Medium Modifications of Hadrons and Electromagnetic Probes

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Outline

QCD and ("accidental") Symmetries

- Theory for strong interactions: QCD

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

- Particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) =$ current quark masses
  - A_μ^a: gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$

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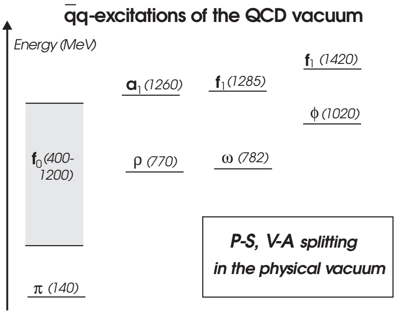
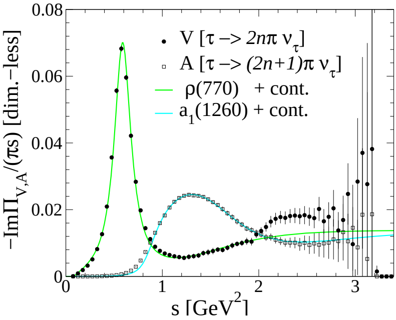
  - A_μ^a: gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$
- Symmetries
  - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry most important connection between QCD and effective hadronic models

Phenomenology from Chiral Symmetry

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





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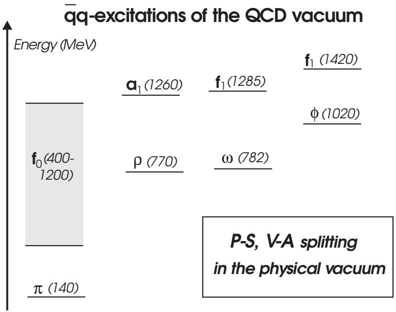

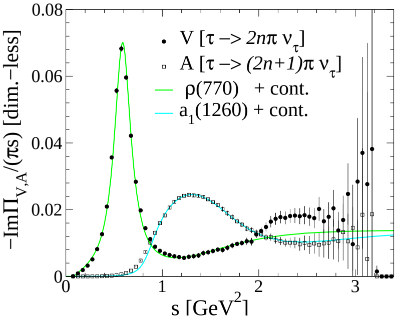

- at high temperature/density: restoration of chiral symmetry
- Lattice QCD: $T_c^\chi \simeq T_c^{\text{deconf}}$

Finite Temperature/Density: Idealized Theory Picture

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

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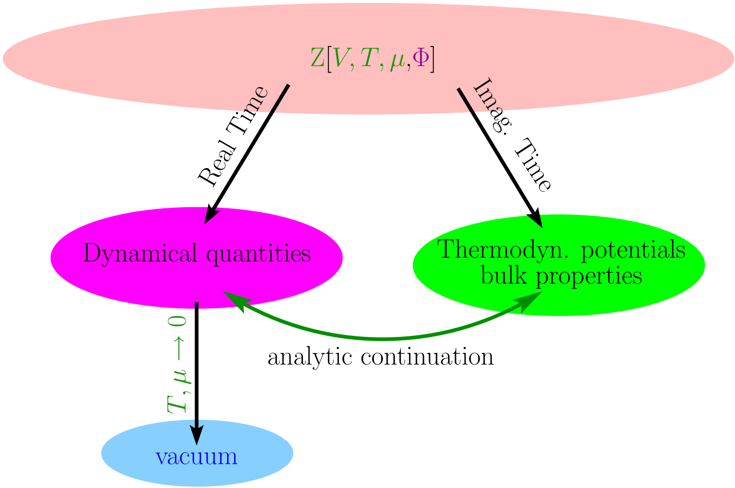
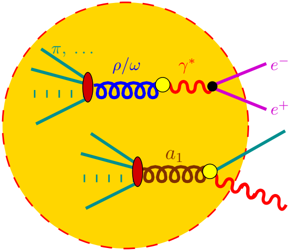


Why Electromagnetic Probes?

