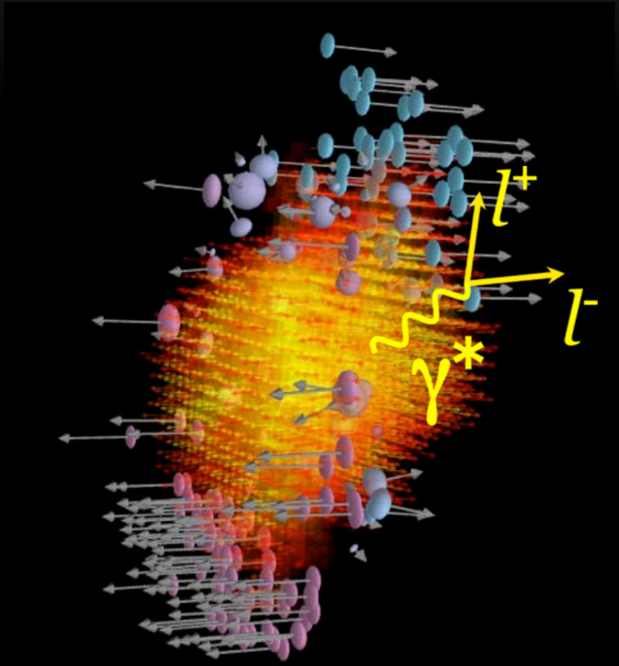
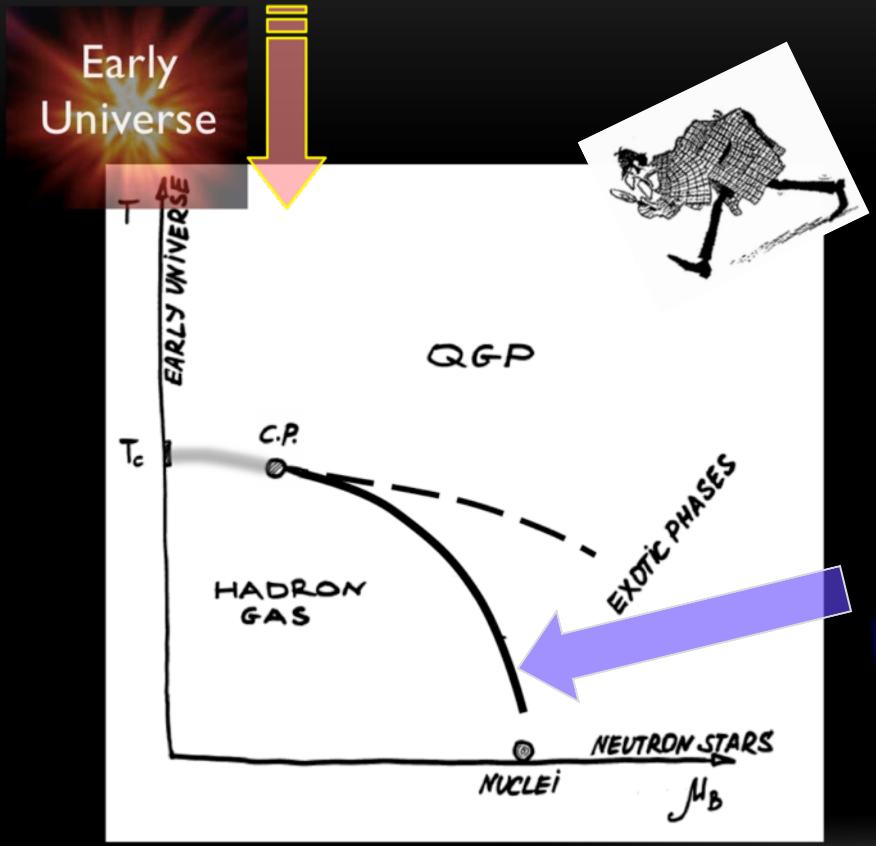


Dilepton production

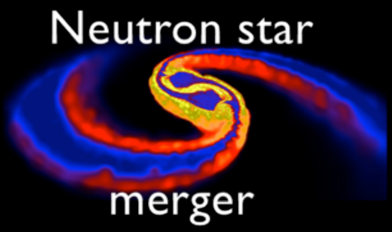
Tetyana Galatyuk

Technische Universität Darmstadt /
GSI Helmholtzzentrum für Schwerionenforschung

Exploring the phase diagram of QCD matter



- What are the properties of matter under extreme temperatures and densities?
- Where are the phase boundaries located?
- Is there a critical point?
- Where are the limits of hadronic existence?



Rosswog

NASA, SN1987A

Experimental approach: high energy heavy-ion collisions

Systematic experimental measurements (E_{beam}, A)

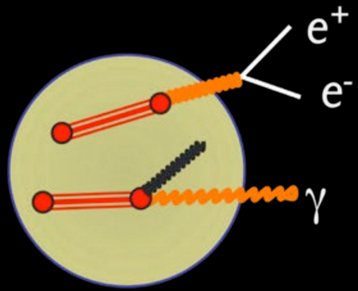
→ Extract numbers that might be related to the QCD phase diagram

→ Objective: use dileptons to probe the nature of Strongly Interacting Matter

Electromagnetic Emission Rates

Electromagnetic current-current correlation function:

$$\Pi^{\mu\nu}_{EM}(M,q;\mu_B,T) = -i\int d^4x e^{iq\cdot x}\Theta(x_0)\left\langle\left[j^{\mu}_{EM}(x), j^{\nu}_{EM}(0)\right]\right\rangle_T$$



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

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

Photon self-energy

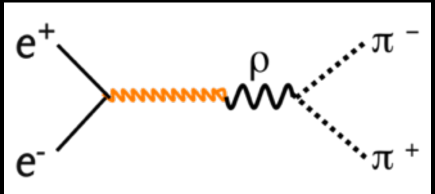
Dileptons provide unique direct access to in-medium spectral function!

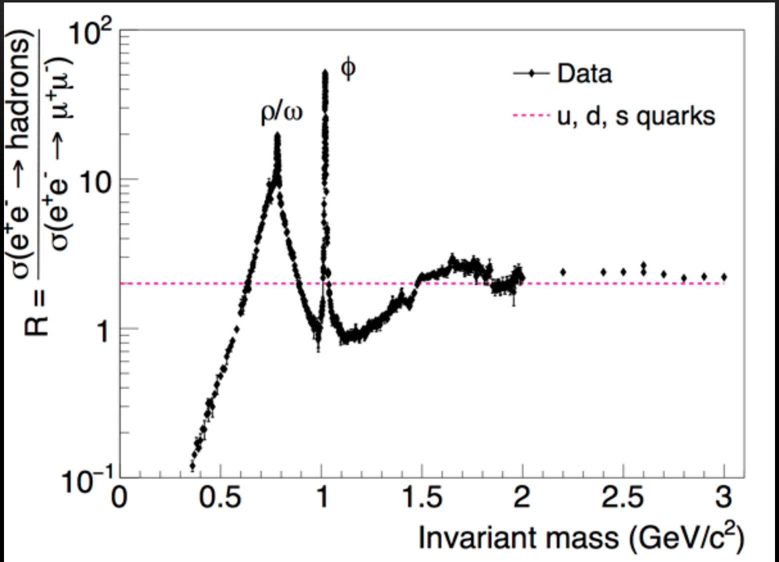
<u>In heavy-ion collisions</u>

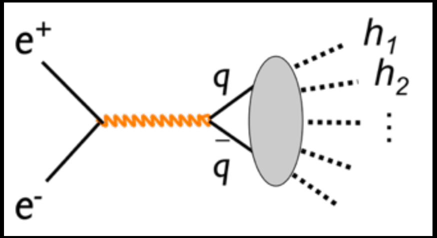
- ☐ Source strength: dependence on T, μ_B, μ_p, medium effects, …
- ☐ System evolution: V(τ), T(τ), $\mu_B(\tau)$, transverse expansion, …
- ☐ Non-thermal sources: Drell-Yan, open-charm, hadron decays, …

Electromagnetic correlator in vacuum

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







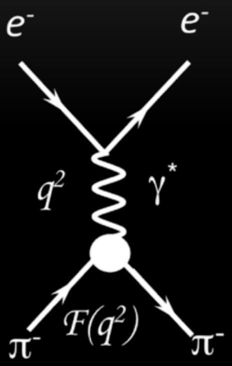
$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{EM}}(M) = \begin{cases} \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \mathrm{Im}D_v^{\mathrm{vac}}(M)\ , & M < M^{\mathrm{vac}}_{\mathrm{dual}} \simeq 1.5\,\mathrm{GeV/c^2} \\ -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \ldots\right) N_c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

Vector Meson Dominance (with ρ playing a dominant role)

pQCD continuum

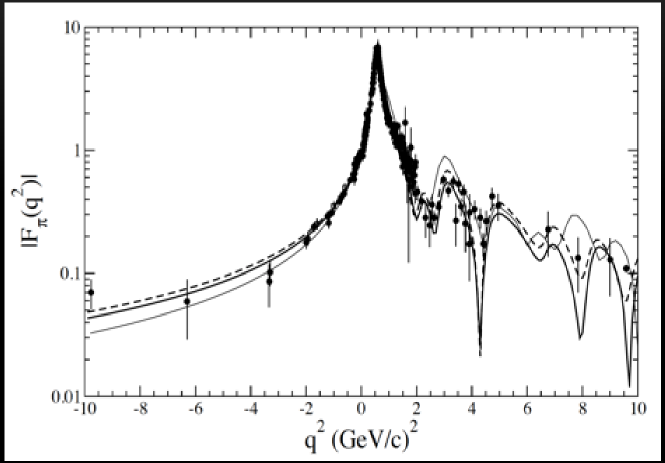
How do photons couple to hadrons?

