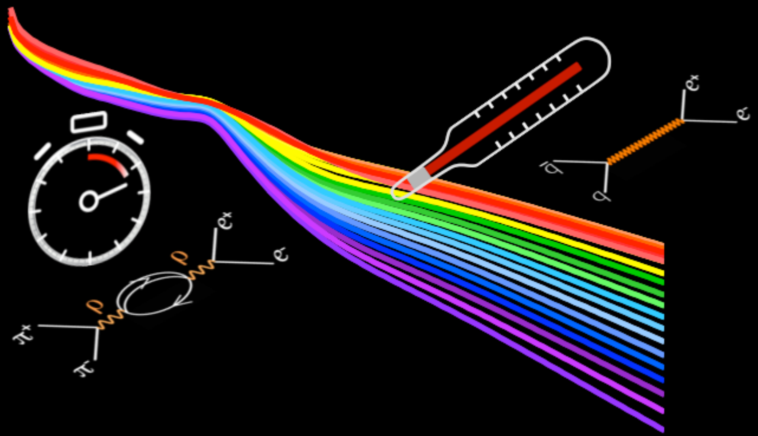
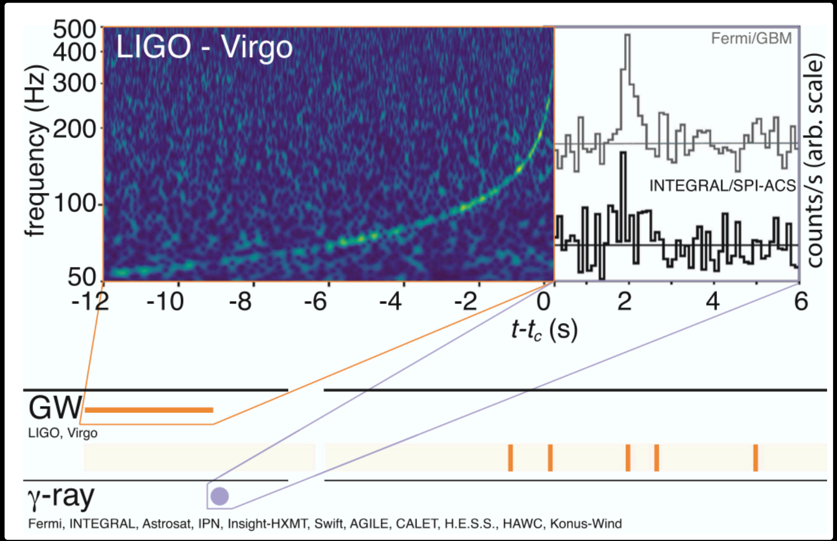
Dilepton measurements



Tetyana Galatyuk

GSI / Technische Universität Darmstadt

MULTI-MESSENGER SIGNALS FROM NEUTRON STAR MERGER

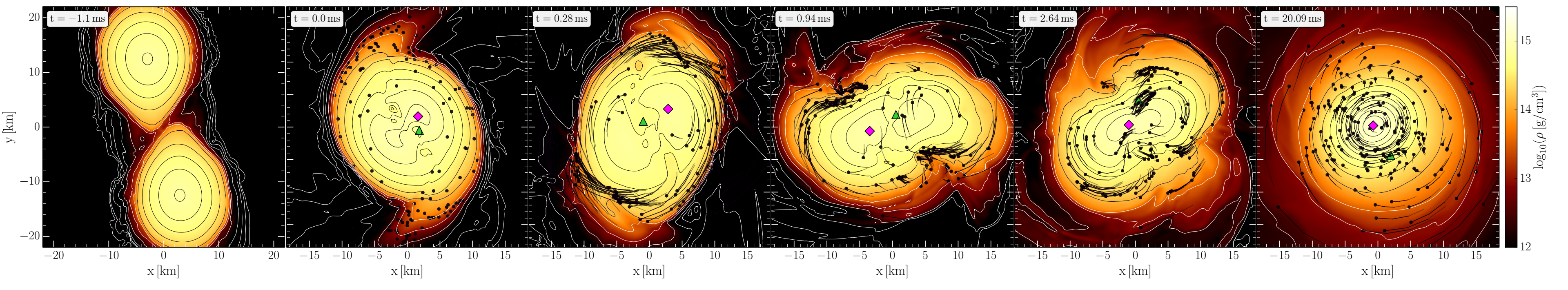


- GW170817 17 Aug 2017 12:41:04 UTC
  First detection of a binary neutron start mergers through gravitational waves
  LIGO + VIRGO, PRL 119 (2017) 1611001

- GRB 170817A ~1,7 s later
  Observation of the same event through electromagnetic waves (gamma-ray burst)
  Fermi GBM + INTEGRAL + LIGO + Virgo, Astrophys.J.Lett. 848 (2017)

ASTROPHYSICAL COLLIDER

$1.35{+}1.35 M_\odot \quad \emptyset = 10\ km \quad \tau{\sim}20\ ms \quad \rho{\sim}2-3\rho_0 \quad T < 70\ MeV$



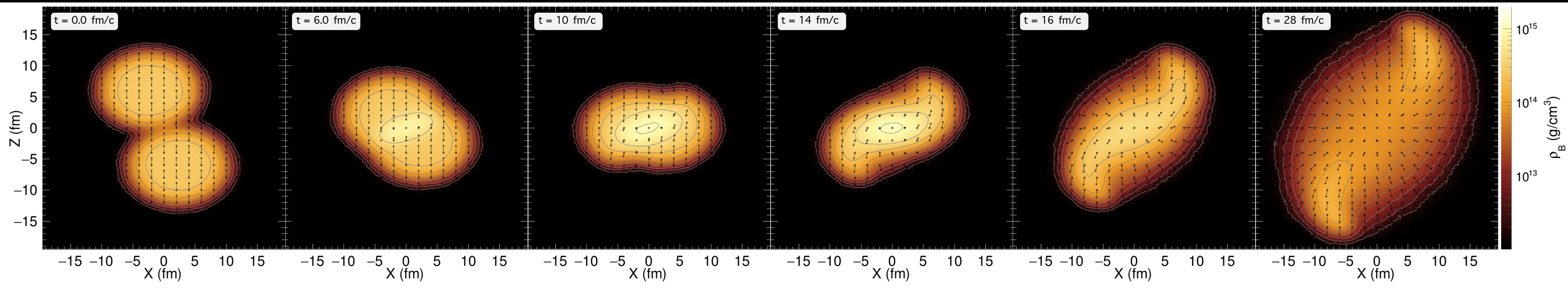
M. Hanauske, Journal of Phys.: Conf. Series 878 (2017) 012031
L. Rezzolla et al., Phys. Rev. Lett. 122, no. 6, 061101 (2019)

- Violent Universe can now be
  - heard through gravitational waves
  - seen through electromagnetic radiation

What laboratory experiments can tell us about extreme environments in the Universe?

LABORATORY STUDIES OF THE MATTER PROPERTIES IN COMPACT STELLAR OBJECTS

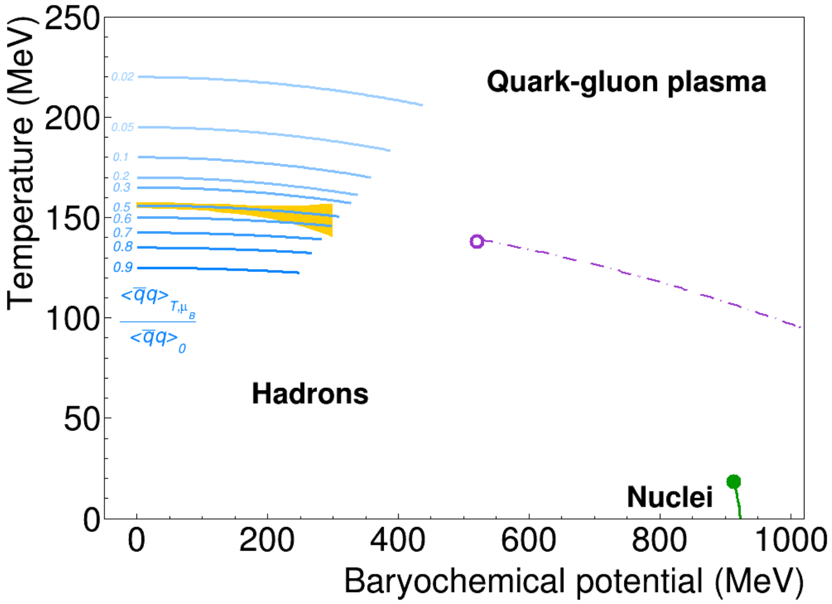
Au+Au $\sqrt{s_{NN}} = 2\ GeV$ $\quad \emptyset = 16\ fm$ $\quad \tau \sim 10^{-23} s$ $\quad \rho \sim 2 - 3\rho_0$ $\quad T < 70\ MeV$



time ~ 10^{-23} s

- Collision of heavy-ions at (ultra-)relativistic energies:
  - produce and investigate transient states of QCD matter under extreme conditions of temperature and density
  - unique role played by electromagnetic radiation

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM

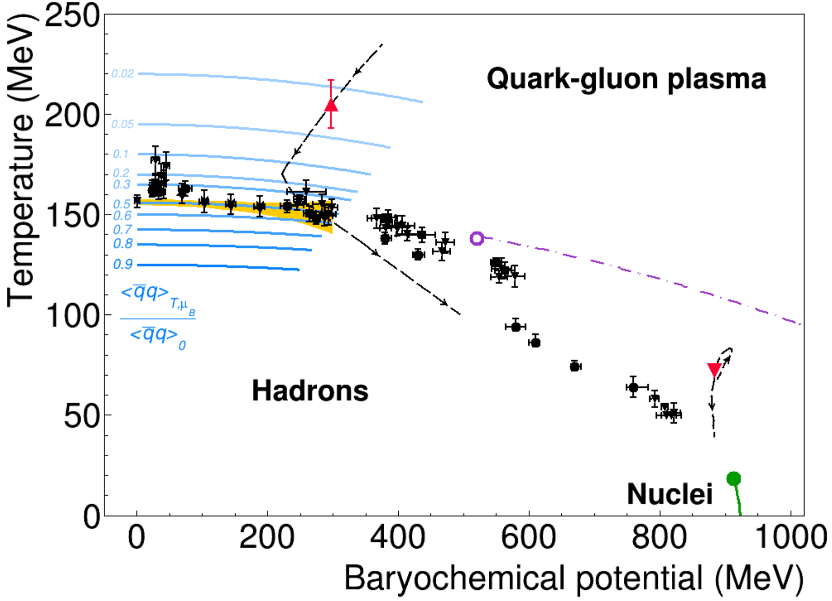


- ☐ **Vanishing μ_B, high T (lattice QCD)**
  - ☐ Crossover
  - ☐ No critical point indicated by lattice QCD at μ_B < 400 MeV, T >140 MeV (for physical quark masses)
- ☐ **Large μ_B moderate T (lQCD inspired models)**
  - ☐ Limits of hadronic existence?
  - ☐ 1st order transition?
  - ☐ QCD critical point?
  - ☐ Equation-of-State of dense matter?

High μ_B region – large discovery potential!

