(SWANSEA 22-FEB-2008

"QUARKS & HADRONS IN STRONG QCD" St. GOAR 18. MAR. 2008

ON SOME OPEN PROBLEMS IN COLOR CONFINEMENT

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UNIV. PISA & I.N.F.N.

1) M. D'ELIA, A. DI GIACOMO, C. PICA
TWO FLAVOR QCD & CONFINEMENT
PHYS. REV. D72, 114510 (2005) hep-lat 0503030

2) M. D'ELIA, A. DI GIACOMO C. PICA & G. COSSU
arXiv 0706 4470
TWO FLAVOR QCD & CONFINEMENT II

3) G. COSSU, M. D'ELIA, A. DI GIACOMO, G. LACAGNINA, C. PICA
MONOPOLE CONDENSATION IN $N_f=2$ ADJOINT QCD P.R.D in PRESS
arXiv 0802.1795 SWO

I. INTRODUCTION. (STATEMENT OF THE PROBLEM.)

- COLOR CONFINEMENT: NO QUARKS OBSERVED IN NATURE. UPPER LIMITS:

OBSERVED	EXPECTED
$R_q \equiv \dfrac{n_q}{n_p} \leq 10^{-27}$	$R_q \simeq 10^{-12}$ (S.C.M.)
$n_q \equiv$ ABUNDANCE OF QUARKS $n_p \equiv$ " OF PROTONS	
$\sigma_q \equiv \sigma(p+p \to q(\bar{q})+X) \leq 10^{-40}\,cm^2$	$\sigma_q \simeq 10^{-25}\,cm^2$

INHIBITION FACTOR $< 10^{-15}$!

ONLY NATURAL EXPLANATION:

$R_q = 0$ $\qquad\qquad$ $\sigma_q = 0$

PROTECTED BY SOME SYMMETRY: CONFINEMENT AN ABSOLUTE PROPERTY.

$\Downarrow$

DECONFINEMENT IS AN ORDER-DISORDER TRANSITION. CANNOT BE A CROSSOVER!

- ANALOGOUS SITUATION IN SUPERCONDUCTIVITY

PERMANENT CURRENT IN A LOOP $T > 10^5 y$

$$\frac{\rho_{sc.}}{\rho_{nor.}} \leq 10^{-16} \implies \rho_{sc} = 0$$

SYMMETRY : U(1) HIGGS BREAKING

TRANSITION TO NORMAL IS ORDER - DISORDER.

WORKING HYPOTHESIS: (W.H)

DECONFINEMENT IS AN ORDER-DISORDER TRANSITION.

IF NOT TRUE A FINE TUNING $\leq 10^{-15}$ NEEDED.

I WILL ADDRESS TWO MAIN QUESTIONS:

- WHAT IS THE SYMMETRY?

COLOR IS AN EXACT SYMMETRY. IS THERE ROOM FOR AN EXTRA SYMMETRY IN QCD?

- IS THE W. H. CONSISTENT WITH LATTICE OBSERVATIONS?

APPARENTLY NOT:

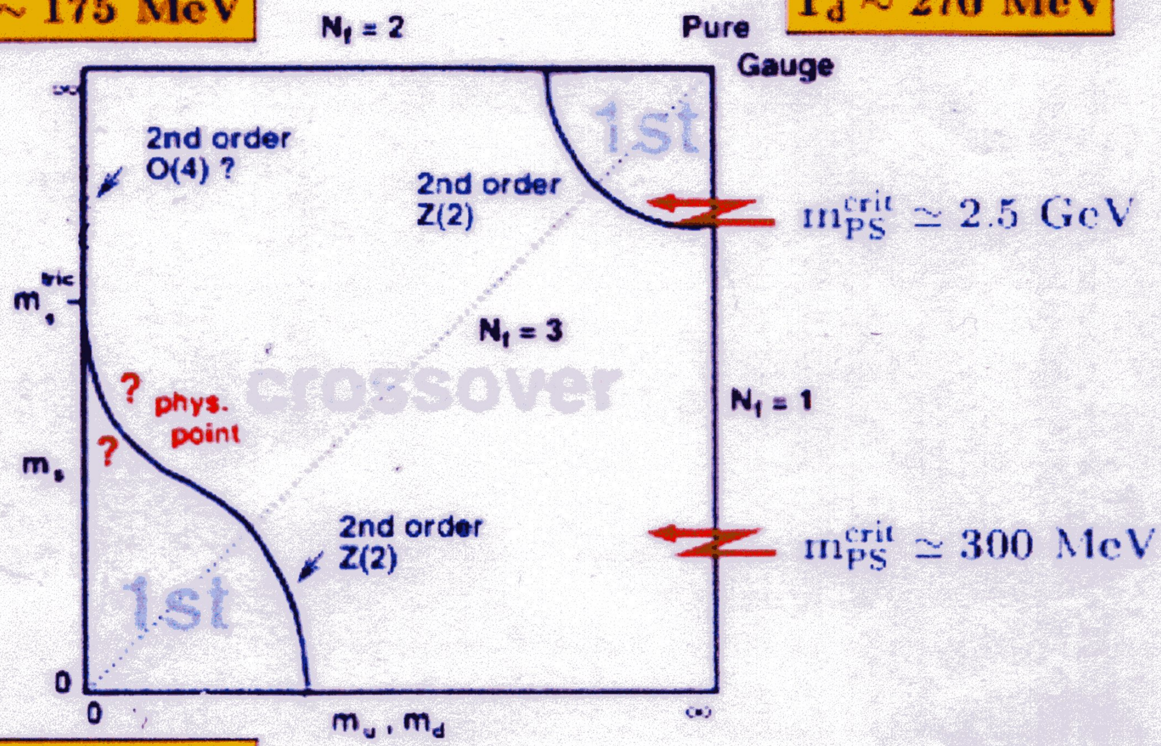
THE OFFICIAL PHASE DIAGRAM IS FULL OF CROSS-OVER'S.

(fig)

3-flavor phase diagram

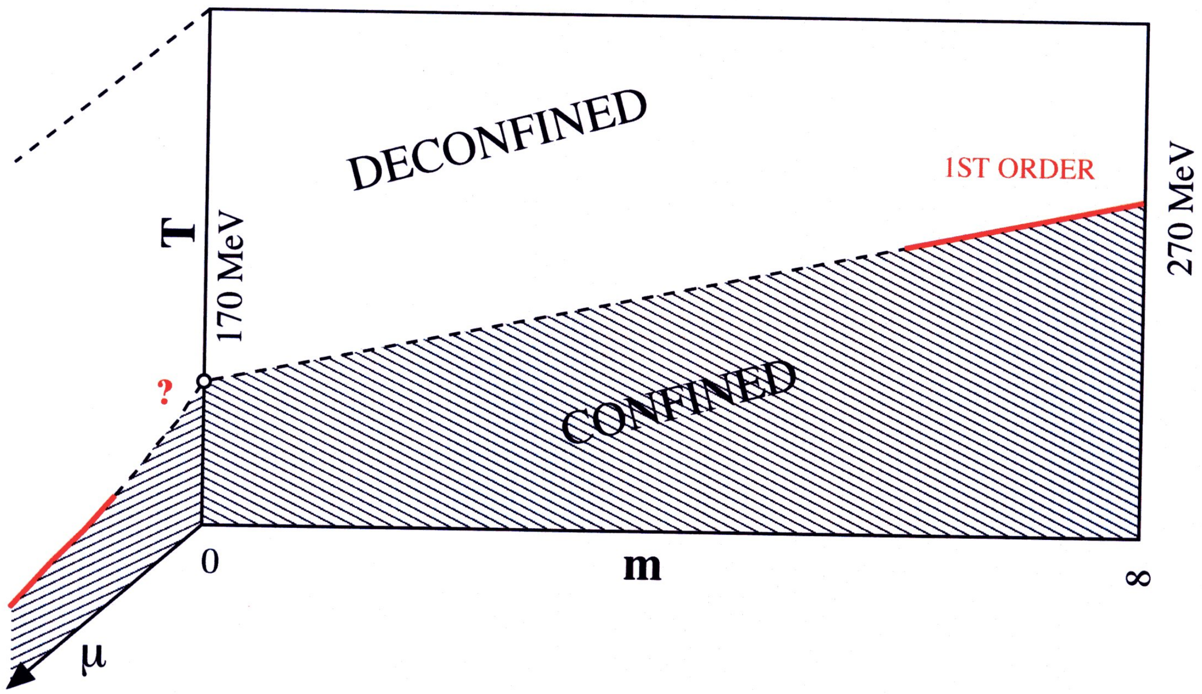
$T_\chi^{n_f=2} \sim 175$ MeV

$T_d \sim 270$ MeV



$T_\chi^{n_f=3} \sim 155$ MeV

BIELEFELD GR



DECONFINED
1ST ORDER
T
170 MeV
270 MeV
?
CONFINED
0
m
∞
μ

II SYMMETRY

IIa. IS COLOR A WIGNER SYMMETRY ($T_a^c |0\rangle = 0$) ?

- YES IN PERTURBATION THEORY -

- $O(x)$ A COLORED OPERATOR, GAUGE INV., OBEYING CLUSTER PROPERTY:

$$\langle O^+(x)\, O(0)\rangle \underset{|x|\to\infty}{\simeq} |\langle O\rangle|^2 + C e^{-mx}$$

$\langle O\rangle$ ORDER PARAMETER

- WIGNER $\langle O\rangle = \emptyset \quad \forall O$

- HIGGS BROKEN $\langle O\rangle \neq \emptyset$ FOR SOME O

- $\langle O\rangle \neq 0$ REQUIRES O GAUGE INVARIANT [SCHWINGER, ELITSUR]

- QED [U(1)] [DIRAC]

$$\psi_{GI}(x) = \psi(x)\, e^{iq\int A_\mu(y)\, W^\mu(x-y)\, d^4y}$$

$$\partial_\mu W^\mu(z) = \delta^4(z)$$

G.T $\psi \to \psi e^{iq\Lambda(x)}$ $\quad A_\mu \to A_\mu + \partial_\mu \Lambda(x)$ $\quad \boxed{\psi_{GI}(x) \to \psi_{GI}(x)}$ G.I

IF $W(x) \underset{|x|\to\infty}{\longrightarrow} 0$

GLOBAL T. $\quad \psi \to \psi e^{iq\Lambda} \quad A_\mu \to A_\mu$

$$\psi_{GI} \to \psi_{GI}\, e^{iq\Lambda} \quad \text{(CHARGED)}$$

$W^\mu(z) = \delta^{\mu 0}\, \theta(z_0)\, \delta^3(\vec{z})$ $\longrightarrow$ NO CLUSTER PROPERTY.

1d SUPPORT

$$W^\mu(z) = \begin{cases} 0 & \mu=0 \\ \frac{\vec{z}\,\delta(z_0)}{4\pi z^3} & \mu=1,2,3 \end{cases}$$

(DIRAC)

CLUSTER PROPERTY OBEYED.

3d support

- QCD -

- DIRAC ARGUMENT ONLY FOR 1.d SUPPORT
  NO CLUSTER PROPERTY
- NO KNOWN WAY TO BUILD A GAUGE INVARIANT O WITH CLUSTER PROPERTY
- IF IT WERE POSSIBLE $\Rightarrow$ NO CONFINEMENT

. WE SHALL ASSUME WIGNER -

II. WHAT CAN BE AN EXTRA SYMMETRY (BESIDES COLOR), WHICH CAN CHARACTERIZE CONFINEMENT & DECONFINEMENT?

. QUENCHED THEORY (NO QUARKS) Z_N.

- $\mathcal{L}$ BLIND TO Z_N
- ORDER PARAMETER $\langle L \rangle$ $L = \mathrm{Tr}\,P \int_0^{1/T} e^{iA_0(t)dt}$

$$V(\vec{x}) \underset{|x|\to\infty}{=} -T \ln \langle L^+(x)\, L(0)\rangle \qquad \langle L^+(x) L(0)\rangle \underset{x\to\infty}{\simeq} |\langle L\rangle|^2 + C e^{-\frac{\sigma x}{T}}$$

$\langle L\rangle = 0$ $\quad V(x) \underset{x\to\infty}{=} \sigma x$ $\quad$ (CONFINED)

$\langle L\rangle \neq 0$ $\quad V(x) \underset{|x|\to\infty}{=} \text{const}$ $\quad$ (DECONFINED)

- Z_N EXPLICITLY BROKEN BY QUARKS

Z_N CANNOT BE THE SYMMETRY OF W.K.

- CONSERVATIVE ATTITUDE: (WRONG)
  THE ONLY POSSIBLE EXTRA SYMMETRY IS
  CHIRAL SYMMETRY AT $m_q \simeq 0$.
  (UNNATURAL CHOICE, NO WAY TO DEFINE CONFINED + DECONFINED)

- OPEN POSSIBILITY : DUALITY

  EXTRA SYMMETRIES EXPOSED IN THE DUAL DESCRIPTION, EXCITATIONS WITH NON TRIVIAL SPATIAL$^{(D-1)}$ HOMOTOPY

2d ISING · KINKS $j_\mu = \varepsilon_{\mu\nu} \partial_\nu \sigma$ $\partial^\mu j_\mu = 0$

3d X-Y VORTICES $j_\mu = \varepsilon_{\mu\nu\rho} \partial^\nu A_\rho$ $A_\rho = \partial_\rho \theta$

. . . . VIOLATION OF BIANCHI ID. $\partial_\mu j^\mu = 0$

CONSERVED CURRENTS CAN BE DEFINED AND THE CORRESPONDING SYMMETRIES CAN BE EITHER WIGNER OR HIGGS (GOLDSTONE)

- IN 3+1 DIM, A NON TRIVIAL π_2 IS REQUIRED
  AND THE CONFIGURATIONS ARE MONOPOLES.

[IN 2+1 DIM π_1 IS THE HOMOTOPY AND THE CONFIGURATIONS ARE VORTICES.]

QCD MONOPOLES $j^a_\mu = \partial^\nu \varepsilon_{\mu\nu\rho\sigma} F^a_{\rho\sigma}$ VIOL BIANCHI ID.

$F^a_{\rho\sigma}$ = 't HOOFT TENSOR $a = 1, \dots N-1$

$\partial_\mu j^a_\mu = 0$

- IN THE LANGUAGE OF WITTEN'S "GEOMETRIC LANGLAND'S PROGRAM" A THEORY ON A SPACE TIME WITH A FINITE (ARBITRARY) NUMBER OF LINE-LIKE SINGULARITIES (MONOPOLES + DIRAC STRINGS)

- THE MAGNETIC SYMMETRY CAN BE WIGNER (NORMAL STATE) OR HIGGS BROKEN (DUAL SUPERCOND.)
  ↓ DECONFINED ↓ CONFINED

- IF μ CREATES A MONOPOLE $\langle\mu\rangle$ CAN BE AN ORDER PARAMETER

  $\langle\mu\rangle = 0$ DECONFINED WIGNER $\langle\mu\rangle \neq 0$ CONFINED HIGGS

- μ ADDS A SINGULARITY TO THE FINITE # OF EXISTING SINGULARITIES, INDEPENDENT OF THE "ABELIAN PROJECTION"

- TO CONCLUDE THIS SECTION

(i) A CANDIDATE SYMMETRY EXISTS FOR CONFINEMENT, FOR GEOMETRIC REASONS IT IS DUAL SUPERCONDUCTIVITY

- $\langle\mu(x)\rangle$ LOOKS NON LOCAL IN TERMS OF A_μ. IT IS LOCAL IN THE DUAL DESCRIPTION. IT OBEYS CLUSTER PROPERTY [40'ALESSANDRO et al N.P.B 2007]

- KINK IN 2d ISING
- $\langle\mu\rangle$ WELL DEFINED BOTH IN QUENCHED AND FULL QCD

III THE PHASE DIAGRAM ($N_f = 2$)

Fig

- ORDER OF THE CHIRAL TRANSITION ($m = 0$)

$$\boxed{\text{ASSUME THAT CHIRAL d.o.f DOMINATE}}$$

[Pisarski, Wilczek 84)

$$\phi_{ab} = \bar{\Psi}_a (1 - \gamma_5) \Psi_b$$

- 4 - ε APPROACH : 1) WRITE THE MOST GENERAL RENORMALIZABLE EFFECTIVE ACTION
  2) LOOK FOR I.R. STABLE FIXED POINTS (NECESSARY CONDITION FOR 2nd ORDER)

RESULTS : $N_f \geq 3$ NO FIXED POINT $\Rightarrow$ 1st ORD

$N_f = 2$
- 2nd ORDER O(4) — $U_A(1)$ $m_{\eta'} \neq 0$
- 1st ORDER — $U_A(1)$ $m_{\eta'} = 0$

- IF 2nd ORDER A CROSSOVER AT $m, \mu \neq 0$ A TRICRITICAL POINT EXISTS, (UNNATURAL)
- IF 1st ORDER : 1st ORDER ALSO AT $m, \mu \neq 0$. NO TRICRITICAL POINT (NATURAL)

- TO BE DECIDED BY EXPERIMENT (SEARCH OF TRICRITICAL POINT).

