LHC Data & Aspects of New Physics

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Alanne,SDC,Tuominen; arXiv:1303.3615

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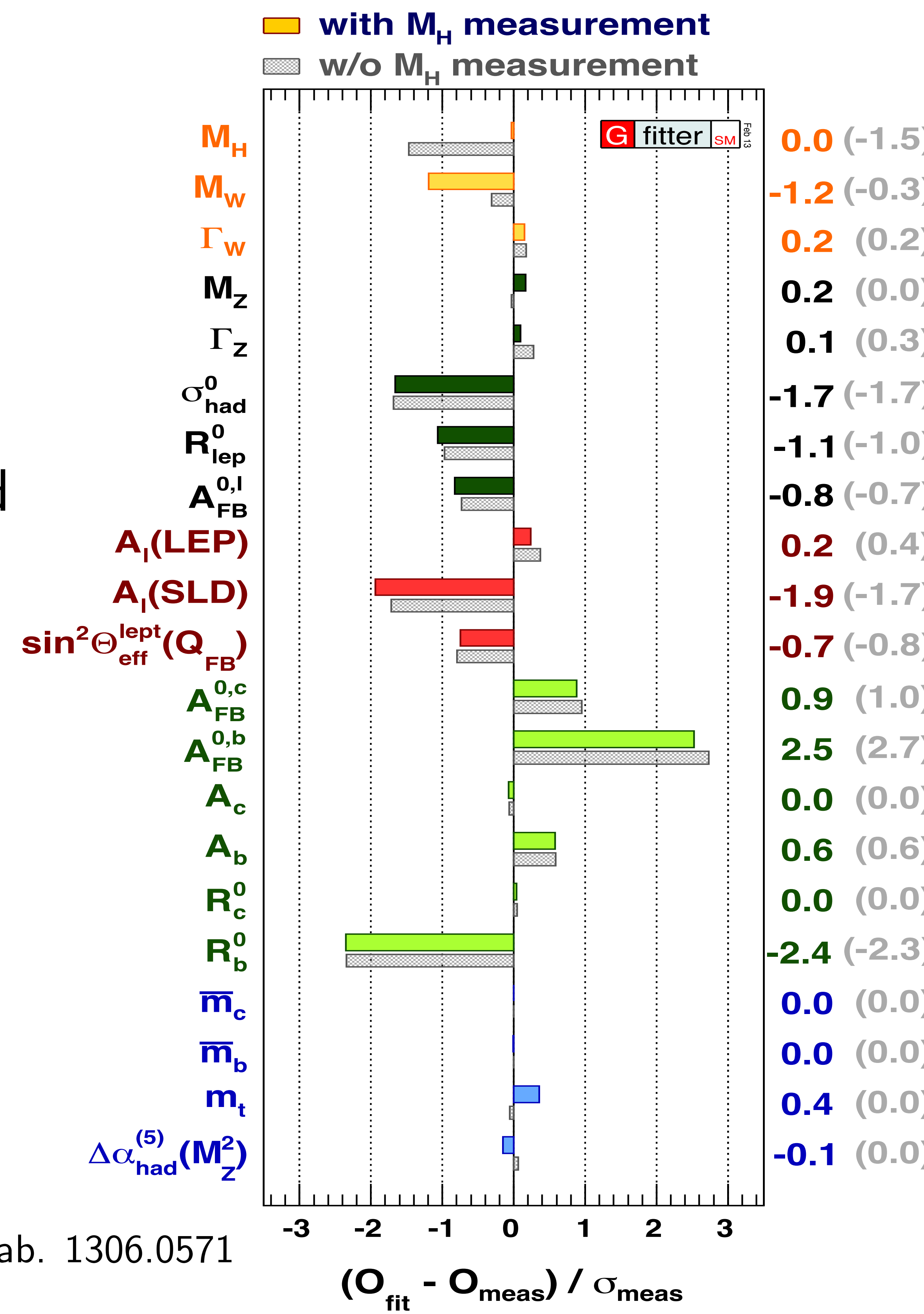
Outline

- LHC data and Need for New Physics
- Technicolor (TC), Extended TC, and Near-Conformality
- Goodness of Fit Analysis of a TC Model
- Conclusions

EW Observables

All the Standard Model (SM) free parameters can be determined from experiment: the SM fits satisfactorily the data.

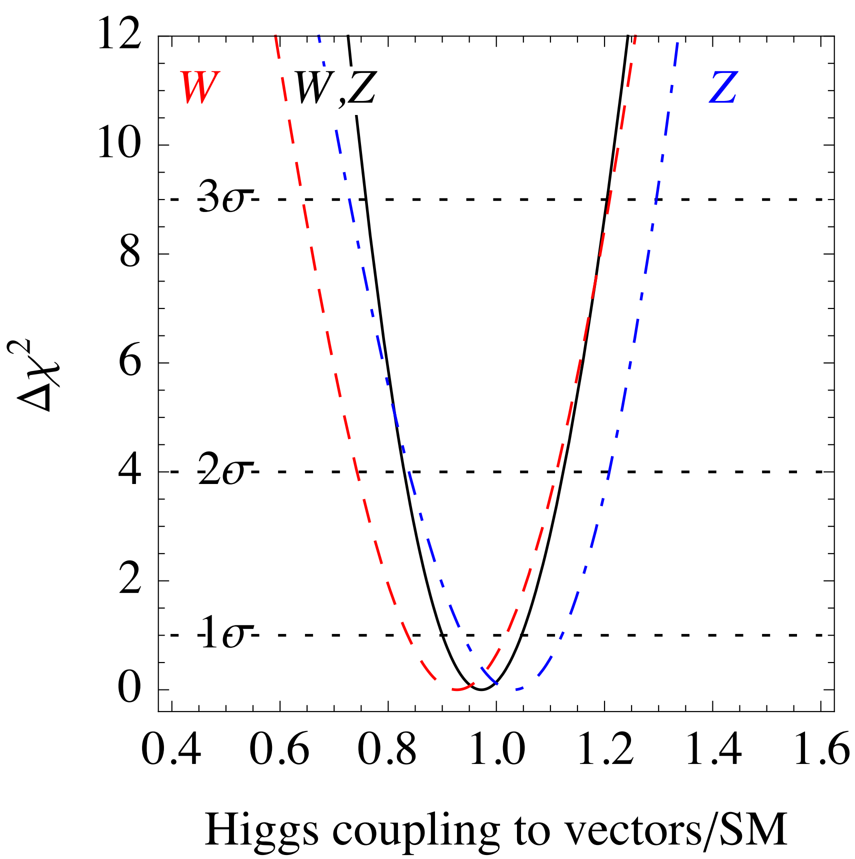
No deviation between prediction and measurement of EW observables is larger than 3 σ:

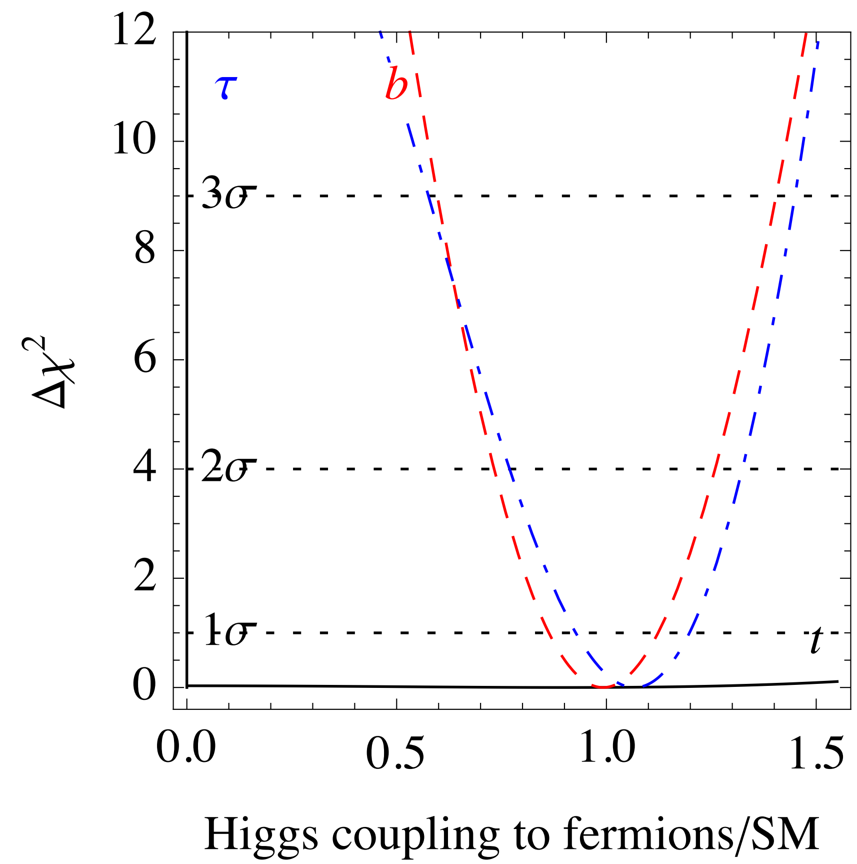


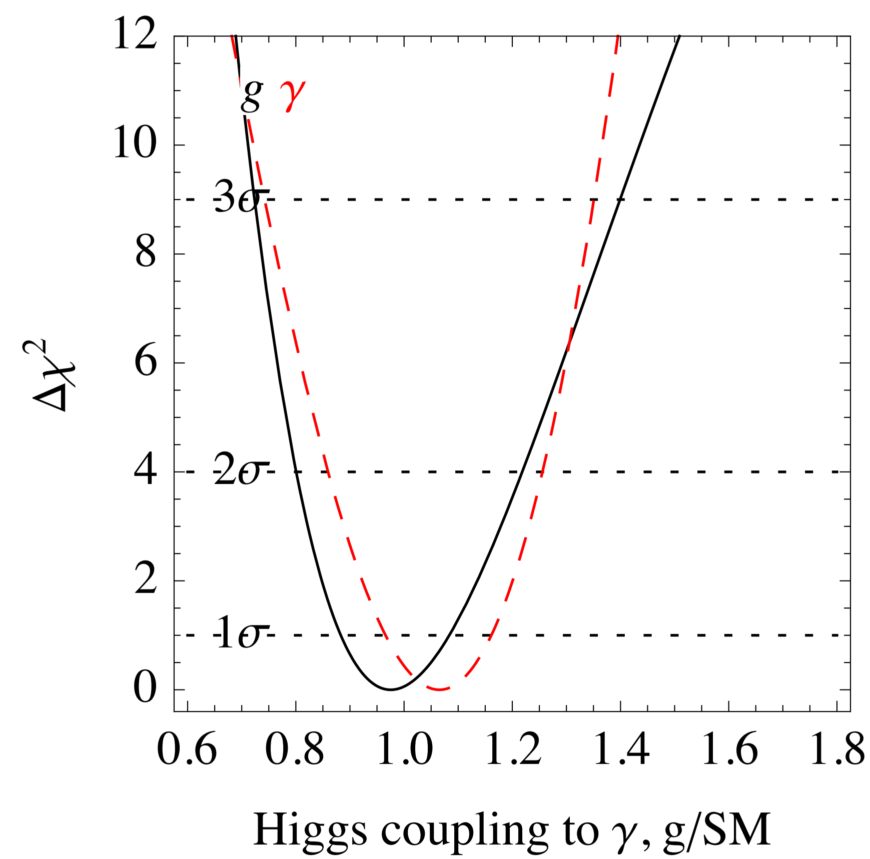
GFitter collab. 1306.0571

Higgs Linear Couplings

The measured Higgs boson couplings fit within 1 σ the SM prediction:







Only tension in $H \to \gamma\gamma$ coupling strength measured by ATLAS:

$$a_{\gamma\gamma}^{\text{ATLAS}} = 1.65^{+0.35}_{-0.30}\,, \quad a_{\gamma\gamma}^{\text{CMS,MVA}} = 0.78^{+0.28}_{-0.26}\,, \quad a_{\gamma\gamma}^{\text{CMS,Cut-B.}} = 1.11^{+0.32}_{-0.30}$$

New physics states lower limits generally at $O(1)$ TeV.

