Medium Modifications of Hadrons and Chiral Symmetry

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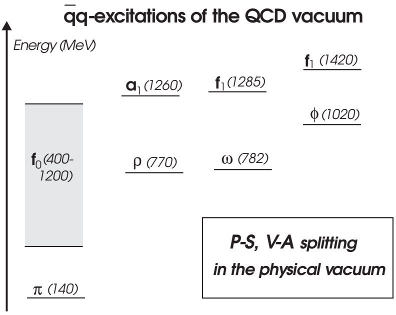
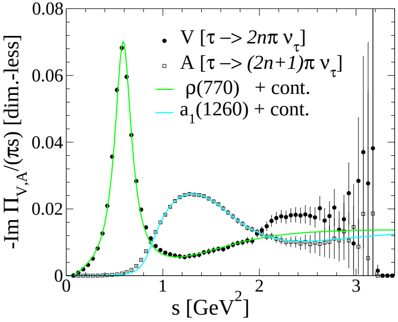
  - A_μ^a: gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$
- Symmetries
  - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry most important connection between QCD and effective hadronic models

Phenomenology from Chiral Symmetry

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





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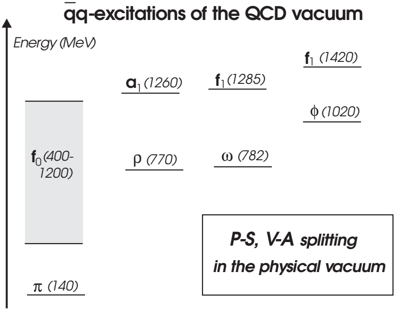

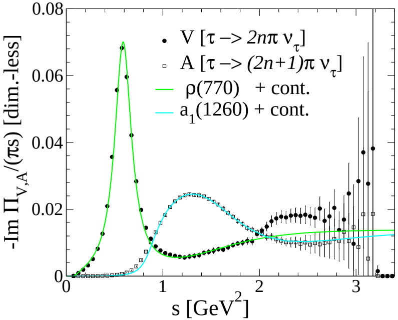

- at high temperature/density: restoration of chiral symmetry
- Lattice QCD: $T_c^{\chi} \simeq T_c^{\text{deconf}}$

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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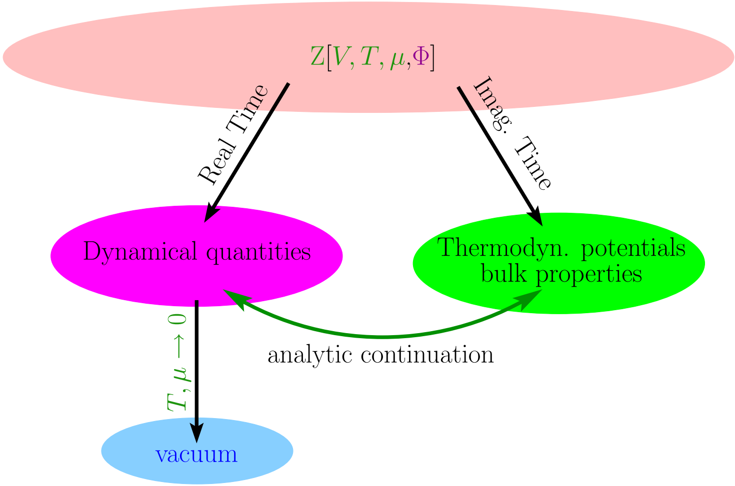

Medium Modifications of the Δ

- Nucleon and Δ in hot/dense matter
- photo absorption on nuclei
- πN invariant-mass spectra

Medium Modifications of the Δ

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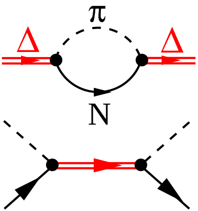
- photo absorption on nuclei
- πN invariant-mass spectra
- hadronic model: N, π, $\Delta(1232)$, higher resonances
- pions fully relativistic, baryons anti-particle poles neglected
- πNΔ vertex: p wave
- πNB^* vertices: lowest angular momentum coupling
- Form factors

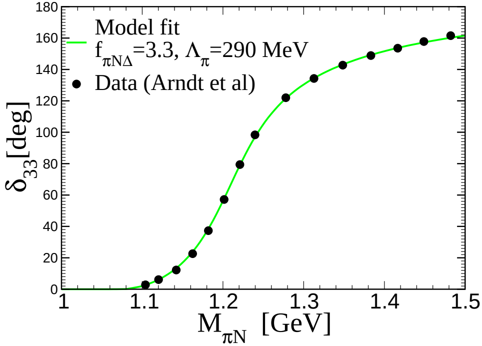
  $F_{\text{mono}}(|\vec{k}|)=\Lambda^2/(\Lambda^2+\vec{k}^2)$ (s- and p-waves)

