22^{nd} Winter Workshop on Nuclear Dynamics La Jolla, CA, 12-18 March, 2006 A Summary

Hendrik van Hees

Texas A&M University

March 16, 2006

Outline

- Bulk properties
- Lattice QCD
- Hadronic models

M. Csanàd: Elliptic analytic hydro solution

$$\partial_\mu (n u^\mu) = 0, \quad \partial_\mu T^{\mu\nu} = 0$$
$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu}$$
$$\epsilon = \kappa p, \quad p = nT$$

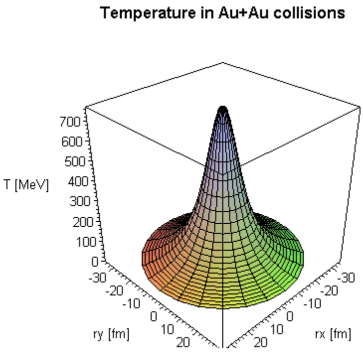
Class of ellipsoidal scaling solutions

$$s = \frac{x^2}{X^2(\tau)} + \frac{y^2}{Y^2(\tau)} + \frac{z^2}{Z^2(\tau)}$$

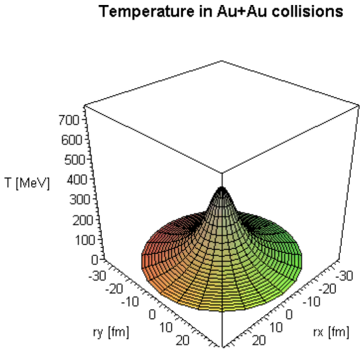
Exact solution with arbitrary scaling function $\nu > 0$

$$u^\mu = \frac{x^\mu}{\tau}, \quad n = n_0 \left(\frac{\tau_0}{\tau}\right)^3 \nu(s),$$
$$p = p_0 \left(\frac{\tau_0}{\tau}\right)^{3+3/\kappa},$$
$$T = T_0 \left(\frac{\tau_0}{\tau}\right)^3 \frac{1}{\nu(\tau)}$$

M. Csanàd: Elliptic analytic hydro solution



$\kappa = 3/2$



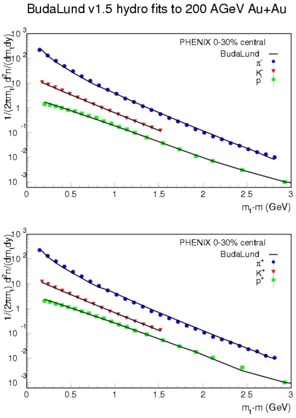
$\kappa = 3$

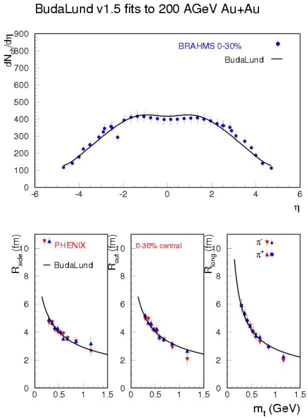
- Different EoS/initial conditions $\Rightarrow$ same hadronic final state
- EoS cannot be extracted from hadronic observables

M. Csanàd: Buda-Lund Model

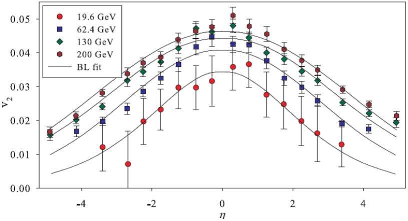
- EoS: $\kappa = 3/2$, 3D scaling solution ("anisotropic Hubble expansion")

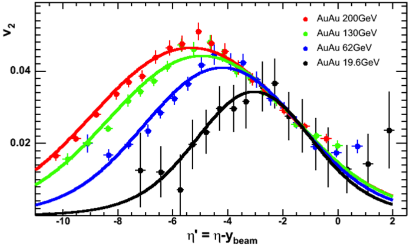
$$v_{2n} = \frac{I_n(w)}{I_0(w)}, \quad w = \frac{p_t^2}{4m_t}\left(\frac{1}{\partial_x T} - \frac{1}{\partial_y T}\right)$$