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



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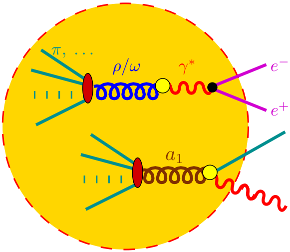

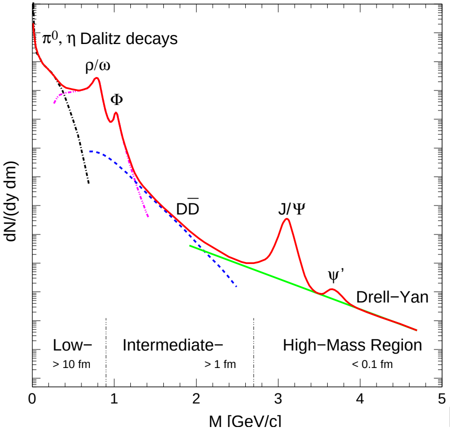

Fig by A. Drees

Vector Mesons and electromagnetic Probes

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

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

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

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

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

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

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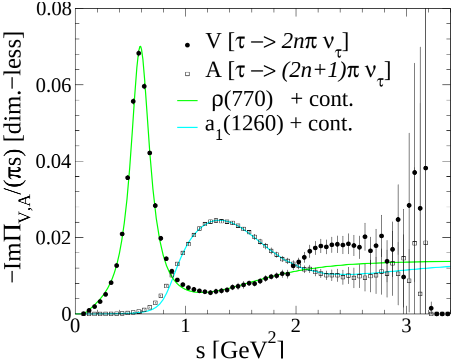
- Ward-Takahashi Identities from chiral symmetry $\Rightarrow$ Weinberg-sum rules

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

$$-\frac{\pi}{2}\alpha_s \langle \mathscr{O}_{\chi\text{SB}} \rangle = -\int_0^\infty \frac{\mathrm{d}p_0^2}{\pi} [\mathrm{Im}\,\Pi_V(p_0,0) - \mathrm{Im}\,\Pi_A(p_0,0)]$$

- 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



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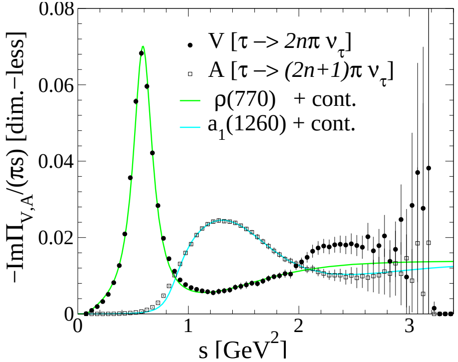

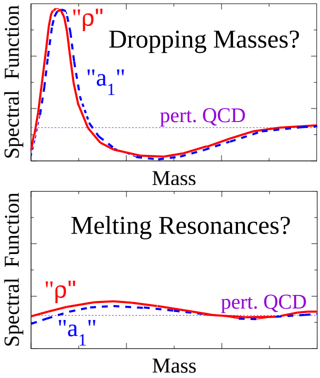

Models

- different models with chiral symmetry: equivalent only on shell (“low-energy theorems”)

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- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations

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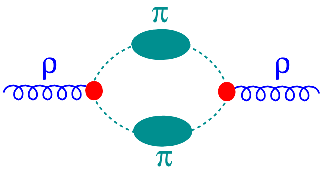
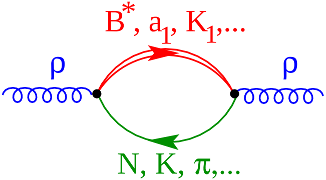
- different models with chiral symmetry: equivalent only on shell ("low-energy theorems")
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- use phenomenological hadronic many-body theory (HMBT) to assess medium modifications of vector mesons

