Effective theories of electroweak symmetry breaking

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- Introduction: the SM as an effective theory
- The "standard" Higgs sector
- Breaking the electroweak symmetry without the Higgs
  - Heavy vectors in in the EW Chiral Lagrangian
  - The strongly-interacting light Higgs framework
- The fermion sector and the flavour problem
- Conclusions

Introduction: the SM as an effective theory

Particle physics is described with good accuracy by a simple and *economical* theory:

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i)$$

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- *Natural*
- Experimentally tested with high accuracy
- Stable with respect to quantum corrections
- Higly symmetric

$$\mathscr{L}_{\rm gauge} = \Sigma_a - \frac{1}{4g_a^2}(F_{\mu\nu}^{a})^2 + \Sigma_i \bar{\psi}_i \not{D} \psi_i$$

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ *local symmetry*
- $U(3)^5$ *global flavour symmetry*
  [3 *identical replica of the 5 basic basic fermion fields*]

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- *Ad hoc*
- Necessary to describe data [*clear indication of a non-invariant vacuum*] but not tested in its dynamical form
- Not stable with respect to quantum corrections

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Particle physics is described with good accuracy by a simple and *economical* theory. However, this is likely to be only an *effective theory* (or the low-energy limit of a more fundamentaly theory):

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(\phi, A_a, \psi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \psi_i)$$

$\mathscr{L}_{\rm SM}$ = renormalizable part of $\mathscr{L}_{\rm eff}$

[= all possible operators with $d \leq 4$

compatible with the gauge symmetry]

general parameterization of the new (heavy) degrees of freedom above the electroweak scale

N.B.: beside theoretical prejudices, we now have convincing experimental arguments (*dark matter* & *neutrino masses*) that force us to go beyond $\mathscr{L}_{\rm SM}$

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$$\mathscr{L}_{\rm SSB}(\pi, A_a, \psi_i)$$

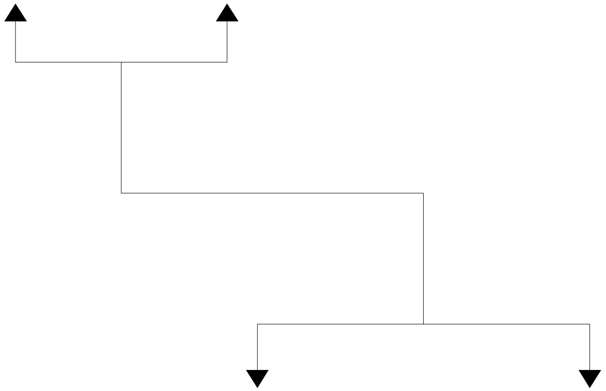
Three key questions:

- Which are the light degrees of freedom of the effective th. (is there a light Higgs filed ?)
- Which is the energy scale of New Physics (or the cut-off of the effective theory ?)
- Which is the symmetry structure of the new degrees of freedom

The "standard" Higgs sector

One elementary $SU(2)_L$ scalar doublet with ϕ^4 potential is the most economical & simple choice to acchieve the $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$ spontaneous breaking required by experiments, but certainly is not the only allowed possibility

$$\mathscr{L}_{\rm Higgs}(\phi, A_i, \psi_i) = D_\mu \phi^+ D^\mu \phi + \mu^2 \phi^+ \phi - \lambda (\phi^+ \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi$$



So far only the ground state determined by this Lagrangian

$$v = \langle \phi \rangle = 246 \text{ GeV} \quad \Leftrightarrow \quad \begin{array}{l} m_W^2 = g^2 v^2/4 \\ m_Z^2 = (g^2+g'^2)\, v^2/4 \end{array}$$

has been tested with good accuracy

$$v = \langle \phi \rangle \qquad m_h = \left. \frac{\partial^2 V}{\partial \phi^2} \right|_{\phi = \langle \phi \rangle}$$

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N.B.: in the limit g', $Y \to 0$, $V(\phi)$ has a $SO(4)$ global symmetry

$$V(\phi) = V(\phi_1{}^2+\phi_2{}^2+\phi_3{}^2+\phi_4{}^2)$$

spontaneoulsy broken into $SO(3)$

The "standard" Higgs sector

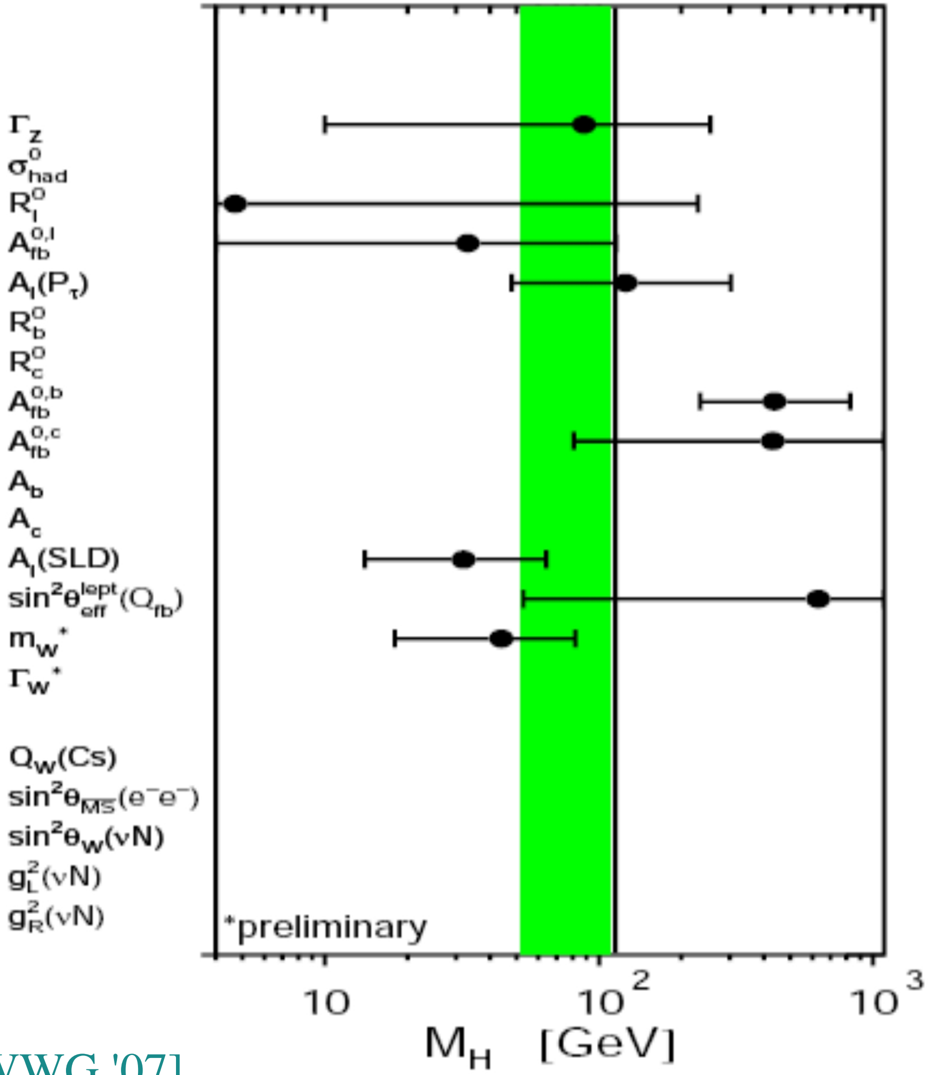
At present the only dynamical information about the Higgs sector is derived by the electroweak precision observables (EWPO):

E.g.:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

$$\Delta r(m_h) \propto \ln(m_h/v) \sim 0.1\%$$

Subleading effect with respect to gauge and quark-mass corrections, but non negligible given the present exp. resolution



