Chiral Symmetry and Electromagnetic Probes

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Outline

QCD and Chiral Symmetry

Vector Mesons and electromagnetic Probes

Challenges for experiment (and theory)

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
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- Symmetries
  - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - dilation symmetry (scale invariance)

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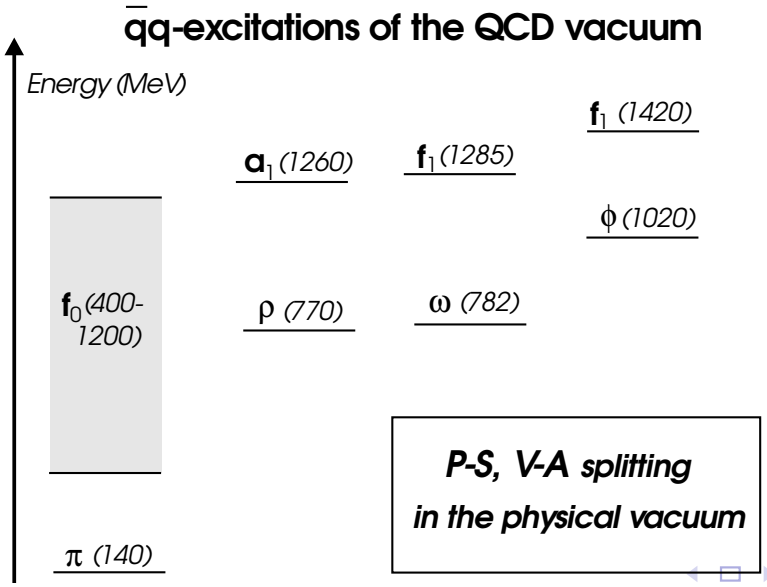
  - "real world": chiral symmetry slightly explicitly broken by quark masses $\hat{M} \neq 0$

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

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

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

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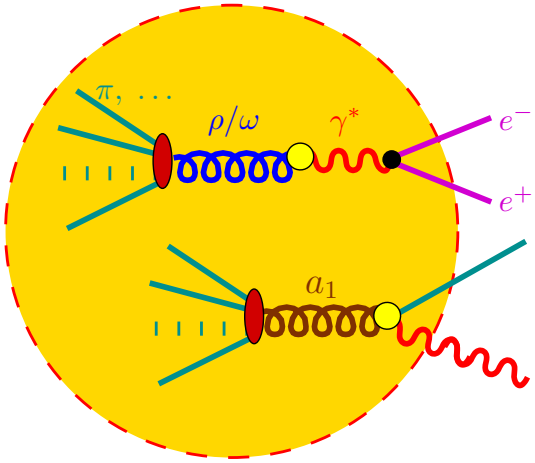
- Free energy: $\Omega = -\frac{T}{V} \ln Z = -P$
- Quark condensate: $\left\langle \bar{\psi}_q \psi_q \right\rangle_{T,\mu_q} = \frac{V}{T} \frac{\partial P}{\partial m_q}$
- Lattice QCD indicates: Chiral symmetry restoration $\leftrightarrow$ deconfinement phase transition (same T_c)

Why Electromagnetic Probes?

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



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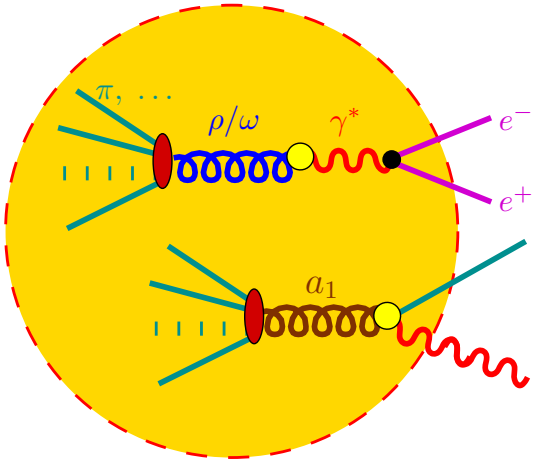

