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Particle physics phenomenology with orthogonal symmetries

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Outline

- Brief introduction to symmetries in high energy physics
- The custodial symmetry of the Standard Model:
  any new physics at the electroweak scale?
- The Higgs as a composite Nambu-Goldstone boson:
  new composite particles at multi-TeV scale?
- Grand Unification Theories:
  – predictive leptogenesis at high scale
  – composite unification at low scale

10^{-1}

10^{+1}

10^{+13}

Energy (TeV)

sociology slide

Students I collaborated with

Supervised undergraduate internships:

- **Damien TANT** (M1 CCP Montpellier, 2012) → PhD @ IPHC, Strasbourg
- **Sylvain LACROIX** (M1 ENS Lyon, 2013) → PhD @ ENS, Lyon
- **Nicolas BIZOT** (M2 CCP Montpellier, 2013) → PhD @ L2C, Montpellier
- **Brice BASTIAN** (M1 CCP Montpellier, 2015) → PhD @ IPNL, Lyon
- **Jeremy LEZMY** (L3 physique Montpellier, 2017) → Master CCP Montpellier

PhD students which contributed to the subjects of the HDR thesis:

- **Michal MALINSKY** (SISSA, Trieste, 2004) → Charles U., Prague
- **Pierre HOSTEINS** (IPhT, Saclay, 2008) → IFSTTAR, Paris
- **Javi SERRA** (IFAE, Barcelona, 2011) → TUM, Munich
- **Alfredo URBANO** (IFAE, Barcelona, 2011) → INFN & SISSA, Trieste

Supervised PhD theses:

- **Nicolas BIZOT** (L2C, Montpellier, 2013-2016, co-supervised with Marc Knecht and Jean-Loïc Kneur): *Higgs couplings, new fermions, non-perturbative methods to study spectrum of composite states*
  → Postdoc @ IPNL, Lyon
- **Rupert COY** (L2C, Montpellier, 2016-2019): *composite axions, clockwork mechanism, effective field theory for lepton observables, B-meson anomalies*
  → Postdoc @ ULB, Brussels

Standard Model structure

established physics slide

Standard Model (SM): the (relativistic quantum field) theory of Nature, valid for energies up to ~ 1 TeV = 10^{12} eV , as of early 2019...

Space-time (Minkowski) symmetry group: *ISO(1,3)*

Local internal (gauge) symmetry group: $U(1)_Y \times SU(2)_w \times SU(3)_c$

Kinetic terms (particles propagation): Spin-1 Spin-1/2 Spin-0

Scalar potential

Fermion-scalar (Yukawa) interactions

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\psi_a^\dagger \overline{\sigma}_\mu^\mu \psi_a + D^\mu H^\dagger D_\mu H - V(H) - \frac{1}{2}\left(y_{ab}\psi_a\psi_b H + h.c.\right)$$

$SU(3)^5$:
five fermion species, each coming in three replicas (families)

Linear σ – model with **SO(4)** symmetry (4 real scalar fields) spontaneously broken to **SO(3)**

Radial mode *h* observed at Large Hadron Collider (LHC): the Bruxelles-Edinburgh boson !

Yukawa couplings preserve only baryon & lepton numbers
$U(1)_B \times U(1)_L{}^3$

Yukawa's also observed at LHC !

(Approximate) global internal symmetries

mathematics slide

SO(N) symmetries

Orthogonal Lie groups *SO(N)* generated by orthogonal Lie algebras *so(N)*: $R(\theta_{ij}) = \exp\left(i\theta_{ij}T_{ij}\right)$

All irreducible representations derive from the Fundamental and Spinor representations:

$$\dim F_{so(N)} = N \qquad \dim S_{so(2n+1)} = \dim S_{so(2n+2)} = 2^n$$

rank	$N = 2n$	$N = 2n+1$
$n = 1$	$so(2) \simeq u(1)$	$so(3) \simeq su(2) \simeq sp(2)$
$n = 2$	$so(4) \simeq su(2) \times su(2)$	$so(5) \simeq sp(4)$
$n = 3$	$so(6) \simeq su(4)$	$so(7)$
$n = 4$	$so(8)$	$so(9)$
$n = 5$	$so(10)$	$so(11)$
$\dots$	$\dots$	$\dots$