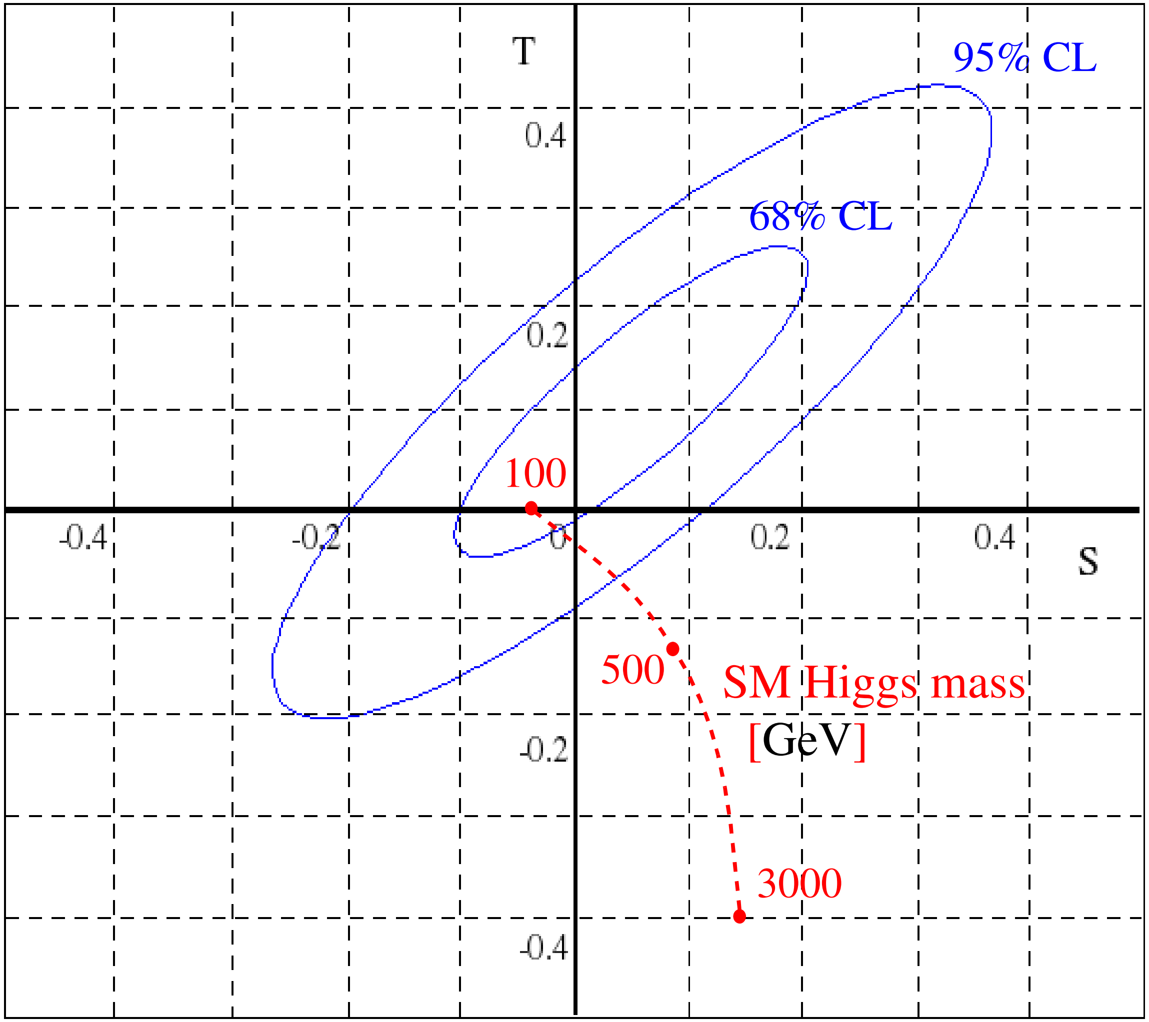
[LEP-EWWG '07]

Despite the mild sensitivity of each observable, the consistency of the Higgs mechanism (& the indcation of a light m_h) is quite high compared to alternatives:

Fit to EWPO beyond the SM with generic new-physics modifying W and Z two-point functions:

$$S = \frac{g}{g'} \frac{d\Pi_{30}(q^2)}{dq^2}\Big|_{q^2=0}$$

$$T = \frac{\Pi_{33}(0) - \Pi_{WW}(0)}{m_W^2}$$



Peskin, Takeuchi, '90
Altarelli, Barbieri, '91
⋮
Barbieri, Pomarol, Rattazzi, Strumia, '04

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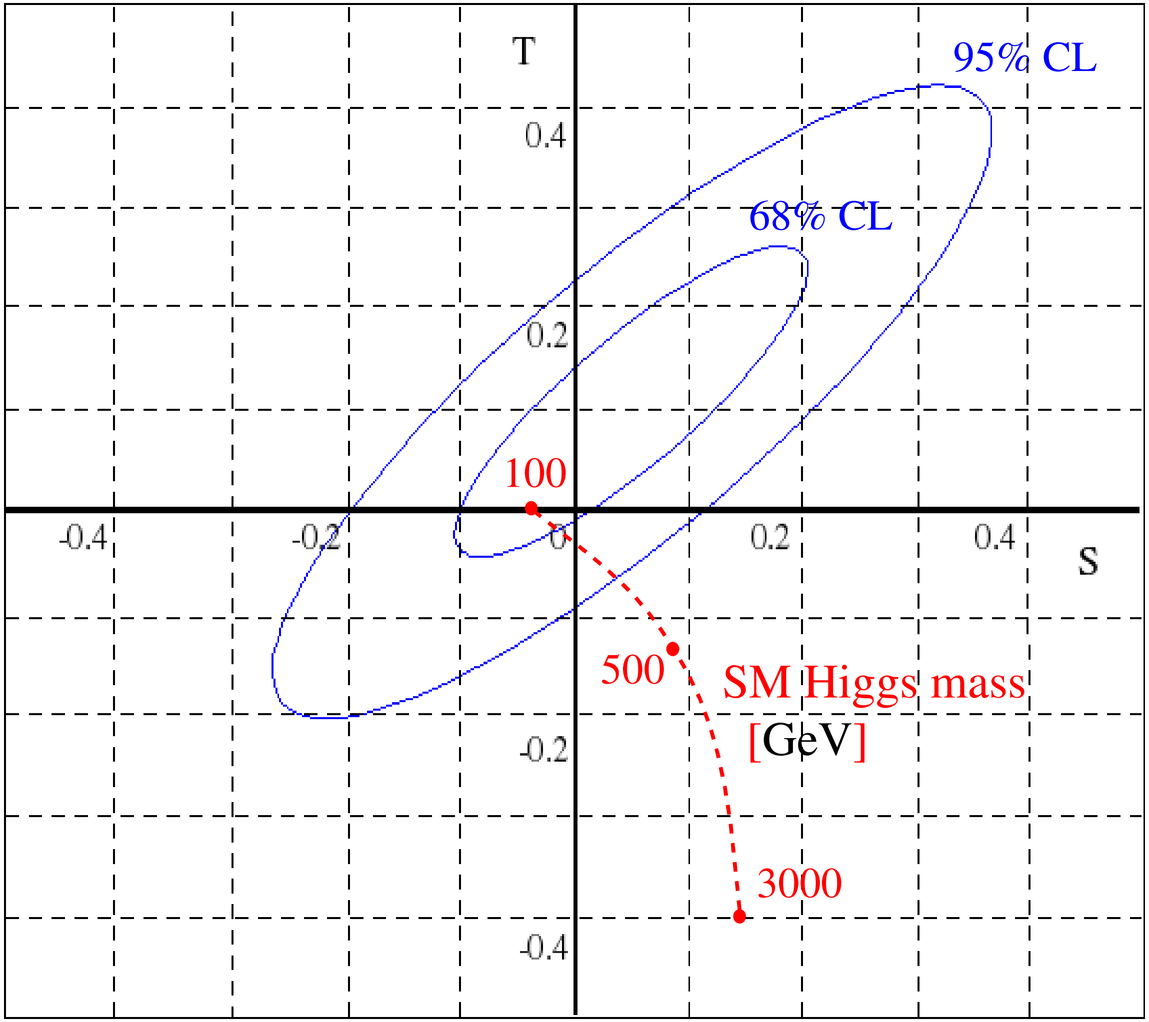
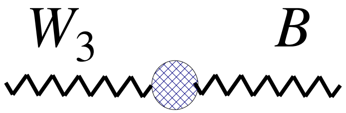


$S \sim$ 

$$T \sim \frac{1}{\alpha}\left[\frac{M_W^2}{\cos^2\theta_W\, M_Z^2} - 1\right]$$

T = 0 is a consequence of the residual SO(3) ~ SU(2) global symmetry of the Higgs potential (*custodial symmetry*)

Introducing the tower of higher-dimensional operators:

$$\Delta S \Leftrightarrow \frac{c_S}{\Lambda^2}\ \mathrm{Tr}(W_{\mu\nu}\, H B_{\mu\nu} H^+) \qquad \Delta T \Leftrightarrow \frac{c_T}{\Lambda^2}\ [\ \mathrm{Tr}(\sigma_3\, H D_\mu H^+)\ ]^2$$

$$\left(\begin{array}{l} H(x) = \dfrac{v + h(x)}{\sqrt{2}}\, U(x) \qquad \mathscr{L}_{\text{Higgs-gauge}} = \dfrac{1}{2}\ \mathrm{Tr}(D_\mu H^+ D^\mu H) \\ U = \text{unitary } 2\times 2 \text{ matrix of the 3 Goldstone fields} \end{array} \right)$$

The result of the EPWO fit implies:

m_h ~100 GeV & $\Lambda > 5$ TeV (for $c_{S,T} = 1$)

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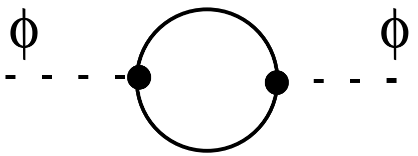
The result of the EPWO fit implies:

$m_h \sim 100$ GeV & $\Lambda > 5$ TeV (for $c_{S,T} = 1$)

The indication of a light m_h under the hypothesis of an heavy cut-off for the SM (viewed as an effective theory) poses a severe fine tuning problem:



$\Delta m_h^2 \sim \Lambda^2$

Not a natural effective theory !!