LQCD: A. Bazavov et al., Phys.Lett.B 795 (2019) 15-21
LQCD: S. Borsanyi et al. [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
O. Philipsen, Lattice 2019, 1912.04827 [hep-lat]

SEARCHING FOR LANDMARKS OF THE QCD MATTER PHASE DIAGRAM

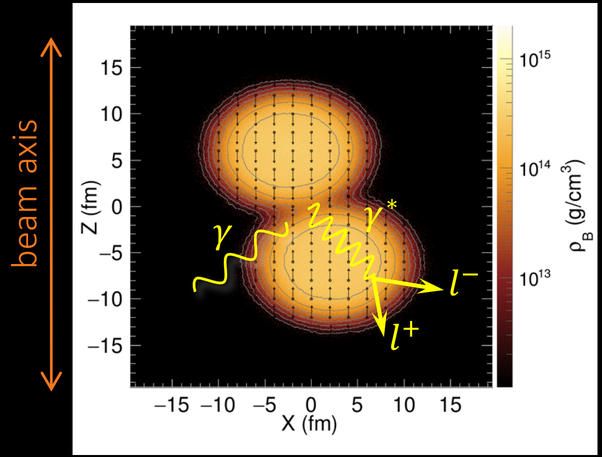


HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045
A. Andronic et al., Nature 561 (2018) no.7723

- **Experimental challenge:**
  - Locate the onset of QGP
  - Detect the conjectured QCD critical point
  - Probe microscopic matter properties
- **Measure with utmost precision:**
  - Flavour production (multi-strange, charm)
  - E-b-e correlations and fluctuations
  - **Dileptons (emissivity of matter)**

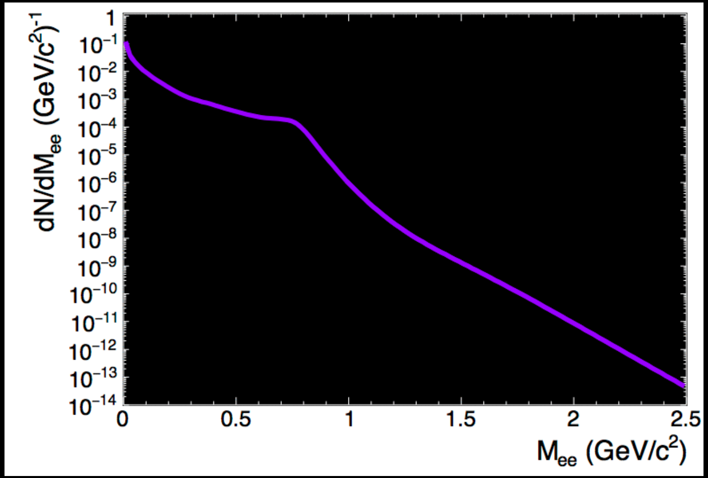
Almost unexplored (not accessible) so far in the high μ_B region

SHINE A LIGHT! *When matter shatters*



- Electromagnetic radiation (γ, γ^*)
  - Penetrating probe
    ⤳ mean free path length ≫ size of the fireball
  - Reflect the whole history of a collision
  - No strong final state interaction
    ⤳ leave reaction volume undisturbed

- Encodes information on matter properties
  - Change in degrees of freedom
  - Restoration of chiral symmetry
  - Transport properties
  - Temperature, lifetime, acceleration, polarization



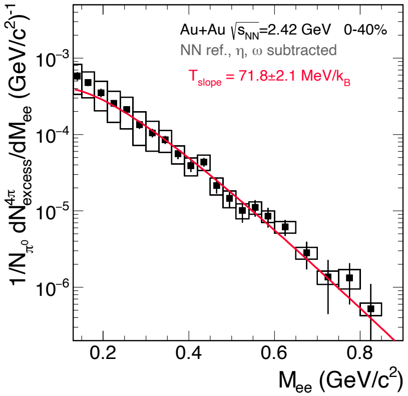
TAKE HOME MESSAGE

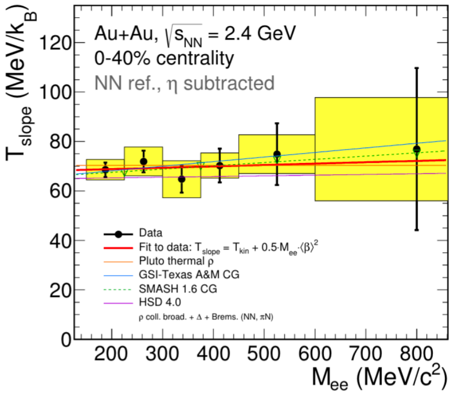
Dileptons carry invaluable information in terms of their four-momentum

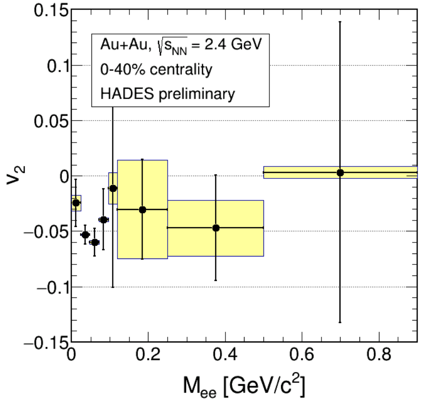
- **Spectrometer**
- **Chronometer**

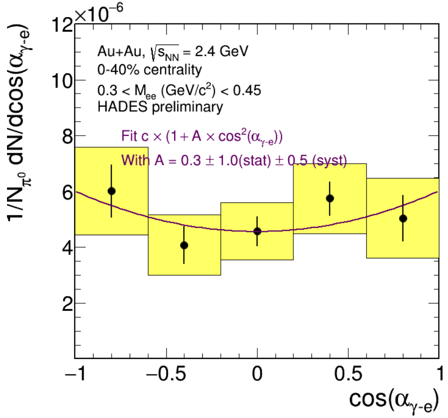
  $\int_{0.3\,GeV}^{0.7\,GeV} \frac{dN}{dM} \sim \tau$
- **Thermometer**

  $if\ \frac{Im\Pi^{\mu\nu}_{EM}}{M^2} \sim const.$
- **Barometer**
  - $T_{slope}\ vs.\ M$
  - $v_2\ vs.\ M$
- **Polarimeter**
  - γ^* polarization via lepton angular distribution









CG: $T = 65\ MeV;\ \langle\beta_{ee}\rangle = 0.19$
HSD: $T = 74\ MeV;\ \langle\beta_{ee}\rangle = 0.05$

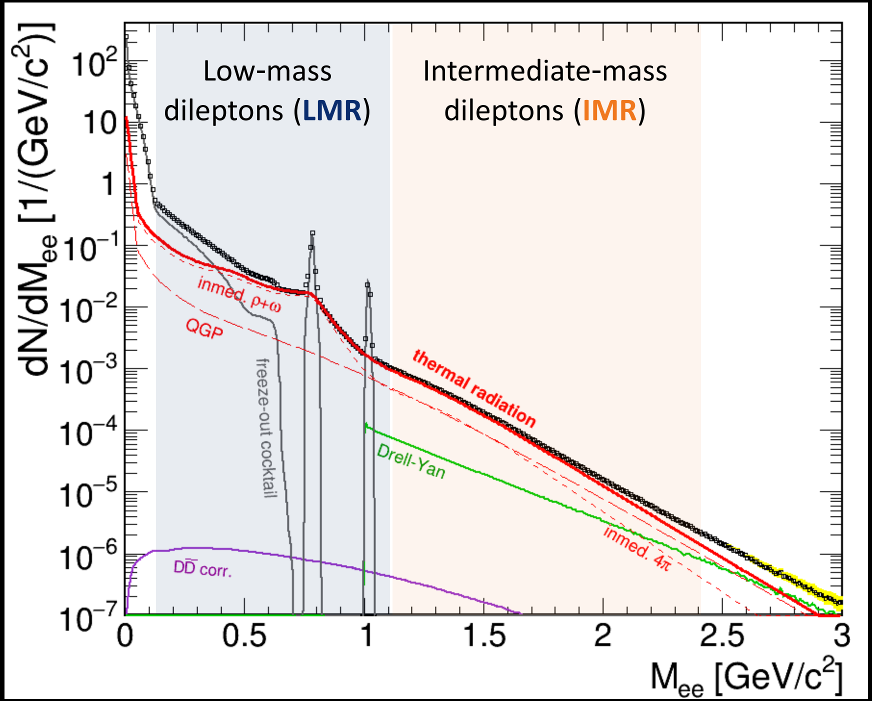
v_2 consistent with zero for $M_{ee} > 0.12\ MeV/c^2$

NA60 Collab., PRL 96 (2009) 222301
HADES Collab., PRC 84 (2011) 014902
E. Speranza et al., PLB 782 (2018)

HADES Collab., Nature Phys. 15 (2019) 10, 1040-1045

DILEPTON INVARIANT MASS SPECTRA

Characteristic features



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

- ‘Primodial’ $q\bar{q}$ annihilation (Drell-Yan):
  - $NN \to e^+e^-X$
- Thermal radiation from QGP and hadron gas:
  - $q\bar{q} \to e^+e^-, \;\; \pi^+\pi^- \to e^+e^-$
  - Short-lived states $\Delta, N^*, \ldots$
  - Multi-meson reactions (‘4π’): $\pi\rho, \pi\omega, \pi a_1, \ldots$
- Decays of long-lived mesons:
  - $\pi^0, \eta, \omega, \varphi$, correlated $D\bar{D}$ pairs, …

Necessary ingredients:
⤳ Realistic emission rates
⤳ Accurate description of fireball evolution

ELECTROMAGNETIC PRODUCTION RATE

EM current-current correlation function

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

Determines both photon and dilepton rates

- ☐ Photons characterized by “transverse” momentun:

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

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

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

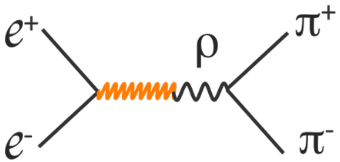
L.D. McLerran, T. Toimela, Phys.Rev. D31, 545 (1985)
H.A. Weldon, Phys.Rev. D42, 2384-2387 (1990)
C. Gale, J. Kapusta, Phys.Rev. C35, 2107 (1987) & Nucl.Phys. B357, 65-89 (1991)

EM CORRELATOR IN THE VACUUM

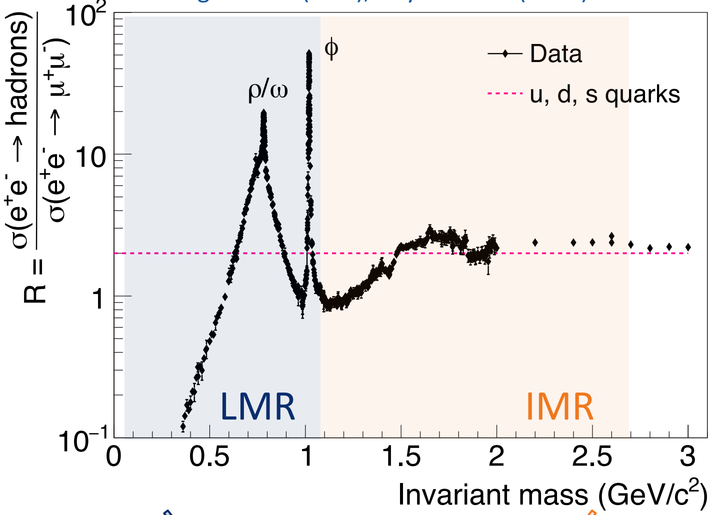
Accurately known from e^+e^-annihilation $R \propto \frac{Im\Pi_{em}^{vac}}{M^2}$

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)

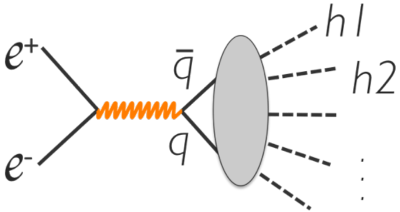


J. Beringer et al. (PDG), Phys. Rev. D (2012) 010001



Intermediate-mass regime

Perturbative QCD continuum (quark degrees of freedom)



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

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

J.J. Sakurai, Ann.Phys. 11 (1960)

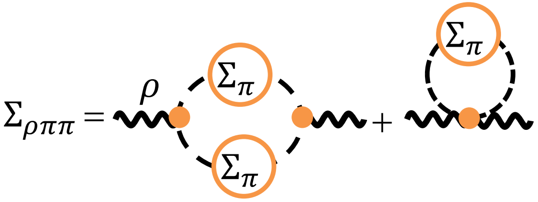
IN-MEDIUM SPECTRAL FUNCTIONS FROM HADRONIC MANY BODY THEORY

ρ meson in medium interacts with hadrons from heat bath

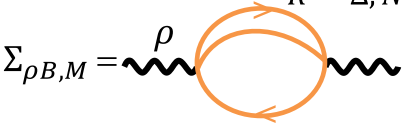
Additional contributions to the ρ-meson self-energy

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

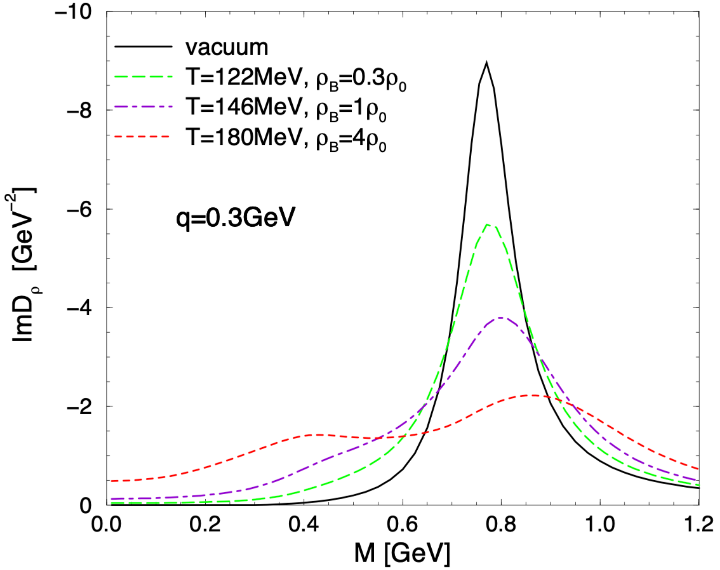
In-medium pion cloud



Direct ρ-hadron scattering



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



⇝ **ρ-peak undergoes a strong broadening**
⇝ **baryonic effects are crucial**

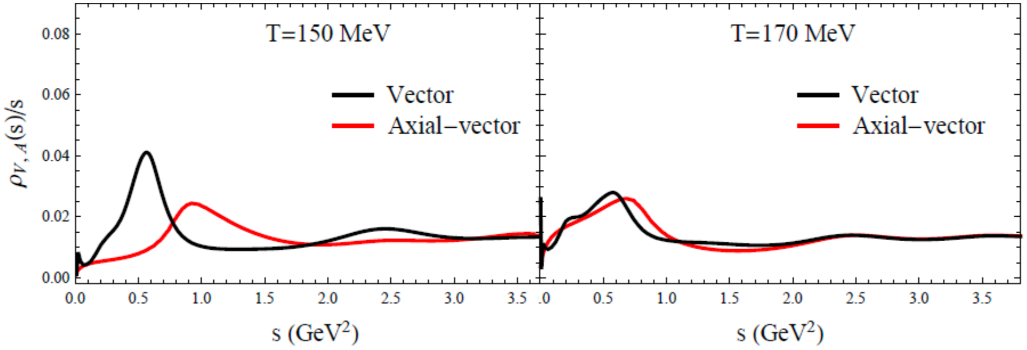
J. Alam et al., Annals Phys.286, 159 (2001)
S. Leupold, V. Metag, U. Mosel, Int.J.Mod.Phys. E19, 147 (2010)
R. Rapp, Acta Phys.Polon. B42, 2823-2852 (2011)

