Criticality and nongaussian moments in heavy ion collisions

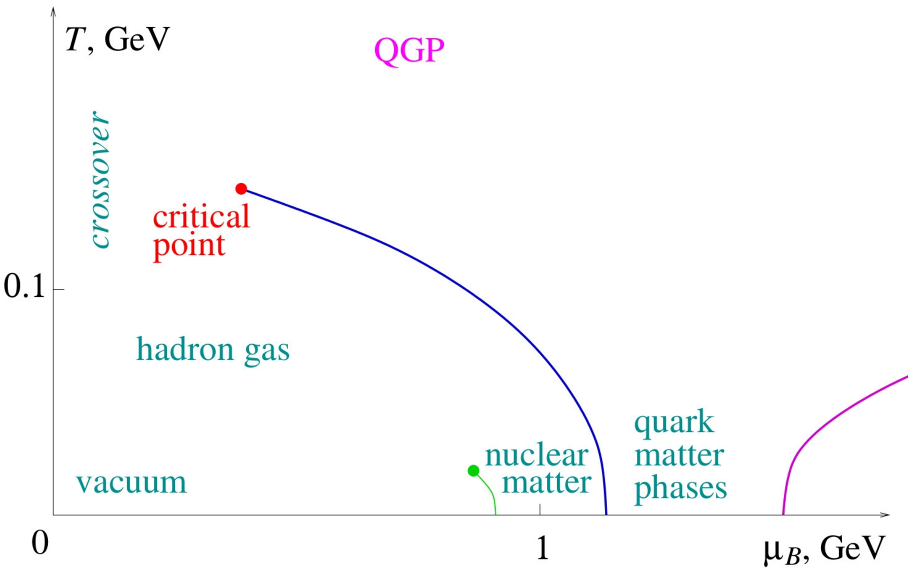
In collaboration with Jiunn-Wei Chen, Jian Deng and Hiroaki Kohyama

Lance Labun

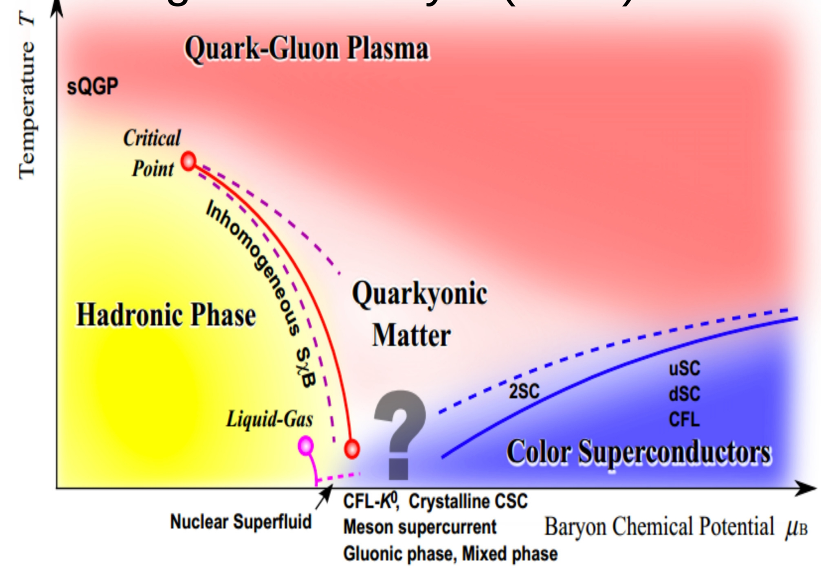
Center for High Energy Density Science
Dept. of Physics
University of Texas
labun@utexas.edu

Searching for a Critical End Point

Hypothetical phase diagrams:
Stephanov, PoS LAT2006



Fukushima & Hatsuda,
Prog. Theor. Phys. (2010)



- Models of chiral symmetry breaking suggest First Order Line at high μ_B
- Collider experiments plus lattice establish crossover at $\mu_B \rightarrow 0$

  [Gupta et al., Science (2011), MILC lattice, Phys. Rev. D (2009) and many others]

>> Critical end point at moderate μ_B ? Accessible to heavy-ion collisions?

Experimental evidence needed! Important input on QCD phase diagram

Basic signature of critical phenomena is diverging correlation length

CEP is boundary between 1st order line and crossover
>> phase transition is 2nd order on CEP

$$T<T_c \quad T\sim T_c \quad T>T_c$$

At 2nd order transition,
Mass of order parameter field --> 0

$$\kappa_2 = \langle \sigma^2 \rangle = \frac{T}{V}\frac{1}{m_\sigma^2} = \frac{T}{V}\xi^2 \rightarrow \infty$$

At m->0 there is no scale in the system
>> fluctuations the same at all length scales (critical opalescence)

Baryon number couples to order parameter:

$$\langle \delta N^2 \rangle \sim \kappa_2 \qquad \delta N = N - \langle N \rangle$$

** Requires (quasi)-equilibrium to achieve large correlation length
(correlations can only grow as fast as velocity of sound)

In real system correlation length does not diverge

Fireball in heavy ion collisions is expanding and finite size

Want a hierarchy $$\frac{1}{V^{1/3}}, \frac{1}{t_{\exp}} \ll m_\sigma \ll T$$

Ensure correlation length is largest dynamical length scale $\frac{1}{m_\sigma} \sim \xi \rightarrow \infty$

And approximately infinite system (finite size corrections small)

Equivalent to dropping derivatives in σ effective potential

Can relax the slow expansion condition by taking into account memory effects [Mukherjee et al Phys. Rev. C (2015), arXiv:1605.09341]

For finite correlation length, investigate observables that diverge with higher power of ξ

$$\langle \delta N^3 \rangle \sim \kappa_3 = \langle \sigma^3 \rangle \sim \xi^6 \qquad \langle \delta N^4 \rangle \sim \kappa_4 = \langle \sigma^4 \rangle - 3 \langle \sigma^2 \rangle^2 \sim \xi^8$$