Electroweak custodial symmetry

Composite Higgs symmetry

Grand Unification symmetry

The only essentially non-orthogonal SM symmetry is

$su(3) \subset so(6)$

The custodial symmetry

The spin-zero sector of the Standard Model:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} h_1 + i h_2 \\ h_3 + i h_4 \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_H &= (\partial_\mu H)^\dagger (\partial^\mu H) - \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 \\ &= \frac{1}{2} \sum_{i=1}^4 (\partial_\mu h_i)(\partial^\mu h_i) - \frac{\lambda}{4} \left(\sum_{i=1}^4 h_i^2 - v^2 \right) \end{aligned}$$

SO(4) symmetry spontaneously broken to SO(3) at potential minimum.
One physical Higgs boson *h* is SO(3) singlet.
Three Nambu-Goldstone bosons $\pi_{1,2,3}$ form SO(3) triplet.

$$\frac{SO(4)}{SO(3)} \ \text{coset}$$

Gauge interactions: $\pi_{1,2,3}$ eaten by spin-one bosons $W_{1,2,3}$, moreover custodial symmetry is broken by *g'*

$$\partial^\mu H \ \rightarrow \ D^\mu H \equiv \left(\partial^\mu - i g W_a^\mu \tau_a - i g' B^\mu \frac{1}{2} \right) H$$

$$\frac{m_Z^2}{m_W^2} = 1 + \frac{g'^2}{g^2}$$

Yukawa interactions: custodial symmetry is broken by difference between top and bottom quarks

$$\mathcal{L}_{yuk} = -y_t \overline{q_L} i \sigma^2 H^* t_R - y_b \overline{q_L} H b_R + h.c.$$

$$\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} = \frac{3}{32\pi^2} (y_t - y_b)^2$$

Additional violation of custodial by new physics is experimentally constrained with per-mil precision.

Example: new vector-like fermions can have large mixing with top and bottom quarks,
only if they fill complete *SO(4) = SU(2)$_L$ x SU(2)$_R$* multiplets!

Bizot-Frigerio '15

Are new chiral fermions ruled out?

All SM fermions are chiral: they receive mass only from Higgs vacuum expectation value (vev). Did LHC prove that no other chiral fermions exist in Nature?

Requirements:
- all gauge anomalies must cancel
- all multiplet components must acquire a mass above collider bounds
- corrections to *h-g-g* and *h-γ-γ* couplings must be small
- corrections to electroweak precision parameters must be small

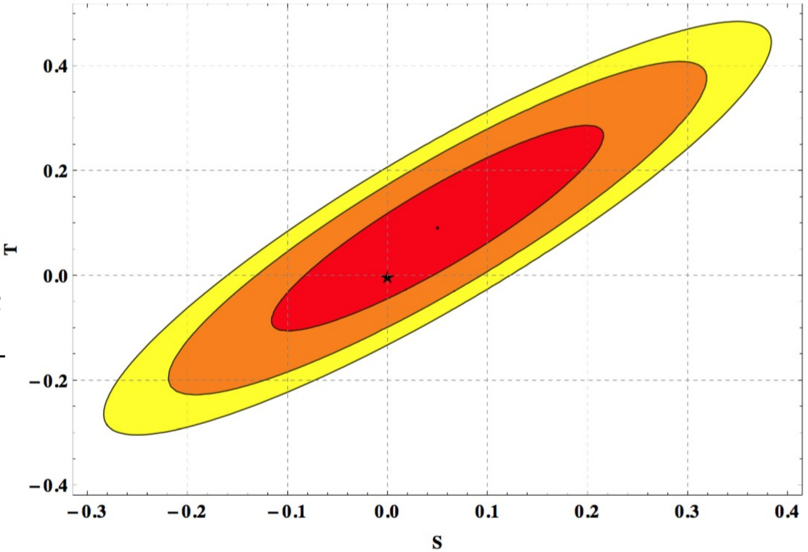
All possible sets of chiral multiplets excluded, except one:

Bizot-Frigerio '15

$$[\mathbf{SU(2)_w}]_{U(1)_Y} \quad : \quad D_L \sim \mathbf{2}_Y \ , \ S_{R\pm} \sim \mathbf{1}_{Y\pm 1/2} \ ; \quad D'_L \sim \mathbf{2}_{-Y} \ , \ S'_{R\pm} \sim \mathbf{1}_{-Y\pm 1/2}$$

