Conformal Standard Model

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Based on K. Meissner and HN, PLB648(2007)090001 and joint work with

P. Chankowski, A. Lewandowski and K. Meissner,
Mod. Phys. Lett. A30(2015)1550006, arXiv:1404.0548
A. Latosinski, A. Lewandowski and K. Meissner,

JHEP1510 (2015) 170, arXiv:1507.01755

Related/previous work (not complete...)

- Survival of SM up to M_{PL} [Froggat, Nielsen(1996)]
- Conformal symmetry and electroweak hierarchy [Bardeen (1995);Meissner,HN(2007)]
- Coleman-Weinberg symmetry breaking [Elias et al.(2003); Hempfling(1996);Foot et al.(2010);...]
- Conformal symmetry and phenomenology [Holthausen, Kubo, Lindner, Smirnov(2013;...)]
- Conformal models with (B L) gauging [Iso,Okada,Orikasa(2009); + Takahashi(2015)]
- Asymptotic safety and conformal fixed point at M_{PL} [Wetterich,Shaposhnikov(2010)]
- $\nu MSM \mod l$ [Asaka, Blanchet, Shaposhnikov(2005);...]

The electroweak hierarchy problem

A main focus of BSM model building over many years:

 $m_R^2 = m_B^2 + \delta m_B^2$, $\delta m_B^2 \propto \Lambda^2$ and $m_R^2 \ll \Lambda^2$

But is this really a problem?

- Not in renormalized perturbation theory because Λ → ∞ and because renormalisation "does not care" whether an infinity is quadratic or logarithmic! (as exemplified by dimensional regularisation which does not even "see" quadratic divergences for d = 4 + ε).
- Yes, if SM is embedded into Planck scale theory and Λ is a *physical* scale (cutoff) ⇒ quadratic dependencies on cutoff imply extreme sensitivity of low energy physics to Planck scale physics.

Two popular proposed solutions

- Low energy supersymmetry: exact cancellation of quadratic divergences by (softly broken) supersymmetry \Rightarrow choice of cutoff Λ does not matter, can formally send $\Lambda \rightarrow \infty$ and adopt any convenient renormalisation scheme.
- Technicolor (motivated by QCD): no fundamental scalars \Rightarrow no quadratic divergences \Rightarrow H boson would have to be composite (could still be true...)
- ... as well as a number of other ideas

NB: these proposals would only solve the *technical part* of the hierarchy problem (= stabilising small numbers against large perturbative corrections), but would *not* explain the observed hierarchy of scales!

Low energy supersymmetry?

