Lattice Inputs for Composite Higgs

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strong dynamics paradigm

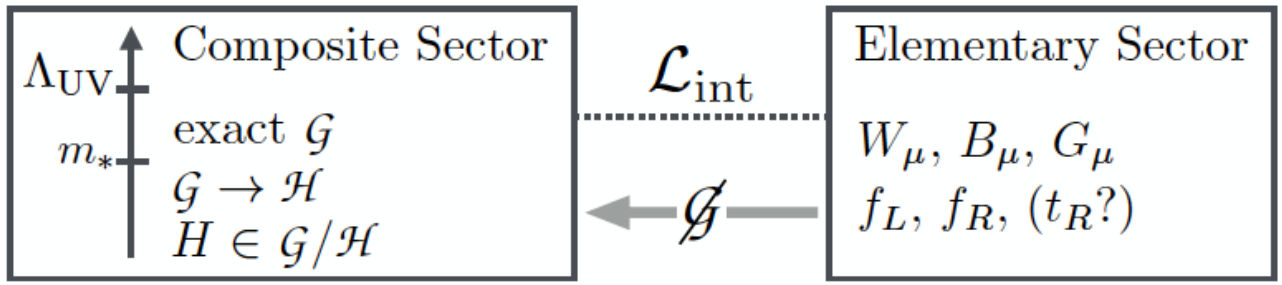


Figure 1.3: The basic structure of the composite Higgs scenario.

[Panico & Wulzer 15]

- computations in the strongly coupled regime by MC simulations
- computationally expensive, difficult to explore the “space of theories”
- focus on what can be computed

strong interactions and partial compositeness

(1) Higgs boson is a pNGB

(2) top quark mass due to mixing with a composite fermionic state

global symmetry: $G_F \to H_F, \quad H_F \supset G_{\rm cus} \supset G_{\rm SM}$

$$G_{\rm cus} = {\rm SU}(3)_c \times {\rm SU}(2)_L \times {\rm SU}(2)_R \times U(1)_X$$
$$G_F/H_F \ni (1,2,2)_0$$

UV completion:
asymptotic freedom + unitary gauge group + several irreps (LH Weyl)

$$\text{fermions} \in mR_1 + 3R_2 + 3R_3$$
$$G_F = {\rm SU}(m) \times {\rm SU}(3) \times {\rm SU}(3)' \times {\rm U}(1) \times {\rm U}(1)'$$

[Ferretti & Karateev 13]

lattice for LHC phenomenology

- pheno described in terms of effective lagrangians
- strong dynamics encoded in LECs in the effective theory
- compare EFT predictions with experimental results
- strong dynamics via lattice simulations
  $\hookrightarrow$ first principles informations about LECs
- expensive simulations - can only simulate *one* model at a time
- lattice input for pheno: potential impact of lattice simulations

Ferretti's model - UV description

	$G_{\rm HC}$	$G_{\rm F}$				
	$SU(4)$	$SU(5)$	$SU(3)$	$SU(3)'$	$U(1)_X$	$U(1)'$
ψ	$\mathbf{6}$	$\mathbf{5}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
χ	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$5/3$
$\tilde{\chi}$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$1/3$	$5/3$

[Ferretti 14, 16a,16b]

massless fermions, SSB of the global symmetry

$$\mathrm{SU}(5) \longrightarrow \mathrm{SO}(5)$$
$$\mathrm{SU}(3) \times \mathrm{SU}(3)' \longrightarrow \mathrm{SU}(3)_c$$

[Georgi & Kaplan 84]

Higgs: composite pNGB

$$\mathrm{SU}(5) \longrightarrow \mathrm{SO}(5) \supset \mathrm{SO}(4) \simeq \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$$

SM group: $T_L^a \in \mathrm{SU}(2)_L, \quad T_R^3 \in \mathrm{U}(1)$

$$\begin{aligned} 14\,\mathrm{NGB}: \quad & 1_0 + 2_{\pm 1/2} + 3_0 + 3_{\pm 1} \\ & \eta \qquad H \qquad \Phi_0 \quad \Phi_\pm \\ & \Pi = H + H^\dagger + \Phi_0 + \Phi_+ + \Phi_+^\dagger\,, \quad \Sigma = \exp\left(\frac{i\Pi}{f}\right) \\ & U = \Sigma\Sigma^T\,, \quad U \mapsto g U g^T \end{aligned}$$

exotic Higgses with $Q = m_L + m_R$:

$$\begin{aligned} \Phi_0 &\supset (\phi_0^-, \phi_0^0, \phi_0^+) \\ \Phi_+ &\supset (\phi_+^-, \phi_+^0, \phi_+^+) \end{aligned}$$

