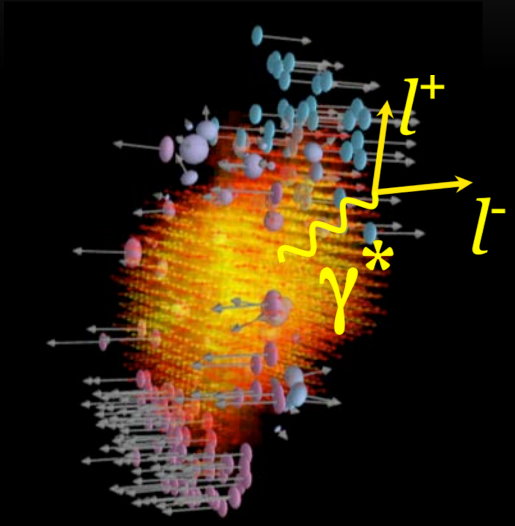
ExtreMe Matter Institute EMMI
EMMI Workshop
Constraining QCD Phase Boundary with Data from Heavy Ion Collisions
GSI, Darmstadt, Germany
February 12-14, 2018



Exploring QCD phase diagram with dileptons

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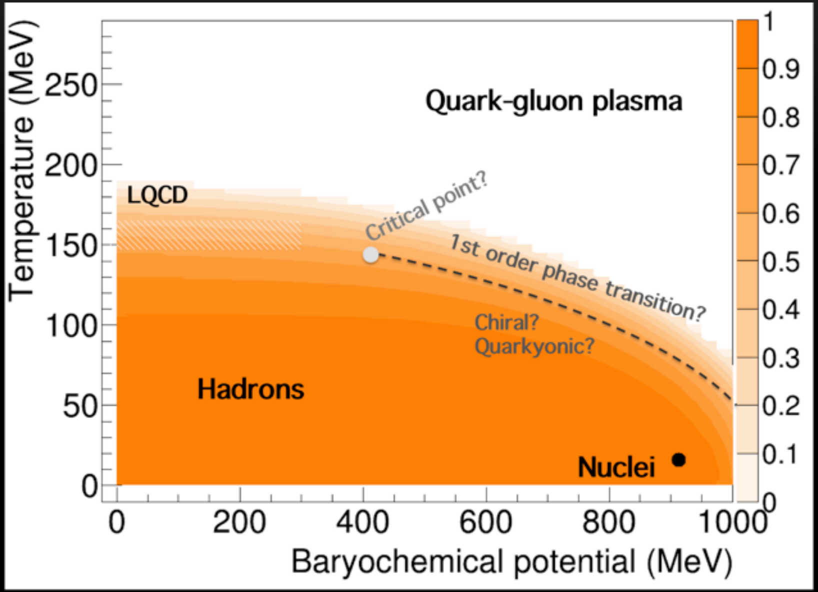
CRC-TR 211
Strong-interaction matter under extreme conditions

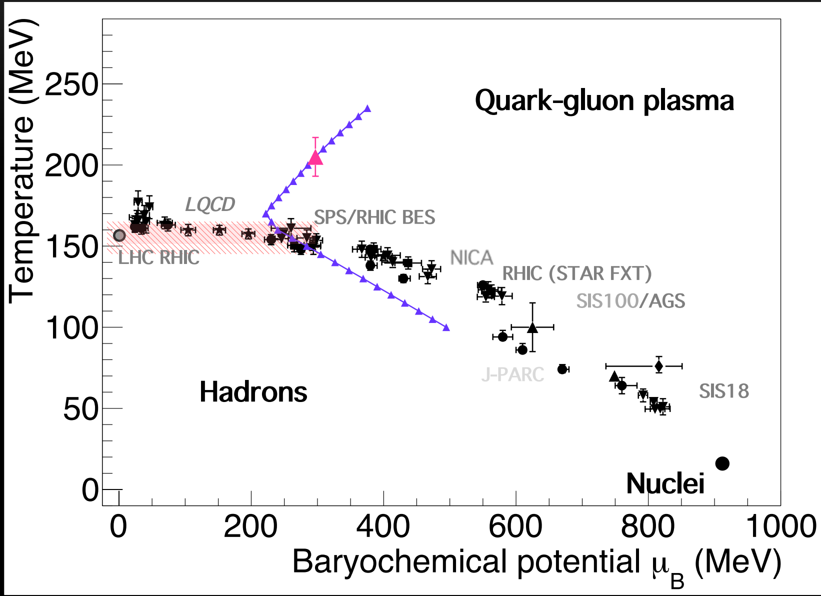
Theoretical guidance



$\frac{<\bar{q}q>_{T,\mu_B}}{<\bar{q}q>_{T=0,\mu_B=0}}$: *B.J. Schaefer and J. Wambach*

- Vanishing μ_B, high T (Lattice QCD)
  - Crossover transition
  - $\varepsilon_c \sim 1$ GeV/fm^3, $T_c \sim 155$ MeV
- Large μ_B, moderate T (effective, Lattice QCD inspired models)
  - 1st order transition
  - QCD critical point
  - Melting of the condensate (order parameter $\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \neq 0$)

Searching for landmarks of the QCD matter phase diagram

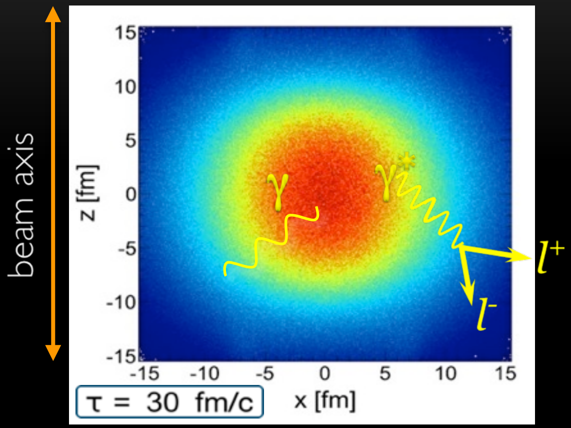


O. Kaczmarek et al., PRD 83 (2011) 014504
S. Borsanyi et al. [Wuppertal-Budapest Coll.], JHEP 1009 (2010) 073
A. Andronic et al., arXiv:1710.09425 [nucl-th]
F. Becattini et al., Phys. Lett. B 764 (2017) 241
J. Cleymans et al., Phys. Rev. C 73 (2006) 034905
L. Adamczyk et al. [STAR Coll.], arXiv:1701.07065 [nucl-ex]
G. Agakishiev et al. [HADES Coll.], Eur. Phys. J. A 52 (2016) 178
X. Lopez et al. [FOPI Coll.], Phys. Rev. C 76 (2007) 052203
H. J. Specht et al. [NA60 Coll.], AIP Conf. Proc. 1322 (2010)

- Experimental approach:
  - Probe with highest precision different regions of the QCD matter phase diagram
- Observables:
  - Flavor production (multi-strange, charm)
  - Emissivity of matter (dileptons)
  - Higher moments of e-b-e multiplicities (B, S, Q)

Electromagnetic radiation

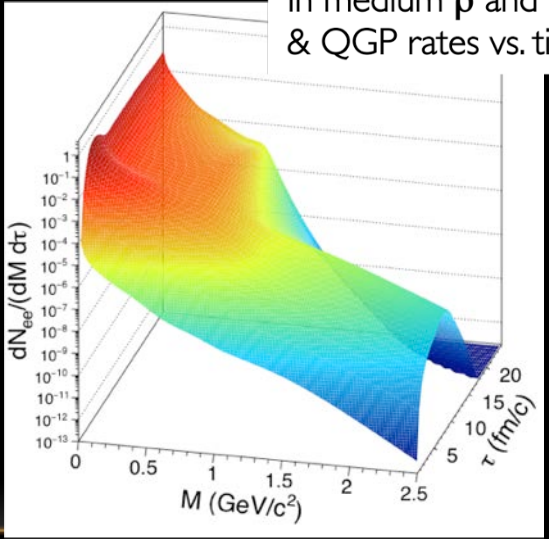
Photons and lepton pairs probe the interior of fireballs – "PET" of the fireball



- EM radiation contains contributions from throughout the collision
- EM probes leave collision zone undisturbed

- Real γ characterized by transverse momentum (blue shifted)
- Lepton pairs carry extra information: invariant mass

In medium ρ and ω SF & QGP rates vs. time



The vector correlator is directly accessible in HIC

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

→ Unique direct access to in-medium spectral function

Electromagnetic correlator in vacuum

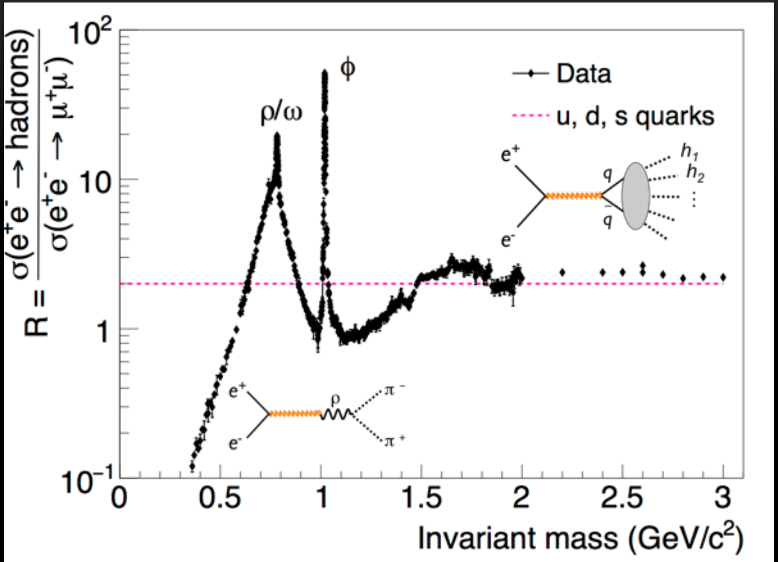
McLerran-Toimela formula

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

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

- If $\frac{\mathrm{Im}\Pi_{EM}^{\mu\nu}}{M^2} \sim const.$ thermal dilepton emission will follow a Bose distribution