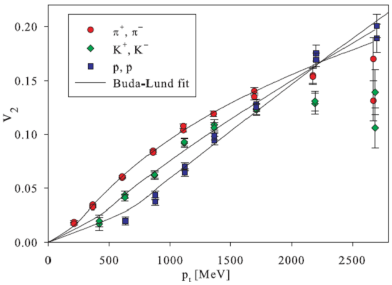
M. Csanàd: Buda-Lund Model

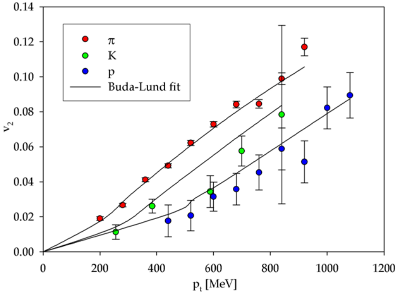




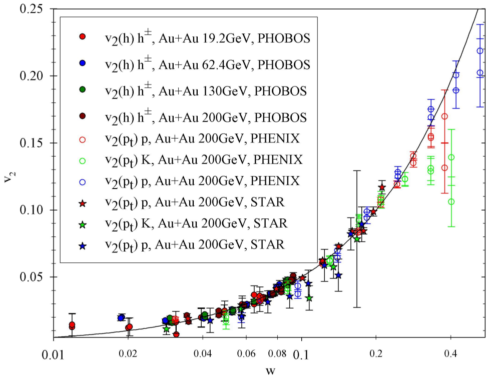
- high $\eta \Rightarrow$ emission asymmetry vanishes $\Rightarrow v_2 \to 0$
- Reasons: 3D Hubble fow + finite size

M. Csanàd: Buda-Lund Model





M. Csanàd: Buda-Lund Model



M. Csanàd: Buda-Lund Model

- η-dependence of v_2
  - width determined by longitudinal expansion, $\Delta\eta$
  - height determined by eccentricity, ϵ
  - two-parameter fit
  - $\Delta\eta$, ϵ increase with $\sqrt{s}$
  - vanishing at high η: 3D-Hubble expansion + finite long. size
- p_T-dependence
  - depends on temperature gradients and transverse flow
  - two-parameter fit
  - increasing centrality $\Rightarrow$ increasing transverse flow
  - inhomogeneous temperature, depending on PID
  - v_2 follows predicted scaling function
  - perfect fluid at all η!

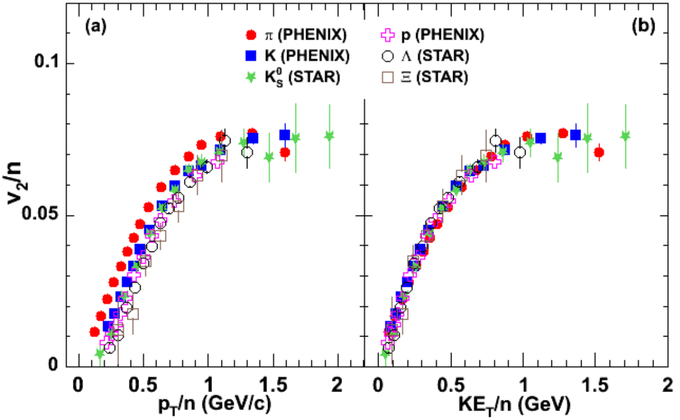
M. Bleicher: UrQMD

- reproduce correct non-flow correlations
- part of v_2 might come from hadronic stage
- correct mass ordering
- constituent-quark scaling reproduced without coalescence!
- transport models without QGP have lack of pressure

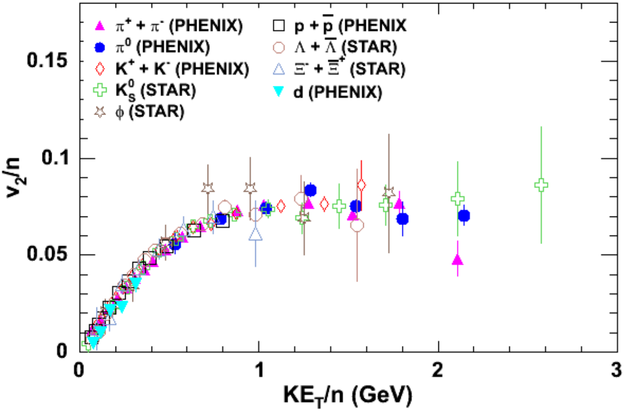
M. Issah (PHENIX): Scaling characteristics of v_2 at RHIC

