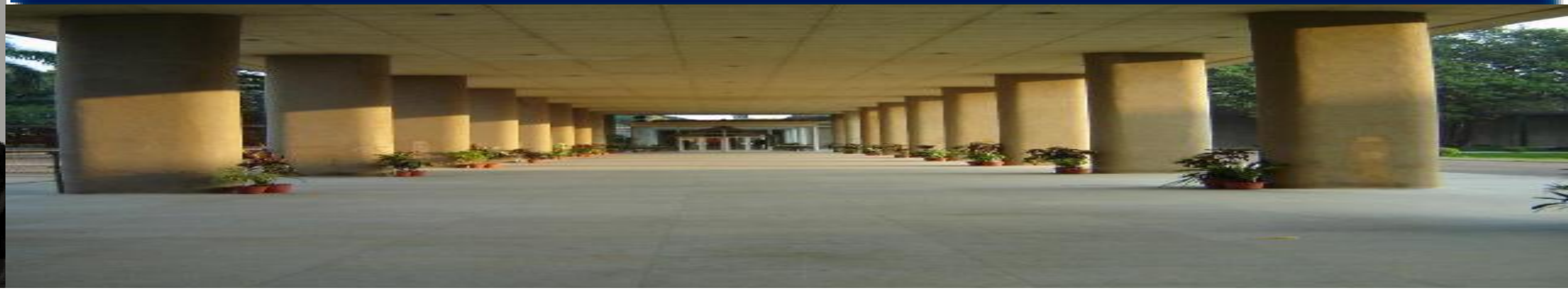
Strong Interaction In The 21st Century



Strong Interactions and Finite Baryon Density: The Lattice Approach

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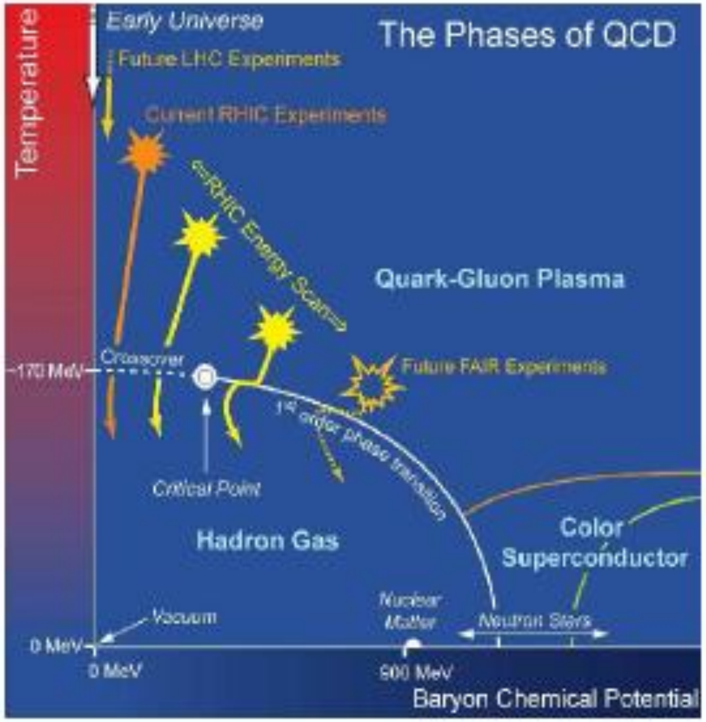
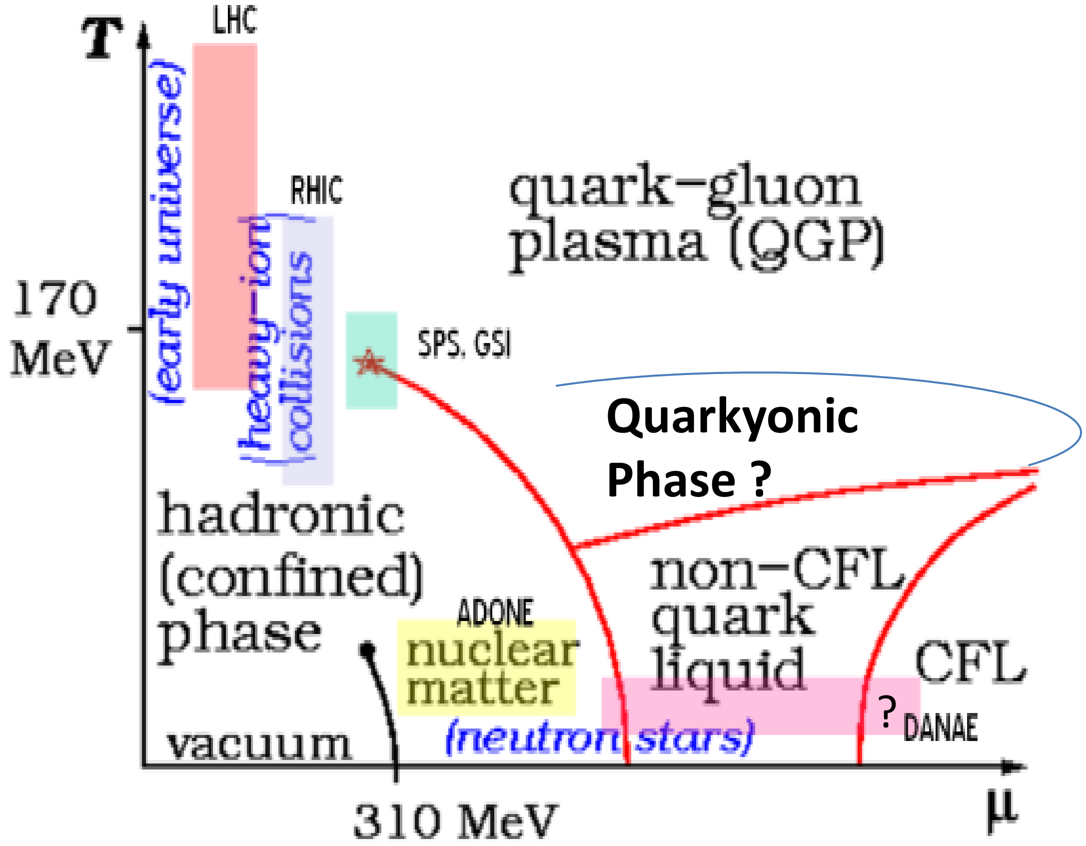
The QCD Phase Diagram



