MCRG Minimal Walking Technicolor

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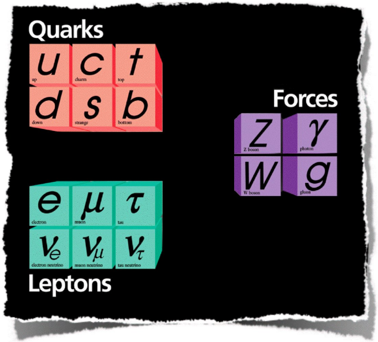
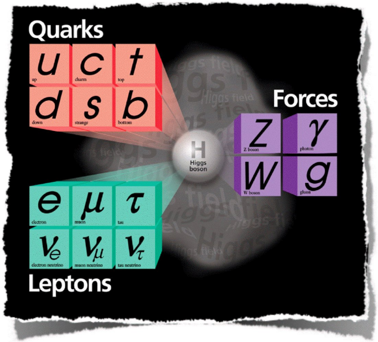
The Standard Model



Fermilab

- Standard Model is well verified experimentally
- Electroweak Symmetry breaking included (i.e. mass of W/Z bosons)
- But EWSB mechanism remains a mystery

The Higgs Mechanism



Fermilab

- Higgs mechanism will be tested at the LHC, but
  - Ad hoc: all fermion masses and mixings arbitrary parameters
  - Trivial: without new physics, Higgs decouples
  - Unnatural: quadratically sensitive to Planck scale, so requires fine tuning
- So thought to be an effective description of a more fundamental theory, e.g. SUSY, Technicolor, ...

Technicolor

- SM without Higgs already has some EW symmetry breaking.
- Quark condensate gives M_W of the order of the pion decay constant:

$$\langle \overline{u}_L u_R + \overline{d}_L d_R \rangle \neq 0 \rightarrow M_W = \frac{gF_\pi}{2} \sim 30MeV$$

- So why not have some more 'techni-quarks' that form a condensate at a higher scale ($F_\pi^{TC} \sim 250GeV \sim \Lambda_{TC}$)

Weinberg 78, Susskind 78

Extended Technicolor

- Add interactions between SM quarks and techni-quarks at some high scale Λ_{ETC}
- Get SM quark mass terms in effective low energy lagrangian:

Quark Masses

$$\frac{\langle\overline{\Psi}\Psi\rangle_{ETC}\overline{\psi}\psi}{\Lambda^2_{ETC}}$$

Dimopoulos, Susskind 79 - Eichten, Lane 80

Flavour Changing Neutral Currents

- But also get FCNC term:

Quark Masses

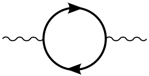
$$\frac{\langle\overline{\Psi}\Psi\rangle_{ETC}\overline{\psi}\psi}{\Lambda_{ETC}^2}$$

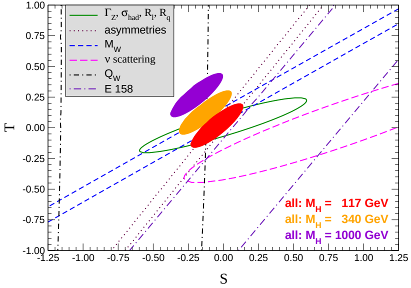
FCNC

$$\frac{\overline{\psi}\psi\overline{\psi}\psi}{\Lambda_{ETC}^2}$$

- Naively scaling up QCD leads to a problem:
- Need large $\Lambda_{ETC} \sim 1000\,TeV$ to suppress Flavour Changing Neutral Currents
- But this gives a strange quark mass that is ~ 50 times too small

S, T Parameters

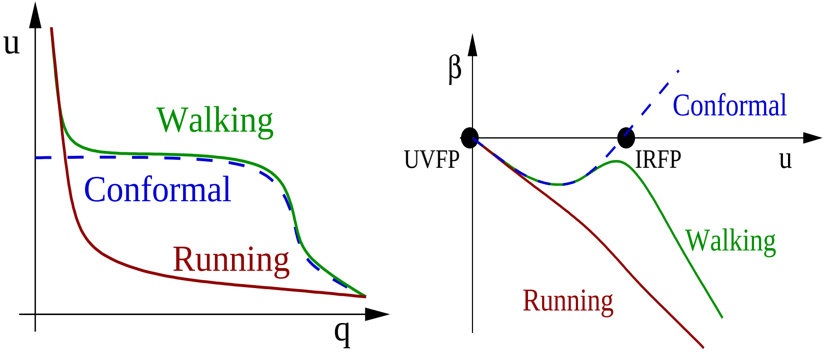




Particle Data Group 2008

- S,T parameters measure deviation from SM caused by new physics
- Naive QCD scaling gives $\sim 2\sigma$ disagreement with experiment
- Perturbative estimate: $S = \frac{1}{6\pi}\frac{N_f}{2}d(R) = 0.16$

