Scattering and resonances in composite Higgs models

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Outline

1. Outline - you are here
2. SM Higgs
3. Composite Higgs
4. SU(2) with 2 fundamental flavours
5. SU(4) with multiple representations of fermions

Standard Model Higgs

Mass terms incompatible with electroweak symmetry

$$m(\psi_L^\dagger \psi_R + \psi_R^\dagger \psi_L)$$

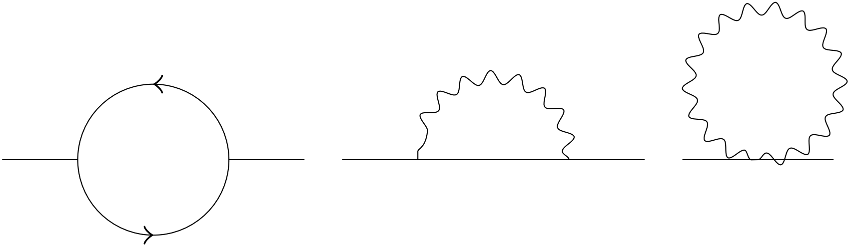
not invariant under $SU(2)_L$. Electroweak symmetry breaking due to potential

$$\mathcal{L} \supset (D_\mu \Phi)^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

If $\mu^2 < 0$, $\langle \Phi^a \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$, which breaks the EW symmetry $SU(2)_L \times U(1)_Y \to U(1)_{em}$ This gives masses to $W^\pm$ and Z bosons. Fermion masses generated by Yukawa interactions

$$\mathcal{L} \supset Y_{ij}^d \Psi_{Li}^\dagger H \Psi_{Rj} + Y_{ij}^u \Psi_{Li}^\dagger (i\sigma^2) H^* \Psi_{Rj} + h.c.$$

SM Higgs mass quadratically sensitive to the cutoff (i.e. new physics scale) of the theory.



Let Λ be the scale up to which SM is valid.

$$m_H^2 = m_R^2(\Lambda) - \Sigma(\Lambda)$$

with

$$\delta m_H^2 \propto \Lambda^2.$$

But $m_H^2 = 126\mathrm{GeV}$ $\rightarrow$ large cancellation between UV (m_R^2) and IR (Σ) contributions?

Motivation - Composite Higgs

Why is the Higgs so light?

- Could be a composite particle - either a bound state (technicolor) or a pseudo-Goldstone boson ("composite Higgs")
- Standard model Higgs doublet transforms as (2,2) under $SU(2)_L \times SU(2)_R \sim SO(4)$ global custodial symmetry
- Symmetry breaking at Λ_{TC} creates Goldstone bosons which form a Higgs doublet.
- After EW symmetry breaking, Higgs doublet becomes the Higgs boson + 3 longitudal polarisations of W and Z bosons

Possible symmetry breaking patterns

- Minimal composite Higgs model $SO(5) \to SO(4)$, but no known UV completion with fermions
- Next-to-minimal composite Higgs $SO(6) \to SO(5)$. This creates 5 Goldstone bosons in (2,2) and (1,1) representations of SO(4).
- $SO(6) \to SO(4)$ - 9 Goldstone bosons all in (3,3) rep of SO(4). **Not a viable composite Higgs model**, but can be a viable technicolor model (Minimal Walking Technicolor)
- $SU(5) \to SO(5)$ - 14 Goldstone bosons
- For other, less minimal patterns see Mrazek et. al. 1105.5403, table 1

Symmetry breaking patterns

On a fundamental level, all quark multiplets will exhibit $SU(N_f)$ symmetry. Formation of the condensate breaks the symmetry depending on the representation:

- Real - $q \to gq$, $g = g^*$

$$\psi^T = (q_L \quad Cq_R^*)$$

$$SU(2N_f) \to SO(2N_f)$$

- Pseudo-real - $q \to gq$, $g^* = S^{-1} g S$

$$\psi^T = (q_L \quad CSq_R^*)$$

$$SU(2N_f) \to Sp(2N_f)$$

- Complex - $q \to gq$, g and g^* independent
  Separate left and right-handed multiplets

$$SU(N_f) \times SU(N_f) \to SU(N_f)$$

Symmetry breaking patterns

Using $SO(4) \sim SU(2) \times SU(2)$, $SO(5) \sim Sp(4)$, $SO(6) \sim SU(4)$

- $SO(6) \to SO(5) \sim SU(4) \to Sp(4)$ - 2 flavours in pseudo-real representation
- $SO(6) \to SO(4) \sim SU(4) \to SO(4)$ - 2 flavours in real representation
- $SU(5) \to SO(5)$ 5 Weyl fermions (2.5 Dirac) in real representation

Vacuum alignment

In $G \to H$ symmetry breaking, some generators of $G \in SU(2)$ electroweak group. These are gauged, so that

$$g = exp(T^a \theta^a(x) + X^a \phi^a) \in G$$

where $T \in su(2)$ and $X \notin su(2)$
But also

$$g = exp(T_G^a \alpha^a(x) + T_H^b \beta^b(x))$$

where $T_H \in h$ and $T_G \notin h$.

