PANIC08 Eilat

Phase Structure in Hadronic/Quark Models and its Implementation in Heavy-Ion Simulations

OUTLINE

- basics of hadronic model
- nuclear matter properties
- generating an EOS with a critical endpoint
- molecular / hydro simulation

- including quark degrees of freedom
- first results on phase diagram
- simulations in progress

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hadronic model based on non-linear realization of chiral symmetry

Degrees of Freedom **SU(3) multiplets:**

Baryons

$\mathbf{n\ (ddu)}$ $\mathbf{p\ (uud)}$

$\mathbf{\Sigma^- (sdd)}$ $\mathbf{\Sigma^0\ \Lambda\ (sdu)}$ $\mathbf{\Sigma^+ (suu)}$

$\mathbf{\Xi^- (ssd)}$ $\mathbf{\Xi^0 (ssu)}$

} **hyperons**

Scalar Mesons

$\mathbf{\kappa^0\ (\bar{s}d)}$ $\mathbf{\kappa^+ (\bar{s}u)}$

$\mathbf{\delta^- (\bar{u}d)\ \delta^0, \sigma, \zeta\ \ \delta^+ (\bar{d}u)}$

$\mathbf{\kappa^- (\bar{u}s)}$ $\mathbf{\bar{\kappa}^0 (\bar{d}s)}$

$\sigma \sim <\bar{u}u + \bar{d}d>$ $\zeta \sim <\bar{s}s>$ $\delta^0 \sim <\bar{u}u - \bar{d}d>$

Vector Mesons

$\mathbf{K^{*0}\ (\bar{s}d)}$ $\mathbf{K^{*+} (\bar{s}u)}$

$\mathbf{\rho^- (\bar{u}d)\ \rho^0, \omega, \phi\ \ \rho^+ (\bar{d}u)}$

$\mathbf{K^{*-} (\bar{u}s)}$ $\mathbf{\bar{K}^{*0} (\bar{d}s)}$

plus pseudoscalars, axial vectors and gluonic field χ

construction of the model

A) SU(3) interaction

$\sim \mathrm{Tr}\,[\,\bar{B}, M\,]_{\pm}\, B \quad , \quad (\,\mathrm{Tr}\,\bar{B}\,B\,)\,\mathrm{Tr}\,M$

B) meson interactions

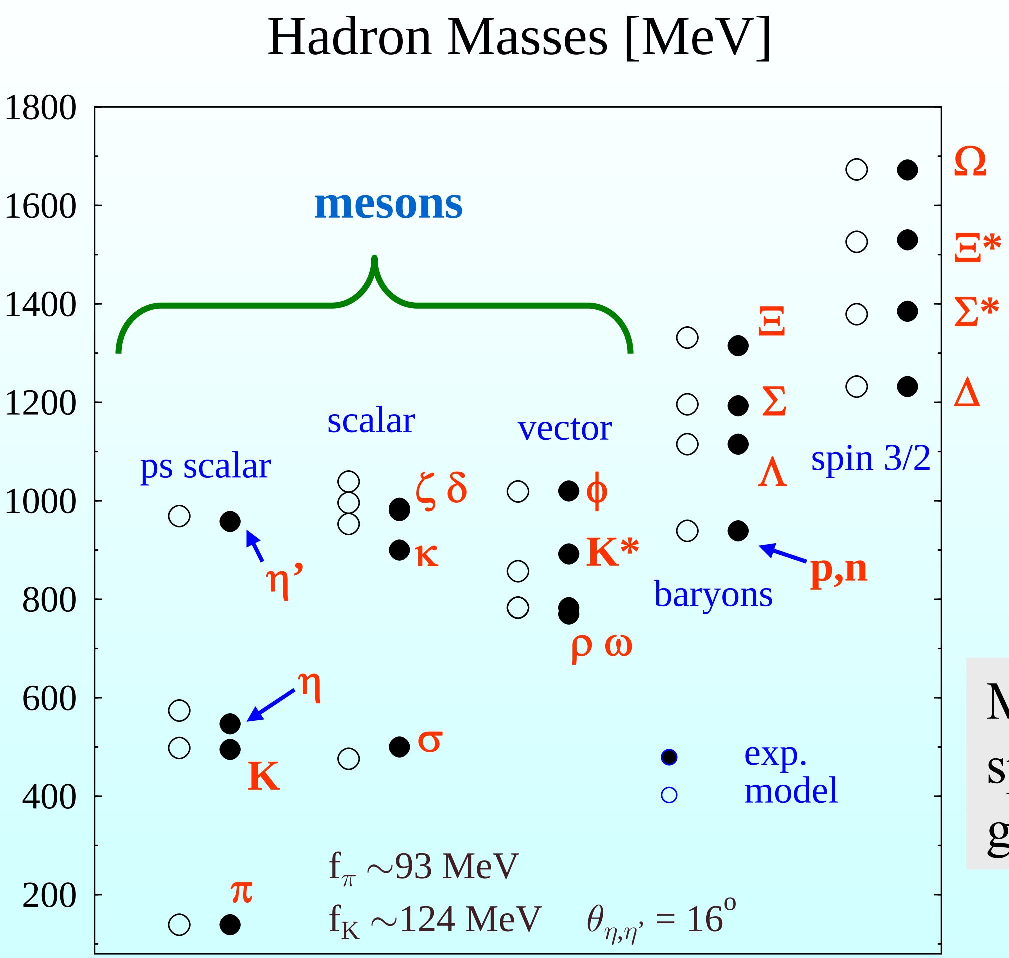
$\sim V(M) \qquad \langle\sigma\rangle = \sigma_0 \neq 0 \qquad \langle\zeta\rangle = \zeta_0 \neq 0$

C) chiral symmetry $\Rightarrow \; m_\pi = m_K = 0$

explicit breaking $\sim \mathrm{Tr}\,[\,c\,\Sigma\,] \quad (\cong m_q\,\bar{q}\,q\,)$

$\Rightarrow$ light pseudoscalars, breaking of SU(3)

fit parameters to hadron masses



Model can reproduce hadron spectra via dynamical mass generation

Lagrangian (in mean-field approximation)

$$L = L_{BS} + L_{BV} + L_V + L_S + L_{SB}$$

baryon-scalars:

$$L_{BS} = - \Sigma \, \bar{B}_i \, (g_i^\sigma \, \sigma + g_i^\zeta \, \zeta + g_i^\delta \, \delta \,) \, B_i$$

baryon-vectors:

$$L_{BV} = - \Sigma \, \bar{B}_i \, (g_i^\omega \, \not{\phi} + g_i^\rho \, \not{\phi} + g_i^\phi \, \not{\phi} \,) \, B_i$$

meson interactions:

$$L_{BS} = - k_0/2 \, \chi^2 \, (\sigma^2 + \zeta^2 + \delta^2 \,) + k_1 \, (\sigma^2 + \zeta^2 + \delta^2 \,)^2$$
$$+ k_2/2 \, (\sigma^4 + 2 \, \zeta^4 + \delta^4 + 6 \, \sigma^2 \, \delta^2 \,) + k_3 \, \chi \, \sigma^2 \, \zeta$$
$$- k_4 \, \chi^4 \, - \chi^4 \ln \chi/\chi_0 \, + \varepsilon \, \chi^4 \ln [(\sigma^2 - \delta^2) \, \zeta / \, (\sigma_0{}^2 \zeta_0)]$$

