Dileptons from Heavy-Ion Collisions

past and future

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dedicated to Johanna Stachel

Motivation

URHIC's and photons

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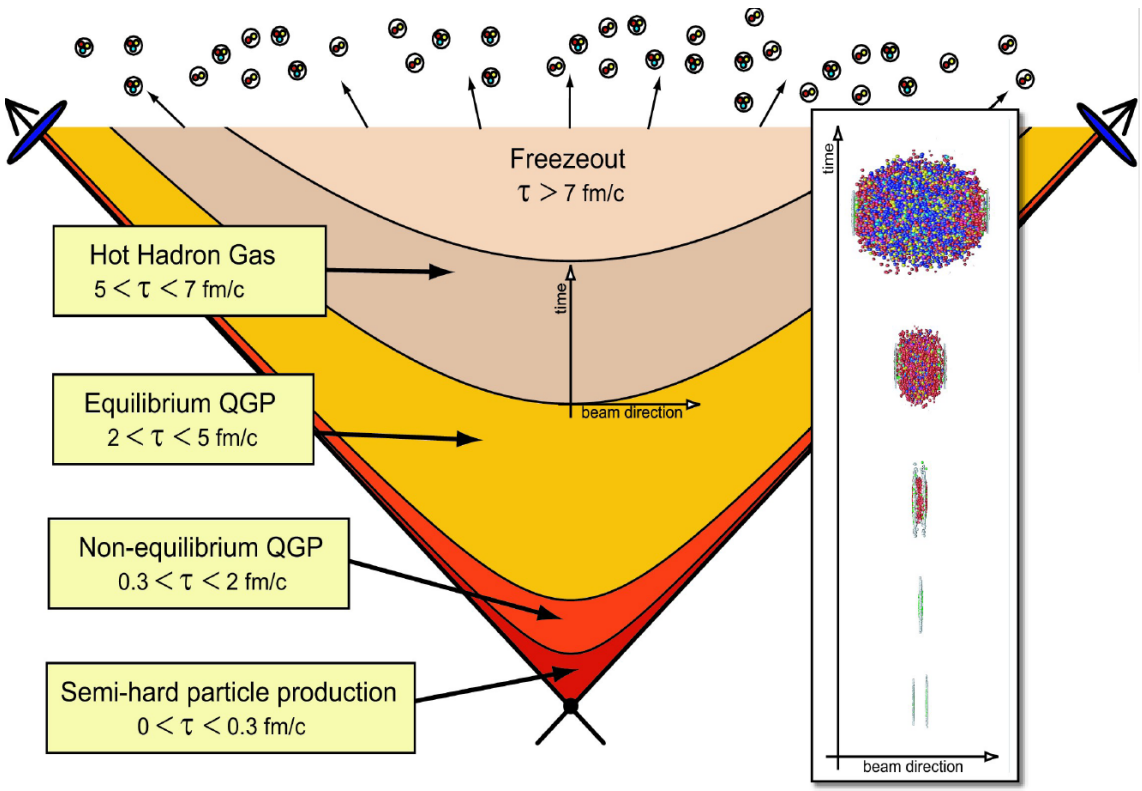
as compared to the size of the fireball photons have a long mean free path

$\rightarrow$ leave the interaction zone undisturbed

E. Feinberg, Nuovo Cimento A34, 391 (1976), E. Shuryak, Phys. Lett. B 78, 150 (1978)



Dileptons

theoretical background

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dilepton rate: (local thermal equilibrium)

$$\frac{dN_{l^+l^-}}{d^4x d^4q} \equiv \frac{d^4R}{dq^4} = L_{\mu\nu}(q) W^{\mu\nu}(q); \quad W^{\mu\nu}(q) = \frac{1}{e^{\omega/T}-1} \mathrm{Im}\Pi^{\mu\nu}_{em}(\omega, \vec{q})$$

electromagnetic correlator:

$$\Pi^{\mu\nu}_{em}(\omega, \vec{q}) = -i \int d^4x \; e^{i(\omega t - \vec{x}\cdot\vec{q})} \Theta(t) \left\langle \left[j^\mu_{em}(x), j^\nu_{em}(0) \right] \right\rangle$$

electromagnetic current: (below $2m_c$)

$$j^\mu_{em} = \frac{2}{3} \bar{u}\gamma^\mu u - \frac{1}{3} \bar{u}\gamma^\mu d - \frac{1}{3} \bar{s}\gamma^\mu s$$

vacuum:

$$\mathcal{R}(M) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = -\frac{12\pi}{M^2} \mathrm{Im}\Pi^{vac}_{em}(M)$$

Dileptons

e^+e^- - annihilation in the vacuum

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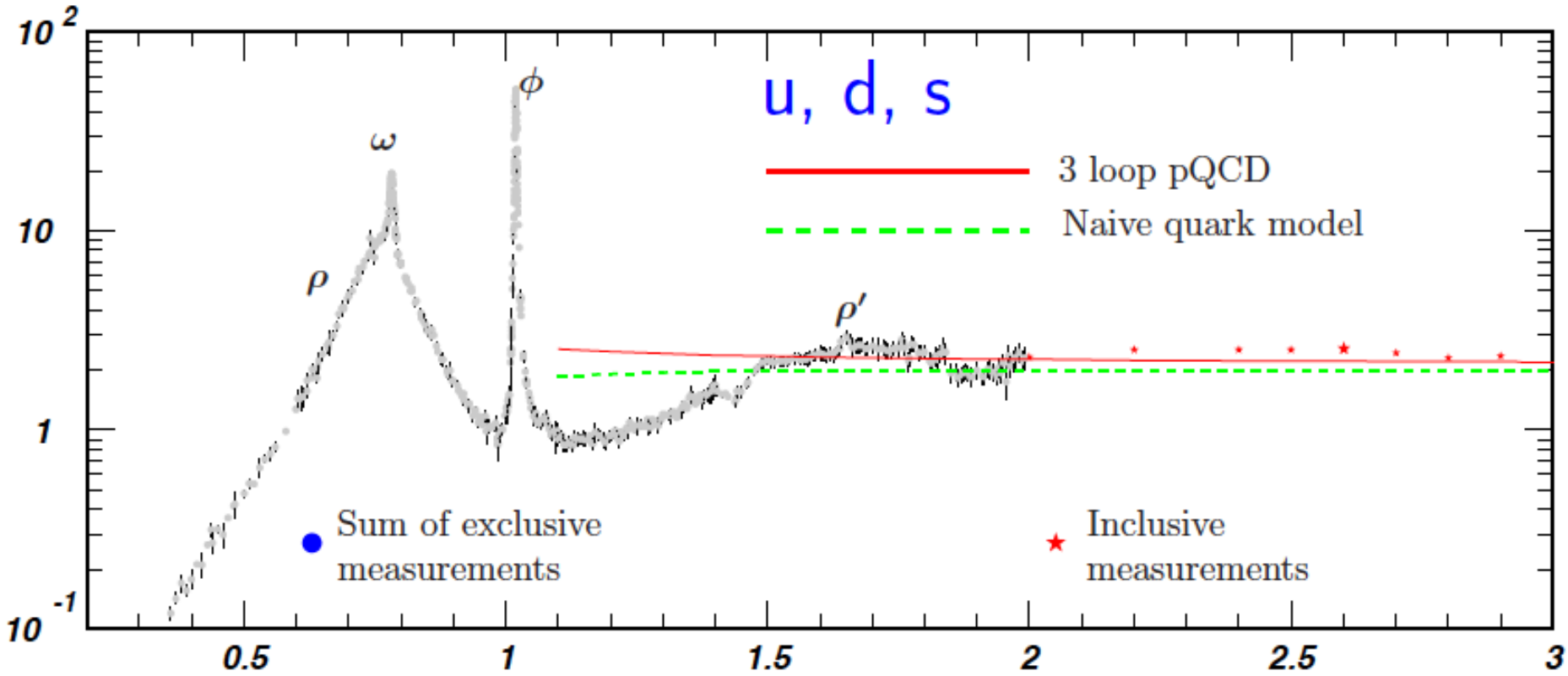

$$\text{quarks}: \quad \mathcal{R}^q = N_c \sum_i e_i^2 = 3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}\right) = 2$$

Low-mass Dileptons

theoretical background

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two regimes:

VDM: $$j^\mu_{em} = \frac{m_\rho^2}{g_\rho}\rho^\mu + \frac{m_\omega^2}{g_\omega}\omega^\mu + \frac{m_\phi^2}{g_\phi}\phi^\mu; \quad M < 1 \text{ GeV}$$

'partonic': $$j^\mu_{em} = \sum_{q=u,d,s} e_q \bar{q}\gamma^\mu q; \qquad 1.5 < M \leq 3 \text{ GeV}$$

with

$$j^\rho_\mu = \frac{1}{2}\left(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d\right); \quad j^\omega_\mu = \frac{1}{6}\left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right); \quad j^\phi_\mu = -\frac{1}{3}\left(\bar{s}\gamma_\mu s\right)$$

$$\rightarrow \quad \mathcal{R} \sim \left[\text{Im}D_\rho + \frac{1}{9}\text{Im}D_\omega + \frac{2}{9}\text{Im}D_\phi\right] \qquad \rho - \text{meson dominates!}$$

thus

$$\mathcal{R}(M) = -\frac{12\pi}{M^2}\begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \text{Im}D_V^{\text{vac}}(M) & , M < 1 \text{ GeV}, \\ -\frac{M^2}{12\pi}\left(1 + \frac{\alpha_s(M)}{\pi} + \ldots\right) N_c \sum_{q=u,d,s}(e_q)^2 & , M > 1.5 \text{ GeV} \end{cases}$$