		ATLAS SUSY	Searches* - 95% CL Lower Limits (Status	s: Dec 2012)
******	MSUGRA/CMSSM : 0 lep + j's + E _{T,miss} MSUGRA/CMSSM : 1 lep + i's + E _T	L-5816", 8 TeV (ATLAS-CONF-2012-199)	tsonev q=gmass	
1929	Phano model : 0 ien + i's + F-	1-6810" 8 TAV (ATI AS, COME 50-12, 1001	118 TeV 0 mass (min < 2 TeV liete	ATLAS
89	Pheno model : 0 lep + i's + E-	L=58/b" 8 WV (ATLAS-CONF-2012-109)	1 38 TeV Q MASS Im(Q < 2 TeV lot)	Preliminary
8	Gluino med $\overline{\gamma}^* (\overline{0} \rightarrow 0 \overline{0} \overline{\gamma}^*) : 1 \text{ lep } + i \text{'s } + \overline{F}$	1-1710" 7 TeV11208 48881	500 GeV 000855 (m/2) < 200 GeV m/2) -	(more samion)
-01	GMSB (INI SP) 2 Ion (OS) + i'e + E	L=4.710 ¹ , 7 TeV (1208, 4680)	134 TeV 0 mass (tabl < 15)	1-01 1-1-120
91	GMSB (T NLSP) : 1-2 t + 0-1 lep + i's + E	LATIN T BUTCHA HEAD	Lan Tay 0 mass (hool > 20)	
NS	GGM (bino NLSP) :vv + E ^{T,mass}	7-4310 7.0001000.0750	I MEAN G MASS (ME) STO GAV	fine int to me
8	GGM (wino NLSP) :y + lep + E ^{T,miss}	1-5810" 2 Tov (ATL 85, 000E-3012, 141)	ere devi di mass	Lot = (2.1 - 13.0) 10
5	GGM (hippsino-bino NLSP) : $y + b + E^{T,miss}$	T-ARTS T THE ISSUE OF A	900 GeV 000 900 (m/m) > 220 GeV/	S-7 8 ToV
	GGM (higgsing NISP) +7 + jots + F-	LEAST A THURSDAY AND ANY ANY ANY	G mass (m() > 200 Gell	1S=7,016V
	Gravitino LSP : 'monoiet' + F	LISSING STRUCTURE OF CONFIDENCES	escov ginass (incrisizo dev)	
1004301	S her hitself - Oler - 2 hits - 5	LINE STOLEN AND AND AND AND AND		
88	g-bby (virtual b) to tep +3 b-15 + CT,mks	LTIZED B TRY (ALAS-CONF-2112-145)		
E	g-+itx (vinuari) 2 lep (55) +) 5 + ET,mks	LEGRID A HEY (ALLAD COMP-2010-100)	and dev. g mans (mg) < 300 dev)	8 TeV results
86	g → fty (vinual t): 3 lep + is + E _{T,miss}	Lett.0 Ib , 6 TeV (ATLAS-CONF-2012-151)	aso devi gimass (m(c) coo dev)	
응급	g-+tty (virtual): 0 iep + multi-js + c T,miss	Lessie . a nev (Allas-cone-cone-cono) (a)	Tob tev g mass (mg (200 dev)	7 TeV results
	g→tty_jvirtualt): 0 tep + 3 b-1s + ET_miss	L=12.8 R , 8 TW (ATLAS-CONF-2012-145)	1.35 16V. g mass (mg) < 200 GeV)	
. U) C	$DD, D \rightarrow D\chi$: U lep + 2-0-jets + $E_{T,miss}$	Letz a ter (ATLAS-CONF-2012-185)	520 GeV D ITIASS (m(x) < 120 GeV)	
품물	$DD, D \rightarrow ty : 3 lep + j's + E_{T,mixis}$	L=13.0 % . 8 TeV [ATLAS-CONF-2012-151]	405 GeV D IBASS $(m(\chi_i) = 2m(\chi_i))$	
the dia	It (right), $1 \rightarrow 0\chi$: 1/2 rep (+ b-jet) + $E_{T,miss}$	1=47.15 7 Tev [1208.4005 12002102]87 Ge	I mass (m(y_) = 55 GeV)	
10 B	It (medium), $t \rightarrow b\chi$, ± 1 isp + b-jet + $E_{T,miss}$	L=13.0 fb , 8 TeV [ATLAS-CONF-2012-166]	150-350 GeV I mass $(m(\chi_1) = 0 \text{ GeV}, m(\chi_1) = 150 \text{ GeV})$	
8 4	II (medium), $1 \rightarrow D\chi_1$: 2 lep + E _{T.miss}	L=13.0 % , 8 TeV [ATLAS-CONF-2012-167]	160-440 GeV I mass $(m(y_{ij}) = 0 \text{ GeV}, m(y_{ij}) \cdot m(y_{ij}) = 10 \text{ GeV})$	
d B	$\lim_{n \to \infty} \frac{11}{n!} 1 \rightarrow 1\chi_1 : 1 \text{ kep } + D - 181 + E_{T, miss}$	L=13.0 fb , 8 TeV [ATLAS-CONF-2012-186]	230-560 GeV 1 mass (m(x,) = 0)	
