Constraining composite Higgs models with direct and indirect searches

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in collaboration with Peter Stangl and David M. Straub

based on arXiv:1508.00569

ICHEP Chicago. August 5th, 2016.

Introduction

Composite Higgs Models with partial compositeness

are well-motivated New Physics scenarios addressing

- the hierarchy problem
- the flavour puzzle

Lightness of the Higgs explained by being pseudo-Nambu Goldstone boson of some global coset

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Our goal

use a bottom-up EFT parametrization of CHM's to constrain parameter space

- realistic electroweak symmetry breaking
- direct seaches @ colliders
- indirect constraints (precision observables, flavour, ...)

Concentrate on calculable effects where EFT description works (further effects are even more constraining)

Model selection

Protection of EWPO

Custodial symmetry

$\mathsf{SU}(2)_\mathsf{L} \subset \mathsf{SU}(2)_\mathsf{L} \times \mathsf{SU}(2)_\mathsf{R} = \mathsf{SO}(4)$

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$\mathsf{SO}(5)/\mathsf{SO}(4)$ breaking
$\rightarrow$ only one Higgs doublet

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use fundamental $\mathbf{5}$ representations

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2-site description
$\rightarrow$ only one level of resonances

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dimensional deconstruction
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trivial (purely elementary) lepton sector

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Minimal 4D Composite Higgs Model

[De Curtis, Redi, Tesi ’11]

Alternative models: [Panico,Wulzer ’11; Marzocca,Serone,Shu ’12]

Particle content

	elementary sector	composite sector
Higgs	—	$\exp(\pi^{\hat{a}} \mathsf{T}^{\hat{a}}/f)$ (pNGb)
Gauge sector	gauge bosons of $\mathsf{SU}(3)_\mathsf{c} \times \mathsf{SU}(2)_\mathsf{L} \times \mathsf{U}(1)$ G_μ , W_μ, B_μ	resonances in SO(4) adjoint $\mathbf{adj.} = (\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3}) \oplus (\mathbf{2},\mathbf{2})$ + $\mathsf{U}(1)_\mathsf{X}$ + gluon resonances $\rightsquigarrow$ heavy Z', W', G' resonances
Fermion sector	chiral fermions $\begin{pmatrix} u_\mathsf{L} \\ d_\mathsf{L} \end{pmatrix}$ u_R d_R	vectorlike fermions $\Psi_u \in \mathbf{4}_{\frac{2}{3}}$ $\Psi_d \in \mathbf{4}_{-\frac{1}{3}}$ $\widetilde{\Psi}_u \in \mathbf{4}_{\frac{2}{3}}$ $\widetilde{\Psi}_d \in \mathbf{4}_{-\frac{1}{3}}$ $\rightsquigarrow$ quark partners + exotically charged fermions

Electroweak symmetry breaking and flavour

Composite-elementary mixings...

$$\mathcal{L} \supset (\text{elementary}) + (\text{composite}) + \epsilon_{ij}\, \bar{\psi}^{(i)}_{\text{elem}}\, \Psi^{(j)}_{\text{comp}}\, \exp(\text{Higgs})$$

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EWSB

... break global symmetries explicitly

→ Higgs potential dymanically generated via the Coleman-Weinberg mechanism

$$V_{\text{eff}}(h) \sim \text{tr}\left[M^4(h)\ \log(M^2(h))\right]$$

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Flavour

... lead to flavour mixing

→ assume global flavour symmetries that are only broken by comp-elem-mixings to generate CKM

4 scenarios:

- $U(3)_L$, $U(3)_R$
- $U(2)_L$, $U(2)_R$

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4 scenarios:

- $\text{U}(3)_\text{L}$, $\text{U}(3)_\text{R}$
- $\text{U}(2)_\text{L}$, $\text{U}(2)_\text{R}$

⇒ interesting to investigate both phenomena in a global analysis

Analysis

Goal

Find parameter points $\vec{\theta}$ that satisfy all experimental constraints.