IN-MEDIUM EM SPECTRAL FUNCTIONS

Connection to chiral symmetry χ_c

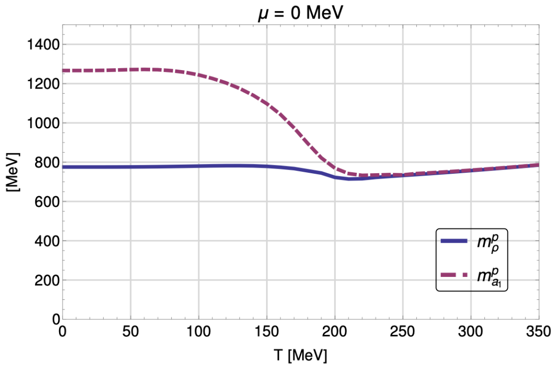
- Spontaneously broken in the vacuum
- Restoration of χ_c at finite T and μ_B manifests itself through mixing of vector and axialvector correlators
- ρ meson melts in hot/dense matter, a_1 mass decreases and degenerates with near ground-state mass

Chiral mass splitting "burns off", resonances melt



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

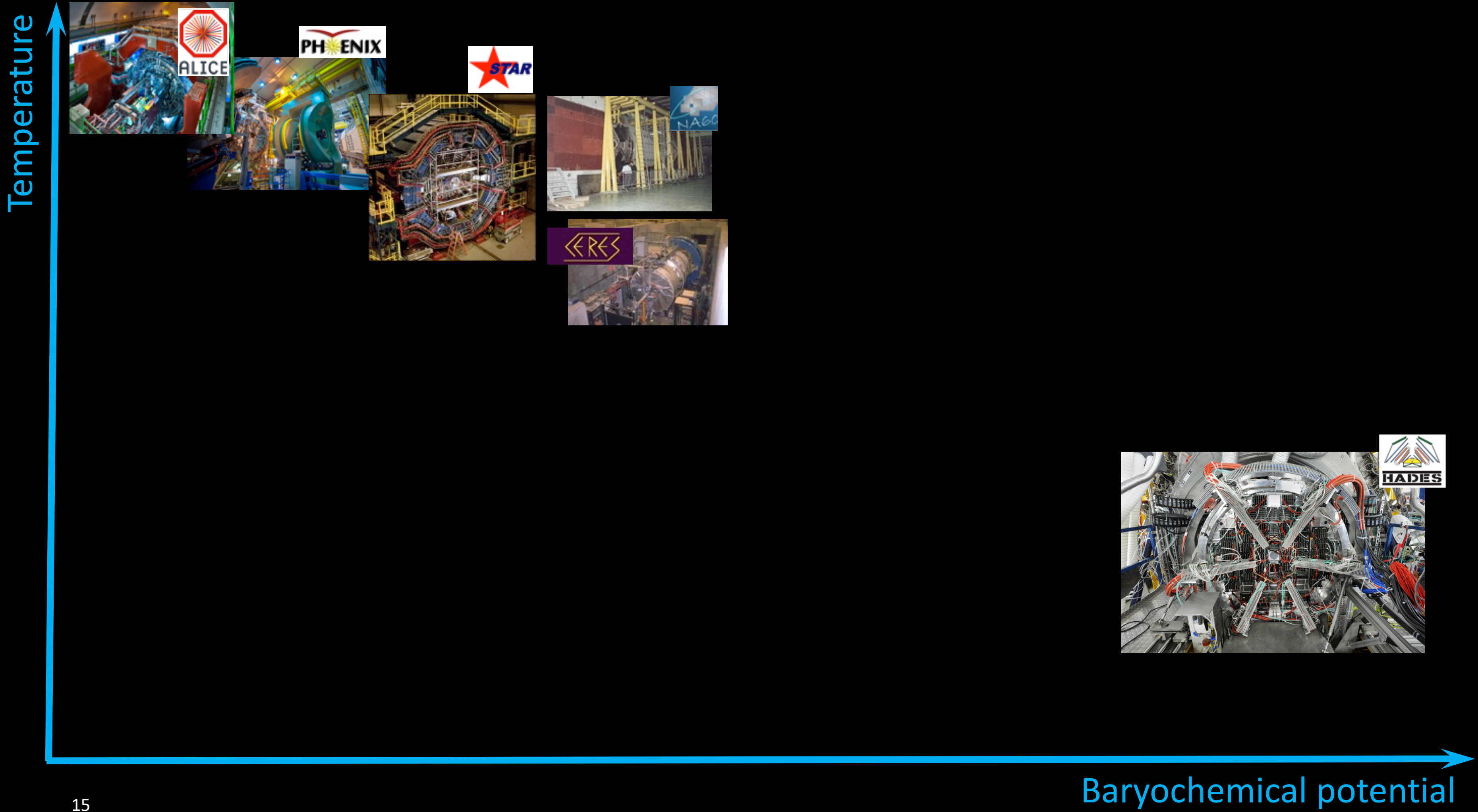
Degeneracy of hadronic chiral partners



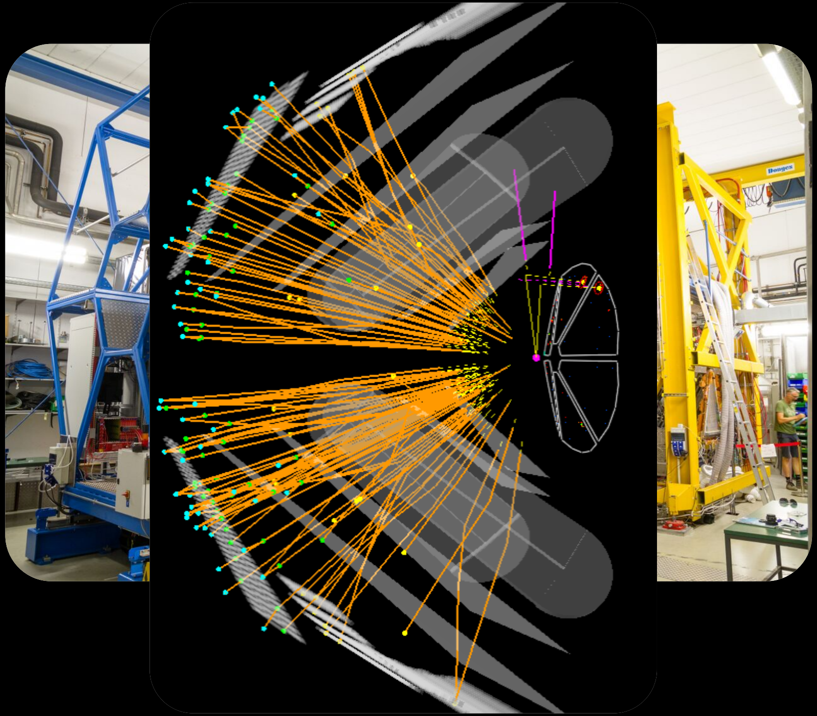
C. Jung, F. Rennecke, R.-A. T., L. von Smekal, J. Wambach, Phys.Rev. D95, 036020 (2017)

„If you want to detect something new,
build a dilepton spectrometer“

S. Ting

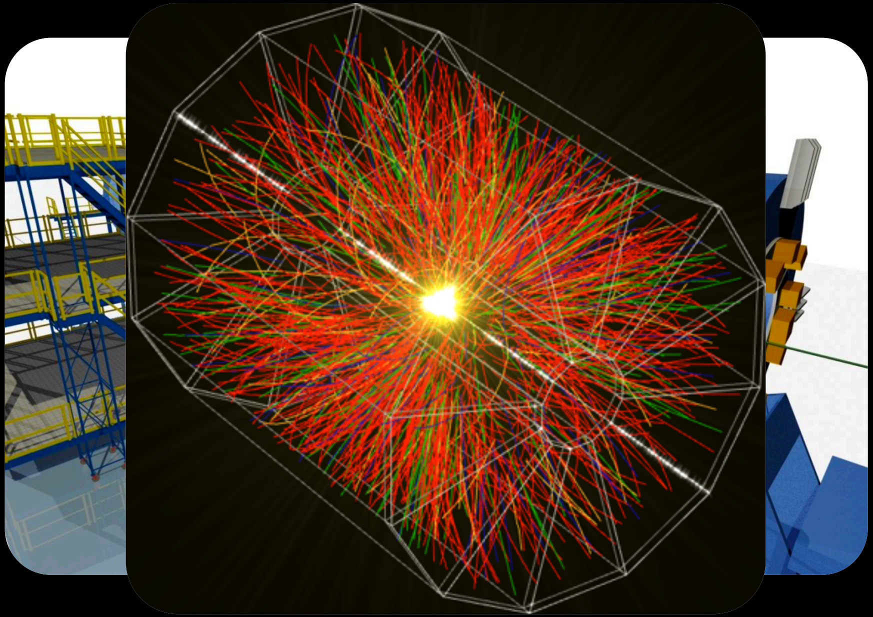

Temperature
ALICE
PHENIX
STAR
CERES
HADES
Baryochemical potential

High Acceptance DiElectron Spectrometer
HADES at SIS18, GSI



Fixed-target Experiment

Solenoidal Tracker At RHIC
STAR at RHIC, BNL



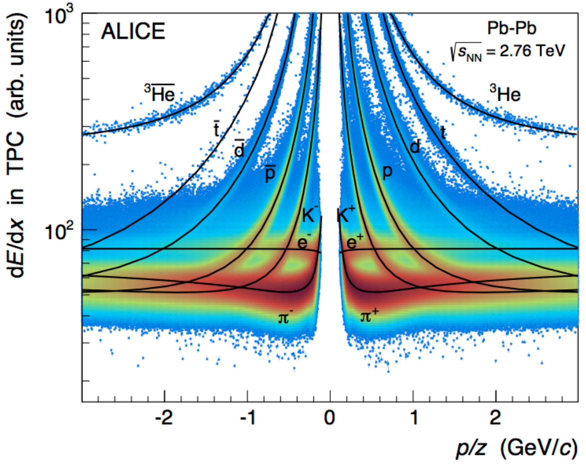
Collider Experiment

LEPTON IDENTIFICATION

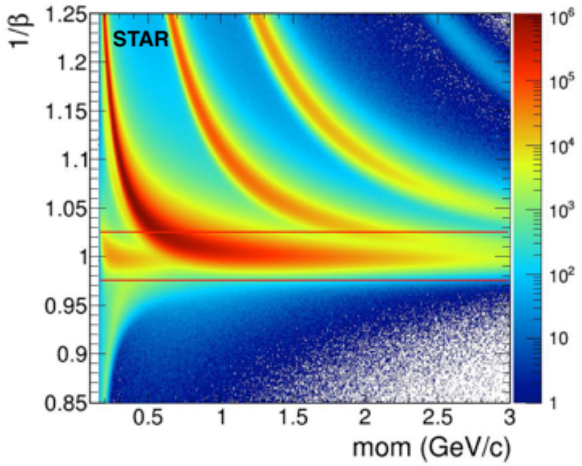
Electron identification by means of:

momentum, specific energy loss, velocity, RICH information

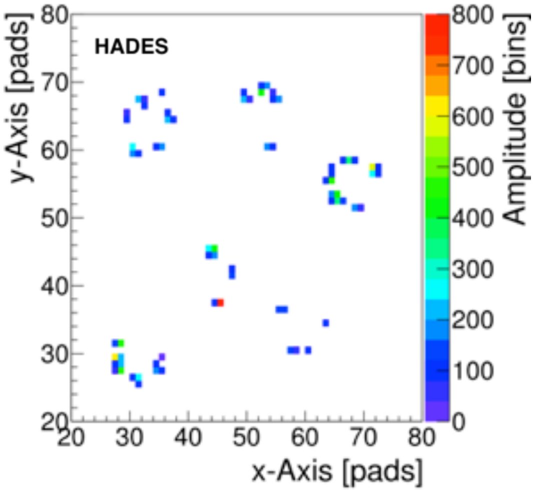
dE/dx in Time Projection Chamber



Velocity in Time-of-Flight



Rings in RICH

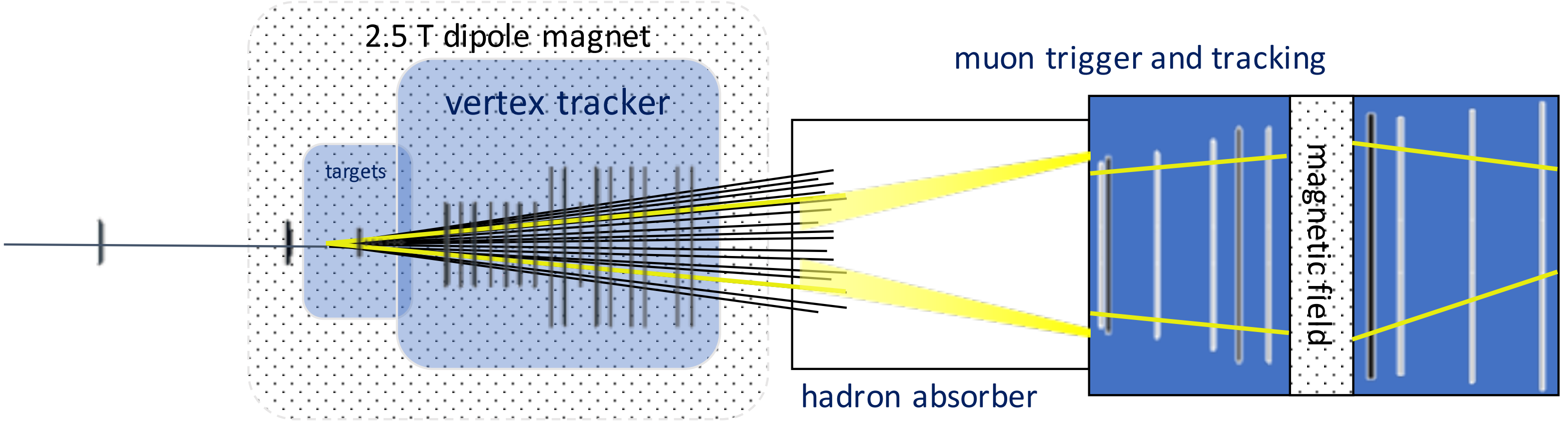


All combined in a multivariate analysis (neural network)

⤳ Best purity and efficiency

LEPTON IDENTIFICATION

Muon identification using absorber technique

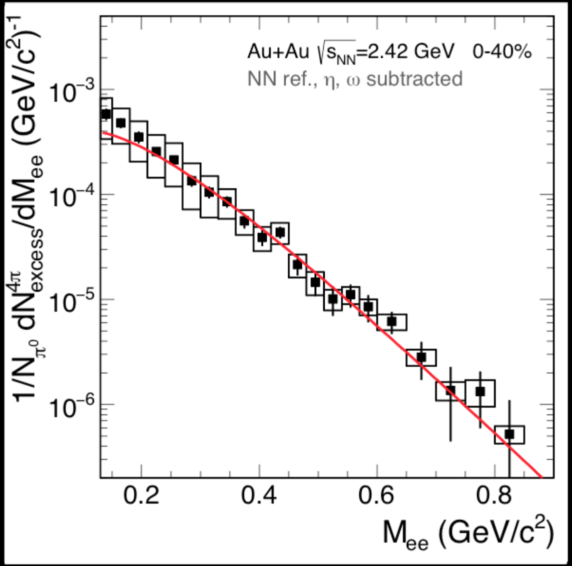


THE EXPERIMENTAL CHALLENGE …

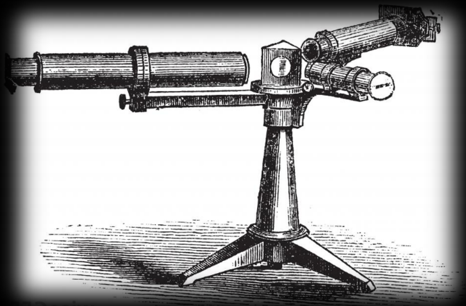
- Lepton pairs are rare probes (λ^2)
- At few GeV energy regime $Yield_\rho \times \Gamma_{ee}/\Gamma_{tot}$ ⇝1 decay per 1.000.000 events
- Large combinatorial background
  - in e^+e^- from Dalitz decays ($\pi^0 \rightarrow e^+e^-\gamma$) and conversion pairs
  - in $\mu^+\mu^-$: weak π, K decays
- Isolate the contribution to the spectrum from the hot/dense stage
- Low-momentum coverage

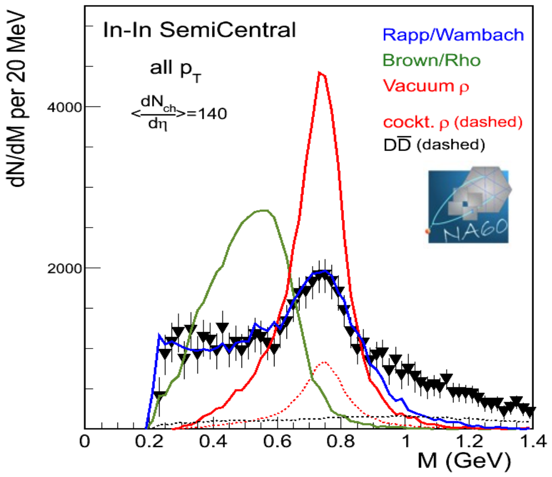
There is no such thing as a free lunch

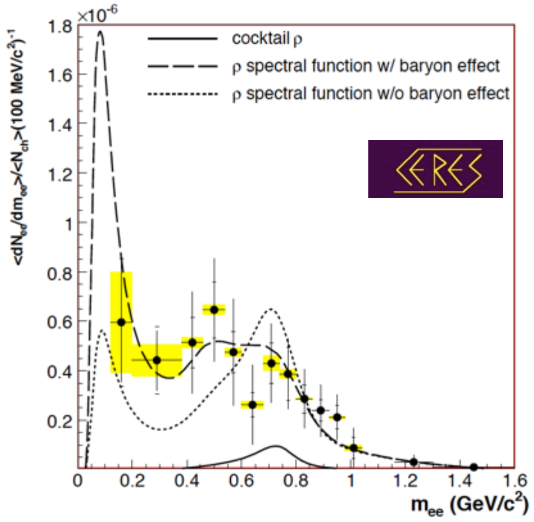
Just few steps ;)



DILEPTONS AS SPECTROMETER

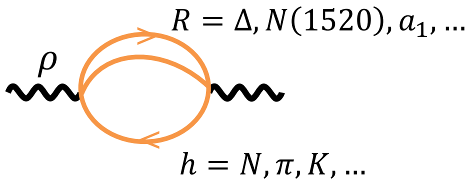






Are narrow in-medium vector meson states with substantial shifted pole mass observed?

- Disfavours "dropping mass" scenario ($m_{had} \sim \langle \bar{q} q \rangle$)
- Excess dilepton invariant-mass spectrum strongly supports melting of ρ, in particular due to baryon-induced effects:

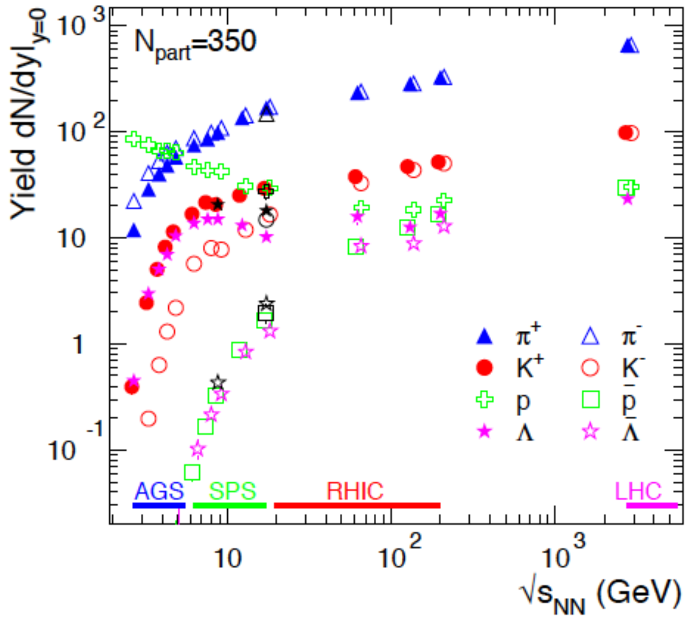


NA60 Collab., Eur. Phys. J. C 59 (2009) 607-623
CERES Collab., Phys.Lett. B666 (2008)
Calculations: R. Rapp and J. Wambach, Eur. Phys. J. A6 (1999)

FROM SPS to RHIC to LHC

	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, Int.J.Mod.Phys.A 29 (2014) 1430047

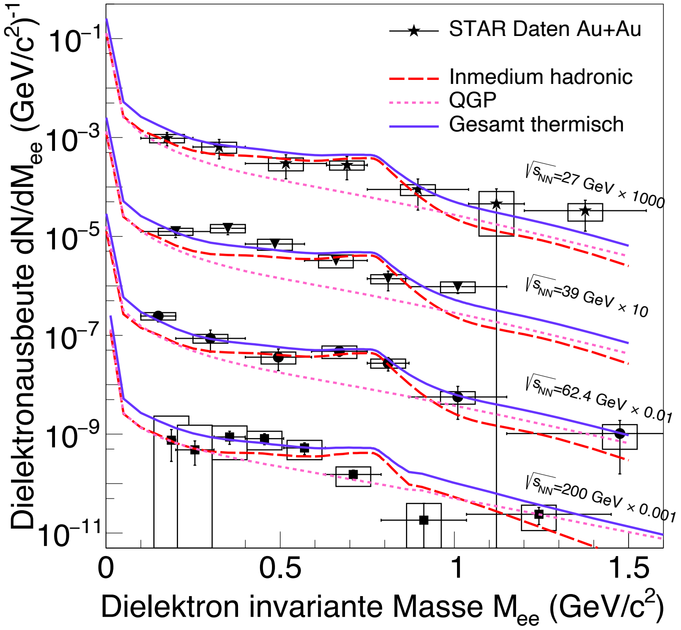


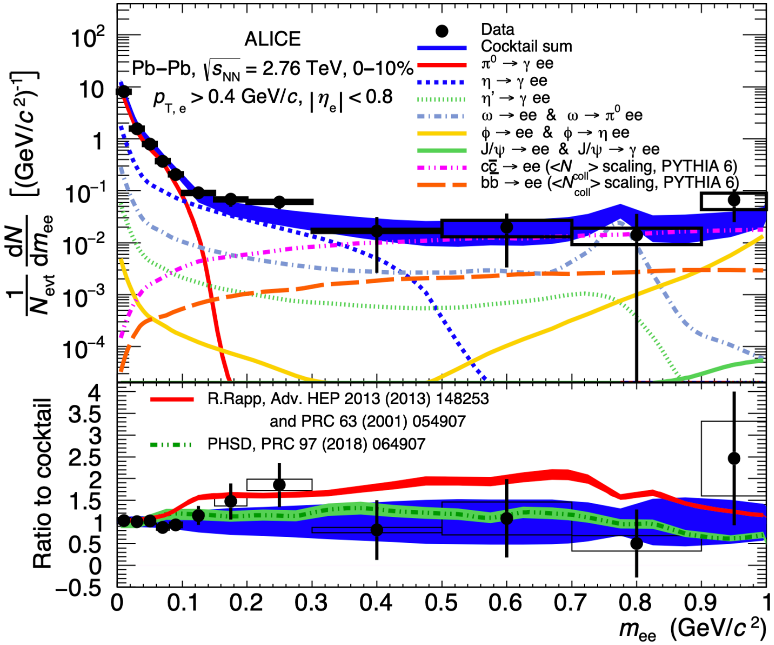
- Although the **NET-**baryon density is different at SPS, RHIC and LHC, baryon density is practically the same!
- Baryon effects important even at $\rho_{B_{tot}} = 0$! sensitive to $\rho_{B_{tot}} = \rho_B + \rho_{\bar{B}}$ (ρN and $\rho \overline{N}$ interactions identical)
- RHIC, LHC: higher initial temperature, open charm contribution becomes very significant

DILEPTON MASS SPECTRA FROM SPS to LHC ENERGIES

STAR Collab., Phys.Lett. B750 (2015)
STAR Collab., arXiv:1810.10159 [nucl-ex]
See also E.T. Atomssa, PHENIX, Nucl.Phys.A 904-905 (2013) 561c-564c

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

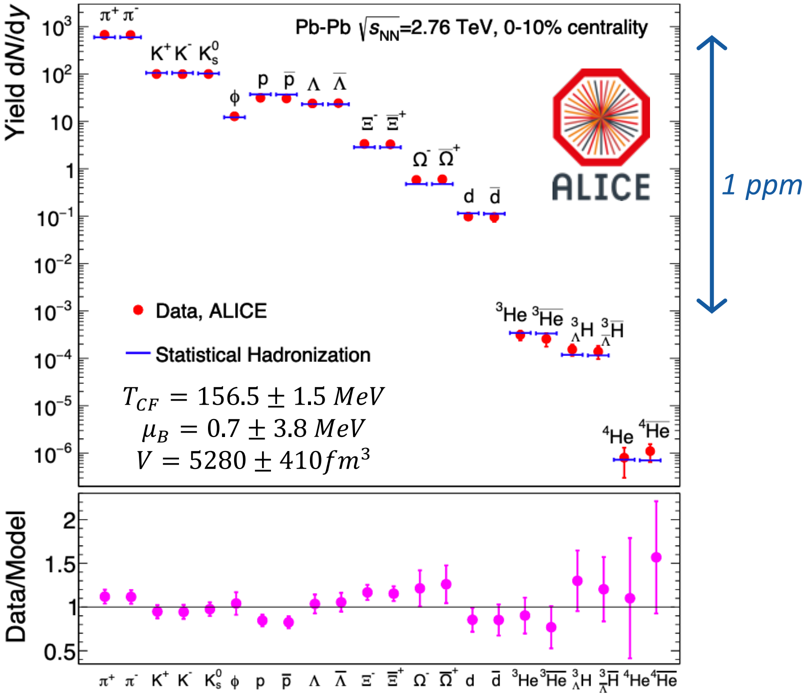




- In-medium spectral function R. Rapp and J. Wambach, Eur. Phys. J. A6 (1999) consistently describes the low-mass dilepton excess for SPS – RHIC BES – RHIC – LHC energies

ARE WE CREATING A THERMAL MEDIUM IN EXPERIMENTS?