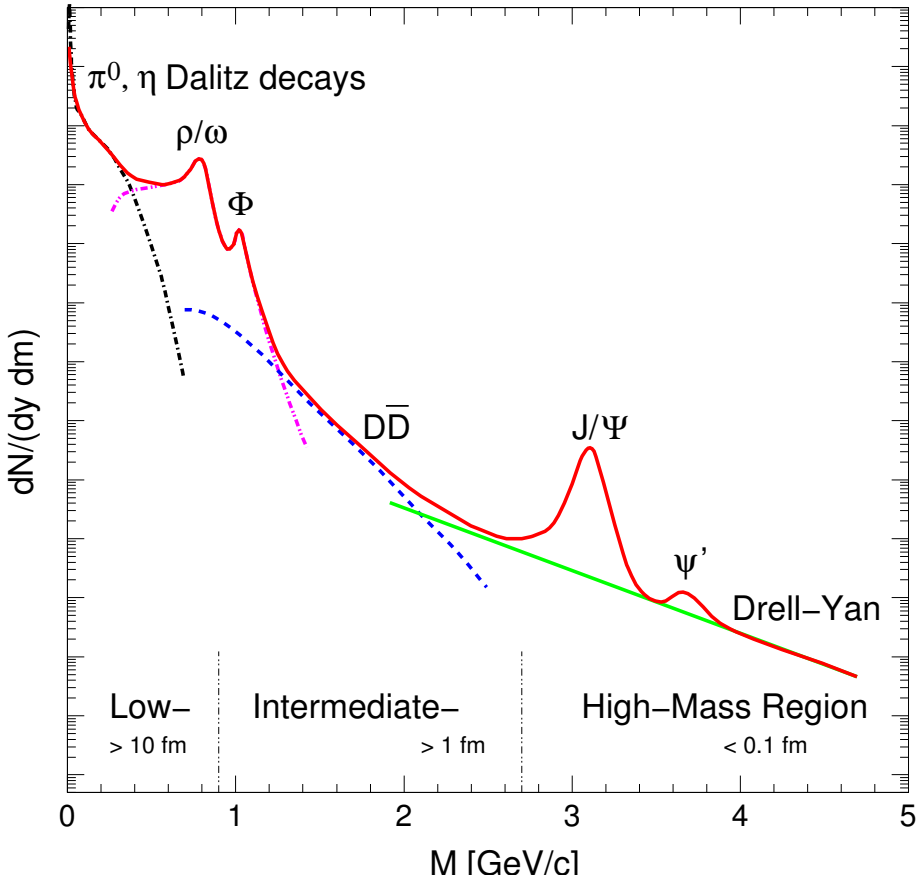

Fig. by A. Drees (from [RW00])

Vector Mesons and electromagnetic Probes

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

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

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

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

- to lowest order in α: $e^2\Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential Ω!

