VACUUM STRUCTURE AND DECONFINEMENT

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apeNEXT: Computational Challenges and First Physics Results
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1 – INTRODUCTION

The QCD vacuum state is characterized by a few fundamental properties which are not predictable by perturbation theory and which rule the phenomenology of strongly interacting matter at the low energy scale

Color Confinement

Experimental evidence gives an upper limit to the presence of free quarks which is a factor 10^{-15} lower than what expected from the standard Cosmological model.
$\Longrightarrow$ **Fundamental fields of QCD do not correspond to asymptotic states.**

That's what we call Color Confinement: it emerges as an absolute property of strongly interacting matter. The natural attitude is to search for an interpretation of it in terms of the realization of some exact symmetry. Which symmetry is yet not clear.

Chiral Symmetry Breaking

The symmetry under flavour symmetry $SU_L(3) \otimes SU_R(3)$, which is exact in the zero mass limit, is spontaneously broken. In particular the axial generators

$$\psi \to e^{i\omega_a T_a \gamma_5}\psi$$

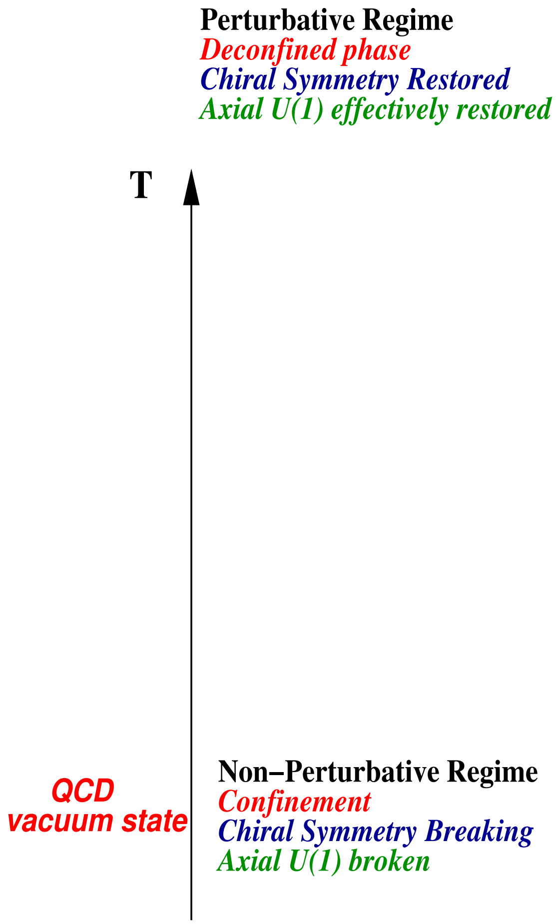
are broken by a non-zero chiral condensate $\langle\bar{\psi}\psi\rangle$. Light mesons play the role of (pseudo)Goldstone bosons

Fate of $U_A(1)$ symmetry

The symmetry under axial transformations $\psi \to e^{i\alpha\gamma_5}\psi$ is explicitely broken by the axial anomaly

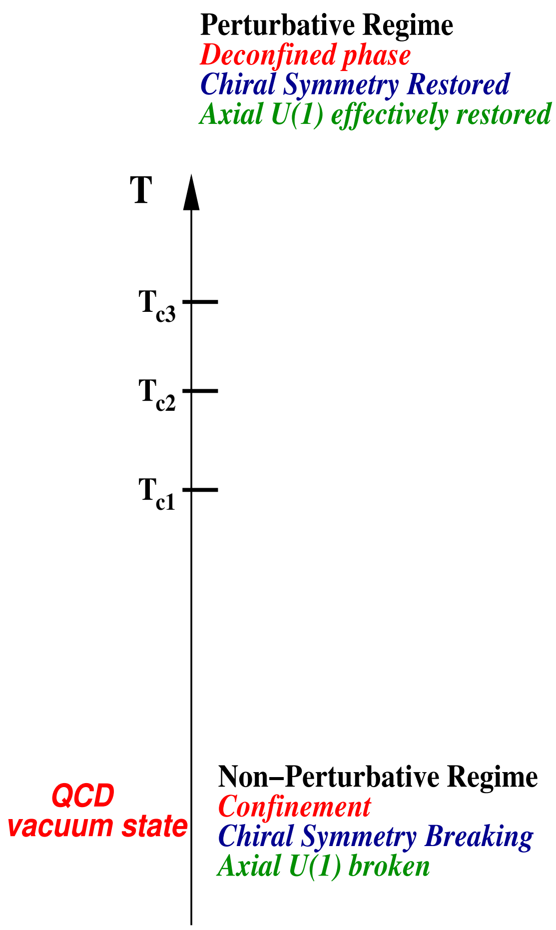
$$\partial_\mu j^5_\mu = 2N_f Q(x) \quad ; \quad j^5_\mu = \sum_{i=1}^{N_f} \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$$

where $Q(x)$ is the topological charge density. The presence of topological fluctuations (instantons) populating the QCD vacuum links the axial anomaly to important properties of hadron phenomenology, like the mass of the η' particle, which is related to the topological susceptibility $\chi = \langle Q^2\rangle_{quench}/V$ by the Witten-Veneziano formula.

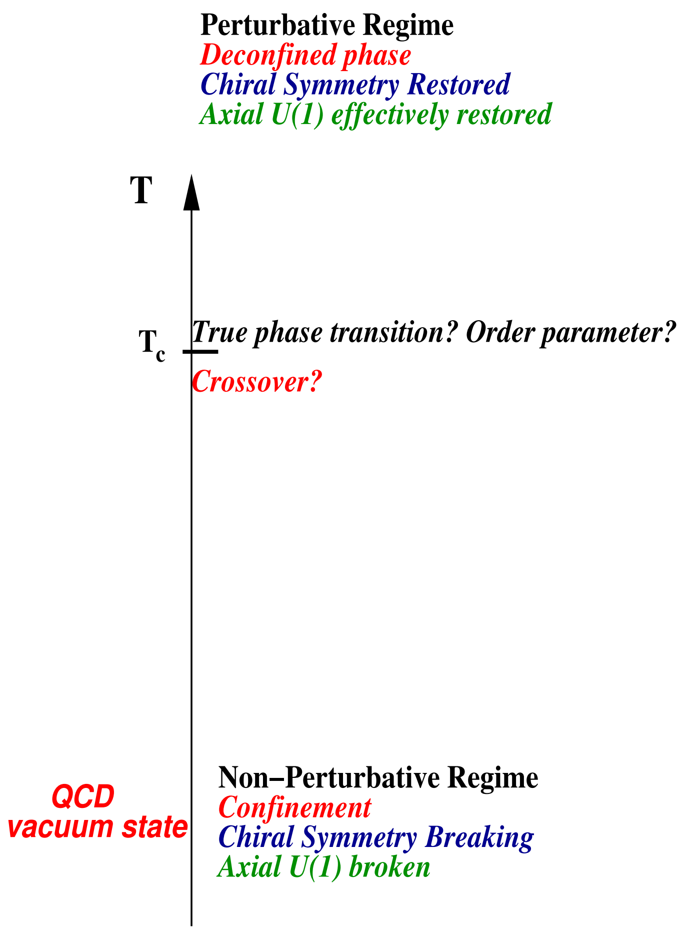


For a system of strongly interacting matter in equilibrium at temperature T, those non-perturbative properties are expected to disappear as the perturbative regime is reached at high temperatures.

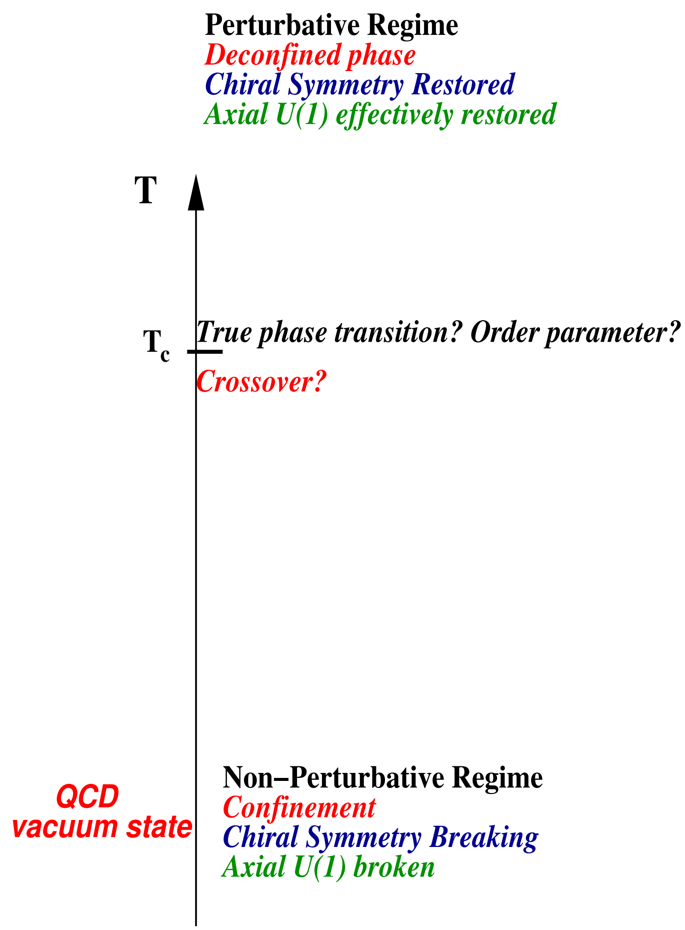
How that happens is the subject of theoretical and experimental investigations.



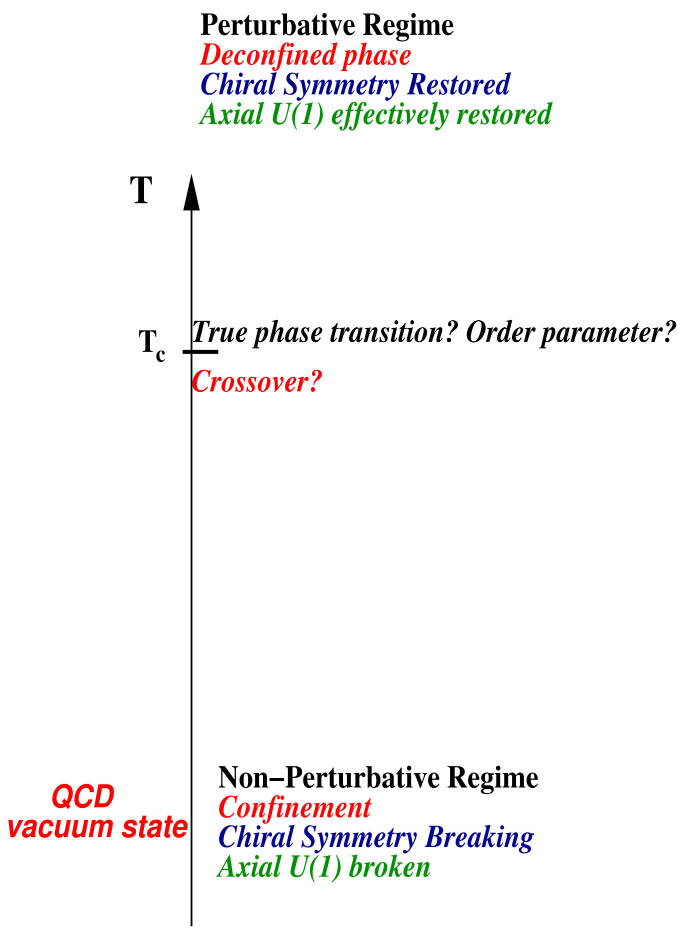
The interrelation among the three distinct phenomena is still not clear. In principle, three different transitions could take place at three different temperatures. The nature of the transitions and their mutual positions could be understood in terms of the structure of the QCD vacuum, or could help in understanding vacuum symmetries.



In practice, numerical lattice simulations show that, at least in ordinary QCD, a single transition takes place. The question whether it corresponds to a true phase transition or to a simple crossover and, in the first case, about which is a sensible order parameter, is still debated. The problem is a fundamental one.



Chiral Symmetry is exact as $m_q \to 0$. A phase transition is surely expected in that limit, with the chiral condensate $\langle \bar{\psi}\psi \rangle$ being a possible order parameter.