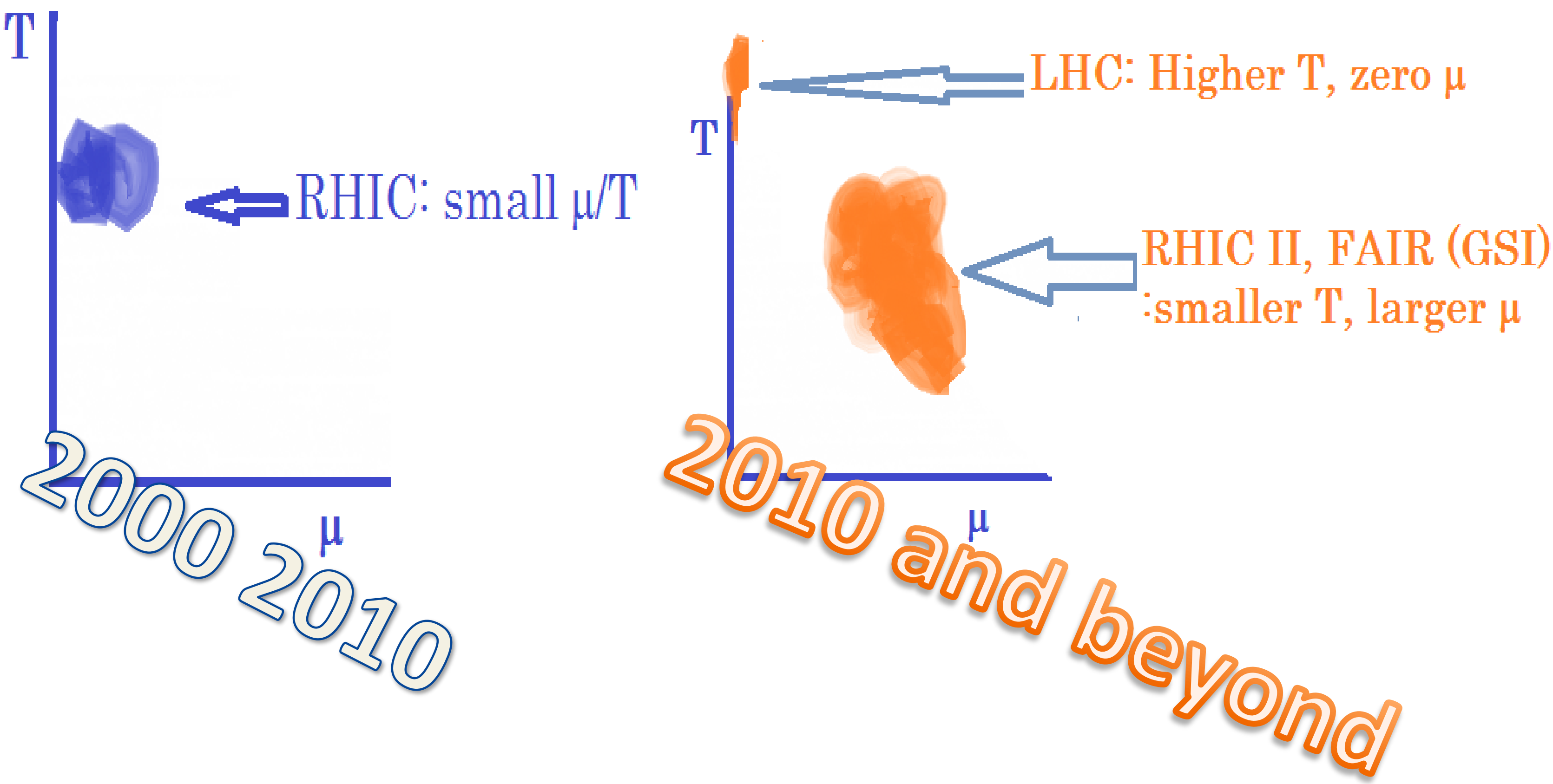
US NSAC Long RangePlan

Nonzero baryon density tells us about general properties of strong interactions

- Asymptotic freedom
- Confinement, Chiral Symmetry
- Quarkyonic Phase **Mc Lerran**



Strong Interactions and Finite Baryon density in the XXI Century: shift of the focus at the turn of the decade



OUTLINE

INTRODUCTION

RESULTS ON THE PHASE DIAGRAM:

CRITICAL ENDPOINT
PHYSICS OF THE FREEZOUT LINE
THE QUARKYONIC PHASE

The theoretical apparatus: QCD, the Field Theory of Strong Interactions

$$\mathcal{L} = \mathcal{L}_{YM} + \bar{\psi}(i\gamma_\mu D_\mu + m + \mu\gamma_0)\psi$$

Lattice QCD allows first principles calculations from the QCD Lagrangian

$$\mathcal{L} = \mathcal{L}_{YM} + \bar{\psi}(i\gamma_\mu D_\mu + m + \mu\gamma_0)\psi$$

We can tune physical parameter, as in real experiments: baryon chemical potential, temperature, isospin chemical potential, strangeness,..

We can also play with number of color and number of flavor.

We can address phenomenological issues as well as theoretical questions.

Computational Schemes

$$\mathcal{Z} = \int d\phi d\bar{\psi} dU e^{-S(\phi,\bar{\psi},U)}; S(\phi,\bar{\psi},U) = \int_0^{1/T} dt \int d^d x \mathcal{L}(\phi,\bar{\psi}U)$$

$$\mathcal{L}_{QCD} = \mathcal{L}_{YM} + \bar{\psi}(i\gamma_\mu D_\mu + m)\psi + \mu\bar{\psi}\gamma_0\psi$$

Two options:

1. Integrate out gluons first:

   $$\mathcal{Z}(T,\mu,\bar{\psi},\psi,U) \simeq \mathcal{Z}(T,\mu,\bar{\psi},\psi) \rightarrow$$

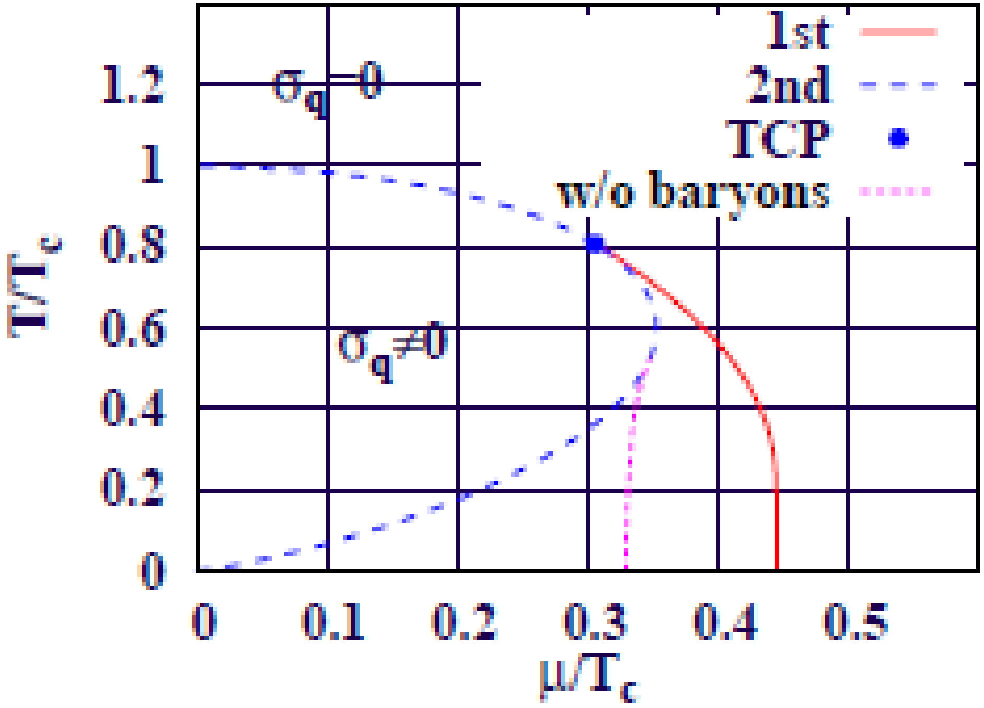
   effective approximate fermion models
2. Integrate out fermions exactly as S is bilinear in $\psi, \bar{\psi}$
   $S = S_{YM}(U) + \bar{\psi}M(U)\psi$