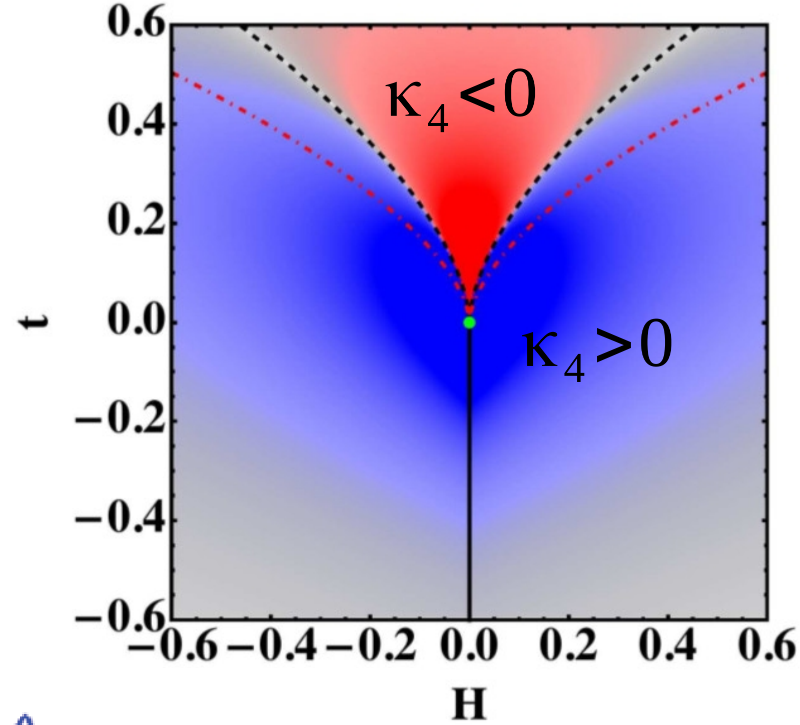
[Stephanov Phys. Rev. Lett (2009), (2011)]

Universality: Long-wavelength physics of correlation length the same within universality class (effective field theory)

QCD near the CEP belongs to Ising-model class

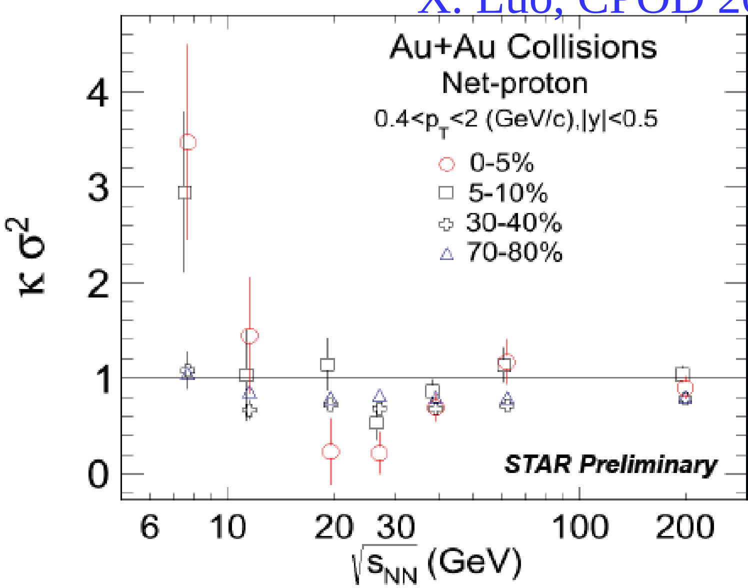
Mapping from QCD coordinates to Ising coordinates not known

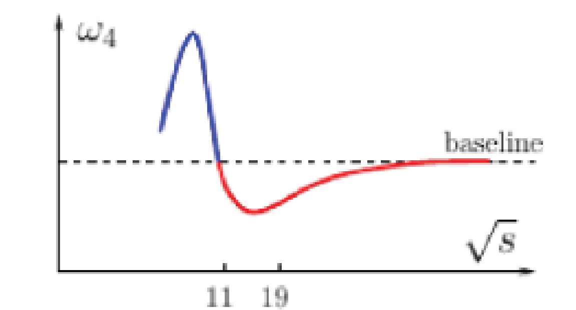
$$(\mu_B, T) \rightarrow (H, t)$$



Can compare qualitative behaviour to observables

X. Luo, CPOD 2014





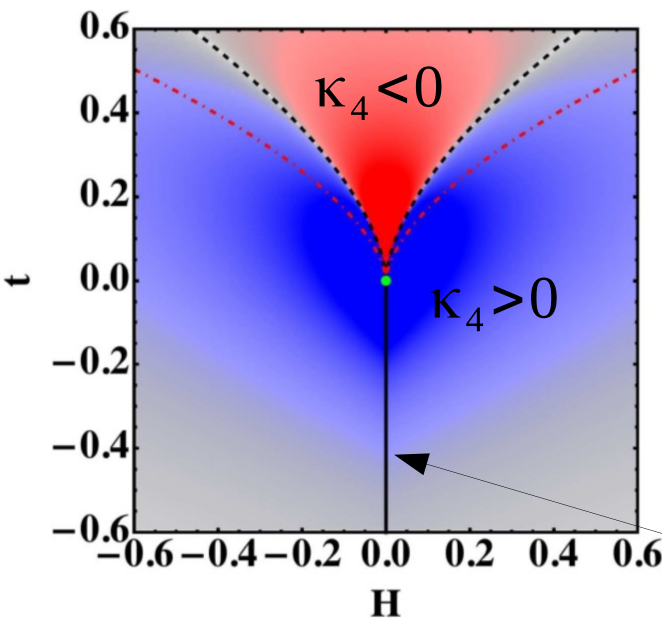
[Stephanov Phys. Rev. Lett (2011)]

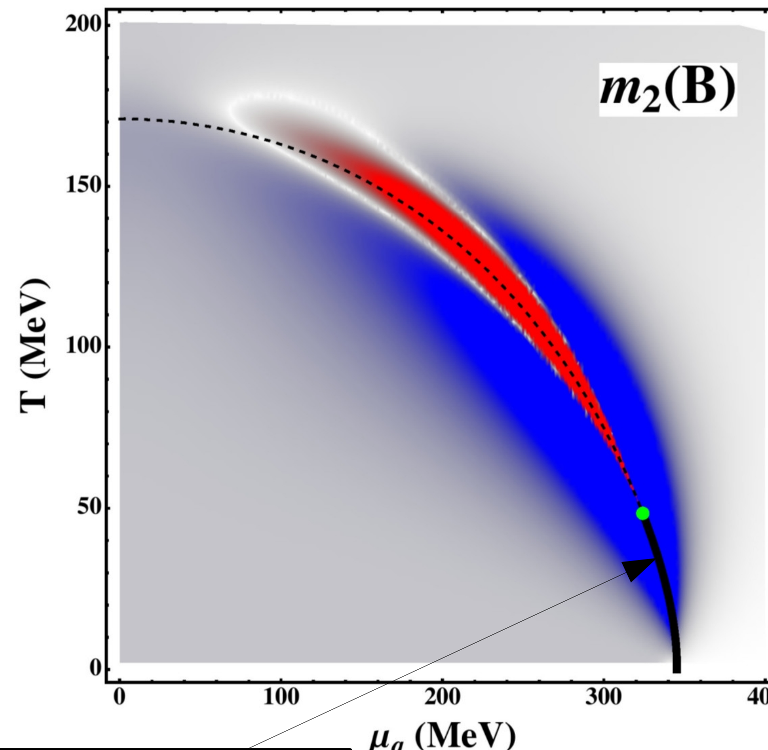
Universality: use NJL model also in Ising/QCD class