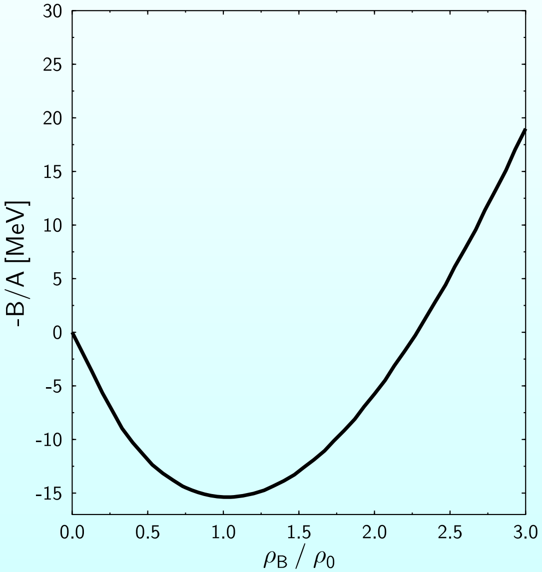
$$L_V = - k'_0/2 \, \chi^2 \, (\omega^2 + \rho^2 + \phi^2 \,) + g_4 \, (\omega^4 + \rho^4 + \phi^4 \, + 6 \, \omega^2 \rho^2)$$

explicit symmetry breaking: $L_{SB} = - (\chi/\chi_0)^2 \, (c_1 \, \sigma + c_2 \, \zeta)$

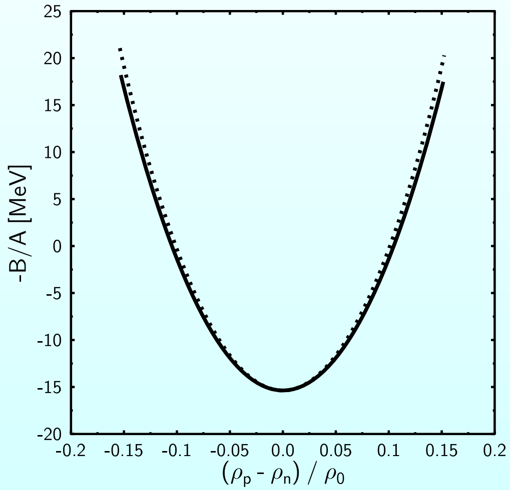
important reality check

nuclear matter properties at saturation density

equation of state **E/A (ρ)**



asymmetry energy
E/A (ρ_p- ρ_n)



binding energy E/A ~ -15.2 MeV saturation $(\rho_B)_0$ ~ .16/fm^3

compressibility **~ 223 MeV** **asymmetry energy** **~ 31.9 MeV**

phenomenology: 200 - 250 MeV 30 - 35 MeV

Task: self-consistent relativistic mean-field calculation
coupled 7 meson/photon fields + equations for nucleons in 1 to 3 dimensions

parameter fit to known nuclear binding energies and hadron masses

2d calculation of all measured (~ 800) even-even nuclei

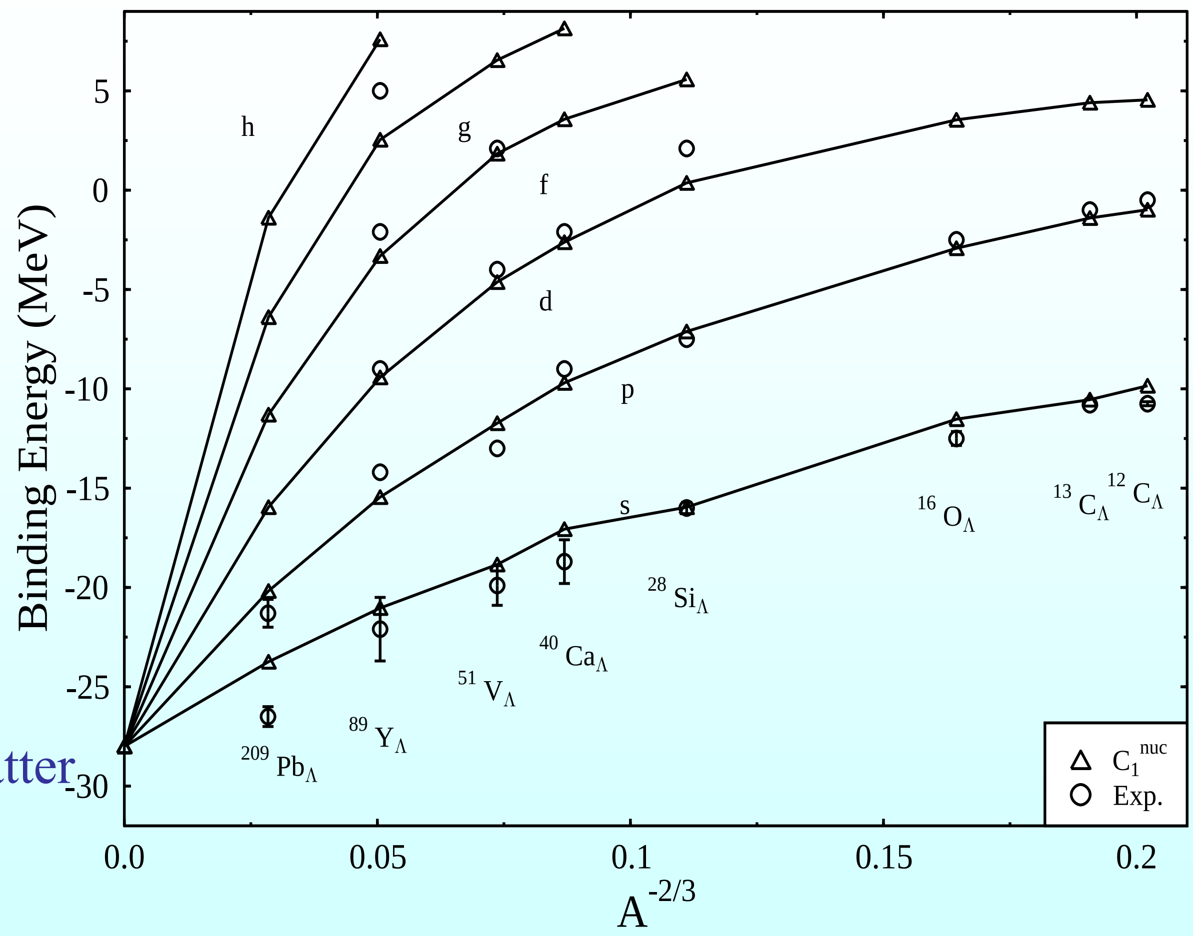
error in energy ε (A $\geq$ 50) ~ 0.21 % (NL3: 0.25 %)
ε (A $\geq$ 100) ~ 0.14 % (NL3: 0.16 %)

relativistic nuclear structure models

good charge radii δr_{ch} ~ 0.5 % (+ LS splittings)

SWS, Phys. Rev. C66, 064310 (2002)

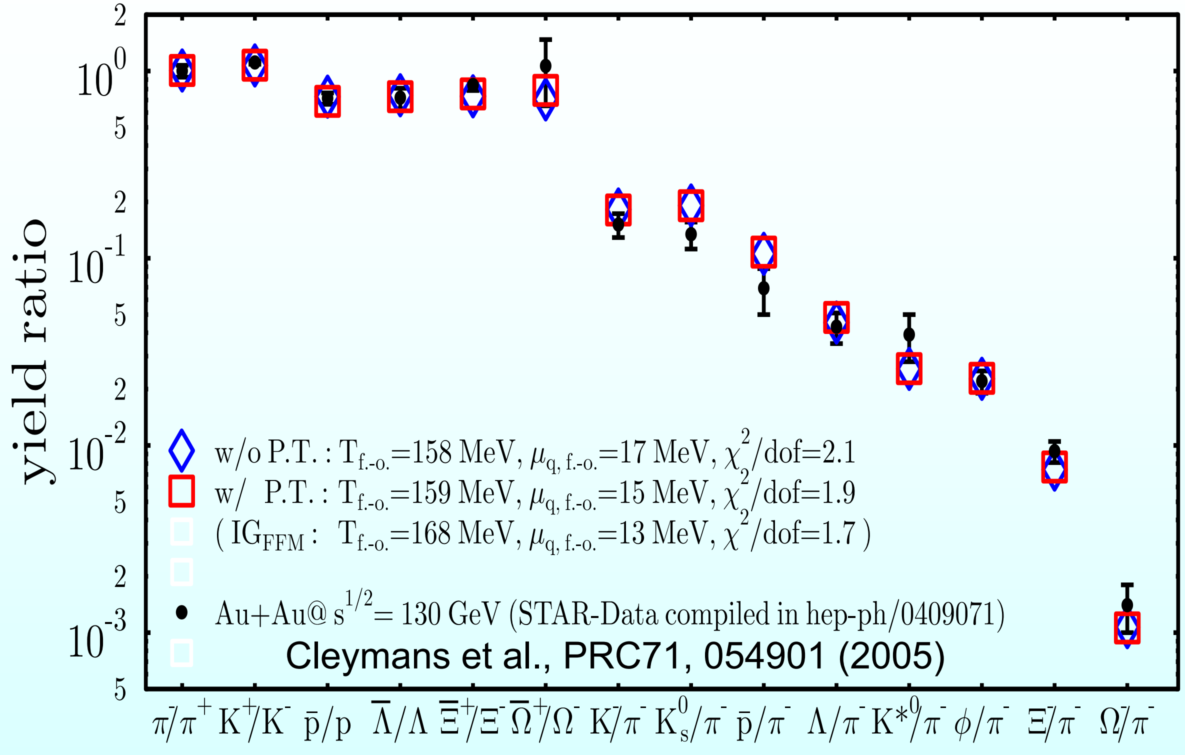
Hypernuclei - Λ single-particle energies



