CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?

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WHY STUDY QCD?

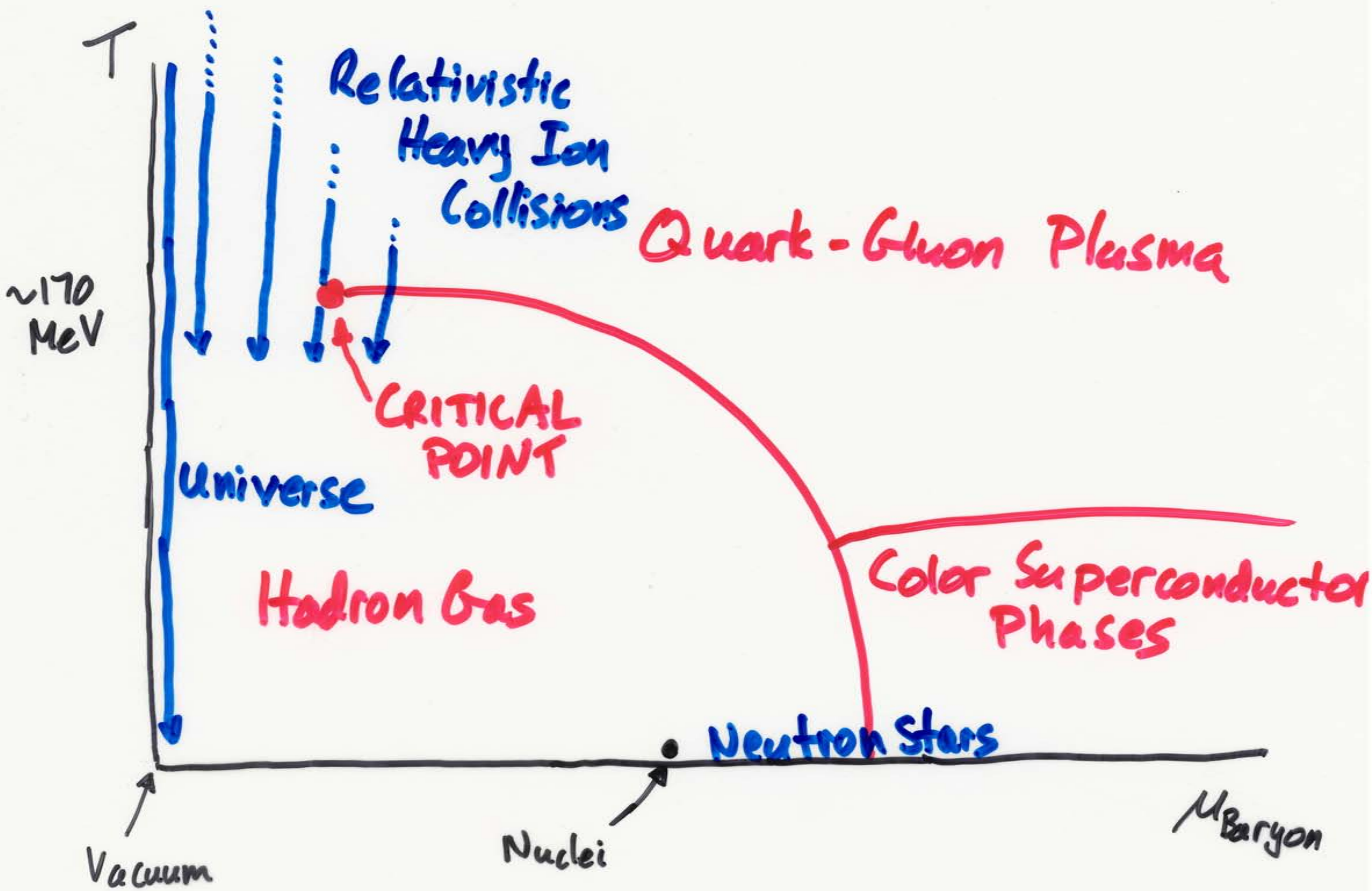
WHY IS IT A CHALLENGE?

- The only example we know of a strongly interacting gauge theory.
- We understand the theory at short distances.
- The quasiparticles — the excitations of the vacuum — are hadrons, which do not look at all like the short distance quark & gluon degrees of freedom.

HOW CAN WE RESPOND TO THIS CHALLENGE, EXPERIMENTALLY?

- Study the structure of the hadrons. (Eg, RHIC Spin)
- Get away from the vacuum. Understand other phases of QCD, and their quasiparticles. Map the QCD phase diagram.

EXPLORING THE PHASES OF QCD



$T \neq 0$; $\mu = 0$

- vertical axis
- we know a lot from lattice QCD. eg →
- QCD describes a transition

FROM	TO
gas of hadrons	plasma of quarks and gluons
with chiral symmetry badly broken	with chiral sym. almost restored.

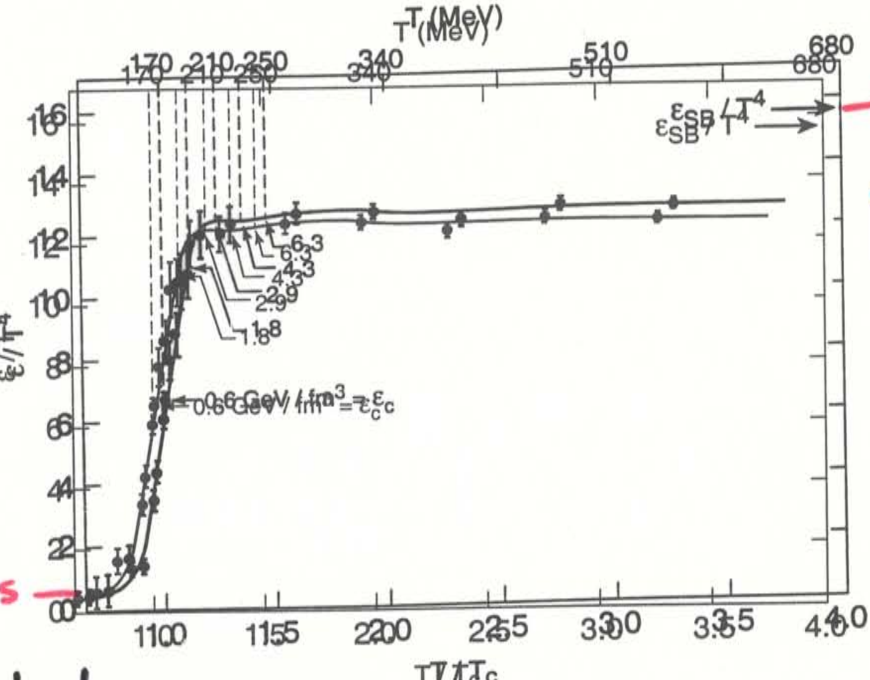
- $T_c \simeq 175 \pm 15$ MeV
- The transition is a smooth crossover, like ionization of a gas, occurring in a narrow range of T,

IF $m_s \gtrsim \frac{1}{5} m_s^{\text{physical}}$, and ∴ in nature.