Define scalar measure of “how good” a parameter point is

$$\chi^2(\vec{\theta}) \equiv \sum_{i,j\in\text{observables}} \left(\mathcal{O}_i^{\text{th}}(\vec{\theta}) - \mathcal{O}_i^{\text{exp}}\right) \left[\sigma^2_{\text{total}}\right]^{-1}_{ij} \left(\mathcal{O}_j^{\text{th}}(\vec{\theta}) - \mathcal{O}_j^{\text{exp}}\right)$$

$\Rightarrow$ Minimize $\chi^2(\vec{\theta})$!

Technically challenging

- large dimensionality (44 parameters for U(2), 30 for U(3))
- complicated functions of all parameters

$\Rightarrow$ Use Markov Chain Monte Carlos so sample parameter space !

Constraints

- SM parameters
  - Masses
  - CKM mixings
  - Higgs mass & vev

- Diagonalization of (Higgs dependent) mass matrices
  $\rightarrow$ interpret as values at $\mu = m_t$
- SM-RGE running of exp. values up to scale m_t
- Neglect RGE running above m_t

- CKM elements through tree-level W-vertices
- CKM matrix not unitary
  $\rightarrow$ constraints on compositeness

Constraints

- SM parameters
  - Masses
  - CKM mixings
  - Higgs mass & vev
- S- and T-parameter

T-parameter

- tree-level: custodially protected
- one-loop level: consider only fermion constributions

S-parameter

- already at tree-level
- effectively lower bound on spin-1 resonance masses

$$S \sim \frac{1}{m_\rho^2}$$

Constraints

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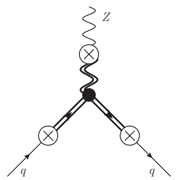
- Z-couplings

Z width



- bound on degree of compositeness [Straub '13]
- Tree-level $Z q_{d\mathrm{L}} q_{d\mathrm{L}}$ protected by custodial protection [Agashe et al. '06]
- We neglect loop contributions

Constraints

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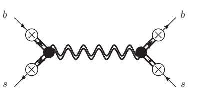
- Flavour observables
  - meson-$\overline{\text{meson}}$-mixing
  - rare B decays

meson-$\overline{\text{meson}}$-mixing

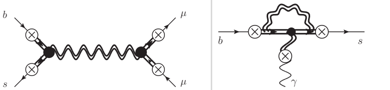
[Barbieri et al. '12]



We consider B_d, B_s and K mixing

B decays

[König,Neubert,Straub '14]



We consider $B_s \to \mu\mu$ and $b \to s\gamma$.
We do not impose $B \to K^*\mu\mu$

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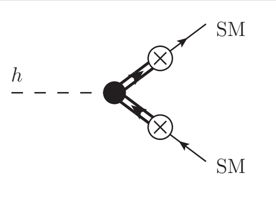
- Higgs physics

Higgs production and decay



We calculate signal strengths

- $h \to \{WW, ZZ, b\bar{b}, \tau^+\tau^-\}$ @ tree-level
- $h \to \{gg, \gamma\gamma\}$ @ 1-loop level

Constraint on Higgs-nonlinearities
(i.e. on f)

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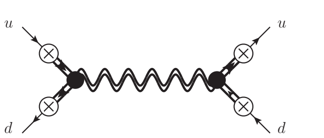
- Higgs physics
- Contact interactions

1st generation quarks

[de Vries '14]



- Constrained by dijet angular distribution @ LHC
- Important if light quarks are composite (e.g. U(3) models)

Constraints

- SM parameters
  - Masses
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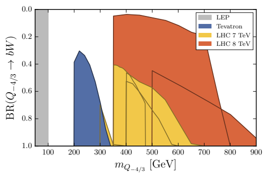
- Higgs physics
- Contact interactions
- Direct searches @ colliders

Quark partners [ATLAS,CMS,CDF]



- $Q_{\text{NP}} \to q_{\text{SM}}\ V_{\text{SM}}$
- $Q_{\text{NP}} \to q_{\text{SM}}\ h$

Spin-1 partners [ATLAS,CMS]

Experimental searches only apply if decay into fermion resonances is kinematically not possible
Criterion: $\Gamma/m \leq 5\%$

Results!

