The Hierarchy Problem & Compositeness

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The Stardard Model as an Effective Theory

with fundamental scale $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$

$$\mathcal{L}_{SM} \;=\; \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2$$

d=4

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d=4

$$+ \quad \frac{b_{ij}}{\Lambda_{UV}} L_i L_j H H$$

$$+ \quad \frac{c_{ijkl}}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell \; + \; \frac{c_{ij}}{\Lambda_{UV}} \bar{F}_i \sigma_{\mu\nu} F_j G^{\mu\nu} + \ldots$$

$$+ \quad \ldots$$

d>4

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d>4

$\Lambda_{UV} \to \infty$ (pointlike limit) nicely accounts for 'what we see'

The Stardard Model as an Effective Theory

with fundamental scale $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$

$$+ c\Lambda^2_{UV}\, H^\dagger H$$

d<4

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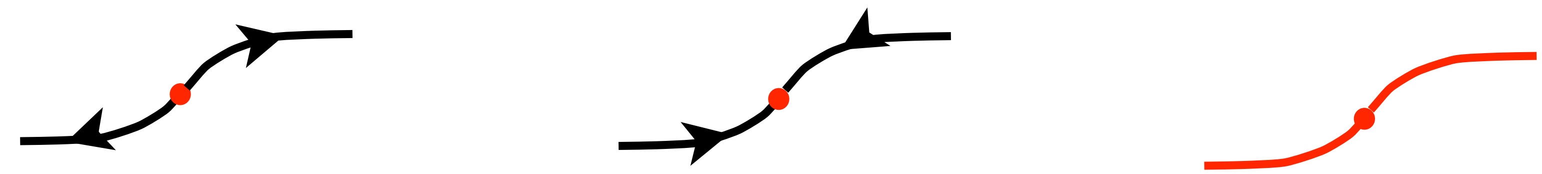
Λ_{UV}

$\sim$ scale invariance

Λ_{IR}

hierarchy's naturalness $\Longleftrightarrow$ fixed point stability



unstable stable marginal

$$m_H^2 \equiv$$ ***strongly relevant*** perturbation

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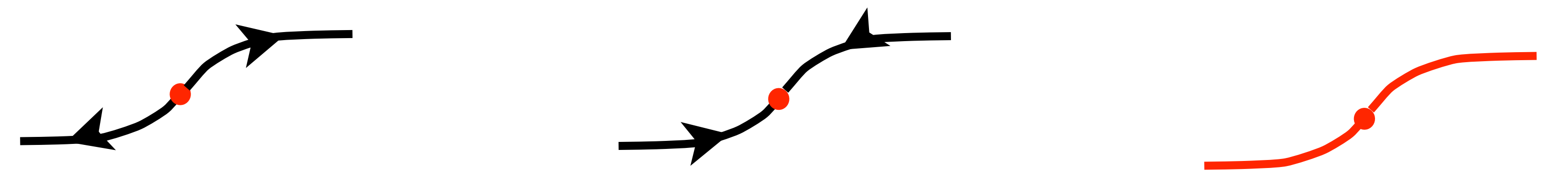

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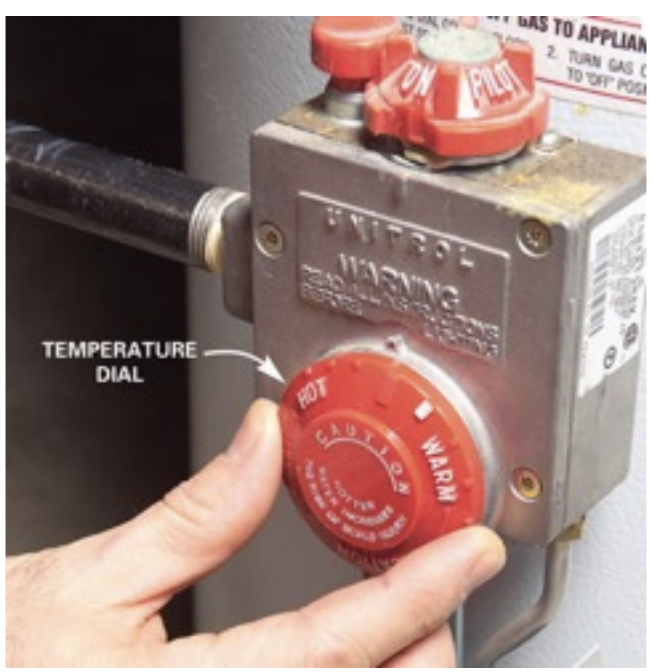

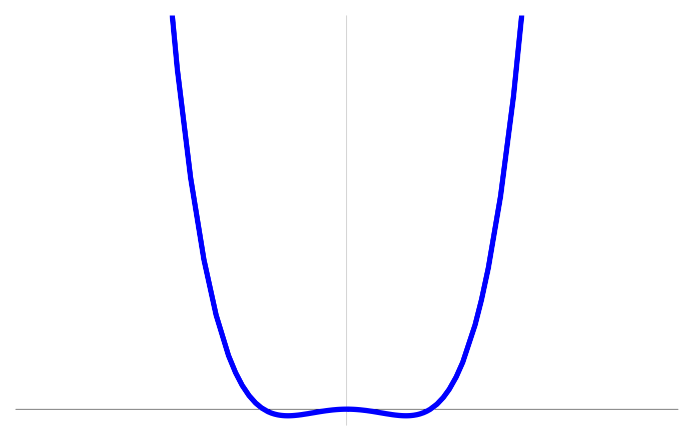

$$|T - T_c| \ll T$$

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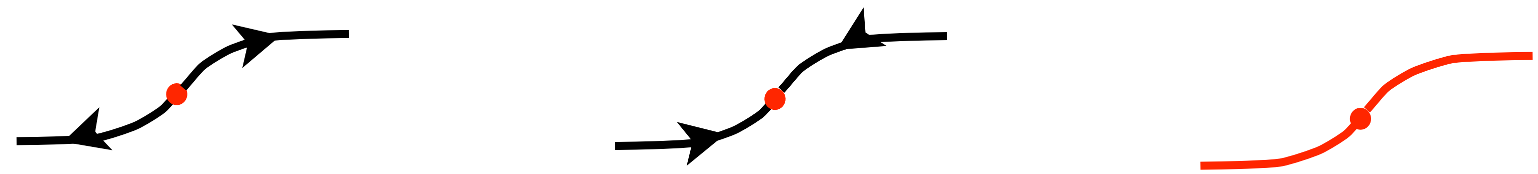