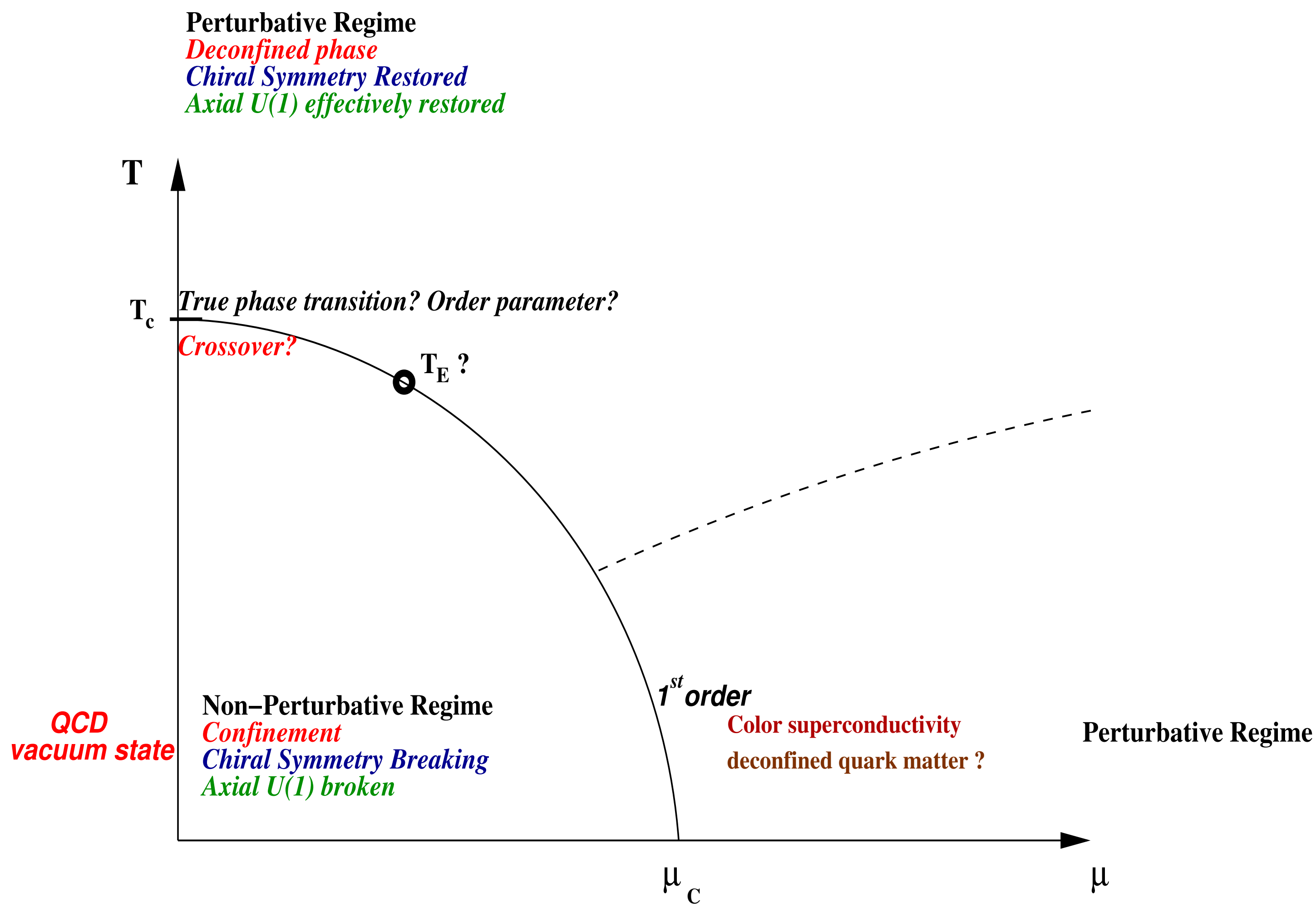


Color Confinement: a definite answer about the underlying symmetry is still lacking.

Z_3 **Center symmetry is exact only in the pure gauge theory, i.e. as all quark masses** $m_q \to \infty$**: the Polyakov loop is a good order parameter only in that limit.**

Models of Color Confinement $\Longrightarrow$ **better symmetries and order parameters**

A deconfinement crossover would be puzzling: Is it compatible with our view of confinement as an absolute property? Should we change our mind?



The answer reveals particularly interesting when considering the QCD phase diagram in presence of a finite baryonic chemical potential.

Models predict a first order transition at $T = 0$

crossover at $\mu = 0 \implies$ critical endpoint T_E with clear experimental signatures.

Understanding the structure of the QCD vacuum state is therefore strictly linked to clarifying the structure of the QCD phase diagram.

- Structure and symmetry of the vacuum $\Longrightarrow$ guidance and order parameters for studying the phase transition(s)
- Numerical study of the QCD phase diagram $\Longrightarrow$ precious information for clarifying the structure and the symmetry of the vacuum.

The activity of our group has been dedicated to various interrelated aspects of this subject since many years, by studying both the properties of the vacuum state and the nature of the deconfinement transition. I will review in the following the status and the prospects of a few projects which, being particularly demanding in terms of computer power, are strictly dependent on the availability of the apeNEXT machines.

2 – OUTLINE

- **Order of the chiral transition for $N_f = 2$**
- **Topology and the η' mass across the deconfinement transition**
- **Deconfinement and chiral phase transitions in QCD with adjoint fermions**
- **Deconfinement in finite density QCD**

Not touched **(pure gauge projects running on APEmille or on PC clusters)**

- **Confinement in theories with different gauge groups (G2)**
- **Field strength correlators and confinement**
- **Phenomenological parameter of the Dual Superconductor Model**

People involved: **C. Bonati, G. Cossu, A. Di Giacomo, G. Lacagnina, E. Meggiolaro, G. Paffuti (Pisa)**
S. Conradi, A. D'Alessandro, M. D'E. (Genova)
B. Lucini (Swansea), C. Pica (Brookhaven)

3 – CHIRAL TRANSITION FOR $N_f = 2$

G. Cossu (Pisa), M. D'E. (Genova), A. Di Giacomo (Pisa), C. Pica (Brookhaven)

The order of the phase transition for QCD with two flavors ($N_f = 2$) in the chiral limit ($m_q = 0$) is still an open problem.

It is quite relevant for various reasons

- **It is quite close to the physical case**
- **Its properties determine the nature of the phase transition for finite masses**
- **It is a testground for clarifying important properties of the phase diagram and of the QCD vacuum**

In the chiral limit $\langle\bar{\psi}\psi\rangle$ is a good order parameter

We are sure that a phase transition takes place: predictions about its nature can then be obtained by a renormalization group analysis of the effective chiral model:

R. D. Pisarski and F. Wilczek, Phys. Rev. D 29, 338 (1984)

$$\tilde{\phi}: \quad \phi_{ij} \equiv \langle \bar{q}_i(1+\gamma_5)q_j\rangle \quad (i,j = 1,\ldots,N_f)$$

Under chiral and $U_A(1)$ transformations of the group $U_A(1)\otimes SU(N_f)\otimes SU(N_f)$, $\tilde{\phi}$ transforms as

$$\tilde{\phi} \to e^{i\alpha}U_+\tilde{\phi}U_-$$

so that by the usual symmetry arguments, and neglecting irrelevant terms

$$\mathcal{L}_\phi = \frac{1}{2}Tr\{\partial_\mu\phi^\dagger\partial^\mu\phi\} - \frac{m_\phi^2}{2}Tr\{\phi^\dagger\phi\} - \frac{\pi^2}{3}g_1\left(Tr\{\phi^\dagger\phi\}\right)^2 - \frac{\pi^2}{3}g_2 Tr\{(\phi^\dagger\phi)^2\} + c\left[\det\phi + \det\phi^\dagger\right]$$

The last term describes the anomaly: indeed it is $SU(N_f)\otimes SU(N_f)$ invariant, but not $U_A(1)$ invariant.

For $N_f = 2$

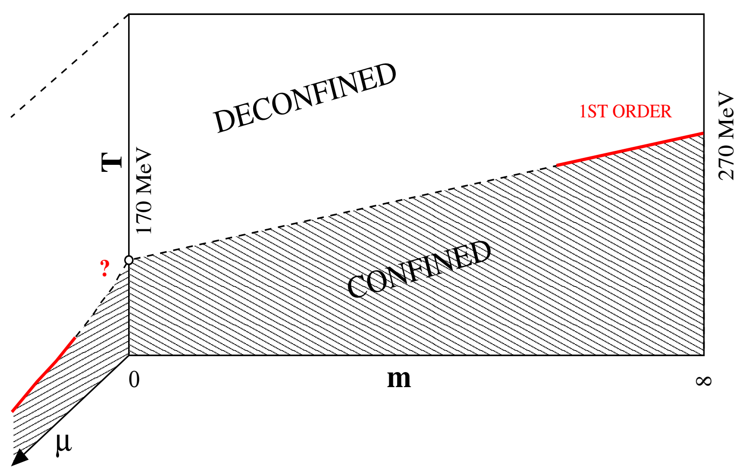
- $U_A(1)$ anomaly effective (no light η') $\Longrightarrow$ the model has a fixed point chiral transition could be second order in $O(4)$ universality class (not exclusive of different possibilities: first order, mean field, ...).

- $U_A(1)$ anomaly not effective (η' is light) $\Longrightarrow$ the model does not have a fixed point $\Longrightarrow$ first order but see also F. Basile, A. Pelissetto, E. Vicari, 2005

Different scenarios are open by the two possibilities

- Second order at $m_q = 0$ $\Longrightarrow$ crossover at finite small quark masses $\Longrightarrow$ critical point in the T, μ plane.

- First order $\Longrightarrow$ first order also away from the chiral point.



The problem can be settled by numerical lattice computations and a Finite Size Scaling (f.s.s.) analysis. There are however a few difficulties

- **Simulations on large volumes and with light quark masses are necessary for a reliable f.s.s. analysis $\Longrightarrow$ huge computational power required**

- **f.s.s. behavior is given in terms of two different scales**

free energy density scaling $\Longrightarrow$ $\frac{\mathcal{L}}{kT} \simeq L_s^{-d} \phi \left(\tau L_s^{1/\nu}, a m_q L_s^{y_h} \right)$

L_s **is the spatial size**

τ **is the reduced temperature,**

ν **is the critical index of the correlation length ($\xi \sim \tau^{-\nu}$)**

y_h **is the magnetic critical index**

specific heat $\Longrightarrow$ $C_V - C_0 \simeq L_s^{\alpha/\nu} \phi_c \left(\tau L_s^{1/\nu}, a m_q L_s^{y_h} \right)$

order parameter susceptibility $\Longrightarrow$ $\chi - \chi_0 \simeq L_s^{\gamma/\nu} \phi_\chi \left(\tau L_s^{1/\nu}, a m_q L_s^{y_h} \right)$

The problem has been investigated in the past by different groups

Staggered quarks (where O(2) could be more appropriate - Karsch, 1994)

M. Fukugita, H. Mino, M. Okawa and A. Ukawa, PRL 65, 816 (1990); PRD 42, 2936 (1990)

F. R. Brown, *et al*, PRL 65, 2491 (1990)

F. Karsch, PRD 49, 3791 (1994)

F. Karsch and E. Laermann, PRD 50, 6954 (1994)

S. Aoki et al. (JLQCD collaboration), PRD 57, 3910 (1998)

C. Bernard *et al*, PRD 61, 054503 (2000)

J. B. Kogut and D. K. Sinclair, PRD 73 (2006) 074512

Wilson fermions

A. A. Khan et al. (CP-PACS collaboration), PRD 63, 034502 (2001)

Main strategies adopted:

Search for metastabilities

Scaling of pseudocritical temperatures with the quark mass

Approximate scaling for susceptibilities (assuming the infinite volume limit $L_s \to \infty$)

Equation of state for the order parameter

No clear answer in favour or disfavour of $O(4)$ or $O(2)$ critical behaviour

Our contribution

M. D'E, A. Di Giacomo and C. Pica, PRD 72, 114510 (2005)

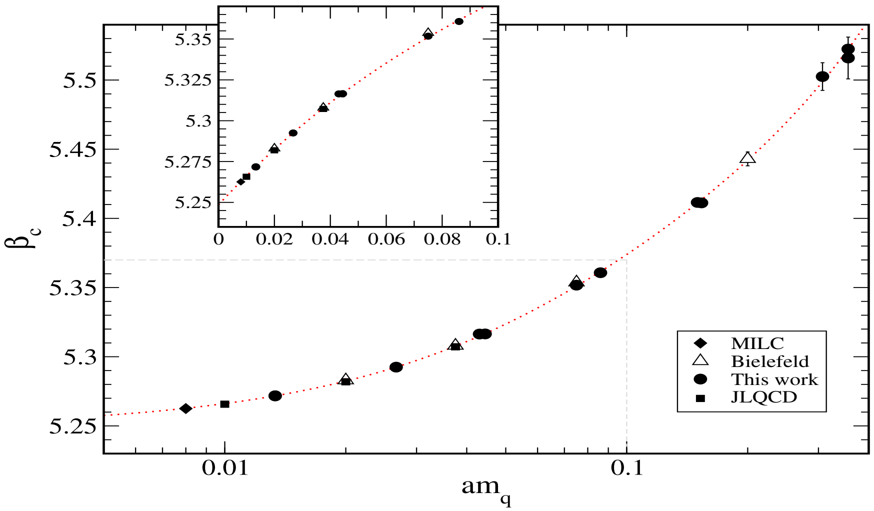
We have approached the problem for the case of staggered fermions, obtaining some progress by using a novel strategy for the f.s.s., together with the availability of relevant resources of computer power (APEmille).