AND BY LATTICE SIMULATIONS (FINITE SIZE SCALING ANALYSIS)

AT PRESENT : NO EVIDENCE FROM EXPERIMENT
LATTICE STILL OPEN BUT IMPROVING.

III THE PHASE DIAGRAM ($N_f = 2$)

F.J.

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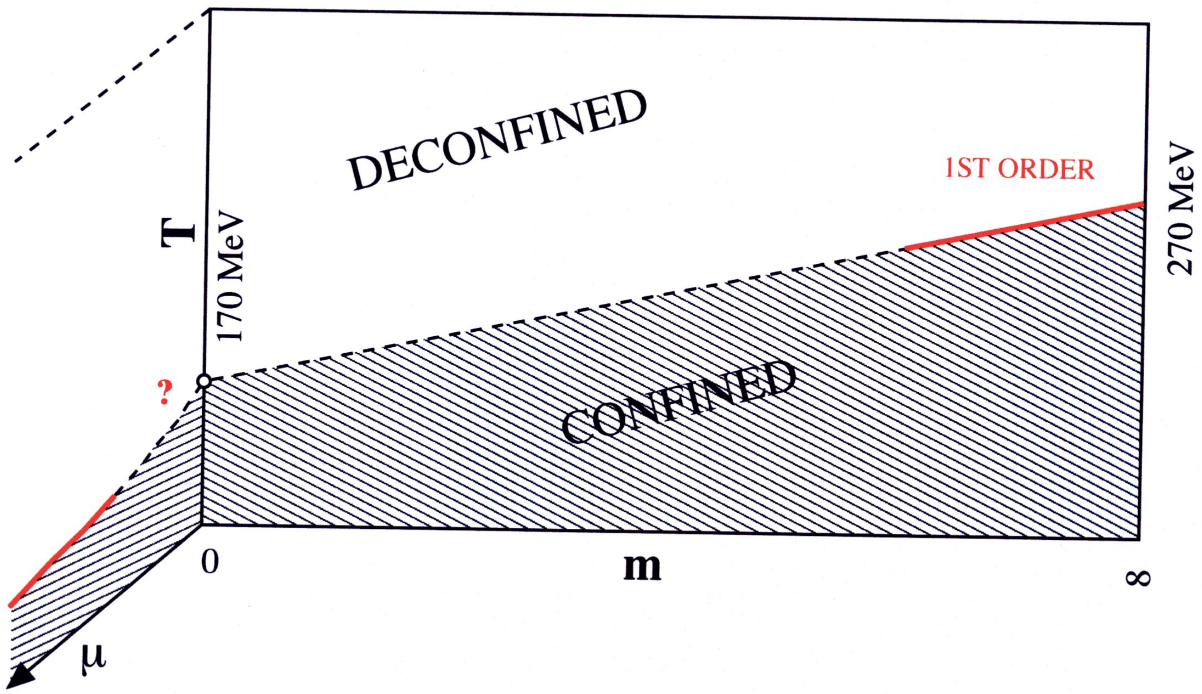
AT PRESENT : NO EVIDENCE FROM EXPERIMENT

LATTICE STILL OPEN [NO EVIDENCE FOR O(4)] BUT IMPROVING.

SW7


DECONFINED
1ST ORDER
T
170 MeV
270 MeV
?
CONFINED
0
m
∞
μ

$\boxed{\text{DO CHIRAL d.o.f DOMINATE? [IS THERE ANYTHING BESIDES CHIRAL SYMMETRY?]}}$

- aQCD — QUARKS IN THE ADJOINT REPRES.

- POLYAKOV LINE A GOOD ORDER PARAMETER
- $\langle \mu \rangle$

- A DECONFINING TRANSITION AT T_d
  FIRST ORDER $\langle \mu \rangle$ $\langle L \rangle$
  - A CHIRAL TRANSITION AT T_{ch} $T_{ch} > T_d$
    CROSS OVER at $m \neq 0$, 2nd ORDER at $m = 0$
    $\langle \bar\psi \psi \rangle$ [ENGELS et al] Fig.

IN QCD WITH FUNDAMENTAL QUARKS THE TWO TRANSITIONS COINCIDE. ($\langle \mu \rangle$, $\langle \bar\psi \psi \rangle$)

|| CHIRAL SYMMETRY IS NOT THE ONLY SYMMETRY.

ALSO FOR $N_f = 2$ AND QUARKS IN FUND. REPR

AT $m = 0$ TRANSITION IS CHIRAL

+ DECONFINEMENT.

- FINITE SIZE SCALING : DETERMINING THE ORDER OF THE TRANSITION

$$\mathcal{F}(aL_s, a, \lambda, m)$$

DENSITY OF FREE ENERGY (CRITICAL)

DIMENSIONAL ANALYSIS

$$\mathcal{F} \simeq L_s^{-d} \mathcal{F}\left(\frac{a}{L_s}, \frac{\lambda}{L_s}, m L_s^{y_h}\right)$$

$\lambda \gg a$ SCALING $a = 0$

$$\mathcal{F} \approx L_s^{-d} \bar{\mathcal{F}}\left(\frac{\lambda}{L_s}, m L_s^{y_h}\right)$$

$$\tau \equiv 1 - \frac{T}{T_c}$$

$$\lambda \underset{\tau \to 0}{\propto} \tau^{-\nu}$$

$$\tau = \tau(\beta, m)$$

$$\mathcal{F} \simeq L_s^{-d} \tilde{\Phi}\left(\tau L_s^{1/\nu}, m L_s^{y_h}\right)$$

FINITE SIZE SCALING

$$\Downarrow$$

$$C_V - C_0 \simeq L_s^{\alpha/\nu} \Phi_c\left(\tau L_s^{1/\nu}, m L_s^{y_h}\right)$$

$$\chi - \chi_0 = L_s^{\gamma/\nu} \Phi_\chi\left(\tau L_s^{1/\nu}, m L_s^{y_h}\right)$$

ν, α, γ, y_h CRITICAL INDEXES (ANOMALOUS DIMENSIONS)

TYPICAL OF THE UNIVERSALITY CLASS.

VALID ALSO FOR 1st ORDER (WEAK)

SW

CRITICAL INDEXES

	$1/\nu$	y_h	α	γ	δ	
O(4)	1.34	2.48	-.24	1.48	4.85	
O(2)	1.5	2.48	-.005	1.32	4.82	
WEAK 1st	3	3	1	1	∞	

- FITTING SCALING LAW TO DATA AT DIFFERENT $L_s \longrightarrow$ DETERMINATION OF CRITICAL INDEXES FROM L_s DEPENDENCE

C_V INDEPENDENT ON ANY PREJUDICE ON THE ORDER PARAMETER

- LATTICE $L_t \times L_s^3$ $\quad T = \dfrac{1}{a L_t} \quad a = a(\beta)$

- AT FINITE L_s, L_t F, $C_V - C_0$, χ ARE ANALYTIC: SINGULARITIES AS $L_s \to \infty$ (LEE, YANG)

O(4) O(2) CROSSOVER AT $m \neq 0$

ONLY SINGULARITIES $m = 0$

WEAK 1st ORDER SINGULARITY ALONG THE PSEUDO CRITICAL LINE.

2 SCALING VARIABLES: $\tau L_s^{1/\nu}$, $m L_s^{y_h}$

STRATEGY: ~~FEX~~ FIX ONE IN TURN, OBSERVE SCALING IN THE OTHER ONE.

[M. D'Elia, A. Di G., C. Pica]

I KEEP $m L_s^{y_h}$ FIXED $= K$ — $O(4)\, O(2)$ $y_h = 2.48$; weak 1st $y_h = 3$

$$\Phi(\tau L_s^{1/\nu}, m L_s^{y_h}) = \phi(\tau L_s^{1/\nu}, K)$$

$$(C_V - C_0)/L_s^{\alpha/\nu} = \phi_c(\tau L_s^{1/\nu}, K)$$

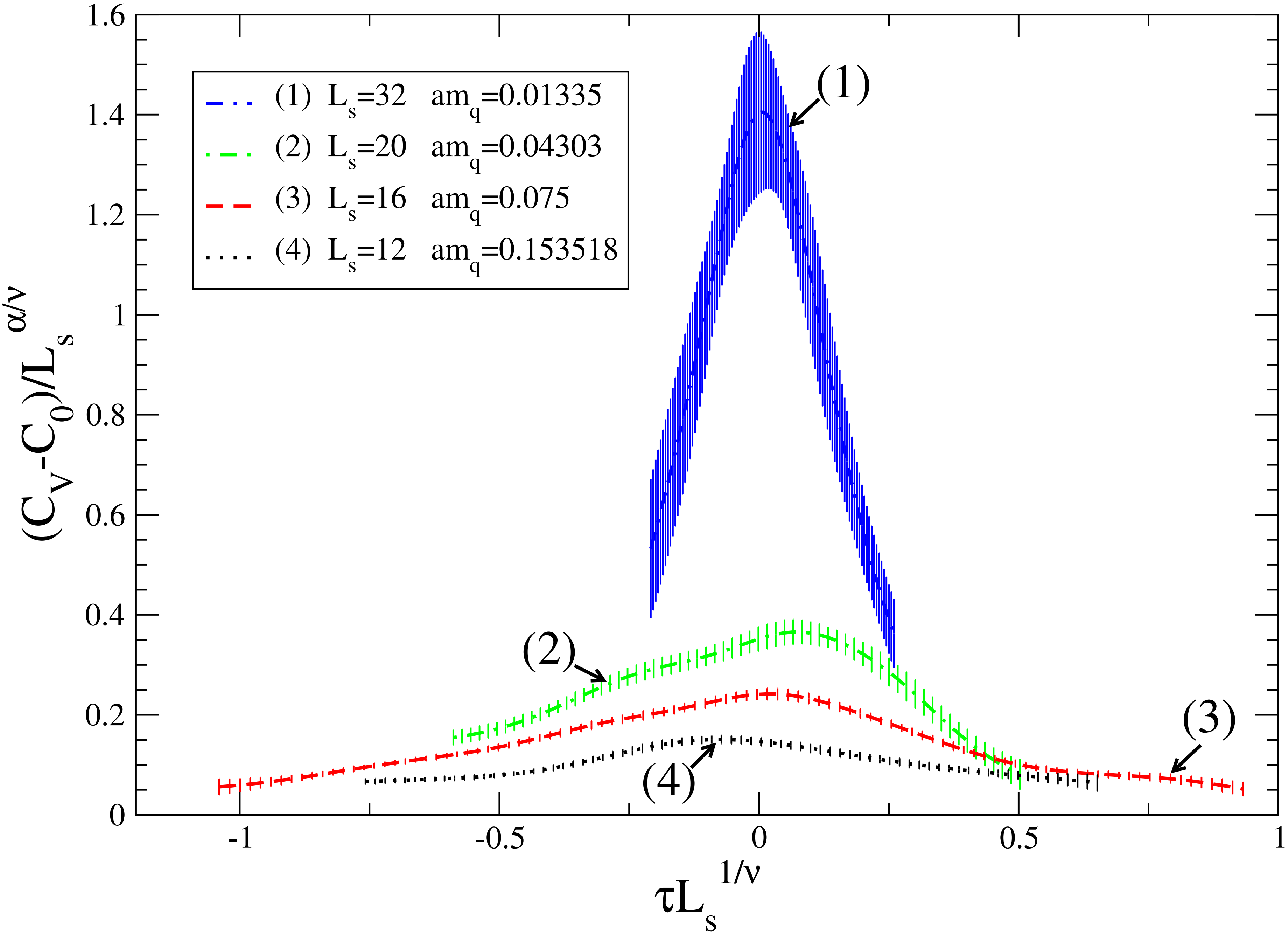
$$(\chi - \chi_0)/L_s^{\gamma/\nu} = \phi_\chi(\tau L_s^{1/\nu}, K)$$

$C_V - C_0$, $\chi - \chi_0$ MEASURED α, ν, γ KNOWN,
PLOT VS $\tau L_s^{1/\nu}$ UNIVERSAL CURVE.
BOTH THE HEIGTH & THE WIDTH.

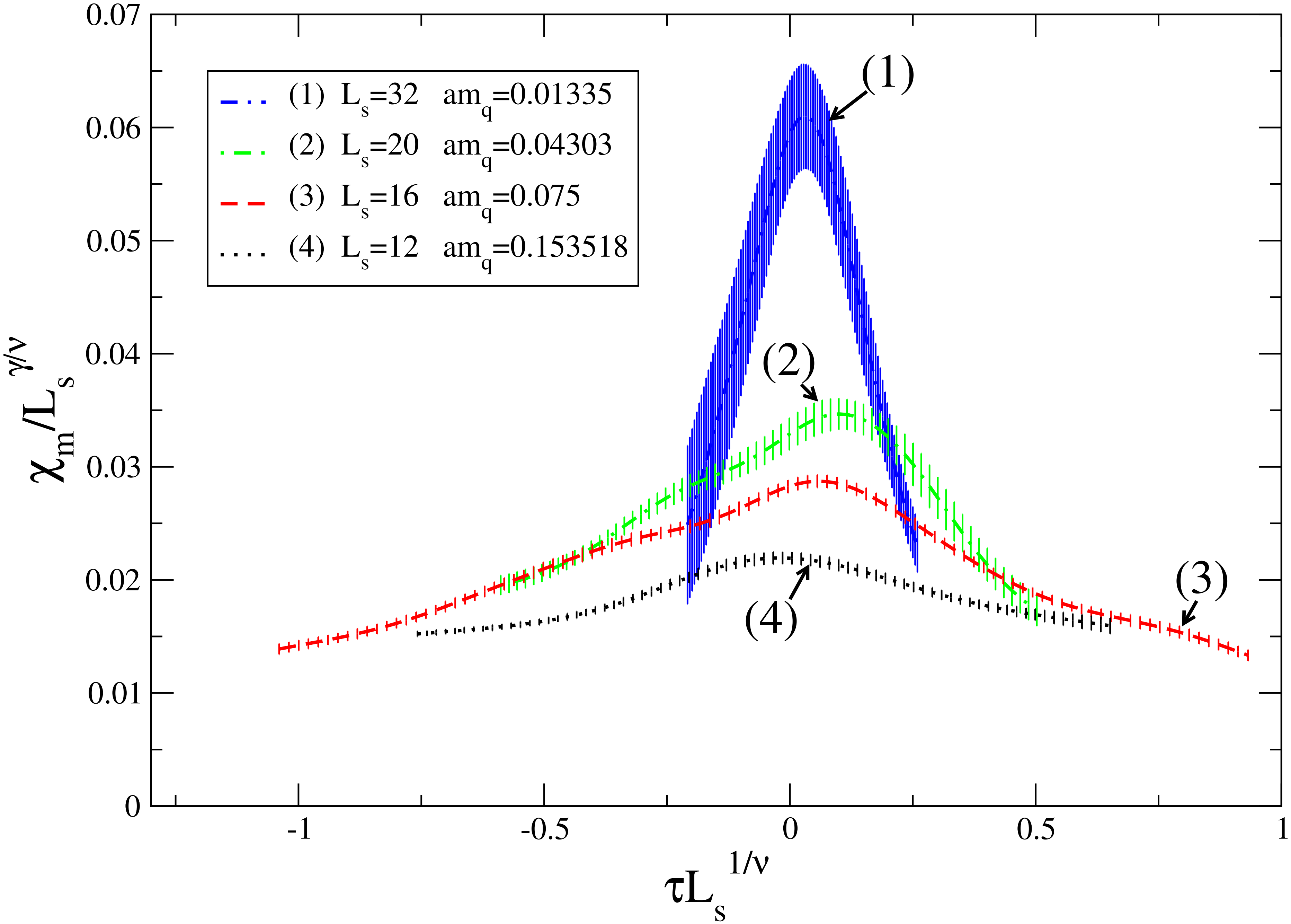
FIG. 3,4 O(4) [O(2)]

