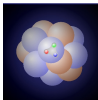


Dileptons in Hot and/or Dense Matter and the Chiral Phase Transition

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Theoretische Physik**



- 1 QCD and Chiral Symmetry
- 2 Chiral Symmetry and Hadron Phenomenology
- 3 Vector Mesons and electromagnetic Probes
- 4 Effective Models for Hadronic Many-Body Theory
- 5 Comparison with dilepton data@SPS and RHIC
- 6 Conclusions and Outlook

QCD and (“accidental”) Symmetries

- Theory for strong interactions: QCD

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a + \bar{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- Particle content:
 - ψ : Quarks, including flavor- and color degrees of freedom, $\hat{M} = \text{diag}(m_u, m_d, m_s, \dots)$ = current quark masses
 - A_μ^a : gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$
- Symmetries
 - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
 - in light-quark sector: approximate chiral symmetry
 - dilation symmetry (scale invariance for $M \rightarrow 0$)

"Fate" of Symmetries

- classical field theory: continuous symmetry $\Rightarrow$ **conserved current**
- chiral limit: $\hat{M} \rightarrow 0 \Rightarrow$, scalar and pseudoscalar $U(1)$ symmetries
 - $\psi \rightarrow \exp[-i(\alpha_s + \gamma_5 \alpha_p)]\psi$
 - scalar and pseudoscalar currents:
 $\vec{j}_\mu^{(0)} = \bar{\psi}\gamma^\mu\psi, \quad \vec{j}_{A\mu}^{(0)} = \bar{\psi}\gamma_5\gamma^\mu\psi$
 - $U(1)_A$ does **not** survive quantization (**Anomaly**)
 - $\partial^\mu \vec{j}_{A\mu}^{(0)} = \frac{3}{8}\alpha_s \epsilon^{\mu\nu\rho\sigma} A_{\mu\nu}^a A_{\rho\sigma}^a$
 - Not a "bug" but a feature:
 - η' **not** a (pseudo-)Goldstone boson
 - correct rate for $\pi^0 \rightarrow 2\gamma$

Remark: Anomalies potential trouble in standard model of strong and "electroweak" interactions $\leftrightarrow$ "cured" by particle content, because anomaly contributions from quarks and leptons cancel exactly!

"Fate" of symmetries

- in classical field theory: each continuous symmetry defines **conserved current** (Noether's theorem)
- chiral limit: $\hat{M} \rightarrow 0 \Rightarrow$, vector-axial-vector symmetries
 - $\psi \rightarrow \exp[-i(\vec{\alpha}_V + \gamma_5 \vec{\alpha}_A)\vec{T}]\psi$
 $\vec{T}$: generators of $SU(2)_{\text{flavor}}$ (or $SU(3)_{\text{flavor}}$)
 - **conserved vector and axial-vector currents:**

$$\vec{j}_V^\mu = \bar{\psi}\vec{T}\gamma^\mu\psi, \quad \vec{j}_A^\mu = \bar{\psi}\vec{T}\gamma_5\gamma^\mu\psi$$

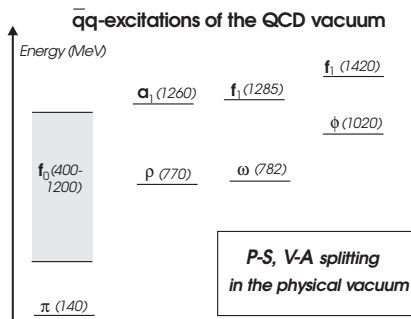
- in vacuum, chiral symmetry **spontaneously broken** by **quark condensate**:
 $\langle 0 | \bar{\psi}\psi | 0 \rangle \neq 0$
- (approximate) Goldstone bosons: π , K , η (pseudoscalar octet)
- "real world": chiral symmetry slightly **explicitly broken** by quark masses
 $\hat{M} \neq 0$: $SU_L(2) \times SU_R(2) \Rightarrow SU_V(2)$
- **isospin symmetry** slightly broken by light-quark-mass differences

"Fate" of Symmetries

- classical field theory: continuous symmetry $\Rightarrow$ conserved current
- $\hat{M} \rightarrow 0 \Rightarrow$ dilatation (or scale) symmetry
 - $x \rightarrow \lambda x, \quad \psi \rightarrow \lambda^{-3/2} \psi, \quad A_\mu^a \rightarrow \lambda^{-1} A_\mu^a$
 - dilatation current:
$$j_D^\mu = x_\nu \Theta^{\mu\nu}$$
 - Scale invariance does **not** survive quantization ("Trace" Anomaly)
$$\partial_\mu j_D^\mu = \Theta_\mu{}^\mu = -\frac{\beta(\alpha_s)}{4\alpha_s} A_{\mu\nu}^a A^{a\mu\nu}$$
 - $\beta(\alpha_s)$: Gell-Mann Low function, rules the running of the coupling with renormalization **scale**
 - Not a "bug" but a feature: hadrons get most of their mass from it!