[Georgi & Machacek 85]

pNGB potential - gauging the EW

$$\mathcal{L}_{\rm eff} \supset \frac{f^2}{16}{\rm tr}\left[(D_\mu U)^\dagger D_\mu U\right]$$
$$D_\mu U = \partial_\mu U - igW^a_\mu \left[T^a_L, U\right] - ig' B_\mu \left[T^3_R, U\right]$$

contribution to the potential due to the gauge bosons (Δm_π):

$$V_g = -Bf^4{\rm tr}\left[g^2 T^a_L U T^a_L U^\dagger + g'^2 T^3_R U T^3_R U^\dagger]\right]$$

V_g provides a mass for the pNGBs in the spectrum

$$Bf^4 = C_{LR} \propto \int_0^\infty dq^2\, q^2\, \Pi_{LR}(q^2)$$
$$\left(q^2\delta_{\mu\nu} - q_\mu q_\nu\right)\Pi_{LR}(q^2) = \int d^4x\, e^{iqx}\, \langle J^L_\mu(x) J^R_\nu(0)\rangle$$

[Golterman & Shamir 15]

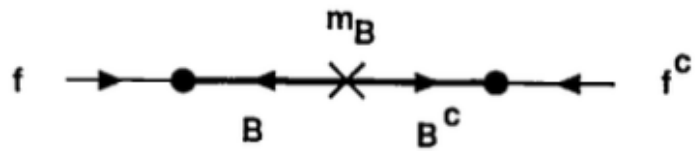
partial compositeness

generates top quark mass and EW symmetry breaking [Kaplan 85]

$$\mathcal{L}_{\rm UV} \supset \frac{\lambda_L}{\Lambda_{\rm UV}^{d_L-5/2}}\bar{q}_L\mathcal{O}_L + \frac{\lambda_R}{\Lambda_{\rm UV}^{d_R-5/2}}\bar{t}_R\mathcal{O}_R + \text{h.c.}$$

in the UV complete model:

$$\mathcal{L}_{\rm UV} \supset \frac{\lambda_L}{\Lambda_{\rm UV}^{d_L-5/2}}\bar{q}_L\mathcal{B}_R + \frac{\lambda_R}{\Lambda_{\rm UV}^{d_R-5/2}}\bar{t}_R\mathcal{B}_L + \text{h.c.}$$



q_L, t_R spurion fields, $\mathcal{B}_{L,R}$ hyperbaryon fields $(\chi\psi\chi)$, in the $(\mathbf{5},\mathbf{3})$ of H_F

[Golterman & Shamir 15]

pNGB potential - elementary fermions

$$V(h) = \alpha \cos \frac{2H}{f} - \beta \sin^2 \frac{2H}{f}$$

[Ferretti 14]

where

$$2\alpha = -C_{LR}(3g^2 + g'^2) < 0$$
$$\beta = -2y^2 C_{\rm top}$$
$$\alpha + 2\beta > 0$$

$$C_{\rm top} \propto \int \frac{d^4p}{(2\pi)^4} \frac{d^4q}{(2\pi)^4} \frac{p_\mu}{p^2} \frac{q_\nu}{q^2} \langle \bar{\mathcal{B}}_{Rk}(p) \gamma_\mu P_R \mathcal{B}_{Ri}(p) \bar{\mathcal{B}}_{Li}(q) \gamma_\nu P_L \mathcal{B}_{lk}(p) \rangle$$

[Golterman & Shamir 15]

$$\boxed{\begin{aligned} \xi = v^2/f^2 = -\alpha/(2\beta) \\ \alpha/f^4 = \frac{1}{4} \frac{m_h^2}{v^2} \frac{\xi^2}{\xi - 1} \end{aligned}}$$

fermionic mass term

$\Psi \in (\mathbf{5},\mathbf{3})_{2/3}$ of $\mathrm{SO}(5)\times\mathrm{SU}(3)\times\mathrm{U}(1)$

$$\mathcal{L}_{\rm eff} \supset \frac{M}{2}\bar{\Psi}\Psi + \lambda_q f \bar{q}_L \Sigma \Psi_R + \lambda_t f \bar{t}_R \Sigma^* \Psi_L + \dots$$

$$\lambda_q = \lambda_L \left(\frac{\Lambda}{\Lambda_{\rm UV}}\right)^{\gamma_L} \sqrt{Z_B}\,, \quad \lambda_t = \lambda_R \left(\frac{\Lambda}{\Lambda_{\rm UV}}\right)^{\gamma_R} \sqrt{Z_B}$$

$$\Psi = \frac{1}{\sqrt{2}} \begin{pmatrix} iB - iX \\ B + X \\ iT + iY \\ -T + Y \\ \sqrt{2} iR \end{pmatrix}$$