Custodial symmetry breaking:

$$T \simeq \frac{(y_+ - y_-)^2}{32\pi^2\alpha}$$



Isospin symmetry breaking: $S \simeq \dfrac{1 - 4Y \log(y^+/y_-)}{6\pi}$

Higgs to 2 photons (8 TeV data):

$$\mu_{\gamma\gamma} \simeq \frac{|\mathcal{A}^{\gamma\gamma}_{SM} + \mathcal{A}^{\gamma\gamma}_{new}|^2}{|\mathcal{A}^{\gamma\gamma}_{SM}|^2} = 1.2 \pm 0.2$$

$$\mathcal{A}^{\gamma\gamma}_{new} = \frac{4(1+4Y^2)}{3} \quad \Rightarrow \quad |Y| \lesssim 0.15$$

But 13 TeV data (summer '18) give $\mu_{\gamma\gamma}$ = 1.0 ± 0.1

Game Over !

Higgs as Nambu-Goldstone boson

Naturalness problem: a scalar mass m_h is sensitive to any heavy physical scale Λ coupled to h, because of quantum corrections:

$$\delta m_h^2 \sim \Lambda^2$$

To agree with data & minimise the tuning of the theory parameters, we need
(I) a mechanism to push Λ a factor 10-100 above m_h = 0.125 TeV
(II) a mechanism to keep Λ stable against quantum corrections

(I) Some symmetry group G spontaneously broken to a subgroup K at scale Λ, with the Higgs arising as a Nambu-Goldstone (NG) boson:

$$\boxed{G/K = SO(N+1)/SO(N) \supseteq SO(4) \quad \Rightarrow \quad \pi_i = (h_1,\ h_2,\ h_3,\ h_4,\ \eta_1,\ \ldots, \eta_N - 4)}$$

Higgs mass only from (top Yukawa) loop corrections:

$$m_h \sim v \sim f = \frac{\Lambda}{4\pi}$$

Below Λ, the NG bosons constitute a non-linear σ-model, which preserves custodial symmetry.

Still, non-linearities amount to ***v^2 / f^2* corrections to SM predictions: data imply f ≥ 1 TeV**

The NG bosons h and η have specific derivative interactions.
η can play the role of dark matter candidate.

Frigerio-Pomarol-Riva-Urbano '12

Higgs compositeness

(II) Quantum stability of m_h requires a radical assumption on the new dynamics at Λ :

*** compositeness (no elementary spin-zero boson),**
* supersymmetry (boson $\leftrightarrow$ fermion)
* …

Explicit model for compositeness:

a new gauge theory defined at the ultraviolet cutoff scale Λ_{UV} that

- becomes strongly-coupled in the infrared
- develops a mass gap $\Lambda << \Lambda_{UV}$
- spontaneously breaks its global symmetries $G \rightarrow K$

Colour $SU(3)_C$
Quarks & gluons
$\Lambda_C \sim 1$ GeV
$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$
Mesons & baryons

The infrared theory is made of composite states, whose masses have cutoff Λ !

Hyper-Colour gauge theory with mass gap $\Lambda_{HC} \sim 10$ TeV
Take four hyper-quarks, in a pseudo-real representation of hyper-colour. Then:

$$\psi^a \sim \mathbf{4}_{SO(6)} \;, \quad \langle \psi^a \psi^b \rangle \sim \Lambda_{HC}^3 \;\Rightarrow\; G = SO(6) \rightarrow K = SO(5)$$

Five-plet of composite NG bosons: the 4 Higgs components h_i plus a SM singlet η ,
accompanied by several massive meson resonances …