→ Dileptons as thermometer



$$\mathrm{Im}\Pi_{EM}^{vac}(M \le 1.5\mathrm{GeV}) = \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \mathrm{Im}D_v^{vac}(M)$$

⇒ Vector Meson Dominance: $J^P = 1^-$ for both γ^* and VM (with ρ playing a dominant role)

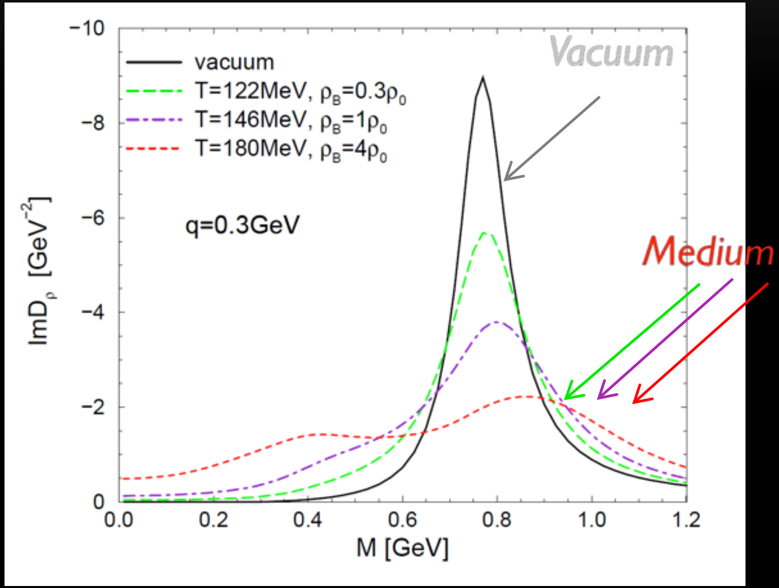
$$\mathrm{Im}\Pi_{EM}^{vac}(M > 1.5\mathrm{GeV}) = -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \ldots\right) N_c \sum_{q=u,d,s} (e_q)^2$$

⇒ pQCD continuum

ρ meson in hot and dense medium

interacts with hadrons from heat bath → additional contributions to the ρ-meson self-energy

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

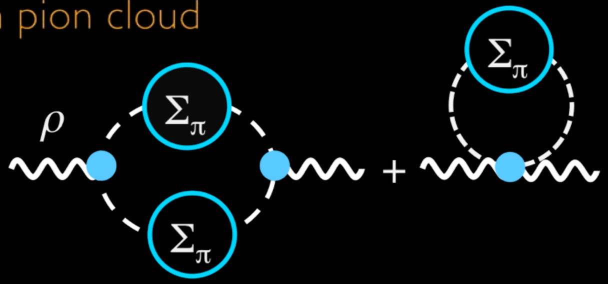


Baryon effects important even at $\rho_{B,tot} = 0$: sensitive to $\rho_{Btot} = \rho_B + \rho_B$ (ρ-N and ρ-$\bar{N}$ interactions identical)

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

In-medium pion cloud

$\Sigma_{\rho\pi\pi} =$



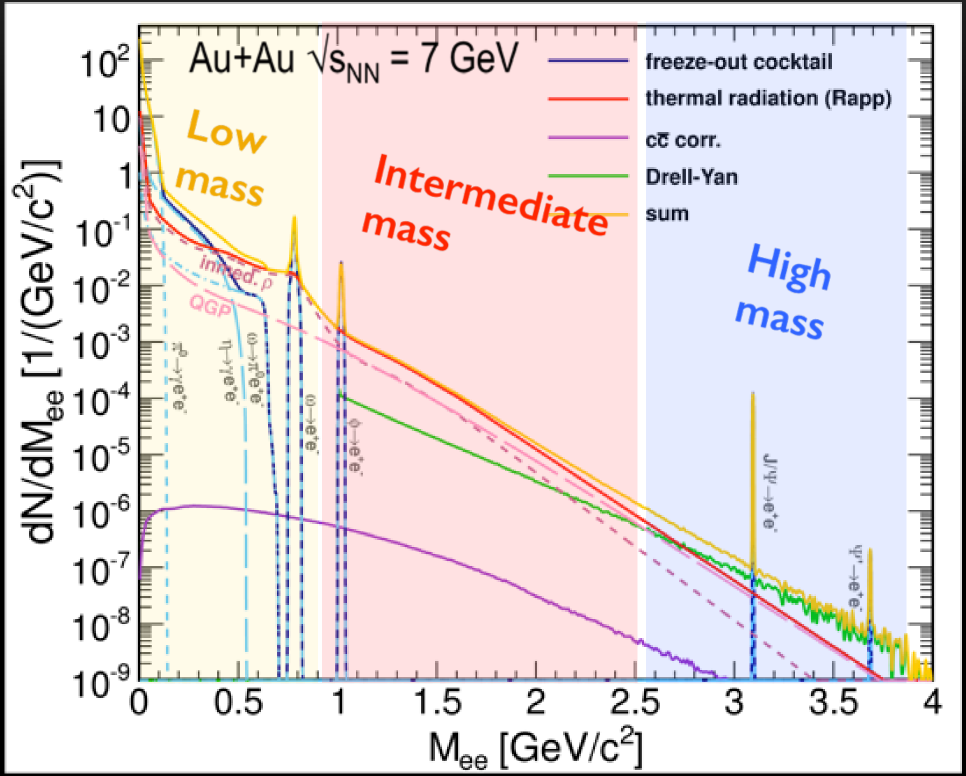
Direct ρ-hadron scattering

$R = \Delta, N(1520), a_1, K_1, ..$

$\Sigma_{\rho B,M} =$

$h = N, \pi, K$

Characteristic regimes in invariant e^+e^- mass



- Drell-Yan: power-low ~M^n
- Heavy-flavor: $c\bar{c} \rightarrow l^+l^-$
  - Becomes significant at RHIC and LHC
- Thermal radiation: ~$exp(-M/T)$
  - QGP – highest T, no flow
  - "4π annihilation": $\pi a_1 \rightarrow l^+l^-$
  - In-medium ρ, ω – moderate T, flow
- Final state decays (hadron cocktail): $\pi^0, \eta \rightarrow \gamma e^+e^-$

$$M^2 = (P_{e+} + P_{e-})^2$$

p_t, v_2, $\cos\theta$

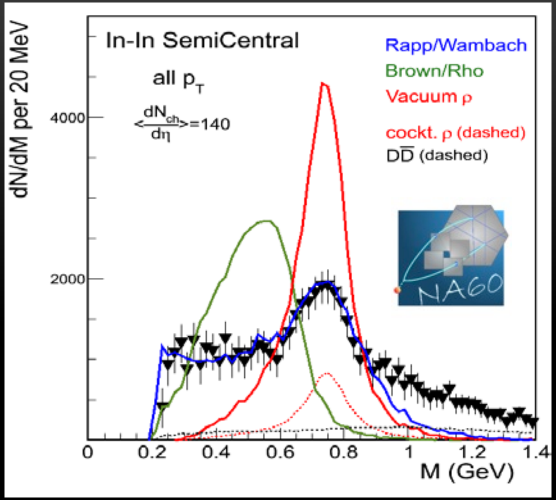
The experimental challenge …

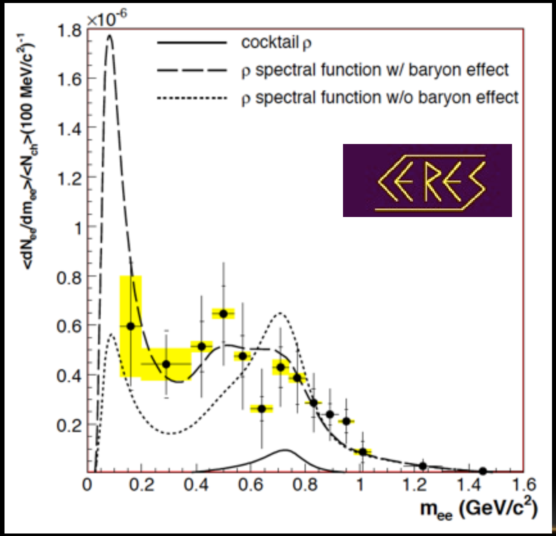
There is no such thing as a free lunch

- Lepton pairs are rare probes (BR < 10^{-4})
- at SIS energies sub-threshold vector meson production
  → $M_r \times \Gamma_{ee}/\Gamma_{tot}$ decay per 10 mio events
- Large combinatorial background
  - in e^+e^- from Dalitz decays ($\pi^0 \rightarrow e^+e^-\gamma$) and conversion pairs ($e^+e^-$)
  - in $\mu^+\mu^-$: weak π, K decays
- Isolate the contribution to the spectrum from the dense stage
- Low-momentum coverage!

DATA QUALITY

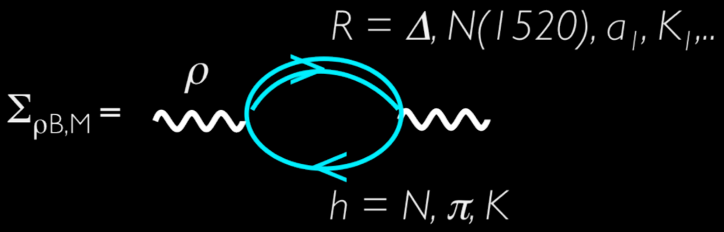
- The decisive parameters: Number of Interactions and Signal/Background
  - Range of B/S: 20 - 100 → B/S >>1;
    - Effective sample size: $S_{eff} \sim I \times S/B$ reduction by factors of 20-100
    - Systematics: $\delta S_{eff}/S_{eff} = \delta B/B \times B/S$ $\delta B/B = 2\ldots5\times10^{-2}$





Are narrow in-medium vector meson states with substantially shifted pole mass observed?