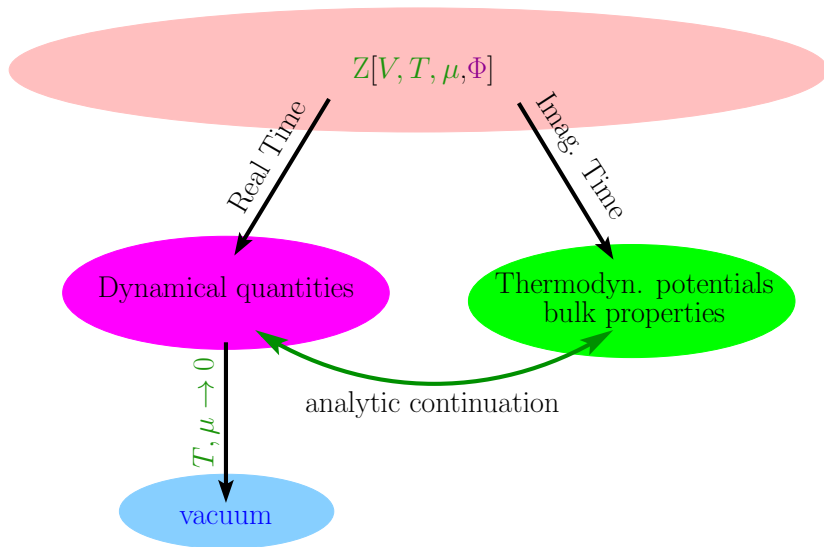
Phenomenology from Chiral Symmetry

- Use (approximate) **chiral symmetry** to build effective models
- **Ward identities**
 - PCAC: $\langle 0 | \partial^\mu j_{A\mu}^k | \pi^j(\vec{k}) \rangle = i F_\pi m_\pi^2 \delta^{kj}$
 - $m_\pi^2 F_\pi^2 = -(m_u + m_d) \langle 0 | \bar{u}u | 0 \rangle$ (GOR relation)
- Spontaneous breaking causes splitting of chiral partners:



Finite Temperature/Density: Idealized theory picture

- partition sum: $Z(V, T, \mu_q, \Phi) = \text{Tr}\{\exp[-(\mathbf{H}[\Phi] - \mu_q \mathbf{N})/T]\}$



- Asymptotic freedom $\Rightarrow$ quark condensate melts at high enough temperatures
- all bulk properties from partition sum:

$$Z(V, T, \mu_q) = \text{Tr}\{\exp[-(\mathbf{H} - \mu_q \mathbf{N})/T]\}$$

- Free energy: $\Omega = -\frac{T}{V} \ln Z = -P$
- Quark condensate: $\langle \bar{\psi}_q \psi_q \rangle_{T, \mu_q} = \frac{V}{T} \frac{\partial P}{\partial m_q}$
- Lattice QCD indicates: Chiral symmetry restoration $\leftrightarrow$ deconfinement phase transition (same T_c)

Why Electromagnetic Probes?

- $\gamma, \ell^\pm$: only e. m. interactions
- reflect whole “history” of collision
- chance to see chiral symm. rest. directly?

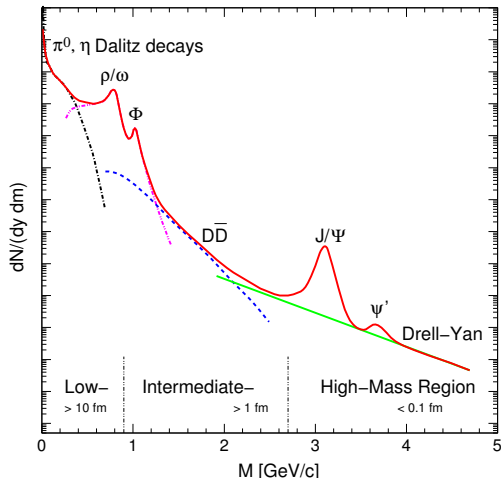
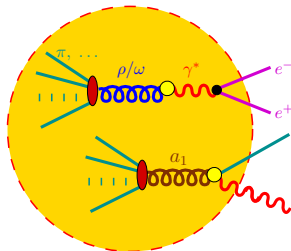


Fig. by A. Drees [R. Rapp, J. Wambach, Adv. Nucl. Phys. 25, 1 (2000)]

Vector Mesons and electromagnetic Probes

- **photon** and **dilepton** thermal emission rates given by **same electromagnetic-current-correlation function** ($J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f$)

[L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

$$\Pi_{\mu\nu}^<(q) = \int d^4x \exp(iq \cdot x) \langle J_\mu(0) J_\nu(x) \rangle_T = -2 f_B(q_0) \text{Im } \Pi_{\mu\nu}^{(\text{ret})}(q)$$

$$q_0 \frac{dN_\gamma}{d^4x d^3\vec{q}} = \frac{\alpha}{2\pi^2} g^{\mu\nu} \text{Im } \Pi_{\mu\nu}^{(\text{ret})}(q) \Big|_{q_0=|\vec{q}|} f_B(q_0)$$

$$\frac{dN_{e^+e^-}}{d^4x d^4q} = -g^{\mu\nu} \frac{\alpha^2}{3q^2\pi^3} \text{Im } \Pi_{\mu\nu}^{(\text{ret})}(q) \Big|_{q^2=M_{e^+e^-}^2} f_B(q_0)$$

- to lowest order in α : $e^2 \Pi_{\mu\nu} \simeq \Sigma_{\mu\nu}^{(\gamma)}$
- **vector-meson dominance** model:

$$\Sigma_{\mu\nu}^\gamma = \text{[diagram: a red wavy line (photon) connected to a blue wavy line (vector meson) via two yellow circles, with a label } G_\rho \text{ above the blue line]}$$

- derivable from **partition sum** $Z(V, T, \mu, \Phi)$!