space-like photons



$q^2<0$

$\Delta p \Delta x \geq \hbar/2$

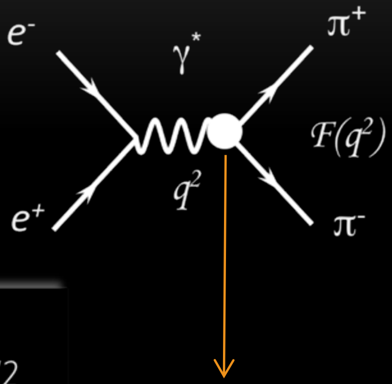


De Melo et al., Phys. Rev. D73 (2006) 070413

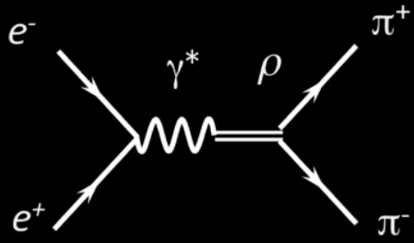
$q^2>0$

$\Delta E \Delta t \geq \hbar/2$

time-like photons



$J^P = 1^-$ for both γ^* and Vector Meson



$$F(q^2) = \frac{d\sigma/dq^2}{\left(d\sigma/dq^2\right)_{point\ like}}$$ → *Form factor*

$$q^2 = (\Delta E)^2 - (\Delta p)^2$$ → *Squared 4-momentum*

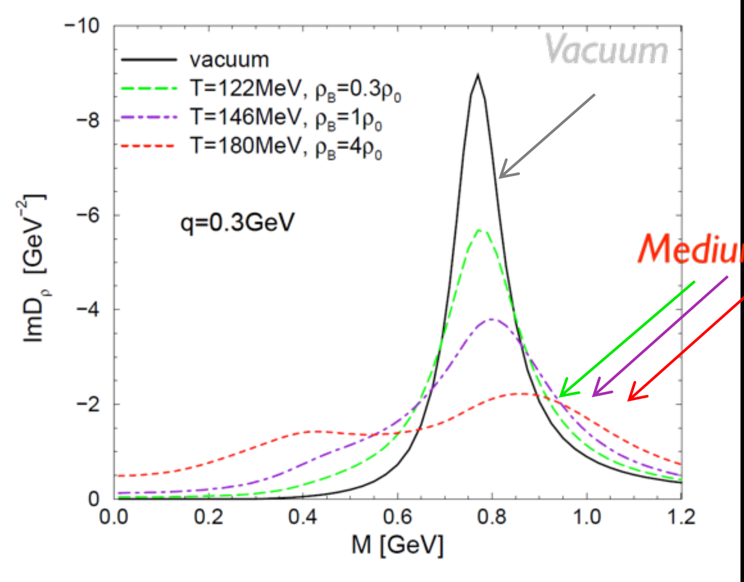
- Strong coupling of γ^* to Vector Meson → Vector Meson Dominance model
- Observable: vector mesons (ρ, ω, ϕ)

ρ meson in hot and dense medium

interacts with hadrons from heat bath →

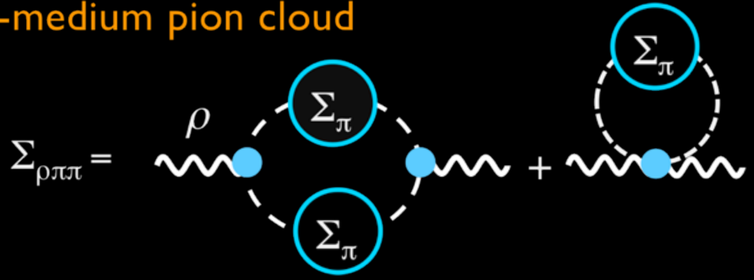
additional contributions to the ρ-meson self-energy in the medium

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

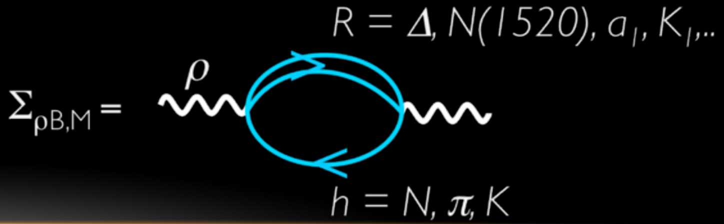


$$D_\rho(M,q;\mu_B,T) = \frac{1}{\left[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}\right]}$$

In-medium pion cloud

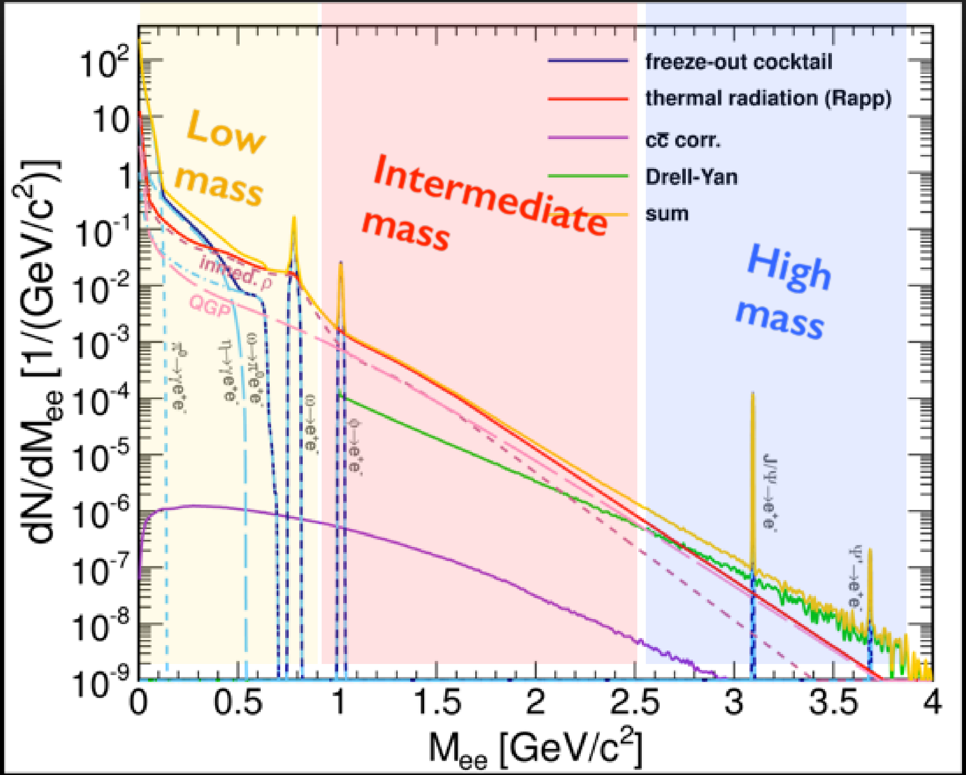


Direct ρ-hadron scattering



The ρ spectral function **strongly broadens** in the medium because the **ρ couples to baryons!**

Characteristic regimes in invariant e^+e^- mass



- Drell-Yan: power-low $\sim M^n$
- Heavy-flavor: $c\bar{c} \rightarrow l^+l^-$
- Thermal radiation: $\sim exp(-M/T)$
  - 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): $\pi^0, \eta \rightarrow \gamma e^+e^-$

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

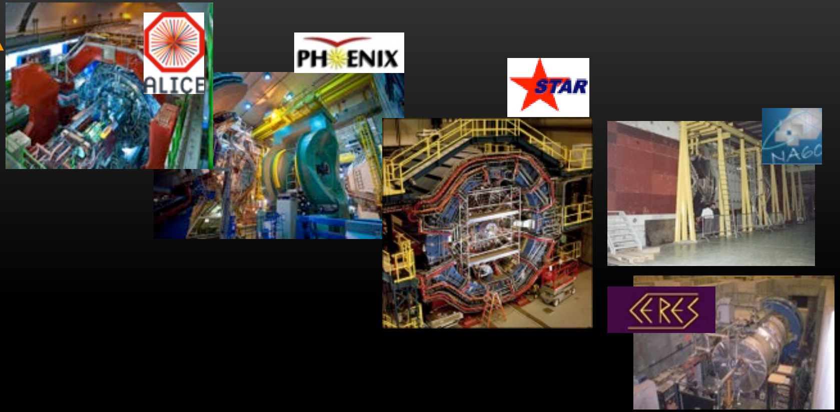
The experimental challenge …

- 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: $S_{eff} \sim 1 \times S/B$ reduction by factors of 20-100
    - Systematics: $\delta S_{eff}/S_{eff} = \delta B/B \times B/S$ $\delta B/B = 2 \ldots 5 \times 10^{-2}$

