THE ROLE OF BARYON RESONANCES IN THERMAL DILEPTON RADIATION

Joachim Stroth

EMMI RRTF – Electromagnetic Structure of Strange Baryons

GSI, October 22–25, 2018

QCD PHASE DIAGRAM AND DILEPTONS

THERMAL DILEPTON RADIATION

ρ SPECTRAL FUNCTION AND χ SYMMETRY RESTORATION

STRANGENESS PRODUCTION AND THERMALIZATION

TESTS OF VDM IN EM BARYON TRANSITIONS

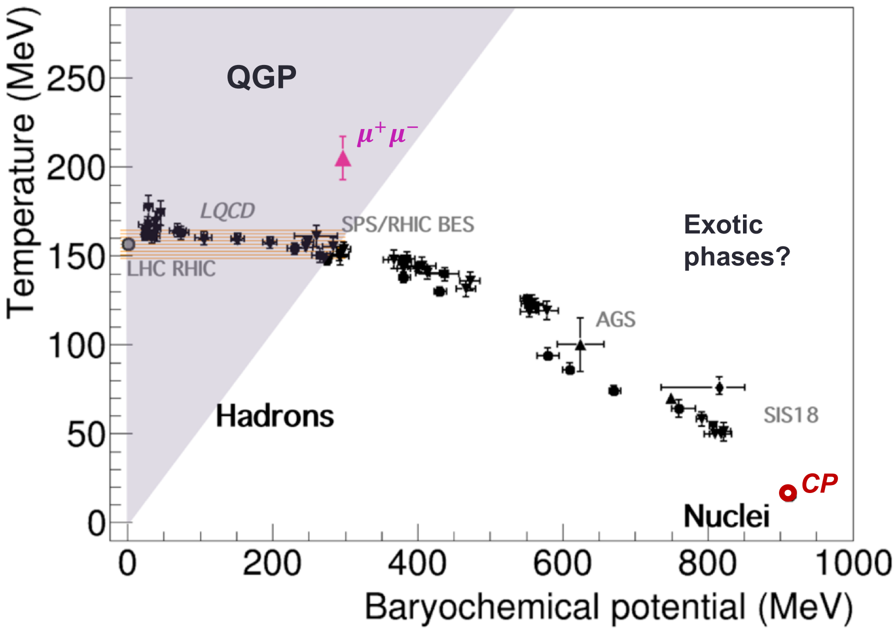
QCD PHASE DIAGRAM AND DILEPTONS

The exploration of the QCD Phase Diagram

Fireballs of QCD matter formed in (ultra-) relativistic heavy-ion collisions seem to freeze out along a universal curve.

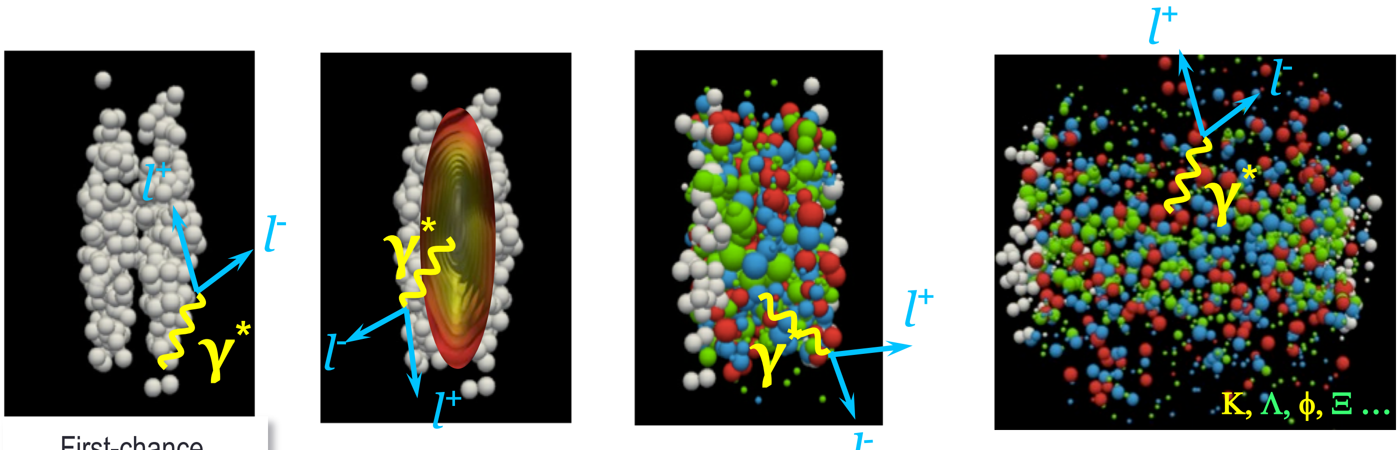
At vanishing μ_B the location of this curve coincides with the pseudo-critical temperature extracted from lattice-QCD.

The QCD phase diagram is experimentally mapped by measurements of comparing particle abundancies to a Statistical Hadronization Model (SHM) and by direct temperature measurements using dileptons.



T. Galatyuk, QM2018, Venice

Stages of a heavy-ion collision



First-chance NN collisions or parton collisions

QGP?