Hadron Yields and Statistical Hadronization Model

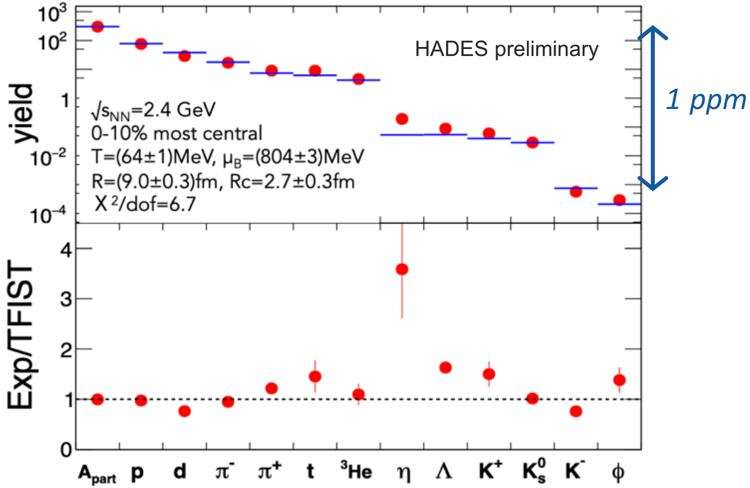


A. Andronic et al., Nature 561 (2018) no.7723

- Factor 1000 in beam energy / factor ~2 in temperature
- Hadron abundances described in framework of SHM
  - Strangeness canonical treatment at low beam energies
  - Include feed-down from $^4He,\ ^4H,\ ^4Li$

D. Hahn, H. Stöcker, Nucl.Phys.A 476 (1988) 718-772

E. Shuryak, J. M. Torres-Rincon Phys.Rev.C 101 (2020) 3, 034914

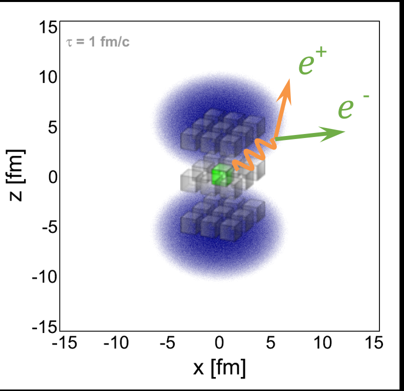


COARSE-GRAINED TRANSPORT APPROACH

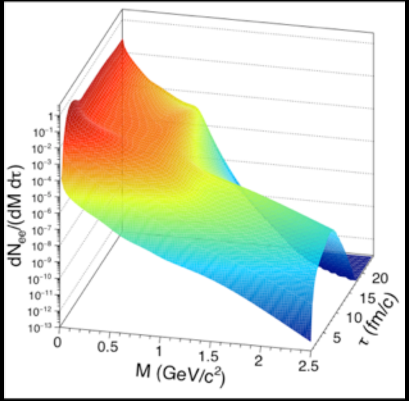
Bulk evolution from microscopic transport

Apply equilibrium rates locally

- ☐ Simulate events with a transport model
  → ensemble average to obtain smooth space-time distributions
- ☐ Divide space-time in 4-dimensional cells
  21×21×21 space cells (1fm³), 30 time steps → ~ 280 k cells
- ☐ Determine for each cell the bulk properties like T, ρ_B, μ_π, collective velocity



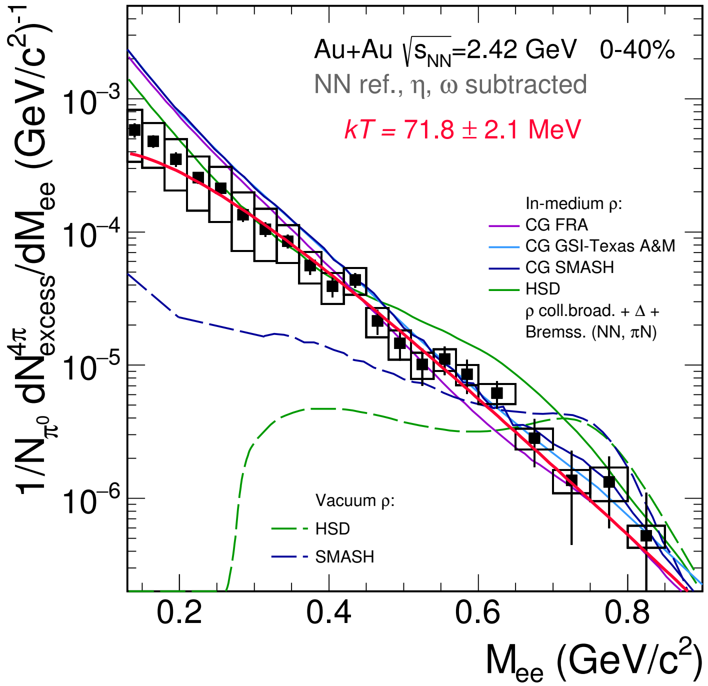
- ☐ Use in-medium ρ & ω spectral functions to compute EM emission rates
  → parameterization of RW in-medium spectral function
- ☐ Sum up contributions of all cells



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: Phys.Rev.C 98 (2018) 5, 054908

THERMAL DILEPTONS at SIS ENRGY REGIME

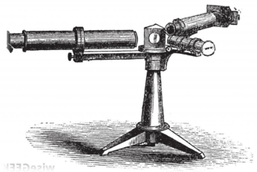
HADES Collab., Nature Physics 15 (2019) 1040



CG FRA: Phys. Rev. C 92, 014911 (2015)
CG GSI-Texas A&M: Eur. Phys. J. A, 52 5 (2016) 131
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908
HSD: Phys. Rev. C 87, 064907 (2013)

- Thermal rates folded with coarse-grained medium evolution from transport works at low energies
- Radiation from a long-lived source ($\tau \approx 13\ fm$) in local thermal equilibrium
- Supports baryon-driven medium effects at SPS, RHIC, LHC

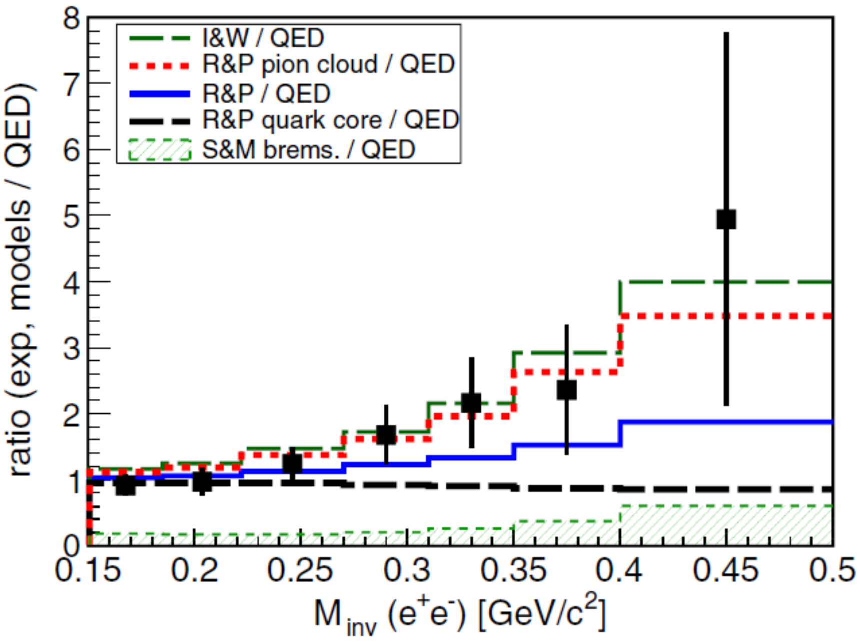
Robust understanding of emissivity of matter across QCD phase diagram

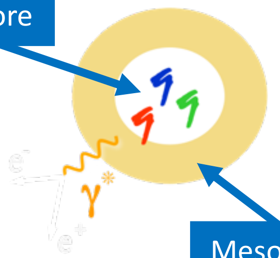


MESON CLOUD

Exclusive analysis of $pp \rightarrow ppe^+e^-$

HADES Collab., PRC 95, 065205 (2017)
HADES Collab., 2004.08265 [nucl-ex]





⤳ **Studying the structure of the nucleon as an extended object**

⤳ **Excitation of a baryon can be carried by the meson cloud**

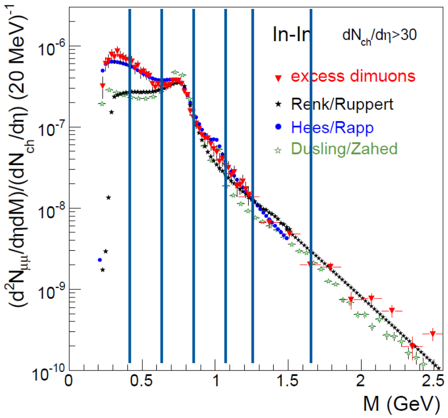
- ☐ QED: point like $\gamma *$NR, Heavy Ion Phys. 17, 27 (2003)
- ☐ I&W: two component quark model, PRC 69, 055204 (2004)
- ☐ R&P: covariant constituent quark model, PRD 93, 033004 (2016)
- ☐ S&M bremsstrahlung: PRC 82, 062201 (2010)

E. Speranza et al., Phys.Lett. B764 (2017) 282
G. Ramalho, T. Pena Phys. Rev. D95 (2017), 014003,
D. Nitt, M. Zetenyi, M. Buballa, in preparation

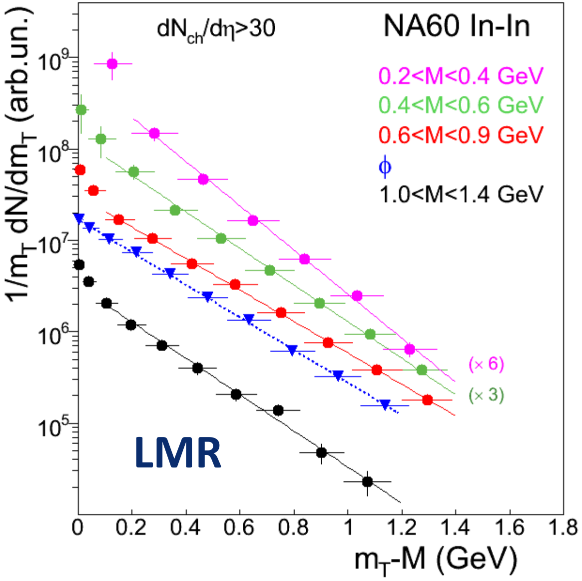
DILEPTONS AS BAROMETER

TRANSVERSE MASS DISTRIBUTIONS OF EXCESS

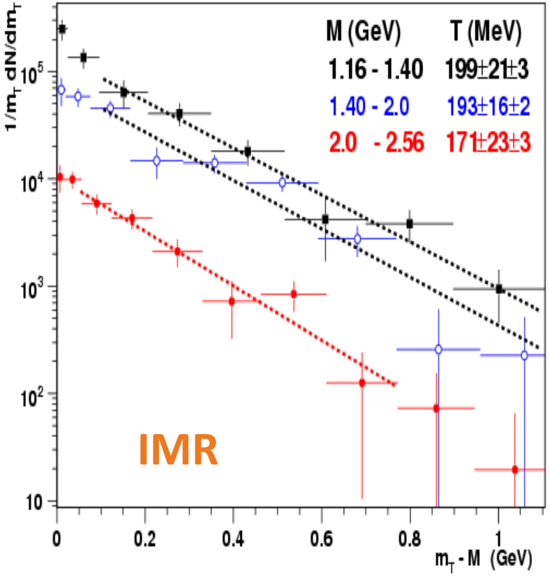
For each bin of $\mu^+\mu^-$ project transverse mass spectrum: $m_T = \sqrt{p_T^2 + M^2}$



