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

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Outline

QCD and ("accidental") Symmetries

- Theory for strong interactions: QCD

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

- Particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) =$ 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 $M \to 0$)

"Fate" of Symmetries

- classical field theory: continuous symmetry $\Rightarrow$ conserved current
- chiral limit: $\hat{M} \to 0 \Rightarrow$, scalar and pseudocalar $U(1)$ symmetries
  - $\psi \to \exp[-\mathrm{i}(\alpha_s + \gamma_5 \alpha_p)]\psi$
  - scalar and pseudoscalar currents:
    $\vec{j}_{\mu}^{(0)} = \bar{\psi}\gamma^{\mu}\psi, \quad \vec{j}_{A\mu}^{(0)} = \bar{\psi}\gamma_5\gamma^{\mu}\psi$
  - $\mathrm{U}(1)_A$ 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 $\pi^0 \to 2\gamma$

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
  - $\psi \rightarrow \exp[-\mathrm{i}(\vec{\alpha}_V + \gamma_5 \vec{\alpha}_A)\vec{T}]\psi$
    $\vec{T}$: generators of $\mathrm{SU}(2)_{\text{flavor}}$ (or $\mathrm{SU}(3)_{\text{flavor}}$)
  - conserved vector and axial-vector currents:

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

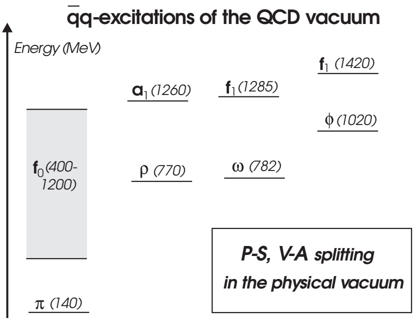
  - in vacuum, chiral symmetry spontaneously broken by quark condensate: $\langle 0 | \bar{\psi}\psi | 0 \rangle \neq 0$
  - (approximate) Goldstone bosons: π, K, η (pseudoscalar octet)
  - "real world": chiral symmetry slightly explicitly broken by quark masses $\hat{M} \neq 0$: $\mathrm{SU}_L(2) \times \mathrm{SU}_R(2) \Rightarrow \mathrm{SU}_V(2)$
  - 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!

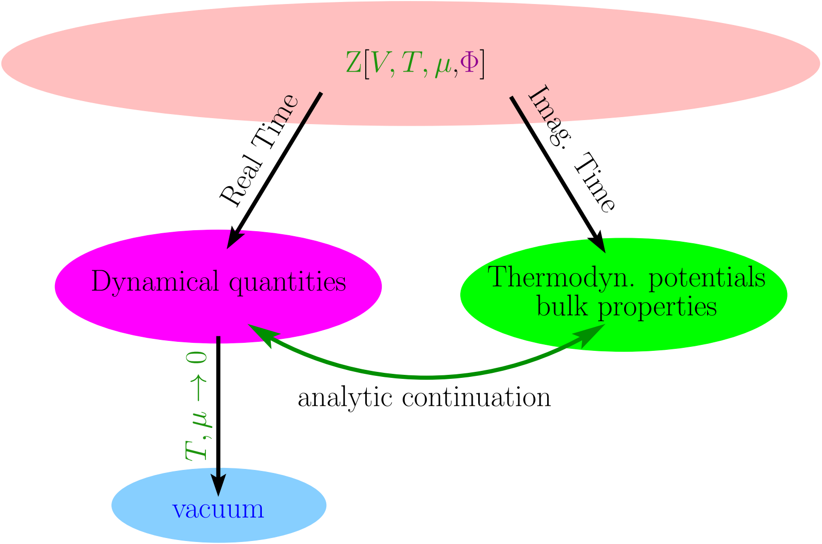
Phenomenology from Chiral Symmetry

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



Finite Temperature/Density: Idealized theory picture

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



[. . .,K. Chou, Z. Su, B. Hao, L. Yu 85, N.P. Landsmann, C.G. van Weert 87,. . .]

