



Magnetic Shift of the Chemical Freezeout and Electric Charge Fluctuations



Kenji Fukushima

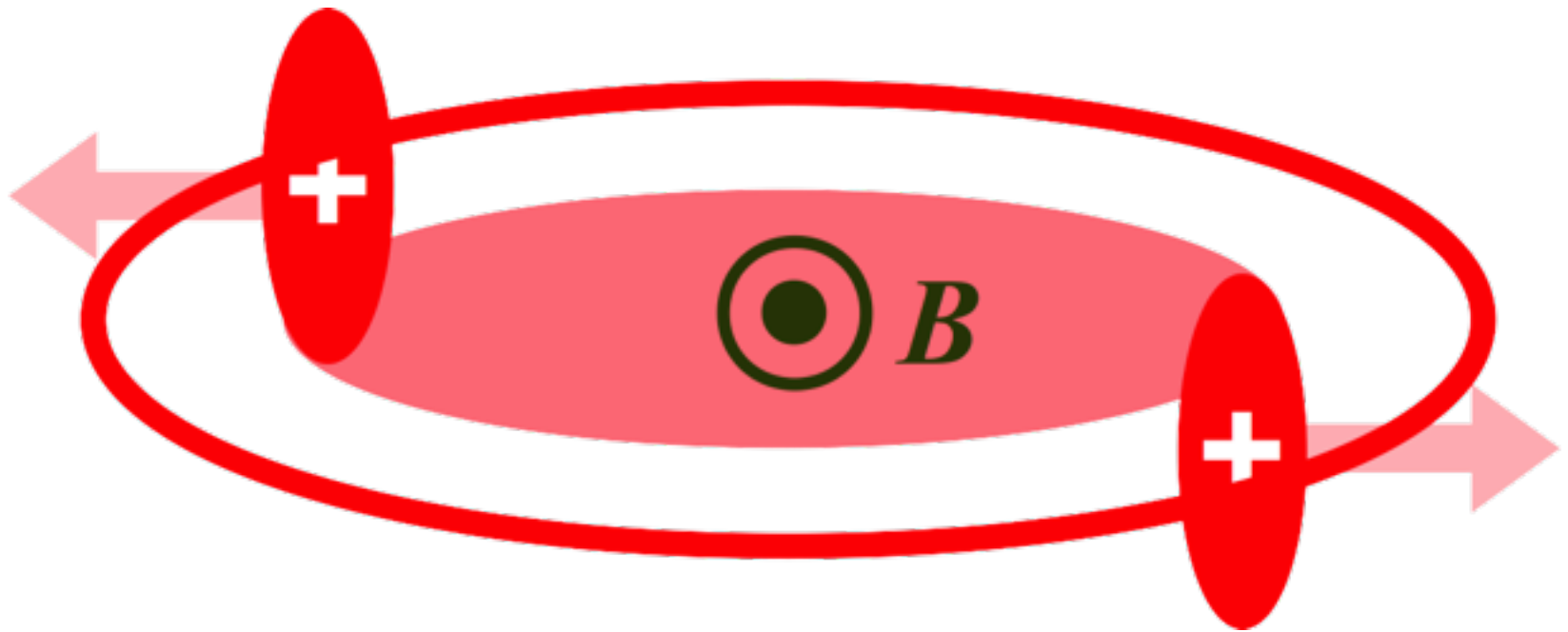
The University of Tokyo

Based on: Fukushima-Hidaka, arXiv:1605.01912

Copinger-Fukushima, arXiv:1605.05957

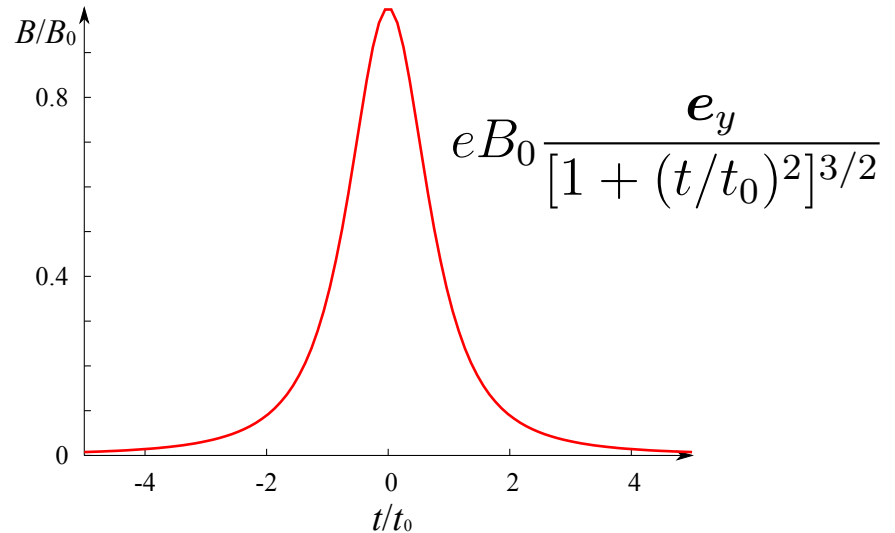
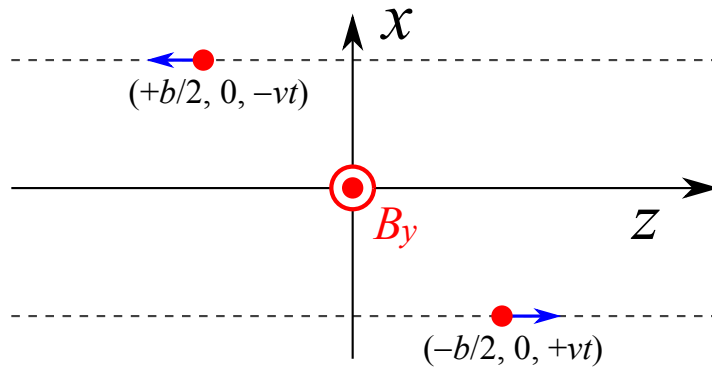
— Critical Point and the Onset of Deconfinement 2016 —

Strong B in Heavy-Ion Collisions



Handy Formula

Simplification (point-particle approx.)



Handy Formula

$$eB_0 = (47.6 \text{ MeV})^2 \left(\frac{1 \text{ fm}}{b} \right)^2 Z \sinh Y \quad t_0 = \frac{b}{2 \sinh Y}$$

$$eB \sim (\text{a few GeV})^2$$

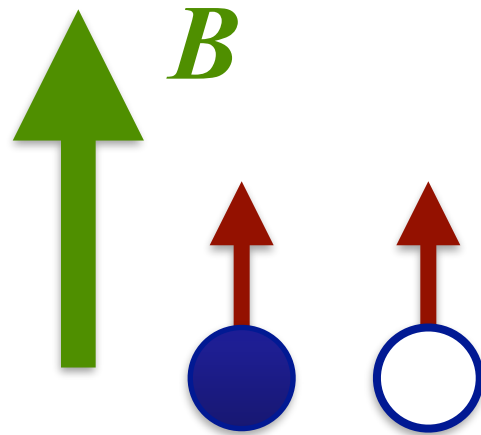
Discussed by Rafelski, Mueller (1976~)

Effects of $eB > (\Lambda_{QCD})^2$ on QCD?

Magnetic Catalysis

Klimenko, Shovkovy, Miransky, Gusynin, Shushpanov, Smilga, ...