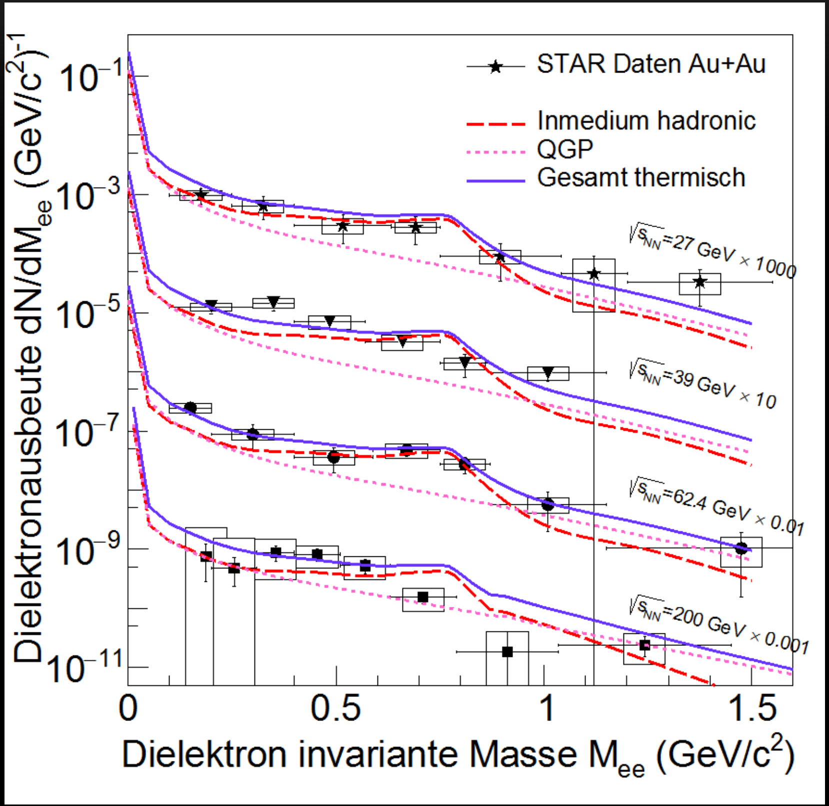
- Disfavors "dropping mass" scenario: $m_{had} \sim \langle \bar{q}q \rangle$
- Strongly supports in-medium broadening



Data NA60: Phys. Rev. Lett. 96 (2006) 162302
Data CERES: Phys.Lett. B666 (2008)
Calculations: R.Rapp and H. van Hees, 2008

Dielectron mass spectra from STAR BES I

Au+Au $\sqrt{s_{NN}}$ = 19.6 - 200 GeV

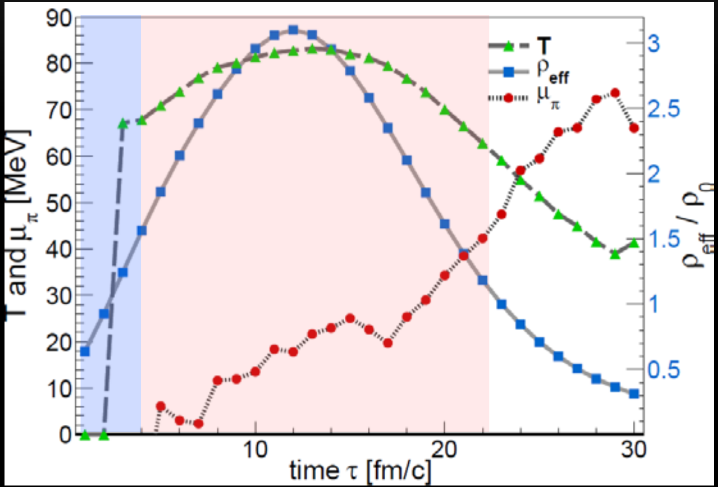


Phys.Lett. B750 (2015) 64-71
J. Butterworth et al., arXiv:1612.05484 [nucl-ex]
Model: Rapp/Wambach/Hees

- Isolation of the excess by subtracting the measured decay cocktail
- Acceptance corrected spectra
- In-medium broadened ρ spectral function consistently describes the low-mass electron-positron excess for all the energies 19.6-200 GeV

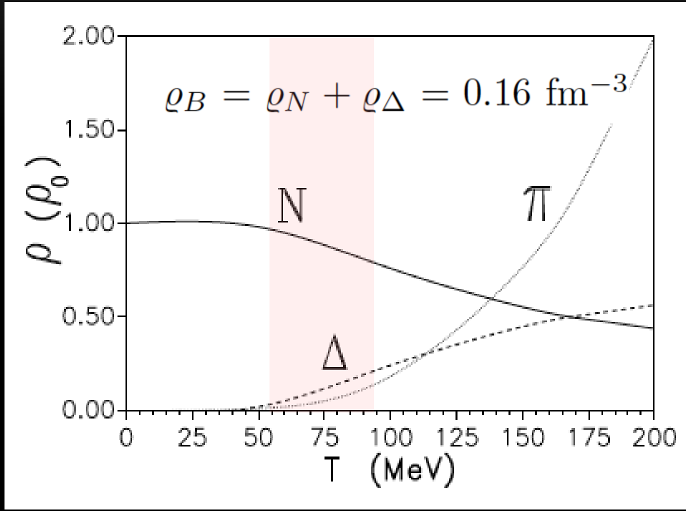
Baryonic matter at few GeV beam energy *Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV*

Central cell (3x3x3 fm3) thermodynamic properties from coarse graining UrQMD



TG, F. Seck et al., Eur. Phys. J. A 52 (2016) 131

Composition of a hot πΔN gas

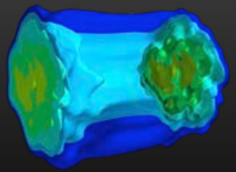


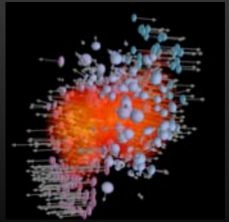
Rapp, Wambach, Adv. Nucl. Phys. 25 (2000)

- Long interpenetration times
- Comparatively long lifetime of the dense "fireball" (ρ_{max} ≈ 3 ρ_0)

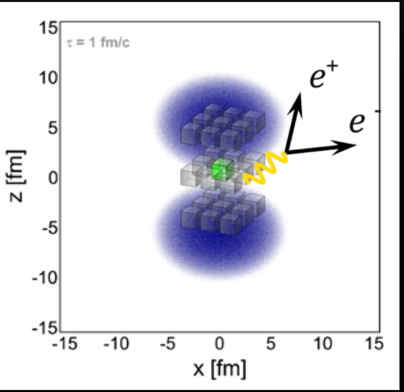
- Moderate temperatures: T < 90 MeV
- Baryon-dominated system throughout the evolution (N_π/A_{part} ≈ 10%)

Coarse-grained transport approach

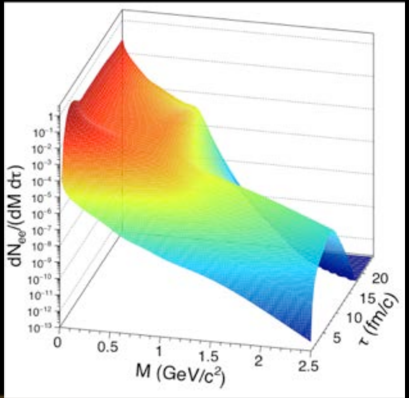




- "Combine" the advantages of two descriptions: hydrodynamics & transport
- Simulate events with a transport model
  → ensemble average to obtain smooth space-time distributions



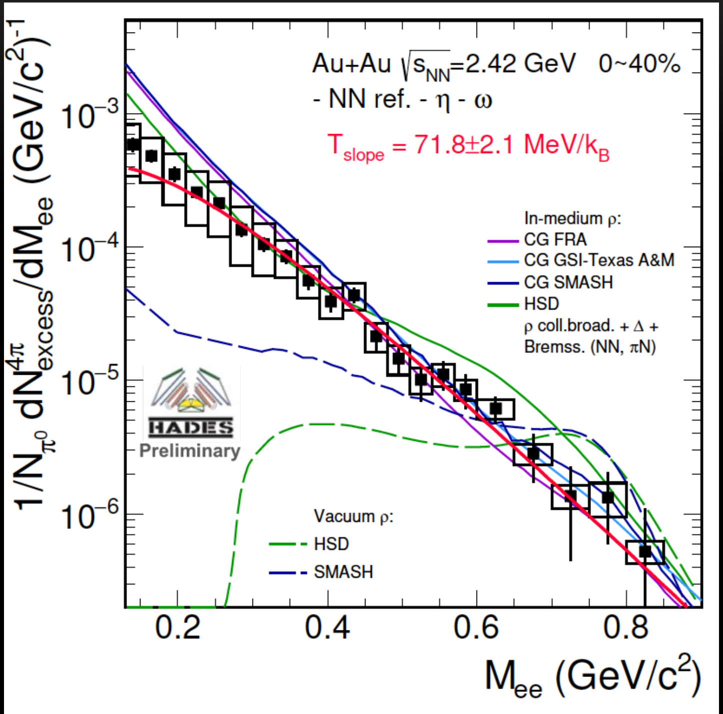
- Divide space-time evolution into 4-dimensional cells
  21 x 21 x 21 space cells (1fm^3), 30 time steps → ~ 280 k cells
- Determine for each cell the bulk properties like T, μ_B , μ_π, collective velocity



- Apply in-medium ρ & ω spectral functions to compute EM emission rates
  → parameterization of RW in-medium spectral function
- Sum up contributions of all cells

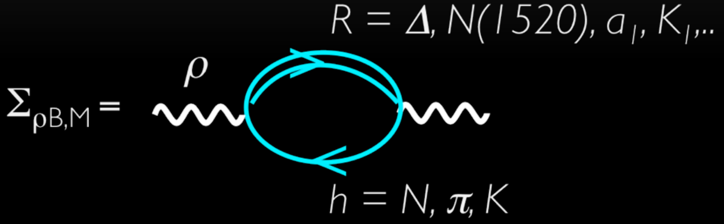
Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J. A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1

Dielectron mass spectra at $\sqrt{s_{NN}}$ = 2.42 GeV



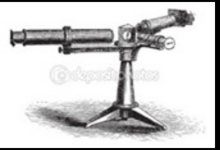
HADES., to appear soon

- Strong broadening of the in-medium ρ due to direct ρ-hadron scattering

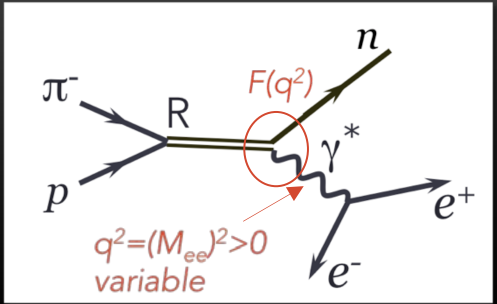


- Thermal rates folded over coarse-grained UrQMD medium evolution works at low energies
- Supports baryon-driven medium effects at SPS and RHIC (LHC)!