   $$\mathcal{Z}(T,\mu,U) = \int dU e^{-(S_{YM}(U) - log(detM))} \rightarrow$$

   starting point for numerical calculations

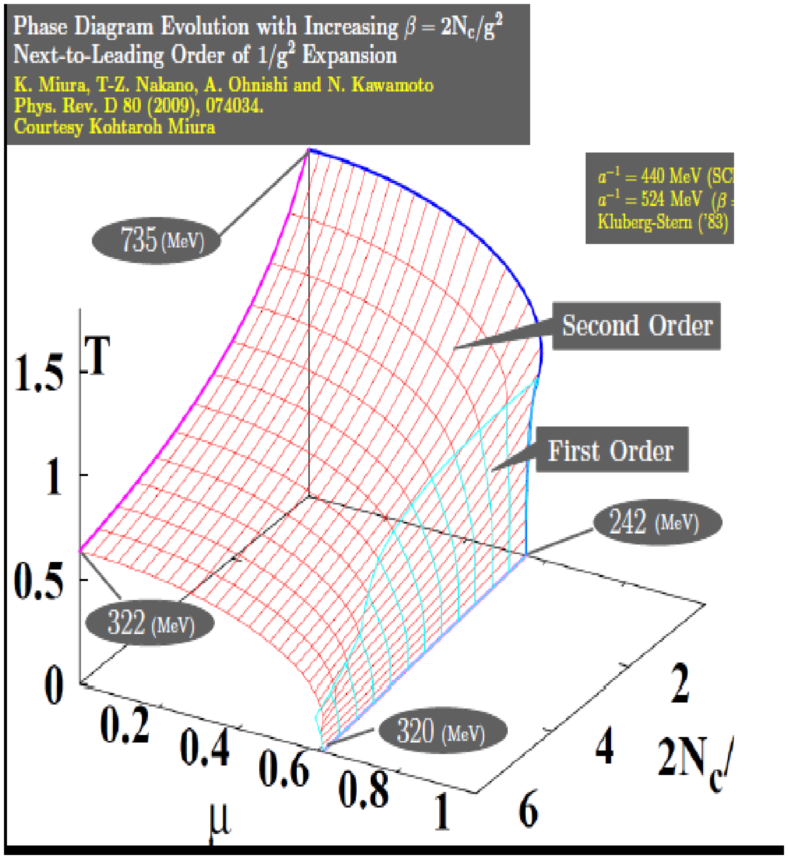
Option1: The strong coupling expansion

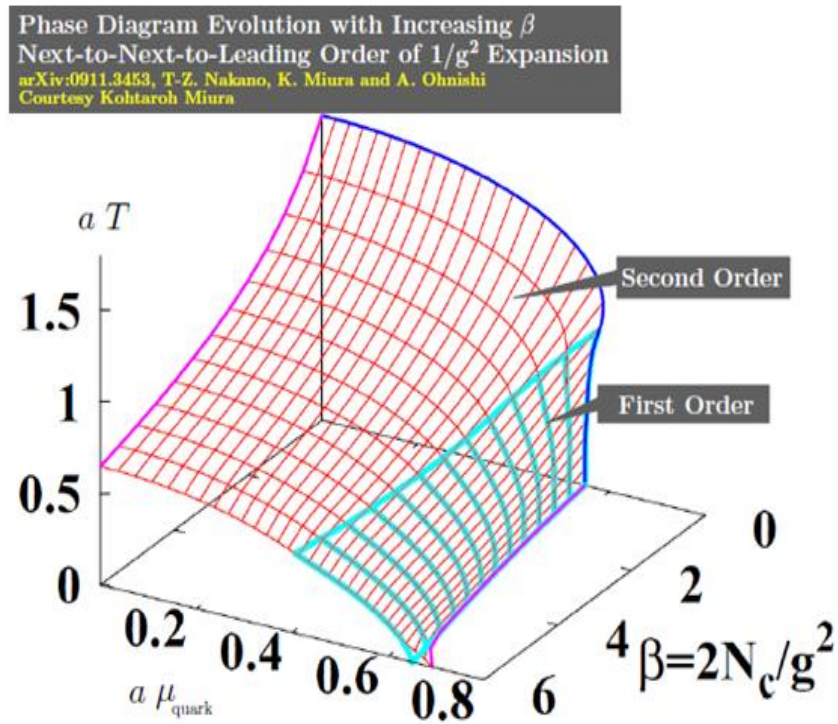
A long history..



Kawamoto, Miura, Onishi 2007

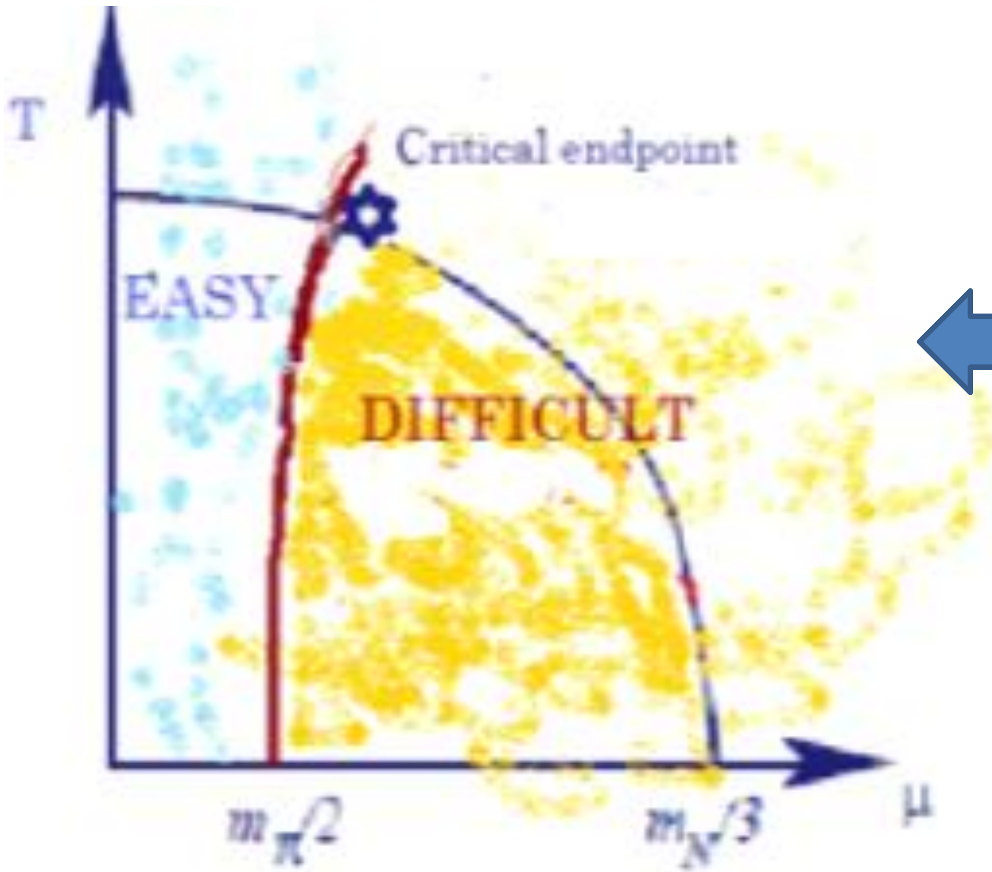
The Strong Coupling Expansion approaching the continuum limit





Option 2 : Integrate over fermions and ..

The $m_\pi/2$ barrier



Summary Of our efforts!!

