Theoretical issues
and
Non-QCD Physics*

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ECFA Workshop on HPC in Lattice Field Theory

DESY Zeuthen,

6/7 Oct 2000

thanks to:

Z. Fodor

I. Montvay

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R. Sommer

...

* in ECFA-99-200, CERN-2000-002:

Requirements For High Performance Computing

For Lattice QCD:

Report of the ECFA Working Panel

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Requirements for High Performance Computing

for Lattice QCD:

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6 Theoretical issues and Non-QCD Physics

6.1 Electroweak physics: QED, SM, MSSM

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interesting non-perturbative physics ... selected examples ...

6.1 Electroweak physics: QED, SM, MSSM

- QED
  - not asymptotically free
  - non-perturbative regime at SD, Landau pole
  - conceptual and structural problems
  - computational resources no limiting factor
- SM, MSSM
  - the electroweak phase transition
  - heavy fermions (strong Yukawa coupling sectors)
  - vacuum stability and mass bounds
  - the heavy (strongly interacting) Higgs sector

proper handling of chiral fermions and supersymmetry may be crucial here!

1. Electroweak baryogenesis: all 3 Sakharov conditions concern difficult non-perturbative features (shaleron rate, spontaneous CP violation, properties of the EW phase transition)

$\Rightarrow$ suitable for study on the lattice.

2. Electroweak phase transition: extending the perturbative regime valid for light Higgs masses towards the non–perturbative region of heavier Higgs masses by means of lattice simulations. In the bosonic sector yield a first-order phase transition line in a (T_c, m_H)–plot, which is essentially linear, passing through $(90, 50)$ GeV and ending at about $(110, 75)$ GeV in a second-order endpoint (one expects little change if fermions would be included).

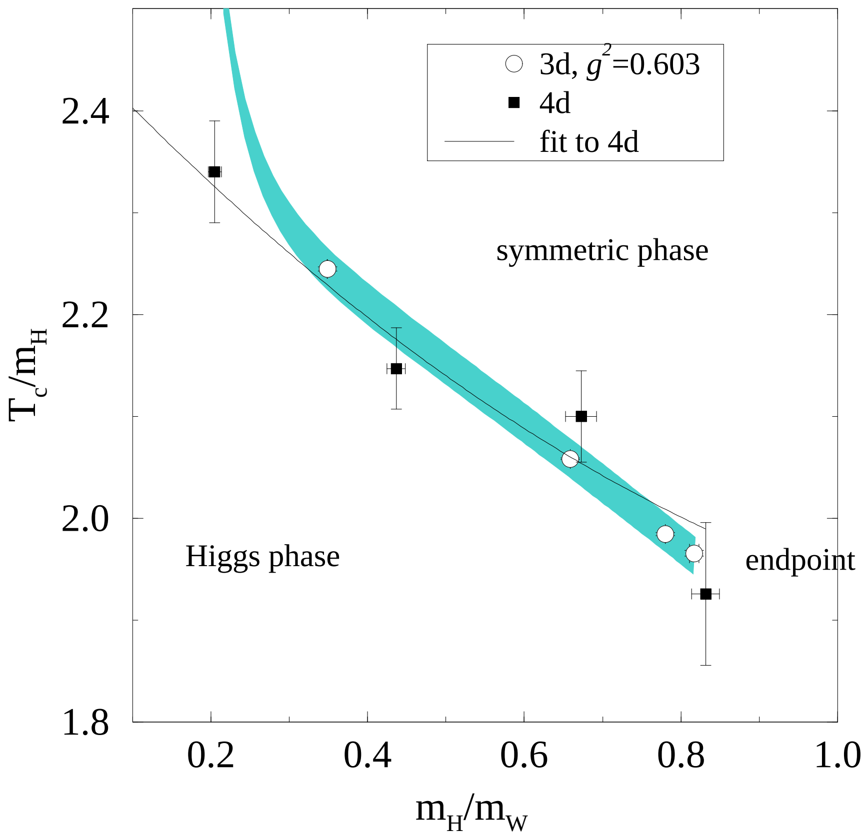

Figure 1: A comparison of the phase diagrams obtained from direct 4d simulations (squares) and from dimensionally reduced 3d simulations (shaded region).

Investigation of the SM basically finished in the bosonic sector. $D = 4$ and dimensional reduction to $D = 3$ yields consistent results. Although real-time evolution processes still not well understood one does not see a chance that the SM is able to explain baryogenesis.

Note: observed BA requires strong 1st order transition!