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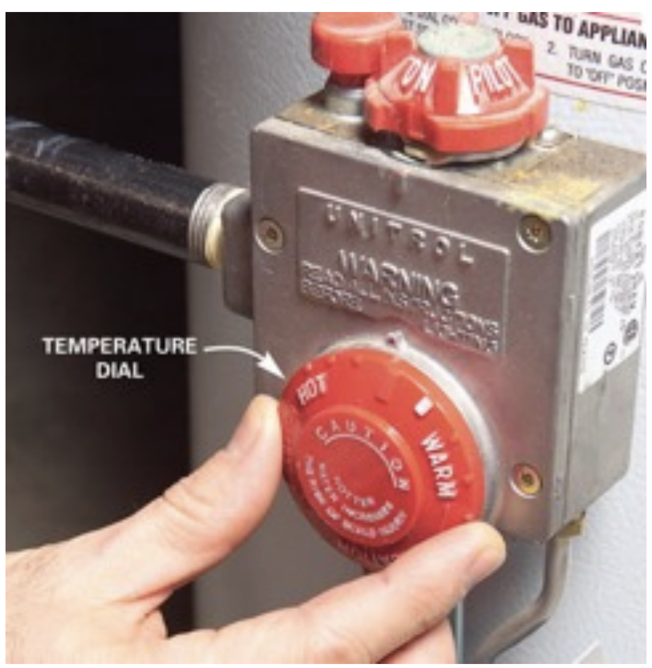

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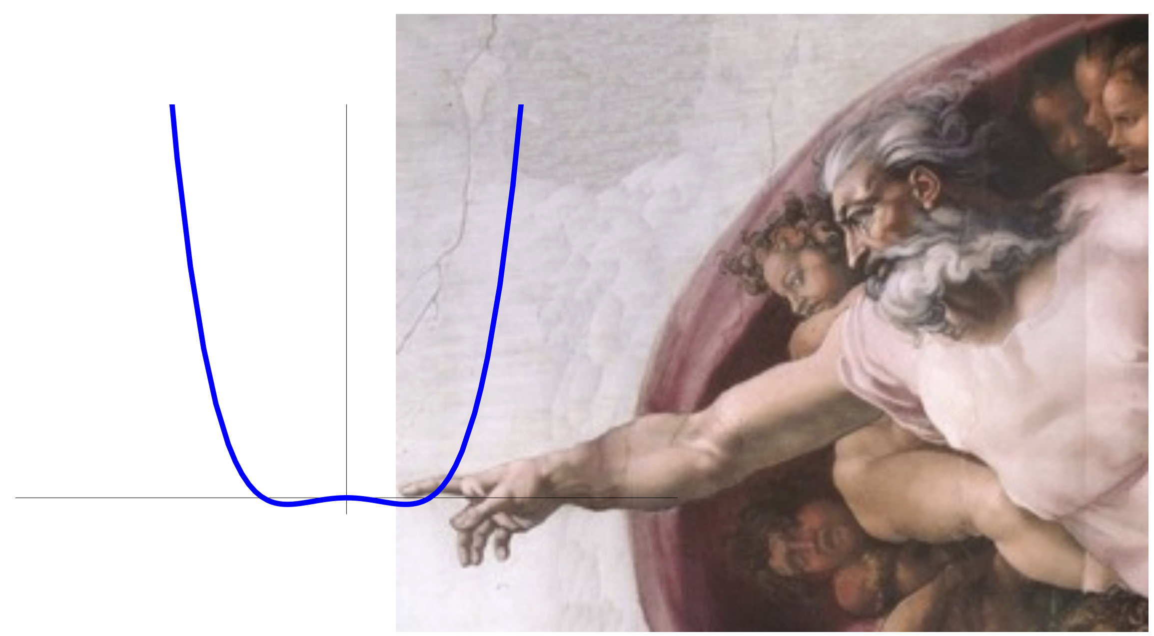
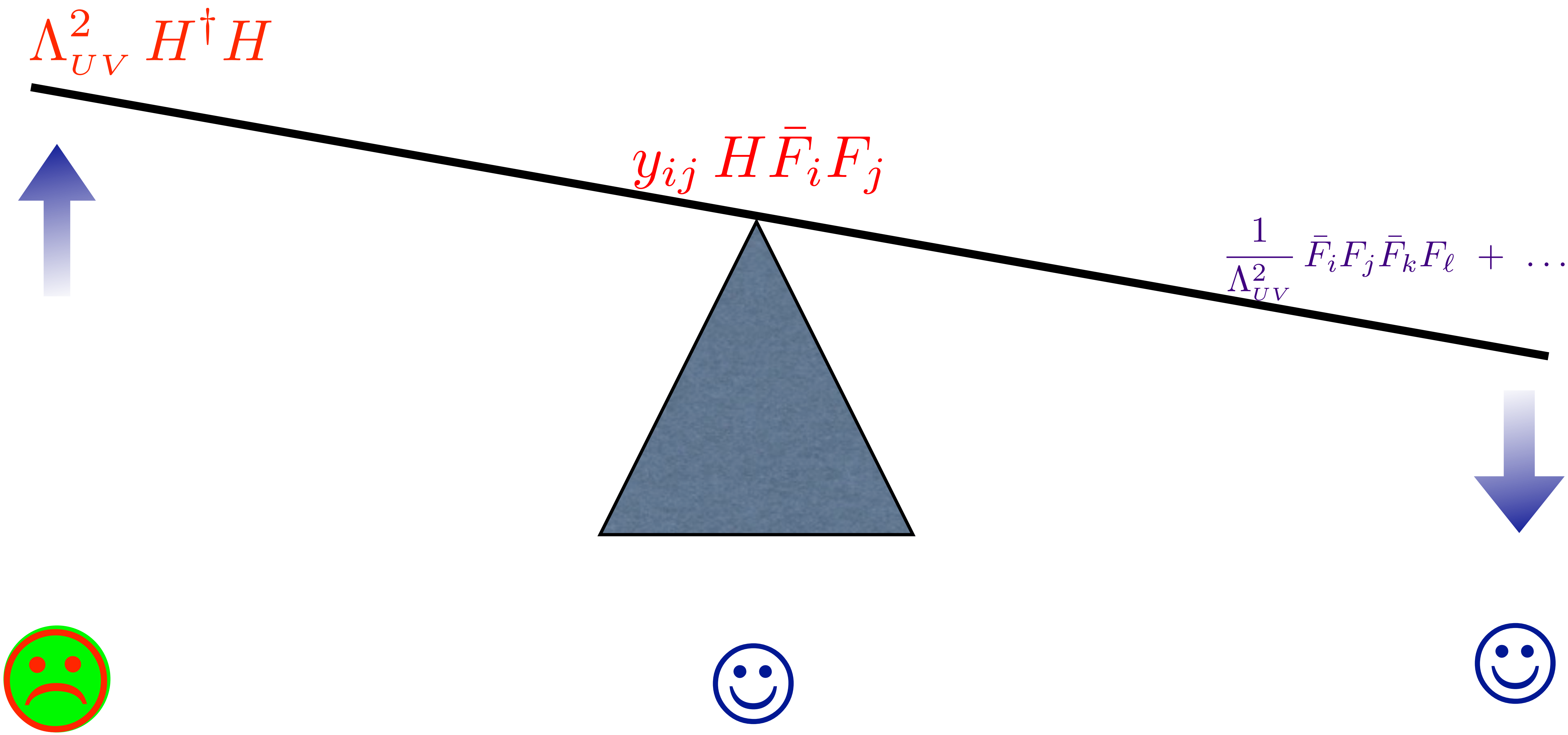