B favors more chiral symmetry breaking



Scalar condensate : $J=0$ with $S=1$ and $L=1$

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Inverse Magnetic Catalysis

Preis, Rebhan, Schmitt, etc...

B disfavors chiral sym breaking at high μ_B

Inverse Magnetic Catalysis (Magnetic Inhibition)

Bali, Endrodi, Bruckmann, Schafer, Fodor, Szabo, etc...

B disfavors chiral sym breaking at high T

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Magnetic Catalysis

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B favors more chiral symmetry breaking

Inverse Magnetic Catalysis

KF-Pawlowski

Physics understandable in the mean-field level

B disfavors chiral sym breaking at high μ_B

Inverse Magnetic Catalysis (Magnetic Inhibition)

Physics *beyond* the mean-field level

KF-Hidaka, many others

B disfavors chiral sym breaking at high T

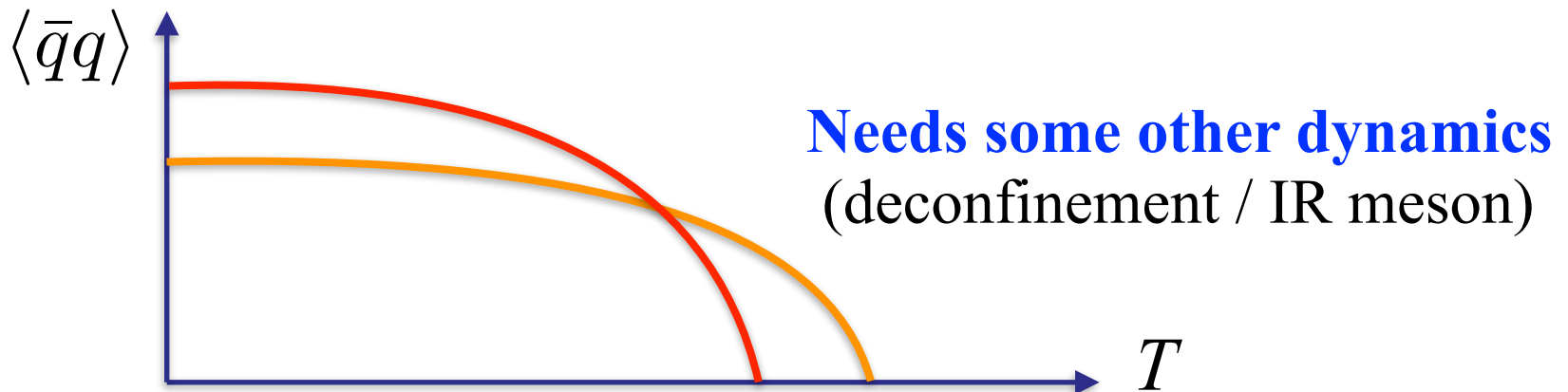
Effects of $eB > (\Lambda_{QCD})^2$ on QCD?

Difficulty in understanding the IMC

Critical T in BCS: $T_c \propto \underline{\Delta(T = 0)}$

$\langle \bar{q}q \rangle$ in QCD

Reconcile? $\langle \bar{q}q \rangle(T = 0)$ is increased at finite B
 T_c is decreased at finite B



Effects of $eB > (\Lambda_{QCD})^2$ on QCD?

Phase Diagram

Klimenko, Shovkovy, Miransky, Gusynin, Shushpanov, Smilga, ...

Preis, Rebhan, Schmitt, etc...

Bali, Endrodi, Bruckmann, Schafer, Fodor, Szabo, etc...

Fraga, Noronha, Palhares, Blaizot, Ruggieri, Gatto, etc...

Infinite B limit?

Fermions infinitely heavy (quenched limit)

Reduced to anisotropic pure Yang-Mills

1st-order Phase Transition!

Endrodi, Cohen-Yamamoto

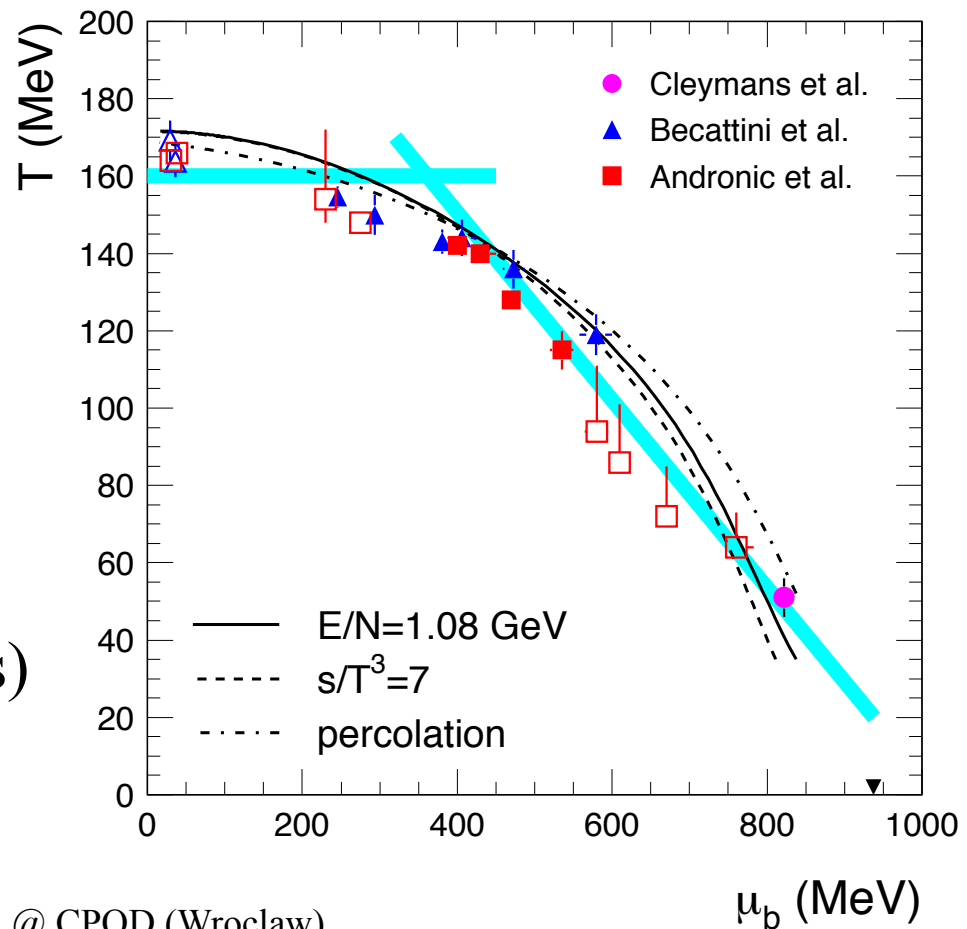
Effects of $eB > (\Lambda_{QCD})^2$ on QCD?

Chemical Freezeout ???

Nobody so far...

Experimentally seen
“Phase Diagram”

Keep in mind:
**Quark matter could be
ferromagnetic!**
(Origin of B on magnetars)



(Inverse) MC explained in HRG?