历日	$tl, t \rightarrow t\chi$: 0/1/2 lep (+ b-jets) + E _{T,miss}	L=4.716 ', 7 TeV [1208.1447,1208.2590,1209.4	185) 230-465 GeV I MBSS $(m(\chi) = 0)$	
	II (natural GMSB) $(Z \rightarrow II) + D - JeI + E$	1-217b 7 WV [1204.6736]	319 GeV 1 mass (115 < m(x) < 230 GeV)	
14	LL, I-+IX, : 2 lep + ET, miss	L=4.715", 7 TeV (1208.2884) 854195	Gev Imass $(m(x_i) = 0)$	
N DB	$\chi_{\chi}, \chi \rightarrow hv(hv) \rightarrow hv\chi_{\chi}: 2 \text{ lep } + E_{T,miss}$	L=4.716 ⁻ , 7 %V [1208.2884]	116-340 GeV χ mass $(m(\chi) < 10 \text{ GeV}, m(\chi) = \frac{1}{2}(m(\chi) + m(\chi)))$	
비님	$\chi_1 \chi_2 \rightarrow I_V (I(VV), IM) (IVV) : 3 iep + E_{T,miss}$	L=13.0 10 . 8 TeV [ATEAS-CONF-2012-154]	580 GeV χ mass $(m(\chi) = m(\chi), m(\chi) = 0, m(\chi)$ as	above)
100.000	$\chi_{1}\chi_{2} \rightarrow W^{*}\chi_{1}Z^{*}\chi_{2}: 3 \text{ lep } + E_{T,\text{mag}}$	L=13.0 fb , 8 TeV [ATLAS-CONF-2012-154]	140-295 GeV χ_1 mass $(m(\chi_1) = m(\chi_2), m(\chi_1) = 0$, sleptons decoupled)	
2	Direct χ_1 pair prod. (AMSB) : long-lived χ_1	L=4.7 fb ⁻¹ , 7 TeV (1210.2052) 2	20 GeV χ_1 mass $(1 < \tau(\chi_1) < 10 \text{ ns})$	
ille Bille	Stable g̃ R-hadrons : low β, βγ (full detector)	1-471077369[1211.1007]	ses gev. g mass	
슬문	StableTR-hadrons : low β, βγ (full detector)	3-4776° 7 %v(1211.1997)	660 GeV I Mass	
E E	GMSB : stable T	Let710 ¹ ,7 feV [1211.1807]	300 GeV T MBSS (5 < tanß < 20)	
	$\overline{\chi} \rightarrow qqu (RPV)$: μ + heavy displaced vertex	L=4.415", 7 TeV [1210.7451]	700 GeV q mass (0.3×10° <) 211 < 1.5×10°, 1 mm	< c1 < 1 m,g decoupled)
	LFV : pp→v,+X, v,→e+µ resonance	L=1610 7 TeV (Preiminary)	1.51 TeV V, mass (X ₂₁₁ =0.10, X ₂₀	=0.05)
	LFV : $pp \rightarrow \overline{v}_{\tau} + X, \overline{v}_{\tau} \rightarrow e(\mu) + \tau$ resonance	Let610', 7 TeV (Preiminery)	1.10 TeV V, MASS (λ ₀₁₀ =0.10, λ ₁₀₂₀₃ =0.05	i) .
2	Bilinear RPV CMSSM : 1 lep + 7 j's + E _{T.miss}	L+4.716 7 TeV (ATLAS-CONF-2012-140)	1.2 TeV $\vec{q} = \vec{g} \text{ mass } (cr_{LP} < 1 \text{ mm})$	
00	$\overline{\chi}, \overline{\chi}, \overline{\chi}^* \rightarrow W \overline{\chi}^*, \overline{\chi}^* \rightarrow eev_u e \mu v_u : 4 lep + E_{T miss}$	L=13.015 1, 8 TeV [ATLAS-CONF-2012-153]	700 GeV χ_1 MBSS $(m(\chi_1)) > 300 \text{ GeV} \lambda_{12} \text{ or } \lambda_{122}$	> 0)
	(1,1→ 1χ, χ, →θev, θμv : 4 lep + E _{T miss}	L=13.0 10 . 8 TeV (ATLAS-CONF-2012-153)	430 GeV mass (m(x) > 100 GeV, m(k) = m(k), X ₁₂₁ or	$\lambda_{122} > 0$
	g → qqq : 3-jet resonance pair	L=4.8.16 ¹ , 7 TeV (1210.4813)	ess GeV g mass	
	Scalar gluon : 2-jet resonance pair	L=4.6 fb ² , 7 TeV (1210.4826)	00-287 Gev sgluon mass (nct limit from 1110, 2693)	
WIM	Pinteraction (D5, Dirac X) : 'monojet' + E	L-18.5 1 B TWY (ATLAS-CONF-3012(47)	704 Gev M* scale (m, < 80 GeV, limit of < 68 7 Ge	V for (P8)
		10-1	4	10
		10		10
* Onl	y a selection of the available mass limits on new st	ates or phenomena shown		Mass scale [TeV
All lie	mite available are observed minus. For theoretical aim	a al cos os concelios um canta intu		5