UB: In world with $m_u = m_d = m_s$, crossover if $m_a \gtrsim \frac{1}{1?} m_s^{\text{physical}}$ Bielefeld Columbia

T(MeV), assuming $T_c = 170$ MeV.
(estimate is $140 < T_c < 190$)

$\frac{\varepsilon}{T^4}$



— ideal QGP

ion gas —

DECONFINEMENT

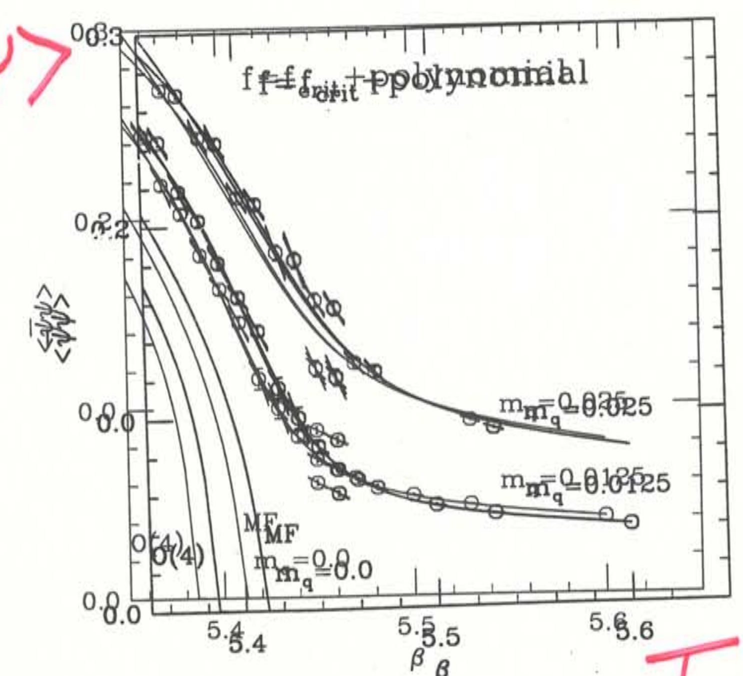
(IONIZING THE HADRONS)

Karsch Laermann Peikert (Heinz)

T/T_c

&

$\langle \bar{\psi}\psi \rangle$



lum
eTar
MILC
ollab.

CHIRAL SYMMETRY RESTORATION

(MELTING THE VACUUM)

ON THE LATTICE

T

(funny units)

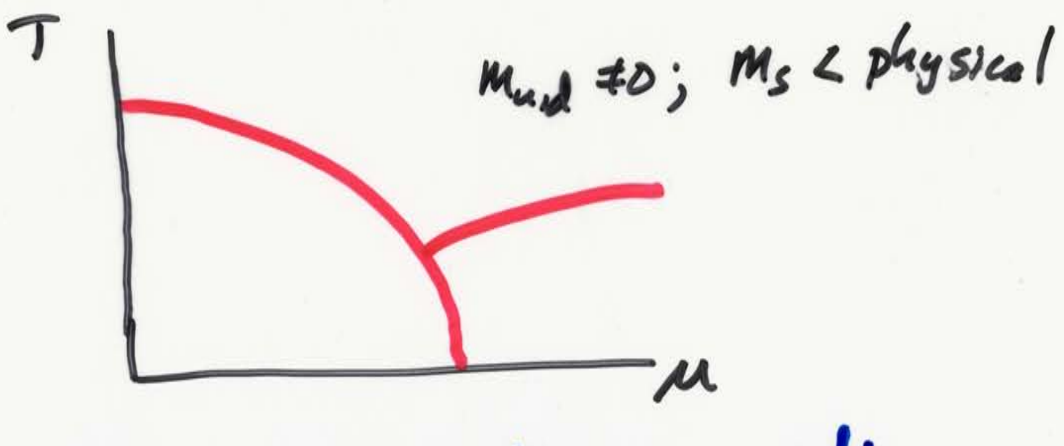
$N_f = 2$

$m_q \neq 0$

∴ smooth crossover

WHY EXPECT A CRITICAL POINT?

- Models; lattice QCD calculations at $\mu=0$ with varying quark masses; suggest:



- Need lattice calculations with $T\neq 0$, $\mu\neq 0$ to locate it
- Universality class known (Ising)

$T \neq 0$; $\mu \neq 0$; μ/T NOT LARGE

$\mu \neq 0 \rightarrow$ complex Euclidean action.
$\rightarrow$ sign problem that makes difficulty of standard Monte Carlo $\sim e^V$.

Nevertheless, we are learning about this regime from lattice calculations that rely on smallness of μ/T.

These methods may be used to locate the...

CRITICAL POINT

A 2nd order point in the phase diagram where a line of 1st order transitions end. (Location is sensitive to quark masses. Moves leftward as masses $\downarrow$.)

LOCATING THE CRITICAL POINT

Range of estimates: $\ulcorner$ NB: $\mu_B = 3\mu$ $\lrcorner$

$$\frac{\mu_B^{\text{Endpoint}}}{T_c(\mu=0)} \sim 1, \sim 2, \gtrsim 3$$

Gavai Gupta — Fodor Katz — Ejiri et al

Error estimates uncertain and clearly still large. Not at all like calculations of Tc. Yet.

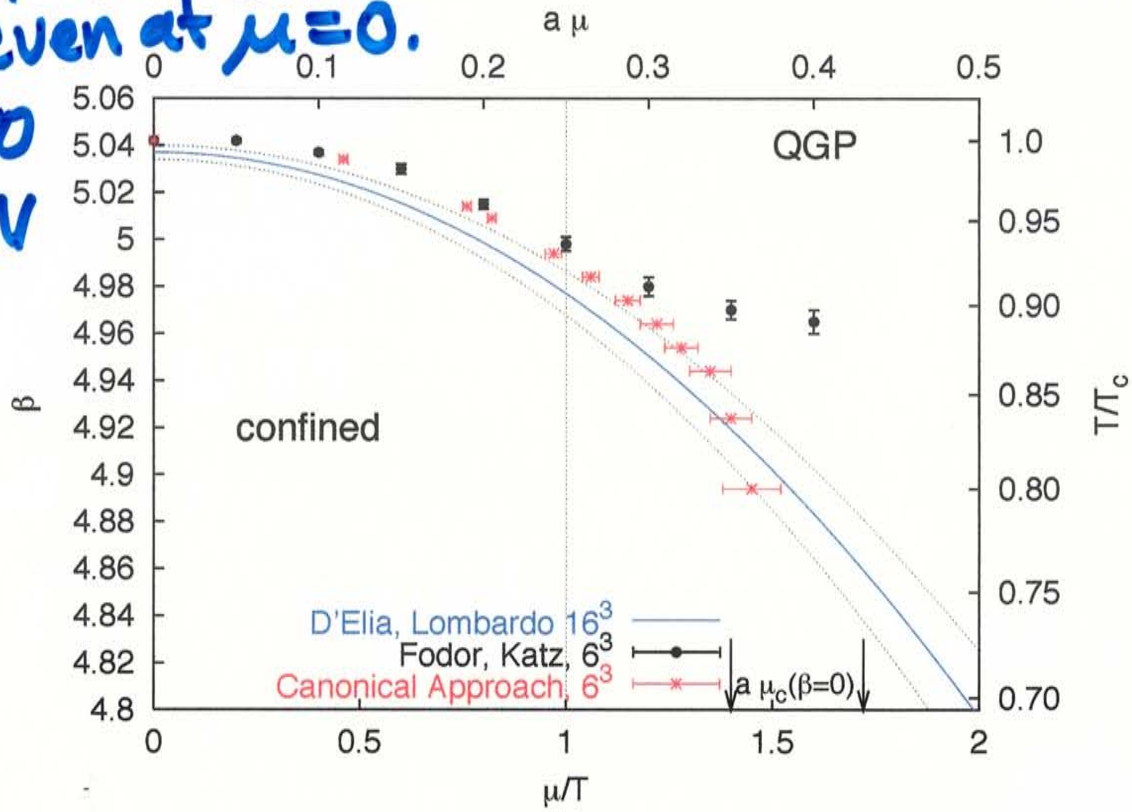
Race between lattice QCD and experiment to locate the critical point....