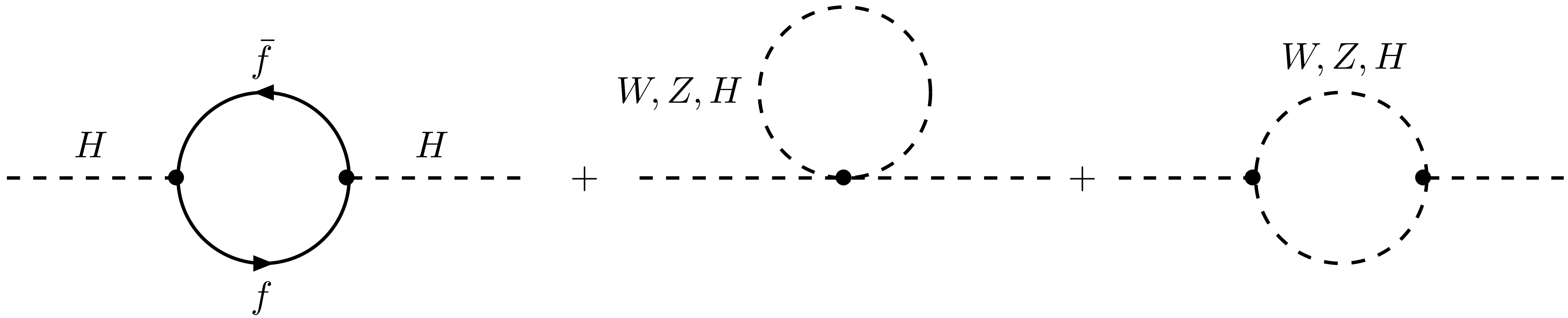
Giardino et al. 1303.3570 ATLAS-CONF-2013-012 CMS-PAS-HIG-13-001

SM Fine Tuning

SM Higgs mass at one loop:

$$M_H^2 = \left(M_H^0\right)^2 + \Delta M_H^2, \quad \left(M_H^0\right)^2 = \frac{\lambda v^2}{2},$$

$$\Delta M_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left(M_H^2 - 4m_t^2 + 2M_W^2 + M_Z^2\right) + O\left(\log\frac{\Lambda^2}{v^2}\right) =$$



If $\Lambda = 2.4 \times 10^{18}$ GeV (Planck scale) $\Rightarrow \frac{\Delta M_H^2}{M_H^2} \simeq 10^{32}$: λ has to be fixed up to the 32nd digit to cancel miraculously the quantum correction ...

Dynamical EW Symmetry Breaking

In QCD at a scale Λ_{QCD} the interaction becomes strong and the quarks form a bound state with non-zero vev:

$$\langle 0|\,\bar{u}_L u_R+\bar{d}_L d_R\,|0\rangle \neq 0\,,\; T_L^3+Y_L = Y_R = Q \;\Rightarrow\; SU(2)_L\times U(1)_Y \rightarrow U(1)_{EM}$$

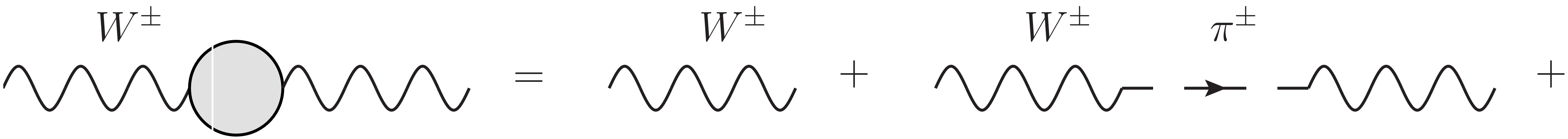
Redefine fields in terms of composite colorless states, like pions:

$$q=(u,d)\,,\;\; j_{5a}^{\mu}=\bar{q}\gamma^{\mu}\gamma^{5}\frac{\tau_a}{2}q=f_{\pi}\partial^{\mu}\pi_a$$

and plug in $\mathcal{L}_{k-f}$

$$\mathcal{L}_{k-f}\supset\frac{g}{2}f_{\pi^+}W_{\mu}^{+}\partial^{\mu}\pi^{+}+\frac{g}{2}f_{\pi^-}W_{\mu}^{-}\partial^{\mu}\pi^{-}+\frac{g}{2}f_{\pi^0}W_{\mu}^{0}\partial^{\mu}\pi^{0}+\frac{g'}{2}f_{\pi^0}B_{\mu}^{+}\partial^{\mu}\pi^{0}$$

QCD



$$= \frac{1}{p^2} + \frac{1}{p^2}(gf_{\pi^\pm}/2)^2\frac{1}{p^2} + \ldots = \frac{1}{p^2 - (gf_{\pi^\pm}/2)^2}$$

The EW bosons have acquired mass:

$$M_W^{QCD} = gf_{\pi^\pm}/2,\ \ \rho = \frac{M_W^{QCD}}{\cos\theta_w M_Z^{QCD}} = 1,$$

Given the experimental value for the pion decay constant

$$f_\pi = 93\,\mathrm{MeV} \quad \Rightarrow \quad M_W^{QCD} = 29\,\mathrm{MeV!}$$

Technicolor

The effective Lagrangian expansion breaks down at

$$\Lambda_{QCD} \simeq 4\pi f_\pi = 1.2\,\mathrm{GeV} \Rightarrow \Lambda_{TC} \simeq 4\pi v = 3\,\mathrm{TeV},\; v = 246\ \mathrm{GeV}\,.$$

A Technicolor (TC) model able to give the right masses to the EW gauge bosons is simply "scaled up" QCD:

$$SU(N)_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y\,.$$

No fundamental scalar $\Rightarrow$ no fine-tuning!

The mass spectrum can be estimated by multiplying the mass of QCD composite states by v/f_π.

Susskind '79

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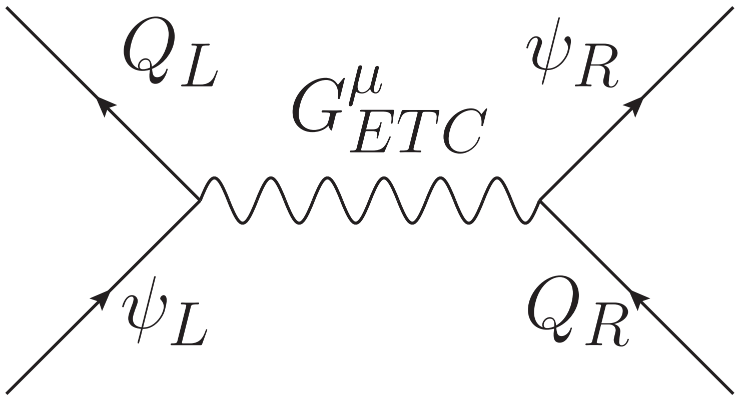
To generate the SM fermion masses an Extended Technicolor (ETC) interaction is necessary.

Susskind '79

Extended Technicolor

If the ETC gauge group gets broken at some large scale $\Lambda_{ETC} \gg \Lambda_{TC}$, the massive ETC gauge bosons can be integrated out.

Four fermion interactions, technifermion condensate $\Rightarrow$ SM mass terms



$$\rightarrow \frac{g^2_{ETC}}{M^2_{ETC}} (\bar{Q}_L Q_R)(\bar{\psi}_R \psi_L) \Rightarrow m_\psi \approx \frac{g^2_{ETC}}{M^2_{ETC}} \langle \overline{Q} Q \rangle \ .$$

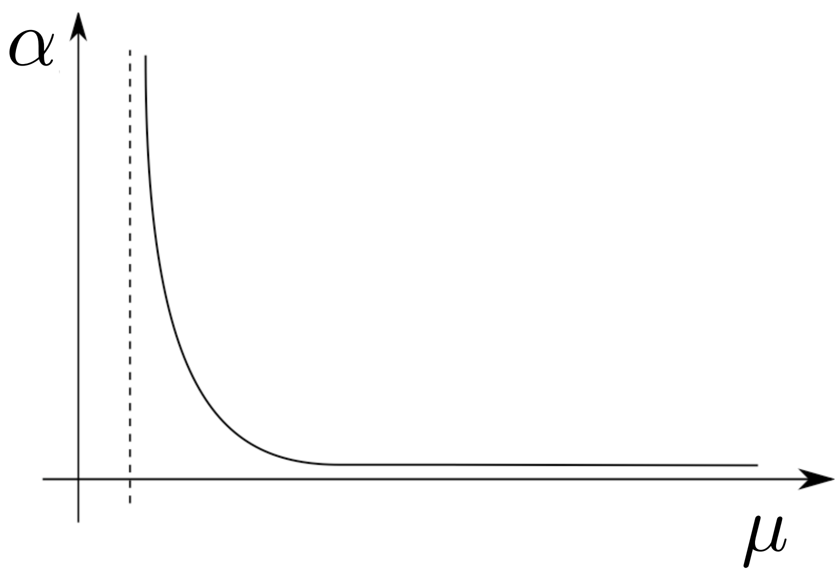
The lowest ETC scale is determined by the heaviest mass:

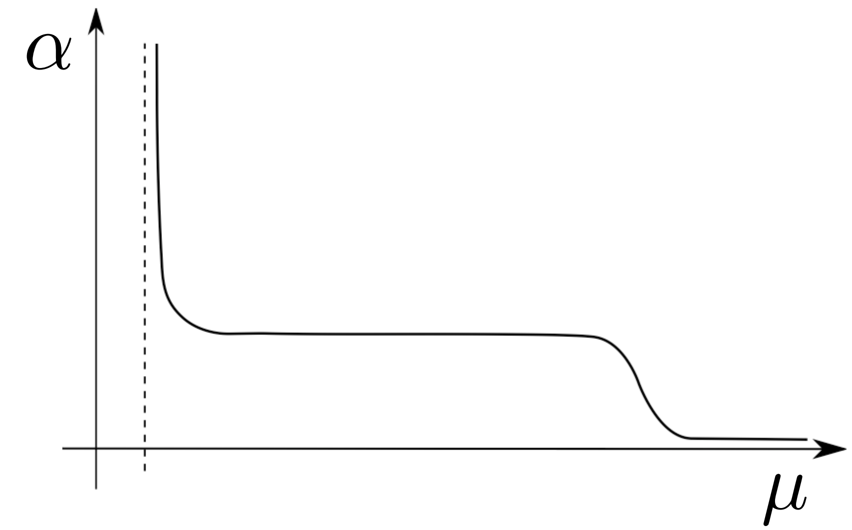
$$m_t = 173 \text{ GeV} \approx \frac{\Lambda^3_{TC}}{\Lambda^2_{ETC}} \Rightarrow \Lambda_{ETC} \simeq 10 \, \text{TeV}$$

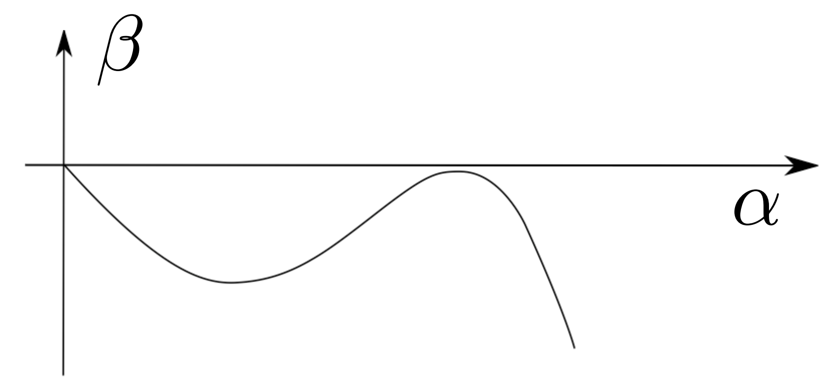
This limit would be incompatible with FCNC which require $\Lambda_{ETC} > 10^4$ TeV, but...

