Non-perturbative Gauge-Higgs Unification

Dedicated to Yannis

Nikos Irges, NTUA

Summer School and Workshop on the Standard Model and Beyond, Corfu, 7 Sept. 2016

Based on

- N.I. and F. Knechtli (NP B719, 121, 2005), F. Knechtli, B. Bunk and N.I. (LAT2005), N.I. and F. Knechtli (hep-lat/0604006), N.I. and F. Knechtli (NP B775, 283, 2007), N.I., F. Knechtli and M. Luz (JHEP 0708, 028), N.I., F. Knechtli and K. Yoneyama (NP B865, 541, 2012), N.I., F. Knechtli and K. Yoneyama (PL B722, 378, 2013)

- N. I. and F. Knechtli, JHEP 1406 (2014) 070

- M. Alberti, N.I., F. Knechtli and G. Moir, JHEP 1509 (2015) 159 and work in progress

- Work in progress with A. Chatziagapiou

- Work in progress with F. Koutroulis

Quantum Field Theory

- Define the Classical Theory:
  (Fields, Symmetries, Dimensionality, signs
- Compute the Path Integral:

$$< \mathcal{O} > \sim \int D\Phi \mathcal{O} e^{-S[\Phi]}$$

(there are issues of approximation, regularization, renormalization, scheme…)

The Standard Model

$$SU(3) \times SU(2) \times U(1)$$

Quantum gauge fields coupled to fermionic matter and Higgs field(s) in a spontaneously broken EW symmetry phase in 4 space-time dimensions.

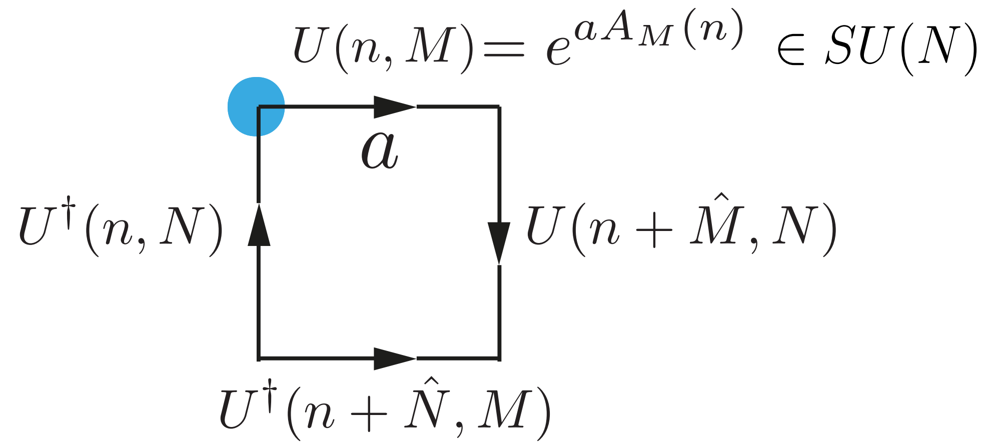
The Higgs sector has a naturalness issue that can be resolved by extra symmetry (susy, compositeness, 5d gauge symmetry, etc) or dynamically (e.g. simply by a low cut-off and/or by weird cancellations) or by a combination-correlation of both.
Behind its innocent perturbative nature, subtle non-perturbative effects may be hiding in the details (such as the reason for the relative sign in the Higgs potential).

Thus, apart from the usual perturbative machinery, we will also need a non-perturbative regulator.

The lattice regularization

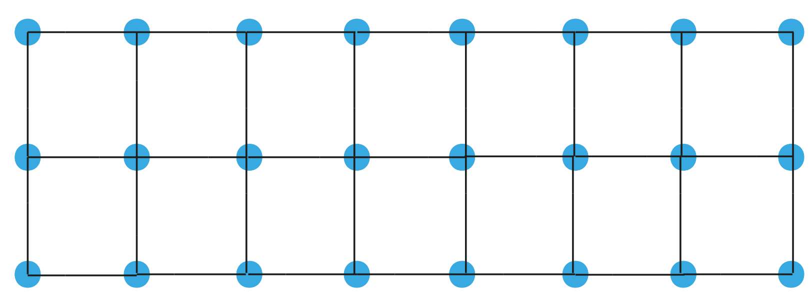
$x \to n \to$

plaquette $U_{\mu\nu}(n)$:

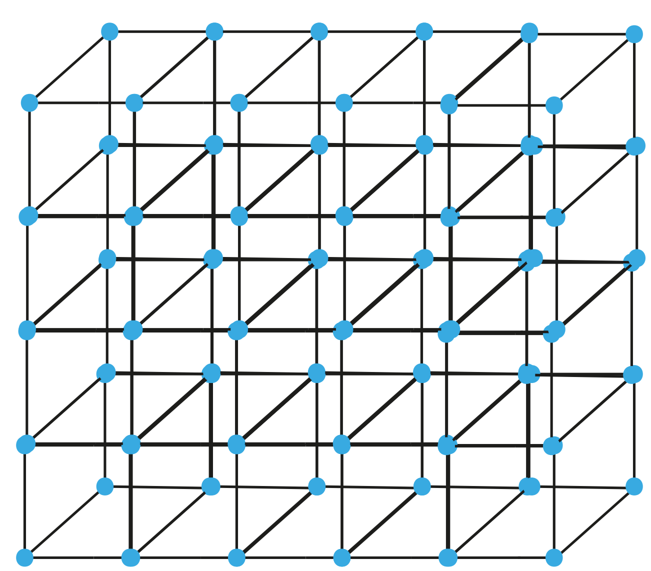


$$\to -\frac{1}{4}a^2 F_{MN}^2 + O(a^4)$$

$2d$



$3d$



In d dimensions the pure gauge action is:

$$S_W = \beta \sum_n \sum_{1 \leq \mu\nu \leq d} \left[1 - \frac{1}{2} \mathrm{tr} \left\{ U_{\mu\nu}(n) \right\} \right]$$

This is the "Wilson plaquette action".
The Path Integral is well defined, yielding a gauge invariant, cut-off theory with $\Lambda \sim 1/a*$.
It can be sometimes computed analytically and in principle always numerically.
It is particularly useful for investigating non-perturbative properties.

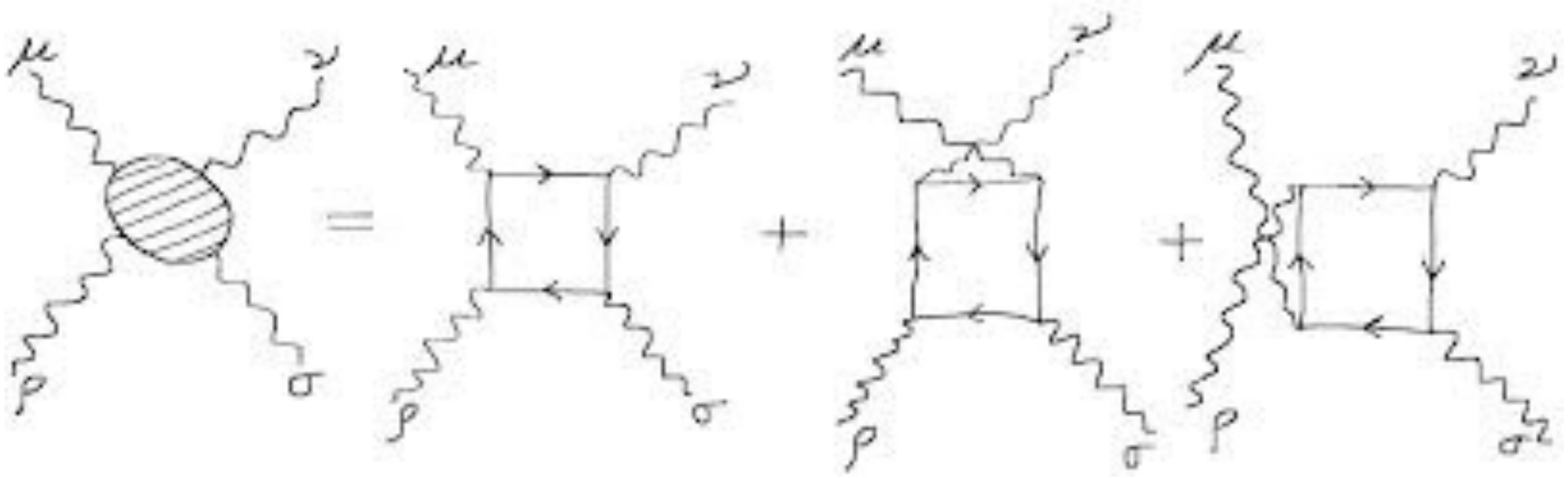
- QED: Renormalizable + Perturbative; No lattice necessary
- SU(N), N=2,3 for d=4: Confinement; Lattice is crucial
- SU(N) for d>4: Non-renormalizable + Bulk Phase Transition; Lattice is crucial
- The SM Electroweak sector: confusing because of the Higgs

*careful: in general there is no simple connection to the continuum

QED

QFT instruction: live and die by perturbation theory.