NA60, Phys. Rev. Lett. 100 (2008) 022302

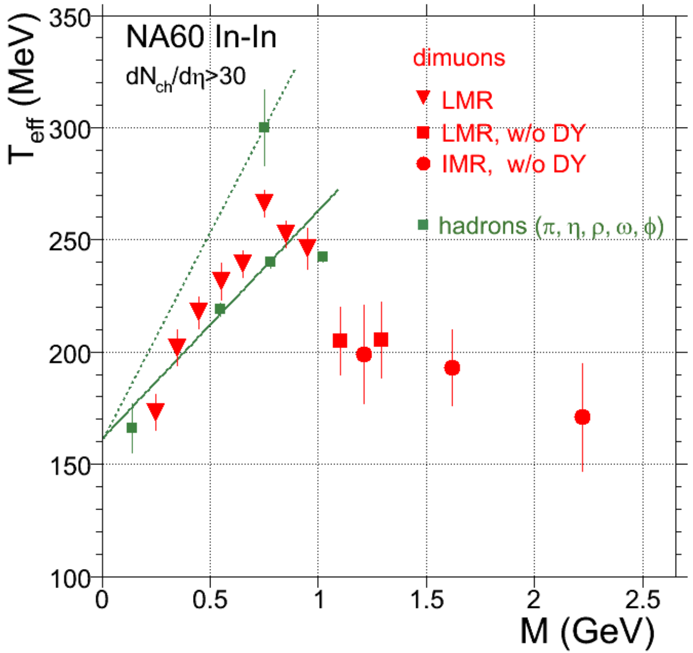


NA60, Eur. Phys. J. C 59 (2009) 607



- m_T spectra exponential for $m_T - M > 0.1\ GeV$ $(< 0.1\ GeV??)$
- Fit with $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp\left(-\frac{m_T}{T_{eff}}\right)$
- Extract T_{eff} and plot vs M

THE RISE AND FALL OF T_{eff} OF THERMAL DIMUONS

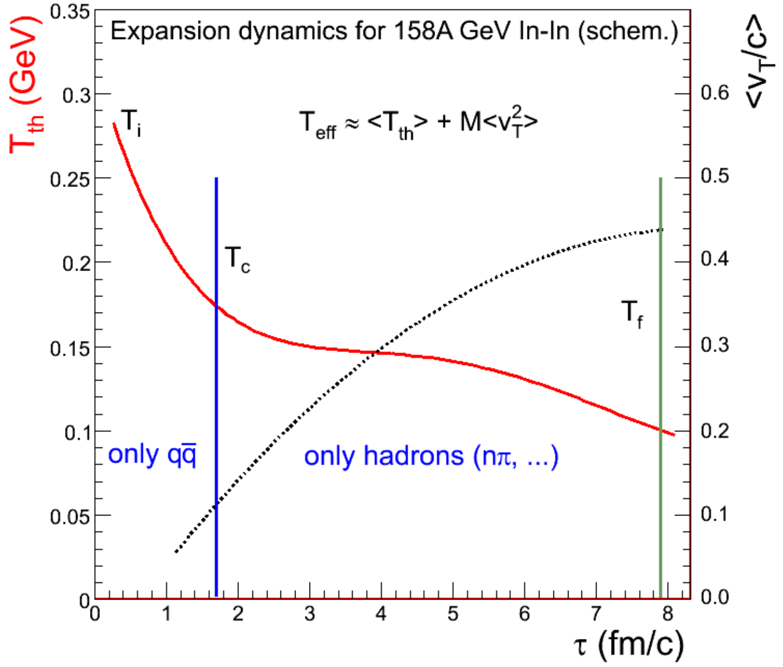


NA60, Phys. Rev. Lett. 100 (2008) 022302

- $M < 1\ GeV$
  - Strong, almost linear rise of T_{eff} with dimuon mass
  - Follows trend set by hadrons
- $M > 1\ GeV$
  - Drop of T_{eff} by $\sim 50\ MeV$
  - 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

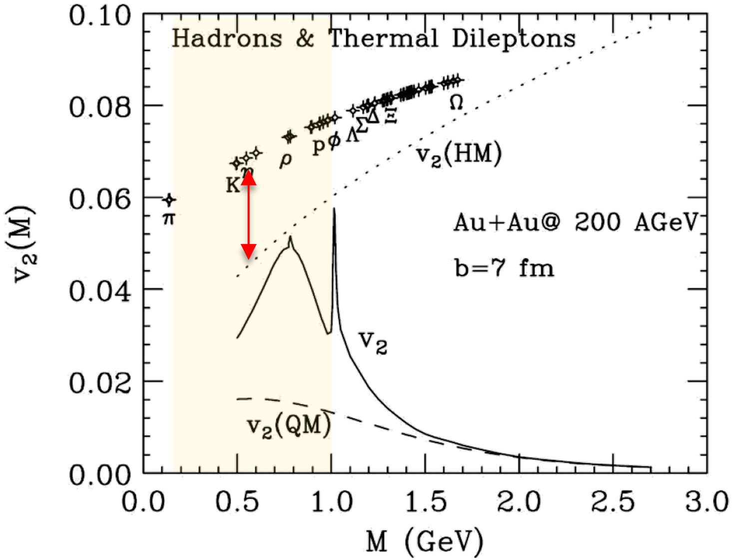


- Hadron p_T spectra: determined at $T_{kin.f.o.}$ (restricted information)
- Dilepton p_T spectra: superposition from all fireball stages
  - Early emission → high T_{th}, low v_T
  - Late emission → low T_{th}, high v_T
- Final spectra from space-time folding over T_{th} & v_T history from $T_{initial} \rightarrow T_{kin.f.o.}$
  note: small flow in the QGP phase

For $M > 1\ GeV$:
$\rightsquigarrow$ T_{eff} independent of M, negligible flow
$\rightsquigarrow$ $\langle T_{th} \rangle \sim 200\ MeV > T_{pc}$
→ Early emission, dominance of partons!

AZIMUTHAL ANISOTROPY OF VIRTUAL PHOTONS

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



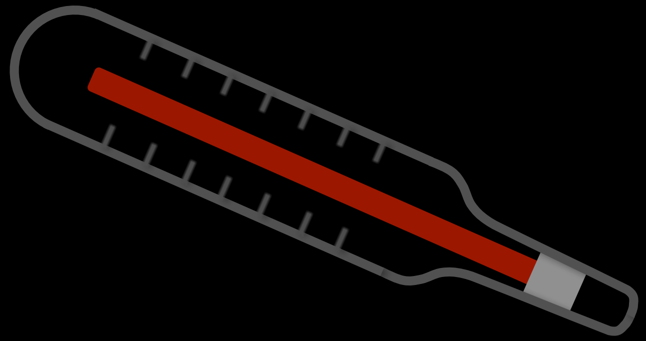
- Very cleans tool to diagnose the collective expansion dynamics, i.e. origin of the electromagnetic emission source
- Challenging v_2 vs M analysis
  - Early emission (partonic matter) → small v_2
  - Late emission (hadronic matter) → large v_2

So far:

↝ **STAR v_2 of inclusive e^+e^- (not of excess)**

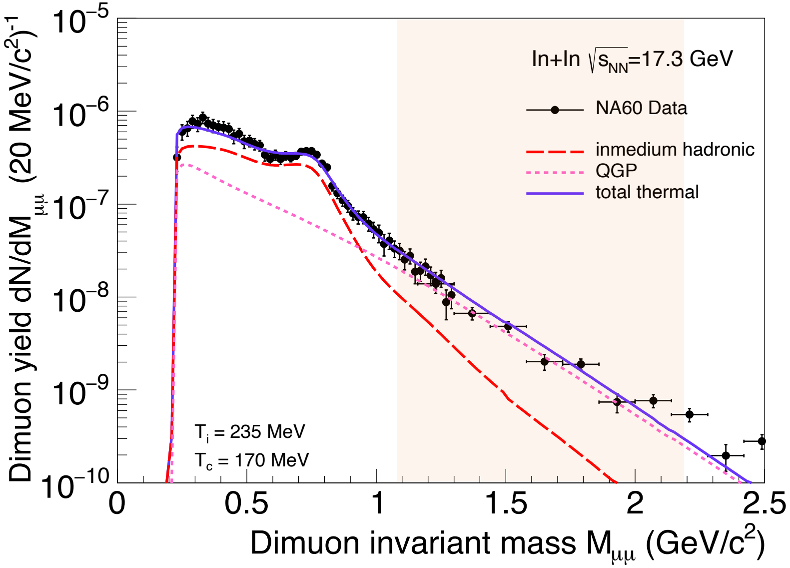
↝ **HADES v_2 of excess radiation (in prep.)**

DILEPTONS AS THERMOMETER



DILEPTONS AS THERMOMETER

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



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

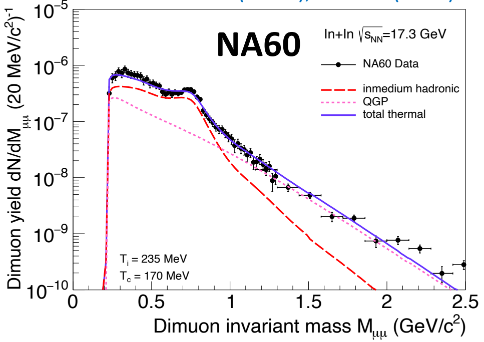
- ☐ IMR spectrum falls exponentially
- ☐ In the **IMR** the dilepton rate $\frac{dR_{ll}}{dM} \propto (MT)^{\frac{3}{2}} \exp(-\frac{M}{T})$
- ☐ Independent of flow: no blue shift!

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

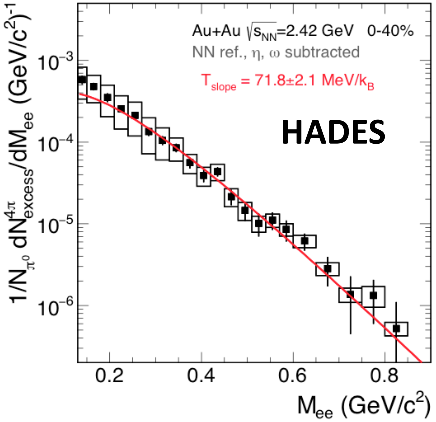
⤳ **the only explicit temperature measurement above T_{pc} in heavy-ion collisions!**

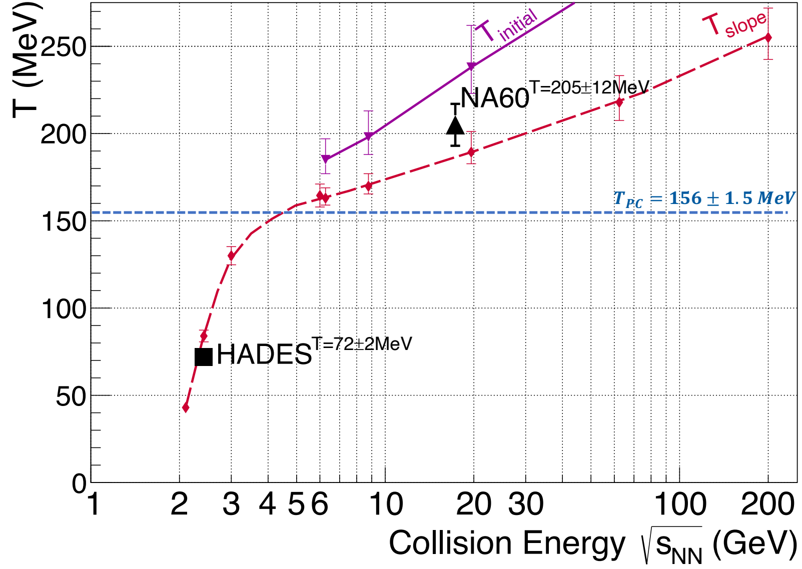
MAPPING QCD CALORIC CURVE (T vs ε)

R. Arnaldi et al. (NA60), EPJC 61(2009) 711



HADES, Nature Phys. 15(2019) 1040





R. Rapp and H. v. Hess, PLB 753 (2016) 586
TG et al.: EPJA 52 (2016) 131

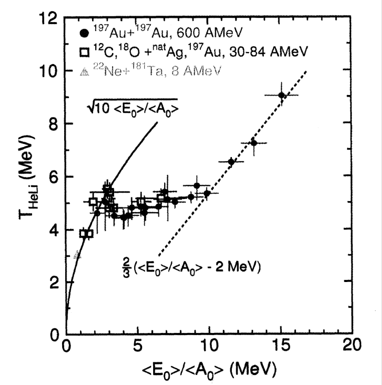
A. Bazavov et al., Phys.Lett.B 795 (2019) 15-21

Signature for phase transition?