T



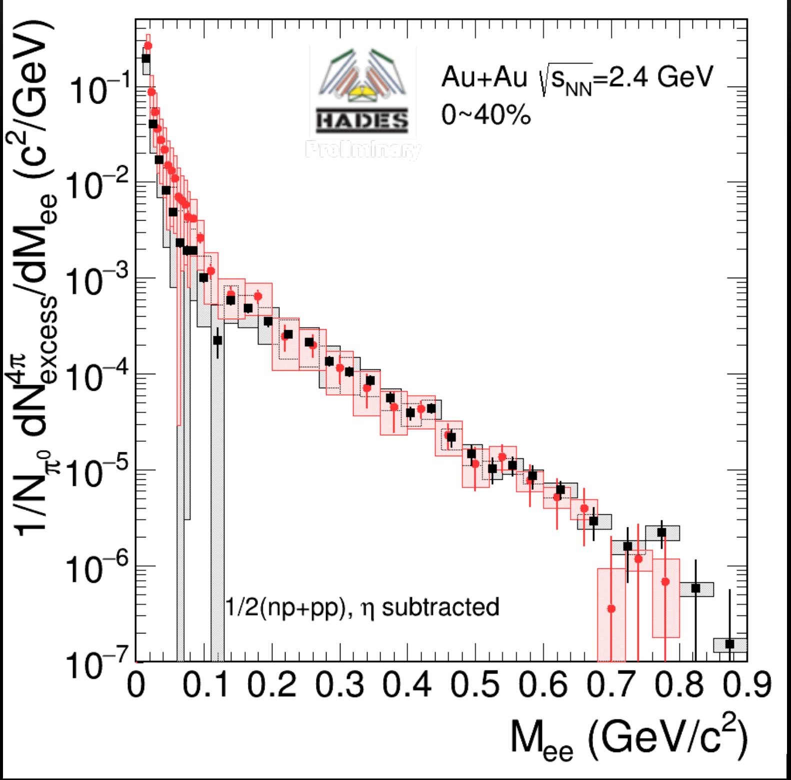
Highly interesting results from

LHC, RHIC BES, SPS, SIS18

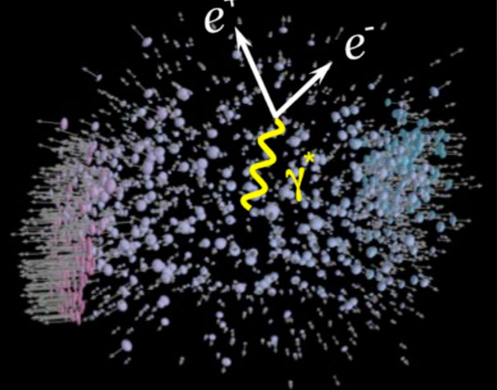
→ Lepton pairs as true messengers of the dense phase

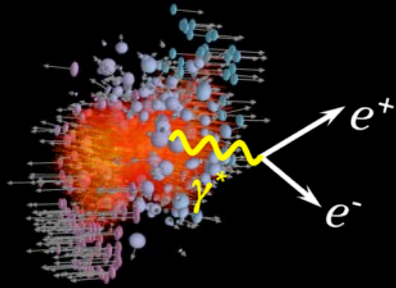
μ_B

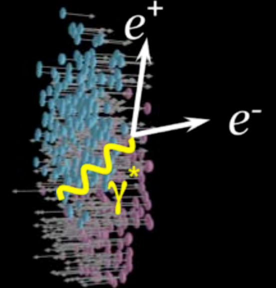
Just few steps ;)



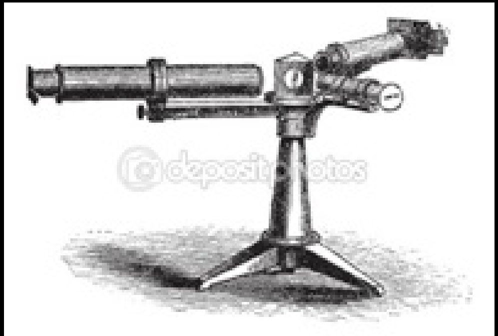
Tracking
↓
Electron identification
↓
π^0 and γ conversion rejection
↓
Pairing
↓
Subtraction of background
(like-sign or event mixing)
↓
Efficiency correction
↓
Isolation of excess radiation
↓
Acceptance correction



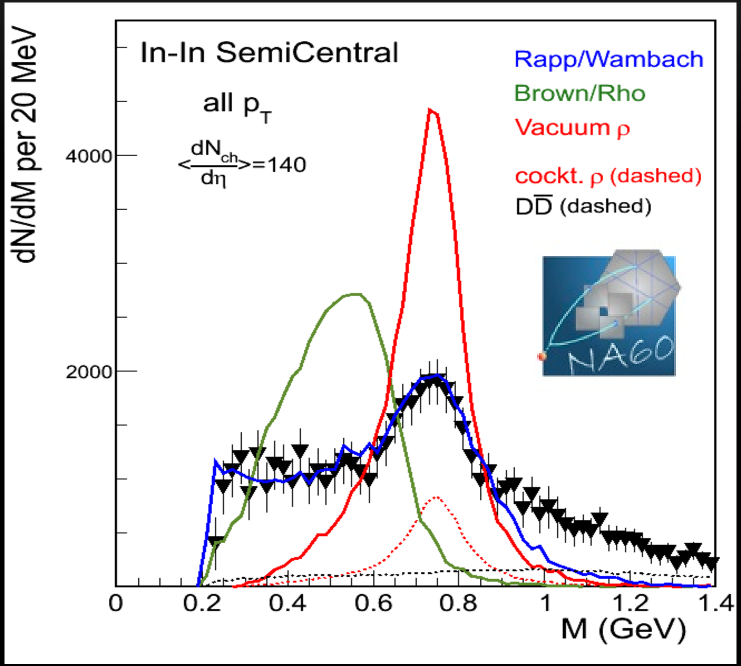




Dileptons as spectrometer



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



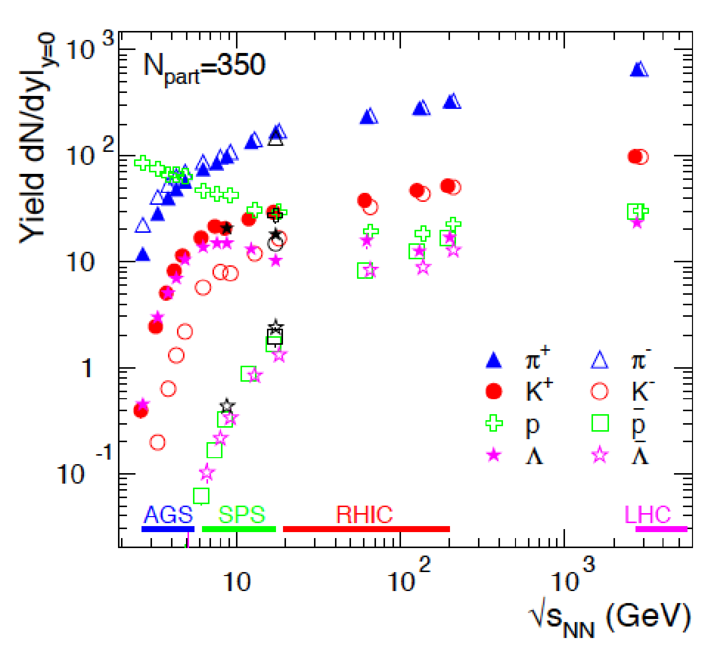
Data: Phys. Rev. Lett. 96 (2006) 162302
Calculations: R.Rapp and H. van Hees, 2008

NA60:

- Disfavors "dropping mass" scenario
- Strongly supports in-medium broadening

From SPS to RHIC

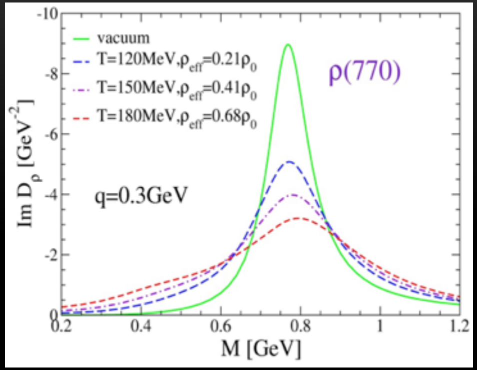
	SPS (Pb+Pb)	RHIC (Au+Au)
$dN(\bar{p})/dy$	6.2	20.1
produced baryons (p, $\bar{p}$, n, $\bar{n}$)	24.8	80.4
$p - \bar{p}$	33.5	8.6
particpating nucleons $(p - \bar{p})A/Z$	85	21.4
total baryon number	110	102

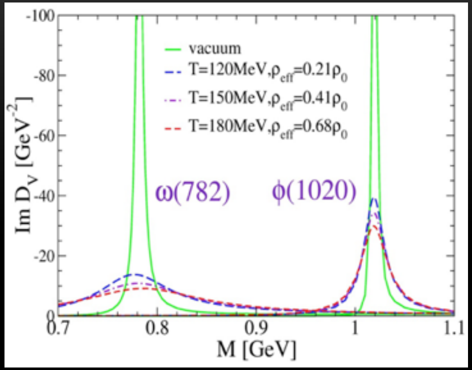


A. Andronic, arXiv:1407.5003

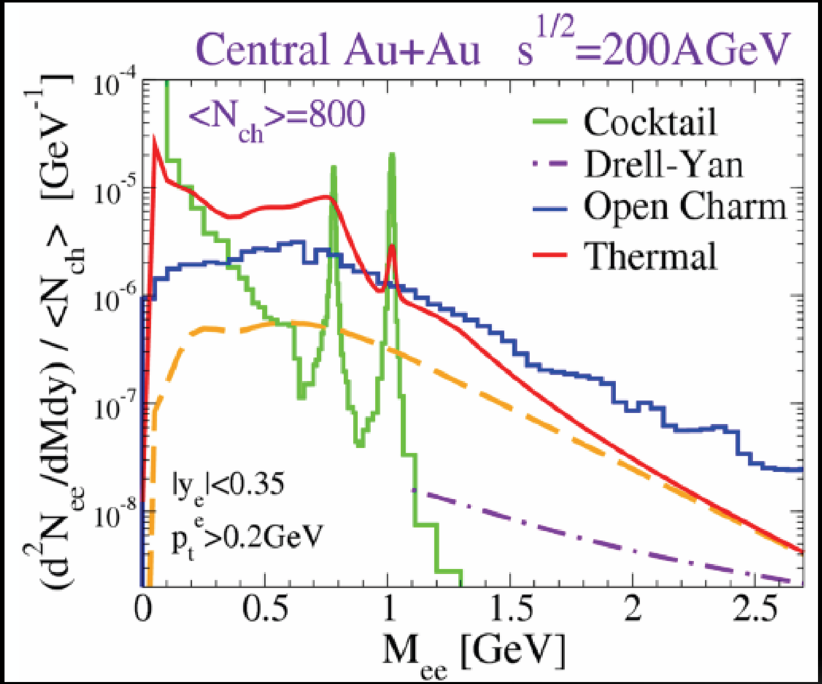
- Although the NET baryon density is different at SPS and RHIC, baryon density is practically the same!
- Baryon effects important even at $\rho_{B,tot} = 0$: sensitive to $\rho_{Btot} = \rho_B + \rho_{\bar{B}}$ (ρ-N and ρ-$\bar{N}$ interactions identical)
- Higher initial temperature at RHIC