Breaking the ElectroWeak symmetry without the Higgs

Do we really need a fundamental Higgs field ?

Not really: The only clear indication of EWPO is that we need the spontaneous breaking of $SU(2)_L \times U(1)_Y$ and that the breaking mechanism must respect, to a good accuracy, the custodial symmetry

▶ *Breaking the ElectroWeak symmetry without the Higgs*

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↓

General formulation of the symmetry breaking mechanism in absence of a fundamental Higgs (or for large Higgs masses) in terms of a *Chiral Lagrangian*:

$$\mathscr{L}_\chi^{(2)} = \frac{v^2}{4}\,\mathrm{Tr}(D_\mu U^+ D^\mu U) + \frac{v'^2}{4}\,[\mathrm{Tr}(\sigma_3\, U D^\mu U^+)]^2$$

Weinberg, '79
Longhitano, '80-'81
Appelquist & Bernard, '80-81

Most general $O(p^2)$ Chiral Lagrangian compatible with $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$

$$U \rightarrow g_Y\, U\, g_L^{+} = e^{\,i\pi/v}$$

3 Goldstone bosons of the SM

The bounds on $\Delta T \Rightarrow v'/v = O(10^{-2})$

Breaking the ElectroWeak symmetry without the Higgs

The structure of the O(p^2) electroweak Chiral Lagrangian is further simplified (and requires no fine-tuning) if we promote the SU(2) custodial symmetry to be a fundamental property of the new dynamics (in the g', Y → 0 limit):

$$\mathscr{L}_\chi^{(2)} = \frac{v^2}{4}\,\mathrm{Tr}(D_\mu U^+ D^\mu U) + \xcancel{\frac{v'^2}{4}\,[\mathrm{Tr}(\sigma_3 U D^\mu U^+)]^2}$$

custodial symmetry

$$\Updownarrow$$

$$\mathscr{L}_{\mathrm{Higgs}} = \frac{1}{2}\,\mathrm{Tr}(D_\mu H^+ D^\mu H) - V(\,\mathrm{Tr}(H^+ H)\,)$$

exact correspondence for $m_h \to \infty$

$$U \to g_R\, U\, g_L^+ = e^{i\pi/v}$$

3 Goldstone bosons of the SM

global:

$$SU(2)_L \times \underbrace{SU(2)_R \times U(1)_{B\text{-}L}} \to SU(2)_{L+R} \times U(1)_{B\text{-}L}$$

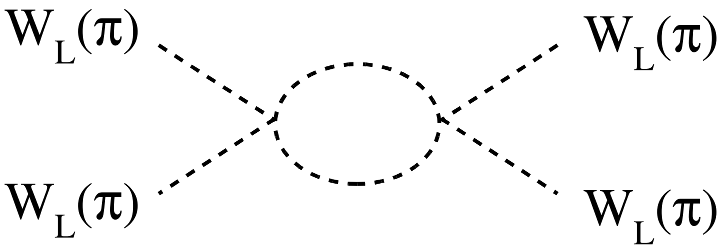
local:

$$SU(2)_L \times \qquad U(1)_Y \qquad \to U(1)_Q$$

$$D_\mu U = -ig'B_\mu U + igUW_\mu$$

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm gauge}(A_i, \psi_i) + \mathscr{L}_{\rm Yukawa}(U, \psi_i) + \frac{v^2}{4}\,{\rm Tr}(D_\mu U^+ D^\mu U)$$

This Lagrangian contains all the degrees of freedom we have directly probed in experiments



Naive cut-off dictated by the convergence of EW loops: $\Lambda^{\rm NDA} = 4\pi v \sim 3$ TeV

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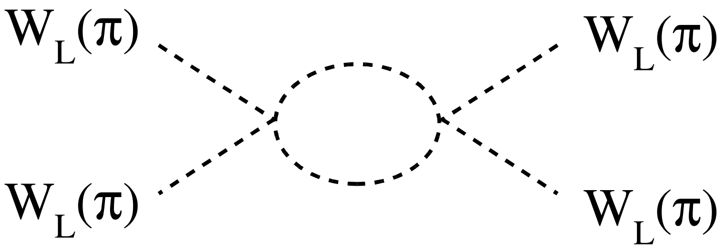

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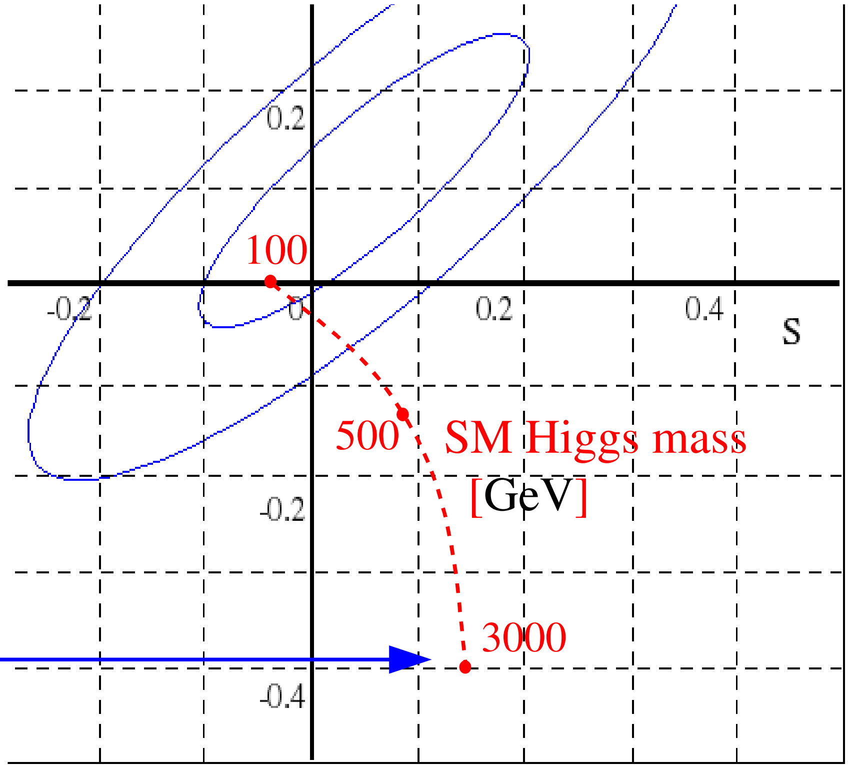
$\mathscr{L}_{\rm eff}$ with a 3 TeV cut-off perfectly describe present phenomenology of particle physics (beyond the tree level) with only 1 drawback: a bad S & T fit



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Naive cut-off dictated by the convergence of EW loops: $\Lambda^{\rm NDA} = 4\pi v \sim 3$ TeV

for CHPT fans:

$T \sim [\, F_{\pi^+}/F_{\pi^0} - 1\,]/\alpha$

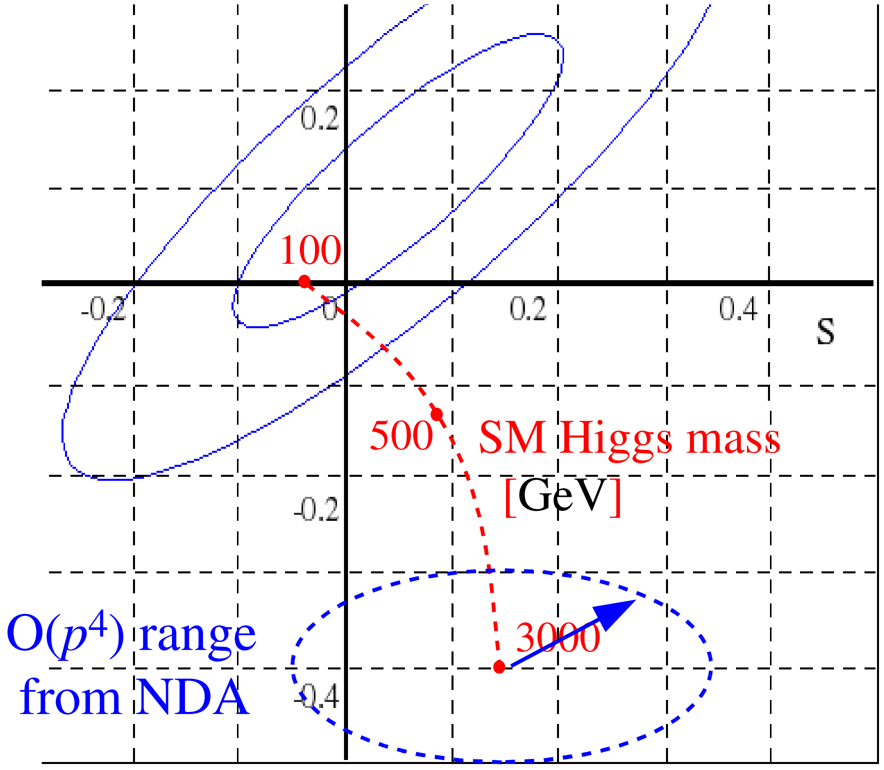
$S \sim 16\pi L_{10}$

$\mathscr{L}_{\rm eff}$ with a 3 TeV cut-off perfectly describe present phenomenology of particle physics (<u>beyond the tree level</u>) with only 1 drawback: a bad S & T fit