Finite Temperature

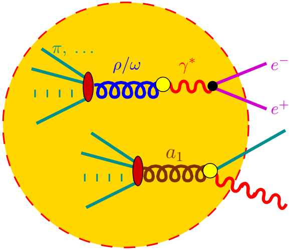
- Asymptotic freedom $\Rightarrow$ quark condensate melts at high enough temperatures
- all bulk properties from partition sum:

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

- Free energy: $\Omega = -\frac{T}{V} \ln Z = -P$
- Quark condensate: $\left\langle \bar{\psi}_q \psi_q \right\rangle_{T,\mu_q} = \frac{V}{T} \frac{\partial P}{\partial m_q}$
- 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?



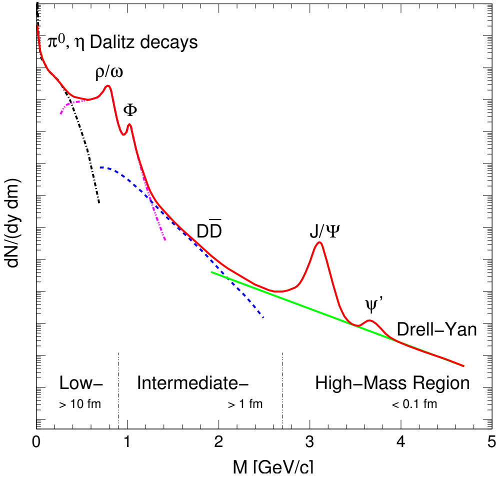


Fig. by A. Drees [R. Rapp, J. Wambach, Adv. Nucl. Phys. **25**, 1 (2000)]

Vector Mesons and electromagnetic Probes

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

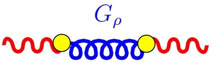
  [L. McLerran, T. Toimela 85, H. A. Weldon 90, C. Gale, J.I. Kapusta 91]

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 f_B(q_0) \, \mathrm{Im} \, \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

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

$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4 x \mathrm{d}^4 q} = -g^{\mu\nu} \frac{\alpha^2}{3 q^2 \pi^3} \, \mathrm{Im} \, \Pi^{(\mathrm{ret})}_{\mu\nu}(q) \Big|_{q^2 = M^2_{e^+e^-}} f_B(q_0)$$

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

$\Sigma^{\gamma}_{\mu\nu} =$ 

- 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

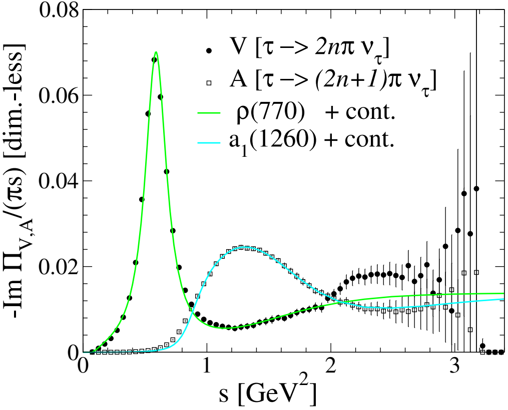
$$\Pi^{\mu\nu}_{V/A}(p) := \int \mathrm{d}^4 x \exp(\mathrm{i} p x) \left\langle J^{\nu}_{V/A}(0) J^{\mu}_{V/A}(x) \right\rangle_{\text{ret}}$$

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

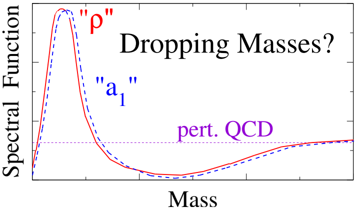
$$f_\pi^2 = -\int_0^\infty \frac{\mathrm{d}p_0^2}{\pi p_0^2} [\operatorname{Im}\Pi_V(p_0,0) - \operatorname{Im}\Pi_A(p_0,0)]$$

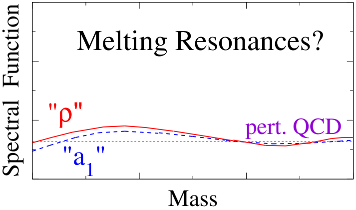
- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to order parameters of chiral symmetry!