- eccentricity scaling holds over broad range of centralities $\Rightarrow$ indication for thermalization
- comparison to hydro model $\Rightarrow$ estimate of c_s^2 $\Rightarrow$ compatible with soft EoS
- KE$_t$ scaling of baryons and mesons together for $p_T < 1$ GeV $\Rightarrow$ indication of partonic dof's
- universal constituent-quark KE$_t$ scaling over broad range of centralities and PID

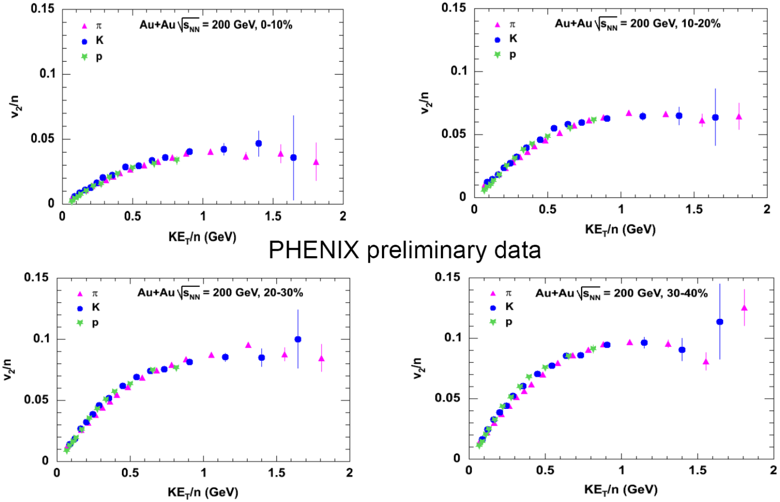
M. Issah (PHENIX): Scaling characteristics of v_2 at RHIC



M. Issah (PHENIX): Scaling characteristics of v_2 at RHIC



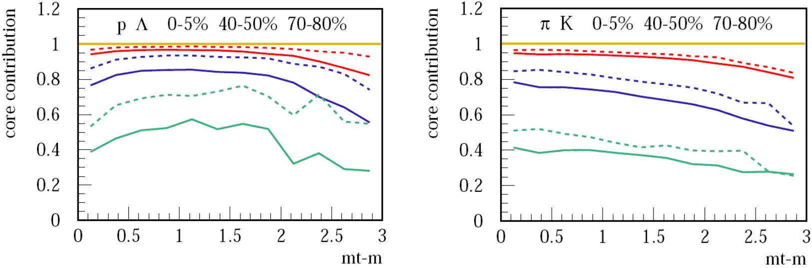
M. Issah (PHENIX): Scaling characteristics of v_2 at RHIC



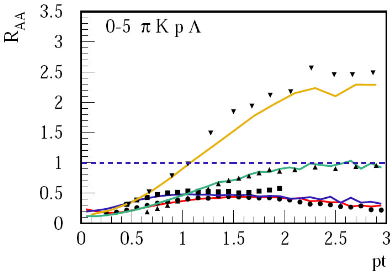
K. Werner: Surface effects in Au-Au at RHIC

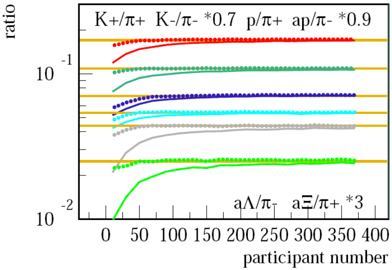
- peripheral nucleons in AA-collisions perform independent pp- or pA-like collisions
- goal: subtract this "corona background" from core
- use EPOS for pp- and pA-collsions
  - initial binary collisions create partons with initial- and final-state radiation
  - hadronization via strings
  - regions with string density $> \rho_0 = 1\text{fm}^{-3}$: core
  - rest: corona
  - connected high-density areas: cluster
- clusters hadronize at ϵ_{had} statistically (micro canonical)
- have radial flow with linear radial rapidity profile (y_{rad})
- anisotropy by multiplying v_x and v_y by $1 \pm \epsilon f_{\text{ecc}}$