$\Rightarrow$ (because of the observed BA and experimental lower bound on $m_H \gtrsim 108$ GeV) lattice simulations have “proven” that there is new physics beyond the SM.

3. Extension to MSSM: larger number of fields, larger parameter space, what means bosonic sector of MSSM? No supersymmetry, its broken anyway, but should be softly broken only ...; so far just extra bosonic fields.

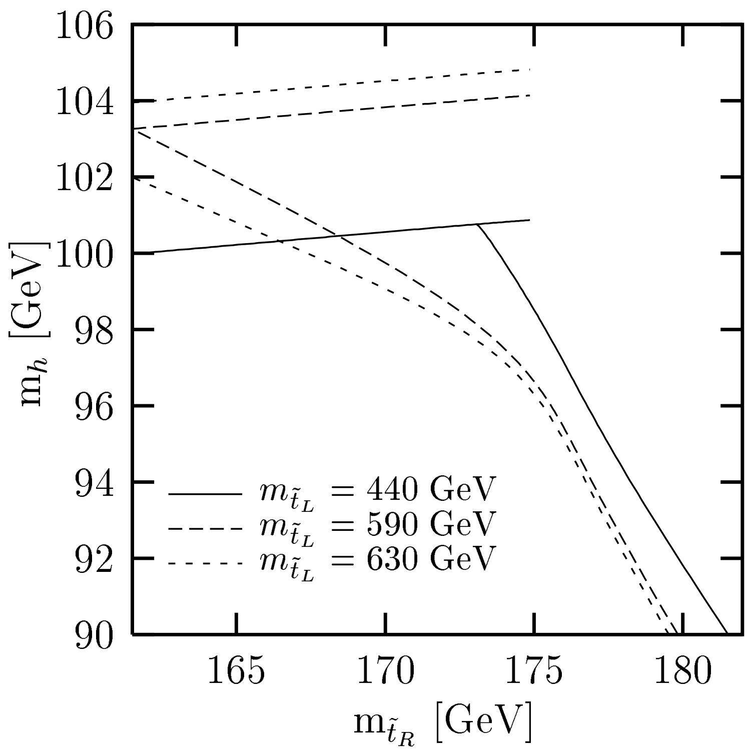

Figure 2: The cosmologically relevant $v/T_c > 1$ region is below the lines.

Compare:

in SM: endpoint of critical line (2nd order transition)

$$\boxed{m_H = (\ 72 \pm 2)\ \text{GeV}}$$

in MSSM: $\exists$ upper bound on m_H at boundary strong 1st order transition!

$$\boxed{m_H = (103 \pm 4)\ \text{GeV}}$$

Not far from current bound! has Higgs been seen at 113 GeV ?

I would not conclude that the observed BA requires physics beyond the MSSM. There is room for improvements by, maybe, important details, certainly more powerful computers will help.

6.2 Supersymmetric Yang Mills (SYM) theories

$N = 2$ supersymmetric $SU(2)$ Yang–Mills theory

Seiberg–Witten duality conjecture

$$g \Leftrightarrow 1/g$$

Seiberg–Witten duality Ansatz

exact solution for the non-perturbative low energy effective Lagrangian

makes SUSY simulations on lattice very exciting

- very interesting non–perturbative features
- high degree of symmetry $\Rightarrow$ access to non–perturbative physics by analytical methods
- strong coupling properties may be obtained by analytic continuation of weak coupling results
- important goal: numerical verification of SW–conjecture

May or may not have implications for non-supersymmetric theories like ordinary QCD

Start with simpler system: like $N = 1$ supersymmetric Yang–Mills theory

Lattice studies are at the beginning (Montvay et al. and others)

$\rightarrow$ requires formulation of Majorana fermions on the lattice $\rightarrow$ can be done by multi-boson algorithm

Costs: comparable to simulation of QCD with dynamical fermions

Present, typically: Montvay et al. $12^3 \times 24$ lattice $SU(2)$
1 year 4h/day 200(50) Gflops

Result: spontaneous discrete chiral SB $Z_4 \rightarrow Z_2$ caused by gaugino condensate $m_{\tilde{g}} = 0$ SUSY restoration point.

many questions to be answered, need small fermion masses, like chiral symmetry supersymmetry is broken on the lattice and must be recovered in the continuum limit.

scaling up lattice by factor 2 $\rightarrow$ requires 1 Tflop sustained. Will answer

- mass spectrum
- SUSY potential
- SUSY Ward identities
- Phase transition at $m_{\tilde{g}} = 0$ for $SU(2)$ and $SU(3)$ SYM

$N = 2$ SUSY: first steps only

more complicated parameter space $\rightarrow$ requires exploration of phase boundaries etc. no final answers expected soon.