1. if $\{T^a\} \subset \{T_H^a\}$ - $G \to H$ does not break EW symmetry (composite Goldstone Higgs limit)
2. if $\{T^a\} \subset \{T_G^a\}$ - $G \to H$ breaks EW symmetry completely (technicolor limit)
3. In general $T^a = \sin\theta T_G^a + \cos\theta T_H^a$ where θ is a vacuum (mis)alignment angle.

Phenomenology

	$\theta = 0$	$\theta = \pi/2$
EW symmetry	unbroken	broken
model	composite Higgs	Technicolor
pions	$W^{\pm}$, Z, H + others	$W^{\pm}$, Z + others
Higgs	pion	scalar resonance

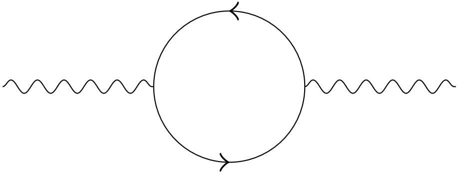
In general, Higgs is a superposition of a Goldstone boson and a σ-like resonance.
Connection to electroweak physics:

$$f_{PS} \sin\theta = v = 246\mathrm{GeV}$$

$$\Lambda_{TC} \sim f_{PS} = \frac{246\mathrm{GeV}}{\sin\theta}$$

In isolation θ can be an arbitrary angle. SM interactions will tend to push θ towards Technicolor limit.

An important phenomenological constraint comes from Peskin-Takeuchi parameters. They are defined using W and Z vacuum polarisation functions:

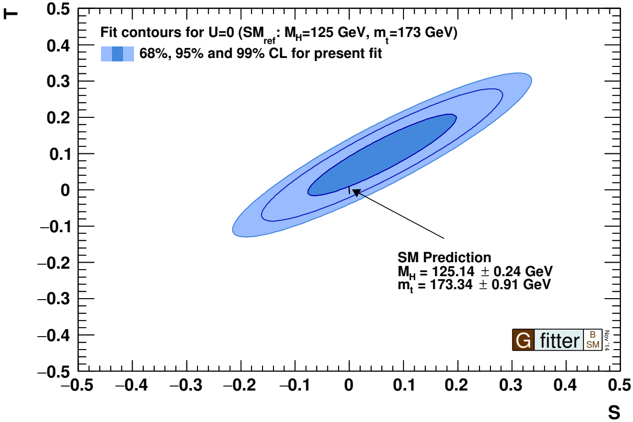


$$S \equiv \frac{4c^2s^2}{\alpha}\left(\frac{\Pi^{new}_{ZZ}(m_Z^2)-\Pi^{new}_{ZZ}(0)}{m_Z^2}-\frac{c^2-s^2}{cs}\frac{\Pi^{new}_{Z\gamma}(m_Z^2)}{m_Z^2}-\frac{\Pi^{new}_{\gamma\gamma}(m_Z^2)}{m_Z^2}\right)$$

$$T \equiv \frac{1}{\alpha}\left(\frac{\Pi^{new}_{WW}(0)}{m_W^2}-\frac{\Pi^{new}_{ZZ}}{m_Z^2}\right)$$

$$U \equiv \frac{4s^2}{\alpha}\left(\frac{\Pi^{new}_{WW}(m_W^2)-\Pi^{new}_{WW}(0)}{m_W^2}-\frac{c}{s}\frac{\Pi^{new}_{Z\gamma}(m_Z^2)}{m_Z^2}-\frac{\Pi^{new}_{\gamma\gamma}(m_Z^2)}{m_Z^2}\right)-S$$

Peskin-Takeuchi parameters - phenomenological values



$$S = 0.05 \pm 0.11$$

$$T = 0.09 \pm 0.13$$

$$U = 0.01 \pm 0.11$$

Constraints from EW precision observables

- U does not give strong constraints on BSM physics
- T can be set to 0 by imposing global $SU(2)_L \times SU(2)_R \sim SO(4)$ symmetry ("custodial symmetry")
- S provides the strongest constraints on new physics. We can see that at 1-loop the contribution of new particles goes as

  $$S \propto N_f d(R)$$

  where N_f is the number of new quark flavours and $d(R)$ is the dimension of the representation of the gauge group they are in.
- In composite Higgs models $S \propto \sin\theta$.

