QCD Critical Point and Its Effect on Physical Observables

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August 2008

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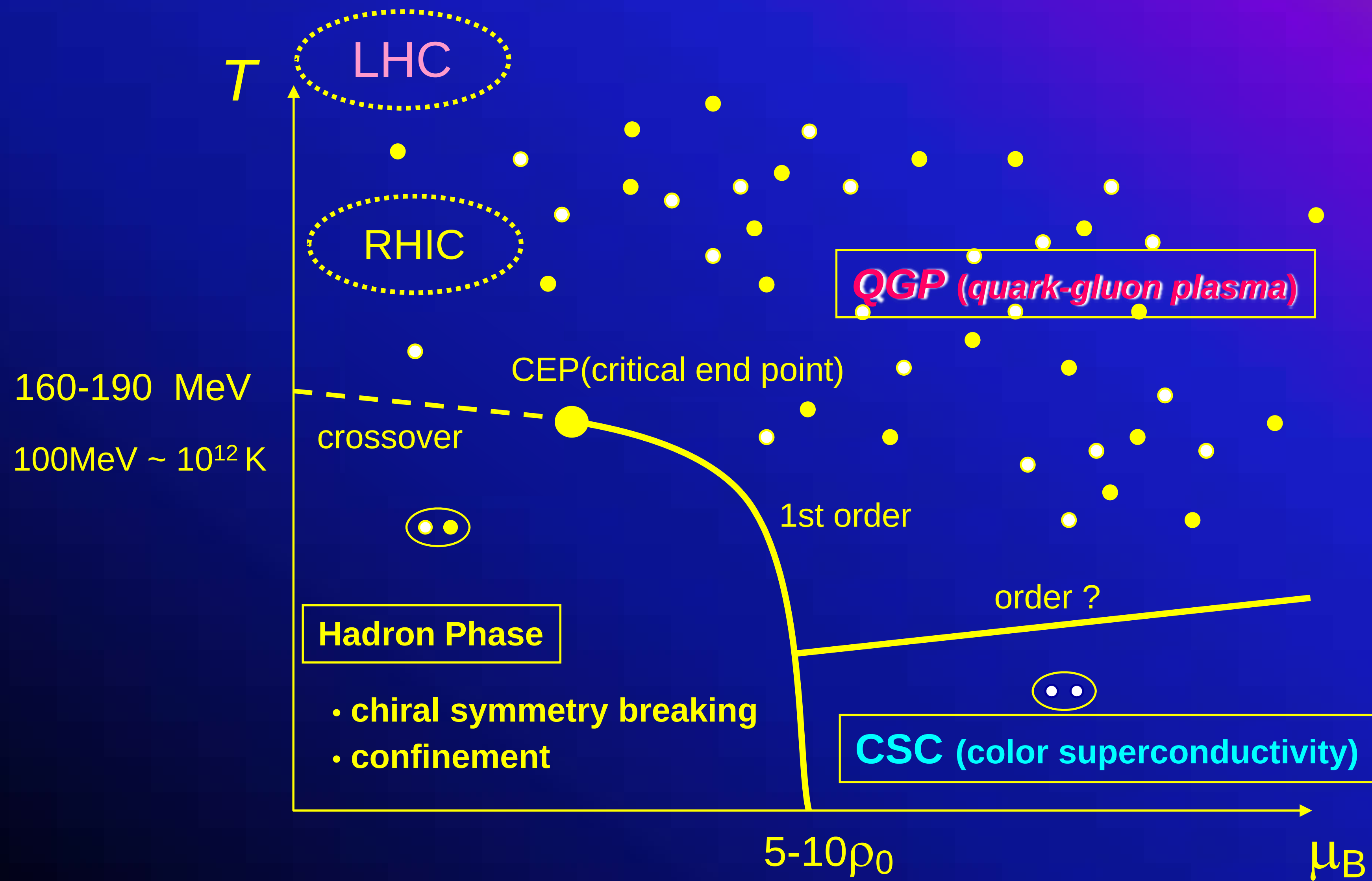
QCD Phase Diagram



M. Asakawa (Osaka University)

20th Anniversary of CEP in QCD

Nuclear Physics **A504** (1989) 668–684
North-Holland, Amsterdam

CHIRAL RESTORATION AT FINITE DENSITY AND TEMPERATURE

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Received 2 May 1988
(Revised 24 April 1989)

M. Asakawa, K. Yazaki / Chiral restoration

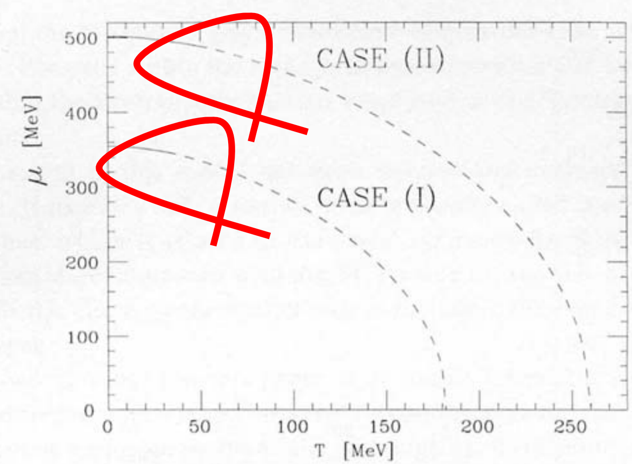
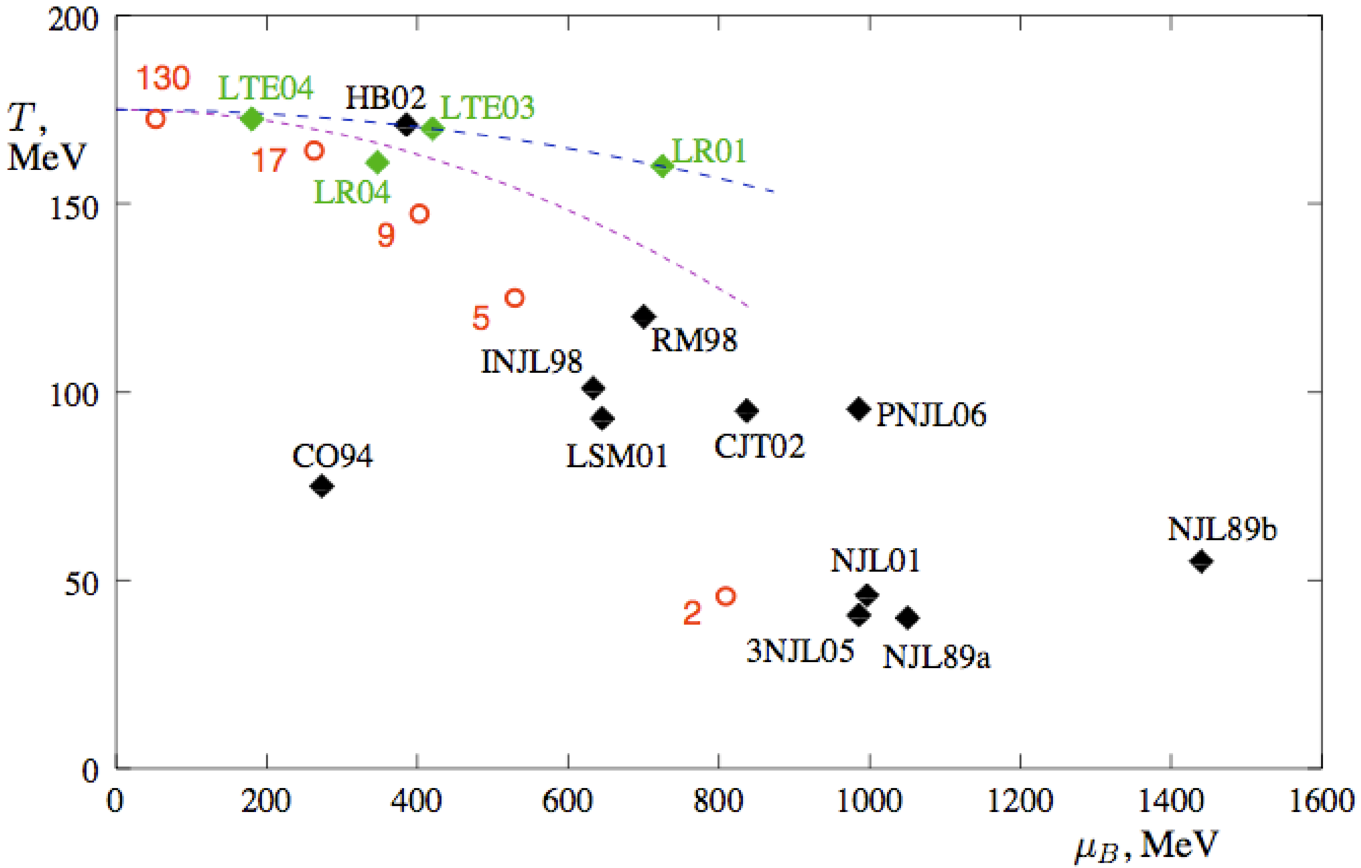