Walking Technicolor Cartoon



Walking Technicolor Quark Masses

$$\langle\overline{\Psi}\Psi\rangle_{ETC} = \langle\overline{\Psi}\Psi\rangle_{TC}\, exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} \gamma(\mu) d \ln \mu\right)$$

- In QCD this gives logarithmic enhancement:

$$\langle\overline{\Psi}\Psi\rangle_{ETC} = \log\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma} \langle\overline{\Psi}\Psi\rangle_{TC}$$

- But a walking coupling gives power enhancement:

$$\langle\overline{\Psi}\Psi\rangle_{ETC} = \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma} \langle\overline{\Psi}\Psi\rangle_{TC}$$

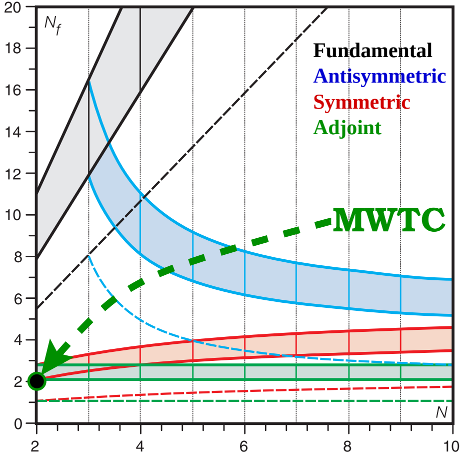
Walking Technicolor S Parameter

- Walking seems to reduce S parameter compared to running case.
- And other sectors of the theory, such as new leptons, are expected to contribute negatively

Dietrich, Sannino, Tuominen [arXiv:hep-ph/0505059]

- But ideally this also needs to be studied non-perturbatively

Phase Diagram



[arXiv:hep-ph/0611341]

- MWTC: 2 dirac fermions transforming under the adjoint representation of SU(2)

Saninno, Tuominen
[arXiv:hep-ph/0405209]

Scheme dependence

- Walking/Running of coupling is scheme dependent
- Want to measure physical, scheme independent quantities:
    - **Existence** of fixed point
    - **Anomalous mass dimension** at the fixed point

Wilson Renormalisation Group

- Spatially average locally / integrate out UV modes
- Leaves IR physics intact
- Look at evolution of all couplings

$$\hat{\xi}^{(0)} \quad , \quad \{g_i^{(0)}\}$$

Wilson Renormalisation Group

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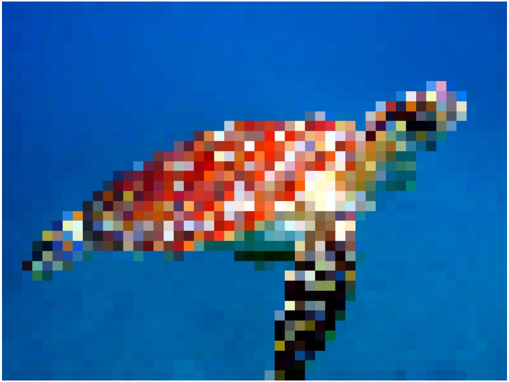
$$\hat{\xi}^{(1)} = \hat{\xi}^{(0)}/2 \quad , \quad \{g_i^{(1)}\}$$

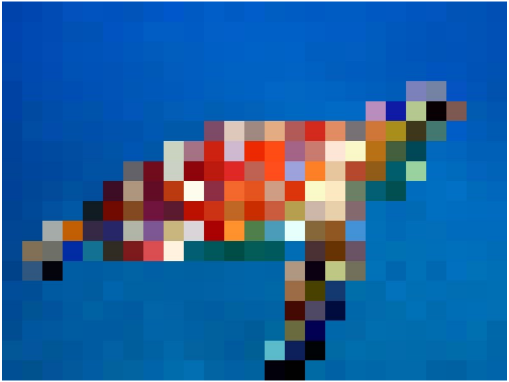
Wilson Renormalisation Group



- Spatially average locally / integrate out UV modes
- Leaves IR physics intact
- Look at evolution of all couplings