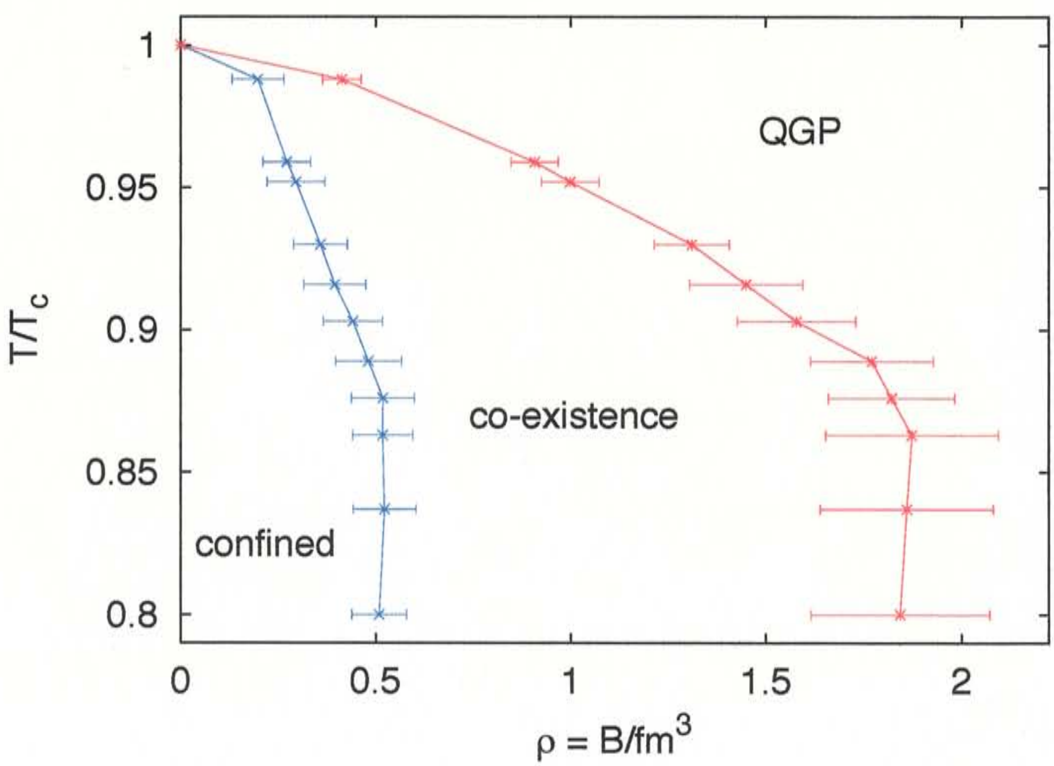
LATTICE CALCULATIONS AT FIXED n_B

$N_f = 4 \to$ 1st order even at $\mu = 0$.

$m_\pi = 350$ MeV

de Forcrand Kratochvila



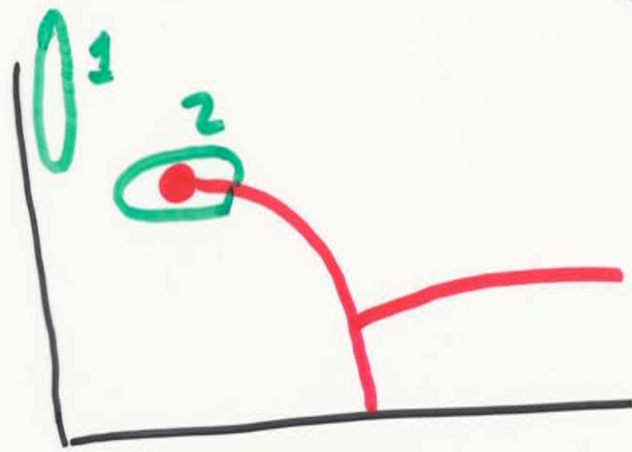


Calculation on 6^3 lattice, with $0 < B < 30$. $(V \sim (2\,fm)^3)$

- Will be very interesting to see what they find with $N_f = 2+1$.
- Determining the location of the critical point this way will have very different "systematic error" relative to calculations relying on $\mu/T < 1$. (ie reweighting Fodor Katz or Taylor expansion Ejiri et al, Gavai Gupta)
- In principle can be pushed to larger μ/T, but remains to be seen how large a V can be reached at a given μ or n_B.

GOALS FOR EXPERIMENTS

Given a phase diagram:



what do we want to learn from heavy ion collisions?

1. Characterize the properties of the quark-gluon plasma at $T > T_c$. RHIC is doing so.

2. Equally important, discover and hence locate the critical point. Mapping the phase diagram. Finding <u>the</u> landmark that would go in any future book on QCD. Can RHIC do this?

HOW CAN EXPERIMENTS LOCATE THE CRITICAL POINT?

① Need evidence that at large $\sqrt{s}$, ie small μ, collisions equilibrate well above the crossover. V_2@RHIC.

② Decrease $\sqrt{s}$, moving freezeout point to larger and larger μ_B.

③ Look for signatures:

a) Of the critical point itself. Those relying on the long wavelength gaussian fluctuations occurring only near ●. Rise and then fall as μ_B increases.

b) Onset of signatures of <u>non-equilibrium</u> "lumpy" final state expected after cooling through a first order transition.

Mishustin; Dumitru Paech Stöcker; Randrup; Koch Majumder Randrup; ...

SIGNATURES OF THE CRITICAL POINT

In those collisions that pass near the critical point as they cool, find long wavelength oscillations of a mode that is a linear combination of σ (means fluctuations couple to $\pi\pi$) and baryon number. The more effectively equilibrium is maintained, the longer the correlation length ξ gets, the bigger the signatures: Fujii Ohtani; Son Stephanov

- Gaussian event-by-event fluctuations of specific observables, calculable in magnitude in terms of ξ. Stephanov KR Shuryak
- Vary μ by varying $\sqrt{s}$, search for enhancement of these fluctuations in a window in $\sqrt{s}$, ie μ.
- Examples .... But first :

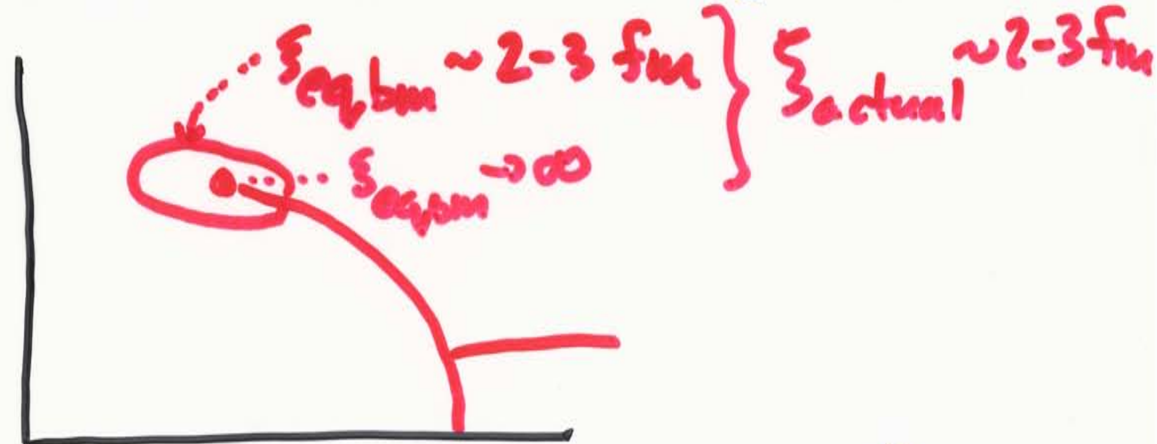
HOW LARGE CAN ξ GET?

HOW CLOSE TO ● NEED WE BE?

Obviously ξ limited by finite size of system. But, turns out that finite time is a more severe limitation.

Berdnikov KR; Asakawa Nonaka

- Finite time spent in critical region means that even if equilibrium value of ξ is much larger, actual ξ won't grow bigger than 2-3 fm.
- Means no need to hit ● precisely.