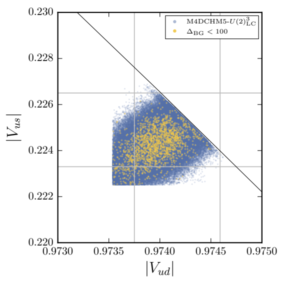
(only a few)

Compositeness of light quarks

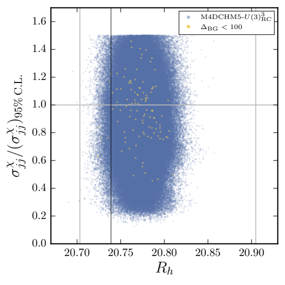
Constrained by

- (first-row) CKM unitary
- hadronic Z width
- dijet angular distributions

Left compositeness



Right-compositeness



Failure of U$(3)^3_{\mathsf{LC}}$

We did not find viable points for the U$(3)^3_{\mathsf{LC}}$ flavour structure.

U$(3)_{\mathsf{LC}}$ connects compositeness of light quarks to (large) compositeness of t-quark.
$\rightarrow$ strong constraints from CKM unitarity.

We will not consider it further.

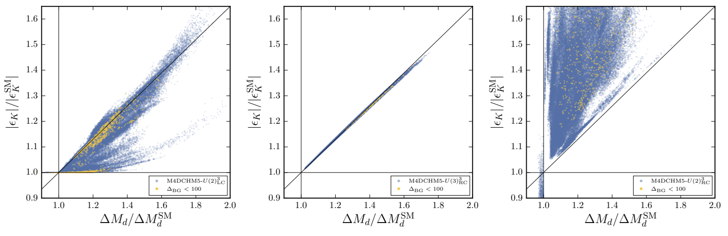
Flavour Observables

ΔM_d vs. ΔM_s

Large effects (up to saturating exp. bounds) are possible
$\rightarrow$ mainly enhancement relative to SM

ϵ_K vs. ΔM_d

$\mathrm{U}(2)^3_{\mathrm{LC}}$ $\mathrm{U}(3)^3_{\mathrm{RC}}$ $\mathrm{U}(2)^3_{\mathrm{RC}}$



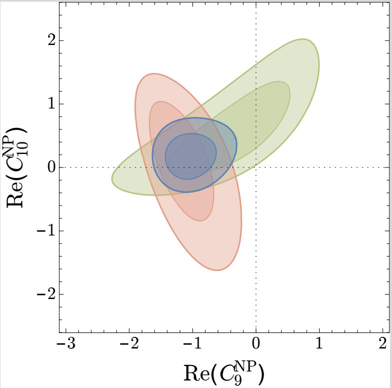
This allows to distinguish flavour structures!

$B \to K^*\mu\mu$ anomalies

Global analyses...

[Altmannshofer et al. '15; Beaujean et al. '13; Descotes-Genon et al. '15]

... of $b \to s\ell\ell$ favour NP contributions to C_9 (and possibly C_{10})



[Picture taken from Altmannshofer,Straub '15]

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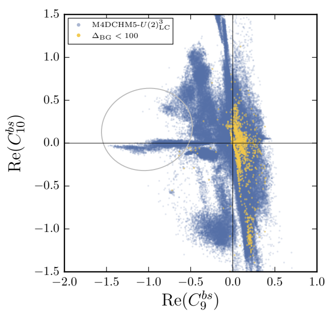

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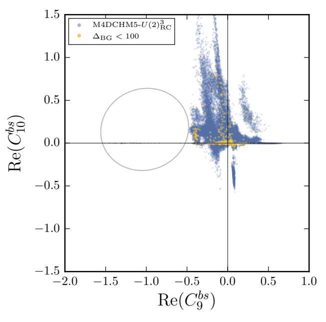

Anomalies can be explained!