Quark masses

Fermion masses generated via a 4-quark operator

$$\frac{c}{\Lambda_{UV}^2}\bar{\psi}_L\psi_R\bar{Q}Q$$

where ψ are SM fermions and Q are the technifermions.
The fermion masses are generated dynamically when technifermions condense $\langle\bar{Q}Q\rangle \sim \Lambda_{TC}^3$
The same processes that generate these 4-quark operators at Λ_{UV} also generate FCNC operators, e.g. $\bar{s}d\bar{s}d$, which are constrained by neutral meson mixing

$$\Delta M_K \sim \frac{g_{UV}^2 f_K^2 m_K}{\Lambda_{UV}^2}$$

gives $\Lambda_{UV} \approx 10^3\mathrm{TeV}$.
Problem with making quark masses large enough.

Partial compositeness

Generation of fermion masses in composite models:

- Higgs-like

$$\mathcal{L} \supset \frac{c}{\Lambda_{UV}^{d-1}} \bar{\psi} O \psi \to \frac{c}{\Lambda_{UV}^{d-1}} \bar{\psi} \langle O \rangle \psi + \ldots$$

  what we discussed so far with $O = \bar{Q}Q$.
  Difficult to produce the top quark mass.

- Partial compositeness

$$\frac{\lambda_L}{\Lambda_{UV}^{d-5/2}} \bar{Q}_L O_R + \frac{\lambda_R}{\Lambda_{UV}^{d-5/2}} \bar{t}_R O_L$$

  like W and Z bosons in SM
  'physical' quark (mass eigenstate) becomes a superposition of fundamental field q and composite operator O.

- We can predict the resonance spectrum in vector boson scattering
- This follows from Goldstone boson equivalence theorem: at large energies, external vector boson states equivalent to Goldstone boson states
- e.g. $\rho \to \pi^+\pi^-$ corresponds to vector resonance in W^+W^- scattering

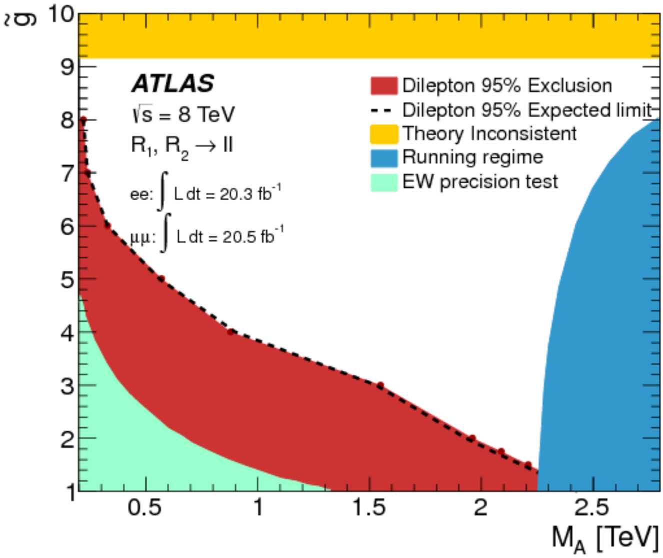
Effective Lagrangian:

$$\mathcal{L}_{eff} = g_{\rho\pi\pi}\rho^{\mu}_{[ij]}\partial_\mu\pi_i\pi_j$$

In QCD $\rho^{\mu}_{[ab]} = f_{abc}\rho^{\mu}_{c}$.

Predictions 2

Example: Minimal walking technicolor.



SU(2)

SU(2) with 2 fundamental flavours

SU(2) model, 2 Dirac fermions in fundamental representantion [1402.0233].
$SU(2) = Sp(2) \sim SO(3)$ smallest non-abelian Lie group.

$$\mathcal{L} = -\frac{1}{4} F^{a\mu\nu} F^{a}_{\mu\nu} + i\bar{U}\gamma^{\mu} D_{\mu} U + i\bar{D}\gamma^{\mu} D_{\mu} D$$

Fundamental representation of SU(2) is pseudo-real $\rightarrow$ we can construct a flavour multiplet

$$Q = \begin{pmatrix} u_L \\ d_L \\ -i\sigma^2 C \bar{u}_R^T \\ -i\sigma^2 C \bar{d}_R^T \end{pmatrix}$$

$\mathcal{L}$ is symmetric under SU(4) flavour group (locally isomorphic to SO(6)).