Fig 5 1st ORDER

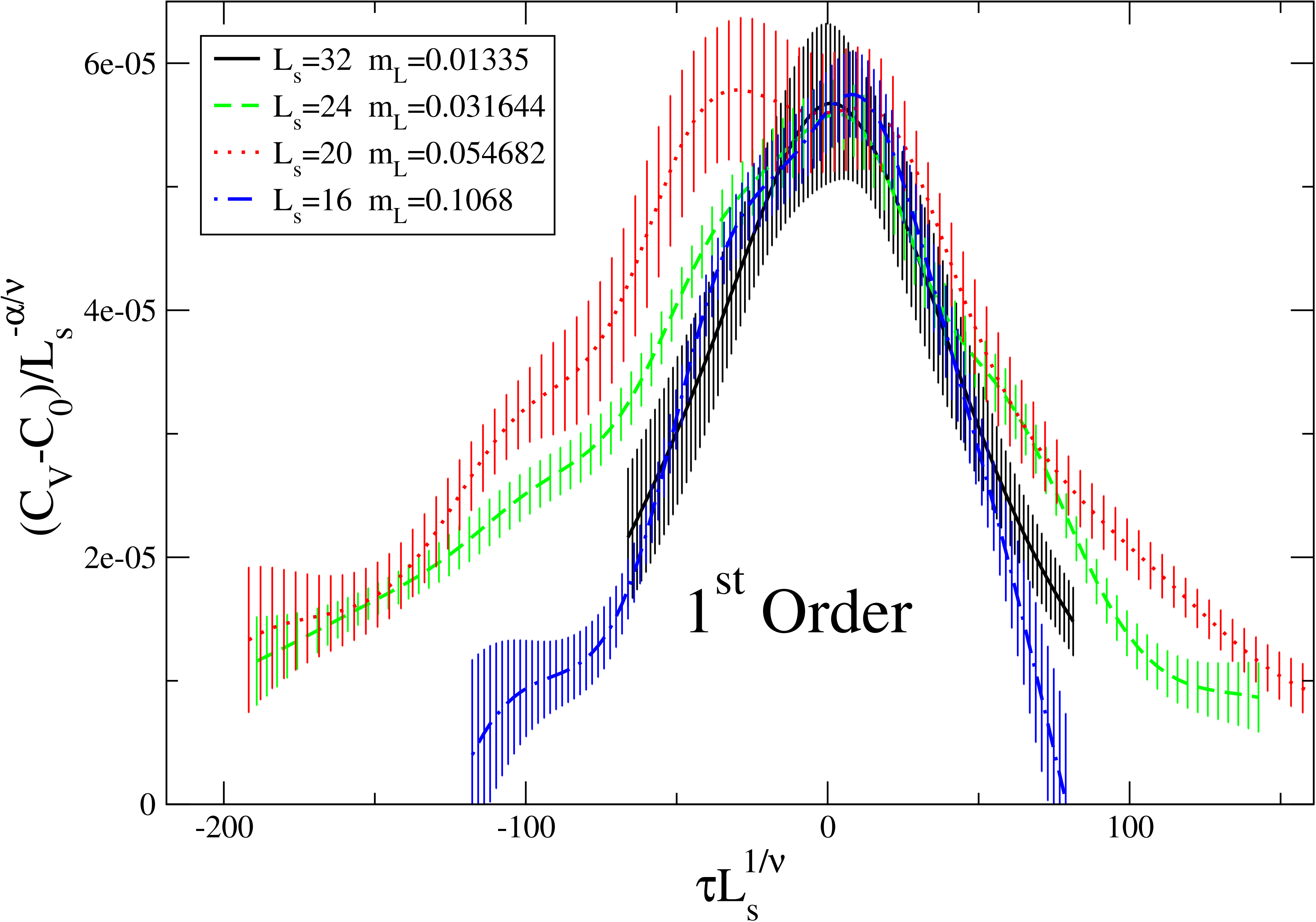
FIRST ORDER CONSISTENT O(4) O(2)
EXCLUDED : CHECK THE CONTINUUM LIMIT
$N_T = 6$ IMPROVED ACTION.



(1) L_s=32 am_q=0.01335
(2) L_s=20 am_q=0.04303
(3) L_s=16 am_q=0.075
(4) L_s=12 am_q=0.153518
(1)
(2)
(3)
(4)
$(C_V - C_0)/L_s^{\alpha/\nu}$
$\tau L_s^{1/\nu}$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
-1
-0.5
0
0.5
1



(1) L_s=32 am_q=0.01335
(2) L_s=20 am_q=0.04303
(3) L_s=16 am_q=0.075
(4) L_s=12 am_q=0.153518
(1)
(2)
(3)
(4)
$\chi_m/L_s^{\gamma/\nu}$
$\tau L_s^{1/\nu}$
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
-1
-0.5
0
0.5
1



L_s=32 m_L=0.01335
L_s=24 m_L=0.031644
L_s=20 m_L=0.054682
L_s=16 m_L=0.1068
1^st Order
(C_V-C_0)/L_s^-α/ν
τL_s^1/ν
6e-05
4e-05
2e-05
0
-200
-100
0
100

II. KEEP $\tau L_s^{1/\nu}$ FIXED, LOOK AT $m L_s^{y_h}$

2nd ORDER

$$c_v - c_0 = L_s^{\alpha/\nu} \phi_c(\tau L_s^{1/\nu}, m L_s^{y_h})$$

$$\chi - \chi_0 = L_s^{\gamma/\nu} \phi_c(\tau L_s^{1/\nu}, m L_s^{y_h})$$

AS $L_s \to \infty$ $m \neq 0$ EVERYTHING ANALYTIC

$$c_v - c_0 \simeq m^{-\alpha/(\nu y_h)} f_c(\tau L_s^{1/\nu})$$

$Q = \int d\tau (c_v - c_0) \propto L_s^{-1/\nu}$

$$\chi - \chi_0 \simeq m^{-\gamma/(\nu y_h)} f_\chi(\tau L_s^{1/\nu})$$

1st ORDER DEVELOPS A SINGULARITY

$$c_v - c_0 \simeq m^{-1} f_c(\tau L_s^3) + L_s^3 g_c(\tau L_s^3)$$

$$Q = m^{-1} L_s^{-3} \int f_c(x) dx + \int g_c(x) dx$$

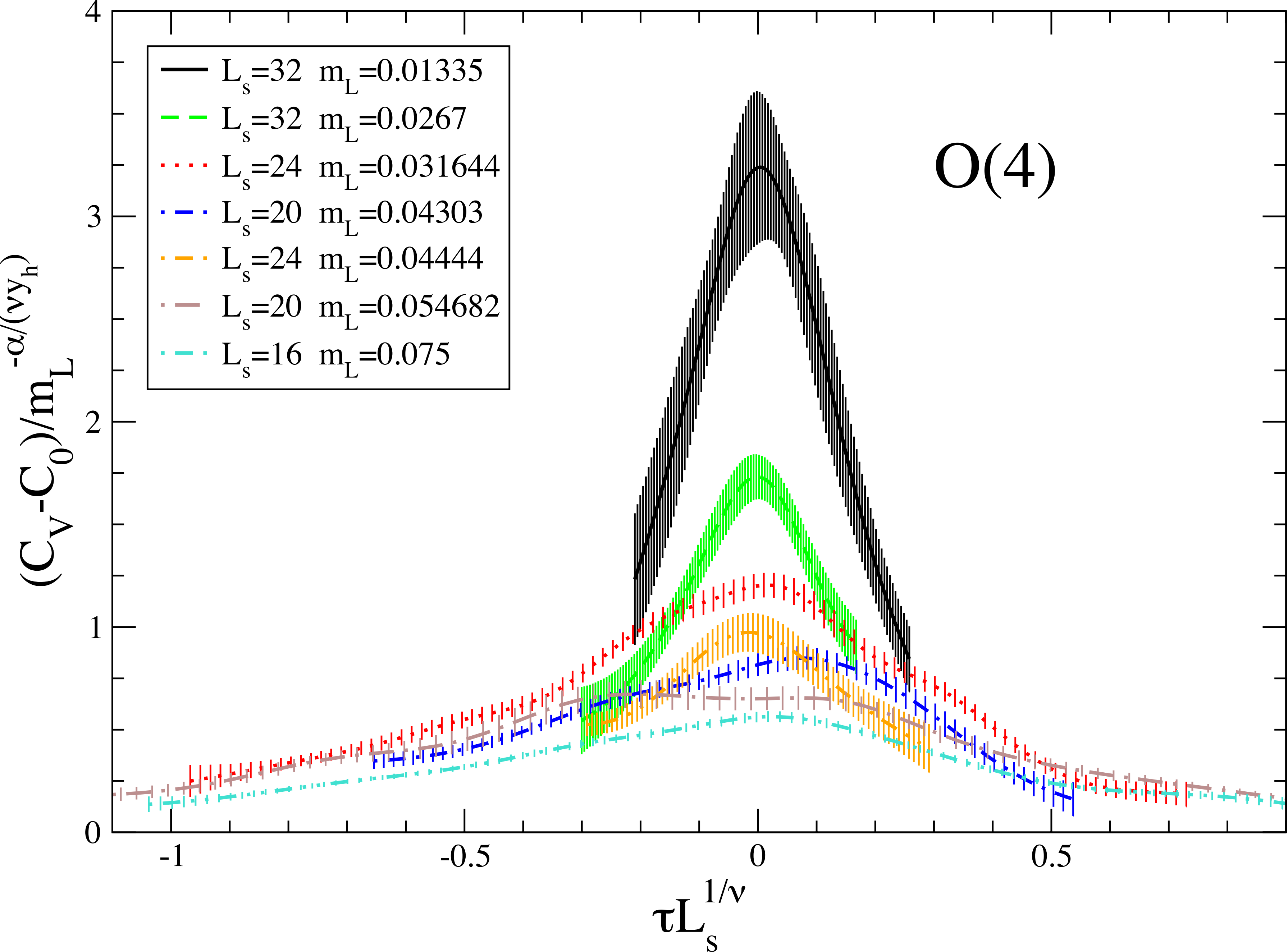
$(\delta(\tau))$ LATENT HEAT

$$\chi - \chi_0 \simeq m^{-1} f_\chi(\tau L_s^3) + L_s^3 g_\chi(\tau L_s^3)$$

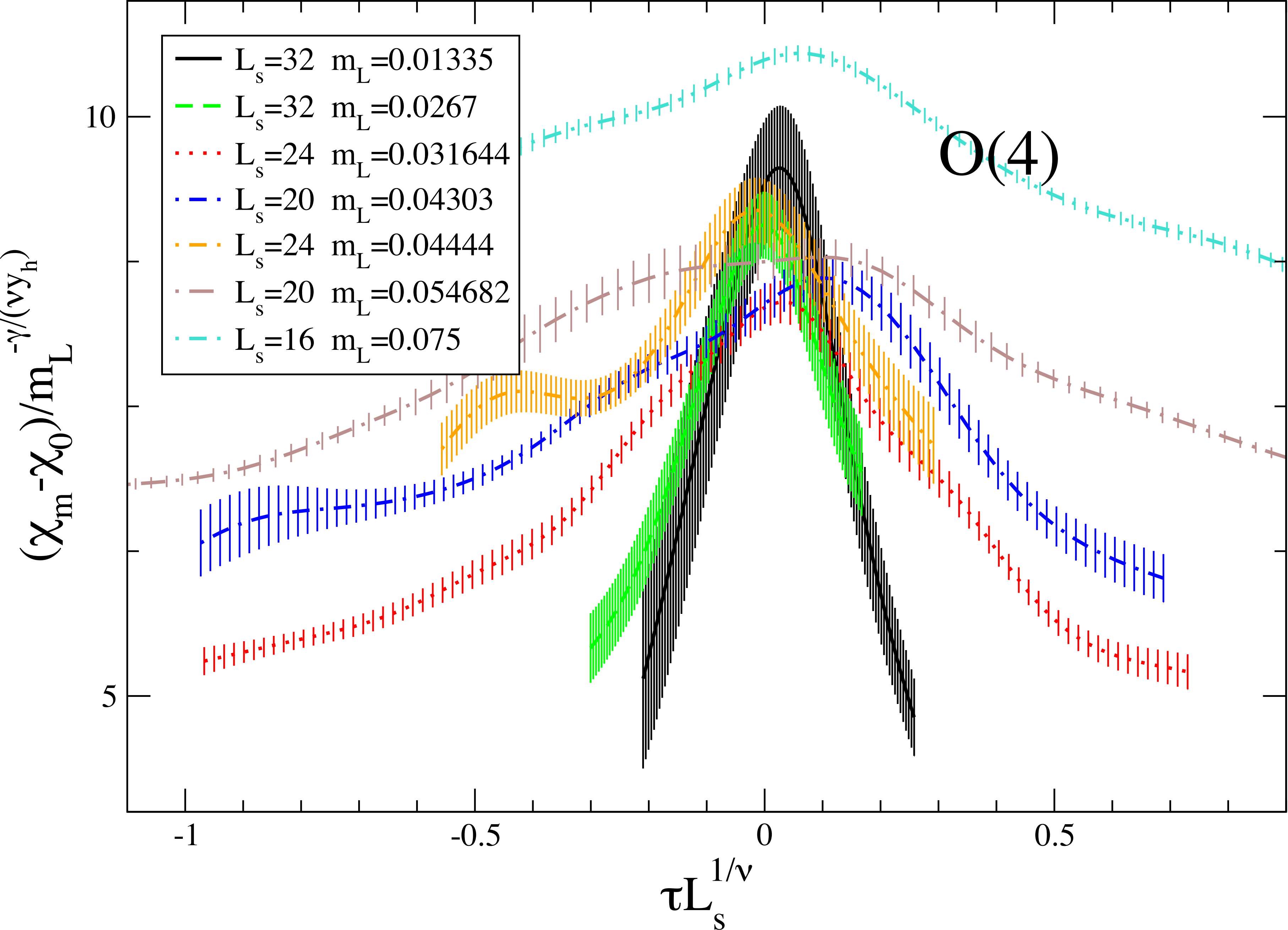
JUMP IN $\bar{\psi}\psi$

Fig. 6, 7, 8

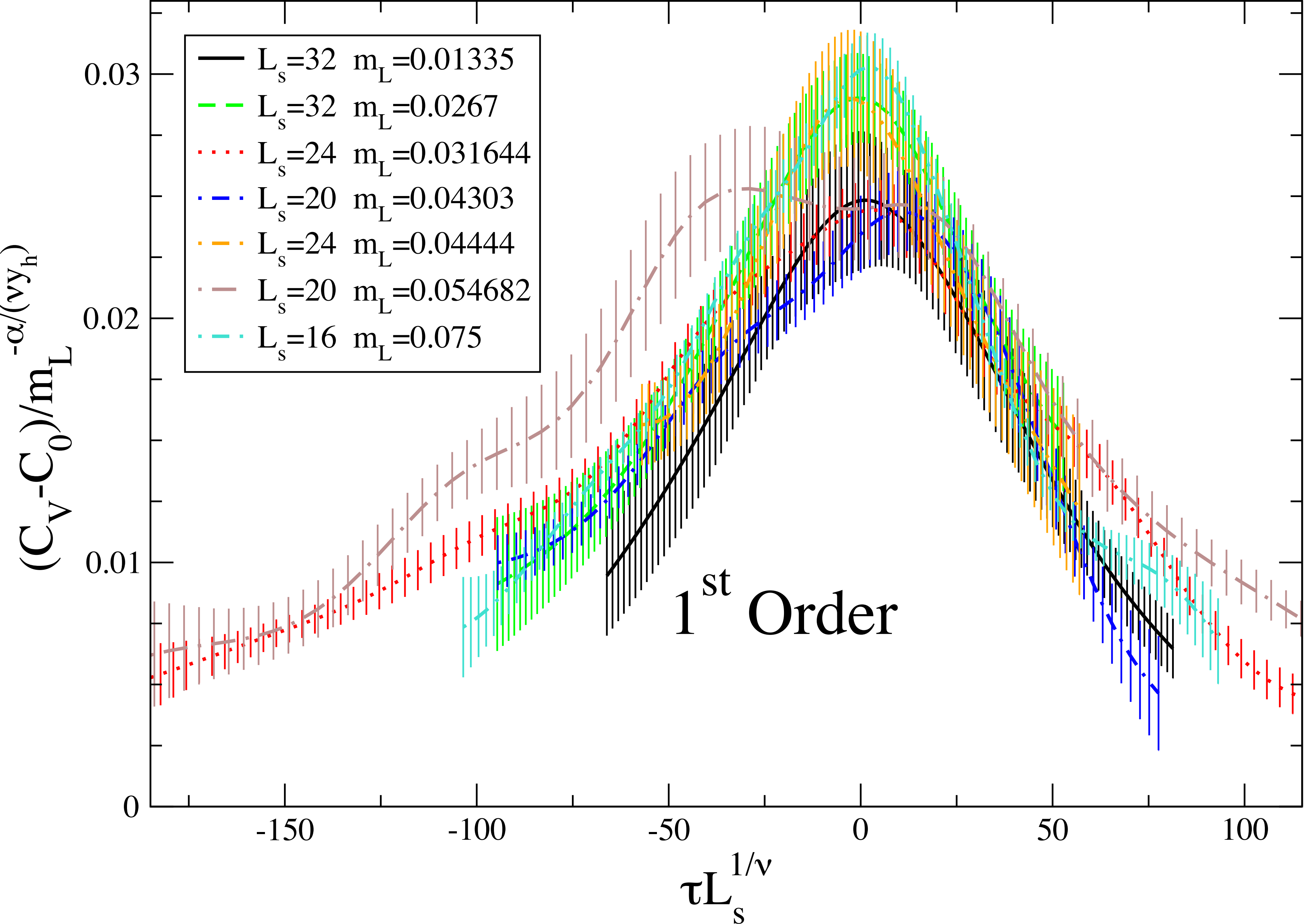
DATA EXCLUDE O(4) [O(2)], CONSISTENT WITH FIRST ORDER WITH 2nd TERM NEGLIGIBLE $\longrightarrow$ GO TO BIGGER VOLUMES (SW12