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

↝ **future high statistics experiments**

Nuclear liquid-gas phase transition

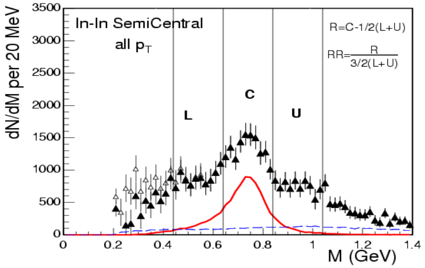


J. Pochodzalla et al., PRL 75 (1995), 1040-1043

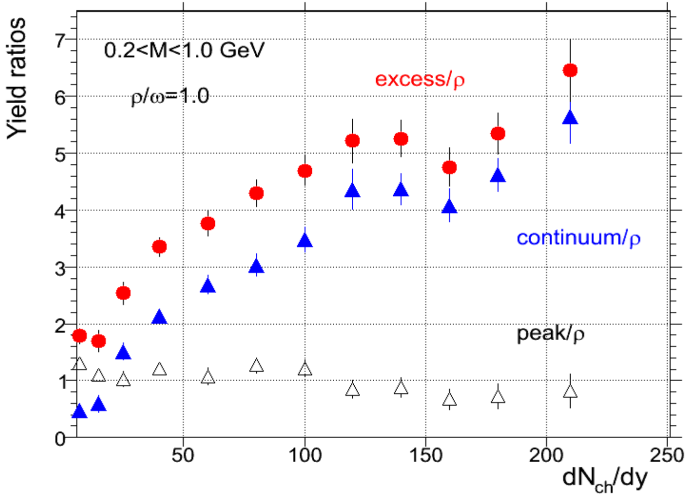
DILEPTONS AS CHRONOMETER

THE DILEPTON CLOCK

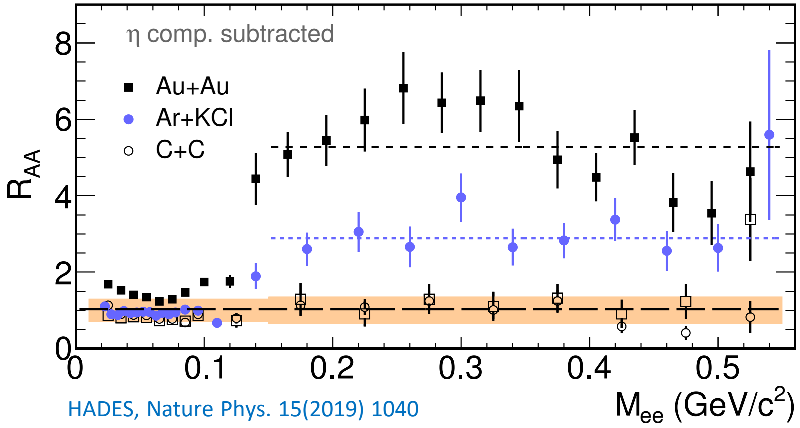
Centrality dependence of spectral shape



“ρ-clock”



System size dependence of excess

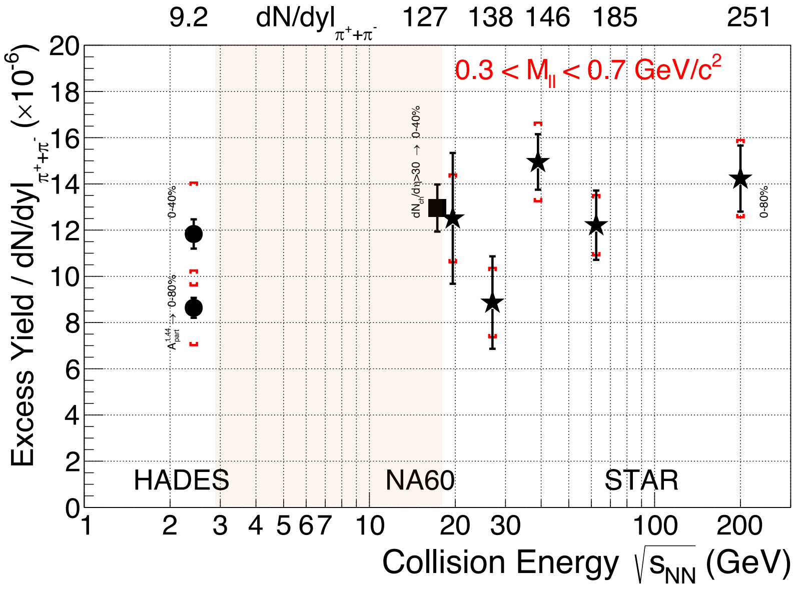


HADES, Nature Phys. 15(2019) 1040

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

DILEPTONS AS A CHRONOMETER

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



- 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)
R. Rapp, H. van Hees, PLB 753 (2016) 586

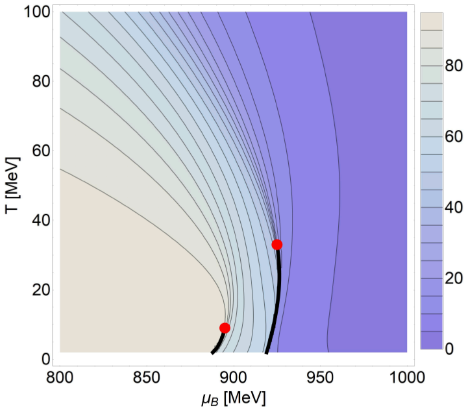
- High statistics measurements needed

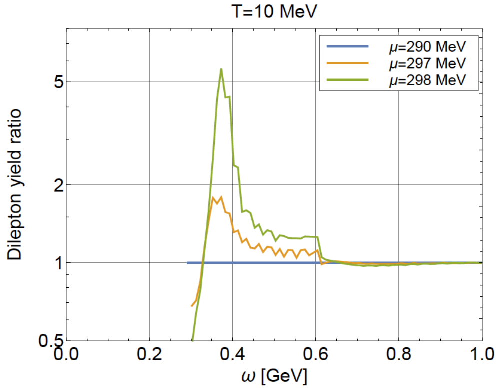
Signature for phase transition (and critical point)?
⇝ latent heat ⇝ longer life time ⇝ extra radiation

DILEPTON SIGNATURE OF A FIRST-ORDER PHASE TRANSITION

- EM SF from analytically continued FRG flow equations
- Dilepton rates at CEP $\boldsymbol{T=10\ MeV}$, $\boldsymbol{\mu=292\ MeV}$

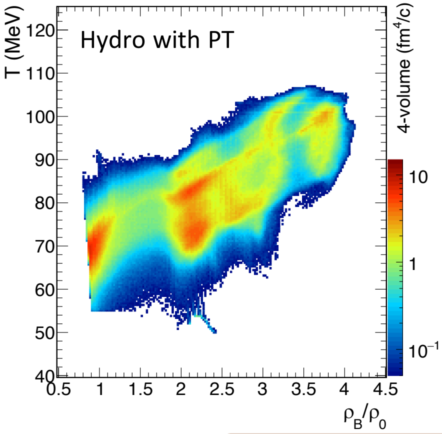
R.-A. Tripolt, C. Jung, N. Tanji, L. v. Smekal, J. Wambach, Nucl. Phys. A982 (2019) 775
C. Jung, F. Rennecke, R.-A. Tripolt, L. v. Smekal, J. Wambach, Phys. Rev. D 95, 036020 (2017)

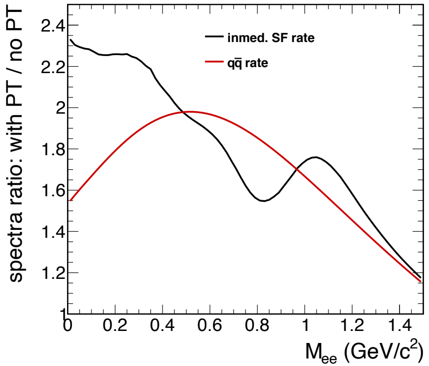




- Dilepton radiation in hydrodynamical simulations
- Factor of ~2 extra radiation in case of hydro with PT

F. Seck, TG, A. Mukherjee, R. Rapp, J. Steinheimer, J. Stroth, arXiv:2010.04614 [nucl-th]
See also F. Li and C.M.Ko, Phys. Rev. C 95 (2017) no.5, 055203



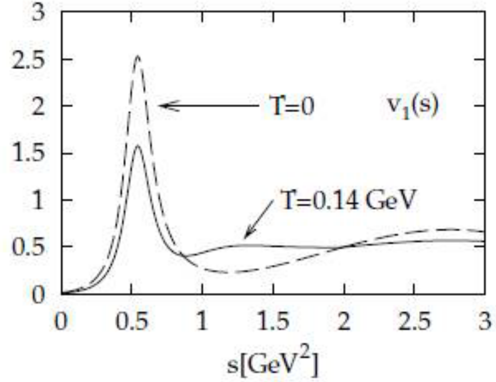


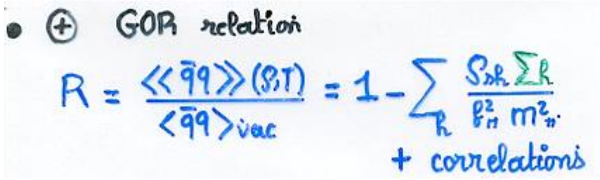
CRC–TR 211

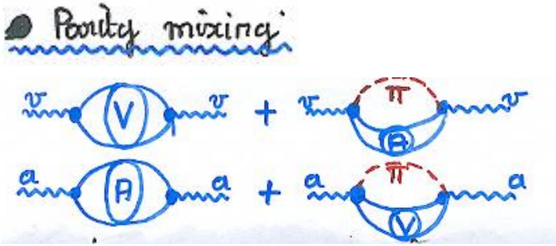
SIGNATURE FOR CHIRAL SYMMETRY RESTORATION

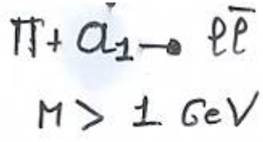
- Changes in yield and shape at $M_{ee} > 1.1\ GeV$ due to **$\rho - a_1$ chiral mixing**
- $\sqrt{s_{NN}} < 6\ GeV$: negligible $c\bar{c}$, decrease of QGP, significant reduction of Drell-Yan (pA measurements!)
- $\pi a_1 \rightarrow \gamma^* \rightarrow l^+l^-$ (chiral mixing) is a dominant hadronic source in IMR

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

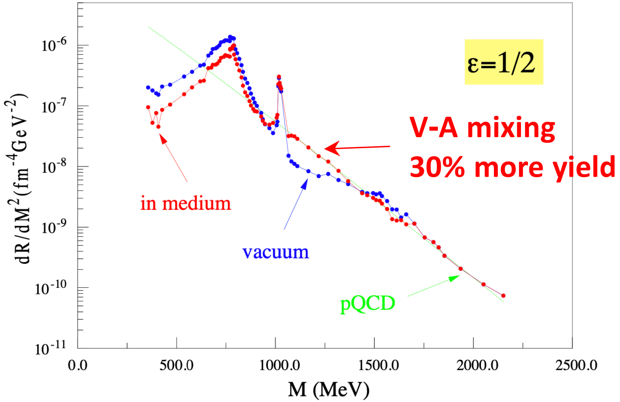








R.Rapp, J. Wambach, Adv.Nucl.Phys. 25 (2000)