Then, we predict a light neutral vector resonance (with large BR into $t\bar{t}$)

Conclusion

Comprehensive numerical analysis of M4dCHM$_5$ respecting all relevant direct and indirect bounds with realistic EWSB

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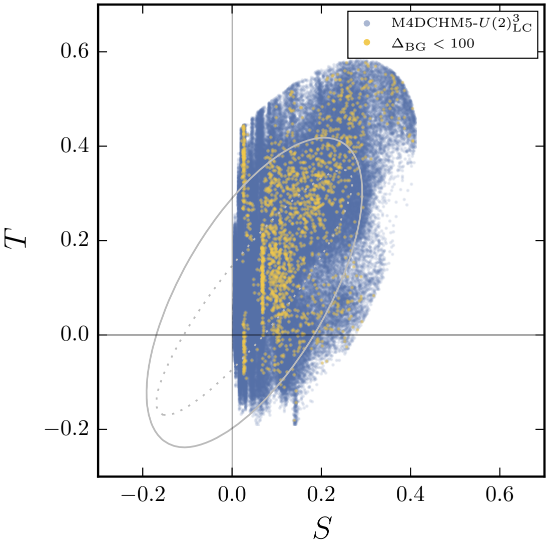
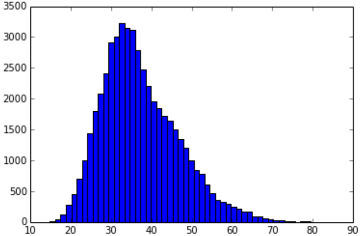
- U$(3)_{\text{LC}}$ flavour structure disfavoured
- Fine tuning $\Delta_{\text{BG}} < 100$ possible
- $B \to K^* \mu\mu$ anomalies can be explained
- Identified most promising channels for exp. searches

Backup slides

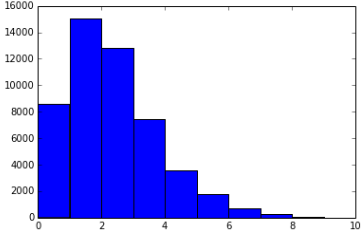
Oblique Corrections



Properties of our Markov Chains



Distribution of the total χ^2.
48 individual contributions to χ^2.
(here for U$(2)_{\text{LC}}$)



Number of individual constraints that are violated by more than 2σ.
(here for U$(2)_{\text{LC}}$)

Mass matrices - Fermions

u_R	Q_{uR}^{+-}	$\widetilde{Q}_{uR}^{+-}$	Q_{uR}^{-+}	$\widetilde{Q}_{uR}^{-+}$	Q_{dR}^{++}	$\widetilde{Q}_{dR}^{++}$	S_{uR}
0	$-\Delta_{u_L} \cos^2\left(\frac{h}{2f}\right)$	0	$\Delta_{u_L} \sin^2\left(\frac{h}{2f}\right)$	0	$-\Delta_{d_L}$	0	$\frac{1}{\sqrt{2}} \Delta_{u_L}$ si
0	m_U	m_{Y_U}	0	0	0	0	0
$-\frac{1}{\sqrt{2}} \Delta_{u_R}^{\dagger} \sin\left(\frac{h}{f}\right)$	0	$m_{\widetilde{U}}$	0	0	0	0	0
0	0	0	m_U	m_{Y_U}	0	0	0
$-\frac{1}{\sqrt{2}} \Delta_{u_R}^{\dagger} \sin\left(\frac{h}{f}\right)$	0	0	0	$m_{\widetilde{U}}$	0	0	0
0	0	0	0	0	m_D	m_{Y_D}	0
0	0	0	0	0	0	$m_{\widetilde{D}}$	0
0	0	0	0	0	0	0	m_U
$-\Delta_{u_R}^{\dagger} \cos\left(\frac{h}{f}\right)$	0	0	0	0	0	0	0