$(T,B) \in (\mathbf{3},\mathbf{2})_{1/6}\,, \;\; R \in (\mathbf{3},\mathbf{1})_{2/3}\,, \;\; (X,Y) \in (\mathbf{3},\mathbf{2})_{7/6}$

fermionic mass term

quadratic term involving the fermion fields

$$\mathcal{L}_{\rm eff} \supset (\bar{t}_L, \bar{T}_L, \bar{Y}_L, \bar{R}_L) \cdot \mathcal{M}_T \cdot \begin{pmatrix} t_R \\ T_R \\ Y_R \\ R_R \end{pmatrix} + \dots$$

top quark mass given by the lowest eigenvalue:

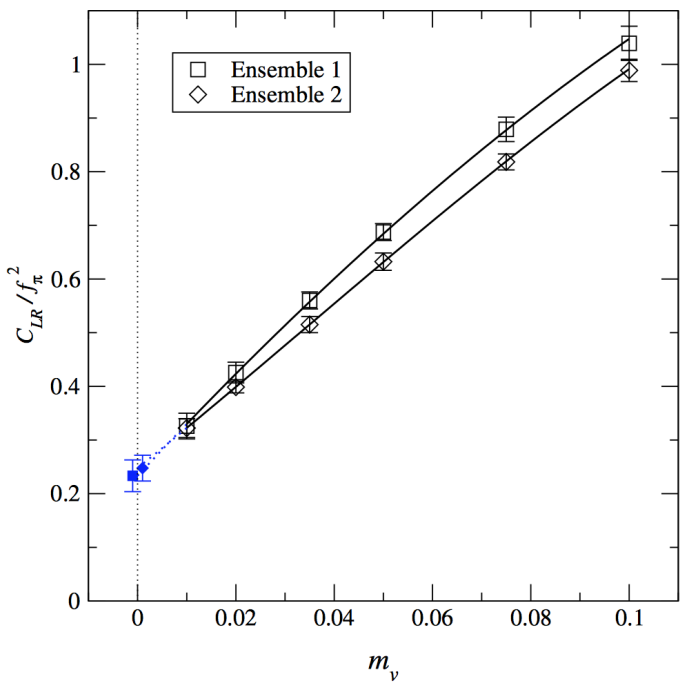
$$\boxed{m_t/v = \sqrt{2}\frac{f}{M}\frac{1}{\sqrt{1+\lambda_q^2\frac{f^2}{M^2}}\sqrt{1+\lambda_t^2\frac{f^2}{M^2}}}}$$

summary of lattice observables

- consensates driving $G_F \to H_F$, $\langle\psi\psi\rangle$, $\langle\chi\tilde{\chi}\rangle$
- f scale of SU(5) breaking, set the scale of simulations
- $C_{\rm LR}, C_{\rm top} \Longrightarrow \alpha, \beta$
  condition for EWSB & ξ
- anomalous dimensions of $\mathcal{B}_{L,R}$
- M mass of the baryon $\rho_M = f/M$
- rest of the spectrum