picture courtesy of V. Rychkov
who stole it anyway

Hierarchy see-saw

Standard Model up to some $\Lambda_{UV}^2 \gg 1\,\mathrm{TeV}$



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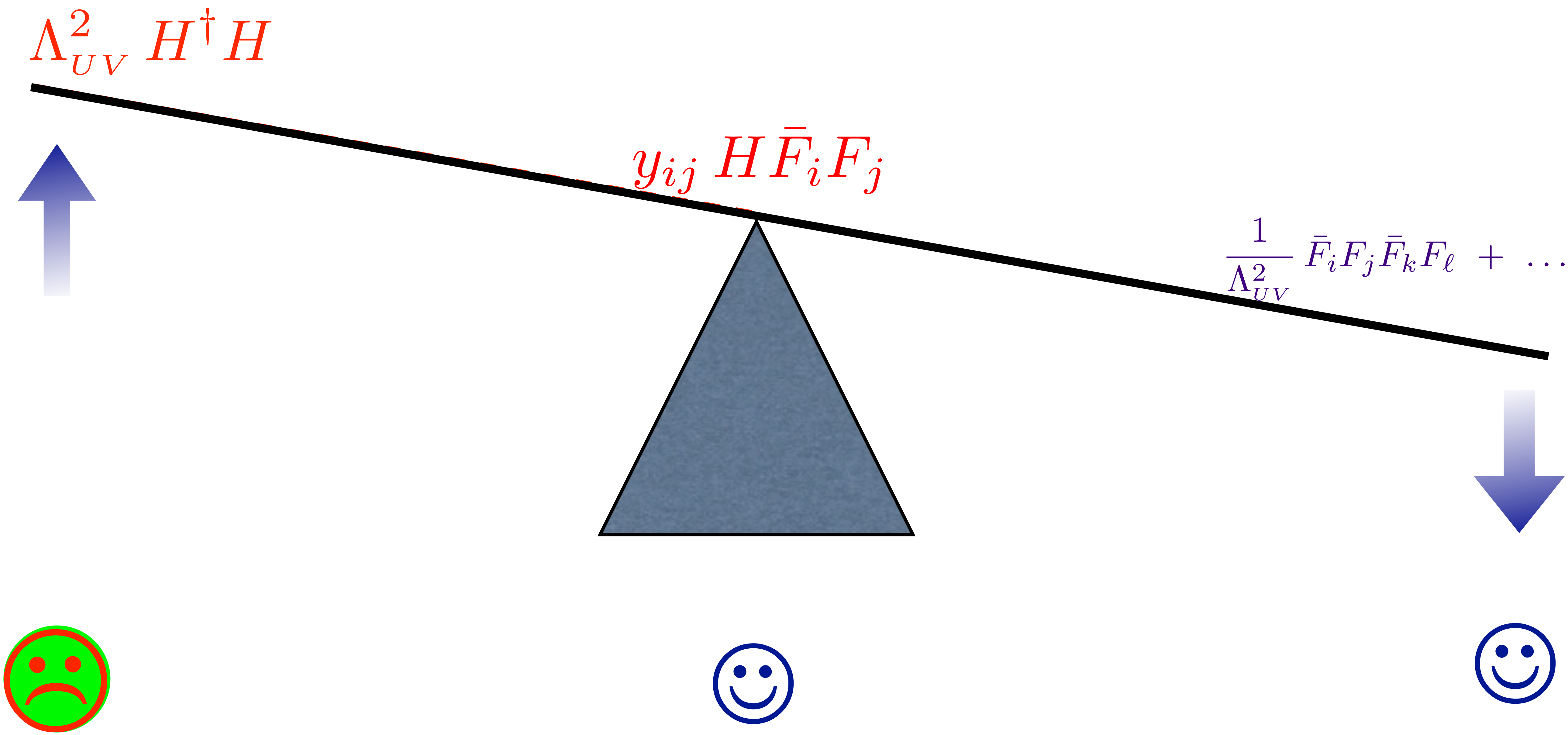
Standard Model up to some $\quad \Lambda^2_{UV} \gg 1\,\mathrm{TeV}$



