Strong Phases from first Principles

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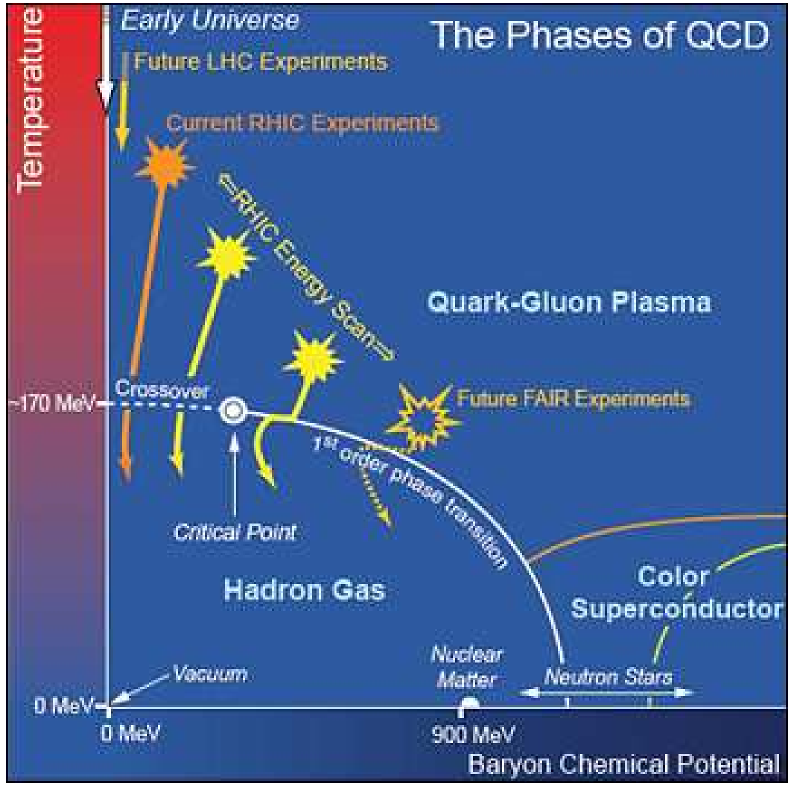
Aim: The QCD phase diagram from first principles

Sketch RHIC



Nonperturbative problem

Aim today: Possibilities within Discovery

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1) Non-Gaussianity and the sign problem

2) A new direction in the phase diagram

Matter antimatter asymmetry ($\mu \neq 0$)

$$N > 0$$

Here: Fact which we adopt into QCD

Grand canonical approach: *Fix μ determine N*

$$N = \frac{1}{V}\partial_\mu \log Z(\mu)$$

How to include μ in Z

μ is conjugate variable to N

$$\mu N = \mu\langle q^\dagger q\rangle = \mu\langle \bar{q}\gamma_0 q\rangle$$

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(D + \mu\gamma_0 + m)q + \mathrm{Gluons}$$

The sign problem

$$Z = \int dA \, \det(D + \mu\gamma_0 + m) \, e^{-S_{\mathrm{YM}}}$$

Anti Hermitian

Hermitian

$$\det(D + \mu\gamma_0 + m) = |\det(D + \mu\gamma_0 + m)| e^{i\theta}$$

The measure is not real and positive

The sign problem

$$Z = \int dA \, \det(D + \mu\gamma_0 + m) \, e^{-S_{\mathrm{YM}}}$$

Anti Hermitian Hermitian

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No QCD inequalities *hadron masses not what you think*

The sign problem

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Anti Hermitian Hermitian

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The measure is not real and positive

No QCD inequalities *hadron masses not what you think*

No Vafa-Witten theorem *symmetries not what you think*

The sign problem

$$Z = \int dA \, \det(D + \mu\gamma_0 + m) \, e^{-S_{\mathrm{YM}}}$$

Anti Hermitian Hermitian

$$\det(D + \mu\gamma_0 + m) = |\det(D + \mu\gamma_0 + m)| e^{i\theta}$$

The measure is not real and positive

No QCD inequalities — *hadron masses not what you think*

No Vafa-Witten theorem — *symmetries not what you think*

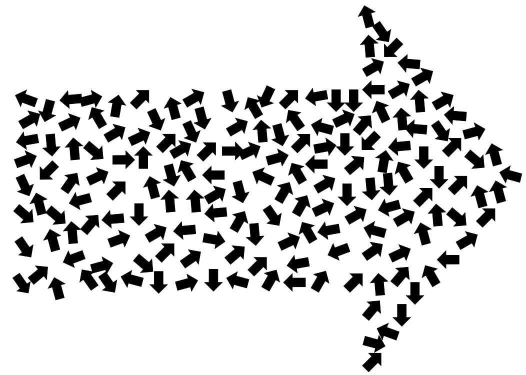
No Elitzur theorem — *local symmetries not what you think*

