Electromagnetic Spectra at CERN-SPS and the QCD phase diagram

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Outline

QCD and ("accidental") symmetries

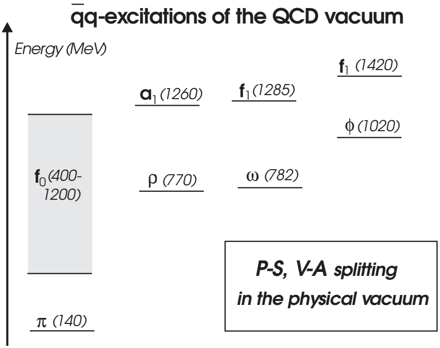
- Theory for strong interactions: QCD

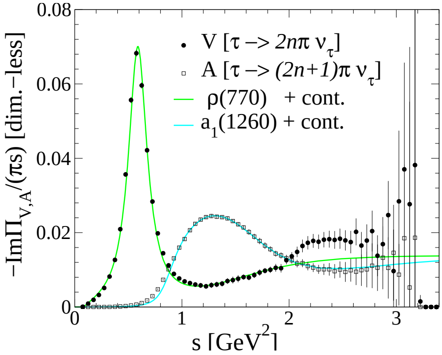
$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu} + \bar{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- 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^a_μ: 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
  - chiral symmetry most important connection between QCD and effective hadronic models

Phenomenology and Chiral symmetry

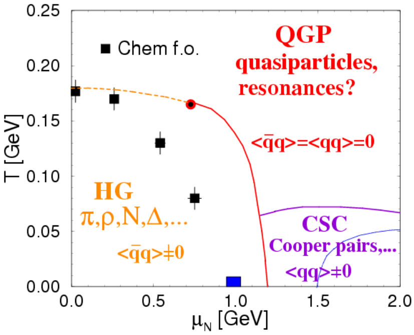
- In vacuum: Spontaneous breaking of chiral symmetry
- $\Rightarrow$ mass splitting of chiral partners

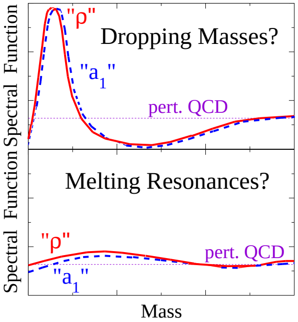




The QCD-phase diagram

- at high temperature/density: restoration of chiral symmetry
- Lattice QCD: $T_c^{\chi} \simeq T_c^{\text{deconf}}$

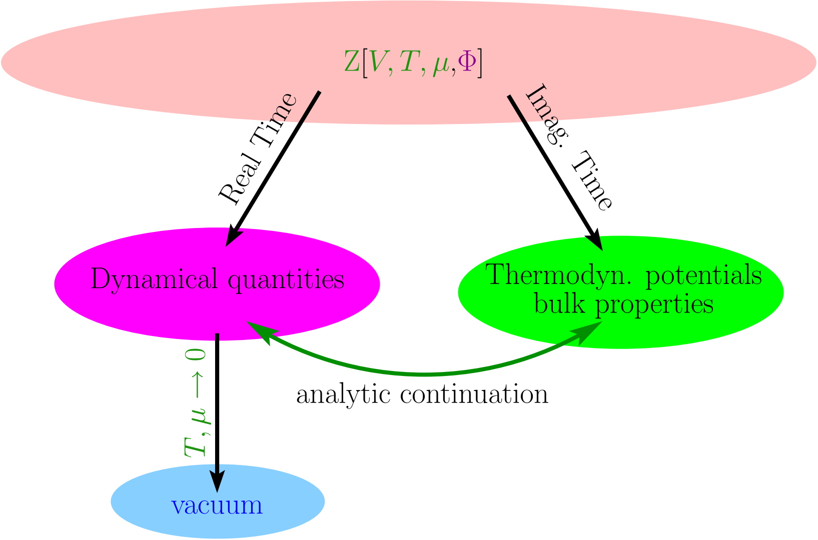




- Mechanism of chiral restoration?
- Two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \bar{\psi}\psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
  - More theoretical question: Realization of chiral symmetry in nature?

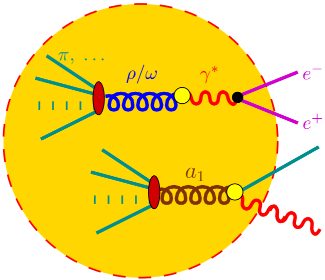
Finite Temperature/Density: Idealized theory picture

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



Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: no strong interactions
- reflect whole "history" of collision
- chance to see chiral symm. rest. directly?