THE CHALLENGE

Importance Sampling and The Positivity Issue

$$\mathcal{Z}(T, \mu, U) = \int dU e^{-(S_{YM}(U) - log(\det M))}$$

$\det M > 0 \longrightarrow$ Importance Sampling MonteCarlo Simulations

To assess sign problem consider $M^\dagger(\mu_B) = -M(-\mu_B)$

- $\mu = 0 \longrightarrow \det M$ is real
  Particles-antiparticles symmetry : MC Simulations OK
- Imaginary $\mu \neq 0 \longrightarrow \det M$ is real
  (Real) Particles-antiparticles symmetry : MC Simulations OK
- Real $\mu \neq 0$ Particles-antiparticles asymmetry
  $\longrightarrow \det M$ is complex in QCD

QCD with a real baryon chemical potential: use information from the accessible region

$$Real\mu = 0, Im\mu \neq 0$$

TOWARDS THE REAL SOLUTION

COMPLEX LANGEVIN?
→Gert Aarts

DENSITY OF STATE METHODS?
→Christian Schmidt

NEW ALGORITHMS?
→Shailesh Chandrasekharan

LEARNING FROM SIMPLER SYSTEMS?
→David Kaplan

Many discussions at this meeting ..not covered in this talk

THE 'EASY' SOLUTION : EXTRAPOLATE

QCD AT NONZERO BARYON DENSITY: METHODS

Multiparameter Reweighting ($\mu = 0$):

Fodor, Katz, Csikor, Egri, Szabo, Toth

Derivatives ($\mu = 0$):

Gupta, Gavai and collaborators; MILC; QCD-Taro

Expanded Reweighting ($\mu = 0$)

Bielefeld-Swansea

Analyitic continuation from Imaginary μ

Strong Coupling QCD *MpL*

Dim. Reduced QCD *Laine, Hart, Philipsen*

QCD *de Forcrand, Philipsen,Kratochvila*

D'Elia, MpL, Di Renzo

Azcoiti, Di Carlo, Galante, Laliena, Staggered

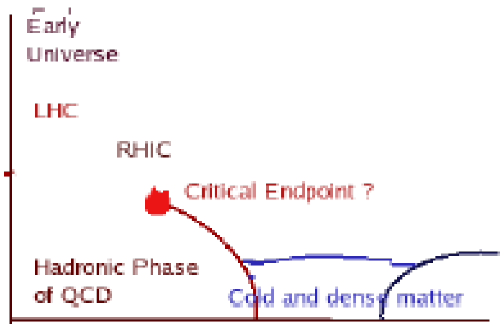
Luo et al. Wilson

Models *Giudice, Papa; de Forcrand, Kim....*

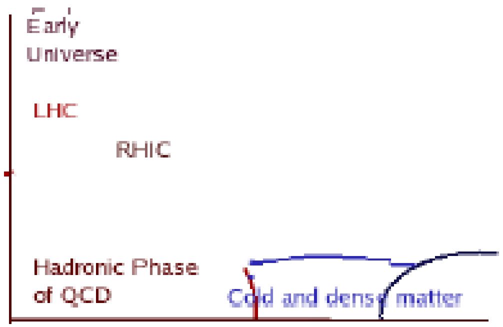
The results on the phase diagram presented in the following were obtained by these 'easy' approaches

CRITICAL ENDPOINT

The critical endpoint

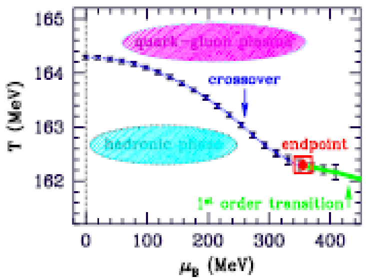


OR



Both scenario are compatible
with model calculations and universality

STRATEGY 0 : FODOR KATZ , REWEIGHTING FROM $\mu = 0$



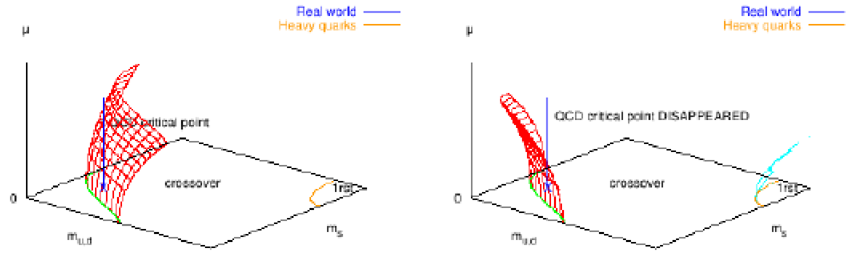
CRITICISM:
Critical point is close to the phase quenched threshold where reweighting fails at T=0

HOWEVER :
Important contribution from the phase does not necessarily hamper reweighting : overlap might still be large or correlation with the phase might be small.

Splittorff, Verbaarschot, MpL , in progress

CHALLENGING THE ENDPOINT

STRATEGY I : FORCRAND-PHILIPSEN



Scenario I or Scenario II ? To decide, measure slope K in

$$\frac{m_c(\mu)}{m_c(0)} = 1 + K\left(\frac{\mu}{T}\right)^2 + \ldots$$

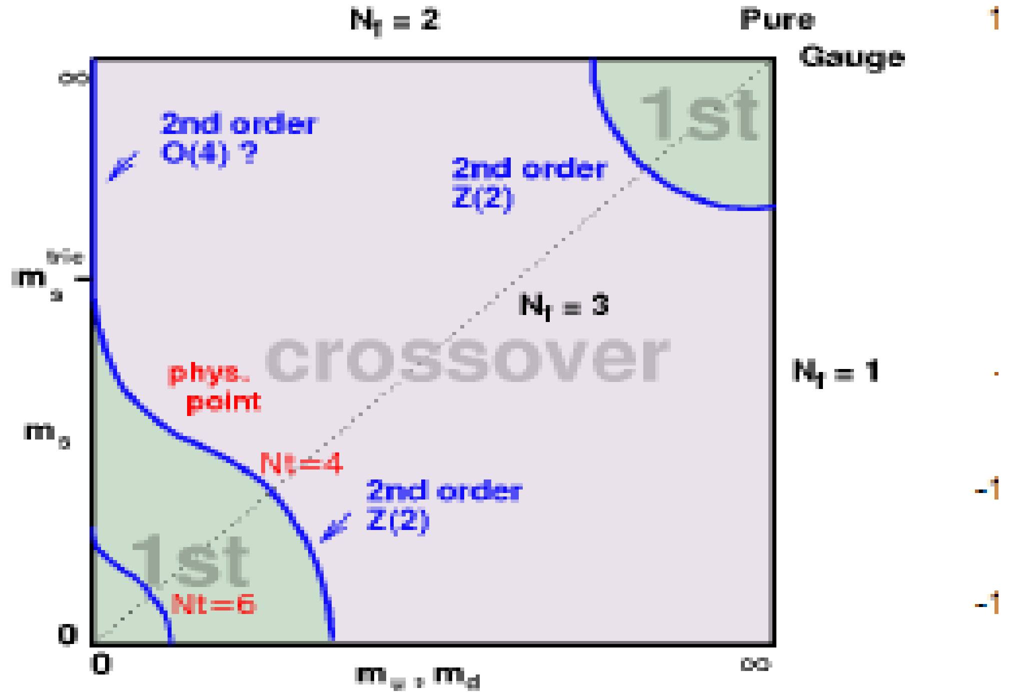
$K > 0$: Scenario I , critical endpoint at small μ_B