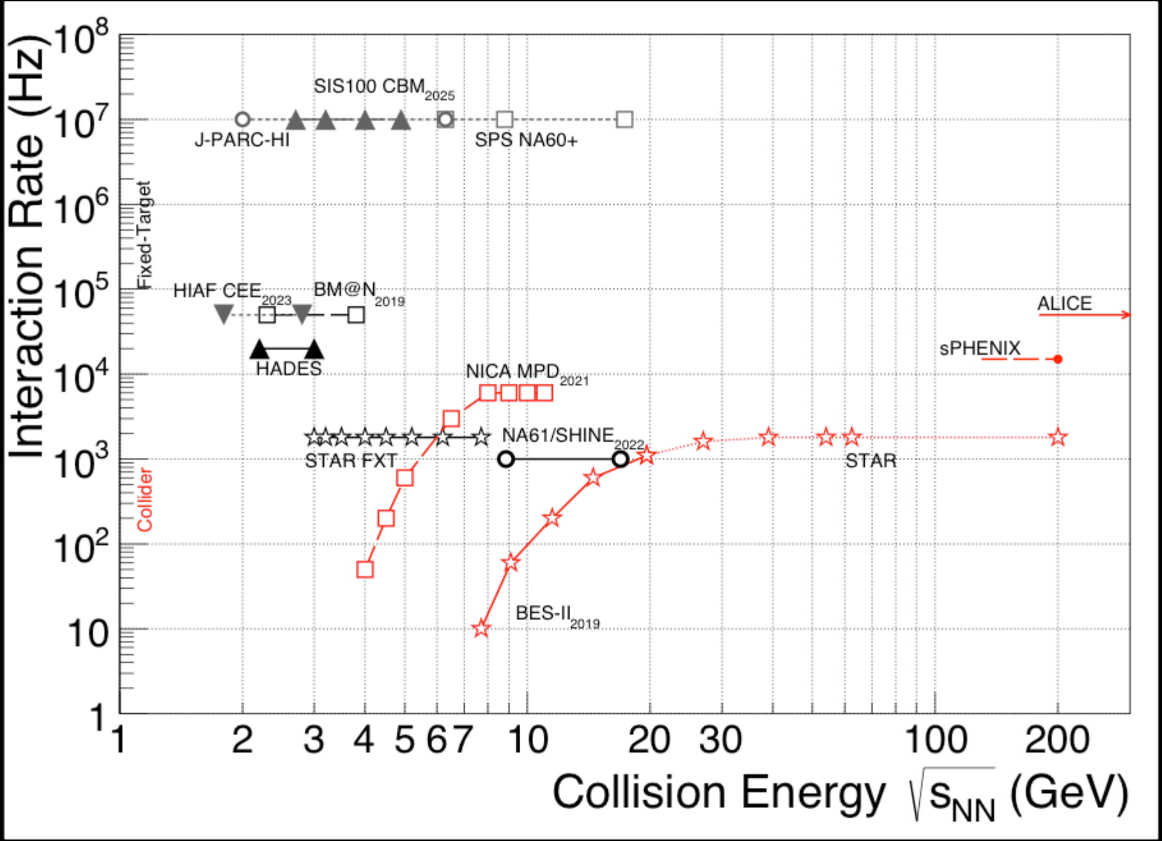


Guy Chanfray, 1999 Lecture Notes

FUTURE

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

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



Program needs high precision data

- ☐ High intensity beams
- ☐ Multipurpose detectors:
  - ☐ Large acceptance, high efficiency
  - ☐ Trigger-less, free streaming read-out electronics with high bandwidth online event selection
- ☐ High-performance / scientific computing

⤳ Strong interest internationally

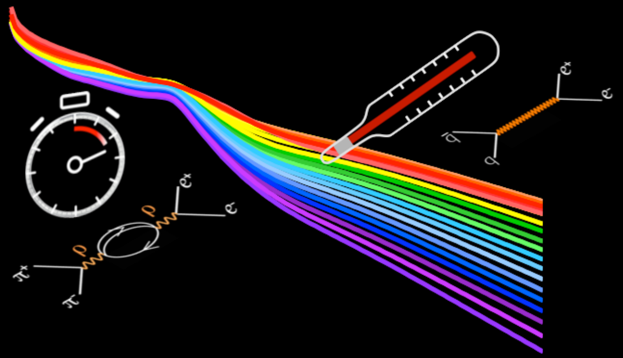
RÉSUMÉ AND PROSPECTS

There is no mission impossible

- 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
  - Degrees of freedom of the medium
  - Restoration of chiral symmetry
  - Transport properties
  - Fireball lifetime and temperature

- 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)

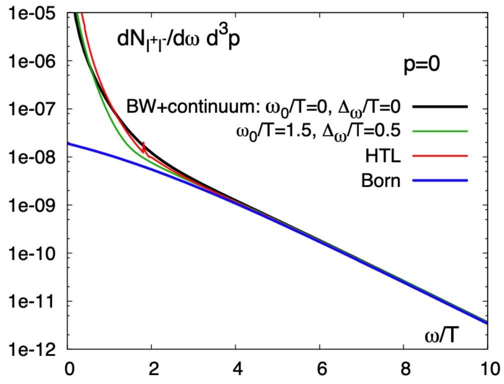
⇝ substantial progress in understanding of QCD phenomena



THANK YOU FOR YOUR ATTENTION!

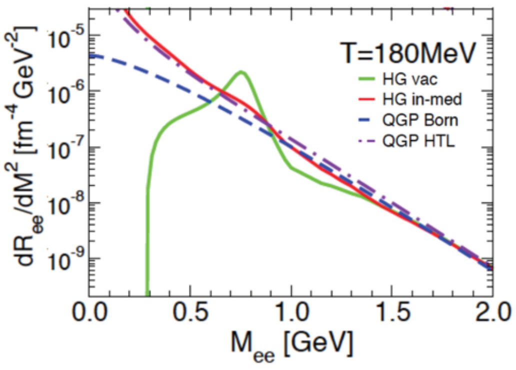
COMPONENTS OF EM PROBES

Degrees of freedom of the medium



H.-T. Ding et al., Phys.Rev.D 83 (2011) 034504

- Thermal dilepton rate in 2-flavor QCD:
  - HTL curve is for a thermal quark mass $\frac{m_T}{T} = 1$
  - Born rate is obtained by using the free spectral function



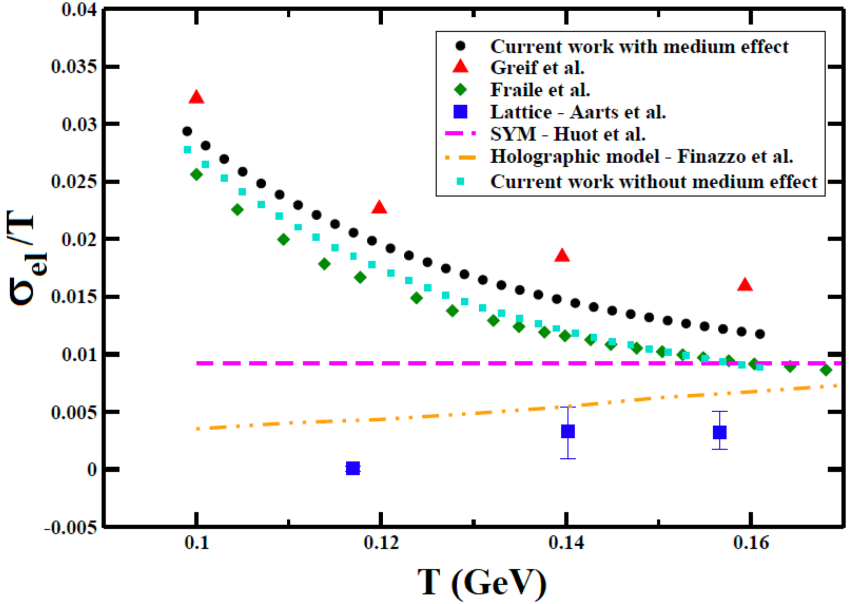
R.Rapp, J. Wambach, Adv.Nucl.Phys. 25 (2000)

Spectral function merges into QGP description

→ Direct evidence for transition hadrons to quarks & gluons

COMPONENTS OF EM PROBES

Transport properties



Electric conductivity
→ probes soft limit of EM spectral function

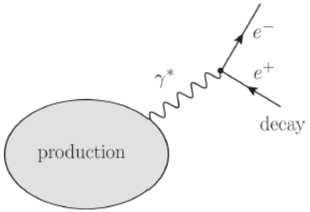
$$\sigma_{EM}(T) = -e^2 lim_{q_0 \to 0} \left[\frac{\partial}{\partial q_0} Im\Pi_{EM}(q_0, q = 0; T)\right]$$

S. Ghosh, S. Mitra, S. Sarkar, Nucl.Phys. A969, 237 (2018)

M. Greif, C. Greiner, G.S. Denicol, Phys.Rev. D93, 096012 (2016)

Dileptons as polarimeter

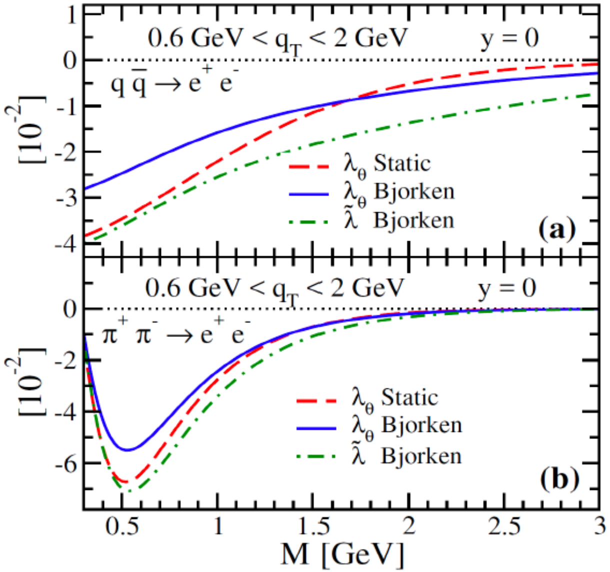
Angular distribution of dilepton rate in the photon rest frame:



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

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

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



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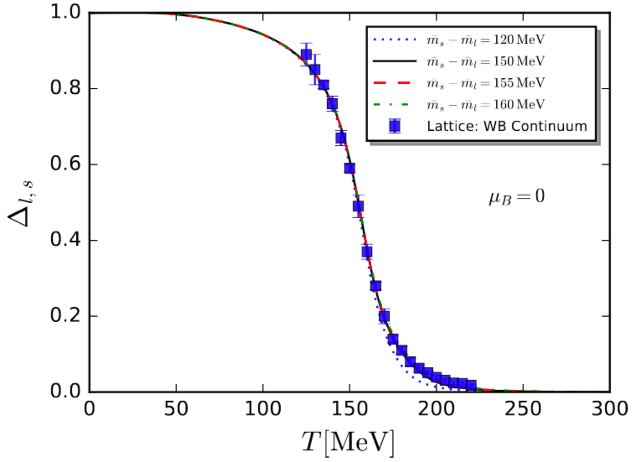
[E. Speranza, A. Jaiswal, B. Friman, Phys.Lett. B782, 395-400 (2018)]
[E.L. Bratkovskaya, O.V. Teryaev V.D. Toneev, Phys.Lett. B348, 283 (1995)]
[E. Speranza, M. Zétényi, B. Friman, Phys.Lett. B764, 282 (2017)]

CHIRAL SYMMETRY of QCD

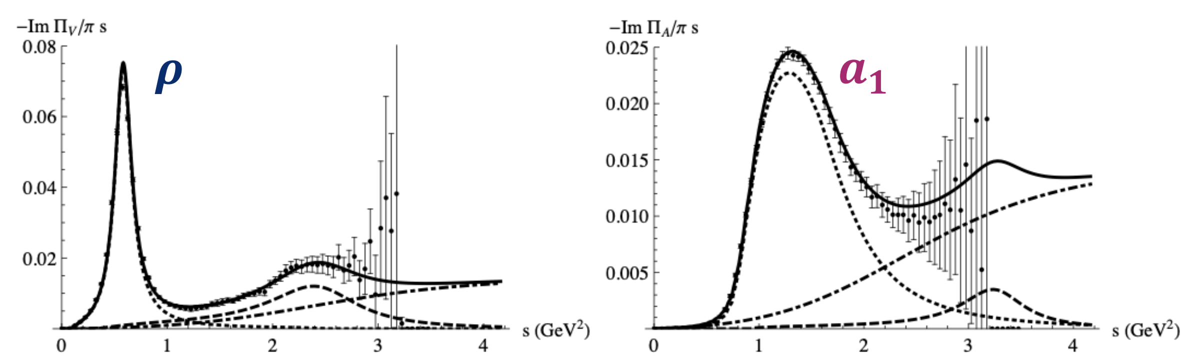
- QCD Lagrangian has chiral symmetry (χ_c) in the limit of vanishing quark masses
- χ_c is broken spontaneously by dynamical formation of a quark condensate $\langle\bar{\psi}\psi\rangle$
- Quantitative agreement of the quark condensate with lattice QCD (for both FRG and sum rules)

W.j.Fu, J. M. Pawlowski and F. Rennecke, Phys. Rev. D101, no.5, 054032 (2020)
P.M. Hohler and R. Rapp, Phys. Lett. B731 (2014), 103-109
S. Borsanyi et al. (Wuppertal-Budapest), JHEP 09, 073 (2010)

Functional Renormalization Group (FRG)

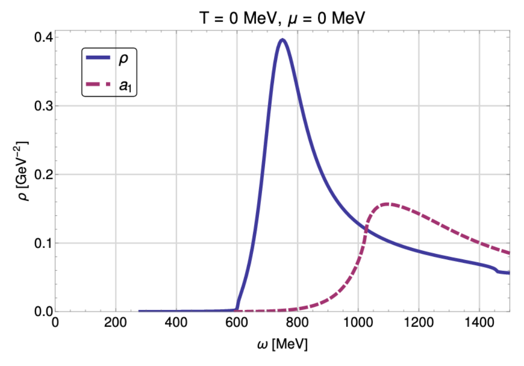


Vacuum EM spectral functions from **sum rules**



Data: R. Barate et al. [ALEPH], Eur. Phys. J. C 4 (1998) 409
P.M. Hohler and R. Rapp, Nucl. Phys. A892 (2012) 58-72

from **aFRG**



C. Jung, L. von Smekal, Phys.Rev.D 100 (2019) 11, 116009