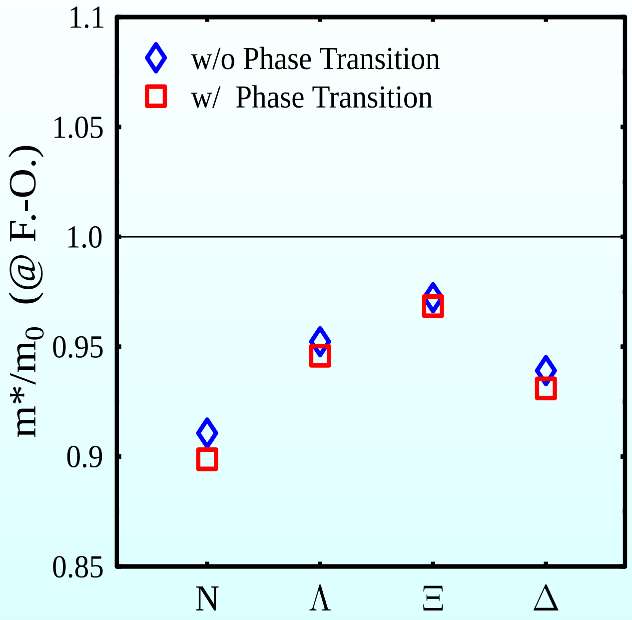
Nuclear matter

Model and experiment agree well

fitting particle ratios measured at RHIC



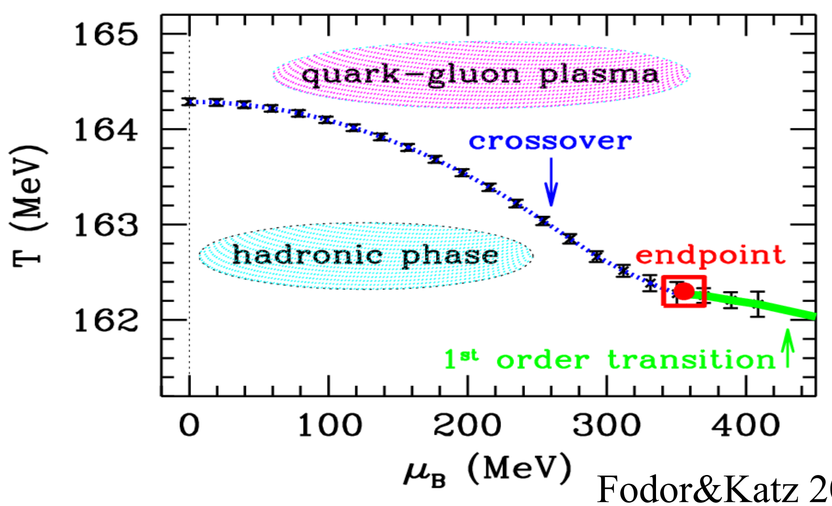
particle ratios



baryon masses

	T [MeV]	μ_B [MeV]
	158.0	**51.0**
ideal gas	**168.0**	**39.0**

QCD Phase diagram



Fodor&Katz 2004

→ models relying exclusively on order parameter dynamics predict significantly lower T_c in dense matter (Stephanov 2004)

→contribution of heavy hadronic states substantial at high T (Gerber and Leutwyler 1989)

→Hadron resonance gas gives reasonable description of lattice thermodynamics (Karsch, Redlich, Tawfik 2003)

→m_π dependence of T_c far too strong in chiral order parameter σ- models (Dumitru, Röder, Ruppert 2004). Reduced by heavy states (Gerber and Leutwyler 1989).

Chiral SU(3) model:
only baryon octet included, then the chiral transition is crossover

But: by including additional d.o.f., the transition can become first order

Investigate role of heavy hadronic states on the location of the chiral critical point in the chiral SU(3) model

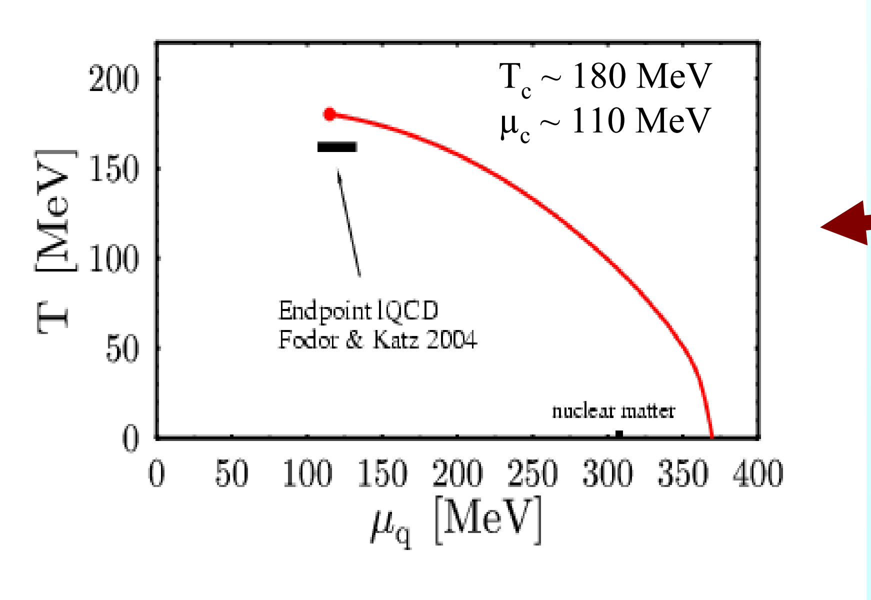
phase transition compared to lattice simulations

heavy states/resonance spectrum is effectively described by single resonance with adjustable scalar and vector couplings