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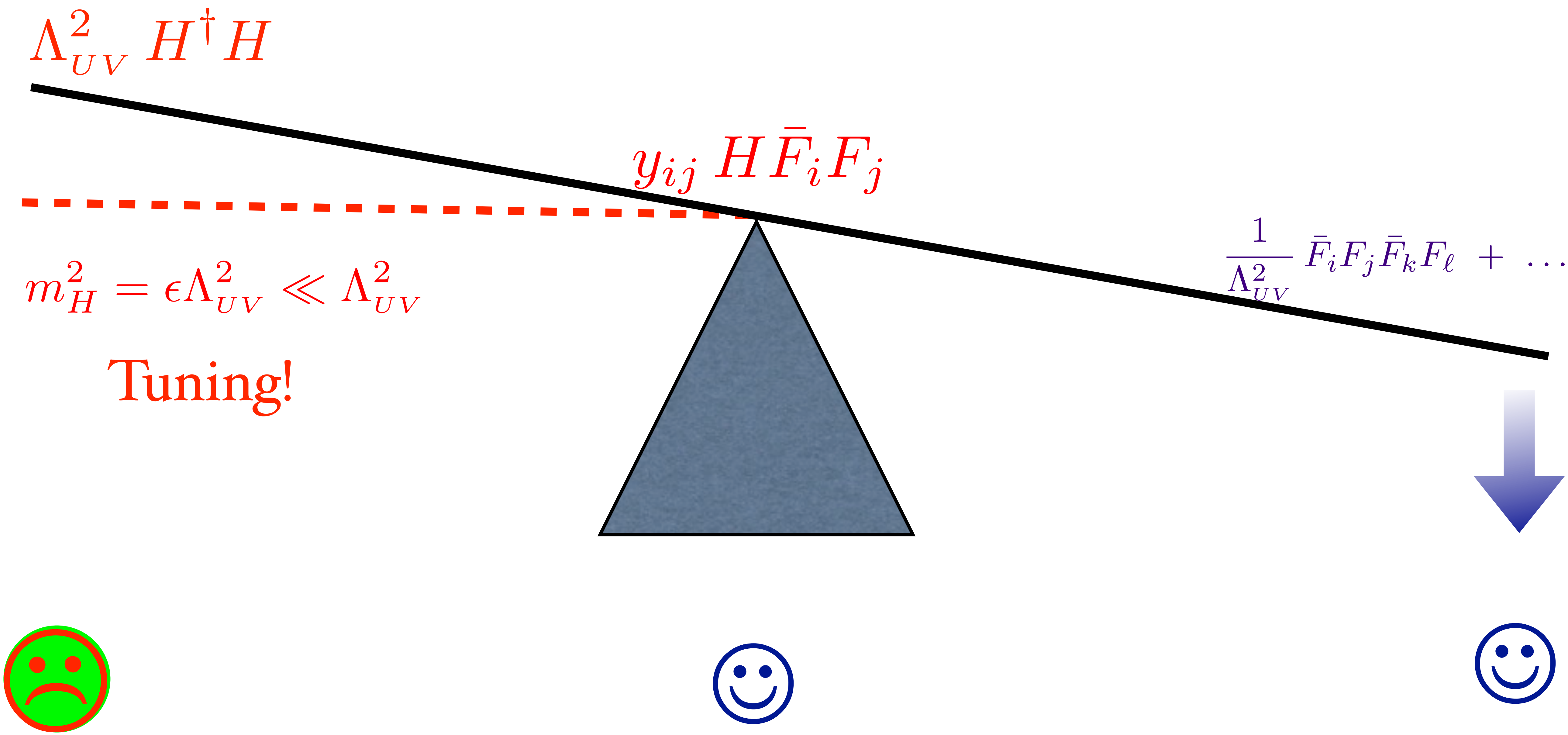
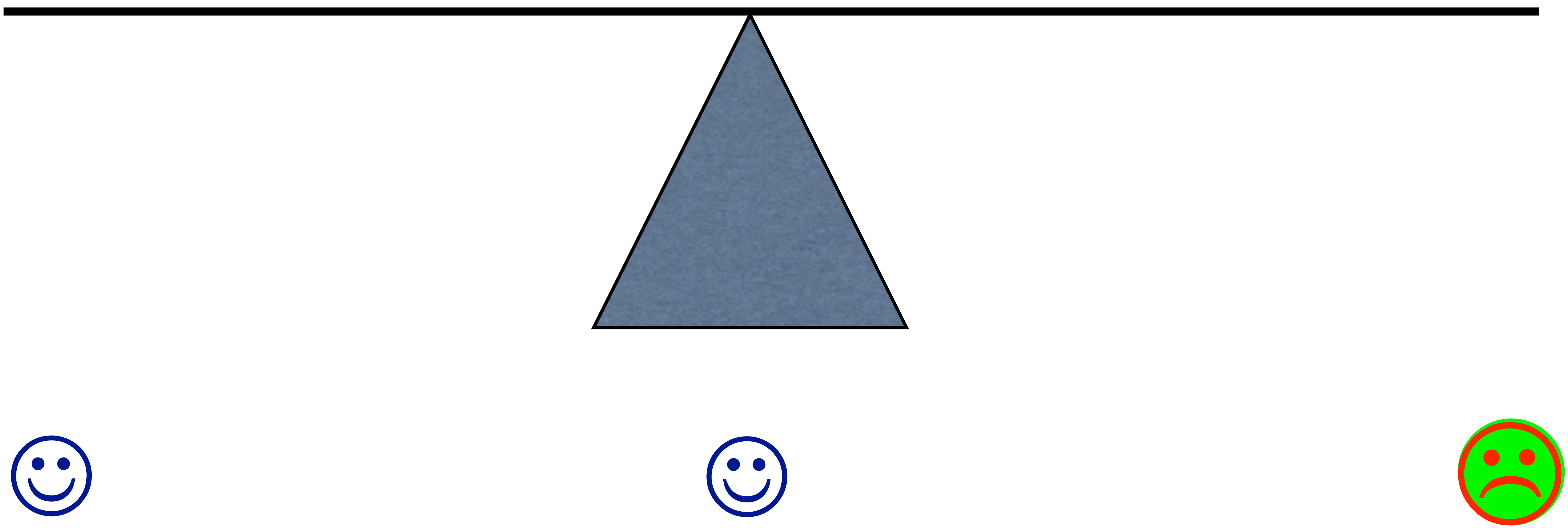