Hadronic medium

Lattice EoS

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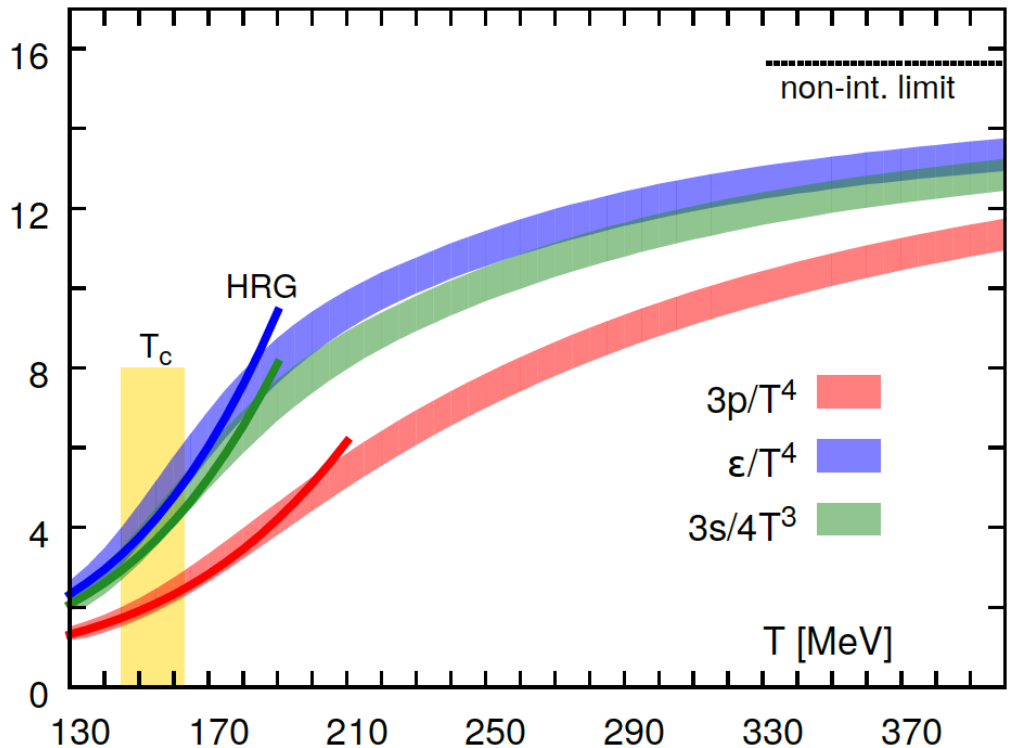
hot and dense gas of mesons and baryons



A. Bazavov et al. (HOTQCD Collaboration) arXix:1407.6387 [hep-lat]

in-medium modification of propagators described by hadronic many-body theory

ρ - meson

in the hadronic medium

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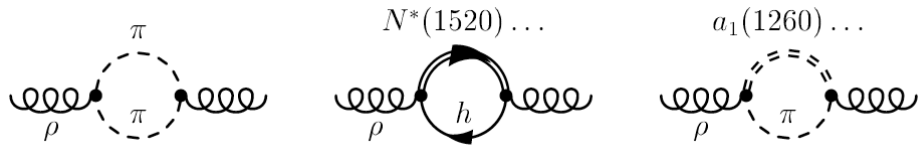
L/T decomposition relative to the heat bath:

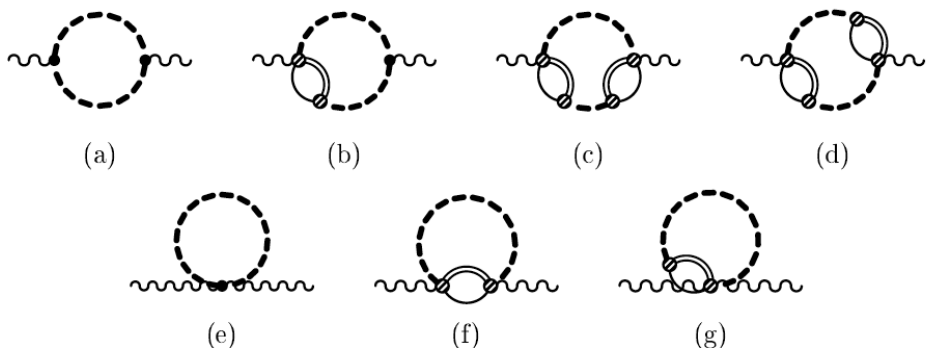
$$D_V^{\mu\nu} = \underbrace{\left(M^2 - m_V^2 - \Sigma_V^L(\omega,\vec{q})\right)^{-1}}_{\text{longitudinal: } D_V^L(\omega,\tilde{q})} P_L^{\mu\nu} + \underbrace{\left(M^2 - m_V^2 - \Sigma_V^T(\omega,\vec{q})\right)^{-1}}_{\text{transverse: } D_V^T(\omega,\tilde{q})} P_T^{\mu\nu}$$

ρ-meson selfenergy:

$$\Sigma_\rho^{L/T} = \Sigma_{\rho\pi\pi}^{L/T} + \Sigma_{\rho M}^{L/T} + \Sigma_{\rho B}^{L/T}$$



vertex corrections from dressed pions:



ρ - meson

in the hadronic medium

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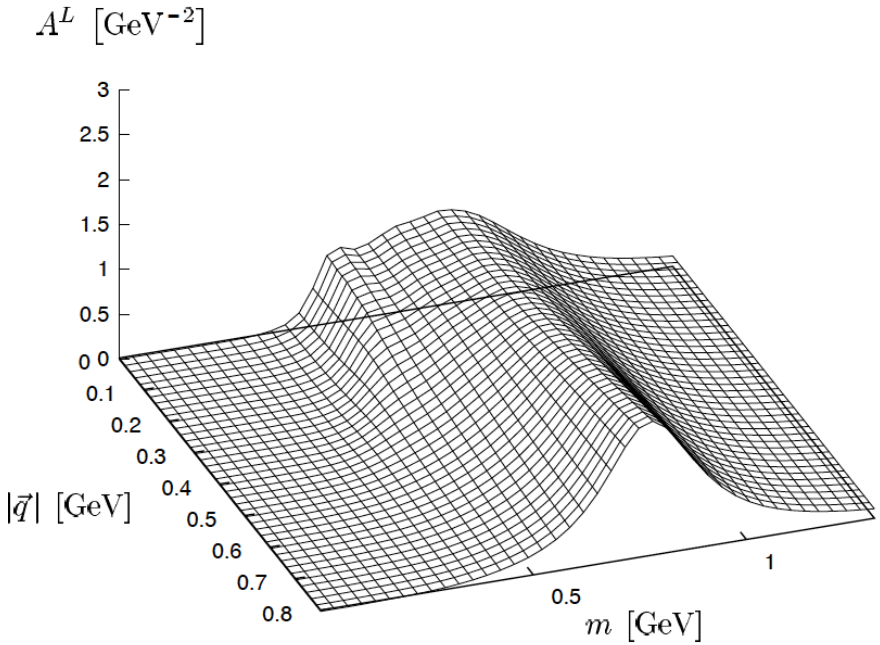
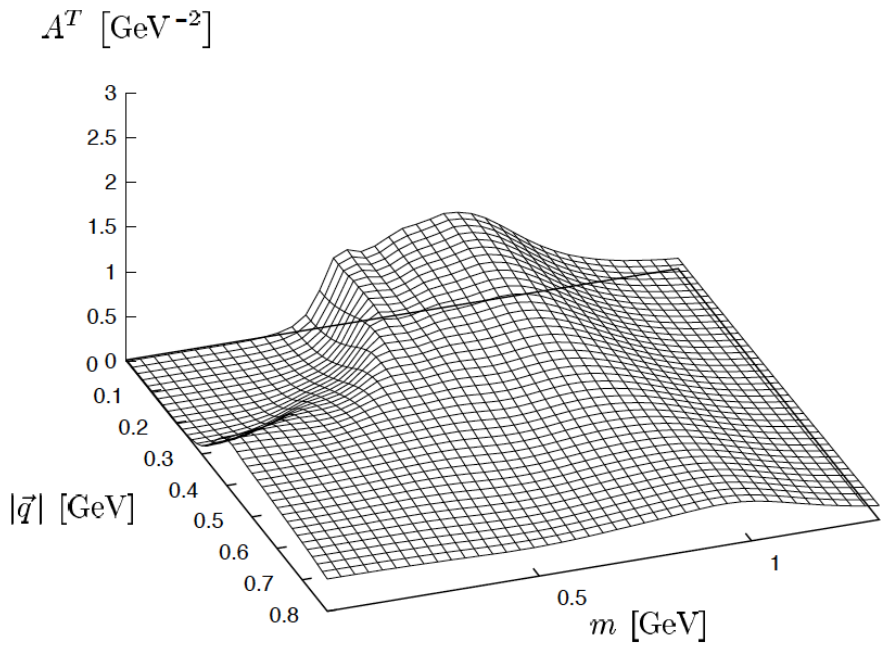
ρ-spectral functions: (low temperature)