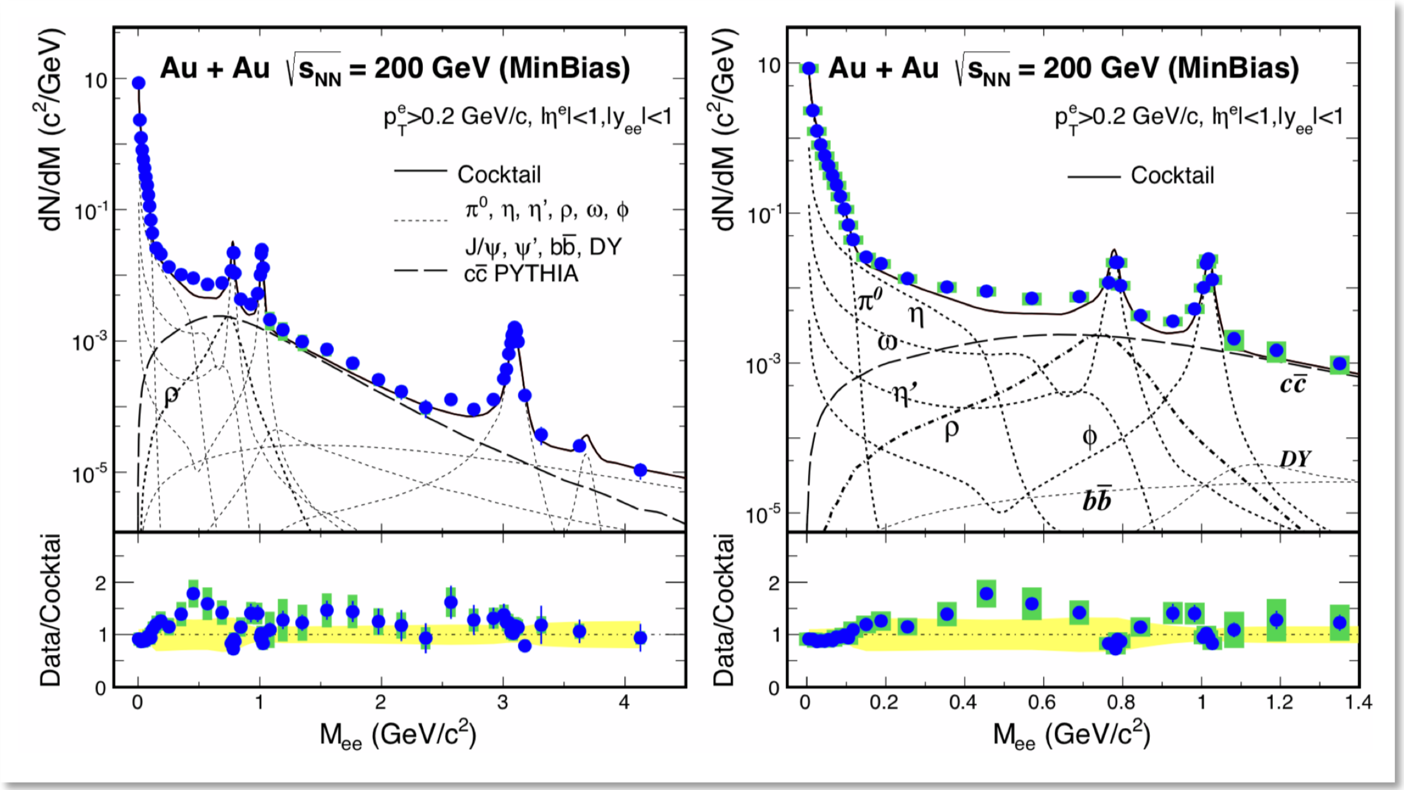
Hadronic matter

Freeze-out

τ ~10 – 30 fm/c

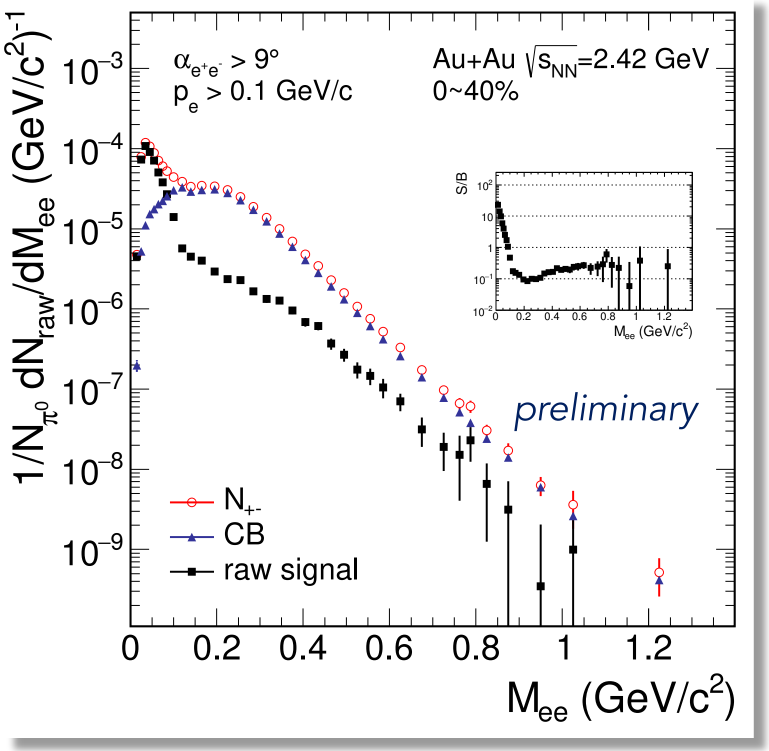
hard* – *thermal* – *chemistry/flow

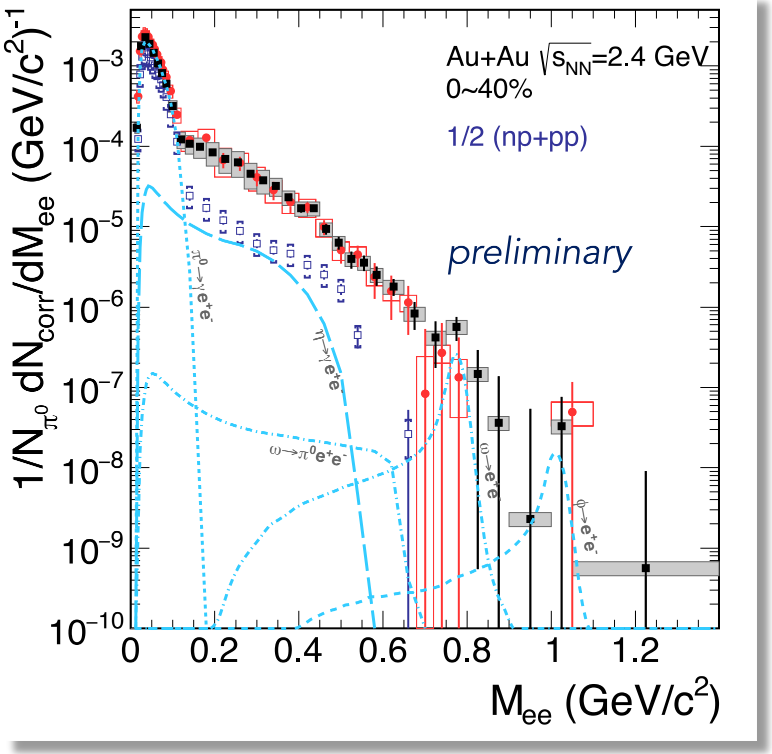
Dilepton invariant mass spectrum from STAR



STAR collaboraion, 1504.01317

Inclusive dielectron yields: $Au + Au$ ($\sqrt{s} = 2.4\ AGeV$)





HADES collaboraion, submitted for pub.

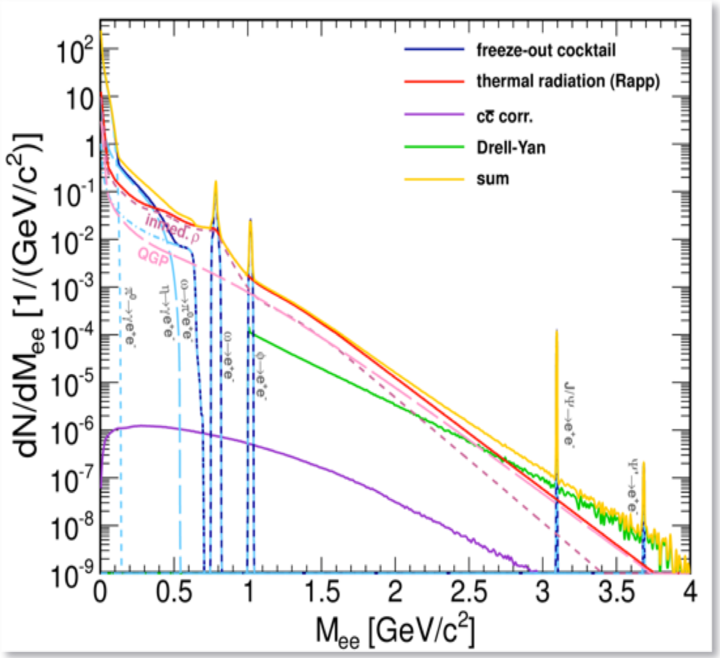
THERMAL DILEPTON RADIATION

Theoretical approaches to medium radiation

Medium radiation from ***Thermal Emission Rates*** (ϵ):

$$\frac{d^4N}{dMdydp_t d\alpha} = \int \frac{\alpha^2}{\pi^3 M^2} f_B(q_0;\ T)\ \mathrm{Im}\Pi_{\mathrm{EM}}[M, q; T, \mu_B, \vec{v}]\, d\boldsymbol{x}$$

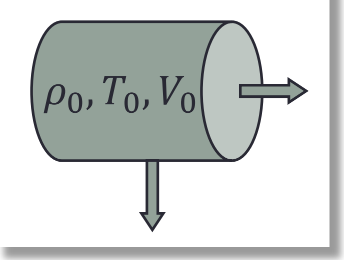
$$\equiv \int \frac{d^4\epsilon}{d\boldsymbol{q}} [T(\boldsymbol{x}), \mu_B(\boldsymbol{x}), \vec{v}(\boldsymbol{x})]\, d\boldsymbol{x}$$



coarse graining

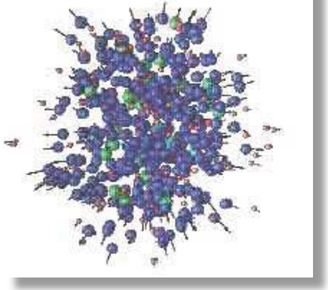
or

isentropic expansion



shining

UrQMD



Dilepton emission from *Microscopic Transport*.

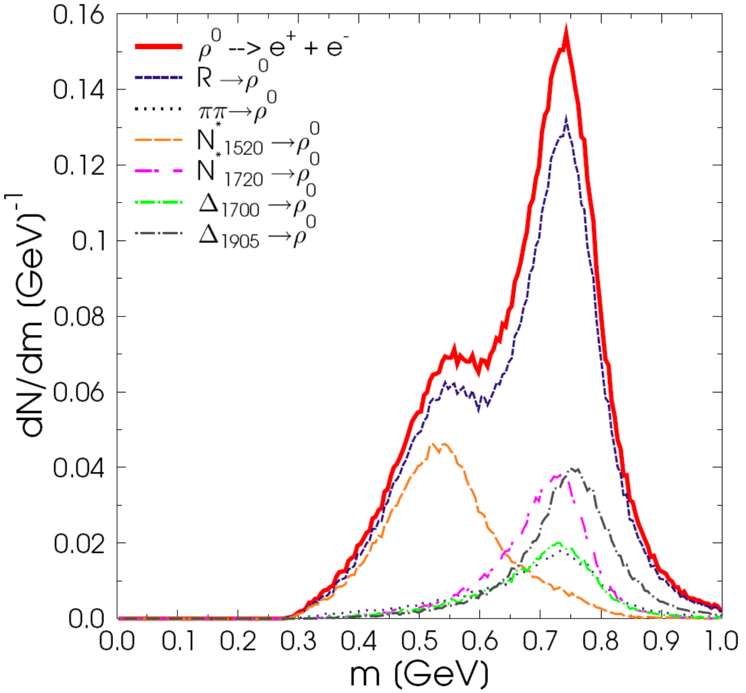
$\rho \to \ell^+\ell^-$ production in a hadronic cascade (UrQMD)

Shining approach to dilepton production from ***intermediary ρ decay*** for a $C + C$ collision at $2A$ GeV calculated with UrQMD.

The dileptons are calculated in a „perturbative“ approach scanning the history file after each collision and deriving respective dilepton yields by application of the proper partial decay width.