Vector Mesons and chiral symmetry



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





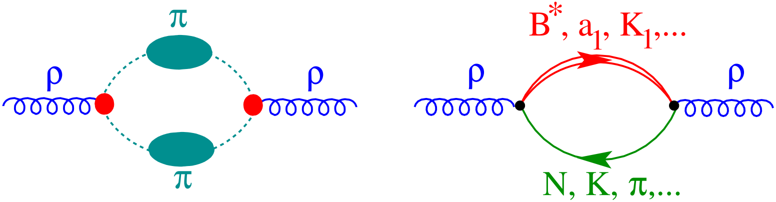
from [R. Rapp, J. Phys. G **31**, S217 (2005)]

Models

- 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 χS: $m_\rho \to 0$ ("dropping mass")
  - generalized hidden local symmetry (ρ and a_1 as gauge fields): "normal realization" of χS: $m_\rho \simeq$ const ("melting resonances")
- use phenomenological hadronic models + many-body techniques to assess medium modifications of vector mesons

Models

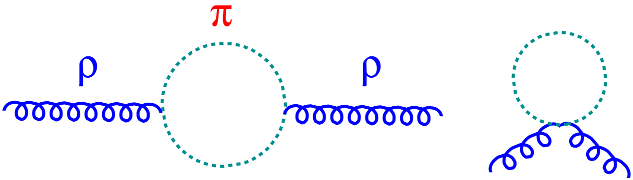
- Phenomenological hadronic models [Chanfray et al, Herrmann et al, Rapp, Wambach et al, . . .] for vector mesons
- important incredients: $\pi\pi$ interactions
  baryonic excitations

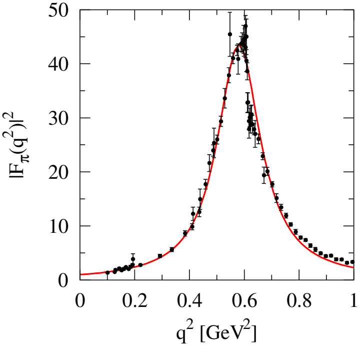


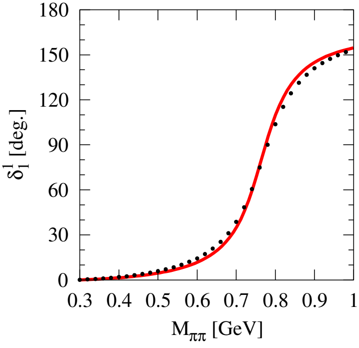
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP invariance of strong interactions)

The ρ-meson (vacuum)

- most important for ρ-meson: pions

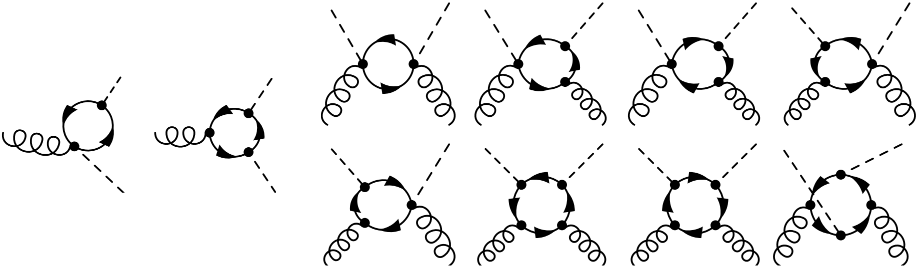






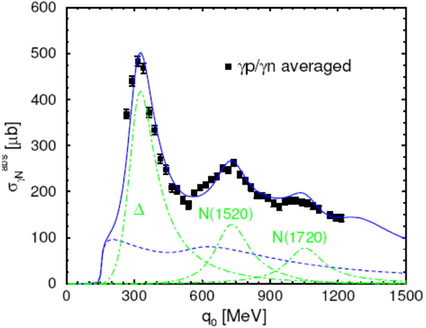
The ρ-meson (cold matter)

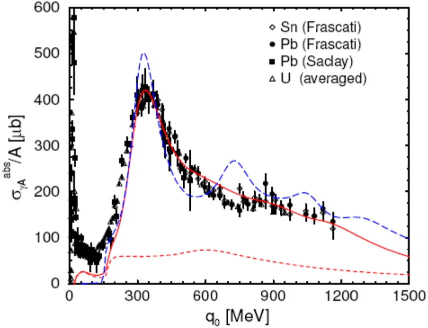
- $P = 1$-baryons: p-wave coupling to ρ:
  N(939), Δ(1232), N(1720), $\Delta(1905)$
- $P = -1$-baryons: s-wave coupling to ρ:
  N(1520), Δ(1620), Δ(1700)
- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi $\Rightarrow$ vertex corrections mandatory!