SU(2) with 2 fundamental flavours

SU(4) symmetry is broken spontaneously by a fermion condensate $\Sigma^{ab} = \langle Q^a(i\sigma_c^2)CQ^b\rangle$ [1109.3513] to the subgroup which leaves it invariant:

$$U^T \Sigma U = \Sigma \quad U \in Sp(4) \sim SO(5).$$

This produces 5 Goldstone bosons ("pions").
In full theory (+SM), interactions with SM particles give the vacuum a preferred direction.
On the lattice we add an explicit mass term:

$$-m(\bar{u}u + \bar{d}d) = \frac{m}{2} Q^T(-i\sigma^2)CEQ + h.c.$$

$$E = \begin{pmatrix} 0 & 1_2 \\ -1_2 & 0 \end{pmatrix}$$

Some phenomenology

- top quark interaction will tend to align the vacuum with TC vacuum $\theta = \pi/2$ [1402.0233]
- In TC limit Goldstone bosons can combine to produce a DM candidate [1511.04370]
- No DM candidate outside of TC limit - η decays to gauge bosons via anomaly.
- Consistent with LHC measurements even in TC limit [1502.04718]
- No partial compositeness in this model :(

Ensemble parameters

Wilson clover + Symanzik gauge generated using HiRep

L	T	b	m0	stat	therm	acc	P	proba
16	32	1.25	-0.6000	6500	1000	1.00	0.496	1.00
16	32	1.30	-0.6000	6500	1000	1.00	0.520	1.00
16	32	1.35	-0.6000	6500	1000	1.00	0.546	1.00
16	32	1.35	-0.7000	1666	1000	0.80	0.562	1.05
16	32	1.40	-0.6000	1500	450	1.00	0.572	1.00
16	32	1.40	-0.6100	1392	450	1.00	0.574	1.00
16	32	1.40	-0.6200	1218	450	0.99	0.576	1.00
16	32	1.40	-0.6300	1621	1000	0.97	0.577	0.99
16	32	1.40	-0.6400	1795	1000	0.92	0.579	0.97
16	32	1.40	-0.6500	1585	1000	0.76	0.581	0.89
16	32	1.40	-0.6570	2779	1000	0.83	0.583	0.87
16	32	1.45	-0.5500	2000	1000	1.00	0.591	1.00
24	48	1.45	-0.5500	1828	1000	0.97	0.591	1.00
16	32	1.45	-0.5700	4156	1000	0.92	0.594	1.00
24	48	1.45	-0.5700	1684	1000	0.93	0.594	1.00
16	32	1.45	-0.5800	1791	1000	0.93	0.595	1.03
24	48	1.45	-0.5800	1485	450	0.92	0.595	1.02
16	32	1.45	-0.5900	1602	1000	0.79	0.597	0.91
24	48	1.45	-0.5900	1020	450	0.83	0.597	0.95
16	32	1.45	-0.6000	1766	1000	0.74	0.599	0.86
16	32	1.45	-0.6050	2371	1000	0.96	0.600	0.97
16	32	1.45	-0.6100	3424	1000	0.88	0.601	0.90
16	32	1.50	-0.5000	1500	450	1.00	0.608	1.00
16	32	1.50	-0.5100	1500	450	0.99	0.610	1.00
16	32	1.50	-0.5200	1513	1000	0.99	0.611	1.00
24	48	1.50	-0.5200	1225	450	0.89	0.610	1.02
16	32	1.50	-0.5300	1500	450	0.92	0.612	1.02
16	32	1.50	-0.5400	1325	450	0.79	0.613	0.99
16	32	1.50	-0.5500	1750	1000	0.81	0.614	0.94
16	32	1.50	-0.5525	2214	1000	0.78	0.614	0.91
16	32	1.50	-0.5550	4117	1000	0.86	0.615	0.92
24	48	1.50	-0.5560	1673	1000	0.86	0.615	0.91
16	32	1.60	-0.4000	1500	450	1.00	0.637	1.00
16	32	1.60	-0.4500	1810	1000	0.80	0.640	1.01
24	48	1.60	-0.4500	2693	1000	0.98	0.640	1.00
16	32	1.60	-0.4700	2432	1000	0.82	0.641	0.90
24	48	1.60	-0.4700	1991	1000	0.95	0.641	1.00
16	32	1.60	-0.4800	2106	1000	0.86	0.642	0.92
24	48	1.60	-0.4800	1758	1000	0.84	0.642	0.92
16	32	1.60	-0.4900	2866	1000	0.11	0.642	0.13
16	32	1.80	-0.2500	500	450	1.00	0.681	1.00
16	32	1.80	-0.3000	500	450	0.98	0.683	1.00
16	32	1.80	-0.3500	2500	1000	1.00	0.684	1.00
16	32	1.80	-0.3850	1917	1000	1.00	0.685	1.00
16	32	2.00	-0.2000	500	450	1.00	0.717	1.00
16	32	2.00	-0.2500	500	450	1.00	0.717	1.00
16	32	2.00	-0.3000	500	450	0.96	0.718	1.07

Table 1: Summary runs: Large volume. proba :$e^{-\Delta S}$; P : Plaquette; acc: acceptance