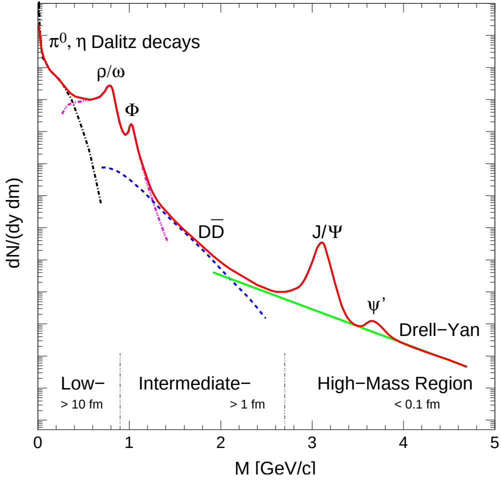


Fig. by A. Drees

Vector Mesons and electromagnetic Probes

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

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

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

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

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

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

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

$$f_\pi^2 = -\int_0^\infty \frac{\mathrm{d}q_0^2}{\pi q_0^2} [\mathrm{Im}\,\Pi_V(q_0,0) - \mathrm{Im}\,\Pi_A(q_0,0)]$$

$$-\frac{\pi}{2}\alpha_s \langle \mathscr{O}_{\chi\text{SB}} \rangle = -\int_0^\infty \frac{\mathrm{d}q_0^2}{\pi} [\mathrm{Im}\,\Pi_V(q_0,0) - \mathrm{Im}\,\Pi_A(q_0,0)]$$

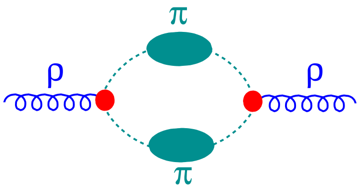
- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to order parameters of chiral symmetry!

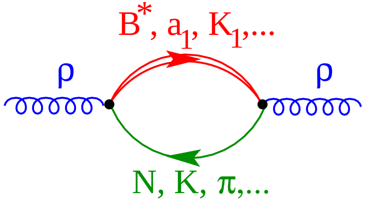
Model dependence

- 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
    - Hidden-Local Symmetry model: dropping masses ($M_\rho, M_{a_1} \rightarrow 0$ for $T \rightarrow T_c$) [Harada, Sasaki 06]
    - Massive Yang Mills model: $M_\rho \uparrow$, $M_{a_1} \downarrow$ + broadening [Song 93]
- use hadronic many-body theory (HMBT) to assess medium modifications of vector mesons

Hadronic many-body theory

- HMBT [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...] for vector mesons
- $\pi\pi$ interactions and baryonic excitations

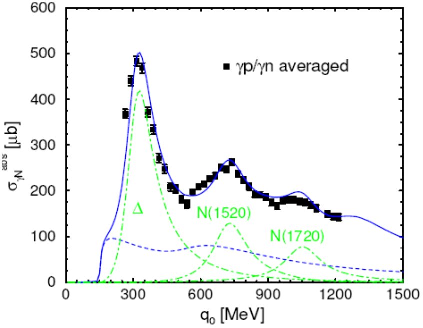


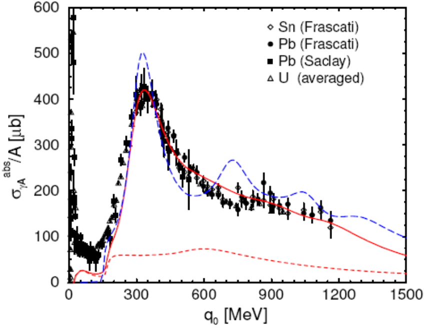


- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

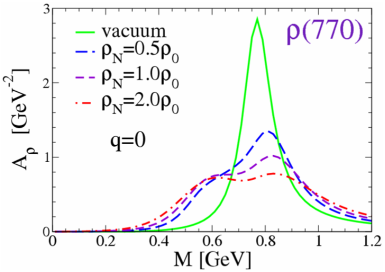
Constraints on spectral functions

- vacuum: em. pion-form factor, decay widths
- cold nuclear matter: Photo-absorption on nucleons and nuclei

