Constraining composite Higgs models with direct and indirect searches

Christoph Niehoff

Excellence Cluster Universe & Technische Universität München

in collaboration with Peter Stangl and David M. Straub

based on arXiv:1508.00569

Lyon, November 25, 2015

Introduction

The hierarchy problem...

... can be solved elegantly and naturally (!) if the Higgs is a Composite pseudo-Nambu-Goldstone boson.
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Our goal...

... is to perform a comprehensive numerical analysis including all relevant experimental constraints.
Such as:

- realistic electroweak symmetry breaking
- indirect constraints (e.g. from flavour)
- direct collider searches

Our philosophy...

... is to concentrate on calculable effects (other effects would increase the constraints)

Selection of the model

Leading principles

- Study 4D description of Composite Higgs with partial compositeness
- Minimality in the model setup and number of parameters, but still realistic

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SO(5)/SO(4) symmetry breaking
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Concentrate on quark flavour

trivial (elementary) lepton sector

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Model

We choose the $M4dCHM_5$. [De Curtis,Redi,Tesi '11]
Alternative models: [Panico,Wulzer '11; Marzocca,Serone,Shu '12]

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Flavour structure

[Barbieri,Buttazzo,Sala,Straub '12; Redi,Weiler '11; Cacciapaglia et al. '07]

Generic flavour structure leads to too large flavour violation

Assume flavour symmetries broken only by couplings to the elementary sector

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

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$U(3)^3$ left compositeness

$$\epsilon_L \propto \mathbb{1}, \quad \epsilon_R \propto \text{diag}.V_{\text{CKM}}$$

$U(3)^3$ right compositeness

$$\epsilon_L \propto V^\dagger_{\text{CKM}}.\text{diag}, \quad \epsilon_R \propto \mathbb{1}$$

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U(3)^3 right compositeness

$$\epsilon_L \propto V^\dagger_{\text{CKM}}.\text{diag}, \quad \epsilon_R \propto \mathbb{1}$$

U(2)^3 left compositeness

$$\epsilon_L \propto \text{diag}, \quad \epsilon_R \propto \begin{pmatrix} \mathbf{\Delta} & \mathbf{V} \\ 0 & y_3 \end{pmatrix}$$

U(2)^3 right compositeness

$$\epsilon_L \propto \begin{pmatrix} \mathbf{\Delta} & \mathbf{V} \\ 0 & y_3 \end{pmatrix}, \quad \epsilon_R \propto \text{diag}$$

Electroweak symmetry breaking

Higgs potential

radiatively generated via Coleman-Weinberg mechanism

$$V_{\text{eff}}(h) \propto \sum_n m_n^4(h) \log\left[m_n^2(h)\right]$$

$m_n(h)$: Higgs dependent mass; bosonic, fermionic

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General structure [Marzocca,Serone,Shu '12; Panico,Wulzer '12]

$$V_{\text{eff}}(h) \approx -(\gamma_{\text{fermion}} + \gamma_{\text{boson}}) \sin^2(h/f) + \beta_{\text{fermion}} \sin^4(h/f) + \dots$$

small Higgs mass: $\gamma_{\text{fermion}} \approx -\gamma_{\text{boson}}$ $\Rightarrow$ strong correlation

Strategy

Goal

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

Define scalar measure of "how good" a parameter point is

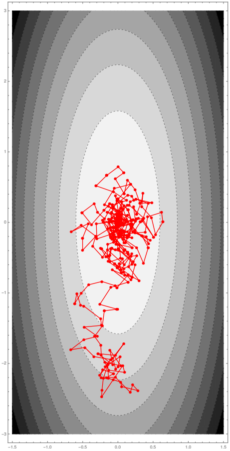
$$\chi^2(\vec{\theta}) \equiv \sum_{i,j \in \text{observables}} \left(\mathcal{O}_i^{\text{th}}(\vec{\theta}) - \mathcal{O}_i^{\text{exp}}\right) \left[\sigma^2_{\text{total}}\right]^{-1}_{ij} \left(\mathcal{O}_j^{\text{th}}(\vec{\theta}) - \mathcal{O}_j^{\text{exp}}\right)$$

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

Technically challenging

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

Numerics



Find minima of $\chi^2(\vec{\theta})$

1. Generate (random) starting point
2. Use global minimizer [NLopt] to find minimum
3. Use Markov Chain Monte Carlo [PyPMC] to sample around minimum and generate good points
4. Keep only points that satisfy every individual constraint on 3σ level

Computations

performed on the C2PAP computing cluster in Munich

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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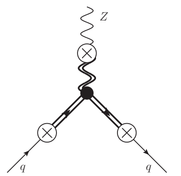
- Z-couplings