→

$$m_R = m_0 + g_R \sigma$$

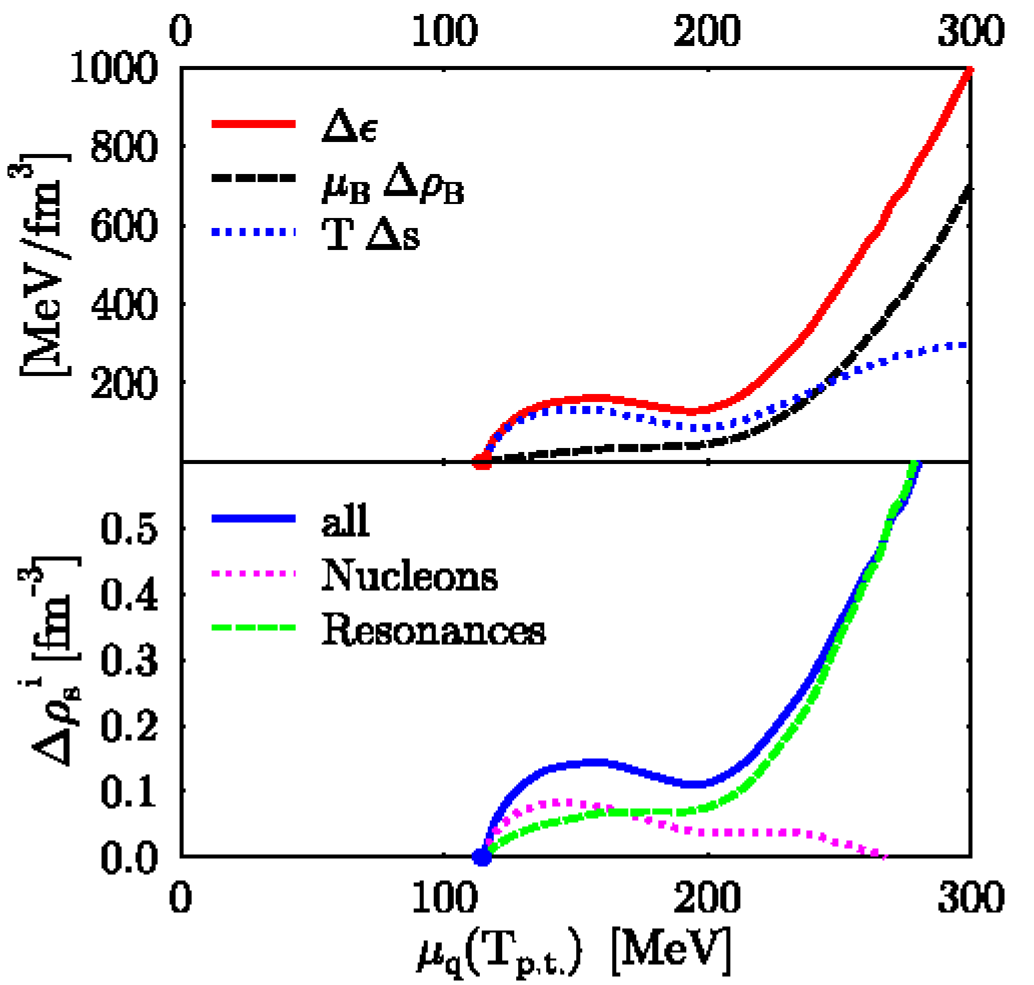
$$g_{R\omega} = r_v g_{N\omega}$$



reproduction of LQCD phase diagram, especially T_c, μ_c
+
successful description of nuclear matter saturation

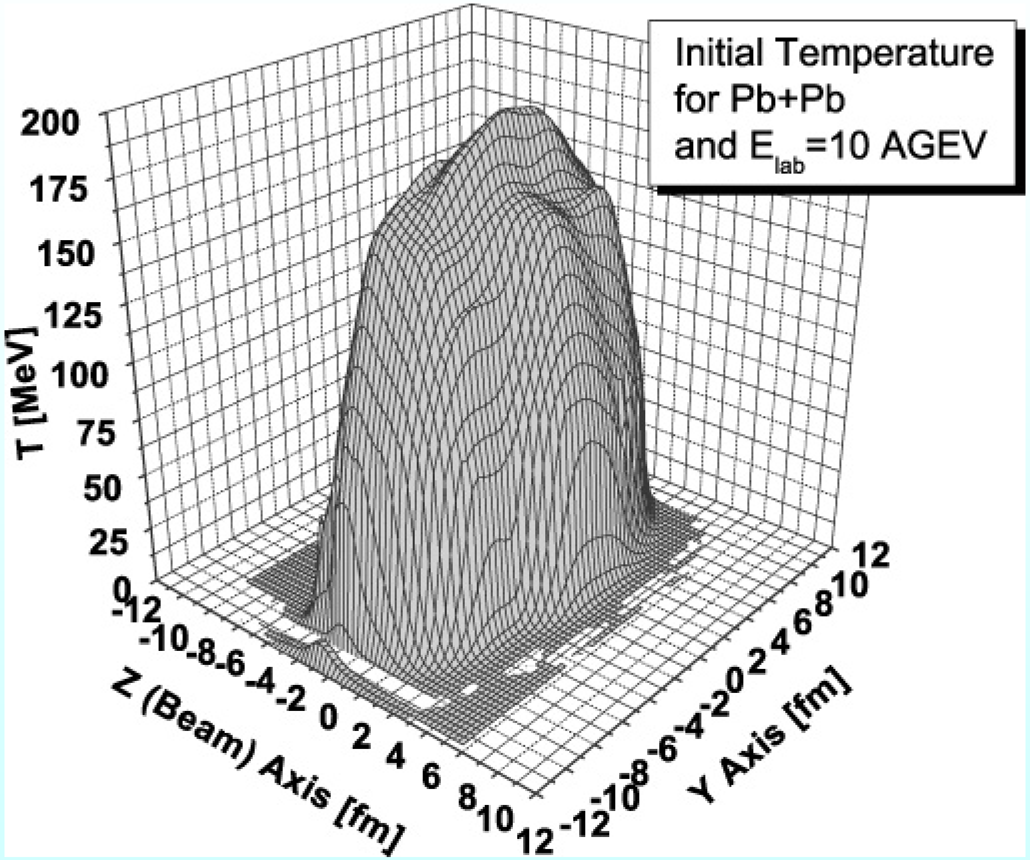
phase transition becomes first-order for degenerate baryon octet $\sim N_f = 3$ with $T_c \sim 185$ MeV

D. Zschiesche et al. JPhysG 34, 1665 (2007) latent energy as function of chemical potential



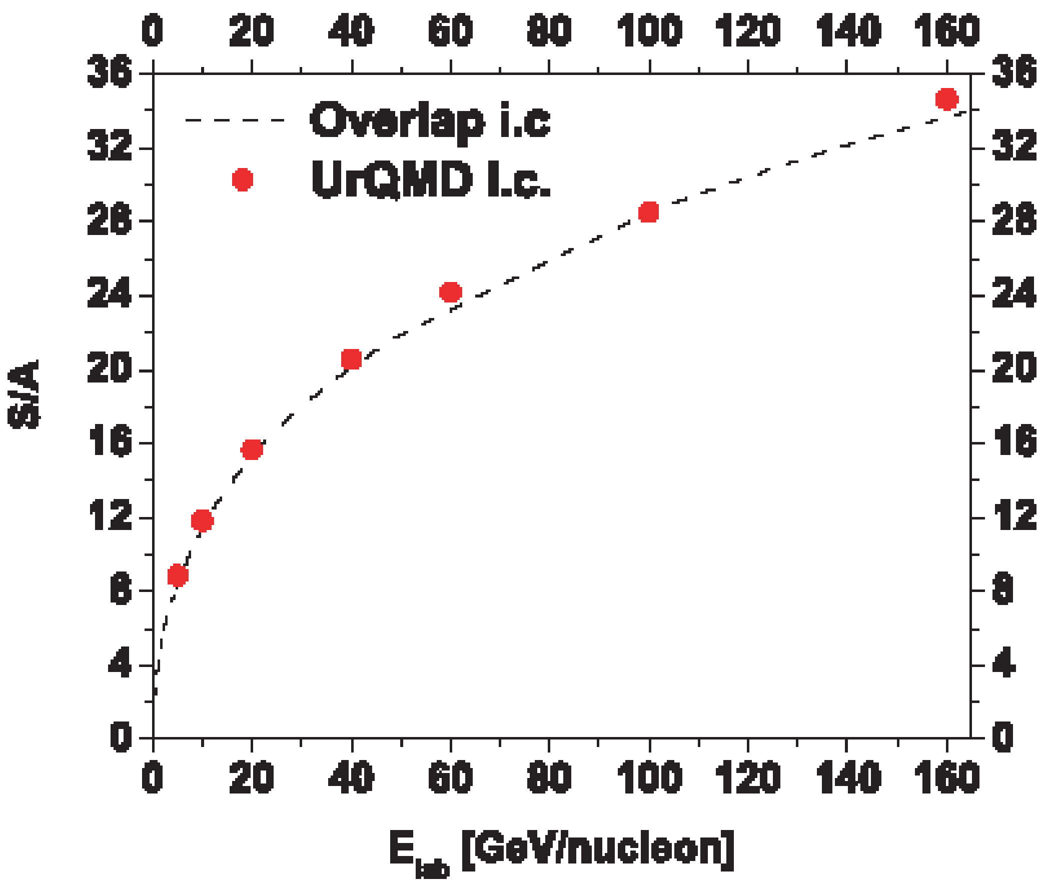
D. Zschiesche et al. JPhysG 34, 1665 (2007)