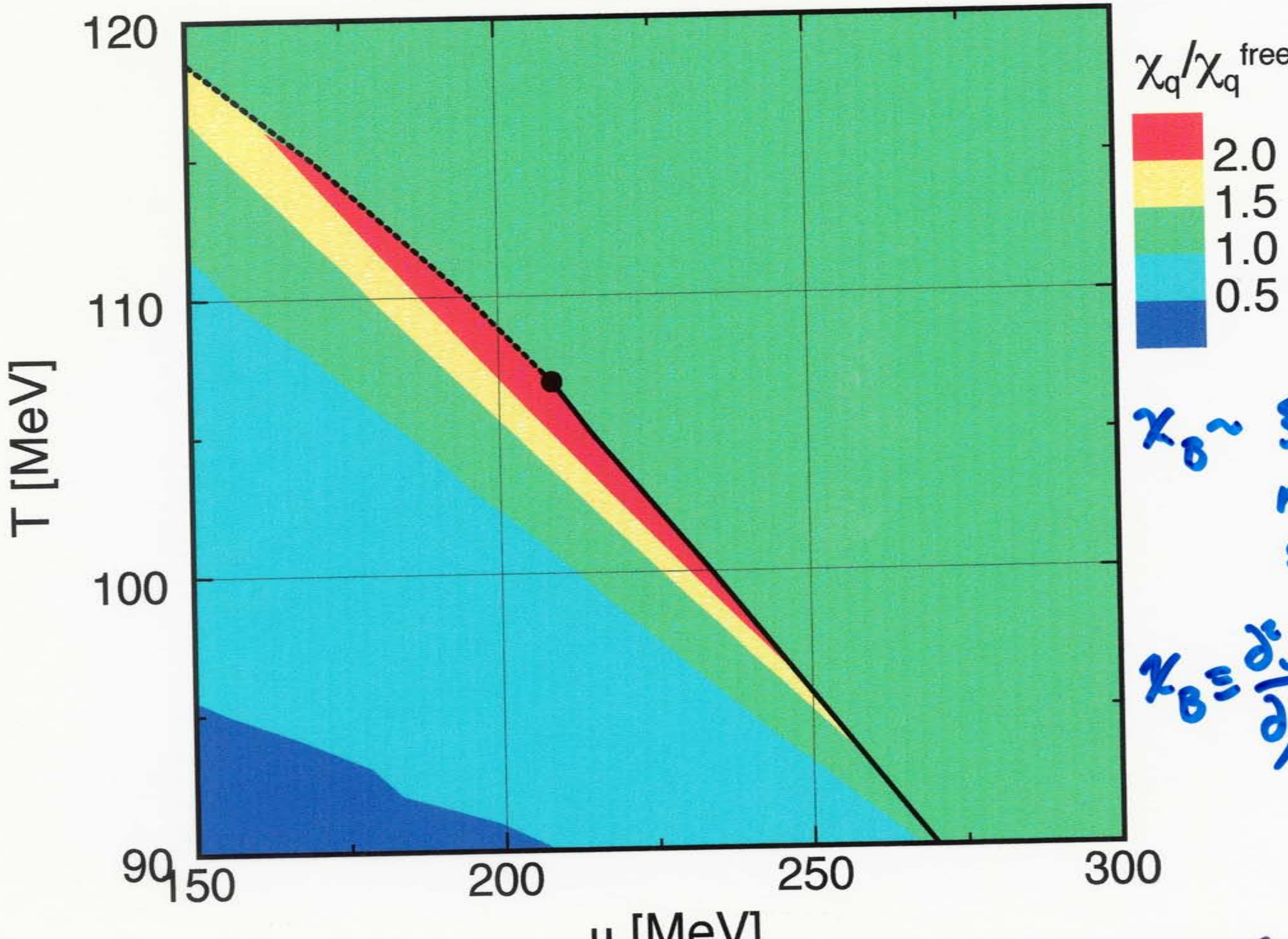
Signatures will be just as big if you pass anywhere in ⬭. No bigger, even if you hit ●.

- Hatta + Ikeda calculated "$\bigcirc$'s" in a model, but did so with contours of χ_B rather than ξ. → Figs.

  The robust point is that the extent of these $\bigcirc$'s in μ_B is not small. Width in μ_B is ~ 100 MeV, an estimate that is both crude and uncertain.
  Can this be obtained on lattice??
- NB also: since ξ cannot be > 2-3 fm, heavy ion collision experiments can *never* be used to measure the critical exponents of the 2nd order critical point. That's OK: we know it is Ising. What we don't know, and need experiments for, is *where* it is located.

