm (transport properties)
  - e-b-e correlations and fluctuations (criticality)
  - dileptons (emissivity of matter)

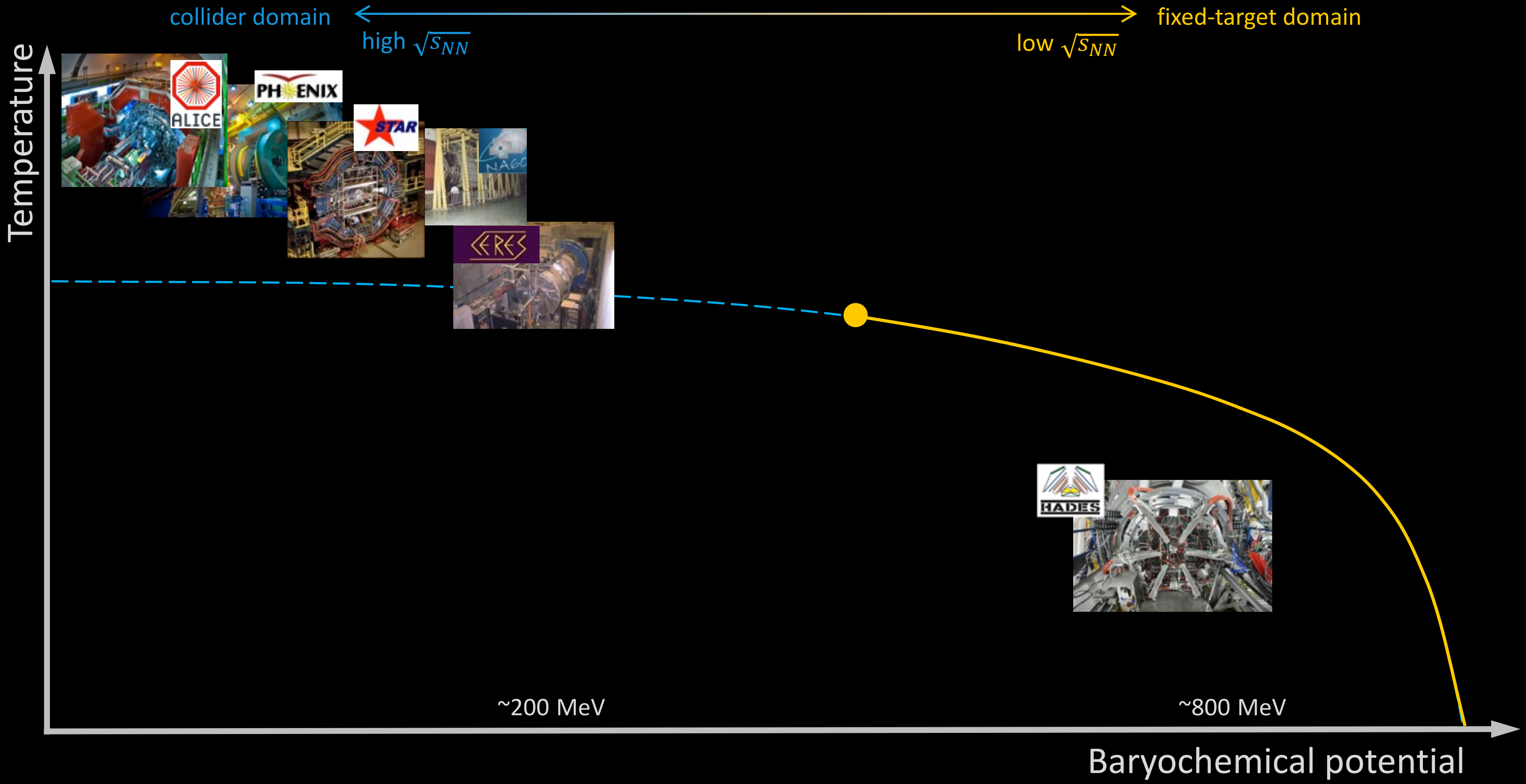
almost unexplored (not accessible) so far in the high μ_B region

QUEST FOR HIGHEST ENERGY
QUEST FOR HIGHEST PRECISION AND SENSITIVITY FOR RARE SIGNALS

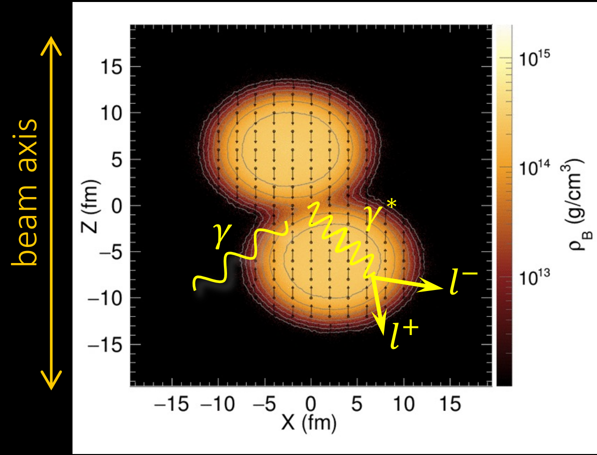
~20 years progress
in technology since AGS
(begin of high μ_B explorations)



THE EXPERIMENTAL LANDSCAPE FOR ELECTROMAGNETIC PROBES



EXTREME AND SHINY



- electromagnetic radiation (γ, γ^*)
  - reflect the whole history of a collision
  - no strong final state interaction
    ↝ leave reaction volume undisturbed
  - encodes information on matter properties

spectrometer

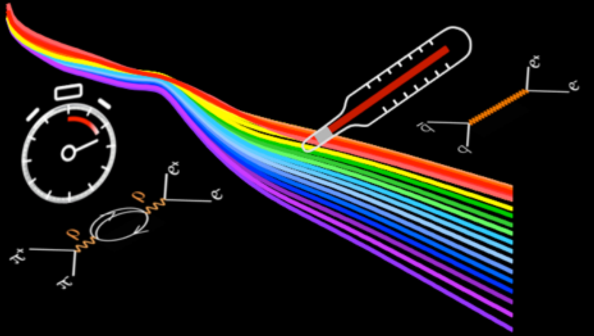
chronometer

barometer

thermometer

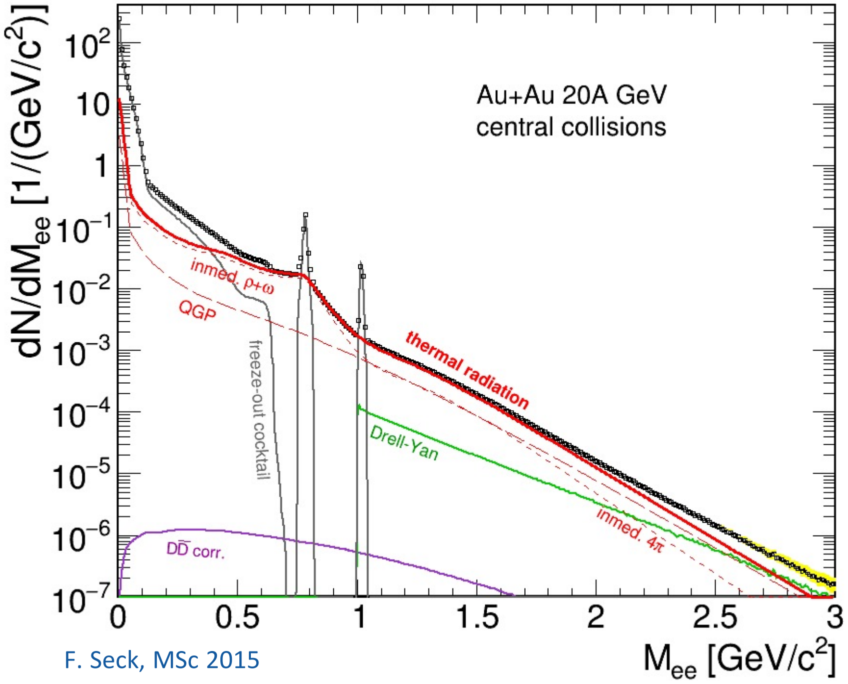
polarimeter

amperemeter



DILEPTON INVARIANT MASS SPECTRA

characteristic features



F. Seck, MSc 2015

i. ‘primodial’ $q\bar{q}$ annihilation (Drell-Yan):
   i. $NN \rightarrow e^+e^-X$
   ii. short-lived states

ii. thermal radiation from QGP and hadronic matter:
- ☐ $q\bar{q} \rightarrow e^+e^-$, $\pi^+\pi^- \rightarrow e^+e^-$
- ☐ short-lived states Δ, N^*, …
- ☐ multi-meson reactions (‘4π’): $\pi\rho, \pi\omega, \pi a_1$, …

iii. decays of long-lived mesons:
- ☐ $\pi^0, \eta, \omega, \varphi$, correlated $D\bar{D}$ pairs, …

excess yield = dilepton yield after subtraction of (measured) decay cocktail (i. and iii.)

ELECTROMAGNETIC PRODUCTION RATE

em current-current correlation function

$$\Pi^{\mu\nu}_{em}(q_0, q) = -i \int d^4x \, e^{iq\cdot x} \theta(x^0) \langle\langle [j^\mu(x), j^\nu(0)] \rangle\rangle$$

determines both photon and dilepton rates

- ☐ photons characterized by "transverse" momentun:

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

- ☐ dileptons carry extra information: invariant mass
  → unique direct access to in-medium spectral function

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha^2_{em}}{\pi^3} \frac{L(M)}{M^2} f^B(q \cdot u; T) \, Im\Pi_{em}(M, q; \mu_B, T)$$

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)

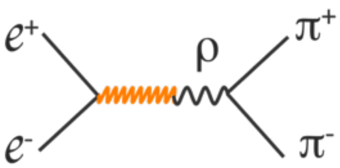
EM CORRELATOR IN THE VACUUM

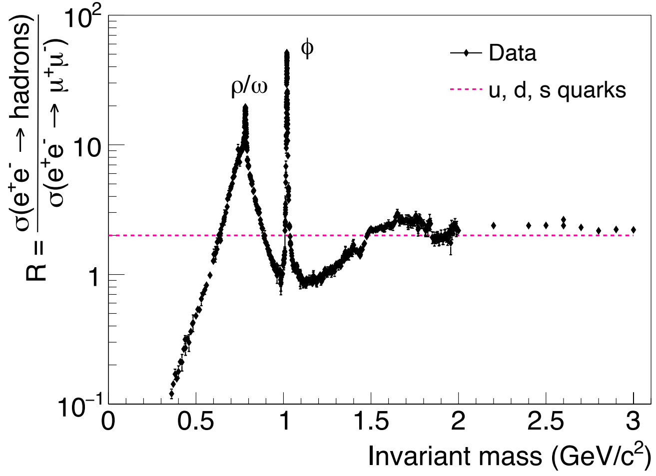
accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

Beringer et al. (PDG), Phys. Rev. D (2012) 010001

low-mass regime

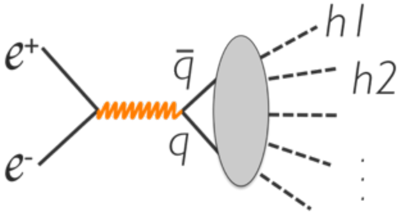
em spectral function is saturated by light vector mesons (VMD $J^P = 1^-$ for both γ^* and VM, ρ playing a dominant role)





intermediate-mass regime

perturbative QCD continuum (quark degrees of freedom)