Predictions for RHIC





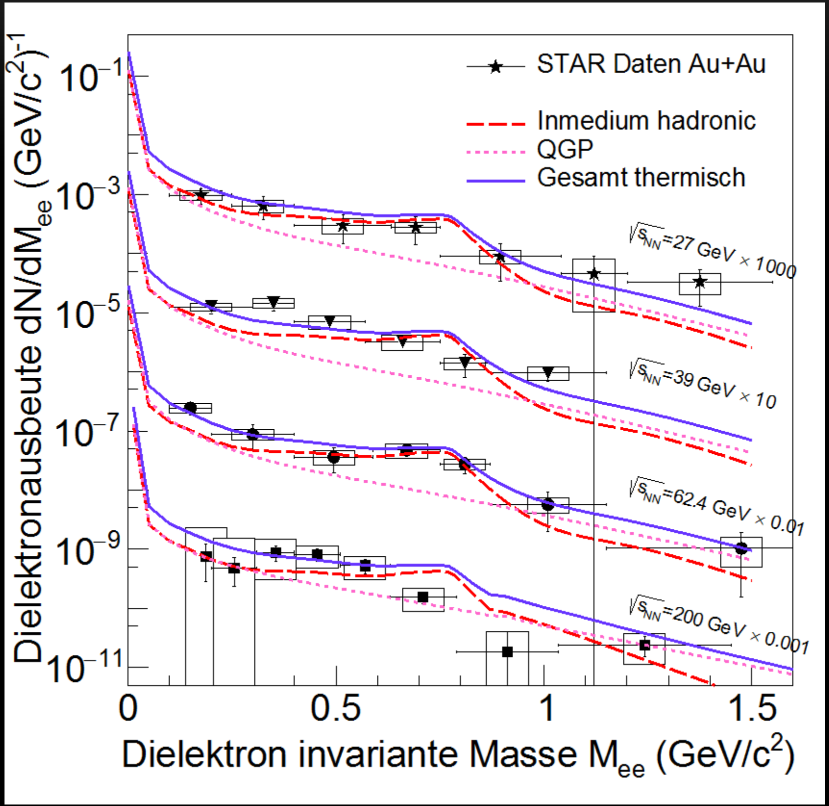
In-medium modifications of vector mesons persists (R. Rapp)



Open charm contribution becomes significant

Dielectron mass spectra from STAR BES I

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

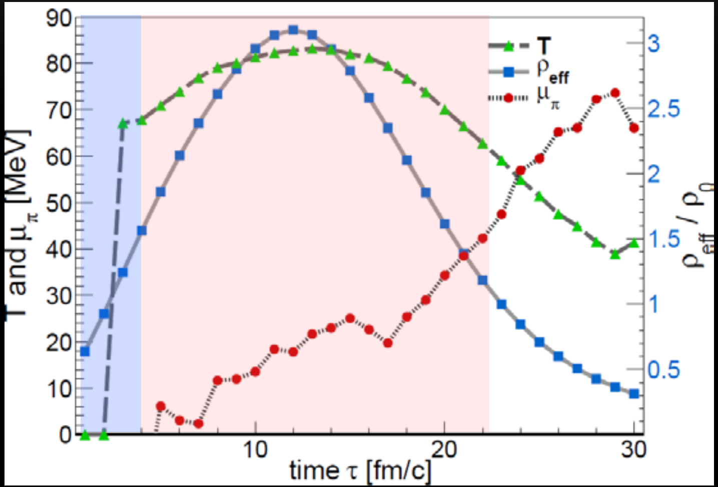


Phys.Lett. B750 (2015) 64-71
J. Butterworth et al., arXiv:1612.05484 [nucl-ex]
Model: Rapp/Wambach/Hees

- 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

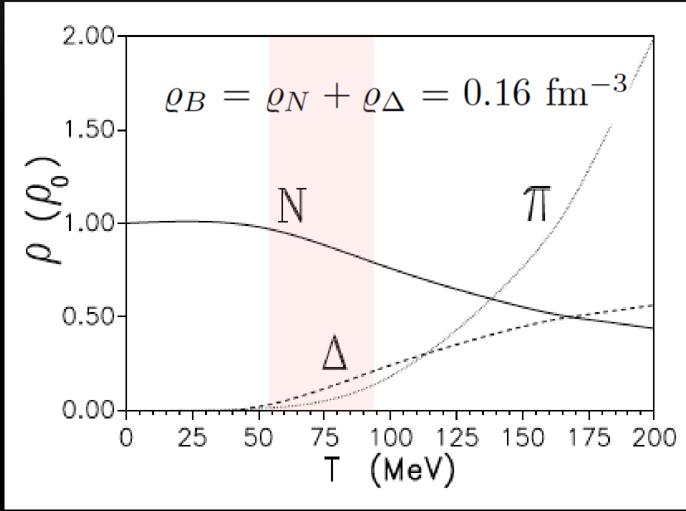
Baryonic matter at few GeV beam energy *Au+Au $\sqrt{s_{NN}}$ = 2.42 GeV*

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



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

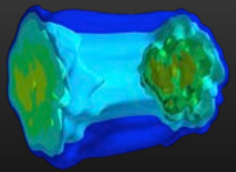
Composition of a hot πΔN gas

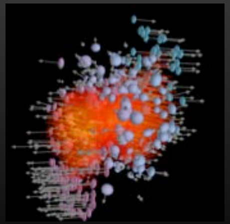


Rapp, Wambach, Adv. Nucl. Phys. 25 (2000)

- 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%)

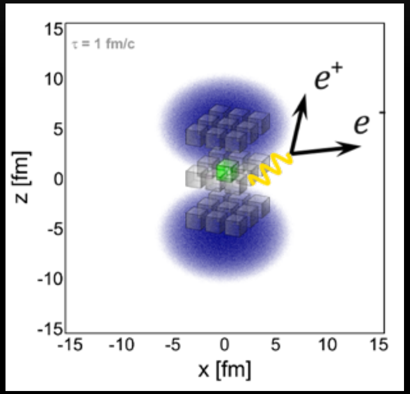
Coarse-grained transport approach





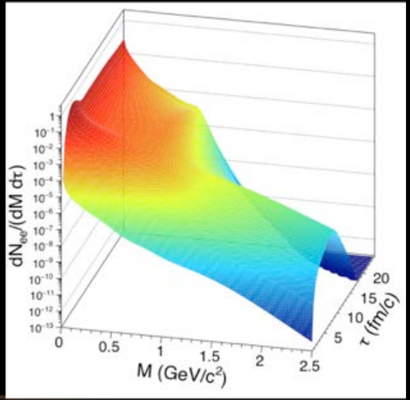
- "Combine" the advantages of two descriptions: hydrodynamics & transport
- Simulate events with a transport model

  → ensemble average to obtain smooth space-time distributions



- Divide space-time evolution into 4-dimensional cells

  21 x 21 x 21 space cells (1fm³), 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

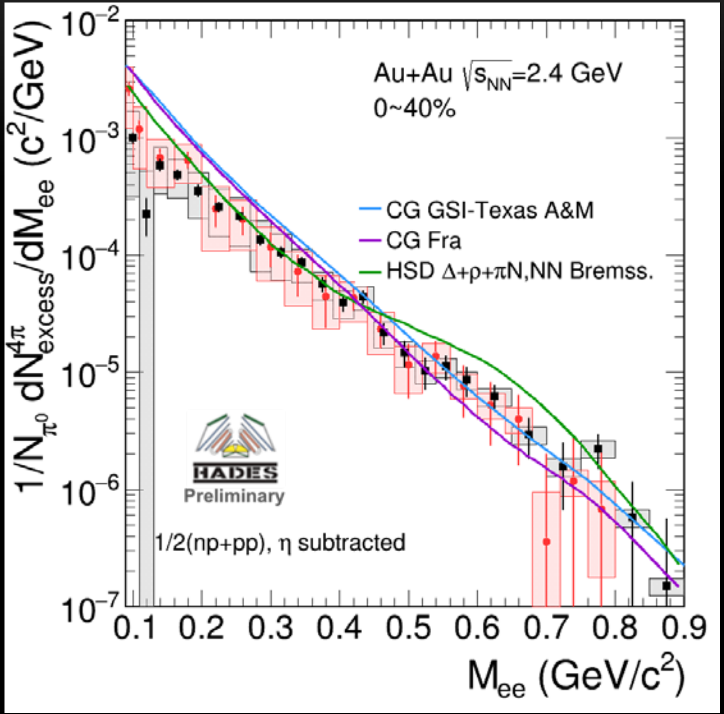
  → parameterization of RW in-medium spectral function
- Sum up contributions of all cells

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

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



HADES., collaboration review

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

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

$h = N, \pi, K$

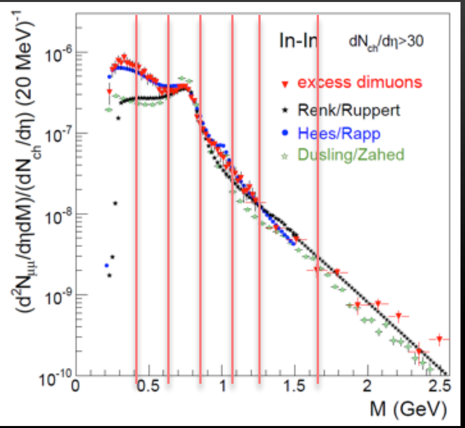
- Thermal rates folded over coarse-grained UrQMD medium evolution works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!