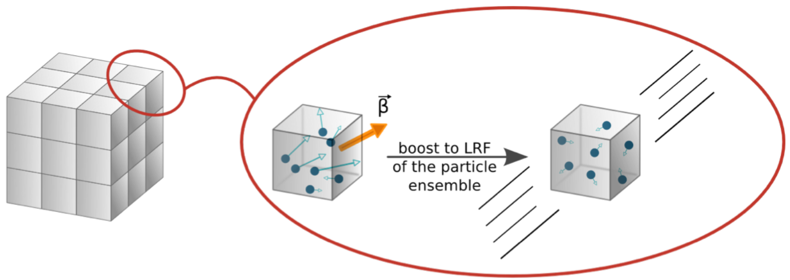
$$\Gamma_{V\to e^+e^-}(M) = \frac{\Gamma_{V\to e^+e^-}(m_V)}{m_V}\frac{m_V^4}{M^3}\sqrt{1-\frac{4m_e^2}{M^2}}\left(1+2\frac{m_e^2}{M^2}\right)$$

Off-shell decays ($N(1520)$) populate the region way below the vector mesons pole mass. Strong effect at low beam energies.

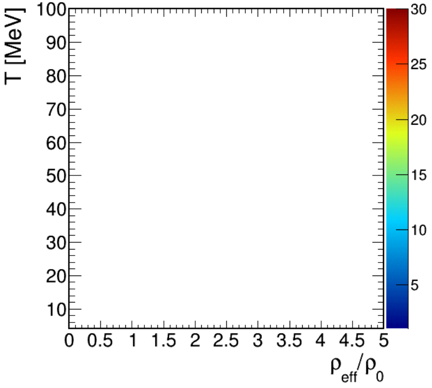


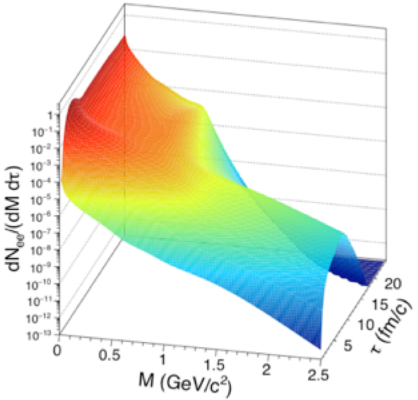
S. Vogel, M. Bleicher, Phys.Rev.C74:014902,2006

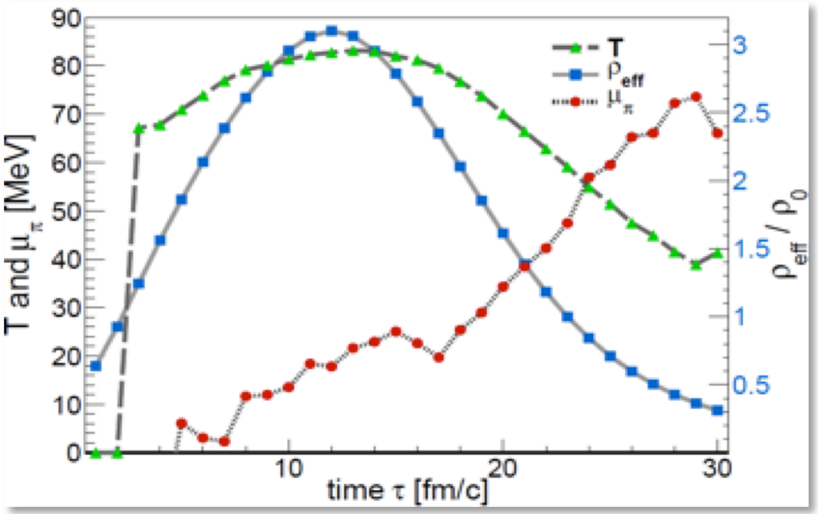
Thermal production using coarse graining



Simulate many cascades under same initial conditions and overlay the particle propagation. Treat particles in cells at ***statistical systems***.



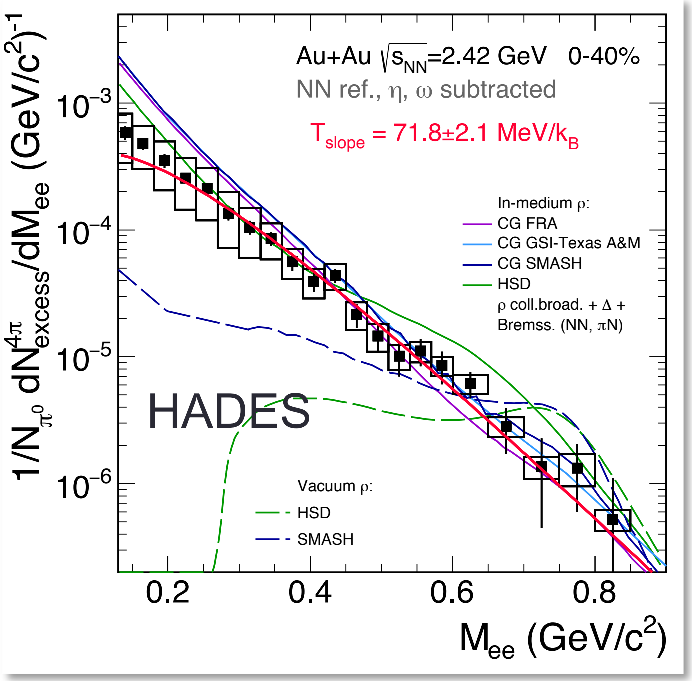


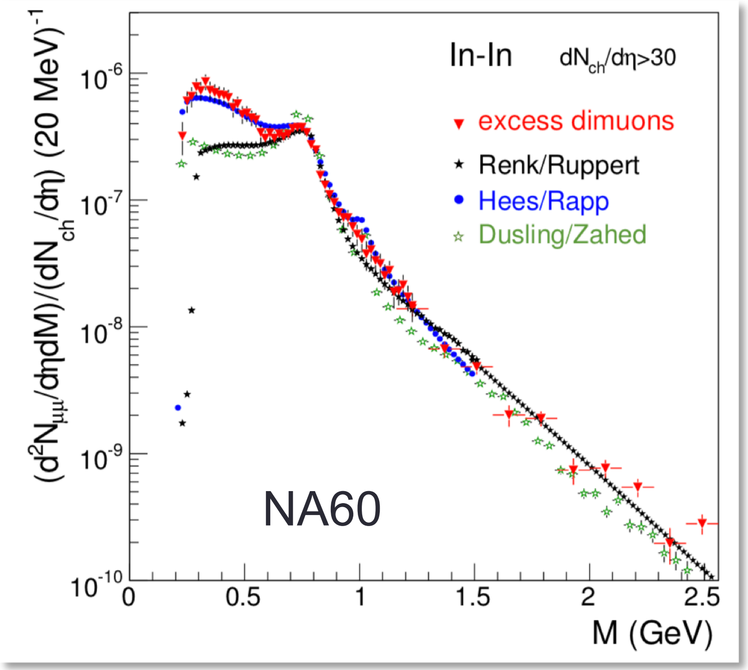


Florain Seck, priv. comm.

T. Galatyuk, F. Seck, R. Rapp, J. Stroth, 1512-08688

Thermal radiation from fireballs



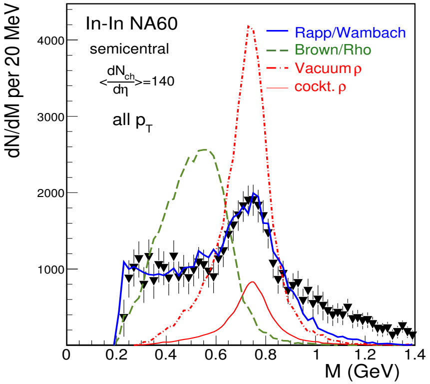


HADES Collab., submitted
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131
CG SMASH: J. Staudenmaier et al., arXiv:1711.10297v1
HSD: Phys. Rev. C 87, 064907 (2013)

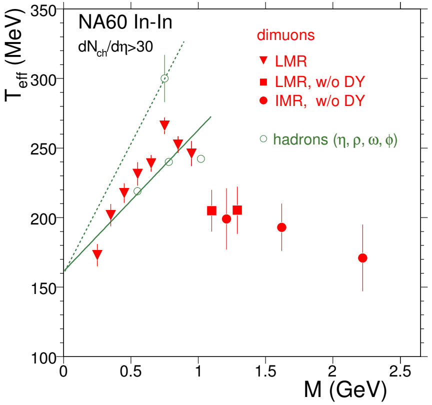
arXiv-1011-0615 HansSpecht ThermalDileptons_NA60
arXiv-0603-0084 RalfRapp on NA60

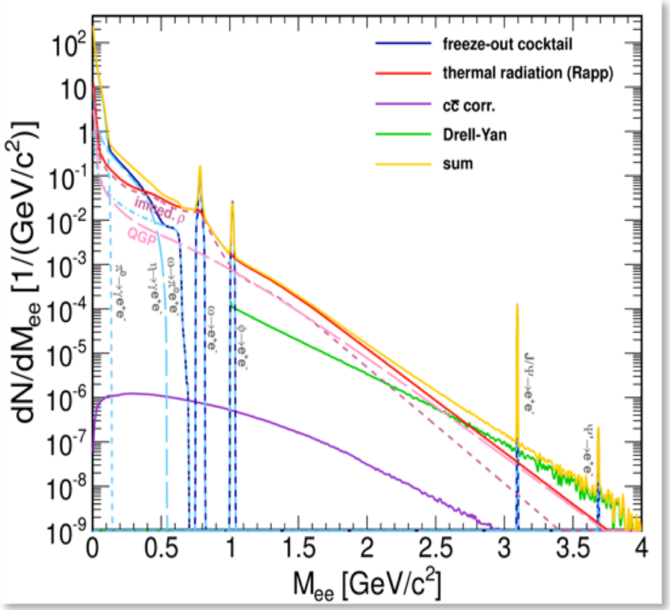
Dileptons as ...