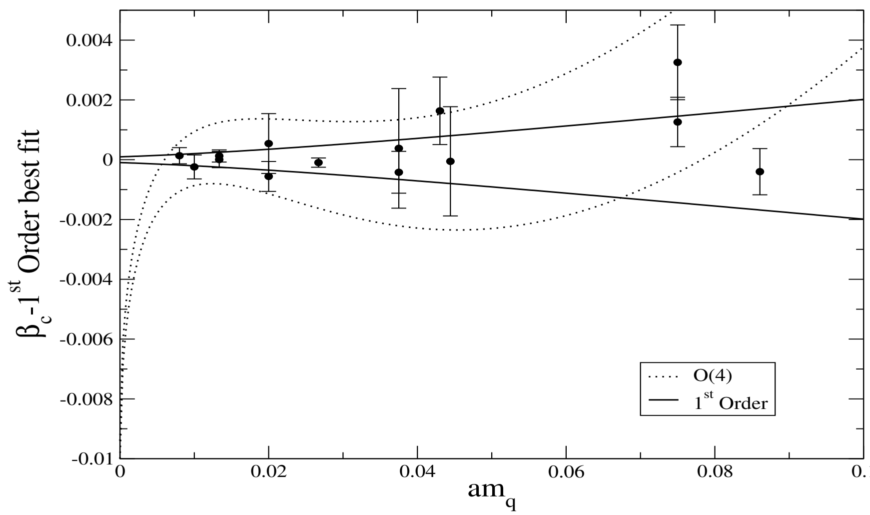
- We have performed series of runs at variable L_s and quark mass am_q, keeping $am_q L_s^{y_h}$ fixed. That reduce the problem again to one scale.
  Assume one particular behavior (fix y_h) $\Longrightarrow$ check it carefully.
  Our choice has been for $O(4)$ ($O(2)$) $\Longrightarrow$ $y_h = 2.49$
- We have reanalyzed the scaling of pseudocritical temperatures and considered also the dependence of T on the quark mass, $T = 1/(N_t a(\beta, m_q))$.
- We have taken into special consideration the specific heat, as it always reveals the correct critical behavior, indipendently of the nature of the order parameter

	y_t	y_h	ν	α	γ
$O(4)$	1.336(25)	2.487(3)	0.748(14)	-0.24(6)	1.479(94)
$O(2)$	1.496(20)	2.485(3)	0.668(9)	-0.005(7)	1.317(38)
MF	$3/2$	$9/4$	$2/3$	0	1
$1^{st} Order$	3	3	$1/3$	1	1

Main results

Pseudocritical couplings alone are not enough to discern the order of the transition

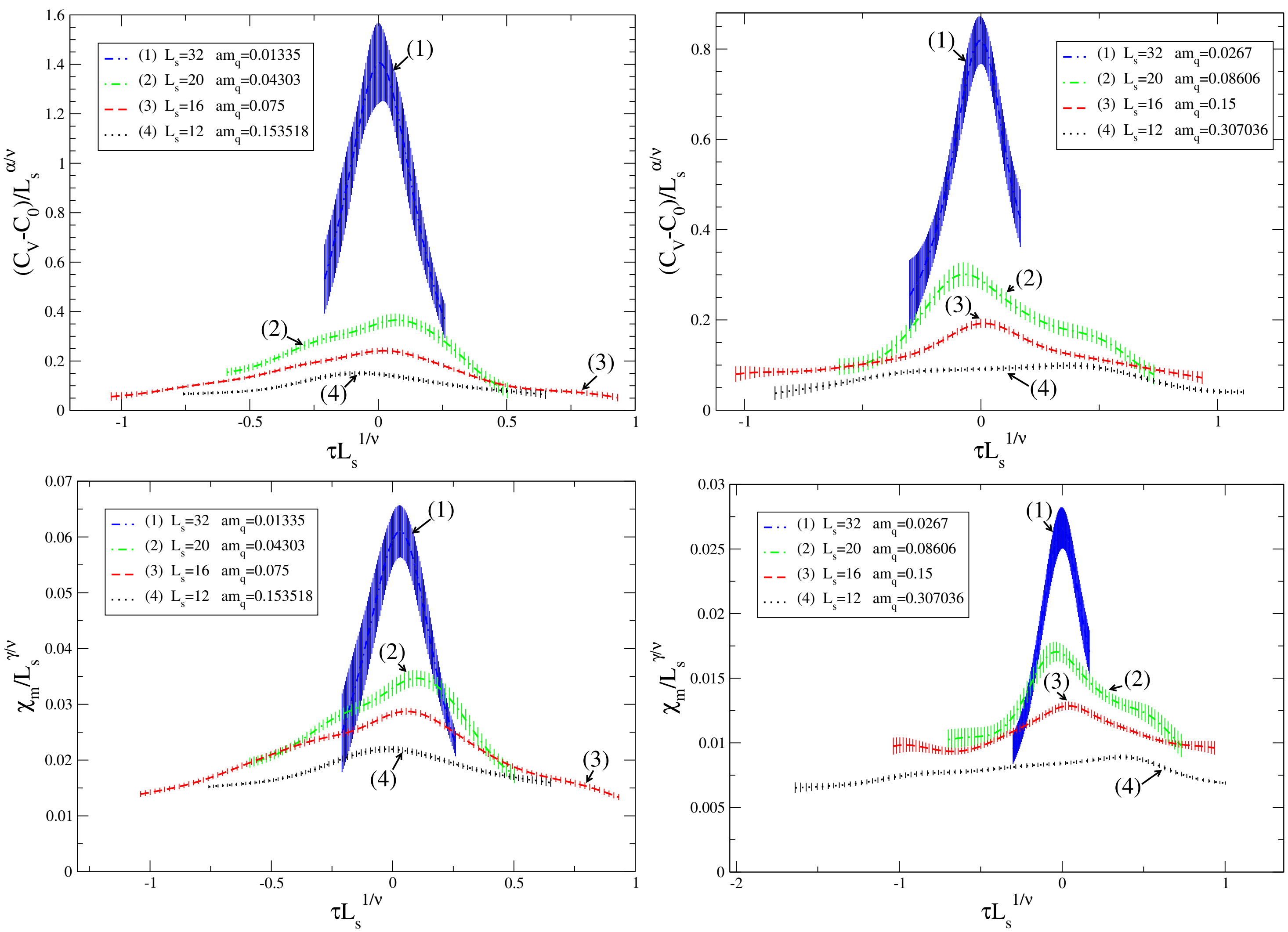




$$\tau \propto (\beta_0 - \beta) + k_m a m_q + k_{m^2} (a m_q)^2 + k_{m\beta} a m_q (\beta_0 - \beta)\,.$$

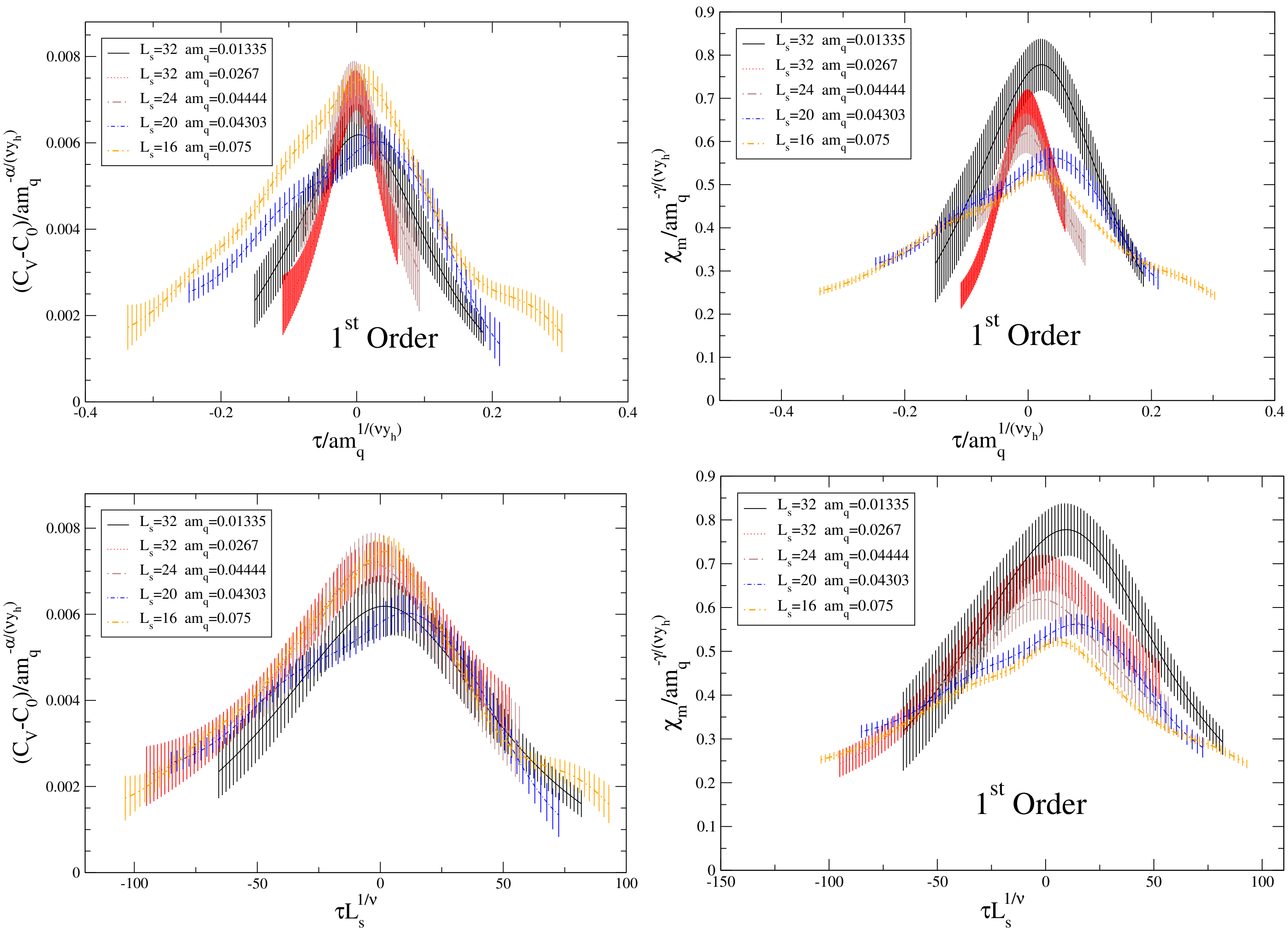
$$\tau = k_\tau (a m_q)^{1/\nu y_h} \quad \text{or} \quad \tau = \mathrm{k}'_\tau \mathrm{L_s}^{1/\nu}\,.$$

The scaling of susceptibilities is not compatible with $O(4)$ ($O(2)$)



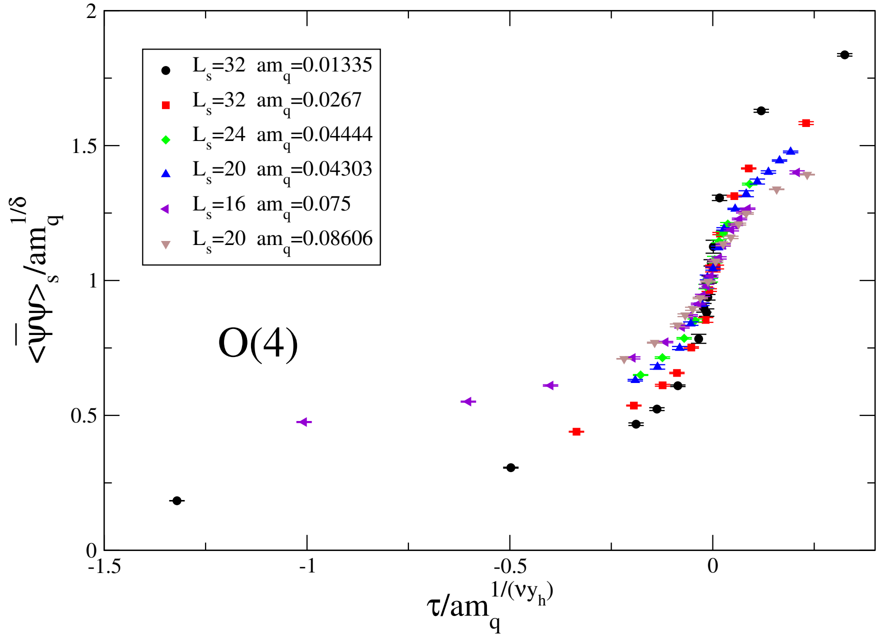
Scaling of the specific heat (top) and χ_m (bottom) for Run1 (left) and for Run2 (right). The curves are obtained by reweighting.