Models

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





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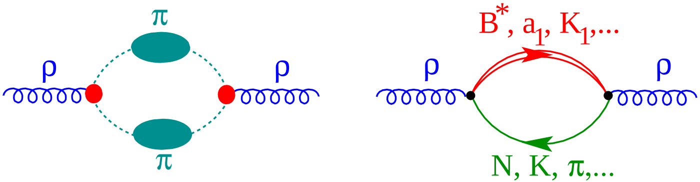
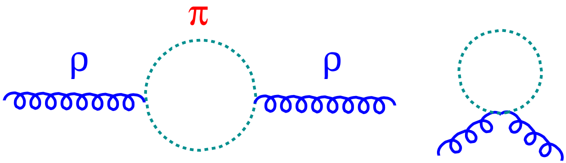
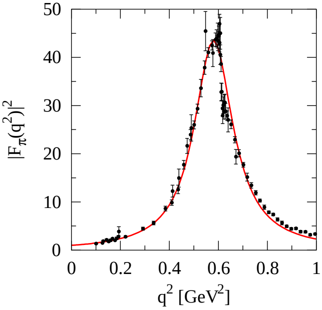


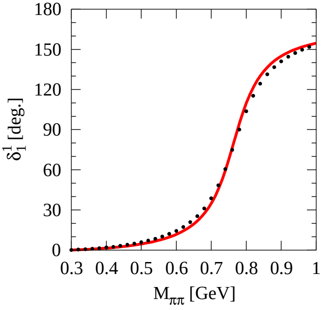
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

The meson sector (vacuum)

- most important for ρ-meson: pions

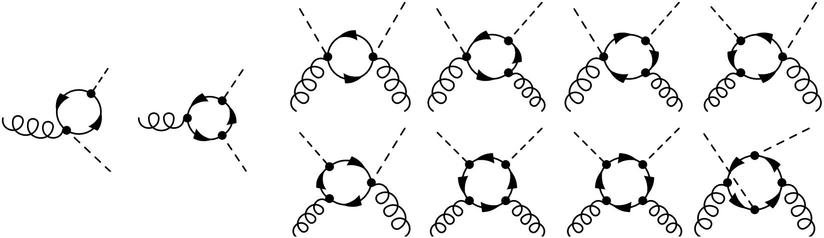




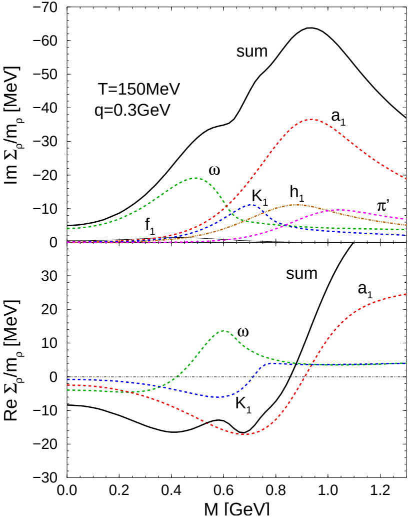


The meson sector (matter)

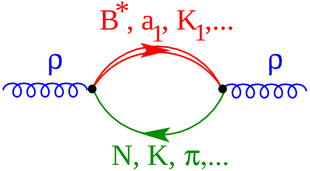
- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi vertex corrections mandatory!



The meson sector (contributions from higher resonances)

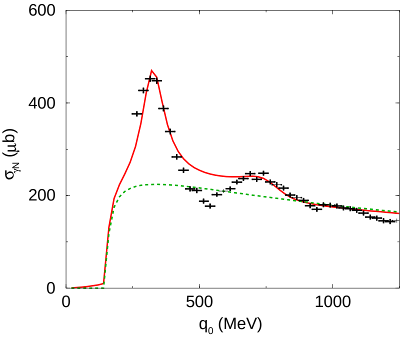


The baryon sector (vacuum)



- $P = 1$-baryons: p-wave coupling to ρ:
  N(939), Δ(1232), N(1720), Δ(1905)
- $P = -1$-baryons: s-wave coupling to ρ:
  N(1520), Δ(1620), Δ(1700)