Mass matrices - Spin-1

W^3_μ	B_μ	$\rho_{\mathrm{L}\,\mu}$	$\rho_{\mathrm{R}\,\mu}$	a^3_μ	ρ_X
$\frac{1}{2}\,g f_1^2$	0	$-\frac{1}{2}\,g g_\rho f_1^2 \cos^2\left(\frac{h}{2f}\right)$	$-\frac{1}{2}\,g g_\rho f_1^2 \sin^2\left(\frac{h}{2f}\right)$	$-\frac{1}{2\sqrt{2}}\,g g_\rho f_1^2 \sin\left(\frac{h}{f}\right)$	0
	$\frac{1}{2}\,g'^{\,2}\left(f_1^2+f_X^2\right)$	$-\frac{1}{2}\,g' g_\rho f_1^2 \sin^2\left(\frac{h}{2f}\right)$	$-\frac{1}{2}\,g' g_\rho f_1^2 \cos^2\left(\frac{h}{2f}\right)$	$\frac{1}{2\sqrt{2}}\,g' g_\rho f_1^2 \sin\left(\frac{h}{f}\right)$	$-\frac{1}{2}\,g' g$
		$\frac{1}{2}\,g_\rho^2 f_1^2$	0	0	0
			$\frac{1}{2}\,g_\rho^2 f_1^2$	0	0
				$\frac{1}{2}\,g_\rho^2 \frac{f_1^4}{f_1^2-f^2}$	0
					$\frac{1}{2}\,g_X^2$

	W^+_μ	$\rho^+_{\mathrm{L}\,\mu}$	$\rho^+_{\mathrm{R}\,\mu}$	a^+_μ
$W^{-\,\mu}$	$\frac{1}{2}\,g^2 f_1^2$	$-\frac{1}{2}\,g g_\rho f_1^2 \cos^2\left(\frac{h}{2f}\right)$	$-\frac{1}{2}\,g g_\rho f_1^2 \sin^2\left(\frac{h}{2f}\right)$	$-\frac{1}{2\sqrt{2}}\,g g_\rho f_1^2 \sin\left(\frac{h}{f}\right)$
$\rho_{\mathrm{L}}^{-\,\mu}$		$\frac{1}{2}\,g_\rho^2 f_1^2$	0	0
$\rho_{\mathrm{R}}^{-\,\mu}$			$\frac{1}{2}\,g_\rho^2 f_1^2$	0
$a^{-\,\mu}$				$\frac{1}{2}\,g_\rho^2 \frac{f_1^4}{f_1^2-f^2}$

Weinberg Sum rules

Cutoff dependence of the Coleman Weinberg potential

$$V_{\text{eff}}(h) = \sum \frac{c_i}{64\pi^2} \left(2\,\text{tr}\left[M_i^2(h)\right]\,\Lambda^2 - \text{tr}\left[\left(M_i^2(h)\right)^2\right]\log\left[\Lambda^2\right] + \text{tr}\left[\left(M_i^2(h)\right)^2\log\left[M_i^2(h)\right]\right]\right)$$

Divergent terms vanish for

$$\text{tr}\left[M_i^2(h)\right] - \text{tr}\left[M_i^2(h=0)\right] = 0,$$
$$\text{tr}\left[(M_i^2(h))^2\right] - \text{tr}\left[(M_i^2(h=0))^2\right] = 0,$$

Metropolis Hastings Algorithm

Given a point x_0:

1. $x_{\text{new}} = \text{random}$
2. $\alpha = \min\left\{1, \frac{\mathcal{L}(x_0)}{\mathcal{L}(x_{\text{new}})}\right\}$
3. Accept x_{new} with probability α
4. Start again at (1)