Spectrometer



Barometer ($dN/dp_\perp$)

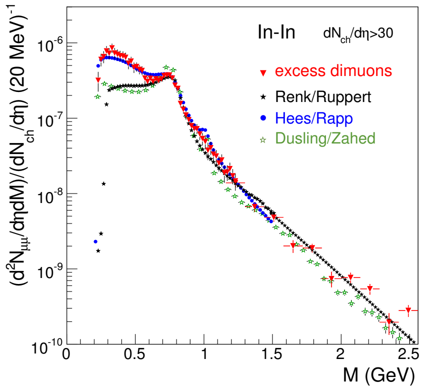




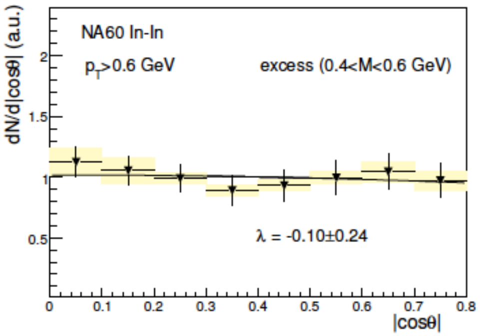
All data from NA60

... of the fireball

Thermometer



Polarimeter



Rapp, Hees Phys.Lett. B753 (2016) 586-590 | Speranza, Jaiswal, Friman Phys.Lett. B782 (2018) 395-400

ρ SPECTRAL FUNCTION AND χ SYMMETRY RESTORATION

Vector Meson Dominance in Hot & Dense Matter

Generalized „Bremsstrahlung“ – Fourier transform of current-current correlation function $\langle \mathrm{j(x), j(0)} \rangle$:

L. McLerran, K. Toimela, Phys. Rev. D31 (1985)

$$\Pi^{\mu\nu}_{EM}(q) = \int d^4x e^{iqx}\,\Theta(x_0)\langle [j^{\mu}_{EM}(x), j^{\nu}_{EM}(0)]\rangle_T$$

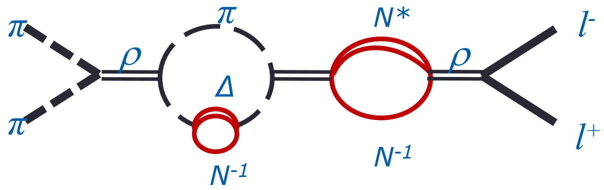
Extension of the Gounaris-Sakurai formula to a thermal pion gas: *C. Gale, J. Kapusta: Nucl. Phys. B357 (1991) 65*

$$j^{\mu}_{EM} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \frac{1}{3}\bar{s}\gamma^{\mu}s = \frac{1}{\sqrt{2}}j^{\mu}_{\rho} + \frac{1}{3\sqrt{2}}j^{\mu}_{\omega} - \frac{1}{3}j^{\mu}_{\phi}$$

Hadronic current can be approximated by the imaginary part of the in-medium ρ propagator.
Inclusion of meson-baryon coupling, ρ only:

$$\mathrm{Im}\Pi^{med.}_{EM}(M) = \left(\frac{m_{\rho}^2}{g_{\rho}}\right)^2 \mathrm{Im}D(M) \qquad D_{\rho}(M, q; \mu_B, T) = \frac{1}{(M^2 - m_{\rho}^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho M} - \Sigma_{\rho B})}$$

R. Rapp, J. Wambach: Adv.Nucl.Phys. 25 (2000) 1
B. Friman, Nucl. Phys. A610 (1996) 358c;
B. Friman and H.J. Pirner, Nucl. Phys. A617 (1997) 496



The in-medium ρ spectral function

Strong broadening of the in-medium due to its coupling to baryon-hole states.

The in-medium electromagnetic current-current correlator can be derived based on the basis of VDM using a many-body-like diagrammatic approach

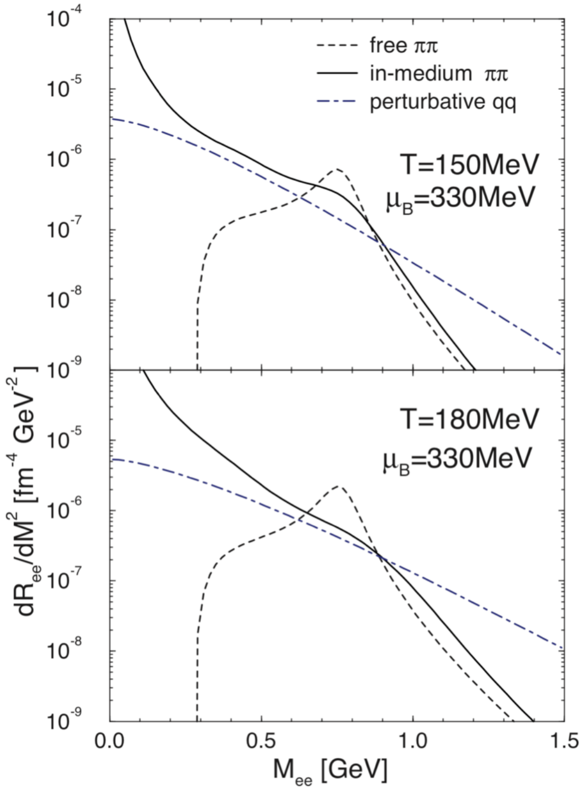
$$\mathrm{Im}\Pi_{em} = \sum \frac{m_V^4}{g_V^2} \mathrm{Im}D_V$$

with the meson propagator (spectral function)

$$D_\rho^{T,L} = \left[M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi}^{T,L} - \Sigma_{\rho M}^{T,L} - \Sigma_{\rho B}^{T,L}\right]^{-1}$$

where T, V stand for the transverse and longitudinal projection, respectively.

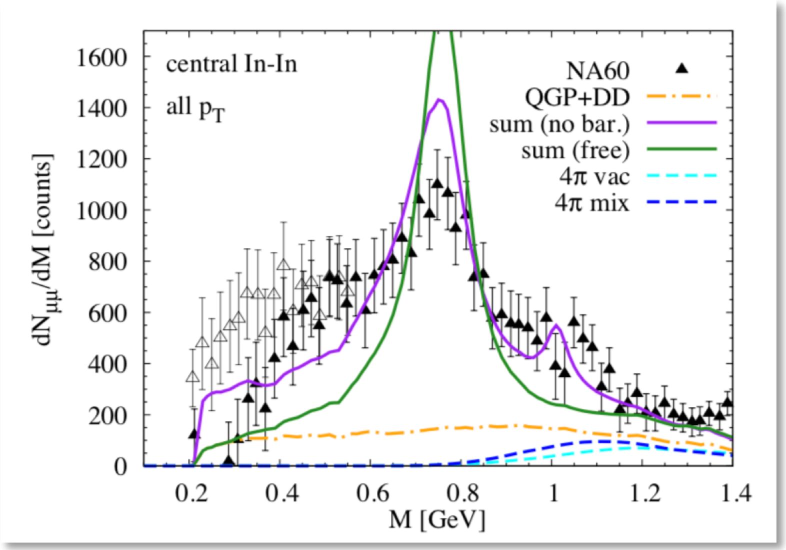
Needs detailed understanding of $\boldsymbol{B_2 \to N\rho}$ and $\boldsymbol{B_3 \to B_1\rho}$ with $(B_1 \to N\pi)$