Photoabsorption on nucleons and nuclei



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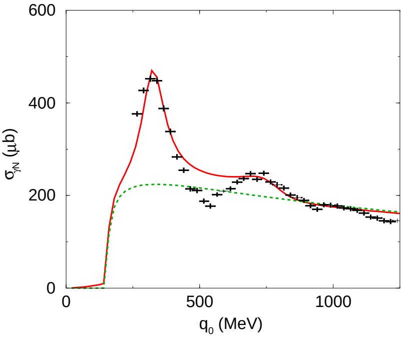
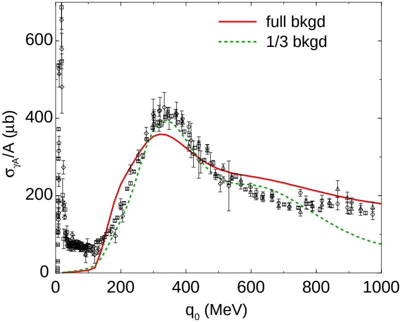
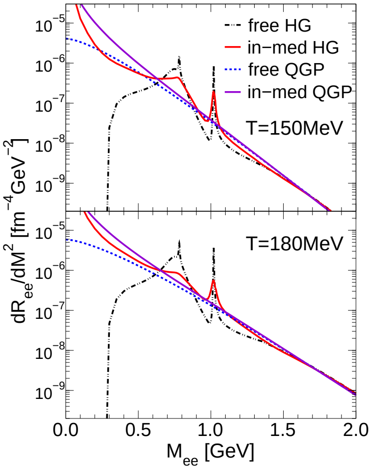


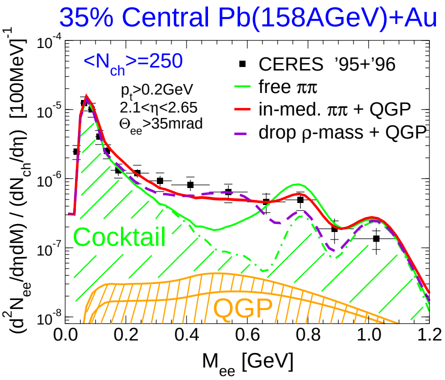


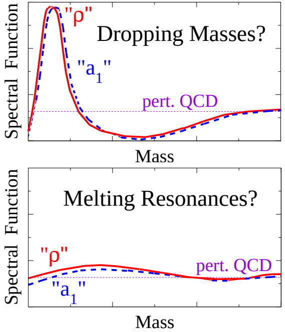
Dilepton rates: Hadron gas $\leftrightarrow$ QGP



- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?
- does it work with chiral model?
- hidden local symm.+baryons? [Harada, Yamawaki et al.]

Dilepton rates at SpS

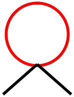


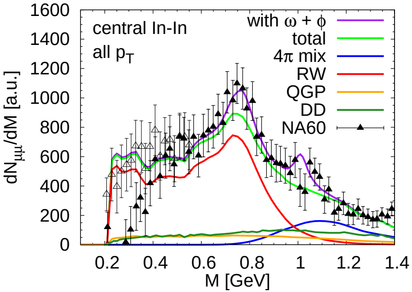


New NA60 Dimuon Data

- intermediate mass range: Mixing of Π_V with Π_A (Dey, Eletsky, Ioffe '90)

$$\Pi_V^{(T)} = (1-\epsilon)\Pi_V + \epsilon \Pi_A, \quad \epsilon = \frac{1}{2}\frac{\mathcal{T}_\pi(T,\mu_\pi)}{\mathcal{T}_\pi(T_c,0)} \propto$$





(hep-ph/0603084)

- Fireball model $\Rightarrow$ time evolution
- absolute normalization!
- good overall agreement with data
- sensitive to ω and ϕ!
- ω: similar model as for ρ
- ϕ: less well known; width assumed $\simeq 80$ MeV