NJL near the CEP also belongs to Ising-model class

Compute experimental observables in NJL for more systematic study how baryon fluctuations connect to order parameter fluctuations

$$\chi_n = \frac{\partial^n \ln Z}{\partial \mu_B^n} \qquad m_2 = \frac{T^2 \chi_4}{\chi_2}$$



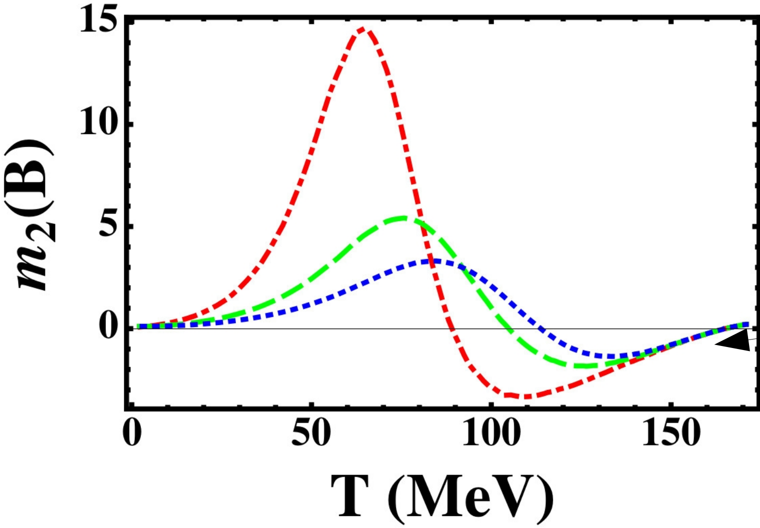


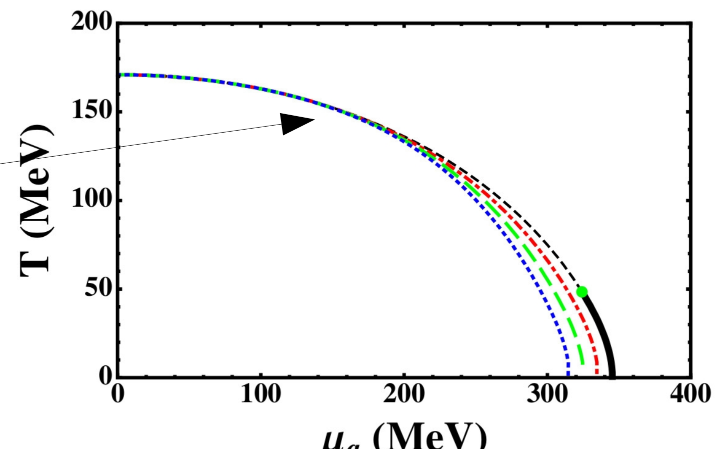
1st order line

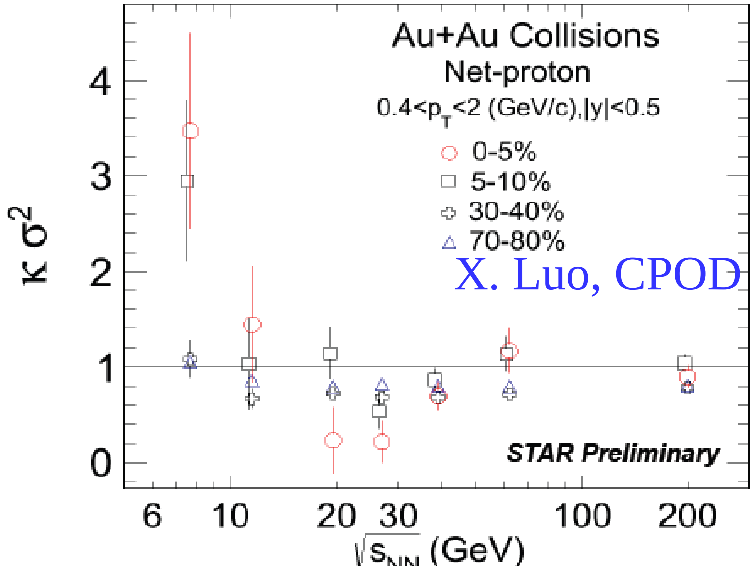
[J.-W. Chen, J. Deng, H. Koyama, and LL PRD (2016)]

Robust characteristics from NJL model investigation

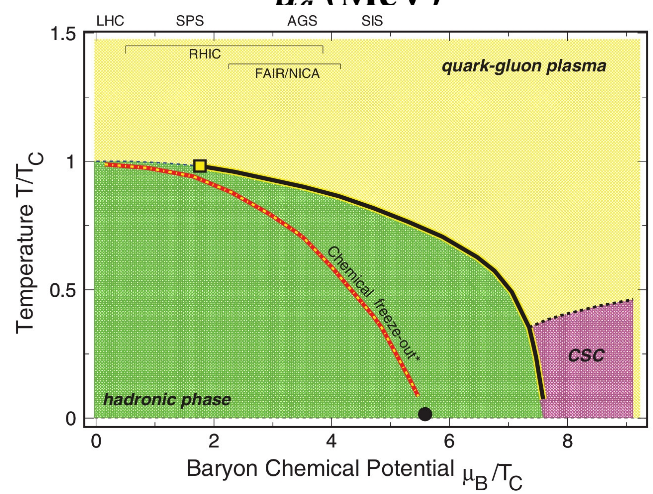
Compare qualitative behaviour along hypothetical freeze-out lines and find robust characteristics