Z width



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

Constraints

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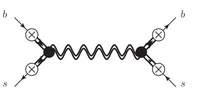
- Flavour observables
  - meson-$\overline{\text{meson}}$-mixing
  - rare B decays

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

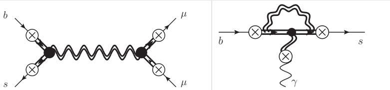
[Barbieri,Buttazzo,Sala,Straub '12]



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 <u>not</u> impose $B \to K^*\mu\mu$

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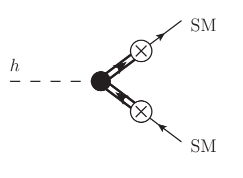
- Higgs physics

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)

Constraints

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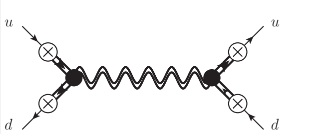
- Higgs physics
- Contact interactions

1st generation quarks [de Vries '14]



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

Constraints

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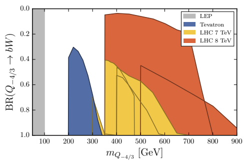
- Higgs physics
- Contact interactions
- Direct searches @ colliders

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]

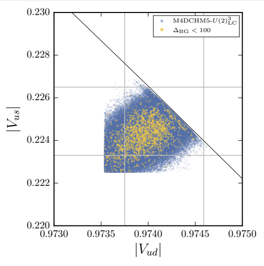
Experimental searches only apply if decay into fermion resonances is kinematically not possible
Criterion: $\Gamma/m \leq 5\%$

Compositeness of light quarks

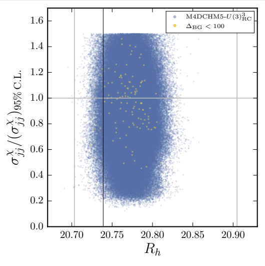
Constrained by

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

Left compositeness



Right-compositeness



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

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

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

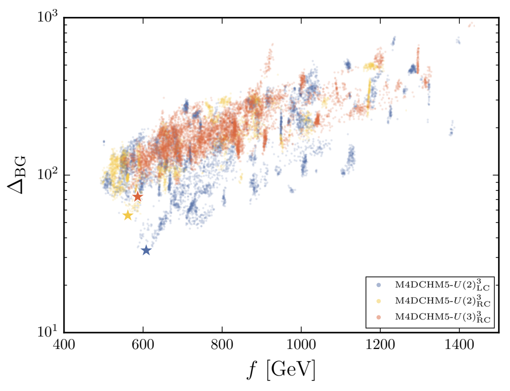
We will not consider it further.

Fine tuning

Barbieri-Giudice measure

[Barbieri,Giudice '88]

$$\Delta_{\text{BG}} = \max_{i \in \text{parameters}} \left| \frac{\partial \ln m_Z}{\partial \ln x_i} \right|$$



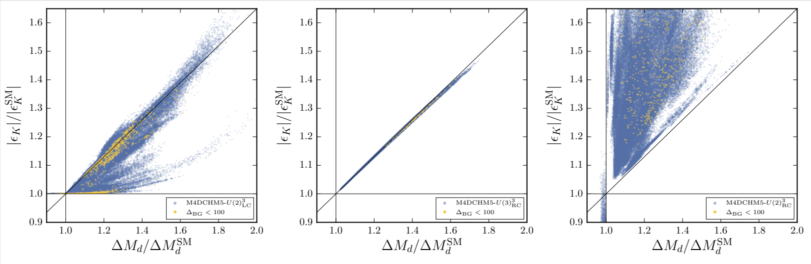
Flavour Observables

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

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

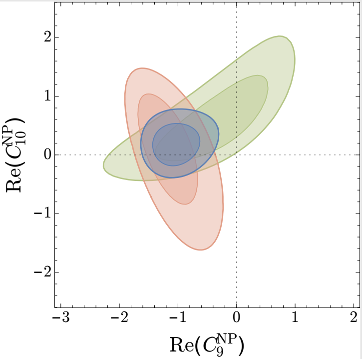


This allows to distinguish flavour structures!