Eichten, Lane '80

Running vs Walking TC







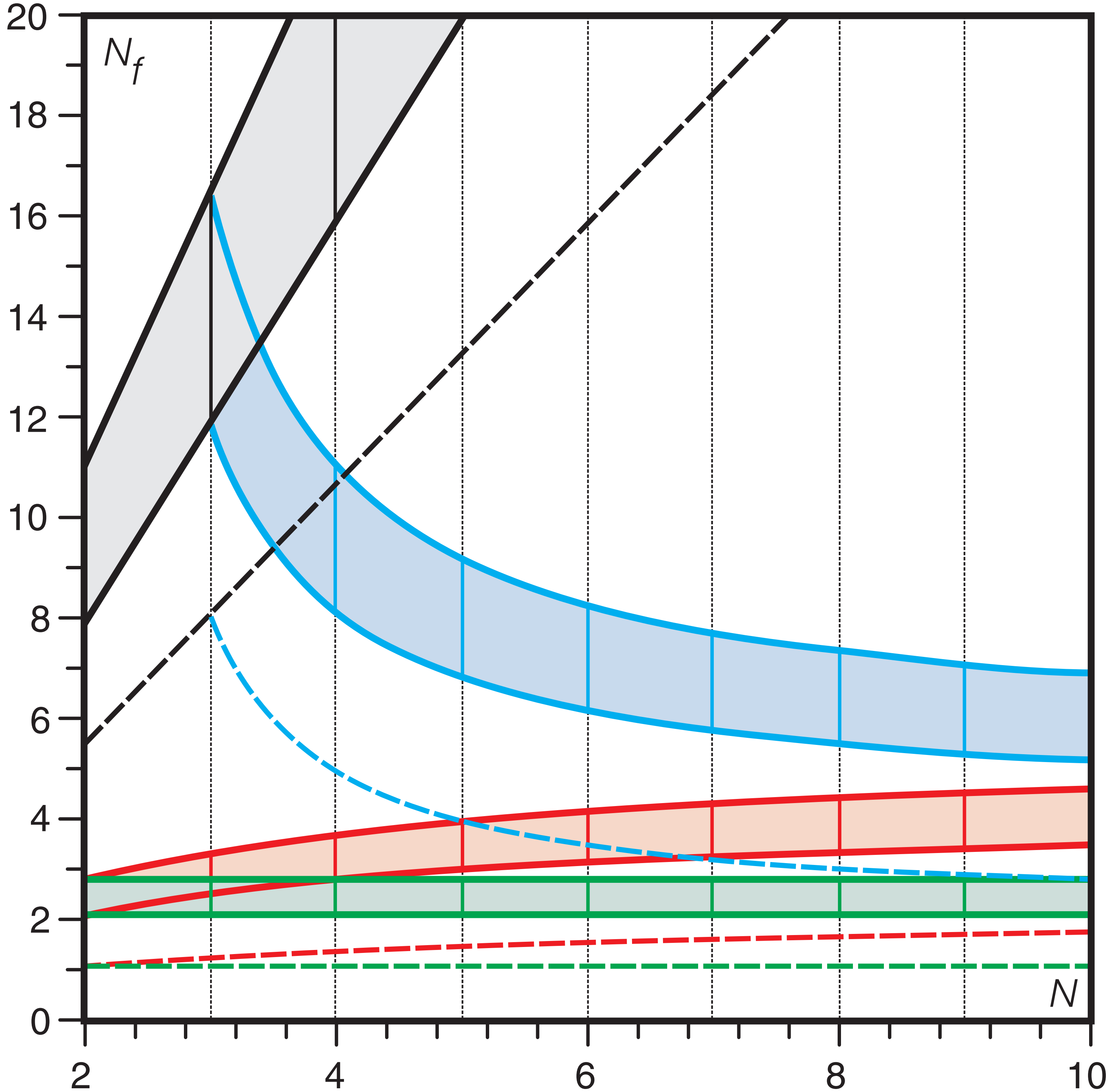
for $\Lambda_{ETC} > \mu > \Lambda_{TC}$:

- Running TC: $\alpha(\mu) \propto \frac{1}{\ln \mu}, \Rightarrow \langle \overline{Q}Q \rangle_{ETC} \simeq \langle \overline{Q}Q \rangle_{TC}$
- Walking TC: $\beta(\alpha_*) = 0 \Rightarrow \langle \overline{Q}Q \rangle_{ETC} \simeq \langle \overline{Q}Q \rangle_{TC} \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)^{\gamma_m(\alpha_*)}$

Walking TC obtains big boost to fermion masses, FCNC are unaffected.

Yamawaki et al. '86, Appelquist et al '86

Walking in the SU(N)



Dietrich, Tuominen, Sannino '05; Dietrich, Sannino '06

Phase diagram for theories with fermions in the:

- fundamental representation (grey)
- two-index antisymmetric (blue)
- two-index symmetric (red)
- adjoint representation (green)

The S parameter for a TC model is estimated by:

$$S_{th} \approx \frac{1}{6\pi} \frac{N_f}{2} d(\mathrm{R}),$$

$$12\pi\, S_{exp} \leq 6 \text{ @ } 95\%$$

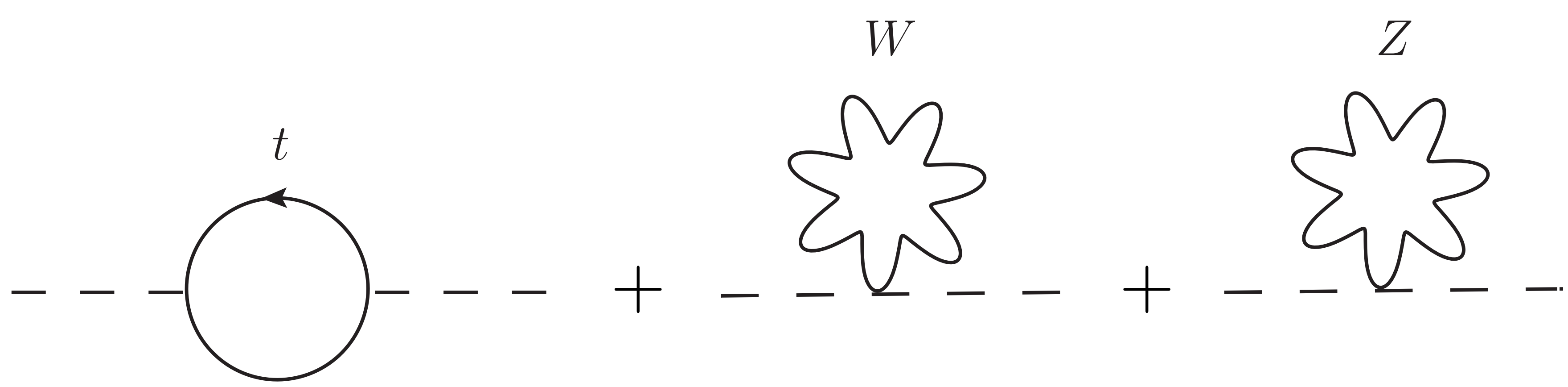
Higgs Mass

In QCD the composite scalar is σ (or $f_0(500)$ in PDG):

$$M_\sigma = 400 - 550 \text{ MeV} \quad \Rightarrow \quad M_H^{TC} \simeq M_\sigma v/f_\pi = 1 - 1.4 \text{ TeV}$$

To this estimate one must add also the (Higgsless) SM loop corrections:

$$M_H^2 \simeq \left(M_H^{TC}\right)^2 + \frac{3 f_\Pi^2}{v^2}\left[-4 r_t^2 m_t^2 + 2 s_\pi \left(m_W^2 + \frac{m_Z^2}{2}\right)\right], \quad r_t, s_\pi = O(1)\ .$$

$\Delta M_H^2 =$ 

For SM-like $f_\Pi = v, r_t = s_\pi = 1, M_H = 125 \text{ GeV} \Rightarrow M_H^{TC} = 550$ GeV.

Foadi et al. '12

Techni-Dilaton

Dilaton=Goldstone boson associated with conformal invariance:

$$\langle 0 \mid \Theta^\mu_\mu \mid D \rangle = -f_D m_D^2 \ , \quad \Theta^\mu_\mu = \beta \frac{\partial \mathcal{L}}{\partial g} \ .$$

For a walking theory $\beta \propto \alpha_c(\alpha_* - \alpha_c)$ is close to zero, therefore

$$m_D^2(N_f^*) \propto N_f^c - N_f^* \ll 1$$

If one could measure $m_D(N_f^* = 1) \equiv 1$ TeV, for two techni-fermions in the symmetric representation ($N_f^c = 2.5$), one would find

$$m_D(N_f^*) = M_H^{TC} = \sqrt{\frac{N_f^c - 2}{N_f^c - 1}} \ \mathrm{TeV} = 600 \ \mathrm{GeV} \ ,$$

which together with the SM loop corrections would be enough to generate $m_H = 125$ GeV.