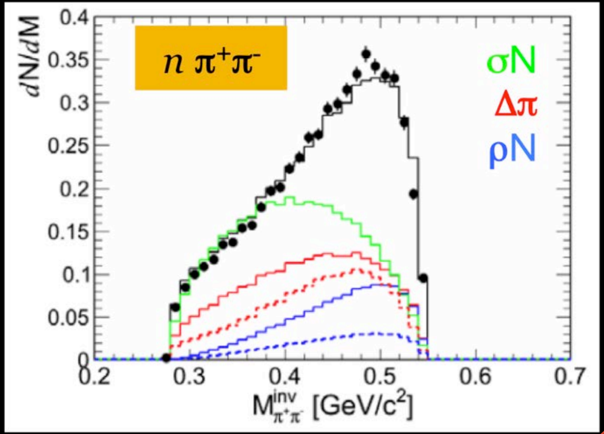
Robust understanding across QCD phase diagram

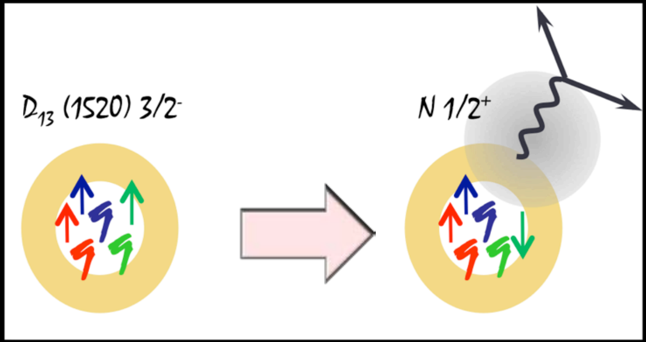


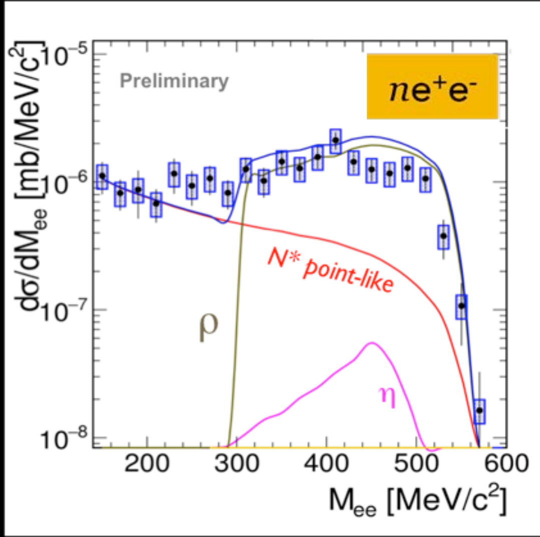
EM baryon-resonance decays
π^- (683,5 MeV/c) p → N*



- Worldwide unique combination of π beams (at low energies) with dilepton spectrometer
- Access to time-like etFF of baryons







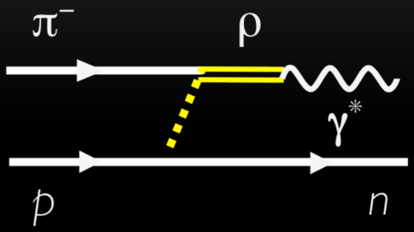
→ D_{13} (1520) is dominant in ρ production!

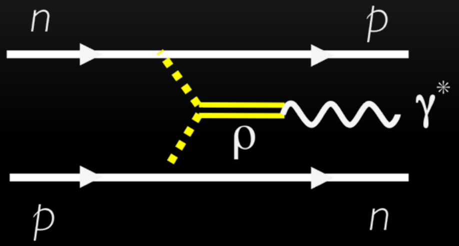
$$\frac{d\sigma}{dM_{ee}} = \frac{d\sigma}{dM_{\pi\pi}} c_\rho \left(\frac{m_\rho}{m_{ee}}\right)^3$$

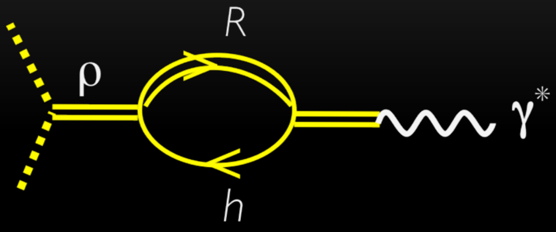
→ First measurement demonstrating the dominant role of intermediate ρ propagation in N* → Ne$^+$e$^-$ transition

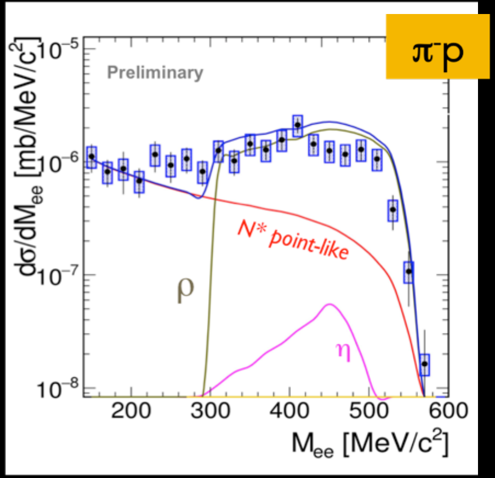
The role of virtual pions in dilepton production

Three different collision systems, three surprises but likely the same underlying mechanism

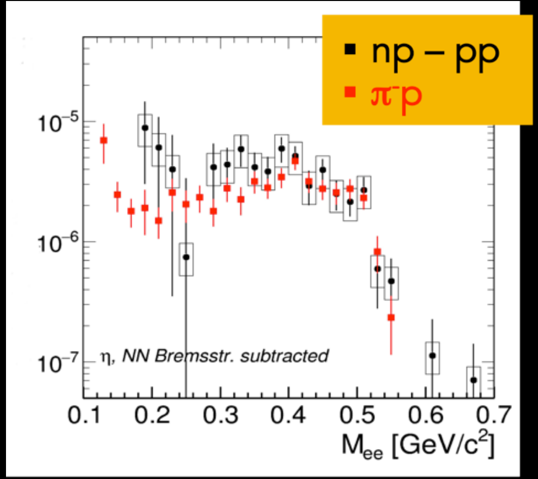




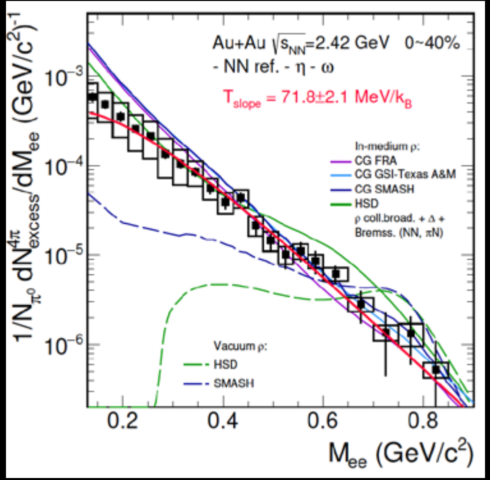




HADES, in preparation



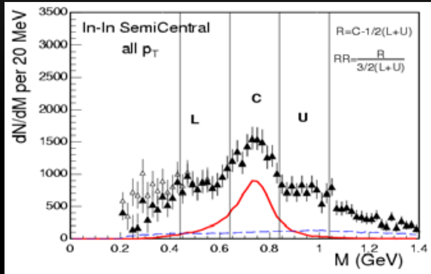
HADES Coll., EPJ A53 (2017) 149
HADES Coll., PRC 95 (2017) 065205