Endrodi (2013)

QCD equation of state at nonzero magnetic fields in the Hadron Resonance Gas model

G. Endrődi,¹

¹*Institute for Theoretical Physics, Universität Regensburg, D-93040 Regensburg, Germany.*

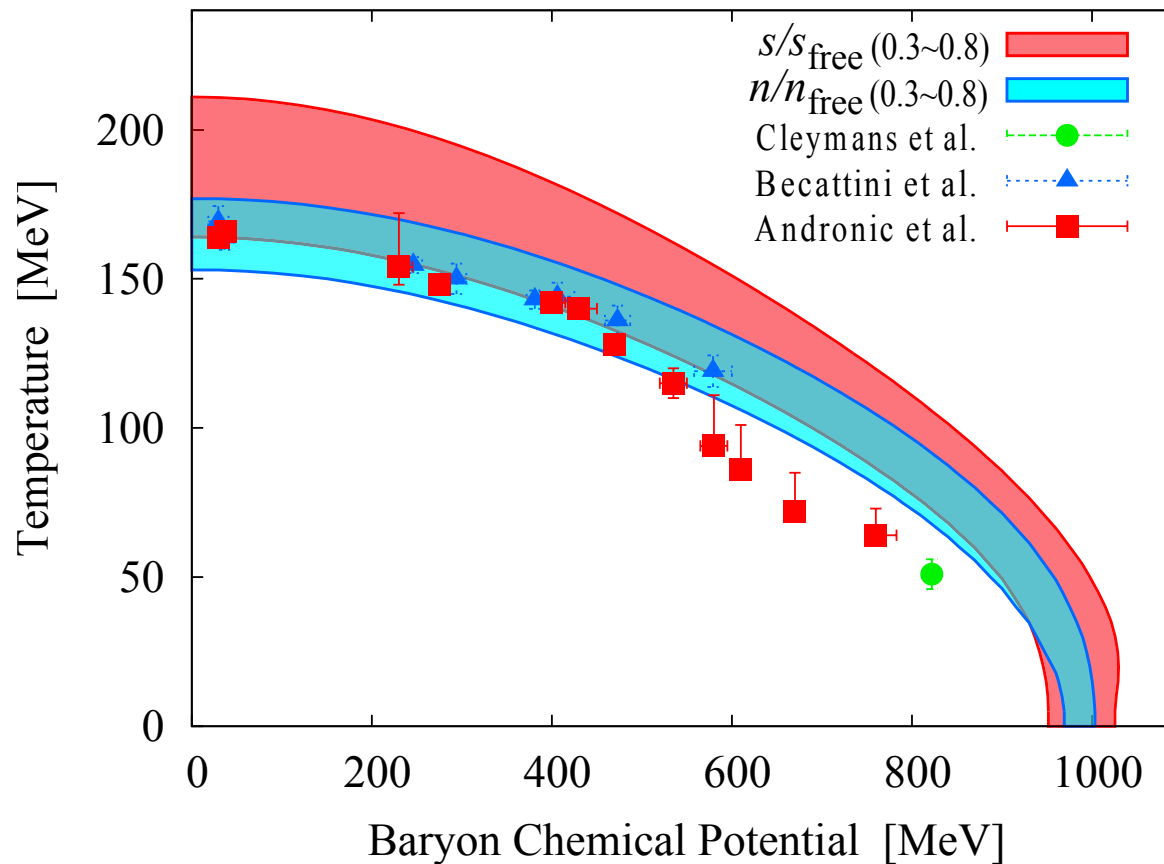
E-mail: gergely.endrodi@physik.uni-regensburg.de

explained the magnetic catalysis *qualitatively*.

For quantitative studies on the chiral condensate, hadron “sigma terms**” are necessary.**

Phase Diagram from HRG

Most model-independent phase diagram from free hadrons



KF (2010)

Empirical Freezeout Conditions

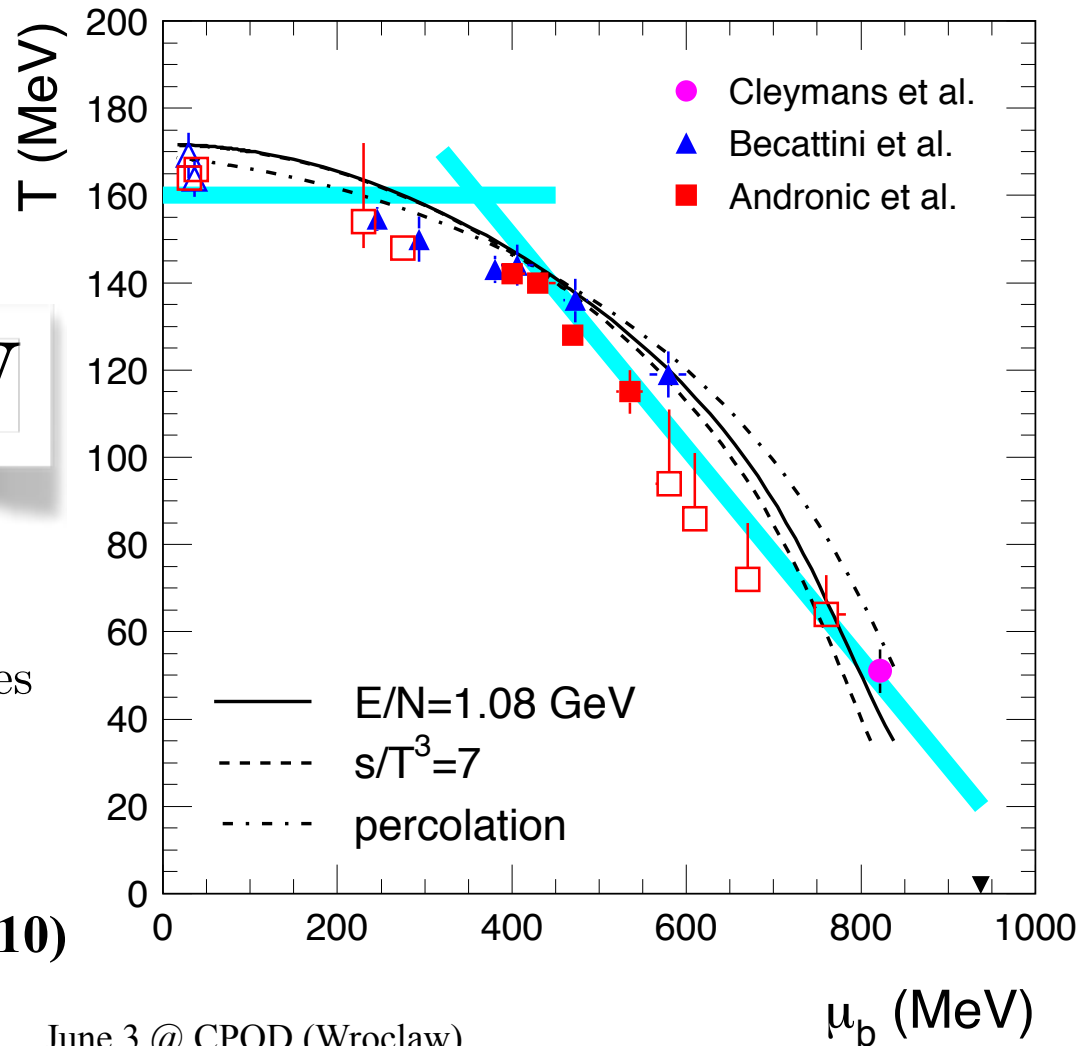
Cleymans-Redlich
(1998)

$$E/N \sim 1 \text{ GeV}$$

E : internal energy

N : particles + antiparticles

Andronic et al. (2010)