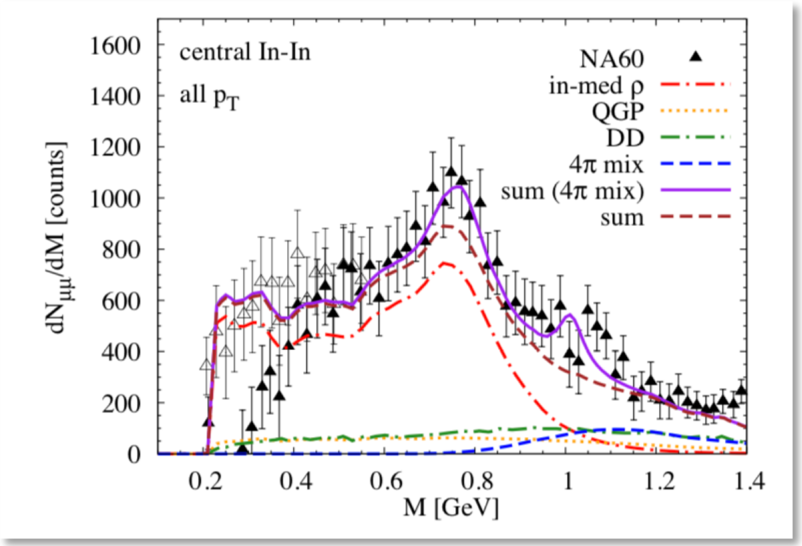
R. Rapp, J. Wambach – hep-ph:9907502

NA60 ρ spectral function

without baryon effects



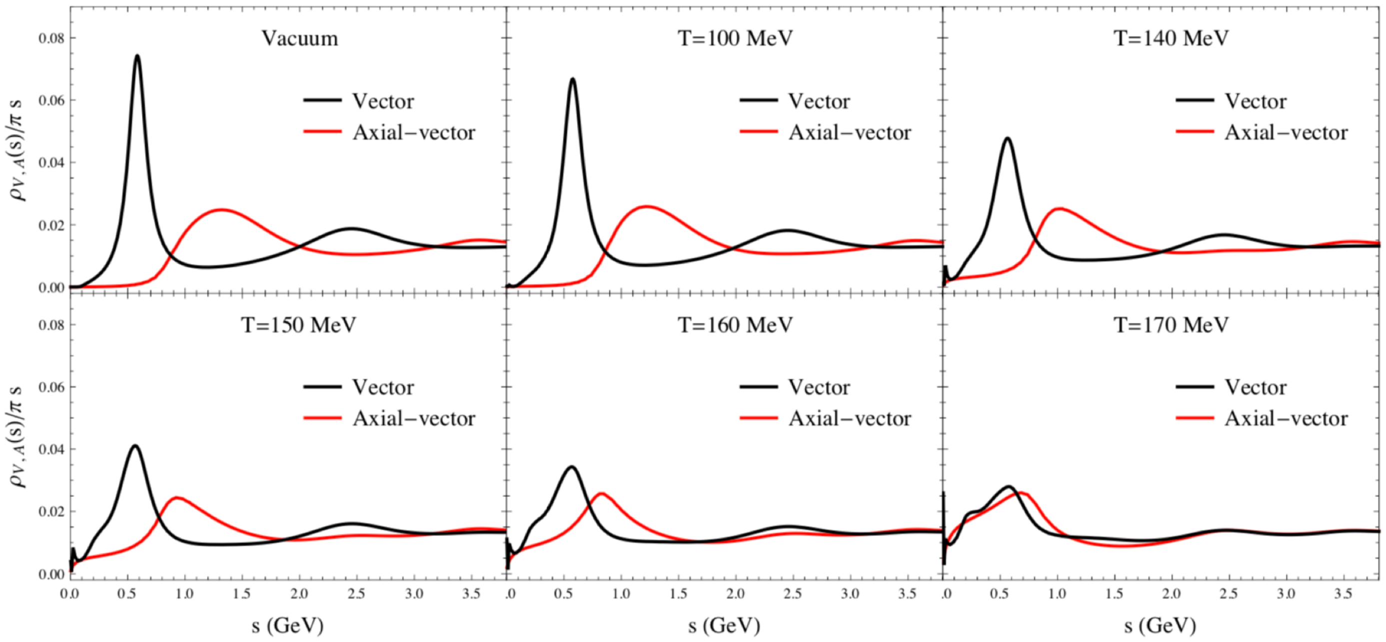
with baryon effects



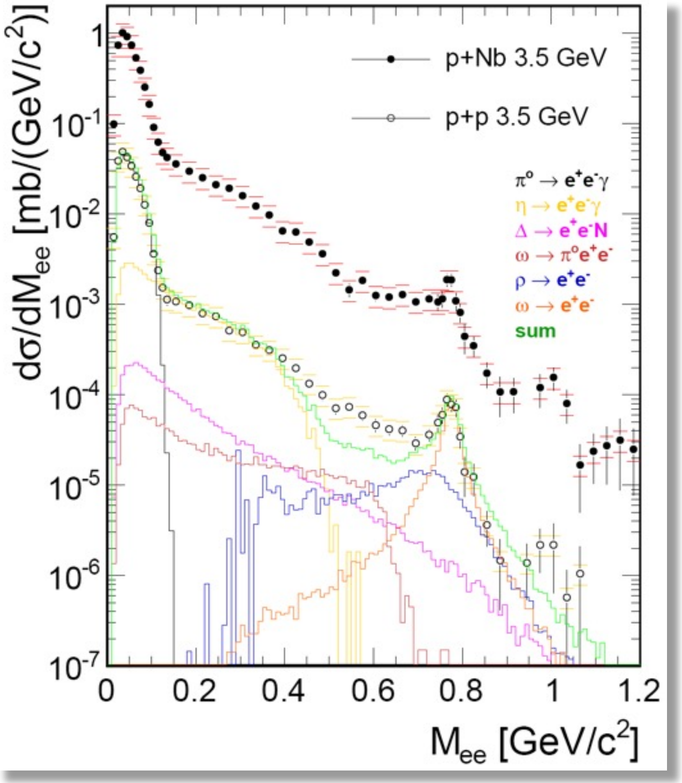
R. Rapp, J. Wambach – hep-ph:9907502

$\rho - a_1$ mixing

Rigorous consequence of chiral symmetry restoration – „alignement" of spectral densities for parity doublets: Weinberg sum-rules.



Dilepton emission in pp and pA collisions

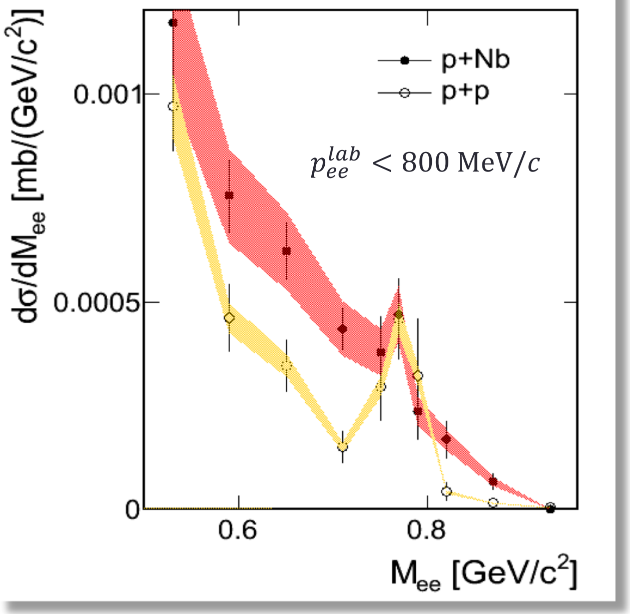


First measurement of ω decay in cold matter in the relevant momentum range. Indication for strong broadening of the ω.

p+p:
extraction of inclusive cross sections by fitting conventional sources to the experimental spectrum:

π°:	17 ± 2.7 ± 1 mb
Δ:	7.5 ± 1.7 mb
η:	1.14 ± 0.2 mb
ω:	0.273 ± 0.07 mb
ρ:	0.223 ± 0.06 mb

p+Nb:
Strong reduction of the ω peak.



STRANGENESS PRODUCTION AND THERMALIZATION

The Hadron Resonance Gas Equation-of-State

Additional ***strange baryons*** beyond PDG (as predicted by quark models and observed in lQCD calculations) change the EOS of the HRG and brings it closer to lattice results (1404.6511).