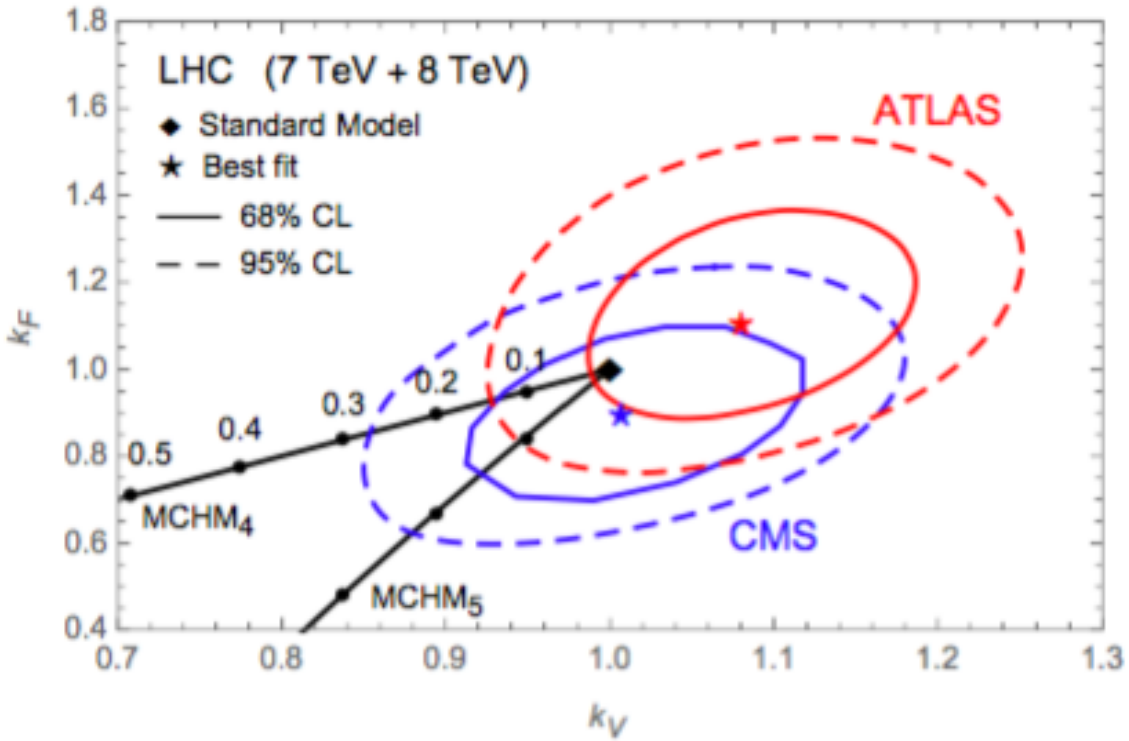
challenges for lattice simulations

- simulations with multiple representations
- extrapolation to the chiral limit
- computation of the baryonic spectrum [Degrand et al 16]
- computation of $C_{\rm LR}$, $C_{\rm top}$ (20% error) [Degrand et al 16]



phenomenology I - modified couplings

Ferretti's model similar to generic MCHM5, $k \sim \sqrt{1-\xi}$ [Contino et al 06]