Vector Mesons and chiral symmetry

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

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

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

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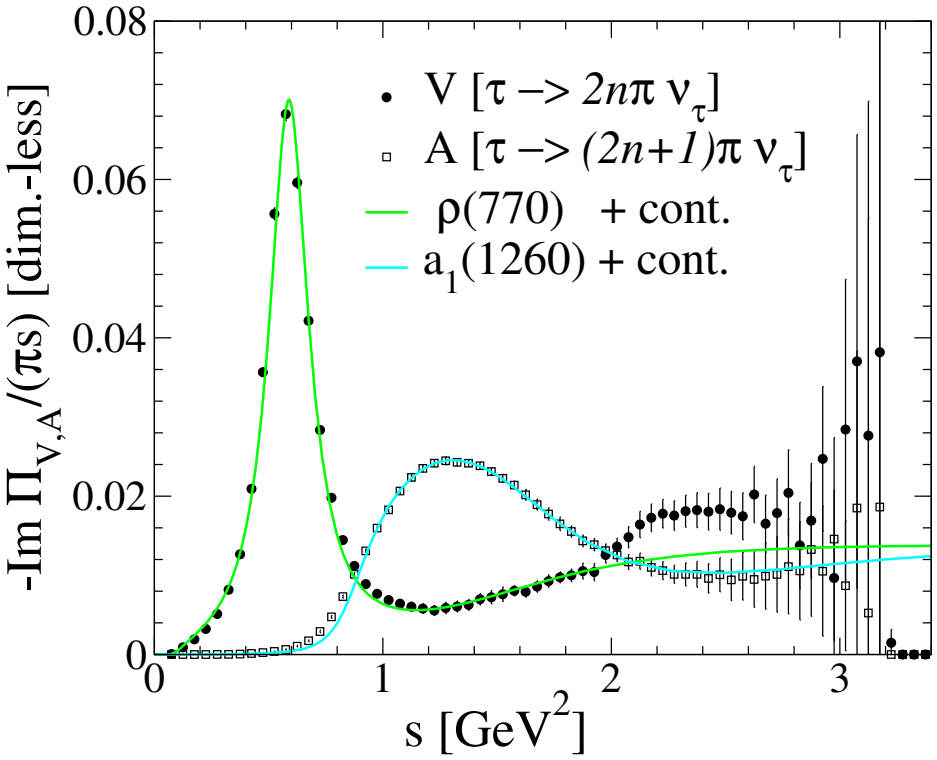
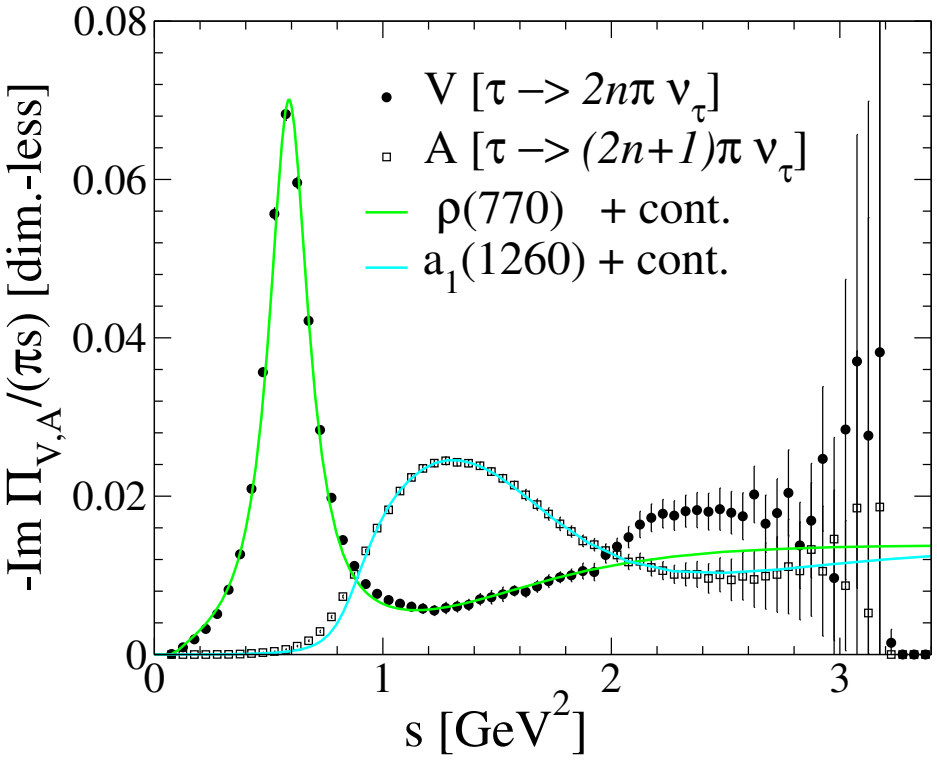
- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to order parameter of chiral symmetry!