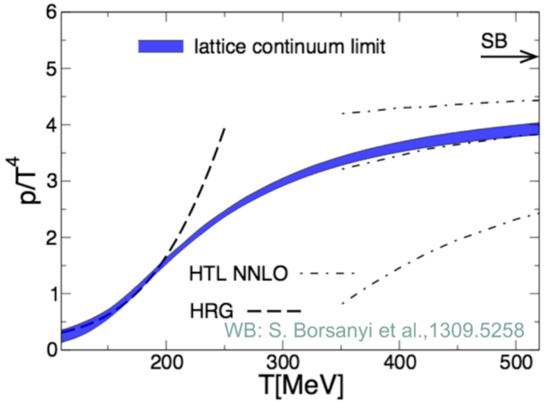
The pressure for an non-interacting HRG is given by

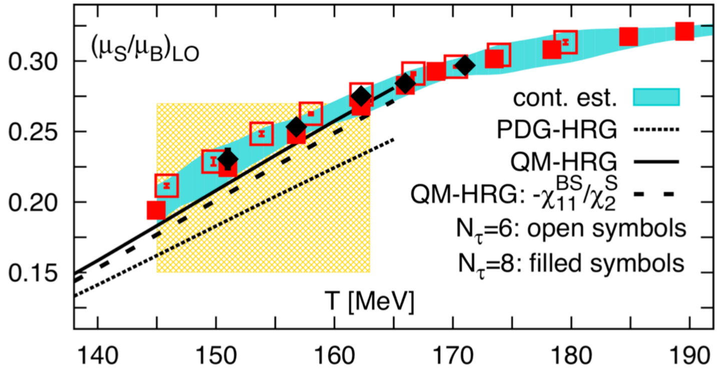
$$\frac{p_{HRG}}{T^4} = \frac{1}{VT^3}\left[\sum_{i\,\in mesons} \ln Z^M_{m_i}(T,V,\mu_x) + \sum_{i\,\in\, baryons} \ln Z^B_{m_i}(T,V,\mu_x)\right]$$

where

$$\ln Z^{M/B}_{m_i} = \mp \frac{V d_i}{2\pi^2}\int_0^\infty dk\, k^2 \ln\left(1 \mp z_i e^{-\epsilon_i/T}\right)$$

is the logarithm of the partition function with the particle's energy/momentum ϵ_i/k_i, degeneracy d_i and fugacities z_i (for all conserved charges B, Q, S, etc.)