O(4)
L_s=32 m_L=0.01335
L_s=32 m_L=0.0267
L_s=24 m_L=0.031644
L_s=20 m_L=0.04303
L_s=24 m_L=0.04444
L_s=20 m_L=0.054682
L_s=16 m_L=0.075
(C_V-C_0)/m_L^{-α/(νy_h)}
τL_s^{1/ν}
0
1
2
3
4
-1
-0.5
0
0.5



L_s=32 m_L=0.01335
L_s=32 m_L=0.0267
L_s=24 m_L=0.031644
L_s=20 m_L=0.04303
L_s=24 m_L=0.04444
L_s=20 m_L=0.054682
L_s=16 m_L=0.075
O(4)
10
5
-1
-0.5
0
0.5
$(\chi_m-\chi_0)/m_L^{-\gamma/(\nu y_h)}$
$\tau L_s^{1/\nu}$



L_s=32 m_L=0.01335
L_s=32 m_L=0.0267
L_s=24 m_L=0.031644
L_s=20 m_L=0.04303
L_s=24 m_L=0.04444
L_s=20 m_L=0.054682
L_s=16 m_L=0.075
1^{st} Order
$(C_V-C_0)/m_L^{-\alpha/(\nu y_h)}$
$\tau L_s^{1/\nu}$
0.03
0.02
0.01
0
-150
-100
-50
0
50
100

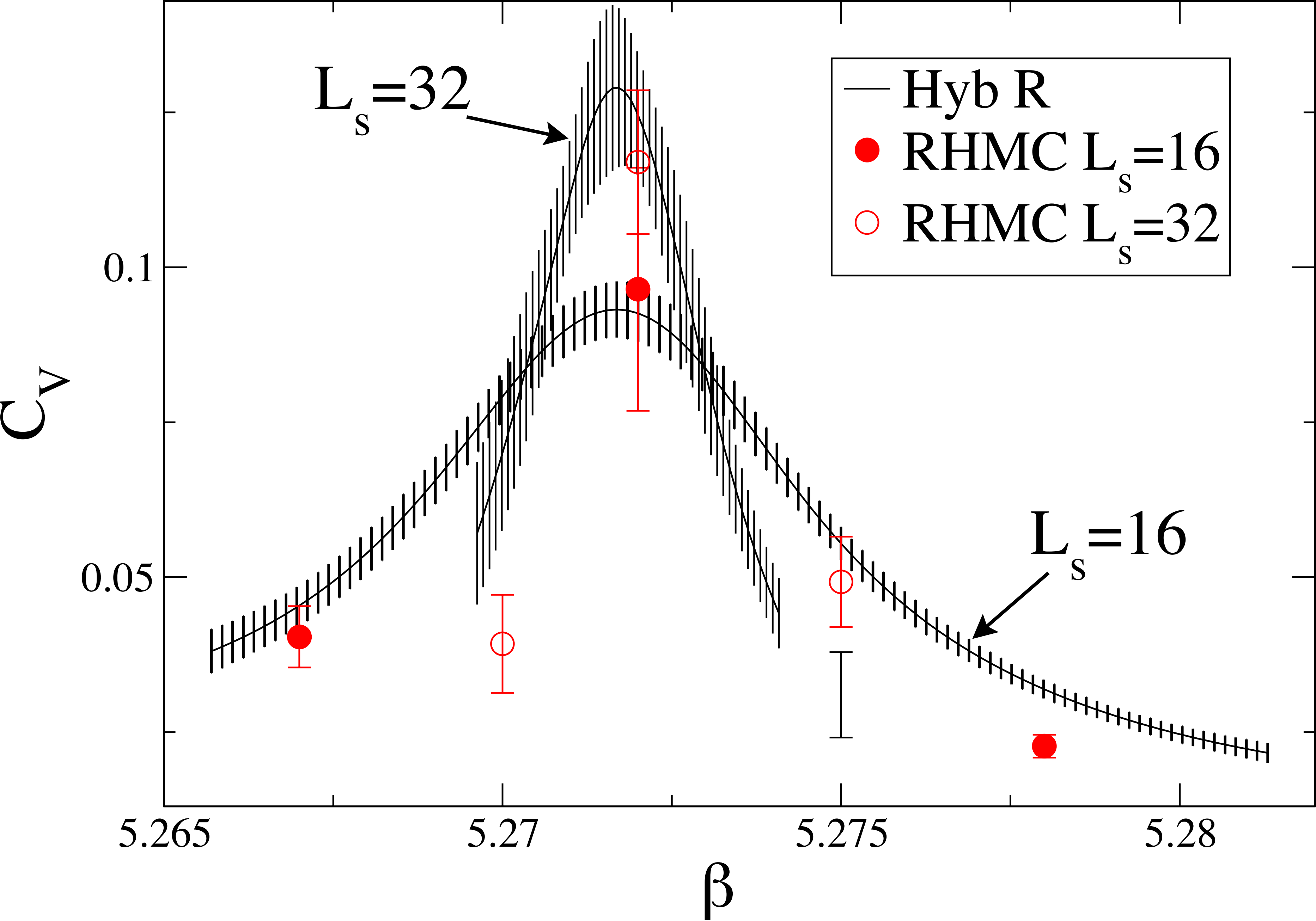
III LARGE VOLUMES AT FIXED m: HUNTING FOR BISTABILITIES

FIG 9 SHOWS THE SPECIFIC HEAT AT $m_q = .0135$ VS τL_s^3 FOR $L_s = 16$, AND $L_s = 32$. THERE IS AN L_s DEPENDENCE BOTH OF THE PEAK VALUE AND OF THE WIDTH, WHICH INDICATES A SINGULAR TERM, EQ.

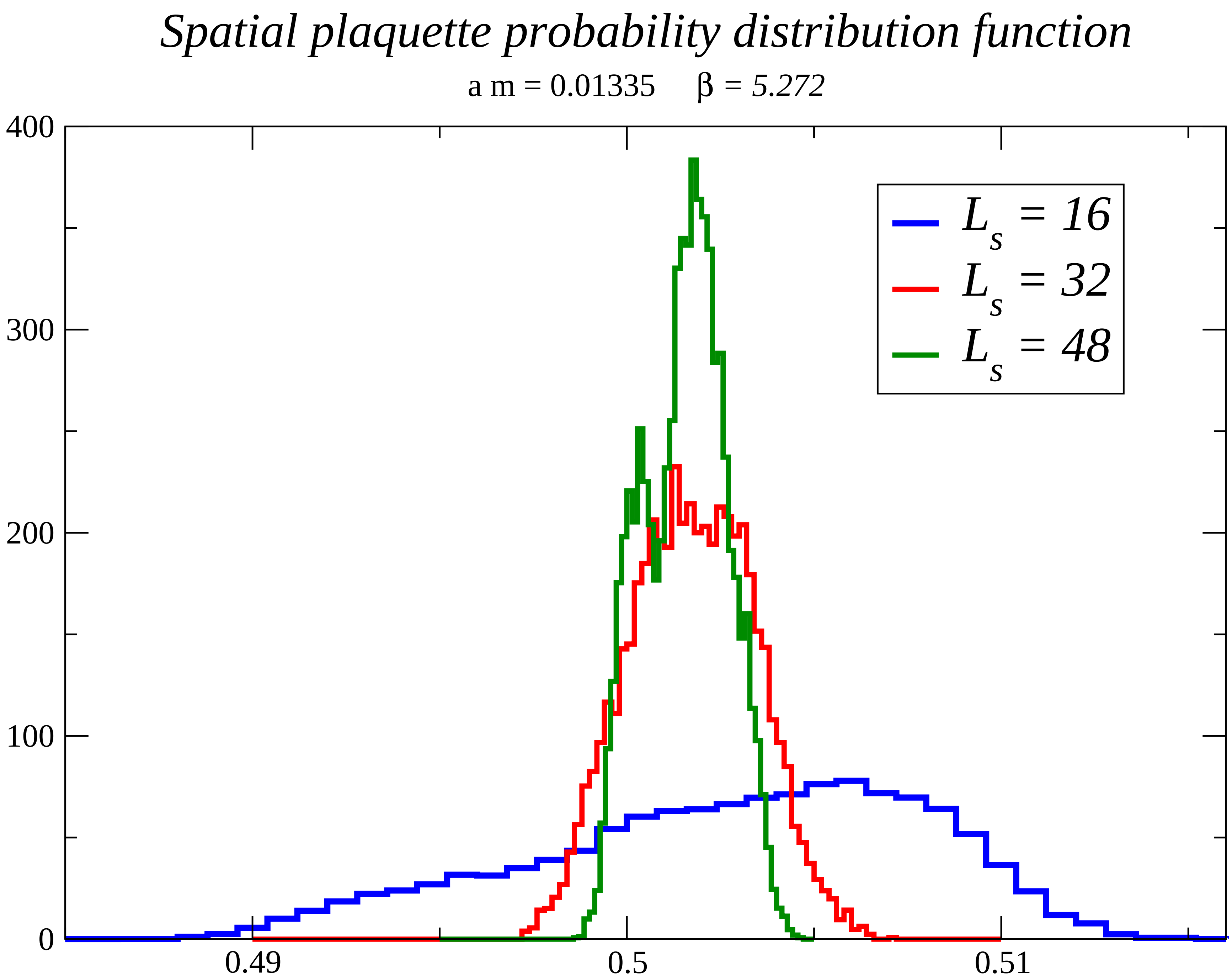
$$C_V - C_0 \simeq m^{-1} f_c(\tau L_s^3) + L_s^3 g_c(\tau L_s^3)$$

WHEN THE SINGULAR TERM BECOMES DOMINANT A TWO PEAK DISTRIBUTION OF THE ACTION VALUE SHOULD BE VISIBLE

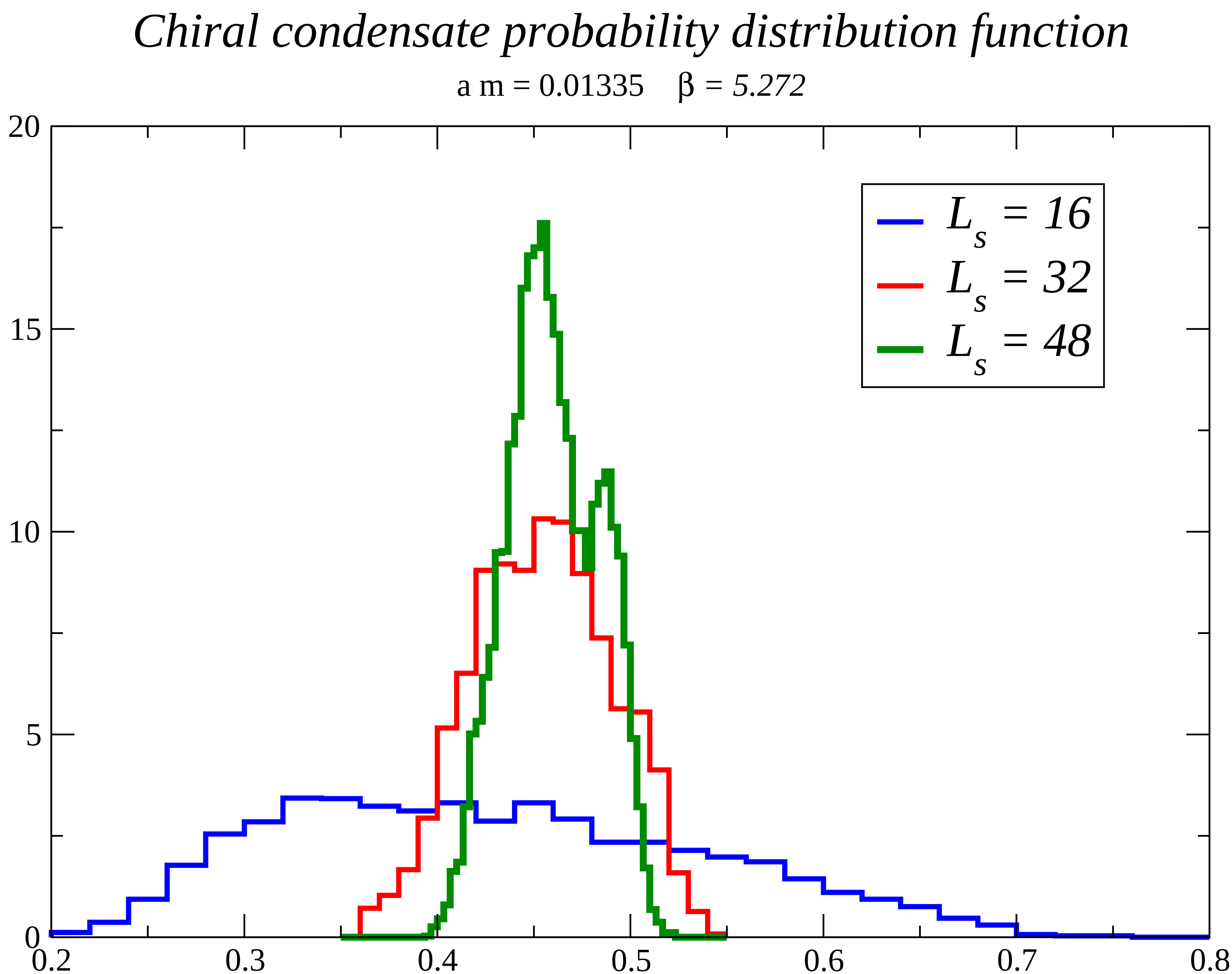
IF THIS IS TRUE THE EFFECT SHOULD BE VISIBLE AT LARGER L_s, SAY $L_s = 48$



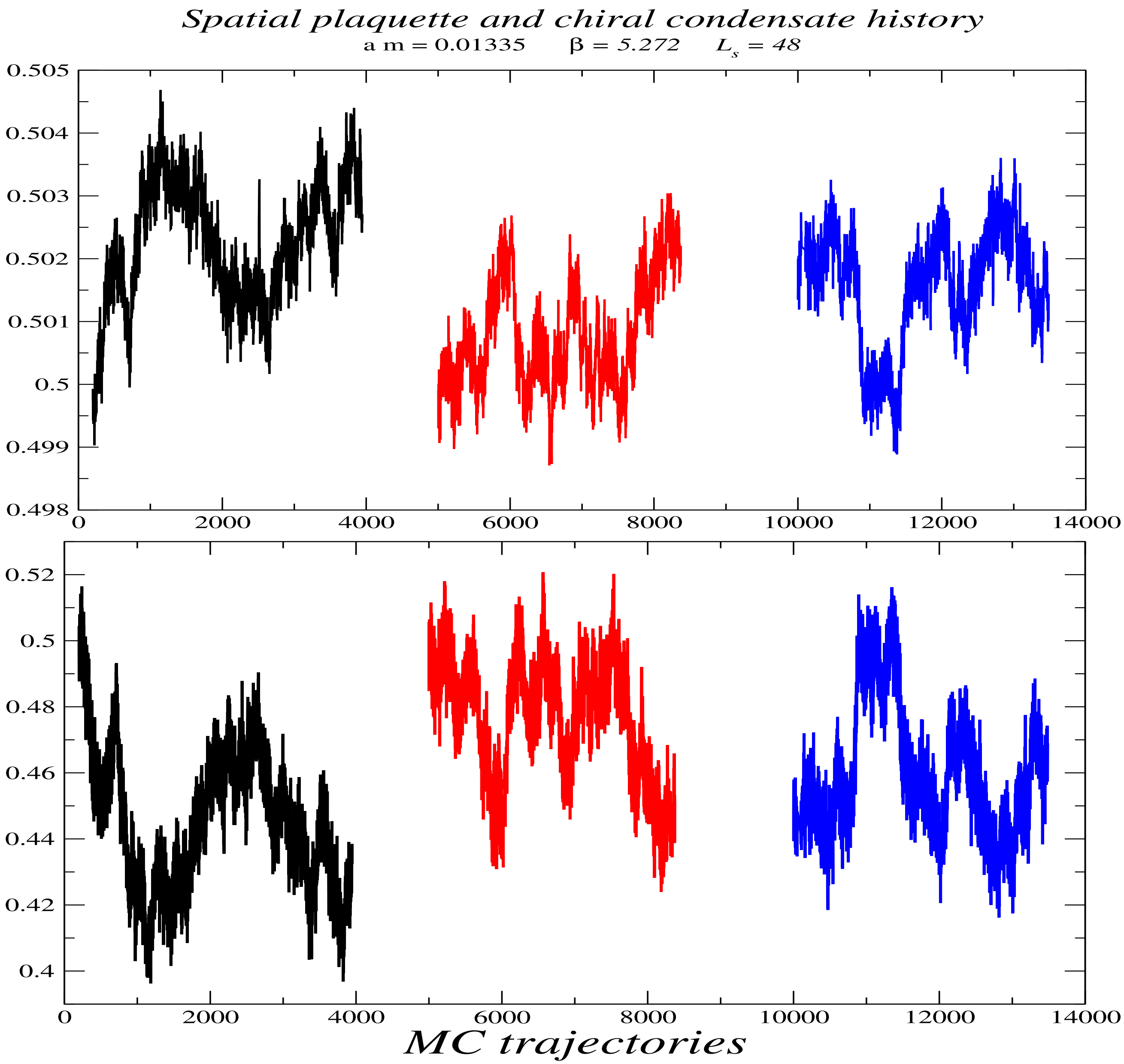
L_s=32
Hyb R
RHMC L_s=16
RHMC L_s=32
0.1
0.05
C_V
L_s=16
5.265
5.27
5.275
5.28
β