Low energy exotics?

		10	80.11	IU Maaa aaala ITa
		10-1	1	10
	Color octet scalar : dijet resonance, m	L=4.8 m 1.7 TeV [12(0.17/#]	tas twy Scalar resonance n	
	H ^m (DY prod., BR(H ^m →eµ)=1) : SS eµ, m	4.04770 7 TeV (1290.0070) 375	Sev H ^{tt} mass	
)	H_ (DY prod., BR(H [*] →II)=1) : SS ee (µµ), m	La47 % 7 TeV (12183678) 40	GeV H ^{**} _L mass (limit at 398 GeV for µµ)	96 (1997) (1193) (1193) (1197)
2	W _R (LRSM, no mixing) : 2-lep + jets	L=2.115 7 TeV (1203.5420)	24 TeV W mass (m(N)	< 1.4 TeV)
2	Major, neutr. (LRSM, no mixing) : 2-len + iets	(2.1 th 1.7 TeV (1203.5420)	Is TeV N mass (m(W) = 2 Te	V)
Te	chni-hadrons (LSTC) : WZ resonance (vill), m	Lut 0 % 7 TeV (1204 1548)	$p_{1}(m_{1}, m_{2}, m_{3}) = m(\pi_{1}) + m_{1} m(\pi_{1}) = 1$	1 m(o))
	Techni-hadrons (LSTC) : dilecton.m	L s43-50 ID ¹ 7 TeV (1200 2935)	BOGAV o ke mass (mo /o.) - m/m) =	M)
101	Excited lepton : l-v resonance, m	LATION IN THE AS CONS 2013 MIL	1 mass (A = m()*	W.
E.	Evolution quarke : diat reconance m	1-216 77eV (1112.3880)	246 TeV q' mass	
	Vector-like quark : NG, mig	Lo4.4 fb 7 TeV (ATLAS-CONF-2012-107)	1.05 TeV VLQ mass (charge 2/3, cou	$p_{ini} g_{N_{inj}} = v_{inj} g_{N_{inj}}$
	Vector-like quark : CC, my	L =4.6 B . 7 TeV [ATLAS-CONF-2012-137]	1.12 TeV VLQ mass (charge -1/3, co	upling $\kappa_{aa} = v/m_a$
	Top partner : $TT \rightarrow tt + A_0A_0$ (dilepton, M_{T_2})	1.74.7 fb ⁻¹ , 7 TeV (1209.4186)	183 GeV: T mass (m(A _g) < 100 GeV)	and the state of the state of the
5	New quark b' : b'b'→ Zb+X, m	L=2.9 fb . 7 TeV (1204.1265) 400	GeV b'mass	
	4 th generation : bb'(T = T _{5/3}) → WtWt	L=47 81 7 TeV (ATLAS-CONF-2012-100)	570 Gev. b' (T) mass	
Ş4888	4 th generation : 11'-→ WhWh	L s4.7 fo 1, 7 TeV [12105468]	sse cev t'mass	
	Scalar LO nair (8=1) : kin vars, in mi, tvij	Lot 7 to 7 ToV (Profining/v)	sas Gev 3 rd gen 10 mass	
	Scalar LO pair (B=1) : kin vars in will will	(= 1.0 m ⁻¹ , 7 TeV (1.001.31.22)	ms quy 2" pen 10 mass	
	Scolar I O pair (R-1) - kin vort	L SALE 10 . 7 TEV [1209:4440]	ZAZ IEV WY MASS	
	W _B (→ ID, SSW) : m _b	L = 1.0 fb . 7 TeV (1205.1016)	1.13 TeV: W'mass	
	W $(\rightarrow 1q, q = 1): m_q$	L=4.7 fb ⁻¹ , 7 TeV [1209.6593] 43	Gev W mass	
	W'(SSM): $m_{T,a/a}$	Lo47%", 7TeV (1209.4446)	2.55 TeV W'mass	
	Z'(SSM):m,,	Lo47 8 7 TeV [1210.6604]	1.4 TeV Z' mass	
	Z'(SSM) :m _{oddau}	1-59-6116 8 TeV (ATLAS-CONF-2012-129)	2.49 TeV Z mass	
	uutt CI : SS dilepton + jets + E T miss	L=10%",7TeV(13025520)	1.7 TeV A	
i.	qqll CI:ee & µµ, m	L+43-50/6 ¹ , 7 TeV (1211.1190)		13.9 TeV A (constructive int.)
	good contact interaction : $\chi(m'')$	Lolato 7 Tev (ATLAS-CONF-2012-0301	7.8 TeV	Δ
	Quantum black hole ; dilet, F (m)	Lo47 6 7 TeV (1210.3778)	LITTEN M. (A=	3
3	ADD BH $(M_{-}/M_{-}=3)$: lentons + lets Σp	Terrue 1 A lev [11110061]	122 10V M (0=0)	CE: 005030
	ADD DH (M (M -3) - CC dim - Hells, M	LINUT IS . / TEV (ATLASCONF-2012-108)	1.9 TeV g _{KK} mass	s = 7.8 Te
	RS1: WW resonance, m _{T,hh}	L=47.00 ¹¹ , 7 TeV (1208.2580)	1.23 TeV Graviton mass (k/M _H = 0.	(1) $Lat = (1.0 - 13.0)$ fb
	RS1 : ZZ resonance, m	Lot 0 fb 7 TeV (1203.0718)	s45 GeV Graviton mass (k/M _n = 0.1)	C. N. M. A. MAN P.
	RS1 : diphoton & dilepton, m, //	1 =4.7-6.0 /b ¹ , 7.TeV [1210.8389]	2.23 TeV Graviton mass (A	$C/M_{pt} = 0.1$
	S ⁵ /Z, ED : dilepton, m,	L+43-60161, 7 TaV [12062616]	4.71 TeV M _{KK} ~	B ⁻¹
	UED : diphoton + E Traise	Lotan ", 7 TeV (ATLAS-CONF-2012-072)	LAT TeV Compact, scale R1	Preliminar
6	Large ED (ADD) : diphoton & dilecton, m	L=47 fb ⁻¹ , 7 TeV (1211,1150)	4 to TeV Mr. (HL)	Z (A S ATLAS
	Large ED (ADD) : monophoton + E-	Land St. Tay Provide Action	LETTEN M. (A=2)	-1
	1 ama ED (ADD) · managet + E	THE REPORT OF MALE PARTY OF THE	- M. 18-	2)

Absence of any evidence (so far) from LHC for either of these options \Rightarrow explore alternative options \Rightarrow

Can the SM survive all the way to Planck scale $M_{\rm PL}$?

In this talk: explore (softly broken) conformal symmetry for a *minimal extension of usual SM* as an alternative option.

NB: this proposal does without *low* energy supersymmetry, but supersymmetry is probably still essential for a finite and consistent theory of quantum gravity.

Realisation of such a scenario would move the SUSY breaking scale back up to the Planck scale, but make no explicit assumptions about Planck scale theory other than its UV finiteness (\equiv UV completeness).