K. Werner: Surface effects in Au-Au at RHIC



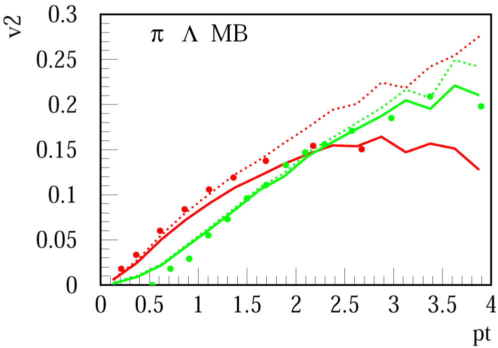
K. Werner: Surface effects in Au-Au at RHIC





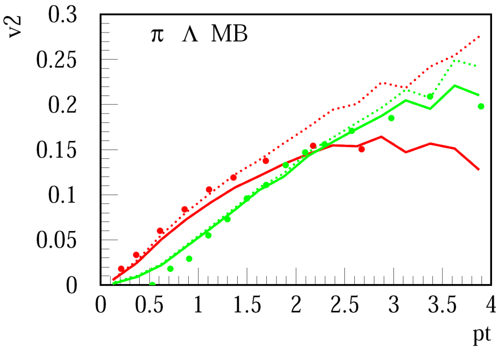
K. Werner: Surface effects in Au-Au at RHIC

Elliptical flow in MB AuAu collisions at 200 GeV.
pions (red) and lambdas (green). data: PHENIX/STAR
Full lines: core + corona; dotted lines: core



K. Werner: Surface effects in Au-Au at RHIC

Elliptical flow in MB AuAu collisions at 200 GeV.
pions (red) and lambdas (green). data: PHENIX/STAR
Full lines: core + corona; dotted lines: core



- core: no centrality dependence (only volume)
- baryons more suppressed in string fragmentation (pp) than in statistical hadronization (core in AA)
- core the same at RHIC and SPS (modulo 30% more flow at RHIC)

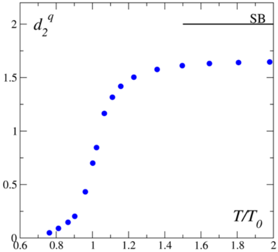
P. Petrecky: Lattice QCD at finite temperature

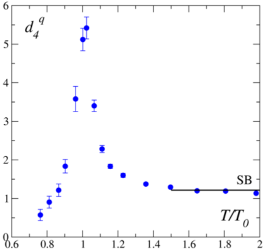
- various number susceptibilities in 2-flavor QCD
- "event-by-event fluctuations"

$$d_n^x := \frac{\partial^n[-p(T,\mu_x)}{\partial(\mu_x/T)^n]}\Big|_{\mu_x=0}$$

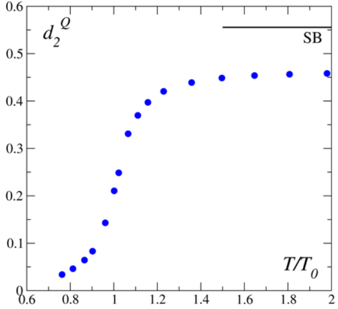
$$d_2^x = \frac{1}{VT^3}\left\langle N_x^2\right\rangle|_{\mu_x=0},$$

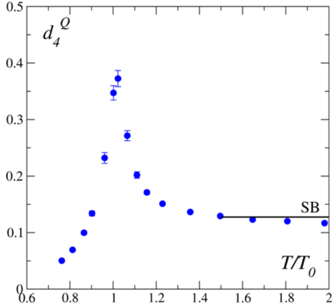
$$d_4^x = \frac{1}{VT^3}\left(\left\langle N_x^4\right\rangle - 3\left\langle N_x^2\right\rangle\right)|_{\mu_x=0}$$