Spatial plaquette probability distribution function
a m = 0.01335 β = 5.272
400
300
200
100
0
0.49
0.5
0.51
L_s = 16
L_s = 32
L_s = 48



Chiral condensate probability distribution function
a m = 0.01335 β = 5.272
L_s = 16
L_s = 32
L_s = 48
0
5
10
15
20
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Spatial plaquette and chiral condensate history
a m = 0.01335 β = 5.272 L_s = 48
0.505
0.504
0.503
0.502
0.501
0.5
0.499
0.498
0
2000
4000
6000
8000
10000
12000
14000
0.52
0.5
0.48
0.46
0.44
0.42
0.4
MC trajectories

IV EQUATIONS OF STATE

IV_1 CHIRAL MAGNETIC EQ. STATE

$$\langle \bar\psi \psi \rangle - \langle \bar\psi \psi \rangle_{pert} = m^{1/\delta} f(\tau\, m^{-1/\nu y_h})$$

O(4): $\frac{1}{\delta} = 0.20$ $\quad \frac{1}{\nu y_h} = 0.54$

WEAK 1st. $\frac{1}{\delta} = 0$ $\quad \frac{1}{\nu y_h} = 1$

FIG 21 FIG. 22.

1st ORDER STRONGLY PREFERRED

IV_2 "MONOPOLE" EQ STATE.

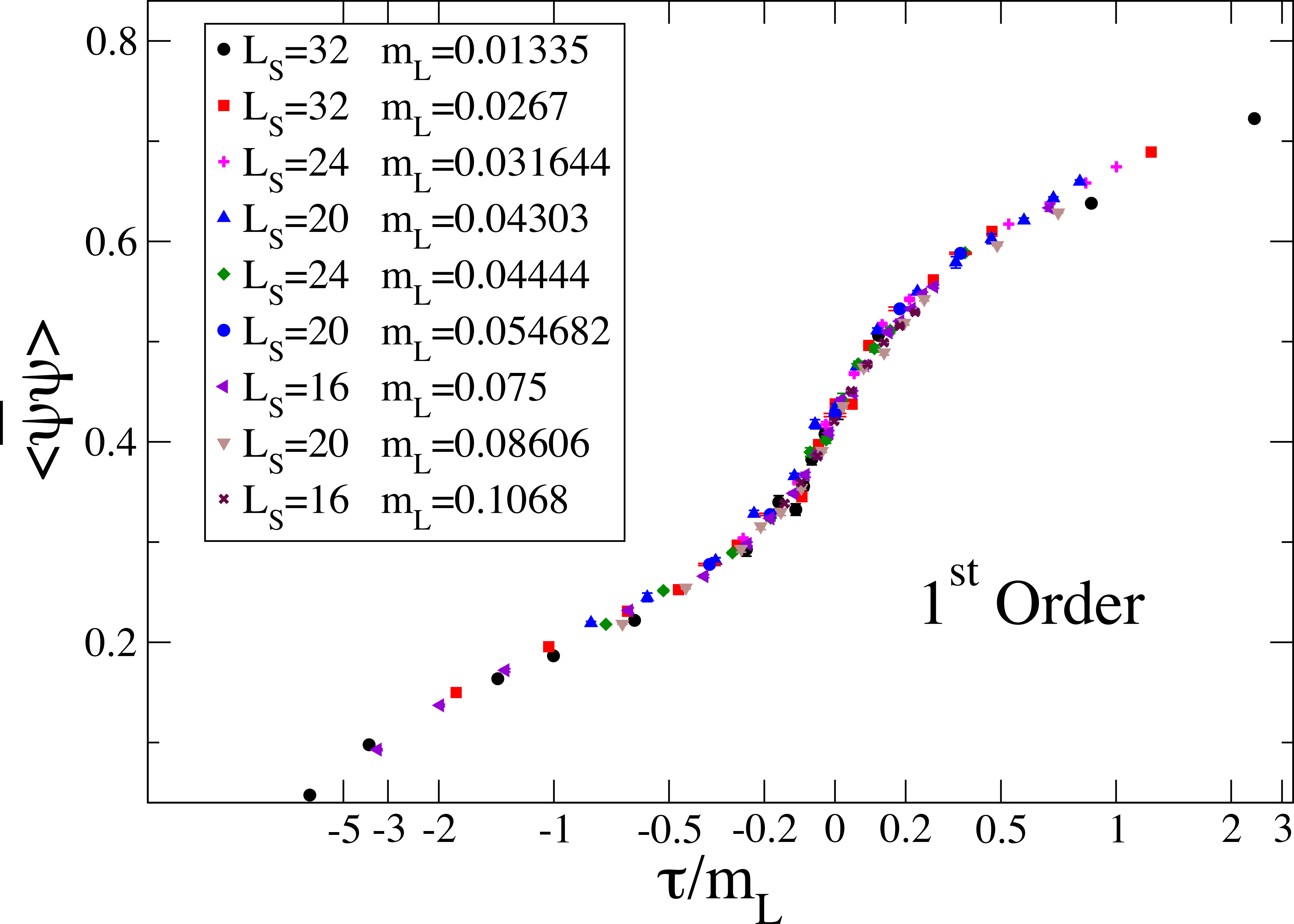
$\mu = \mu(\vec{x}, t)$ THE OPERATOR WHICH CREATES A MONOPOLE AT $(\vec{x}, t)$.

$$\mu(\vec{x}, t) = e^{i \int d^3y\, \vec{E}^{a}(\vec{y}, t)\, \vec{b}_\perp(x-y)\, \frac{m}{2g}}$$

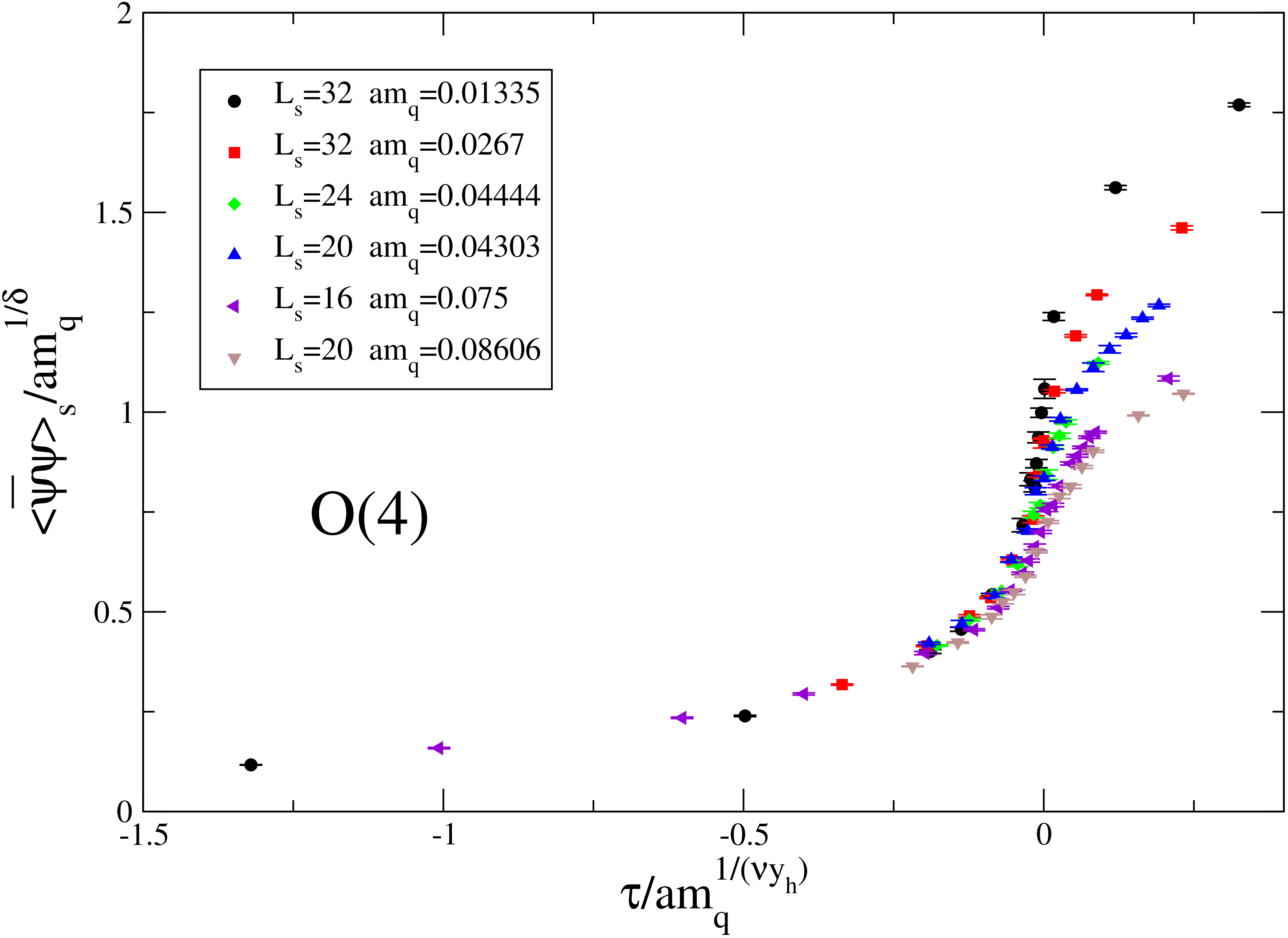
m = magnetic charge in units $\frac{1}{2g}$

$\vec{b}_\perp(z) = \frac{\vec{z} \wedge \vec{n}}{z(\vec{z} - \vec{n}\cdot\vec{z})}$ VECTOR POTENTIAL OF A MAGNETIC MONOPOLE FIELD $\vec\nabla \vec{b}_\perp = 0$

SW 14



0.8
0.6
0.4
0.2
$\langle \bar{\psi}\psi \rangle$
$L_S=32$ $m_L=0.01335$
$L_S=32$ $m_L=0.0267$
$L_S=24$ $m_L=0.031644$
$L_S=20$ $m_L=0.04303$
$L_S=24$ $m_L=0.04444$
$L_S=20$ $m_L=0.054682$
$L_S=16$ $m_L=0.075$
$L_S=20$ $m_L=0.08606$
$L_S=16$ $m_L=0.1068$
1^{st} Order
-5 -3 -2 -1 -0.5 -0.2 0 0.2 0.5 1 2 3
τ/m_L



L_s=32 am_q=0.01335
L_s=32 am_q=0.0267
L_s=24 am_q=0.04444
L_s=20 am_q=0.04303
L_s=16 am_q=0.075
L_s=20 am_q=0.08606
O(4)
$\langle\bar{\psi}\psi\rangle_s/am_q^{1/\delta}$
$\tau/am_q^{1/(\nu y_h)}$
0
0.5
1
1.5
2
-1.5
-1
-0.5
0

$\vec{E}^a = Tr\{U \phi^a_{diag} U^+ \vec{E}\}$

IS THE ELECTRIC FIELD COMPONENT $\vec{E}^a$ ALONG THE RESIDUAL U(1) IN THE ABELIAN PROJECTED GAUGE. IN THAT GAUGE

$$\mu = e^{i\int d^3y\, \vec{E}_\perp(y) \frac{m}{2g} b_\perp(\vec{x}-\vec{y})}$$

$\vec{E}_\perp$ IS THE CONJUGATE MOMENTUM TO $\vec{A}_\perp$

$$e^{ipa}|x\rangle = |x+a\rangle$$

$$\mu(\vec{x},t)\,|A_\perp(\vec{z})\rangle = |A_\perp(\vec{z}) + \frac{m}{2g} b_\perp(\vec{x}-\vec{y})\rangle$$

μ CREATES A MONOPOLE

$$\langle\mu\rangle = \frac{Z(S+\Delta S)}{Z(S)} \qquad \rho = \frac{\partial \ln\langle\mu\rangle}{\partial\beta} = \langle S\rangle_S - \langle S+\Delta S\rangle_{S+\Delta S}$$

$$\langle\mu\rangle = \exp\int_0^\beta \rho(x)\,dx$$

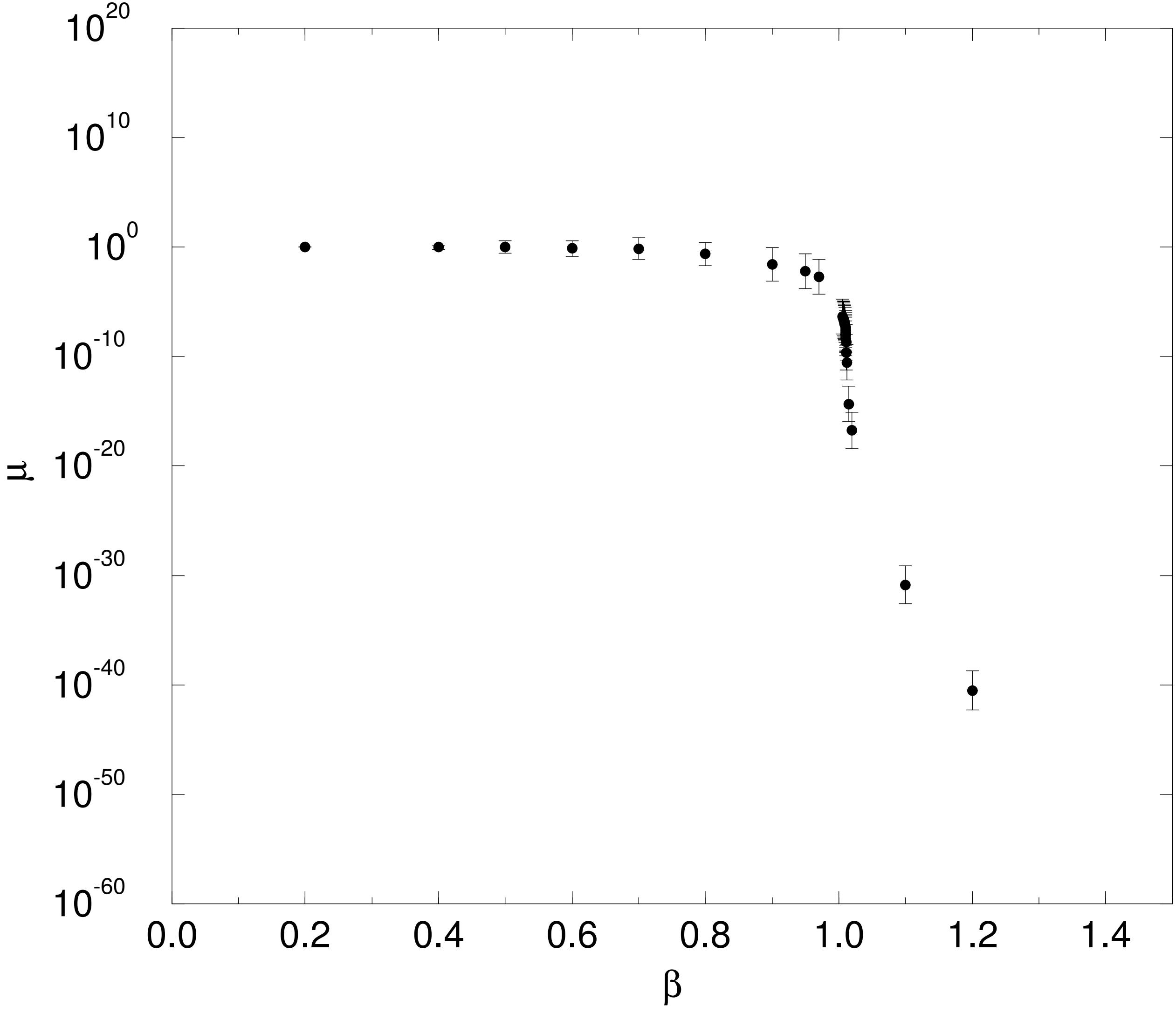
$\beta < \beta_c \qquad \rho \xrightarrow[L_s\to\infty]{} \bar{\rho}$ finite fig.