Natural SM : $\Lambda_{UV}^2 \lesssim 1\,\text{TeV}$

$\Lambda_{UV}^2\, H^\dagger H$ $\quad y_{ij}\, H \bar{F}_i F_j$ $\quad \frac{1}{\Lambda_{UV}^2} \bar{F}_i F_j \bar{F}_k F_\ell + \ldots$



Un-natural SM

The Higgs boson really is * The SM Higgs boson*

Flavor and approx B & L are theoretically appealing

... and experimentally boring

How would one understand the apparent tuning?

- Anthropic selection
- There is more than Effective Field Theory
- Intelligent design

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Natural SM

Supersymmetry

$$m^2\, H^\dagger H$$

$m^2 \;=\; 0$ enhanced UV symmetry

dimensional transmutation

$$m^2 \;\neq\; 0$$

new states at

$$g_W v_F \sim 100\,\mathrm{GeV}$$

Compositeness

$$\dim\left(H^\dagger H\right) \;\geq\; 4$$

$$v_F \;\neq\; 0$$

new states at

$$4\pi v_F \sim 2\,\mathrm{TeV}$$

In both cases, must use ingenuity to satisfy flavor and EW constraints

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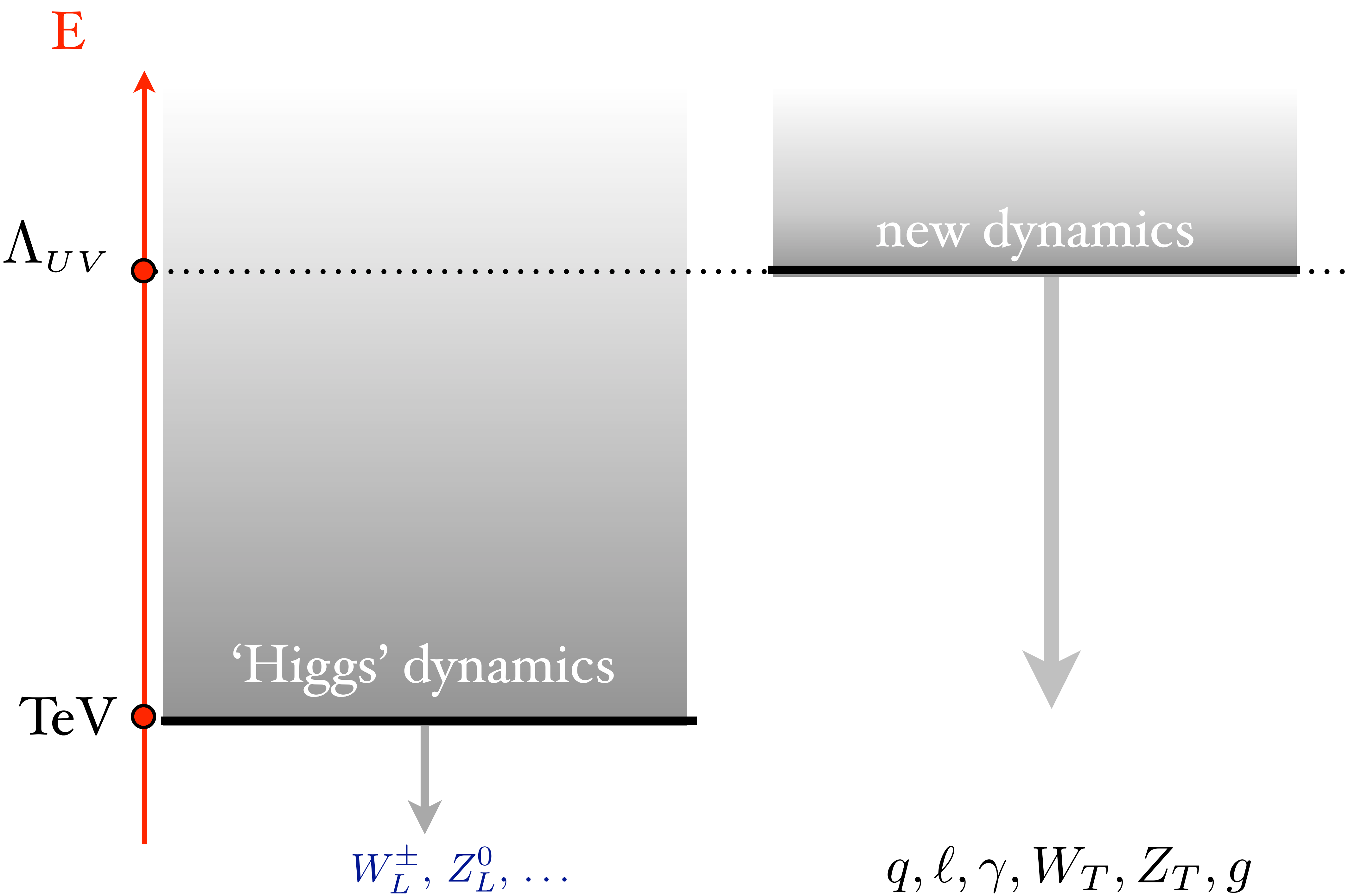
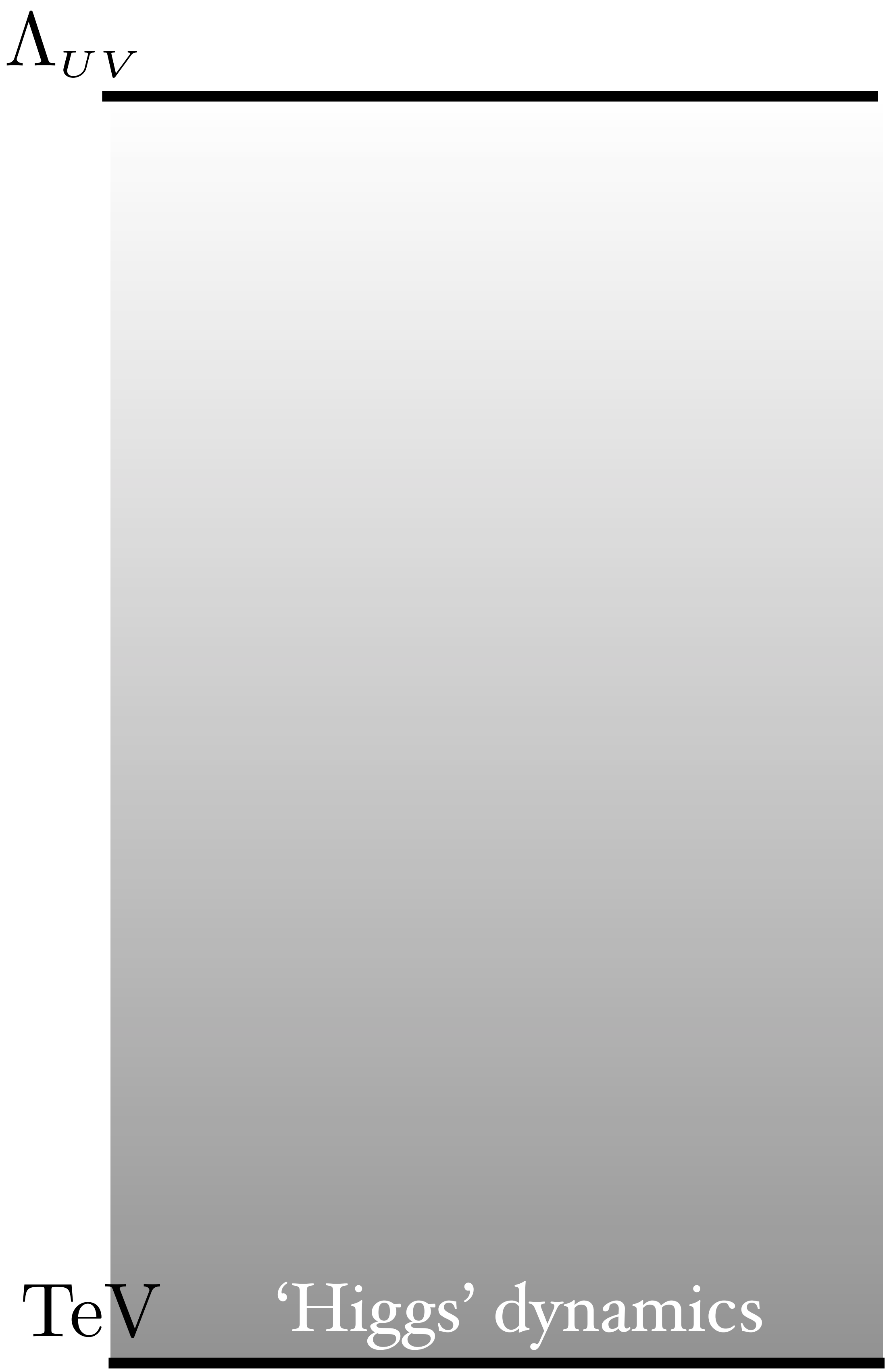
Collider data display no signal of compositeness
for quarks, leptons and ***transversely polarized*** vector bosons

Plausible scenario





Need $\Lambda_{UV} \gg \text{TeV}$
to filter out unwanted effects and produce a realistic Flavor story

Scale (conformal) invariant theories are thus an essential ingredient of model building