↓

Indication of <u>new degrees of freedom below the naive cut-off</u>

N.B: the disagreement with the NDA estimate of $O(p^4)$ terms is not dramatic:



Indication of new degrees of freedom below the naive cut-off
(or non-trivial O(p^4) counterterms)

2 main roads

“light” vector states
(VMD-type framework)

- Techni-VMD in *Technicolor*
- Kaluza-Klein states in *5D theories*
- Massive gauge bosons in *Hidden-gauge* models

⋮

“light” scalar states
(strongly-interacting light-Higgs framework)

- *Higgs as pseudo-Goldstone boson*
- Higgs as 5th component of a gauge field in *5D theories*
- *Little-Higgs* models

⋮

Several explicit models proposed in the recent literature

The main features of both approaches can be analysed using appropriate effective theories with the minimum number of new degrees of freedom

Heavy vectors in the EW Chiral Lagrangian

A minimal set-up to analyse the role of ("light") heavy vectors is obtained under the following (rather general) assumpitons:

Barbieri, GI, Richcov, Trincherini '08

- *The dynamics that breaks the SM e.w. symmetry is invariant a global* $SU(2)_L \times SU(2)_R$ *and under the discrete* $L \leftrightarrow R$ *parity*
- *One vector* (V), *or one vector + one axial-vector* (V+A), *both belonging to the adjoint representation of* $SU(2)_{L+R}$ *(triplets), are the only light fields below a cut-off* Λ = 2-3 TeV
- *The SM fermions interact with the new states only via the SM gauge fields*

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...which are nothing but a "translation" to high energies of the main properties of the VMD chiral Lagrangian of QCD [Ecker *et al.* '89].

As in the QCD case, in a low-energy effective-theory perspective it is more convenient to work describing the heavy spin-1 states by means of <u>antisymmetric tensors</u> ($V^{\mu\nu}$, $A^{\mu\nu}$)

Gasser & Leutwyler, '84

The dynamics of the system below the cut-off is described by 3 + 2 parameters: $(M_V, G_V, F_V) + (M_A, F_A)$.

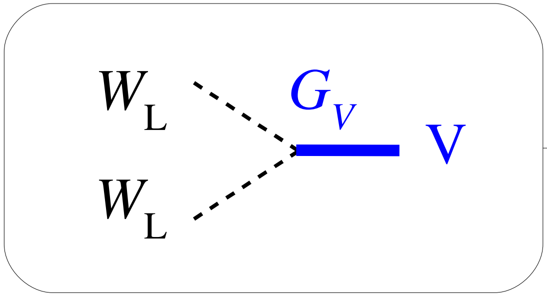
Naive dimensional analysis implies $F_{V(A)}$, $G_V = O(v)$

$$\mathcal{L}_{\rm int} = \frac{i}{2\sqrt{2}}\, G_V\, \mathrm{Tr}\left(V^{\mu\nu}[u_\mu, u_\nu]\right) + \frac{1}{2\sqrt{2}}\, F_V\, \mathrm{Tr}\left(V^{\mu\nu}(u\hat{W}^{\mu\nu}u^\dagger + u^\dagger\hat{B}^{\mu\nu}u)\right)$$
$$+ \frac{1}{2\sqrt{2}}\, F_A\, \mathrm{Tr}\left(A^{\mu\nu}(u\hat{W}^{\mu\nu}u^\dagger - u^\dagger\hat{B}^{\mu\nu}u)\right)$$

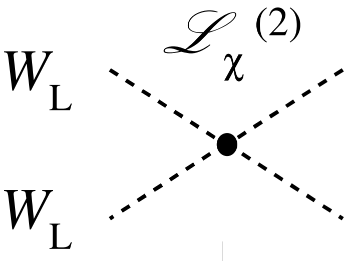
$[\ u_\mu = i\, u^+ D_\mu U u^+ \quad u^2 = U\ ]$

Specific UV completions of this effective theory correspond to specific choices of the free parameters.

For instance, in *hidden gauge models* (or 4D deconstructions of 5D theories), such as $SU(2)_L \times SU(2) \times SU(2)_R$, we always have $F_V = 2\, G_V$



Control unitarity of W_LW_L scattering



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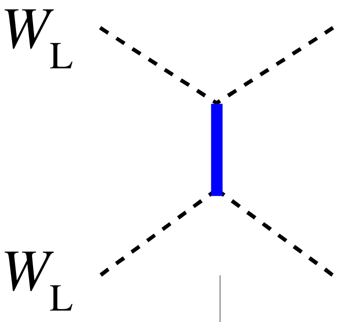

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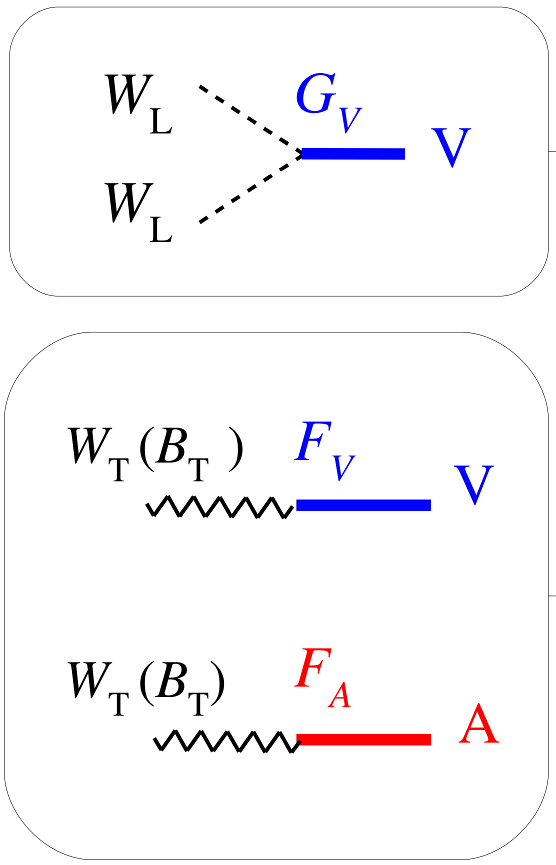
no tree-level violation of unitarity for

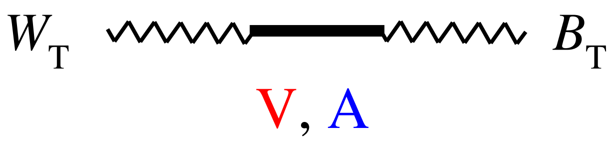
$$\boxed{G_V^2 \approx \frac{v^2}{3}}$$

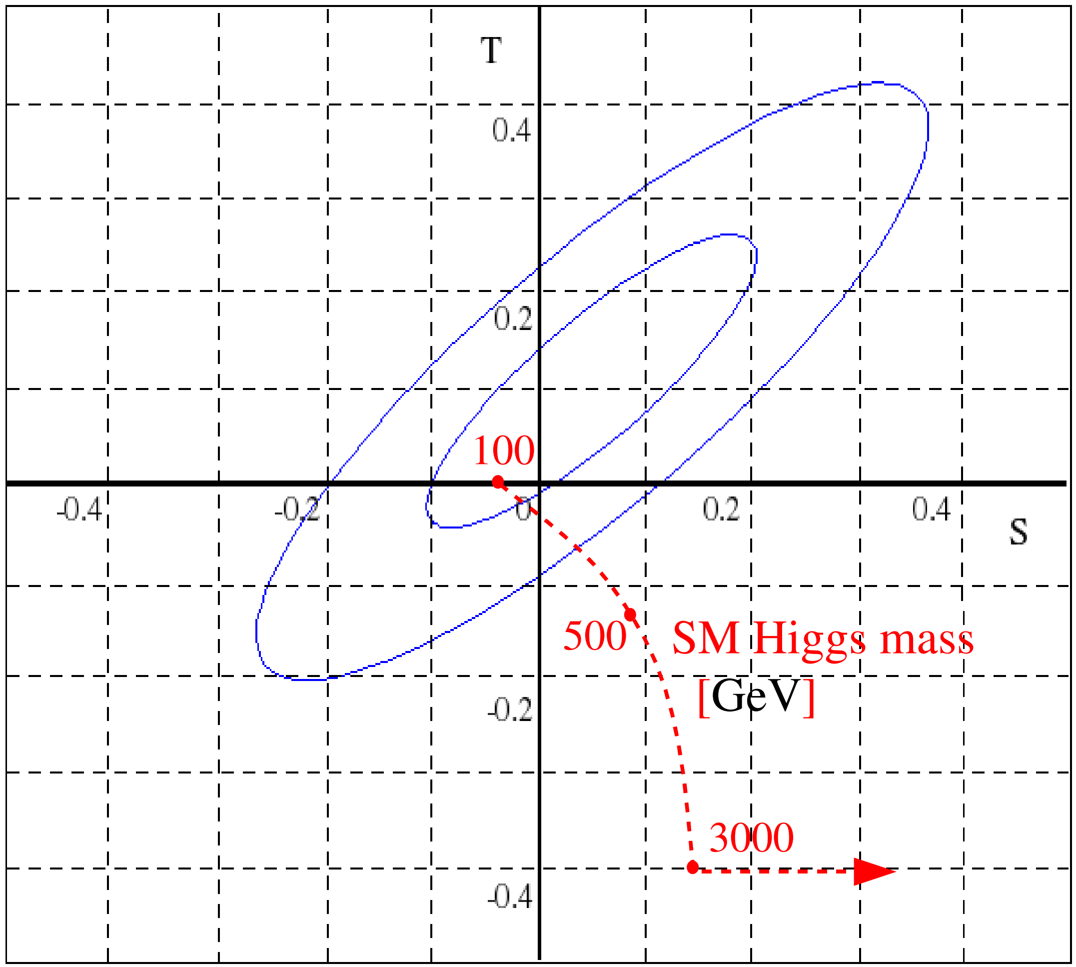
$$A = \frac{s}{v^2} - \frac{G_V^2}{v^4}\left[3s + M_V^2\left(\frac{s-u}{t-M_V^2}+\frac{s-t}{u-M_V^2}\right)\right]$$