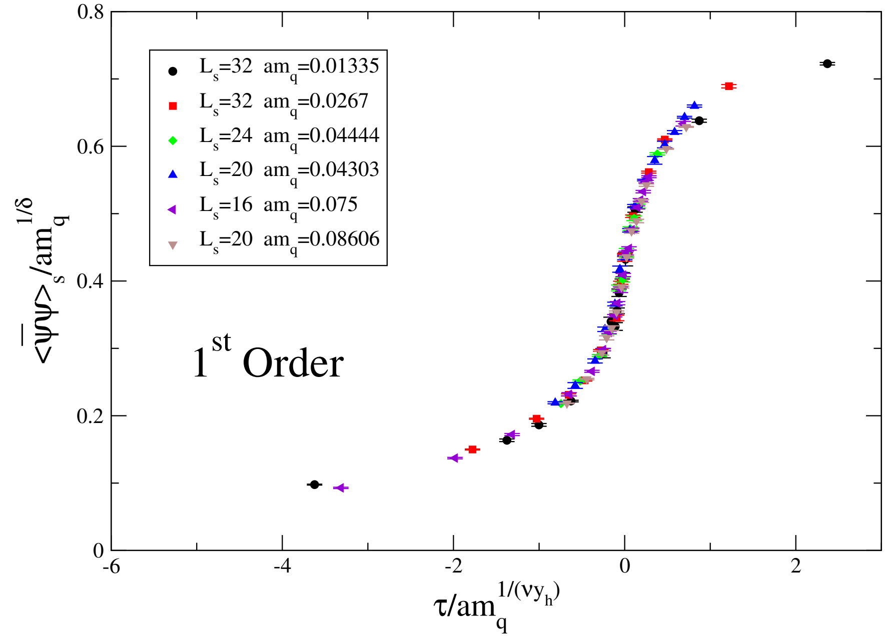
ne other hand, approximate scaling laws are marginally compatible with first order



Approximate scaling, assuming $L_s \to \infty$ (top) or at $\tau L_s^{1/\nu}$ fixed (bottom)

The equation of state for the order parameter gives similar results





Data are not compatible with $O(4)$ ($O(2)$) scaling, but suggest instead a first order transition.

We have achieved some progress, but several questions are still left open ...

- We have used a non exact R algorithm $\Longrightarrow$ check with exact algorithm
- We should directly test 1^{st} order $\Longrightarrow$ new run series with $y_h = 3$
- If the transition is 1^{st} order also at finite mass, we should find metastabilities on large enough volume
- The complete specific heat should be reconstructed, not only the most singular pieces
- We should check for finite cutoff effects: we have used standard gauge and staggered actions with $N_t = 4$ ($a \sim 0.3\, fm$) $\Longrightarrow$ repeat the analysis for $N_t = 6$ and/or improved action

... which we are considering and hope to settle in the near future. Some points will be particularly computer expensive, apeNEXT will be a precious resource.

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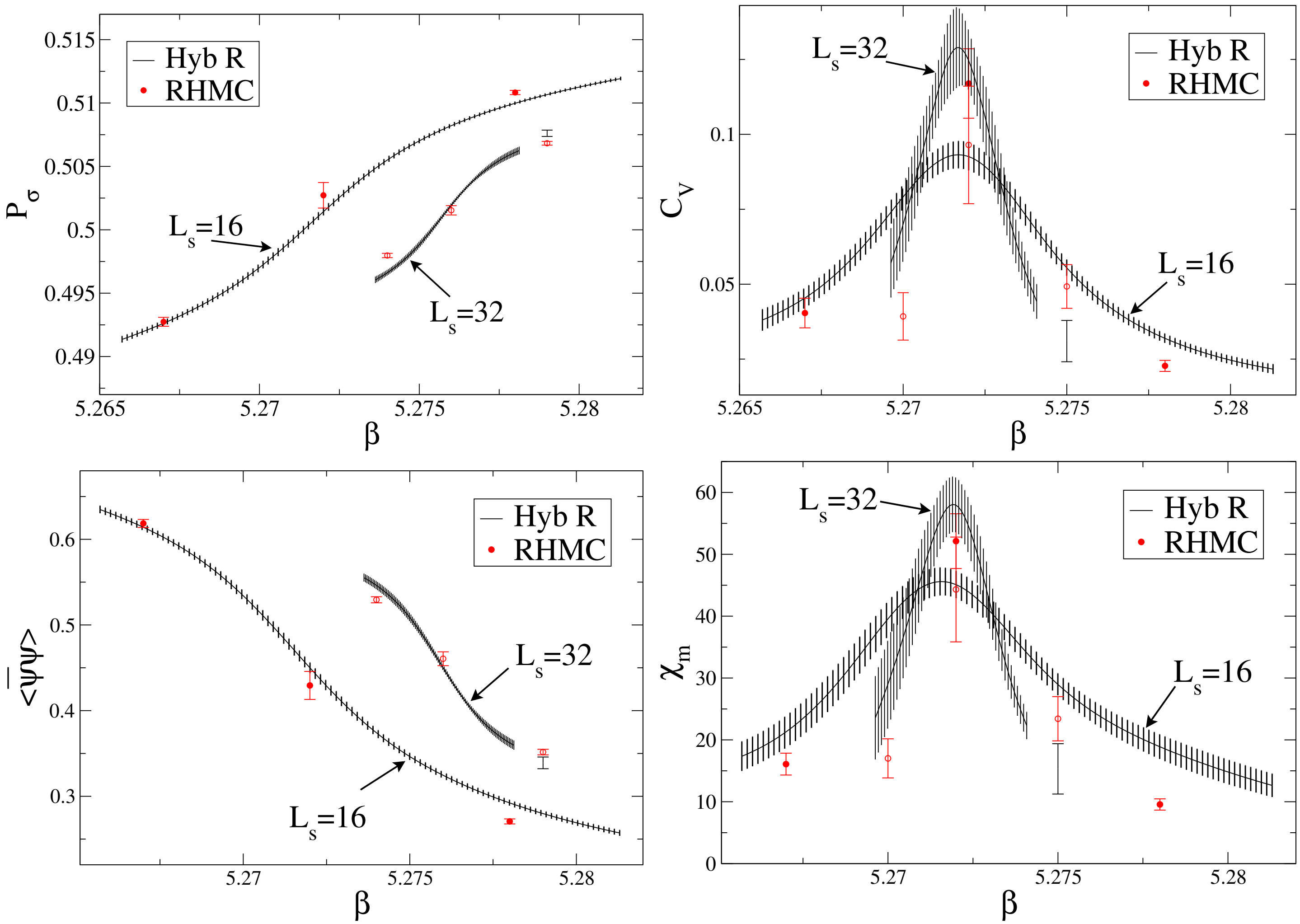
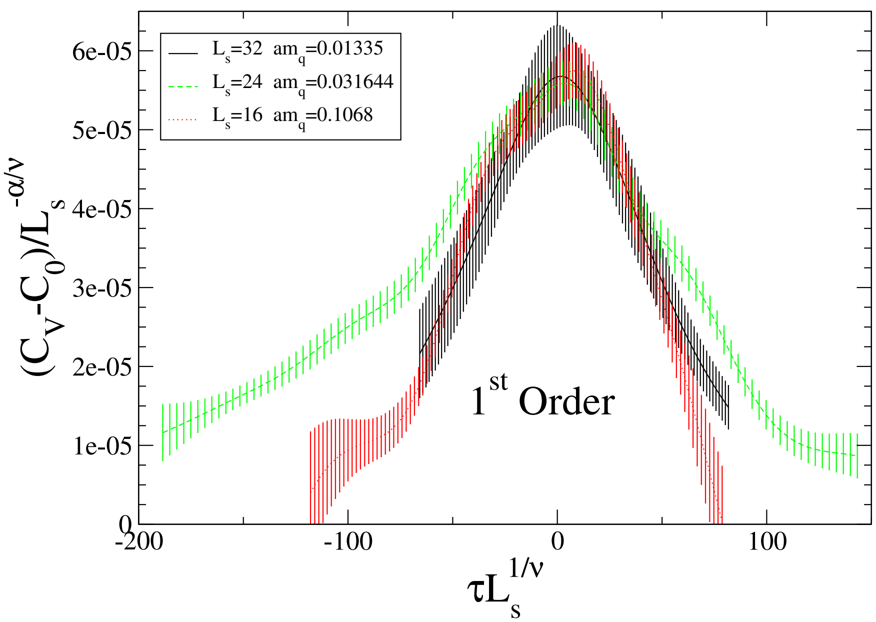
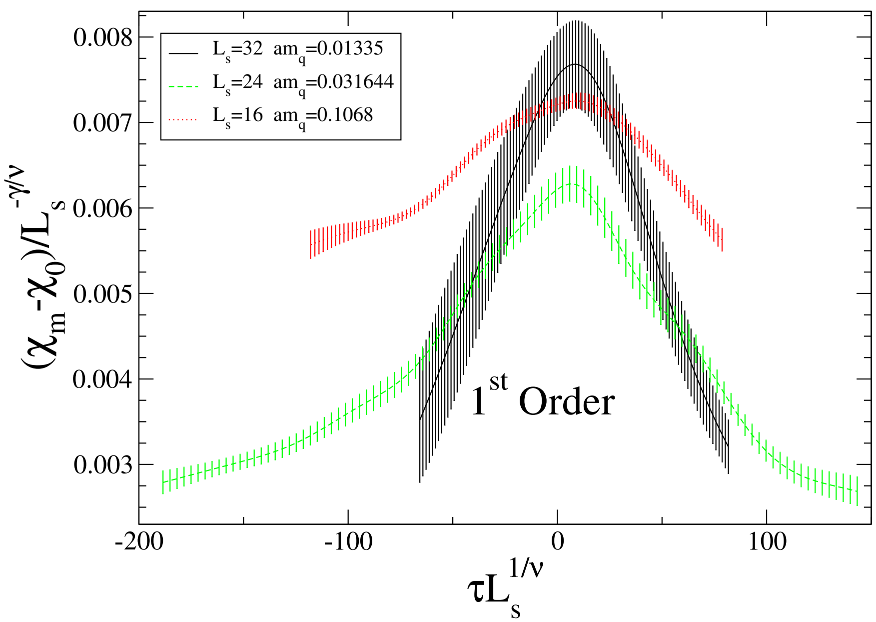
We have compared our old results with an exact RHMC at our lowest mass, $am_q = 0.01335$



no significat discrepancy has been found

Direct test of the first order hypothesis





Chiral susceptibility shows some deviations: probably we are too far from the chiral limit. We are considering other possible systematic effects

The specific heat shows a quite good scaling

Looking for alternative order parameters ...

Can we study the transition with order parameters directly related to Color Confinement ? Dual Superconductivity of the QCD vacuum ('t Hooft, Mandelstam) $\Longrightarrow$ Confinement is related to the spontaneous breaking of an abelian magnetic symmetry.

An order parameter can be constructed in that framework, which is the expectation value of an operator with a non trivial magnetic charge, $\langle \mu \rangle$
μ can be for instance the creation operator of a magnetic monopole.

Such an operator has been developed and studied on the lattice by the Pisa group, extensively for the pure gauge theory. Similar parameters also in Bari, Moscow.

Measuring $\langle \mu \rangle$ is like measuring the expectation value of a dual variable (imagine a kink in Ising $2d$) in the original theory (where it appears as a topological defect).
In this case we do not know the theory which is dual to QCD, but we can try guessing the form of the dual variables.