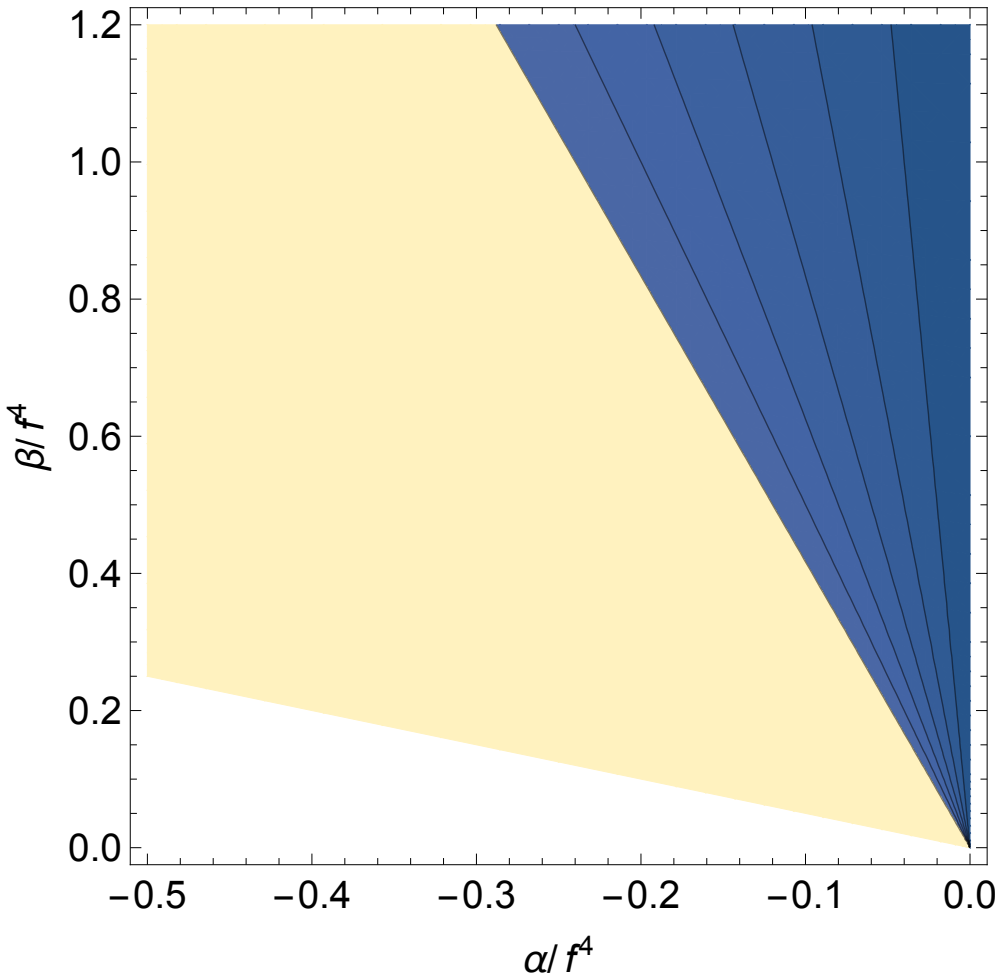


[Panico & Wulzer 15]

$$\xi < 0.15, \quad \xi \to 0 \Longleftrightarrow \mathrm{SM}$$

phenomenology I - modified couplings

$$\xi = -\alpha/(2\beta)$$



phenomenology II - our parameter scan

- $\xi \in [0, 0.1]$
- exotic Higgs masses: free parameters

$$m > 200 \text{ GeV} > m_H$$

- exotic top partners: $M > 1.5 \text{ TeV}$
  our scan: $M/\text{TeV} \in [1.5, 3.5]$

[Aad et al 12, CMS Collaboration 16, Matsedonskyi 15]

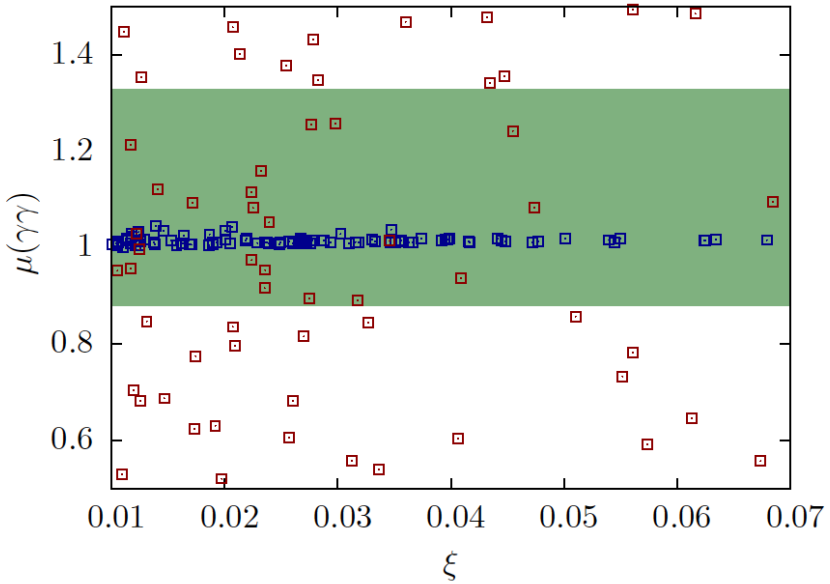
- $\lambda_t \in [0, 4\pi]$
  λ_q fixed by top mass

- pair produced color octet states: no evidence from Run-1, or first 13 TeV searches

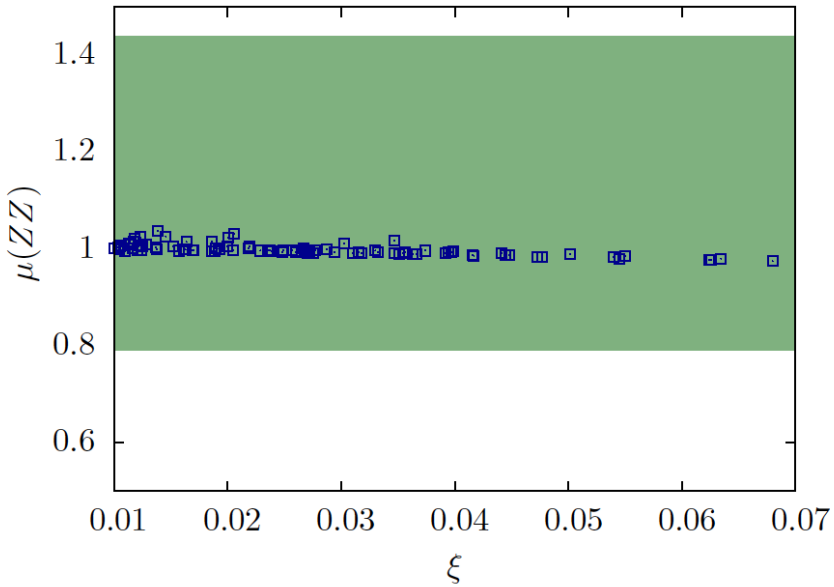
  $\text{SU}(3) \times \text{SU}(3) \to \text{SU}(3)$ breaking scale $> 6.5 \text{ TeV}$