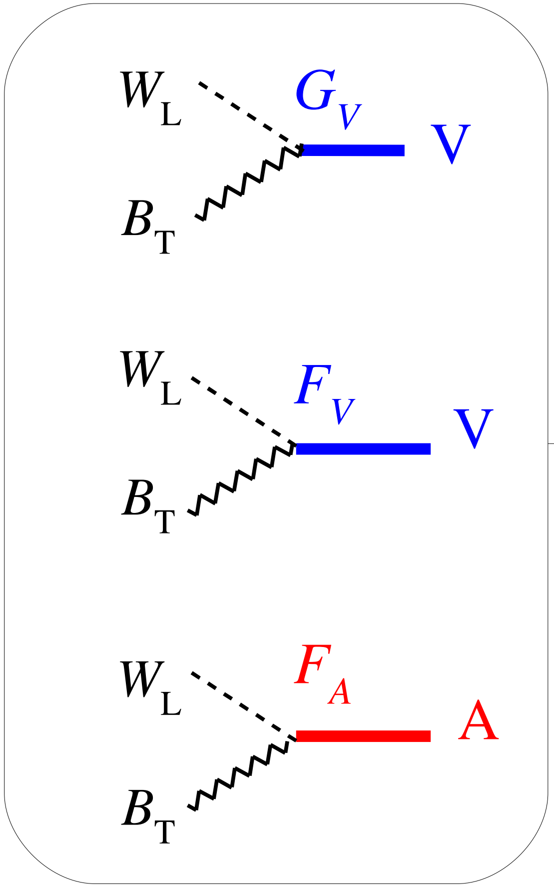
<u>Control unitarity</u> of $W_L W_L$ scattering

<u>Tree-level positive contribution to S:</u>
(which worsen the agreement with EWPO)