μ **is written as a translation operator which shifts the quantum gauge field by the classical field of a monopole.**

$$\mu(\vec{x},t) = \exp\left[i\int d\vec{y}\ \vec{E}_{\perp\ diag}(\vec{y},t)\vec{b}_{\perp}(\vec{x}-\vec{y})\right]$$

On the lattice it can be written as the ratio of two partition functions

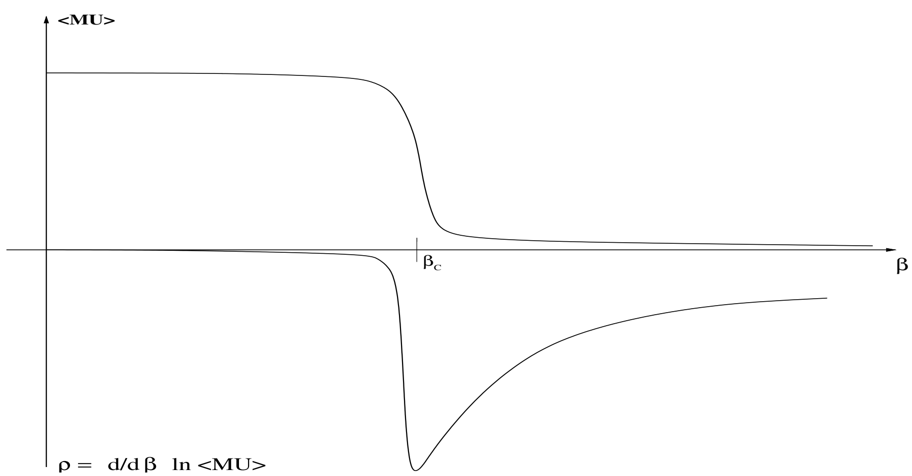
$$\langle\mu\rangle = \frac{\tilde{Z}}{Z}\,, \quad Z \quad = \quad \int (\mathcal{D}U)\det M(\mu)e^{-\beta S}\,, \quad \tilde{Z} = \int (\mathcal{D}U)\det M(\mu)e^{-\beta\tilde{S}}$$

Determining the ratio of two partition functions is difficult. One usually measures

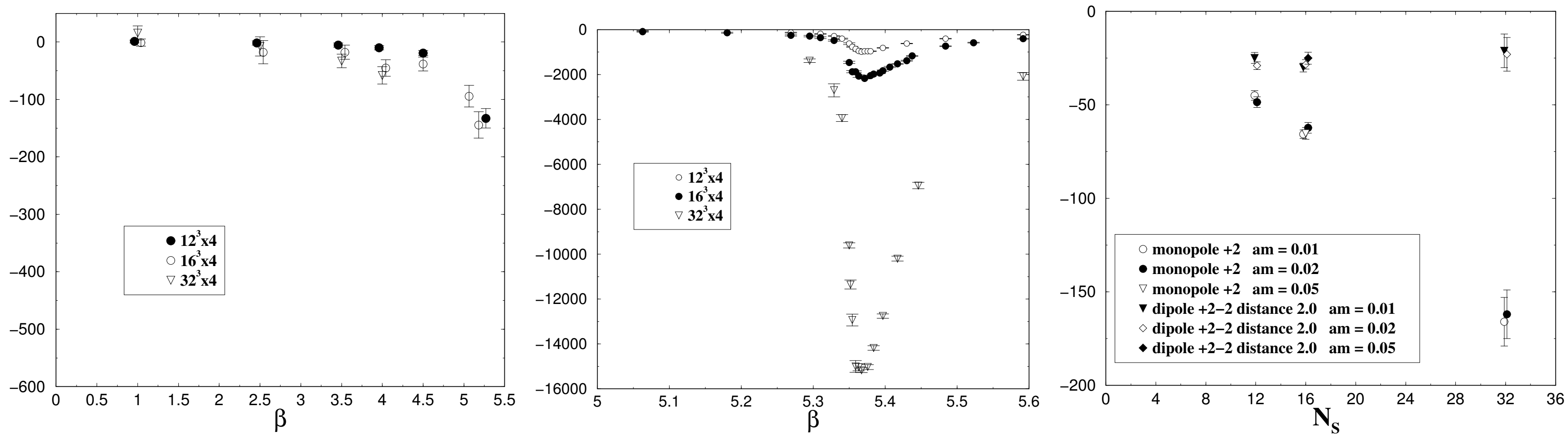
$$\rho = \frac{d}{d\beta}\ln\langle\mu\rangle = \langle S\rangle_S - \langle\tilde{S}\rangle_{\tilde{S}}$$

from which the order parameter can be reconstructed

$$\langle\mu\rangle(\beta) = \exp\left(\int_0^\beta \rho(\beta')\mathrm{d}\beta'\right)$$

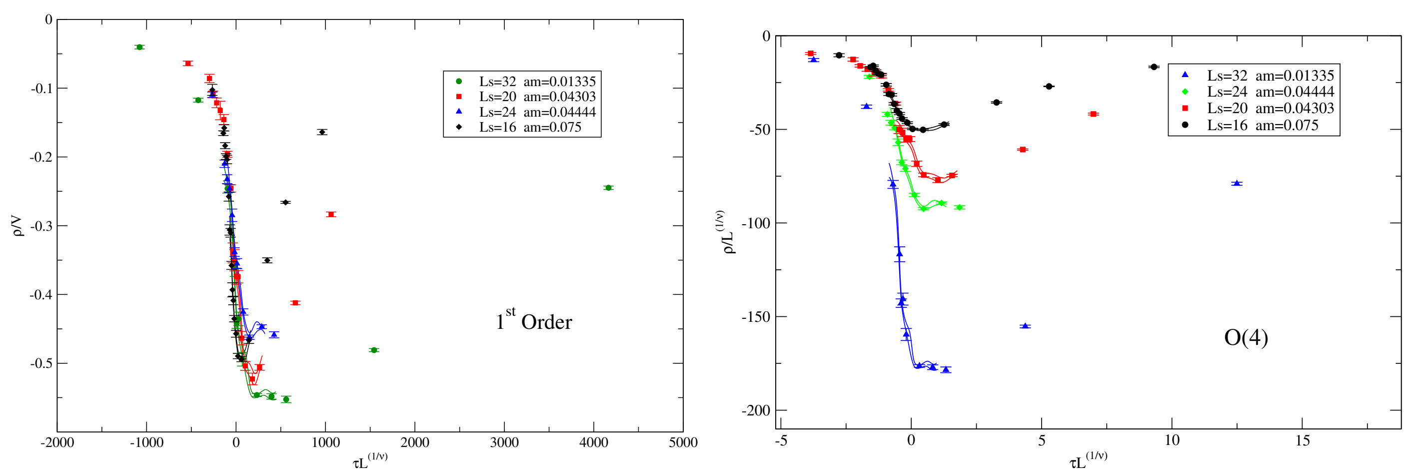


$\langle \mu \rangle$ is a good order parameter also in presence of dynamical fermions



J. M. Carmona, L. Del Debbio, M. D'E., A. Di Giacomo, B. Lucini, G. Paffuti, Phys. Rev. D 66, 011503 (2002).

and it scales according to first order around the chiral transition



M. D'E., A. Di Giacomo, B. Lucini, G. Paffuti, C. Pica, Phys. Rev. D 71, 114502 (2005).

4 – TOPOLOGY AND THE η' MASS

B. Alles (Pisa), G. Cossu, M. D'E. (Genova), A. Di Giacomo (Pisa), C. Pica (Brookhaven)

The fate of the $U_A(1)$ symmetry may influence the order of the chiral transition for $N_f = 2$. A new light pseudoscalar degree of freedom changes the renormalization group analysis of the effective chiral model, favouring a first order.

see also a recent strong coupling calculation: S. Chandrasekharan, A.C. Mehta, hep-lat/0611025

A study of the behavior of $m_{\eta'}$ across the transition is therefore a due complement to our previous analysis.

Determinations of the η' mass on the lattice are notoriously difficult, because of disconnected diagrams entering the η' propagator which are very noisy.

for recent determinations see:

K. Schilling, H. Neff and T. Lippert, Lect. Notes Phys. 663 (2005) 147, [hep-lat/0401005]

C. R. Allton *et al*, Phys. Rev. D70 (2004) 014501, [hep-lat/0403007]

CP-PACS Collaboration, Phys. Rev. D67 (2003) 074503, [hep-lat/0211040] and [hep-lat/0610021]

E. B. Gregory, A. C. Irving, C. McNeile, C. M. Richards, [hep-lat/0610044].

We follow a different approach, based on the study of topological charge correlators.

The two point function of the topological charge density operator

$$Q(x) = \frac{g^2}{64\pi^2}\epsilon_{\mu\nu\rho\sigma}F^a_{\mu\nu}(x)F^a_{\rho\sigma}(x) = \partial_\mu K_\mu(x) \ ,$$

is dominated at large distances by the lightest physical state coupled to Q, that is a pseudoscalar singlet meson (η') in presence of dynamical fermions.

In particular we can write for the temporal correlator at zero momentum

$$\lim_{t\to\infty}\int d^3x\langle Q(\vec{x},t)Q(0)\rangle \sim Ae^{-m_{\eta'}t}$$

with the constant $A < 0$ by reflection positivity.

$m_{\eta'}$ can thus be determined by studying topological charge correlators

Any definition of the discretized topological charge density $Q_L(x)$ can be adopted, with proper care about renormalizations and contact terms

In the simplest approximation $\langle Q_L(x)Q_L(0)\rangle$ is related to $\langle Q(x)Q(0)\rangle$ by

$$\langle Q_L(x)Q_L(0)\rangle = Z^2\langle Q(x)Q(0)\rangle + c_L(x)$$

Z is a multiplicative renormalization and $c_L(x)$ a delta-like positive contact term: a similar term is present also in the continuum definition, ensuring $\chi = \langle Q^2\rangle/V > 0$. **Actually, mixings with other pseudoscalar fermion operators are present, which do not change the asymptotic behaviour of $\langle Q_L(x)Q_L(0)\rangle$, since they all couple to the η'**

$c_L(x) \neq 0$ in a finite region of size S_{O_L} around $x = 0$, where reflection positivity $\langle Q_L(x)Q_L(0)\rangle < 0$ is violated. S_{O_L} depends on the extension of $Q_L(x)$. Therefore

$$C(t) \equiv \sum_{\vec{x}} \langle Q_L(\vec{x},t)Q_L(0)\rangle \sim Z^2 A e^{-m_{\eta'} t}$$

for large enough t, provided also $t > S_{O_L}$. Z^2 is not relevant for determining $m_{\eta'}$

Our choice for $Q_L(x)$ is that of a simple discretization of $Q(x)$ given in terms of gauge fields only. We consider for instance the sequence of smeared operators

$$Q_L^{(i)}(x) = \frac{-1}{2^9\pi^2} \sum_{\mu\nu\rho\sigma=\pm1}^{\pm4} \tilde{\epsilon}_{\mu\nu\rho\sigma} \mathbf{Tr} \left(\Pi_{\mu\nu}^{(i)}(x)\Pi_{\rho\sigma}^{(i)}(x)\right) \ ,$$

where $\Pi_{\mu\nu}^{(i)}(x)$ is the plaquette operator constructed with i–times smeared links $U_\mu^{(i)}(x)$, which are defined as

$$\begin{aligned} U_\mu^{(0)}(x) &= U_\mu(x) \ , \\ \overline{U}_\mu^{(i)}(x) &= (1-c)U_\mu^{(i-1)}(x) + \frac{c}{6} \sum_{\substack{\alpha=\pm1 \\ |\alpha|\neq\mu}}^{\pm4} U_\alpha^{(i-1)}(x)U_\mu^{(i-1)}(x+\hat{\alpha})U_\alpha^{(i-1)}(x+\hat{\mu})^\dagger, \\ U_\mu^{(i)}(x) &= \overline{U}_\mu^{(i)}(x) \, / \, (\frac{1}{3}\mathbf{Tr}\overline{U}_\mu^{(i)}(x)^\dagger\overline{U}_\mu^{(i)}(x))^{1/2} \end{aligned}$$

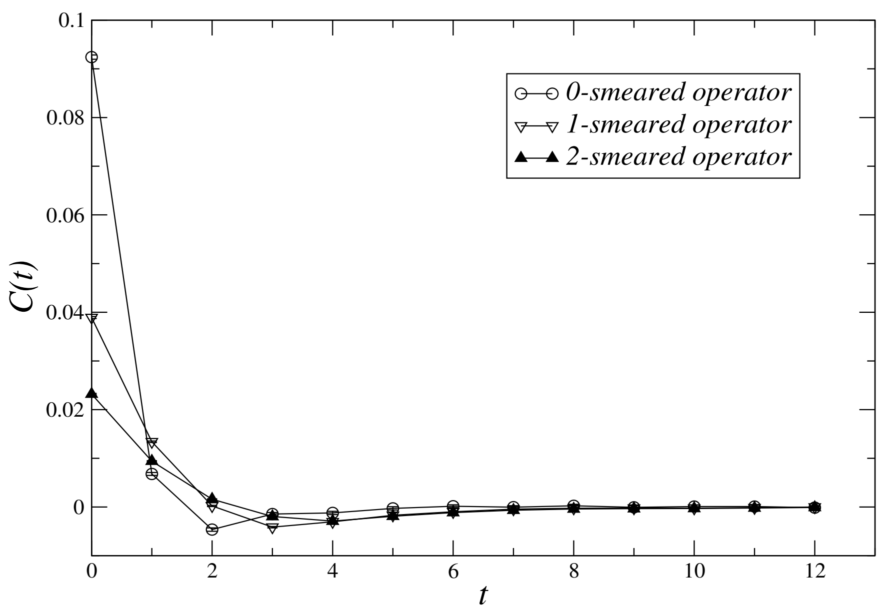
The asymptotic behavior of the correlator is independent of the operator and solely related to the η' mass. However, comparison of determinations of $m_{\eta'}$ obtained with different operators gives an estimate of systematic errors.