(you can use the lattice but it is an overkill)



there is a Landau pole, very very far...

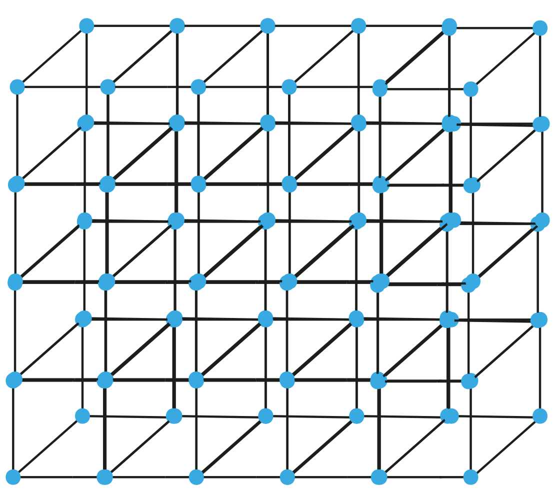
Pure gauge SU(2) (or SU(3)) in d=4, T=0

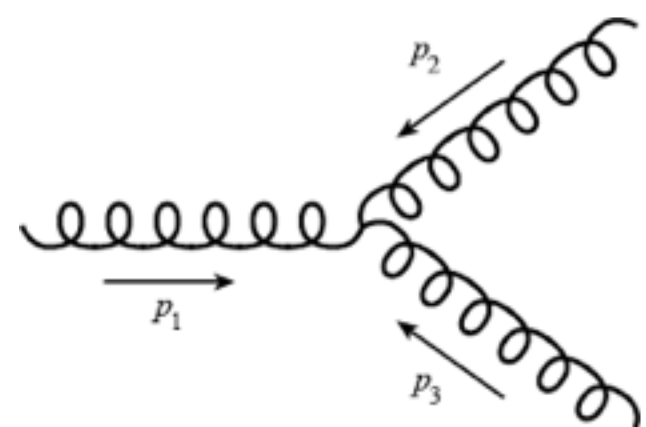
$\mathrm{Flux-tubes,\ glueballs}\cdots$ Λ_{QCD} Asymptotic freedom β

Long distances Confined phase **Short distances**

physics very non-perturbative
usually we use the lattice,
and rarely analytical techniques

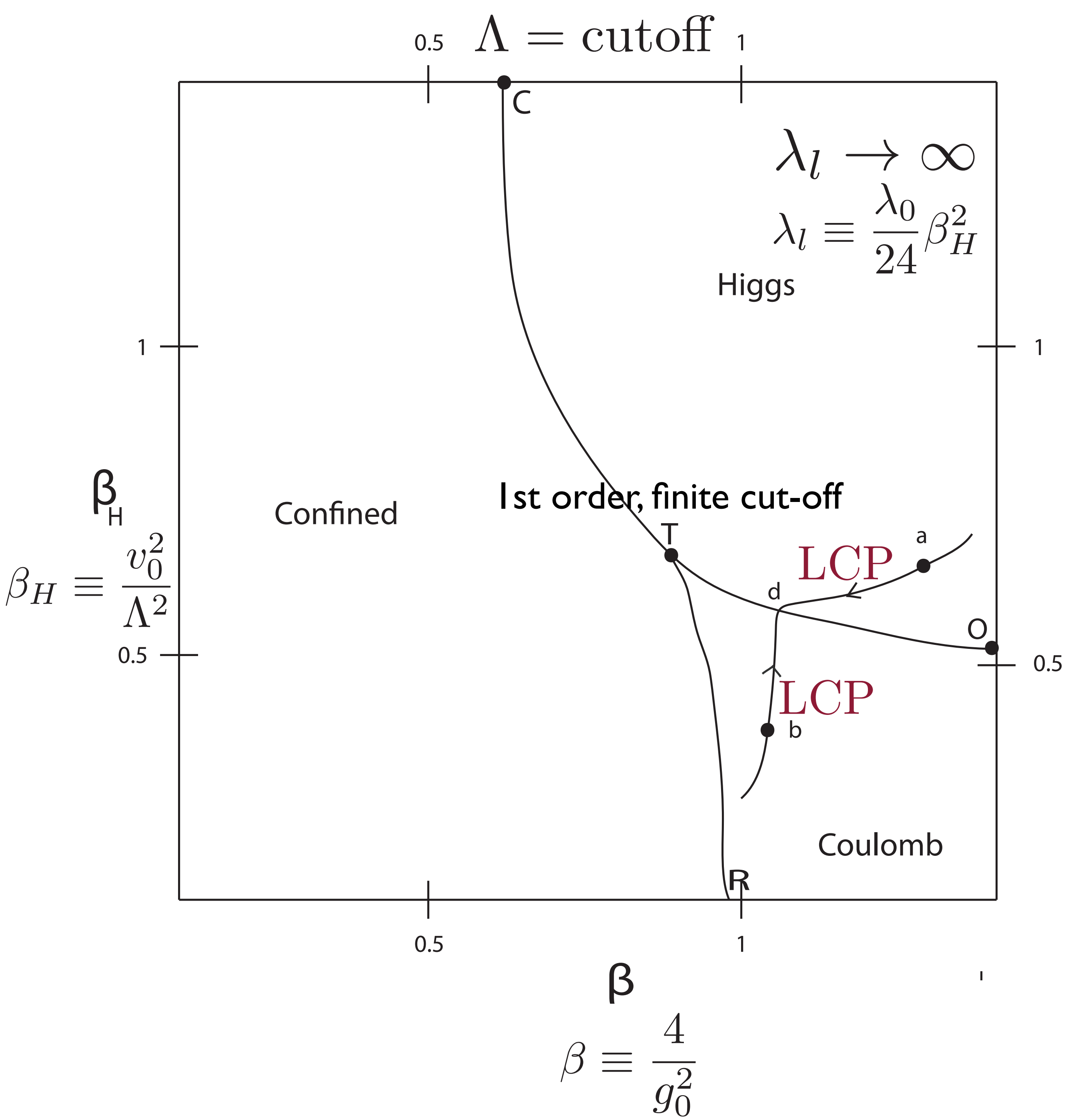
use perturbation theory





A toy model for the EW sector: the Abelian-Higgs model in d=4

$$\mathcal{L}_{\text{AH}} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{2\xi}(\partial_\mu A^\mu)^2 + |D_\mu H|^2 + m_0^2|H|^2 - \frac{\lambda_0}{6}|H|^4 + \text{const.}$$



Definition:
An LCP is a line on the phase diagram on which least some of the physical quantities are kept constant. Example:

- $m_Z = 91\, GeV$
- $m_H = 125\, GeV$
- $\lambda_R = 0.12$

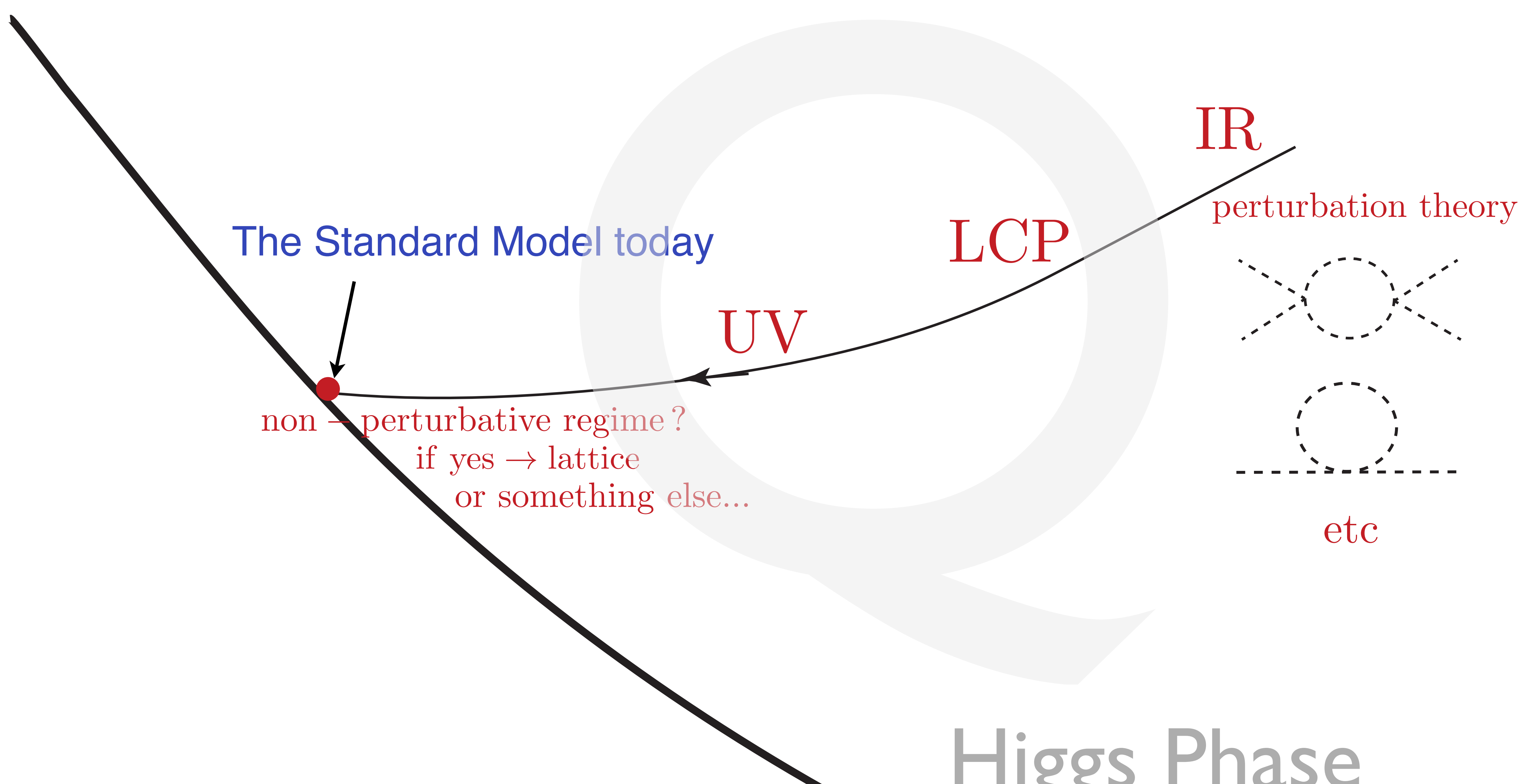
Existence of non-fine-tuned* LCP equivalent to stabilising the Higgs

*similar meaning as in SUSY, technicolor etc

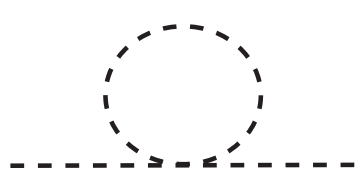
Let us assume that the AH model describes our world and that

a) we are sitting near a 1st order phase transition
b) the LCP terminates on the phase transition

b) can be checked on the lattice only God knows about a)…



According to perturbation theory, in the UV regime,
there is a severe fine tuning problem!

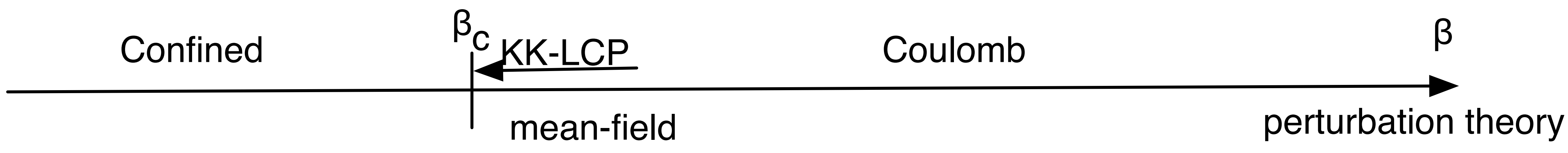


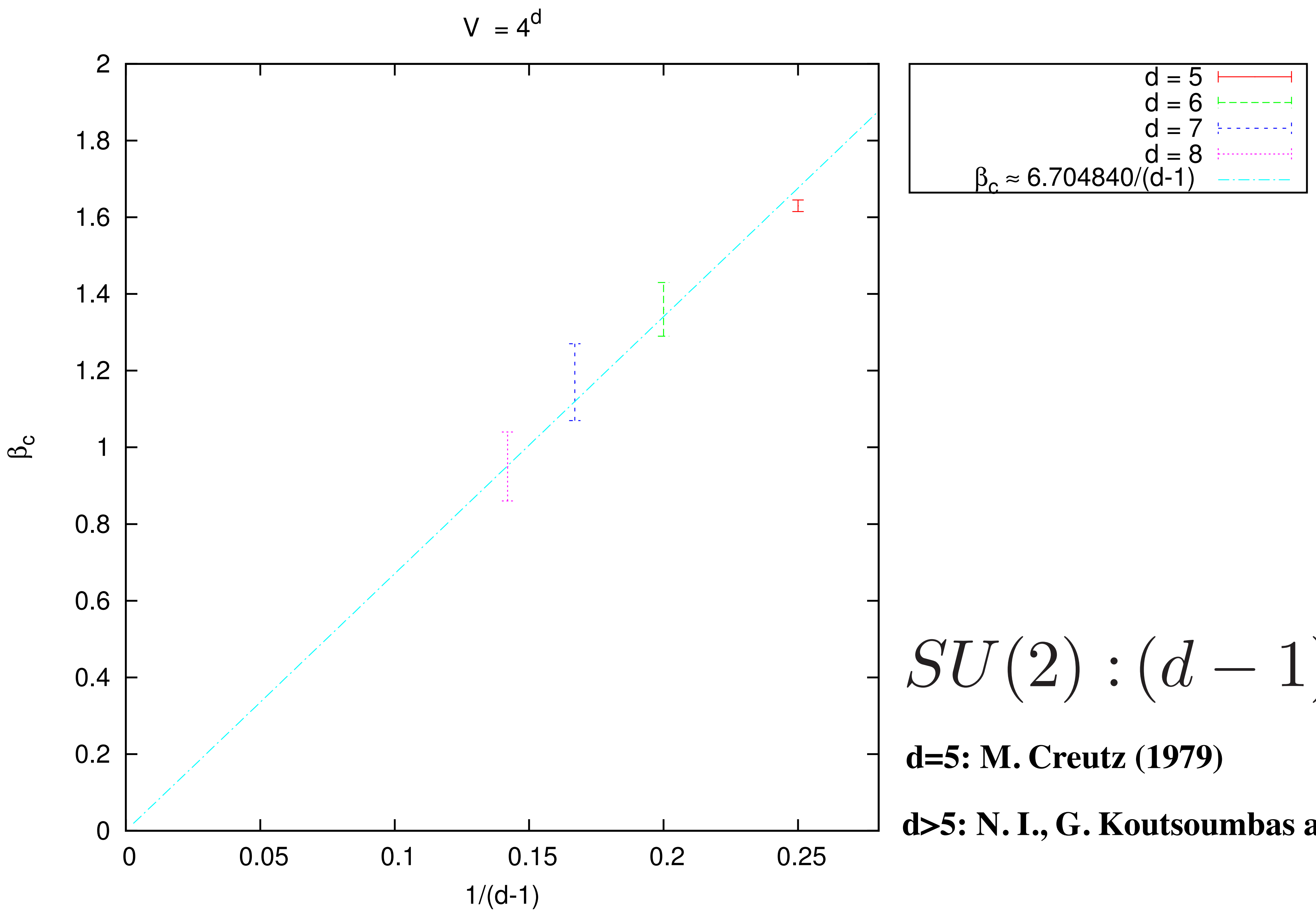
Lesson:

If you are hoping for a solution to the Higgs naturalness problem with the SM sitting on the brink of a “bulk” or “quantum” phase transition, find some UV completion that possesses such phase transitions and where the hierarchy is somehow protected.

Here we have in mind a framework where the protection mechanism is purely bosonic, that is, not of the susy or technicolor type.