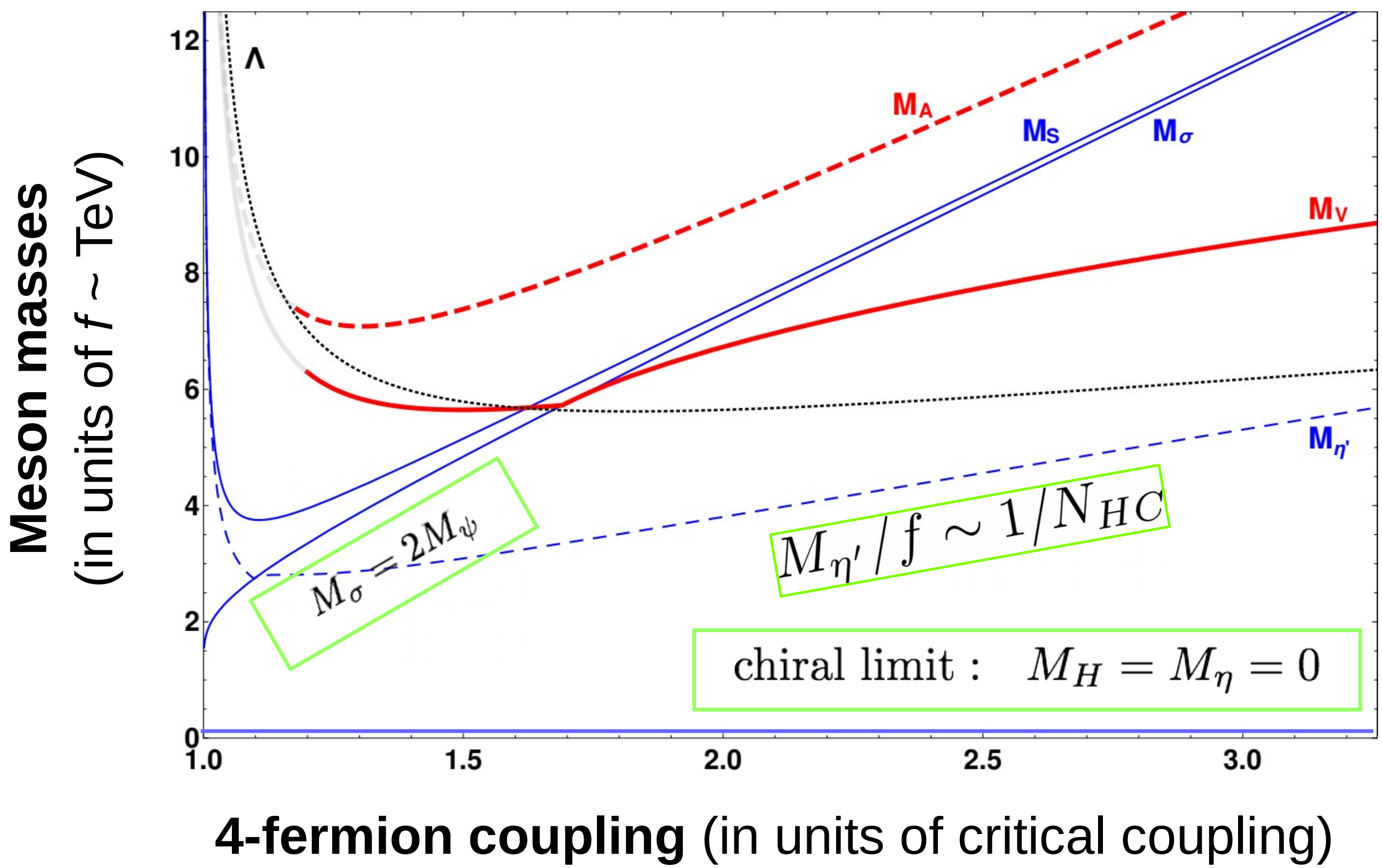
Bizot-Frigerio-Knecht-Kneur '17

Spectrum of meson resonances

Below confinement, dynamics can be approximated by four-fermion interactions (à la Nambu Jona-Lasinio: hypergluon acquires a dynamical mass and is integrated out).

Correlation functions between two fermion bilinears can be computed resumming leading diagrams in $1/N_{HC}$. The resulting poles give the meson masses.