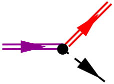
  $F_{\text{dip}}(|\vec{k}|)=[2\Lambda^2/(2\Lambda^2+\vec{k}^2)]^2$ (d waves)

Hadronic model in the vacuum



π N scattering phase shift

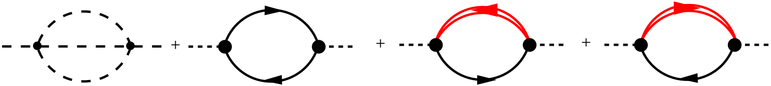




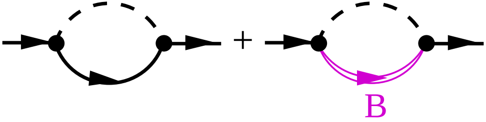
$B^* \Delta/N\pi$ vertex $\leftrightarrow$ partial decay widths
e.g. $N^*(1440)$ (s wave),
$N^*(1520)$ (s+d waves), ...

Medium modifications of the pion and the nucleon

- pions: $\pi\pi$-interactions, nucleon- and Δ-hole excitations

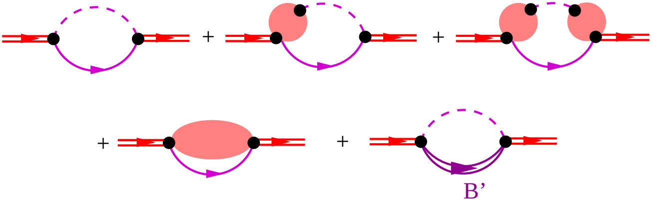


- nucleons: πN and πB, B=$\Delta(1232)$, $N^*(1440)$, $N^*(1535)$, $\Delta^*(1600)$, $\Delta^*(1620)$
- coupling constants fitted to partial decay widths $B \to \pi N$



Medium modifications of the Δ

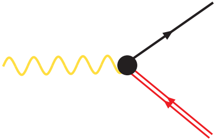
- diagram as in vacuum with dressed π- and N propagators
- vertex corrections: same resummed Migdal loops as for the π
- 4-fermion vertices: same Migdal parameters as for the pion

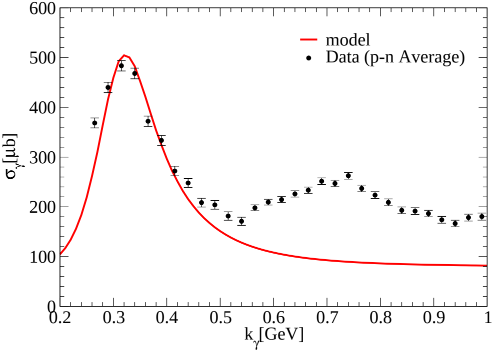


- B'=Δ(1232), N^*(1440), N^*(1520), Δ^*(1600), Δ^*(1620), N^*(1700), Δ^*(1700)

Cold nuclear matter

- photo absorption on the nucleon





Cold nuclear matter

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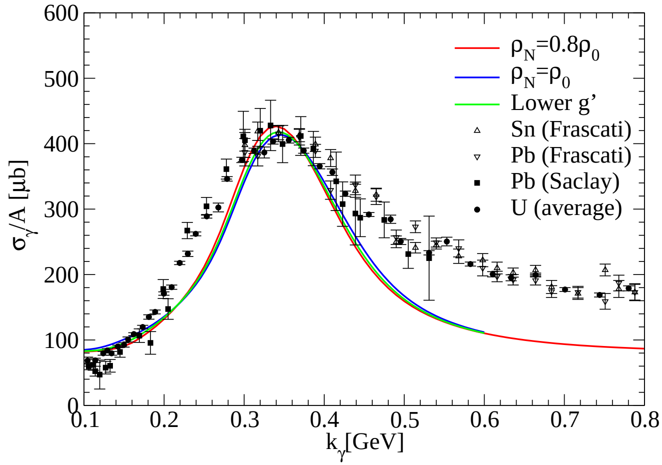
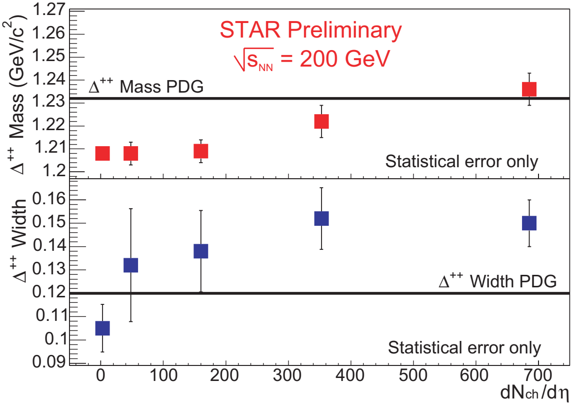