Fact 1: Quantum phase transitions are ubiquitous in d>4, SU(N)





$$SU(2) : (d-1)\beta_c \simeq 6.704840$$

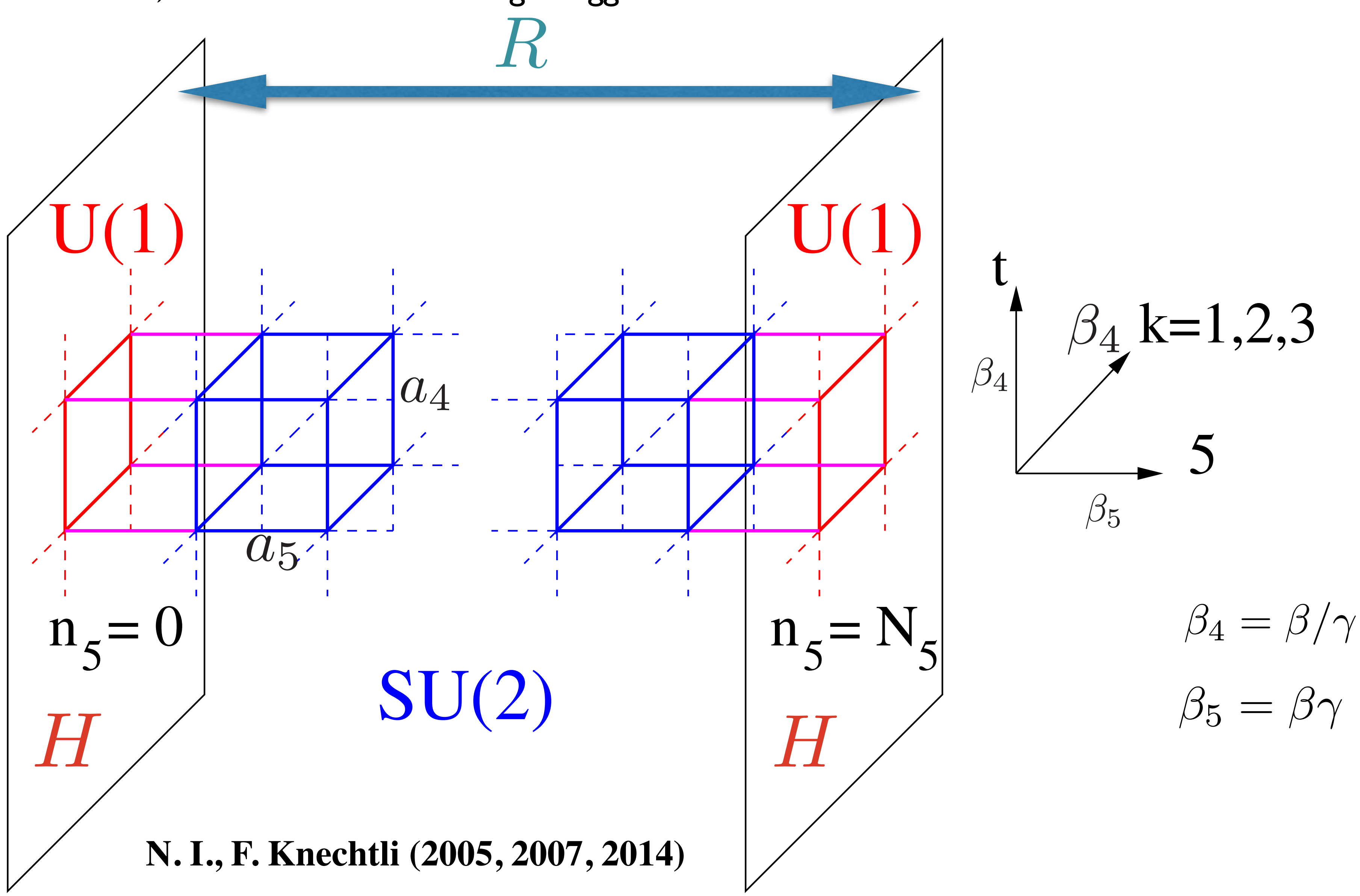
d=5: M. Creutz (1979)

d>5: N. I., G. Koutsoumbas and K. Ntrekis (2015)

Fact II: Extra dimensions can generate the Higgs out of gauge fields (Gauge-Higgs Unification)

N. Manton (1979), Y. Hosotani (1983, 1989)

Let us consider now a 5d model, an SU(2) 'lattice orbifold'. On the boundaries we have the spectrum of a 4d (Abelian-Higgs) model U(1) + H + excited states. Local and global symmetries are just 'right' so that all phases can be described in a gauge invariant way. Note: in (1-loop) perturbation theory the Higgs mass is independent of the cut-off and Spontaneous Symmetry Breaking of the boundary symmetry is possible only in the presence of fermions (Hosotani mechanism). Non-perturbatively however, we see SSB even in the pure gauge theory.
Thus, we call this new version of GHU, "Non-Perturbative Gauge-Higgs Unification".



N. I., F. Knechtli (2005, 2007, 2014)

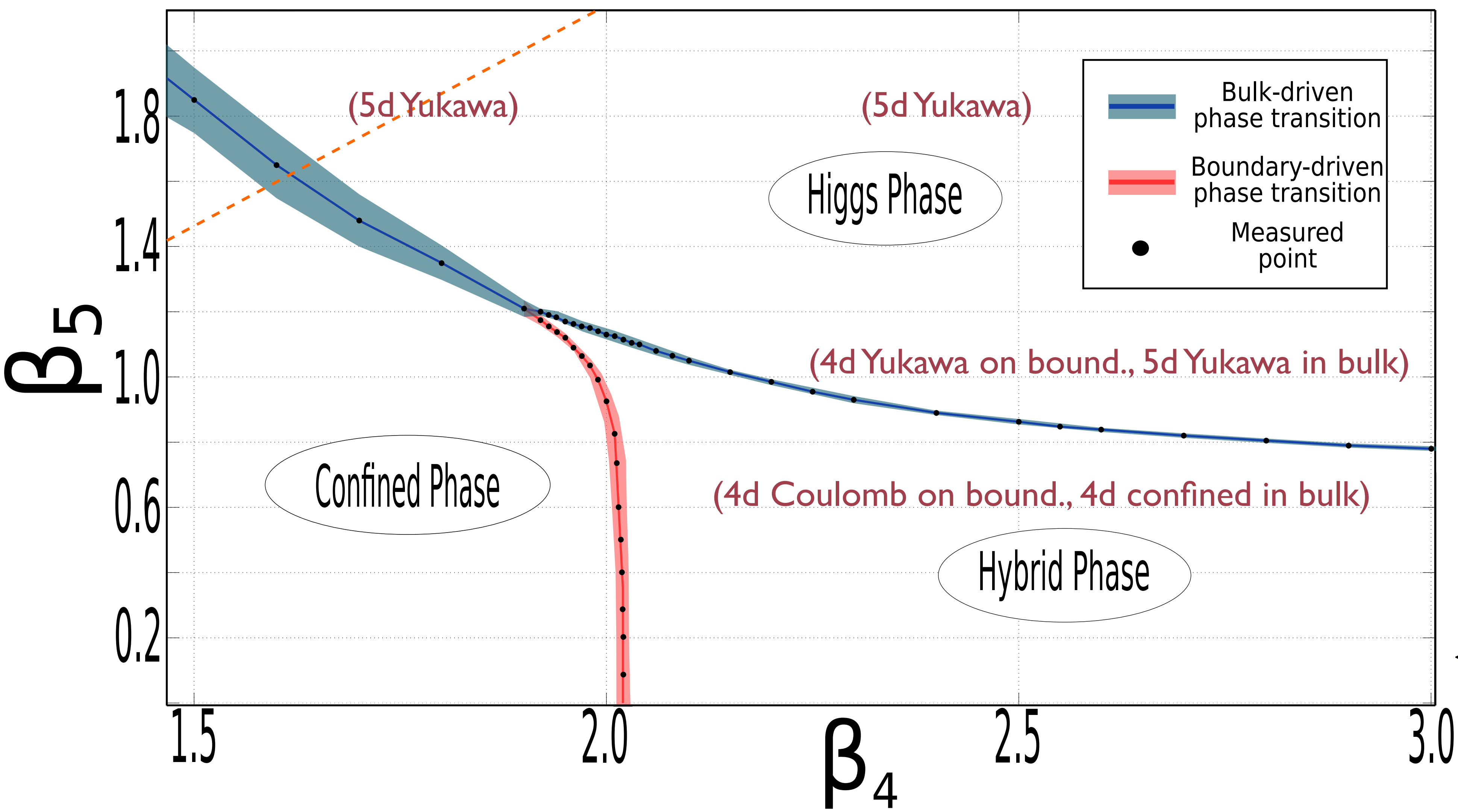
dimensionless parameters: $\beta = 4a_4^2/g_5^2 \ , \gamma = a_4/a_5 \ , N_5 = \pi R/a_5$