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

Photoabsorption on nucleons and nuclei

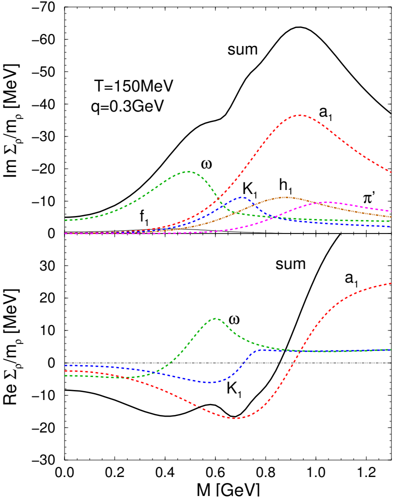




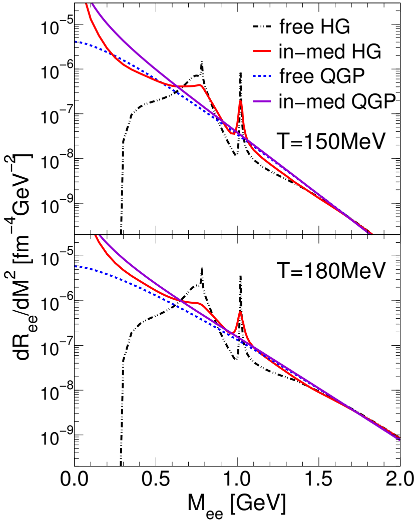
The ρ-meson (hot medium: +higher mesonic resonances)

- 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 $T \simeq T_c$: HG $\simeq$ QGP
- QGP rate
    - HTL improved $\overline{q} + q \rightarrow \ell^+ + \ell^-$
    - in good agreement with lQCD 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]

$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4x \int \mathrm{d}y \int M\mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4x\mathrm{d}^4q}\mathsf{Acc}(M, q_T, y)$$

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

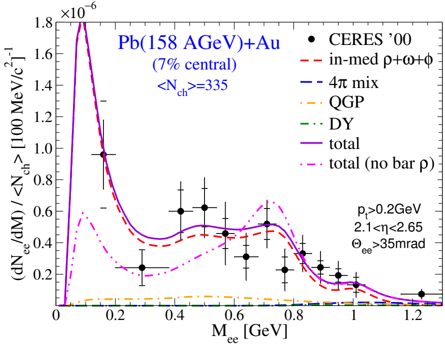
[Cooper, Frye 1975]

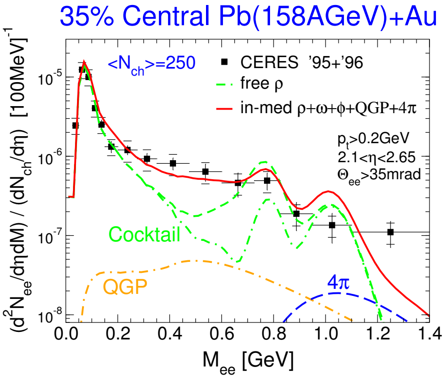
$$N^{(\text{fo})} = \int \frac{\mathrm{d}^3q}{q_0} \int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T)\frac{\Gamma_{\text{meson}\rightarrow\ell^+\ell^-}}{\Gamma_{\text{meson}}}\mathsf{Acc}$$

- use simple homogeneous cylindrical fireball of thermalized medium

CERES/NA45 dielectron spectra

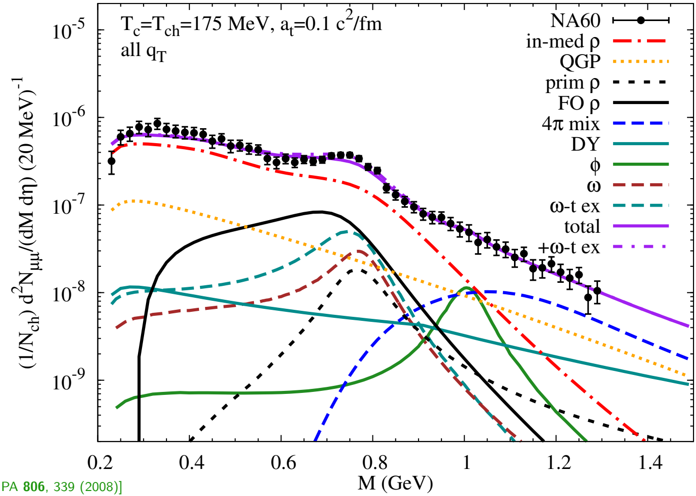
- good agreement also for dielectron spectra in $158\ \mathrm{GeV}$ Pb-Au
- low-mass tail from baryon effects