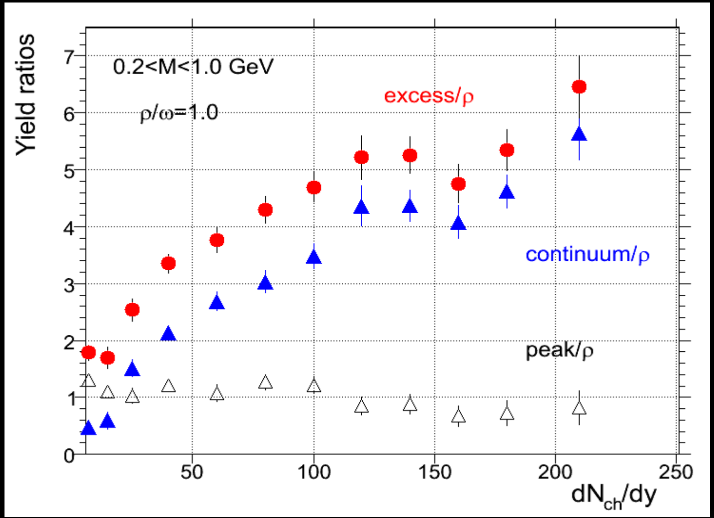
HADES., to appear soon

The dilepton clock

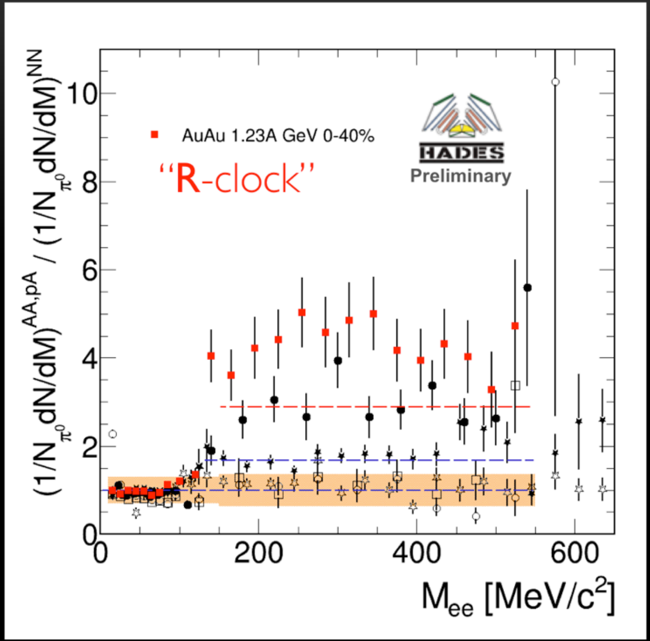
Centrality dependence of spectral shape



"ρ-clock"



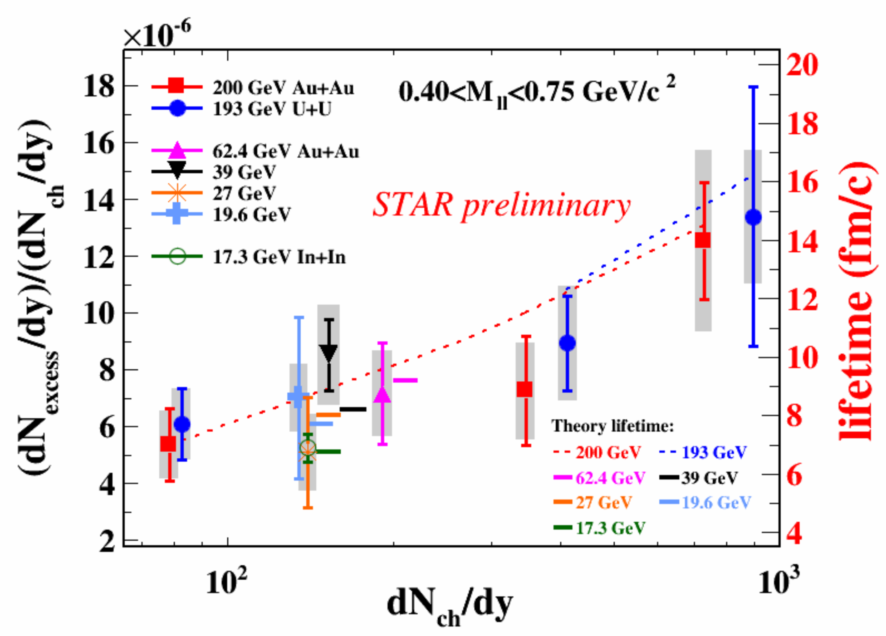
System size dependence of excess

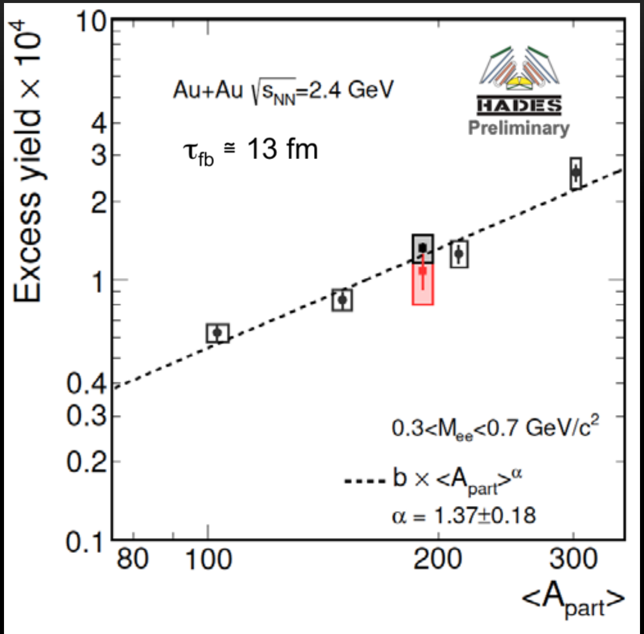


Rapid increase of relative yield reflect the number of ρ's / R's regenerated in fireball

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)

The lifetime of the interacting fireball



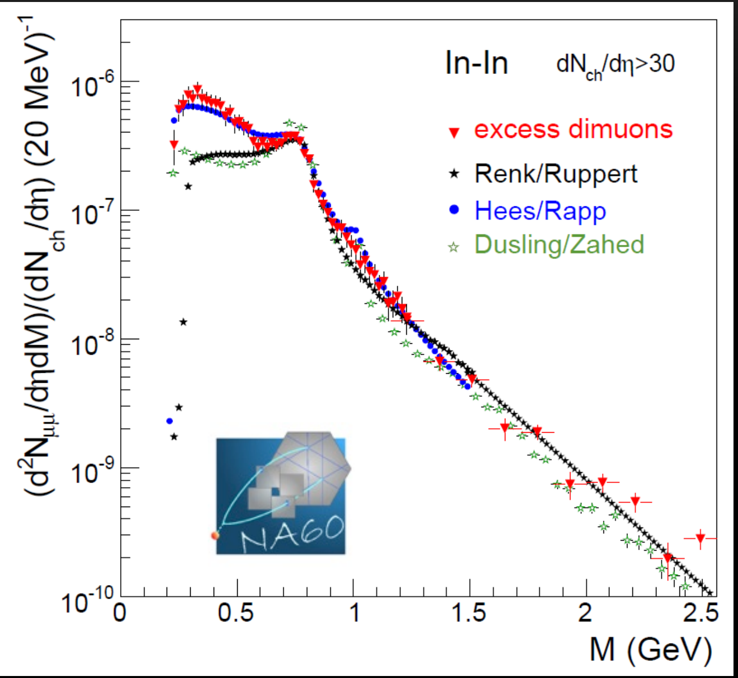


STAR data: arXiv:1612.05484 [nucl-ex]
Model: R. Rapp, H. van Hees, PLB 753 (2016) 586

- Normalized excess yields for the mass region $0.3<M<0.7$ GeV/c^2 is proportional to the lifetime of the interacting fireball
- Note: normalization to the number of pions should be done when going down with energy!

Dileptons as thermometer

Measurement of radiating source temperature



- Acceptance corrected excess yield
- $M_{\mu\mu}>1$ GeVc^2 ~ exponential fall-off - 'Planck-like'

→ measurement of radiating source temperature

→ fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ to range

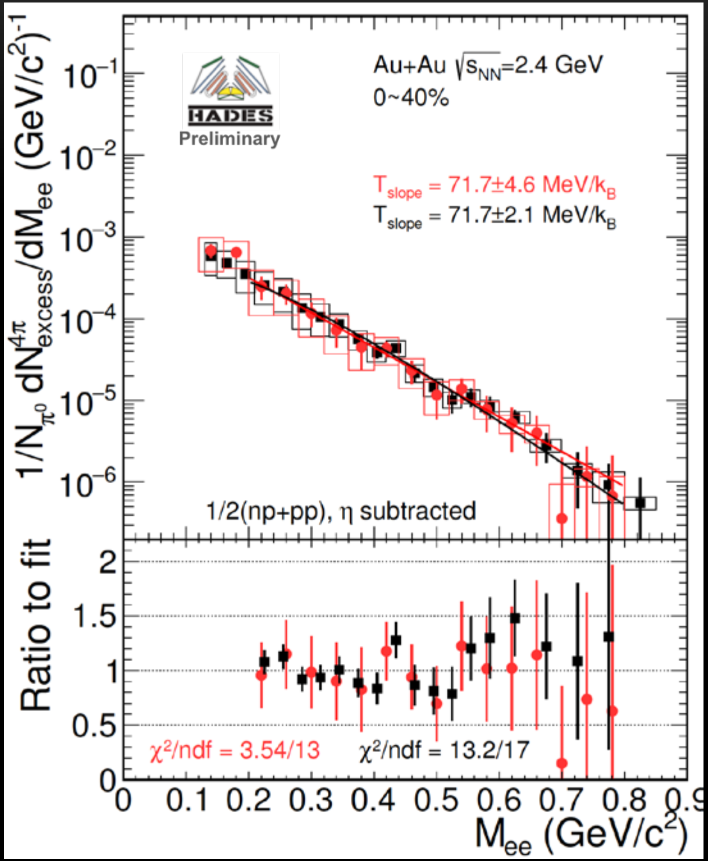
→ *$M=1.1$-2.0 GeV/c^2: $\langle T\rangle_{\text{emitting source}}=205\pm12$ MeV/k_B*

→ *$M=1.1$-2.4 GeV/c^2: $\langle T\rangle_{\text{emitting source}}=230\pm10$ MeV/k_B*

Eur. Phys. J. C 59 (2009) 607-623
CERN Courier 11/ 2009, 31-35
Chiral 2010, AIP Conf.Proc. (2010) 1322

"M_{ll} is the only Lorenz-invariant thermometer of the field"