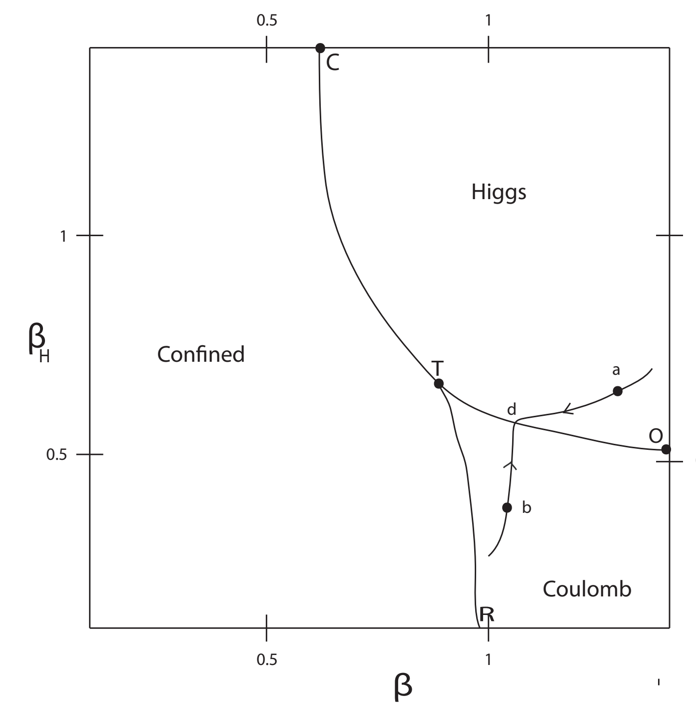
dimension-ful parameters: a_4, a_5, R, g_5

The Monte Carlo phase diagram (N5=4)

G. Moir, M. Alberti, N. I., F. Knechtli (2015)

phases + dimensional reduction



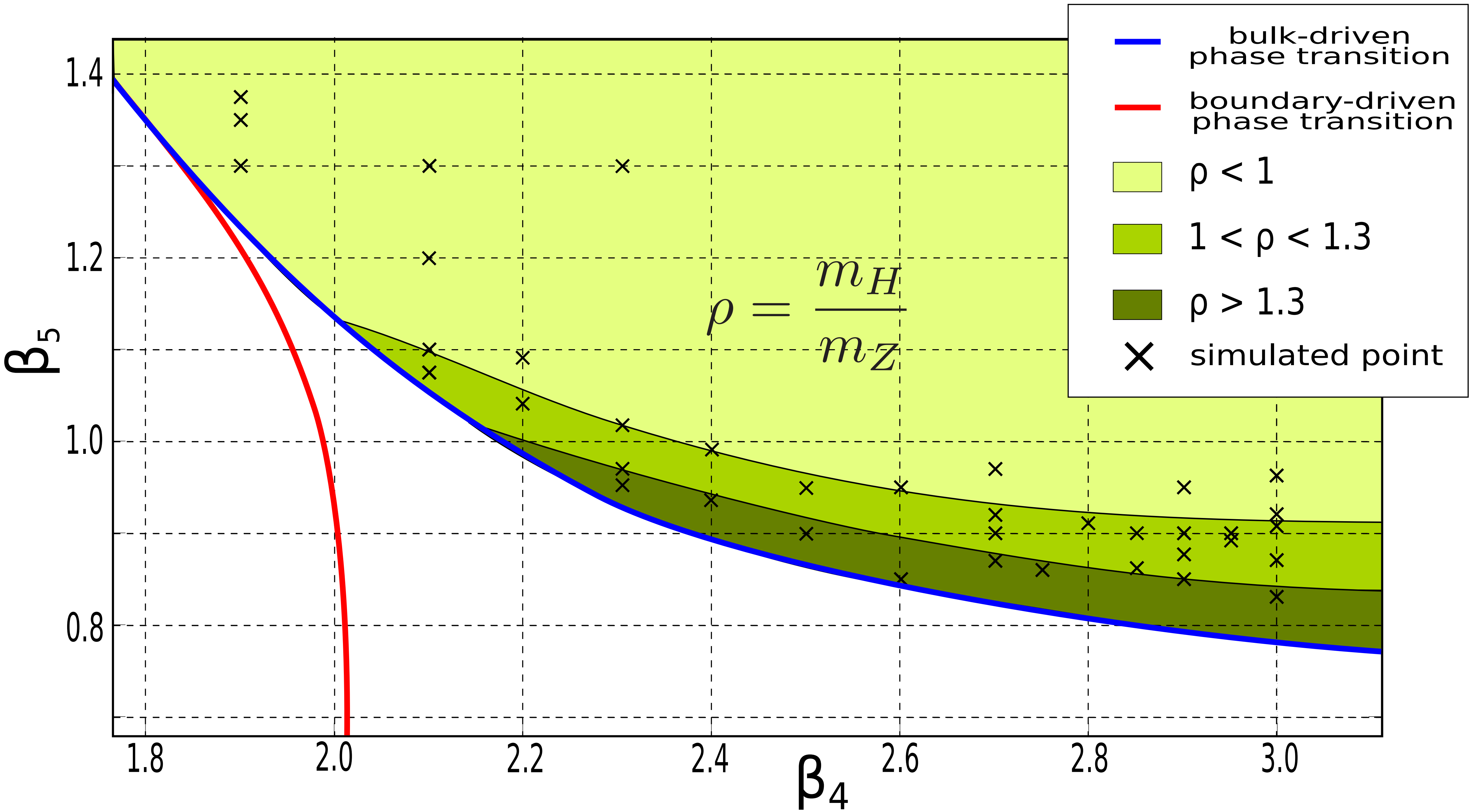


Note: this part of the phase diagram is reminiscent of the phase diagram of the (q=2) 4d Abelian-Higgs model, which is not unexpected since the two models have identical low lying spectra.

All phase transitions 1st order, effective theories must have a finite cut-off.