P. Petrecky: Lattice QCD at finite temperature

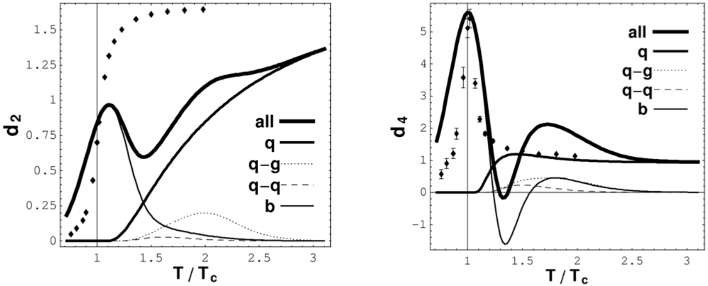




- Close to Stefan-Boltzmann limit of parton gas for $T \gtrsim 1.5\, T_c$
- Relevant degrees of freedom: partonic (quasi) particles

P. Petrecky: Lattice QCD at finite temperature

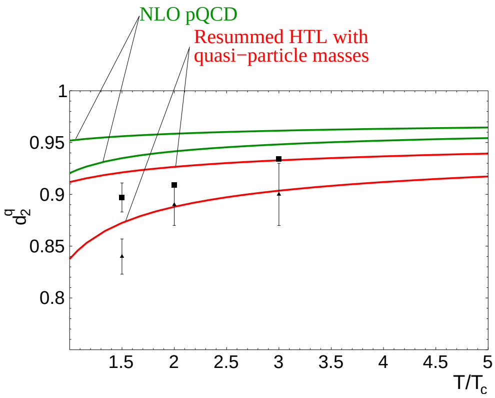
- Comparison to sQGP model
  Lian, Shuryak, PRD **73**, 014509 (2006)
- significance of qg- and qq-bound states



- Bound states not compatible with lQCD
- Ejiri, Karsch, Redlich, PLB **633**, 275 (2006)
  Koch, Majumber, Randrup, PRL **95**, 182301 (2005)

P. Petrecky: Lattice QCD at finite temperature

- Comparison to pQCD and CJT-improved HTL
- different renormalization scales ($\bar{\mu} = \pi T \ldots 4\pi T$)
- Lattice data: 2 different continuum extrapolations
- Blaizot, Iancu, Rebhan hep-ph/0303185



P. Petrecky: Lattice QCD at finite temperature

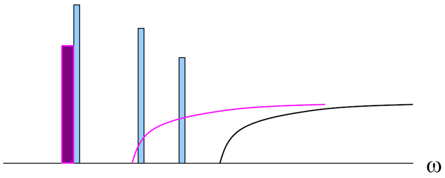
- bulk thermodynamic observables
  - dominant degrees of freedom for $T > 1.2T_c$ are quarks and gluons
  - perturbation theory can account for deviation from free-gas limit for $T > 1.5T_c$
  - sQGP models inconsistent with lattice data
- Heavy quarks
  - no evidence for "strongly coupled Coulomb phase", $\alpha_s(r,T) < \alpha_s(r,T=0)$
  - 1S charmonia (J/ψ, η_c) survive till $T > 1.5T_c$
  - 1P charmonia melt (χ_{c0}, χ_{c1}) at $T \gtrsim 1.1T_c$
  - 1S bottomonia (Υ, η_c) survive till $T \gtrsim 3T_c$
  - 1P bottomonia melt at $T \gtrsim 1.5T_c$
- light meson correlators
  - no evidence for bound states
  - low-mass dilepton rates suppressed in lQCD (artifact, generation of quasi-particle masses?)

À. Mòcsy: Quarkonia above deconfinement

- use simple toy model to compare lattice correlators to potential models

$$G_H(\tau,T) := \left\langle \mathbf{j}_H(\tau)\mathbf{j}_H^\dagger(0)\right\rangle_T = \int \mathrm{d}\omega\,\sigma(\omega,T)K(\tau,\omega,T)$$

$$K(\tau,\omega,T) = \frac{\cosh[\omega(\tau-1/(2T))]}{\sinh[\omega/(2T)]}$$



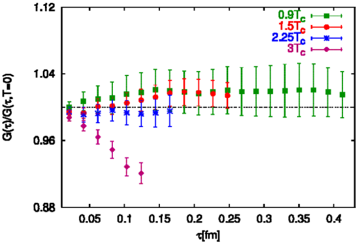
$$\sigma(\omega) = \sum_i 2M_i F_i^2 \delta(\omega^2 - M_i^2) + \frac{3}{8\pi^2}\omega^2\Theta(\omega - s_0) f(\omega, s_0),$$