Fig. 8. The phase transition line in the cases (I) and (II).

Where is CEP, if any?



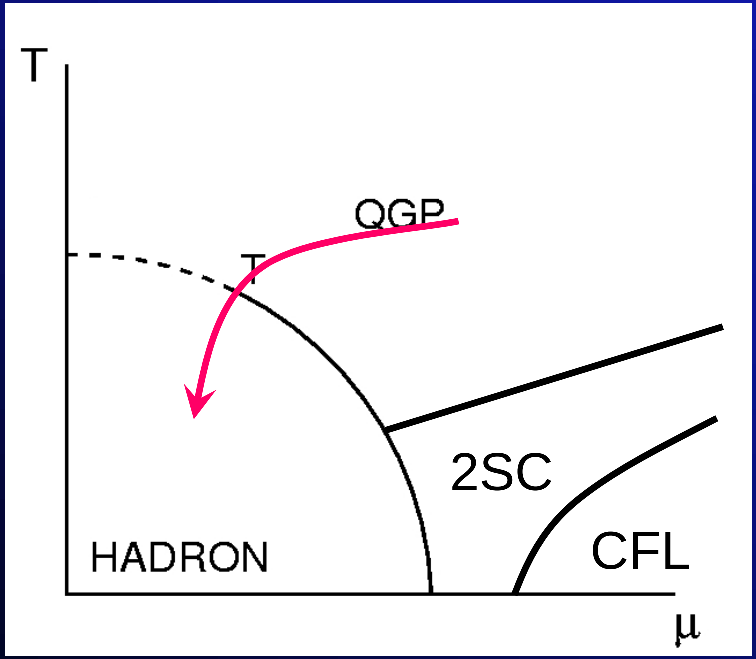
Stephanov,hep-lat/0701002

CEP = 2nd order phase transition, but...

CEP =
2nd Order Phase Transition Point

Divergence of Fluctuation
Correlation Length
Specific Heat ?

If expansion is adiabatic



even if the system goes right through the critical end point…

There is no conservation law that slows down the change of those quantities !

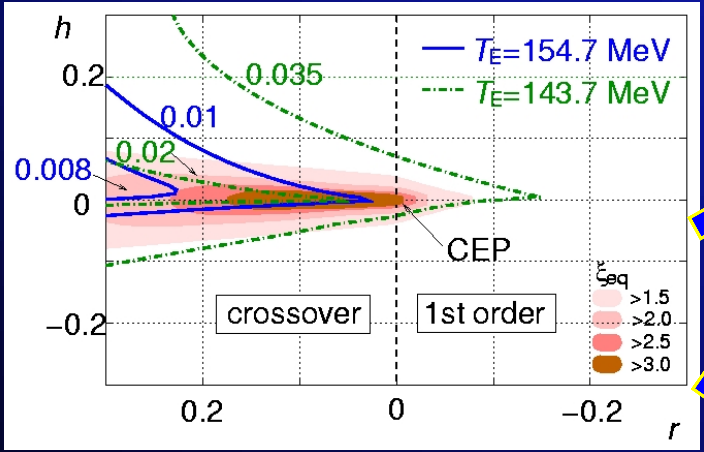
Subject to Final State Interactions

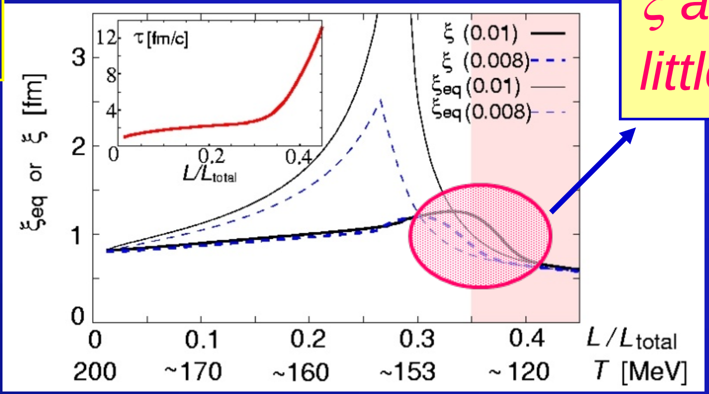
M. Asakawa (Osaka University)

Furthermore...