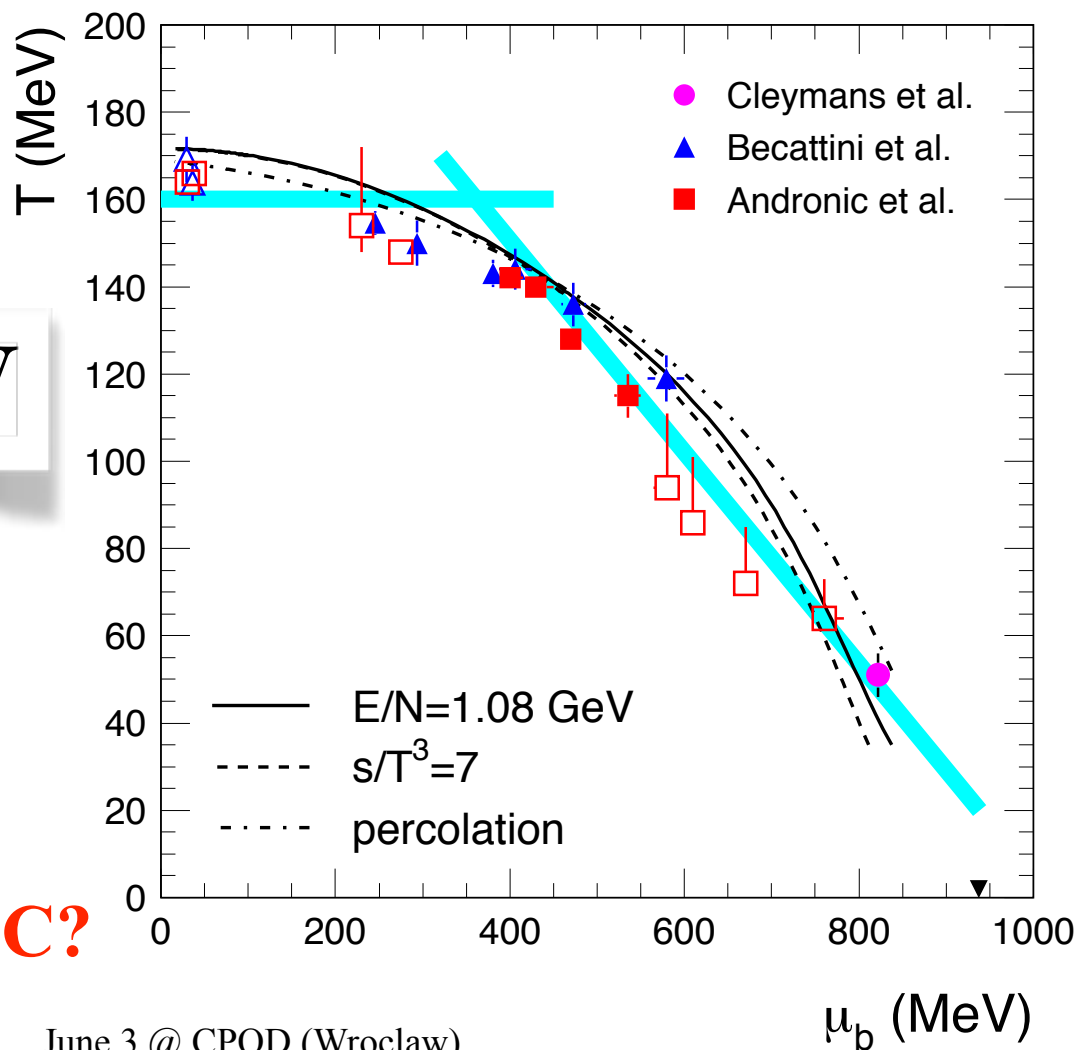


Our Idea

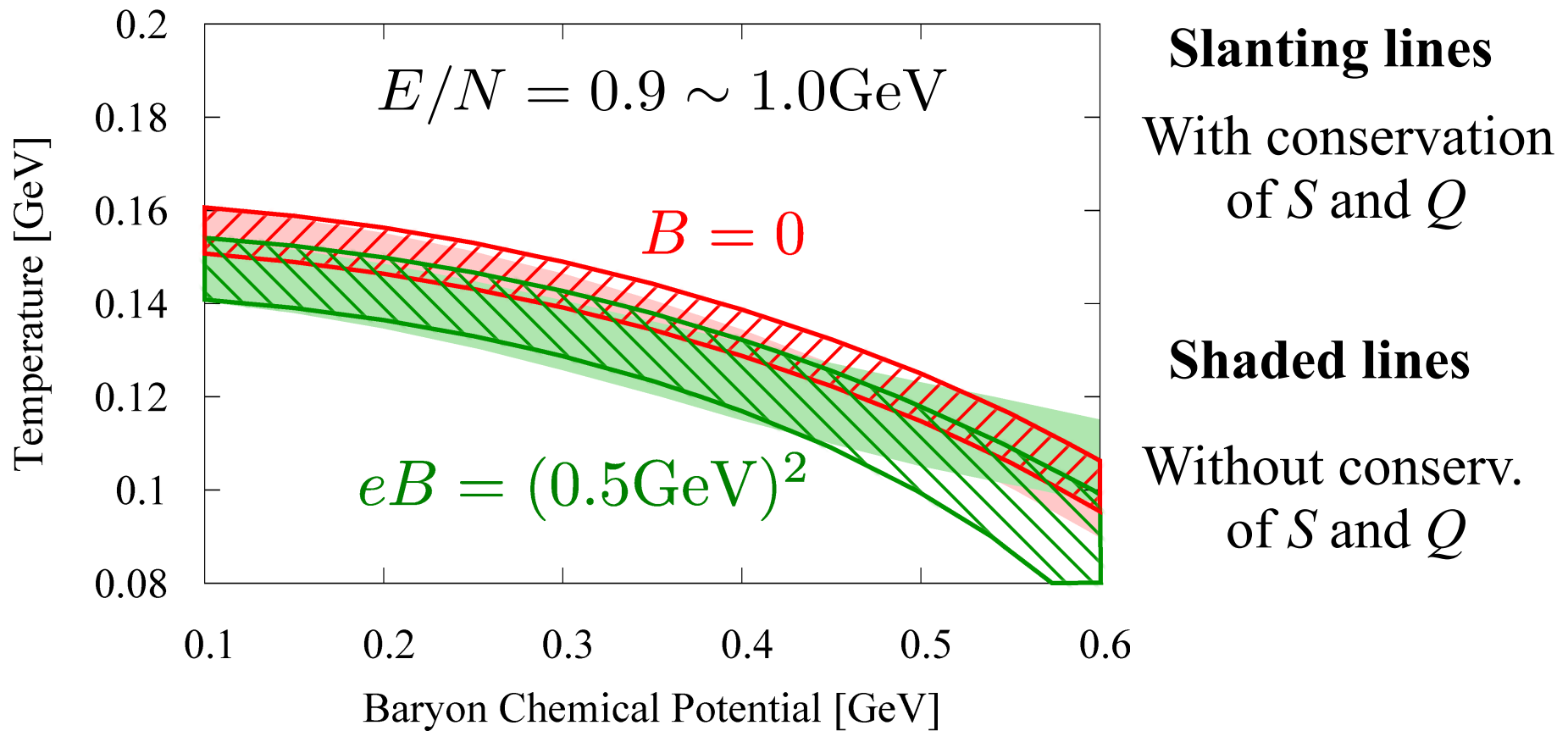
Assume:
empirical condition
not changed by B

$$E/N \sim 1 \text{ GeV}$$

How these curves
modified by B ?
Consistent with IMC?