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

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

Sakurai, Ann.Phys. 11 (1960)

IN-MEDIUM EM SPECTRAL FUNCTIONS

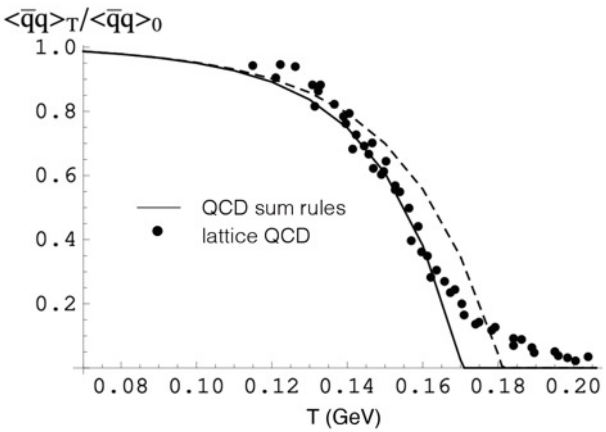
S. Weinberg, Phys. Rev. Lett. 18 (1967) 507

connection to chiral symmetry χ_c

QCD and chiral sum rules…

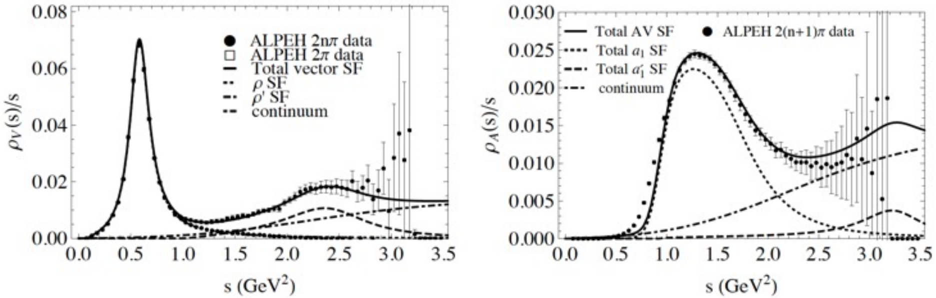
$$\int_0^\infty \frac{ds}{\pi}\left[\Pi_V(s) - \Pi_{AV}(s)\right] = m_\pi^2 f_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

- χ_c is broken spontaneously by dynamical formation of a quark condensate $\langle\bar{q}q\rangle$
- condensates $\langle\bar{q}q\rangle$ constrained by lattice QCD



Hohler and Rapp, Annals Phys. 368 (2016) 70-109
Holt, Hohler, Rapp, Phys.Rev. D87 (2013) 076010

… accurately satisfied in vacuum



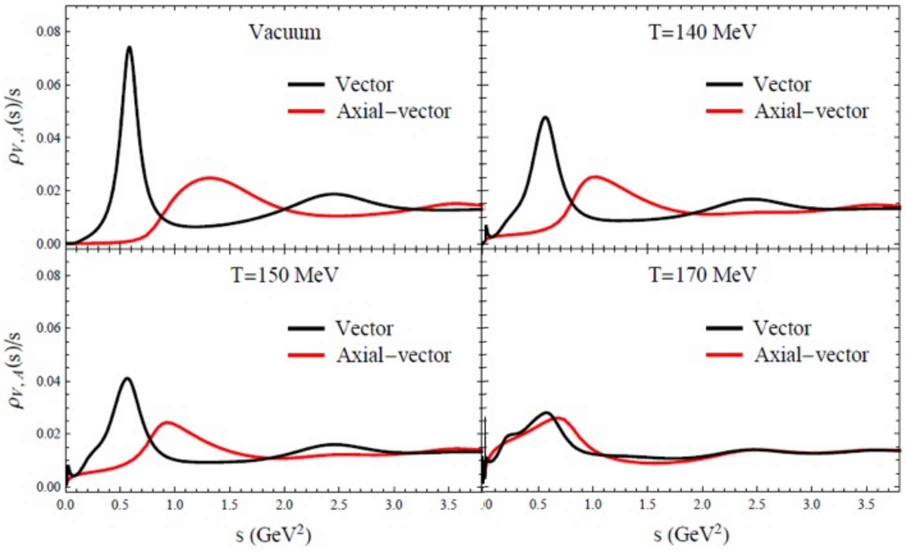
… remain valid in medium

Kapusta and Shuryak, Phys.Rev. D49 (1994) 4694

- restoration finite T and μ_B manifests itself through mixing of vector and axial-vector correlators

IN-MEDIUM EM SPECTRAL FUNCTIONS

connection to chiral symmetry χ_c

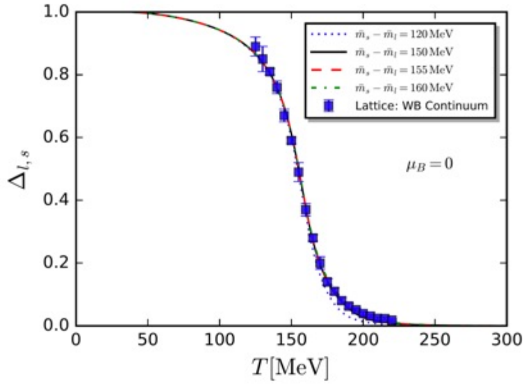


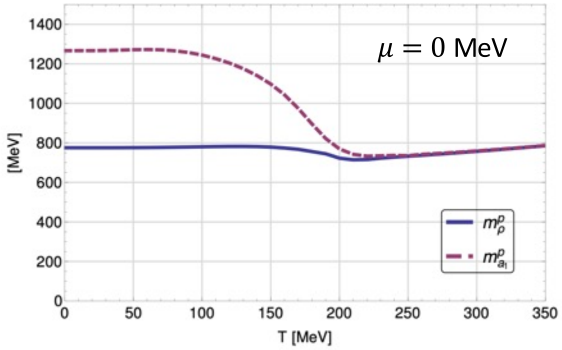
ρ meson melts, a_1 mass decreases and degenerates with near ground-state mass

Hohler and Rapp, Phys. Lett. B 731 (2014) 103

Functional Renormalization Group

quantitative agreement of the $\langle \bar{q}q \rangle$ with lattice QCD



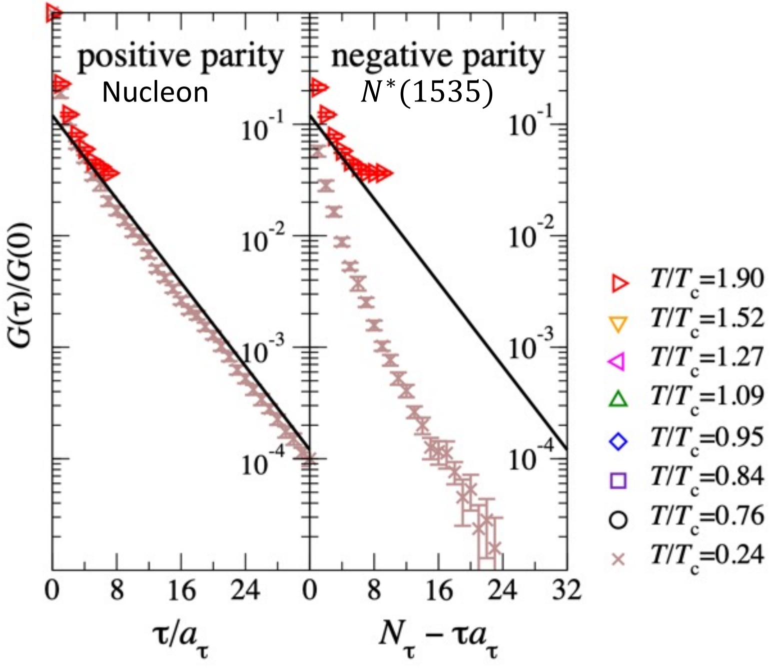


Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020
Tripolt, Jung, Tanji, v. Smekal, Wambach, NPA982 (2019) 775
Fu, Pawlowski and Rennecke, Phys. Rev. D101 (2020) no.5, 054032

LATTICE-QCD RESULTS FOR $N(939) - N^*(1535)$

parity doubling occur at high T

Euclidean correlator ratios

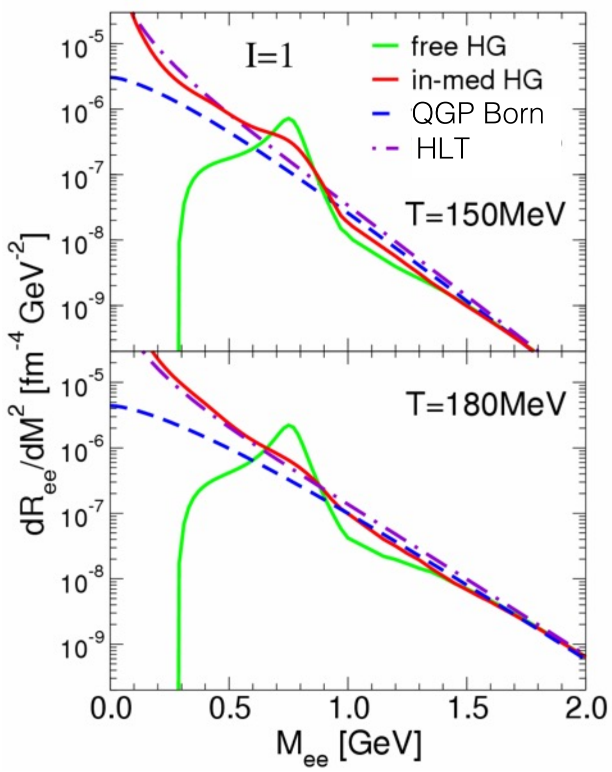


- m_N is found to be independent of the hadronic medium
- indicates $m_{N^*}(T) \to m_N(T) \approx m_N^{vac}$

Aarts *et al.*, Phys. Rev. D 92 (2015) no.1, 014503
Allton *et al.*, PoS LATTICE2015 (2016) 183

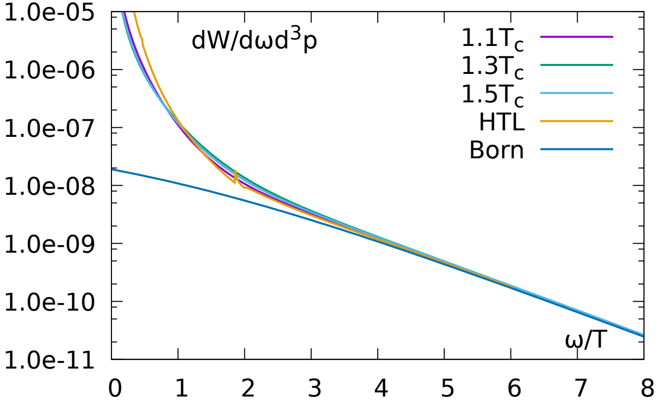
DEGREES OF FREEDOM OF THE MEDIUM

quark-to-hadron transition



Rapp and Wambach, Adv.Nucl.Phys. (2000) 25

thermal dilepton rate in 2-flavor QCD (quenched lattice QCD)



Ding *et al.*, Phys.Rev.D 83 (2011) 034504
Ding *et al.*, Phys.Rev.D 94 (2016) 3, 034504

⇝ ρ-meson melts

⇝ spectral function merges into QGP description

direct evidence for transition hadrons to quarks and gluons?