Bizot-Frigerio-Knecht-Kneur '17



spin-0 & **spin-1** meson masses are related in the NJL approximation

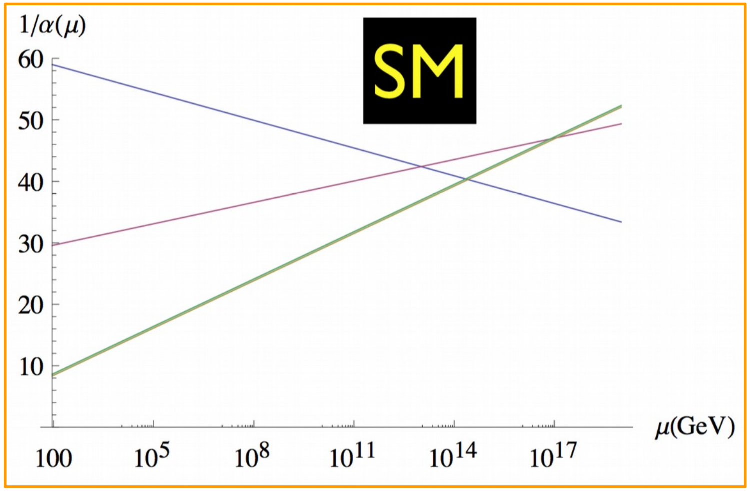
Components of each SO(5) multiplet have degenerate masses (electroweak splitting neglected)

$$\frac{M}{f} \sim \sqrt{\frac{1}{N_{HC}}}$$

here $N_{HC} = 4$

SO(10) unification

Motivation for a Grand Unified Theory:
the Renormalisation Group evolution of the three SM gauge couplings points to a common value (precision requires ~20% new physics thresholds)



Unification of the three SM gauge groups into one simple group:

$$\boxed{U(1)_Y \times SU(2)_w \times SU(3)_c \subset \left\{ \begin{array}{c} SU(5) \times U(1)_X \\ SO(4) \times SO(6) \end{array} \right\} \subset SO(10)}$$

custodial x Pati-Salam

Additional GUT benefits:
- charge quantisation
- quantum numbers of SM fermions
- anomalies cancellation automatic [in SO(10)]
- fermion mass relations
- non-zero neutrino masses automatic [in SO(10)]

Assuming multi-TeV scale supersymmetry
- gauge coupling unification is precise
- the large hierarchy of scales is stable under quantum corrections

Fermion masses in SO(10)

SO(10) representations: the fundamental **10** and the spinor **16**

$$\mathbf{10} = (\mathbf{5} + \overline{\mathbf{5}})_{SU(5)} = \left\{ [(3,1)_{-\frac{1}{3}} + \underline{(1,2)_{\frac{1}{2}}}] + \underline{[(\overline{3},1)_{\frac{1}{3}} + \underline{(1,2)_{-\frac{1}{2}}}]} \right\}_{SM}$$

$$\mathbf{16} = (\mathbf{10} + \overline{\mathbf{5}} + \mathbf{1})_{SU(5)} = \left\{ \underline{[(3,2)_{\frac{1}{6}} + (\overline{3},1)_{-\frac{2}{3}} + (1,1)_{1}]} + \underline{[(\overline{3},1)_{\frac{1}{3}} + \underline{(1,2)_{-\frac{1}{2}}}]} + (1,1)_{0} \right\}_{SM}$$

→ 3 families of SM chiral fermions are explained by 3 copies of **16** (without $\overline{\mathbf{16}}$ partners)

→ Higgs doublets embedded as well (with a challenging doublet-triplet splitting required)

Minimal Yukawa superpotential: $$W_y = \frac{1}{2} y_{ij} \mathbf{16}_i \mathbf{16}_j \mathbf{10}_H \quad \Rightarrow \quad y_u = y_d = y_e = y_\nu = y$$

"Split SO(10)": matter and Higgs superfields both in 10 and in 16:

$$W_y = \frac{1}{2} y_{ij} \mathbf{16}_i \mathbf{16}_j \mathbf{10}_H + h_{ij} \mathbf{16}_i \mathbf{10}_j \mathbf{16}_H$$

Frigerio-Hosteins-Lavignac-Romanino '08

$$y_u = y \qquad y_d^T = y_e = h \qquad y_\nu = 0$$

$$h_{ij} \overline{\mathbf{5}}_i^{16} \mathbf{5}_j^{10} \mathbf{1}_H^{16}$$

Extra matter is made heavy by a GUT scale VEV
→ at electroweak scale same SM multiplets as before!

Predictive leptogenesis

SO(10) unification is tailor-made to explain (I) the tiny non-zero neutrino masses, & (II) the baryon asymmetry of the Universe.
But, in most models, low-scale and high-scale flavour parameters are independent.