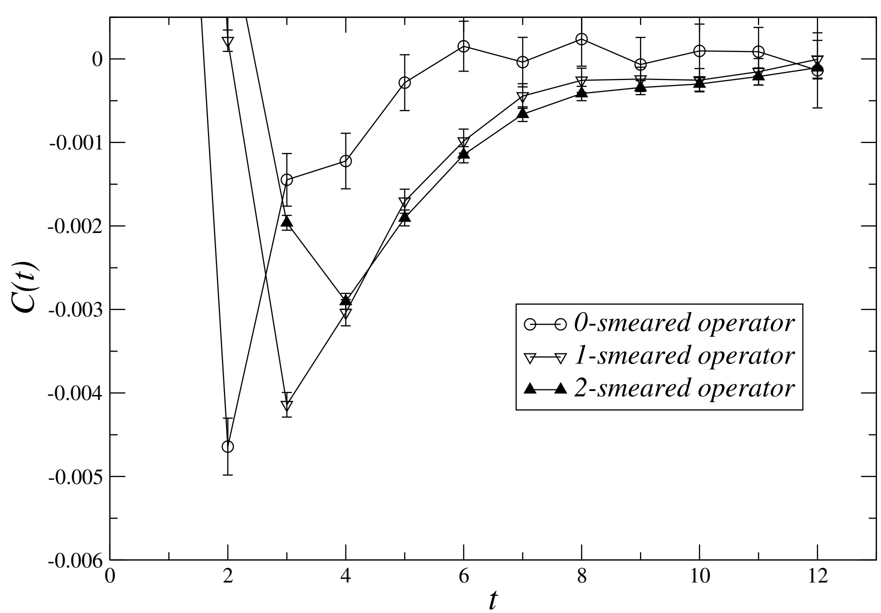
Smearing damps UV fluctuations: noise is reduced and the multiplicative Z^2 renormalization increases, with a great improvement in the signal/noise ratio. Also, the overlap with the lowest energy state may be enhanced.

But smearing also increases the size (in lattice units) of the operator $O_L(x)$, hence the size S_{O_L} of the region where the correlator $C(t)$ is still affected by contact terms.

$\Longrightarrow$ look for optimal balance between the two opposite effects

The problem can be critical because of the large value of $m_{\eta'}$ or limited number of lattice sites available at finite T





Our choice in order to make the problem less critical $\Longrightarrow$ anisotropic lattices

- **a smaller temporal lattice spacing a_t leads to a larger value of temporal lattice sites N_t for a fixed temperature $T = 1/(N_t a_t)$, therefore to an increased number of useful determinations for the correlator $C(t)$. That without an unbearable increase in the required computer power, since a_s can be kept relatively large.**
- **a side (desirable) effect is that $T = 1/(N_t a_t)$ can be fine tuned by simply changing N_t, i.e. without changing the physical scale and/or the spatial volume, thus isolating effects purely due to a change of T.**

Therefore we have started a pilot study with two degenerate staggered flavors, using the action parameters provided in

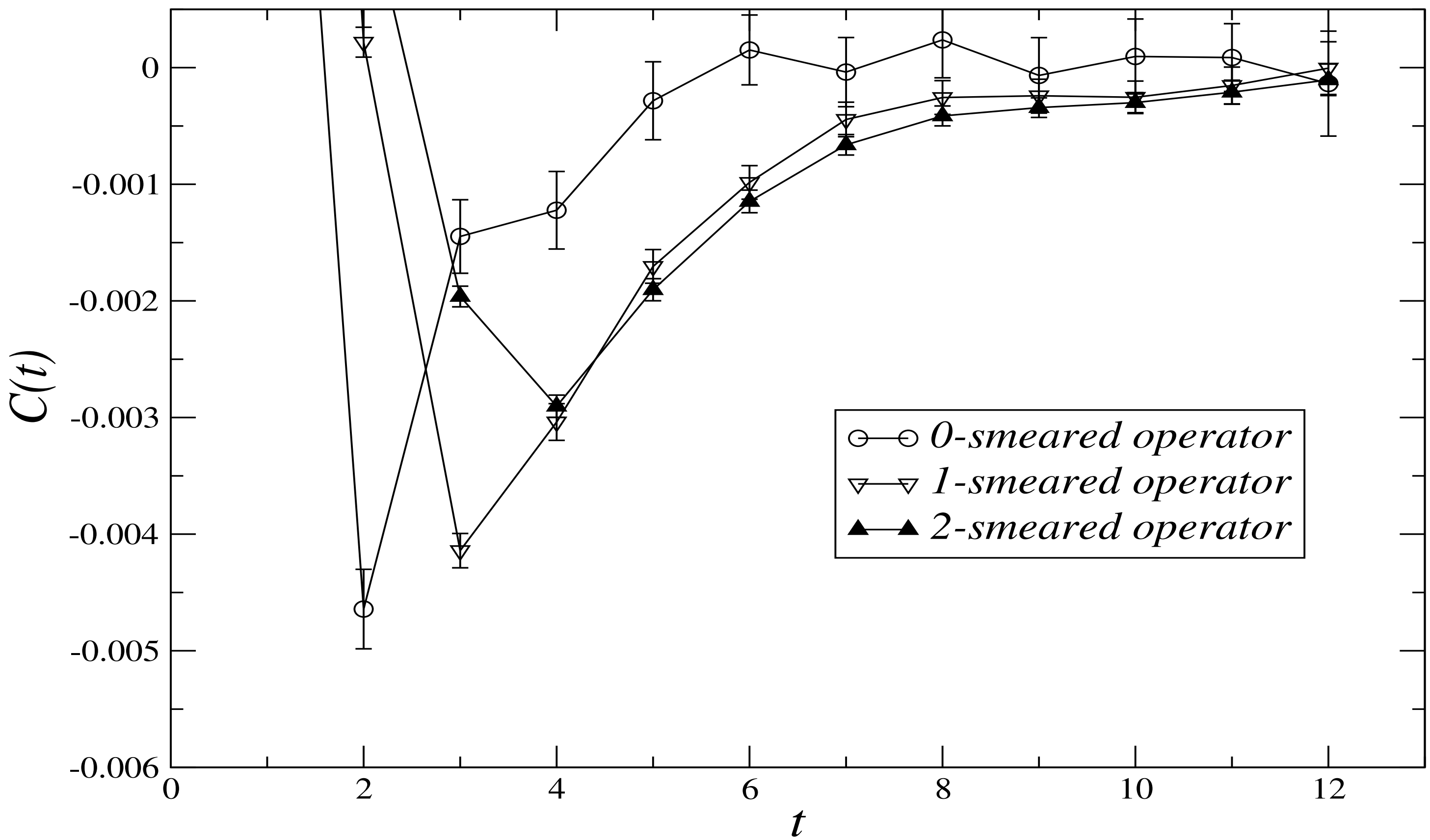
L. Levkova, T. Manke, R. Mawhinney, Phys. Rev. D 73, 074504 (2006).

- **standard gauge and staggered action, $\beta = 5.3$, $am_q = 0.008$, $\xi_0 = 3.0$**
- $m_\pi/m_\rho \sim 0.3$ **;** $a_s \simeq 0.34\,fm$, $a_t \simeq 0.085\,fm \Longrightarrow \xi \equiv a_s/a_t \simeq 4$

Preliminary results

We are performing numerical simulations on lattices with s $N_s = 16$ ($N_s a_s \sim 5\, fm$) and variable N_t. We have so far results with $N_t = 24 \implies T \sim 100 MeV$: we want to check for all systematic effects in this case, before studying the region around T_c

The following results refer to a statistics of about 18K molecular dynamics trajectories of unit length, which have required approximately 1 month on a apeNEXT crate.

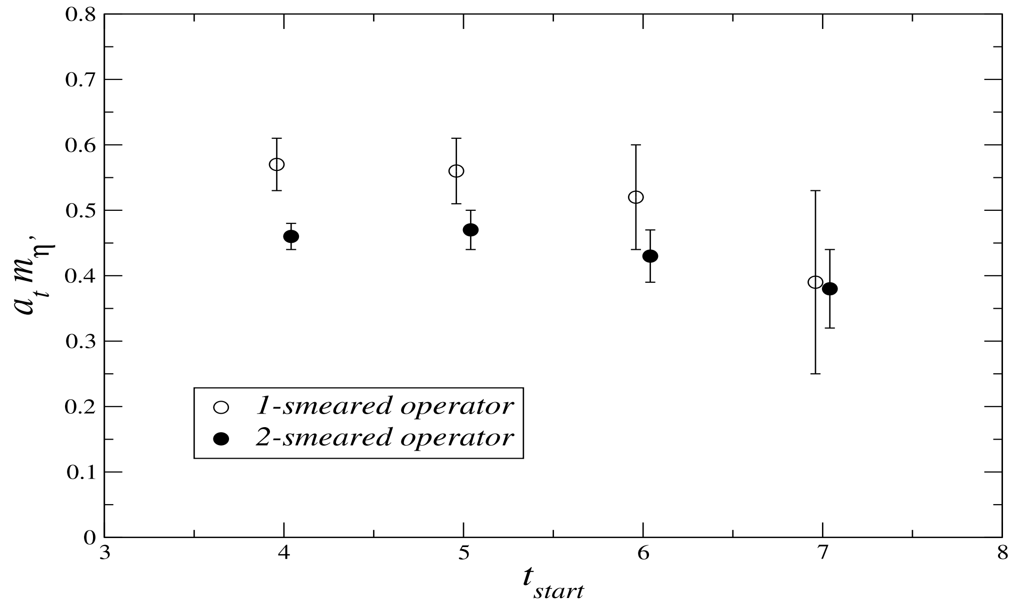


We have performed fits to

$$C(t) = A\exp(-m_{\eta'})$$

taking only data with $t \geq t_{start}$

Results for 1 and 2 smearing are shown in the figure as a function of t_{start}.



- 1 and 2 smearing determinations tend to coincide as t_{start} increases. The 2-smeared operator has probably a better overlap with the η' ground state.
- Our present estimate is $a_t m_{\eta'} \sim 0.40(6) \implies m_{\eta'} \simeq 930 \pm 140\ MeV$
  That seems a very good result ($m'_\eta = 960\ MeV$ from experiment)
  but take into account $N_f = 2$, $\frac{m_\pi}{m_\rho} \sim 0.3$, etc.: it's just a reasonable number ...
- A 5% accuracy would roughly require 8 further months on a crate apeNEXT.
  The use of more improved operators might slightly lower that estimate.
  Reliable determinations around T_c ($N_t \sim 14 - 16$) will require a similar amount of CPU time.

5 – DECONFINEMENT IN QCD WITH ADJOINT FERMIONS

G. Cossu (Pisa), M. D'E. (Genova), A. Di Giacomo (Pisa), G. Lacagnina (Pisa), C. Pica (Brookhaven)

In the analysis of the QCD phase transition it is not clear which are the relevant degrees of freedom regulating the nature of the transition

Chiral degrees of freedom?

Gauge degrees of freedom related to confinement?

There are cases where two different and well separated phase transition take place: they can be the ideal theoretical testground for clarifying some ideas about deconfinement and chiral symmetry restoration.

$\Longrightarrow$ **QCD with 2 flavors in the adjoint representation**

F. Karsch and M. Lutgemeier, NPB 550 (1999) 449

$$S = S_{\text{gauge}}[U_{(3)}] + \big(\bar{q}, D(U_{(8)})q\big)$$

$$U^{ab}_{(8)} = \frac{1}{2} Tr_c(\lambda^a U_{(3)} \lambda^b U^{\dagger}_{(3)})$$

The Polyakov loop is one possible order parameter (Z_3 exact) and show a first phase transition at a lower temperature T_P.