Dietrich, Tuominen, Sannino '05; Yamawachi et al. '12

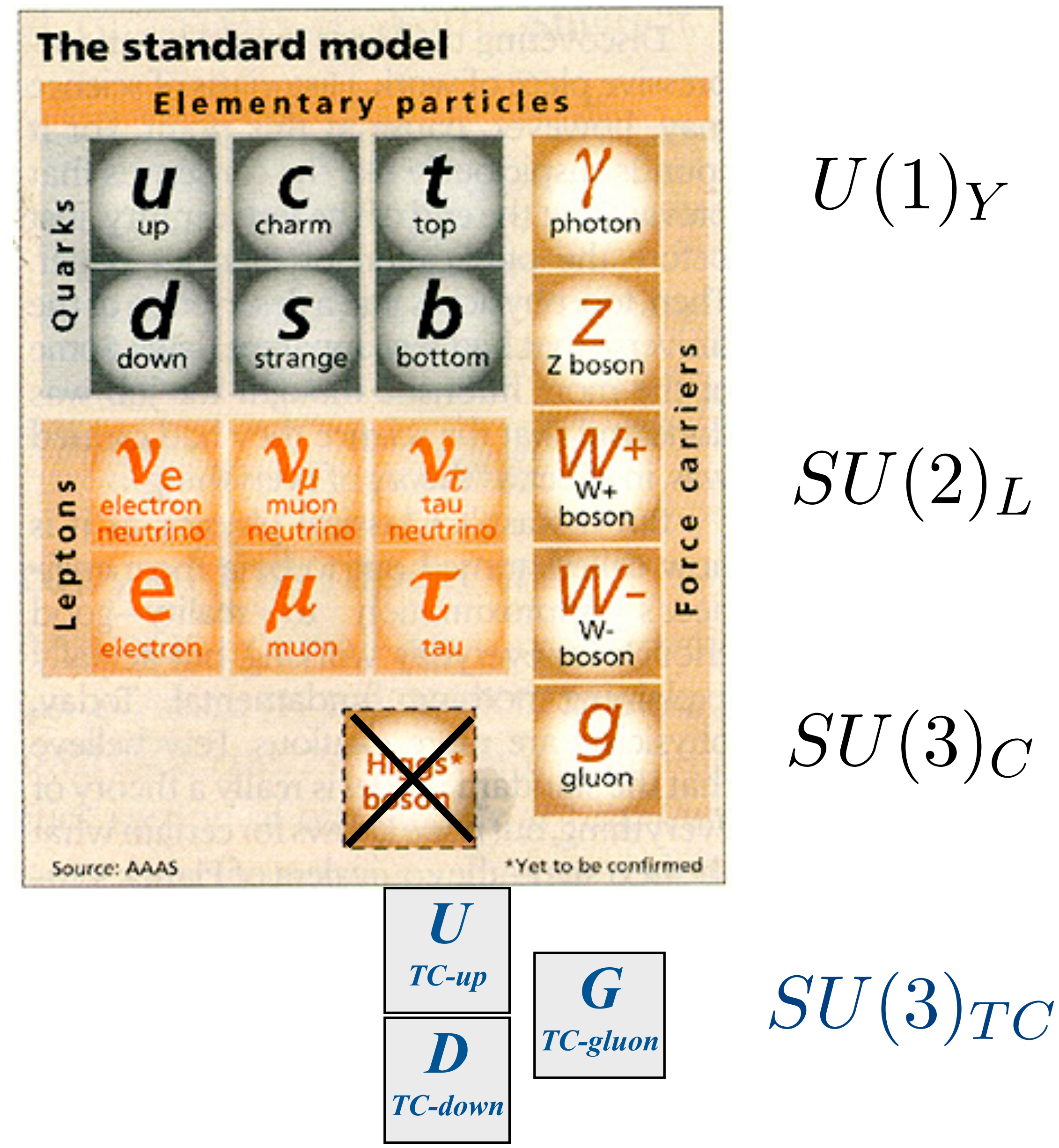
Next to Minimal Walking Technicolor

TC-fermions in the $SU(3)_{TC}$ 2-index symmetric representation: $a = 1, 2, 3$;

$$Q_L^a = \begin{pmatrix} U_L^a \\ D_L^a \end{pmatrix}, \quad Q_R^a = \begin{pmatrix} U_R^a \\ D_R^a \end{pmatrix} .$$

Gauge anomalies cancel for hypercharge assignment

$$Y(Q_L) = 0, \; Y(U_R, D_R) = \left(\frac{1}{2}, -\frac{1}{2}\right) .$$



TC Lagrangian

The elementary TC Lagrangian has a global $SU(2)_L \times SU(2)_R$ symmetry:

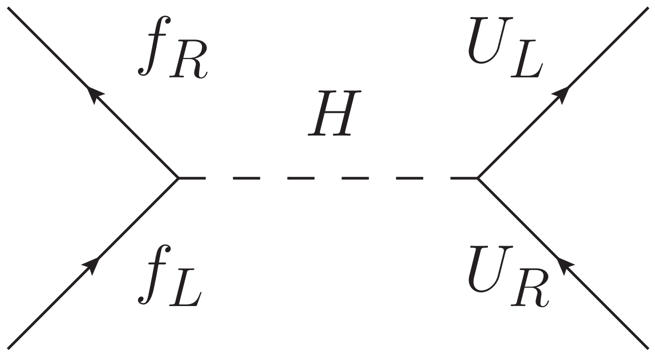
$$\mathcal{L}_{TC} = -\frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^{a\mu\nu} + i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{U}_R\gamma^\mu D_\mu U_R + i\bar{D}_R\gamma^\mu D_\mu D_R,$$

with the covariant derivatives defined by the fields' quantum numbers. The chiral symmetry is broken by the condensate:

$$\langle Q^\alpha_{Ri}\bar{Q}^\beta_{Li}\epsilon_{\alpha\beta}\rangle \neq 0 \qquad \Rightarrow \qquad SU(2)_L \times SU(2)_R \to SU(2)_V$$

The 3 Nambu-Goldstone bosons are absorbed by the Z and W bosons.

Bosonic Technicolor



$$\rightarrow \frac{y_f y_U}{m_H^2}(\bar{U}_L U_R)(\bar{\psi}_R \psi_L) \Rightarrow m_f \approx \frac{y_f y_U}{m_H^2}\Lambda_{TC}^3$$

- No know viable ETC theory exists
- A scalar field coupling with the fermions provides a device to transmit EW symmetry breaking to the SM matter sector
- The scalar can be part of a supersymmetric theory or a composite originating from a dynamical ETC sector

We introduce a SM Higgs scalar with $\mu^2 > 0$ and

$$\mathcal{L} \supset y_{TC} \bar{Q}_L H Q_R \ .$$

Low Energy Lagrangian

Effective Lagrangian has the same global symmetry as fundamental one:

$$\begin{aligned}\mathcal{L}_{\rm bTC} &= D_\mu M^\dagger D^\mu M - m_M^2 M^\dagger M - \frac{\lambda_M}{3!}\left(M^\dagger M\right)^2 \\ &+ \Big[c_3 y_{TC} D_\mu M^\dagger D^\mu H + c_1 y_{TC} f^2 M^\dagger H + \frac{c_2 y_{TC}}{3!}(M^\dagger M)(M^\dagger H) \\ &+ \frac{c_4 y_{TC}}{3!}\lambda_H (H^\dagger H)(M^\dagger H) + \text{h.c.}\Big]\ ,\end{aligned}$$

$$M \sim Q_L \bar{Q}_R\ , \quad M \to u_L M \bar{u}_R\ , \quad \text{with} \quad u_{L,R} \in SU(2)_{L,R}\,.$$

The model that we consider is specified by the effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm bTC},$$

where $\mathcal{L}_{\rm SM}$ contains the SM sectors $\mathcal{L}_{\rm Higgs}$ and $\mathcal{L}_{\rm Yuk}$.

Antola,Tuominen,Sannino '09

EW Symmetry Breaking

The coefficients c_i are estimated by naive dimensional analysis:

$$c_1 \sim \omega\ , \quad c_2 \sim \omega\ , \quad c_3 \sim \omega^{-1}\ , \quad c_4 \sim \omega^{-1}\ ; \quad \omega \lesssim 4\pi\ .$$

The vevs of M and H are constrained by m_W:

$$v_w^2 = v^2 + f^2 + 2c_3 y_{TC} f v = (246\ \mathrm{GeV})^2\ , \quad \langle M \rangle = \frac{f}{\sqrt{2}}\ , \quad \langle H \rangle = \frac{v}{\sqrt{2}}\ .$$

bNMWT low energy theory is equivalent to type-I 2Higgs Doublet Model:

$$\begin{pmatrix} M \\ H \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} A & B \\ -A & B \end{pmatrix} \begin{pmatrix} M_2 \\ M_1 \end{pmatrix}\ , \ A = \frac{1}{\sqrt{1 - c_3 y_{TC}}},\ B = \frac{1}{\sqrt{1 + c_3 y_{TC}}}.$$

Experimental Validation

Parametrization of Lagrangian sector relevant for Higgs physics at LHC:

$$\mathcal{L}_{\text{eff}} = a_V \frac{2m_W^2}{v_w} h W_\mu^+ W^{-\mu} + a_V \frac{m_Z^2}{v_w} h Z_\mu Z^\mu - a_f \sum_{\psi=t,b,\tau} \frac{m_\psi}{v_w} h \bar{\psi}\psi$$
$$+ a_{V'} \frac{2m_{W'}^2}{v_w} h W_\mu'^+ W'^{-\mu} - a_S \frac{2m_S^2}{v_w} h S^+ S^- ,$$

In bNMWT:

$$a_V = s_{\beta-\alpha} , \quad a_f = \frac{c_{\alpha-\rho}}{s_{\beta-\rho}} , \quad \text{with} \quad s_\rho = \sqrt{\frac{1 - c_3 y_{TC}}{2}} ,$$

where α and β are the mixing angles of the neutral and charged scalars, respectively, and $s_\alpha, c_\alpha, t_\alpha = \sin\alpha, \cos\alpha, \tan\alpha$.

Alanne, SD, Tuominen '13

Higgs Physics Data

Signal strengths defined by

$$\hat{\mu}_{ij} = \frac{\sigma_{\rm tot}{\rm Br}_{ij}}{\sigma_{\rm tot}^{\rm SM}{\rm Br}_{ij}^{\rm SM}} \ , \quad {\rm Br}_{ij}^{\rm SM} = \frac{\Gamma_{h\to ij}}{\Gamma_{\rm tot}} \ .$$

Measured values for inclusive processes used in the fit:

ij	ATLAS	CMS	Tevatron
ZZ	1.50 ± 0.40	0.91 ± 0.27	
$\gamma\gamma$	1.65 ± 0.32	1.11 ± 0.31	6.20 ± 3.30
WW	1.01 ± 0.31	0.76 ± 0.21	0.89 ± 0.89
$\tau\tau$	0.70 ± 0.70	1.10 ± 0.40	
bb	-0.40 ± 1.10	1.30 ± 0.70	1.54 ± 0.77

Higgs Physics Data

For exclusive processes total cross section defined by

$$\sigma_{\text{tot}} = \sum_{\Omega = h, qqh, \ldots} \epsilon_\Omega \sigma_{pp \to \Omega}$$

Measured values for exclusive processes used in the fit:

	ATLAS 7TeV	ATLAS 8TeV	CMS 7TeV	CMS 8TeV
$\gamma\gamma JJ$	2.7 ± 1.9	2.8 ± 1.6	2.9 ± 1.9	0.3 ± 1.3
$pp \to h$	22.5%	45.0%	26.8%	46.8%
$pp \to qqh$	76.7%	54.1%	72.5%	51.1%
$pp \to t\bar{t}h$	0.6%	0.8%	0.6%	1.7%
$pp \to Vh$	0.1%	0.1%	0%	0.5%

New Physics Predictions

The new physics predictions are obtained from the SM ones

$$\hat{\Gamma}_{ij} \equiv \frac{\Gamma_{h\to ij}}{\Gamma^{\rm SM}_{h_{\rm SM}\to ij}} \ , \qquad \hat{\sigma}_\Omega \equiv \frac{\sigma_{\omega\to\Omega}}{\sigma^{\rm SM}_{\omega\to\Omega}},$$

in terms of the coupling coefficients in the effective Lagrangian:

$$\begin{aligned} \hat{\sigma}_{hqq} = \hat{\sigma}_{hA} = \hat{\Gamma}_{AA} = |a_V|^2 \quad &, \qquad \hat{\sigma}_{h\bar{t}t} = \hat{\sigma}_h = \hat{\Gamma}_{gg} = \hat{\Gamma}_{\psi\psi} = |a_f|^2 \ , \\ A = W, Z \quad &; \qquad \psi = b, \tau, c, \ldots \end{aligned}$$

The diphoton final states are produced through a loop triangle diagram, and the decay rate is a function of $a_f, a_V, a_S, a_{V'}$ and of the mass spectrum.