Hot nuclear matter (RHIC)



Courtesy: Patricia Fachini

$\Delta m \sim (17 \pm 7)$ MeV, $\Delta\Gamma \sim (45 \pm 14)$ MeV

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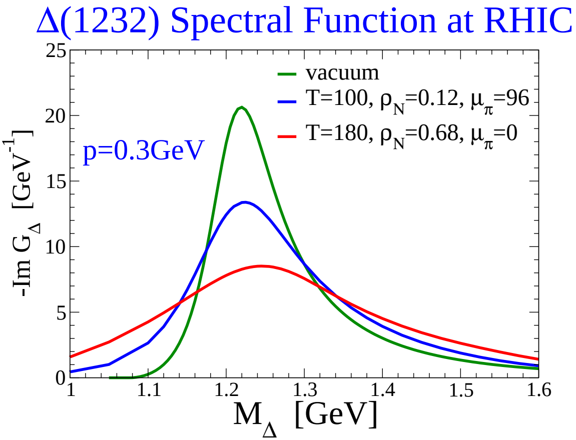
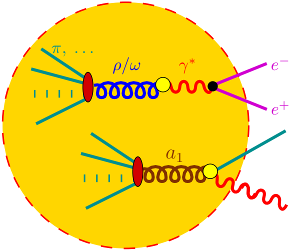


$\Delta m \sim 7$ MeV, $\Delta\Gamma \sim 67$ MeV

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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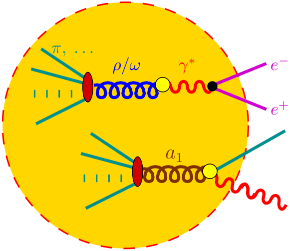

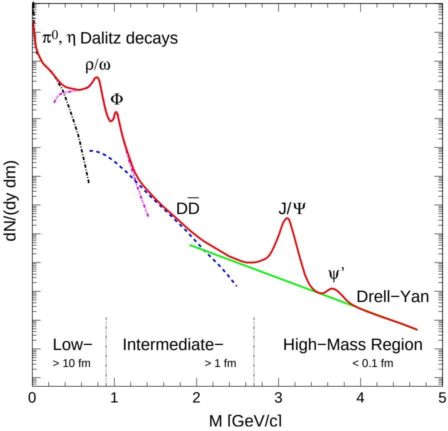

Fig. by A. Drees

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

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

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

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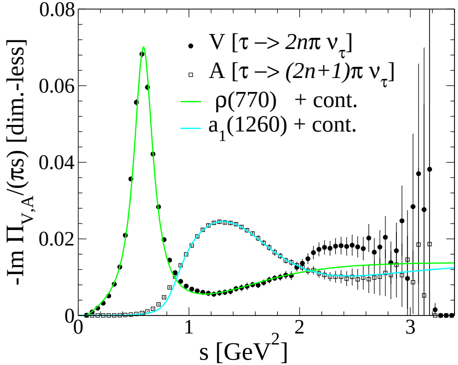
- Ward-Takahashi Identities from chiral symmetry $\Rightarrow$ Weinberg-sum rules

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

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

- 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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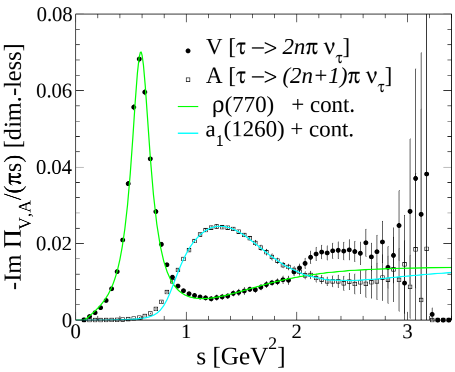