Temperature distribution from UrQMD simulation as initial state for (3d+1) hydro calculation



Use smeared-out particle distributions as starting point for hydro simulation

Comparison of gross properties of initial conditions

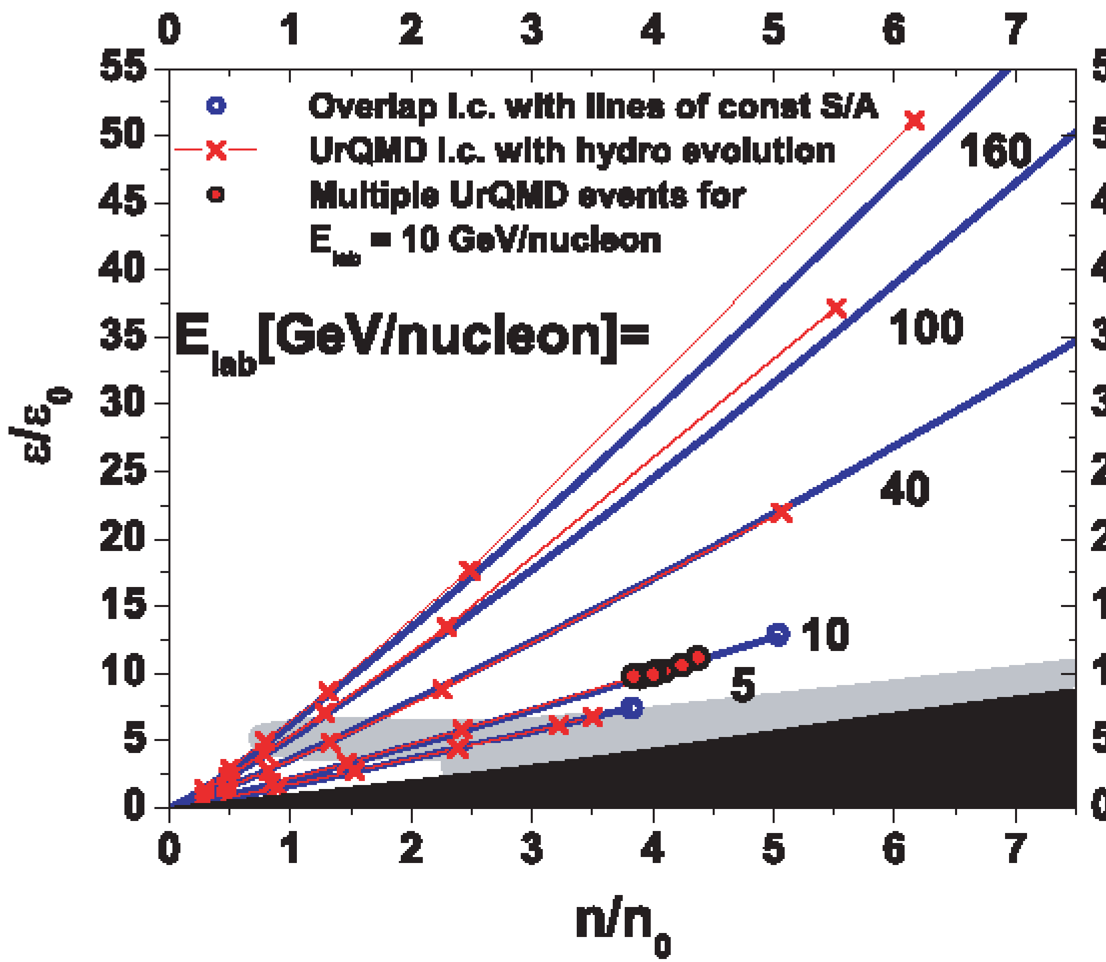


Overlap of projectile and target

$$\rho_B^{\text{initial}} = 2\,\gamma_{\text{c.m.}}\,\rho_0,$$

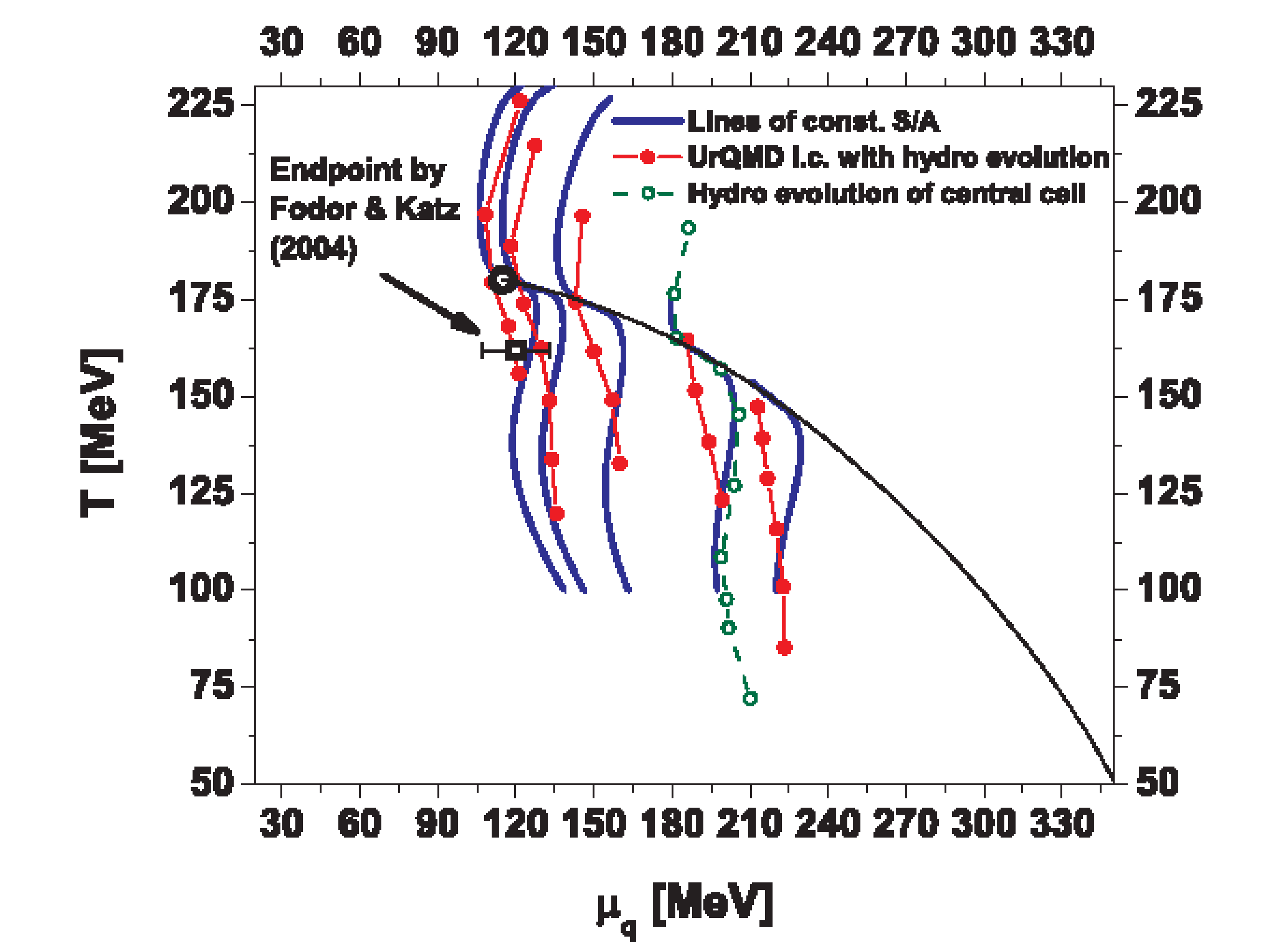
$$\epsilon^{\text{initial}} = \sqrt{s}\rho_0\gamma_{\text{c.m.}}$$