Data Fit

To determine the experimentally favored values of the free parameters $a_f, a_V, a_{V'}, a_S$, we minimize the quantity

$$\chi^2 = \sum_i \left(\frac{\mathcal{O}_i^{\rm exp} - \mathcal{O}_i^{\rm th}}{\Delta^{\rm exp}} \right)^2 ,$$

with $\mathcal{O}^{\rm exp}$ being the experimental measurements (with uncertainty Δ) and $\mathcal{O}_i^{\rm th}$ the theoretical predictions of the Higgs coupling strengths. The best fit values are

$$a_V = 0.97^{+0.10}_{-0.11} , \quad a_f = 1.02^{+0.25}_{-0.32}, \quad a_S = -4.4^{+3.8}_{-3.3} ,$$

with goodness of fit determined by

$$\chi^2_{\rm min}/{\rm d.o.f.} = 0.85 , \quad P\left(\chi^2 > \chi^2_{\rm min}\right) = 62\% , \quad {\rm d.o.f.} = 14.$$

Parameter Space Scan

We minimize the potential and scan the parameter space for viable data points:

- Experimental constraints: all SM particle masses matched to experiment, plus constraints on new physics:

$$m_{H^\pm} = m_{A^0} > 100 \text{ GeV} \ , \ m_{H^0} > 600 \text{ GeV} \ , \ |\frac{s_{\alpha-\rho}}{s_{\beta-\rho}}| < 1 \ ,$$

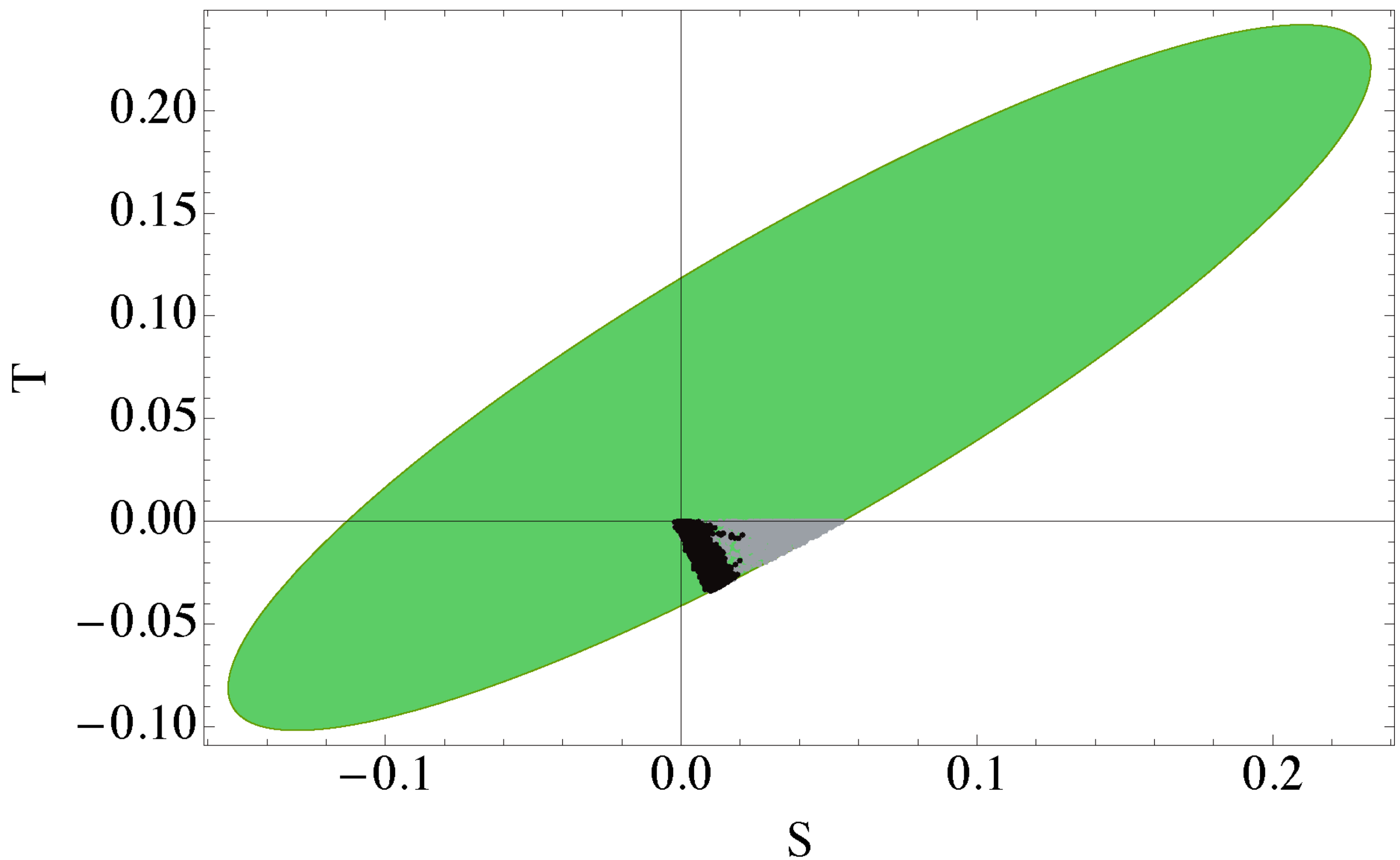
  as well as the constraints on the S & T EW parameters.

- Theoretical constraints:

$$0 < \lambda_H, \lambda_M < (2\pi)^2 \ , \ 2\pi < |c_1|, |c_2|, |c_3^{-1}|, |c_4^{-1}| < 8\pi \ \ |y_\psi| < 2\pi \ ,$$

  as well as a $5\Lambda_{TC}$ cutoff on the mass spectrum.

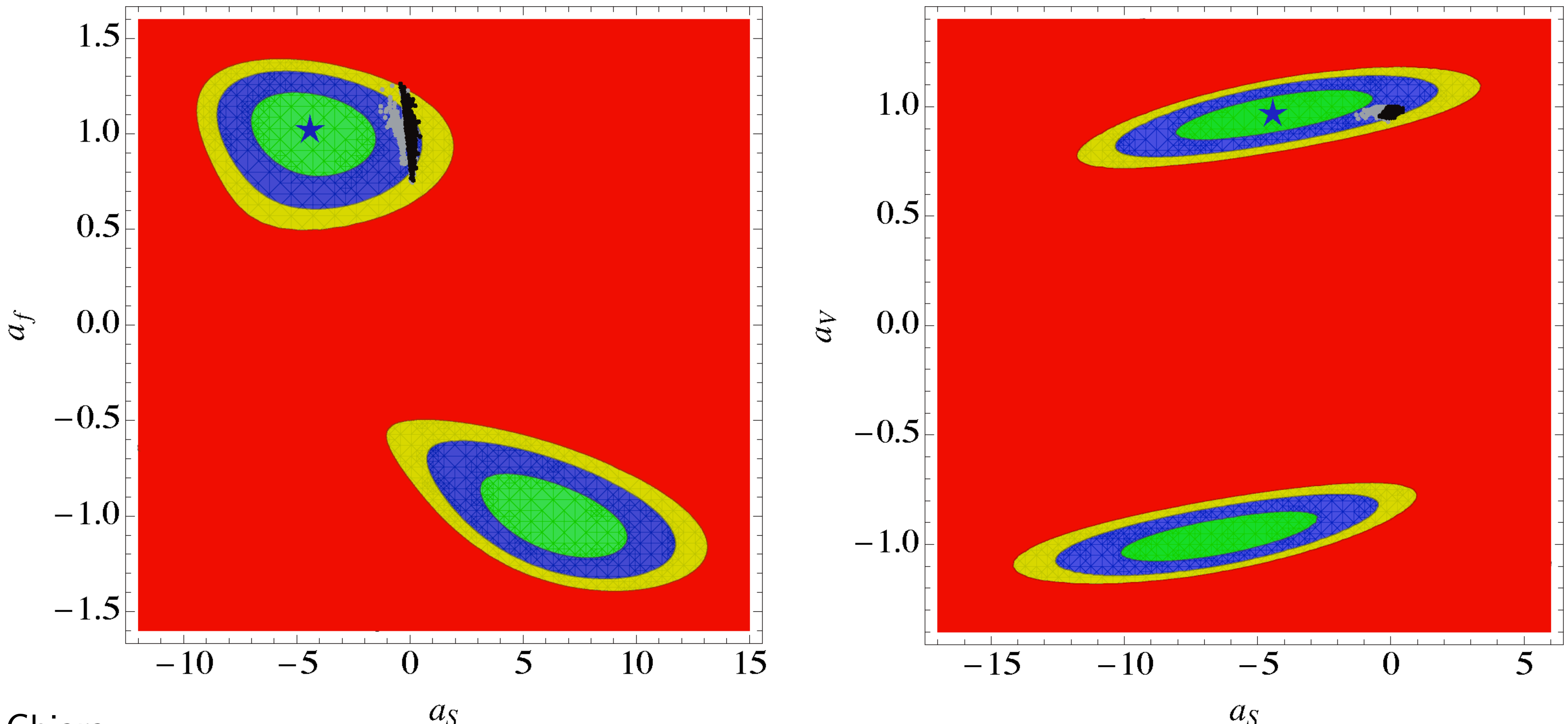
EW S&T Parameters



90%CL viable region (in green) of S & T EW parameters: black (grey) points=EW symmetry breaking by composite (elementary) scalar field.

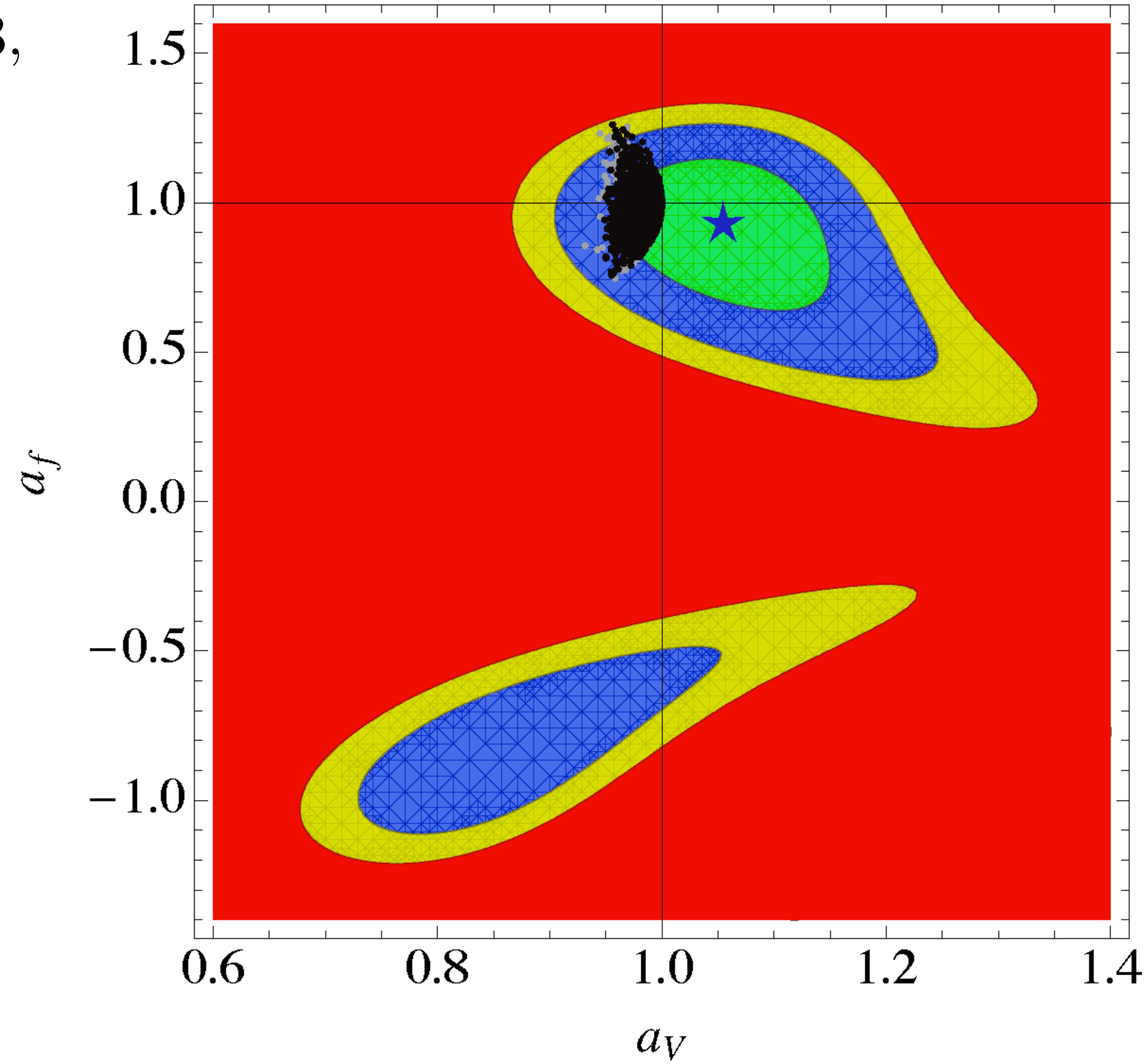
Experimentally Favored Regions

68% (green), 90% (blue), and 95% (yellow) CL region; in black (grey) are the bNMWT (Type-I 2HDM) viable data points; the blue stars mark the optimal signal strengths.