Vector Mesons and chiral symmetry

- **vector** and **axial-vector** mesons $\leftrightarrow$ correlators of the respective currents

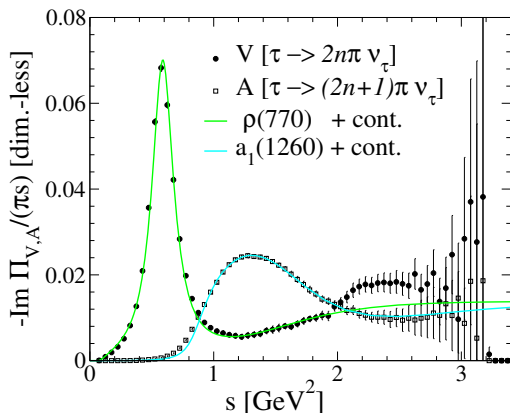
$$\Pi_{V/A}^{\mu\nu}(p) := \int d^4x \exp(ipx) \left\langle J_{V/A}^\nu(0) J_{V/A}^\mu(x) \right\rangle_{\text{ret}}$$

- Ward-Takahashi Identities from chiral symmetry $\Rightarrow$ **Weinberg-sum rules**

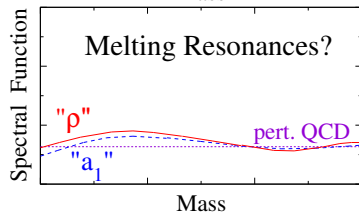
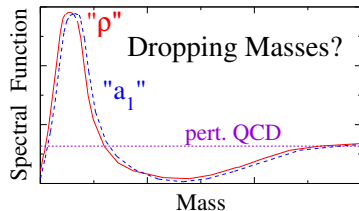
$$f_\pi^2 = - \int_0^\infty \frac{dp_0^2}{\pi p_0^2} [\text{Im } \Pi_V(p_0, 0) - \text{Im } \Pi_A(p_0, 0)]$$

- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to **order parameters of chiral symmetry!**

Vector Mesons and chiral symmetry



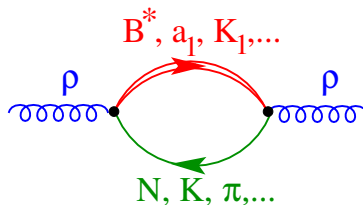
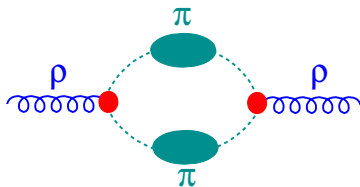
from [R. Rapp, *Pramana* **60**, 675 (2003)]



from [R. Rapp, *J. Phys. G* **31**, S217 (2005)]

- different models with chiral symmetry: equivalent only on shell (“low-energy theorems”)
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- mass spectrum of vector mesons depends on realization chiral symmetry
 - hidden local symmetry [Bando, Kugo, PRL 54, 1215 (1984)] $\Rightarrow$ “vector manifestation” of χ S: $m_\rho \rightarrow 0$ (“dropping mass”)
 - generalized hidden local symmetry (ρ and a_1 as gauge fields): “normal realization” of χ S: $m_\rho \simeq \text{const}$ (“melting resonances”)
- use phenomenological hadronic models + many-body techniques to assess medium modifications of vector mesons

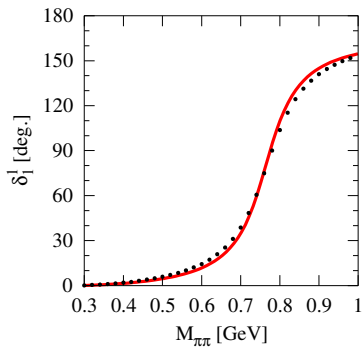
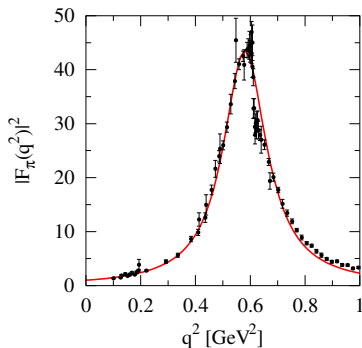
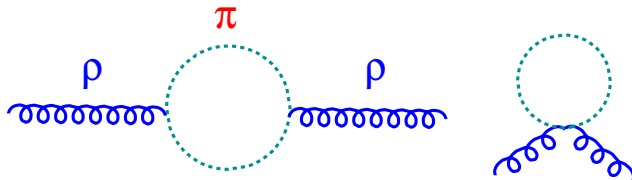
- Phenomenological hadronic models [Chanfray et al, Herrmann et al, Rapp, Wambach et al, . . .] for vector mesons
- important ingredients: $\pi\pi$ interactions
baryonic excitations



- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP invariance of strong interactions)