The chiral transition happens at an higher temperature T_χ and it is in the $O(2)$ universality class at the chiral point

J. Engels, S. Holtmann and T. Schulze, NPB 724 (2005) 357

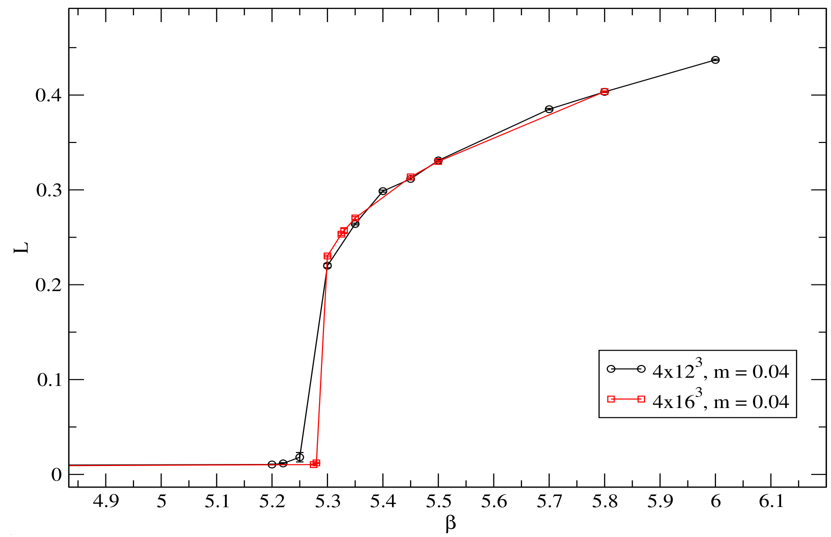
What can we say about other order parameters directly related to confinement?

We are trying to clarify that issue by studying the order parameter for dual superconductivity, $\langle \mu \rangle$.

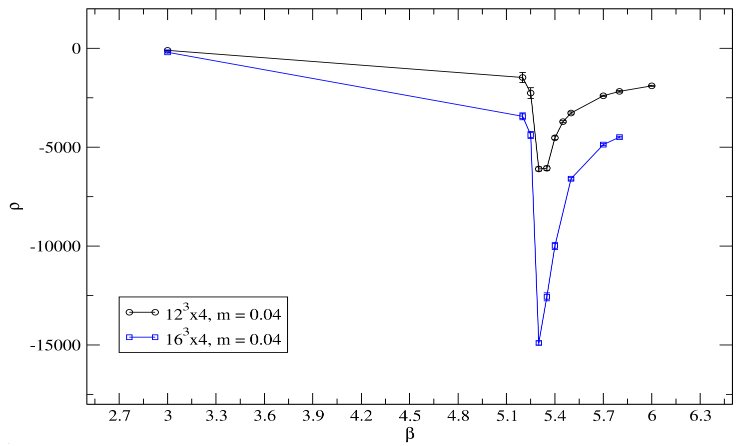
Preliminary results

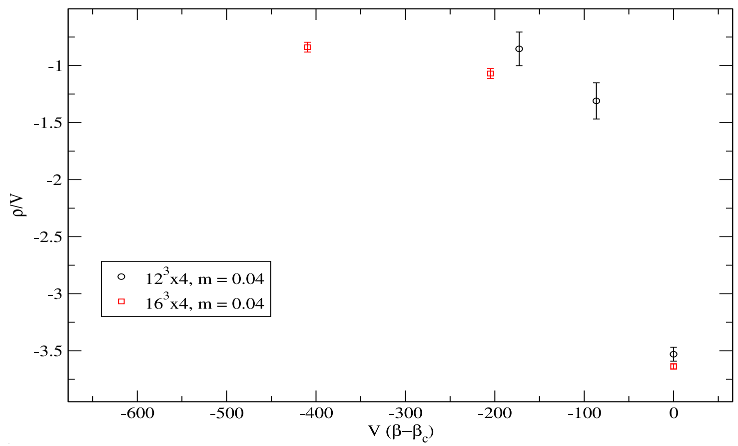
We are simulating the theory at two different masses, $am_q = 0.04$ and $am_q = 0.01$.

At the larger mass only the first order Z_3 transition is clearly visible

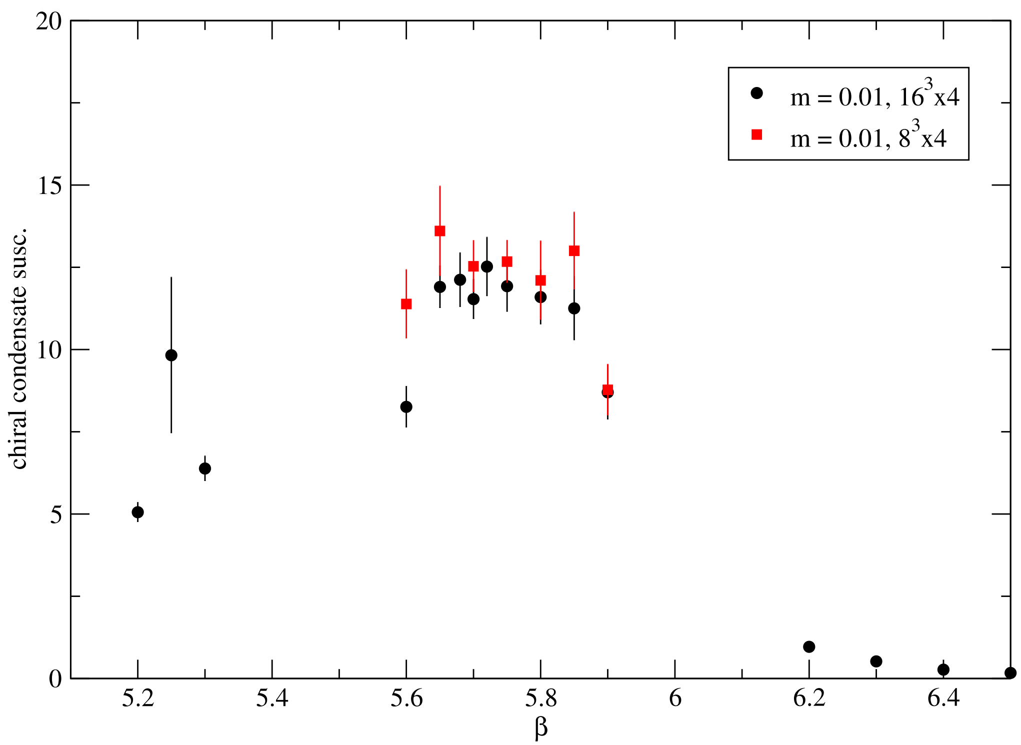


where the disorder parameter for confinement shows the correct scaling behavior

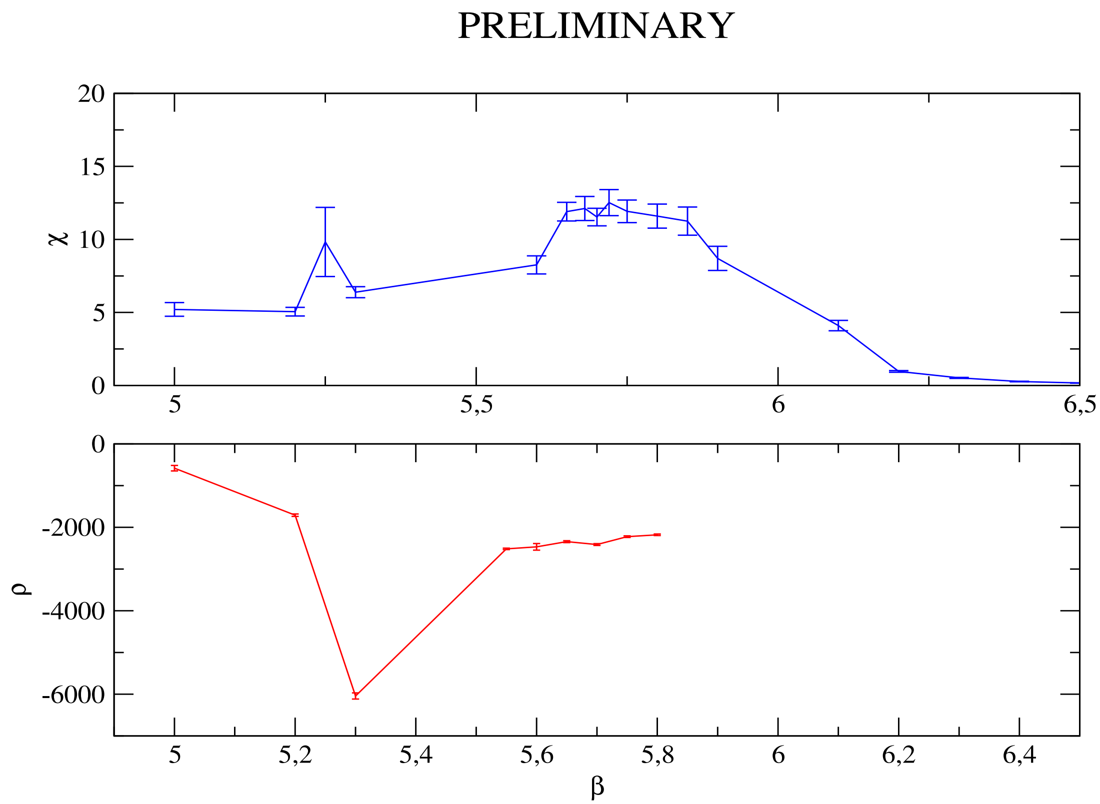




At the lower quark mass also the chiral transition is visible



The disorder parameter $\langle \mu \rangle$ seems to be insensitive to the chiral transition, but only to the Z_3 transition, which we can then be linked to the disappearance of dual superconductivity - confinement



We are now on the way of refining our analysis on the $16^3 \times 4$ lattice which is running on apeNEXT

Simulations with the modified monopole action are particularly expensive (C^* boundary conditions $\Longrightarrow$ Gorkov formalism)

Final results with a f.s.s. scaling analysis will be hopefully ready in a few months

6 – DECONFINEMENT IN QCD AT FINITE DENSITY

S. Conradi (Genova), A. D'Alessandro (Genova), M. D'E. (Genova)

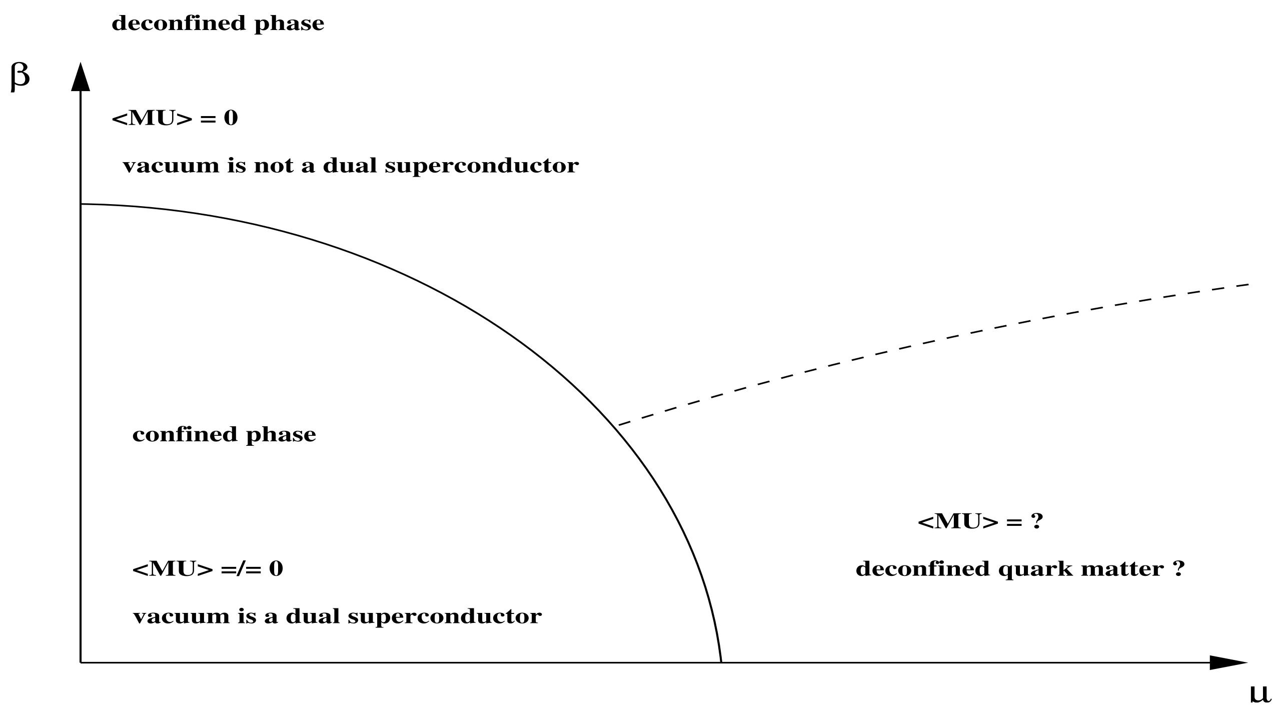
Our goal is to investigate the fate of confining properties of QCD as the finite density phase transition is crossed at low temperatures. That is relevant in order to:

- **understand the nature of deconfinement at high densities and compare it to what happens at high temperatures;**

- **characterize the nature of matter in compact astrophysical objects**

Indications about deconfinement at high density and about its relation to chiral restoration (M. D'E and M.P. Lombardo, PRD 70, 074509 (2004)) **or to diquark condensation** (S. Hands, S. Kim and J. I. Skullerud, arXiv:hep-lat/0604004) **so far have been based on the analysis of the Polyakov loop, which however is not a true order parameter for confinement in presence of dynamical fermions.**

Our plan is to study the behaviour of order parameter for dual superconductivity in the whole $T-\mu$ plane, in order to characterize the confining properties of the various phases in the QCD phase diagram.