W. Peters et al., Nucl. Phys. A632, 109 (1998)

ρ - meson

photoabsorption as a test

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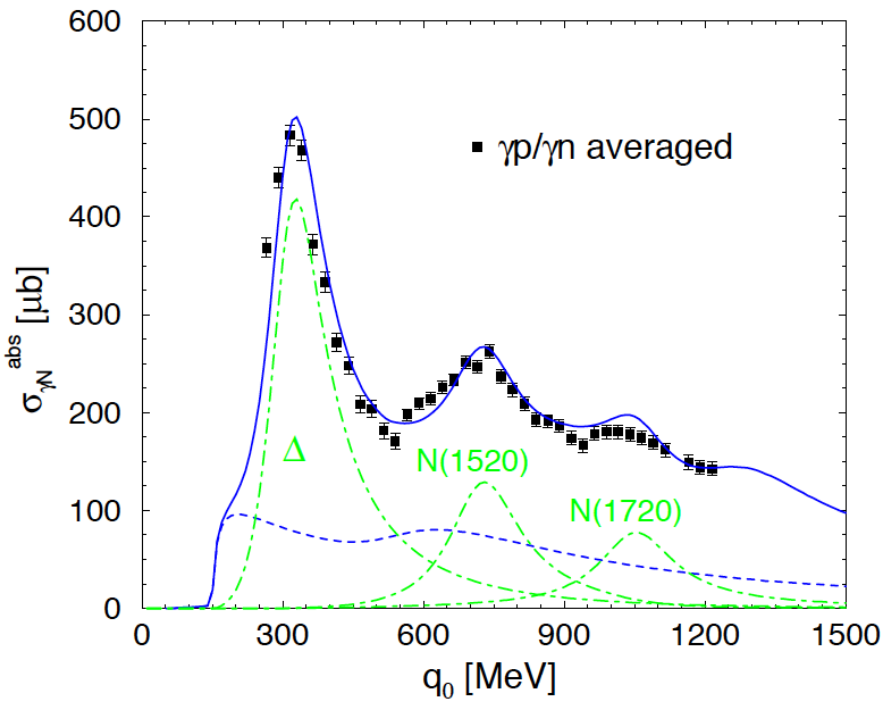
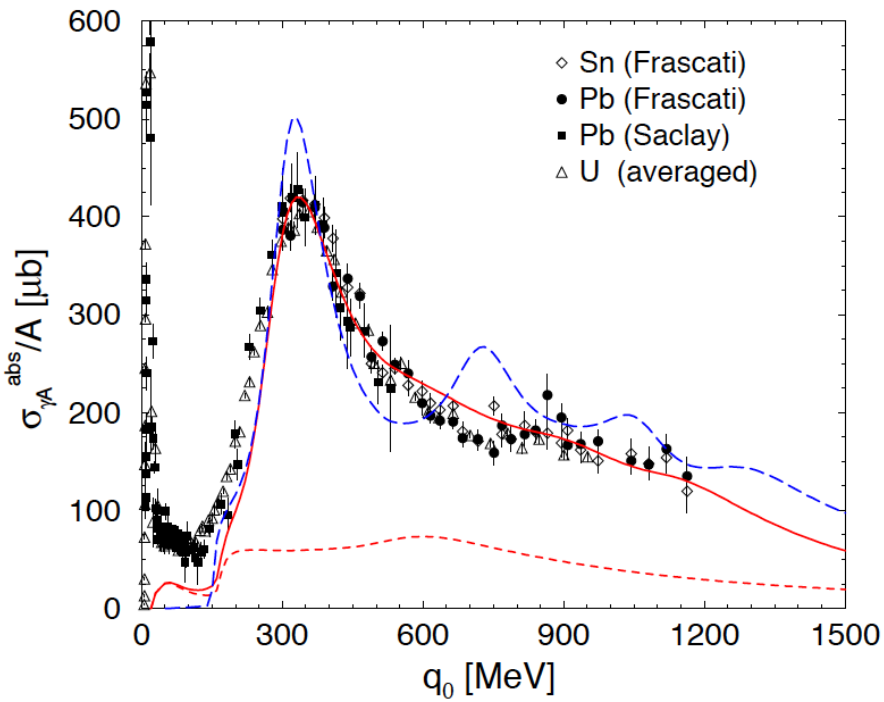
photo-absorption cross section:

$$\frac{\sigma_\gamma}{A} = -\frac{4\pi\alpha}{\omega}\frac{m_\rho^4}{g_\rho^2}\,\mathrm{Im}D_\rho^T(\omega, |\vec{q}| = \omega)$$

nucleon



nucleus



M. Urban et al., Nucl. Phys. A 641, 433 (1998); R. Rapp et al., Phys. Lett. B 417, 1 (1998)

Spectral Functions

in hat and dense matter

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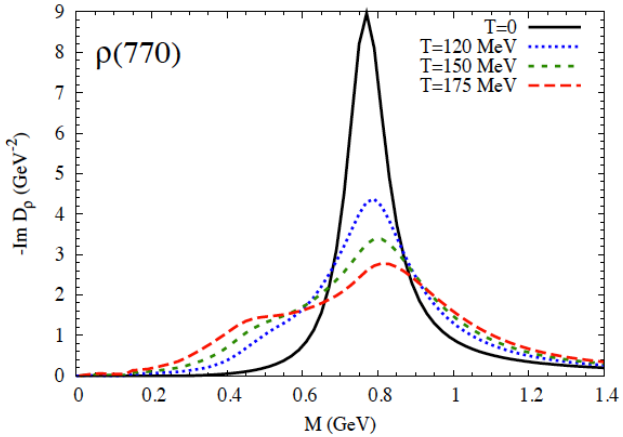
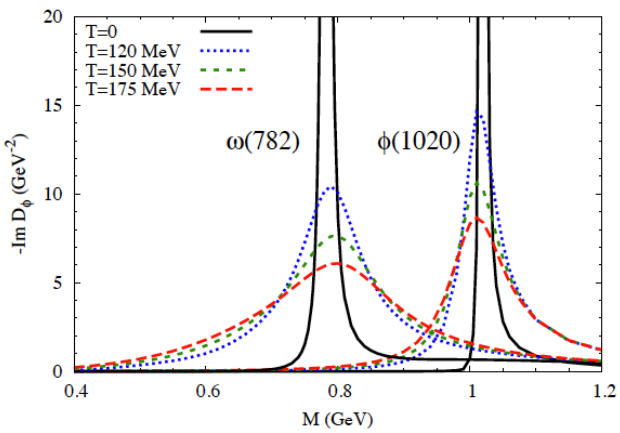
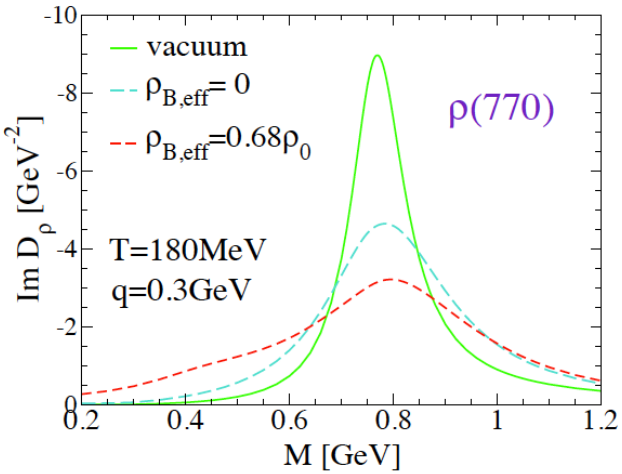
ρ-meson | ω and ϕ-meson

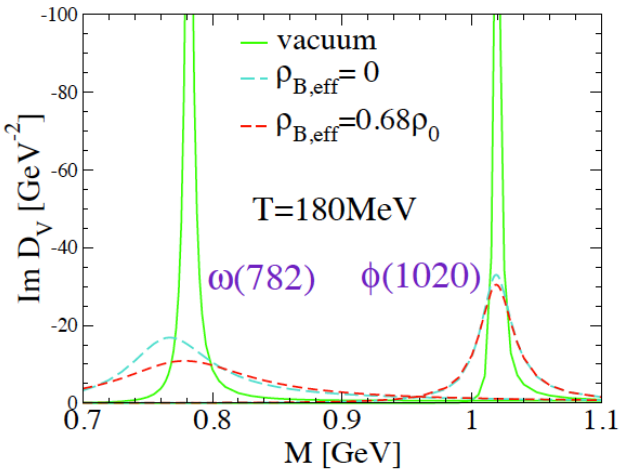
SPS
$\sqrt{s_{NN}}$=17 GeV





RHIC
$\sqrt{s_{NN}}$=200 GeV





H. van Hees and R. Rapp, Nucl. Phys. A 806, 339 (2008)

Dilepton Rates

SPS and RHIC conditions

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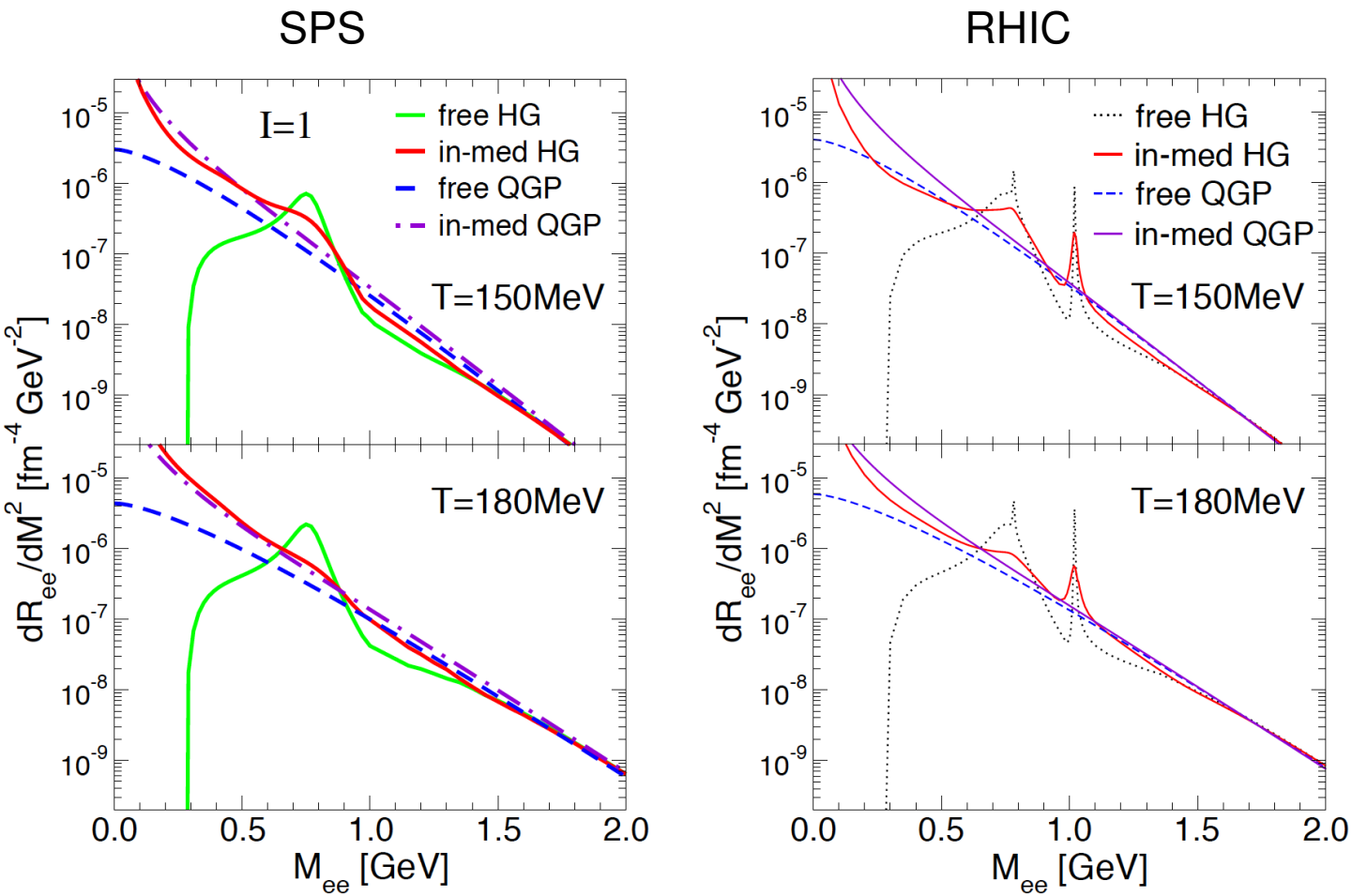