Vector Mesons and chiral symmetry



from [Rap03]

Vector Mesons and chiral symmetry



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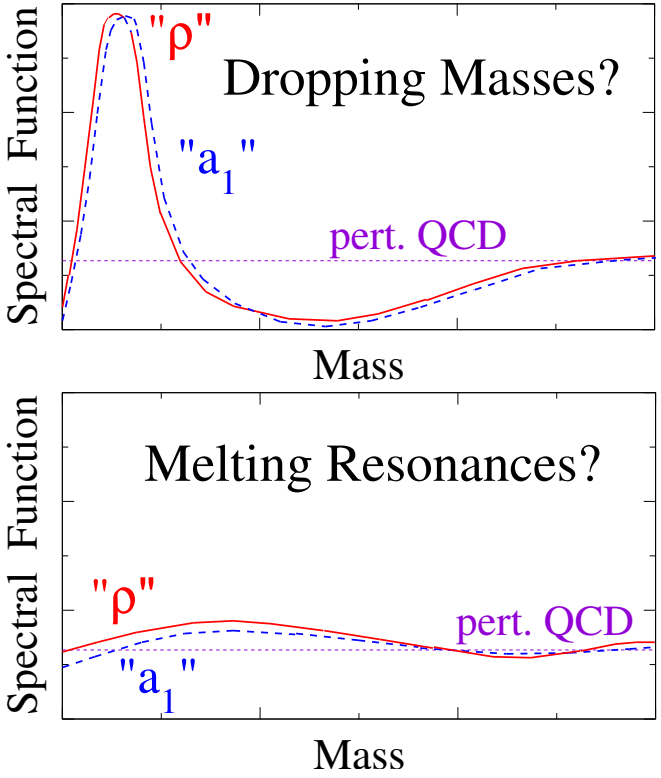

from [Rap05]

Models

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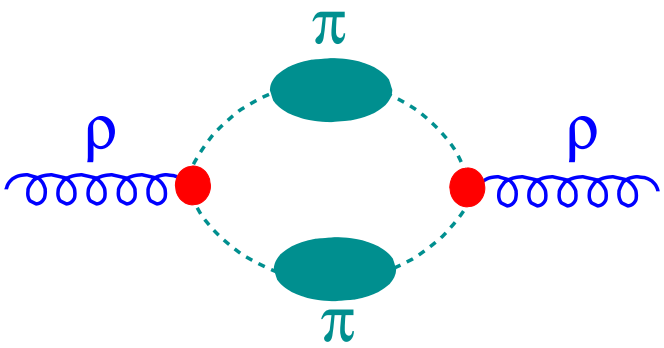
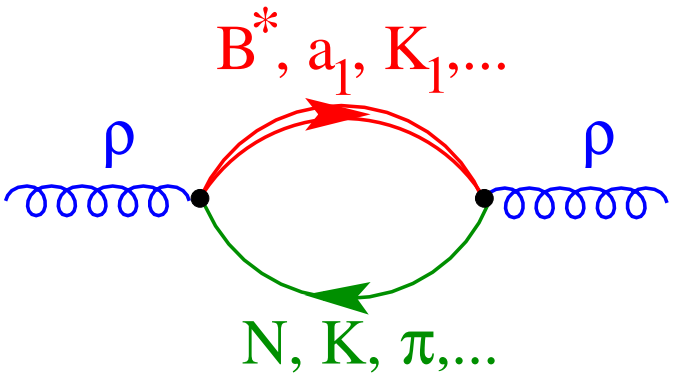
- different models with chiral symmetry: equivalent only on shell ("low-energy theorems")
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- use phenomenological hadronic models + many-body techniques to assess medium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