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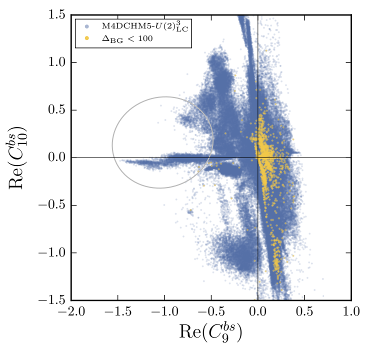

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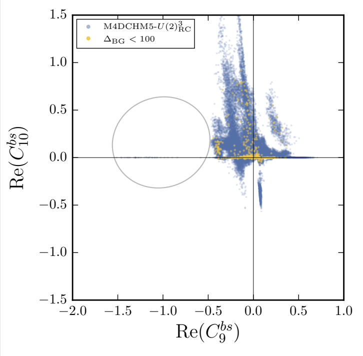


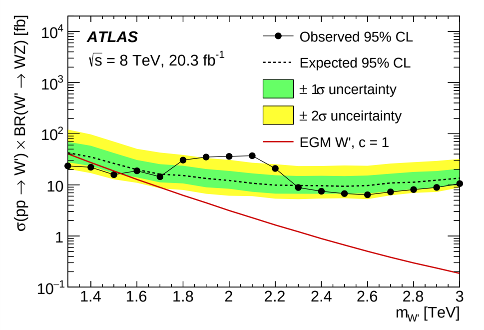
Anomalies can be explained!

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

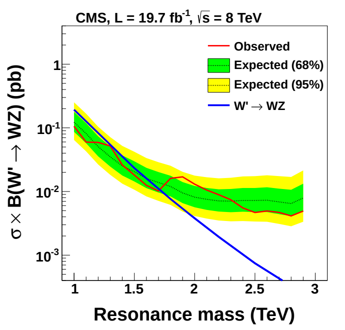
LHC diboson excesses

ATLAS and CMS found excesses in $\rho \to \{WZ, WW, Wh, Zh\}$ searches of around 3σ

[ATLAS-EXOT-2013-08]



[CMS-EXO-12024]



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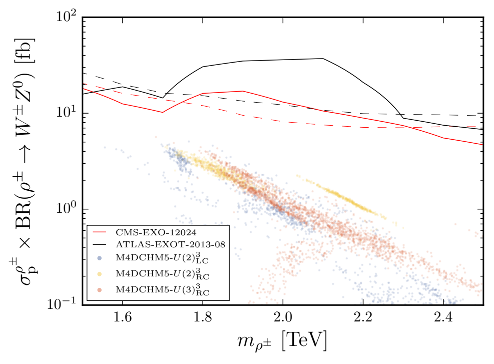
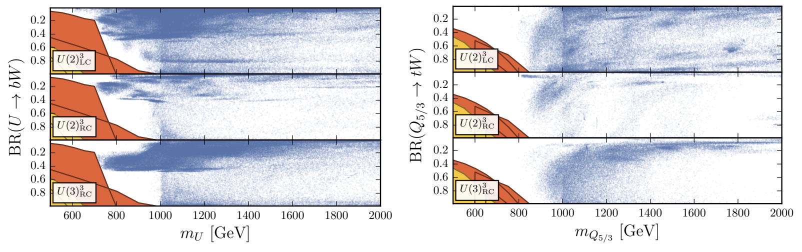


Not a dedicated analysis...

... but this could explain the excesses.

Prospects for direct searches

Quark partners



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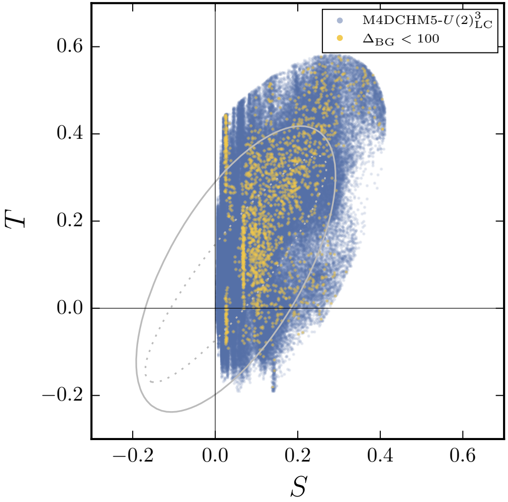
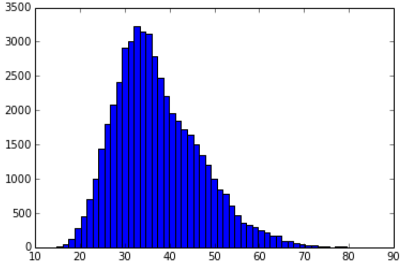
- Fine tuning $\Delta_{BG} < 100$ possible
- $B \to K^* \mu\mu$ anomalies can be explained
- LHC diboson excesses can be explained
- Identified most promising channels for exp. searches

Backup slides

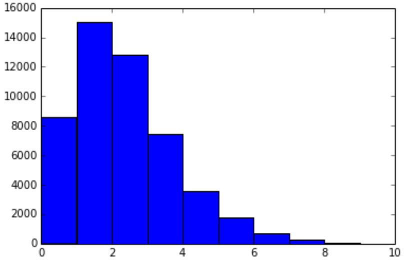
Oblique Corrections



Properties of our Markov Chains



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



Number of individual constraints that a violatied by more than 2σ.
(here for $U(2)_{LC}$)