Experimentally Favored Regions

- bNMWT: $\chi^2_{\text{min}}/\text{d.o.f.} = 0.93$, $P\left(\chi^2 > \chi^2_{\text{min}}\right) = 54\%$, $\text{d.o.f.} = 18$
- 2HDM: $\chi^2_{\text{min}}/\text{d.o.f.} = 0.91$, $P\left(\chi^2 > \chi^2_{\text{min}}\right) = 57\%$, $\text{d.o.f.} = 18$
- SM: $\chi^2_{\text{min}}/\text{d.o.f.} = 0.89$, $P\left(\chi^2 > \chi^2_{\text{min}}\right) = 60\%$, $\text{d.o.f.} = 19$



Favored regions for $a_S = 0$

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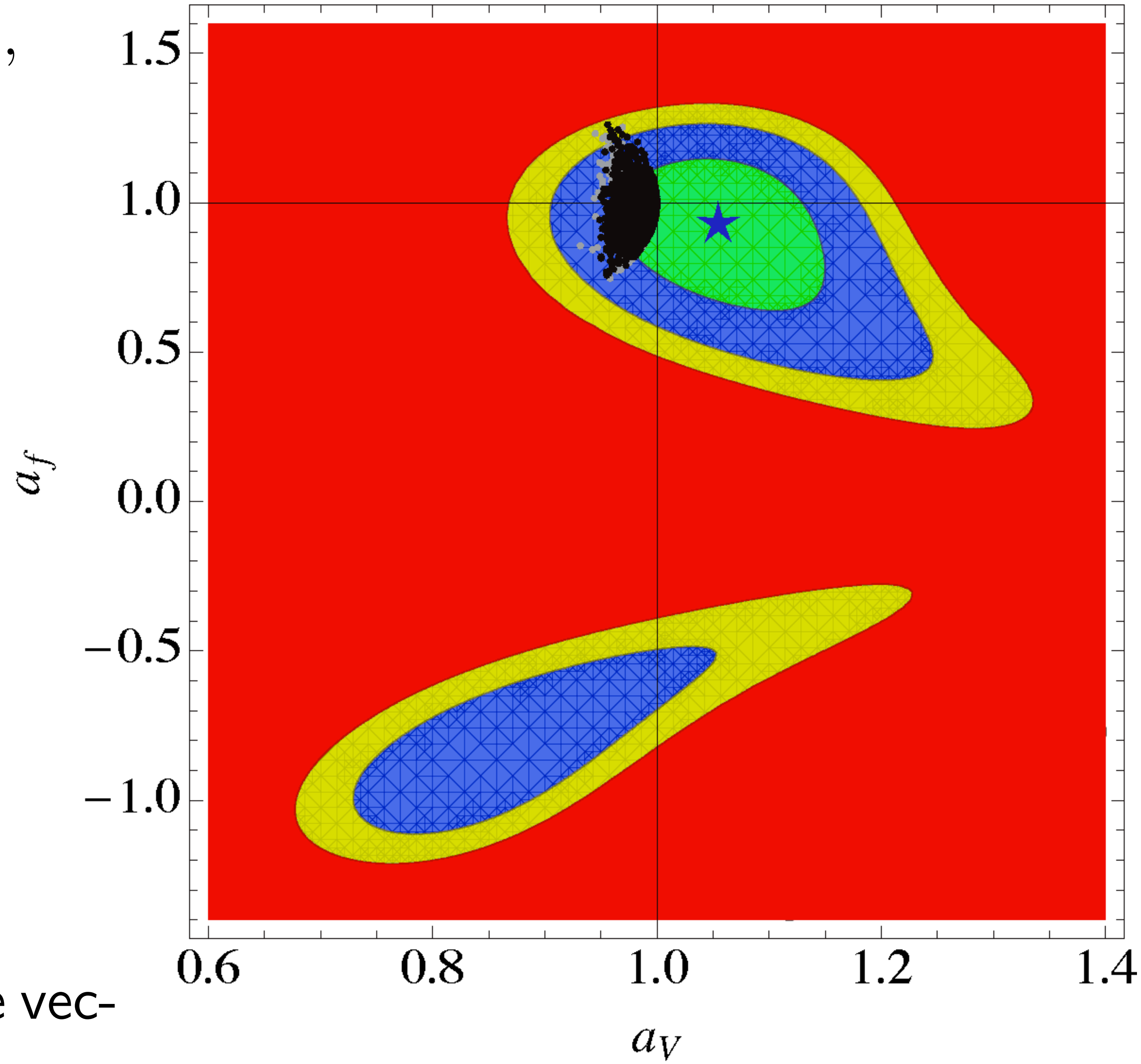


Favored regions for $a_S = 0$

We have not included composite vector resonances in the low energy spectrum, yet...

Composite Vector Bosons

Composite vector bosons described by the traceless Hermitian matrix:

$$A_L^\mu = A_L^{a\mu} \, T^a \ ,$$

where T^a are the $SU(2)$ generators. Under an arbitrary $SU(2)$ transformation, A_L^μ transforms homogeneously (unlike gauge vector bosons):

$$A_L^\mu \ \rightarrow \ u \, A_L^\mu \, u^\dagger \ , \quad \text{where } u \in SU(2) \ .$$

The techniquark content is expressed by the bilinears:

$$A_{Li}^{\mu,j} \sim \ Q_{Li} \sigma^\mu \bar{Q}_L^j - \frac{1}{4} \delta_i^j Q_{Lk} \sigma^\mu \bar{Q}_L^k \ .$$

Replacing L with R above gives the definitions for A_R^μ.

bNMWT Vector Sector

Mass and interaction terms for the composite vectors are introduced via gauge invariant (at the microscopic level) operators:

$$m_A^2 \mathrm{Tr}\left[C_{L\mu}^2 + C_{R\mu}^2\right] \ , \quad C_L^\mu \equiv A_L^\mu - \frac{g_L}{g_{TC}}\tilde{W}^\mu \ , \quad C_R^\mu \equiv A_R^\mu - \frac{g_Y}{g_{TC}}\tilde{B}^\mu \ ,$$

$$\mathcal{L}_{M-P} = -g_{TC}^2 r_2 \mathrm{Tr}\left[C_{L\mu} M C_R^\mu M^\dagger\right] + \frac{g_{TC}^2 r_1}{4}\mathrm{Tr}\left[C_{L\mu}^2 + C_{R\mu}^2\right]\mathrm{Tr}\left[M M^\dagger\right] \ .$$

The global symmetry is the same of the TC microscopic Lagrangian.

Belyaev et al. '08

Vector Mass^2 Matrix

The vector contribution to S and T is zero because we did not introduce new derivative couplings. To simplify our analysis we fix $r_2 = -r_1$, so that the axial-vector $A^\pm$ does not couple to neutral scalar fields. The $(\tilde{W}^\pm, V^\pm, A^\pm)$ squared mass matrix is

$$\begin{pmatrix} m^2_{\tilde{W}} & -\frac{\epsilon m_V^2}{\sqrt{2}} & -\frac{\epsilon m_A^2}{\sqrt{2}} \\ -\frac{\epsilon m_V^2}{\sqrt{2}} & m_V^2 & 0 \\ -\frac{\epsilon m_A^2}{\sqrt{2}} & 0 & m_A^2 \end{pmatrix} ,$$

with

$$m_{\tilde{W}} = \left[x^2 + \left(1+s^2\right)\epsilon^2\right] m_A^2 \ , \quad m_V^2 = \left(1+2s^2\right) m_A^2 \ ,$$

and

$$s \equiv \frac{g_{\mathrm{TC}} f}{2 m_A}\sqrt{r_1} \ , \quad x \equiv \frac{g_L v_w}{2 m_A} \ , \quad \epsilon \ \equiv \frac{g_L}{g_{TC}} \ .$$

Alanne, SD, Tuominen '13

Vector Mixing Only

If the W' coupling is generated only through mixing ($s = 0$):

$$a_V = c_\varphi^2 s_{\beta-\alpha} \ , \quad a_{V'} = s_\varphi^2 s_{\beta-\alpha} \ ,$$

and the total vector contribution to $h^0 \to \gamma\gamma$ is (almost) identical to the no-mixing scenario ($\epsilon = 0$).

Mixing only is experimentally disfavored, since it suppresses a_V: optimally $\epsilon = 0$.

Direct Vector-Scalar Coupling

If direct composite vector coupling to h^0 is non-zero:

$$a_V = \eta_W s_{\beta-\alpha} \ , \quad a_{V'} = (\eta_{W'} + \eta_{W''})\, s_{\beta-\alpha} \ ,$$

with

$$\eta_W + \eta_{W'} + \eta_{W''} = 1 + \frac{2\zeta s^2}{1+2s^2} + O(\epsilon^5) \ , \quad \zeta = s^{-1}_{\beta-\alpha} \frac{c_{\alpha+\rho}}{s_{\beta+\rho}} \ .$$

and the total vector contribution to $h^0 \to \gamma\gamma$ can be greatly enhanced compared to the SM.