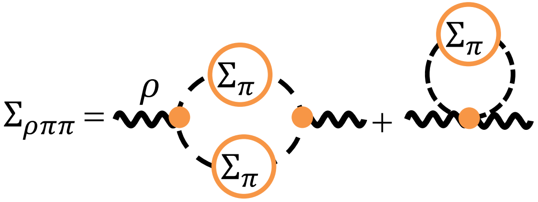
IN-MEDIUM SPECTRAL FUNCTIONS FROM HADRONIC MANY BODY THEORY

ρ meson in medium interacts with hadrons from heat bath

additional contributions to the ρ-meson self-energy

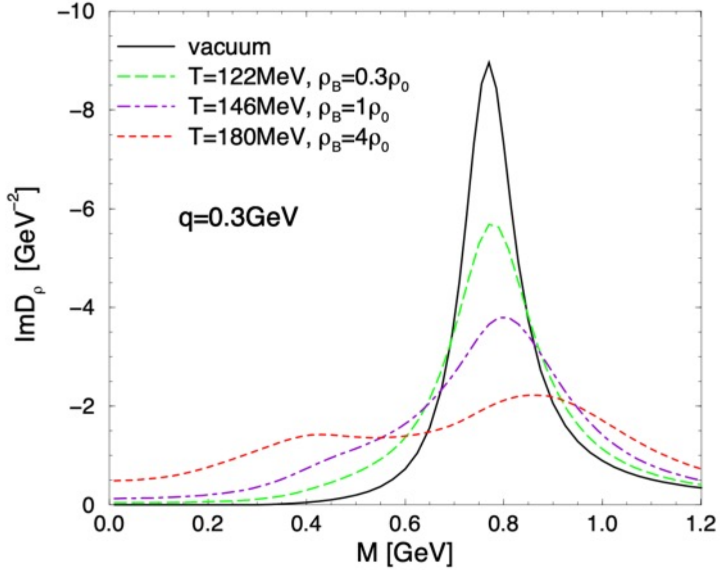
$$D_\rho(M, q, T, \mu_B) = \frac{1}{[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]}$$

in-medium pion cloud



direct ρ-hadron scattering

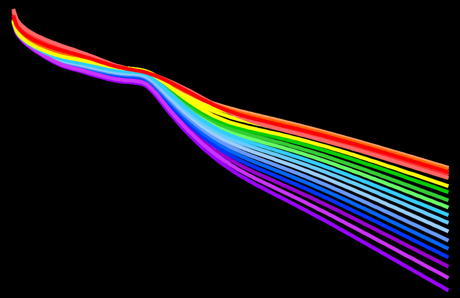
Rapp and Wambach, Eur.Phys.J. A6 (1999)



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

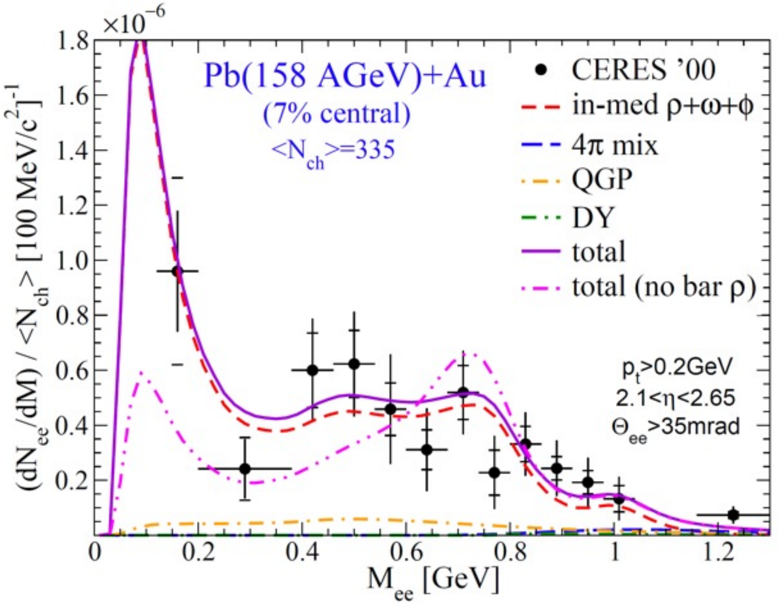
Alam *et al.*, Annals Phys.286 (2001) 159 (2001)
Leupold, Metag, Mosel, Int.J.Mod.Phys. E19 (2010) 147
Rapp, Acta Phys.Polon. B42 (2011) 2823-2852

dileptons as spectrometer

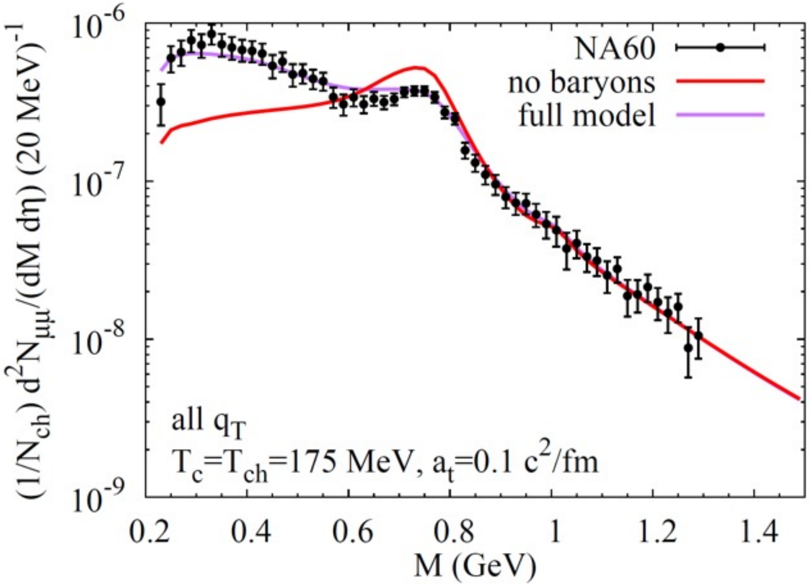


MEASURED EXCESS DILEPTON INVARIANT-MASS SPECTRA

strongly supports melting of ρ, in particular due to baryon-induced effects



[CERES/NA45], Phys.Lett.B 666 (2008) 425

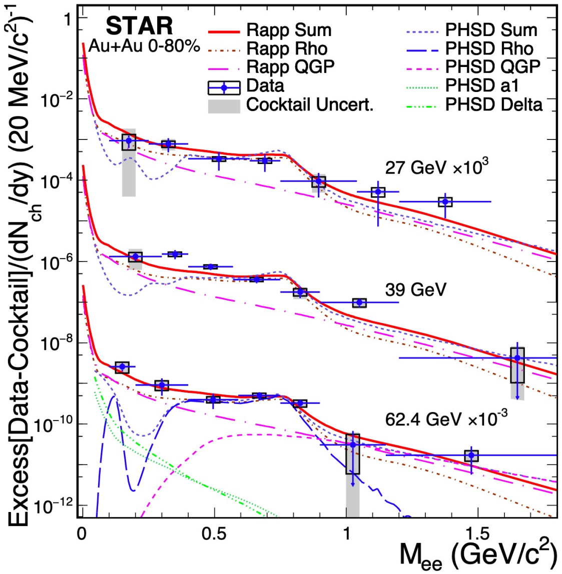


[NA60], EPJC 61(2009) 711

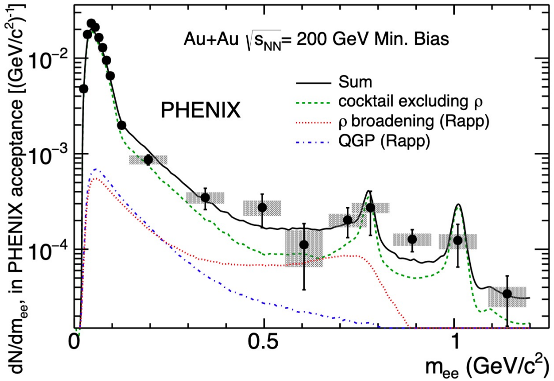
Rapp, Wambach, Eur.Phys.J. A6 (1999) 415-420 (1999)
Rapp, Wambach, van Hees, Landolt-Bornstein 23 (2010) 134

DILEPTON MASS SPECTRA FROM SPS to RHIC to LHC ENERGIES

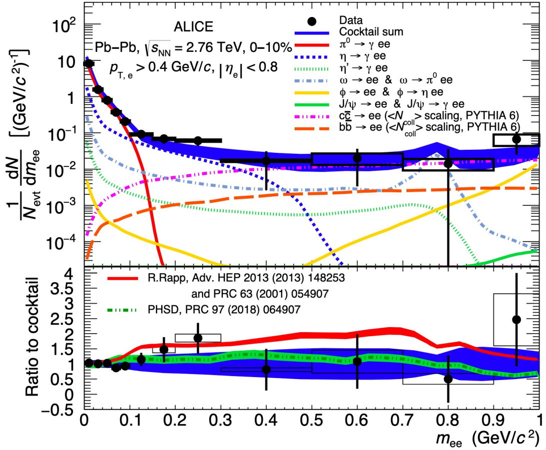
[STAR], Phys. Rev. Lett.113 (2014) 2, 022301
[STAR], Phys. Rev., C92 (2015) 2, 024912
[STAR], Phys.Lett. B750 (2015) 64–71
[STAR], arXiv:1810.10159, 2018
➡ BES 200 – 19.6 GeV



[PHENIX] Phys.Rev. C93 (2016) 1, 014904

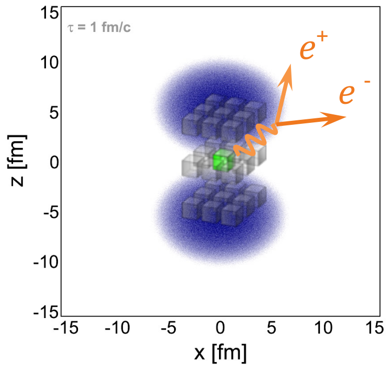


[ALICE] Phys.Rev.C 99 (2019) 2, 024002



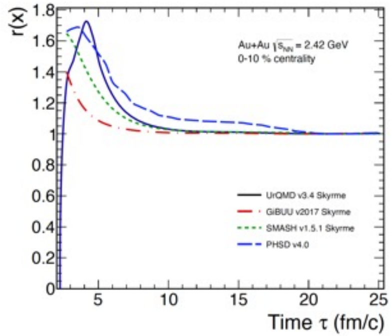
- ☐ baryon effects important even at net-baryon density $\rho_B = 0$
- ☐ sensitive to $\boldsymbol{\rho_{B_{tot}} = \rho_B + \rho_{\overline{B}}}$ (ρN and $\rho \overline{N}$ interactions identical)

TOWARDS FEW GeV ENERGIES



challenges

- ☐ implementation of in-medium effects in microscopic transport simulations
- ☐ justification of thermalization in hydrodynamical simulations