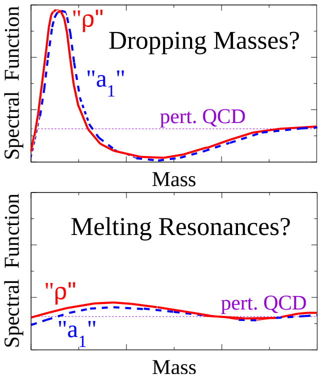

Models

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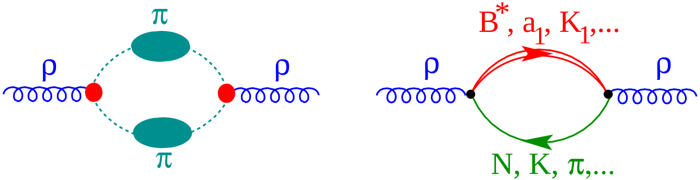
- different models with chiral symmetry: equivalent only on shell ("low-energy theorems")
- model-independent conclusions only in low-temperature/density limit (chiral perturbation theory) or from lattice-QCD calculations
- use phenomenological hadronic models + many-body techniques to assess medium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

Models

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



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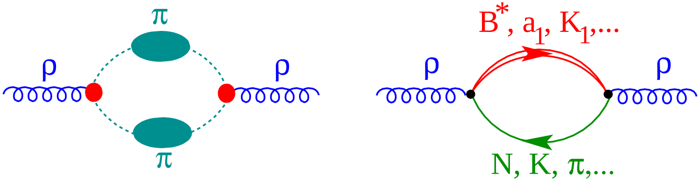
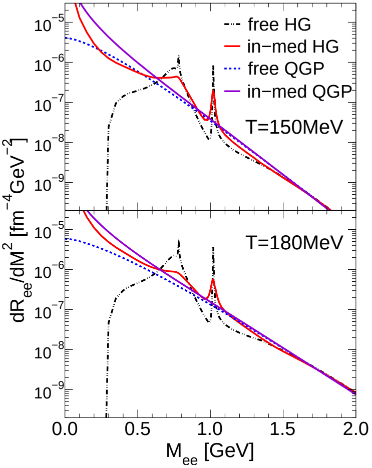


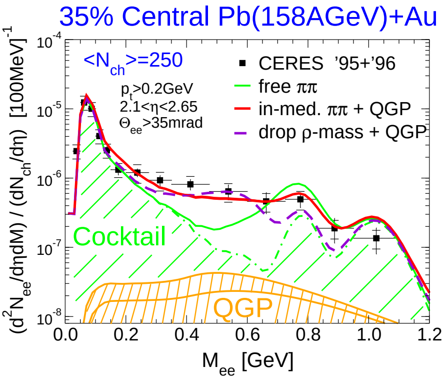
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

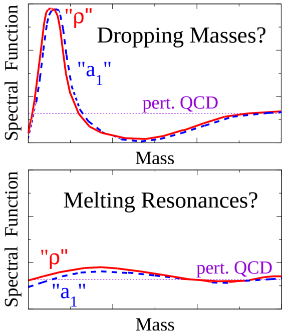
Dilepton rates: Hadron gas ↔ QGP



- 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

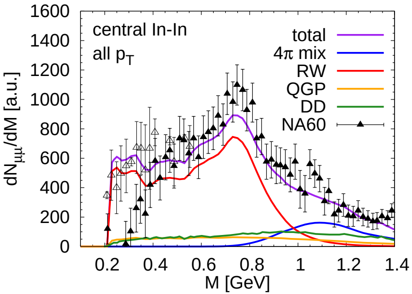




New NA60 Dimuon Data

- 2π contributions$+\rho B$ interactions from Rapp+Wambach '99
- intermediate mass range: Mixing of Π_V with Π_A (Dey, Eletsky, Ioffe '90)

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



- Fireball model ⇒ time evolution
- absolute normalization!
- good overall agreement with data
- room for ω and ϕ?
- "corona ρ's"?

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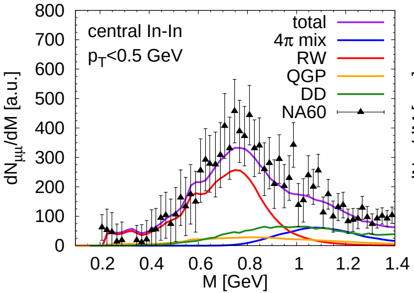
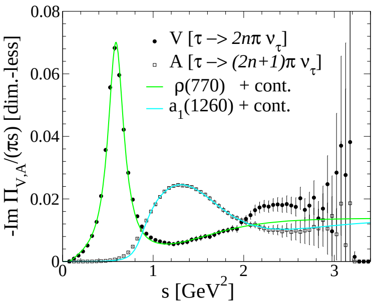
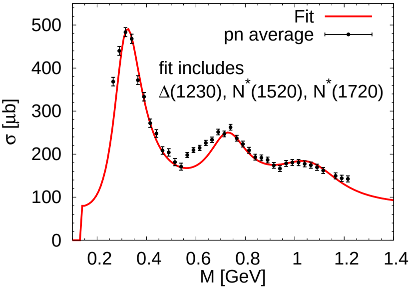


- same absolute normalization!