Robust understanding across QCD phase diagram

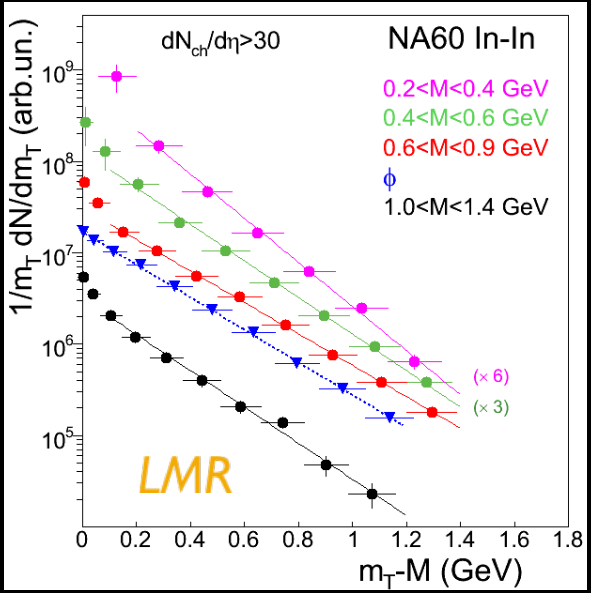
Dileptons as barometer

Transverse mass distributions of excess

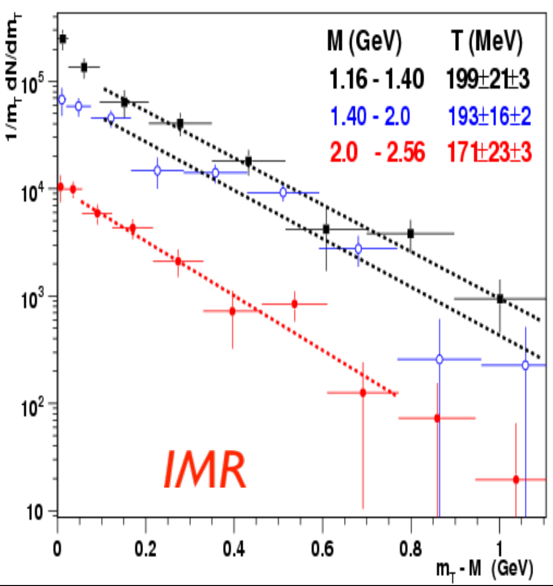
- For each bin of $\mu^+\mu^-$ project transverse mass spectrum: $m_T = (p_T^2 + M^2)^{1/2}$



Phys. Rev. Lett. 100 (2008) 022302

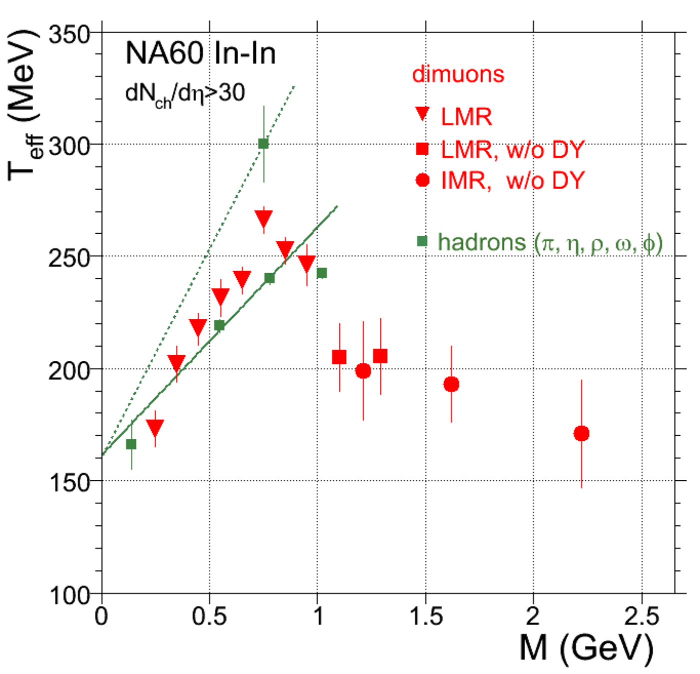


Eur. Phys. J. C 59 (2009) 607



- m_T spectra exponential for m_T-M > 0.1 GeV; <0.1 GeV ??
- Fit with $1/m_T\ dN/m_T \sim exp(-m_T/T_{eff})$
- Extract T_{eff} and create a Nu Xu plot

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



Phys. Rev. Lett. 100 (2008) 022302

- M < 1 GeV/c2
  - Strong, almost linear rise of T_{eff} with dimuon mass
  - Follows trend set by hadrons
- M > 1 GeV/c2
  - 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

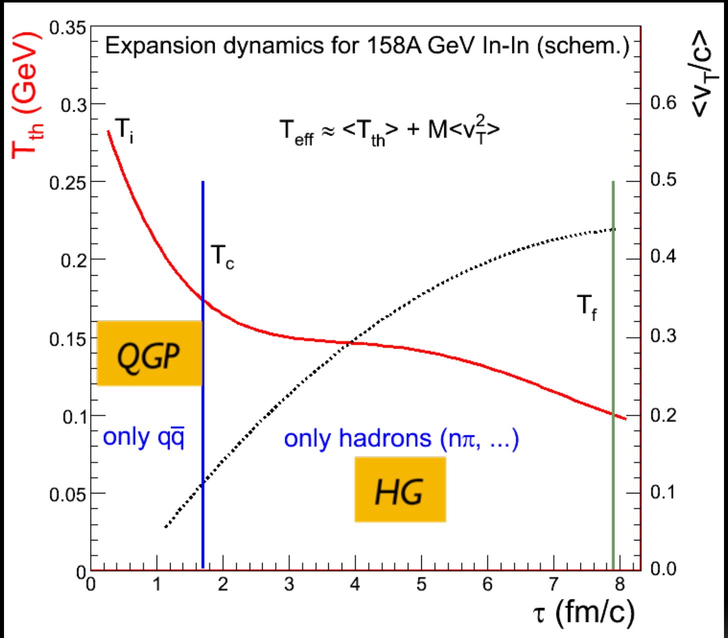
Interpretation of the dilepton m_T (p_T) spectra

T - dependence of thermal distribution of "mother" hadrons/partons

m - dependent collective radial flow (v_T) of "mother" hadrons/partons

(p_T - dependence of spectral function; dispersion relation)

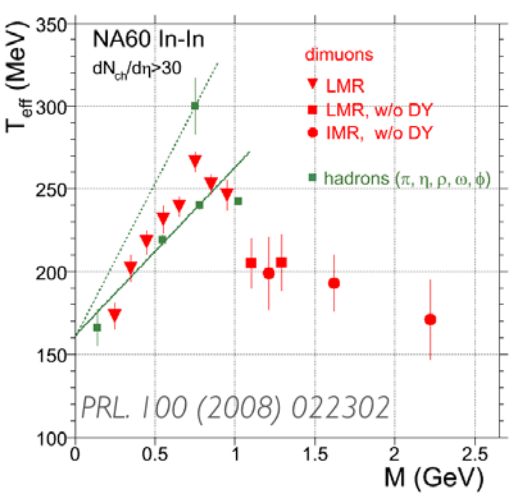
$p_T = p_T^{th} + m\, v_T \quad \rightarrow \quad T_{eff} \sim T_f + ½\, m <v_T>^2$



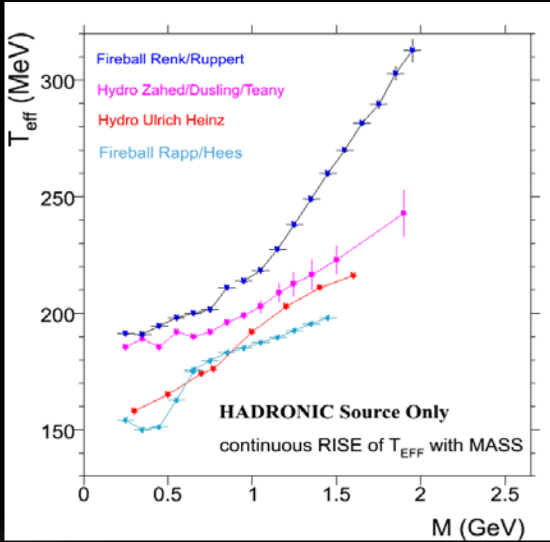
- Hadron p_T spectra: determined at T_{final} (restricted information)
- Dilepton p_T spectra: superposition from all fireball stages
  - early emission → high T, low v_T
  - late emission → low T, high v_T
- Final spectra from space-time folding over T-v_T history from $T_{initial} \rightarrow T_{final}$
  note: small flow in the QGP phase