$K < 0$: Scenario II, NO critical endpoint at small μ_B

CURRENT RESULTS SUGGEST NO CRITICAL ENDPOINT FOR $\mu_B < 600MeV$

NB: assume that endpoint is part of the critical surface at m=0

Towards the continuum



RESCUING THE ENDPOINT

STRATEGY II : GAVAI AND GUPTA, BIELEFELD-RBC

Series expansion for the pressure:

$$P(T,\mu_B) = P(T) + \frac{1}{2}\chi_B^{(2)}(T)\mu_B^2 + \frac{1}{4!}\chi_B^{(4)}(T)\mu_B^4 + \frac{1}{6!}\chi_B^{(6)}(T)\mu_B^6 + \frac{1}{8!}\chi_B^{(8)}(T)\mu_B^8 + \cdots,$$

The quark number susceptibility has the expansion

$$\chi_B(T,\mu_B) = \chi_B^{(2)}(T) + \frac{1}{2}\chi_B^{(4)}(T)\mu_B^2 + \frac{1}{4!}\chi_B^{(6)}(T)\mu_B^4 + \frac{1}{6!}\chi_B^{(8)}(T)\mu_B^6 + \cdots.$$

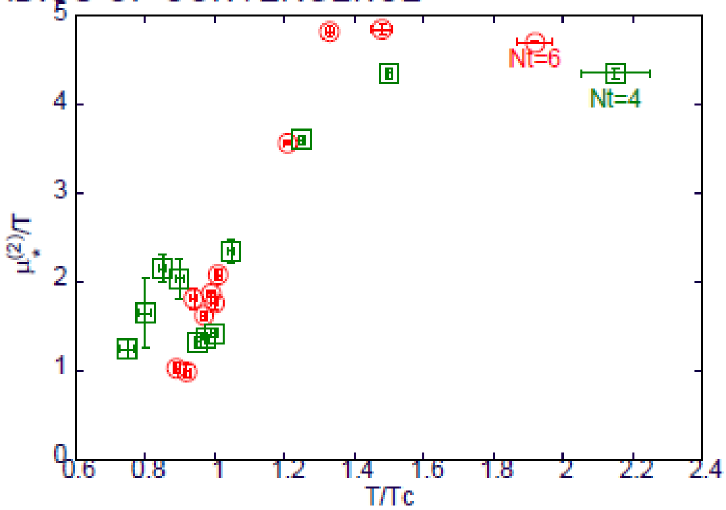
THIS SERIES IS EXPECTED TO DIVERGE AT THE QCD CRITICAL END POINT. RADIUS OF CONVERGENCE IS

$$\lim_{n\to\infty}\mu_*^{(n)} = \sqrt{\frac{1}{n(n-1)}\frac{\chi_B^{(n+2)}}{\chi_B^{(n)}}}.$$

The endpoint is the first singularity in the complex μ plane occurring at real μ.
Coefficients should be all positive at large n

Finite radius of convergence : ENDPOINT

THE RADIUS OF CONVERGENCE



$$\frac{T^E}{T_c} = 0.94 \pm 0.01, \text{ and} \frac{\mu_B^E}{T^E} = 1.8 \pm 0.1.$$

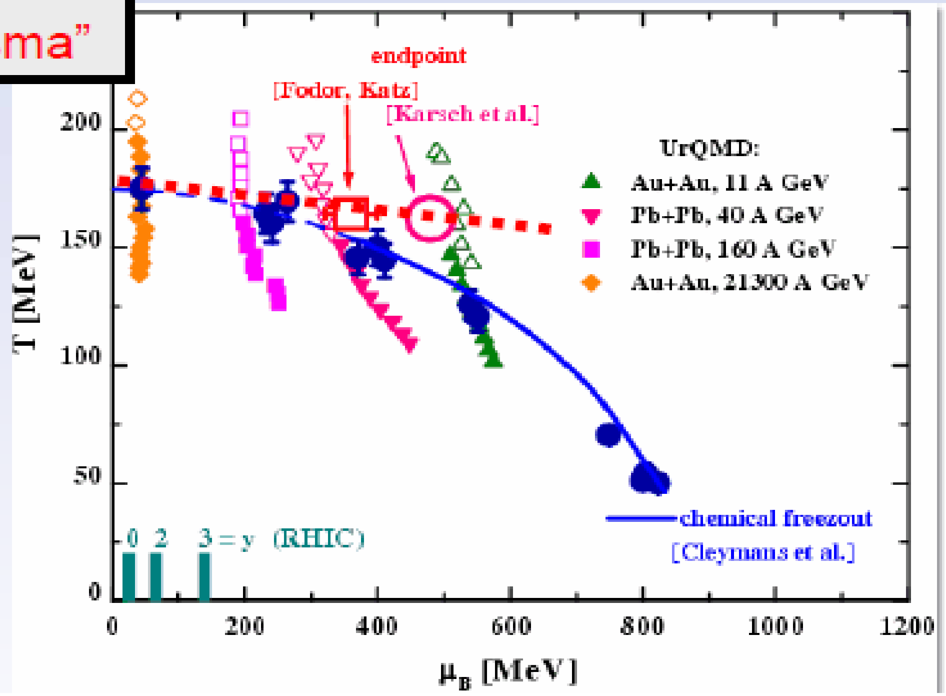
Extrapolation of this result to the thermodynamic limit, $L \to \infty$ on the coarse lattice
:

$$\frac{T^E}{T_c} = 0.94 \pm 0.01, \text{ and} \frac{\mu_B^E}{T^E} = 1.1 \pm 0.1.$$

Gavai Gupta 2007--2009

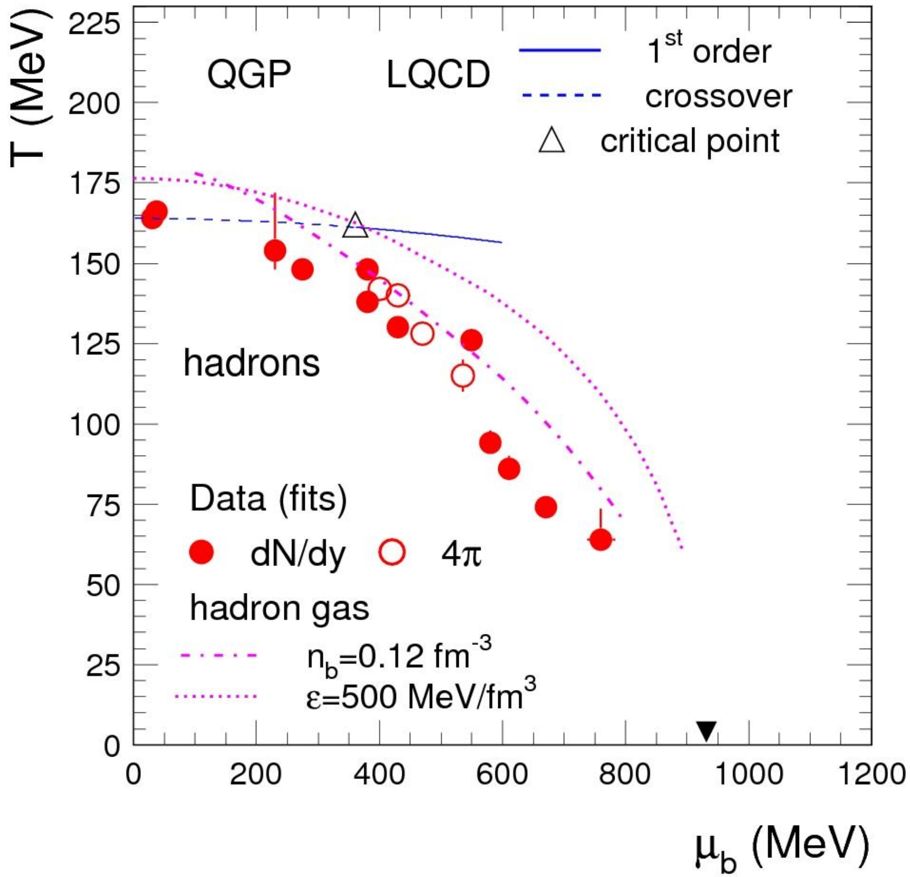
FREEZOUT

lasma”


endpoint
[Fodor, Katz]
[Karsch et al.]
UrQMD:
Au+Au, 11 A GeV
Pb+Pb, 40 A GeV
Pb+Pb, 160 A GeV
Au+Au, 21300 A GeV
T [MeV]
200
150
100
50
0
0
200
400
600
800
1000
1200
μB [MeV]
0 2 3 = y (RHIC)
chemical freezout
[Cleymans et al.]