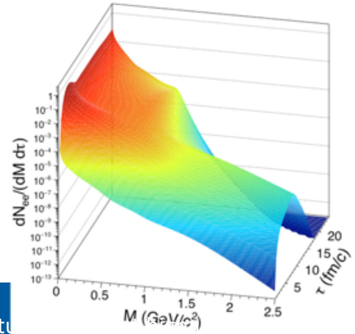


coarse-grained transport approach

➡ bulk evolution from microscopic transport

➡ apply equilibrium rates locally

- ☐ simulate many events
  ⇝ ensemble average to obtain smooth space-time distributions
- ☐ average hadron distributions in suitable space-time
- ☐ determine for each cell the bulk properties like $T, \rho_B, \mu_\pi, \beta$
- ☐ use in-medium spectral functions to compute EM emission rates

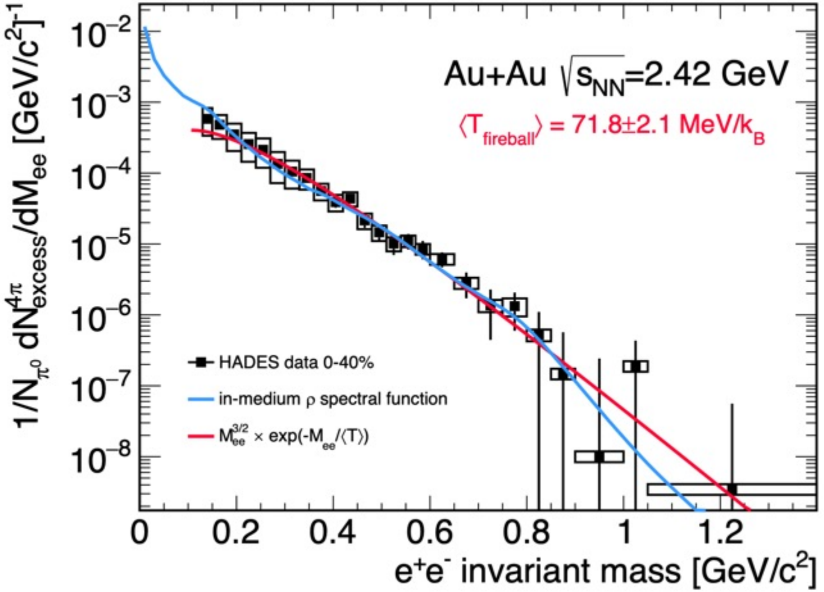


Rapp and Wambach, Adv.Nucl.Phys. (2000) 25
Jung, Rennecke, Tripolt, at al., PRD95 (2017) 036020
Sasaki, Phys.Lett. B801 (2020) 135172

Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J. A52 (2016) no.5, 131
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908

THERMAL DILEPTONS at SIS ENRGY REGIME

[HADES], Nature Phys. 15(2019) 1040

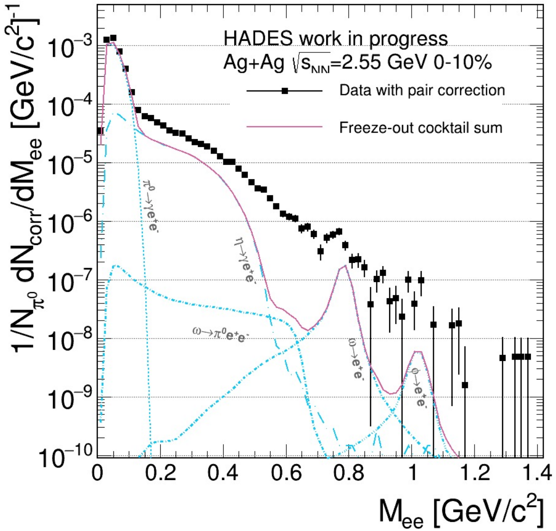


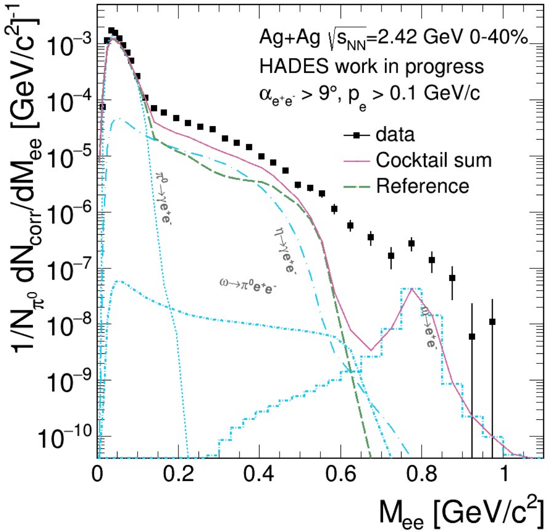
- thermal rates folded with coarse-grained medium evolution from transport works at low energies
- radiation from a baryon-rich source
  - $N_\pi / N_{part} \approx 10\%$
  - π densities a factor ~70 lower as compared to SPS regime
- RW in-medium spectral function consistently describes the low-mass dilepton excess for SIS – SPS – RHIC BES – RHIC – LHC energies

Robust understanding of emissivity of matter across QCD phase diagram

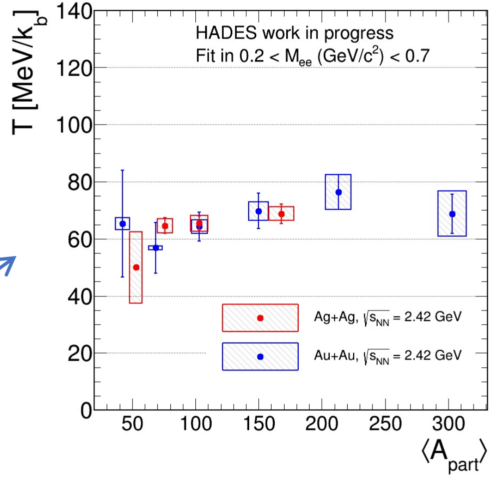
THERMAL DILEPTONS at SIS ENRGY REGIME

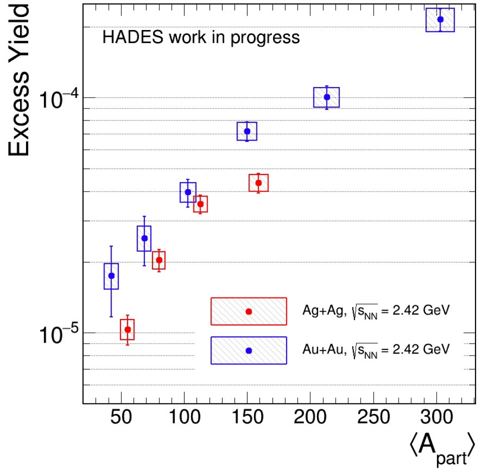
Energy, centrality and system size dependence





acceptance correced





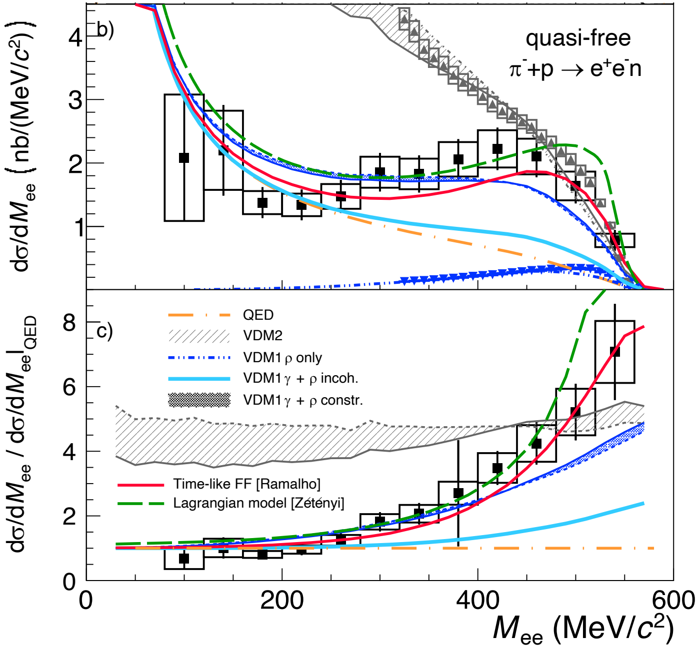
- Ag+Ag $\sqrt{s_{NN}}$=2.55 GeV (4×10^9)
  - vector mesons peaks (ω, ϕ) visible
  - access M_{ee}>1 GeV/c^2
- Ag+Ag $\sqrt{s_{NN}}$=2.42 GeV (6×10^8)
  - 3 days of data taking! e^+e^- statistics similar to the 4 weeks Au+Au run

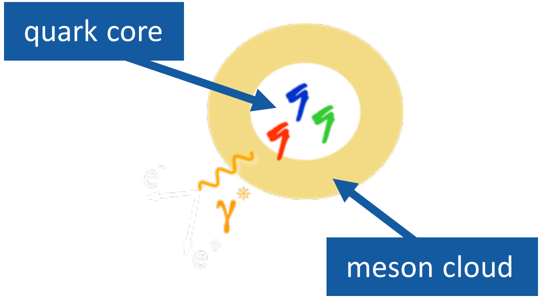
Phase 0
Research Program

MESON CLOUD

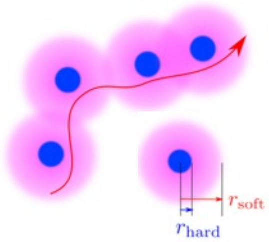
exclusive analysis $\pi^- p \rightarrow e^+ e^- n$

HADES, in preparation





- study the structure of the nucleon as an extended object (quark core and meson cloud)
  ⤳ excitation of a baryon can be carried by the meson cloud
- dominance of the $N^*(1520)$ resonance
  ⤳ Vector Meson Dominance
  (the basis of emissivity calculations for QCD matter)



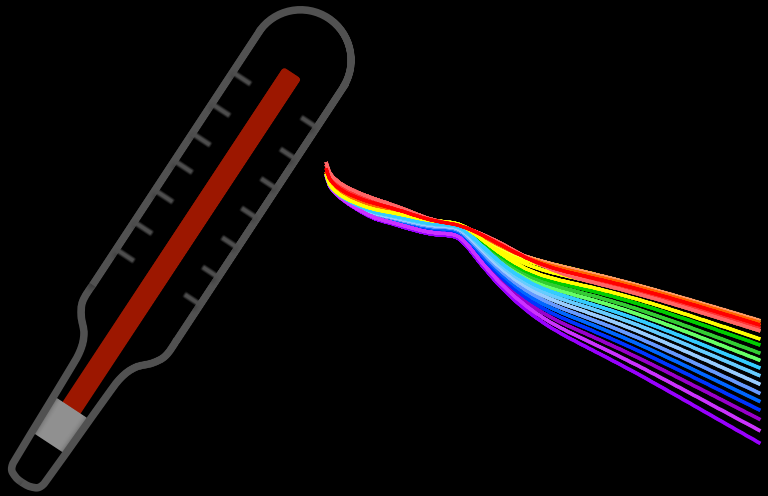
Connection to "soft deconfinement"?