M spectra (in p_T slices)

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



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

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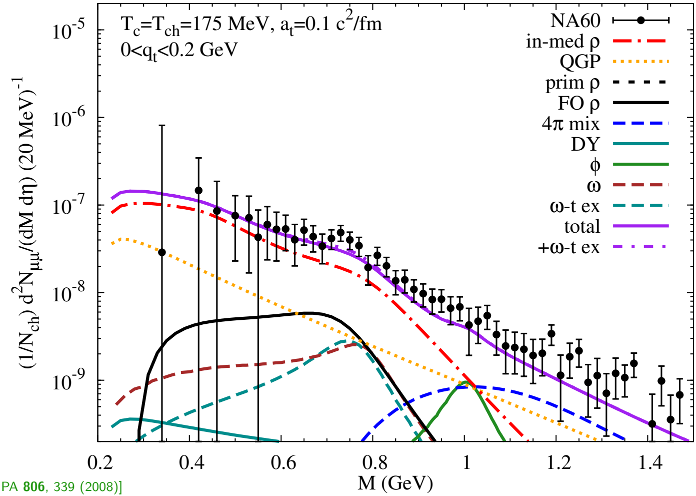

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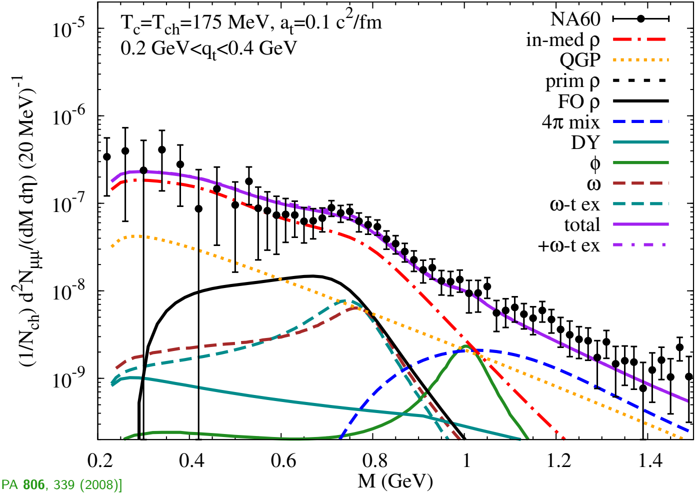

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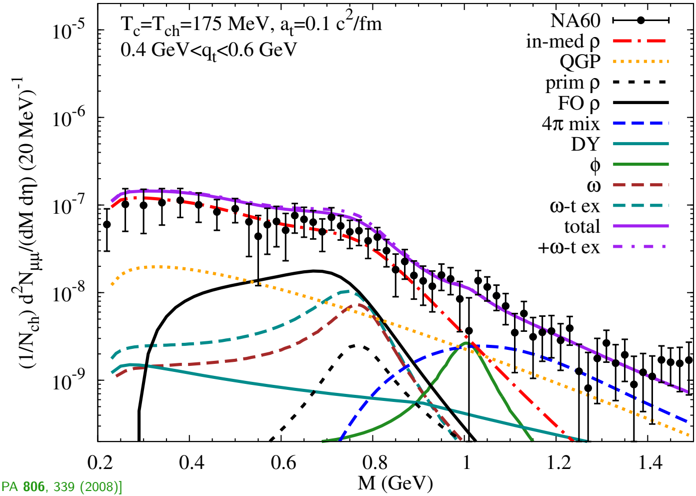