No Monte Carlo sampling of A_η — *lattice QCD not applicable*

The QCD sign problem

Phase transitions in

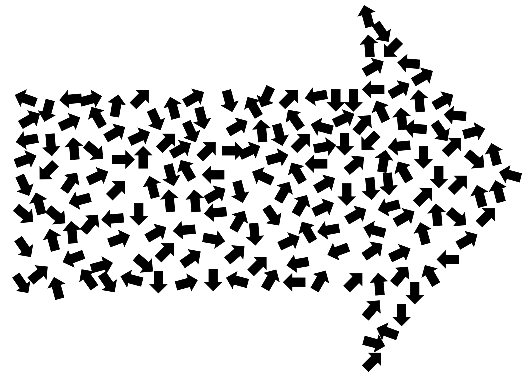
Non-statistical physics



The QCD sign problem

Phase transitions in

Non-statistical physics



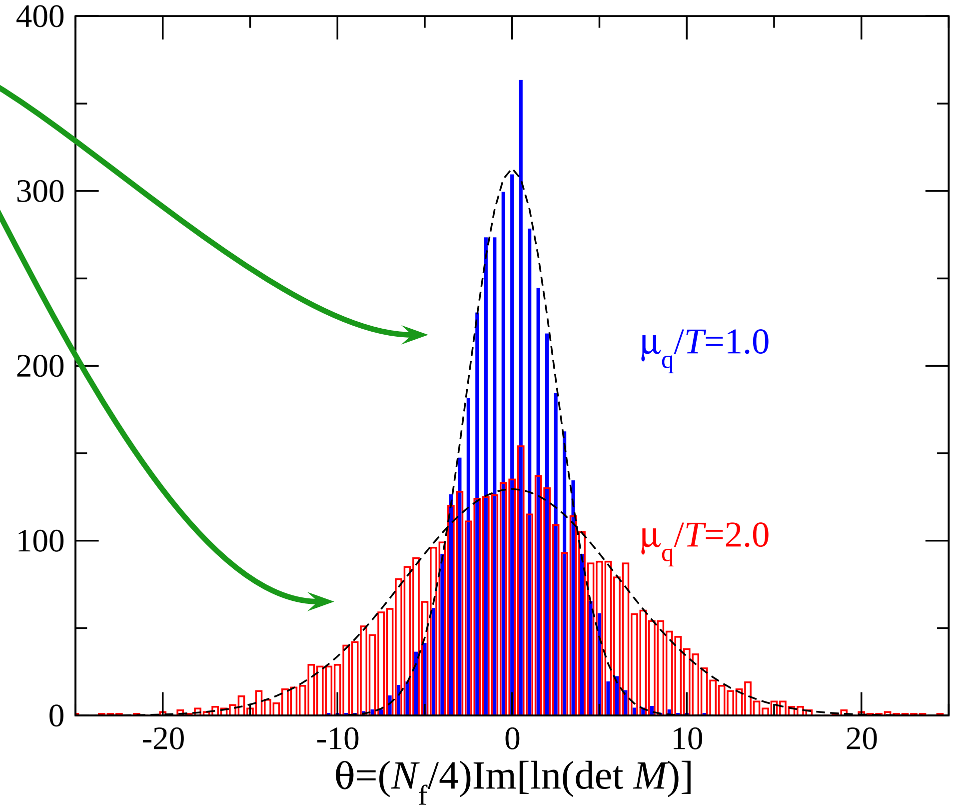
$$\det(D + \mu\gamma_0 + m) = |\det(D + \mu\gamma_0 + m)|e^{i\theta}$$

Is the sign problem really that bad ?