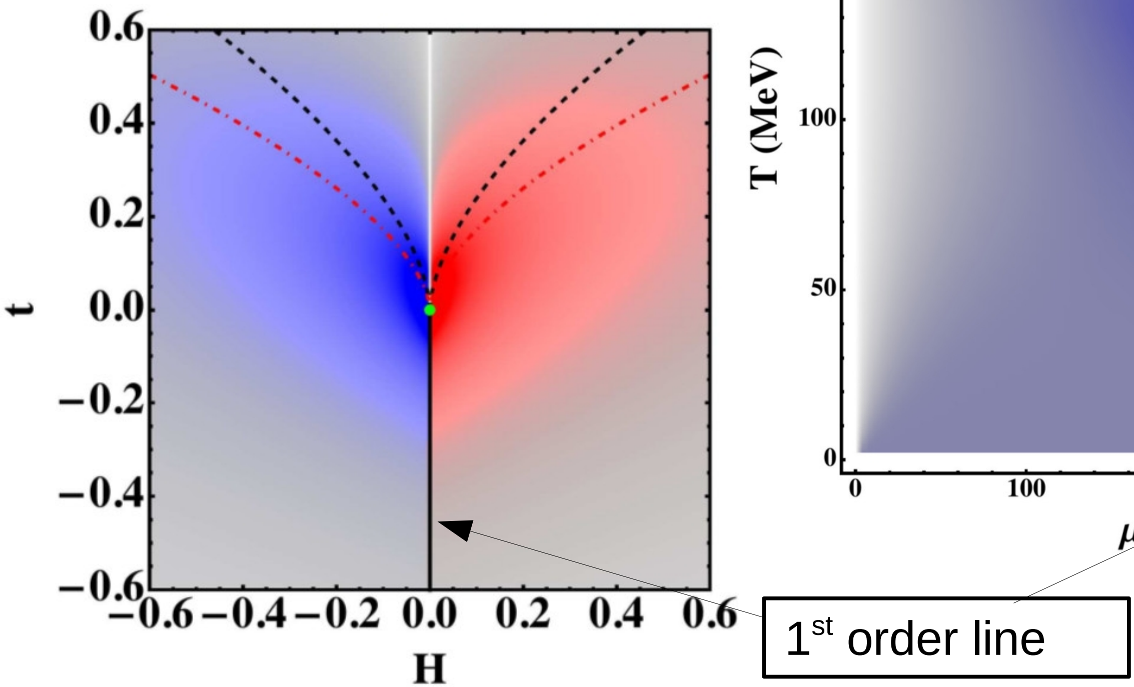
X. Luo, CPOD 2014

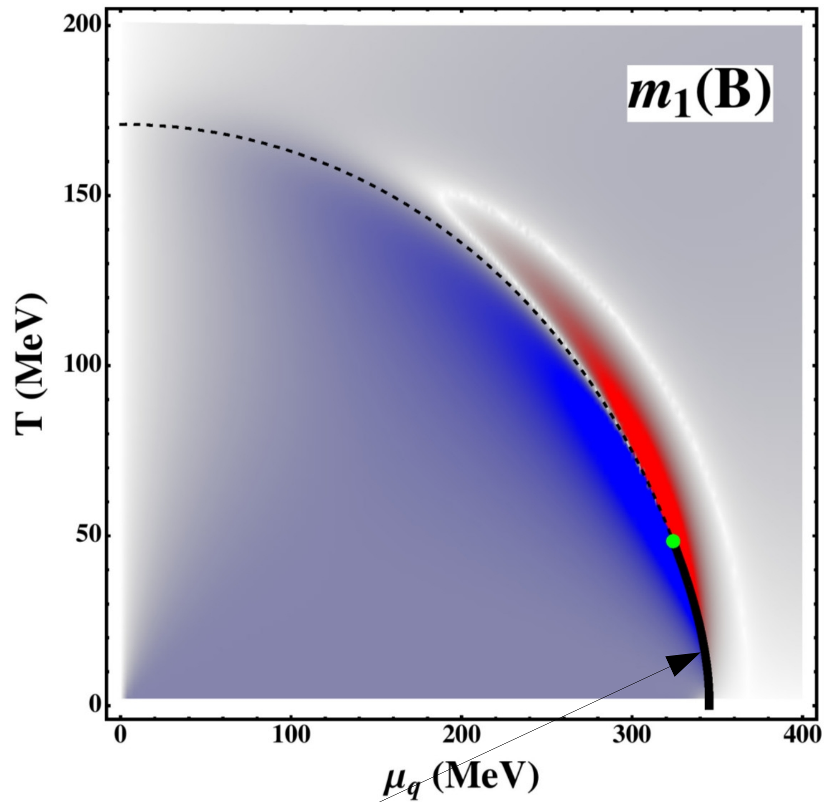


[J.-W. Chen, J. Deng, H. Koyama, and LL PRD (2016)]

Compare multiple observables

$$\chi_n = \frac{\partial^n \ln Z}{\partial \mu_B^n} \qquad m_1 = \frac{T\chi_3}{\chi_2}$$

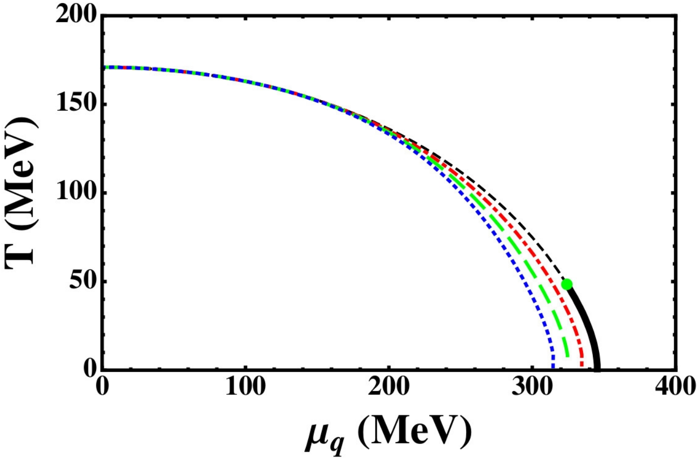


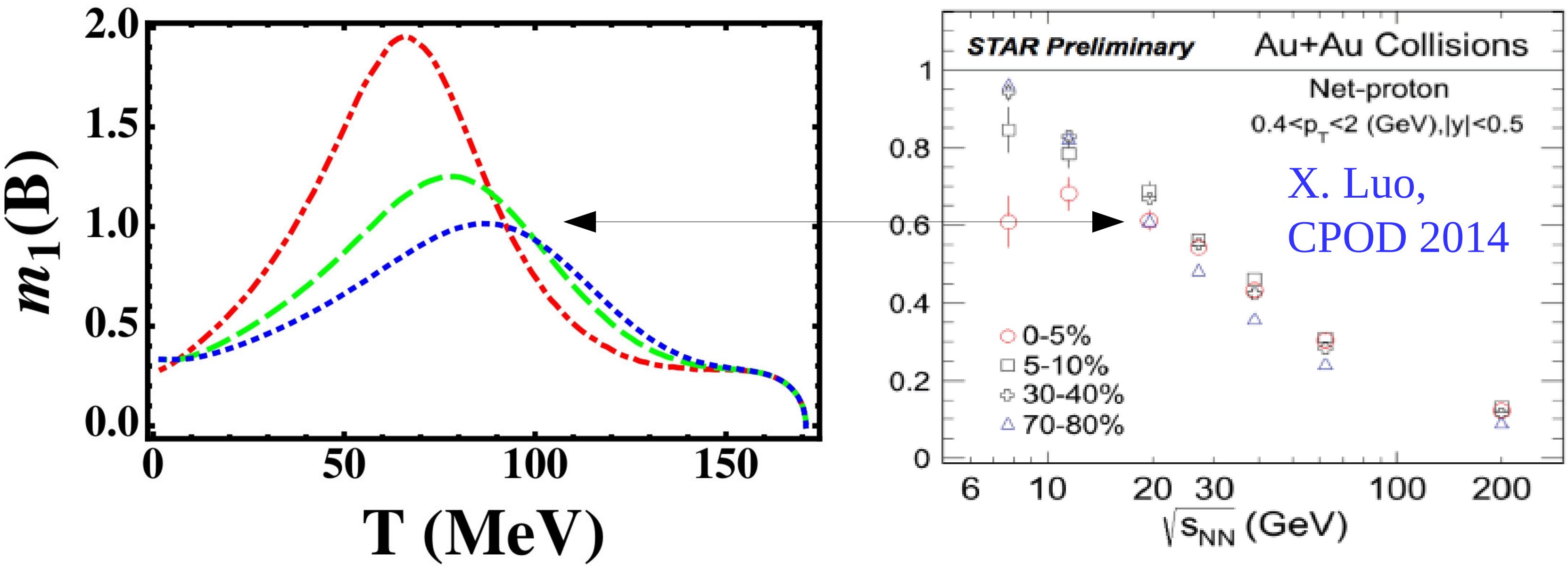


[J.-W. Chen, J. Deng, H. Koyama, and LL arXiv:1603.05198]