→ **Handle on emission region, i.e. nature of emitting source**

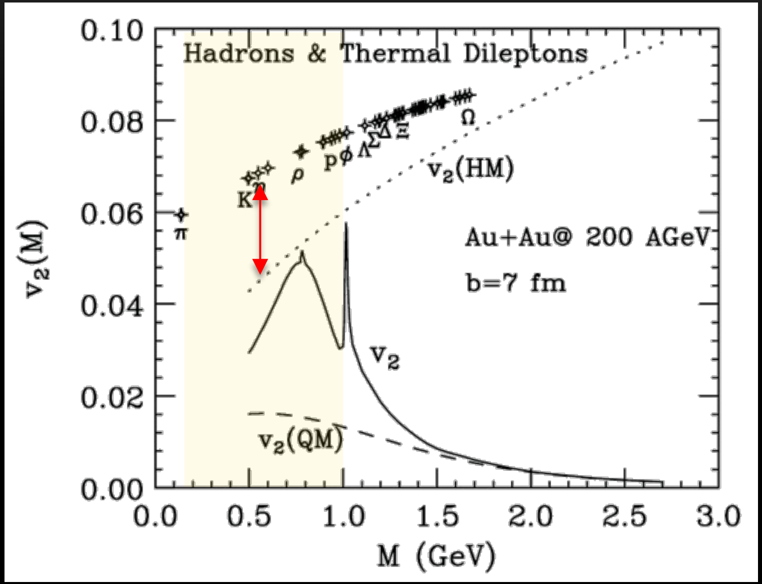
Quantifying the average temparatures $<T_{th}>$



- $M < 1$ GeV/c^2
  - extrapolate T_{eff} to M=0 (zero flow)
  - $<T_{th}>=130 - 140 < T_c=170$ (MeV)
  - → *hadronic phase*
- $M > 1$ GeV/c^2
  - T_{eff} independent of mass, negligible flow
  - $<T_{th}>$ ~200 MeV $> T_c=170$ (MeV)
  - → *partonic phase* ($T_{initial}$ ~250 MeV)
- Dominance of partons for M>1GeV/c^2: support from theory:
  - → Hadronic sources alone ($2\pi+4\pi+a1\pi$) cannot produce a discontinuity
  - → Continuous rise of T_{eff} with mass



Azimuthal anisotropy of virtual photons



R. Chatterjee et al., PRC 75 (2007), 054909

- Very cleans tool to diagnose the collective expansion dynamics, i.e. origin of the electromagnetic emission source
- v_2 vs T_{eff} : T_{eff} is superposition of T and v_T
- M < 1 GeV/c^2: v_2 is large → late emissions → hadronic matter
- M > 1 GeV/c^2: v_2 is small → early emission → partonic matter

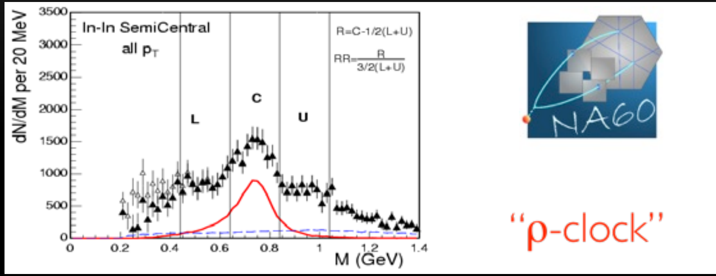
So far:

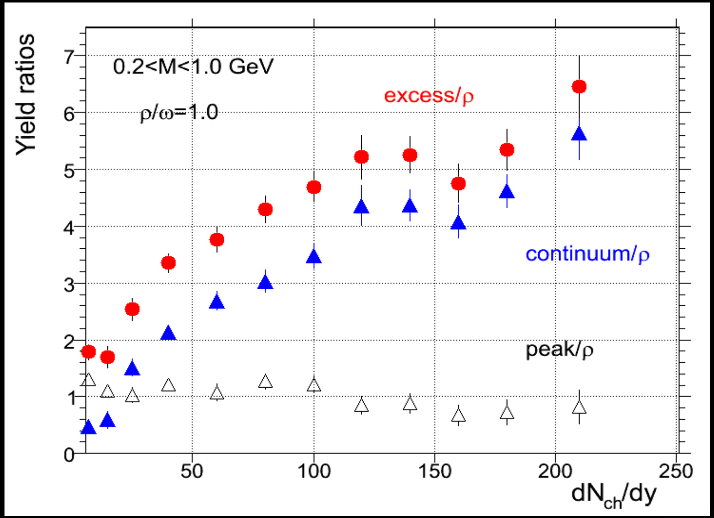
- STAR v_2 of inclusive e^+e^- (not of excess e^+e^-)
- HADES v_2 of excess radiation (coming soon)

Dileptons as chronometer

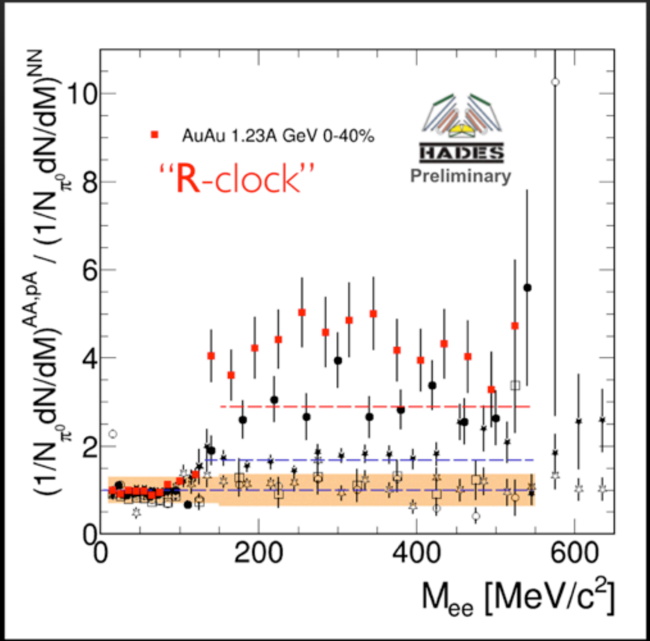
The dilepton clock

Centrality dependence of spectral shape





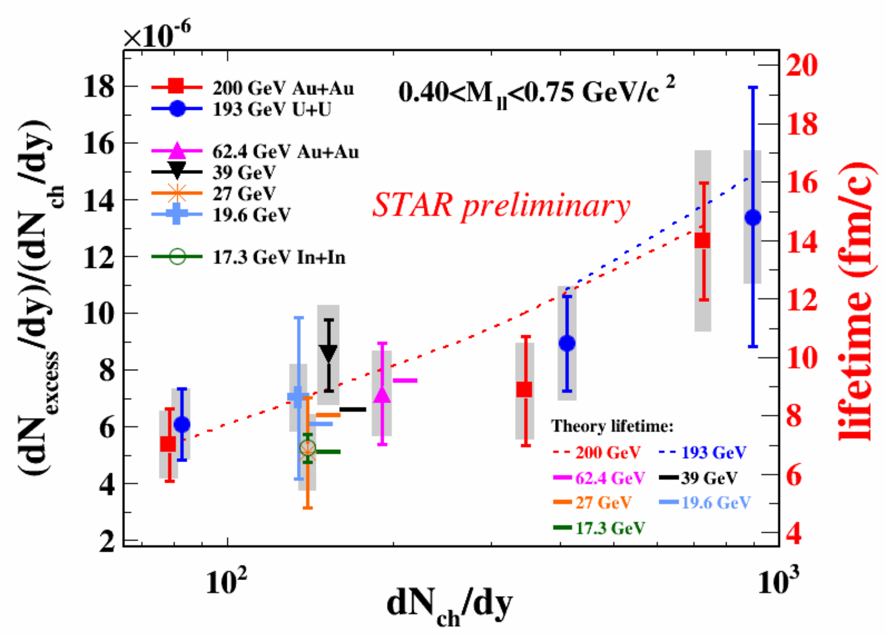
System size dependence of excess



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

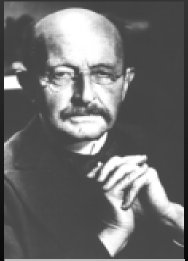
U.W. Heinz and K. S. Lee, PLB 259, 162 (1991)
H.W. Barz, B. L. Friman, J. Knoll and H. Schulz, PLB 254, 315 (1991)

The lifetime of the interacting fireball



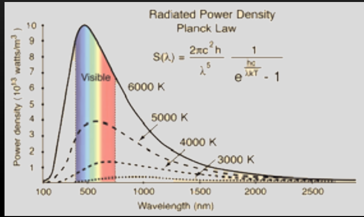
- Normalized excess yields for the mass region $0.3<M<0.7$ GeV/c^2 is proportional to the lifetime of the interacting fireball
- Note: normalization to the number of pions should be done when going down with energy!