New NA60 Dimuon Data

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





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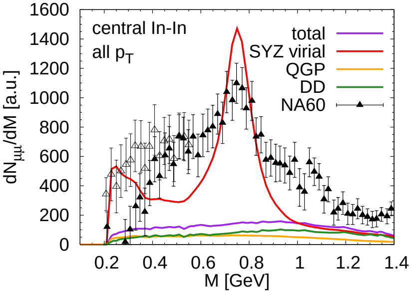

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- intermediate masses: mixing less pronounced
- indication of chiral restoration?

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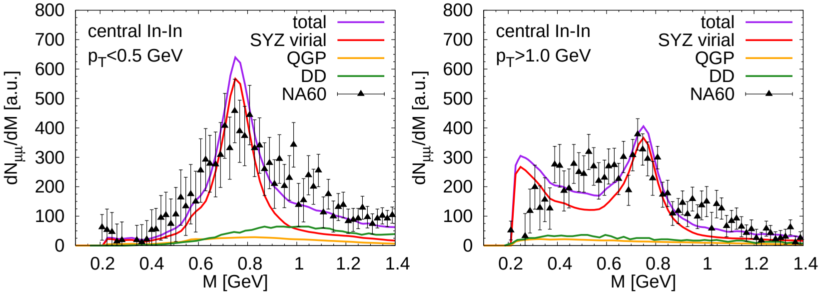

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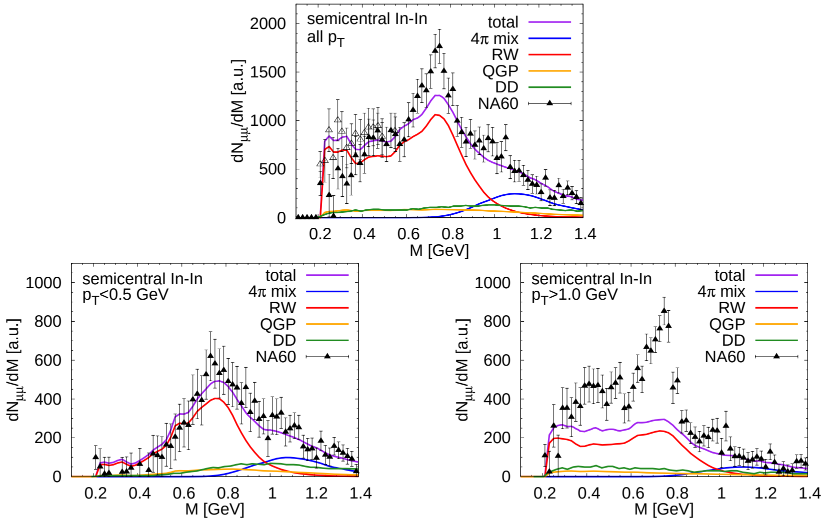
New NA60 Dimuon Data (semicentral)



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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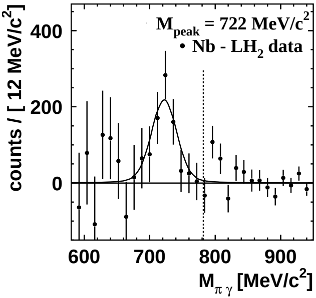
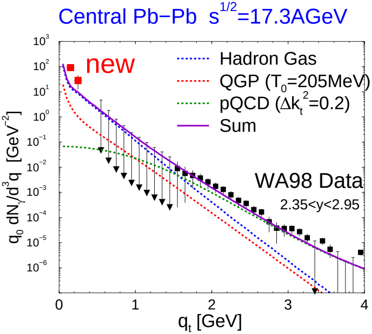


ω-spectral function from CBELSA/TAPS

Challenges for Experiment

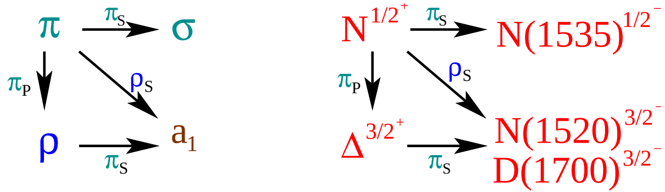
- Photon rate



- $\pi\pi \to \rho \to \pi\pi\gamma$ 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"