Qualitative agreement with data continues...

$$m_1 = \frac{T\chi_3}{\chi_2} \sim S\sigma(\exp)$$



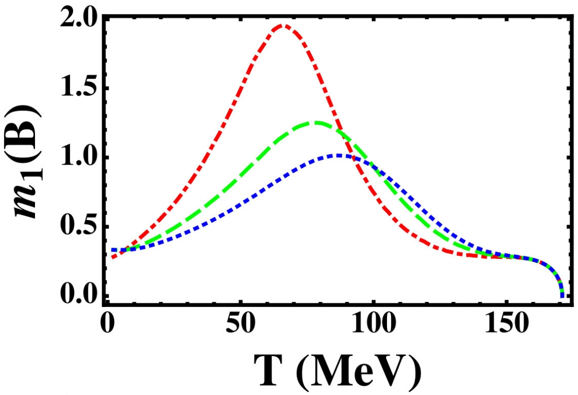


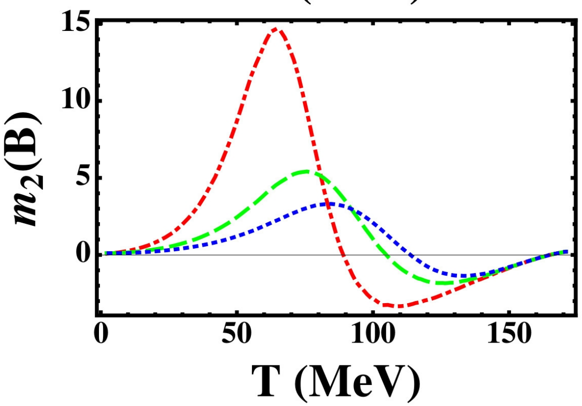
[J.-W. Chen, J. Deng, H. Koyama, and LL arXiv:1603.05198]

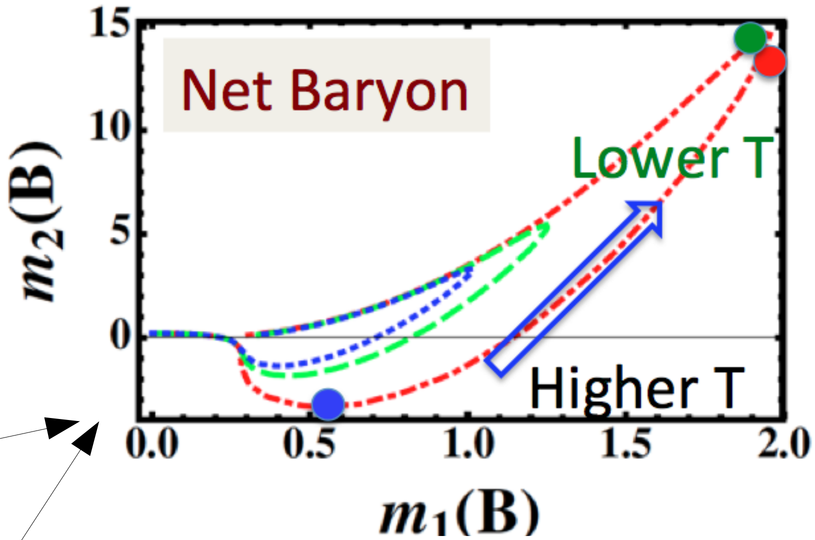
Consistency check: compare observables to each other

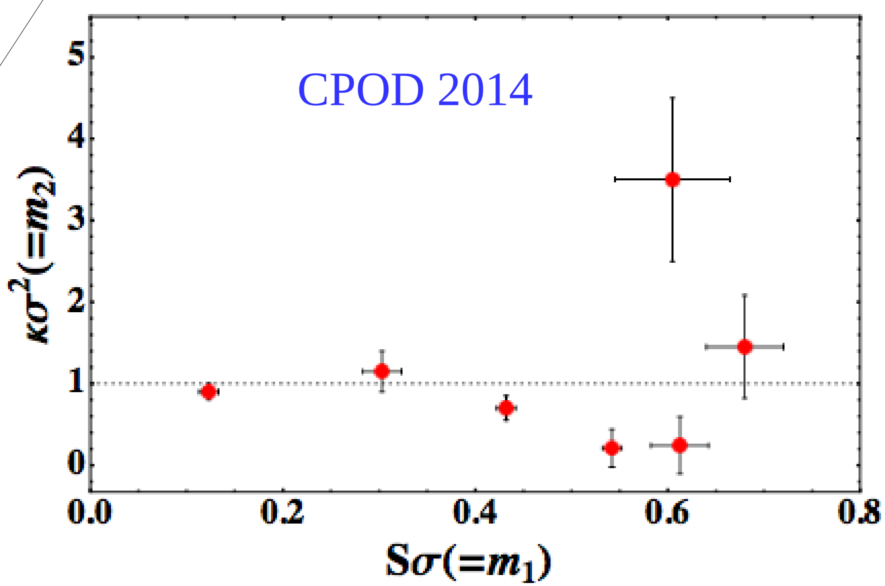
$$\chi_4 = \frac{\partial \chi_3}{\partial \mu_B}$$

Should be a relation, may be robust up to non-thermal effects









[J.-W. Chen, J. Deng, H. Koyama, and LL arXiv:1603.05198]