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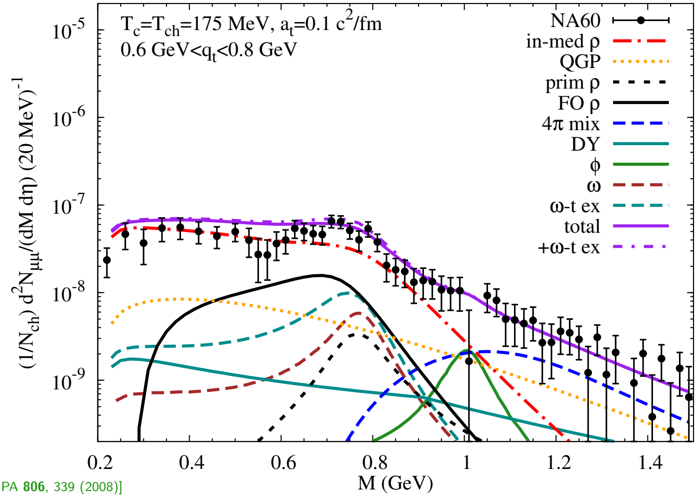

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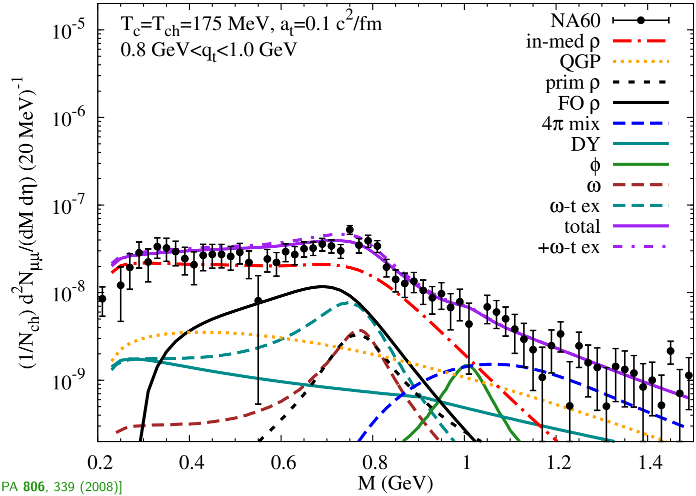

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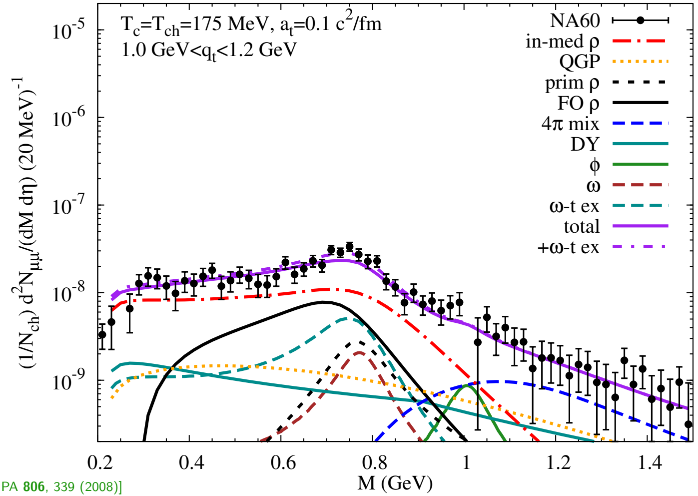

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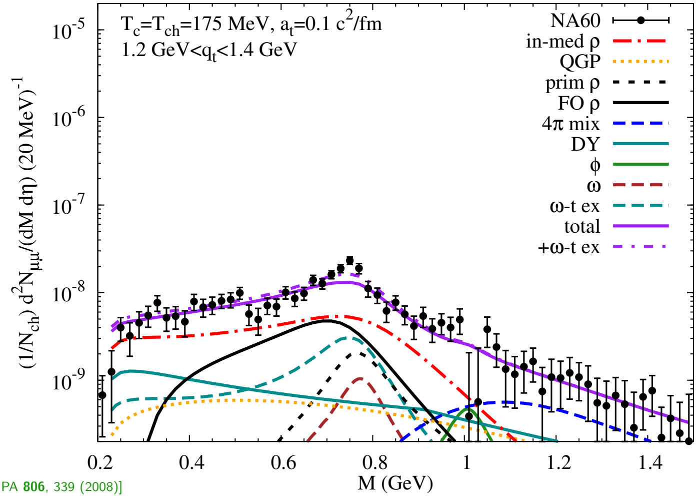