Fukushima, Kojo, Weise, PRD 102 (2020) 9, 096017

Quantum percolation of the interaction meson clouds

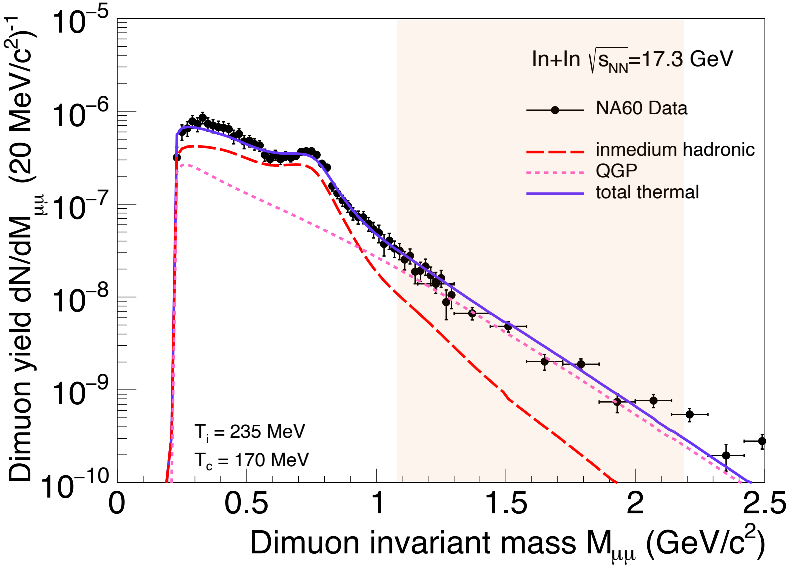
Ramalho, Pena, Phys. Rev. D95 (2017) 014003
Zetenyi, Nitt, Buballa, Galatyuk, Phys. Rev. C arXiv:2012.07546
Speranza *et al.*, Phys.Lett. B764 (2017) 282

dileptons as thermometer



DILEPTONS AS THERMOMETER

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*!*

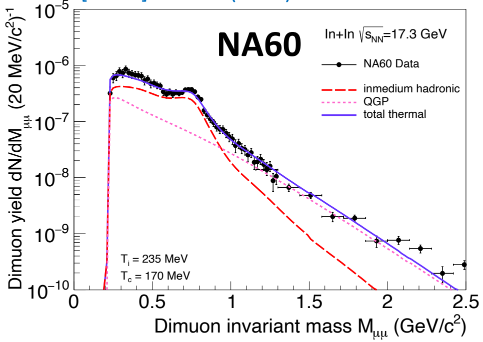
$$\langle T \rangle = 205 \pm 12\ MeV$$

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

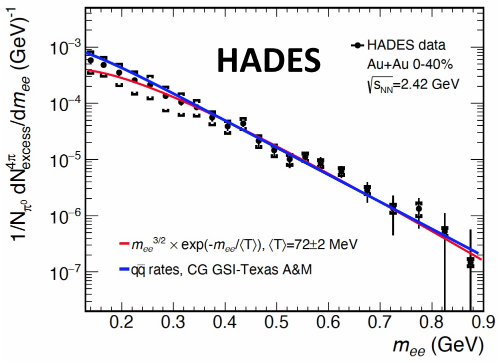
[NA60] EPJC 61(2009) 711
[NA60] Chiral 2010, AIP Conf.Proc. 1322 (2010)
Rapp and v. Hess, PLB 753 (2016) 586

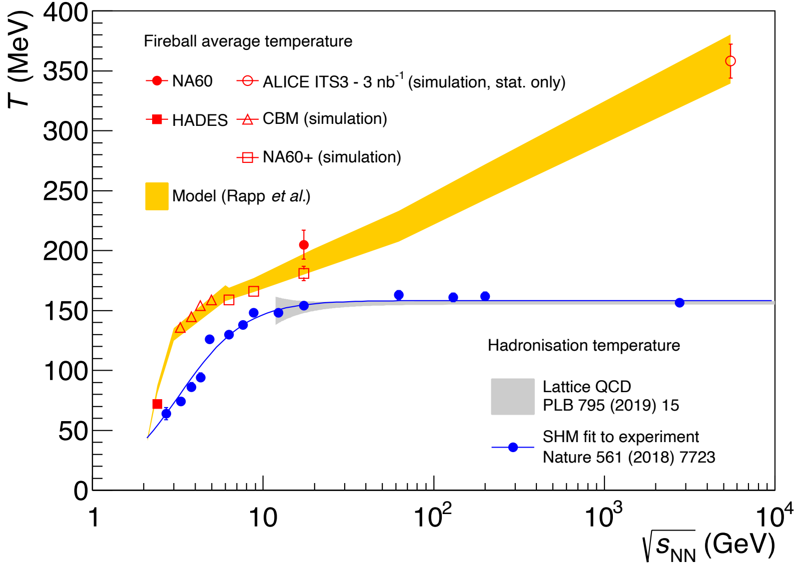
MAPPING QCD "CALORIC CURVE" (T vs ε)

[NA60] EPJC 61(2009) 711



[HADES] Nature Phys. 15(2019) 1040





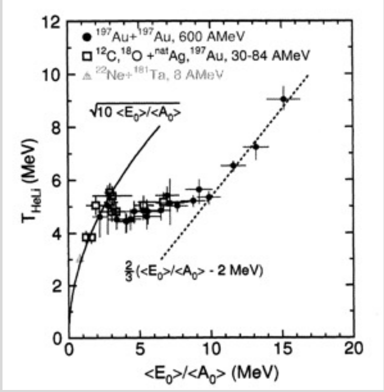
Rapp and v. Hess, PLB 753 (2016) 586
TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

signature for phase transition?

↝ **phase transition may show up as a plateau!**

↝ **future high statistics experiments**

Nuclear liquid-gas phase transition

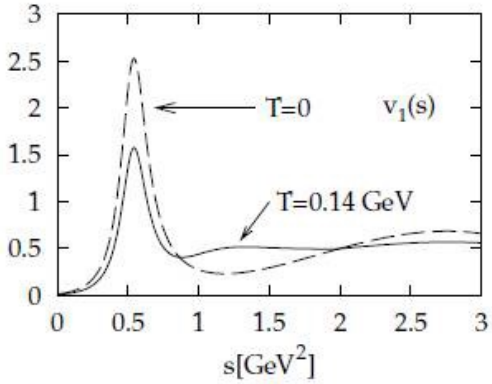


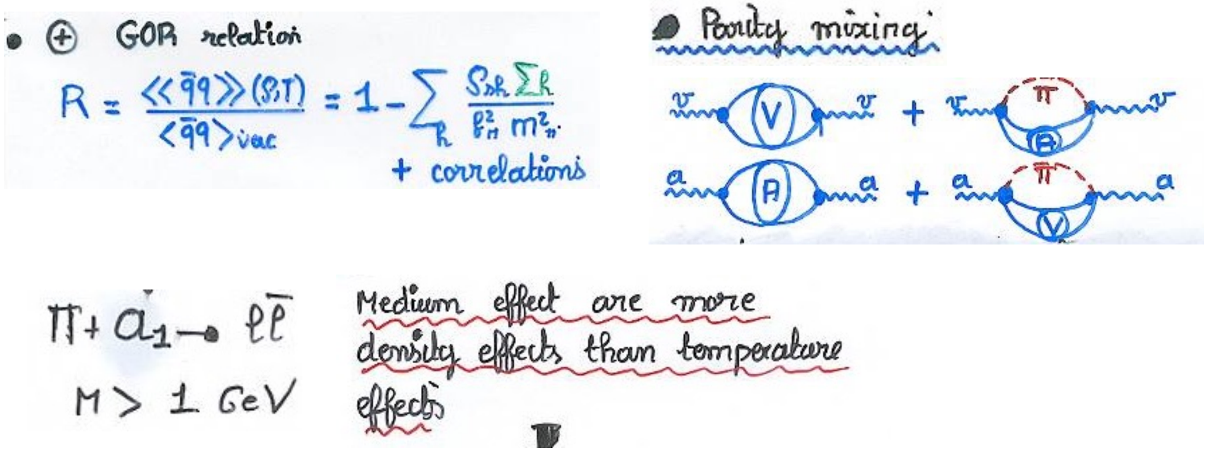
Pochodzalla *et al.*, PRL 75 (1995) 1040

SIGNATURE FOR CHIRAL SYMMETRY RESTORATION

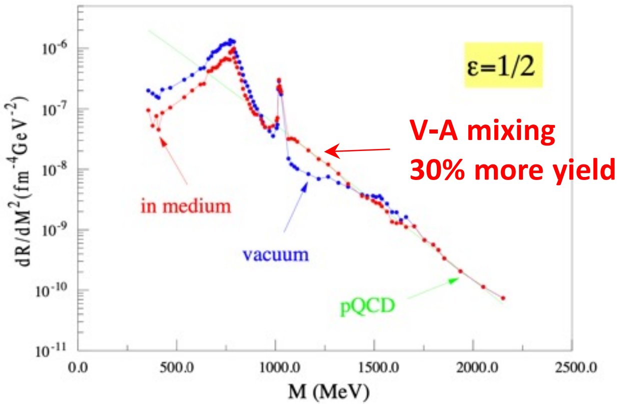
- Changes in yield and shape at $M_{ee} > 1.1$ GeV/c^2 due to $\boldsymbol{\rho - a_1}$ **chiral mixing**
- $\pi a_1 \rightarrow \gamma^* \rightarrow l^+l^-$ (chiral mixing) is a dominant hadronic source in IMR

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





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



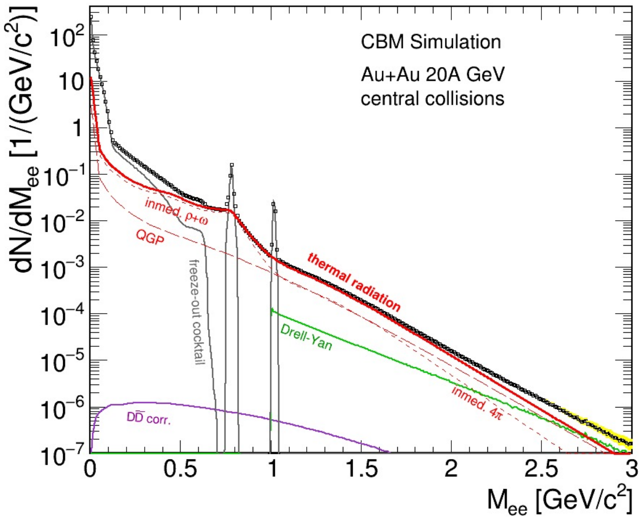
Guy Chanfray, 1999 Lecture Notes

EXPERIMENTAL CHALLENGE

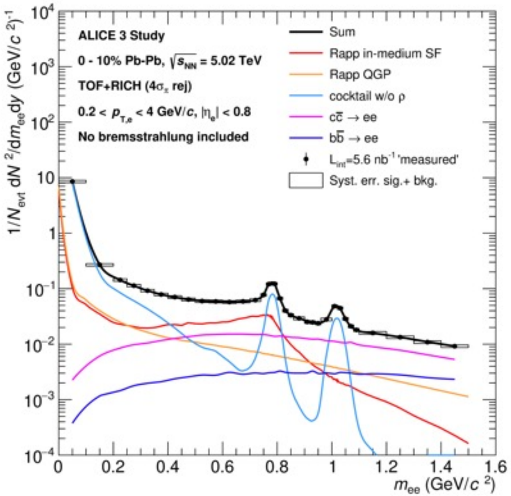
There is no such thing as a free lunch

Physics background ($M_{ll} > 1$ GeV/c^2)