The θ-distribution: $\langle \delta(\theta - \theta') \rangle$

The θ-distribution from the lattice

Gaussian fits



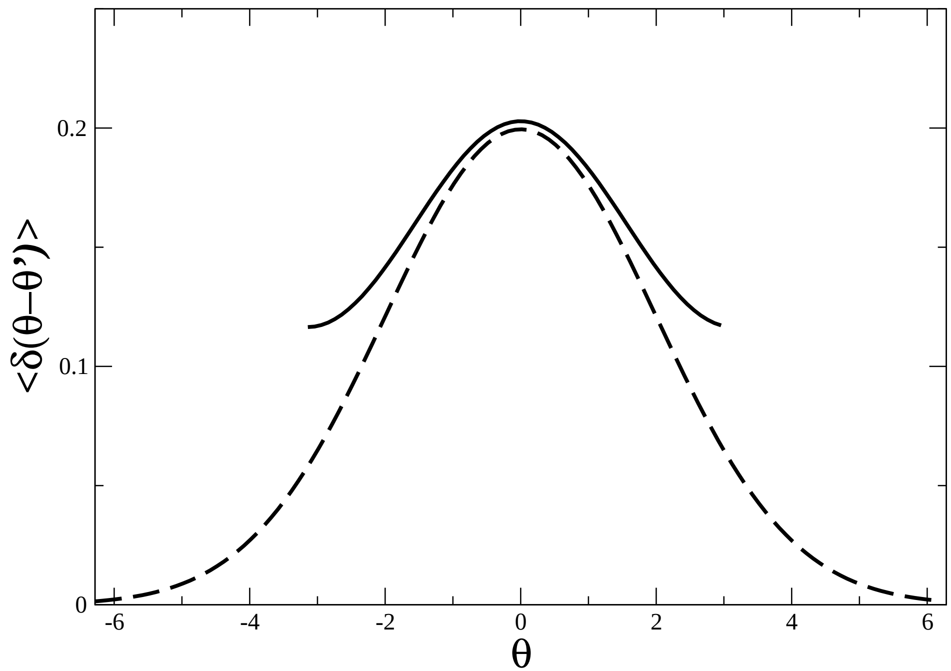
width $\sqrt{V}$

Central limit theorem

Ejiri PRD 77 (2008) 014508

Lombardo, Splittorff, Verbaarschot Phys.Rev. D81 (2010) 045012

Gaussian folded onto $[-\pi : \pi]$



$$\begin{aligned}\langle\delta(\theta-\theta')\rangle &= \frac{1}{Z}\int dA\,\delta(\theta-\theta')|\det(D+\mu\gamma_0+m)|e^{i\theta'}e^{-S_{\mathrm{YM}}}\\ &= \frac{1}{Z}e^{i\theta}\int dA\,\delta(\theta-\theta')|\det(D+\mu\gamma_0+m)|e^{-S_{\mathrm{YM}}}\end{aligned}$$

Goal

Measured

$$\langle\delta(\theta-\theta')\rangle = \frac{1}{Z}\int dA\,\delta(\theta-\theta')|\det(D+\mu\gamma_0+m)|e^{i\theta'}e^{-S_{\mathrm{YM}}}$$

$$= \frac{1}{Z}e^{i\theta}\int dA\,\delta(\theta-\theta')|\det(D+\mu\gamma_0+m)|e^{-S_{\mathrm{YM}}}$$

Goal

Measured

Exponential cancellations

$$\begin{aligned}\langle \delta(\theta-\theta')\rangle &= \frac{1}{Z}\int dA\,\delta(\theta-\theta')|\det(D+\mu\gamma_0+m)|e^{i\theta'}e^{-S_{\rm YM}} \\ &= \frac{1}{Z}e^{i\theta}\int dA\,\delta(\theta-\theta')|\det(D+\mu\gamma_0+m)|e^{-S_{\rm YM}}\end{aligned}$$