We start our investigation for the theory with 2 colors, where numerical simulations at real values of the chemical potential are feasible.

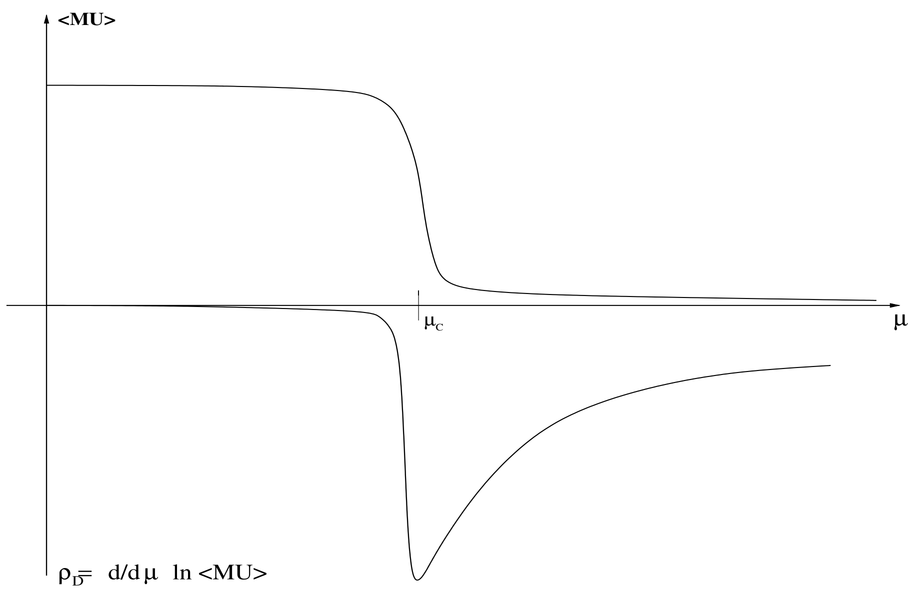
No sensible changes are expected for the confining properties when going from $N_c = 2$ to $N_c = 3$: our results could therefore be relevant also for real QCD.

$\langle\mu\rangle$ **can be studied as a function of** μ_B **by introducing the new parameter**

$$\rho_D \equiv \frac{d}{d\mu_B}\ln\langle\mu\rangle = \frac{d}{d\mu_B}\ln\tilde{Z} - \frac{d}{d\mu_B}\ln Z = \langle N_f\rangle_{\tilde{S}} - \langle N_f\rangle_S$$

from which the value of the order parameter can be reconstructed:

$$\langle\mu\rangle(\beta,\mu_B) = \langle\mu\rangle(\beta,0)\exp\left(\int_0^{\mu_B}\rho_D(\mu_B')\mathrm{d}\mu_B'\right)$$



If the starting point at $\mu_B = 0$ **is in the confined phase, the behaviour expected for** ρ_D **in the case of a deconfinement transition at high density is analogous to that showed by** ρ **across the finite T transition.**

NUMERICAL SIMULATIONS

Staggered fermions and $N_f = 8$ flavors of mass $am = 0.07$. We have used an exact HMC algorithm and standard actions both in the gluonic and in the fermionic sector.

Lattices with a fixed temporal extent $L_t = 6$ and a variable spatial size (only $L_s = 8, 16$ so far) in order to make a finite size scaling analysis of the phase transition.

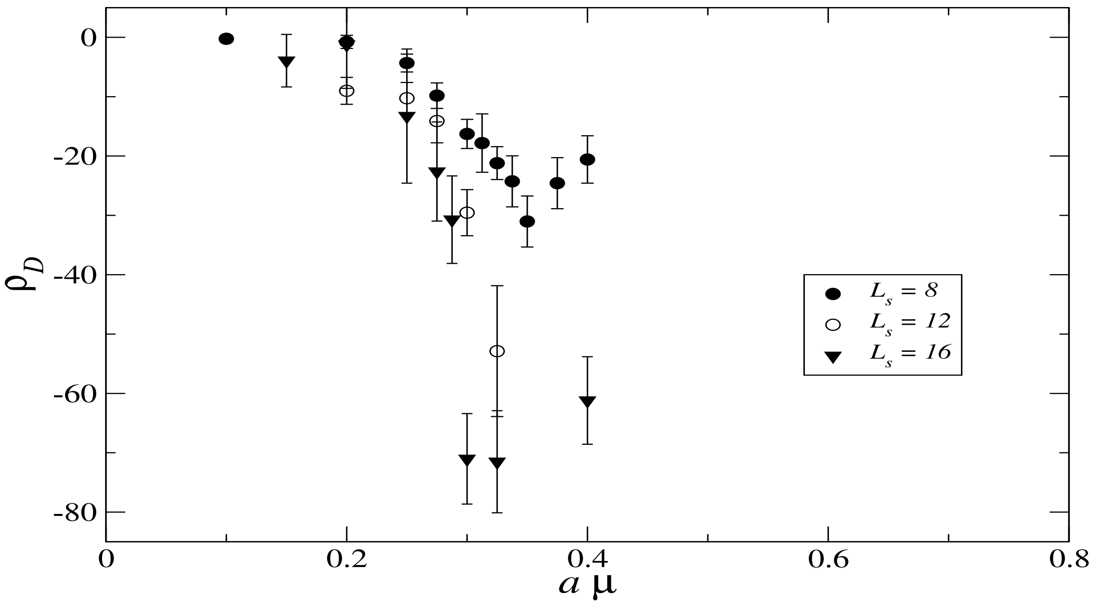
The critical value of β at $\mu = 0$ is $\beta_c \simeq 1.59$. We have varied the chemical potential μ at a fixed value of $\beta = 1.5 < \beta_c$.

Due to a severe critical slowing down around and above μ_c, the availability of APEnext has been essential in order to carry out simulations on the larger lattice ($L_s = 16$).

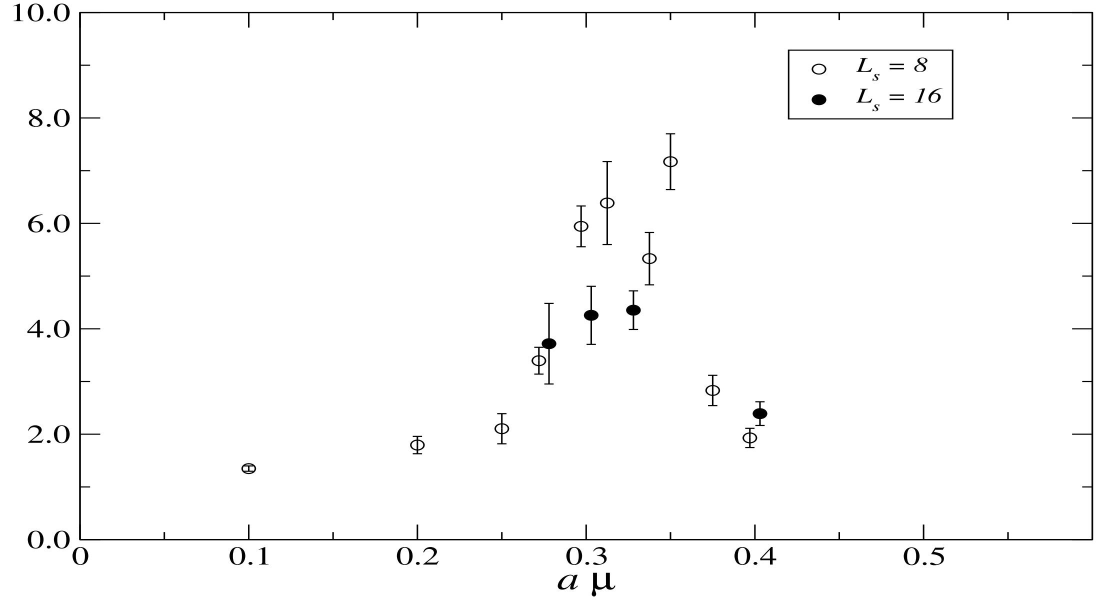
PRELIMINARY RESULTS

ρ_D **shows a clear peak at a critical** $\mu_c \simeq 0.3$.

The peak deepens as the lattice volume is increased, suggesting the presence of a true phase transition at which $\langle\mu\rangle$ **drops to zero and confinement (dual superconductivity) disappears.**



The position of the peak concides with that of the chiral susceptibility

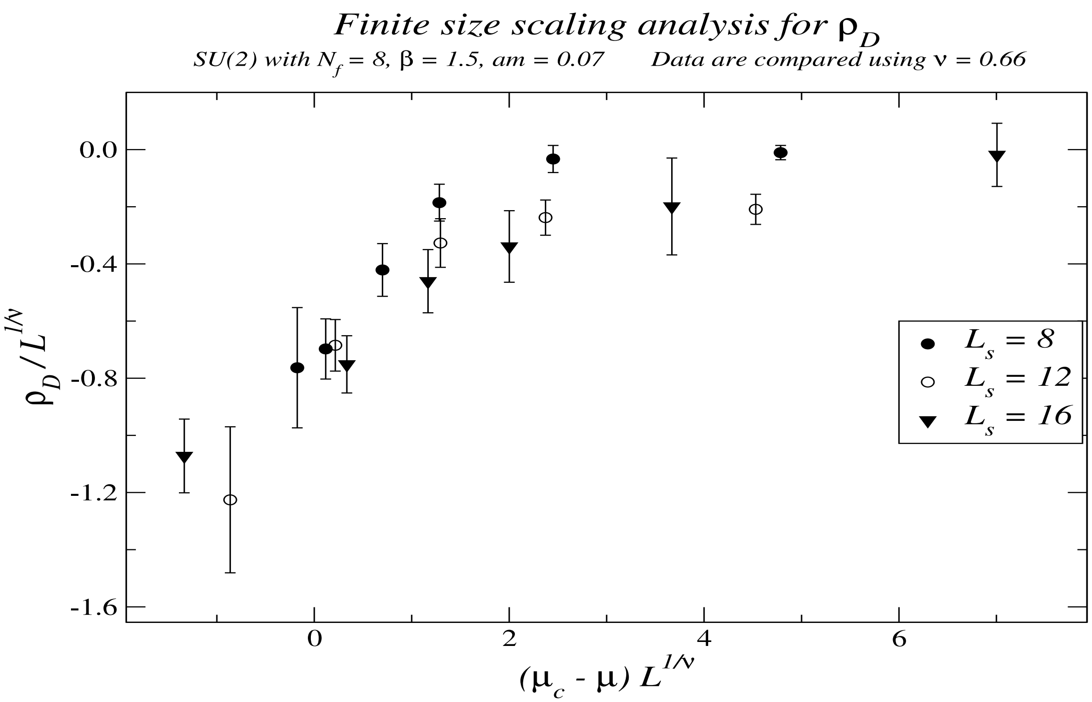


FINITE SIZE SCALING ANALYSIS

At fixed T we can assume the following general scaling form for $\langle\mu\rangle$ around μ_c

$$\langle\mu\rangle = L_s^{-\beta/\nu}\Phi((\mu-\mu_c)L_s^{1/\nu}) \quad \Longrightarrow \quad \rho_D = L_s^{1/\nu}\phi((\mu-\mu_c)L_s^{1/\nu})$$

Our data show a nice scaling with $\nu \sim 0.66$, which is compatible with a second order phase transition in the universality class of ISING3D



We are now running at a lower value of the temperature, where the interplay with a possible phase transition to superfluidity could be clarified.

SUMMARY

We are approaching a number of problems. with the aim of clarifying the nature of confinement, of deconfinement and its relation to other QCD transition

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- $m_{\eta'}$ around T_c
- Deconfinement with adjoint fermions
- Deconfinement at finite density

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Chiral transition for $N_f = 2$

- the problem it is critical for understanding the QCD phase diagram
- it is critical in terms of computer power (in particular for checking the continuum limit)

Times grow to a few years, depending also on the available resources.