Shifted Freezeout Curves



KF-Hidaka (2016)

Comments

It is not obvious that the chemical freezeout curves are shifted down in accord to the inverse MC.

With increasing B :

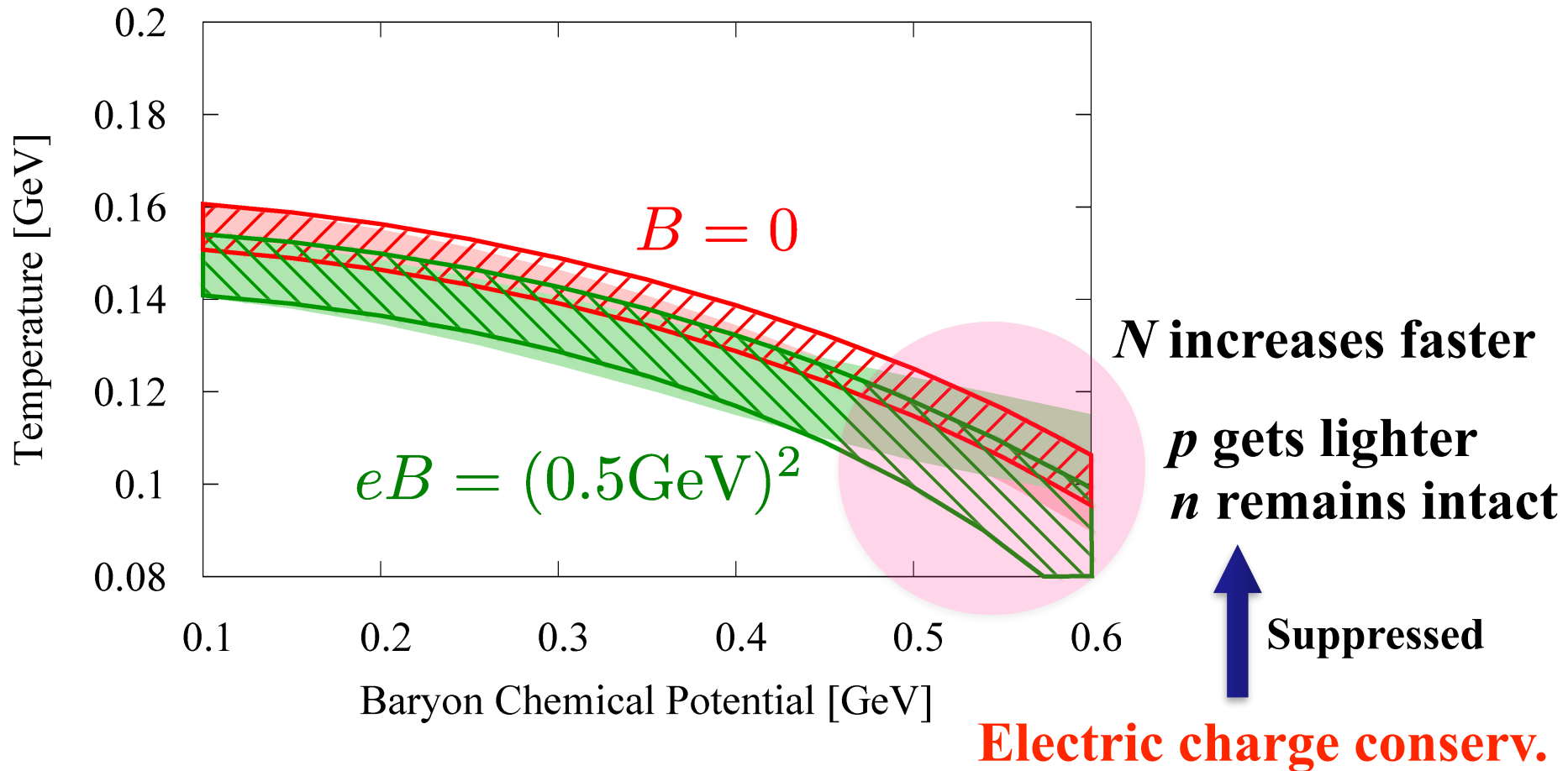
E increases

Which is faster???

N increases

Phase-space of charged particles $\sim \frac{eB}{2\pi}$

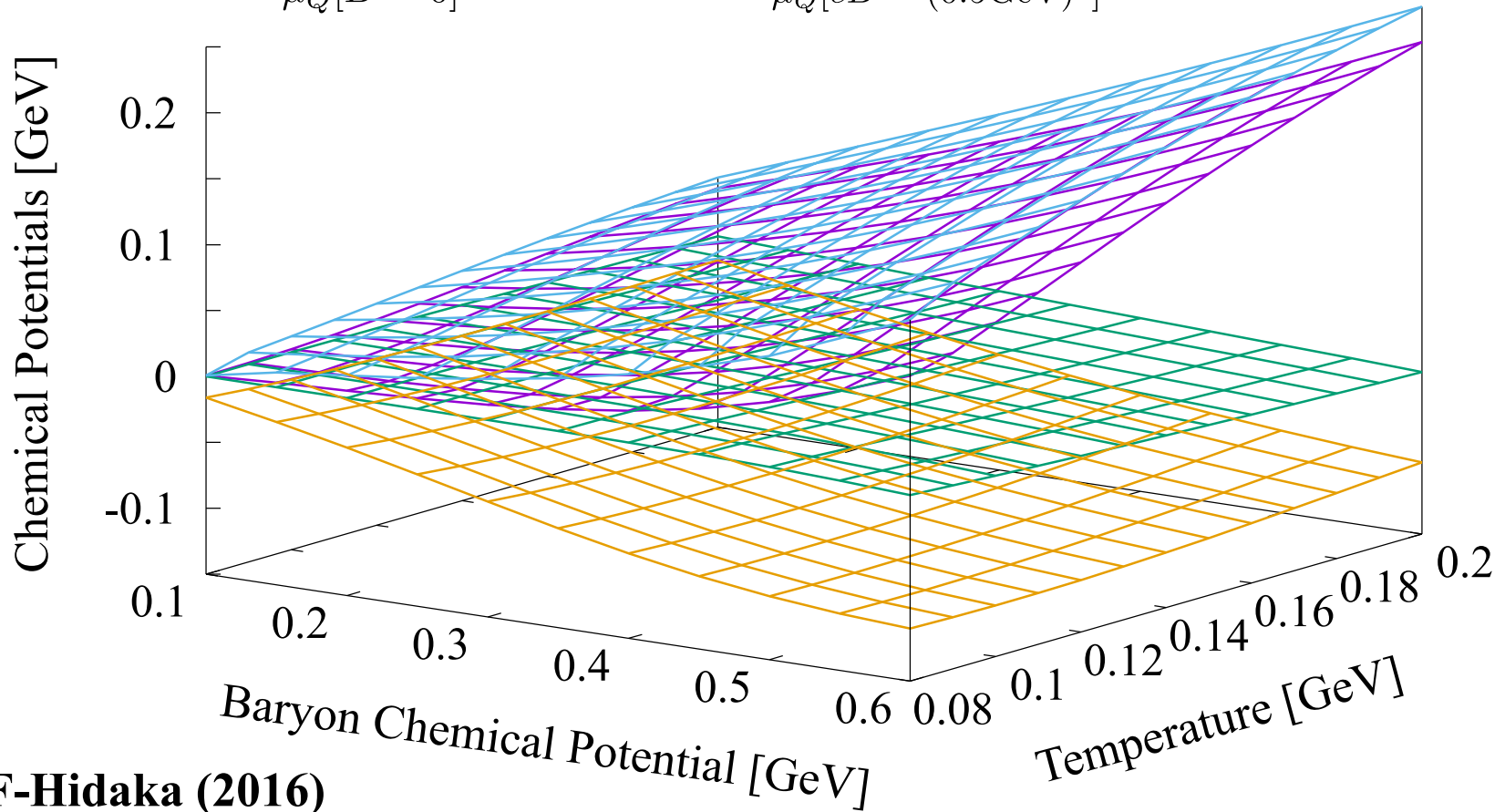
Comments



Charge Conservations



$\mu_S[B = 0]$ — purple line
 $\mu_Q[B = 0]$ — green line
 $\mu_S[eB = (0.5\text{GeV})^2]$ — light blue line
 $\mu_Q[eB = (0.5\text{GeV})^2]$ — orange line