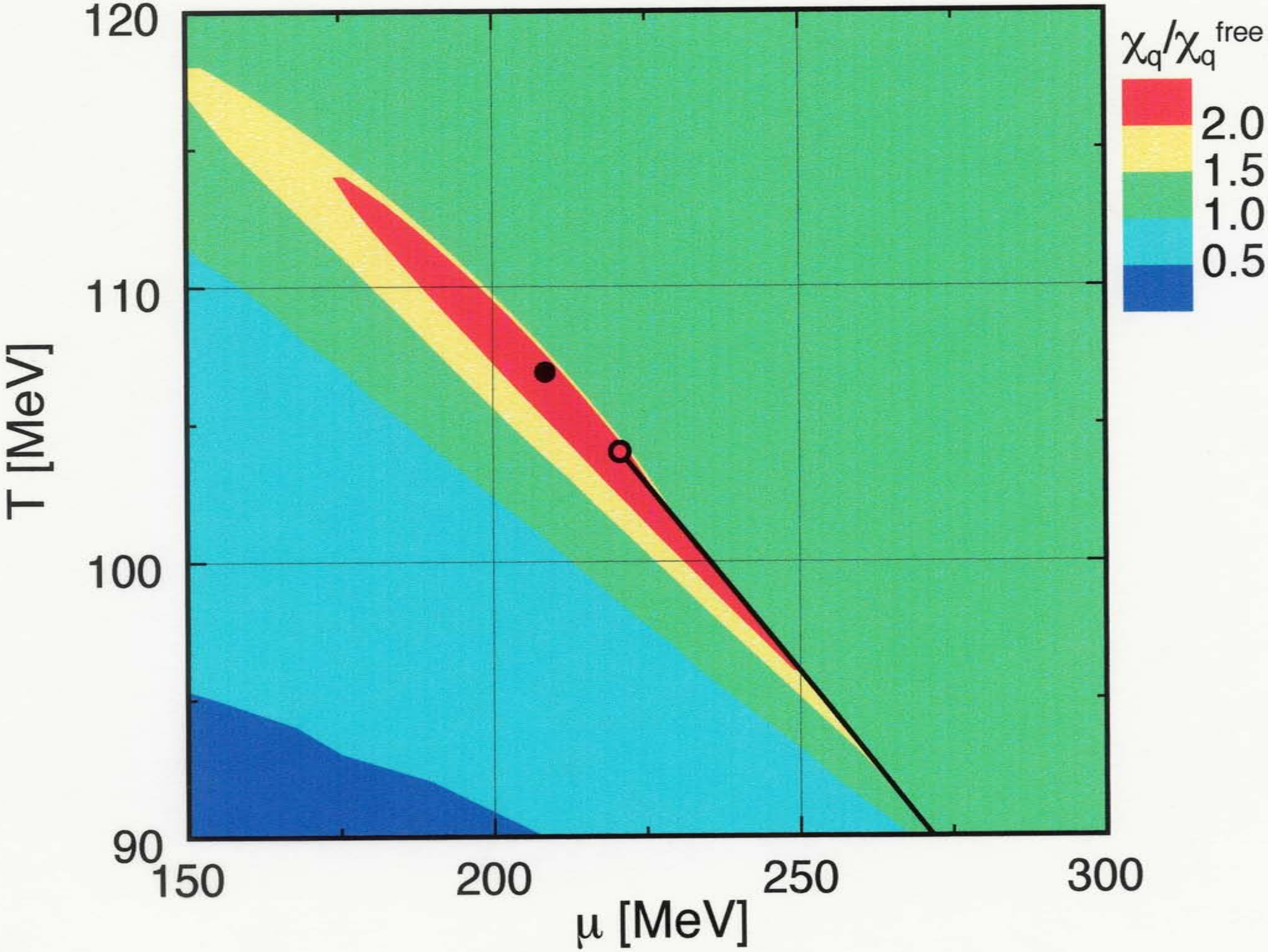
$m_u = m_d = 0$

MODEL ANALYSIS OF EXTENT OF CRITICAL REGION



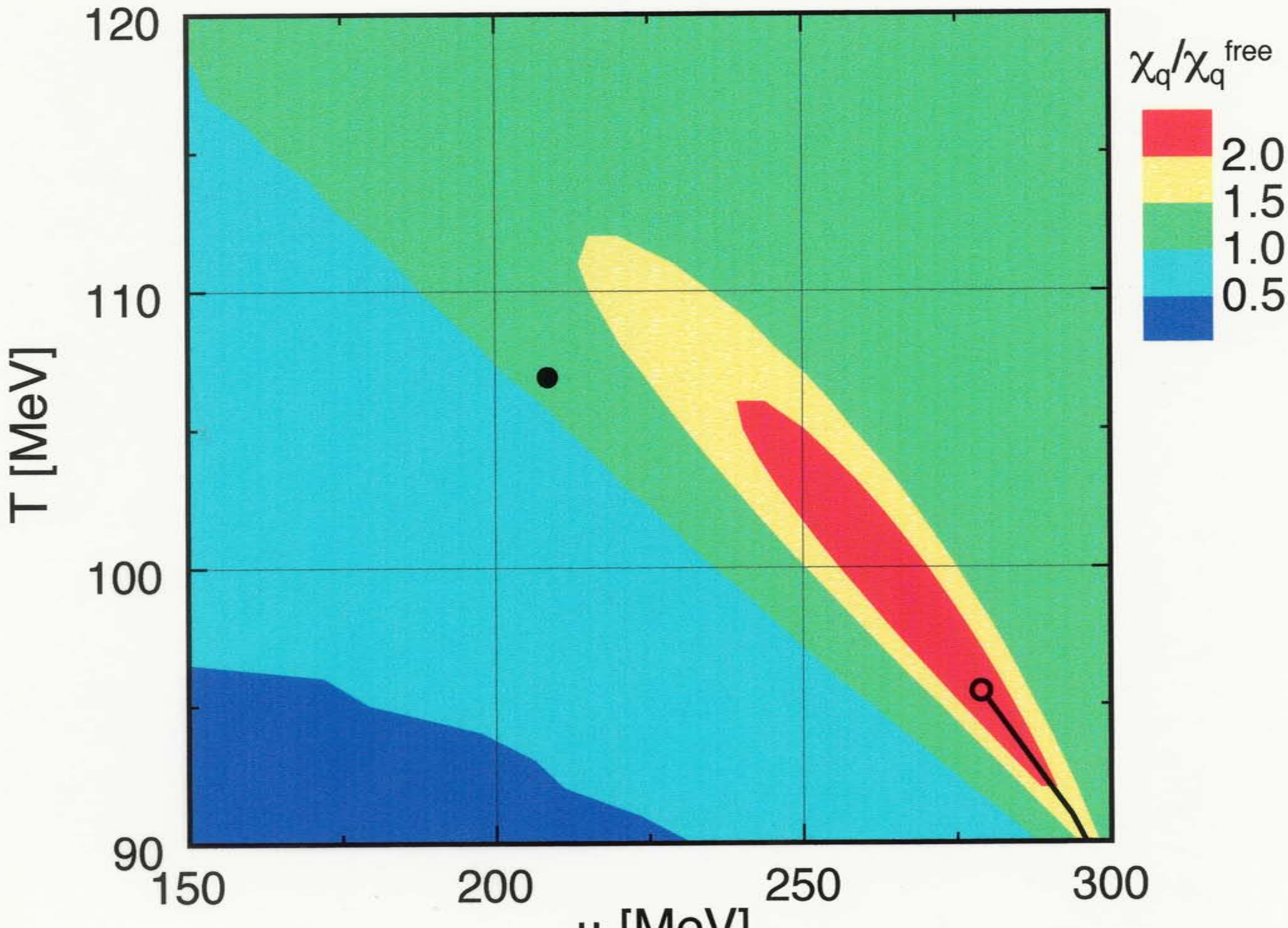
$\chi_B \sim \xi^2 +$ non-singular

$\chi_B \equiv \frac{\partial^2 \Omega}{\partial \mu_B^2}$



120
110
100
90
T [MeV]
150
200
250
300
μ [MeV]
χq/χq free
2.0
1.5
1.0
0.5

$m_u = m_d = 5\,MeV$



Hatta Ikeda

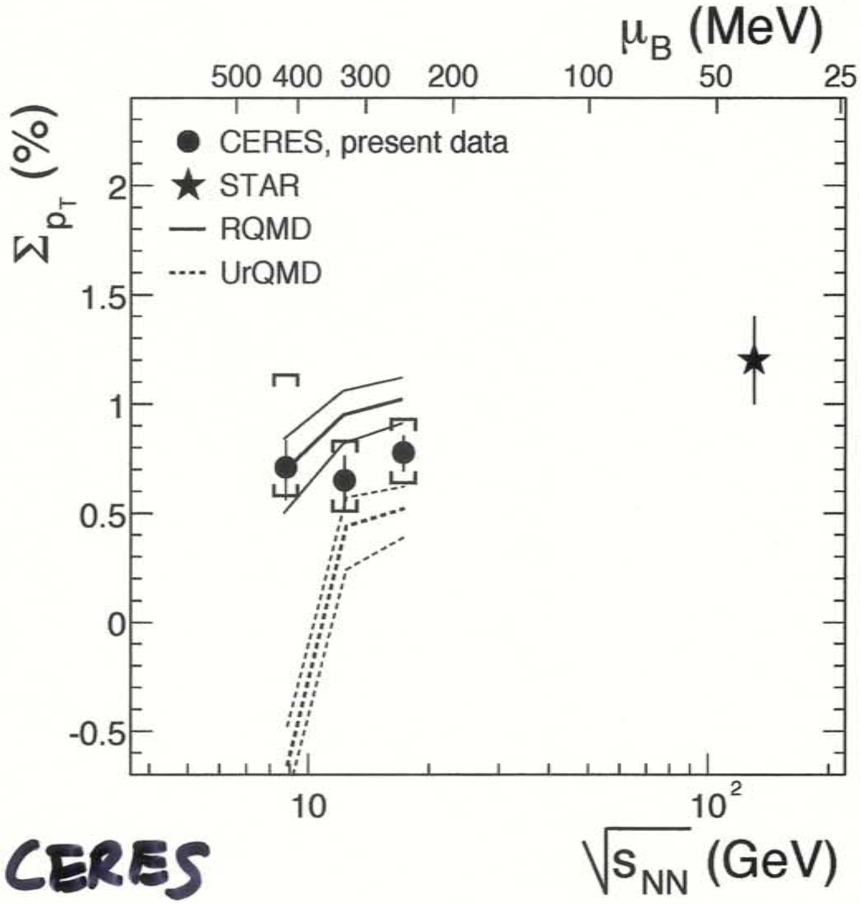
EXAMPLES

Event-by-event fluctuations of:

- Mean p_T of low p_T pions Stephanov KR Shuryak
  - fluctuations should be dominated by fluctuations of pions with $p_T \lesssim 500$ MeV
  - (NOT the case for fluctuations of $\langle p_T \rangle$ at $\sqrt{s} = 200$ GeV. PHENIX)
- Baryon number, and proton number.
  Hatta Ikeda; Hatta Stephanov
  - seen on lattice. Fig→ Ejiri et al
- Particle ratios involving π's and/or p's.
  eg fluctuation of $\langle K \rangle / \langle \pi \rangle$, $\langle p \rangle / \langle \pi \rangle$.
  - will better survive late time hadron gas than p_T-fluctuations. NA49

Also, light σ → increased p-p attraction; and, π-π repulsion. → reduction in flow of protons relative to pions. Shuryak

Data (example): p_T fluctuations (CERES)



CERES

Near the critical point (for CERES acceptance) one expects:

$$\sim 2\% \times \left(\frac{G}{300\text{ MeV}}\right)^2 \left(\frac{\xi_\sigma}{3\text{ fm}}\right)^2$$

$(\xi_\sigma = 1/m_\sigma)$

Signal one is looking for:
non-monotonic dependence on $\sqrt{s}$.