Dileptons as thermometer at SIS18



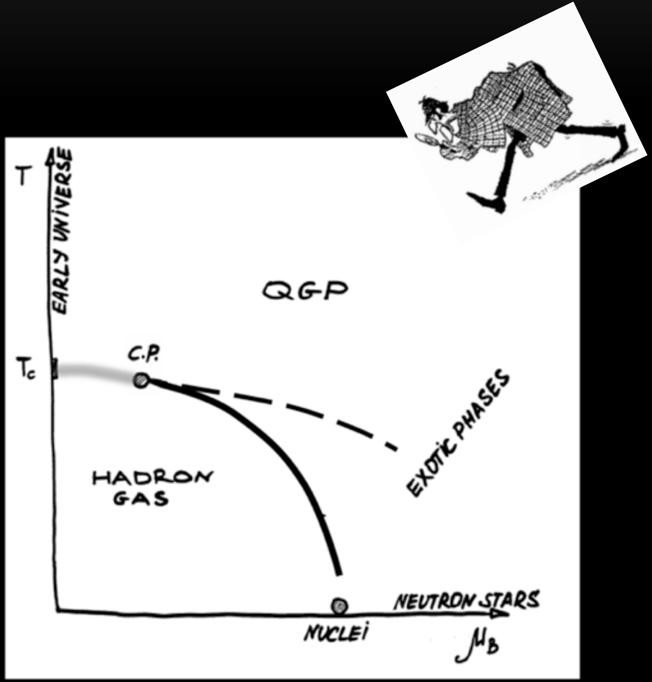
- $T_{initial}$ ~ 3 times lower at SIS18 compared to SPS
- Shifts predominance of early emission from M_{ee}>1.2 GeV/c^2 at SPS to M_{ee}>0.4GeV/c^2 at SIS

→ fit $$\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$$ to range *M=0.2-0.8 GeV/c²*

- $\langle T \rangle_{\text{emitting source}}$ = 72 ± 2 MeV/k_B

HADES., collaboration review

Dileptons and QCD phase diagram of matter

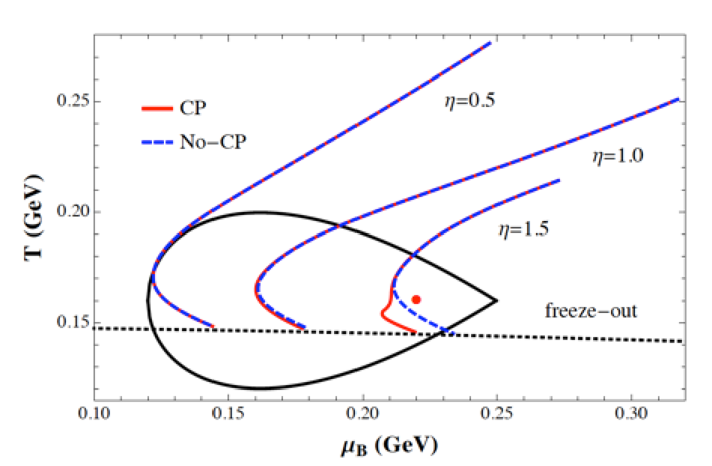


Excitation functions

- Fireball lifetime
- Emitting source temperature

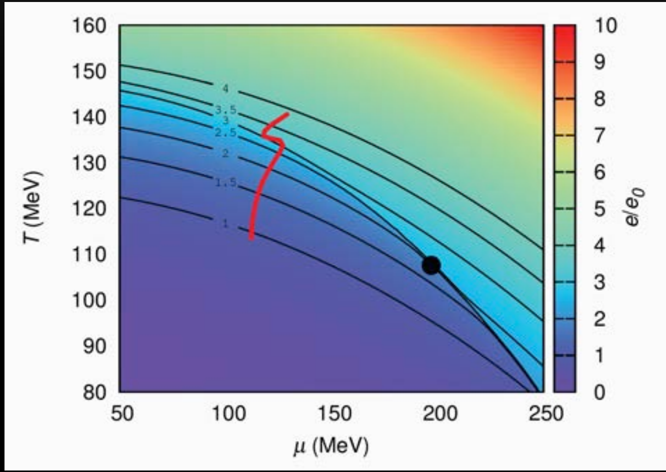
Mapping QCD phase diagram with dileptons

Hydrodynamic evolution trajectories



A. Monnai, S. Mukherjee, Y. Yin: arXiv: 1606.00771

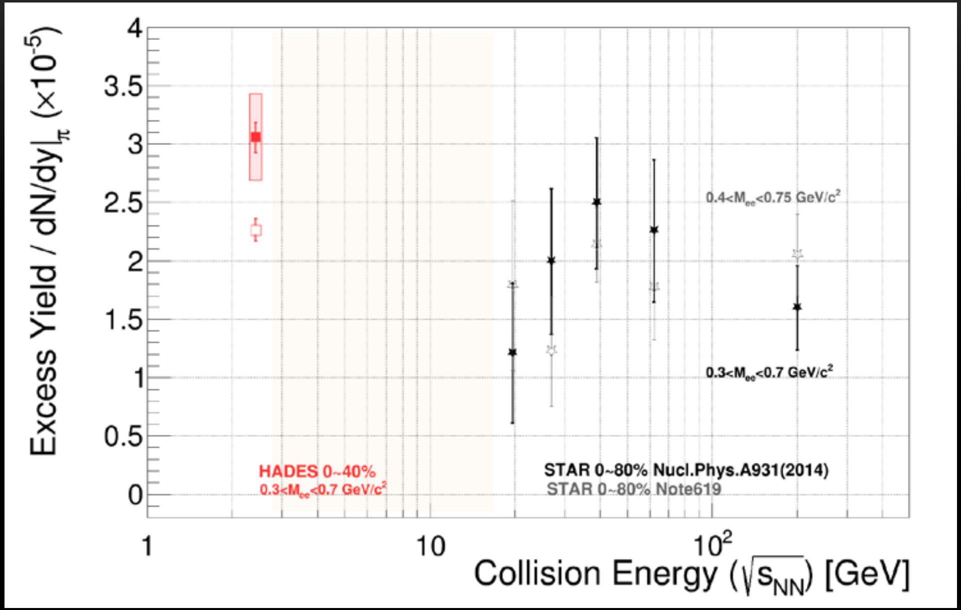
Event-averaged trajectory near the critical point (black dot)



C. Herold, M. Nahrgang, Y. Yan and C. Kobdaj, PRC93 (2016)

What are the possible signatures in dilepton radiation?

Energy dependence of low-mass excess

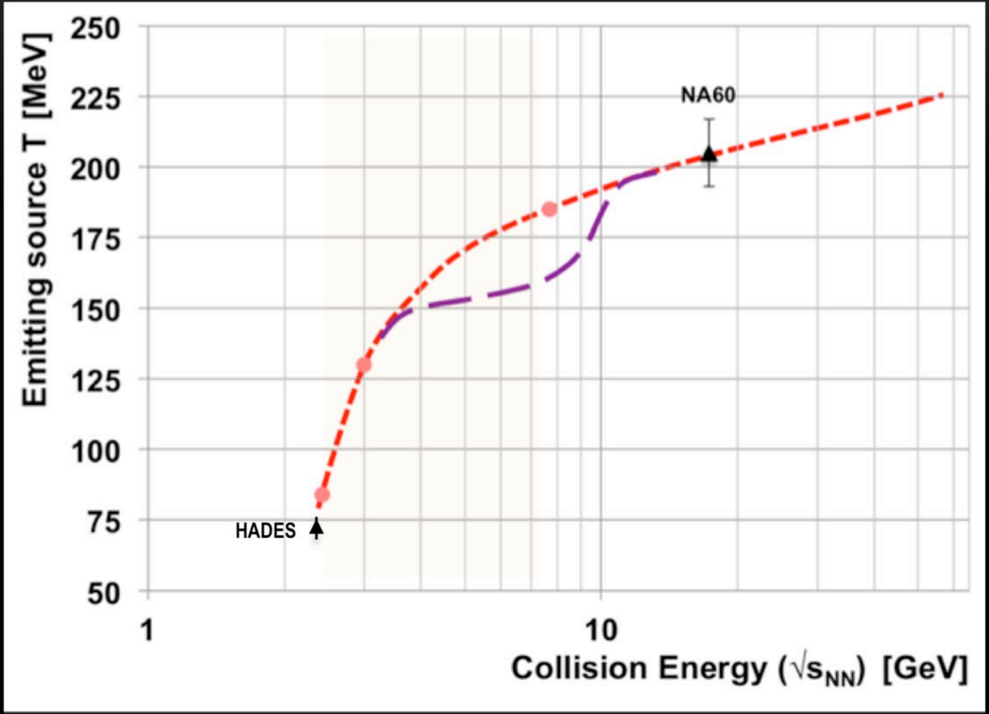


- Yield in low-mass window tracks fireball lifetime

→ Search for anomalous fireball lifetime around phase transition (& critical point?)

- Quite moderate energy dependence
- Dilepton yield determined by interplay between temperature and $V \otimes \tau_{coll}$

Energy dependence of intermediate mass slope



Dashed violet curve corresponds to a speculated shape with phase transition

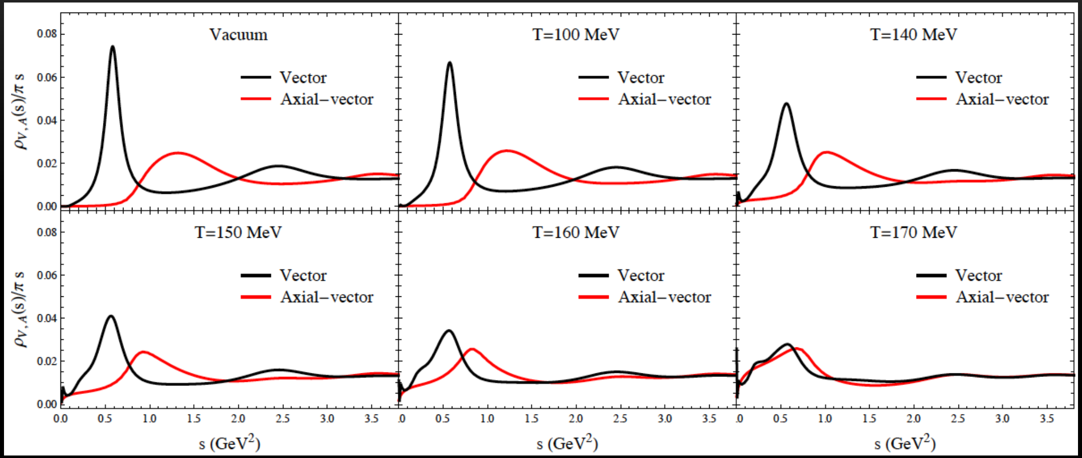
- Measures the emitting source temperature (true, no blue shift)