R. Rapp, Pramana 60, 675 (2003)

Dilepton Rates

LQCD-HTL comparison

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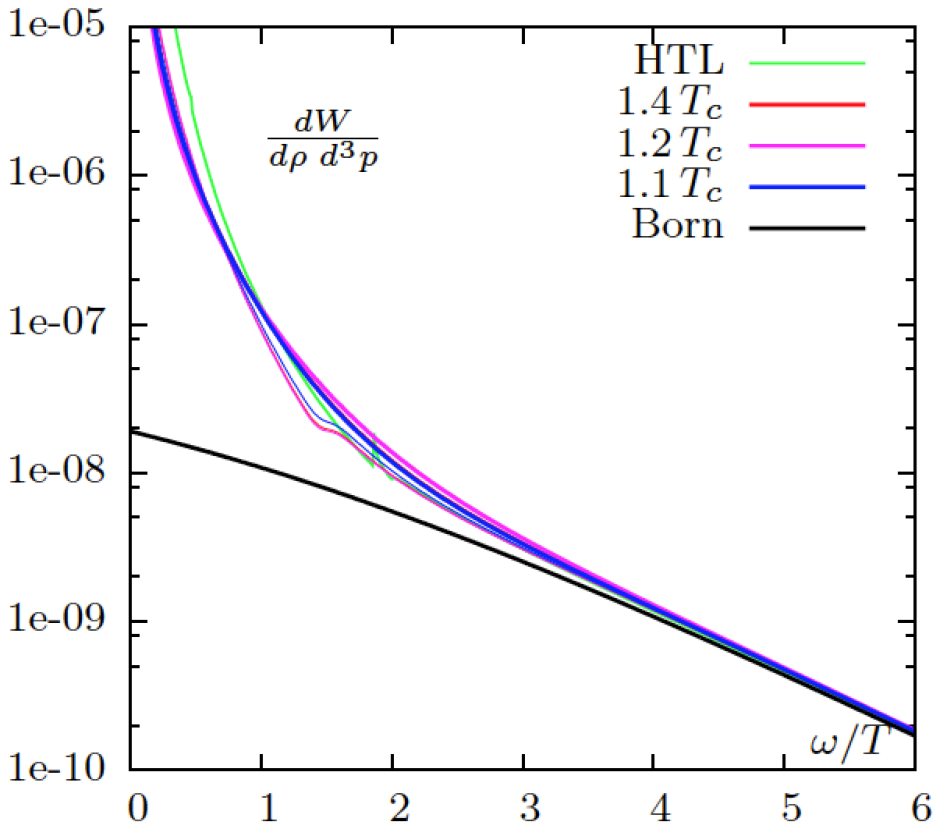

O. Kaczmarek and M. Müller, PoS (Lattice 2013) 175

H.-T. Ding et al., Phys. Rev. D83 034504 (2011)

Space-time Evolution

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$\frac{dN_{l^+l^-}}{d^4x d^4q}(x)$ has to be integrated over the space-time history

- blast-wave parametrizations
- ideal and viscous hydrodynamics
- transport descriptions
- coarse-grained transport theory

Dilepton Data

CERES

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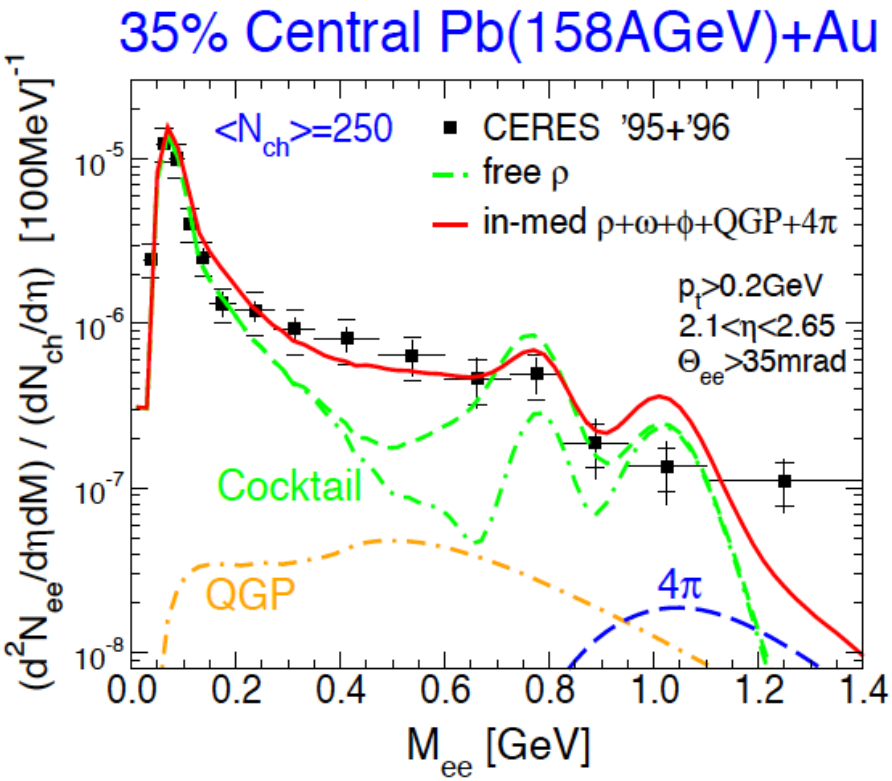

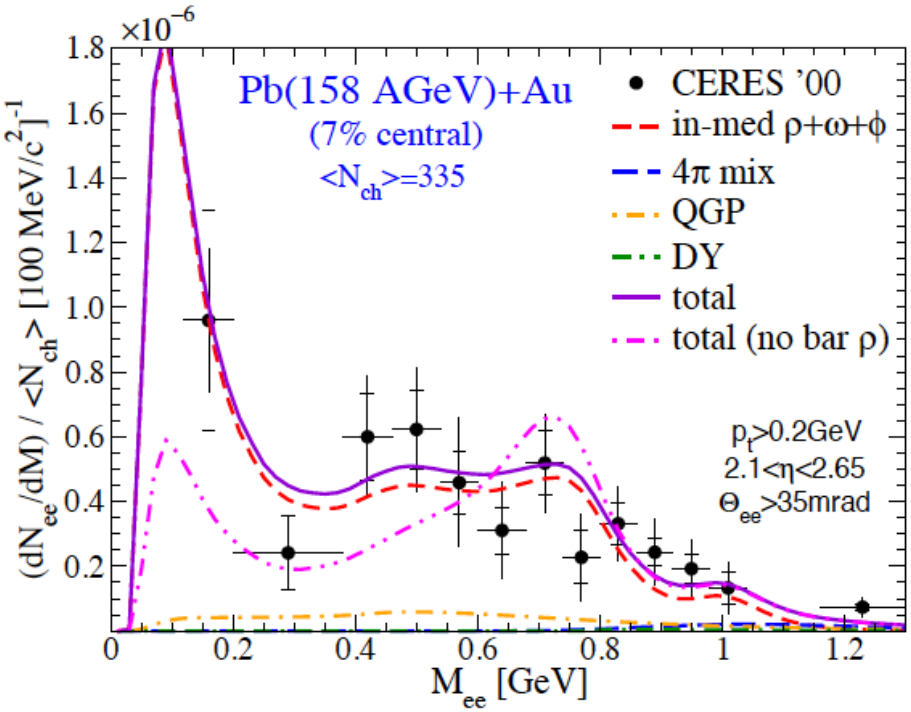

G. Agakichiev et al. (CERES/NA45 Collaboration), Eur. Phys. J. C 41, 475 (2005)
D. Adamova et al. (CERES/NA45 Collaboration), Phys. Lett. B 666, 425 (2008)