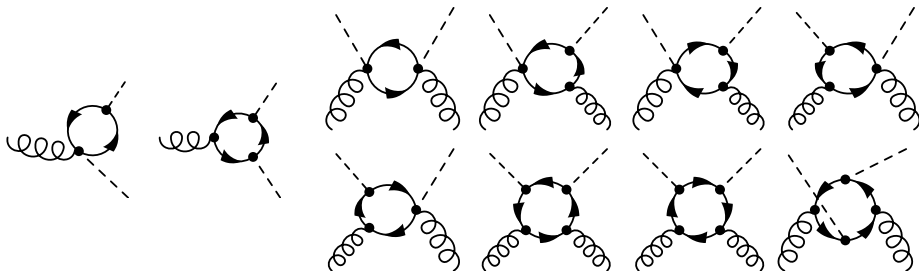
The ρ -meson (vacuum)

- most important for ρ -meson: π ions



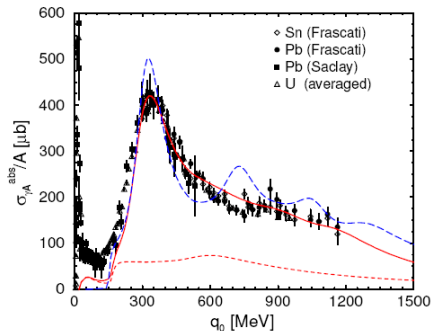
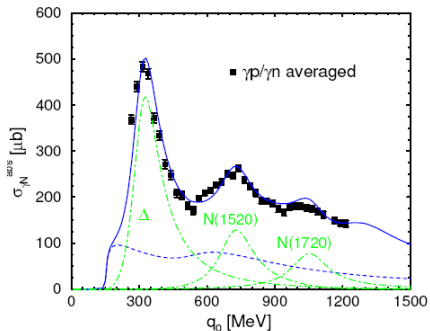
The ρ -meson (cold matter)

- $P = 1$ -baryons: p -wave coupling to ρ :
 $N(939)$, $\Delta(1232)$, $N(1720)$, $\Delta(1905)$
- $P = -1$ -baryons: s -wave coupling to ρ :
 $N(1520)$, $\Delta(1620)$, $\Delta(1700)$
- Pions dressed with N -hole-, Δ -hole bubbles
- Ward-Takahashi $\Rightarrow$ vertex corrections mandatory!



[M. Urban, M. Buballa, R. Rapp, J. Wambach, Nucl. Phys. A **641**, 433 (1998)]

Photoabsorption on nucleons and nuclei

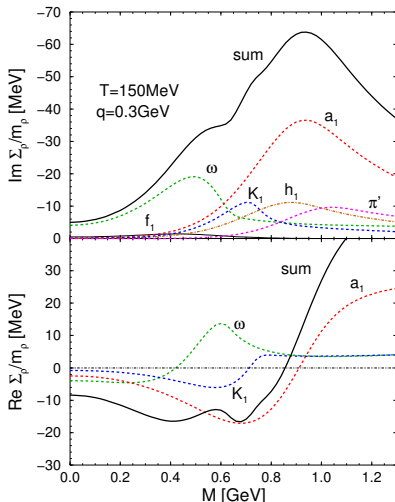


The ρ -meson (hot medium: +higher mesonic resonances)

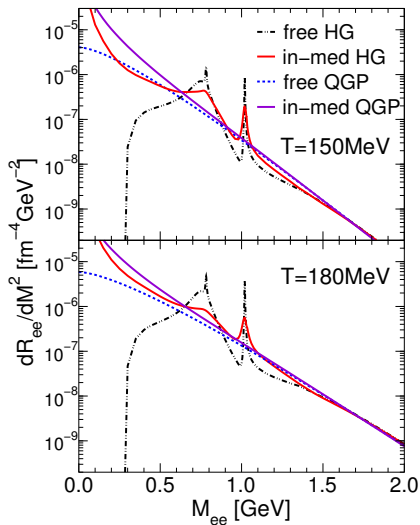
- extension of model with baryonic excitations to finite T

[M. Urban, M. Buballa, R. Rapp, J. Wambach, Nucl. Phys. A **673** 357 (2000)]

- also higher mesonic excitations [C. Gale, R. Rapp, Phys. Rev. C **60**, 024903 (1999)]



Dilepton rates: Hadron gas $\leftrightarrow$ QGP



- at $T \simeq T_c$: $\text{textcoloredHG} \simeq \text{QGP}$
- QGP rate
 - HTL improved $\bar{q} + q \rightarrow \ell^+ + \ell^-$
 - in good agreement with IQCD results
 - similar results also for γ rates
- “quark-hadron duality”?

[R. Rapp, J. Wambach, Eur. Phys. J. A 6, 415 (1999)]

Sources of dilepton emission in heavy-ion collisions

- ① “core” $\Leftrightarrow$ emission from thermal source [McLerran, Toimela 1985]

$$\frac{1}{q_T} \frac{dN^{(\text{thermal})}}{dM dq_T} = \int d^4x \int dy \int M d\varphi \frac{dN^{(\text{thermal})}}{d^4x d^4q} \text{Acc}(M, q_T, y)$$

- ② initial hard processes: Drell Yan

- ③ “corona” $\Leftrightarrow$ emission from “primordial” mesons (jet-quenching)