→ Measure T_s (note, $T_s < T_{initial}$) "caloric curve"

→ Plateau around onset of deconfinement?
[see e.g. M. D'Agostino et al. NPA 749 (2005) 5533]

- Precision measurements are the key
  → CBM at FAIR

QCD and Weinberg sum rules in medium



- Finite T vector and axial-vector spectral functions
- No baryon effects accounted for yet

→ Chiral mass splitting "burns off", resonances melt

Hohler & Rapp, Phys.Lett. B731 (2014)
Jung, Tripolt, von Smekal, Wambach, Phys.Rev. D95, 036020 (2017)

CBM case: 4π processes: $\pi a_1 \rightarrow \gamma^* \rightarrow l^+l^-$ (chiral mixing) is a dominant hadronic source in IMR: correlated charm contribution, Drell-Yan, QGP are suppressed

"You may say I'm a dreamer… but I'm not the only one"

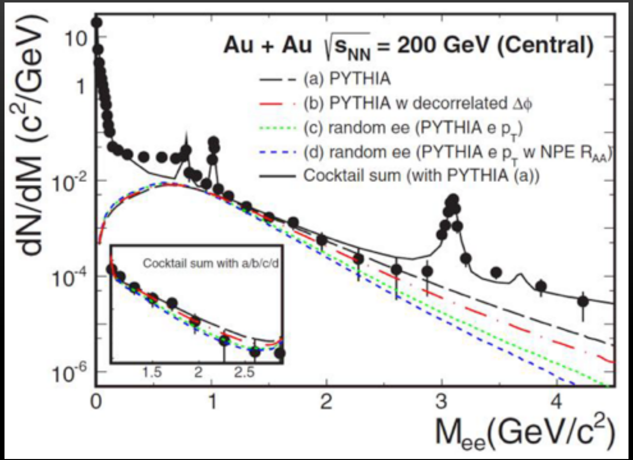
		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
HADES	SIS18			2.5 GeV + pA, pA							
STAR BES	RHIC				8 – 20 GeV			200 GeV			
MPD	NICA				4 – 11 GeV						
CBM	SIS100									2 – 5 GeV	
ALICE*	LHC	5.5 TeV					5.5 TeV				
	J-PARC**			pA 8 GeV						2 – 5 GeV	
NA60+	SPS		LOI						6 – 17 GeV		
PHENIX	RHIC	200 GeV									
STAR	RHIC	200 GeV	pp(500)								
sPHENIX								200 GeV			
BM@N	Nuclotron		2 – 3 GeV								

** - ITS, 50kHz, lower field*

*** - Proposal to J-PARC → If approved, construction of HI injector and detectors in 10 years ?*

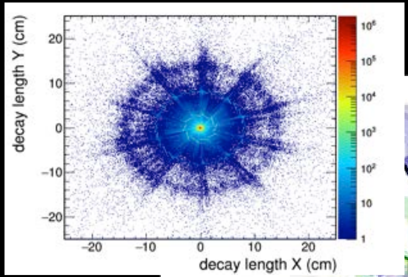
STAR dielectrons ongoing analysis Au+Au $\sqrt{s_{NN}}$ = 200 GeV

- μ_B<<T, i.e. vanishing net-baryon density
- Lattice QCD computations are most powerful
- Measure ρ spectral function and "calibrate" EM rates
- Extract fireball temperature (IMR)

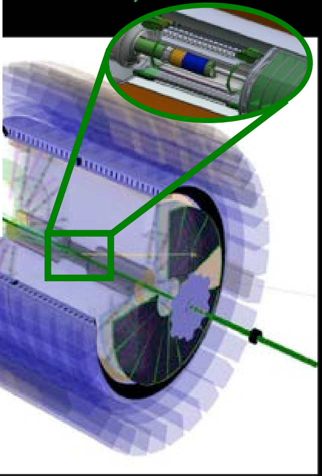


Dielectron reconstruction with HFT

- Reduce uncertainties on charm contribution
- Challenge: γ conversion in HFT detector material
  → use excellent vertexing to reject it
  (looks promising, statistics Runs 10,11,14,16 ~4×10⁹)



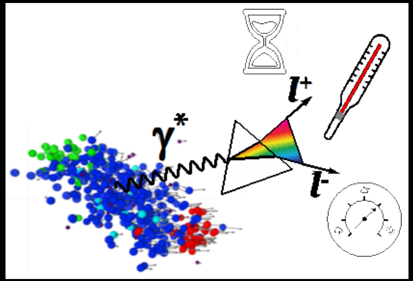
Heavy Flavor Tracker



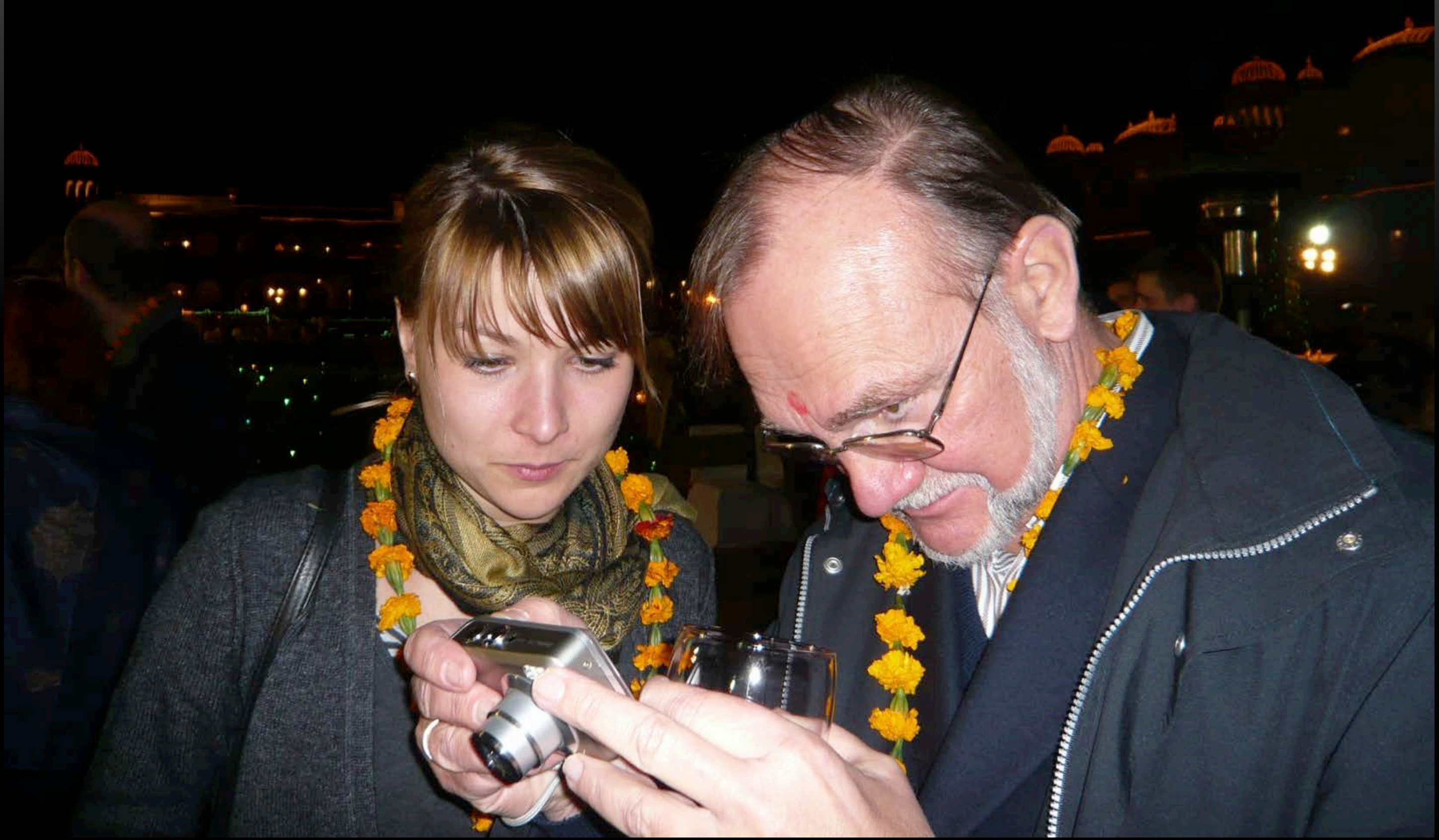
Résumé and prospects

- Unique possibility of characterizing properties of hot and dense QCD matter with dileptons
- Robust understanding of low-mass dilepton excess radiation by ρ-baryon coupling (at top RHIC, RHIC BES, SPS and SIS18 energies)
- Enable unique measurements
  - **Degrees of freedom** of the medium
  - Restoration of **chiral symmetry**
  - **Fireball lifetime**
  - Emitting source **temperature**
- Future experiments allows for overlap and independent confirmation of results

There is no mission impossible



Thank you for your attention!