Models

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





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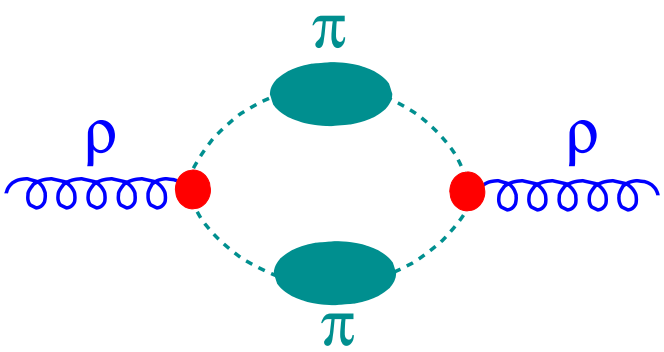
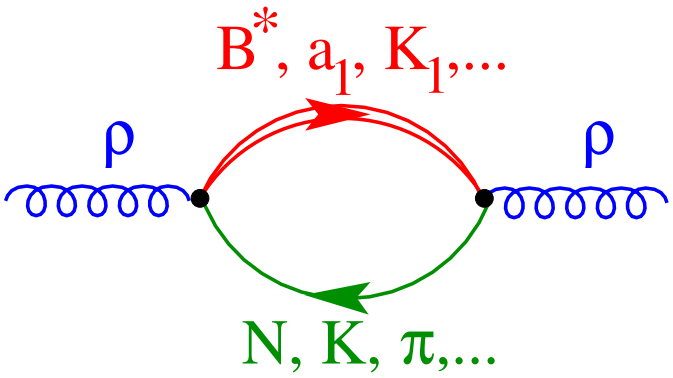
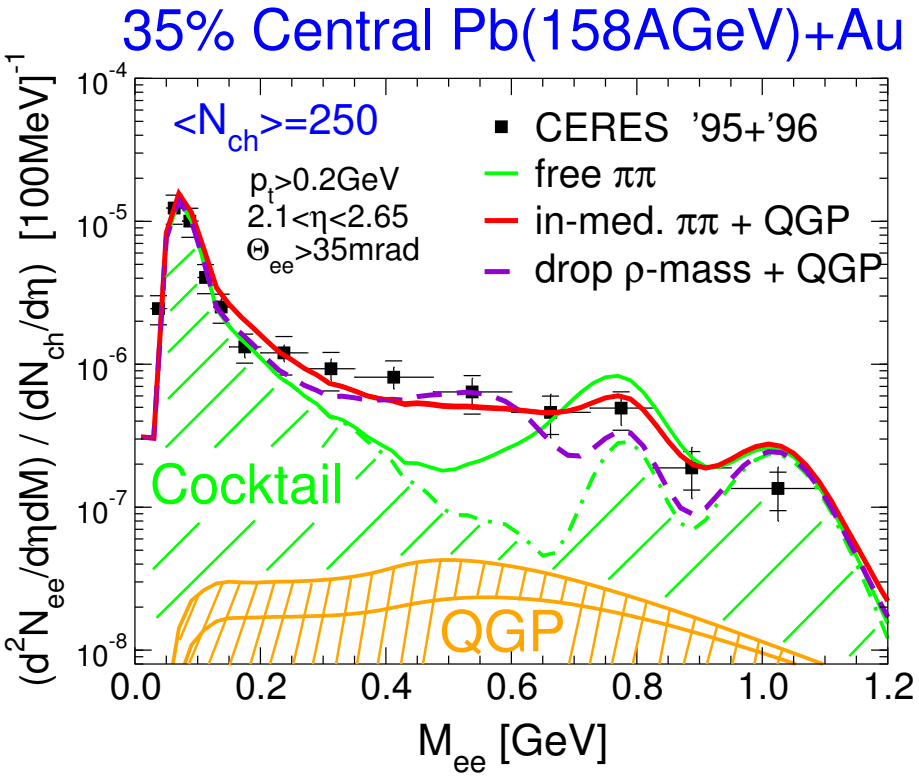
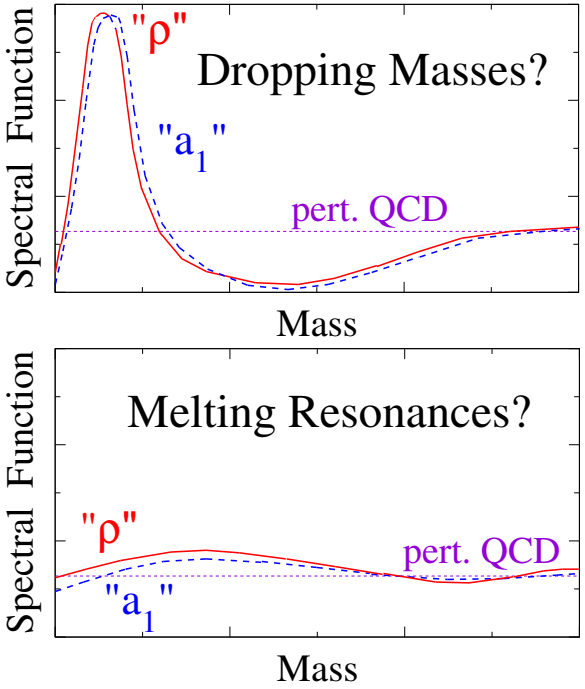




- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP invariance of strong interactions)

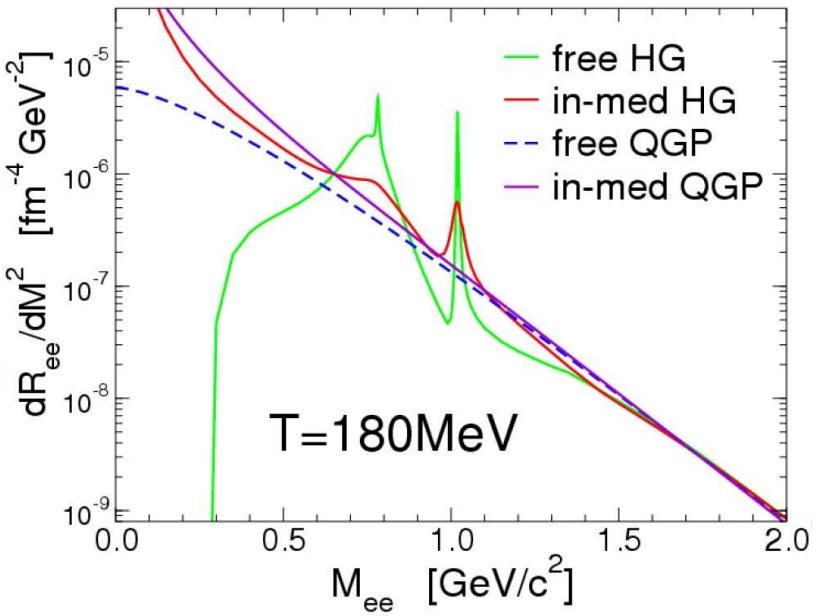
Dilepton rates at SpS

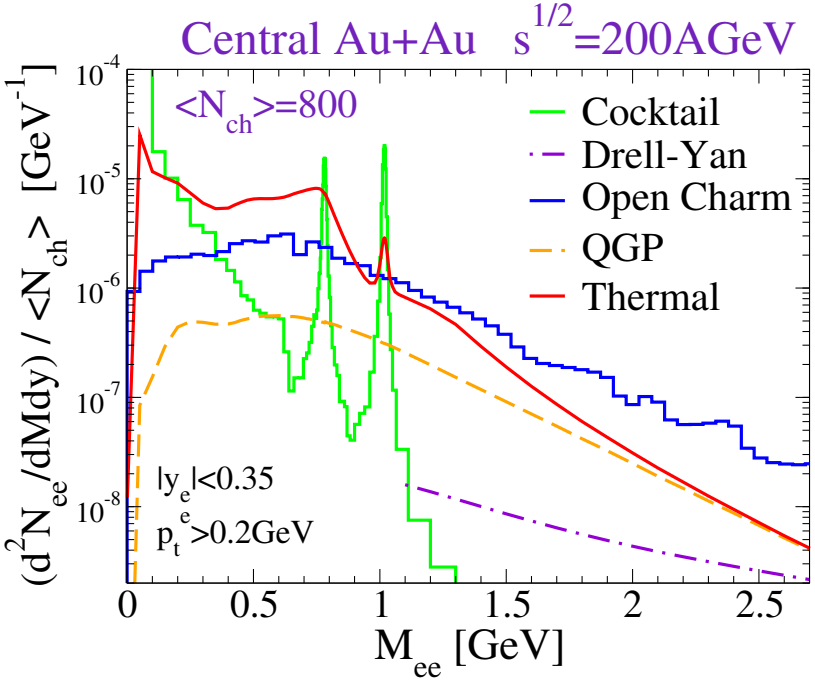




- how to decide about scenario experimentally?

Dilepton rates/spectra at RHIC





- in-medium hadron gas matches with in-medium pQCD
- (similar results also for γ rates)
- "quark-hadron duality"?