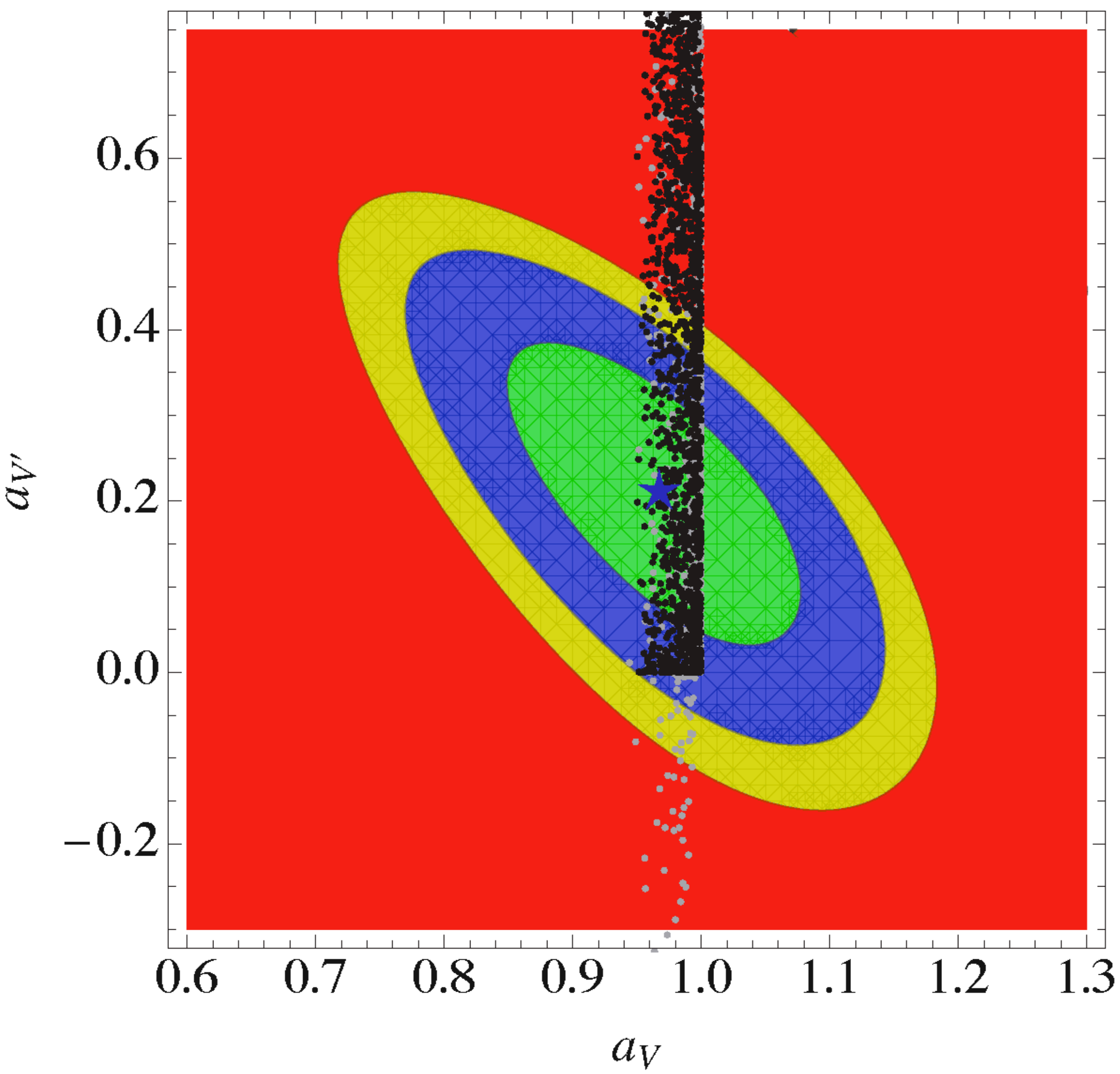
For negligible vector and scalar mixing ($\epsilon = 0, \beta = \alpha + \frac{\pi}{2}$) we find at 95% CL:

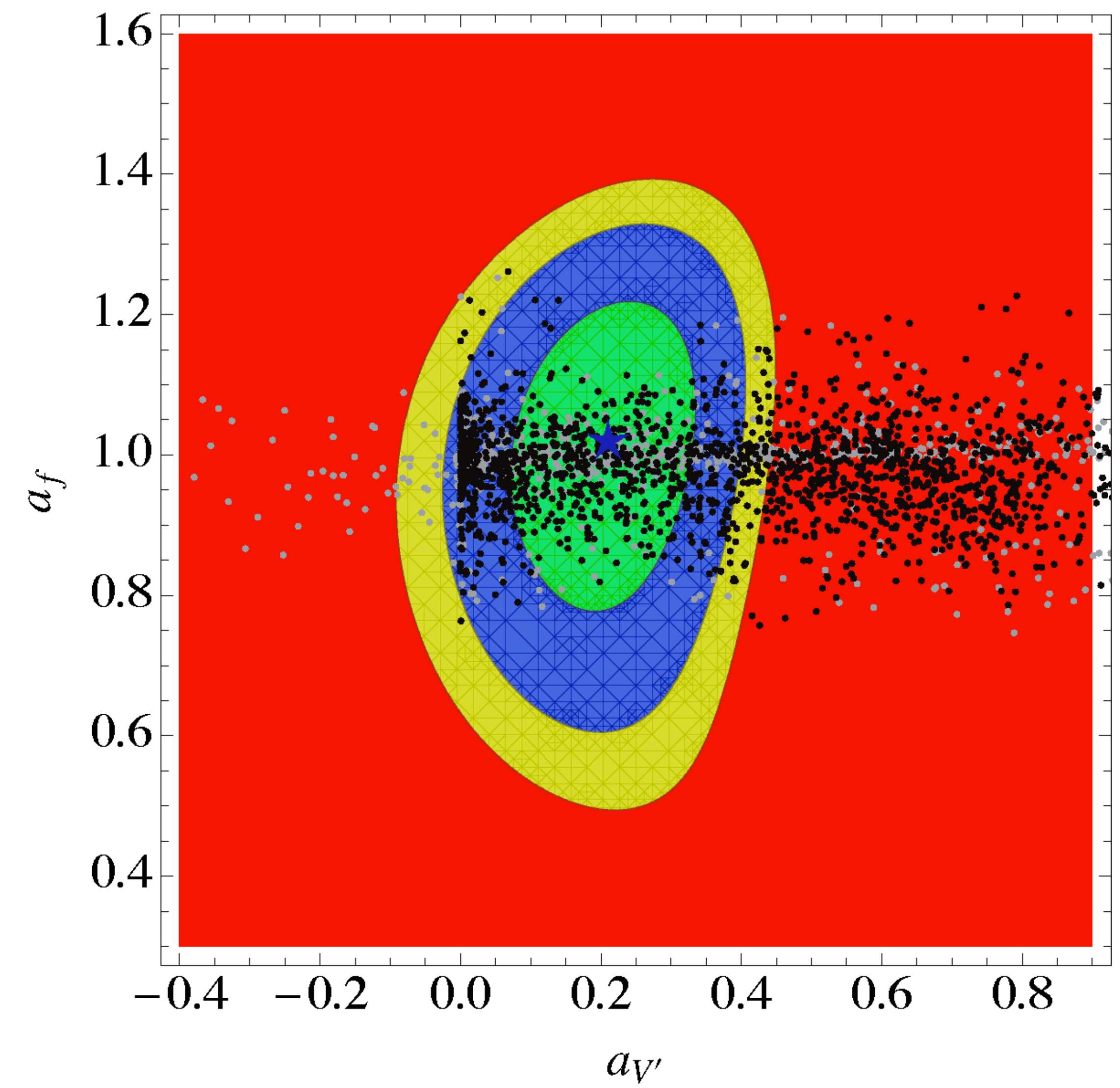
$$a_f = a_V = 1 \ , \quad a_S = 0 \ , \quad a_{V'} = \frac{2s^2}{1+2s^2} \ , \quad \Rightarrow \quad s = 0.32^{+0.17}_{-0.32} \ .$$

Experimentally Favored Regions

68% (green), 90% (blue), and 95% (yellow) CL region; in black (grey) are the bNMWT (Type-I 2HDM+W') viable data points for random values of s and ϵ, with

$$0 \leq s \leq 1 \,, \quad 0 \leq \epsilon \leq 0.1 \,.$$

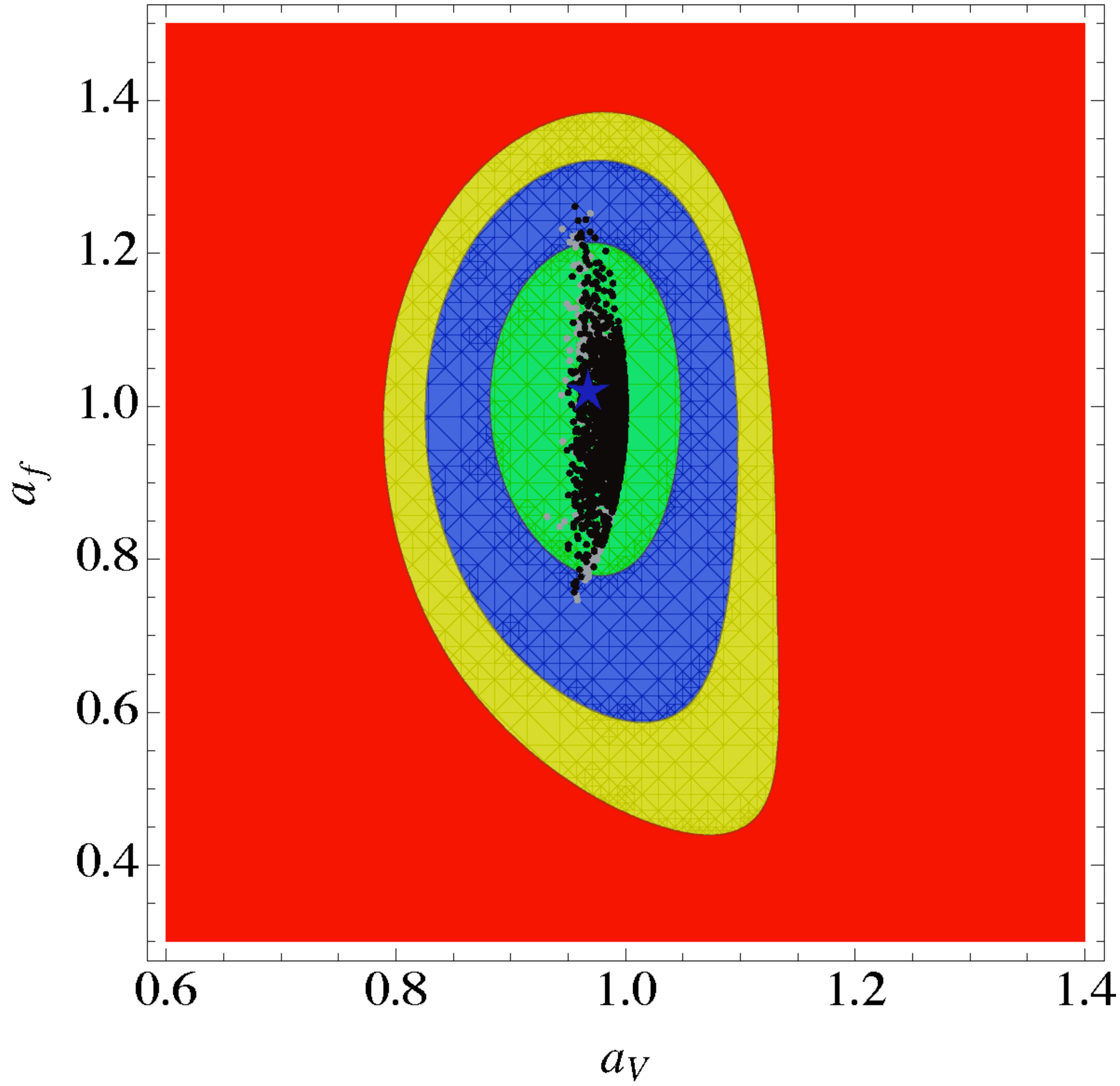




Experimentally Favored Regions

bNMWT & 2HDM+W':
$\chi^2_{\min}/\text{d.o.f.} = 0.83$,
$P\left(\chi^2 > \chi^2_{\min}\right) = 65\%$,
$\text{d.o.f.} = 16.$

Within bNMWT the data favors extra charged vector resonances with direct coupling to h^0.