$$\hat{\xi}^{(2)} = \hat{\xi}^{(0)}/2^2 \quad , \quad \{g_i^{(2)}\}$$

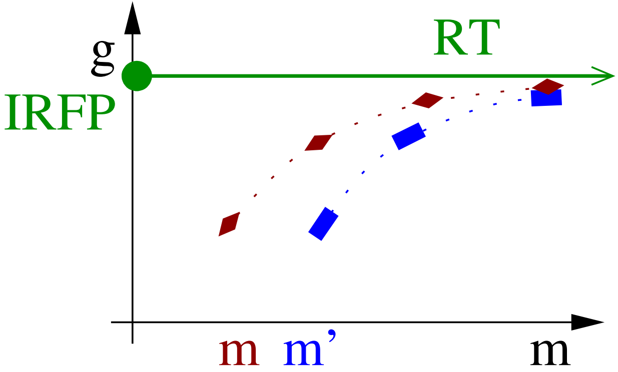
Wilson Renormalisation Group



- Spatially average locally / integrate out UV modes
- Leaves IR physics intact
- Look at evolution of all couplings

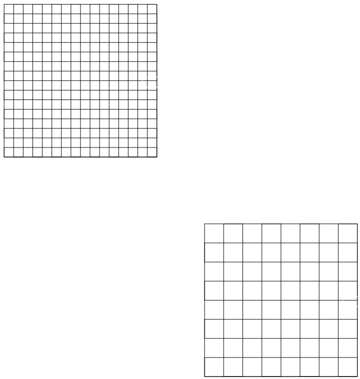
$$\hat{\xi}^{(3)} = \hat{\xi}^{(0)}/2^3 \quad , \quad \{g_i^{(3)}\}$$

Monte Carlo Renormalisation Group

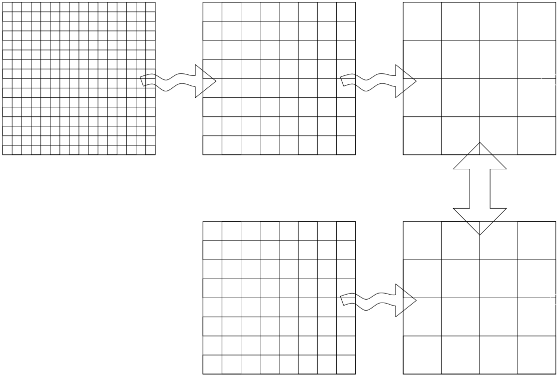


- Match after $n(n-1)$ steps
- $s = 2$ change in scale
- Step scaling of bare couplings

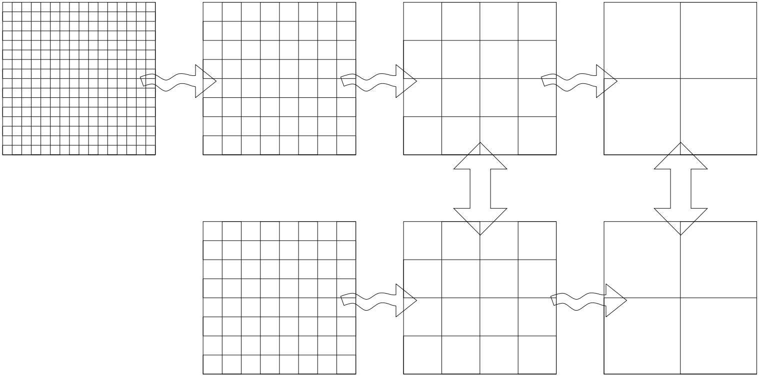
2–Lattice Matching



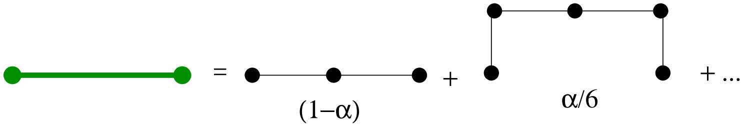
2–Lattice Matching



2–Lattice Matching



Lattice Blocking Transform



- Free parameter α adjusts RG blocking transform
- Optimise α to approach RT quickly such that subsequent steps give the same matching

$$V_{n,\mu} = Proj\left[(1-\alpha)U_{n,\mu}U_{n+\mu,\mu} + \frac{\alpha}{6}\sum_{\nu\neq\mu} U_{n,\nu}U_{n+\nu,\mu}U_{n+\mu+\nu,\mu}U^{\dagger}_{n+2\mu,\nu}\right]$$