- ④ after thermal freeze-out $\Leftrightarrow$ emission from “freeze-out” mesons

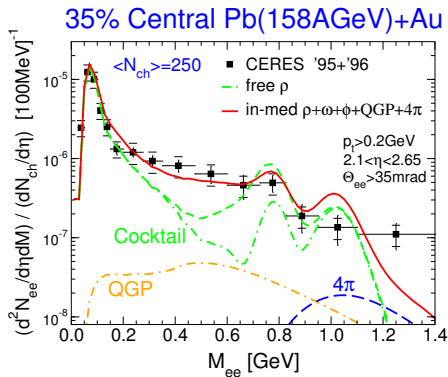
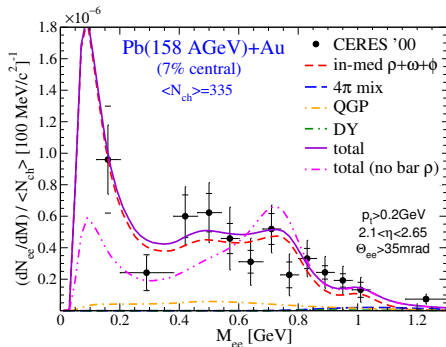
[Cooper, Frye 1975]

$$N^{(\text{fo})} = \int \frac{d^3q}{q_0} \int q_\mu d\sigma^\mu f_B(u_\mu q^\mu / T) \frac{\Gamma_{\text{meson} \rightarrow \ell^+ \ell^-}}{\Gamma_{\text{meson}}} \text{Acc}$$

- use simple homogeneous cylindrical fireball of thermalized medium

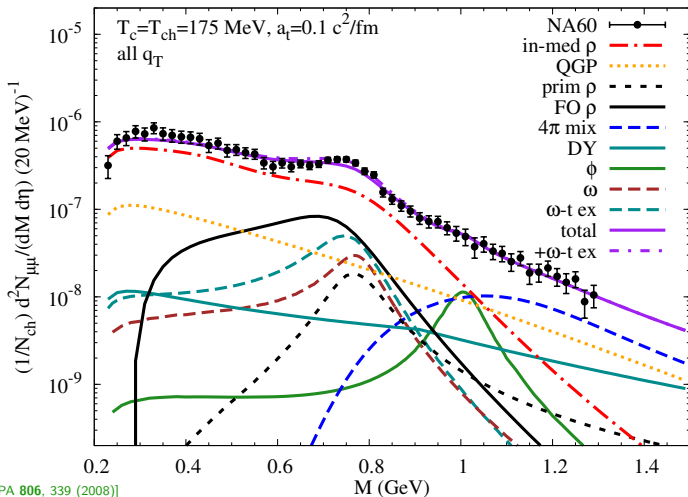
CERES/NA45 dielectron spectra

- good agreement also for **dielectron** spectra in 158 GeV Pb-Au
- **low-mass tail** from **baryon** effects



M spectra (in p_T slices)

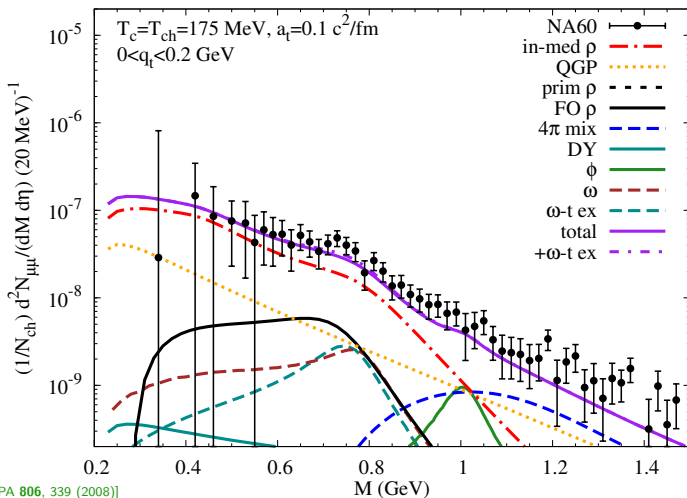
- norm corrected by $\sim 3\%$ due to centrality correction
(min-bias data: $\langle N_{\text{ch}} \rangle = 120$, calculation $N_{\text{ch}} = 140$)



[HvH, R. Rapp, NPA 806, 339 (2008)]

M spectra (in p_T slices)