$\beta > \beta_c \qquad \rho \underset{L_s\to\infty}{\simeq} c_1 - |c_2| L_s \qquad \langle\mu\rangle \xrightarrow[L_s\to\infty]{} 0$ fig.

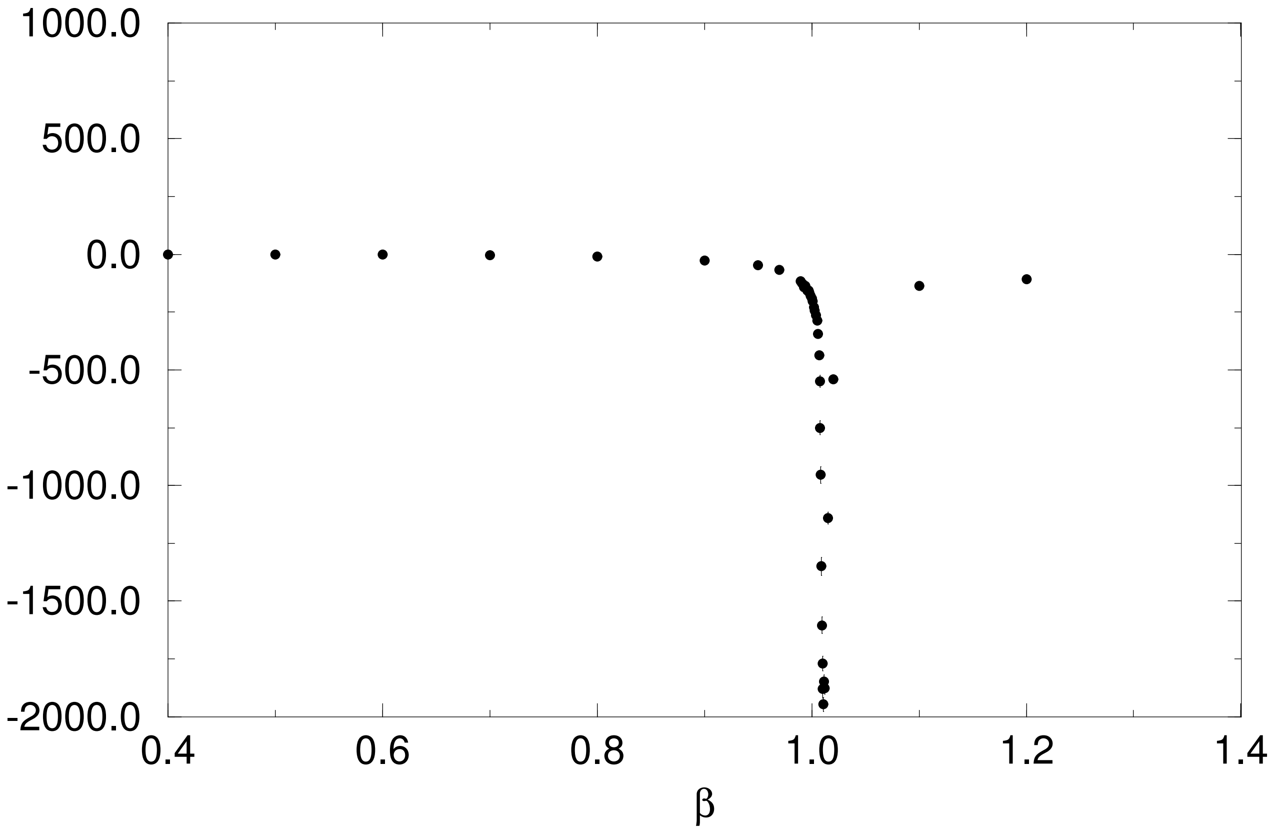
$\beta = \beta_c \qquad \langle\mu\rangle \simeq L_s^{z/\nu}\,\phi(\tau L_s^{1/\nu}, m L_s^{y_h}) \underset{L_s\to\infty}{\simeq} m^{-\frac{z}{\nu y_h}}\,\phi_\mu(\tau L_s^{1/\nu})$

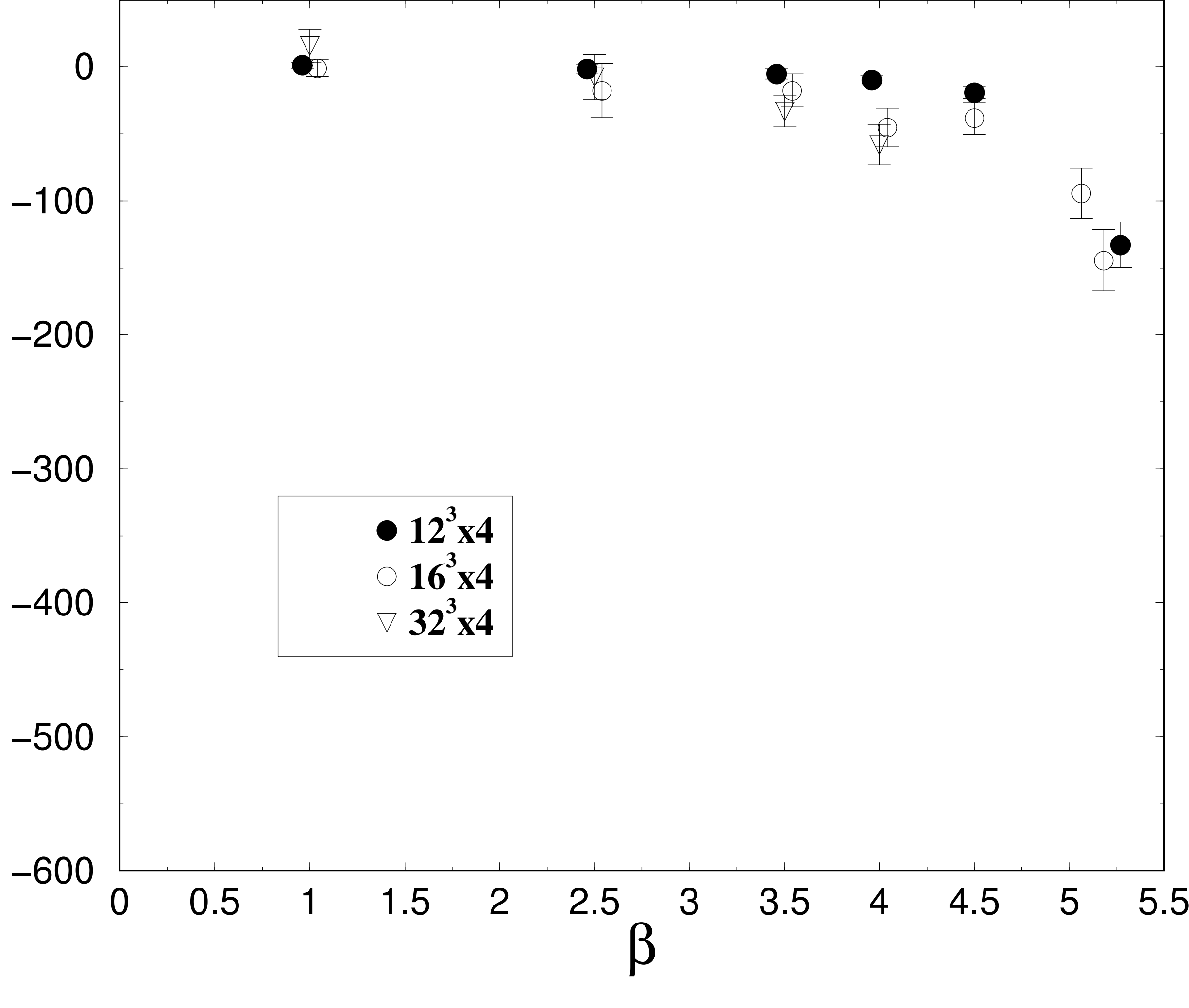
$$\rho = L_s^{1/\nu} f_\mu(\tau L_s^{1/\nu}) \longrightarrow \text{EXTRACT } \nu$$

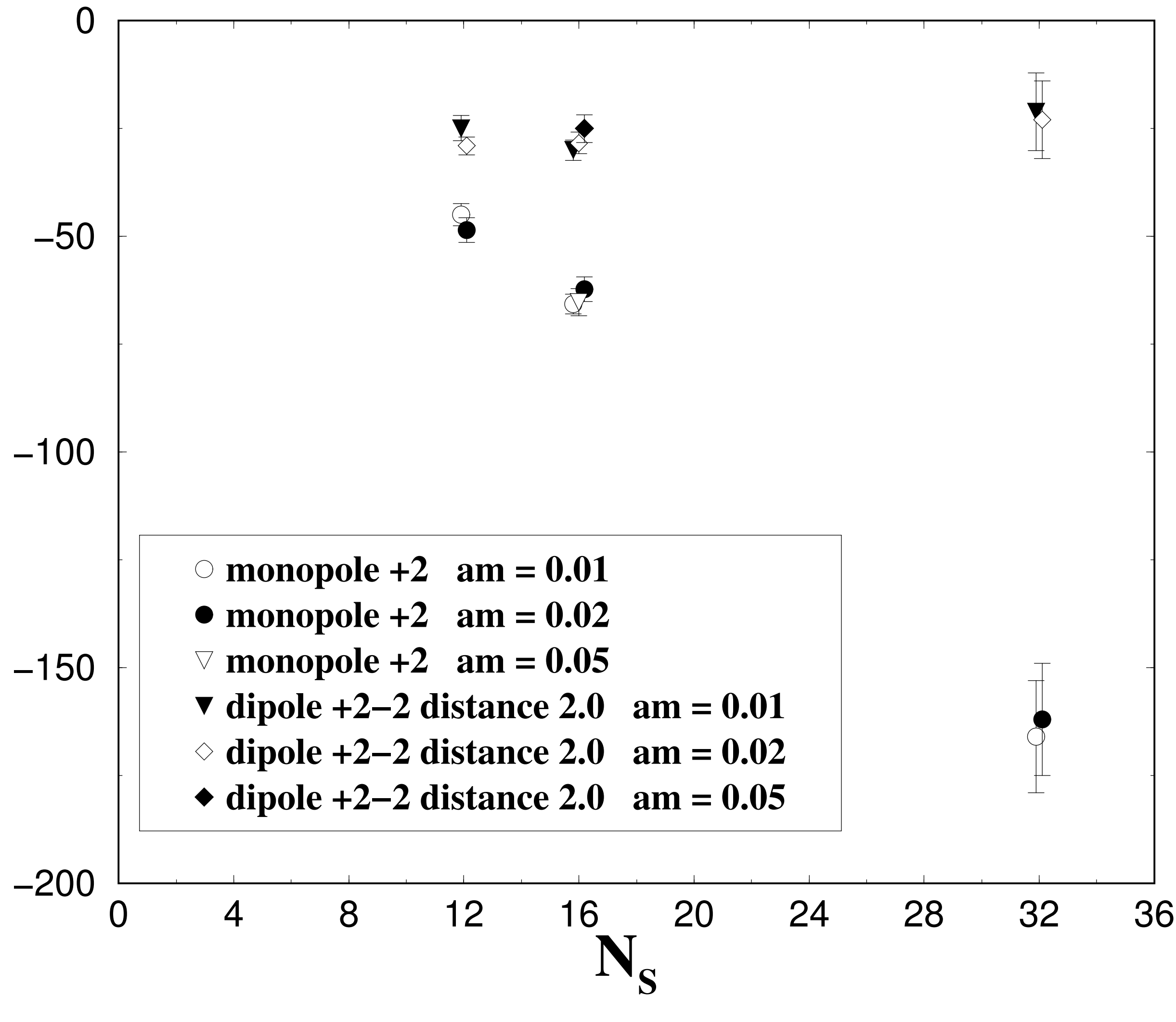
fig fig.



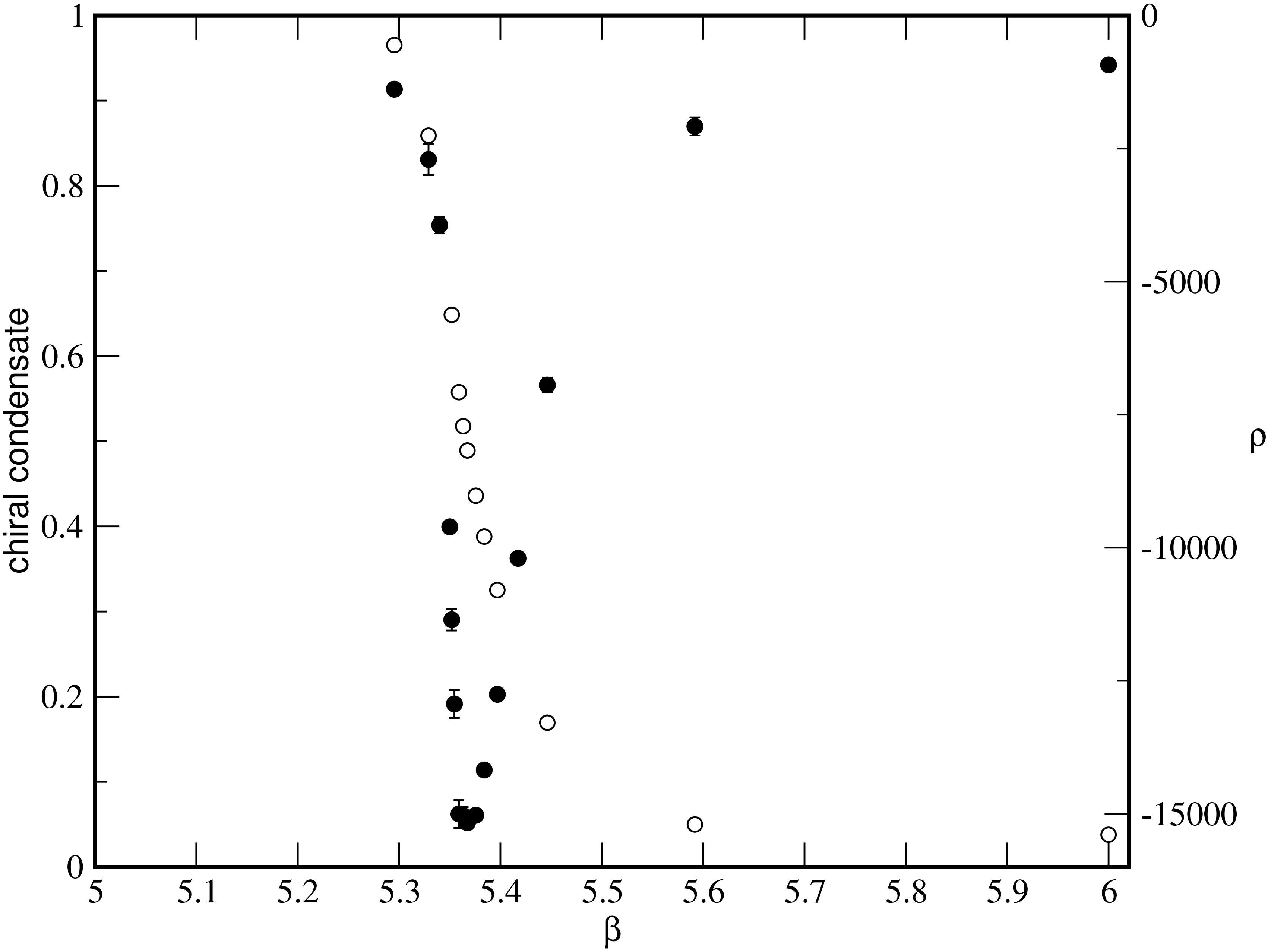
10^{20}
10^{10}
10^{0}
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
10^{-60}
μ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
β