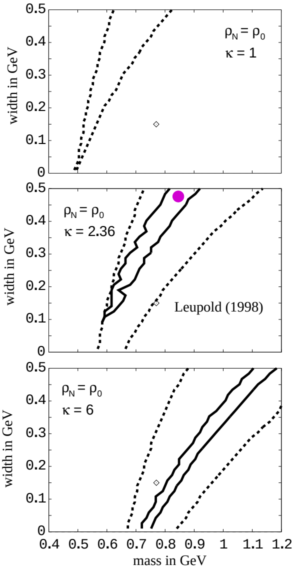




Properties of spectral functions: QCD sum rules



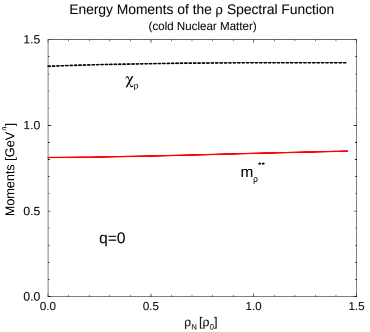
- ρ-spectral function at finite n_B
- consistent with QCD-sum rules



Properties of spectral functions: Moments

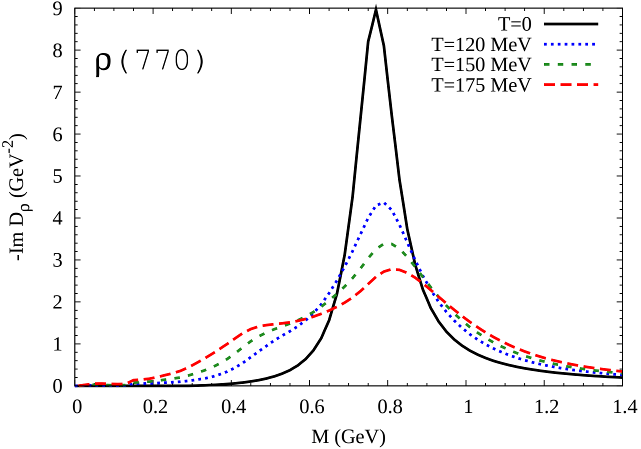
$$\chi_\rho = \int_0^\infty \frac{\mathrm{d}s}{\pi} s^{-1} A_\rho(s, \vec{q}=0)$$

$$(m_\rho^{**})^2 = \int_0^\infty \frac{\mathrm{d}s}{\pi} s A_\rho(s, \vec{q}=0)$$



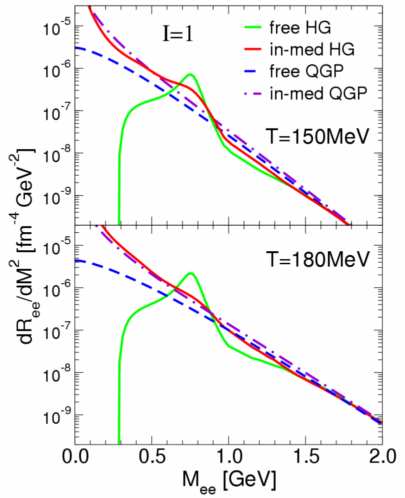
- $m_\rho^{**} \sim$ const $\Rightarrow$ no significant mass shifts!

In-medium spectral functions and baryon effects



- baryon effects important $\leftrightarrow$ $N_B + N_{\bar{B}}$ relevant (not $N_B - N_{\bar{B}}$)
  - some more broadening of the peak
  - responsible for most of the strength at small M

Dilepton rates: Hadron gas $\leftrightarrow$ QGP



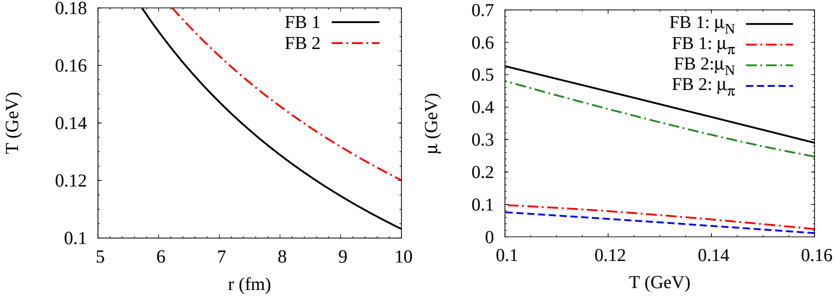
- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"!?
- indirect evidence for chiral-symmetry restoration

Fireball dynamics and hadro-chemistry

- homogeneous thermal fireball model

$$V_{\mathsf{FB}} = \pi(z_0 + v_z t) \left(\frac{a_\perp}{2} t^2 + r_0\right)^2$$

- thermodynamics: isentropic expansion
- hadro-chemistry: hadron ratios fixed for $T < T_{\mathsf{ch}} \Rightarrow \mu_N, \mu_\pi, \mu_K, \ldots$



Fireball 1: $(T_c, \mu_N) = (175, 230)$ MeV, $s_c^{\mathsf{HG}} = 6.1/\mathsf{fm}^3$,

Fireball 2: $(T_c, \mu_N) = (170, 220)$ MeV, $s_c^{\mathsf{HG}} = 4.9/\mathsf{fm}^3$.