MCRG Key Points

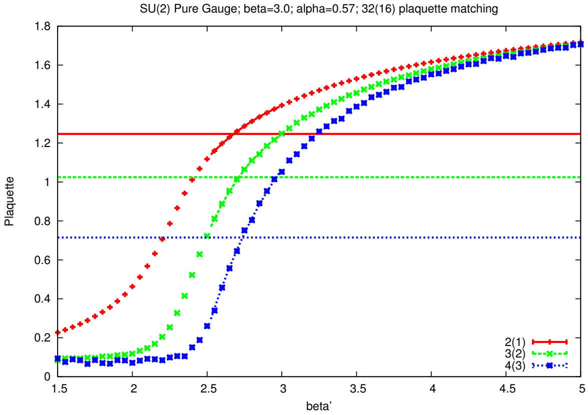
- Find pairs of couplings with identical blocked actions, whose correlation lengths differ by a factor 2
- Identify matching actions by comparing observables on blocked lattices (plaquette, 6-link and 8-link loops)
- Always match between lattices with the same number of points to minimise finite size errors
- Optimise α to approach the RT quickly so that subsequent steps give the same matching

Hasenfratz [arXiv:hep-lat/0907.0919]

Pure Gauge Simulation

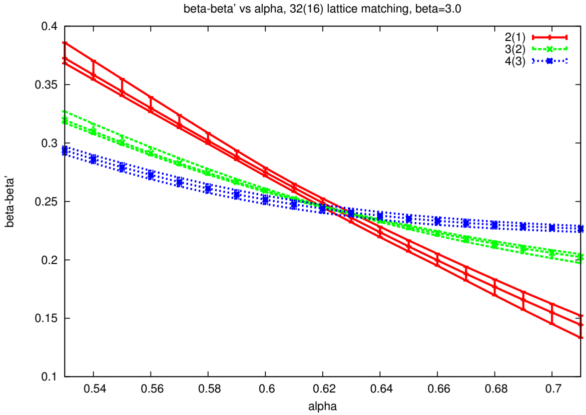
- Simulated on lattices of size L=32,16
- Allows for 3 matchings; 2(1), 3(2), 4(3) steps on the $32^4(16^4)$ lattices
- Optimise α such that these steps predict the same matching coupling
- Repeated this for three different blocking transforms, and on 16(8) lattices

Plaquette Matching



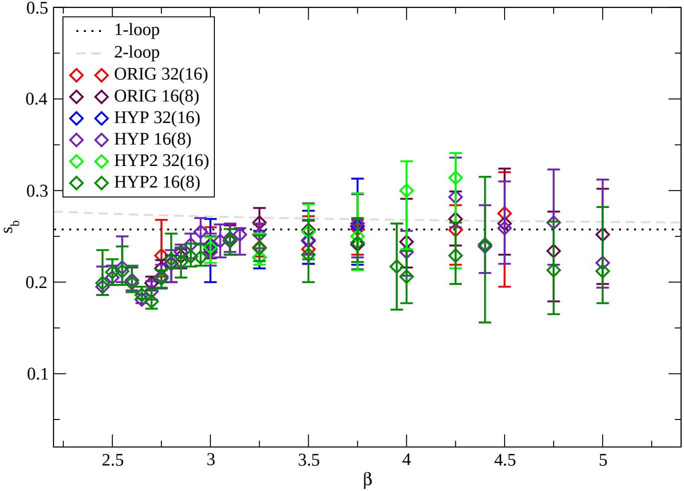
- 32(16) matching
- $\beta = 3.0$
- $\alpha = 0.57$