1000.0
500.0
0.0
-500.0
-1000.0
-1500.0
-2000.0
0.4
0.6
0.8
1.0
1.2
1.4
β

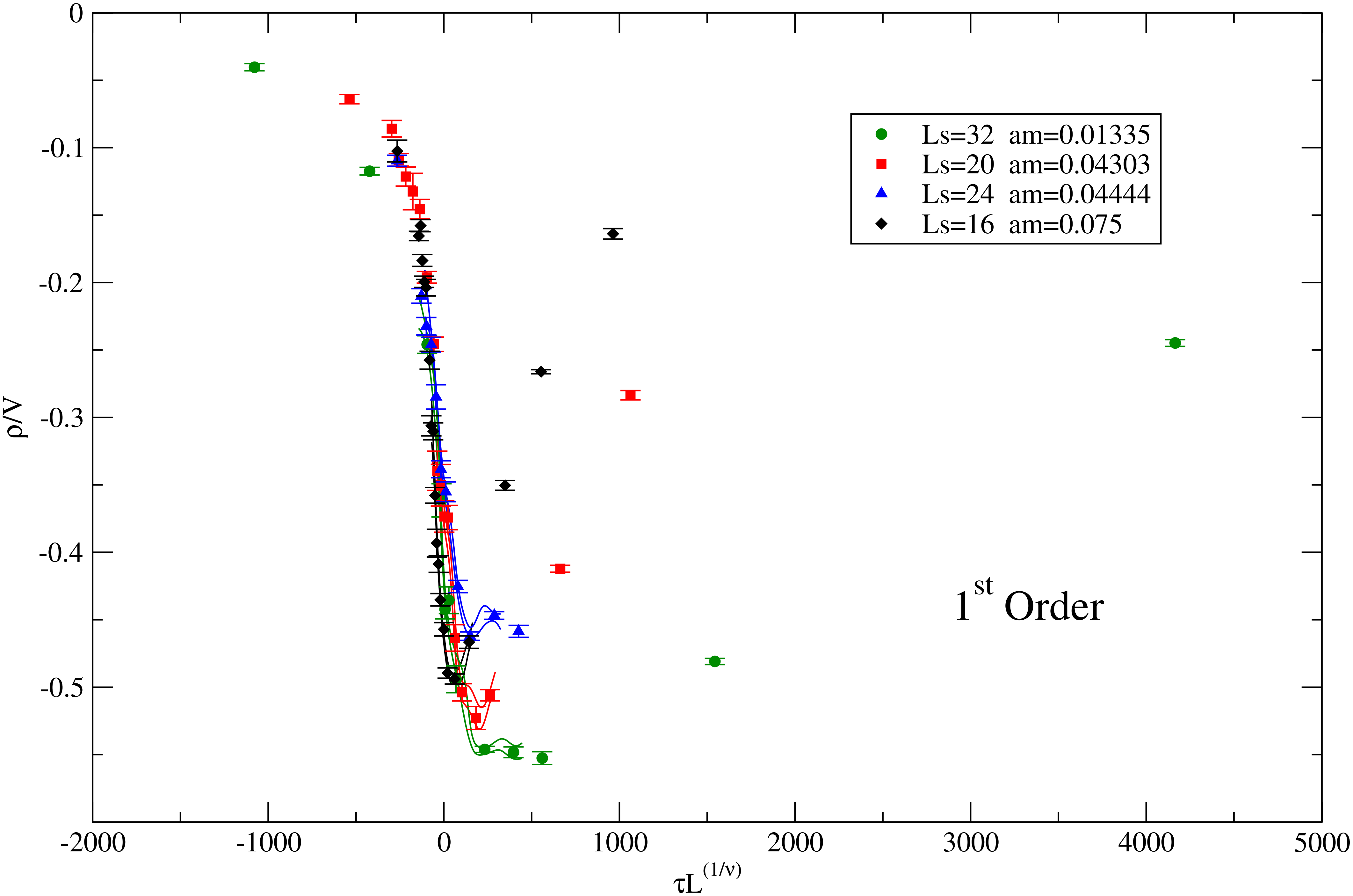

0
−100
−200
−300
−400
−500
−600
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
β
12³x4
16³x4
32³x4



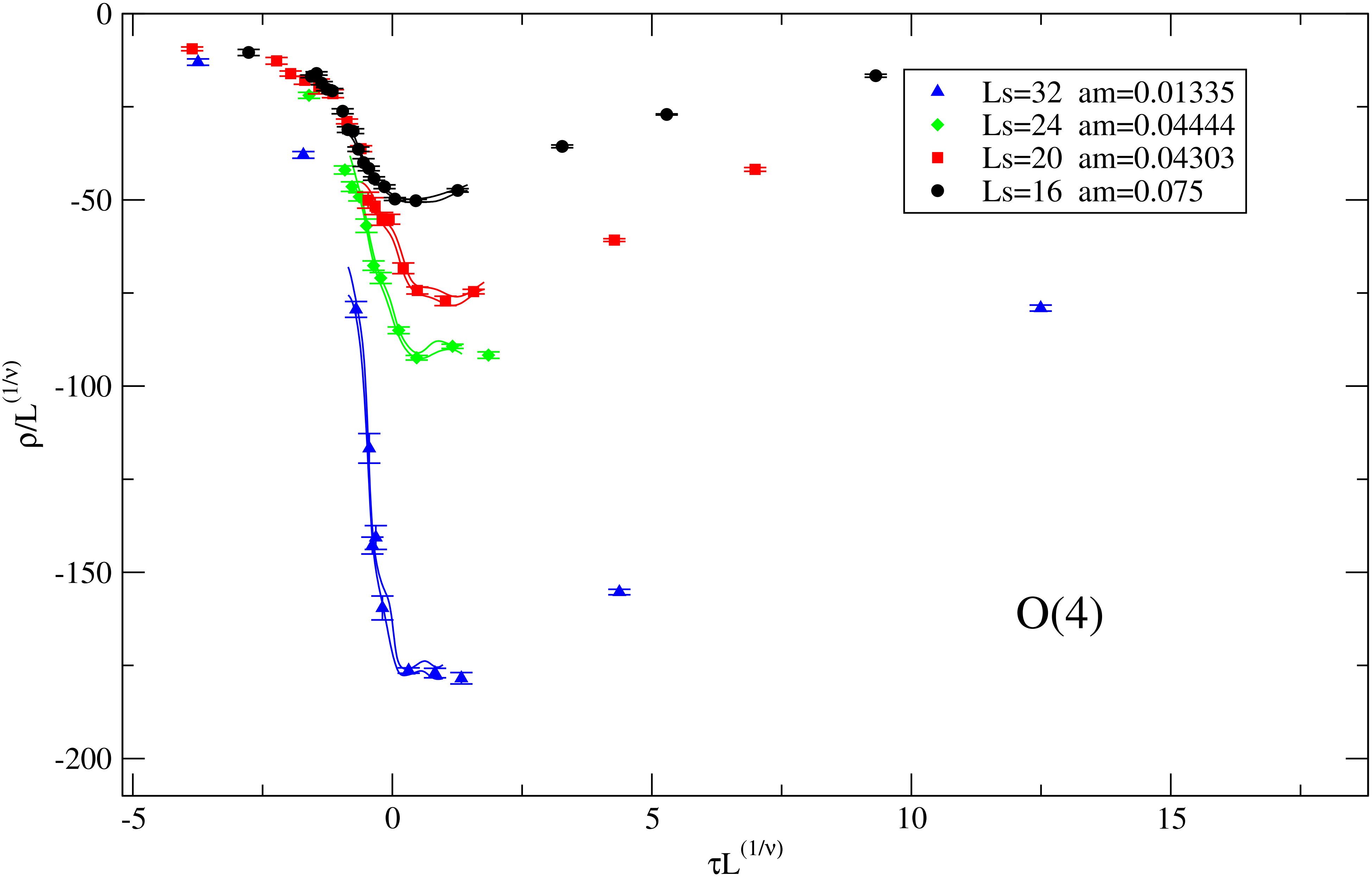
0
−50
−100
−150
−200
0
4
8
12
16
20
24
28
32
36
N_S
monopole +2 am = 0.01
monopole +2 am = 0.02
monopole +2 am = 0.05
dipole +2−2 distance 2.0 am = 0.01
dipole +2−2 distance 2.0 am = 0.02
dipole +2−2 distance 2.0 am = 0.05



chiral condensate
ρ
β
0
0.2
0.4
0.6
0.8
1
5
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
6
0
-5000
-10000
-15000



Ls=32 am=0.01335
Ls=20 am=0.04303
Ls=24 am=0.04444
Ls=16 am=0.075
1st Order
ρ/V
τL^(1/ν)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-2000
-1000
0
1000
2000
3000
4000
5000



Ls=32 am=0.01335
Ls=24 am=0.04444
Ls=20 am=0.04303
Ls=16 am=0.075
O(4)
ρ/L^(1/ν)
τL^(1/ν)
0
-50
-100
-150
-200
-5
0
5
10
15

x|| MONOPOLE EQ. OF STATE SCALES AS 1st ORDER

V ADJOINT QCD (aQCD)

$am = .01$

_ 1st ORDER DECONFINING TRANSITION

$\beta = 5.25$

- POLYAKOV LINE
- $\langle \mu \rangle$

$\Longrightarrow$ 1st ORDER

figs.

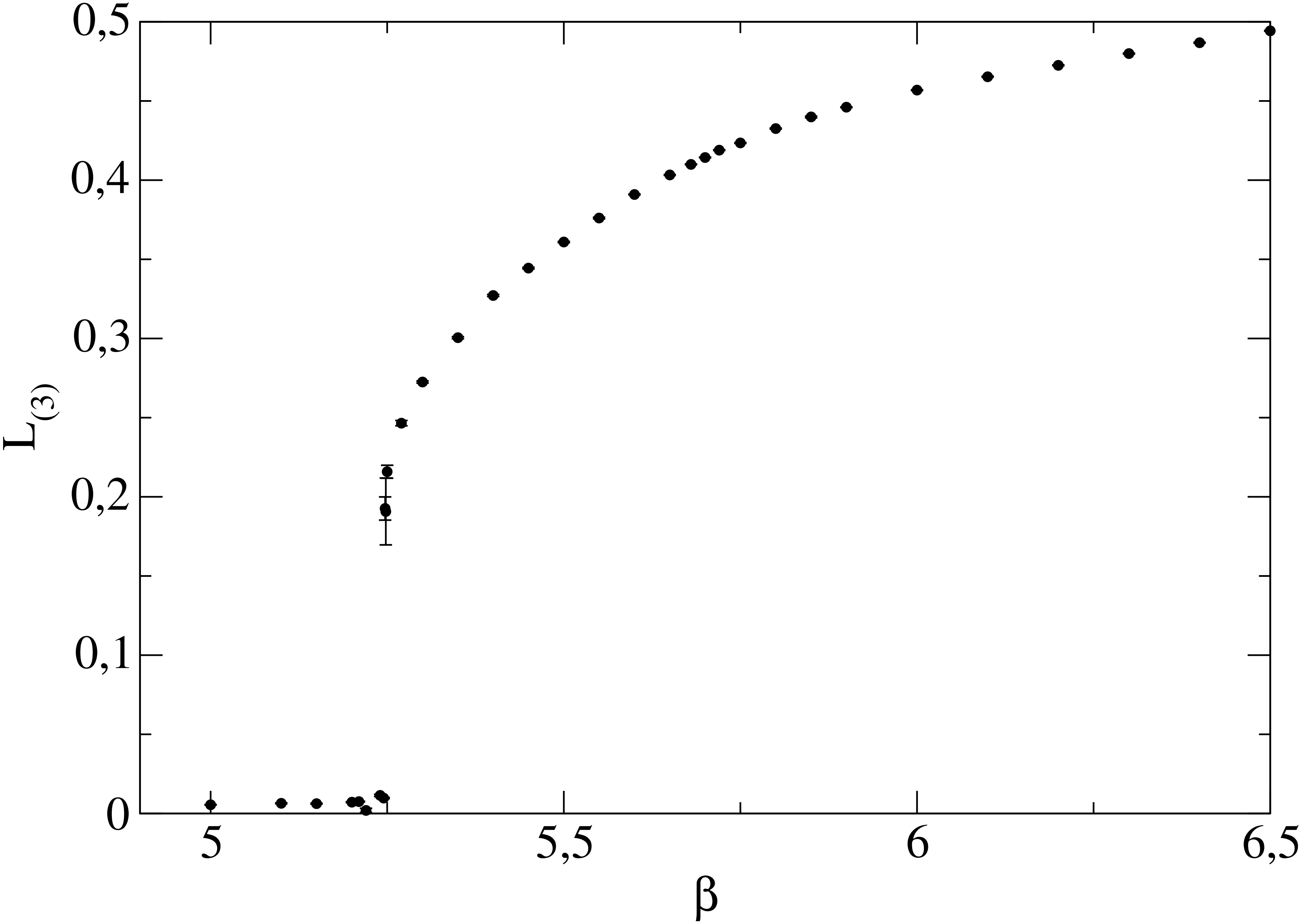
CHIRAL TRANSITION

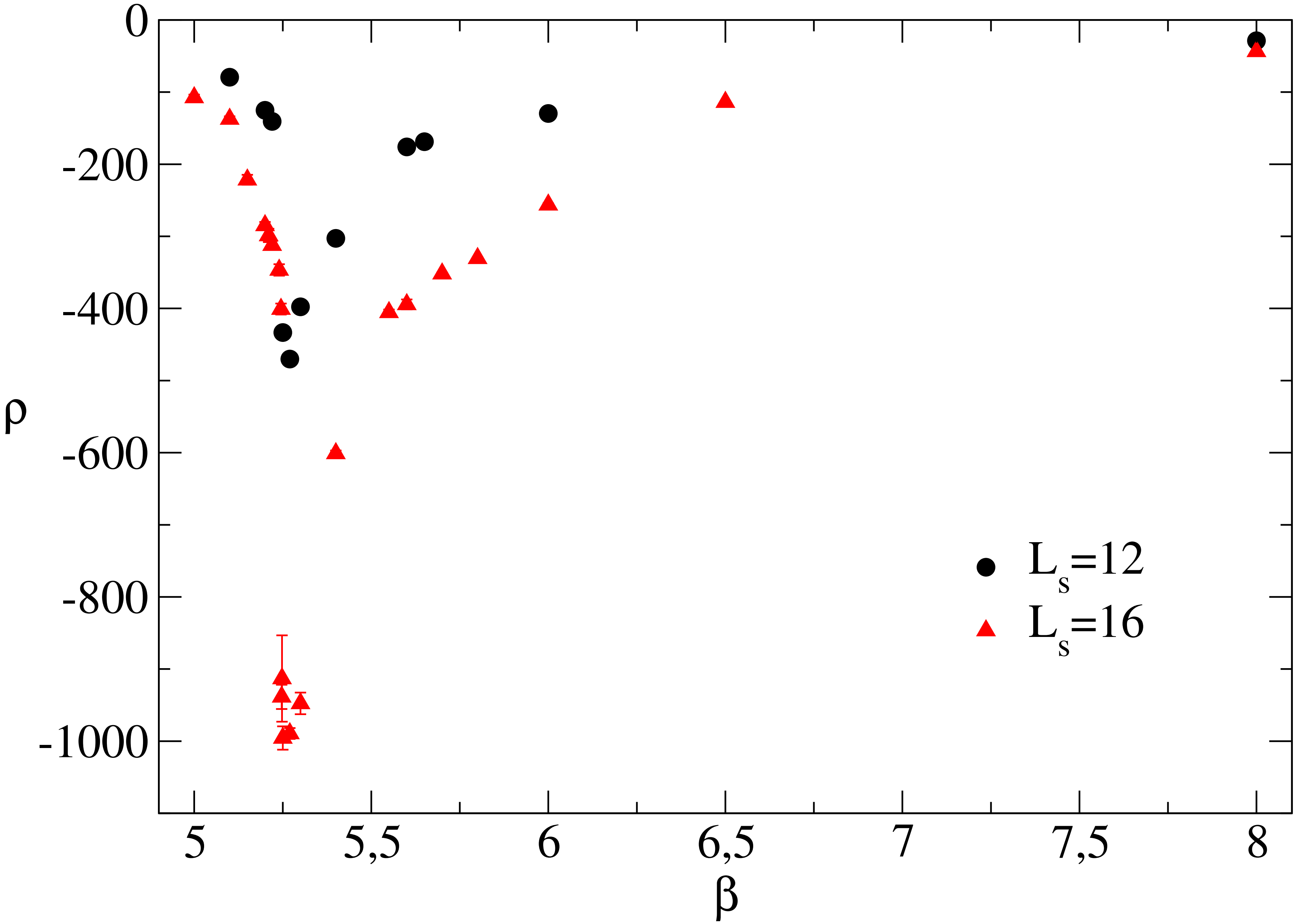
$\beta \simeq 5.75$

A BROAD PEAK IN THE CHIRAL SUSCEPTIBILITY CONSISTENT WITH A CROSSOVER.