Conclusions

- Technicolor solves fine tuning
- Walking dynamics allow to satisfy experimental constraints
- LHC data favor direct Higgs-vector coupling within bNMWT
- Fit of bNMWT to Higgs physics data as good as that of SM

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Backup Slides

Higgs Mechanism

Standard model Higgs scalar:

$$\langle 0|\,\phi\,|0\rangle = \frac{1}{\sqrt{2}}\left(\begin{array}{c} 0 \\ v \end{array}\right) \Rightarrow \quad SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}\,.$$

EW symmetry breaking triggered by potential of the Higgs Lagrangian:

$$\begin{aligned} \mathcal{L}_{\mathcal{H}} &= (D_\mu\phi)^\dagger D^\mu\phi - V(\phi)\,, \\ V(\phi) &= \mu^2\phi^\dagger\phi + \frac{1}{4}\lambda\left(\phi^\dagger\phi\right)^2,\ \mu^2 < 0. \end{aligned}$$

Yukawa couplings allow to give mass also to fermions:

$$\mathcal{L}_Y = -\bar{q}_{Li} Y_{uij}\phi u_{Rj} - \bar{q}_{Li} Y_{dij}\tilde{\phi} d_{Rj} - \bar{L}_{Li} Y_{eij}\phi e_{Rj} + hc.$$

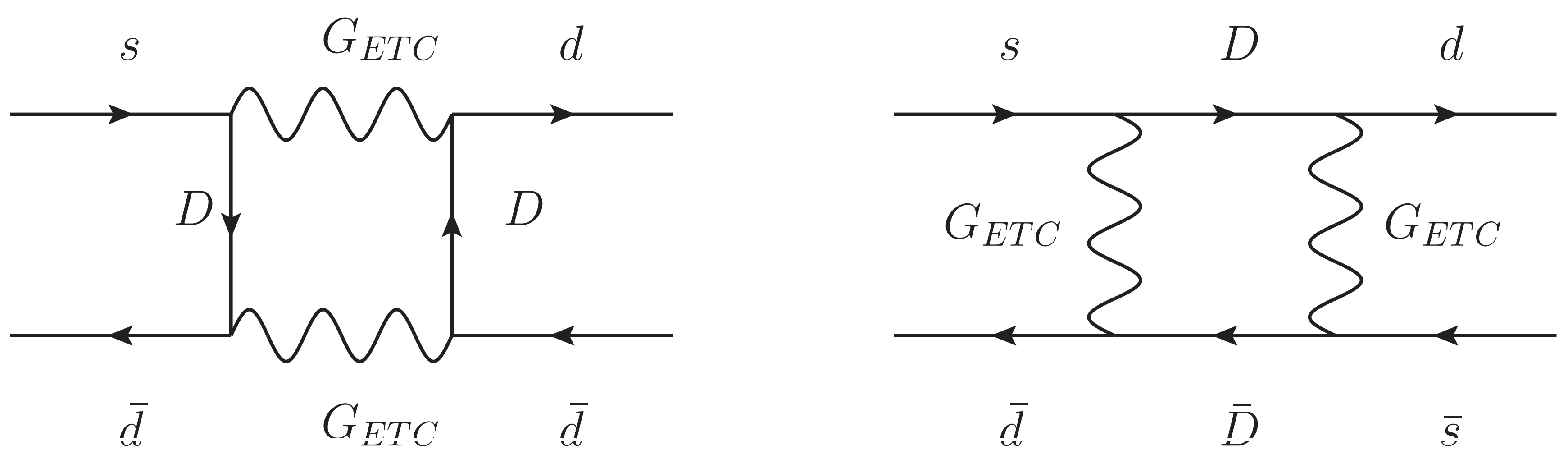
Higgs boson discovered in 2012 at LHC: $M_H = 125$ GeV!

Effective Operators

Without specifying an ETC one can write down the most general ETC sector:

$$\mathcal{L}_{ETC} = \alpha_{ab}\frac{\bar{Q}_L T^a Q_R \bar{Q}_R T^b Q_L}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}_L T^a Q_R \bar{\psi}_R T^b \psi_L}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}_L T^a \psi_R \bar{\psi}_R T^b \psi_L}{\Lambda^2_{ETC}}$$

- first terms generate masses for the uneaten NGB
- second terms generate SM fermion masses
- third terms generate FCNC:
  $\gamma_{sd} \sim \sin^2\theta_c \simeq 10^{-2} \;\Rightarrow\; \Lambda_{ETC} \gtrsim 10^3$ TeV



Fermion Mass Renormalization

The limits on Λ_{ETC} from the large value of m_t and the FCNC experimental data seem to be incompatible, but that was without taking into account renormalization:

$$\gamma_m = \frac{d\log m}{d\log \mu},\ m^3 \propto \langle \overline{Q}Q\rangle \Rightarrow \langle \overline{Q}Q\rangle_{ETC} = \langle \overline{Q}Q\rangle_{TC}\ \exp\left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu}\gamma_m(\mu)\right)$$

Walking TC

Look for Walking TC ($\beta(\alpha_*) = 0$) in theory space (Representation (R), Number of colors (N), Number of flavors (N_f)) by studying

$$\begin{aligned}\beta(g) &= -\beta_0 \frac{\alpha^2}{4\pi} - \beta_1 \frac{\alpha^3}{(4\pi)^2},\ \alpha_* = -4\pi\frac{\beta_0}{\beta_1},\ \beta_0 = \frac{11}{3}C_2(\mathrm{G}) - \frac{4}{3}T(\mathrm{R}),\\ \beta_1 &= \frac{34}{3}{C_2}^2(\mathrm{G}) - \frac{20}{3}C_2(\mathrm{G})T(\mathrm{R}) - 4C_2(\mathrm{R})T(\mathrm{R}).\end{aligned}$$

The conformal window is defined by requiring asymptotic freedom, existence of a Banks-Zaks fixed point, and conformality to arise before chiral symmetry breaking:

$$\begin{aligned}\beta_0 > 0 \quad &\Rightarrow \quad N_f < \frac{11}{4}\frac{d(\mathrm{G})C_2(\mathrm{G})}{d(\mathrm{R})C_2(\mathrm{R})},\\ \beta_1 < 0 \quad &\Rightarrow \quad N_f > \frac{d(\mathrm{G})C_2(\mathrm{G})}{d(\mathrm{R})C_2(\mathrm{R})}\frac{17C_2(\mathrm{G})}{10C_2(\mathrm{G}) + 6C_2(\mathrm{R})}\\ \alpha_* < \alpha_c \quad &\Rightarrow \quad N_f > \frac{d(\mathrm{G})C_2(\mathrm{G})}{d(\mathrm{R})C_2(\mathrm{R})}\frac{17C_2(\mathrm{G}) + 66C_2(\mathrm{R})}{10C_2(\mathrm{G}) + 30C_2(\mathrm{R})}.\end{aligned}$$

TC Models

Walking Technicolor candidate models:

- Fundamental:
  $12\pi S(N=2, N_f=8)=16,$
  $12\pi S(N=3, N_f=12)=36$
- Adjoint:
  $12\pi S(N=2, N_f=2)=6,$
  $12\pi S(N=3, N_f=2)=16$
- 2 I. Symmetric:
  $12\pi S(N=2, N_f=2)=6,$
  $12\pi S(N=3, N_f=2)=12$
- 2 I. Antisymmetric:
  $12\pi S(N=3, N_f=12)=36$

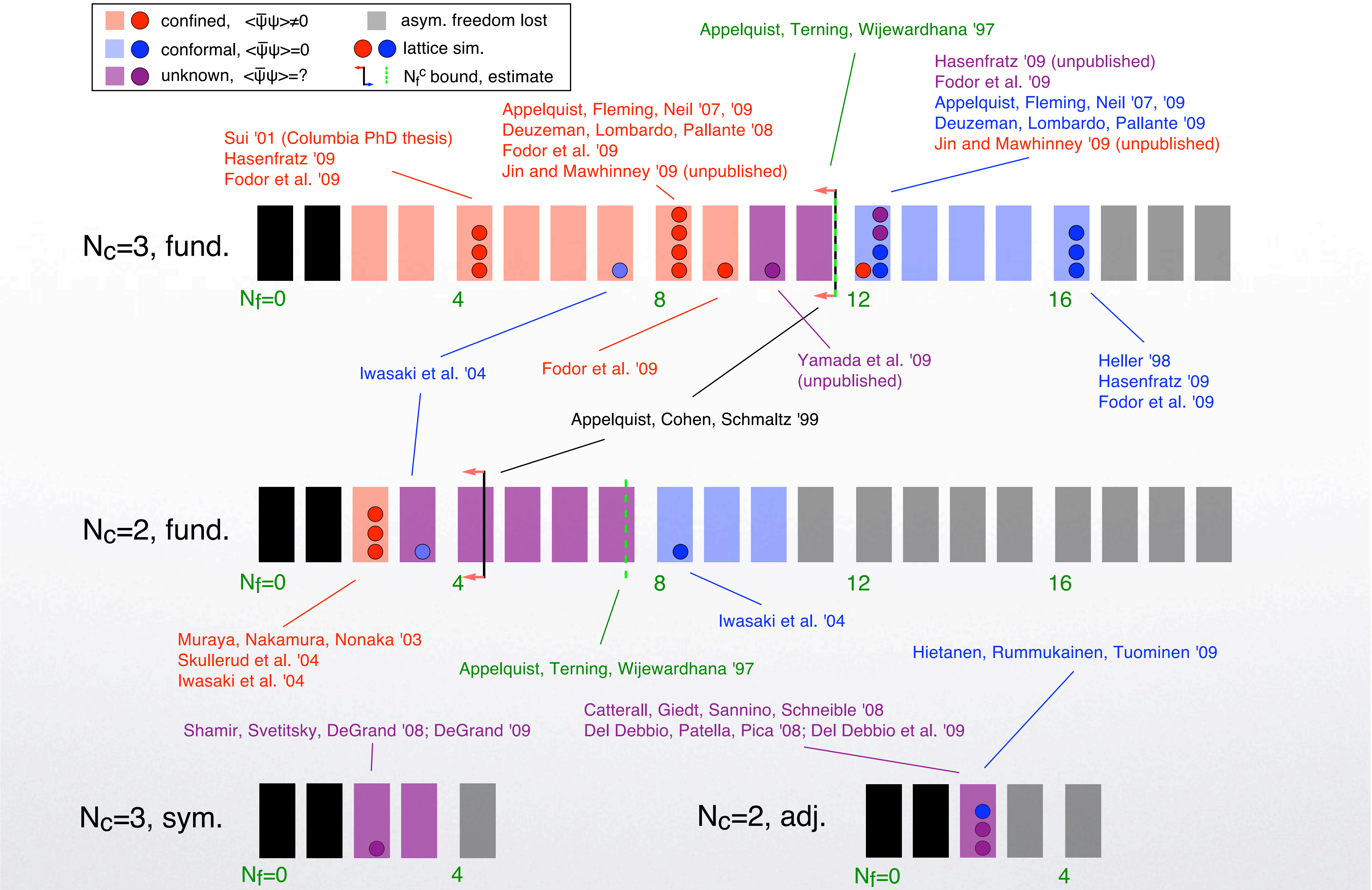
Alternatives to reduce S:

- Partially Gauged TC
- Split TC

The best (fully gauged) Walking TC candidates are:

- $\mathrm{Adj}, N=2, N_f=2$
- 2-IS, $N=3, N_f=2$

Walking on the Lattice



Higgs Decay to Diphoton

$$\Gamma_{h\to\gamma\gamma} = \frac{\alpha_e^2 m_h^3}{256\pi^3 v_w^2}\left|\sum_i N_i e_i^2 F_i\right|^2 ,$$

where N_i is the number of colors, e_i the electric charge, and

$$\begin{aligned} F_A &= \left[2 + 3\tau_A + 3\tau_A\left(2-\tau_A\right)f(\tau_A)\right]a_V \ , \quad A = W, W' \, ; \\ F_\psi &= -2\tau_\psi\left[1 + \left(1-\tau_\psi\right)f(\tau_\psi)\right]a_f \ , \quad \psi = t, b, \tau, \ldots \ ; \\ F_S &= \tau_S\left[1 - \tau_S f(\tau_S)\right]a_S, \ \ \tau_i = \frac{4m_i^2}{m_h^2} \, , \end{aligned}$$

with

$$f(\tau_i) = \begin{cases} \arcsin^2\sqrt{1/\tau_i} & \tau_i \geq 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} - i\pi\right]^2 & \tau_i < 1 \end{cases} .$$

In the limit of heavy $W'^{\pm}$ and $S^{\pm}$: $F_{W'} = 7$, $F_S = -\frac{1}{3}$.