Challenges for Expriment

- 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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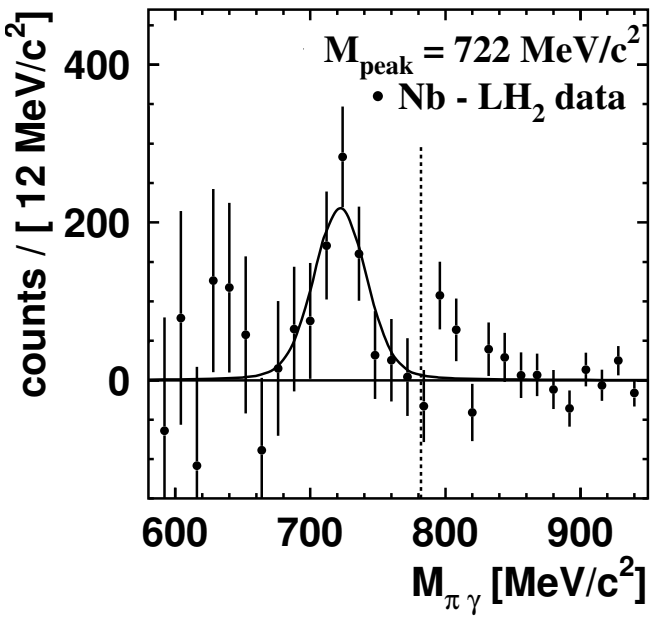
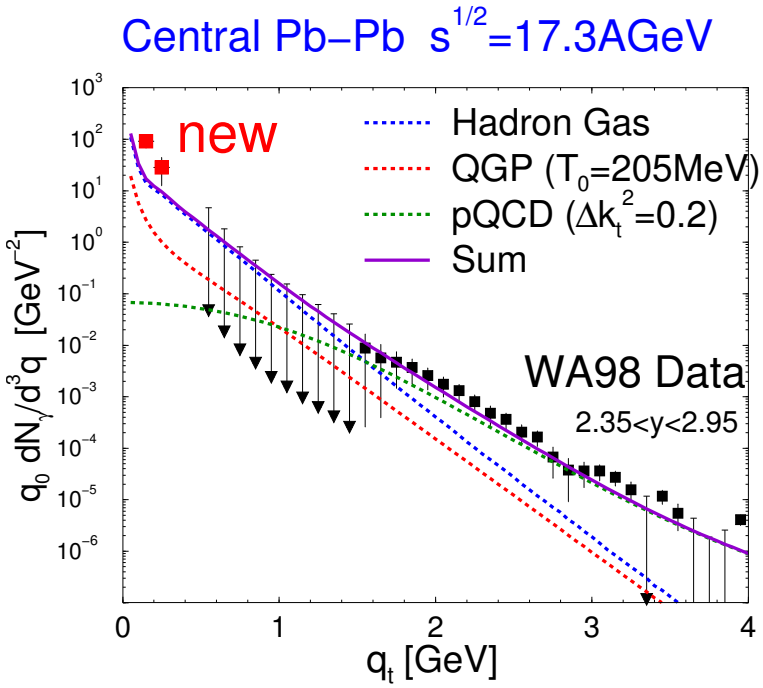


ω-spectral function from [Trn05] (CBELSA/TAPS)