New NA60 Dimuon Data

- 2π contributions$+\rho B$ interactions from Rapp+Wambach '99
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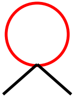
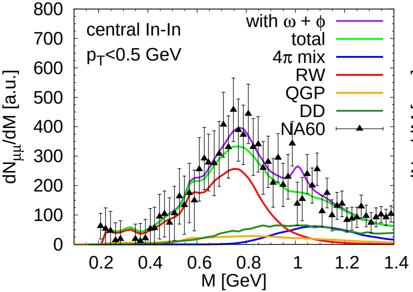
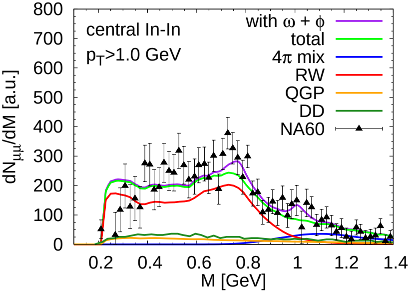


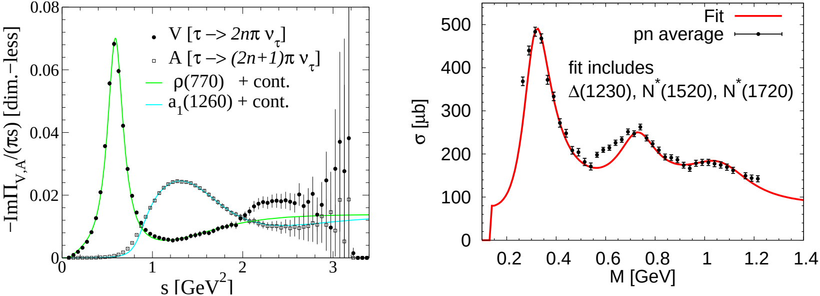




- same absolute normalization!
- "Corona effect" for high p_T?

New NA60 Dimuon Data

- Chiral reduction formalism (Steele, Yamagishi, Zahed '96)
- based on chiral symmetry and Veltman-Bell master equations
- virial expansion $\Leftrightarrow$ medium modifications from vacuum correlators (restricted to low π/B densities)



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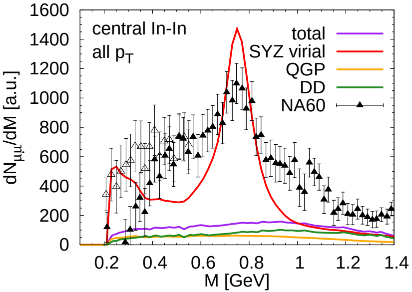

- underestimates medium effects on the ρ
  (due to low-density approximation? No broadening!)
- intermediate masses: mixing less pronounced
- indication of chiral restoration?

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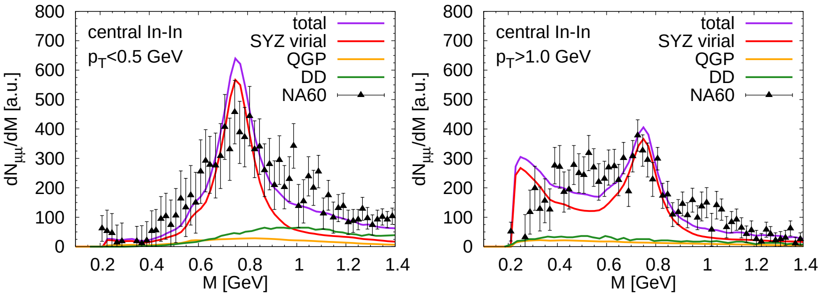