Also: low transverse momenta (thermal, soft)), $p_T < 3T \sim 500$ MeV – where critical point correlations are (cf. CERES data – $p_T < 1.5$ GeV).

Stephanov

$$\frac{\partial^2 \Omega}{\partial \mu_B^2} \rightarrow B\text{-fluctuations} \sim \xi^2 + \text{nonsingular}$$

$$\frac{\partial^2 \Omega}{\partial \mu_I^2} \rightarrow \text{no enhanced } (u-d) \text{ fluctuations} \sim \text{nonsingular}$$

Suggests $\frac{\mu_q}{T} \sim 1$ getting close to .

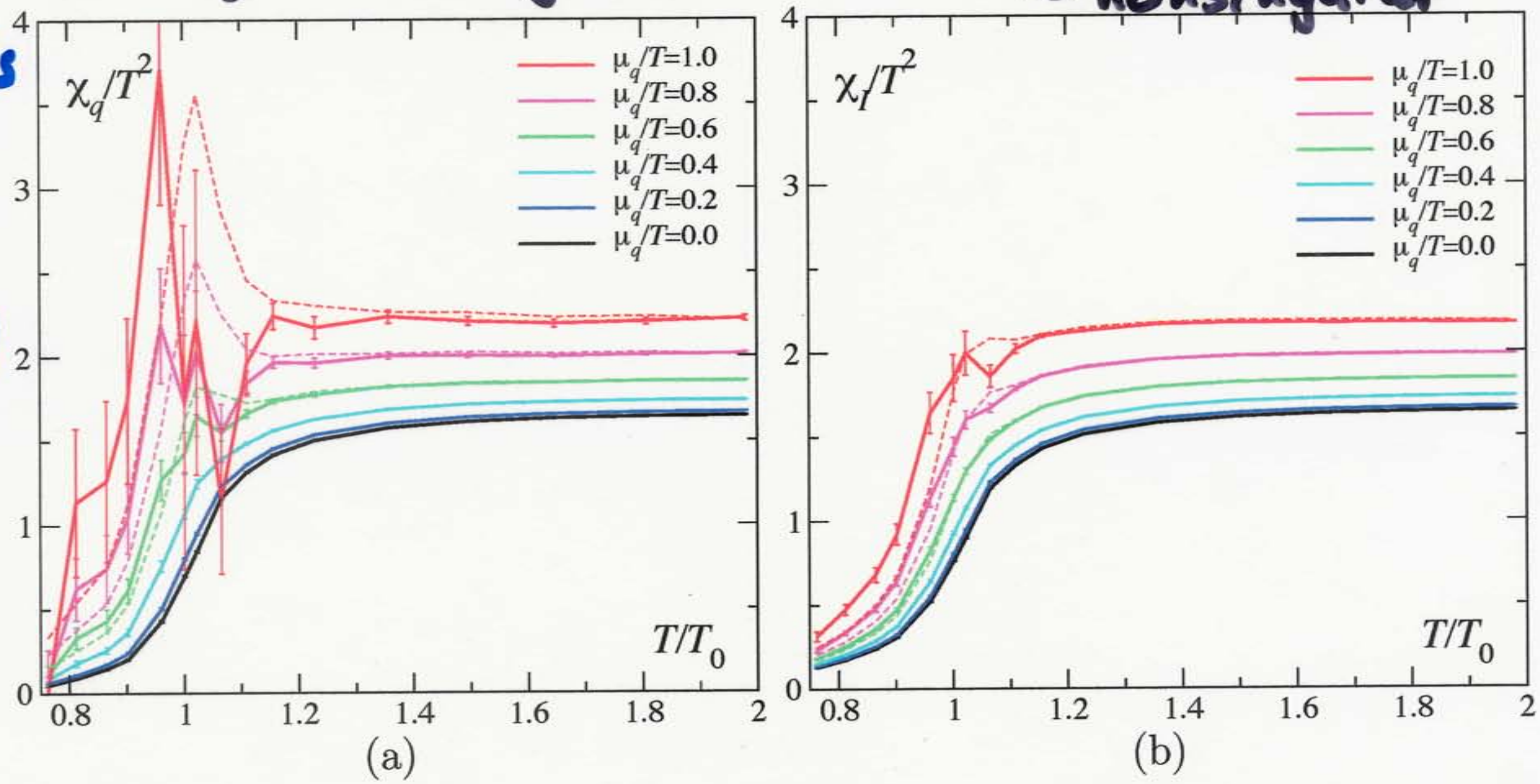


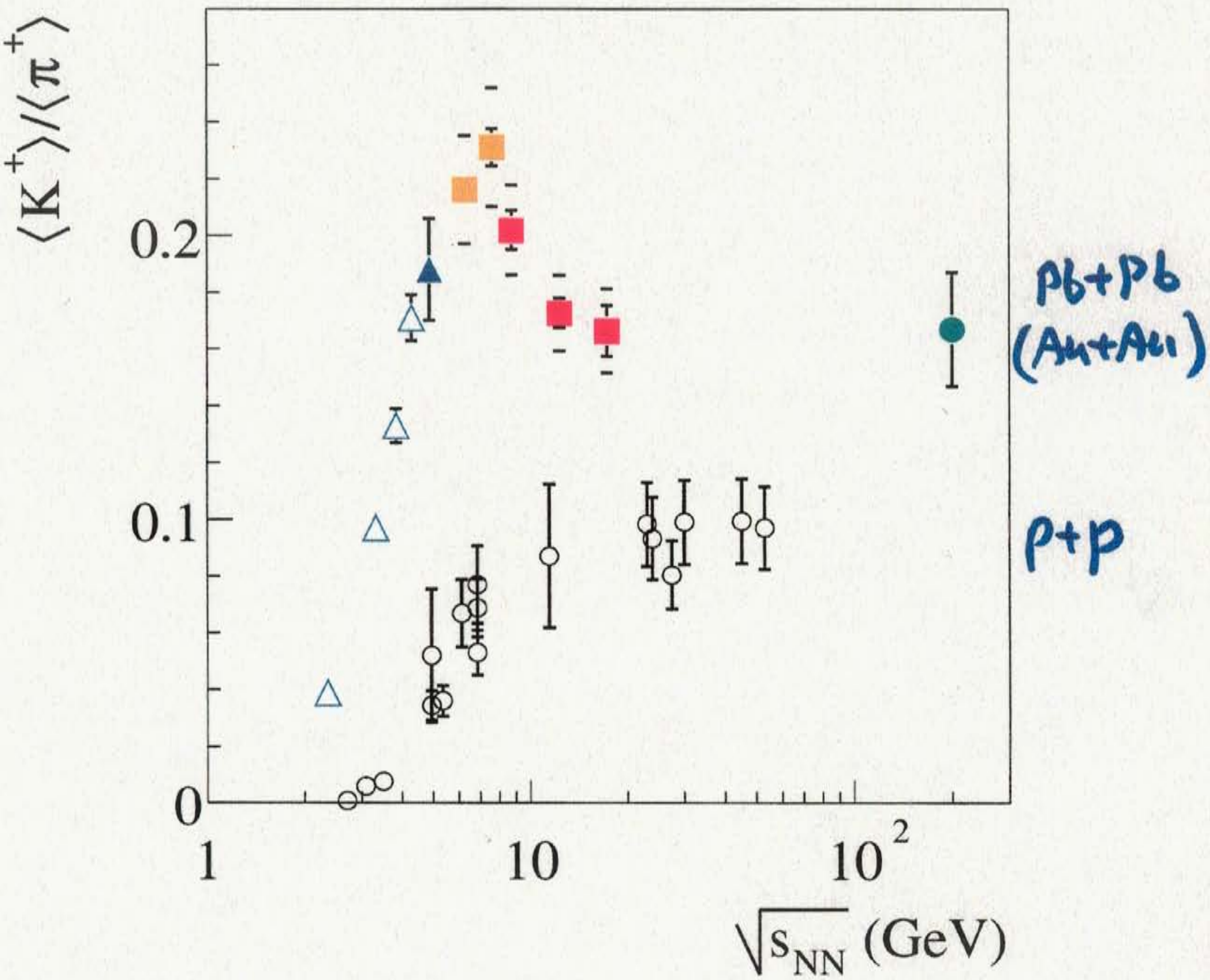
Figure 3.3: The quark number susceptibility χ_q/T^2 (left) and isovector susceptibility χ_I/T^2 (right) as functions of T/T_0 for various μ_q/T ranging from $\mu_q/T = 0$ (lowest curve) rising in steps of 0.2 to $\mu_q/T = 1$, calculated from a Taylor series in 6^{th} order. Also shown as dashed lines are results from a 4^{th} order expansion in μ_q/T.