Evolution of the collision system



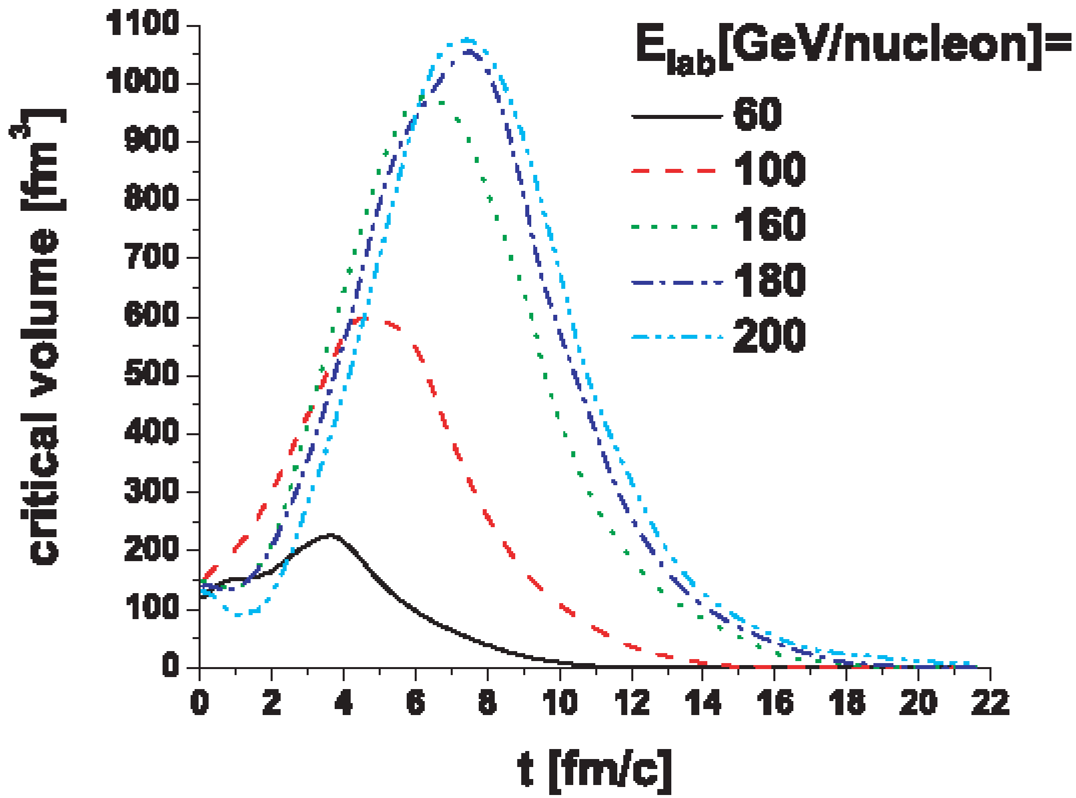
$E_{lab} \approx$ 5-10 AGeV sufficient to overshoot phase border, 100-160 AGeV around endpoint

Isentropes, UrQMD and hydro evolution



lines of constant entropy per baryon, i.e. perfect fluid expansion
S/A ≈ 34 goes through endpoint

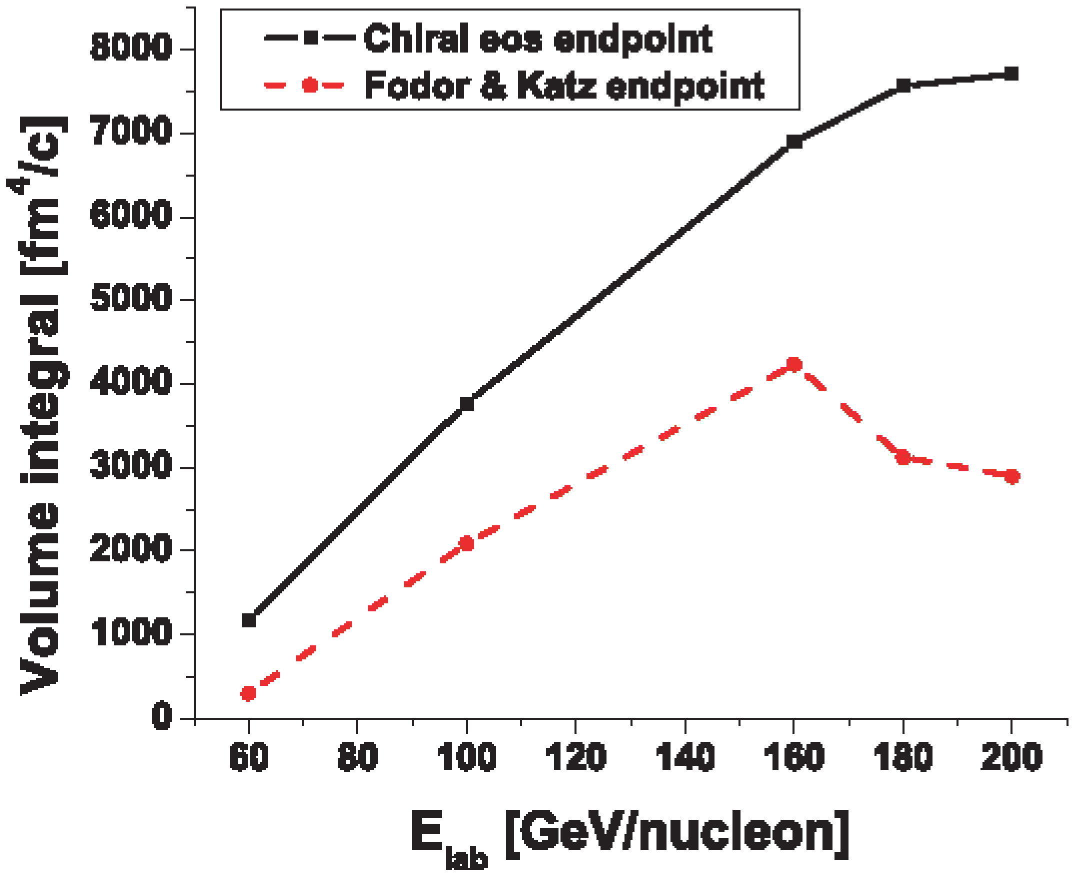
J. Steinheimer et al. PRC77, 034901 (2008) effective volume sampling the critical end point