[CMS]

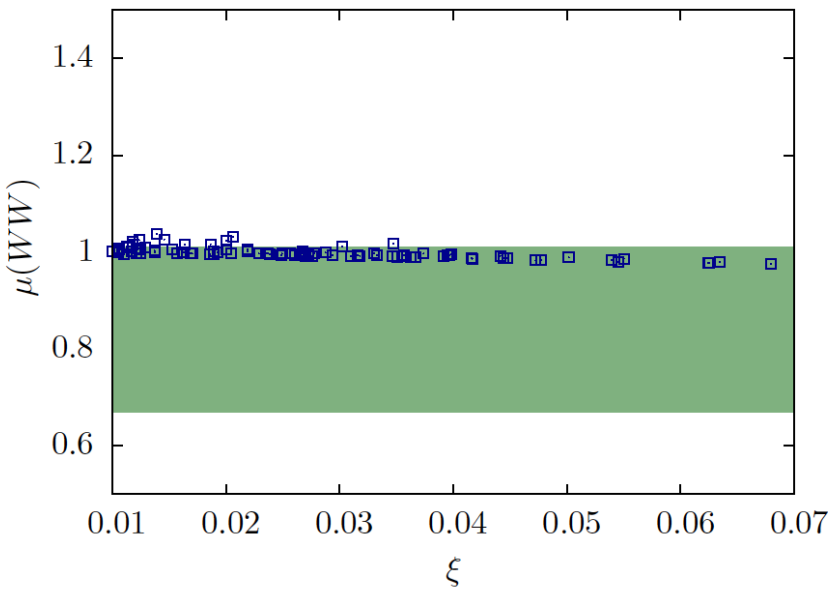
phenomenology III - Higgs signal strength