Sources of dilepton emission in heavy-ion collisions

1. initial hard processes: Drell Yan
2. "core" $\Leftrightarrow$ emission from thermal source [McLerran, Toimela 1985]

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

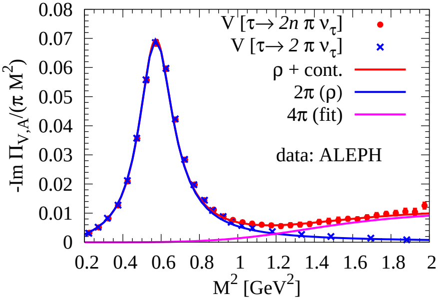
3. "corona" $\Leftrightarrow$ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out $\Leftrightarrow$ emission from "freeze-out" mesons [Cooper, Frye 1975]

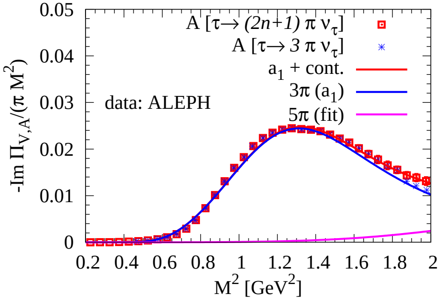
$$\mathrm{d}N^{(\text{fo})} = \int \frac{\mathrm{d}^3q}{q_0} q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T) \frac{\Gamma_{\text{meson}\rightarrow\ell^+\ell^-}}{\Gamma_{\text{meson}}} \text{Acc}$$

- additional factor $\gamma = q_0/M$ compared to thermal emission
- physical reason
  - thermal source rate $\propto \tau_{\text{med}} \frac{\Gamma_{\text{meson}\rightarrow\ell^+\ell^-}}{\gamma}$
  - decay of mesons after fo: rate $\propto \frac{\Gamma_{\text{meson}\rightarrow\ell^+\ell^-}}{\Gamma_{\text{meson}}}$

Intermediate masses: hadronic "4π contributions"

- e.m. current-current correlator $\Leftrightarrow$ $\tau \rightarrow 2n\pi$

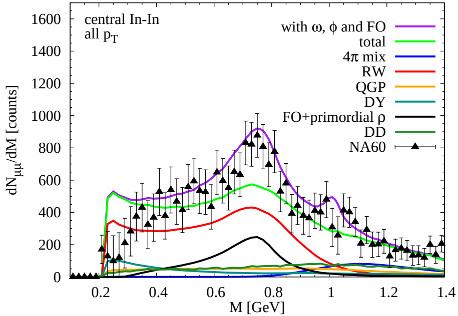




- leading-order virial expansion for "four-pion piece"
- additional strength through "chiral mixing"

NA60 excess spectra: all p_T

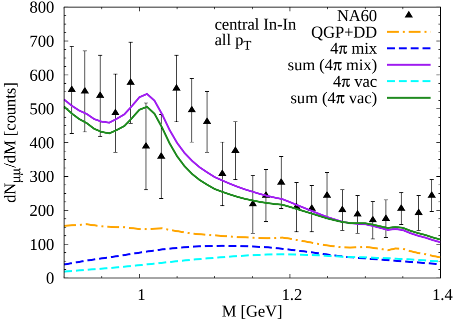
- isentropic expansion: QGP ($T_i \simeq 197$ MeV) via mixed phase ($T_c = 175$ MeV) to thermal freeze-out ($T \simeq 120$ MeV)



- relative normalization of thermal components fixed by in-medium em. spectral functions
- absolute normalization ⇔ fireball lifetime
- good overall agreement with data

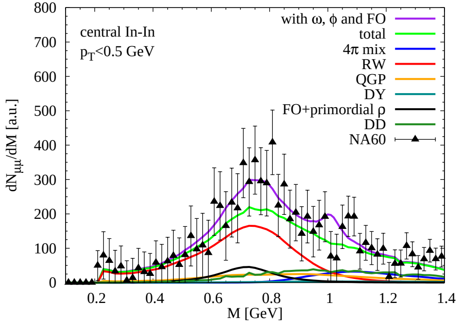
- intermediate masses: hadronic "4π contributions" via model-independent virial estimate!