(Because B fluctuates while isospin does not, proton fluctuations ~ B fluctuations)

Ejiri et al

Here is another quantity — not an e-by-e fluctuation — that varies nonmonotonically with $\sqrt{s}$...

Hadron Multiplicities ($\bar{s}$-QUARK CARRIER)

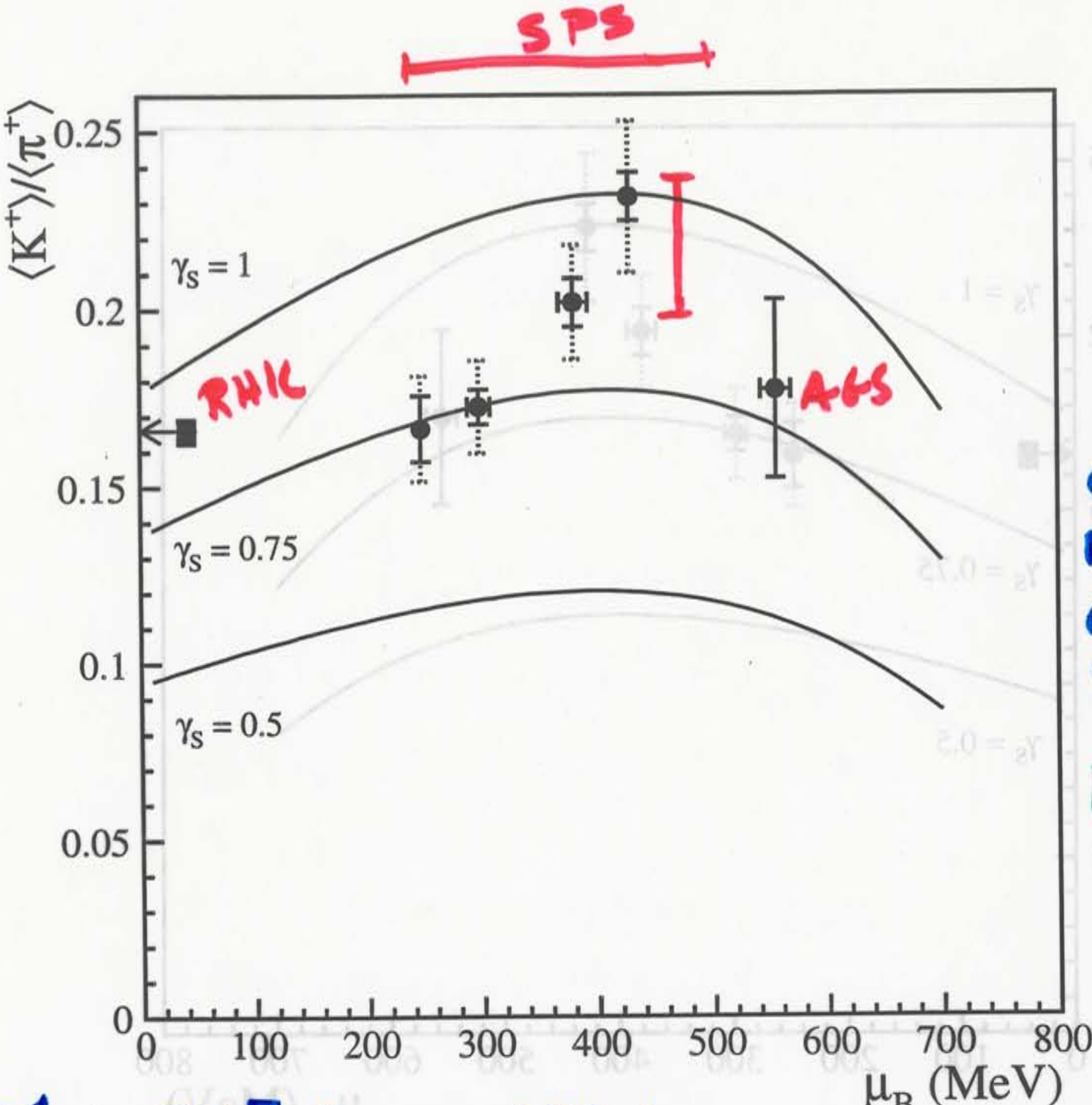


THE HORN

Talk by M. Gazdzicki, QM04, reporting NA49 results.

(Horn also seen in $\frac{K^- + \Lambda}{\pi^-}$.)

FIG. 13: Measured $\langle K^+\rangle/\langle\pi^+\rangle$ratio as a function of the fitted baryon-chemical potential. The full square dot is a preliminary full phase space measurement in Au-Au collisions at $\sqrt{s}_{NN} = 200$ GeV [37] and the error is only statistical; the arrow on the left signifies that its associated baryon chemical potential is lower than that estimated at $\sqrt{s}_{NN} = 130$ GeV [11] used here. For the SPS energy points the statistical errors are indicated with solid lines, while the contribution of the common systematic error is shown as a dotted line. Also shown the theoretical values for a hadron gas along the fitted chemical freeze-out curve shown in fig. 11, for different values of γ_S.



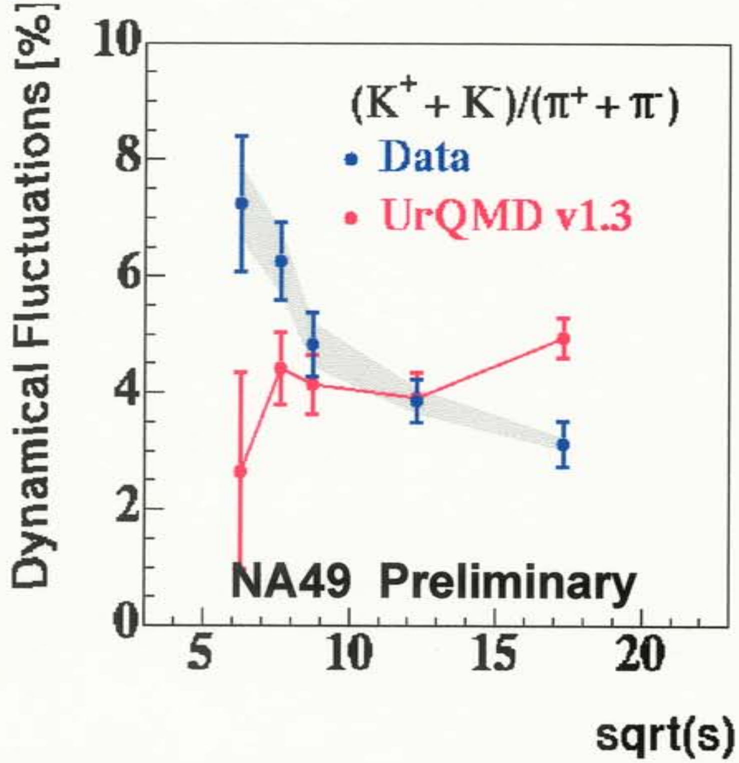
Curves are thermal ratios, calculated by Becattini et al.