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b	m0	L	T	Blk_size	stat	ampac	dampac	amps	damps	afps	dafps	amV	damV
1.25	-0.6000	16	32	100	6500	0.2851	0.0004	1.303	0.002	0.233	0.0024	1.468	0.007
1.30	-0.6000	16	32	100	6500	0.2321	0.0005	1.154	0.002	0.203	0.0025	1.324	0.009
1.35	-0.6000	16	32	100	6500	0.1701	0.0006	0.956	0.003	0.168	0.0025	1.129	0.013
1.35	-0.7000	16	32	10	1666	0.0357	0.0009	0.423	0.006	0.105	0.0035	0.655	0.081
1.40	-0.6000	16	32	10	1500	0.0984	0.0006	0.686	0.003	0.124	0.0022	0.862	0.020
1.40	-0.6100	16	32	10	1392	0.0846	0.0008	0.632	0.005	0.118	0.0032	0.808	0.031
1.40	-0.6200	16	32	10	1218	0.0696	0.0009	0.567	0.006	0.109	0.0034	0.748	0.039
1.40	-0.6300	16	32	10	1621	0.0552	0.0007	0.503	0.005	0.102	0.0024	0.713	0.040
1.40	-0.6400	16	32	10	1795	0.0413	0.0007	0.433	0.005	0.093	0.0025	0.708	0.070
1.40	-0.6500	16	32	10	1585	0.0250	0.0010	0.343	0.010	0.081	0.0040	0.591	0.082
1.40	-0.6570	16	32	10	2779	0.0137	0.0008	0.262	0.010	0.067	0.0036	0.529	0.066
1.45	-0.5500	16	32	10	2000	0.0898	0.0005	0.619	0.003	0.105	0.0016	0.769	0.012
1.45	-0.5700	16	32	20	4156	0.0631	0.0005	0.510	0.003	0.093	0.0013	0.673	0.017
1.45	-0.5800	16	32	10	1791	0.0493	0.0007	0.445	0.005	0.085	0.0019	0.616	0.028
1.45	-0.5900	16	32	10	1602	0.0346	0.0009	0.376	0.007	0.077	0.0027	0.587	0.058
1.45	-0.6000	16	32	10	1766	0.0197	0.0010	0.286	0.010	0.064	0.0033	0.517	0.076
1.45	-0.6050	16	32	10	2371	0.0110	0.0011	0.236	0.013	0.051	0.0049	0.520	0.090
1.45	-0.6100	16	32	20	3424			0.195	0.015			0.541	0.083
1.50	-0.5000	16	32	10	1500	0.0869	0.0006	0.575	0.004	0.091	0.0019	0.703	0.013
1.50	-0.5100	16	32	10	1500	0.0731	0.0007	0.521	0.005	0.084	0.0019	0.650	0.017
1.50	-0.5200	16	32	10	1513	0.0600	0.0007	0.468	0.005	0.078	0.0018	0.611	0.019
1.50	-0.5300	16	32	10	1500	0.0459	0.0008	0.407	0.006	0.072	0.0019	0.557	0.027
1.50	-0.5400	16	32	10	1325	0.0330	0.0010	0.354	0.009	0.062	0.0026	0.545	0.058
1.50	-0.5500	16	32	10	1750	0.0190	0.0010	0.272	0.013	0.050	0.0028	0.453	0.048
1.50	-0.5525	16	32	10	2214	0.0141	0.0010	0.256	0.012	0.041	0.0028	0.555	0.115
1.50	-0.5550	16	32	20	4117	0.0120	0.0011	0.238	0.017	0.038	0.0035	0.465	0.066
1.60	-0.4000	16	32	10	1500	0.0993	0.0005	0.546	0.004	0.071	0.0012	0.617	0.008
1.60	-0.4500	16	32	10	1810	0.0407	0.0007	0.357	0.007	0.048	0.0013	0.480	0.014
1.60	-0.4700	16	32	10	2432	0.0162	0.0011	0.320	0.015	0.022	0.0015	0.502	0.023
1.60	-0.4800	16	32	10	2106	0.0018	0.0016	0.304	0.027	0.002	0.0020	0.501	0.046
1.60	-0.4900	16	32	10	2866	-0.0163	0.0006	0.290	0.012	-0.033	0.0020	0.322	0.021
1.80	-0.2500	16	32	5	500	0.1393	0.0004	0.566	0.004	0.053	0.0009	0.602	0.005
1.80	-0.3000	16	32	5	500	0.0893	0.0004	0.501	0.006	0.045	0.0010	0.548	0.007
1.80	-0.3500	16	32	10	2500	0.0333	0.0003	0.451	0.006	0.019	0.0003	0.464	0.008
1.80	-0.3850	16	32	10	1917	-0.0062	0.0005	0.429	0.007	-0.004	0.0003	0.461	0.007
2.00	-0.2000	16	32	5	500	0.1266	0.0002	0.533	0.004	0.048	0.0009	0.578	0.004
2.00	-0.2500	16	32	5	500	0.0757	0.0003	0.331	0.008	0.038	0.0011	0.365	0.008
2.00	-0.3000	16	32	5	500	0.0250	0.0006	0.234	0.013	0.034	0.0014	0.314	0.020
1.45	-0.5500	24	48	10	1828	0.0899	0.0003	0.621	0.002	0.106	0.0016	0.781	0.025
1.45	-0.5700	24	48	10	1684	0.0628	0.0004	0.509	0.002	0.093	0.0018	0.697	0.052
1.45	-0.5800	24	48	10	1485	0.0487	0.0004	0.444	0.003	0.085	0.0023	0.627	0.088
1.45	-0.5900	24	48	10	1020	0.0340	0.0009	0.369	0.007	0.078	0.0044	0.643	0.081
1.50	-0.5200	24	48	10	1225	0.0603	0.0005	0.465	0.004	0.079	0.0023	0.599	0.040
1.50	-0.5560	24	48	10	1673	0.0100	0.0007	0.188	0.009	0.048	0.0029	0.428	0.096
1.60	-0.4500	24	48	10	2693	0.0404	0.0002	0.319	0.002	0.051	0.0008	0.414	0.010
1.60	-0.4700	24	48	10	1991	0.0151	0.0005	0.195	0.007	0.036	0.0012	0.331	0.043
1.60	-0.4800	24	48	10	1758			0.134	0.012			0.367	0.085