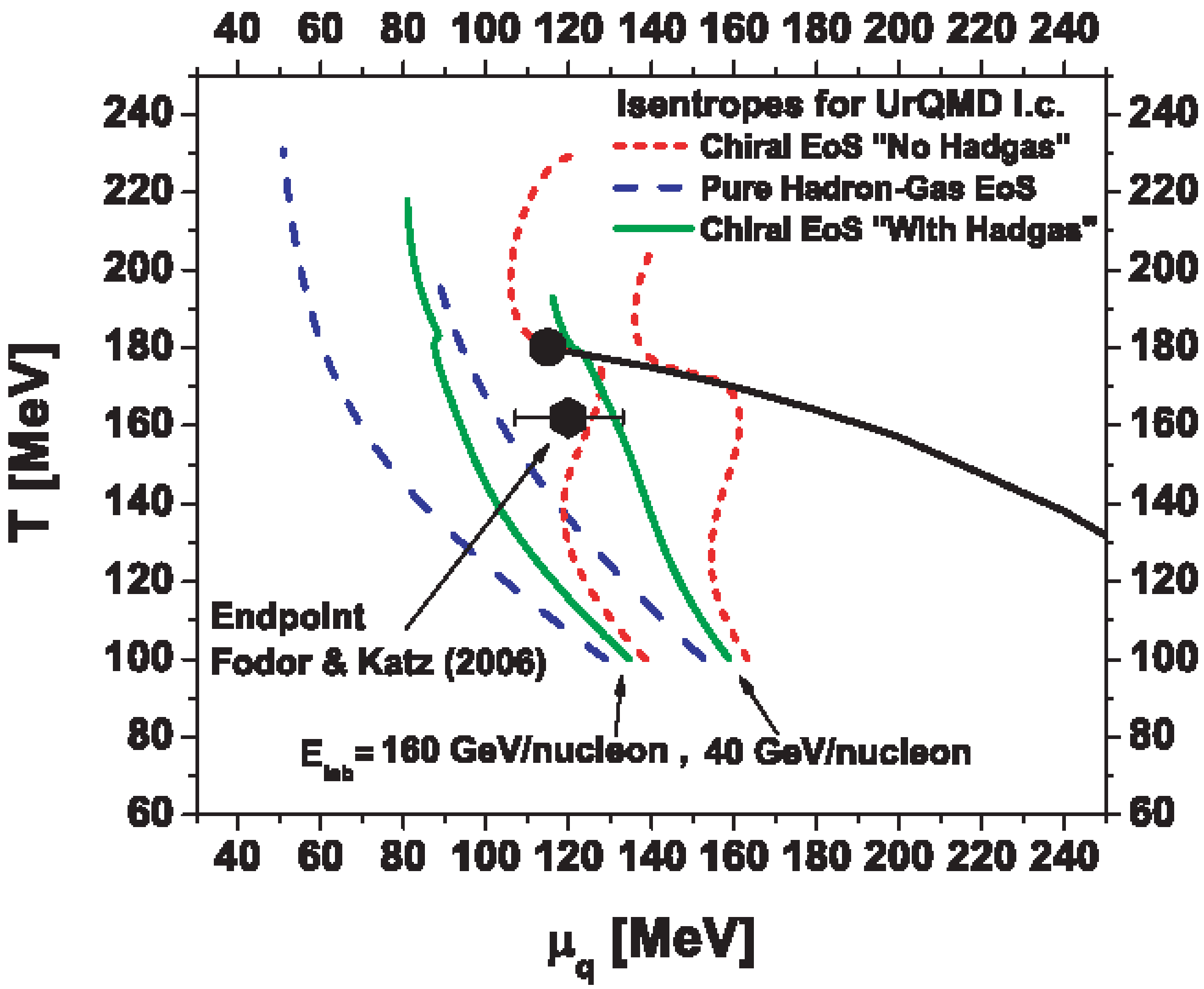
window $T = T_c \pm 10$ MeV $\mu = \mu_c \pm 10$ MeV

maximum shifts in time

time integrated volume around the critical end point



Isentropes for different beam energies in the μ - T diagram



modified PNJL model

$$\Phi = \frac{1}{N_c} \mathrm{Tr}_c L \qquad L(\vec{x}) = \mathcal{P} \exp \left[i \int_0^{\beta} d\tau A_4(\vec{x}, \tau) \right]$$

order parameter of the phase transition

$\langle \Phi \rangle = 0$ confined phase

$\langle \Phi \rangle \neq 0$ deconfined phase

$V(\Phi, \bar{\Phi}; T, \mu)$ effective potential for Polyakov loop

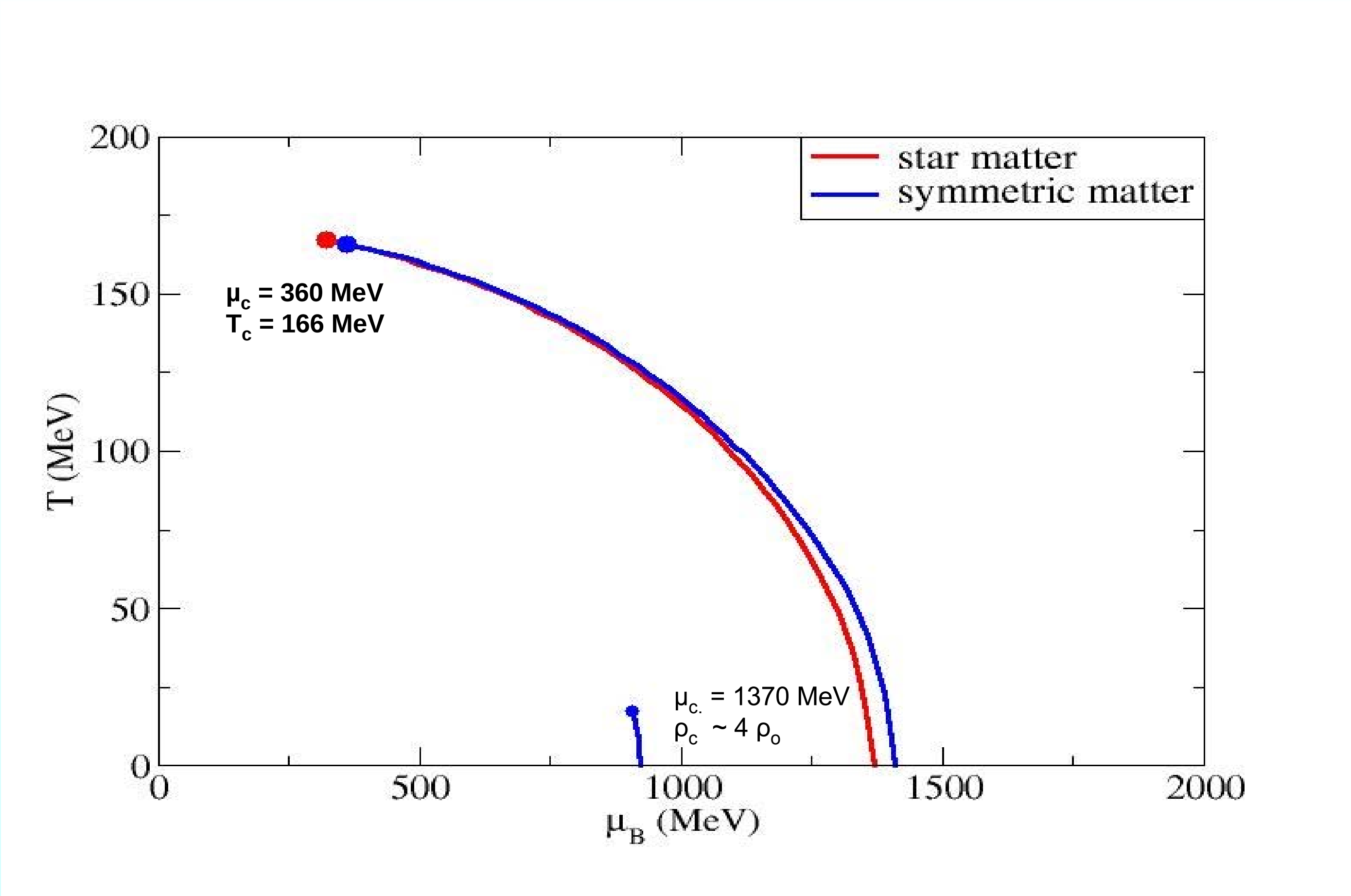
Baryonic and quark mass shift $\delta m_B \sim f(\Phi)$ $\delta m_q \sim f(1-\Phi)$

quarks couple to mean fields via g_σ, g_ω

minimize grand canonical potential

Ratti et al. PRD 73 014019 (2006)
Fukushima, PLB 591, 277 (2004)