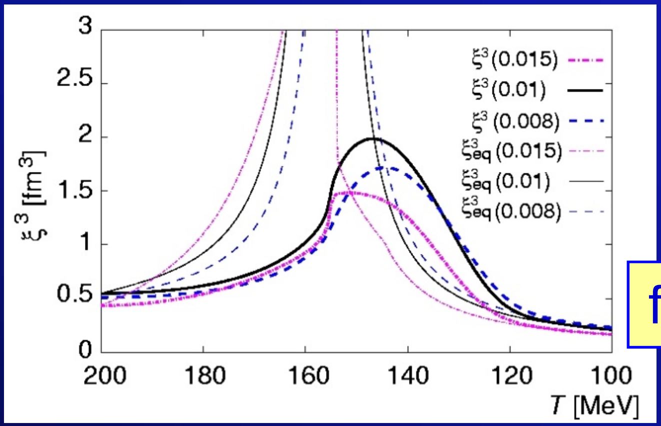
Furthermore,
critical slowing down limits the size of fluctuation, correlation length !

Time Evolution along given isentropic trajectories (n_B/s : fixed)





ξ and ξ_{eq} little difference



fluctuation ~ ξ^3

$$\frac{d}{d\tau} m_\sigma(\tau) = -\Gamma[m_\sigma(\tau)]\left(m_\sigma(\tau) - \frac{1}{\xi_{eq}(\tau)} \right)$$

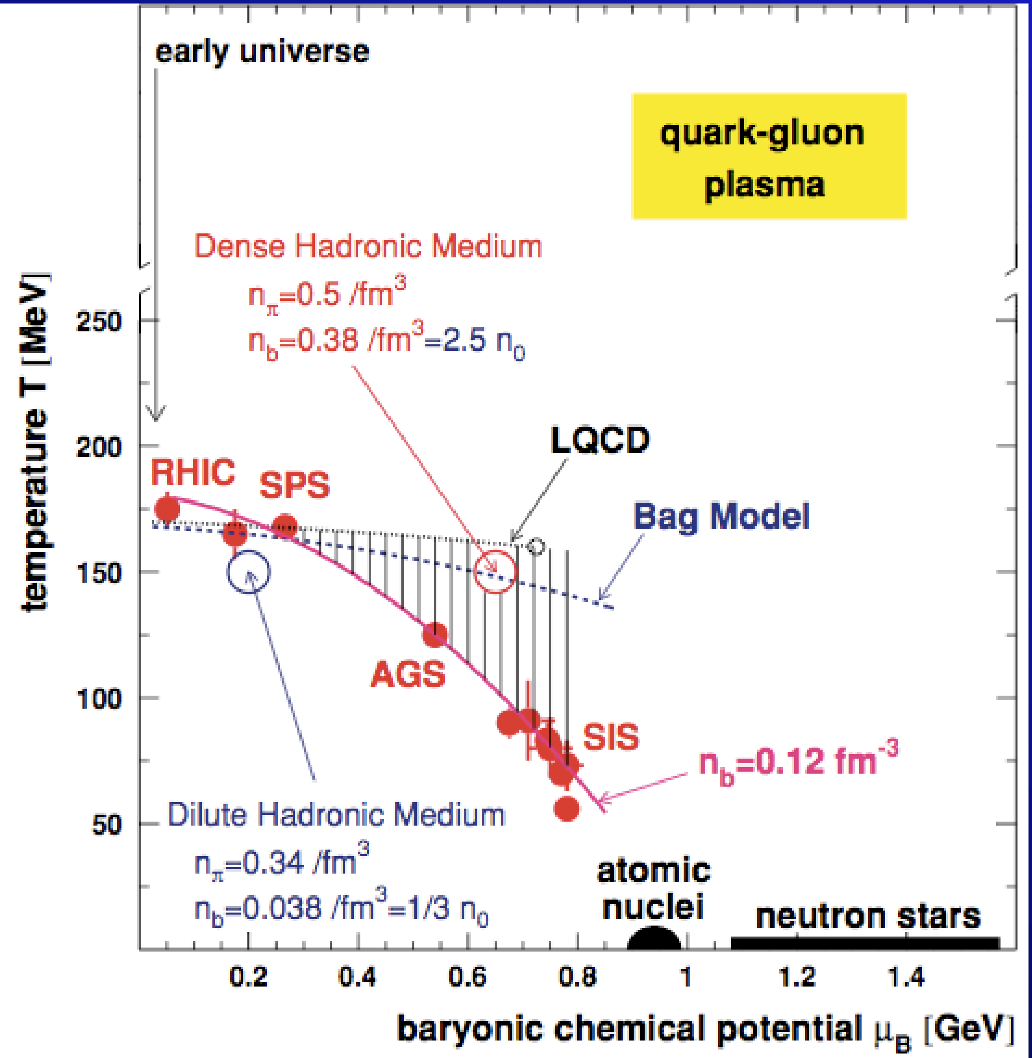
$$\Gamma[m_\sigma(\tau)] = \frac{A}{\xi_0}\left(m_\sigma(\tau)\xi_0\right)^z, \; m_\sigma(\tau) = \frac{1}{\xi(\tau)}$$

$z \approx 3$ Model H (Hohenberg and Halperin RMP49(77)435)