Challenges for Experiment

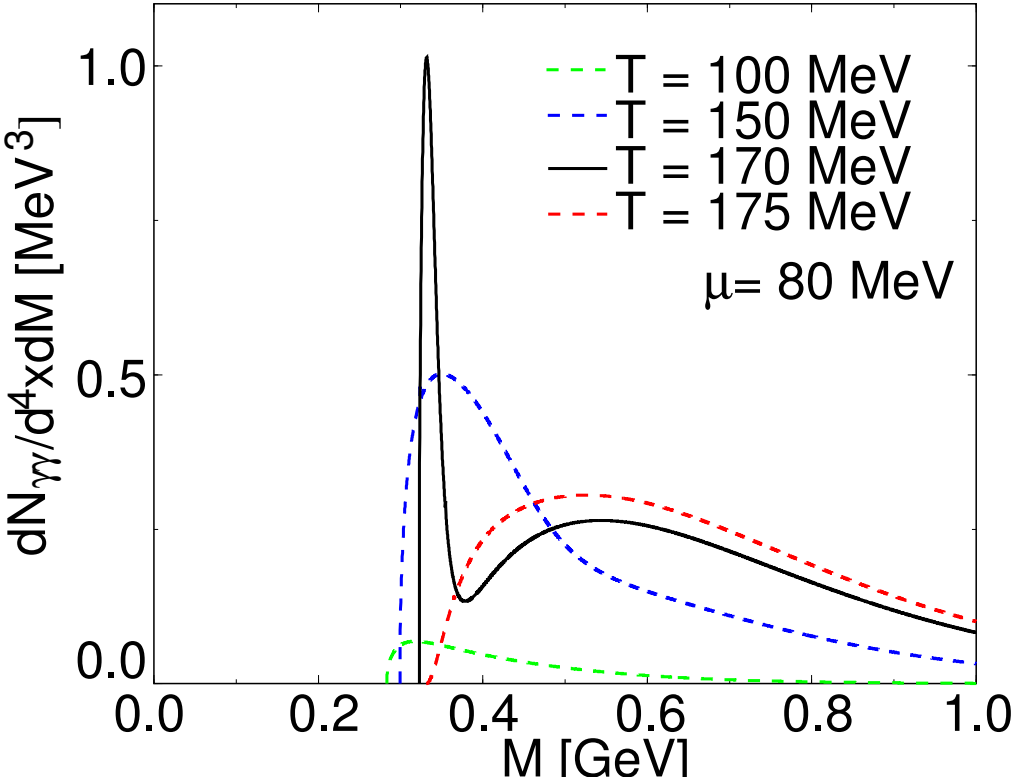
- Photon rate



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

Challenges for Expriment

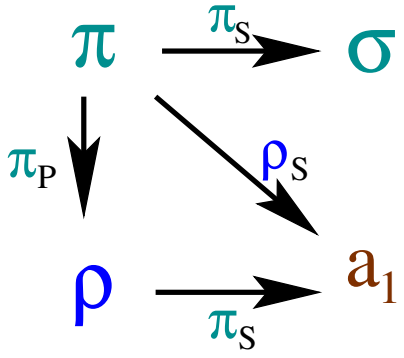
- low-mass $\gamma\gamma$-invariant-mass spectrum
- dropping and narrowing of $\sigma(600)$ for temperatures around T_c

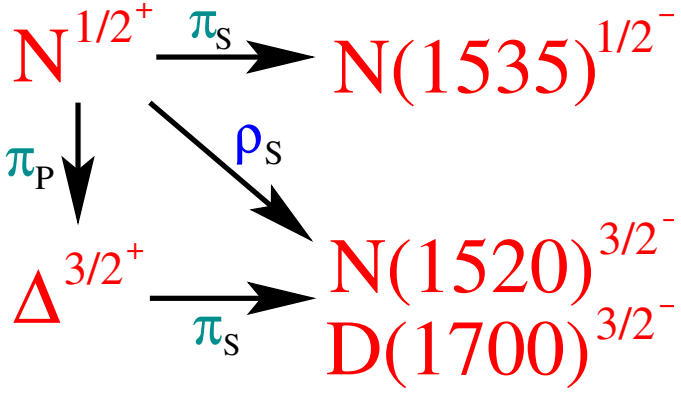


$\pi^+ + \pi^- \to \gamma + \gamma$ from [VKB+98]

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)?

Summary

- chiral symmetry: important feature of low-energy sector of QCD
- one aspect of (s)QGP: how is chiral symmetry restored?
- electromagnetic probes may provide most direct insight
  - invariant-mass spectra for chiral partners: here ρ vs. a_1 ("dropping mass" vs. "in-medium broadening"?)
  - low-energy photons $\leftrightarrow$ dileptons (puzzle?)
  - $\gamma\gamma$ spectra: σ "softening"?
- a lot to do also for theory: consistent chiral scheme for hadrons wanted!

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