Reminder: the conformal group SO(2,4)

This is an old subject! [see e.g. H.Kastrup, arXiv:0808.2730]

Conformal group = extension of Poincaré group (with generators $M_{\mu\nu}, P_{\mu}$) by five more generators D and K_{μ} :

- Dilatations (D) : $x^{\mu} \to e^{\alpha} x^{\mu}$
- Special conformal transformations (K^{μ}) :

$$x'^{\mu} = \frac{x^{\mu} - x^2 \cdot c^{\mu}}{1 - 2c \cdot x + c^2 x^2}$$

 $e^{i\alpha D}P^{\mu}P_{\mu}e^{-i\alpha D} = e^{2\alpha}P^{\mu}P_{\mu} \Rightarrow exact \text{ conformal invariance}$ implies that one-particle spectrum is either continuous $(=\mathbb{R}_{+})$ or consists only of the single point $\{0\}$.

Consequently, conformal group cannot be realized as an exact symmetry in nature.

Conformal Invariance and the Standard Model

Fact: Standard Model of elementary particle physics is conformally invariant at tree level except for explicit mass term $m^2 \Phi^{\dagger} \Phi$ in potential \Rightarrow

Masses for vector bosons, quarks and leptons \rightarrow

Can 'softly broken conformal symmetry' (\equiv 'SBCS') stabilize the electroweak scale w.r.t. the Planck scale?

Concrete implementation of this idea requires

• Consistency conditions:

– absence of Landau poles up to M_{Pl}

- absence of instabilities of effective potential up to M_{Pl}
- Absence of any intermediate mass scales between $M_{\rm EW}$ and $M_{\rm PL}$ ('grand desert scenario').

Evidence for large scales other than M_{Pl} ?

- (SUSY?) Grand Unification: $m_X \ge \mathcal{O}(10^{16} \,\mathrm{GeV})$?
 - But: proton refuses to decay (so far, at least!)
 - SUSY GUTs: unification of gauge couplings at $\geq O(10^{16} \,\mathrm{GeV})$
- Light neutrinos $(m_{\nu} \leq \mathcal{O}(1 \text{ eV}))$ and heavy neutrinos \rightarrow most popular (and most plausible) explanation of observed mass patterns via seesaw mechanism:

[Gell-Mann,Ramond,Slansky; Minkowski; Yanagida]

$$m_{\nu}^{(1)} \sim \frac{m_D^2}{M}, \ m_D = \mathcal{O}(m_W) \Rightarrow m_{\nu}^{(2)} \sim M \ge \mathcal{O}(10^{12} \,\text{GeV})?$$

• Strong CP problem \Rightarrow need *axion* a(x)? Limits e.g. from axion cooling in stars \Rightarrow

$$\mathcal{L} = \frac{1}{4f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad \text{with } f_a \ge \mathcal{O}(10^{10} \,\text{GeV})$$

NB: axion is (still) an attractive CDM candidate.

Conformal Invariance and Quantum Theory

Important Fact: classical conformal invariance is *generically* broken by quantum effects (unlike SUSY!) \Rightarrow

• Impose anomalous Ward identity

$$\Theta^{\mu}{}_{\mu} = \sum_{n} \beta^{(n)}(g) \mathcal{O}^{(n)}(x)$$

[W. Bardeen, FERMILAB-CONF-95-391-T, FERMILAB-CONF-95-377-T] and try radiative symmetry breaking à la Coleman-Weinberg. But: quadratic divergences?

• Admit soft breaking (=explicit mass terms) as is commonly done for MSSM like models, but insist on cancellation of quadratic divergenes

NB: it is known that option (1) does not work for usual SM with one physical Higgs, but with one extra complex scalar (as in our model) there is more freedom.

Coleman-Weinberg Mechanism (1973)

• Idea: spontaneous symmetry breaking by radiative corrections \implies can small mass scales be explained via *conformal anomaly* and *effective potential*?

$$V(\varphi)_{\text{eff}} = \frac{\lambda}{4}\varphi^4 \rightarrow V_{\text{eff}}(\varphi) = \frac{\lambda}{4}\varphi^4 + \frac{9\lambda^2\varphi^4}{64\pi^2} \left[\ln\left(\frac{\varphi^2}{\mu^2}\right) + C_0\right]$$

• But: radiative breaking spurious for pure φ^4 theory as is easily seen in terms of RG improved potential

$$V_{\text{eff}}^{RG} = \frac{1}{4}\lambda(L)\varphi^4 = \frac{\lambda}{4} \cdot \frac{\varphi^4}{1 - (9\lambda/16\pi^2)L} \qquad L \equiv \ln\left(\frac{\varphi^2}{\mu^2}\right)$$

• With more scalar fields finding minima and ascertaining their stability is much more difficult, as there is no similarly explicit formula for $V_{\rm eff}^{RG}(\varphi_1, \varphi_2, ...)$.

Softly broken conformal symmetry (SBCS)

Assume existence of a UV complete and finite fundamental theory, such that Λ is a physical cutoff to be kept finite, and impose vanishing of quadratic divergences at particular distinguished scale Λ (= $M_{\rm PL}$?) :

- Bare mass parameters should obey $m_B(\Lambda) \ll M_{\rm PL}$;
- there should be neither Landau poles nor instabilities for $M_{\rm EW} < \mu < \Lambda$ (manifesting themselves as the unboundedness from below of the effective potential depending on the running scalar self-couplings);
- all couplings $\lambda_R(\mu)$ should remain small (for the perturbative approach to be applicable and stability of the effective potential electroweak minimum).