In “Split SO(10)” a unique Yukawa controls (I) neutrino masses & (II) lepton asymmetry:

$$W_\nu = \frac{1}{2} f_{ij} \mathbf{10}_i \mathbf{10}_j \mathbf{54}_H$$

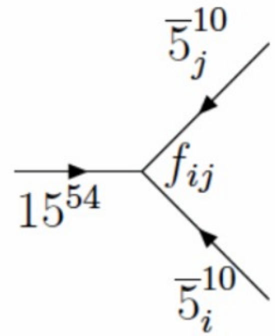
$$\mathbf{54} = (\mathbf{15} + \overline{\mathbf{15}} + \mathbf{24})_{SU(5)}$$

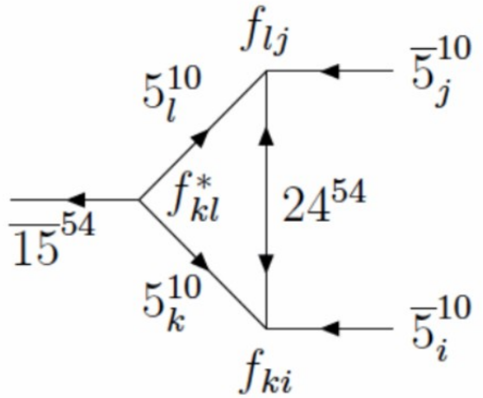
Two-index symmetric representation **54** contains Higgs triplet with VEV ~ v^2/M_{15} (pure type-II seesaw)

$$m_\nu \propto f$$

Higgs decays into leptons induce B-L asymmetry controlled by the matrix f_{ij} only !

Frigerio-Hosteins-Lavignac-Romanino '08





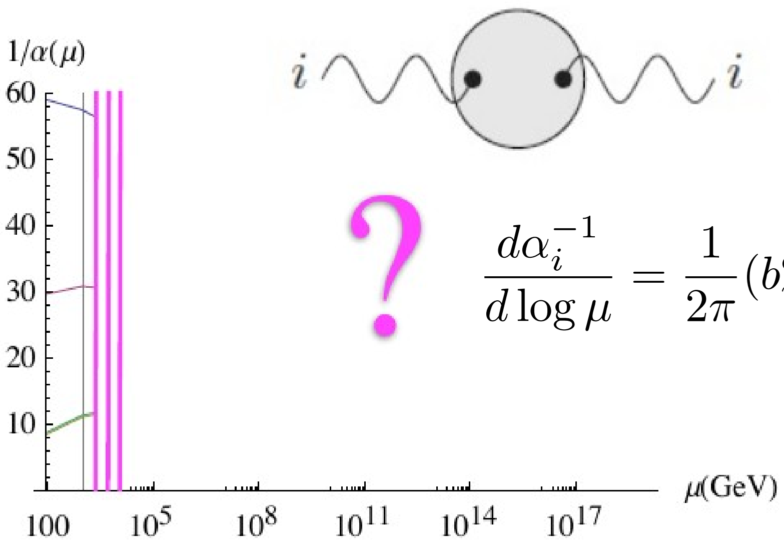
$$\epsilon_{B-L} \simeq \frac{1}{10\pi} \frac{M_{24}}{M_{15}} \frac{\Gamma_{15}^{lep}}{\Gamma_{15}^{tot}} \overline{f}^{2} \frac{\mathrm{Im}[(m_\nu)_{11}(m_\nu^* m_\nu m_\nu^*)_{11}]}{\overline{m_\nu}^4}$$

Decays can be sufficiently out-of-equilibrium (large efficiency) for successful baryogenesis

Hambye-Raidal-Strumia ‘05

Unification from compositeness

Can we study gauge unification if new physics is strongly-coupled at multi-TeV scale ?



?

$$\frac{d\alpha_i^{-1}}{d\log\mu} = \frac{1}{2\pi}\left(b_i^{elem} + b_i^{comp}\right)$$

The composite sector includes Higgs and top-quark partners, therefore it modifies the running of all 3 gauge couplings

$$\boxed{G \supset SU(3)_c \times SU(2)_w \times U(1)_Y}$$

Unification depends only on b_i-b_j !