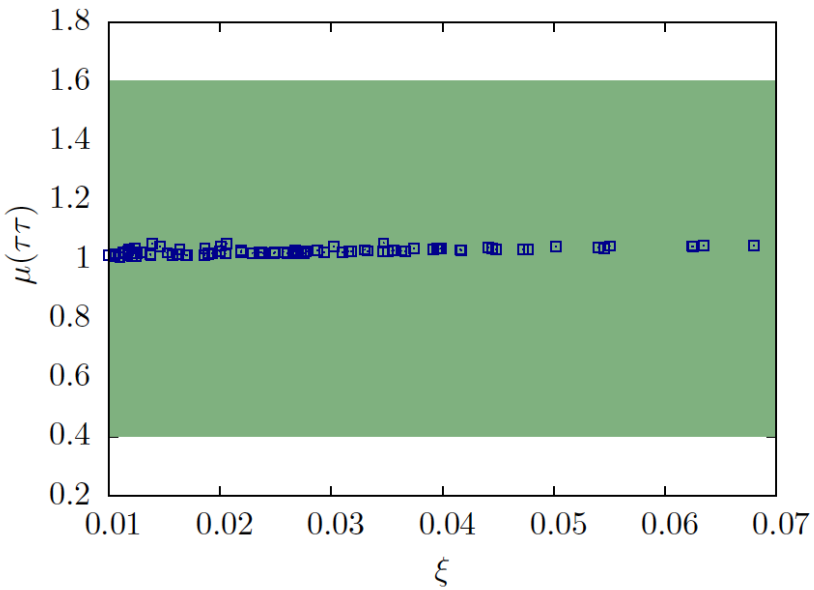
(a) $\gamma\gamma$ signal strength



(b) ZZ signal strength



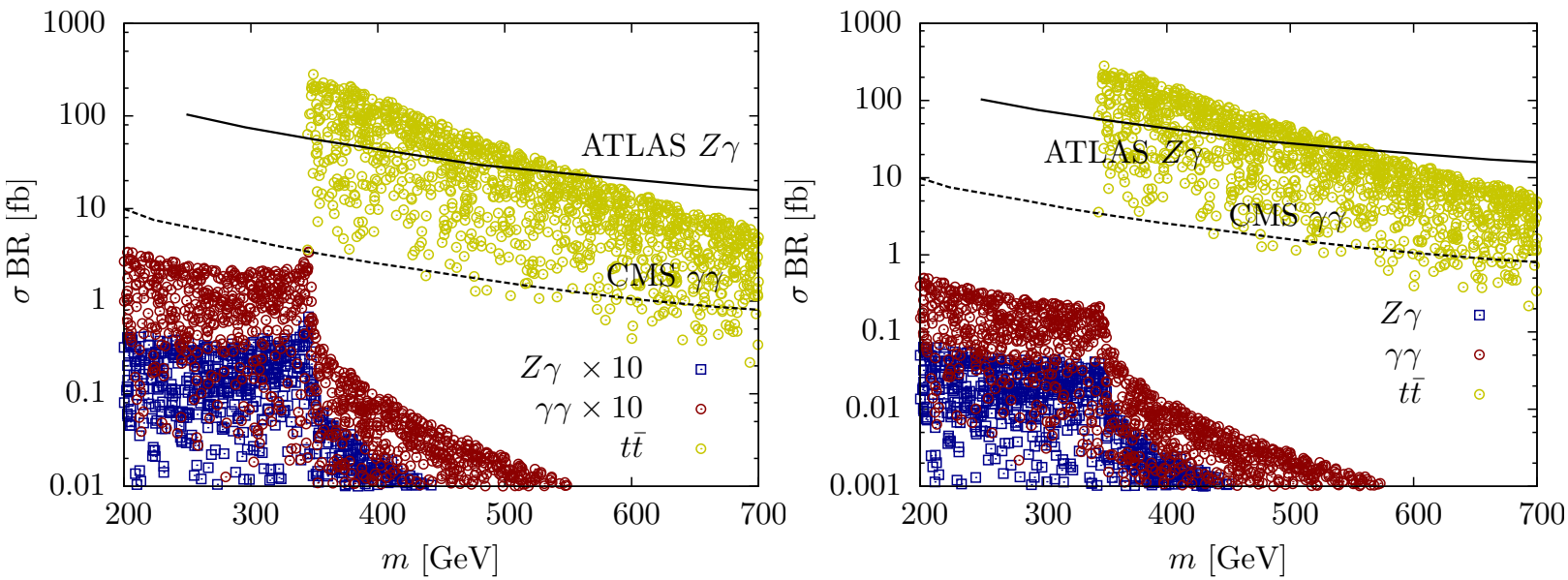
(c) WW signal strength



(d) $\tau\tau$ signal strength

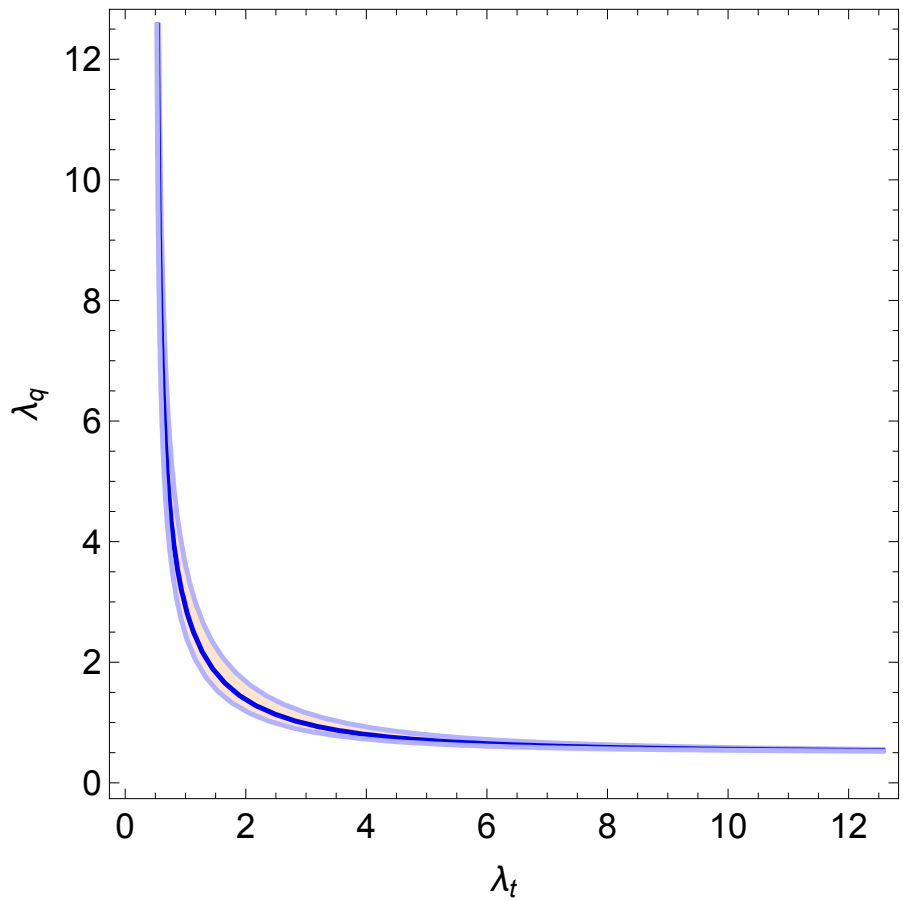
phenomenology IV - exotic Higgs

charged Higgs: LHC not sensitive
neutral Higgs: CP odd/even



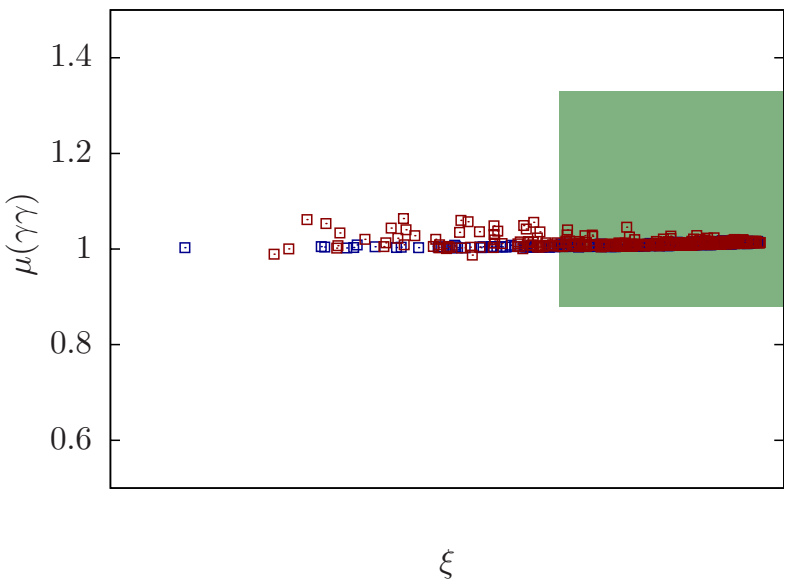
lattice constrained scan

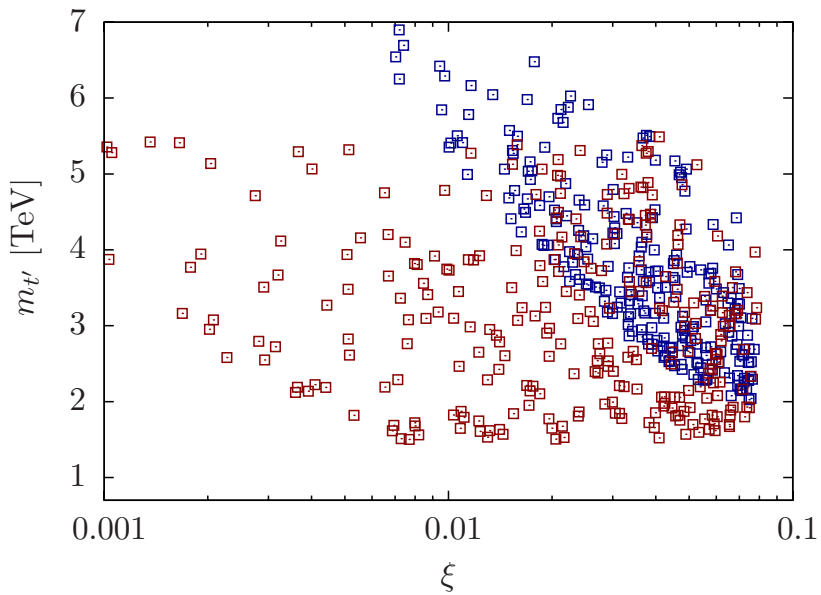
$$m_t/v = \sqrt{2}\frac{f}{M}\frac{1}{\sqrt{1+\lambda_q^2\frac{f^2}{M^2}}\sqrt{1+\lambda_t^2\frac{f^2}{M^2}}}\,, \qquad \rho_M = f/M = 0.2 \pm 0.04$$



lattice constrained scan

use $\rho_M \in [0.2, 0.47]$





work in progress

Ferretti's model is not ruled out by LHC Run1 data

Strong constraints from a lattice computation of α and β

Uncertainty dominated by experimental data currently

The lattice simulation is a difficult computation...

Which UV completion? Nature has not been kind so far...

... theoretical tools, new observables being developed