Freezout

Andronic, Braun-Munzinger, Stachel 2009 – Courtesy of the Authors



Freezout

Values of μ_q^F/T at freezout for the temperatures used in the lattice simulations.

Table 1: Freezout parameters

T/T_c	μ_B^F (GeV)	μ_q^F/T
0.81	0.48	1.16
0.87	0.38	0.85
0.90	0.3	0.65
0.96	0.15	0.30

Previous analysis have shown that for this range of temperatures the Hadron Gas parametrization is satisfied by the first coefficents.

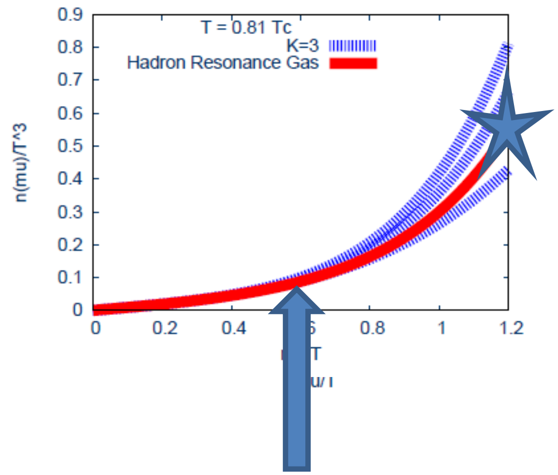
Then, to assess the extent of the convergence, we can directly contrast $n_q^3(T,\mu_{qI})/T^3$ and $n_q^{HG}(T,\mu_{qI})/T^3$, with $F(T) = \frac{2}{3}c_2$.

Lower bound on the radius of convergence And freezout point

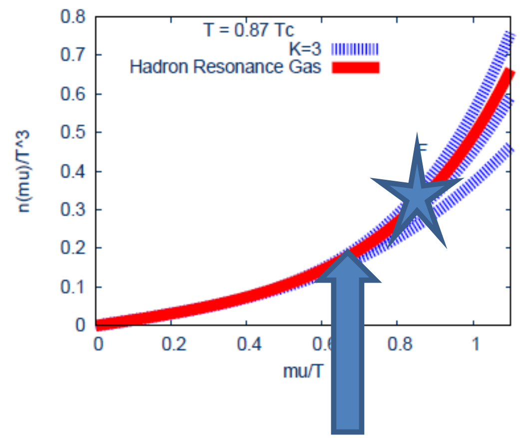
Data from RBC Collaboration Courtesy E. Laermann and C. Schmidt. C. Ratti and MpL QM09