Standard Model-like spectrum near the phase transition,

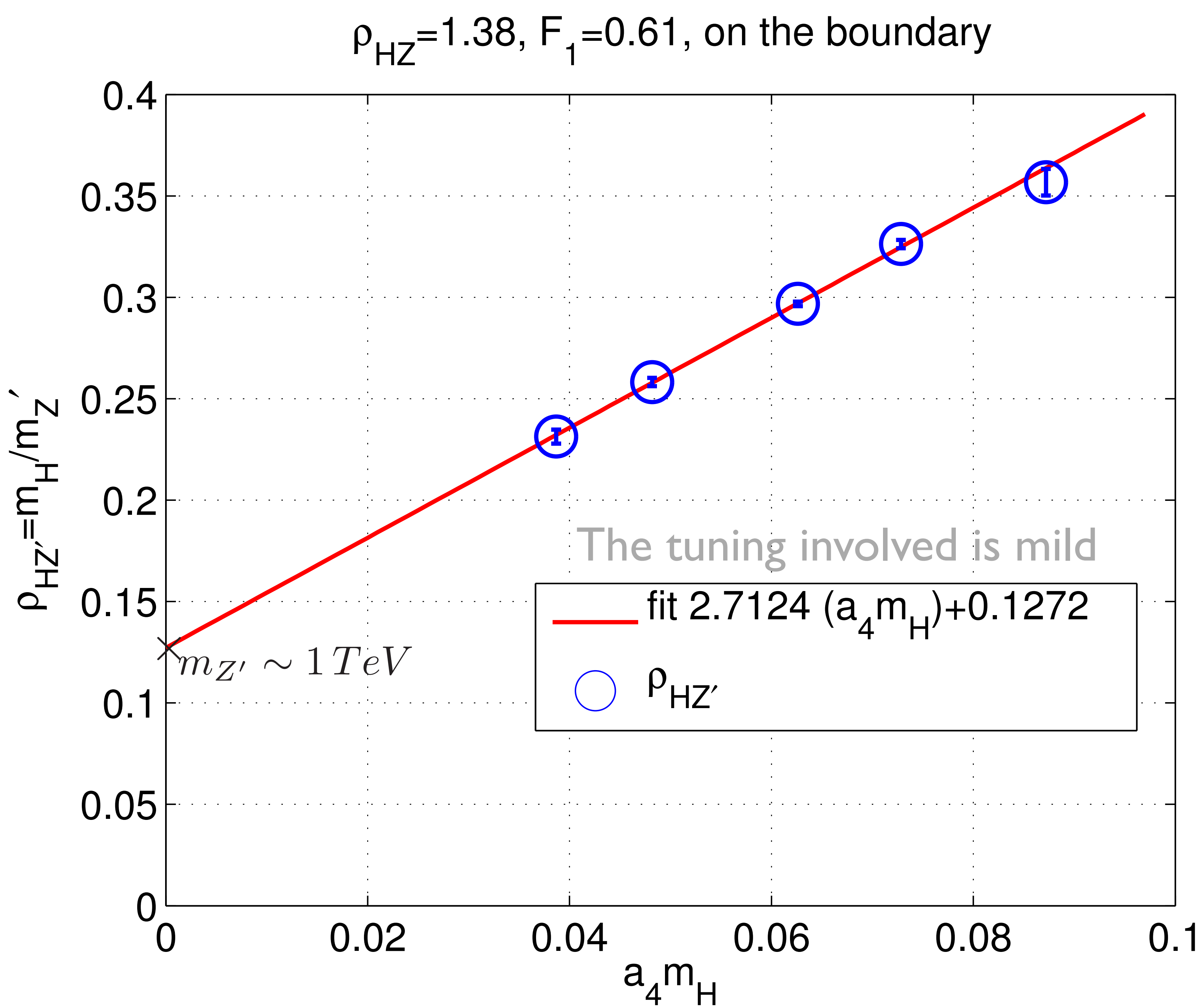
precisely in the 4d Yukawa regime



quantum + bosonic Higgs mechanism…no other such mechanism to our knowledge…

G. Moir, M. Alberti, N. I., F. Knechtli (2015)

A Mean-Field LCP

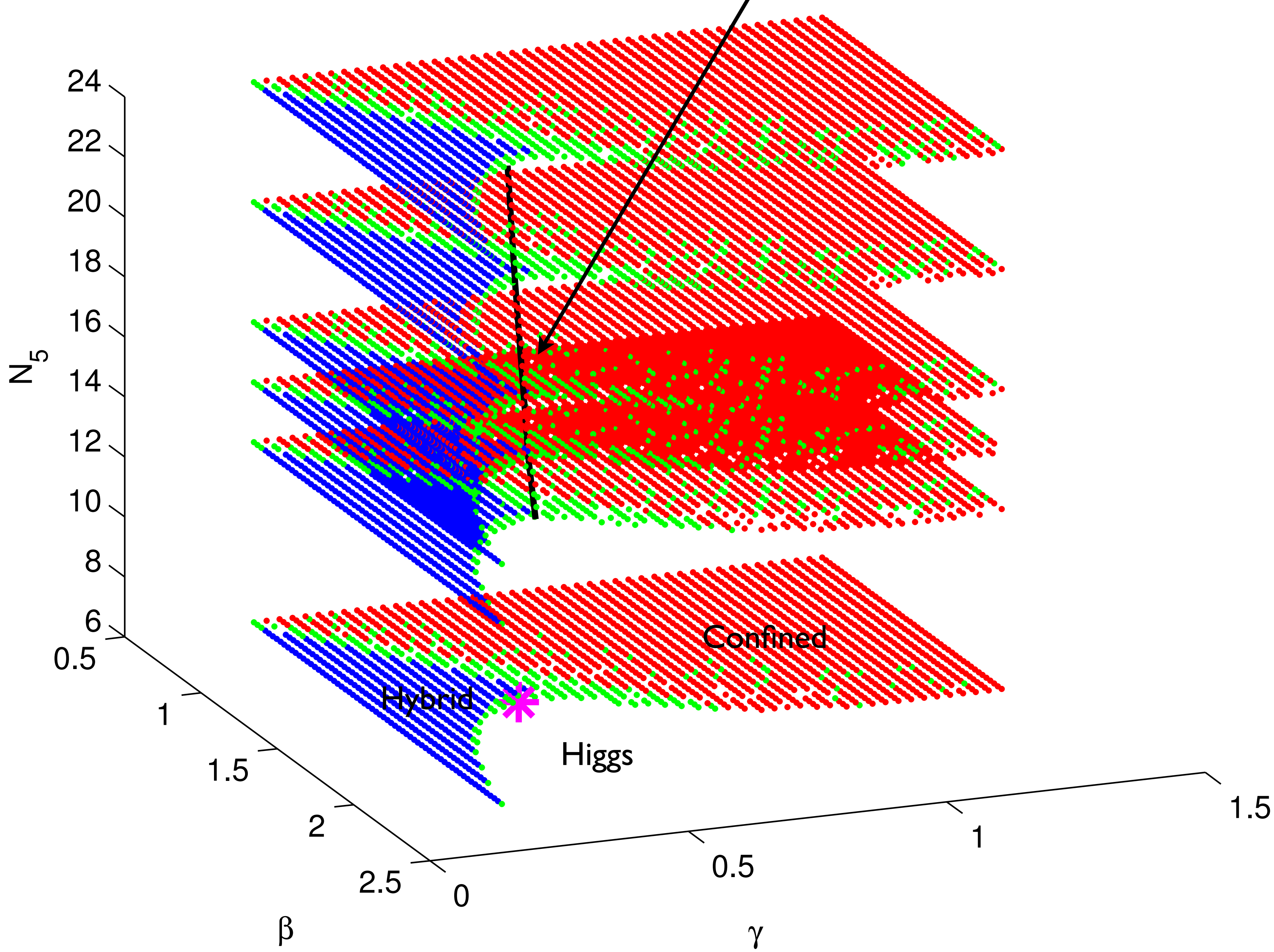


$$\rho_{HZ} = m_H/m_Z$$

$$F_1 = m_H R$$

N. I., F. Knechtli and K. Yoneyama (PL B722, 378, 2013)

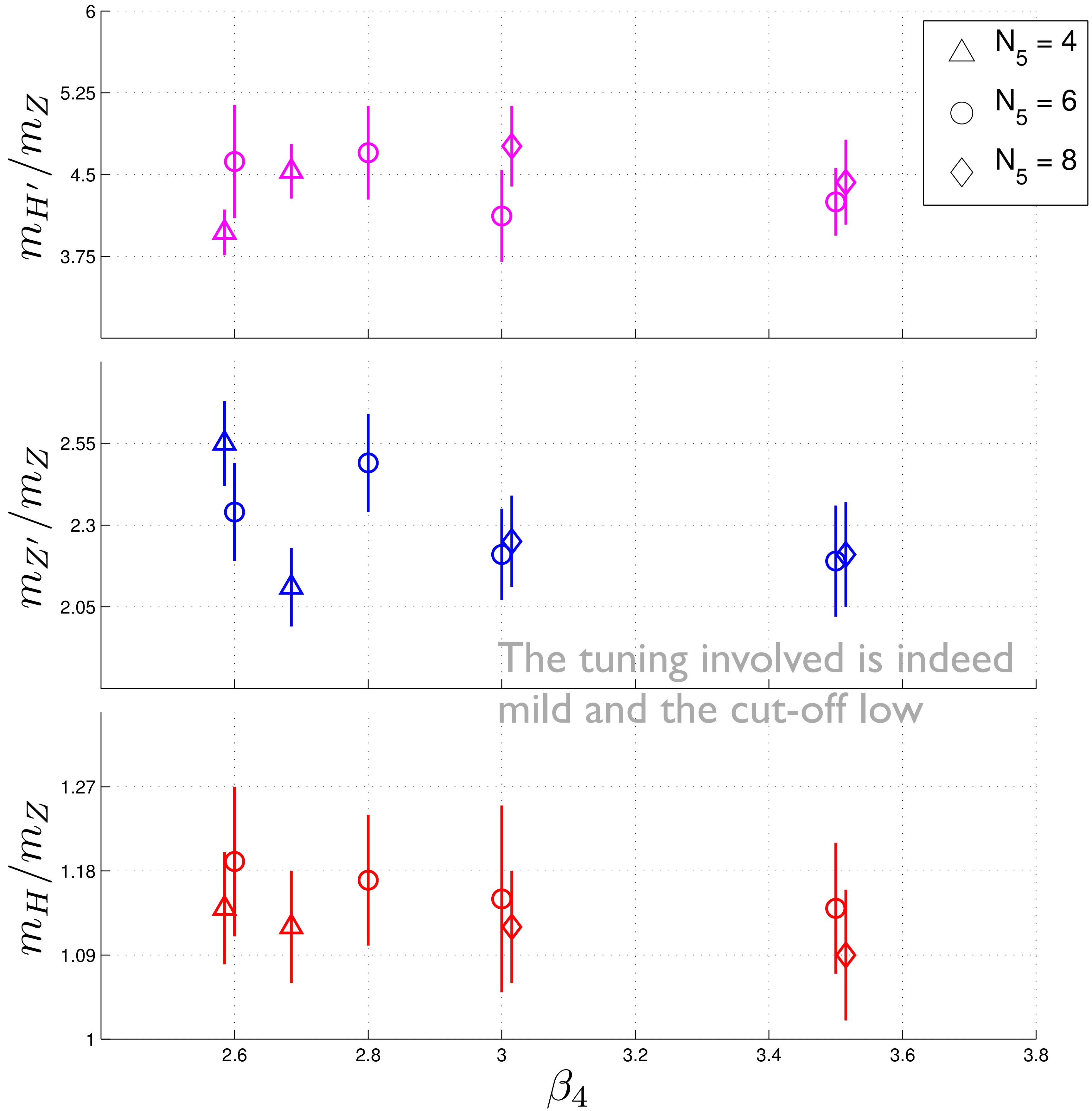
The Mean-Field LCP (3d view)