There is a power that can take away life,
but never the memory of friends

Bonus slides

QCD and Weinberg sum rules

Weinberg Sum Rules…

Weinberg '67, Das et al '67

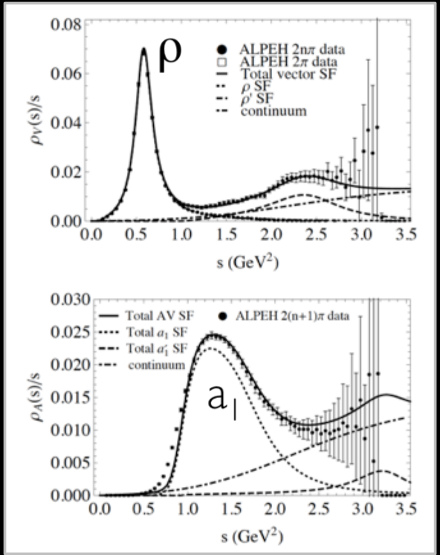
$$\int \frac{ds}{\pi}\frac{1}{s}(\rho_V - \rho_A) = f_\pi^2$$

$$\int \frac{ds}{\pi}(\rho_V - \rho_A) = -m_q\langle\bar{q}q\rangle$$

$$\int \frac{ds}{\pi}\, s\,(\rho_V - \rho_A) = c\alpha_s\langle(\bar{q}q)^2\rangle$$

… accurately satisfied in vacuum

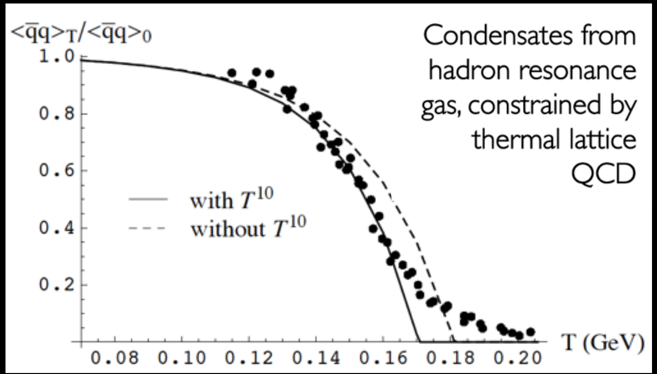
Rapp et al, Annals Phys. 368 (2016)



ρ-a_1 mass splitting due to χ_s breaking ($\sim f_\pi$, $\langle\bar{q}q\rangle$)

… remain valid in medium

J. Kapusta, E. Suryak '94

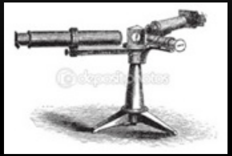


S. Borsanyi et al., JHEP 1009 (2010) 073

→ Test in-medium ρ–a_1 spectral function

Components of EM probes

- Degrees of freedom of the medium:
  - Spectral function merges into QGP description
    Direct evidence for transition hadrons → quarks & gluons



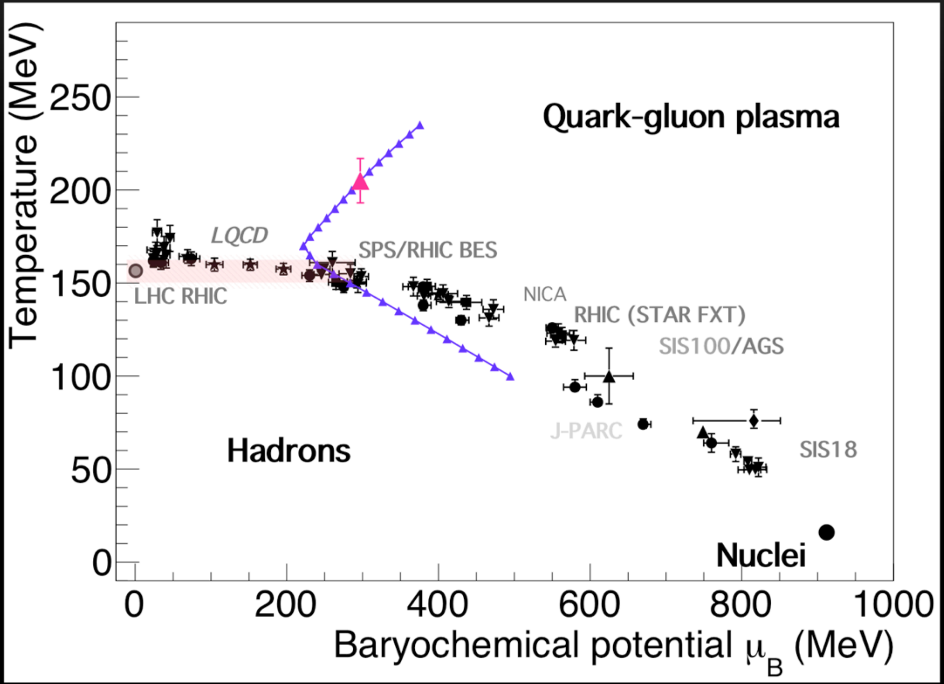
- Restoration of chiral symmetry
  - Condensates constrained by Lattice-QCD
  - Chiral mass splitting "burns off" → resonances melt

- Phenomenological tools → excitation functions
  - Fireball lifetime
  - Emitting source temperature

- Transport properties
  - Electric conductivity → probes soft limit of EM SF

$$\sigma_{EM}(T) = -e^2 \lim_{q_0 \to 0} \left[\frac{\partial}{\partial q_0} \mathrm{Im}\Pi_{EM}(q_0, q=0; T) \right]$$

Trajectories in the phase diagram



- Hadron production: well described by hadron gas in chemical and thermal equilibrium

$$n_i(\mu_B,T)=d_i\int\frac{d^3k}{(2\pi)^3}f(E_k;\mu_B,T)$$

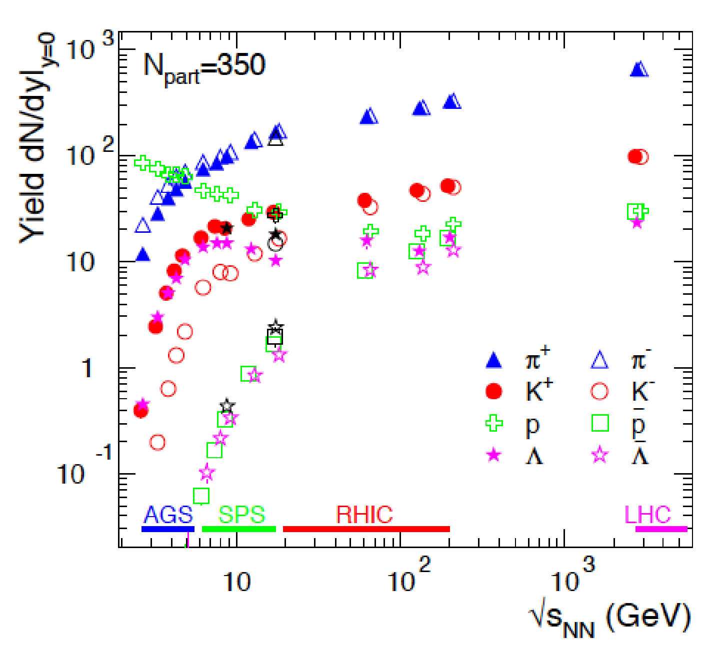
- Dileptons - need to construct evolution:
  - Before up to earliest "formation" time $\tau_0 \leftrightarrow T_0 > T_{chem}$
  - After: down to thermal freezeout $\tau_f \leftrightarrow T_{fo} < T_{chem}$

- Basic assumption: entropy (+baryon-number) conservation → fixes $T(\mu_B)$ in the phase diagram

TG, Hees, Rapp, Wambach

From SPS to RHIC

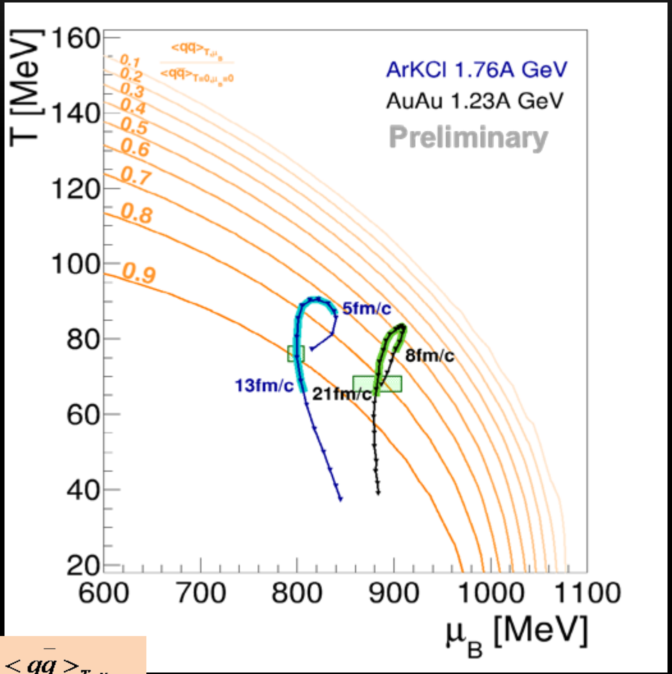
	SPS (Pb+Pb)	RHIC (Au+Au)
$dN(\bar{p})/dy$	6.2	20.1
produced baryons ($p, \bar{p}, n, \bar{n}$)	24.8	80.4
$p - \bar{p}$	33.5	8.6
particpating nucleons $(p - \bar{p})A/Z$	85	21.4
total baryon number	110	102



A. Andronic, arXiv:1407.5003

- Although the NET baryon density is different at SPS and RHIC, baryon density is practically the same!
- Baryon effects important even at $\rho_{B,tot} = 0$: sensitive to $\rho_{Btot} = \rho_B + \rho_{\bar{B}}$ (ρ-N and ρ-$\bar{N}$ interactions identical)
- Higher initial temperature at RHIC

HADES and QCD phase diagram of matter



$\frac{<\bar{q}q>_{T,\mu_B}}{<\bar{q}q>_{T=0,\mu_B=0}}$: *B.J. Schaefer and J. Wambach*

Ar+KCl data: Nucl. Phys. A931 (2014) c785

- Chemical freeze-out from measured particle yields analyzed with SHM
- Trajectories extracted from inner cube of cells with coarse-grained UrQMD
- Time-window of dilepton emission → access to hot and dense stage of the heavy-ion collision

T_{max} = 85 MeV, ρ_{max} = 3 ρ_0
→ Excitation of the vacuum
(melting of condensate)
matches spectral medium effects!

$$\frac{\langle\langle\bar{q}q\rangle\rangle(T,\mu_B)}{\langle\bar{q}q\rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$