Freezout point

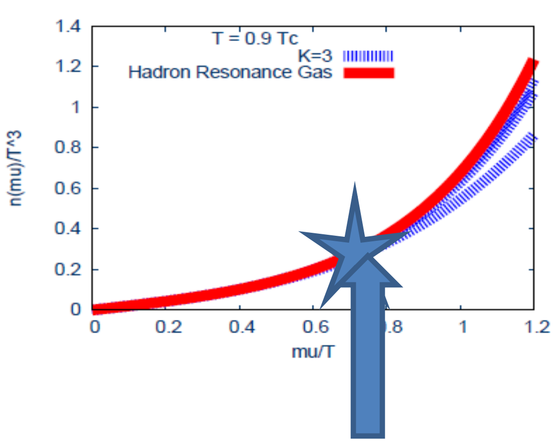
T = 0.81 Tc



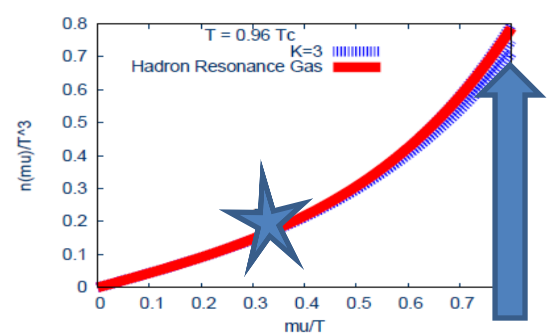
T = 0.87 Tc



T = 0.90 Tc

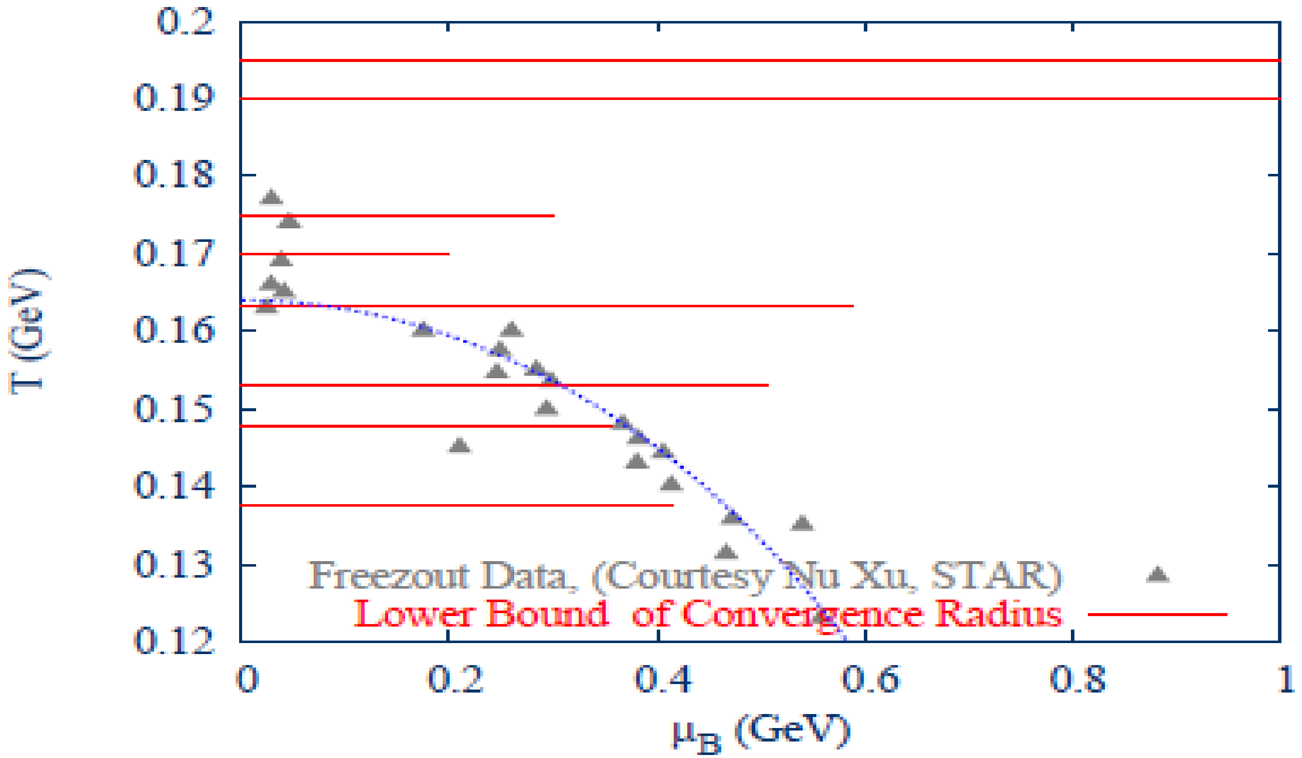


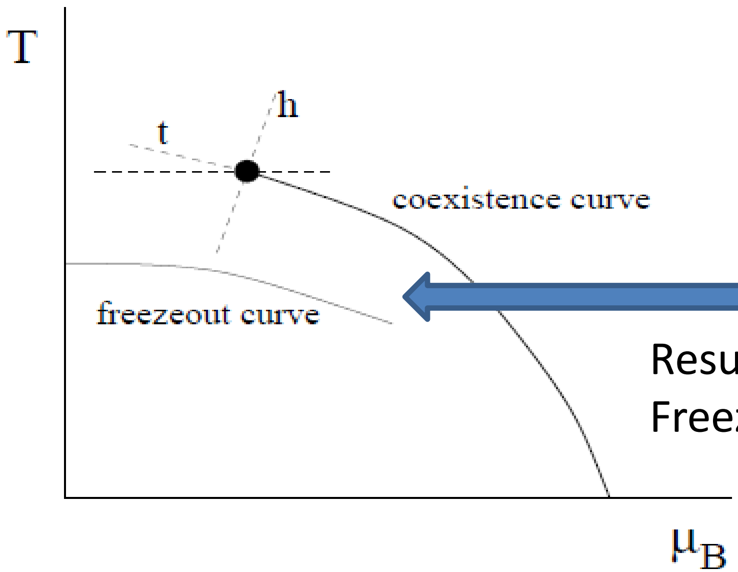
T = 0.96 Tc



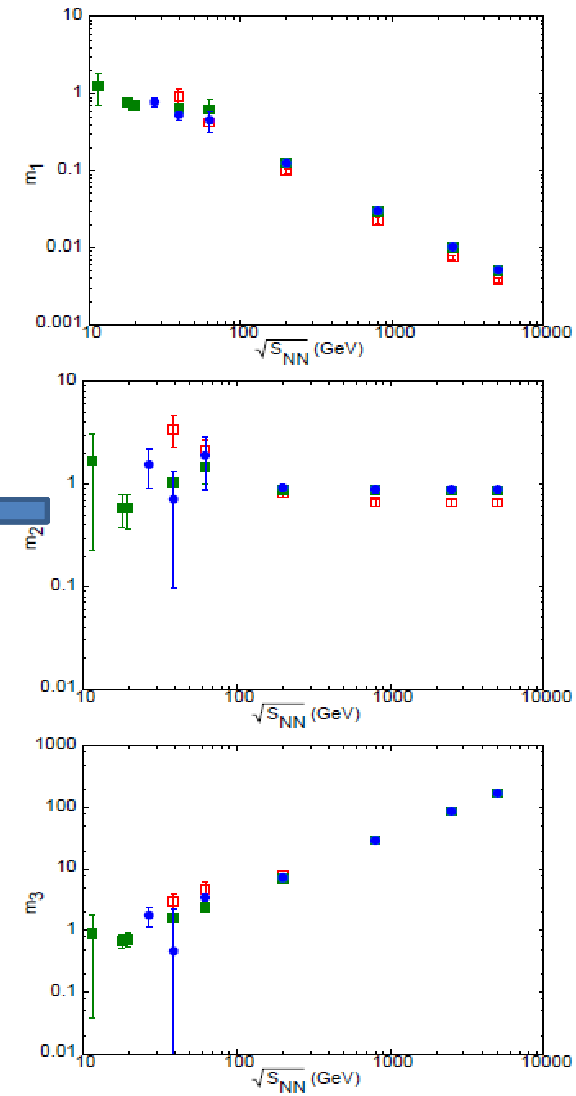
Freezout line might well be amenable to a lattice study

Lattice data from RBC-Bielefeld Collaboration – C. Ratti MpL QM09





Results along the Freezout line



Gavai Gupta 2010

THE QUARKYONIC PHASE

The quarkyonic phase

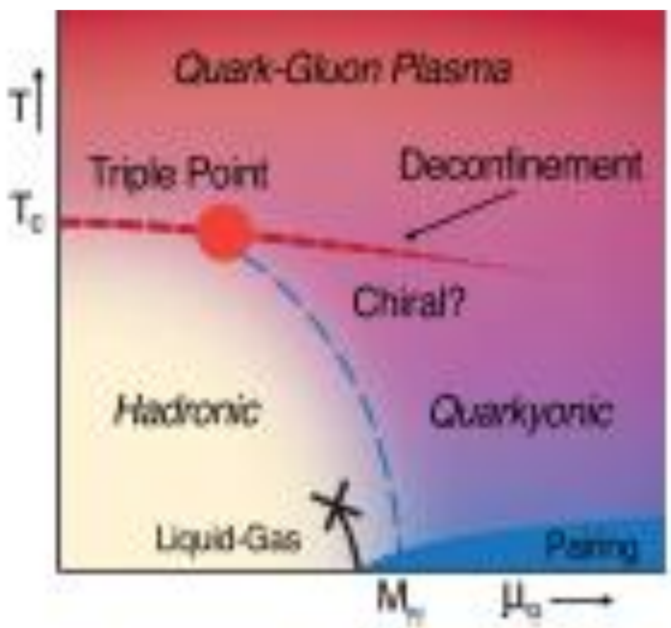
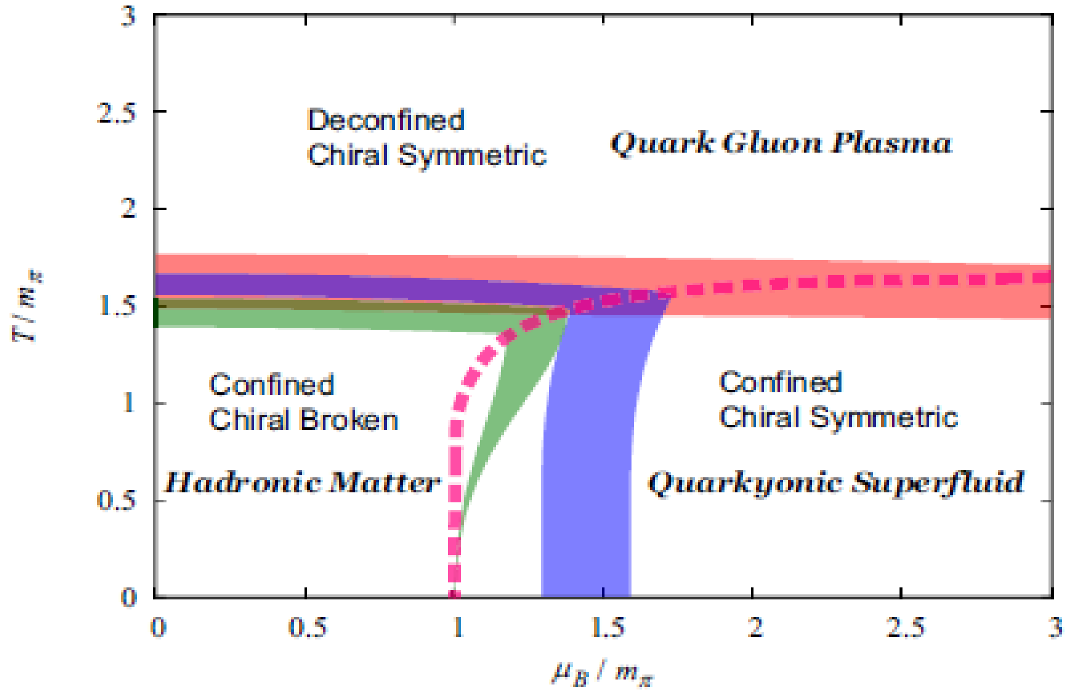


Fig. 5. The phase diagram of strongly interacting matter.