Mass matrices - Fermions

$$
\left(\begin{array}{ccccccccc}
u_R & Q^{+-}_{uR} & \widetilde{Q}^{+-}_{uR} & Q^{-+}_{uR} & \widetilde{Q}^{-+}_{uR} & Q^{++}_{dR} & \widetilde{Q}^{++}_{dR} & S_{uR} & \tilde{S}_{uR} \\
\hline
0 & -\Delta_{u_L} \cos^2\left(\frac{h}{2f}\right) & 0 & \Delta_{u_L} \sin^2\left(\frac{h}{2f}\right) & 0 & -\Delta_{d_L} & 0 & \frac{\mathrm{i}}{\sqrt{2}} \Delta_{u_L} \sin\left(\frac{h}{f}\right) & 0 \\
0 & m_U & m_{Y_U} & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{\mathrm{i}}{\sqrt{2}} \Delta^\dagger_{u_R} \sin\left(\frac{h}{f}\right) & 0 & m_{\widetilde{U}} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & m_U & m_{Y_U} & 0 & 0 & 0 & 0 \\
-\frac{\mathrm{i}}{\sqrt{2}} \Delta^\dagger_{u_R} \sin\left(\frac{h}{f}\right) & 0 & 0 & 0 & m_{\widetilde{U}} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & m_D & m_{Y_D} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & m_{\widetilde{D}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & m_U & m_{Y_U} + Y_U \\
-\Delta^\dagger_{u_R} \cos\left(\frac{h}{f}\right) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_{\widetilde{U}}
\end{array}\right)
$$

Mass matrices - Spin-1

$$
\left(\begin{array}{ccccccc}
W^3_\mu & B_\mu & \rho_{\mathrm{L}\,\mu} & \rho_{\mathrm{R}\,\mu} & a^3_\mu & \rho_{X\,\mu} & a^4_\mu \\
\hline
\frac{1}{2} g f_1^2 & 0 & -\frac{1}{2} g g_\rho f_1^2 \cos^2\left(\frac{h}{2f}\right) & -\frac{1}{2} g g_\rho f_1^2 \sin^2\left(\frac{h}{2f}\right) & -\frac{1}{2\sqrt{2}} g g_\rho f_1^2 \sin\left(\frac{h}{f}\right) & 0 & 0 \\
 & \frac{1}{2} g'^{\,2}\left(f_1^2 + f_X^2\right) & -\frac{1}{2} g' g_\rho f_1^2 \sin^2\left(\frac{h}{2f}\right) & -\frac{1}{2} g' g_\rho f_1^2 \cos^2\left(\frac{h}{2f}\right) & \frac{1}{2\sqrt{2}} g' g_\rho f_1^2 \sin\left(\frac{h}{f}\right) & -\frac{1}{2} g' g_X f_X^2 & 0 \\
 & & \frac{1}{2} g_\rho^2 f_1^2 & 0 & 0 & 0 & 0 \\
 & & & \frac{1}{2} g_\rho^2 f_1^2 & 0 & 0 & 0 \\
 & & & & \frac{1}{2} g_\rho^2 \frac{f_1^4}{f_1^2 - f^2} & 0 & 0 \\
 & & & & & \frac{1}{2} g_X^2 f_X^2 & 0 \\
 & & & & & & \frac{1}{2} g_\rho^2 \frac{f_1^4}{f_1^2 - f^2}
\end{array}\right)
$$

$$
\left(\begin{array}{c|cccc}
 & W^+_\mu & \rho^+_{\mathrm{L}\,\mu} & \rho^+_{\mathrm{R}\,\mu} & a^+_\mu \\
\hline
W^{-\,\mu} & \frac{1}{2} g^2 f_1^2 & -\frac{1}{2} g g_\rho f_1^2 \cos^2\left(\frac{h}{2f}\right) & -\frac{1}{2} g g_\rho f_1^2 \sin^2\left(\frac{h}{2f}\right) & -\frac{1}{2\sqrt{2}} g g_\rho f_1^2 \sin\left(\frac{h}{f}\right) \\
\rho^{-\,\mu}_{\mathrm{L}} & & \frac{1}{2} g_\rho^2 f_1^2 & 0 & 0 \\
\rho^{-\,\mu}_{\mathrm{R}} & & & \frac{1}{2} g_\rho^2 f_1^2 & 0 \\
a^{-\,\mu} & & & & \frac{1}{2} g_\rho^2 \frac{f_1^4}{f_1^2 - f^2}
\end{array}\right)
$$

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

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

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)