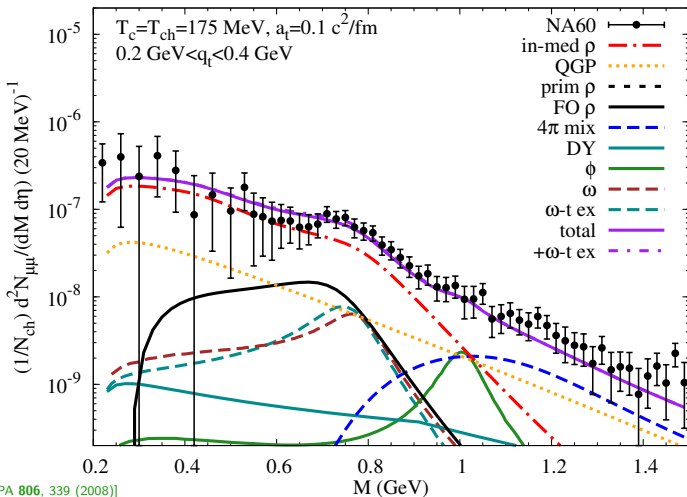
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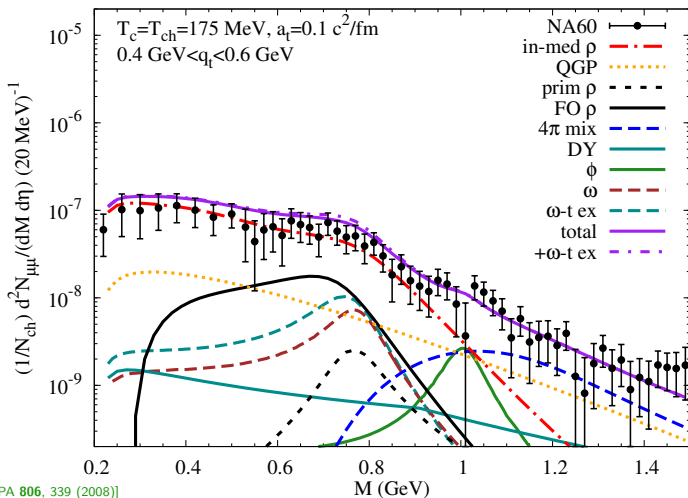
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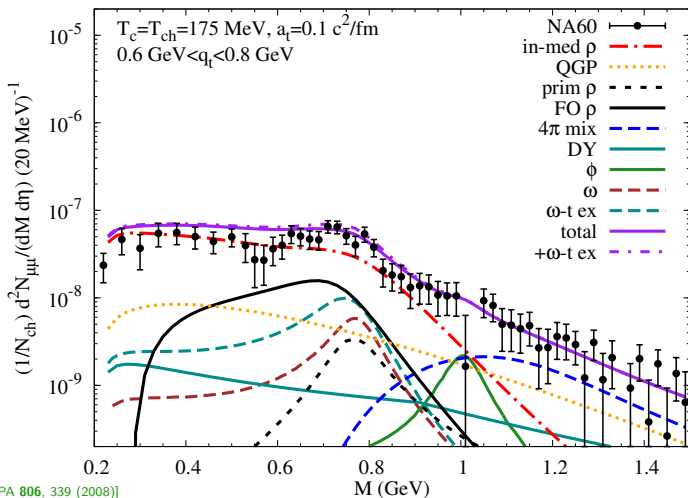
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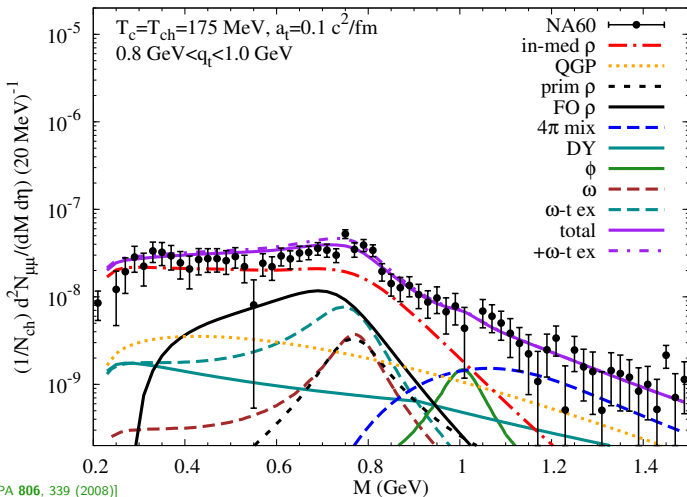
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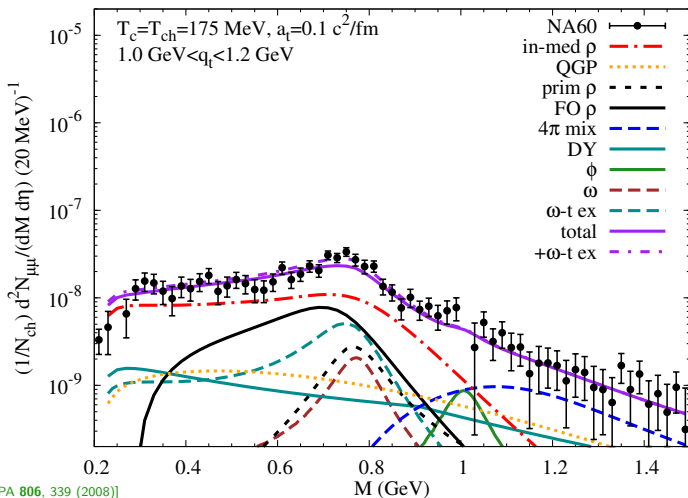
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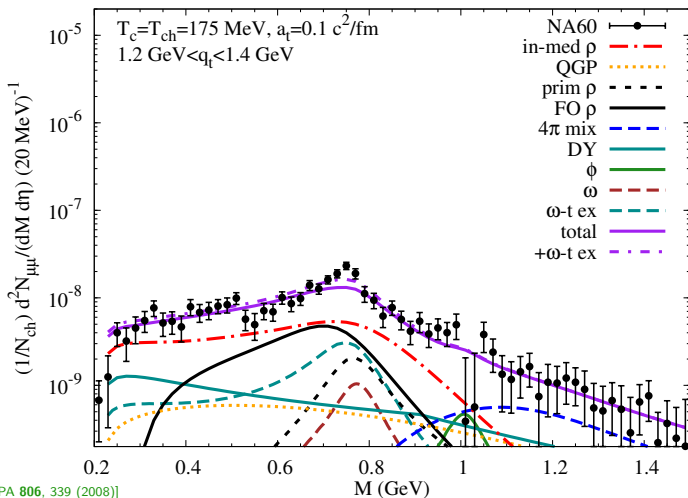
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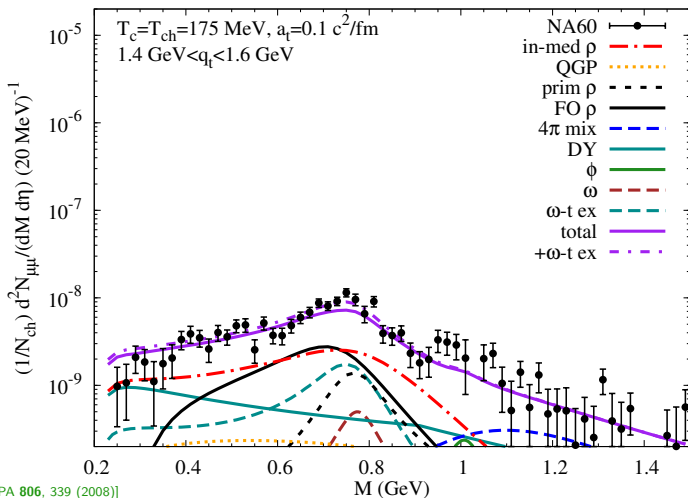