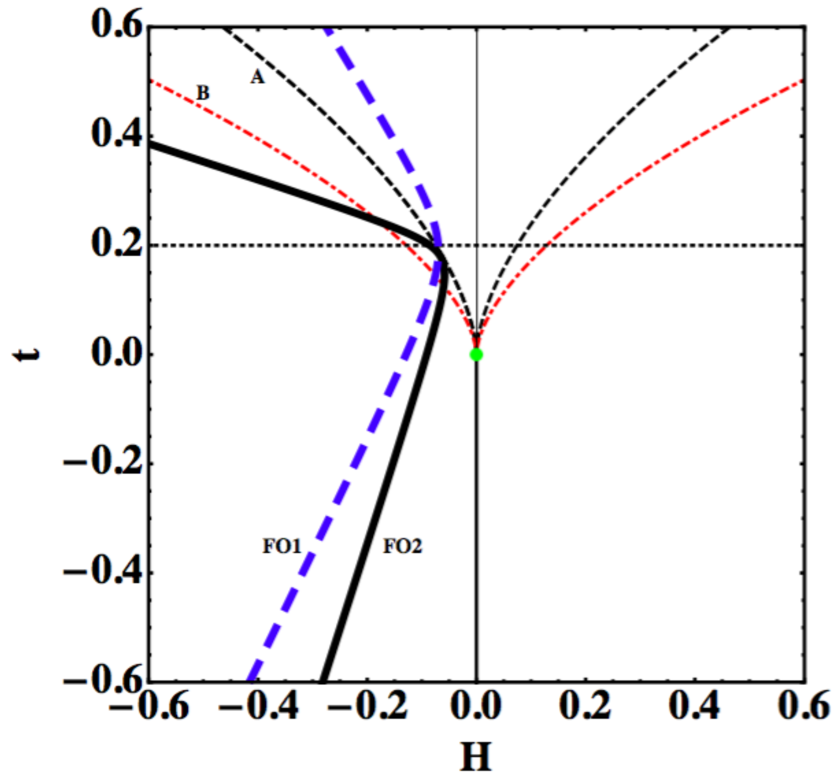
Banana shape may be robust: general argument for ordering of features

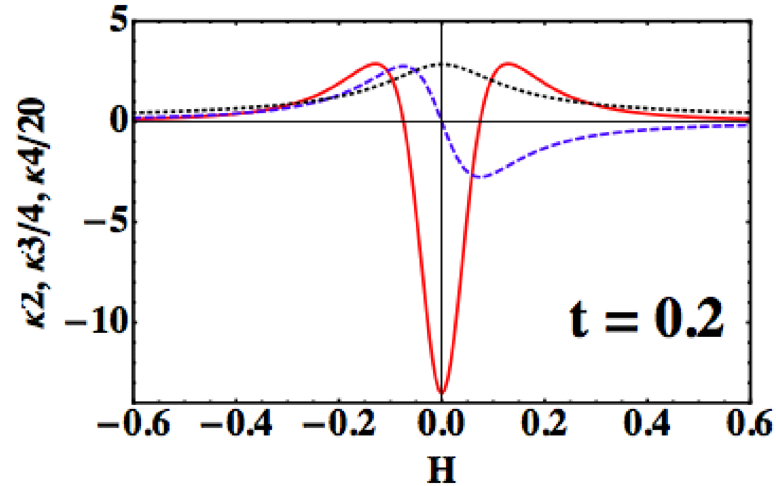
$$T_{min,m_2} > T_{max,m_1} > T_{max,m_2} > T_{CEP}$$

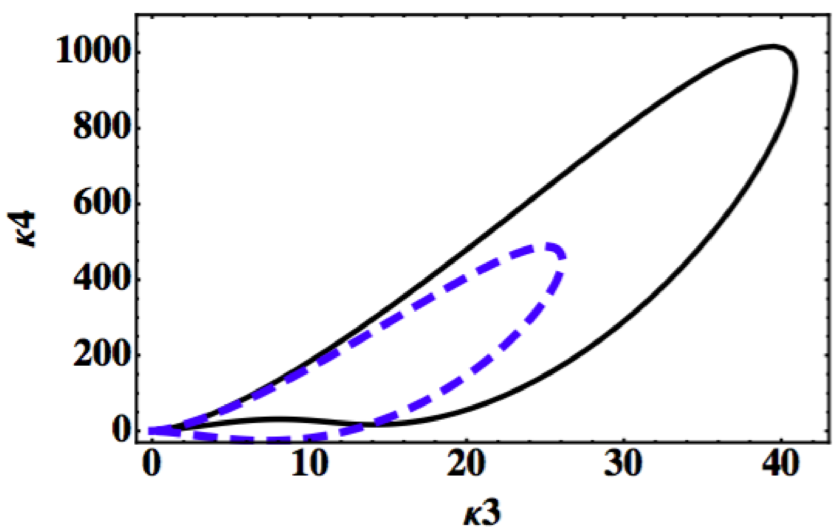
Found also in Gross-Neveu model

[J.W. Chen, J. Deng and LL, Phys. Rev. D (2015)]