Goal

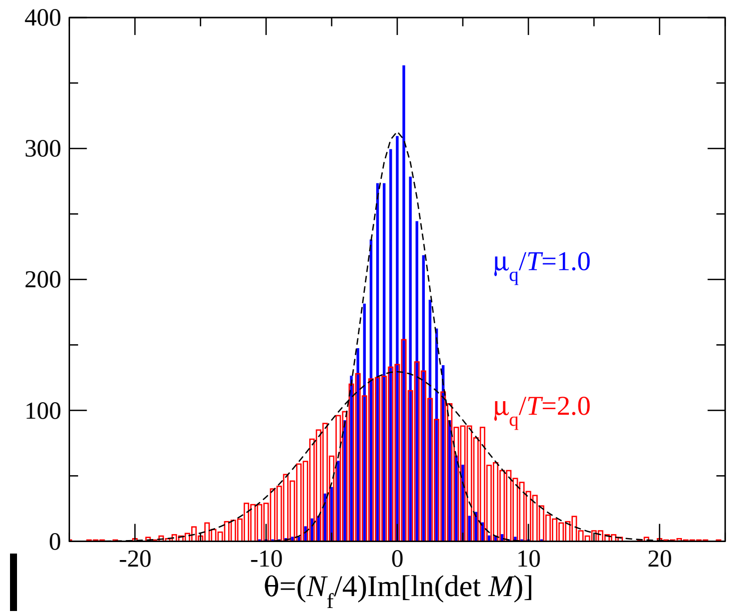
Measured

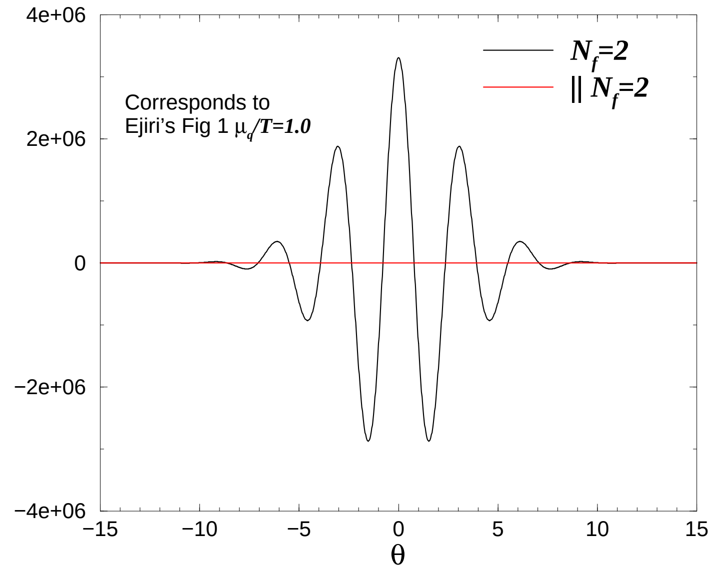
Exponential cancellations

Normalization

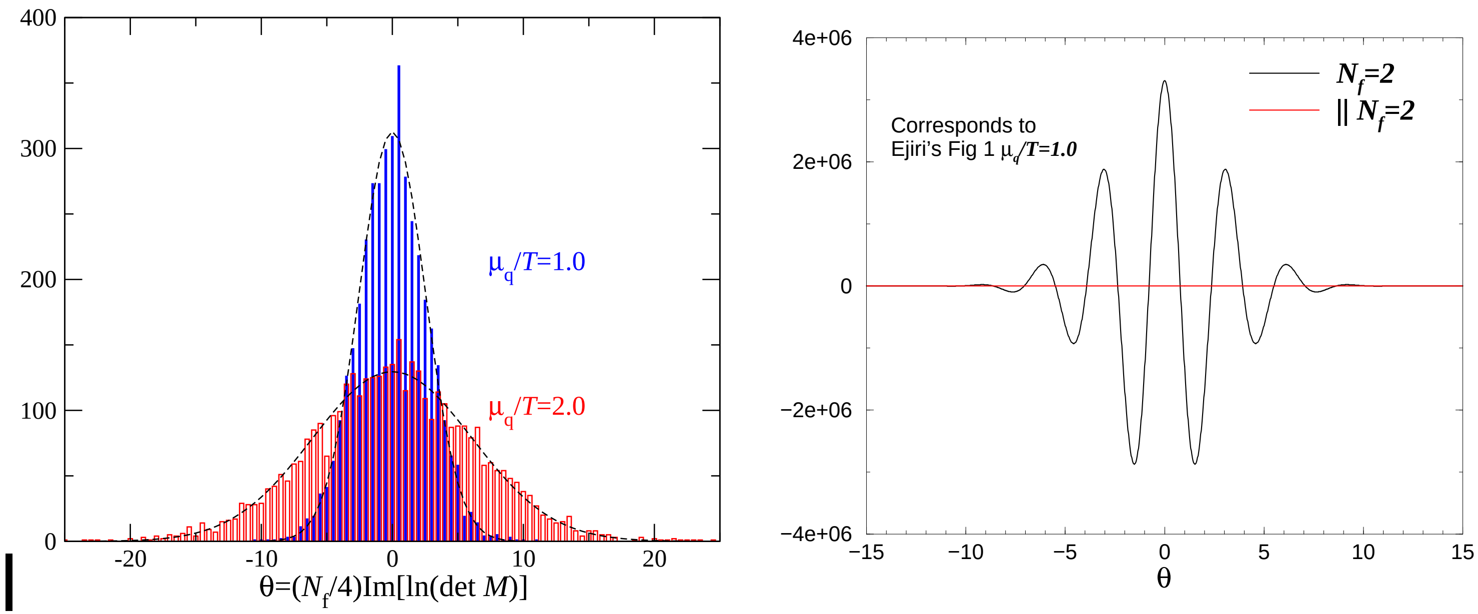
$$\int d\theta\ \langle \delta(\theta-\theta')\rangle = \int d\theta\ e^{i\theta}e^{-\theta^2/V+V}\frac{1}{\sqrt{\pi V}} = 1$$

The exponential cancellations





The exponential cancellations



Need analytic insights to measure observables

New analytic insights: n_B and non-Gaussianity

1) The baryon number is hidden in non-Gaussianity

$$\int d\theta \, \langle n_B \delta(\theta - \theta') \rangle = \int d\theta \, (\text{poly in } \theta) e^{i\theta} e^{-\theta^2/V + V} \frac{1}{\sqrt{\pi V}}$$

New analytic insights: n_B and non-Gaussianity

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2) The noise is due to total derivatives wrt θ !