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

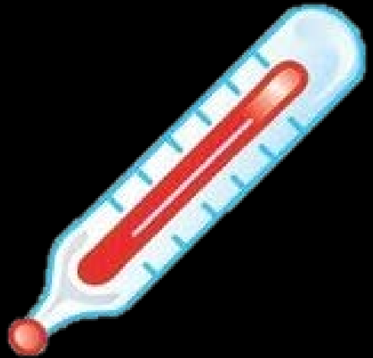


$$E = \hbar \nu = \frac{\hbar c}{\lambda}$$

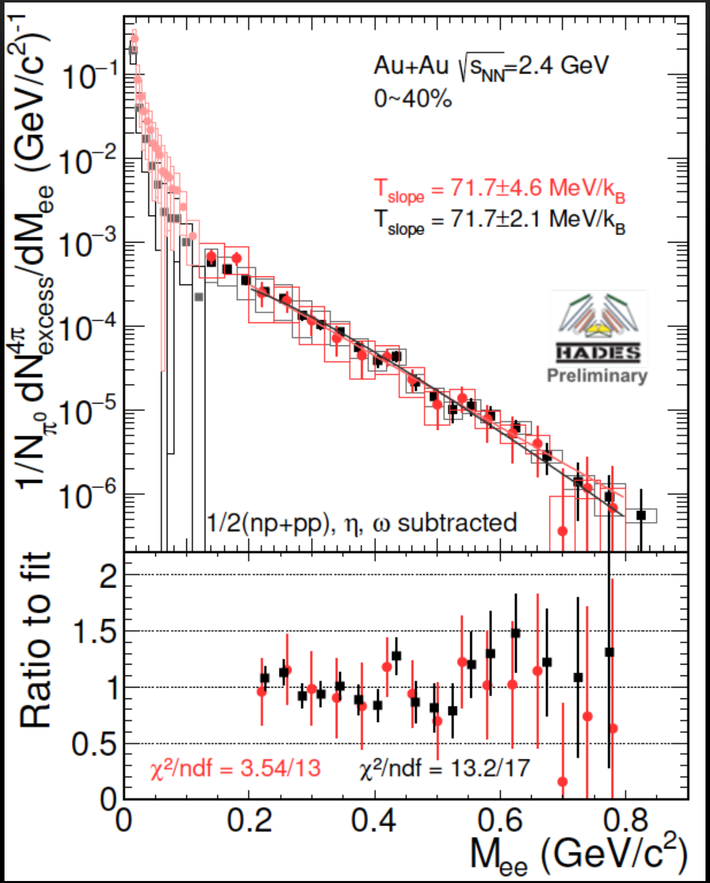
Spectral shape of the light →
temperature of the emitting object



Dileptons as thermometer



Virtual photon emission – fireball thermometer at SIS18



- Acceptance corrected excess yield
- M_{ee}<1 GeVc^2 ~ exponential fall-off - 'Planck-like'

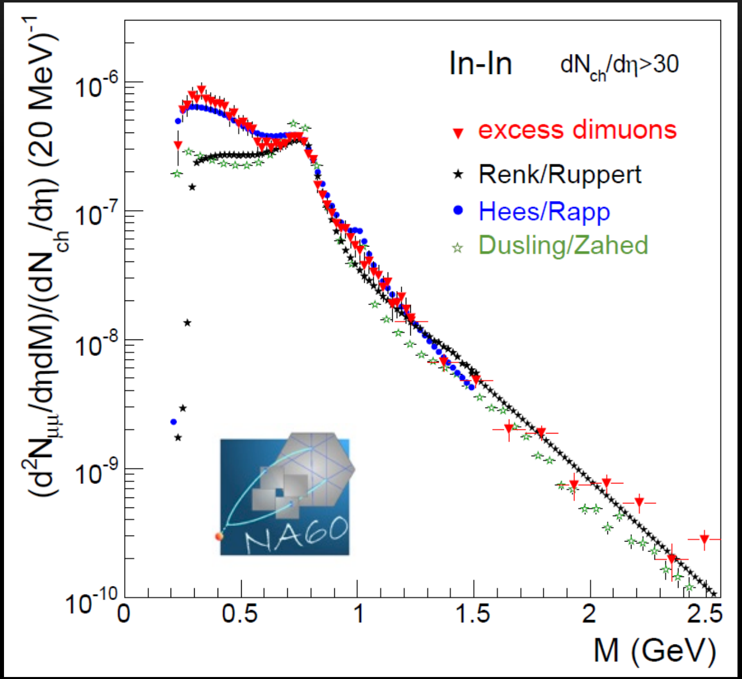
→ measurement of radiating source temperature

→ fit $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$ to range $M=0.1\text{-}0.8$ GeV/c^2

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

HADES., collaboration review

Measurement of radiating source temperature at SPS



- 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

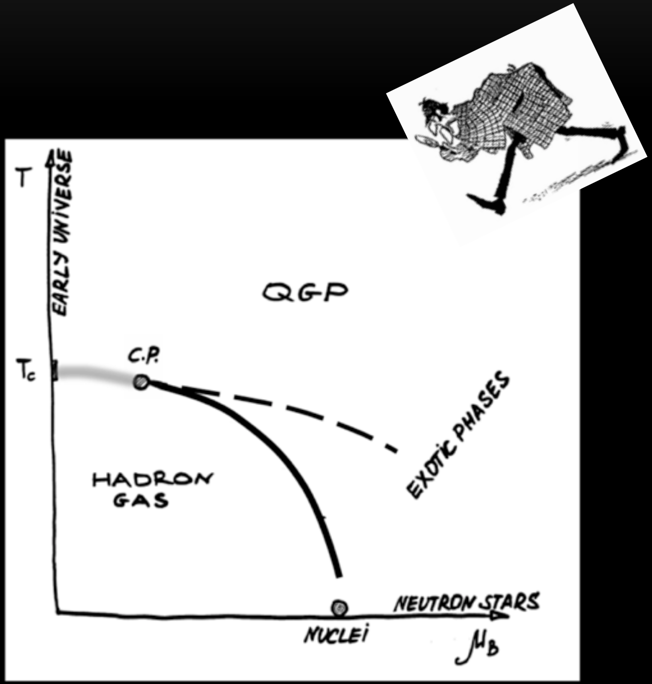
→ $M=1.1\text{-}2.0$ GeV/c^2: $\langle T\rangle_{\text{emitting source}} = 205 \pm 12$ MeV/k_B

→ $M=1.1\text{-}2.4$ GeV/c^2: $\langle T\rangle_{\text{emitting source}} = 230 \pm 10$ 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 is the only Lorenz-invariant thermometer of the field

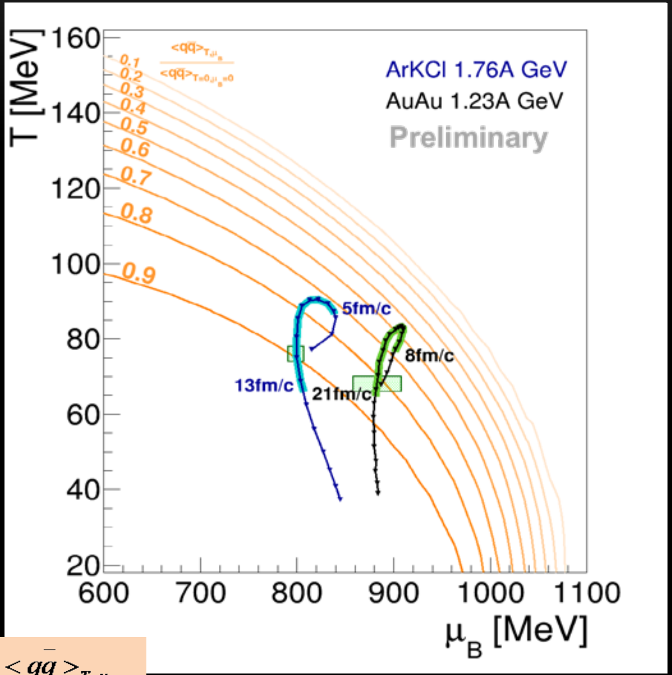
Dileptons and QCD phase diagram of matter



Excitation functions

- Fireball lifetime
- Emitting source temperature

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

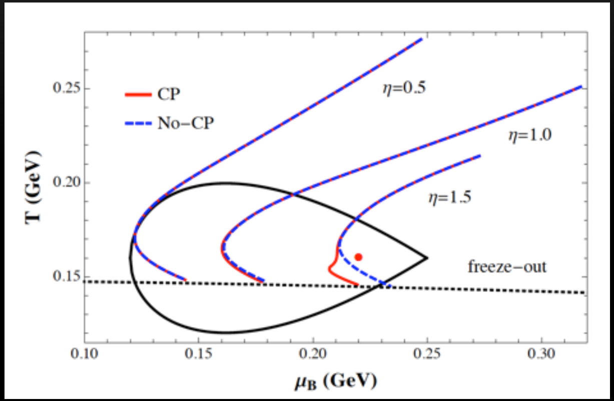
T_{max} = 85 MeV, $\rho_{max} = 3\ \rho_0$

→ Excitation of the vacuum (melting of condensate) matches spectral medium effects!