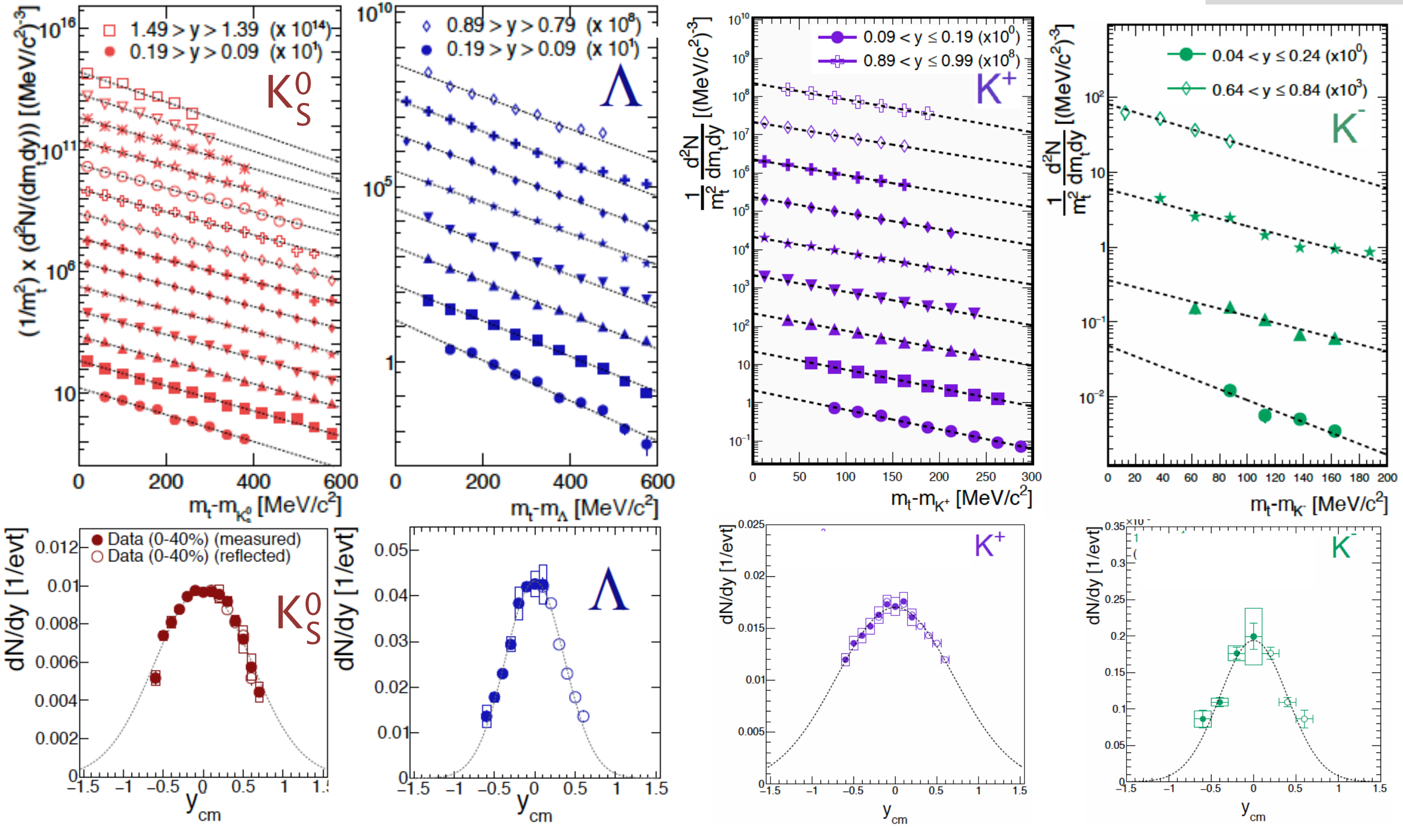




B: A. Bazavov et al. 1404.6511

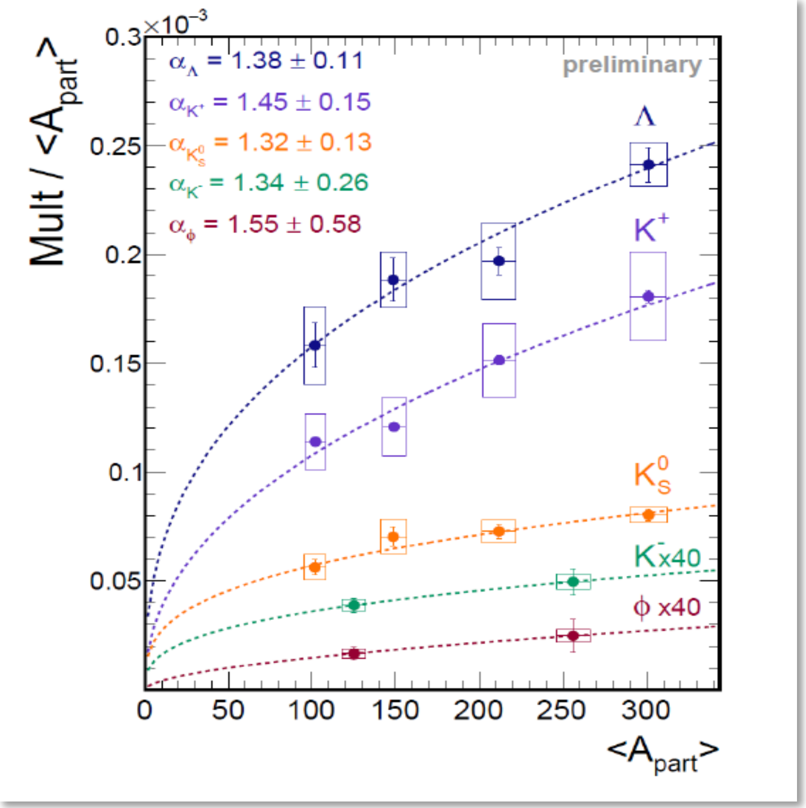
Reconstructed Open Strangeness

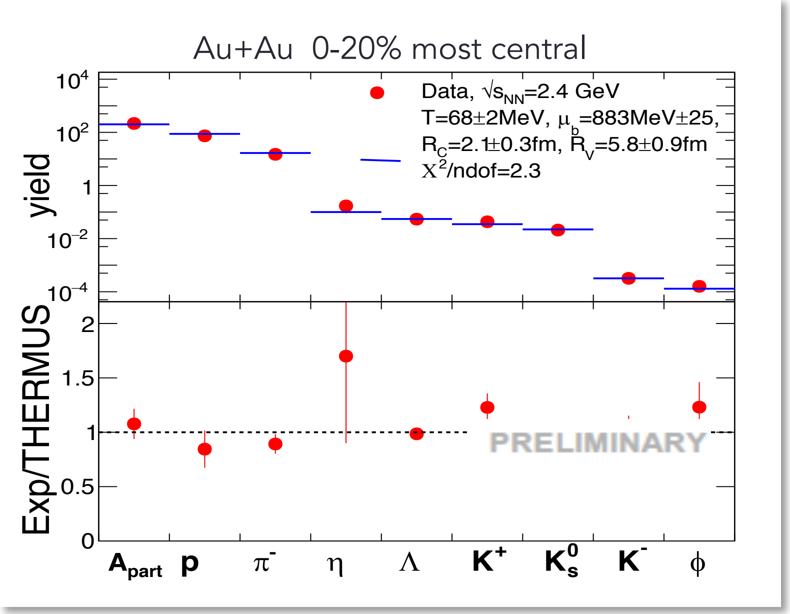
Au+Au @ $\sqrt{s} = 2.4\ A$ GeV



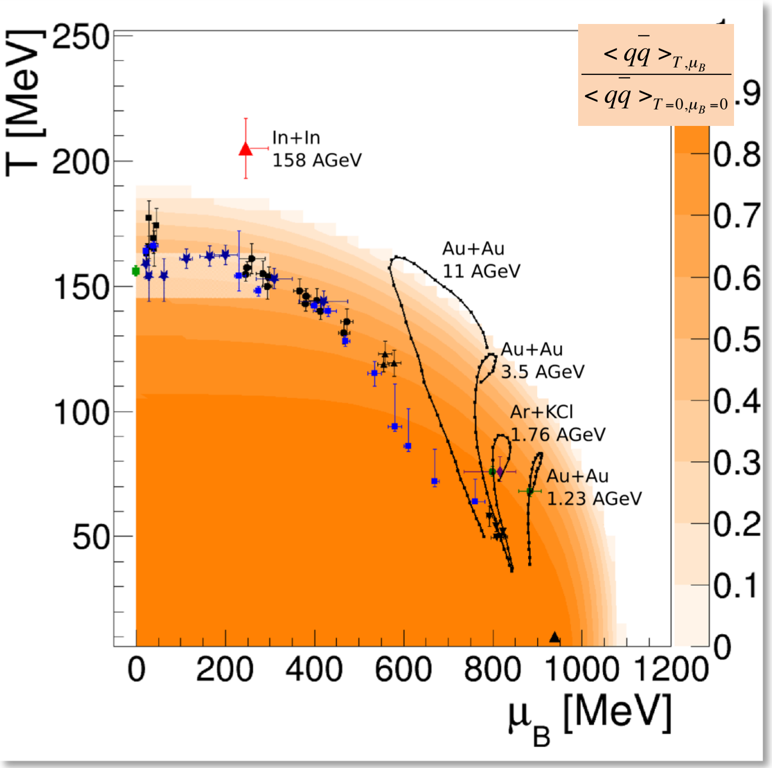
Yields

- All strange hadrons are produced below the free NN threshold: $K^+\Lambda$ $(-160\ \mathrm{MeV})$; K^+K^- $(-470\ \mathrm{MeV})$
- Canonical suppression applied in THERMUS (R_c), ϕ not affected.

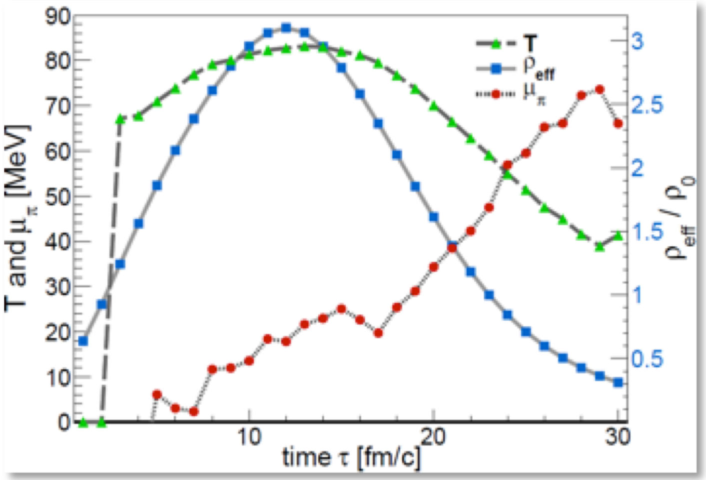


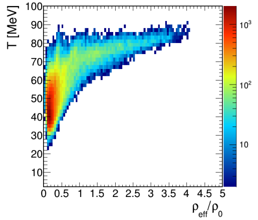


Phase space trajectories from Coarse Grained Transport

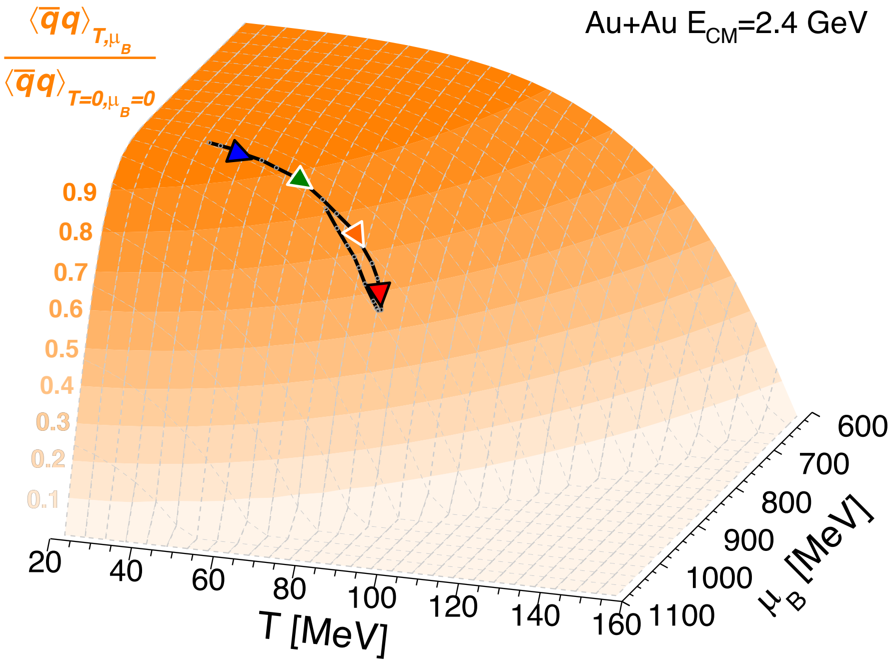


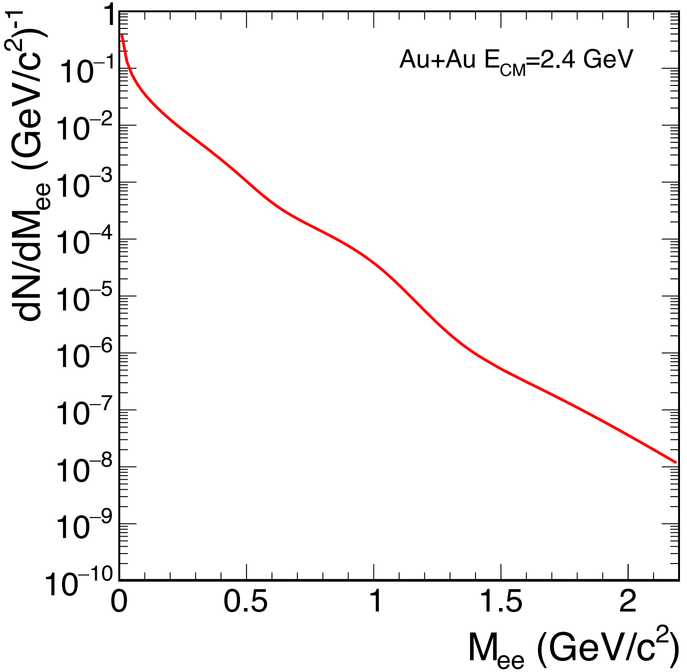
UrQMD, coarse grained in $1\mathrm{fm}^3 \times 1\mathrm{fm}/c$ cells





Dependence of the Emissivity (Standard Candle)

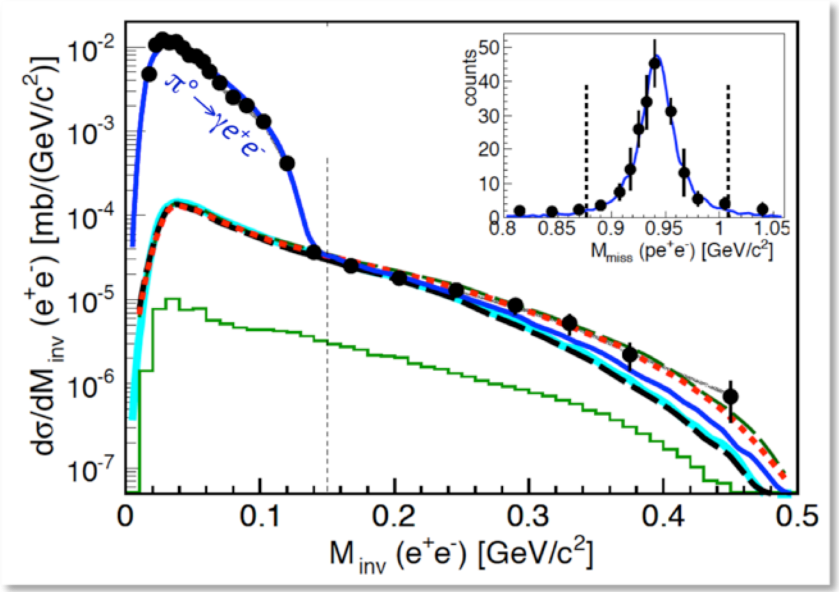




Chiral condensate a.f.o. temperature T and chemical potential μ_B. Shown is the ecpected trajectory of the central region of the heavy-ion collision.