Alpha Optimisation

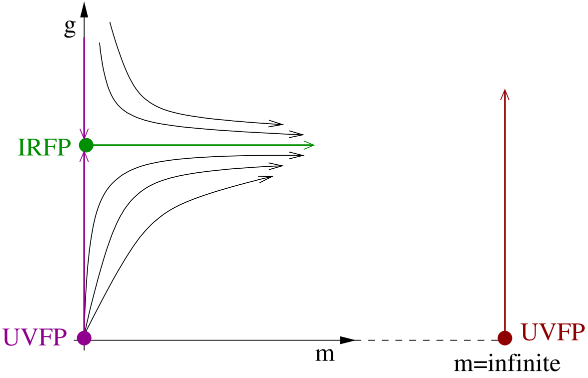


- $\beta = 3.0$
- $\alpha_{opt} \sim 0.63$
- $s_b = 0.24(2)$

Pure Gauge Bare Step Scaling

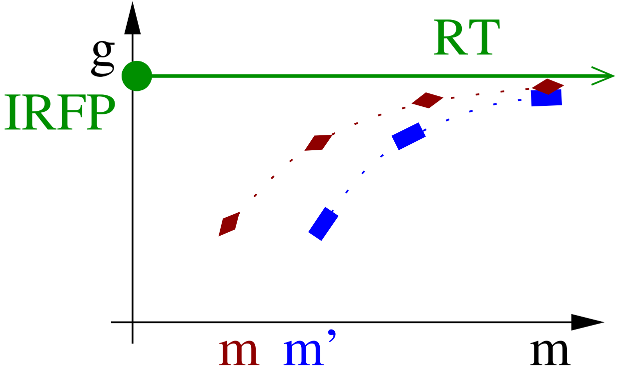


Phase diagram of full theory



- At IRFP:
- m relevant
- g irrelevant
- Near IRFP can match in m, value of g should be irrelevant

Phase diagram of full theory

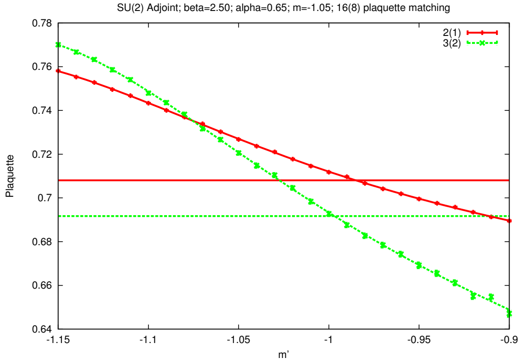


- At IRFP:
- m relevant
- g irrelevant
- Near IRFP can match in m, value of g should be irrelevant

Simulation details

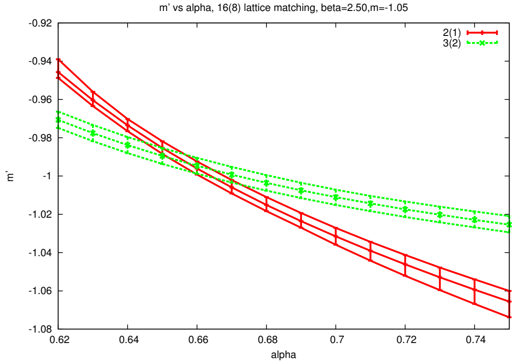
- Simulated on lattices of size L=16,8
- Allows for 2 matchings; 2(1), 3(2) steps on the 16^4(8^4) lattices
- Keep β constant, match in bare mass
- Optimise α such that these all agree to find continuum physics

Plaquette Matching



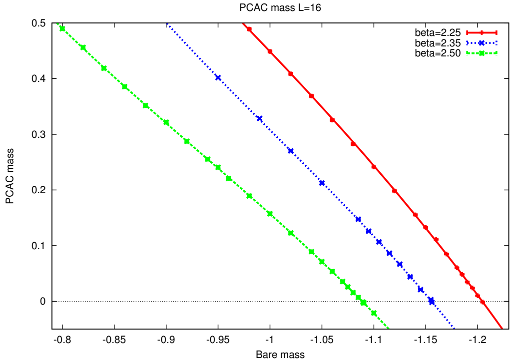
- 16^4 blocked two/three times
- Single mass $m = -1.05$
- 8^4 blocked one/two times
- Many masses $-1.15 < m' < -0.90$

Alpha Optimisation



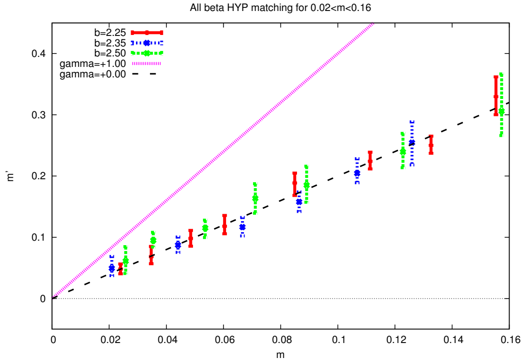
- $\alpha_{opt} \sim 0.66$
- $m = -1.05$
- $m' = -1.01(2)$