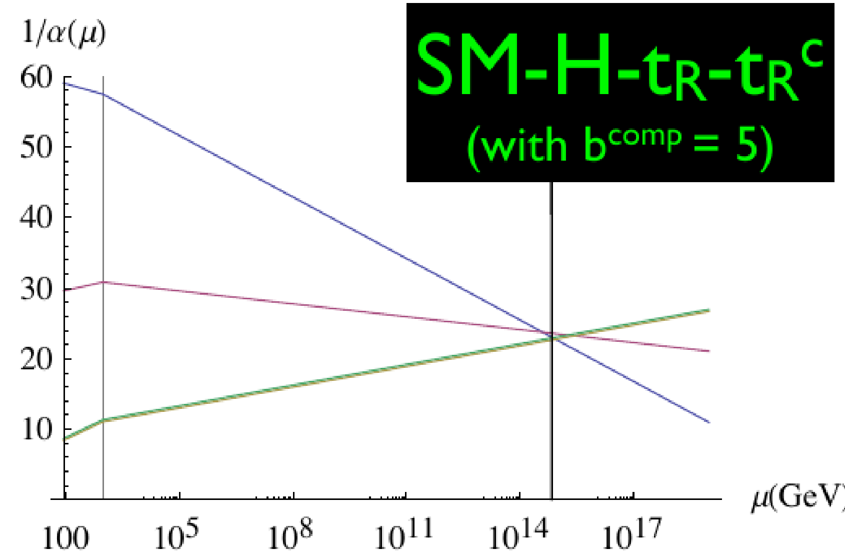
If the composite global symmetry G is simple, then $b_{1,2,3}^{comp} = b^{comp}$

The large top-quark Yukawa indicates that t_R can be a fully composite state, as the Higgs

$$y_t = g_* \epsilon_{q_L} \epsilon_{t_R} \simeq 1$$

$$\boxed{b_i^{elem} = b_i^{SM} - b_i^H - 2b_i^{t_R}}$$

Agashe-Contino-Sundrum '05



Global SO(10) at multi-TeV scale

Explicit realisation of composite unification: ***G/K = SO(11)/SO(10)*** at scale $m_*=g_* f$:
Minimal unified global symmetry containing the custodial SM

Frigerio-Serra-Varagnolo '11

$$[SU(2)_L \times SU(2)_R] \times [SU(3)_C \times U(1)'] \subset SO(4) \times SO(6) \subset SO(10)$$

Higgs and right-handed top quark belong to composite *SO(10)* multiplets:

$\mathbf{10}_H = (H, T)_{B=0}$	Higgs partner is one colour-triplet scalar T
$\mathbf{10}_{t_R} = (t_R, T_R^c, L_R, L_R^c)_{B=1/3}$	Top partners x_R are one colour-triplet and two weak-doublet fermions

Top partners pair with elementary fermions $x_L = (T^c_L, L_L, L^c_L)$ to become massive → Unification !

Mass spectrum: $$m_x \simeq \lambda_x f \qquad m_T \simeq \frac{(N_g g_s^2 + N_x \lambda_x^2) g_*^2}{16\pi^2} f^2 \qquad m_h \simeq \frac{N_x \lambda_x^4}{16\pi^2} \frac{v^2}{f^2} f^2$$

Composite partners ↔ Super-partners of supersymmetric models.
One of them could be dark matter.
TeV-GUT splitting occurs in top sector, rather than in Higgs sector.

Direct searches at LHC push coloured states well above one TeV ...

Perspective

- New physics with *SO(N)* symmetries can address the shortcomings of Standard Model :
  - ➔ Quantum instability of the electroweak scale
  - ➔ (Dark matter candidates)
  - ➔ Non-zero neutrino masses
  - ➔ Baryogenesis
  - ➔ Unification of gauge and Yukawa couplings
  - ➔ (Flavour structure)
  - ➔ ...

- The theories discussed here present some aesthetic features :
  - ✔ *SO(N+1)/SO(N)* straightforward extension of the SM custodial
  - ✔ Confining gauge theories solid framework to study *G/K* symmetry breaking
  - ✔ Grand Unification emerges from several convincing low energy footprints
  - ✔ ...

- As well as some anti-aesthetic features :
  - ✗ Baryon & lepton number conservation often ad-hoc (dark matter stability as well)
  - ✗ The heaviness of the top quark makes the little hierarchy problem painful
  - ✗ Realistic Grand Unification requires subtle splitting of TeV-GUT scale masses
  - ✗ ...

- Some experimental indication of non-standard physics may help.
  Even without positive signals, there is room left for theoretical progress.