H. van Hees and R. Rapp, Nucl. Phys. A 806, 339 (2008)

Dilepton Data

STAR

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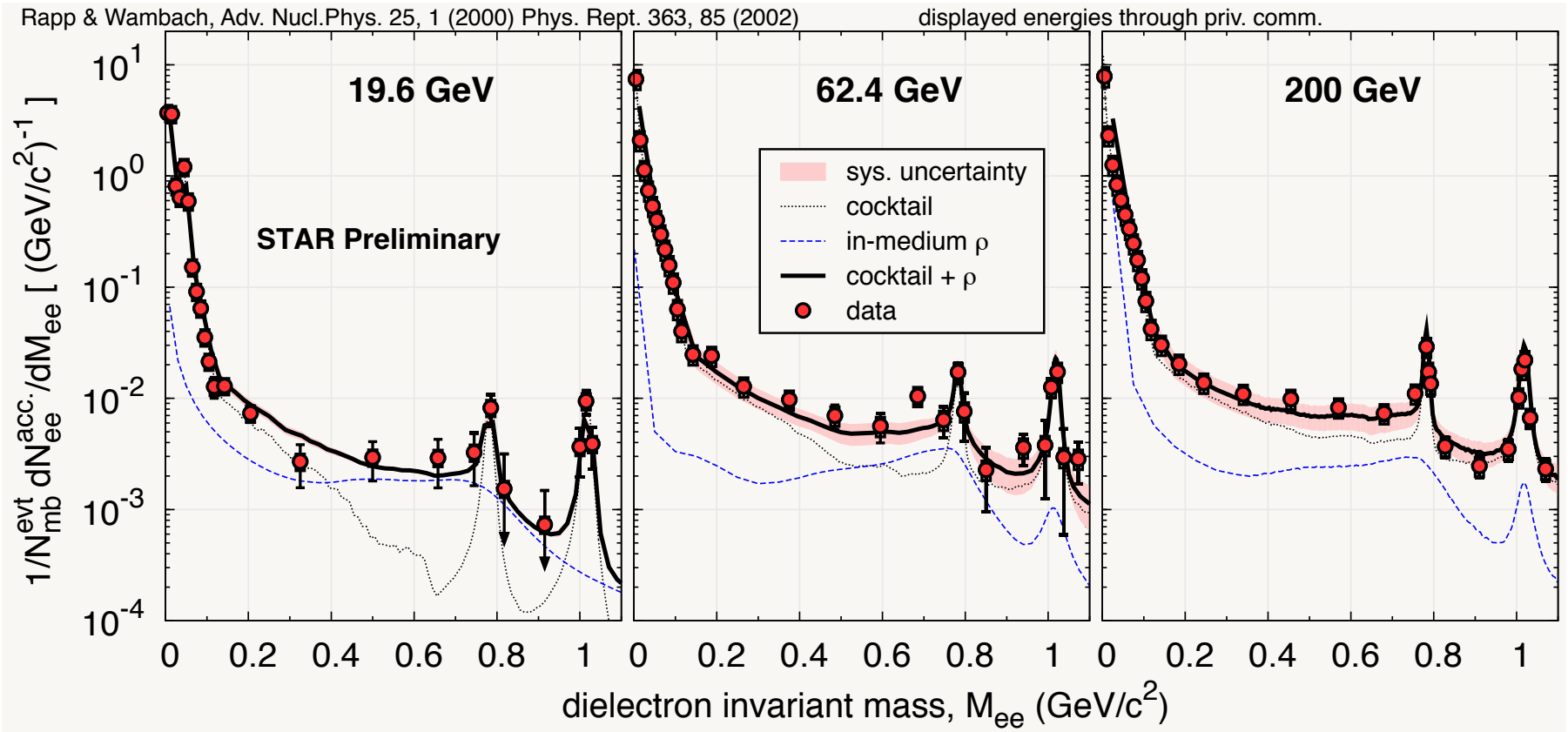

F. Geurts et al. (STARColl.), Nucl.Phys.A904-905 2013, 217c (2013)

Dilepton Data

NA60

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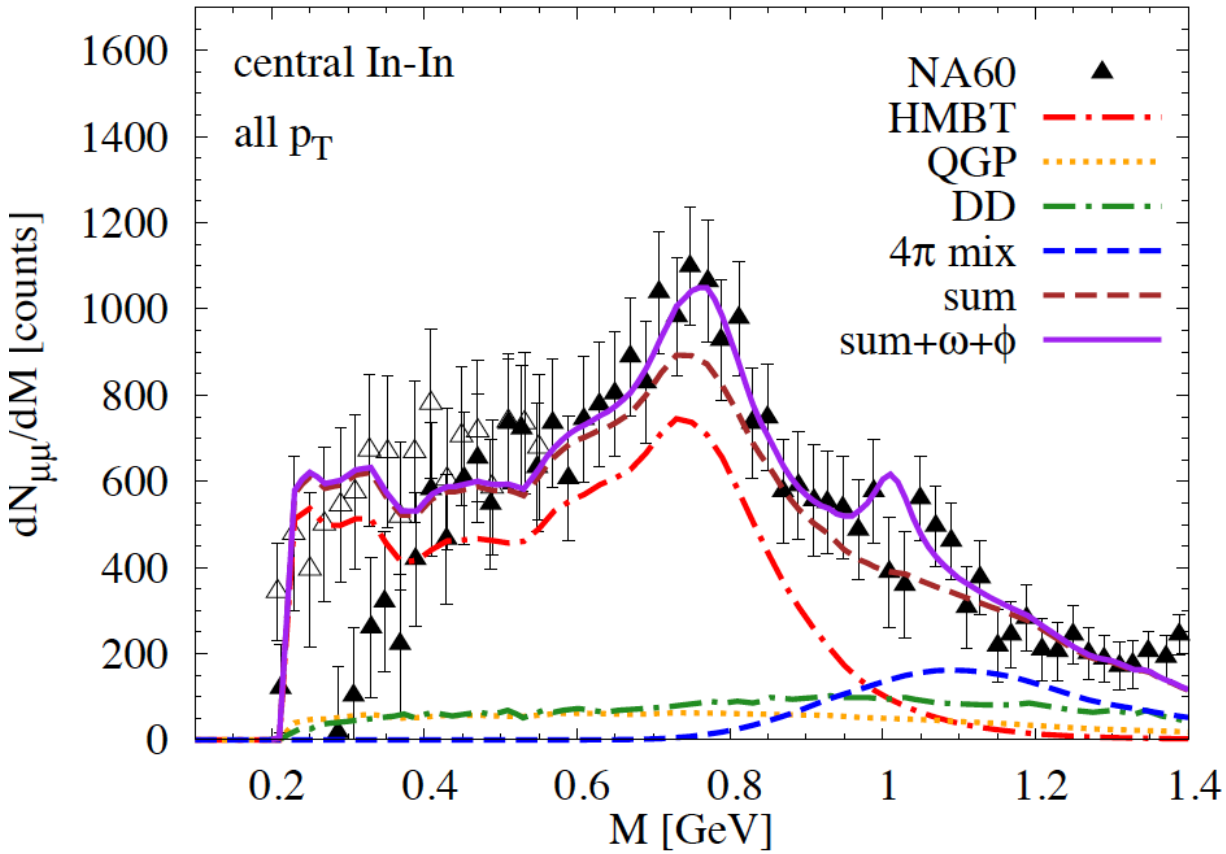

H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)

S. Damjanovic, Nucl.Phys. A774, 715 (2006)

Dilepton Data

NA60

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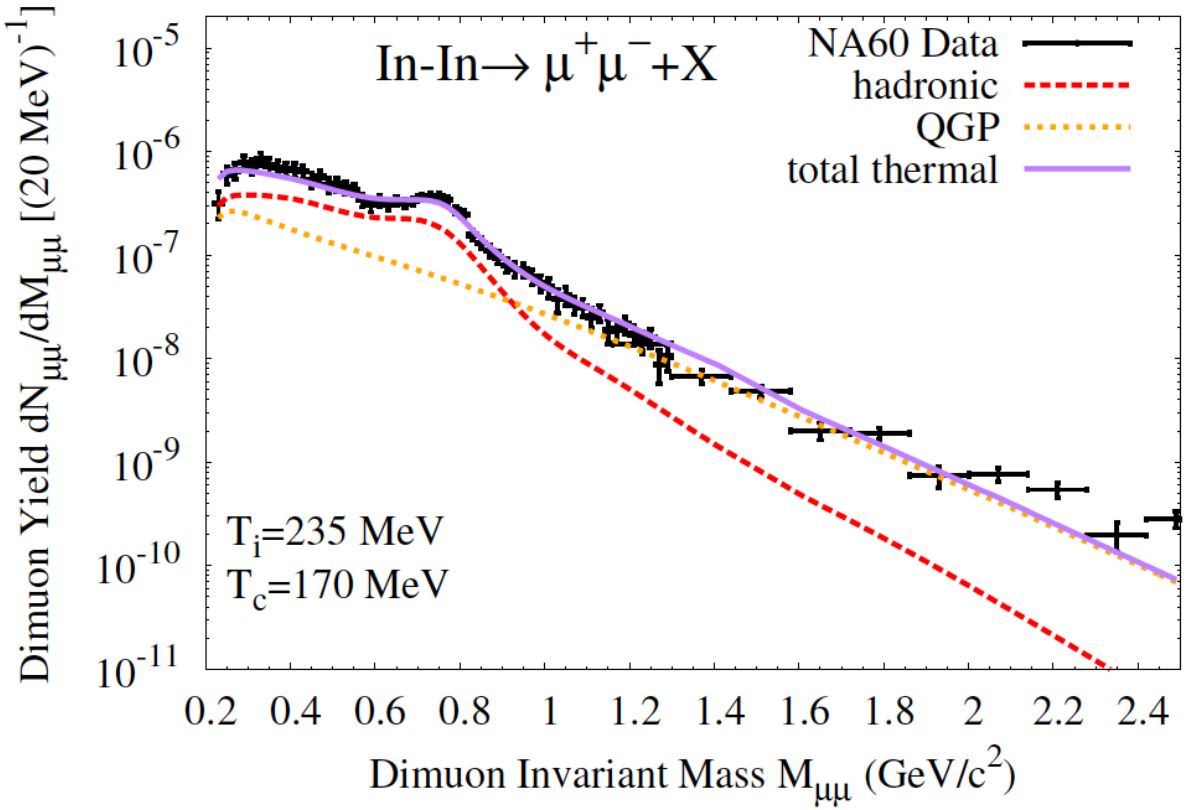