New analytic insights: n_B and non-Gaussianity

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2) The noise is due to total derivatives wrt θ !

CMB inspired analysis of lattice data?

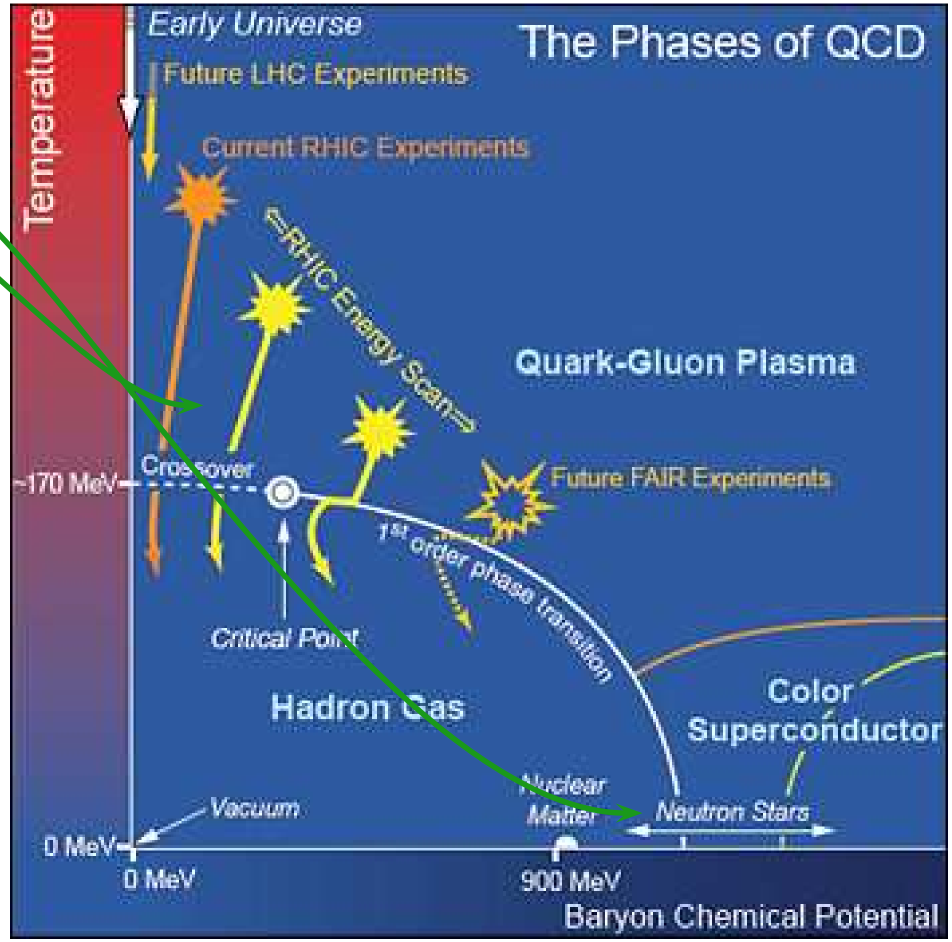
Myers, Splittorff 2012

A new direction in the phase diagram:

- The $(\mu, T, \mathrm{grad}T)$ *space*

Sketch 1 RHIC

'Perfect fluid'



Input from solid state physics

No temperature gradient can form in a superfluid

Input from solid state physics

No temperature gradient can form in a superfluid

$\Longrightarrow$ *A temperature gradient can destroy superfluids*

Input from solid state physics

No temperature gradient can form in a superfluid

$\Rightarrow$ *A temperature gradient can destroy superfluids*

Does the temperature gradients in HIC modify the QGP?

Input from solid state physics

No temperature gradient can form in a superfluid

$\Rightarrow$ *A temperature gradient can destroy superfluids*

Does the temperature gradients in HIC modify the QGP?

Sign problem: Pion superfluid phase in $\left|\det(D+\mu\gamma_0+m)\right|$*-theory*

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Office Fc5 !