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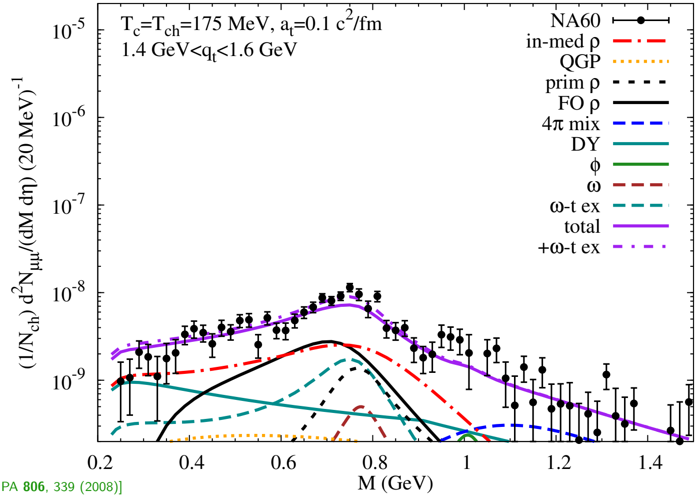

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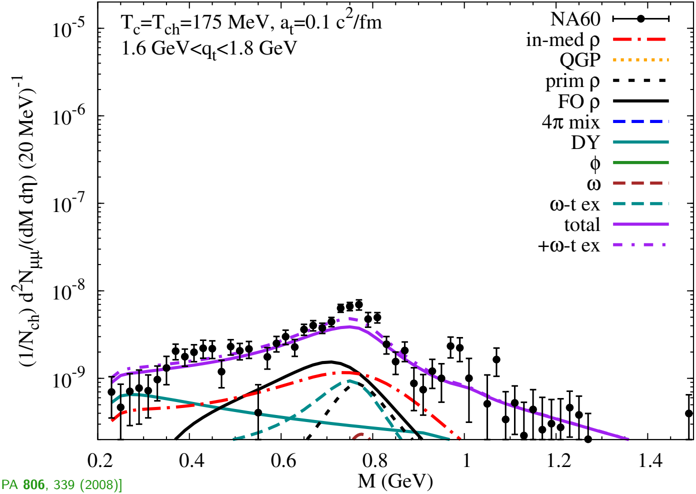

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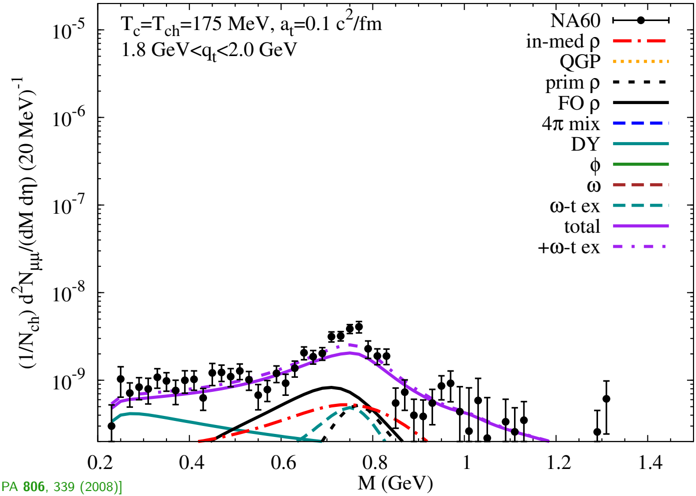

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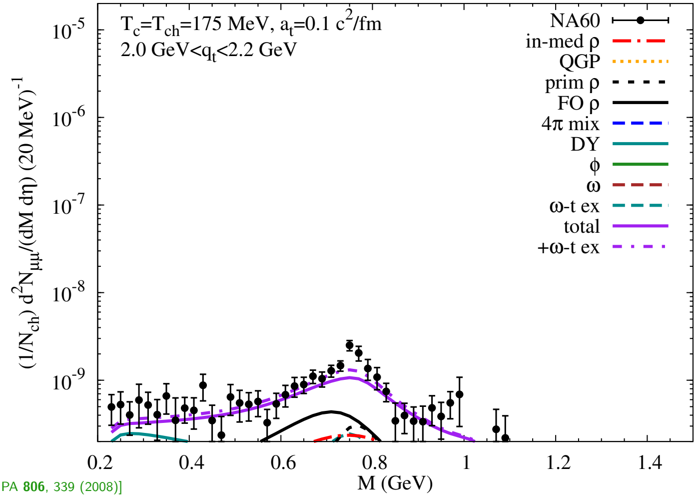