R. Rapp and H. van Hees, arXiv:1411.4612 [hep-ph]

R. Arnaldi et al. (NA60 Collaboration), Eur. Phys. J. C 61, 711 (2009)

H. J. Specht (NA60 Collaboration), AIP Conf.Proc. 1322, 1 (2010)

Dilepton Data

NA60

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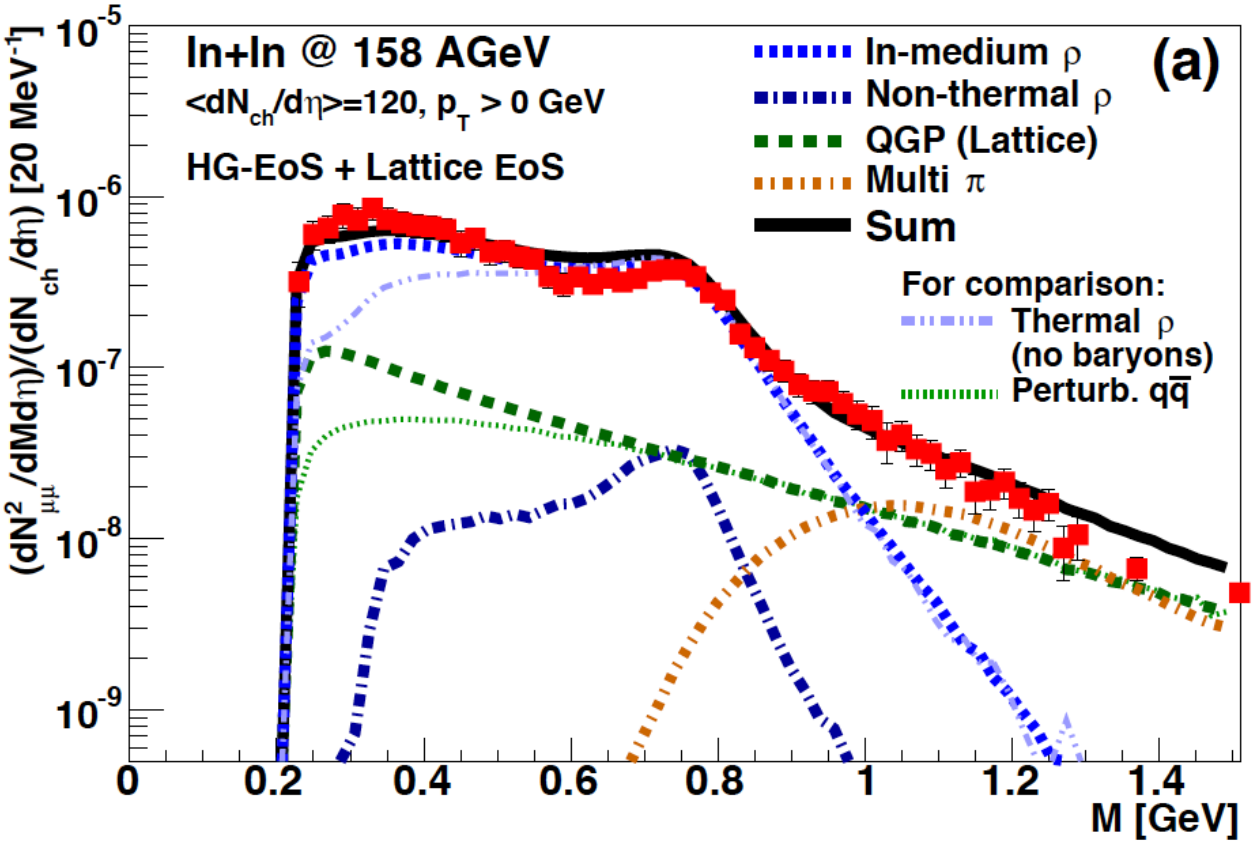

S. Endres et al. arXiv: 1502.01948 [nucl-th]

R. Arnaldi et al. (NA60 Collaboration), Phys. Rev. Lett. 96, 162302 (2006)

Dilepton Data

NA60

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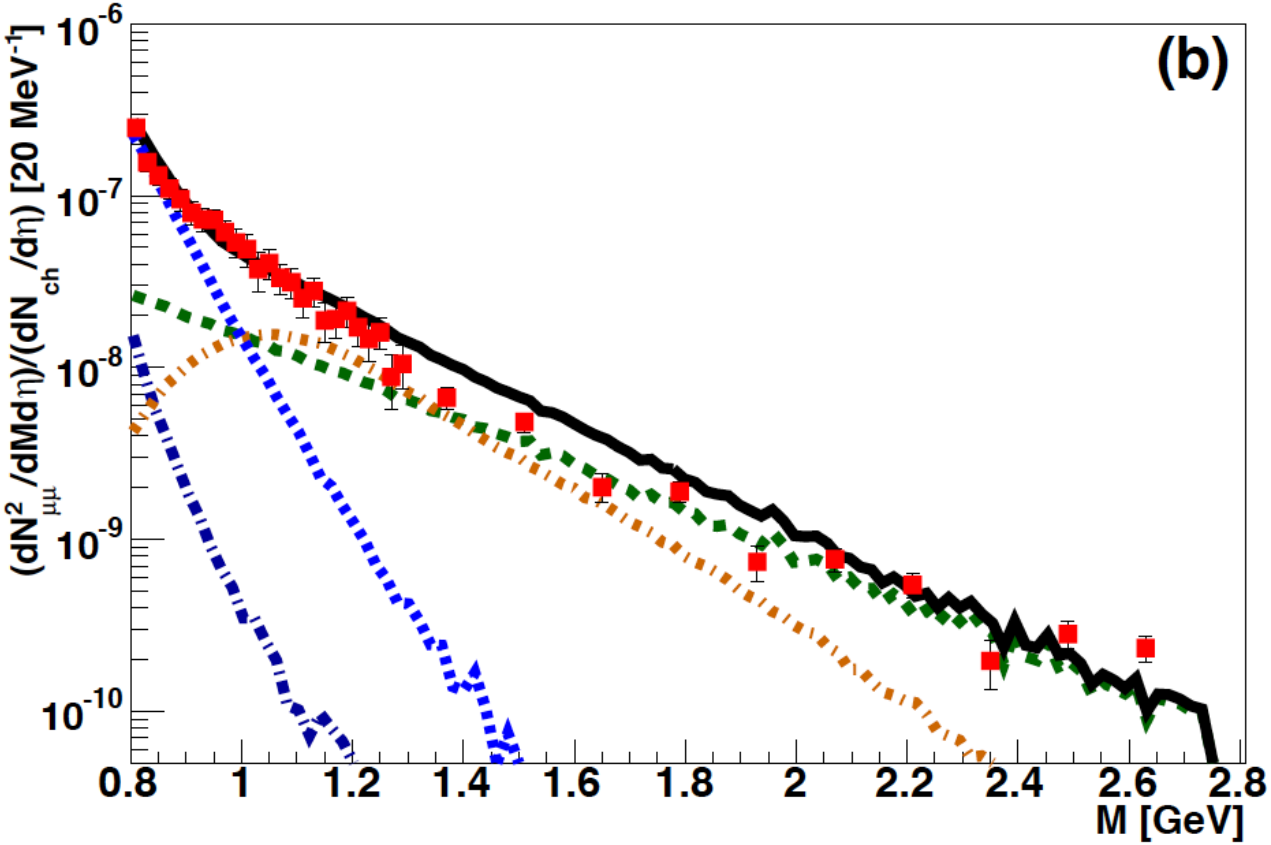

S. Endres et al. arXiv: 1502.01948 [nucl-th]

R. Arnaldi et al. (NA60 Collaboration), Phys. Rev. Lett. 96, 162302 (2006)

Dilepton Data

LHC

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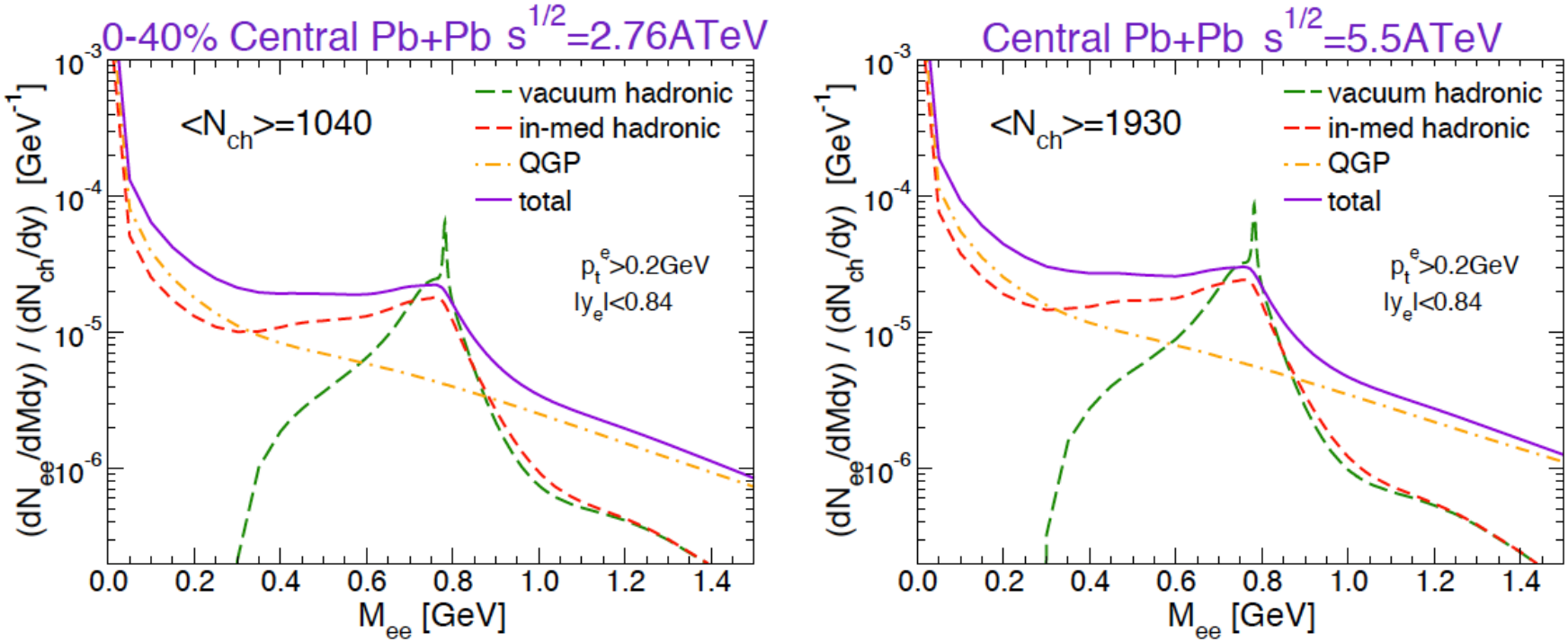