Principles to Look for Other Observables

- We are in need of observables that are not subject to final state interactions

After Freezeout, no effect of final state interactions



Chemical Freezeout

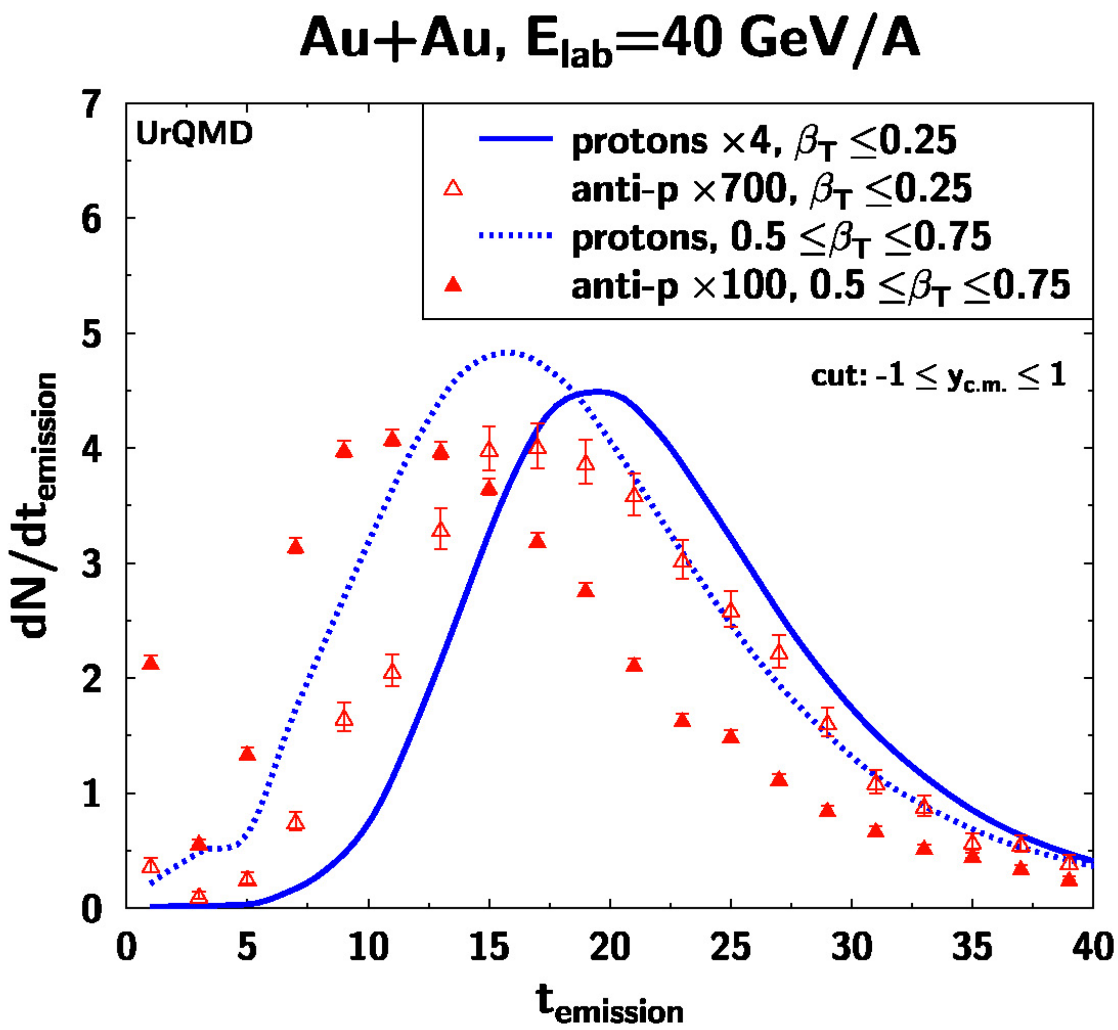
- usually assumed momentum independent
- but this is not right

chemical freezeout time: p_T (or y_T) dependent

✓ Larger p_T (or y_T), earlier ch. freezeout

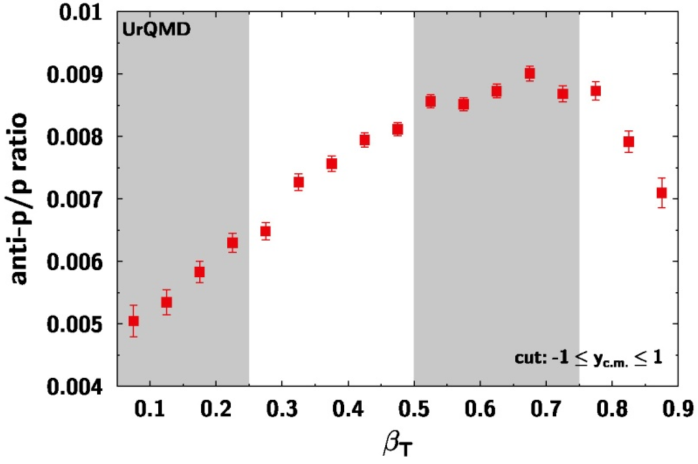
Principle I

Emission Time Distribution



Emission Time

- Larger β_T, earlier emission
- No CEP effect (UrQMD)



Principle II

Universality:

QCD CEP belongs to the same universality class as 3d Ising Model

Lattice QCD at finite density: still in its infancy
For critical behavior: need to carry out V $\longrightarrow \infty$ limit

same universality class

QCD Critical End Point ⟺ *3d Ising Model End Point*

T and μ_B

$$(T,\mu_B) \longleftrightarrow (r,h)$$

$$r = \frac{T - T_C}{T_C}$$

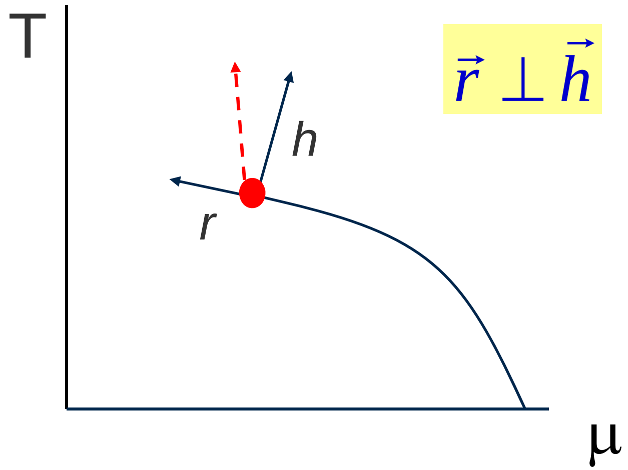
h : external magnetic field

What is not universal

- Further Assumptions
  - Size of Critical Region
    - No general universality
    - Lattice calculation: not yet $V \to \infty$ limit
    - Renormalization group analysis in Effective Models ?

  ⇨ need to be treated as an input, at the moment

  - Mapping



$\vec{r} \perp \vec{h}$

$\vec{r}$ || 1st order PT line is *not* an assumption

EOS on Ising Side

■ Critical Behavior on Ising Side

- parametric representation

$$M = M_0 R^{\beta}\theta$$

$$r = R(1-\theta^2)$$

$$h = h_0 R^{\beta\delta} h(\theta) = h_0 R^{\beta\delta}(\theta - 0.76201\theta^3 + 0.00804\theta^5)$$

$$(R \geq 0, -1.154 \leq \theta \leq 1.154)$$

$$r = \frac{T - T_C}{T_C}$$

h : external magnetic field

$\beta = 0.326$

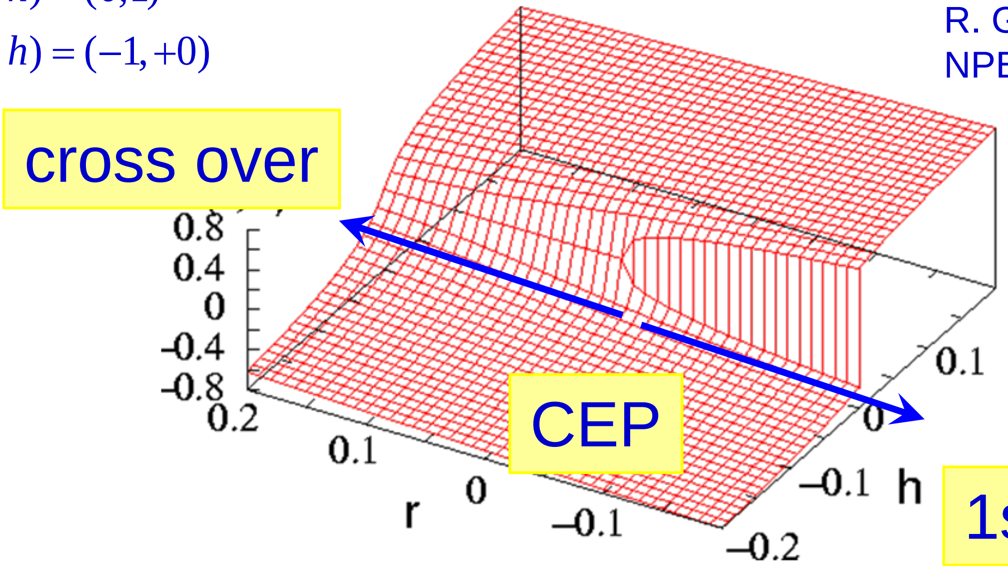
$\delta = 4.8$ (Critical Exponents)