N. I., F. Knechtli and K. Yoneyama (PL B722, 378, 2013)

A Monte Carlo LCP

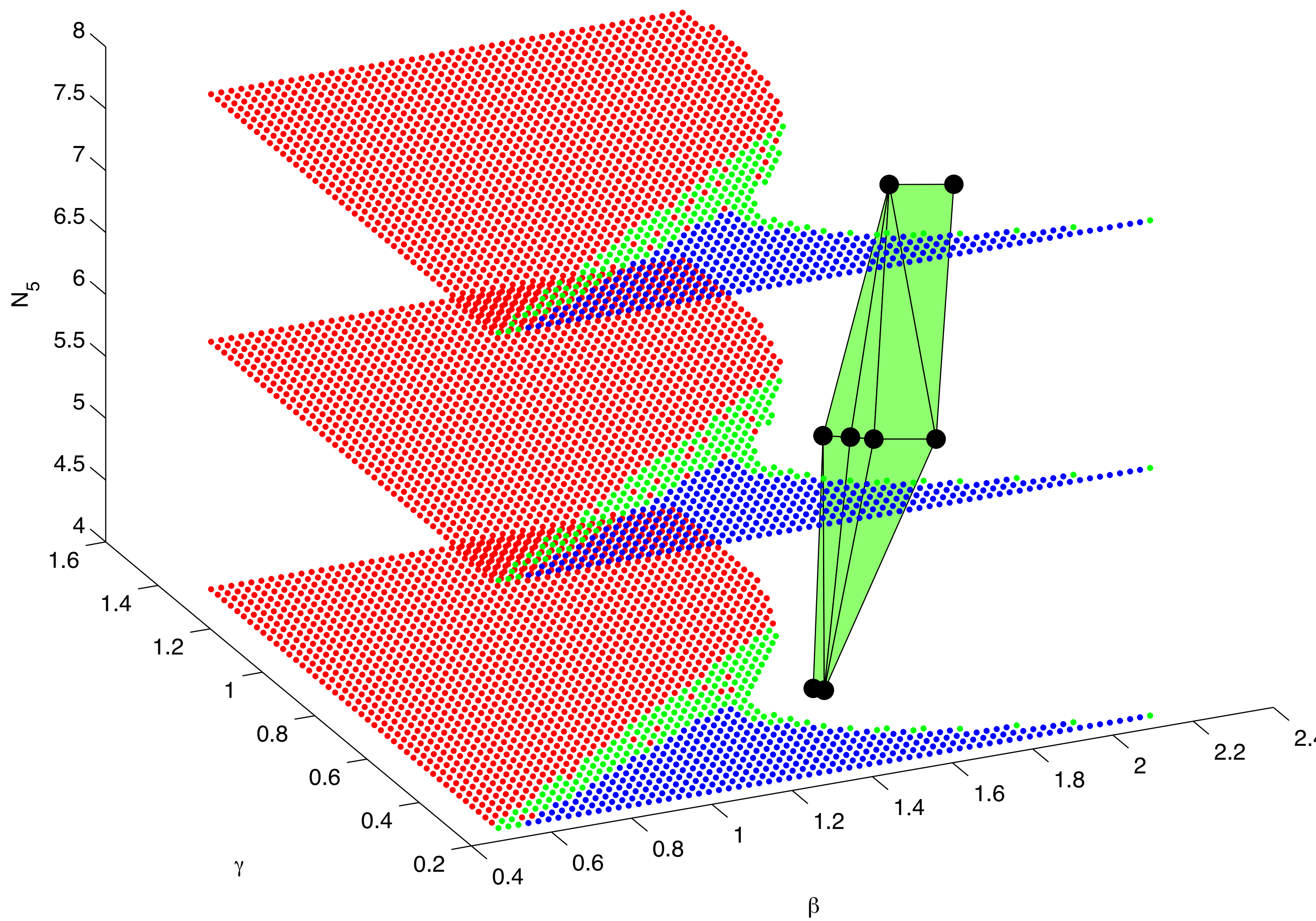
from M.Alberti's talk at the Lattice 2016 conference



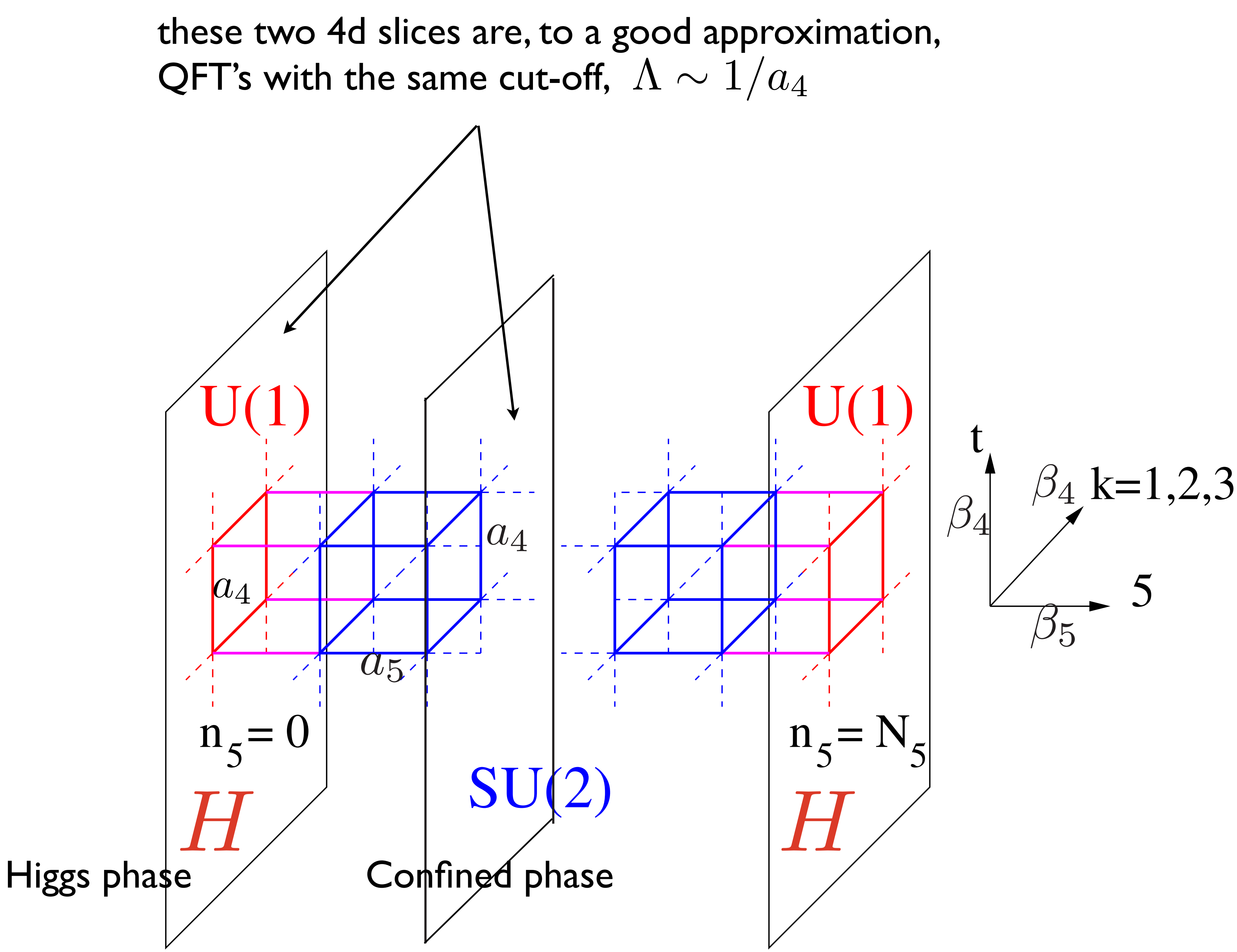
The Monte Carlo LCP (3d view)