And **Ising model**

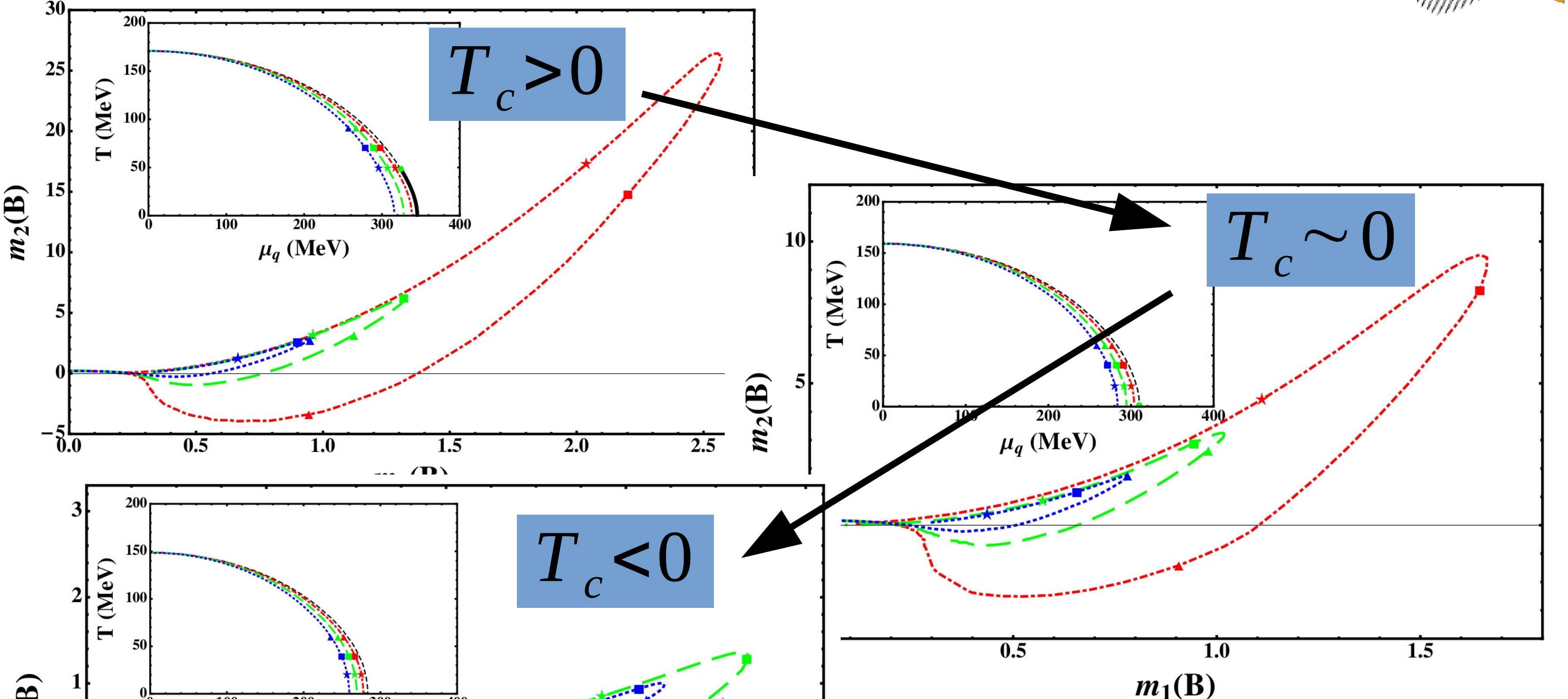


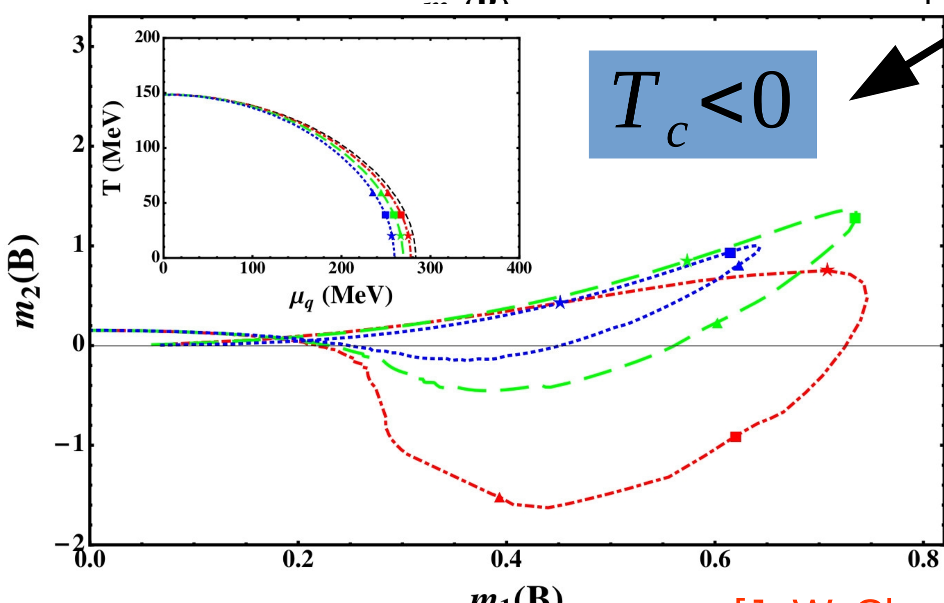




[J.-W. Chen, J. Deng, H. Koyama, and LL arXiv:1603.05198]

Banana shape is a necessary condition, but not sufficient!

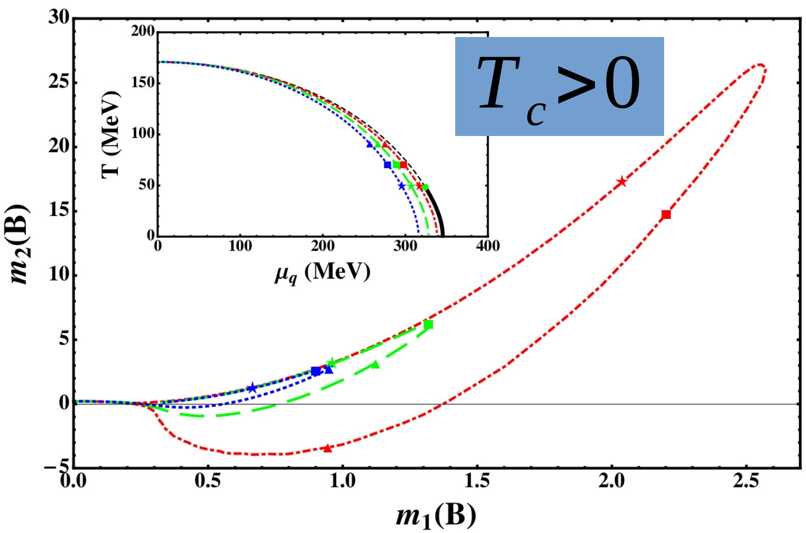


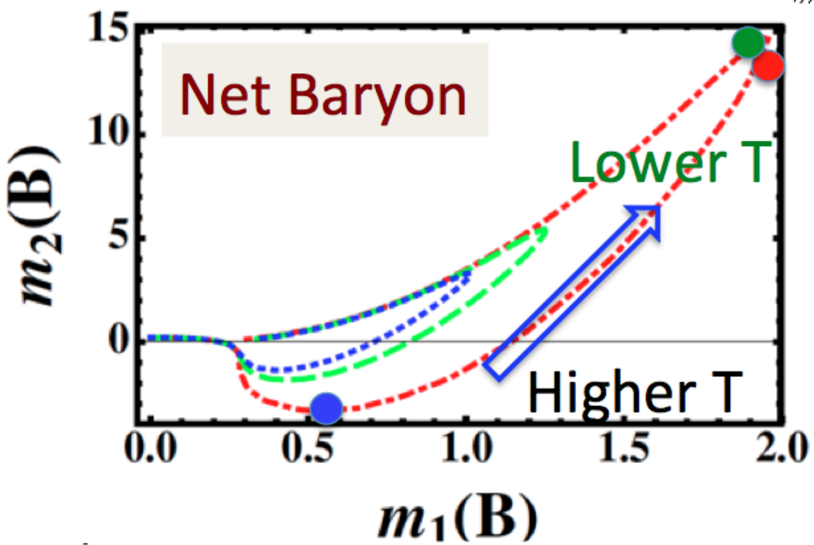


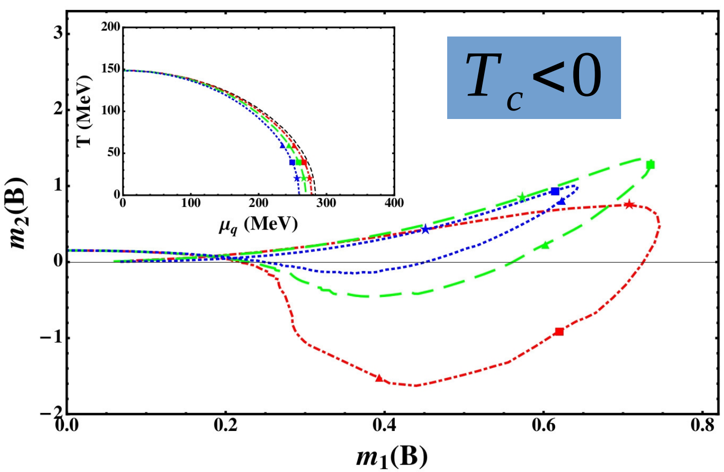
Robustness of banana to CEP at "negative temperature" may be similar to hidden quantum CP in superconductors