KF-Hidaka (2016)

Comments on S

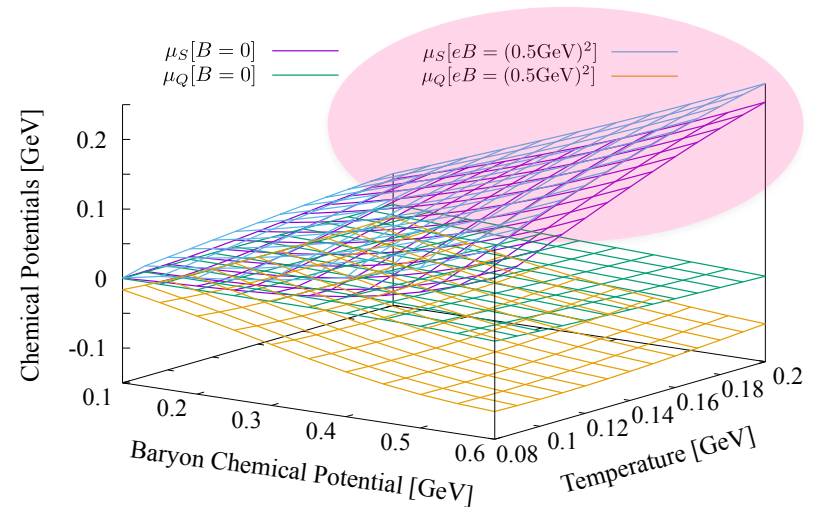
At high T

$$\mu_S \sim \mu_B/3$$

The chemical potential felt by free strange quarks is

$$\mu_B/3 - \mu_S \sim 0 \text{ if } \mu_S \sim \mu_B/3$$

This signals for realization of “**quark deconfinement**” even in HRG without quark d.o.f.