Hadron Production in Ultra-relativistic Nuclear Collisions: Quarkyonic Matter and a Triple Point in the Phase Diagram of QCD

A. Andronic[a], D. Blaschke[b,c], P. Braun-Munzinger[a,d,e,f], J. Cleymans[g], K. Fukushima[h], L.D. McLerran[i,j], H. Oeschler[a], R.D. Pisarski[i], K. Redlich[a,b,k], C. Sasaki[i,f], H. Satz[k], and J. Stachel[m]

Quarkyonic phase – Two color



Brauner, Fukushima, Hidaka 2009

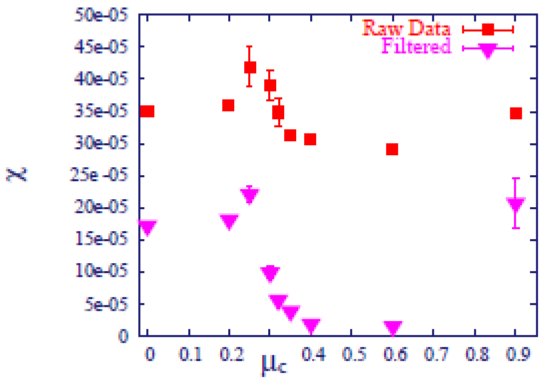
Superfluid phase still confined

GLUONIC OBSERVABLES IN THE BEC PHASE of QC_2D

0^{++} **Glueball : lighter in the BEC phase**

Susceptibility: $\chi = < P^2 > - < P >^2$ **peaks at** μ_c

Normal Phase	
m_π / m_ρ	m_0^{++} / m_ρ
0.40	1.07
0.42	1.26
BEC	
0.64	0.80
0.80	0.23



Lombardo,Petrarca,Paciello,Taglienti,2007

A Quarkyonic Phase in Dense Two Color Matter

Simon Hands
Department of Physics, Swansea University, Singleton Park, Swansea SA2 8PP, U.K.

Seyong Kim
Department of Physics, Sejong University, Seoul 143-747, Korea.

Jon-Ivar Skullerud
Department of Mathematical Physics, National University of Ireland Maynooth, Maynooth, County Kildare, Ireland.

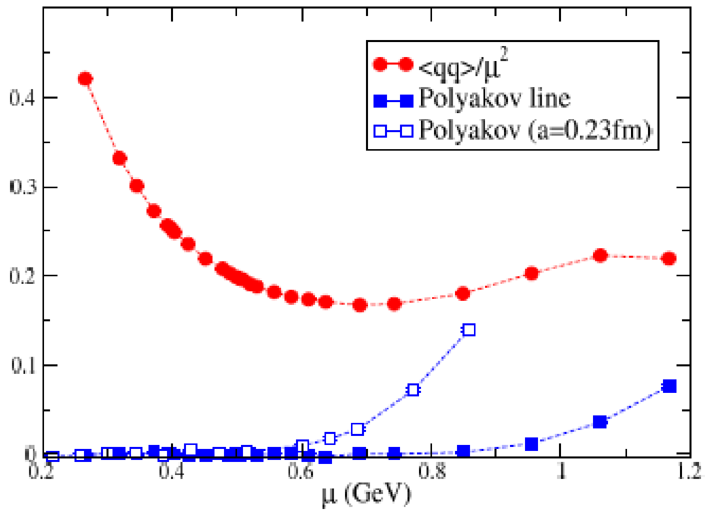
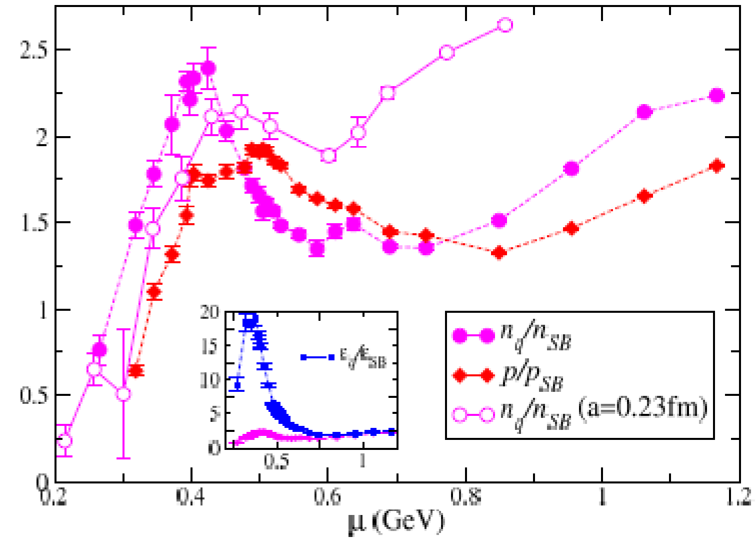
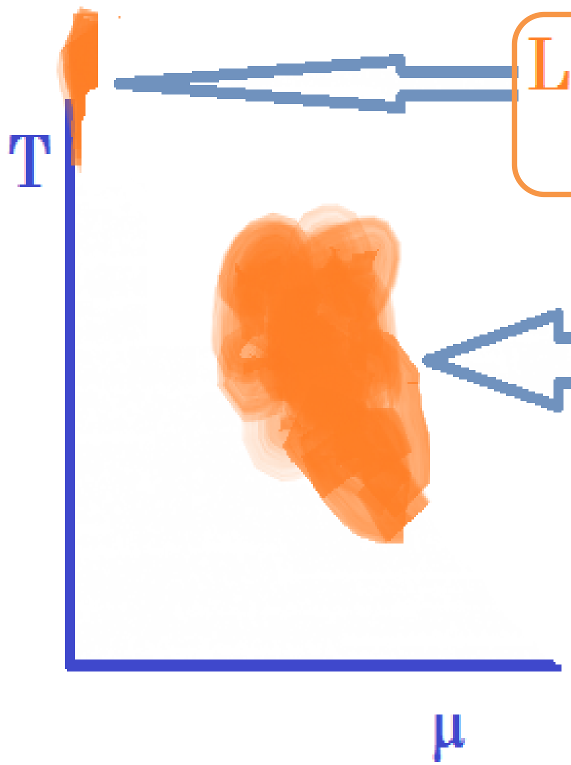


FIG. 4: (Color online) Superfluid order parameter $\langle qq\rangle/\mu^2$ and Polyakov line versus μ.



IG. 1: (Color online) n_q/n_{SB} and p/p_{SB} vs. μ for QC$_2$D. nset shows $\varepsilon_q/\varepsilon_{SB}$ for comparison.

Strong Interactions and Finite Baryon density in the (second decade of) XXI Century:



LHC: Higher T, zero μ

Entering the precision era

RHIC II, FAIR (GSI)
:smaller T, larger μ

Expect Experimental And lattice results on: Critical Endpoint, Freezout region, and (maybe) Exotic phases