courtesy of M. Alberti

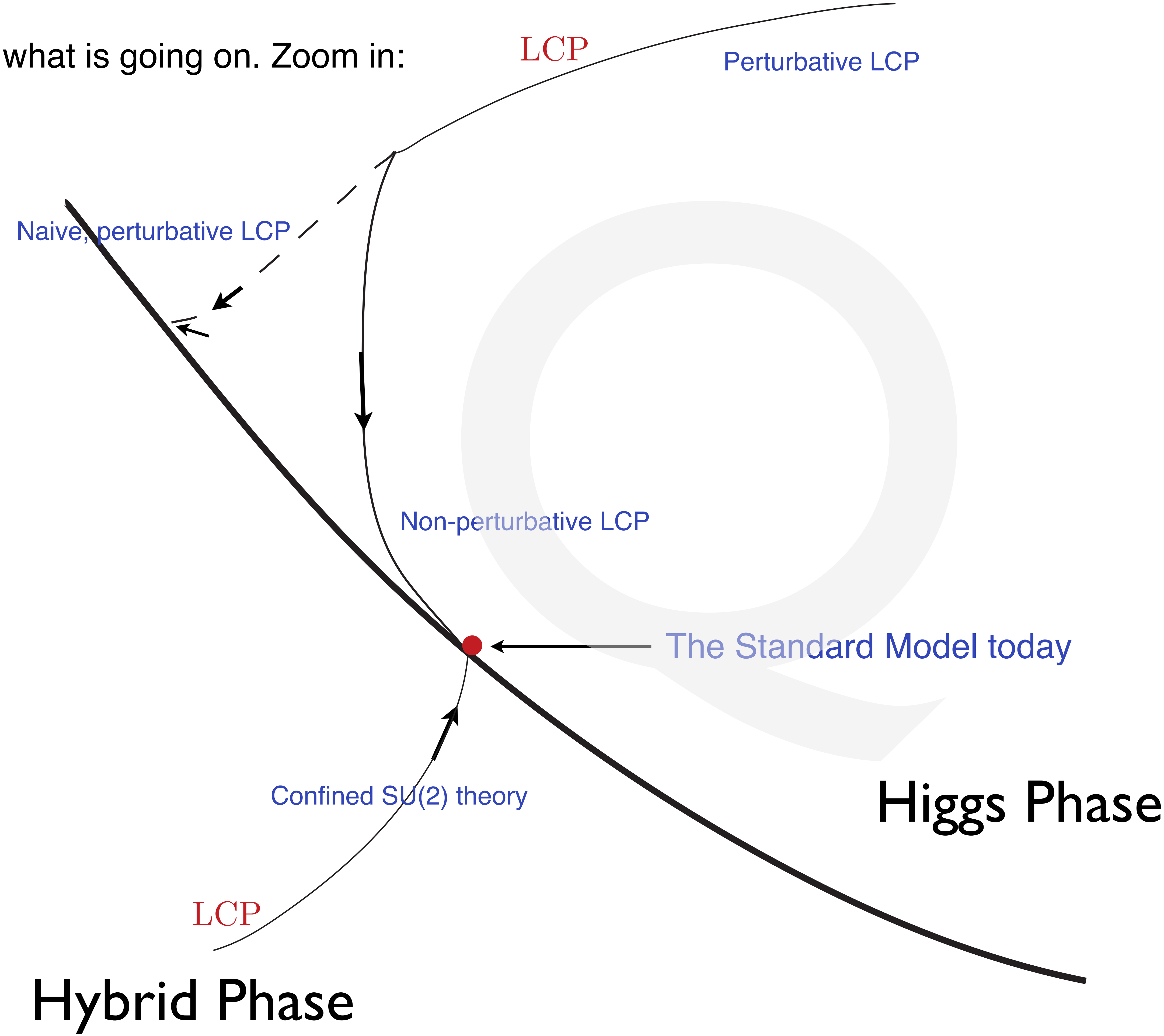
$$m_H/m_Z \simeq 1.15,\ m_{Z'}/m_Z \simeq 2.20$$



Towards an effective action
(i.e. understand the dynamics)



Let us see what is going on. Zoom in:



- This is a gauge invariant way to construct simultaneously two effective field theories, a confined non-Abelian theory and an Abelian gauge-scalar system with the same cut-off

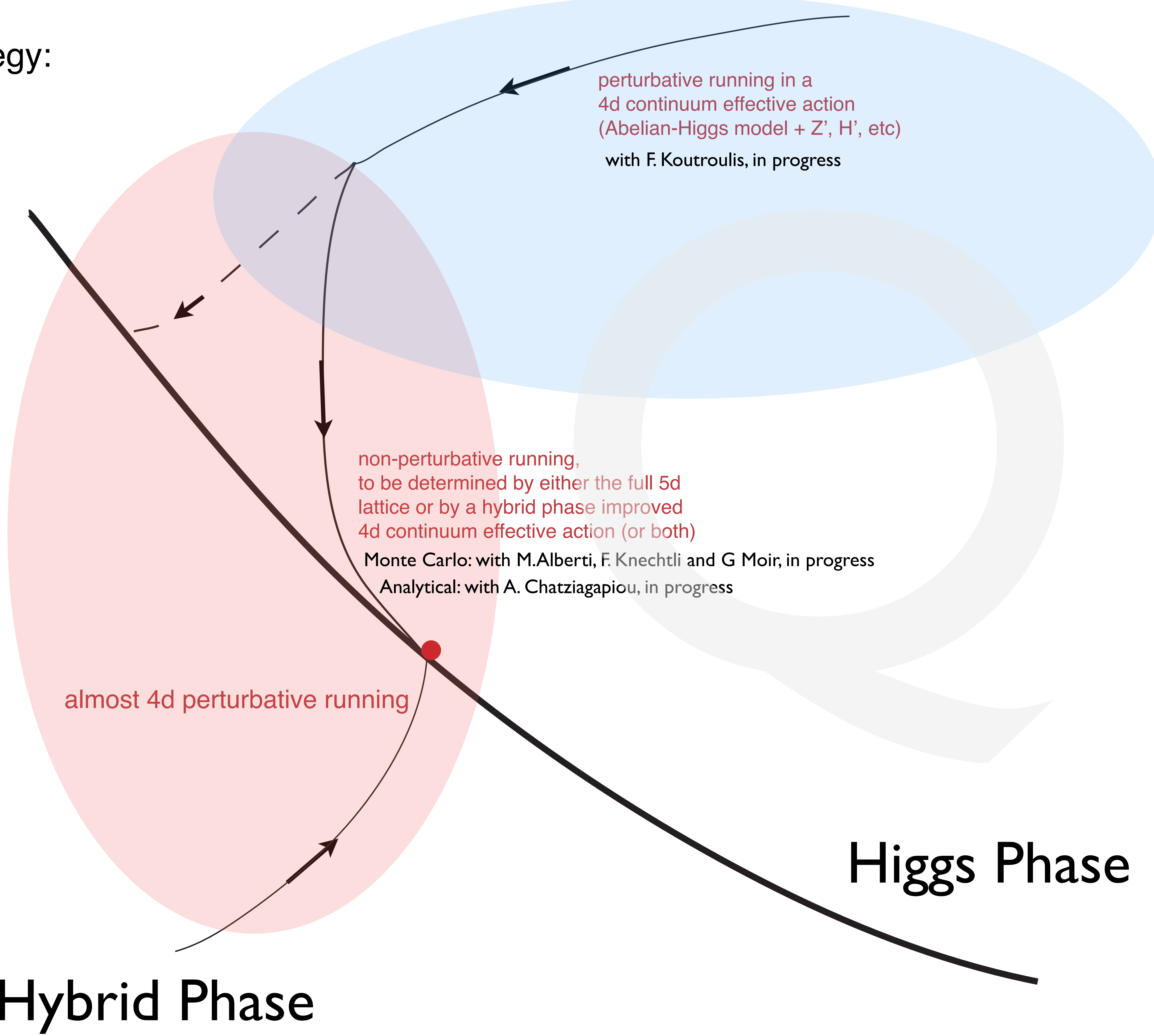
- As the U(1) gauge-scalar theory becomes non-perturbative, the confining SU(2) theory becomes asymptotically free

- According to Monte Carlo simulations, their common cut-off is low (lower than the Planck scale)

- There exist LCP’s from both sides, notably from the Higgs phase side, meaning that the spectrum, including the Higgs mass, is stable as the cut-off varies. The matching of the LCPs determines the absolute scale

- Draw these LCP’s, ending on a point along the phase transition where the Higgs mass is 125 GeV, combining Lattice simulations and an appropriate Effective Field Theory

The strategy:



Conclusions

- We showed the existence of a pure gauge 5d orbifold model where a Higgs mechanism is realised on the weakly coupled 4d boundary in a regime of its phase diagram close to the first order bulk phase transition where the fifth dimension is strongly coupled. Precisely and only in this regime, we simultaneously observe a Higgs slightly heavier than the Z boson and the system being dimensionally reduced to 4-dimensions via localisation. The existence of an LCP points to a Higgs mass whose stability is somehow non-perturbatively guaranteed at least within a certain energy regime by the higher dimensional gauge symmetry. We have proved these statements analytically in the context of a Mean-Field expansion and numerically via extensive Monte Carlo simulations, both on the lattice.

- We described a plausible way to construct a continuum effective field theory that will allow us on one hand to answer the question whether this novel Higgs mechanism is in the same class where the Standard Model Higgs mechanism belongs and understand the dynamics of

Thank you!