Condition for M_0 and h_0

$M(r,h) = 1$ at $(r,h) = (0,1)$

$M(r,h) = 1$ at $(r,h) = (-1,+0)$

R. Guida and J. Zinn-Justin, NPB486 (1997) 626



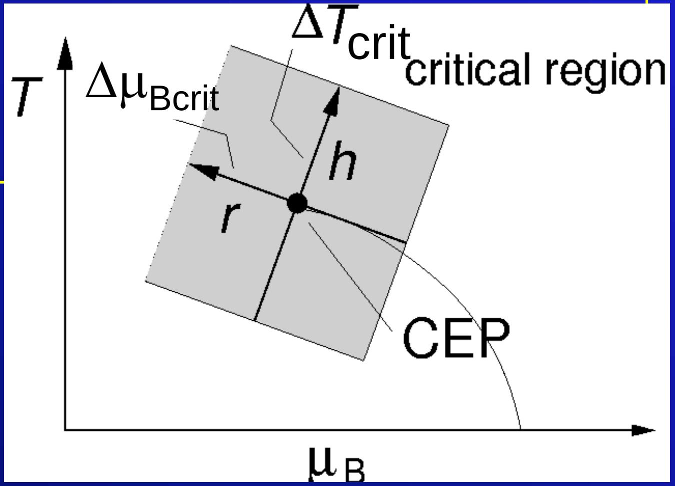
Singular Part + Non-singular Part

- Matching between Hadronic and QGP EOS
  - Entropy Density consists of *Singular* and *Non-Singular* Parts
    - **Only Singular Part** shows universal behavior
- Requirement:
  reproduce both the singular behavior and known asymptotic limits
- Matched Entropy Density

$$s_{\text{real}} = (T, \mu_B) = \frac{1}{2}\left\{1 - \tanh\left[S_c(T, \mu_B)\right]\right\} s_H(T, \mu_B) + \frac{1}{2}\left\{1 + \tanh\left[S_c(T, \mu_B)\right]\right\} s_Q(T, \mu_B)$$

$s_H(T, \mu_B)$: Hadron Phase (excluded volume model)

$s_Q(T, \mu_B)$: QGP phase



- Dimensionless Quantity: S_c

$$S_c(T, \mu_B) = s_c(T, \mu_B)\sqrt{\left(\Delta T_{\text{crit}}\right)^2 + \left(\Delta \mu_{\text{crit}}\right)^2} \times D$$

D: related to extent of critical region

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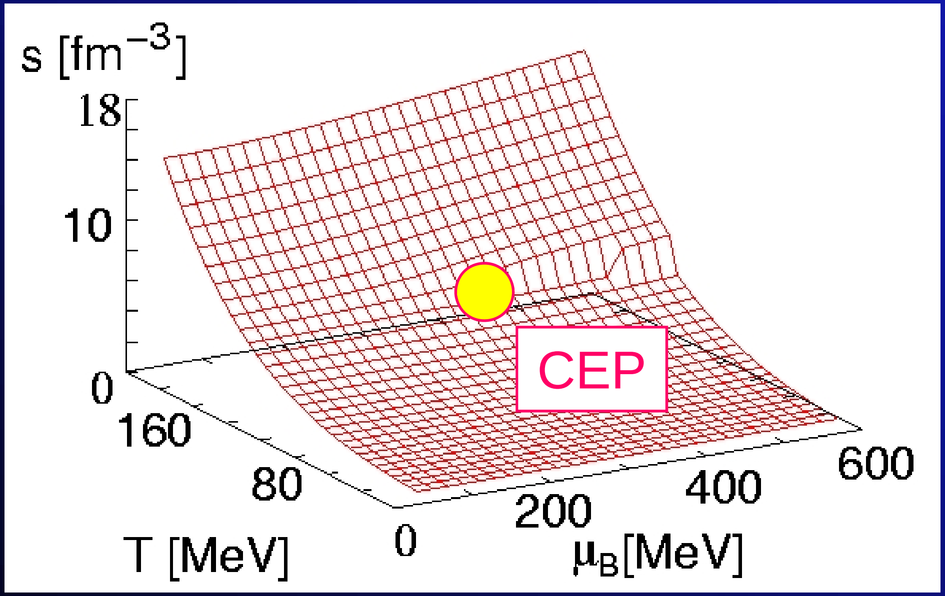
Isentropic Trajectories

- In each volume element, Entropy (S) and Baryon Number (N_B) are conserved, as long as entropy production can be ignored (= when viscosities are small)

Isentropic Trajectories (n_B/s = const.)

An Example



Near CEP s and n_B change rapidly

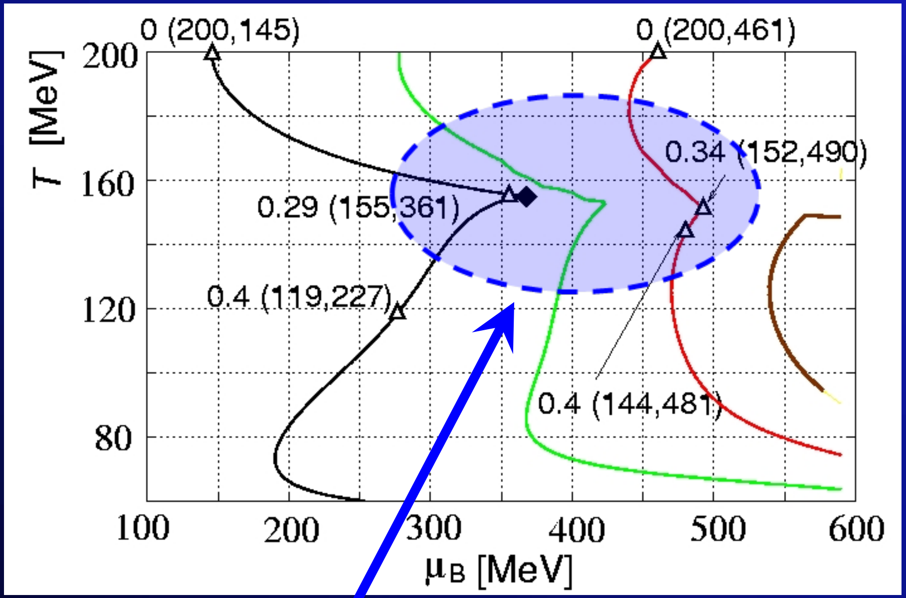
⇒ *isentropic trajectories show non-trivial behavior*