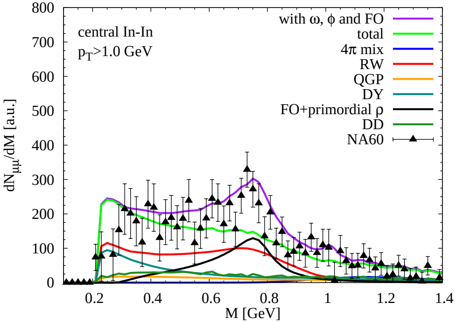
NA60 excess spectra: IMR



- "4π contributions" ($\pi + \omega, a_1 \to \mu^+ + \mu^-$)
- slightly enhanced by VA mixing

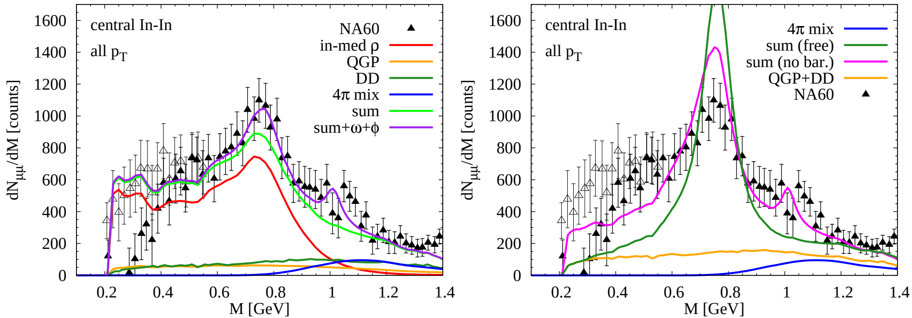
NA60 excess spectra: $p_T < 0.5$ GeV, $p_T > 1.0$ GeV





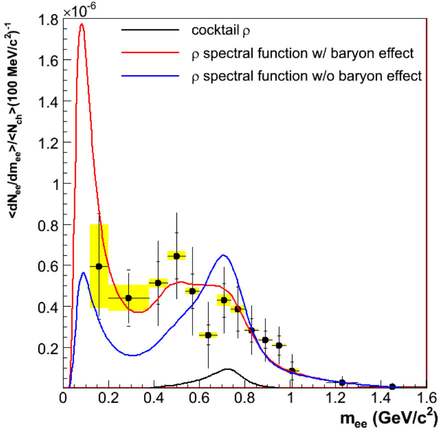
- good description in different p_T bins

Importance of Baryon effects



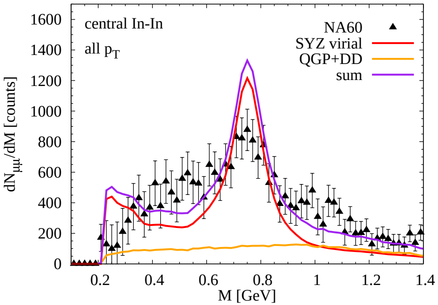
- without baryons
  - not enough broadening
  - lack of strength below ρ peak

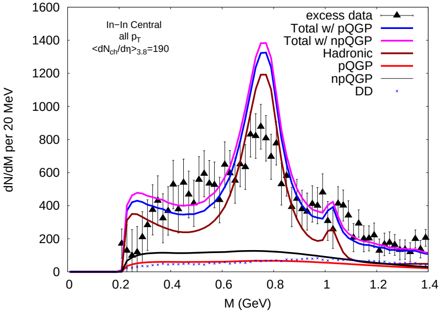
NA45 dielectron spectra



- electrons ⇒ low-mass region
- probes baryon effects!