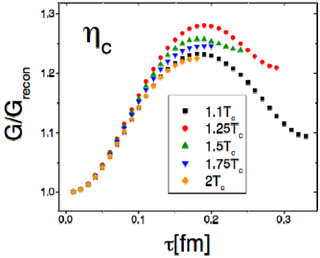
$$f(\omega) = \left(a_H + b_H \frac{s_0}{\omega^2}\right)\sqrt{1 - \frac{s_0^2}{\omega^2}}$$

À. Mòcsy: Quarkonia above deconfinement

For potential models:

$$s_0(T) = 2m + V_\infty(T), \quad M_i = 2m + E_i$$





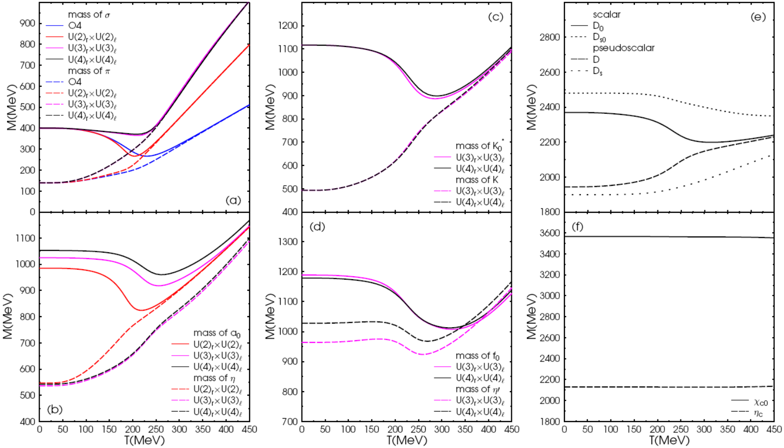
- J/ψ; lattice: no change up to $T = 2T_c$
- potential mod.: first increase due to threshold reduction, then increase due to amplitude reduction
- no agreement with lattice

À. Mòcsy: Quarkonia above deconfinement

- works with toy model
  - no temperature dependent screening
  - continuum threshold reduction
  - no modification of 1s properties
  - melting of 2s and 3s states
  - melting of 1p state
- T-dependent lattice quarkonia correlators neither explained by screened Cornell potential nor lattice internal energy
- simple model without screening works
- screening not responsible for quarkonia suppression

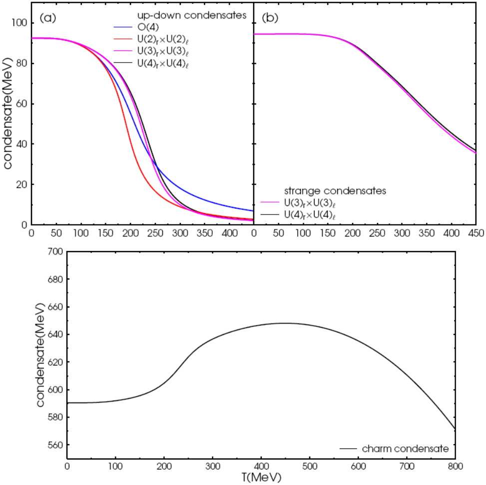
D. Rischke: Chiral symmetry restoration in linear σ models

Masses in HF approximation: Dirk Röder, Jörg Ruppert, DHR, PRD 68 (2003) 016003



D. Rischke: Chiral symmetry restoration in linear σ models

Condensates



D. Rischke: Chiral symmetry restoration in linear σ models

Chiral symmetry restoration in linear sigma models:

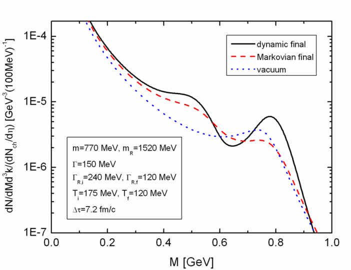
1. **Scalar and pseudoscalar mesons:**
   - $O(4)$ and $U(N_f)_r \times U(N_f)_\ell$ models ($N_f = 2, 3, 4$) in Hartree-Fock approximation
   - $O(4)$ model in 2-loop approximation ($\mathrm{Re}\,\Pi \equiv \Pi_{\text{tadpole}}$)
   - Inclusion of energy-momentum dependent part of $\mathrm{Re}\,\Pi$
   - $U(N_f)_r \times U(N_f)_\ell$ models in 2-loop approximation
2. **Vector and axialvector mesons:**
   - $U(2)_r \times U(2)_\ell$ model in HF approximation
   - Full 2-loop approximation
   - Extension to $N_f = 3, 4$
3. **Baryons**
4. **Coupling to photon**
5. **Dilepton rate, spectrum**

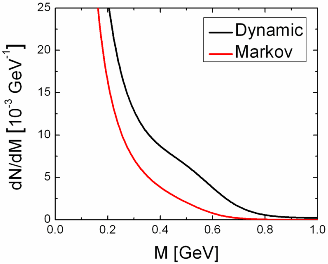
C. Greiner: Nonequilibrium dilepton production

- Kadanoff-Baym equation for vector mesons (real-time contour)

$$\hat{D}_1 G(1,1') = \delta^{(4)}_{\mathscr{C}}(1-1') + \Sigma(1,2) \otimes G(2,1')$$

- nonlocal in time $\Rightarrow$ memory effects
- put in $\mathrm{Im}\,\Sigma_\rho^R$ by hand
- use equilibrium distribution in matrix formalism





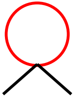
C. Greiner: Nonequilibrium dilepton production

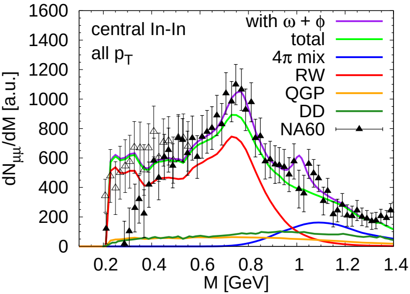
- time scales of retardation $\approx c/\Gamma_{\text{vac}}$ with $c = 2 \ldots 3$
- quantum mechanical interference effects (in Wigner transform)
  Yields postive!
- Non-equilibrium effects on yields compared to adiabatic approximation
- Memory effects important for correct treatment of in-medium modifications

HvH: Medium modifications of hadrons and em. probes

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

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





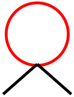
(hep-ph/0603084)

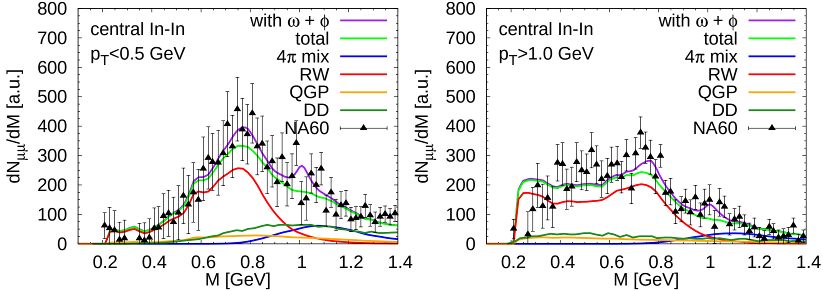
- Fireball model ⇒ time evolution
- absolute normalization!
- good overall agreement with data
- sensitive to ω and ϕ!
- ω: similar model as for ρ
- ϕ: less well known; width assumed $\simeq 80$ MeV

HvH: Medium modifications of hadrons and e.m. probes

- 2π contributions$+\rho B$ interactions from Rapp+Wambach '99
- intermediate mass range: Mixing of Π_V with Π_A

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





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

HvH: Medium modifications of hadrons and e.m. probes

- chiral symmetry: important feature to connect QCD↔ 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 ↔ 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"

Final hint

transparencies/presentations online

http://rhic.physics.wayne.edu/~bellwied/sandiego06/program.html