Table 2: Summary mesons: Large volume.

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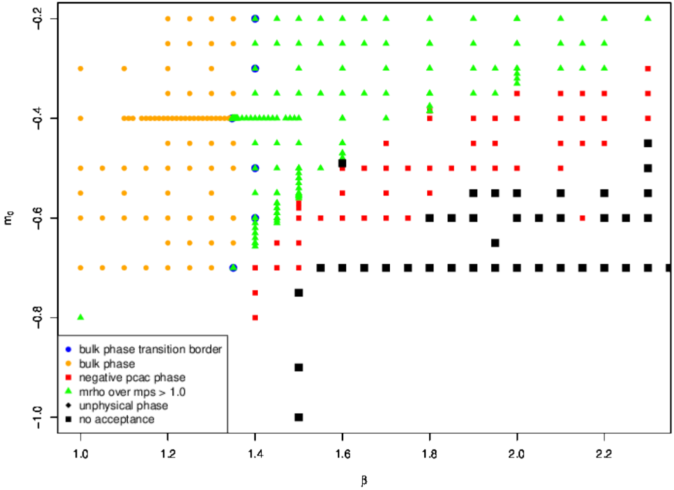
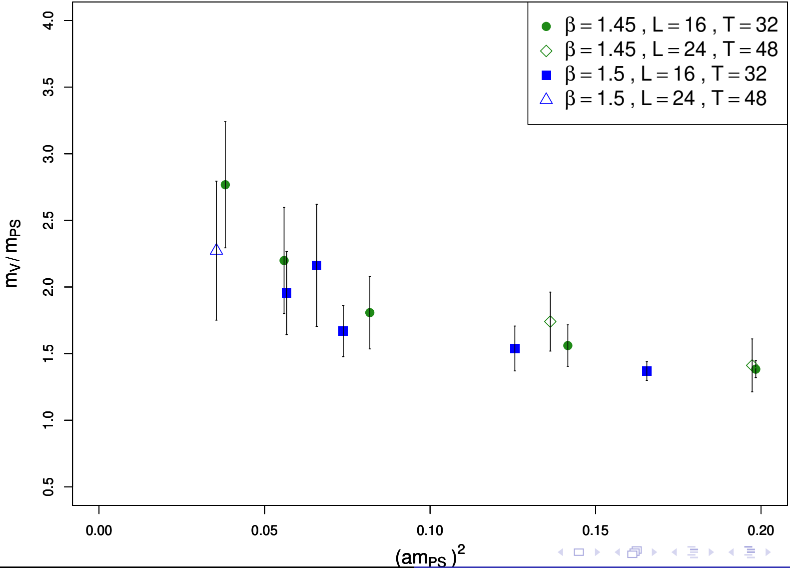
Phase space diagram



Getting unstable ρ



We follow the PACS-CS procedure in 1106.5365.
The correlation functions are given by

$$C_{ij}(t) \equiv \langle 0 \mid O_i^\dagger(t) O_j(0) \mid 0 \rangle = \sum_{n,m} \langle 0 \mid O_i^\dagger \mid n \rangle (e^{-E_n t} \delta_{mn}) \langle m \mid O_j \mid 0 \rangle$$

U and V are square matrices assuming higher-energy states don't contribute.
Then

$$C_{ij}^{-1}(t_0) C_{jk}(t) = V_{in}^{-1} diag \left(e^{-E_n (t - t_0)} \right)_{nm} V_{mj}$$

The spectrum can be extracted from the eigenvalues of $C^{-1}(t_0)C(t)$.