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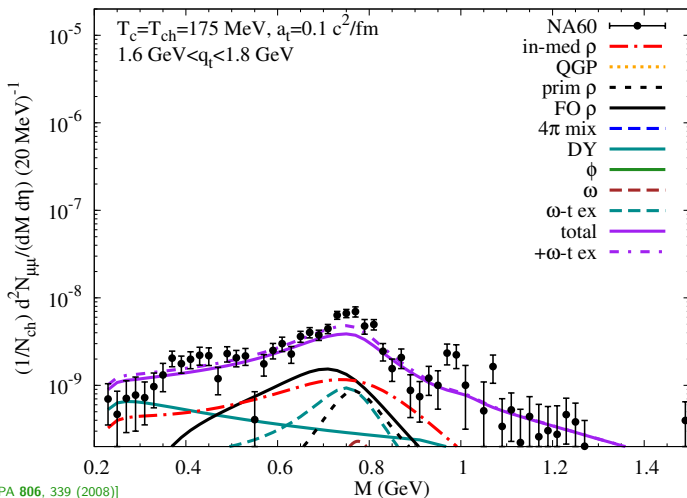
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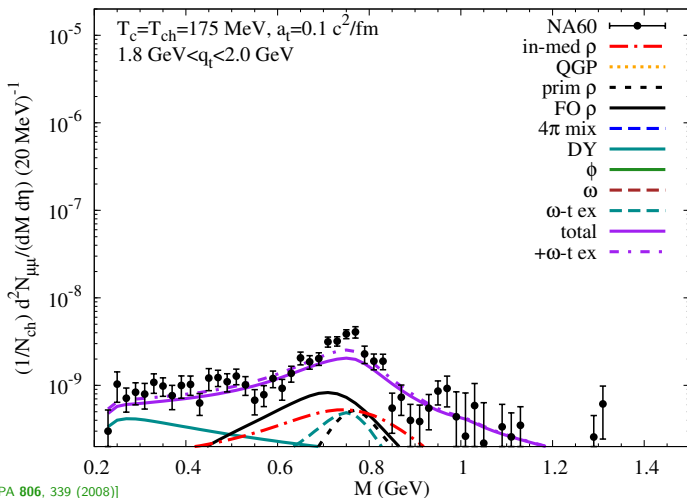
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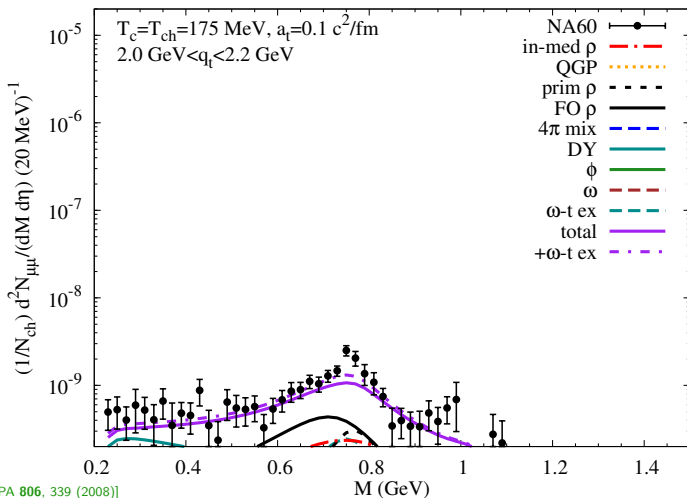
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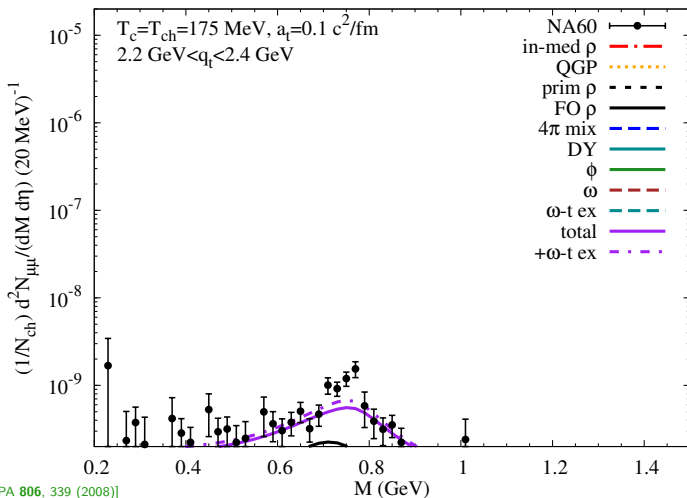
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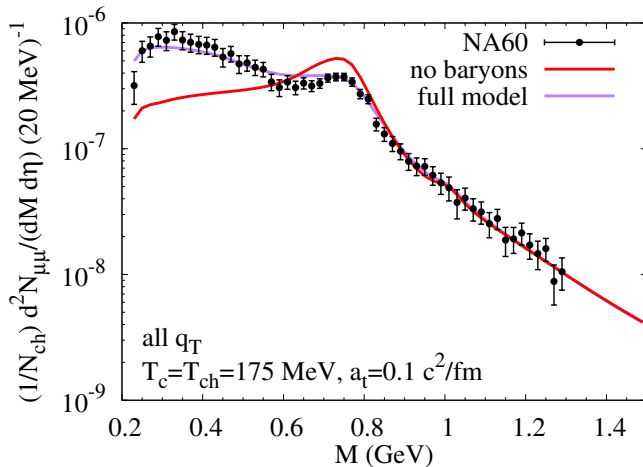
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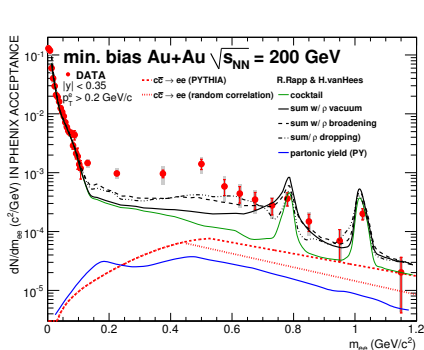
Importance of baryon effects