PCAC Masses



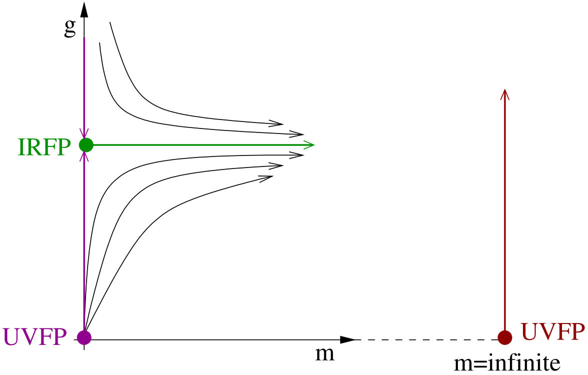
- Have matching bare masses, but additively renormalised quantities
- So need to convert to PCAC masses to be able to extract anomalous dimension

Anomalous Dimension



- Extract γ from ratio of masses:
- $m' = 2^{\gamma+1} m$
- Linear fit gives $\gamma = -0.01(13)$

Phase diagram of full theory

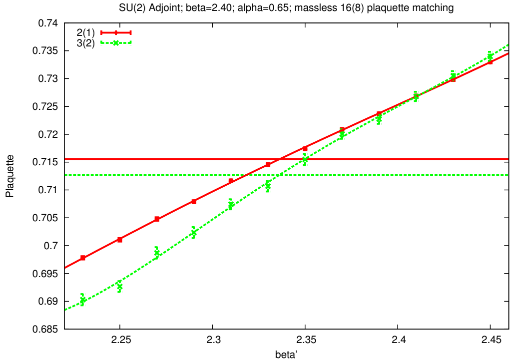


- At IRFP:
- Tune relevant *m* to zero
- Match in 'least-irrelevant' coupling *g*

Simulation details

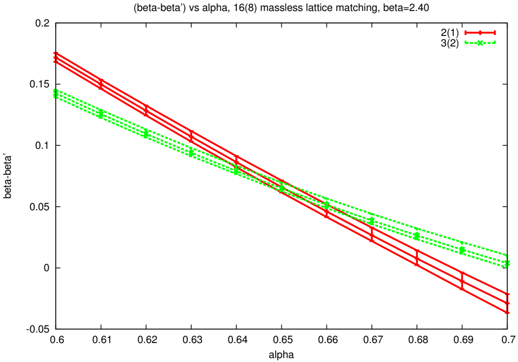
- Simulated on lattices of size L=16,8
- Allows for 2 matchings; 2(1), 3(2) steps on the 16^4(8^4) lattices
- Tune all PCAC masses to zero, then match in β
- Optimise α such that these all agree to find continuum physics

Plaquette Matching



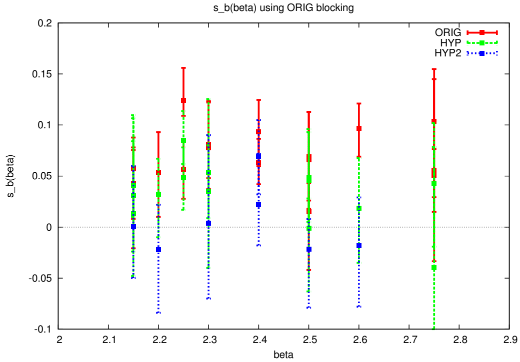
- 16^4 blocked two/three times
- Single $\beta = 2.40$
- 8^4 blocked one/two times
- Many β' values

Alpha Optimisation



- $\alpha_{opt} \sim 0.65$
- $\beta = 2.40$
- $\beta' = 2.34(3)$
- $s_b = 0.06(3)$

Coupling Step Scaling

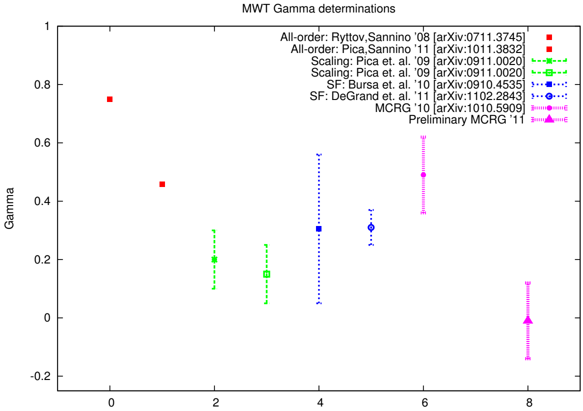


- FP would be indicated by change of sign in s_b
- Data compatible with change of sign
- But errors too large to identify a FP

MCRG Conclusion

- Mass anomalous dimension is small, and independent of β
- We find $\gamma = -0.01(13)$
- Running of the coupling is slow, and consistent with a fixed point
- But our data cannot distinguish the two cases