TESTS OF VDM IN EM BARYON TRANSITIONS

Dielectron from $p(1.25\,GeV)p \rightarrow ppe^+e^-$ reactions



- QED
- I&W
- R&P quark core
- R&P pion cloud
- S&M brems.

HADES Collab. Phys.Rev. C95 (2017) 065205

Krivoruchenkoet al. Phys. Rev. D65(2002) 017502
Iachello, Wan Int. J Mod. Phys. A20 (2005) 1846
Ramalho, Peña, Phys. Rev. D85(2012) 113014
Shyam, Mosel, PRC82 (2010)062201

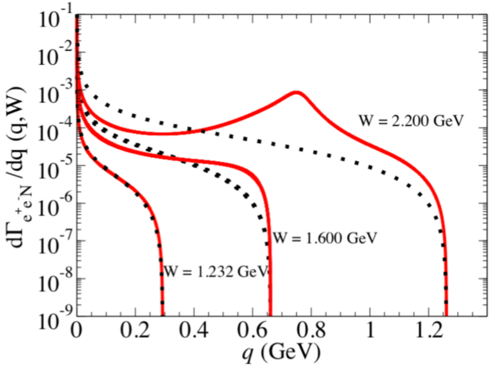
First measurement of the $\Delta(1232) \rightarrow Ne^+e^-$ branching ratio.

BR= $4.19 \pm 0.42^{model} \pm 0.46^{syst.} \pm 0.34^{stat.} \times 10^{-5}$

Access to the electromagnetic transition form factor:

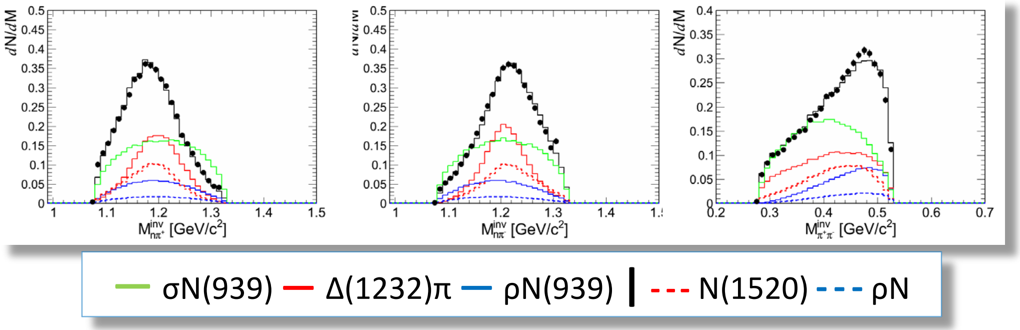
- Significant deviation from point-like (QED)
- Indication for off-shell formation in the meson cloud
- (Ramalho, Pena)

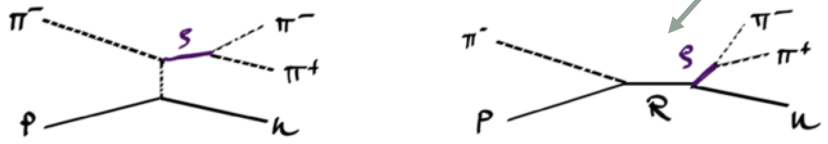
G. Ramalho T. Pena, 1512-03764



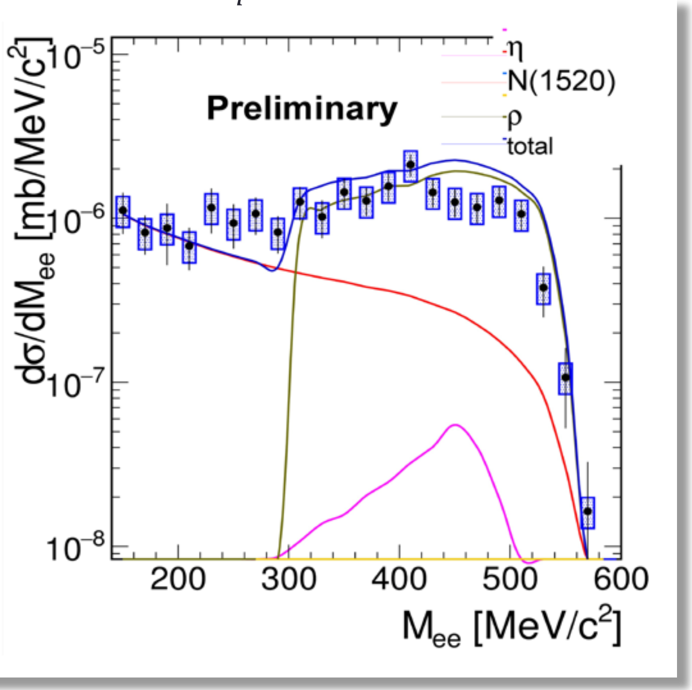
VMD scrutinized ($\pi^- p$ reactions)

$\pi^- + p \rightarrow \pi^- + \pi^+ + n\,;\quad p_{\pi^-} = [656, 690, 748, 800]$ MeV





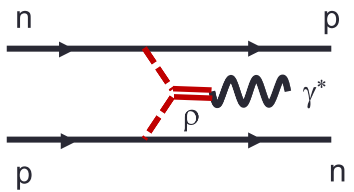
$\pi^- + p \rightarrow e^- + e^+ + n$

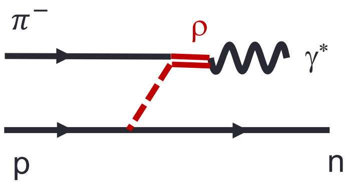


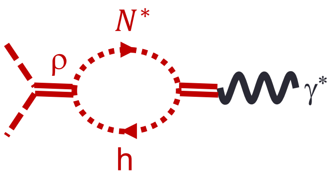
Evidence for intermediate ρ propagation (VMD) in both s and t-channel.

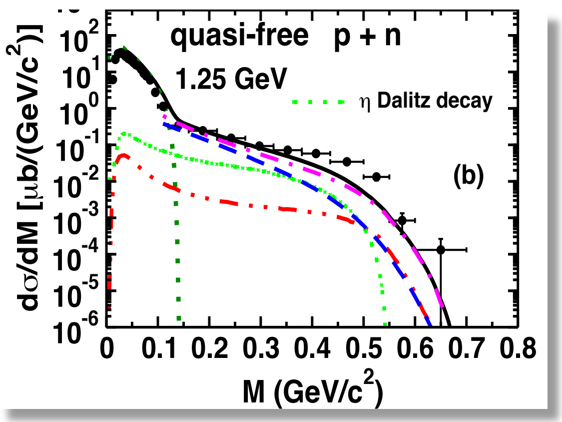
The role of virtual pions in dilepton production

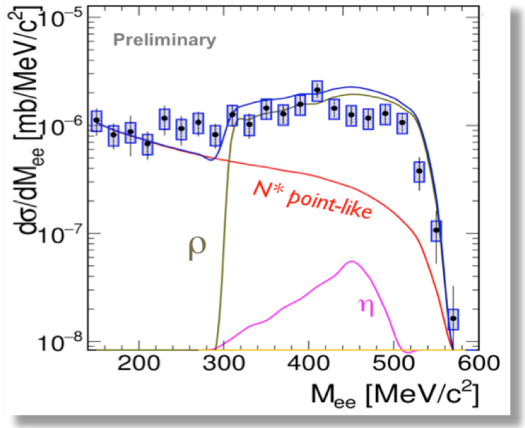
- HADES results for different collision energies.
- Dilepton production involves virtual pions (cloud of baryons)

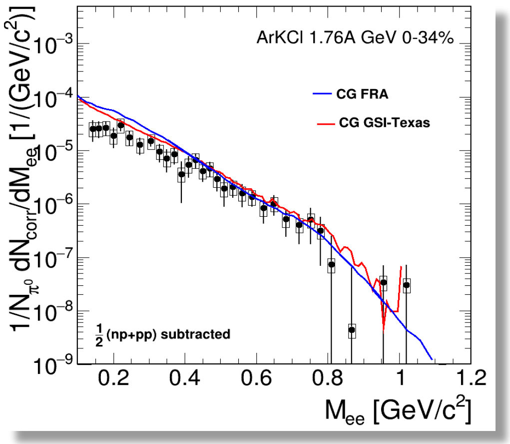












Summary

Dileptons are a formidable tool to ***explore the microscopic structure*** of QCD matter under extreme conditions of temperature and density.

To extract the ***thermal radiation*** with good precision, a detailed knowledge of dilepton radiation from „conventional“ sources is needed (hard processes and meson decays).

The emissivity of hot and dense QCD matter encodes properties of the ***in-medium*** ρ meson and can serve as a "standard candle" of such matter.

Thermal radiation is mediated by intermediary ρ meson which are substantially modified in-medium through their ***coupling to baryon resonances*** (besides the dressing of its pion cloud).

Exclusive measurements of dilepton production off protons in proton and pion beam induced reactions can ***constrain the model calculation*** of the emissivity.