Furthermore use known SM values of couplings and masses as input parameters at $\mu = M_{\rm EW}$.

Bare vs. renormalized couplings

With cutoff Λ and normalization scale μ we have

$$\lambda_B(\mu, \lambda_R, \Lambda) = \lambda_R + \sum_{L=1}^{\infty} \sum_{\ell=1}^{L} a_{L\ell} \,\lambda_R^{L+1} \left(\ln \frac{\Lambda^2}{\mu^2} \right)^{\ell},$$

so that $\lambda_B = \lambda_R$ for $\mu = \Lambda$, and

$$m_B^2(\mu,\lambda_R,m_R,\Lambda) = m_R^2 - \hat{f}^{\text{quad}}(\mu,\lambda_R,\Lambda)\Lambda^2 + m_R^2 \sum_{L=1}^{\infty} \sum_{\ell=1}^{L} c_{L\ell} \lambda_R^L \left(\ln\frac{\Lambda^2}{\mu^2}\right)^\ell$$

Crucial fact: coefficient of Λ^2 can be written as a function of the bare coupling(s) only, *i.e.* $\hat{f}^{\text{quad}}(\mu, \lambda_R, \Lambda) \equiv f^{\text{quad}}(\lambda_B(\mu, \lambda_R, \Lambda))$.

Thus, keeping the physical cutoff Λ finite we can set

$$f^{\text{quad}}(\lambda_B) = 0$$

NB: this condition would not make sense if $\Lambda \to \infty$ where bare couplings are expected to become singular!

Quadratic divergences in Standard Model

[M. Veltman(1982);Y.Hamada,H.Kawai,K.Oda, PRD87(2013)5; D.R.T.Jones,PRD88(2013)098301]



Figure 3: Left: The bare Higgs mass m_B^2 in units of $\Lambda^2/16\pi^2$ vs the UV cutoff scale Λ . The blue (narrower) and pink (wider) bands represent the one and two sigma deviations of m_t^{pole} , respectively. Right: The UV cutoff scale at which the bare mass m_B^2 becomes zero as a function of m_t^{pole} . The solid (dashed) line corresponds to the scale where m_B^2 ($m_{B,1\text{-loop}}^2$) becomes zero. In both panels, we have taken the central values $\alpha_s(m_Z) = 0.1184$ and $m_H = 125.7 \text{ GeV}$.

Only one scalar: $f^{\text{quad}}(\lambda_R(\mu)) = 0$ for $\mu \approx 10^{24} \text{GeV} \gg M_{\text{PL}}$!

Is the Standard Model doomed?

[Y.Hamada,H.Kawai,K.Oda, PRD87(2013)5]



Figure 2: Left: $\overline{\text{MS}}$ running of the quartic coupling λ . The band corresponds to the 1σ deviation $m_t^{\text{pole}} = 173.3 \pm 2.8 \text{ GeV}$. Right: The scale μ_{\min} at which $\lambda(\mu)$ takes its minimum value, as a function of m_t^{pole} . In both panels, low energy inputs are given by the central values $\alpha_s(m_Z) = 0.1184$ and $m_H = 125.7 \text{ GeV}$.

 $\lambda_R(\mu)$ becomes negative for $\mu > 10^{10} \,\text{GeV} \Rightarrow$ instability? \rightarrow might also be relevant to cosmology!

Minimal extension of SM = CSM

[K. Meissner, HN, PLB648(2007)312; Eur.Phys.J. C57(2008)493]

- Start from conformally invariant (and therefore renormalizable) fermionic Lagrangian $\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}'$ $\mathcal{L}' := (\bar{L}^i \Phi Y^E_{ij} E^j + \bar{Q}^i \epsilon \Phi^* Y^D_{ij} D^j + \bar{Q}^i \epsilon \Phi^* Y^U_{ij} U^j + \bar{L}^i \epsilon \Phi^* Y^\nu_{ij} \nu^j_R + \phi \nu^{iT}_R \mathcal{C} Y^M_{ij} \nu^j_R + h.c.) - V(\Phi, \phi)$
- Besides usual SU(2) doublet Φ : new scalar field $\phi(x)$ $\phi(x) = \varphi(x) \exp\left(\frac{ia(x)}{\sqrt{2}\mu}\right)$
- No fermion mass terms, all couplings dimensionless
- Y_{ij}^U , Y_{ij}^E , Y_{ij}^M real and diagonal: $Y_{ij}^M = y_{N_i} \delta_{ij}$ Y_{ij}^D , Y_{ij}^{ν} complex \rightarrow parametrize family mixing (CKM)
- Neutrino masses from usual seesaw mechanism (but with $\langle \phi \rangle < \mathcal{O}(1 \text{ TeV})$ and $Y^{\nu} \sim 10^{-6} \Rightarrow$ no new large scales needed!)