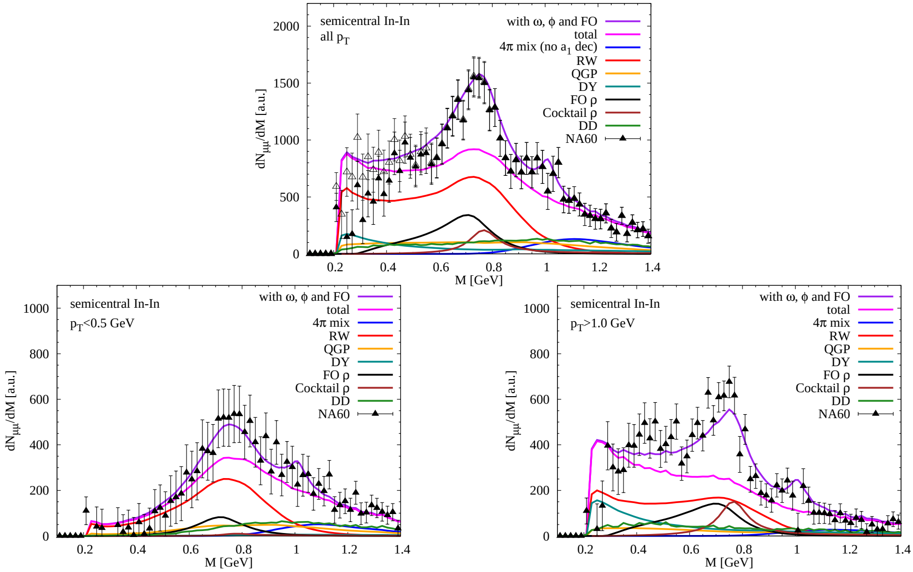
Chiral reduction formalism (virial expansion)





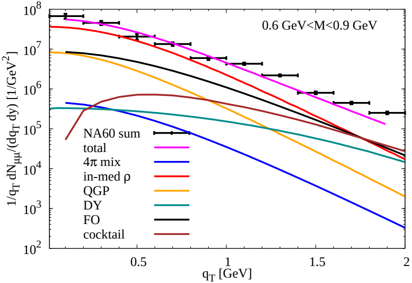
[HvH, Rapp hep-ph/0604269] [Dusling, Teaney, Zahed 06]

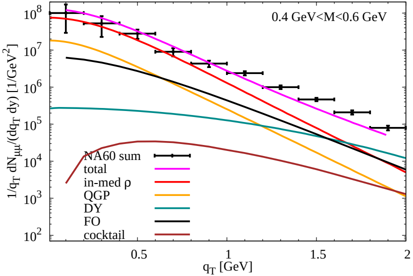
- underestimates medium effects on the ρ (due to low-density approximation no broadening!)
- results with fireball parametrization very similar to hydro!

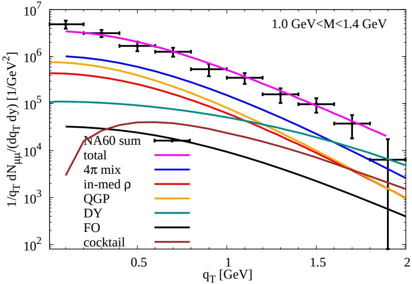


semicentral In-In
all p_T
with ω, φ and FO
total
4π mix (no a_1 dec)
RW
QGP
DY
FO ρ
Cocktail ρ
DD
NA60
$dN_{\mu\mu}/dM$ [a.u.]
M [GeV]
semicentral In-In
p_T<0.5 GeV
with ω, φ and FO
total
4π mix
RW
QGP
DY
FO ρ
Cocktail ρ
DD
NA60
$dN_{\mu\mu}/dM$ [a.u.]
M [GeV]
semicentral In-In
p_T>1.0 GeV
with ω, φ and FO
total
4π mix
RW
QGP
DY
FO ρ
Cocktail ρ
DD
NA60
$dN_{\mu\mu}/dM$ [a.u.]
M [GeV]