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

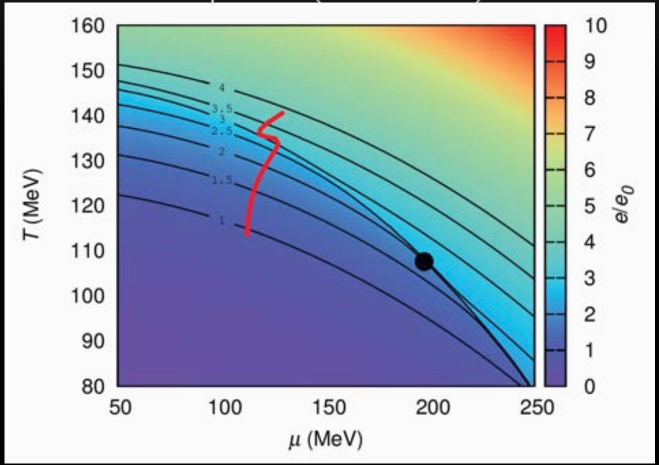
Mapping QCD phase diagram with dileptons

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)

Diverging bulk viscosity at QCD critical point

$$\zeta \sim \tau_\Pi \sim \tau_\sigma \sim \xi^3$$

Bulk viscosity

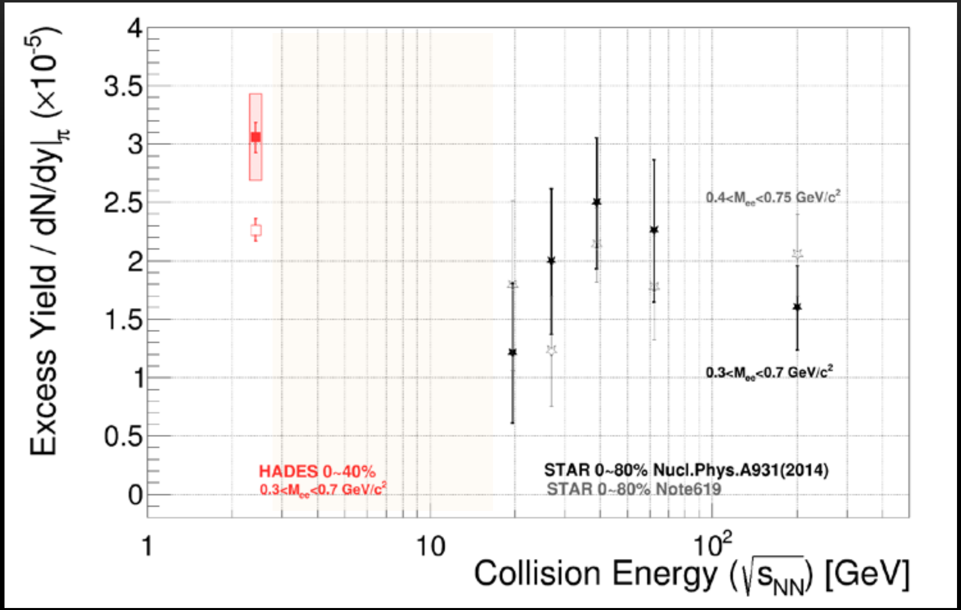
Bulk relaxation time

Relaxation time for the critical mode

Correlation length^3

What are the possible signatures in dilepton radiation?

Energy dependence of low-mass excess



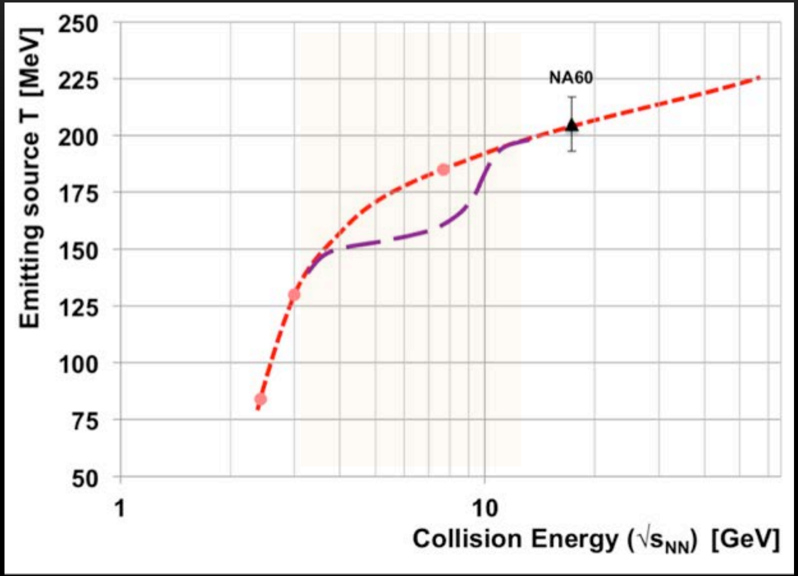
- ❑ Yield in low-mass window tracks fireball lifetime

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

  - 2019 - STAR at RHIC BES II
  - 2024 - CBM at FAIR

- ❑ Quite moderate energy dependence
- ❑ Dilepton yield determined by interplay between temperature and V ⊗ τ_{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
- 2024 - CBM at FAIR

Connection to the fundamental properties of the QCD → Chiral symmetry

Weinberg Sum Rules…

Weinberg '67, Das et al '67

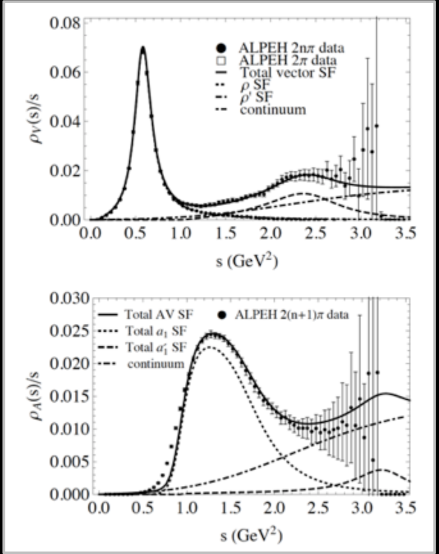
$$\int \frac{ds}{\pi} \frac{1}{s} (\rho_V - \rho_A) = f_\pi^2$$

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

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

…valid in vacuum

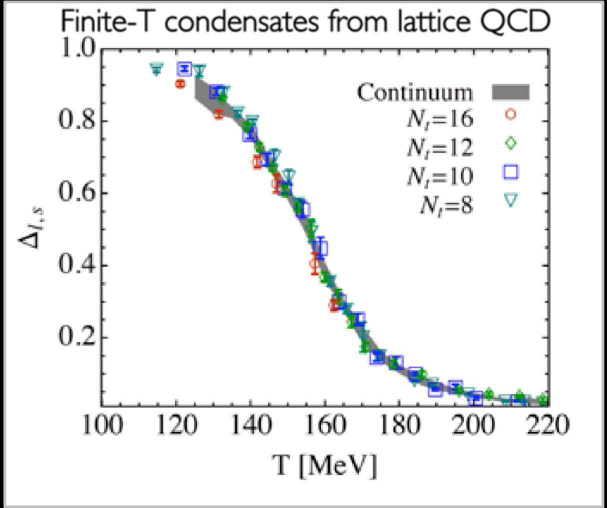
Rapp et al, Annals Phys. 368 (2016)



ρ-a$_1$ mass splitting due to χ_s breaking (~f_π, $<\bar{q}q>$)

… remain valid in medium

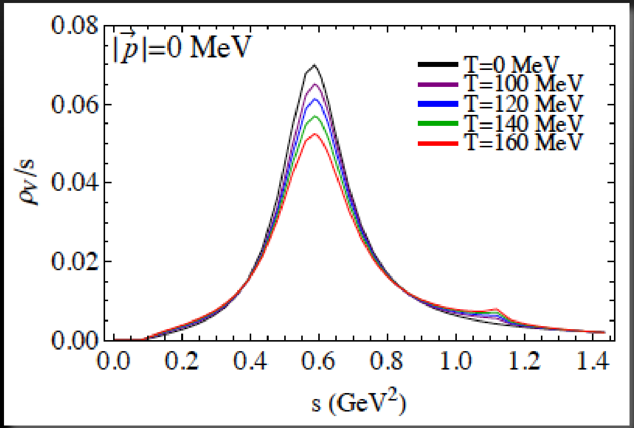
J. Kapusta, E. Suryak '94

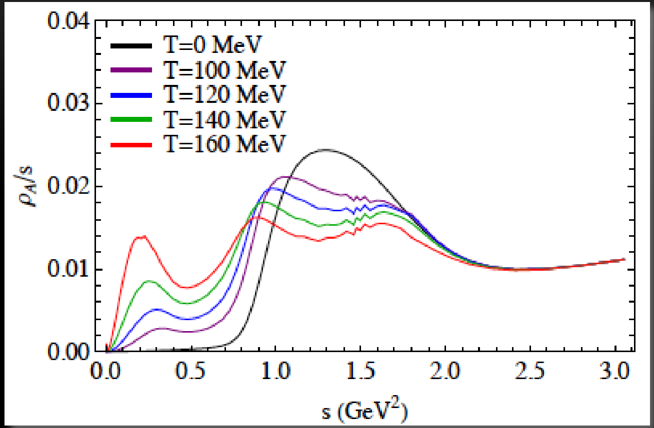


S. Borsanyi et al., JHEP 1009 (2010) 073

ρ-a$_1$ mass degeneracy
→ Test in-medium ρ spectral function

ρ-a$_1$ spectral functions and chiral symmetry





- Vector and axial-vector spectral functions in a pion gas
- No baryon effects accounted for yet

P. Hohler, R.Rapp, arXiv:1510.00454v1 [hep-ph] 2 Oct 2015

- 4π processes: $\pi a_1 \rightarrow \gamma^* \rightarrow l^+l^-$ (chiral mixing) is a dominant hadronic source in IMR
  - No correlated charm contribution!
  - No Drell-Yan!
  - No QGP!?
- Results in elementary collisions provide an important baseline for future explorations in HIC
  → HADES: high statistic π+p and π+A in 2018

“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 ?*

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**

Thank you
for your attention!