⇕

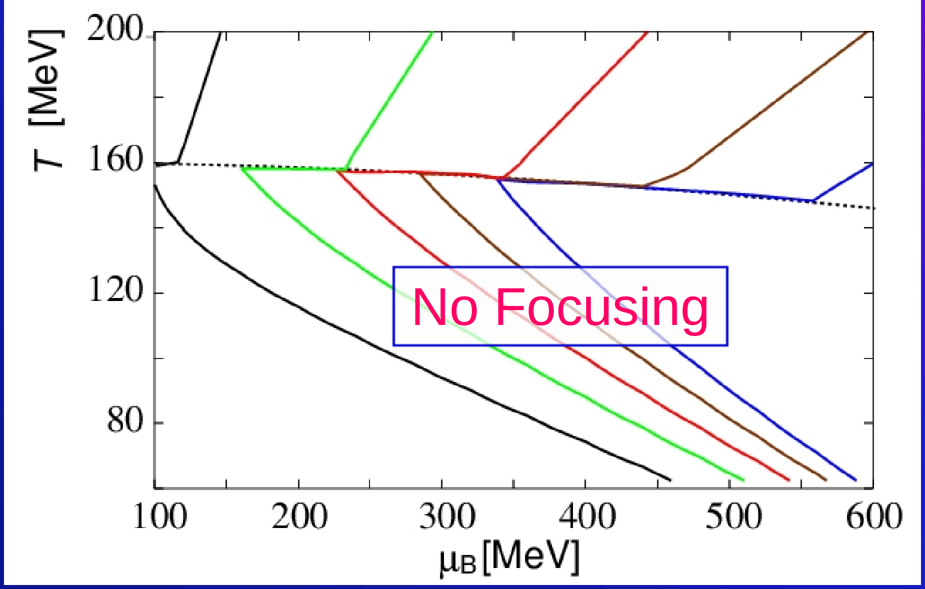
Bag Model EOS case

With Large Critical Region

with CEP



without CEP (EOS in usual hydro calculation)

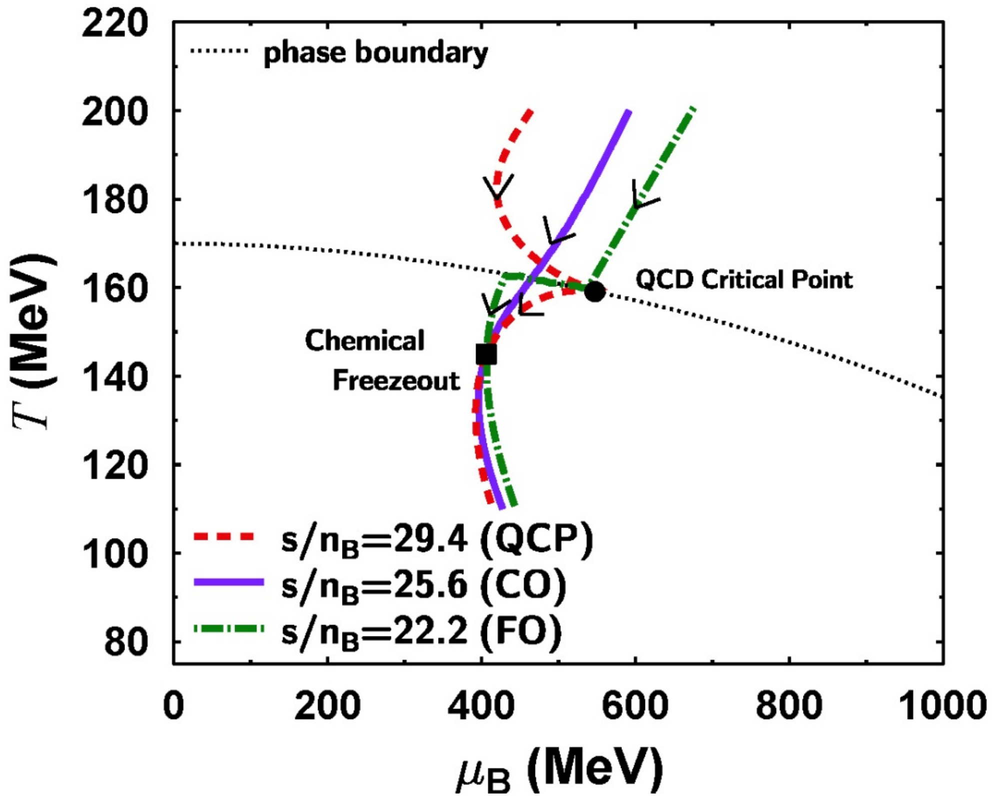


Focusing of Isentropic Trajectories

Excluded Volume Approximation
+ Bag Model EOS

used in most hydro calculations

Consequence



For a given chemical freezeout point, prepare three isentropic trajectories: w/ and w/o CEP

Along isentropic trajectory:

- FO, CO $\frac{\mu_B}{T}$ ↗
- QCP $\frac{\mu_B}{T}$ →

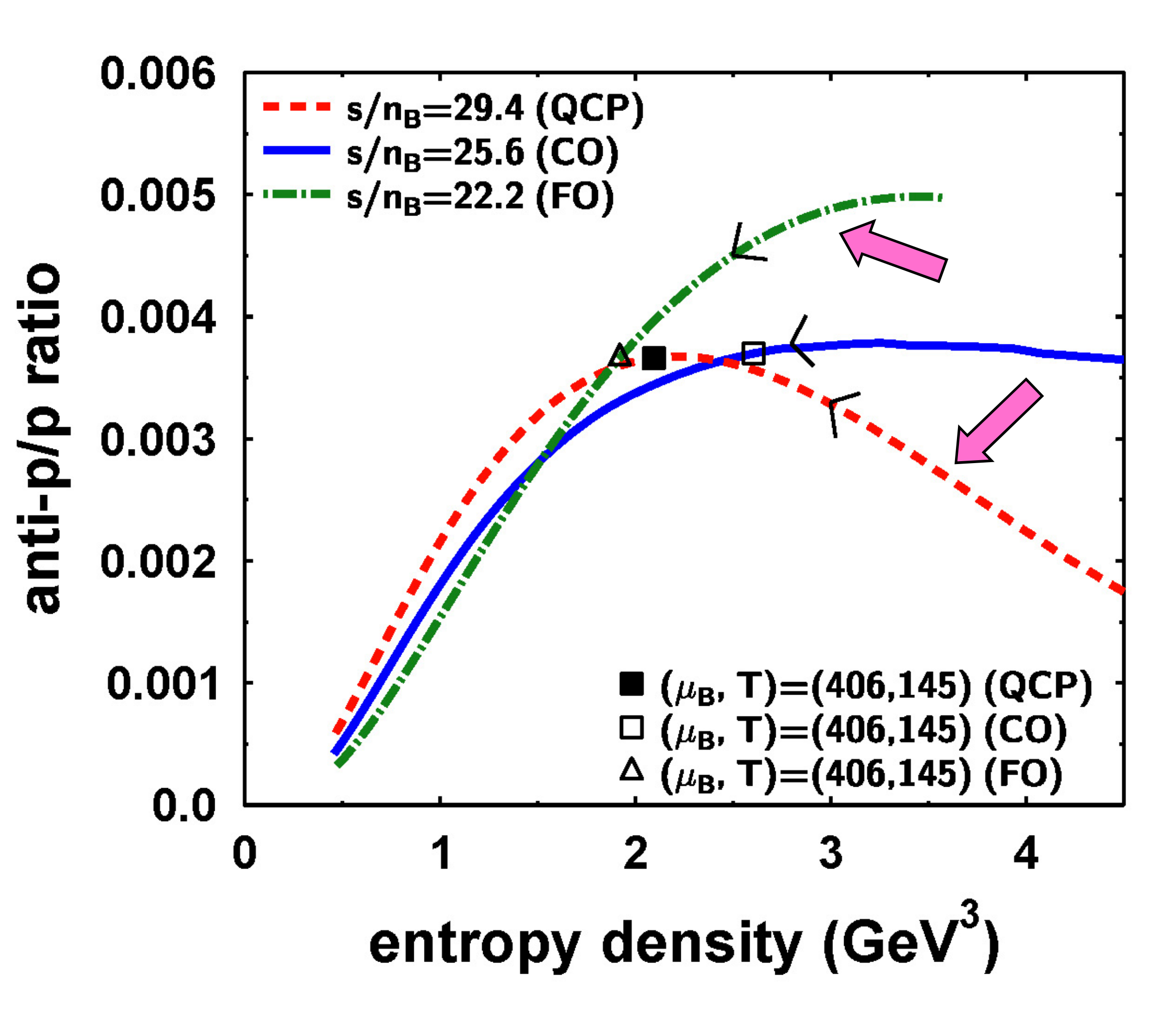
Principle I

As a function of $p_T(y_T)$:

- FO, CO $\frac{\mu_B}{T}$ ↘
- QCP $\frac{\mu_B}{T}$ ↗

➡ $\bar{p}/p$ ratio : near CEP steeper

Evolution along Isentropic Trajectory

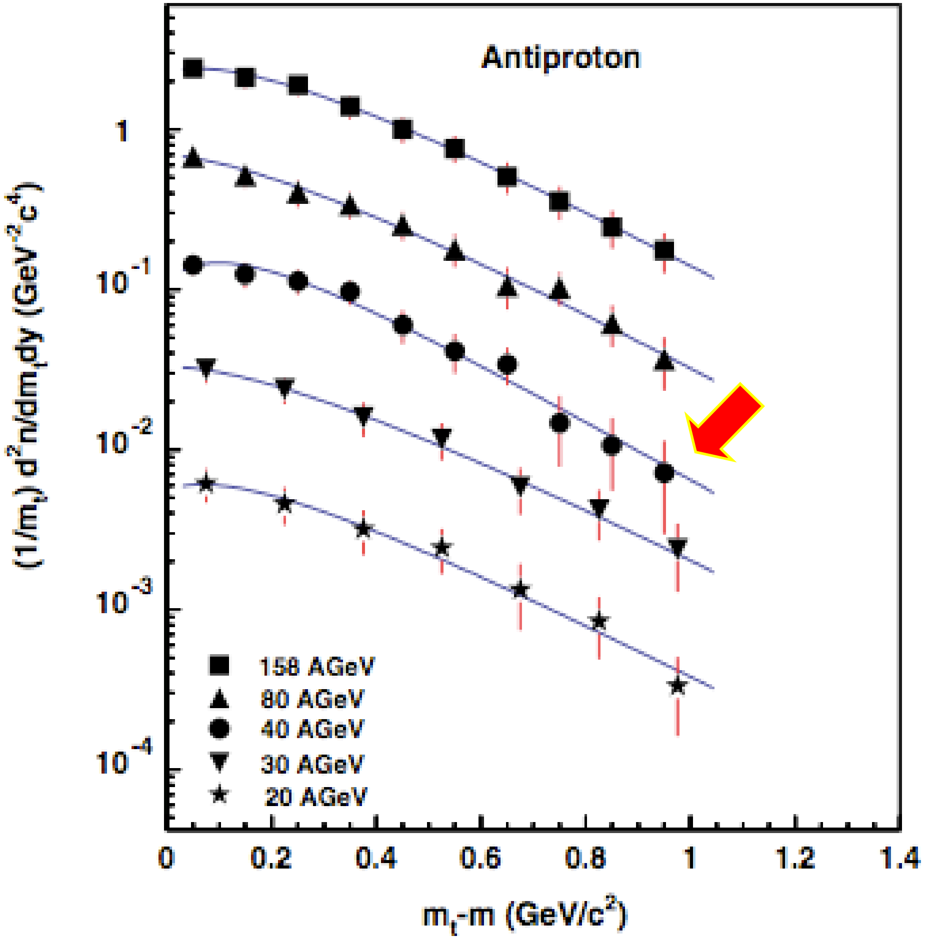


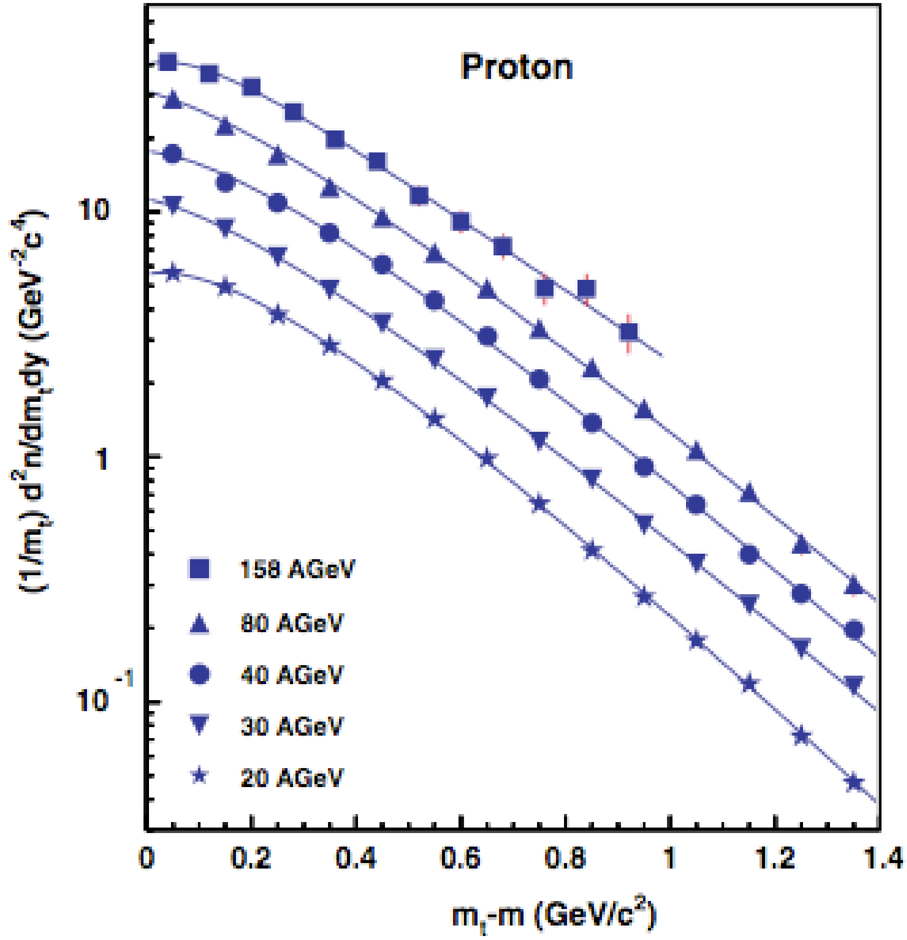
$$\bar{p}/p \sim \exp\left(-\frac{2\mu_B}{T}\right)$$

with CEP

steeper $\bar{p}$ spectra at high P_T

Effect on Spectra ?

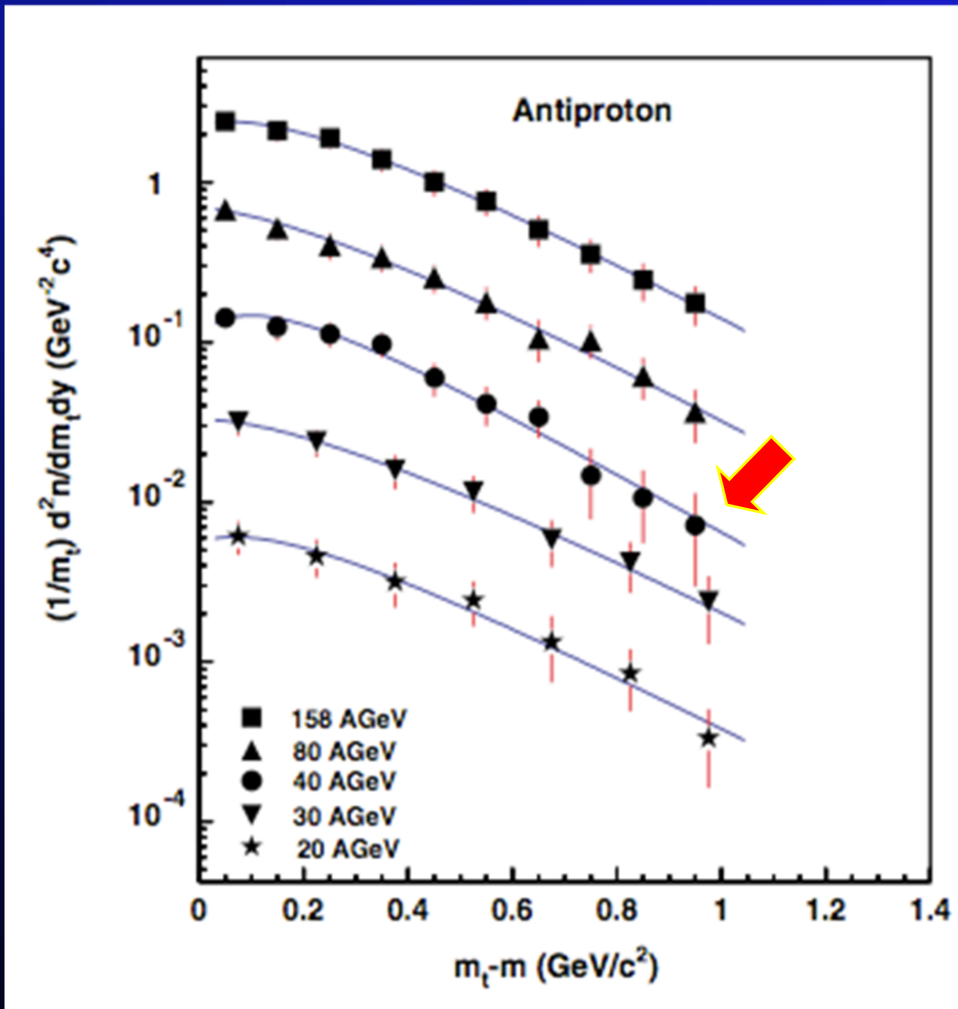




steeper $\overline{p}$ spectra at high P_T

NA49, PRC73, 044910(2006)

Result of One Temperature Fit



NA49, PRC73, 044910(2006)

	E_{beam} (A GeV)	dn/dy	T (MeV)	$\langle m_t \rangle - m$ (MeV/c^2)
$\bar{p}$	158	1.66 ± 0.17	291 ± 15	384 ± 19
	80	0.87 ± 0.07	283 ± 30	385 ± 41
	40	0.32 ± 0.03	246 ± 35	355 ± 51
	30	0.16 ± 0.02	290 ± 45	395 ± 60
	20	0.06 ± 0.01	279 ± 64	394 ± 60
p	158	29.6 ± 0.9	308 ± 9	413 ± 13
	80	30.1 ± 1.0	260 ± 11	364 ± 16
	40	41.3 ± 1.1	257 ± 11	367 ± 16
	30	42.1 ± 2.0	265 ± 10	362 ± 14
	20	46.1 ± 2.1	249 ± 9	352 ± 13

- Only one experimental result for $\bar{p}$ slope
- Still error bar is large

Summary

- Two Principles:

  i) Chemical Freezeout is $p_T(\beta_T)$ dependent

  ii) Isentropic Trajectory behaves non-trivially near CEP (focusing)

  ⇒ $\bar{p}/p$ ratio behaves non-monotonously near CEP

  Information on the QCD critical point:
  such as location, size of critical region, existence…

- We then made a data search
  - turned out NA49 $\bar{p}$ data shows non-trivial behavior around 40 GeV/A
  - still error bar is large, *finer energy scans at SPS, FAIR, RHIC*: desirable

- Effect on Flow ?

  c_s changes differently from the case with EOS used in usual hydro cal.

  (3D hydro cal. with CEP + UrQMD: C. Nonaka in progress)