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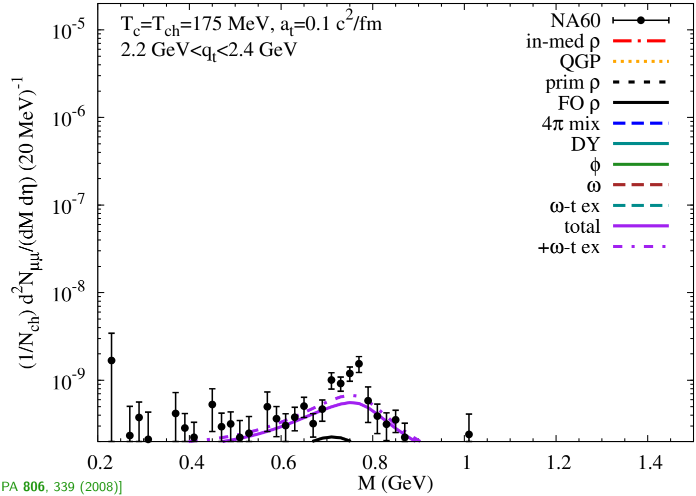

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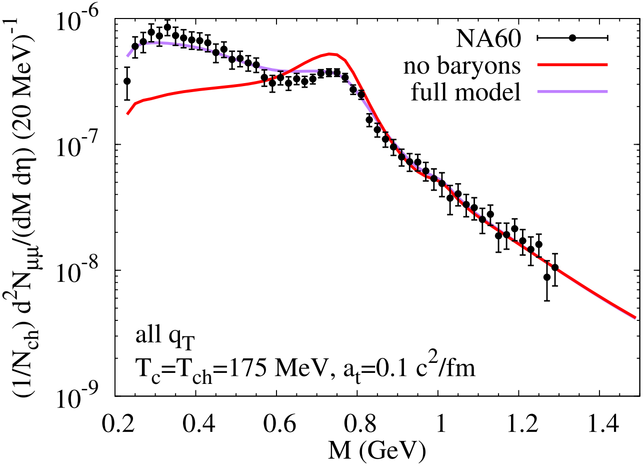
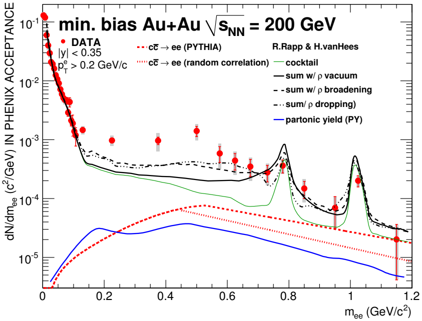
Importance of baryon effects

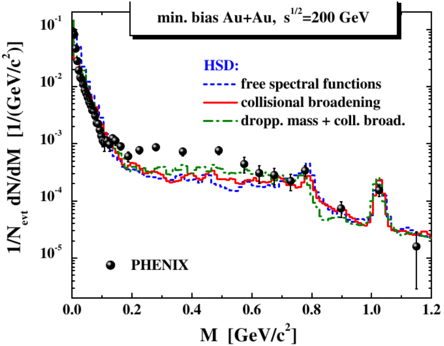
- Baryonic interactions important!
- in-medium broadening
- low-mass tail!



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 ⇔ in-medium em. current correlator
  - insight into fundamental (symmetry) properties of QCD
  - properties of hot/dense strongly interacting matter ⇔ 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
    - ⇔ compatible with chiral-symmetry restoration!
  - dimuons in In-In (NA60), Pb-Au (CERES/NA45), γ in Pb-Pb (WA98)

Conclusions and Outlook

- fireball/freeze-out dynamics ⇔ m_T spectra and effective slopes
  - "non-thermal sources" important for $q_T \gtrsim 1 \text{ GeV}$
  - lower T_c ⇒ higher hadronic temperatures ⇒ 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 lQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!
- recent review: [R. Rapp, J. Wambach, HvH., Landolt-Brnstein, Volume I/23, 4-1 (2010)]

Last but not least...

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."