Interpolating operators

We use singlet representations - A_2^- in MF1 and B_1^- in MF2. We use the following two interpolating operators

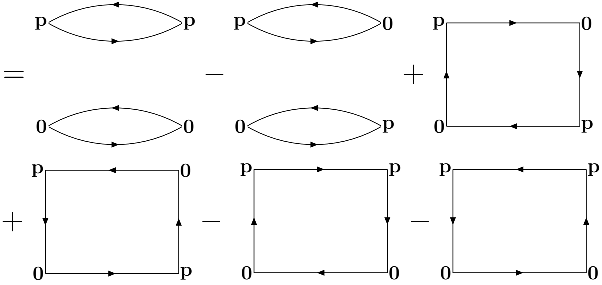
$$O_1(t) = \sum_{x,y} \bar{\psi}(x)\gamma^5\psi(x)\bar{\psi}(y)\gamma^5\psi(y)e^{i\mathbf{p}\cdot\mathbf{x}}$$

$$O_2(t) = \sum_{x} \bar{\psi}(x)(\gamma \cdot \hat{p})\psi(x)e^{i\mathbf{p}\cdot\mathbf{x}}$$

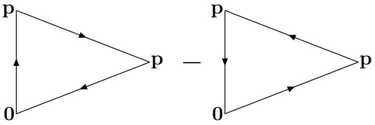
- $p = (0,0,1)$ in MF1 and $p = (1,1,0)$ in MF2
- $O_1(t)$ is by itself not in an irreducible representation, projection is done by choosing the contractions the same way as for $\pi_i(p)\pi_j(0) - \pi_j(p)\pi_i(0)$.

Contractions

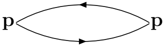
$C_{11}(t) =$



$C_{12}(t) = -C^{*}_{21}(t) =$



$C_{22}(t) =$



Moving frames

Phase shift formula depends on the frame and the representation:

frame	representation	$\tan\delta_1$
COM	T_1^-	$\frac{\pi^{3/2}q}{Z_{00}(1;q^2)}$
MF1	A_2^-	$\frac{\pi^{3/2}q}{Z_{00}(1;q^2)+\frac{2}{\sqrt{5}q^2}Z_{20}}$
MF2	B_1^-	$\frac{\pi^{3/2}q}{Z_{00}(1;q^2)-\frac{1}{\sqrt{5}q^2}Z_{20}+i\frac{\sqrt{3}}{\sqrt{10}q^2}\left(Z_{22}(1;q^2)-Z_{2(-2)}(1;q^2)\right)}$

$$Z_{lm}(s,q^2)=\sum_{n\in\mathbb{Z}^3}\frac{Y_{lm}(n)}{(q^2-n^2)^s}$$

$$\tan\delta_1=\frac{g^2_{\rho\pi\pi}}{6\pi}\frac{p^3}{E_{CM}(m_\rho^2-E_{CM}^2)},\; p=\sqrt{E_{CM}^2/4-m_\pi^2}$$

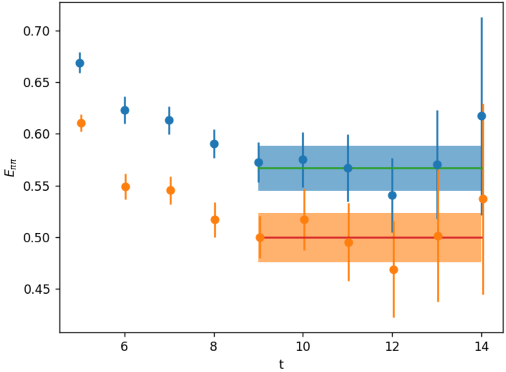
Our ensemble

Wilson clover fermions + Symanzik improved gauge action

β	1.45
m_0	-0.6050
c_{sw}	1.0
am_π	0.2114(8)
am_ρ^{naive}	0.444(9)
am_{pcac}^0	0.01110(7)
af_π	0.0564(3)
# trajectories	1600
# analysed	140