Results in Context



- We find $\gamma = -0.01(13)$
- $\gamma = 1$ is strongly excluded

Prediction for anomalous dimension I

Conjectured all orders beta function

$$\beta(g) = \frac{g^3}{(4\pi)^2} \frac{\beta_0 - \frac{2}{3} T(r) N_f \gamma(g^2)}{1 - \frac{g^2}{8\pi^2} C_2(G) \left(1 + \frac{2\beta_0'}{\beta_0}\right)}$$

$$\beta_0 = \frac{11}{3} C_2(G) - \frac{4}{3} T(r) N_f, \quad \beta_0' = C_2(G) - T(r) N_f$$

- For MWT this predicts anomalous dimension $\gamma = 3/4$ at fixed point
- This is a scheme-independent quantity at a fixed point

Ryttov, Sannino [arXiv:0711.3745]

Prediction for anomalous dimension II

Conjectured all orders beta function

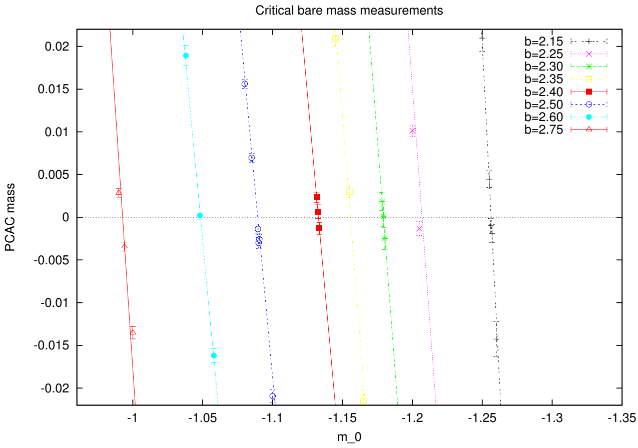
$$\beta(g) = -\frac{g^2}{6\pi}\frac{11C_2(G) - 2T(r)N_f\left(2 + \Delta_R\gamma(g^2)\right)}{1 - \frac{17g}{22\pi}C_2(G)}$$

$$\Delta_R = 1 + \frac{7C_2(G)}{11C_2(R)}$$

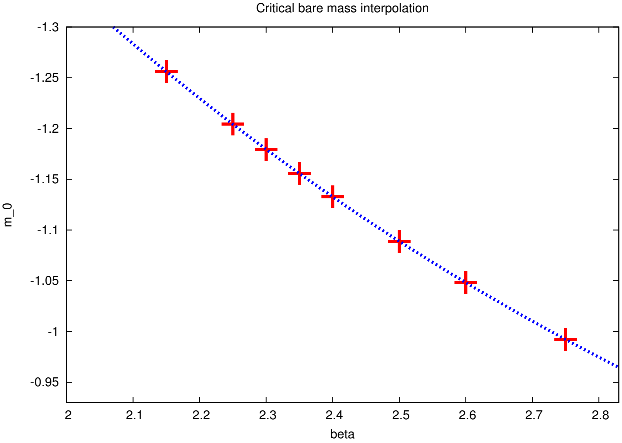
- For MWT this predicts anomalous dimension $\gamma = 11/24 \simeq 0.458$ at fixed point
- This is a scheme-independent quantity at a fixed point

Pica, Sannino [arXiv:1011.3832]

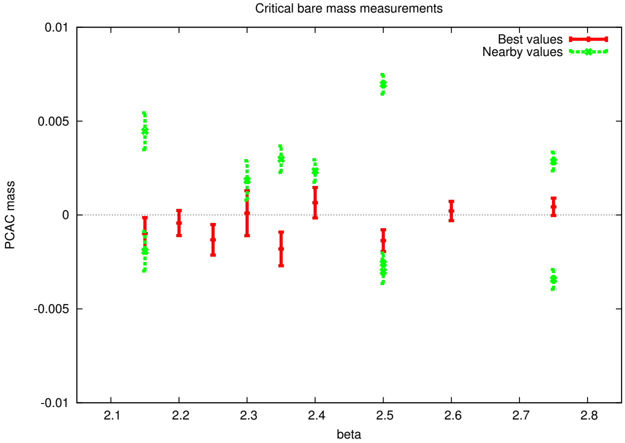
Measured PCAC Masses



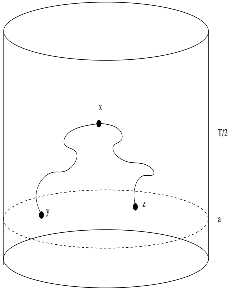
Interpolation in Beta



Massless Runs



PCAC Mass



PCAC mass is defined using the Partially Conserved Axial Current:

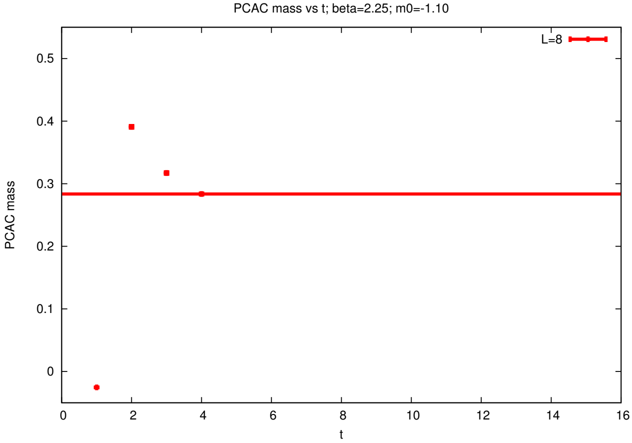
PCAC Mass

$$am(x_0) = \frac{\frac{1}{2}(\partial_0 + \partial_0^*) f_A(x_0)}{2 f_P(x_0)}$$

$$f_A(x_0) = -1/12 \int d^3y\, d^3z\, \langle \overline{\psi}(x_0)\gamma_0\gamma_5\tau^a\psi(x_0)\overline{\zeta}(y)\gamma_5\tau^a\zeta(z)\rangle$$

$$f_P(x_0) = -1/12 \int d^3y\, d^3z\, \langle \overline{\psi}(x_0)\gamma_5\tau^a\psi(x_0)\overline{\zeta}(y)\gamma_5\tau^a\zeta(z)\rangle$$

PCAC Mass Finite Size Effects



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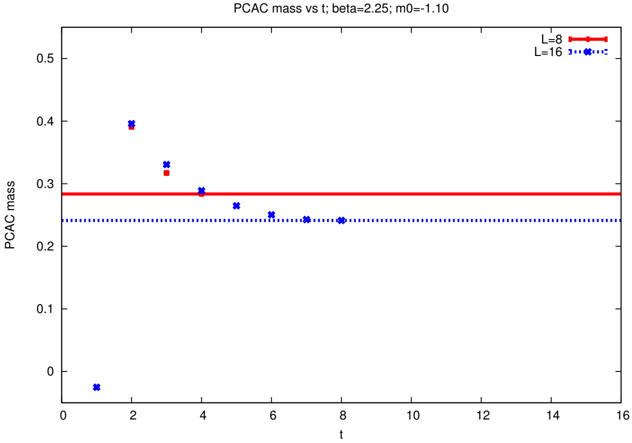

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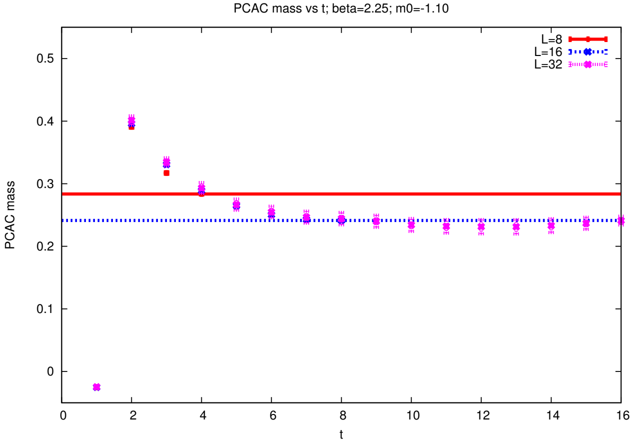

Particle content of MWT

- Fermionic content:
  - (U,D) techni-quark doublet
  - (N,E) new lepton doublet
  - composite techniquark-technigluon doublet
- Composite Higgs from techni-pion

MWT LHC Phenomenology

- details depend on choice of ETC model
- then construct low energy EFT for LHC

Frandsen, Sannino, et. al. [arXiv:0710.4333v1] [arXiv:0809.0793v1]

MWT Dark Matter candidate

- lightest technibaryon is a cold dark matter candidate
- TIMP: Technicolour Interacting Massive Particle
- iTIMP: lightest weak isotriplet technibaryon
- Prospects for discovery/exclusion from both dark matter experiments and LHC

Frandsen, Sannino [arXiv:0911.1570]