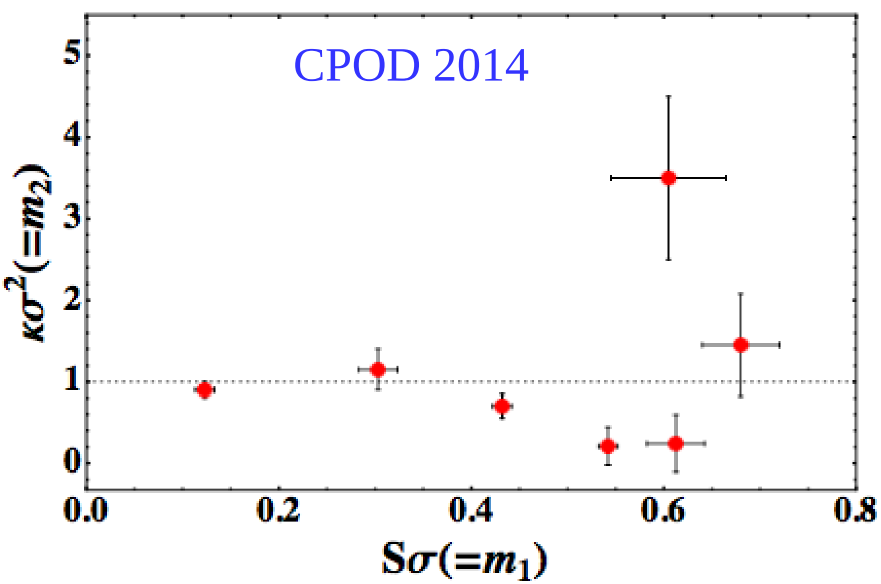
[J.-W. Chen, J. Deng, H. Koyama, and LL arXiv:1603.05198]

Conclusions:
Try to grow a banana but don't bet the farm

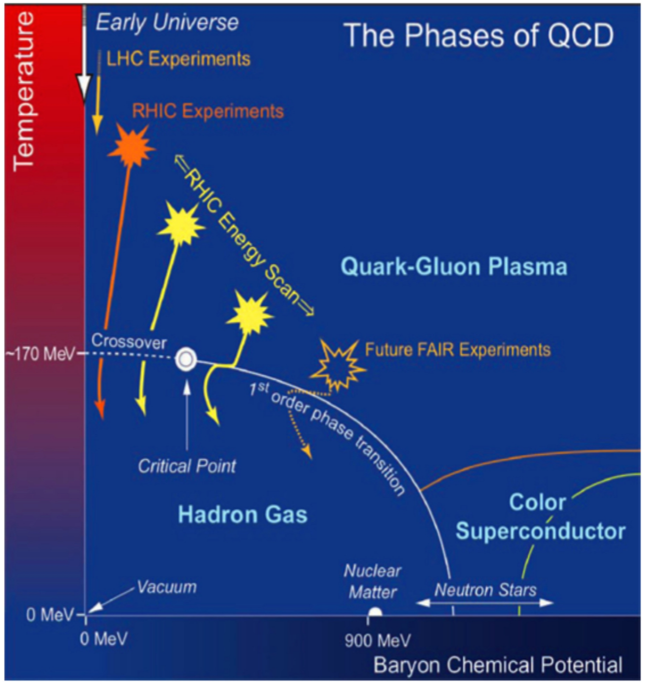






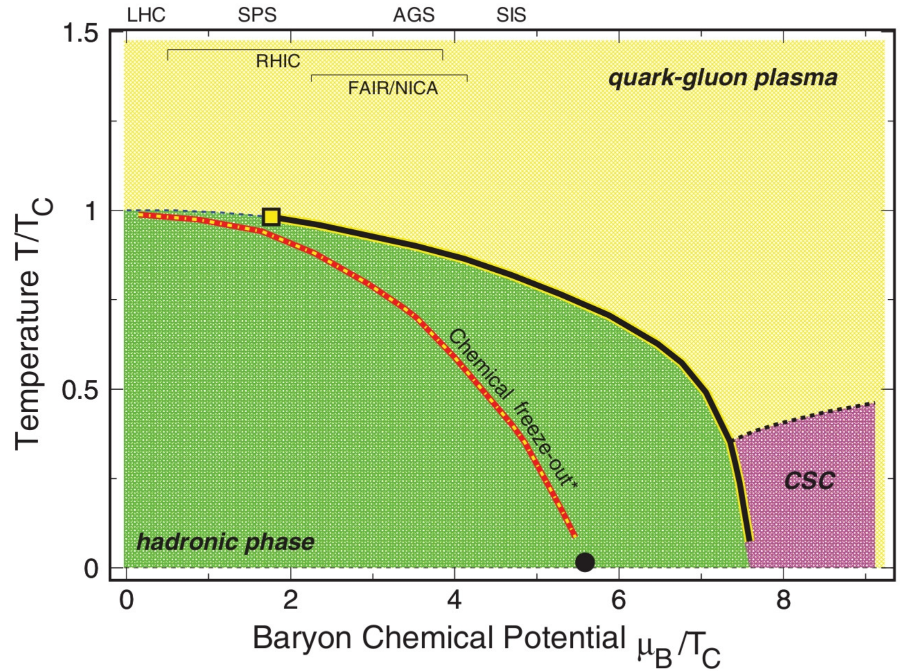


Experimental challenges of the search



STAR White paper 2014

In ideal world:
Simply scan beam energy to create fireballs at different densities and temperatures
>> probe phase diagram along freeze-out line



In real world:
– Systematic changes in observables unrelated to equilibrium phase diagram

– Identification of (μ_B, T) relies on well-motivated models of hadronization, but model-dependence difficult to relate to other models and theory (see below)

Our goal: multiple consistent observables to strengthen interpretation of data

In experimental search for theorized object,
can only predict necessary conditions on observables (consequences of theory)
but not sufficient conditions (there may be many ways to produce similar results)

Best second option:

set of observables over-constrained by theory

Example: Show the 125 GeV boson is THE Higgs

EW Theory
Higgs potential has 2 parameters:

$$\mu^2 < 0, \lambda$$

Solving the potential relates the 3 measurable properties to 2 parameters of theory
>> over-constrained

Collider experiment
Higgs particle involves several measurable quantities:

$$m_H^2 > 0, v, g_3$$

VEV and trilinear coupling