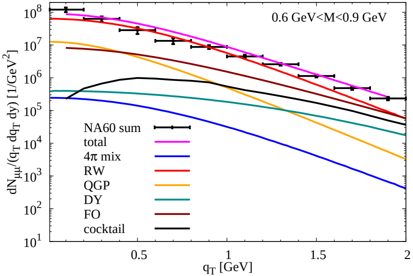
NA60 p_T spectra







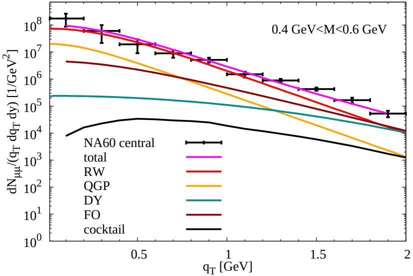
NA60 p_T spectra (central) Fireball 2

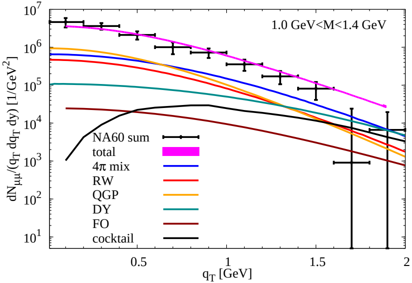


- larger flow
  $(v_{B\perp}^{(2)} = 0.72c$ vs $v_{B\perp}^{(1)} = 0.56c)$
- $T_{\text{eff}}^{(\text{fo})} \simeq T_{\text{fo}} + m \langle v_\perp \rangle^2$
- $T_{\text{eff}}^{(2)} = 291$ MeV vs.
  $T_{\text{eff}}^{(1)} = 223$ MeV

$\Rightarrow$ harder spectra

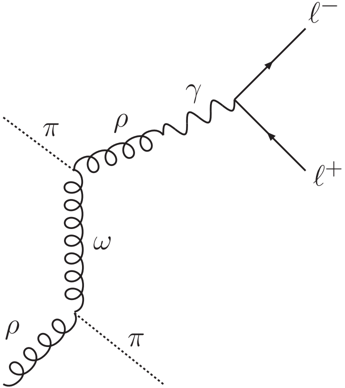
- realistic for 158-GeV-In-In?





New contribution: t-channel meson exchange

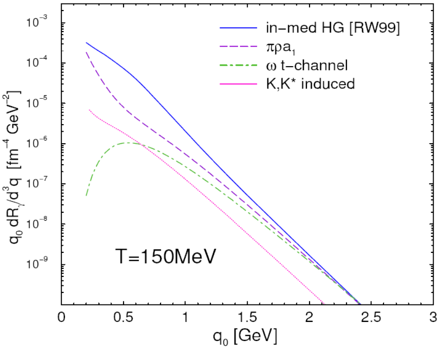
- motivation: p_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far

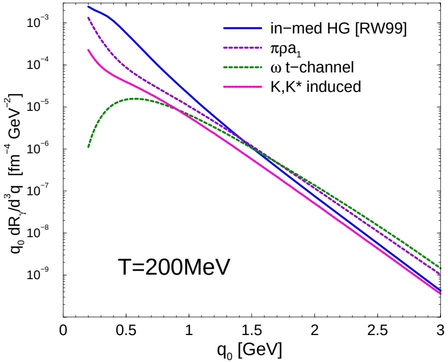


- also for a_1

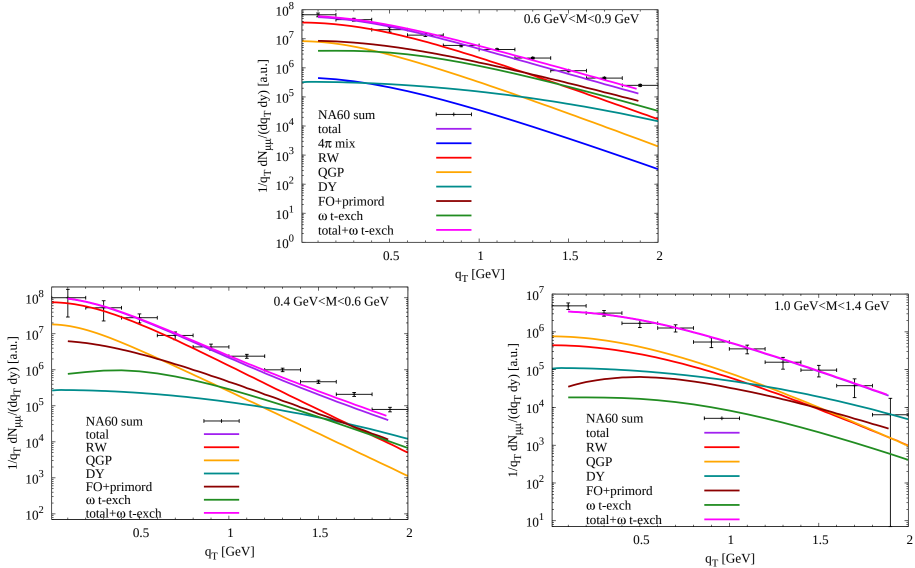
New contribution: t-channel meson exchange

- motivation: p_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far
- also for a_1
- for thermal photons





NA60-p_T spectra (semicentral)