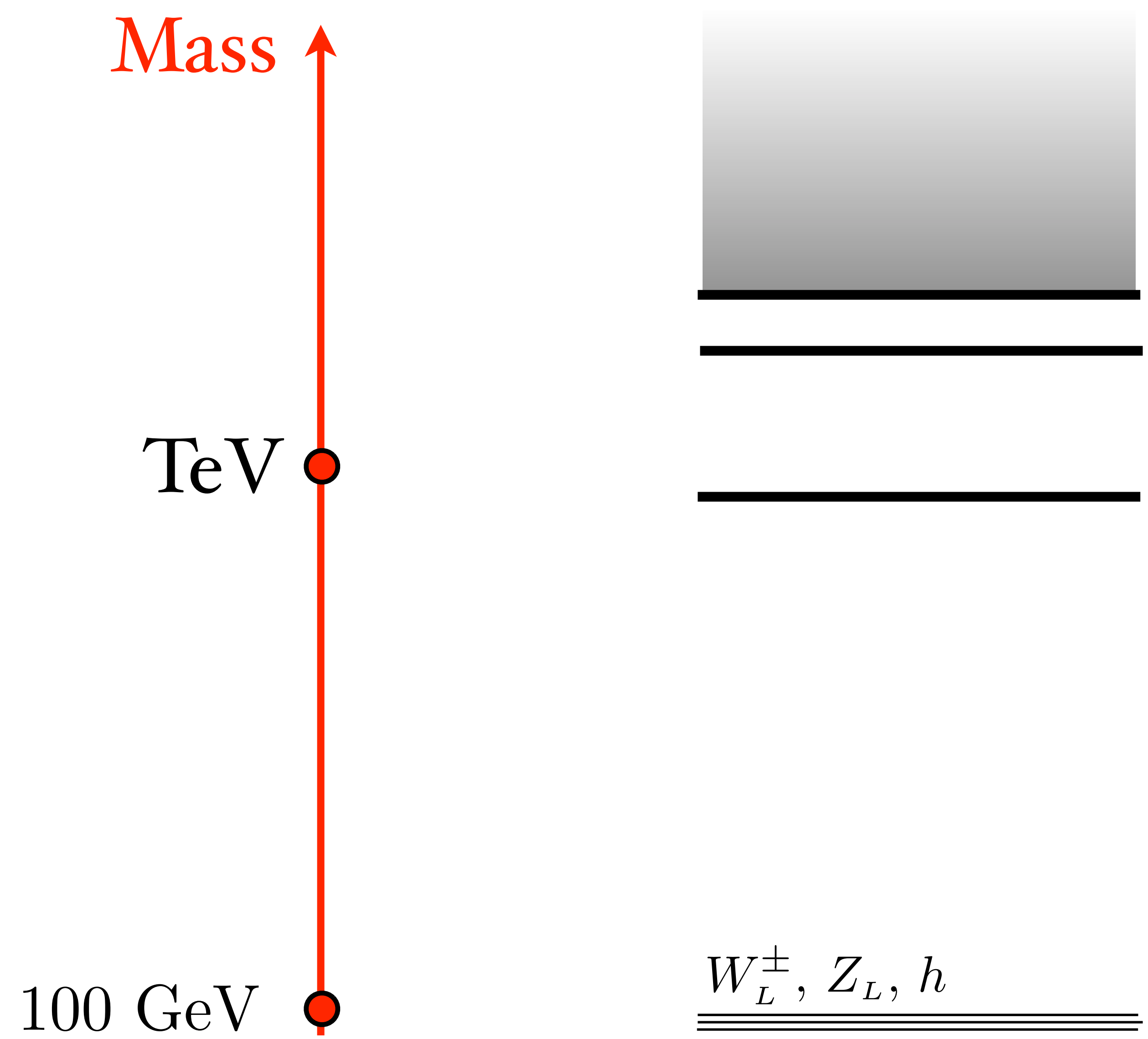
80's : asymptotically free gauge theory
(Technicolor)

2000's : Holographic CFTs
(Randall-Sundrum)

'Abstract CFT'

chracterized by
- symmetry
- operator content

The structure underlying the Higgs sector



$$H = \begin{pmatrix} h_1 + i h_2 \\ h + i h_3 \end{pmatrix}$$

must be a pseudo-Golstone multiplet

Georgi, Kaplan '84
Banks '84

Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

Simplest options compatible with $\rho \simeq 1$

$$SO(5)/SO(4) \longrightarrow H$$

$$SO(6)/SO(5) \longrightarrow H \oplus \eta$$

$$SO(6)/SO(4) \times U(1) \longrightarrow H_1 \oplus H_2$$

$$SO(4,1)/SO(4) \longrightarrow H$$

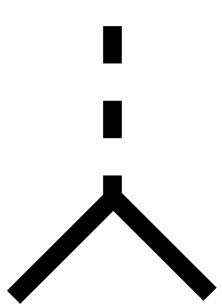
Composite sector is *broadly* described by:

Giudice, Grojean, Pomarol, RR, 2007

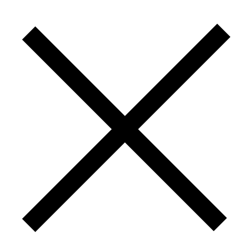
✦ one mass scale m_ρ (of order TeV)

✦ one coupling g_ρ $\qquad g_\rho \sim g_{KK} \qquad g_\rho \sim \frac{4\pi}{\sqrt{N}}$

✦ decay constant $f \sim \frac{m_\rho}{g_\rho}$



$= g_\rho \, \bar{\Psi}\Psi\Phi$



$= \frac{g_\rho^2}{m_\rho^2} \bar{\Psi}\Psi\bar{\Psi}\Psi$

Origin of Higgs potential

strongly coupled Higgs sector

SM matter & gauge fields

global symmetry weakly broken

$$V(h) = \frac{m_\rho^4}{g_\rho^2} \times \frac{\lambda_t^2}{16\pi^2} \times F(h/f)$$

$$\sim \frac{\lambda_t^2}{16\pi^2} m_\rho^2 H^\dagger H + \frac{g_\rho^2}{16\pi^2} \lambda_t^2 (H^\dagger H)^2 + \cdots$$