R. Rapp, arXiv:1304.2309 [hep-ph]

Broken Chiral Symmetry

VA-splitting

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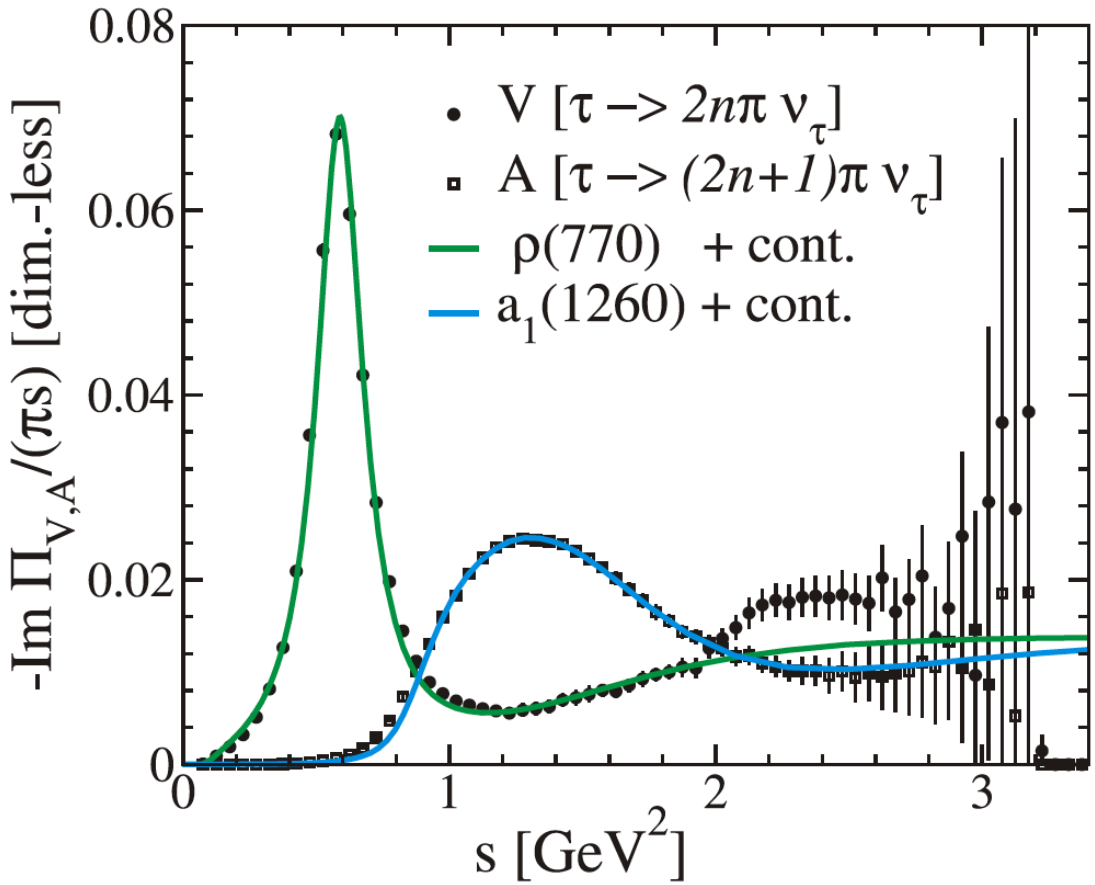

R. Barate et al. (ALEPH Collaboration), Eur. Phys. J. C 4, 409 (1998)

Broken Chiral Symmetry

temperature dependence of the chiral condensate

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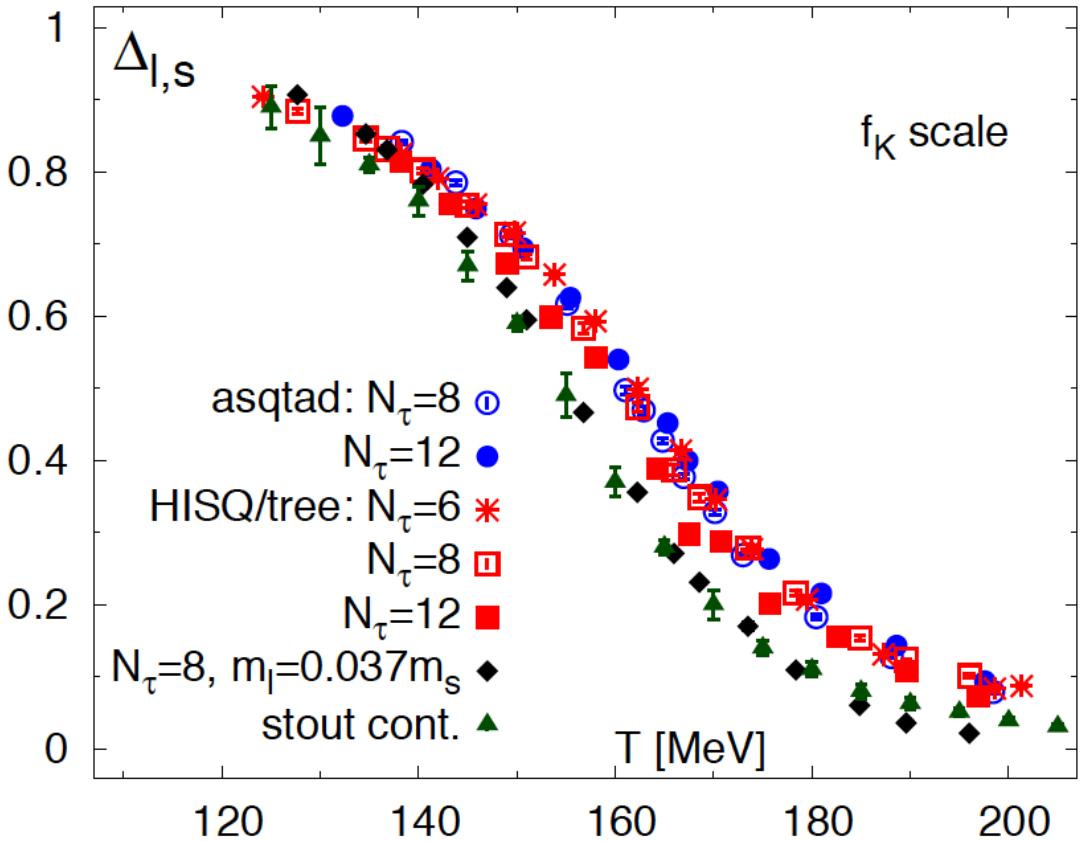

A. Bazavov et al. (HOTQCD collaboration), Phys. Rev. D85, 054503 (2012)

S. Borsanyi et al. (Wuppertal-Budapest Collaboration), JHEP 1009, 073 (2010)

Restoration through V-A mixing

M. Dey, V. L. Eletsky and B. L. Ioffe, Phys. Lett. B252 620 (1990)

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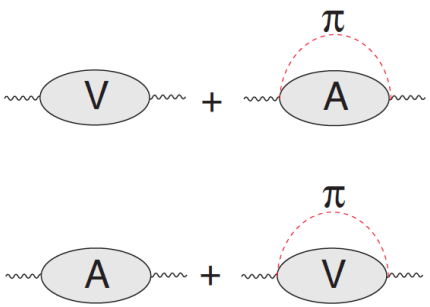
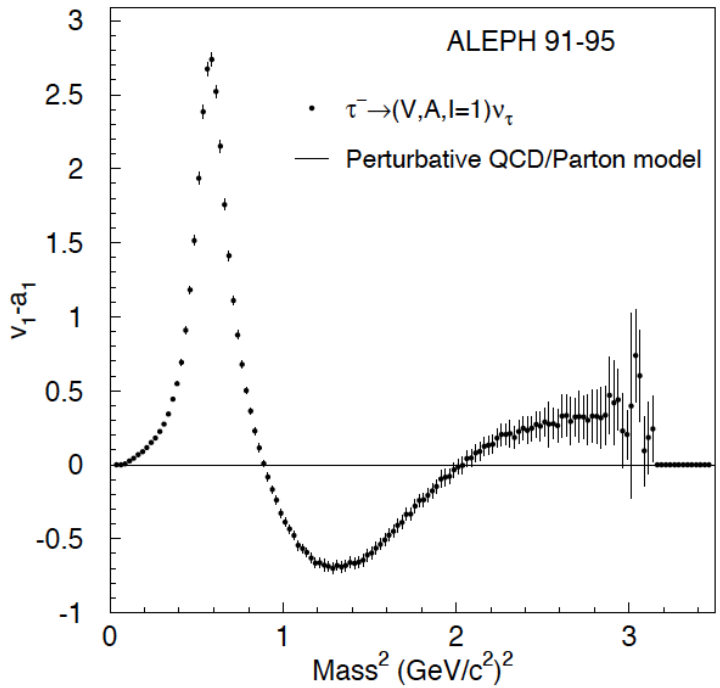
V-A mixing:

through low-momentum pions in the heat bath

$$\Delta(M) = \Pi_V(M) - \Pi_A(M)$$
$$= (1-2\epsilon)\Delta^0(M)$$

$$\Pi_{V,A}(M) = (1-\epsilon)\Pi^0_{V,A}(M) + \epsilon\Pi^0_{A,V}(M)$$





in the chiral limit:

$$\epsilon = T^2/6f_\pi^2$$

$$\epsilon = \frac{1}{2} \rightarrow T_c = \sqrt{3}f_\pi = 160 \text{ MeV}$$

Chiral Reduction Formalism

J. V. Steele, H. Yamagishi and I. Zahed, Phys. Rev. D 56 5605 (1997)

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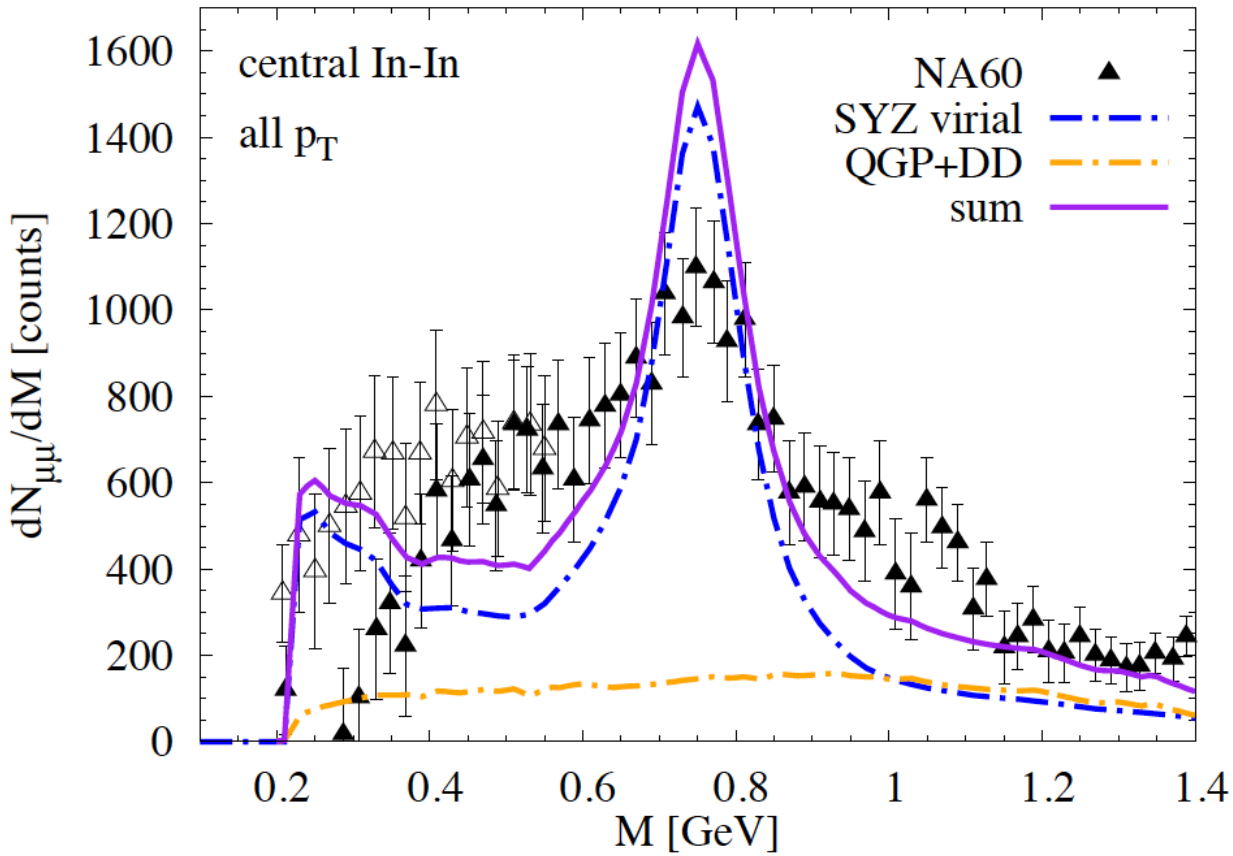

H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)

S. Damjanovic Nucl.Phys. A774, 715 (2006)

Dropping Masses

G. E. Brown and M. Rho, Phys. Rev. Lett. 66, 2720 (1991)

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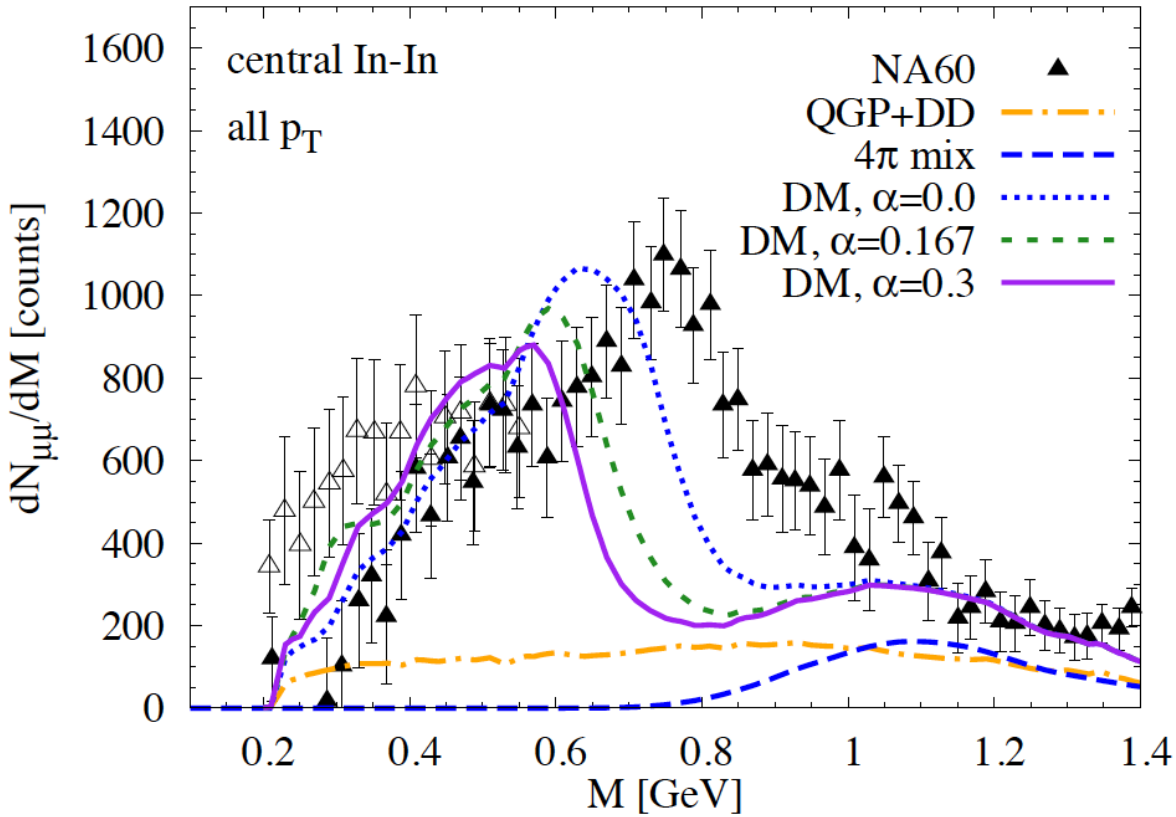
$$m_\rho^* = m_\rho^0 \left[1 - 0.15\rho_B/\rho_0\right] \left[1 - (T/T_c)^2\right]^\alpha$$



H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)

S. Damjanovic Nucl.Phys. A774, 715 (2006)

Spectral Functions from the FRG

R.-A. Tripolt, L. von Smekal and J. Wambach, Phys. Rev. D 90, 074031 (2014)

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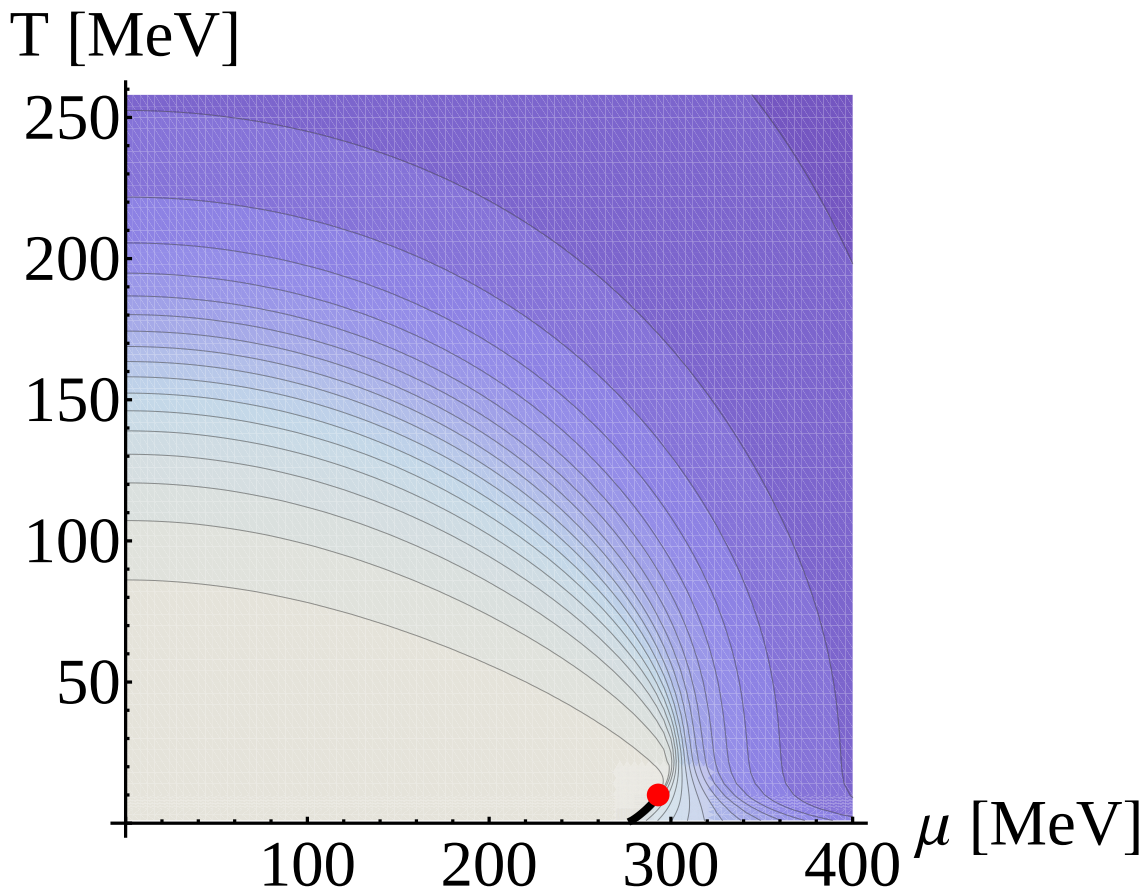

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Happy birthday Johanna!