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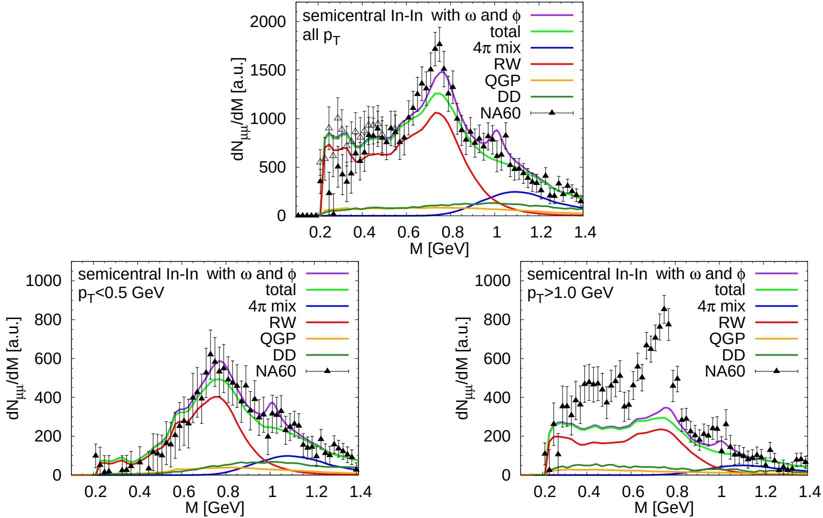
New NA60 Dimuon Data (semicentral)



Challenges for Experiment

- Direct signature for chiral restoration:
  spectra for ρ and a_1 mesons degenerate
- $\pi^{\pm}\gamma$ invariant mass spectrum $\leftrightarrow$ a_1 spectral function

X	$\Gamma_{X\to\pi\gamma}$[MeV]
a_1	0.64
ρ	0.07
ω	only $\pi^0\gamma$!
a_2	0.3
$\pi(1300)$	???

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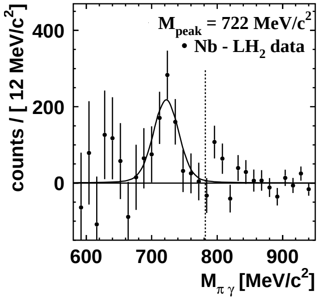
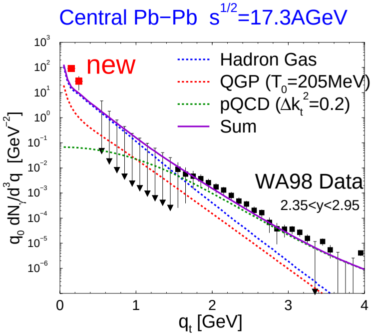


ω-spectral function from CBELSA/TAPS

Challenges for Experiment

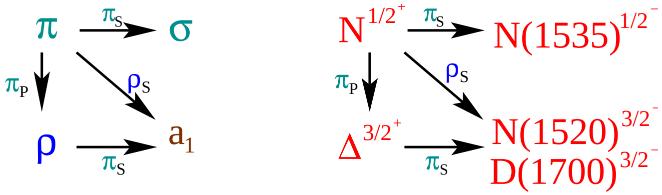
- Photon rate



- $\pi\pi \to \rho \to \pi\pi\gamma$ not enough to explain enhancement
- New development (Liu/Rapp work in progress): $\pi K \to K^* \to \pi K \gamma$
- Consistency with dileptons

Challenges for Theory

- Need a fully chiral model



- How to treat (axial-) vector mesons (gauge model?)
- Approximation scheme for both dynamical properties (spectral functions) and thermodynamic bulk properties (phase diagram)?

Conclusions

- chiral symmetry: important feature to connect QCD$\leftrightarrow$ hadronic effective models
- important property of (s)QGP: How is chiral symmetry restored?
- electromagnetic probes may provide most direct insight
  - invariant-mass spectra for chiral partners: here ρ and a_1
  - low-energy photons $\leftrightarrow$ dileptons (puzzle?)
- a lot to do also for theory
  - consistent chiral scheme for hadrons
  - self-consistent treatment of (axial-) vector particles
  - equation of state including in-medium modifications vs. statistical models with "free hadron properties"