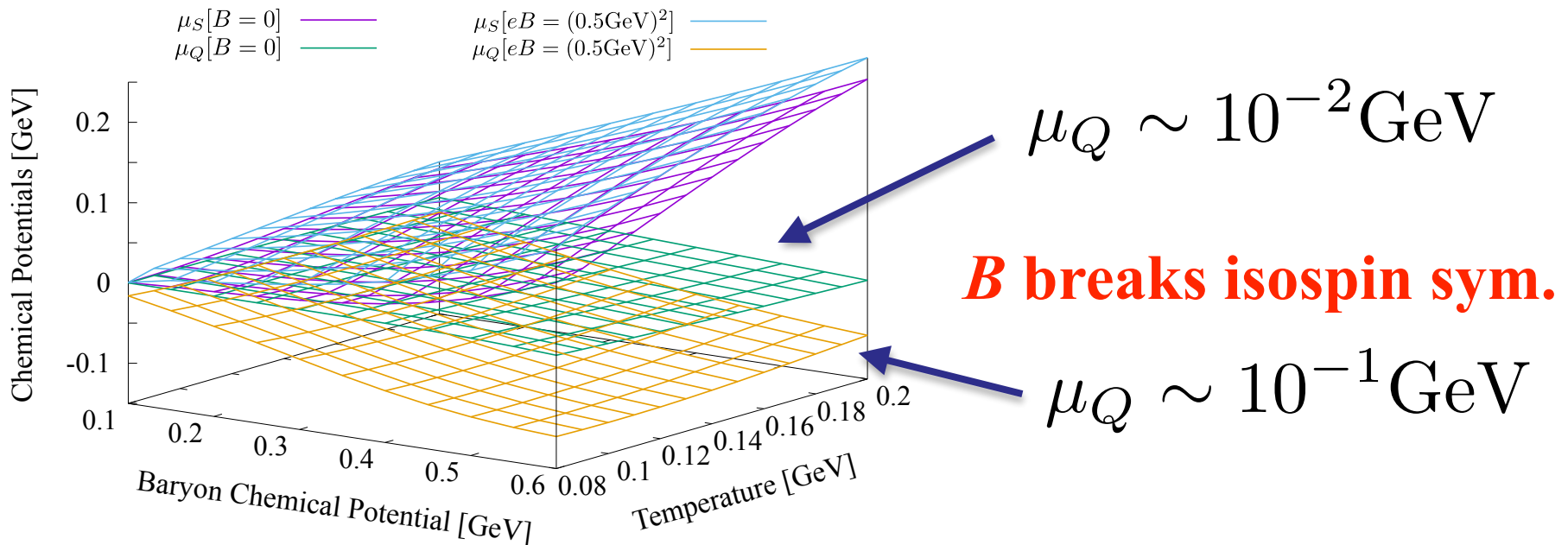


Comments on Q

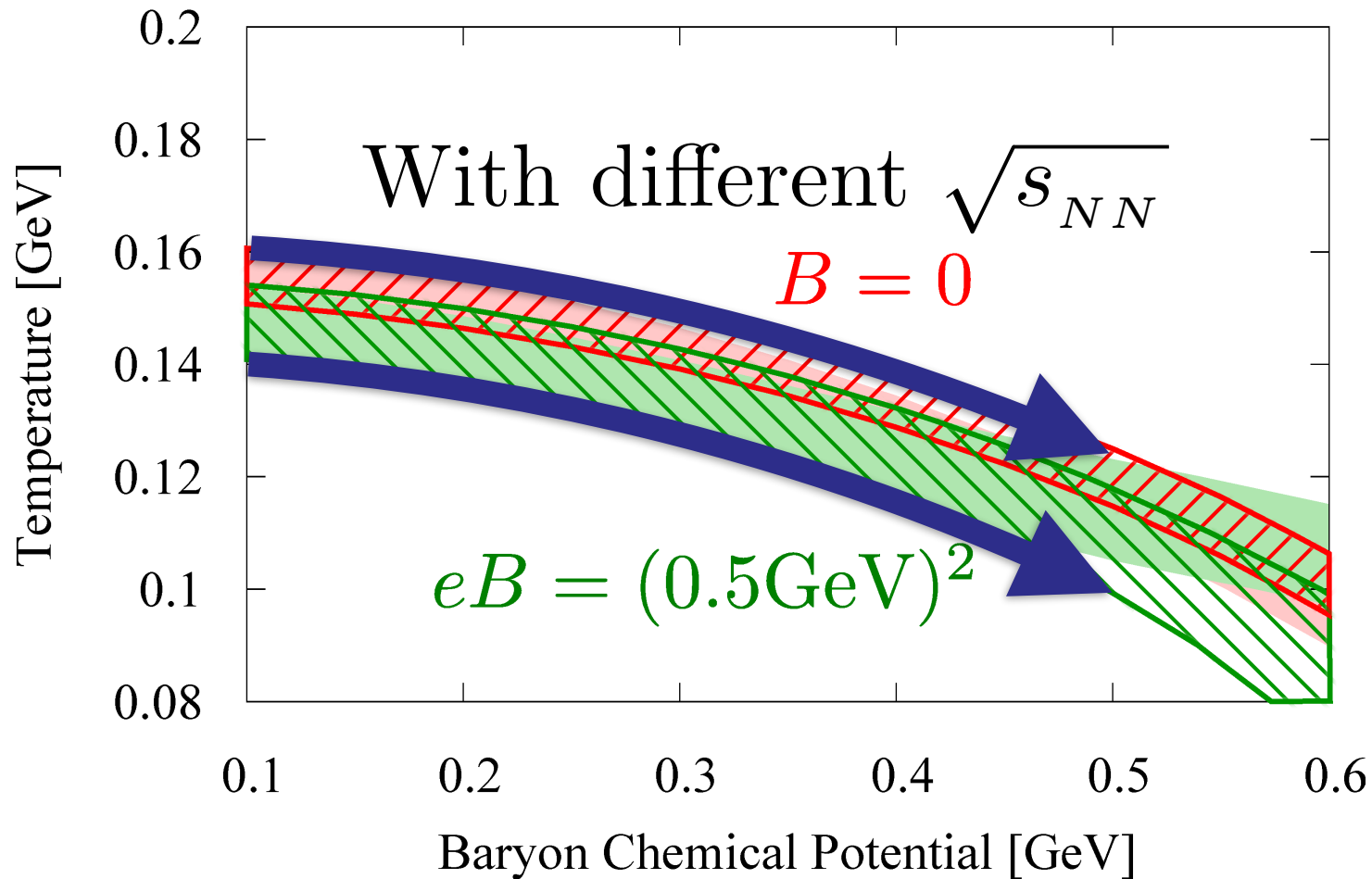
μ_Q is fixed to meet $B/(2Q) = 1.2683$

In (heavy) nuclei there are a bit more neutrons than protons.

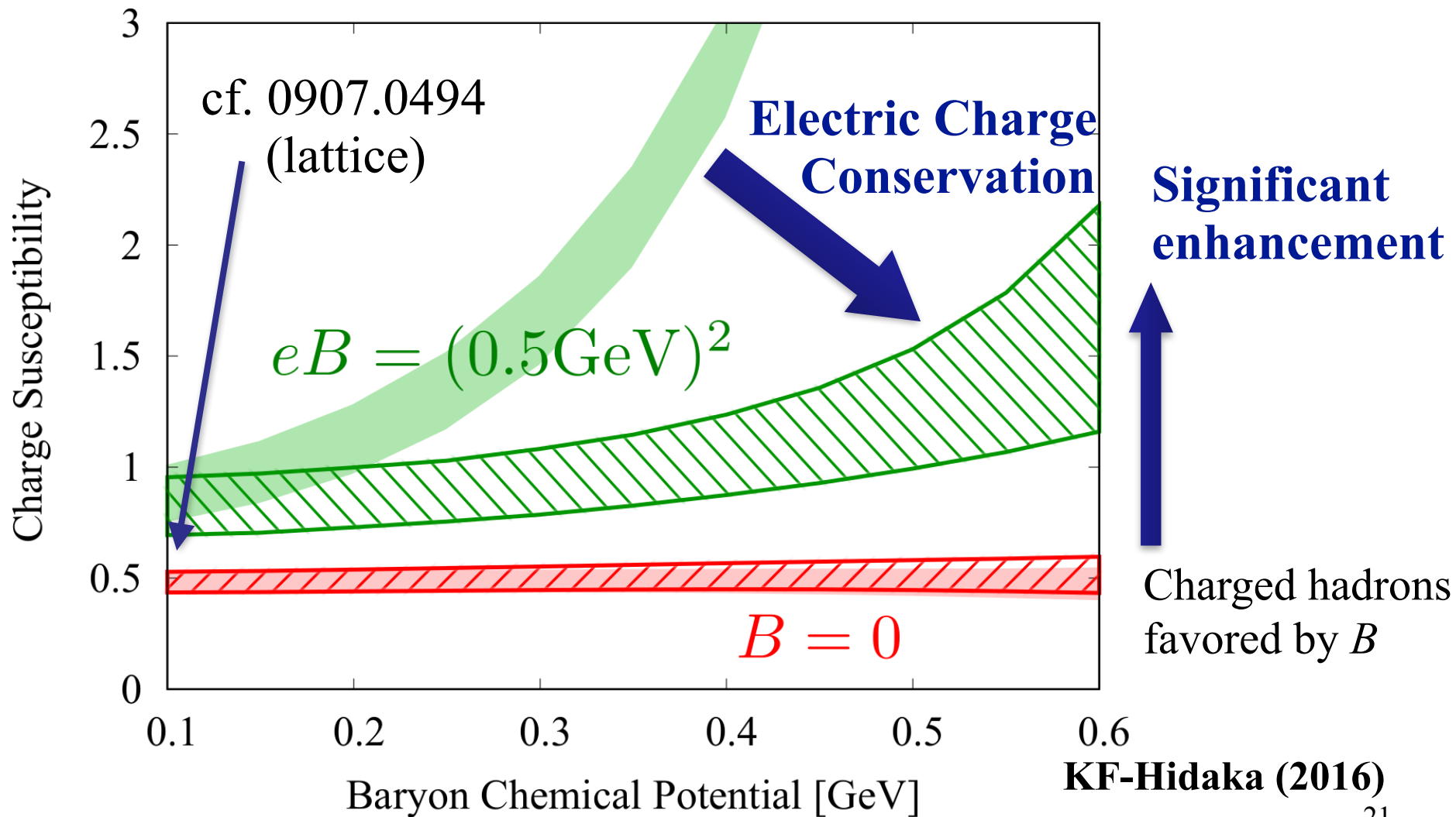
Isospin sym. breaking is minor $\rightarrow \mu_Q$ is nonzero but small.