Scalar Sector of CSM

Right-chiral neutrinos and one complex scalar \Rightarrow

 $V(\Phi, \phi) = m_H \Phi^{\dagger} \Phi + m_{\phi}^2 |\phi|^2 + \lambda_1 (\Phi^{\dagger} \Phi)^2 + 2\lambda_3 (\Phi^{\dagger} \Phi) |\phi|^2 + \lambda_2 |\phi|^4$ where $\Phi = (\Phi_1, \Phi_2)$ is the $SU(2)_{\rm EW}$ doublet and ϕ is the complex extra gauge singlet. At the minimum

$$\sqrt{2}\langle \Phi_i \rangle = v_H \delta_{i2} \ , \quad \sqrt{2}\langle \phi \rangle = v_\phi$$

with mass eigenstates h^0 and φ^0

$$\begin{pmatrix} h^0 \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \sqrt{2}\operatorname{Re}(\Phi_2 - \langle \Phi_2 \rangle) \\ \sqrt{2}\operatorname{Re}(\phi - \langle \phi \rangle) \end{pmatrix}, \quad (1)$$

with masses $M_h < M_{\varphi}$ and $|\tan \beta| < 0.3$ (from existing experimental bounds if $h^0 = SM$ Higgs-Boson).

Scalar sector can be further enlarged \Rightarrow more 'sterile scalars', possibly to also explain axion as a pseudo-Goldstone boson. [cf. arXiv:1507.01755]

Quadratic divergences in CSM

Two physical scalars \Rightarrow two conditions (at one loop)

$$16\pi^{2} f_{1}^{\text{quad}}(\lambda, g, y) = 6\lambda_{1} + 2\lambda_{3} + \frac{9}{4}g_{w}^{2} + \frac{3}{4}g_{y}^{2} - 6y_{t}^{2}$$
$$16\pi^{2} f_{2}^{\text{quad}}(\lambda, g, y) = 4\lambda_{2} + 4\lambda_{3} - \sum_{i=1}^{3}y_{N_{i}}^{2}$$

- Start from known values of electroweak couplings g_y, g_w, y_t at $\mu = M_{\text{EW}}$ and evolve them to $\mu = M_{\text{PL}}$.
- Choose λ_1, y_N and determine λ_2 and λ_3 from $f_k^{\text{quad}} = 0$
- Evolve all couplings back to $\mu = M_{\rm EW}$ and check whether all consistency requirements are satisfied.

 \Rightarrow leads to a range of possible values for new heavy scalar φ^0 and heavy neutrinos (with $m_N < 1 \text{ TeV}$).

$\beta\text{-functions}$ at one loop

$$\begin{split} \tilde{\beta}_{\lambda_{1}}^{(1)} &= 24\lambda_{1}^{2} + 4\lambda_{3}^{2} - 3\lambda_{1} \left(3g_{w}^{2} + g_{y}^{2} - 4y_{t}^{2} \right) + \\ &+ \frac{9}{8}g_{w}^{4} + \frac{3}{4}g_{w}^{2}g_{y}^{2} + \frac{3}{8}g_{y}^{4} - 6y_{t}^{4} \\ \tilde{\beta}_{\lambda_{2}}^{(1)} &= 20\lambda_{2}^{2} + 8\lambda_{3}^{2} + 2\lambda_{2}\sum_{i=1}^{3}y_{N_{i}}^{2} - \sum_{i=1}^{3}y_{N_{i}}^{4} \\ \tilde{\beta}_{\lambda_{3}}^{(1)} &= \frac{1}{2}\lambda_{3} \left\{ 24\lambda_{1} + 16\lambda_{2} + 16\lambda_{3} - \left(9g_{w}^{2} + 3g_{y}^{2}\right) + 2\sum_{i=1}^{3}y_{N_{i}}^{2} + 12y_{t}^{2} \right\} \\ \tilde{\beta}_{g_{w}}^{(1)} &= -\frac{19}{6}g_{w}^{3}, \quad \tilde{\beta}_{g_{y}}^{(1)} = \frac{41}{6}g_{y}^{3}, \quad \tilde{\beta}_{g_{s}}^{(1)} = -7g_{s}^{3}, \\ \tilde{\beta}_{y_{t}}^{(1)} &= y_{t} \left\{ \frac{9}{2}y_{t}^{2} - 8g_{s}^{2} - \frac{9}{4}g_{w}^{2} - \frac{17}{12}g_{y}^{2} \right\}, \\ \tilde{\beta}_{y_{N_{j}}}^{(1)} &= \frac{1}{2}y_{N_{j}} \left\{ 2y_{N_{j}}^{2} + \sum_{i=1}^{3}y_{N_{i}}^{2} \right\} \end{split}$$

where $\tilde{\beta} \equiv 16\pi^2\beta$.