Phase Diagram for HQM model



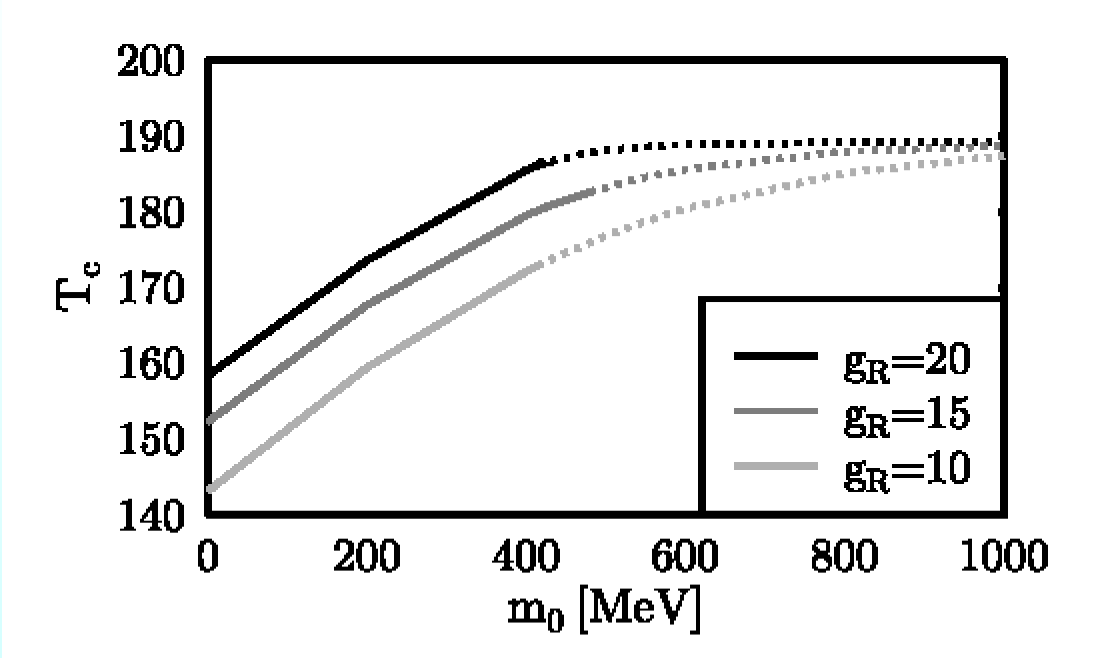
hybrid hadron-quark model - so far SU(2)
critical endpoint tuned to lattice results

see talk by V. Dexheimer

SUMMARY / OUTLOOK

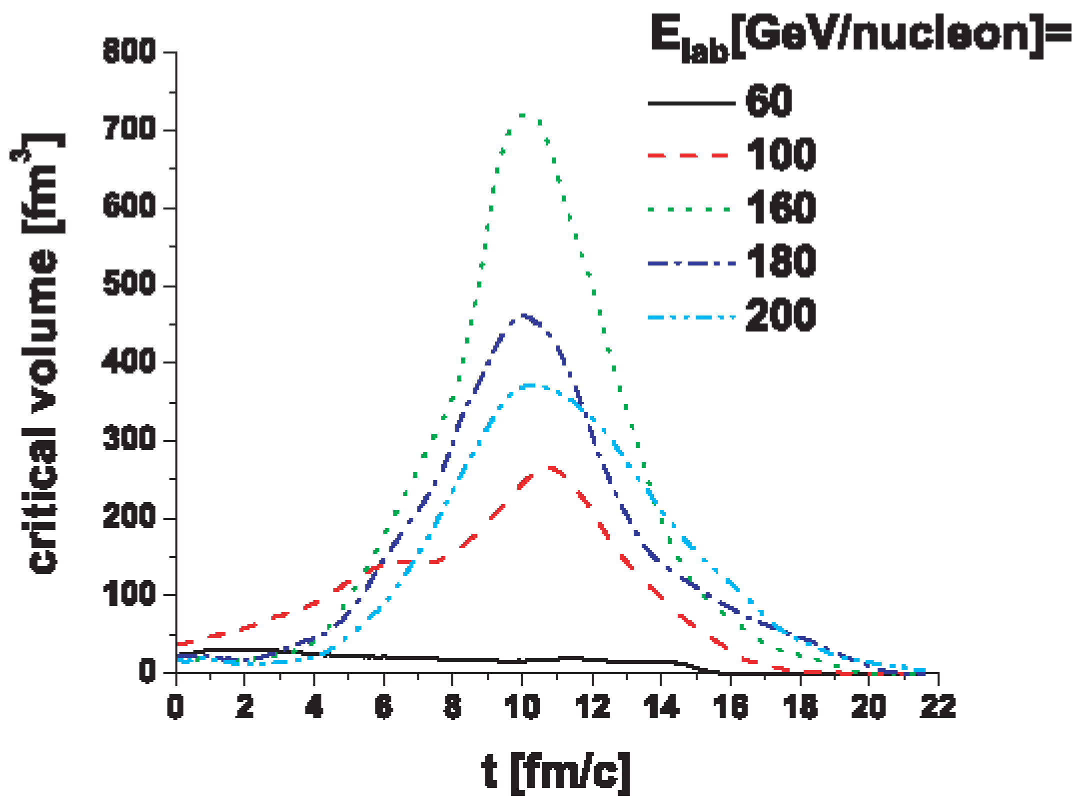
- general hadronic model
- works well with basic vacuum properties, nuclear matter, nuclei, …
- phase diagram with critical end point via resonances
- implement EOS in combined molecular dynamics/ hydro simulations
- quarks included essentially following the PNJL spirit
- realistic phase transition line

- more exhaustive study of the model space (Dexheimer)
- resonances in both phases
- transport study including freeze-out (Petersen, Steinheimer, in progress)

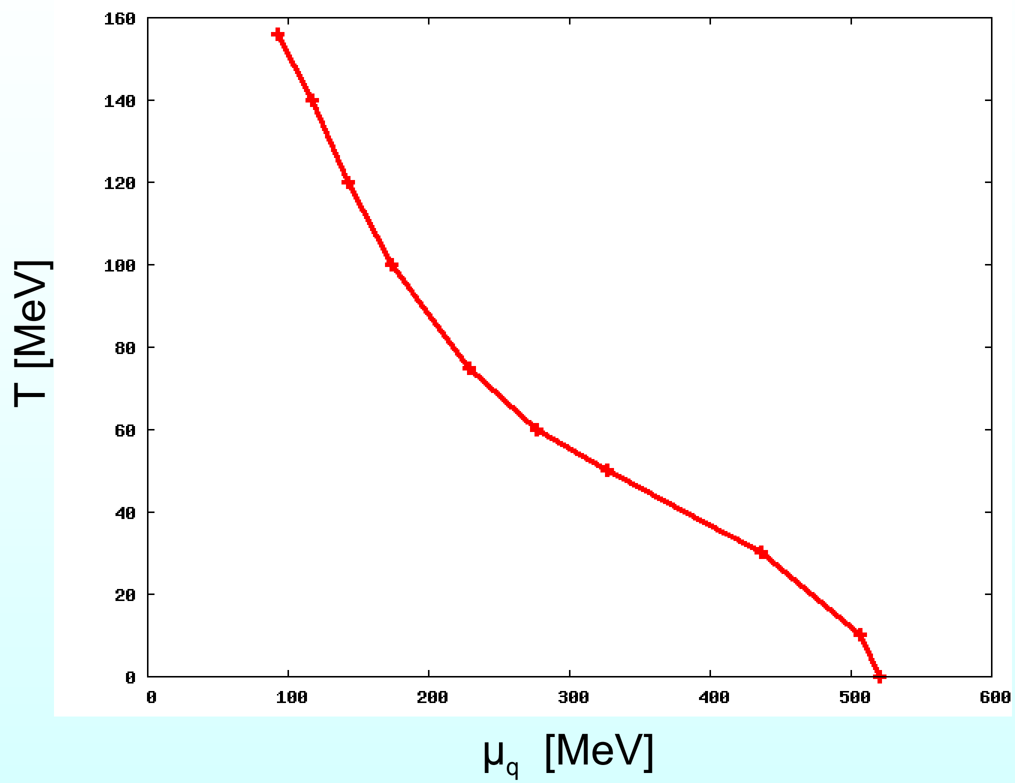


200
190
180
170
160
150
140
T_c
0
200
400
600
800
1000
m_0 [MeV]
g_R=20
g_R=15
g_R=10

amount of volume scanning the critical endpoint (lattice)



Line of 1st order phase transition



hybrid hadron-quark model

critical endpoint at $T = 156$ MeV , $\mu_q = 92$ MeV