Issues for detailed description of p_T spectra

- hadro chemistry
  - sensitive to chemical freeze-out parameters $\leftrightarrow$ "Hagedorn resonance-gas limit"
  - latent heat: duration of QGP and mixed phase
- (hydro) dynamics
  - velocity profile $v_\perp \propto r_\perp$ vs. $r_\perp^{1/2}, \ldots \Rightarrow$ detailed hydro study
  - longitudinal expansion: boost invariant vs. accelerated expansion
  - viscosity effects (see QM 2006 Talk by Teaney)
- complete set of sources
  - thermal (McLerran-Toimela) vs. decay after freeze-out (Cooper-Frye)
  - hard production: Drell-Yan
  - non-thermalized "primordial ρ's"
    - jet-quenching model ($\sigma_{\text{pre-had}} = 0.4$ mb; after τ_{form}: $\sigma_{\text{had}} = 5$ mb)
    - $q_T \lesssim 1$ GeV: N_{part} scaling; $q_T \gtrsim 3$ GeV: N_{coll} scaling
    - "switched" linearly between scaling scenarios
    - $\sim$ compatible with WA98 pion data

Conclusions and Outlook

- Dilepton spectra $\Leftrightarrow$ em. current correlator $\Leftrightarrow$ QCD-phase diagram
- directly related to chiral symmetry (vector and axial-vector currents)
- hadronic many-body theory
  - low-mass region: light vector mesons
  - intermediate-mass region: four-pion continuum, QGP
- medium effects
  - baryons essential for in-medium properties of vector mesons
  - "4π" contributions $(\pi + \omega, a_1 \rightarrow \ell^+ + \ell^-)$
- fireball/freeze-out dynamics $\Leftrightarrow$ p_T spectra
  - complete set of sources
  - need detailed hydro study
  - precise hadro-chemical freeze-out description (latent heat!)

Dileptons from a thermal source

- all calculations done in (local) heat-bath frame
- Dileptons from a thermal source (ρ channel)
- McLerran-Toimela formula + vector-meson dominance:

$$\frac{\mathrm{d}N_{\ell^+\ell^-}^{\text{therm}}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2 m_\rho^4}{\pi^3 g_{\rho\pi\pi}^2}\frac{f_B(q_0)}{M^2}\,\mathrm{Im}\,D_\rho^{(\text{ret})}(q_0,\vec{q})$$

- $\mathrm{d}^4q = M\mathrm{d}M\mathrm{d}^2q_t\mathrm{d}y$

$$\frac{\mathrm{d}N_{\ell^+\ell^-}^{\text{therm}}}{\mathrm{d}M\mathrm{d}^2q_t\mathrm{d}y} = \int_0^{t_{\text{fo}}}\mathrm{d}t\;V_{\text{FB}}(t)\frac{\alpha^2 m_\rho^4}{\pi^3 g_{\rho\pi\pi}^2}\frac{f_B(q_0)}{M}\,\mathrm{Im}\,D_\rho^{(\text{ret})}(q_0,\vec{q})$$

Dileptons from ρ decays after freeze-out

- all calculations done in (local) heat-bath frame
- distribution of ρ mesons at freeze-out
- Cooper-Frye formula

$$\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}d^4q} = \frac{f_B(q_0)}{(2\pi)^3} 2q_0 \delta^{(+)}(q^2 - M^2)$$

- for broad resonance

$$\frac{\mathrm{d}N_\rho}{d^3x d^4q} = -\frac{f_B(q_0)}{(2\pi)^3} \frac{2q_0}{\pi} \operatorname{Im} D_\rho$$

- dilepton rate from decay of freeze-out $(\gamma(\vec{q}) = q_0/M)$

$$\frac{\mathrm{d}N^{\text{fo}}_{\ell^+\ell^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{f_B(q_0)}{(2\pi)^3} \frac{2q_0}{\pi} \operatorname{Im} D_\rho \frac{\Gamma_{\rho \to \ell^+\ell^-}}{\gamma(\vec{q})} \exp\left(-\frac{\Gamma_{\text{tot}}(t - t_{\text{fo}})}{\gamma(\vec{q})}\right)$$

- integration over space-time

$$\frac{\mathrm{d}N^{\text{fo}}_{\ell^+\ell^-}}{\mathrm{d}M\mathrm{d}^2q_t\mathrm{d}y} = -\frac{V_{\text{fo}}}{(2\pi)^3} f_B(q_0) \frac{2}{\pi} \operatorname{Im} D_\rho \frac{\Gamma_{\rho \to \ell^+\ell^-}}{\Gamma_{\text{tot}}} q_0 M$$