As a goal: very interesting and important!

6.3 Other interesting phase transition problems in QFT

phase transition problems are intrinsically non–perturbative in nature $\rightarrow$ require simulation by Monte Carlo methods

existence of a phase transition of order $n \geq 2$ (critical point) $\Leftrightarrow$ existence of a continuum limit

$\rightarrow$ could be very important in connection with extensions of the SM (understanding parameter patterns like CKM matrix elements, mass spectra and the like

- Major challenge: gauge theories with extra fermions

Phase transition as a function of N_f $\rightarrow$ existence of flavor violating phase ? existence of parity violating phase ?

- question of spontaneous violation of P:

crucial for technicolor and preon models as well as for the structure of the QCD vacuum.

Absence of spontaneous parity breaking is essential for the viability of the axion approach to the strong CP problem and its phenomenological consequences.

- simulation with non–standard boundary conditions
- study of the massless spectrum
- study of clustering properties

are special requirements here.

QCD with many flavors $\rightarrow$ infrared stable strong coupling fixed point is expected for $9 \leq N_f \leq 16$

- simulations feasible with the multi–boson algorithm, N_f may be taken to be a continuous variable (exact algorithm)
- number of required boson fields increases with increasing N_f

QCD with $N_f = 3$: requires 64 to 80 fields instead of 24 to 32 in case of the $N = 1$ supersymmetric $SU(2)$ Yang Mills theory (slowing down by a factor of 3 to 6)

3-6 Tflop sustained computers will lead to a reasonable understanding of how the phase structure of QCD depends on N_f

6.4 Chiral Fermions

Chiral fermions on the lattice discovered only recently, lead to new exciting perspectives for a better control of the continuum limit of chiral theories.

➧ [T. Blum, L. Lellouch]

6.5 Chiral condensates in QCD

Chiral symmetry breaking in gauge theories (QCD) imposes strong constraints on the effective low energy behavior of the light degrees of freedom (pions, kaons, etc.)

$\Downarrow$

effective chiral Lagrangians and chiral perturbation theory (χPT)
(crucial tool for chiral extrapolation in LQCD)

Among the most important phenomenological parameters of the χPT approach is the quark (or chiral) condensate which triggers the SχSB

- condensates are non-perturbative quantities wich must be calculated numerically on the lattice
- other effective coupling constants of χPT have to be calculated from LQCD as well

related topics

➧ [A. Di Giacomo]

6.6 Quantum gravity

$\longrightarrow$ space–time dynamics

$\longrightarrow$ random geometries

Simulation:

$\longrightarrow$ random distribution of data in memory

• primary problem: phase structure, in particular existence od 2nd order PT $\Leftrightarrow$ existence continuum limit

$\odot$ Simplicial gravity (triangular lattices, no matter): simple parameter space $\stackrel{?}{\leftrightarrow}$ existence of continuum theory

$\odot$ more realistic modeling: must add matter $\longrightarrow$ more complicated parameter space

? criticality more tricky

? scaling laws

not suitable for parallelization !

one processor $\leftrightarrow$ one copy of geometry

$\downarrow$

few powerful processors

dynamical repartitioning

(integer arithmetics)

Pentium type ideal processor

6.7 Classical electrodynamics and accelerator physics

one example not related to quantum field theory: but of interest for the particle physics community

MAFIA is a widely used package for the solution of MAxwell's equations using a Finite Integration Algorithm

$\equiv$

an implementation of classical electrodynamics on a lattice

- design of structures for new particle accelerators like TESLA at DESY
- realistic 3D simulations are not feasible presently on clusters of high end workstations

at DESY Zeuthen: implementation of part of the MAFIA code on the massive parallel APE computers

Experience: gain by factor 20 on APE 100 vs. high end WS

Long term goal: design of global accelerator structure, beam dynamics calculations, polarization stability investigations and particle tracking in linear accelerators

looks promising: most of these problems look to be memory limited

General structural issues of non-perturbative QFT

Non-QCD non-perturbative QFT essentially unexplored

but could have important impact

- chiral fermions, exact chiral symmetry
- Majorana fermions, exact SUSY ?
- generalized models
- new dynamical mechanisms
- unexpected features

New territories to be discovered !!!