Observables on Freezeout Lines



Electric Charge Fluctuations

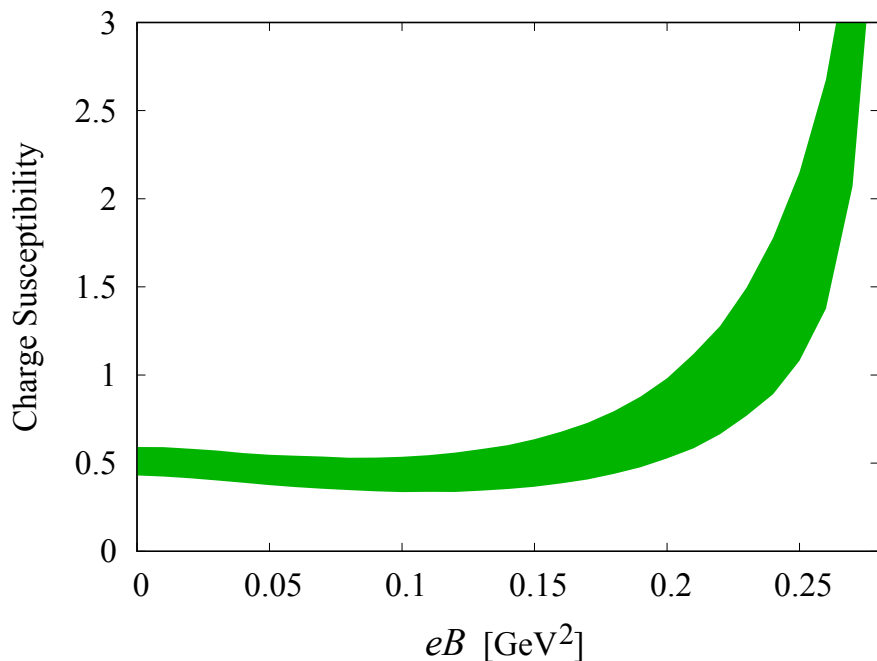


Sensitivity to B

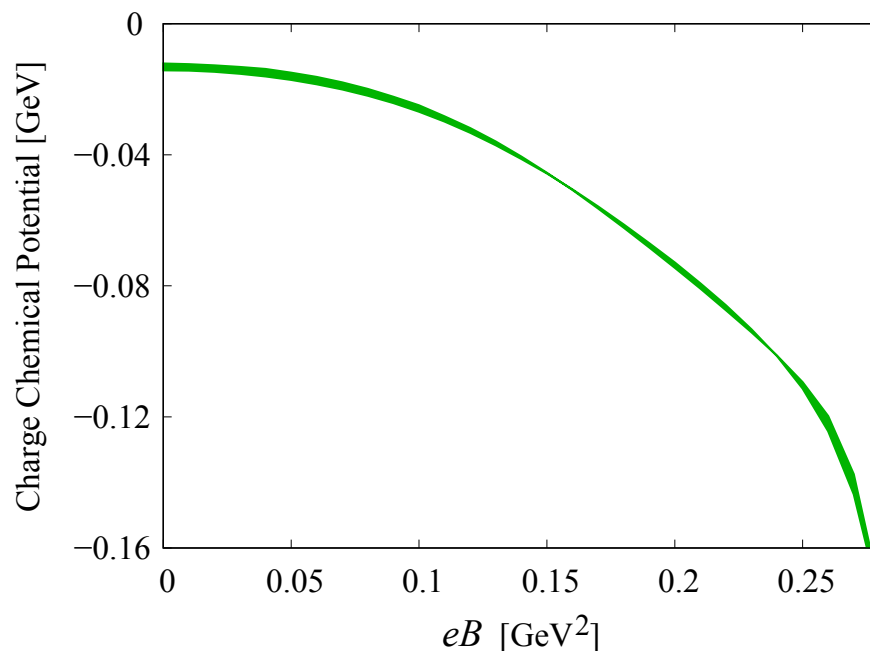


Chemical potential fixed at 0.6GeV

Temperature solved by $E/N=0.9\sim 1\text{GeV}$



Crossover?



More sensitive to B


Most of works assume homogeneous B

What happens for inhomogeneous B ?

Inhomogeneous B

$$\Gamma_E[A] = \int_0^\infty \frac{dT}{T} e^{-m^2 T} \oint \mathcal{D}x \exp \left\{ - \int_0^T d\tau \left[\frac{1}{4} \left(\frac{dx}{d\tau} \right)^2 + ieA \cdot \frac{dx}{d\tau} \right] \right\} \Phi[A]$$

Worldline Formalism


$$\Phi[A] = -\frac{1}{2} \text{tr} \mathcal{P} \exp \left(\frac{ie}{2} \int_0^T d\tau \sigma_{\mu\nu} F_{\mu\nu} \right)$$

$\mathcal{K}_E \times \mathcal{K}_B$ for time-dep. E and space-dep. B

Modulation parameter: $B \sim B_0(1 + \kappa^2 x^2 + \dots)$

The bottom line is:

$$\mathcal{K}_B \sim e^{+\kappa^2 T}$$

Solvable Example

Sauter-type potential:

$$B(x) = B \operatorname{sech}^2(\kappa x_1) \mathbf{e}_3$$

$$\mathcal{K}_B = \sum_{\pm} \frac{1}{2} \operatorname{Tr} \exp(-\hat{H}_B^{\pm} T) \quad \text{There is a “bound state”}$$

$$\hat{H}_B^{\pm} \equiv -\partial_1^2 - \left[\partial_2 + \frac{ieB}{\kappa} \tanh(\kappa x_1) \right]^2 \pm eB \operatorname{sech}^2(\kappa x_1)$$

Lowest eigenvalue is $\lambda = -\kappa^2$

in an approximation with $eB \gg \kappa^2$

Spatially Assisted MC

Effect of inhomogeneous B

$$m^2 \longrightarrow m^2 - \kappa^2$$

Very similar to the Chiral Gap Effect in curved space

$$m^2 \longrightarrow m^2 + \frac{R}{12}$$

Flachi-Fukushima (2014)

Flachi-Fukushima-Vitagliano (2015)

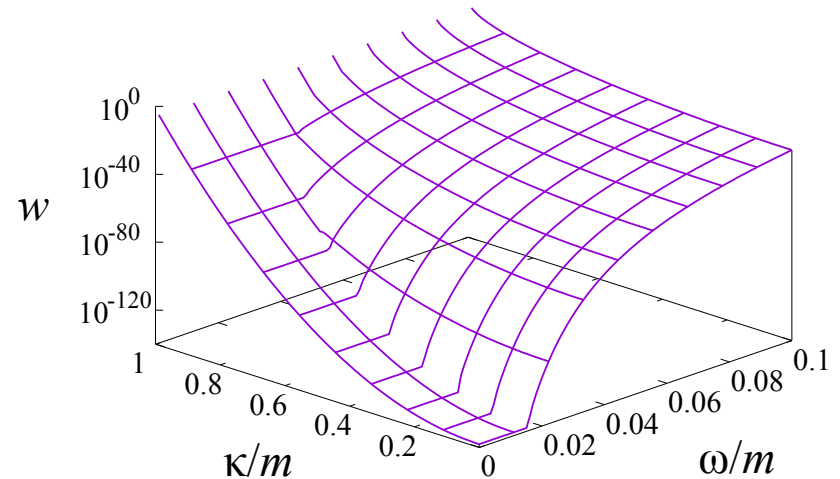
$V_{\text{eff}}(m^2 - \kappa^2) \longrightarrow$ **Larger dynamical mass (MC)**

More Implications

Spatially Assisted Schwinger Mechanism

$$\exp\left[-\frac{\pi m^2}{eE}\right]$$

Mass threshold pushed down



Spatially Assisted Chiral Magnetic Effect

$\mathbf{E} \cdot \mathbf{B}$ creates chirality charge

Transverse modulations enhanced chirality creation

Summary

Signatures for B in HIC

Centrality differentiated thermal parameter analysis

- **Magnetic shift of the chemical freezeout points with different centralities.**

Freezeout T decreases in accord to the IMC.

- **Enhancement of μ_Q with different centralities.**

Easily accessible information from HIC experiment.

- **Enhancement of χ_Q with different centralities.**

A bit challenging but possible experimental signature.

Summary

Spatially modulated B in HIC

■ Spatially Assisted Magnetic Catalysis

Enhancement of chiral symmetry breaking

What happens at finite T ? Inverse MC remains?

■ Spatially Assisted Schwinger Mechanism

Off-equilibrium enhancement of particle production

Avalanche to form a condensate

■ Spatially Assisted Chiral Magnetic Effect

Some relation to Weibel/Chiral-Plasma instabilities?