Admissible parameter ranges

- Couplings remain small (also at two loops)
- M_{φ} grows with decreasing mixing angle β
- Usual seesaw mechanism applies, with small light neutrino masses (for $Y_{\nu} \sim 10^{-6}$) and $m_N < 1 \,\text{TeV}$?
- Stability of electroweak vacuum can be arranged
- Caveats: scheme dependencies, threshold effects?

What might be observed

• h^0 decay width is decreased: $\Gamma_{h^0} = \cos^2 \beta \Gamma_{SM} < \Gamma_{SM}$

•
$$\varphi^0$$
 decay width: $\Gamma_{\varphi^0} = \sin^2 \beta \Gamma_{SM} + \cdots$

- First term: narrow resonance ('shadow Higgs boson')
- Other terms: decay of heavy scalar into two or three h^0 's, and two heavy neutrinos (if kinematically allowed).

$\bullet \rightarrow$ new scalar boson is main prediction!

- \dots but not compatible with diphoton excess at 750 TeV!
- Decay via two h^0 bosons might produce spectacular signatures with 5,...,8 leptons coming out of a single vertex. But: rates *vs.* background?
- Proposal can be easily discriminated against other extensions of SM that might produce similar signatures, but that would come with a lot of extra baggage (accompanying signatures).

Outlook

- Usual SM probably cannot survive to Planck scale
 ⇒ requires *some* extension, if only to accommodate right-chiral neutrinos.
- A conformally motivated extension of the SM can in principle satisfy all consistency requirements, if properly embedded into a UV complete theory.
- Model accommodates axions naturally: $f_a \propto m_W^2/m_{\nu}$.
- Low energy supersymmetry may after all *not* be required for stability of electroweak scale...
- ... but is probably needed for a UV complete theory of quantum gravity and quantum space-time.

Conclusion: Nature is probably still a bit smarter than us, and may have a few more tricks up her sleeve! Conformal invariance from gravity? Here not from scale (Weyl) invariant gravity, but: N = 4 supergravity $1[2] \oplus 4[\frac{3}{2}] \oplus 6[1] \oplus 4[\frac{1}{2}] \oplus 2[0]$ coupled to n vector multiplets $n \times \{1[1] \oplus 4[\frac{1}{2}] \oplus 6[0]\}$ Gauged N = 4 SUGRA: [Bergshoeff,Koh,Sezgin; de Roo,Wagemans (1985)]

- Scalars $\phi(x) = \exp(L_I^A T^I_A) \in SO(6, n) / SO(6) \times SO(n)$
- YM gauge group $G_{YM} \subset SO(6, n)$ with dim $G_{YM} = n + 6$

[Example inspired by 'Groningen derivation' of conformal M2 brane ('BGL', 'ABJM') theories from gauged D = 3 SUGRAs]

Although this theory is *not* conformally invariant, the conformally invariant N = 4 SUSY YM theory nevertheless emerges as a $\kappa \to 0$ limit, which 'flattens' spacetime (with $g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$) and coset space

 $SO(6,n)/((SO(6)\times SO(n)) \ \longrightarrow \ \mathbb{R}^{6n} \ni \phi^{[ij]\,a}(x)$

However: conformality of limit requires extra restrictions, in particular *compact* gauge group:

$$G_{\rm YM} \subset SO(n) \subset SO(6, n)$$

Exemplify this claim for scalar potential: with

$$C_{ai}{}^{j} = \kappa^{2} f_{abc} \phi_{[ik]}{}^{b} \phi^{[jk]c} + \mathcal{O}(\kappa^{3}) \quad , \quad C_{ij} = \kappa^{3} f_{abc} \phi_{[ik]}{}^{a} \phi^{b\,[kl]} \phi_{[lj]}{}^{c} + \mathcal{O}(\kappa^{4})$$

potential of gauged theory is $(m, n = 1, ..., 6; \kappa |z| < 1)$

$$V(\phi) = \frac{1}{\kappa^4} \frac{(1 - \kappa z)(1 - \kappa z^*)}{1 - \kappa^2 z z^*} \left(C_{ai}{}^j C^{ai}{}_j - \frac{4}{9} C^{ij} C_{ij} \right) = \text{Tr} \left[X_m, X_n \right]^2 + \mathcal{O}(\kappa)$$

Idem for all other terms in Lagrangian! Unfortunately

- N = 4 SYM is quantum mechanically conformal theory \rightarrow no conformal anomaly \rightarrow no symmetry breaking!
- Thus need non-supersymmetric vacuum with $\Lambda = 0$
- \Rightarrow must look for a better theory with above features!

Metamorphosis of CW mechanism?

But: if we embed SM in a *UV finite theory of quantum gravity* what is the origin of (conformal) anomalies?

Conjecture: If this (unknown) theory admits a classically conformal flat space limit, CW-like contributions could arise from *finite logarithmic* (in κ) quantum gravitational corrections \Rightarrow identify $v \sim M_{Pl}$!

- CW-like corrections would not be due to UV divergences, but rather to the fact that gravity is *not conformal* – this would be the only 'footprint' that quantum gravity leaves in low energy physics.
- Observed mass spectrum and couplings in the SM could have their origin in quantum gravity.