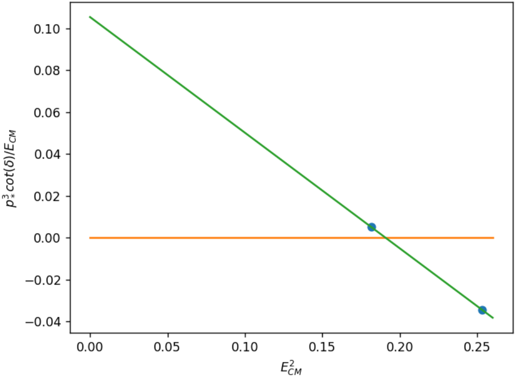
Effective mass plots PRELIMINARY

Eigenvalue $\lambda_i(t) = A \exp\left(-E_i(t - t_0)\right),\ t_0 = 4.$
Effective mass $E_i(t) = \ln \lambda_i(t)/\lambda_i(t+1)$



$E_1 = 0.50(2)\ E_2 = 0.57(2) \quad \Delta E_1 = -0.048(26)\ \Delta E_2 = 0.019(23)$

Extracting $g_{\rho\pi\pi}$ and M_ρ



Fitting central values only (for now) PRELIMINARY:

$$g_{\rho\pi\pi} = 5.84$$

$$aM_\rho = 0.437 \qquad \mathrm{m}_\rho^{\mathrm{naive}} = 0.444(9)$$

SU(4)

Ferretti's model

Gauge group	SU(4)
Fermions	3 Dirac in fundamental representation
	5 Weyl 2AS
Symmetry breaking	F condensate: SU(3) $\times$ SU(3)' $\rightarrow$ SU(3)
	2AS condensate SU(5) $\rightarrow$ SO(5)
	full: SU(5) $\times$ SU(3) $\times$ SU(3)' $\times U(1)_X \times U(1)'$
	$\rightarrow SO(5) \times SU(3)_c \times U(1)_X$

Described by G. Ferretti [1404.7137]

Features:

- Asymptotic freedom
- Anomaly free
- Goldstone bosons contain Higgs doublet
- Top (and bottom) partners (partial compositeness)
- No coloured triplet and sextet states
- Only SU(N) model with the above properties

Toy model

- 2.5 Dirac fermions requires rooting
- Can be achieved using RHMC algorithm (expensive)
- Instead we use SU(4) with 3 fundamental and **2** 2AS fermions
- Symmetry breaking containing electroweak group $SU(4) \to SO(4)$
- Not a composite Higgs model - pGBs all in (3,3) irrep of custodial group - toy model only
- First studied by Ayyar et. al. in "Spectroscopy of SU(4) composite Higgs theory with two distinct fermion representations", 1710.00806
- Phase space analysis has not yet been studied - underway
- Since pNGBs transform as (1,1) of $SO(4) \sim SU(2) \times SU(2)$

$$(1,1) \otimes (1,1) = \bigoplus_{j_1, j_2 = 0}^{2} (j_1, j_2)$$

with (1,1), (1,0), (0,1) and (0,0) containing resonances

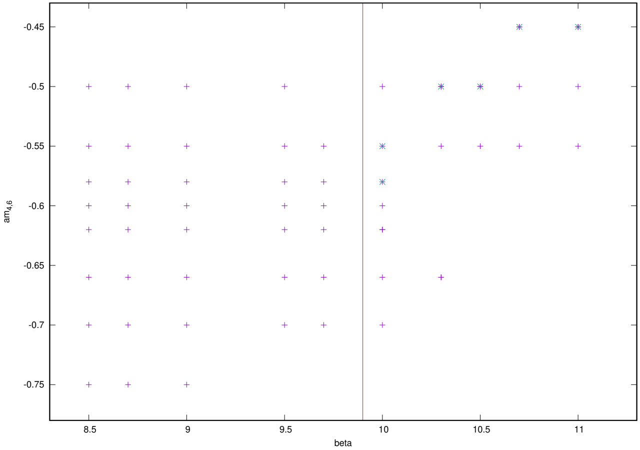
Grid

https://github.com/paboyle/Grid

Features:

- Modular - easy to extend
- Works with arbitrary number of colours
- Multiple representations of fermions implemented
- Low mode deflation
- (In the near future) distillation

SU(4) phase diagram



Pointss with * have $am_\pi^{(4)} < 0.5$, $am_\pi^{(6)} < 1$, $am_{pcac}^{(4)} < 0.1$ and $am_{pcac}^{(6)} < 0.5$

Conclusions

- Composite Higgs models, which address the naturalness problem can be studied using lattice gauge theory techniques
- $\pi\pi$ scattering $=$ W and Z scattering at high energies
- Techniques from lattice QCD can be applied directly, only flavour structure different
- Main difficulty - generating ensembles in the correct phase space region with $m_\rho > 2m_\pi$
- First result for the phase shift in the SU(2) model with 2 fundamental flavours
- Still exploring the phase space of the SU(4) model
- In both cases: more work needs to be done - stay tuned!