F. Seck [CBM], 2015



F. Eisenhut [ALICE], DPG 2021



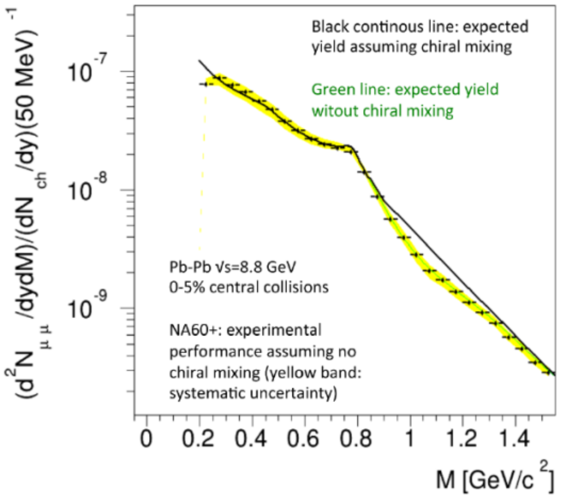
- towards lower energy
  - negligible correlated charm contribution
  - decrease of QGP
  - Drell-Yan contribution
- LHC energies
  - large contribution from $c\bar{c}, b\bar{b}$ and QGP
  - negligible Drell-Yan

There is no mission impossible

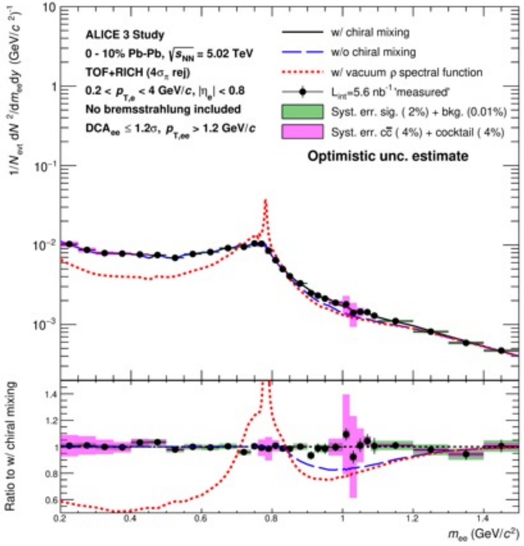
EXPERIMENTAL CHALLENGE

Physics background ($M_{ll} > 1$ GeV/c^2)

Usai [NA60+], 2020

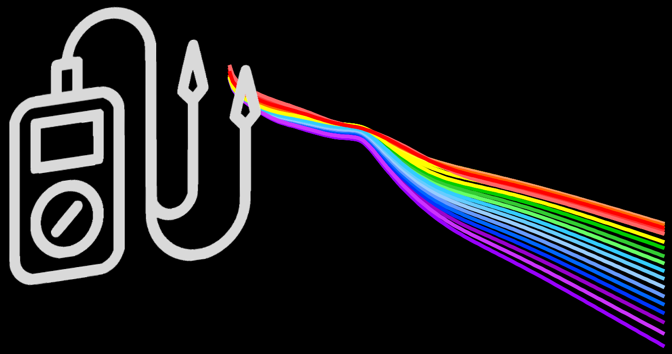


F. Eisenhut [ALICE], DPG 2021



- ☐ 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

dileptons as amperemeter



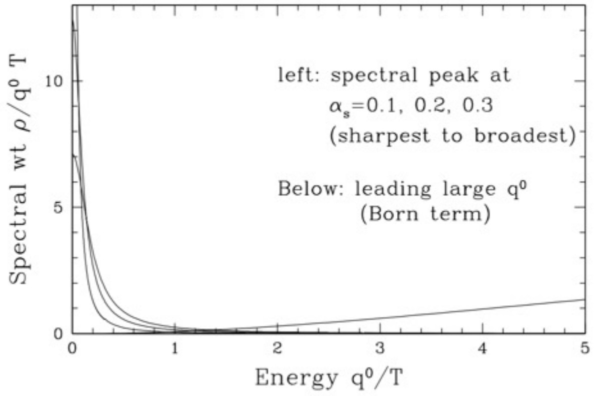
TRANSPORT PROPERTIES OF THE MEDIUM

Electrical conductivity

EM spectral function connected to electrical conductivity:

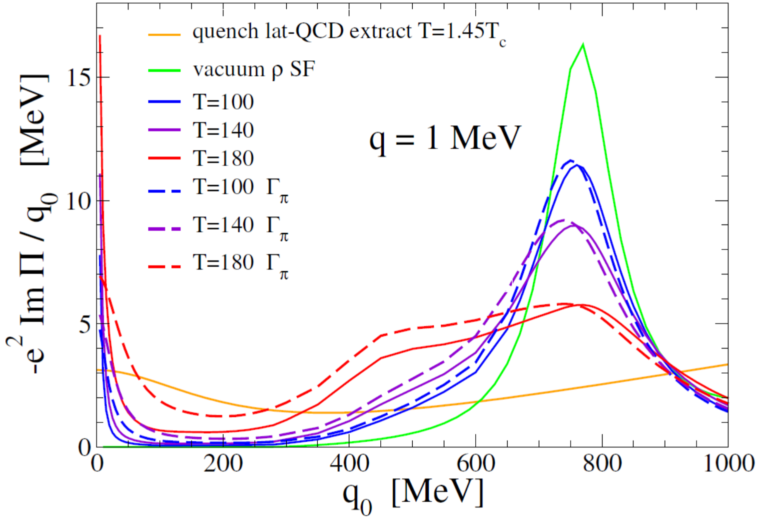
$$\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$$

Transport peak in the limit of very low mass and p_T



Moore and Robert, arXiv:hep-ph/0607172

Rapp, EMMI RRTF 2021

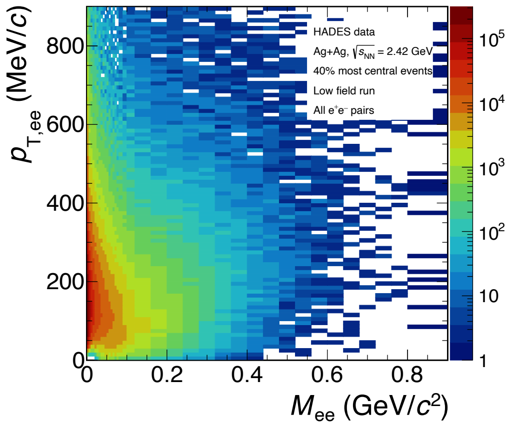


- ☐ conductivity is reduced when thermal-pion interactions included
- ☐ transport peak broadens

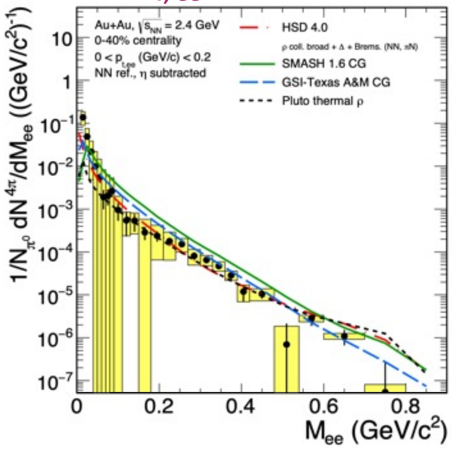
EXPERIMENTAL CHALLENGE

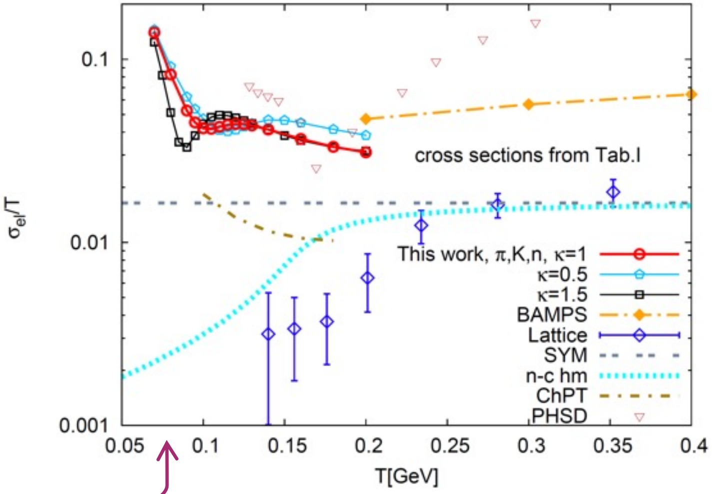
Measure accurately low mass – low p_T thermal excess yiled

HADES, data

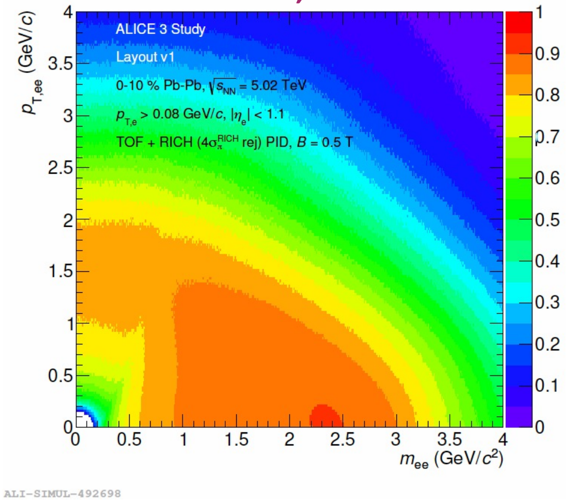


$p_{T,\,ee}$ < 200 MeV/c





ALICE 3, simulations



large spread in literature

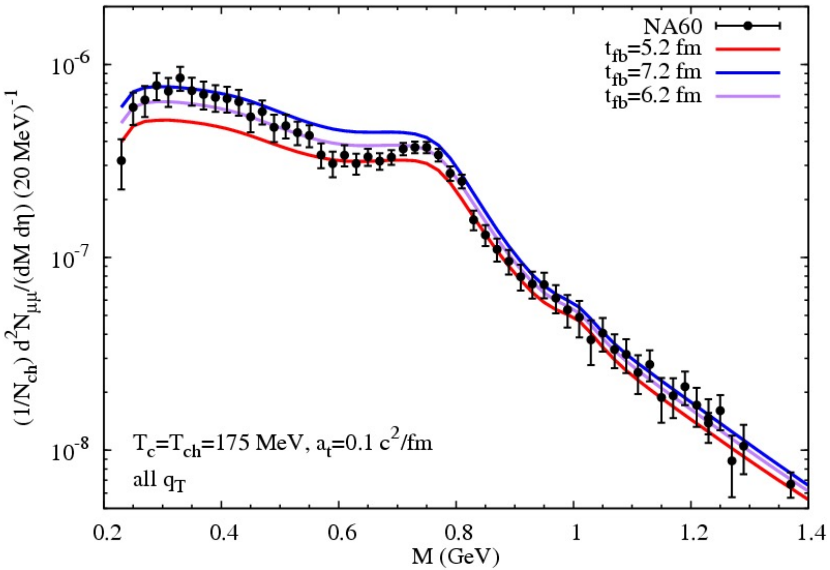
Greif, Greiner, Denicol, Phys.Rev. D93 (2016) 096012
Atchison, Rapp, Phys. Conf.Ser. 832 (2017) 012057 (2017)