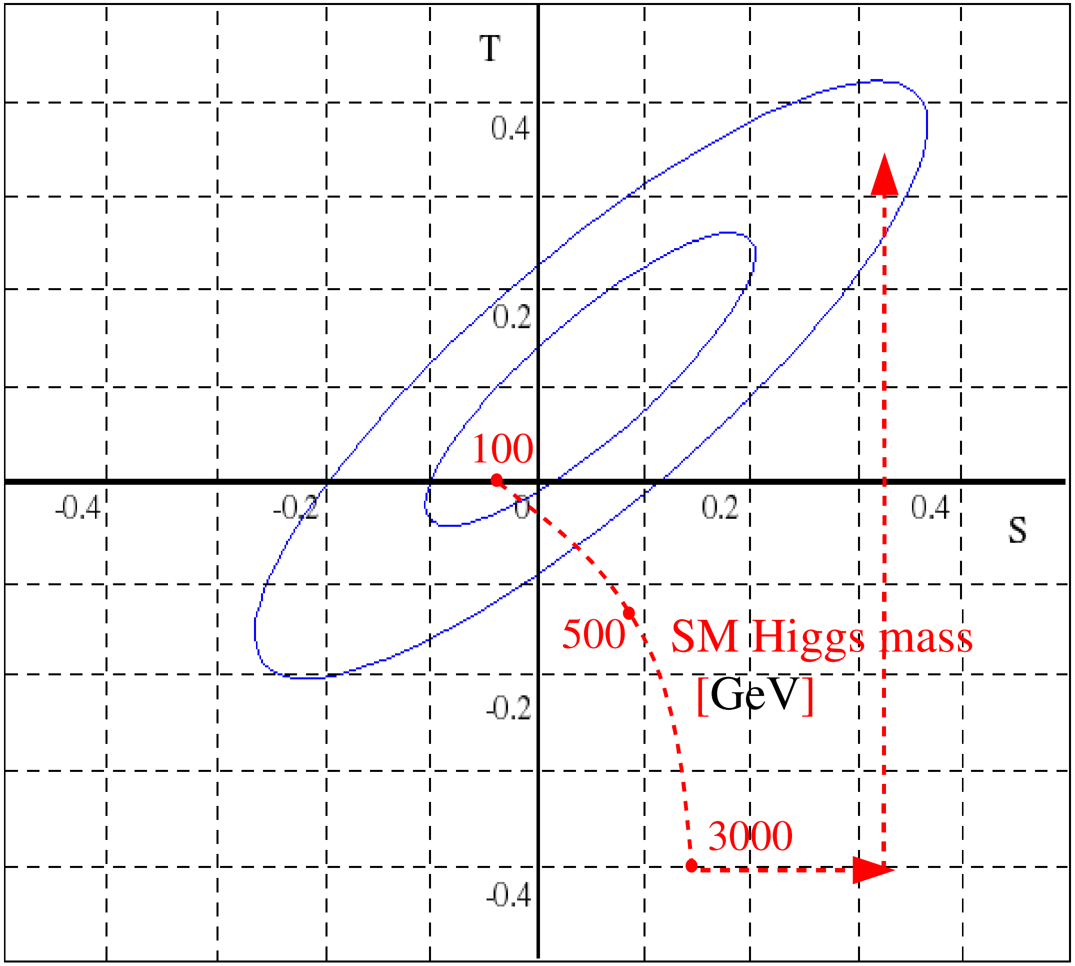


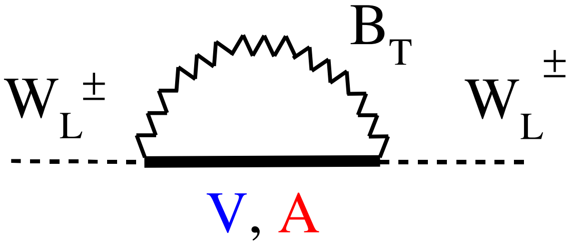


At the one-loop level the situation can become qualitatively very different



Potentially large (quadratically divergent) positive one-loop contribution to T

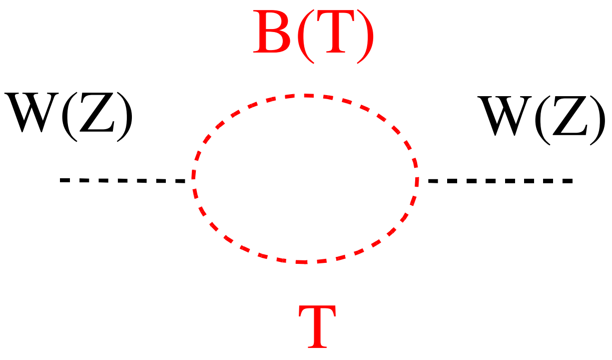




One-loop breaking of the custodial symmetry due to $g' \neq 0$

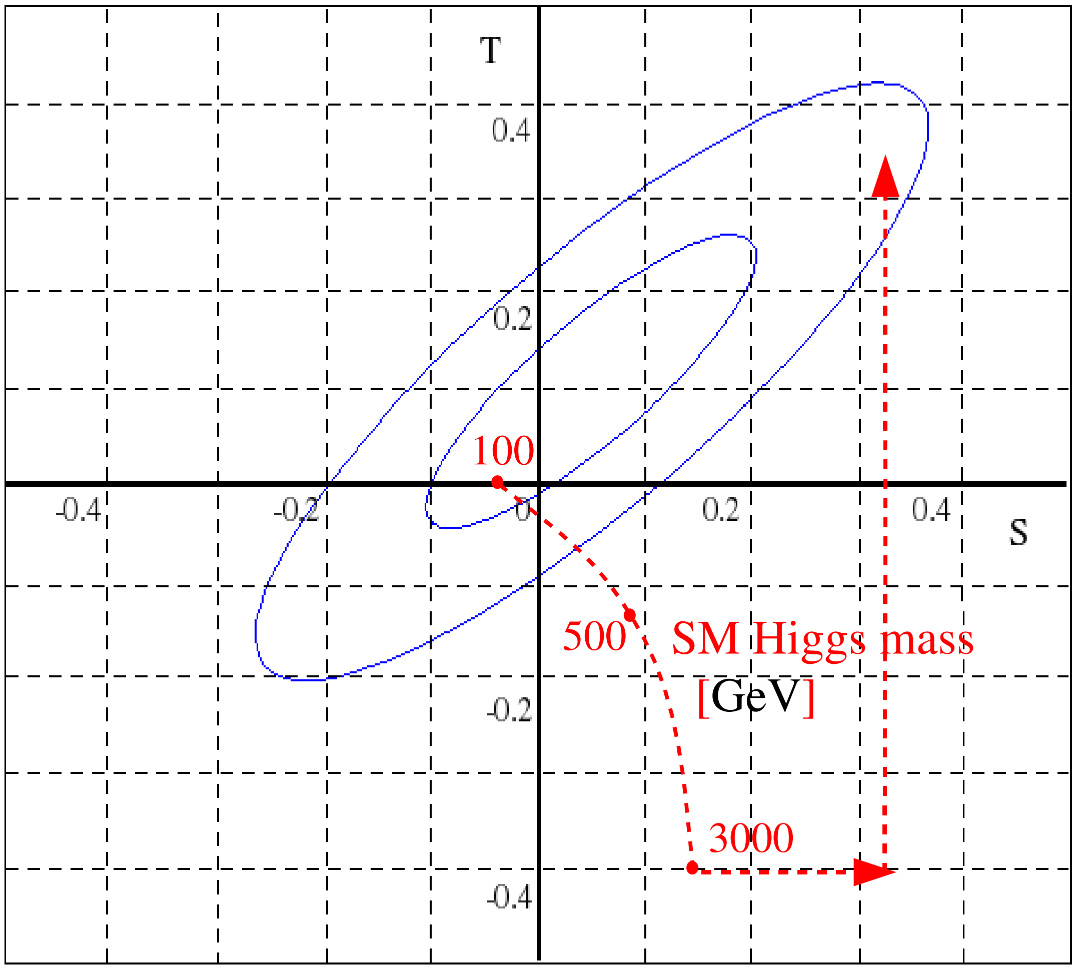
At the one-loop level the situation can become qualitatively very different

Positive contributions to T could also come from *heavy-fermion* loops:



However, in such case one has to tune appropriately the new mass splitting (not easy to find a *natural mechanism* compatible with bounds from flavour physics)

Potentially large (quadratically divergent) positive one-loop contribution to T



The leading contributions to S & T generated by the sole exchange of heavy vector/axial fields are:

$$\Delta\hat{S}\ \substack{\text{vectors}\\\text{(tree)}} = g^2\left(\frac{F_V^2}{4M_V^2} - \frac{F_A^2}{4M_A^2}\right)$$

$$\Delta\hat{T}\ \substack{\text{vectors}\\\text{(1-loop)}} = \frac{3\pi\alpha}{c_W^2}\left[\frac{F_A^2}{4M_A^2} + \left(\frac{F_V - 2G_V}{2M_V}\right)^2\right]\frac{\Lambda^2}{16\pi^2 v^2} + \cdots$$

O(1) factor

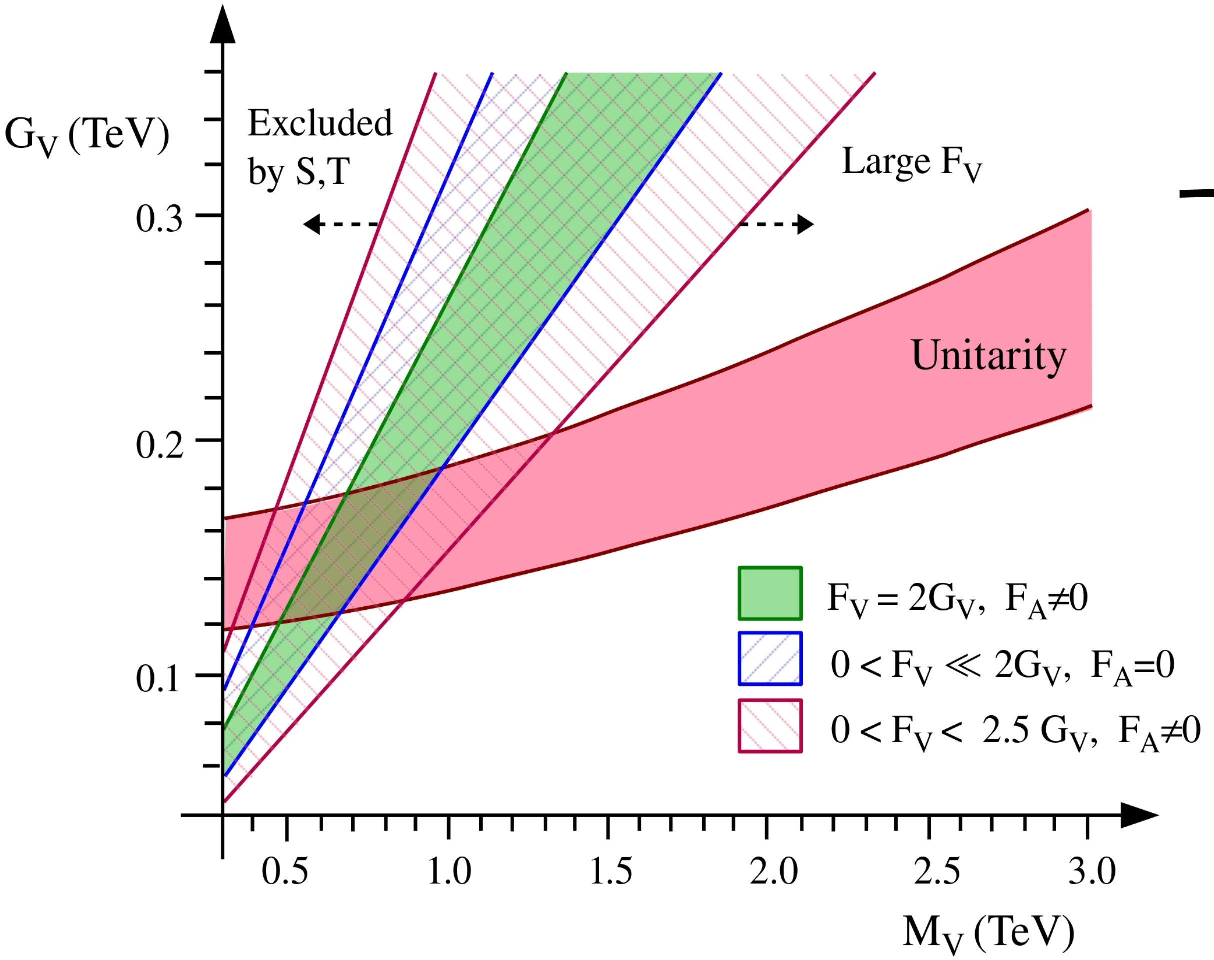
[Λ replaced by some heavy mass]

Two natural ways to accomodate the EWPO bounds:

- Both *V* and *A* light, almost degenerate (good fit with $F_V \approx 2G_V$)
- Only *V* light, with small F_V ($F_V \ll 2G_V$)

→ *this is not a "trivial copy" of QCD*

Putting all the ingredients together, <u>EWPO & unitarity can be accomodated</u> for specific choices of the free parameters:



→ We need at least one relatively light vector field

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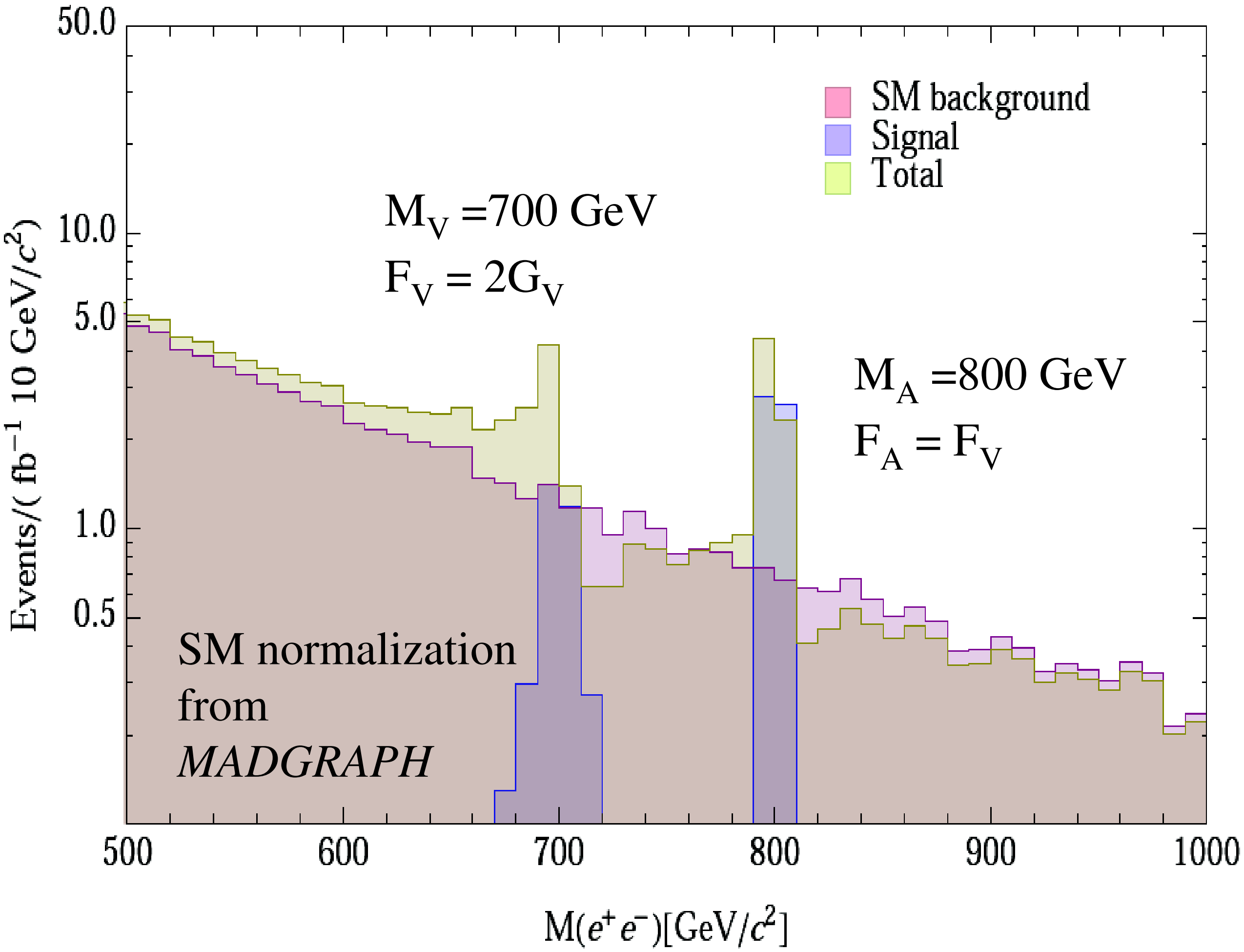
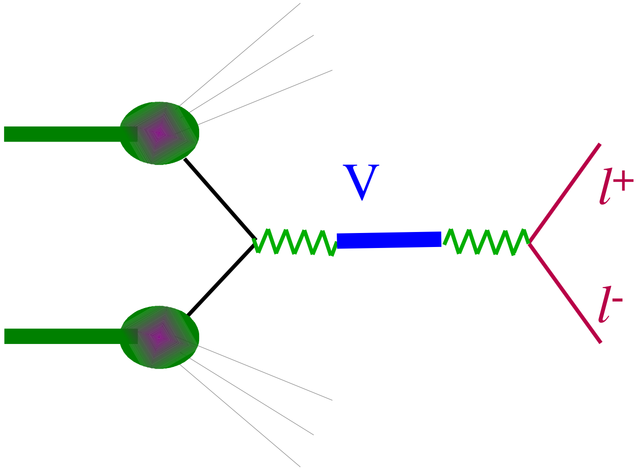


We need at least one relatively light vector field



Interesting and clean LHC phenomenology for the production of such states

Cata, GI, Kamenik, '09

The strongly interacting light Higgs (SILH) framework

A light Higgs-like scalar with a heavy cut-off is very welcome by EWPO, but we need to find a mechanism to stabilise scalar masses from quantum corrections ⇒ Higgs as a pseudo-Goldstone boson

Kaplan, Georgi '84

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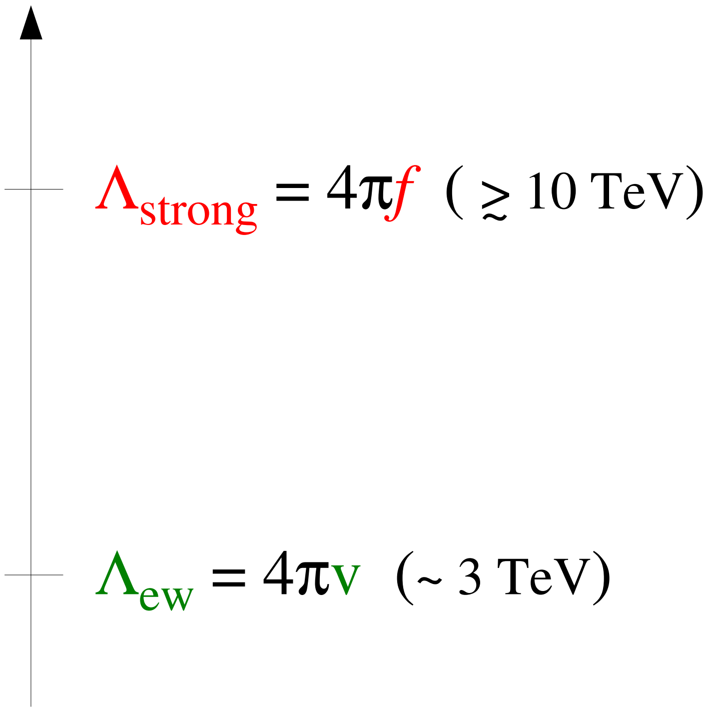
Kaplan, Georgi '84



$\Lambda_{\rm strong} = 4\pi f$ $(\gtrsim 10$ TeV)

Strong dynamics with SSB and a $SU(2)_L$ scalar doublet as Goldstone boson in the $g, g', Y \to 0$ limit

[SO(5)/SO(4) minimal option]

Aghase, Contino, Pomarol, '05

$\Lambda_{\rm ew} = 4\pi v$ $(\sim 3$ TeV)

Higgs potential generated at one-loop via $g, g', Y \neq 0$ responsible for the “standard” SO(4)/SO(3) electroweak symmetry breaking

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$\Lambda_{\mathrm{strong}} = 4\pi f$ ($\gtrsim$ 10 TeV)

$\Lambda_{\mathrm{ew}} = 4\pi v$ (~ 3 TeV)

The bound states of the new dynamics are not necessarily accessible at the LHC

The only "remnant" of the strong dynamics is an Higgs field with non-standard interactions, which can be described by means of an appropriate effective theory

Giudice, Grojean, Pomarol Rattazzi, '07

key parameter: $\xi = \dfrac{v^2}{f^2}$

0 SM [*fine-tuning in* m_h]

1 Technicolor [*fine-tuning in* S & T]

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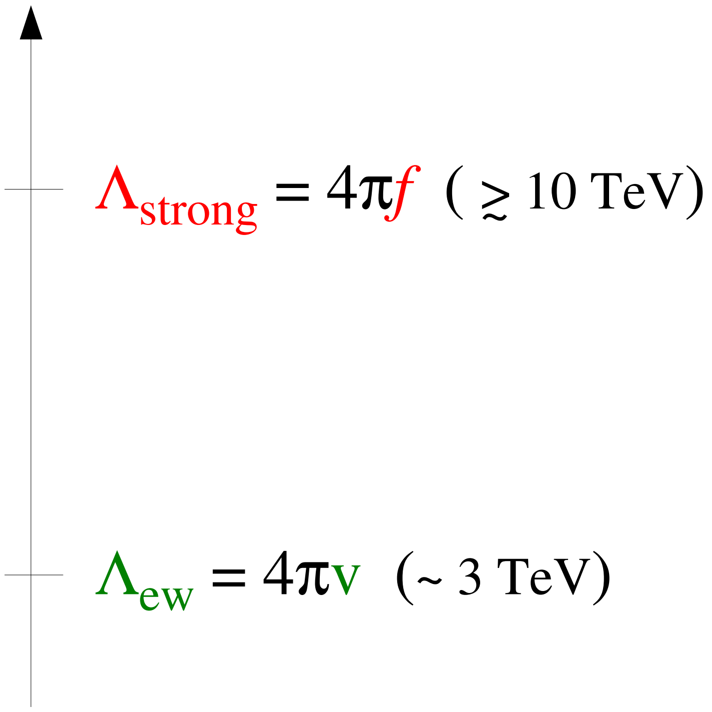