- Baryonic interactions important!
- in-medium broadening
- low-mass tail!



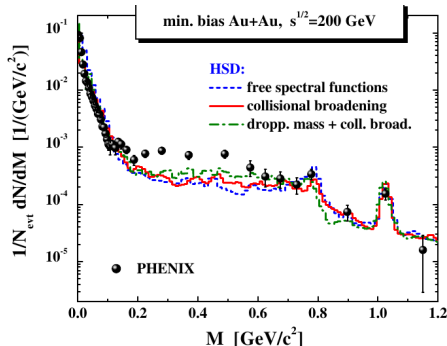
Dileptons@RHIC: New Puzzle?

- huge enhancement in the LMR unexplained yet!



QGP+HMBT: R. Rapp, HvH

[A. Adare et al (PHENIX), arXiv:0912.0244 [nucl-ex]]



HSD: Linnyk, Bratkovskaya, Cassing

[E. L. Bratkovskaya, O. Linnyk, W. Cassing, J. Phys. Conf.Ser. **230**, 012032 (2010)]

Conclusions and Outlook

- dilepton spectra $\Leftrightarrow$ in-medium em. current correlator
 - insight into fundamental (symmetry) properties of QCD
 - properties of hot/dense strongly interacting matter $\Leftrightarrow$ QCD-phase diagram
 - chiral symmetry (restoration)
 - origin of hadron mass?!?
- model for dilepton sources
 - radiation from thermal sources: QGP, ρ , ω , ϕ
 - ρ -decay after thermal freeze-out
 - decays of non-thermalized primordial ρ 's
 - Drell-Yan annihilation, correlated $D\bar{D}$ decays
- invariant-mass spectra and medium effects
 - excess yield dominated by radiation from thermal sources
 - baryons essential for in-medium properties of vector mesons
 - melting ρ with little mass shift robust signal! (independent of T_c)
 - "parton-hadron" duality of rates
 - $\Leftrightarrow$ compatible with chiral-symmetry restoration!
 - dimuons in In-In (NA60), Pb-Au (CERES/NA45), γ in Pb-Pb (WA98)

- fireball/freeze-out dynamics $\Leftrightarrow m_T$ spectra and effective slopes
 - “non-thermal sources” important for $q_T \gtrsim 1$ GeV
 - lower $T_c \Rightarrow$ higher hadronic temperatures $\Rightarrow$ harder q_T spectra
 - to describe measured effective slopes $a_\perp = 0.085c^2/\text{fm} \rightarrow 0.1c^2/\text{fm}$
 - off-equilibrium effects (viscous hydro)?
- Further developments
 - understand recent PHENIX results (large dilepton excess in LMR)
 - vector- should be complemented with axial-vector-spectral functions (a_1 as chiral partner of ρ)
 - constrained with IQCD via in-medium Weinberg chiral sum rules
 - direct connection to chiral phase transition!
- recent review: [R. Rapp, J. Wambach, HvH., Landolt-Börnstein, Volume I/23, 4-1 (2010)]

Greetings from Texas

"I would like to express my appreciation and gratitude for the education and support received from Jochen over the years, and I regret that I could not make it to the meeting in person.

Best of wishes to Jochen from Ralf."