dileptons as chronometer

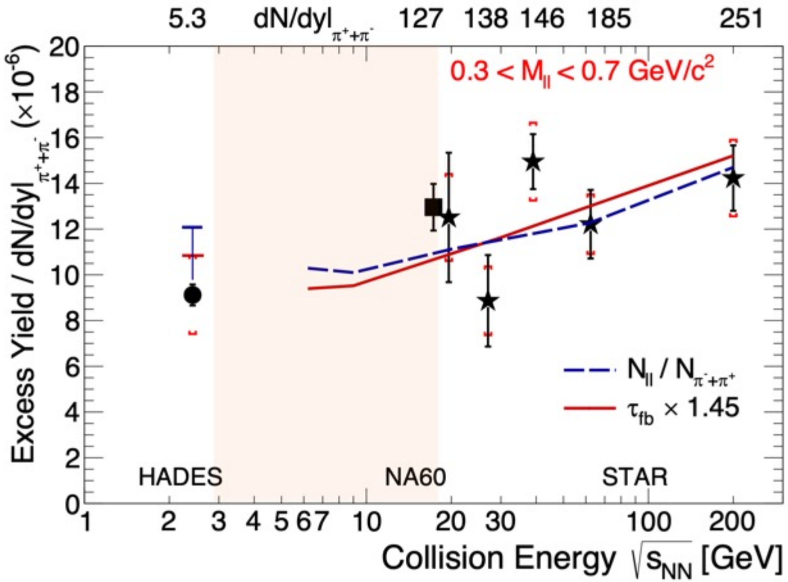
THE FIREBALL LIFETIME

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

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



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



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

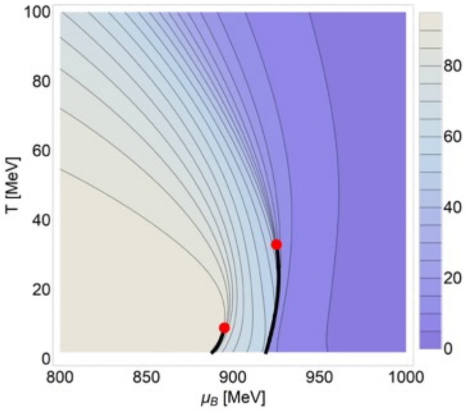
Heinz and Lee, PLB 259, 162 (1991)
Barz, Friman, Knoll and Schulz, PLB 254, 315 (1991)
Rapp, van Hees, PLB 753 (2016) 586

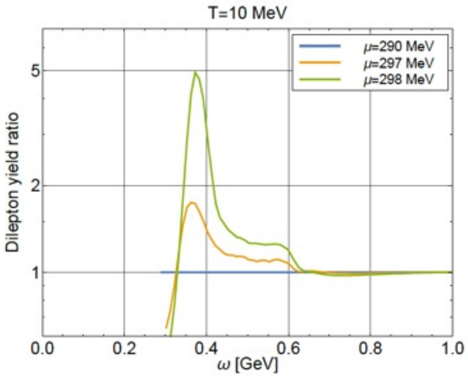
- Signature for phase transition (and critical point)? **⇝ latent heat ⇝ longer life time ⇝ extra radiation**

DILEPTON SIGNATURE OF A 1st ORDER PHASE TRANSITION

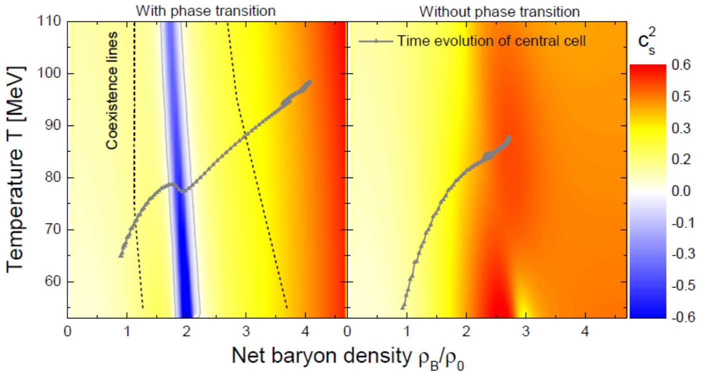
- *em* spectral function from FRG flow equations
- dilepton rates at CEP T=10 MeV, μ=292 MeV

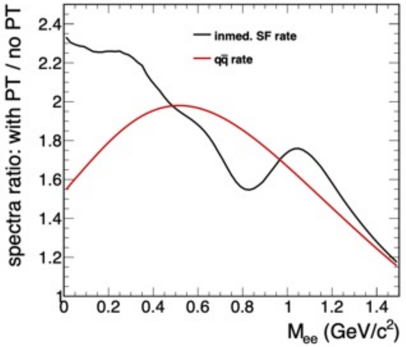
Tripolt, Jung, Tanji, v. Smekal, Wambach, Nucl. Phys. A982 (2019) 775
Jung, Rennecke, Tripolt, v. Smekal, Wambach, Phys. Rev. D 95 (2017) 036020





- dilepton radiation in hydrodynamics
  - implement "strong" 1st-order transition into CMF/PNJL model by increasing scalar quark couplings
- factor of ~2 extra radiation in case of hydro with phase transition

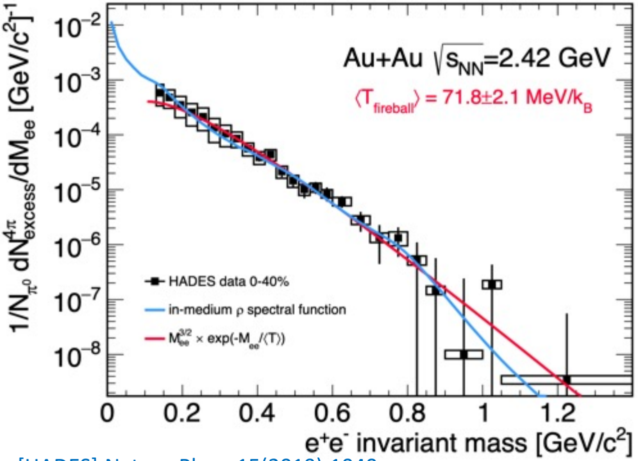




Seck, TG, et al., arXiv:2010.04614 [nucl-th]
Li and Ko, Phys. Rev. C 95 (2017) no.5, 055203

WHAT HAVE WE LEARNT FROM EXCESS RADIATION AT ENERGY OF few GeV?

invariant mass

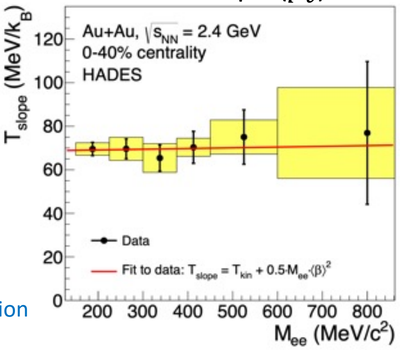


[HADES] Nature Phys. 15(2019) 1040

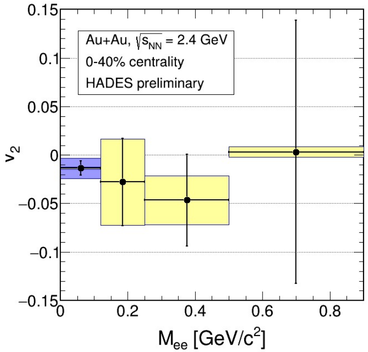
Radiation from a source

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

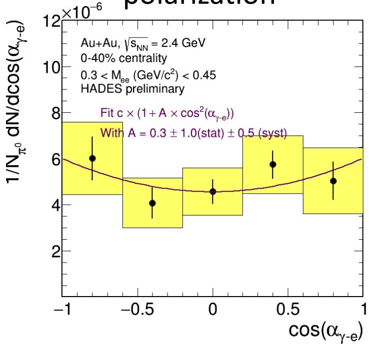
inverse slope (p_t)



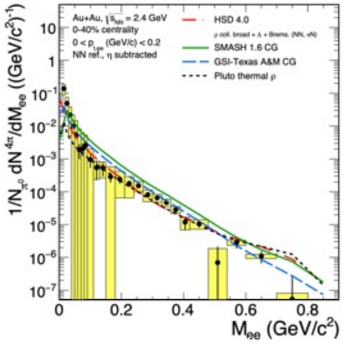
elliptic flow (v_2)



polarization



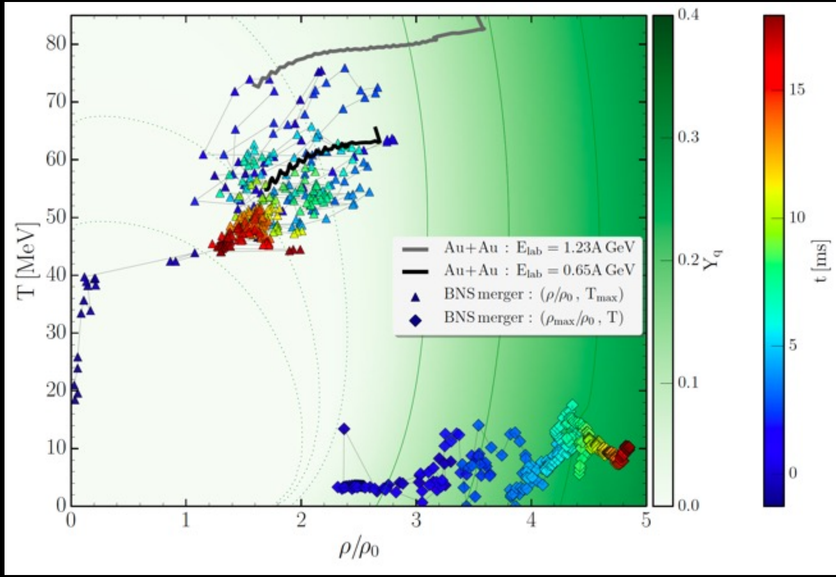
electric conductivity?