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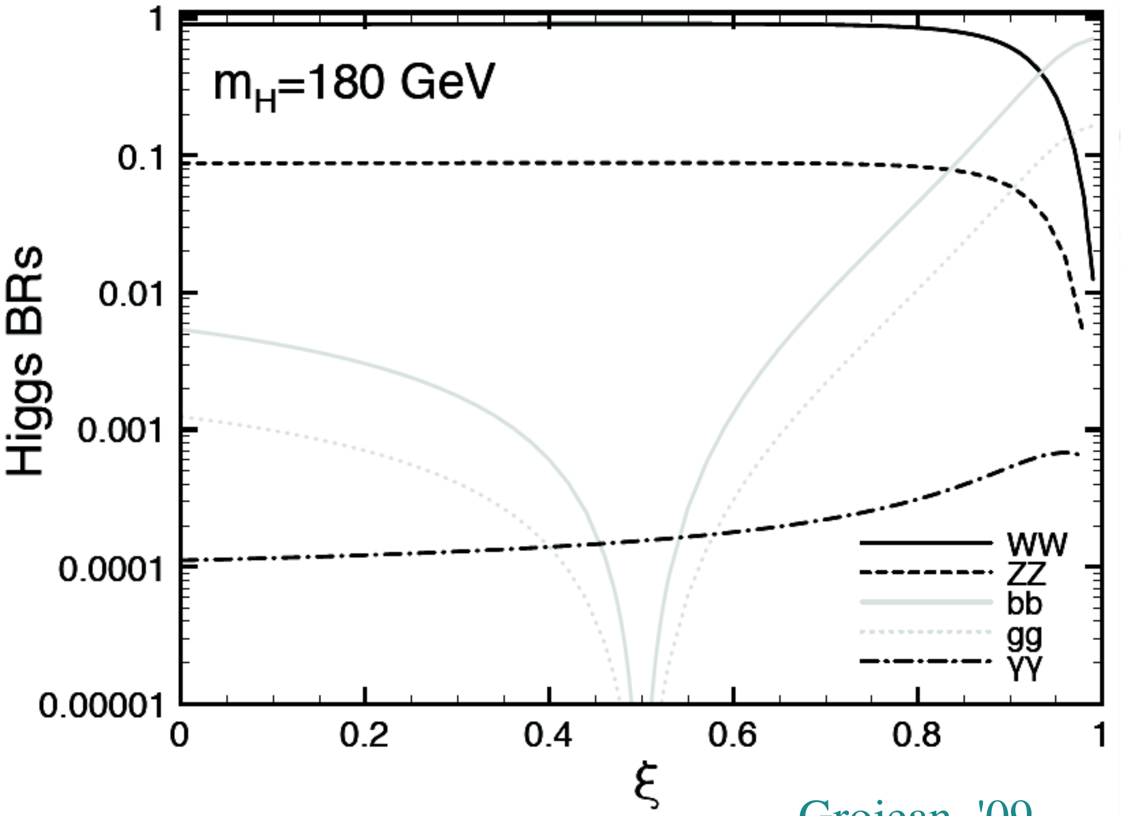

Grojean, '09

Very hard to detect deviations from the SM unless ξ ~ 1

The fermion sector and the flavour problem

The naturalness problem of the SM as effective theory is apparently much more severe if we look at gauge-invariant non-renormalizable operators contributing to flavour-violating processes.

E.g.: $$M(\mathrm{K}\text{-}\bar{\mathrm{K}}) \sim \frac{(y_t V_{ts}{}^{*} V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\,\frac{1}{\Lambda^2}$$

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}}\, O_n{}^d$$

V_{ij} = CKM matrix

The list of dim.6 ops inlcudess $(s_L \gamma_\mu d_L)^2$ which contributes to neutral K mixing at the tree-level

$c_{NP} \sim 1 \;\rightarrow\; \Lambda \gtrsim 2\times10^4$ TeV

[*flavour problem*]

▶ *The fermion sector and the flavour problem*

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E.g.:
$$M(\mathrm{K}\text{-}\bar{\mathrm{K}}) \sim \frac{(y_t V_{ts}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{\mathrm{NP}} \frac{1}{\Lambda^2}$$

$$c_{\mathrm{NP}} \nearrow \;\sim 1 \xrightarrow{\text{generic flavor}} \Lambda \gtrsim 2\times 10^4 \text{ TeV}$$

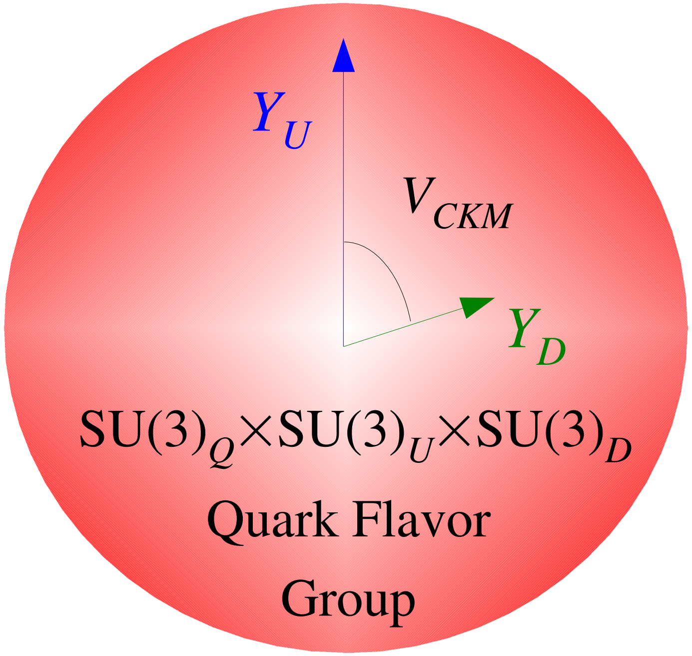
$$c_{\mathrm{NP}} \searrow \;\sim (y_t V_{ts}{}^* V_{td})^2 \xrightarrow{\text{flavour “alignment”}} \Lambda \gtrsim 5 \text{ TeV}$$

The problem can be solved with the help of appropriate flavour symmetries, and symmetry breaking mechanisms, forcing an “alignment” in flavour space with respect to the SM.

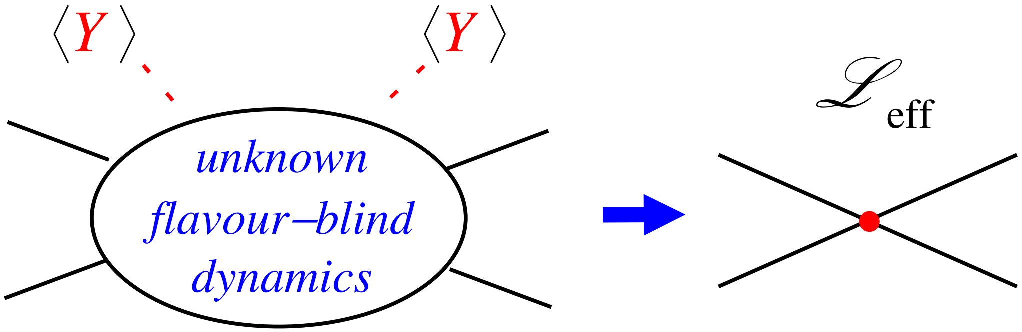
The most efficient mechanism is the so-called MFV hypothesis:
$SU(3)^5$ flavour symmetry + Yukawa couplings as unique sources of flavour symmetry breaking

- Flavour symmetry:
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
  [global symmetry of the SM gauge sector]

- Symmetry-breaking terms:
  $Y_D \sim \bar{3}_Q \times 3_D \qquad Y_U \sim \bar{3}_Q \times 3_U$
  [Yukawa couplings]



General (RGE invariant) principle which can be applied to any TeV-scale new-physics model and allows us to postpone the solution of the flavour problem to very high energies



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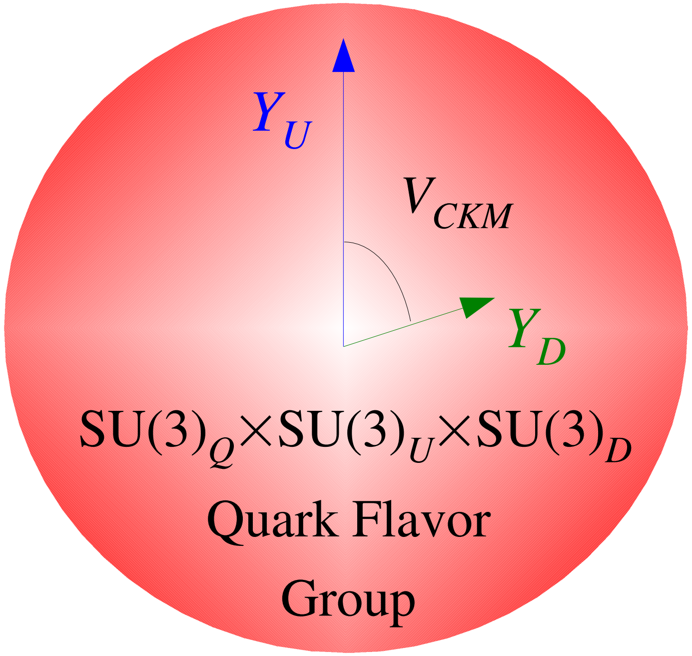

$SU(3)_Q \times SU(3)_U \times SU(3)_D$
Quark Flavor
Group

↓

- Bounds on the effective scale with MFV in the few-TeV range, similar to those from EWPO
- The MFV mechanism works both with and without a light Higgs
- MFV is not the only allowed solution [see e.g. Hirn & Stern '04] however, at present it seems to be the less fine-tuned one

▶ Conclusions

The SM is certainly only an effective theory, of which we have a rather poor knowledge:

Three key questions:

- Which are the light degrees of freedom of the effective th. (is there a light Higgs filed ?)
- Which is the energy scale of New Physics (or the cut-off of the effective theory ?)
- Which is the symmetry structure of the new degrees of freedom ?

No definite answers yet !!

Models with strongly-interacting dynamics around the TeV scale are not ruled out yet

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But there are good chances that LHC will help us to answer the first two questions