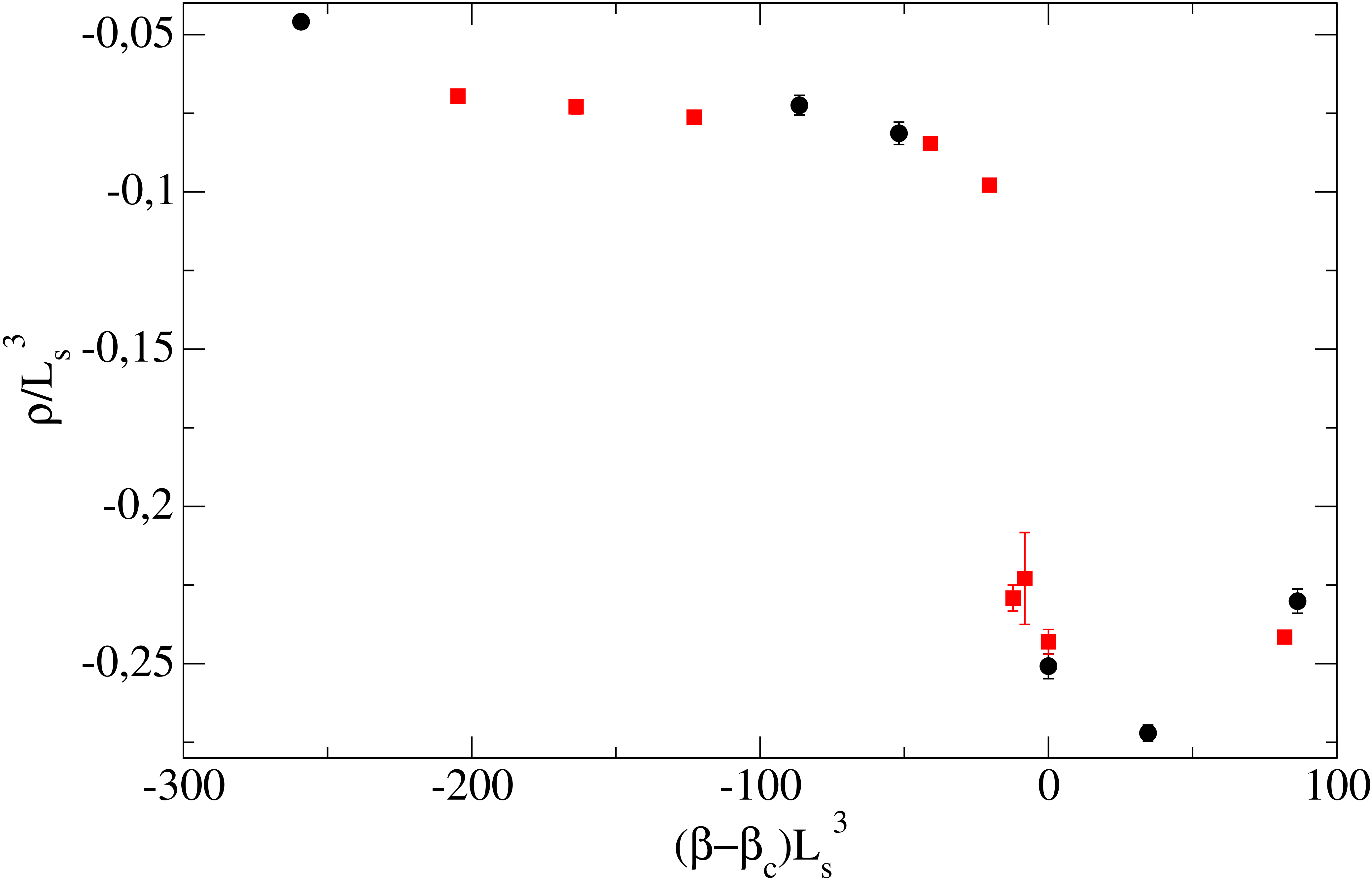
~~TRA~~ INVISIBLE TO POLYAKOV LINE AND TO $\langle \mu \rangle$

CHIRAL d.o.f. $\neq$ CONFINEMENT d.o.f.

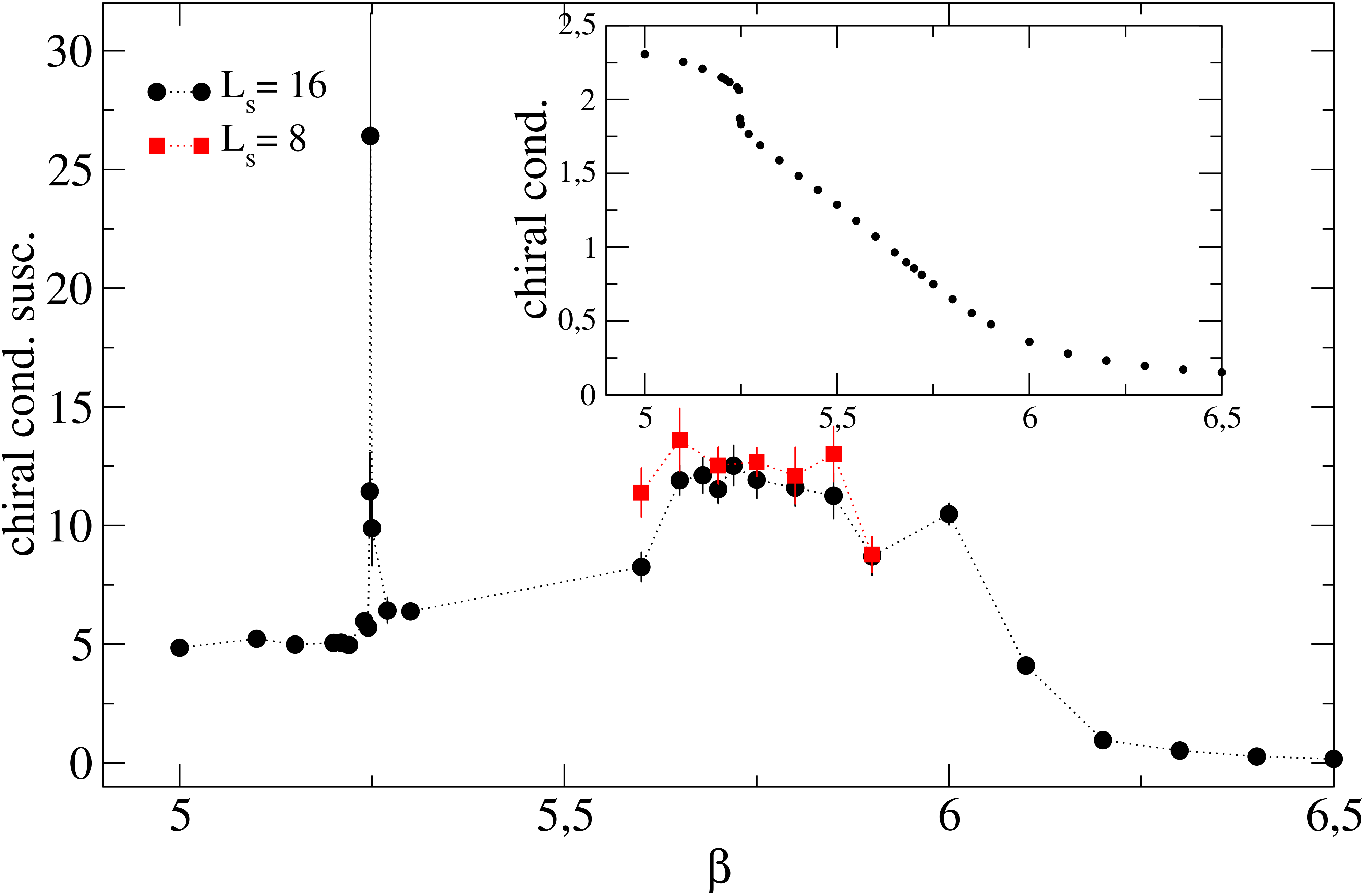

0,5
0,4
0,3
0,2
0,1
0
$L_{(3)}$
5
5,5
6
6,5
β



0
-200
-400
-600
-800
-1000
ρ
5
5,5
6
6,5
7
7,5
8
β
L_s=12
L_s=16



-0,05
-0,1
-0,15
-0,2
-0,25
ρ/L_s^3
-300
-200
-100
0
100
$(\beta-\beta_c)L_s^3$



chiral cond. susc.
β
L_s= 16
L_s= 8
chiral cond.
0
5
10
15
20
25
30
5
5,5
6
6,5
0
0,5
1
1,5
2
2,5

IV CONCLUSIONS

(i) A DUAL SYMMETRY $\exists$ IN QCD, RELATED TO CONFINEMENT. THE DUAL EXCITATIONS CARRY MAGNETIC CHARGE. [aQCD]

μ IS AN ORDER PARAMETER

- THE MECHANISM IS THE SAME IN QUENCHED AND FULL QCD ($N_c \to \infty$)

$\Downarrow$ $\Downarrow$ $\Downarrow$

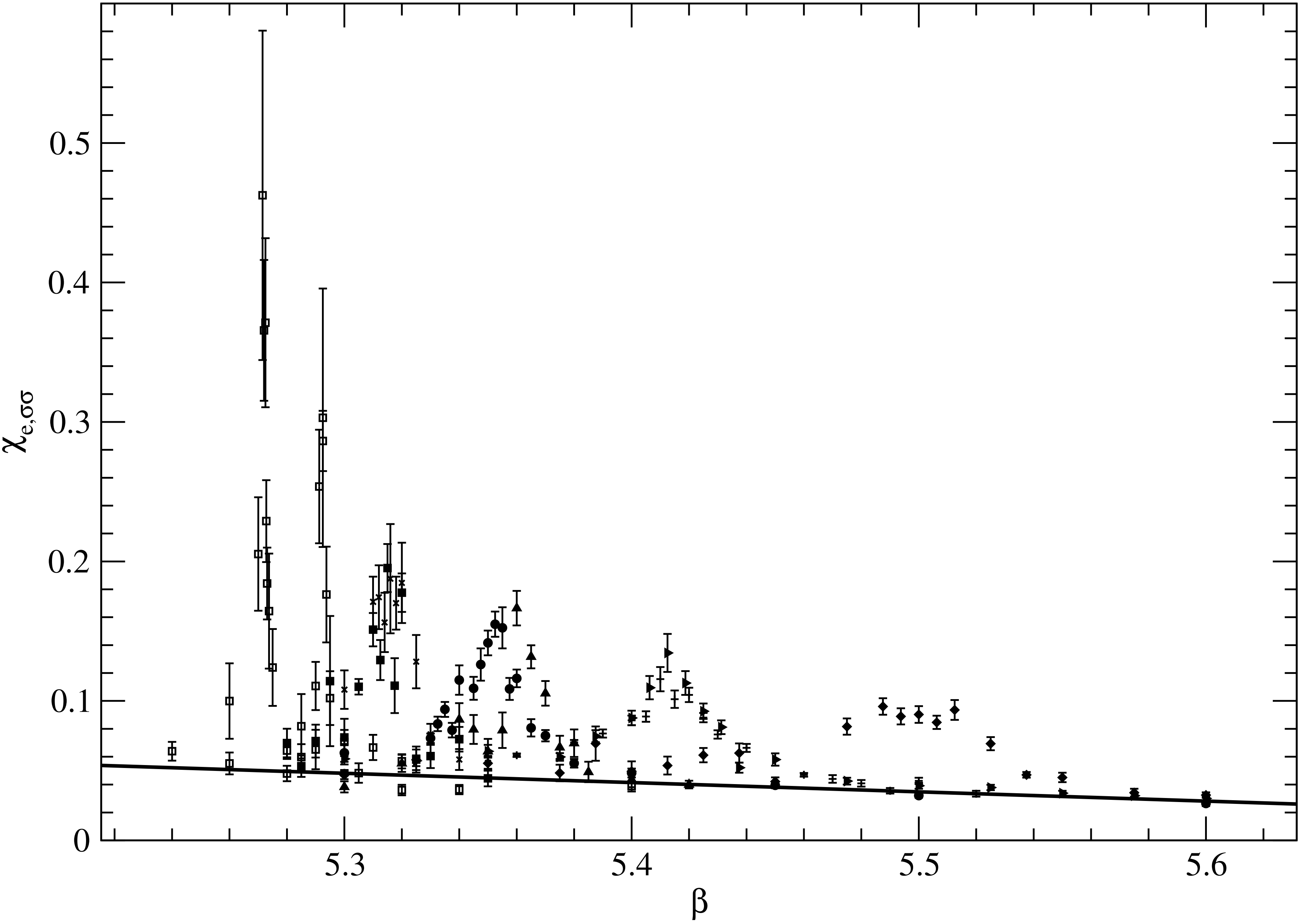
- DECONFINEMENT AN ORDER DISORDER TRANSITION (W.H. OK)

(ii) CRUCIAL TEST: THE ORDER OF THE DECONFINING PHASE TRANSITION.

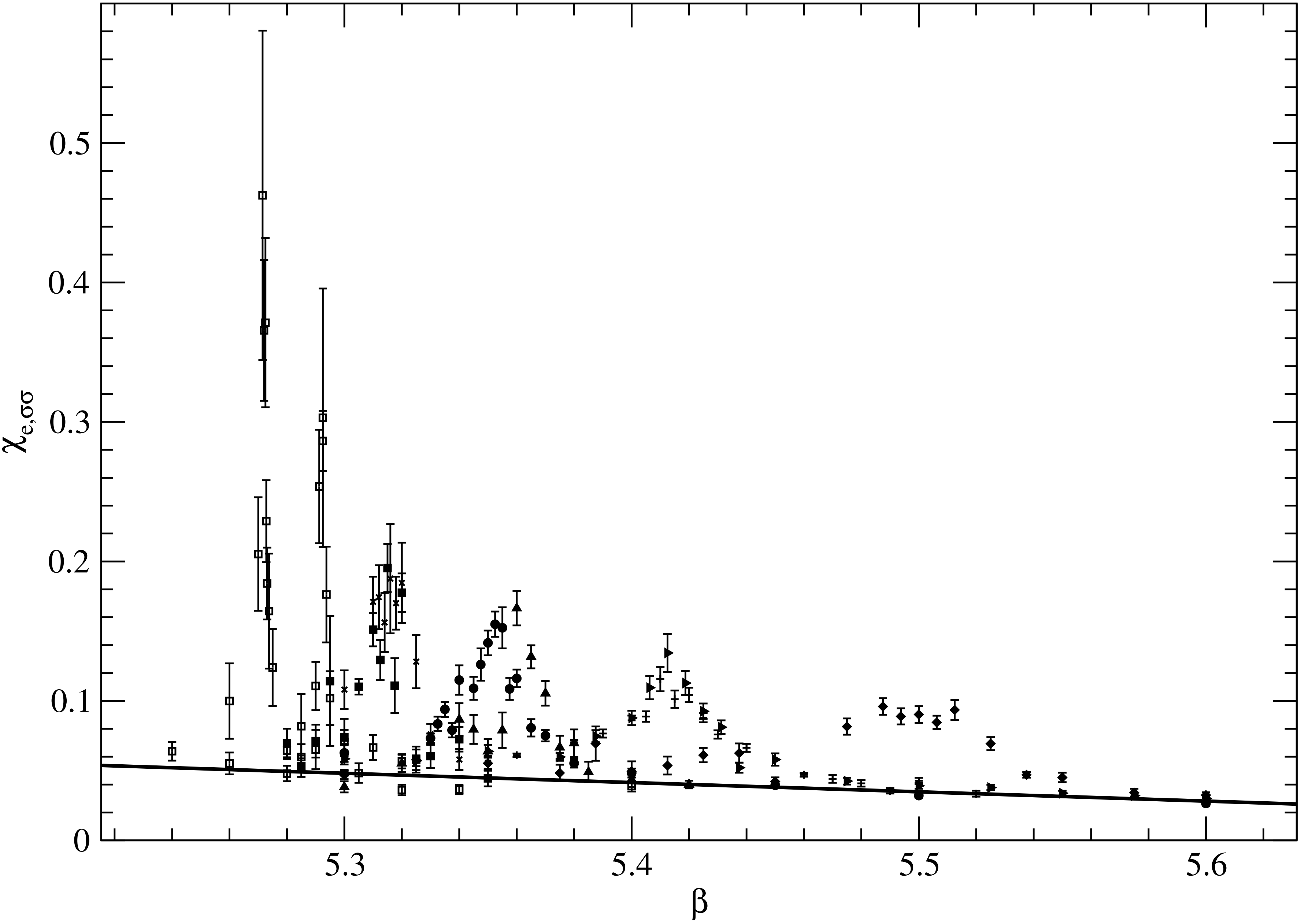
$N_f = 2$ AT $m \simeq 0$: STRONG INDICATION OF VERY WEAK-FIRST ORDER. LARGE SPATIAL VOLUMES NEEDED. FINER LATTICES

- A FUNDAMENTAL ISSUE TO UNDERSTAND COLOR CONFINEMENT.

[SW



0.5
0.4
0.3
0.2
0.1
0
$\chi_{e,\sigma\sigma}$
5.3
5.4
5.5
5.6
β



0.5
0.4
0.3
0.2
0.1
0
$\chi_{e,\sigma\sigma}$
5.3
5.4
5.5
5.6
β