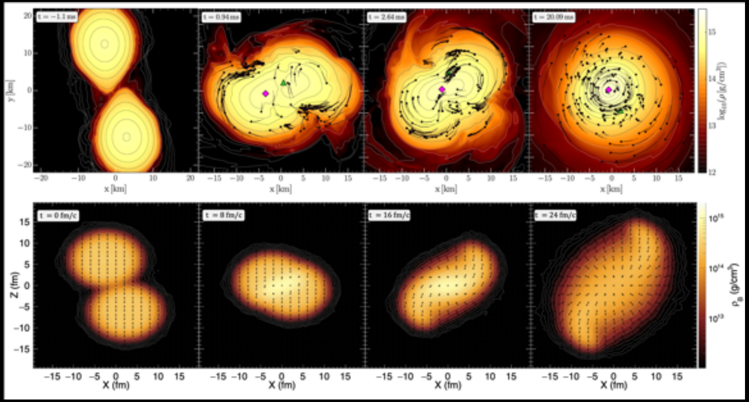
[HADES] in preparation

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



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



NS merger

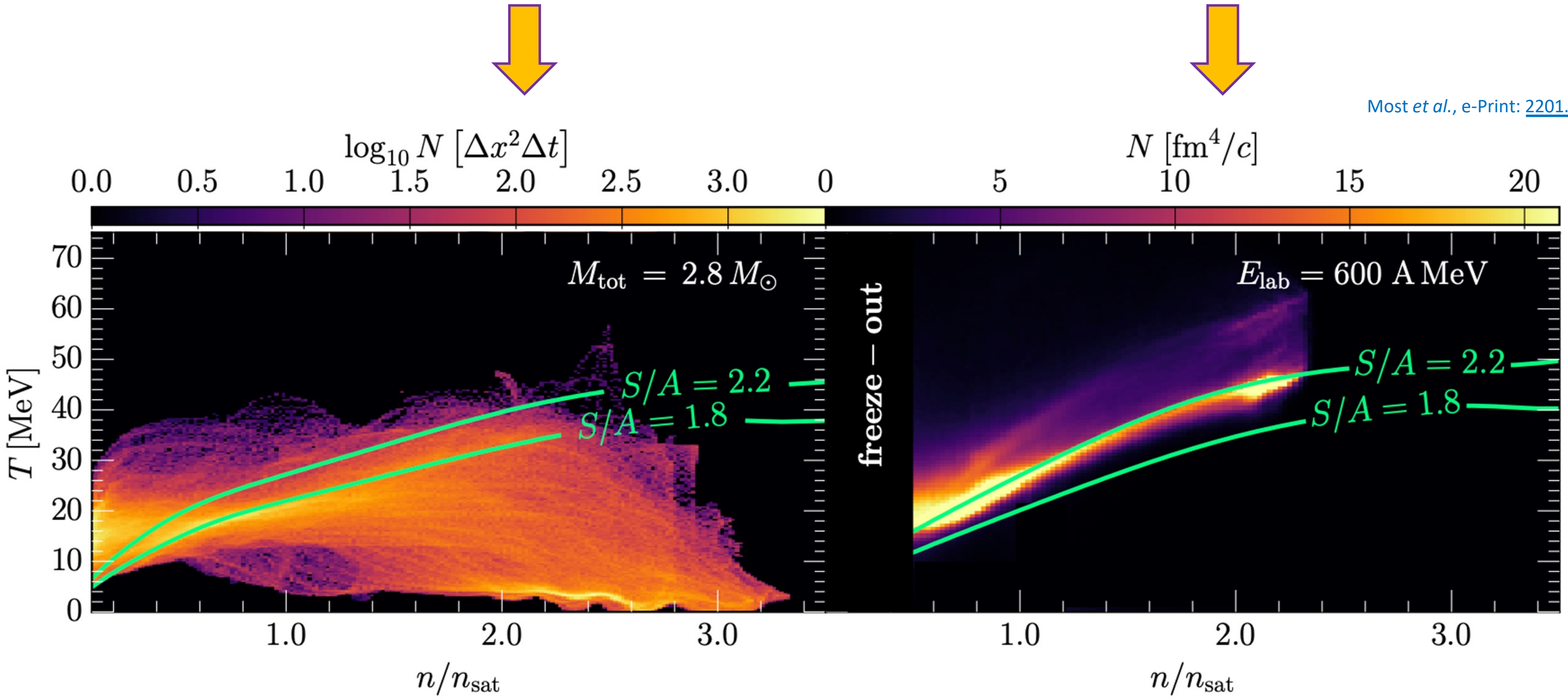
Au+Au
$\sqrt{s_{NN}}$ = 2.4 GeV

- ☐ T < 70 MeV, $\rho < 3\rho_0$ for both (note the different isospin)
- ☐ dileptons sensitive to dense phase
- ☐ important input to constrain the EoS of dense matter

⇝ strong connections between the fields

CONNECTING BNS MERGERS TO HEAVY-ION COLLISIONS

Most *et al.*, e-Print: 2201.13150 [nucl-th]



self-consistent relativistic-hydrodynamic calculations

employing same equation-of-state for simultaneous description of BNS merger and HIC

entropy per baryon (S/A) similar ⇝ BNS merger and HIC E_{lab} < 1 GeV

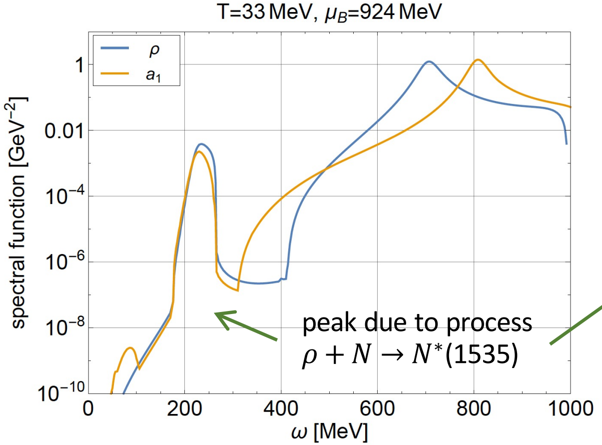
EFFECTIVE THEORY FOR NUCLEAR MATTER

Parity-doublet model describes nuclear liquid-gas transition together with a chiral phase transition

Tripolt, Jung, Smekal, Wambach, Phys. Rev. D 104, 054005 (2021)

provides a natural description for the parity-doubling structure of the low-lying baryons

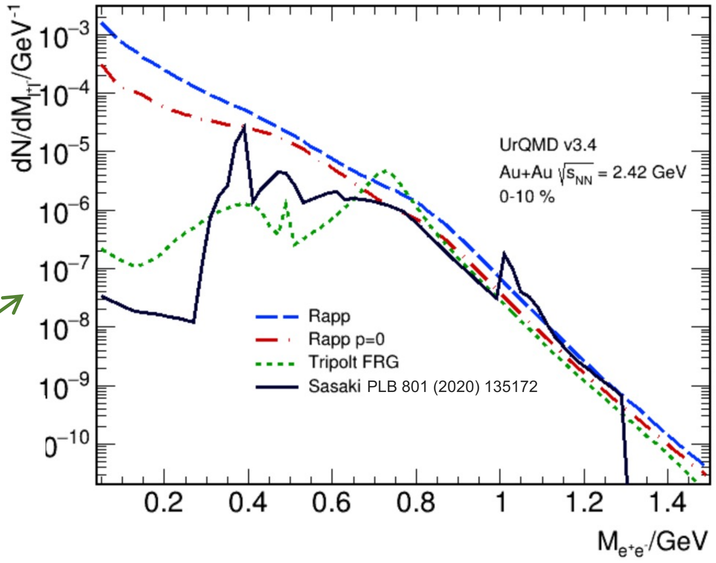
ρ and $a1$ spectral functions near chiral CEP in FRG



peak due to process $\rho + N \to N^*(1535)$

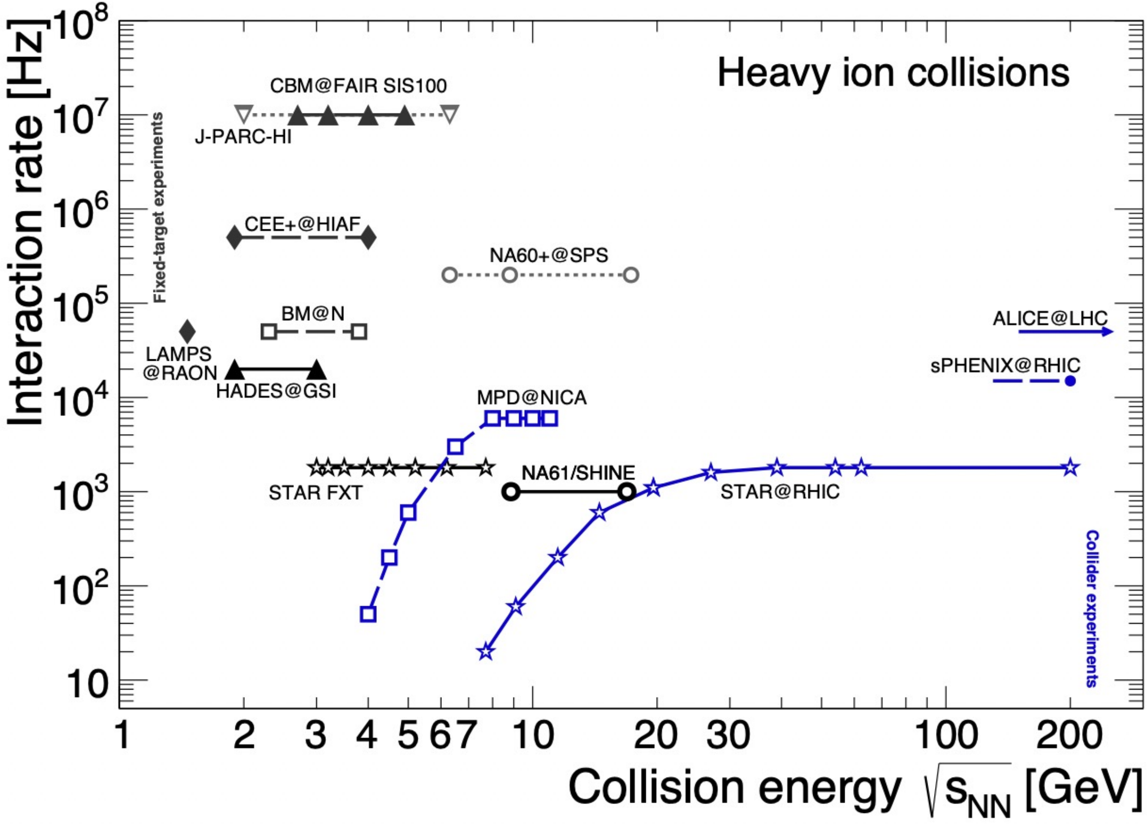
directly translates into enhancement of the thermal dilepton rate

preliminary dilepton spectrum from UrQMD and coarse-grainig



If detected ⇝ strong evidence in support of the parity-doubling scenario as providing the mechanism for chiral symmetry restoration in dense nuclear matter

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

RÉSUMÉ AND PROSPECTS - high μ_B

Open questions:

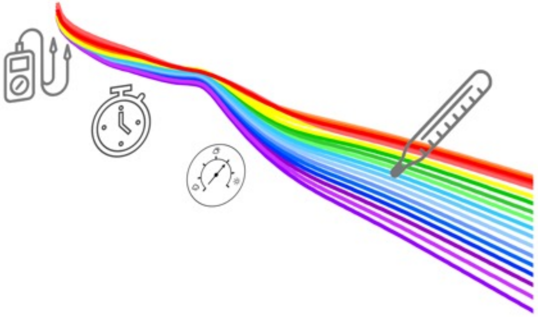
- ☐ Quest for deconfinement / chiral symmetry restoration conditions at high μ_B
- ☐ Quest for the conjectured QCD critical point

Challenges:

- ☐ Rare and statistics „hungry“ observables
- ☐ Many aspects – nature of transitions between the various phases, relevant EoS, spectral properties of hadrons in the medium, collective and transport properties of the medium, ... – await a better understanding

Objectives:

- ☐ Dileptons enable unique measurements
  - ○ Degrees of freedom of the medium
  - ○ Restoration of chiral symmetry
  - ○ Transport properties
  - ○ Fireball lifetime, temperature, acceleration, polarization



⇝ Systematic energy scan with full exploration of all relevant observables offer important complementarities

Thank you for your attention!

Words are powerless to express my gratitude
to you,
to your families,
to your countries for the support of Ukraine!

We will win!
There will be new cities.
There will be new dreams.
There will be a new story.
There will be, there's no doubt!
And those we've lost will be remembered.
And we will sing again.
And we will celebrate anew!

Glory to Ukraine!