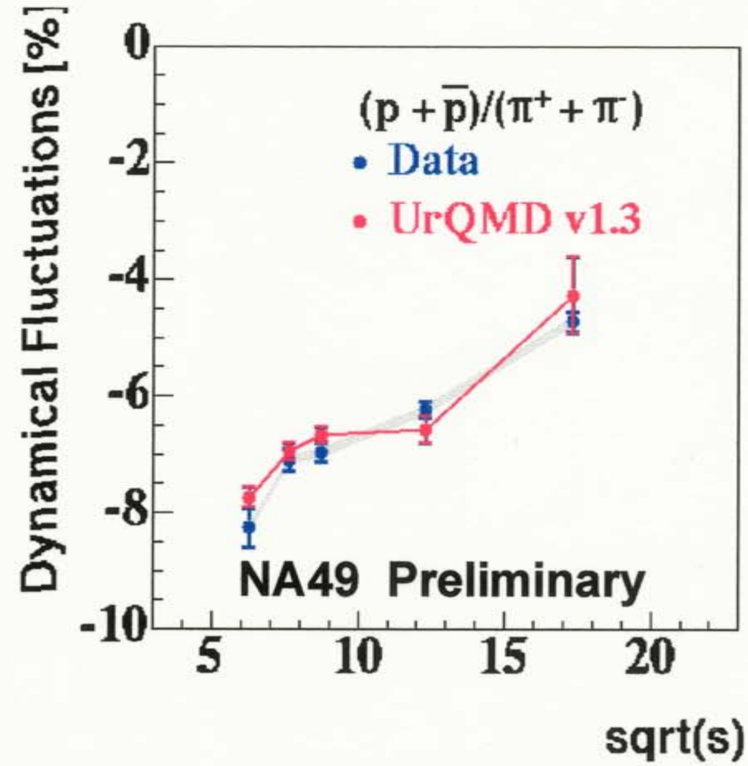
$\gamma_s = 1$: $s + \bar{s}$ in equilibrium

$\gamma_s = 0.75$: $s + \bar{s}$ is 75% of eqbm value

To explain "horn", need $\gamma_s = 1$ at horn and $\gamma_s \sim .7 - .8$ on either side of horn. This spoils other aspects of thermal model fit, however. (Becattini; Cleymans)

Summary





- K/π fluctuations increase towards lower beam energy
  - **Significant enhancement over hadronic cascade model**
- p/π fluctuations are negative
  - **indicates a strong contribution from resonance decays**

Intriguing...

- Large event-by-event fluctuations in K/π at $\mu_B \sim 400-450$ MeV
- Are there P_T fluctuations? Not known
- Are the K/π fluctuations dominated by low P_T π? Apparently not:
- Why no P/π fluctuations??
- Koch Majumder Randrup suggest the K/π fluctuations due to hadronization of "blobs" left by a first order transition.
- If so, expect greater K/π fluctuation, and other non-eqbm fluctuations vs. rapidity, at higher μ_B, lower $\sqrt{s}$.
- And, expect critical point at lower μ_B!
- cf: Fodor Katz $\rightarrow \mu_B^{\bullet} \sim 360$ MeV $\rightarrow \sqrt{s} \sim 8$ GeV

  Gavai Gupta $\rightarrow \mu_B^{\bullet} \sim 180$ MeV $\rightarrow \sqrt{s} \sim 25$ GeV

We have motivation-a-plenty. So....

CAN RHIC FIND THE CRITICAL POINT?

- Gunther Roland will describe the advantages of using a collider vs. fixed target for study of event-by-event fluctuations at varying $\sqrt{s}$.
- I will focus on "what needs to be done". Later speakers (experimental and accelerator physicists) will address what can be done. The goal for the workshop is to understand how best to maximize the intersection.

WHAT NEED BE MEASURED AT EACH ENERGY

- Enough ⟨particle ratios⟩ to first evaluate μ_B — ie you have to know where you are freezing out — and then see whether $\langle K \rangle / \langle \pi \rangle$ enhanced — ie as a bonus confirm (?) the "horn."
- Event-by-event fluctuations in:
  - $\langle p_T \rangle$, with equal or smaller error bars as in CERES data
  - in $\langle K \rangle / \langle \pi \rangle$ and $\langle p \rangle / \langle \pi \rangle$, with smaller error bars than in NA49 data
  - All fluctuation analyses done for $p_T < p_T^{cut}$ for several choices of p_T^{cut} down to $p_T^{cut} \sim 500$ MeV
- v_2 of π & p.

WHAT RANGE OF $\sqrt{s}$, ie μ_B?

- I suggest RHIC explore $\mu_B \lesssim 500$ MeV.
- Want to test NA49 observation of K/π fluctuations at $\mu_B \sim 400-450$.
- Why stop at $\mu_B \sim 500$?
  - If $\mu_B^{\bullet} < 3T_c \sim 500$ MeV, plausibly the different lattice calculations will converge as each improves in the next few years. If $\mu_B^{\bullet} > 500$ MeV, a quantitative comparison with theory is harder to envision.
  - If $\mu_B^{\bullet} > 500$ MeV, it will also be tough to find experimentally. (Low $T_{\text{freezeout}}$; equilibration ???)
- NB: if $\bullet$ is <u>found</u> with $\mu_B^{\bullet} < 500$ MeV, this will give strong motivation for study of non-eqbm signatures of first order transition at larger μ_B, eg at FAIR.

WHAT SPACING BETWEEN μ_B's ?

In the vicinity of a discovery, will want μ_B's separated by ~50 MeV.

- A scan with steps $\lesssim 100$ MeV should allow to make discoveries.
- Other than calculating μ_B, second most important quantity we would like to learn from lattice QCD is width in μ_B of region where $\xi > 2$ fm. Or, say, where $\dfrac{\chi_B}{\chi_B(T_c, \mu=0)} > 4$.

"STRAW MAN" CHOICE OF ENERGIES

hep-ph/0511094

[$\sqrt{s} \leftrightarrow \mu_B$ taken from Cleymans et al's compilation of data where available and empirical fit where there is none.]

$\sqrt{s}$ (AGeV)	μ_B (MeV)	
5	550	
6.27	470	largest fluctuations in $\langle K \rangle / \langle \pi \rangle$
7.62	410	peak of "horn"
8.77	380	
12.3	300	
18	220	
28	150	
60	75	done at RHIC
130	40	
200	30	

CAN WE DISCOVER THE QCD CRITICAL POINT AT RHIC?

Yes, IF:

- Accelerator & detector capabilities permit measurement of the event-by-event fluctuations of the hadronic observables I described, at a sequence of energies like that I described
- Nature is kind, and puts $\mu_B^{\bullet} < 500$ MeV

If YES:

- The landmark discovered. Our map of the QCD phase diagram then anchored by experiment.
- Assuming reasonable progress in lattice QCD, quantitative comparison between theory & experiment for $\mu_B^{\bullet}$
- FAIR (and RHIC) can study the first order phase transition.