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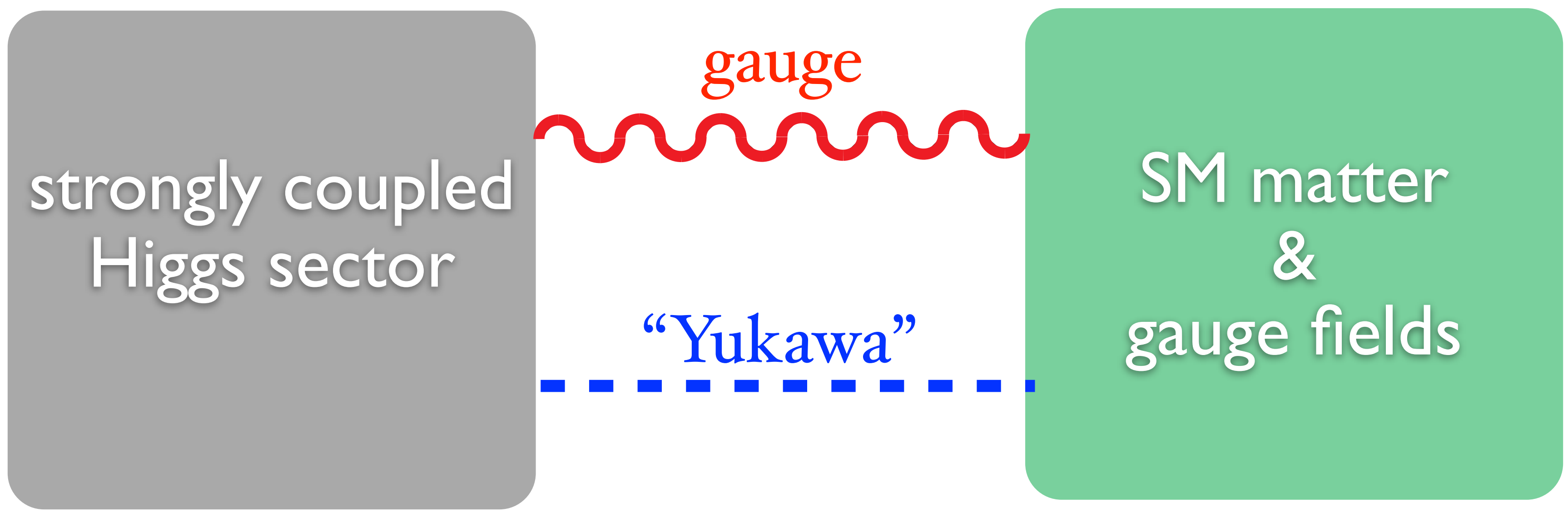

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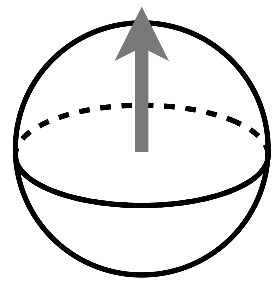
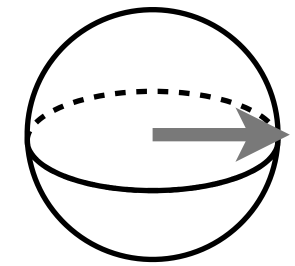
unbroken $SU(2)_L \times U(1)$

maximally broken

Vacuum dynamics



$v = 0$



$v = f$

$$V \propto F(h/f) \qquad \text{generically} \quad \frac{v^2}{f^2} = O(1)$$

EW precision observables

$$\mathcal{O} \sim \frac{v^2}{f^2} \times \mathcal{O}_{\text{TechniColor}}$$

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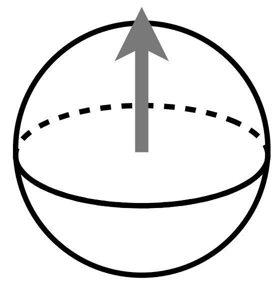

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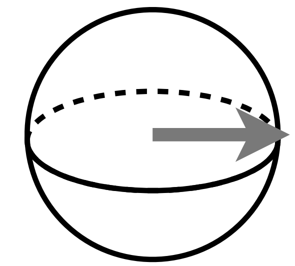

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simply tune $\frac{v^2}{f^2} \sim 0.05 \div 0.1$

be clever : Little Higgs

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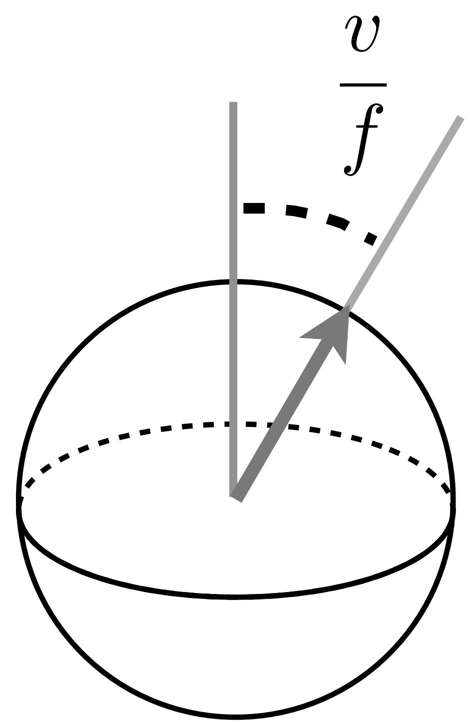

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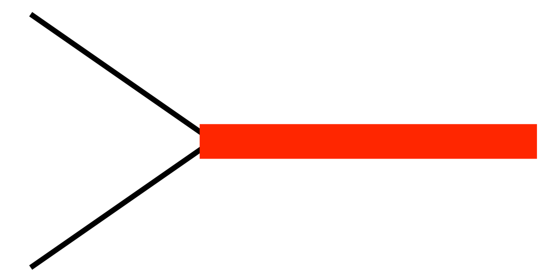
Two Ways to Flavor

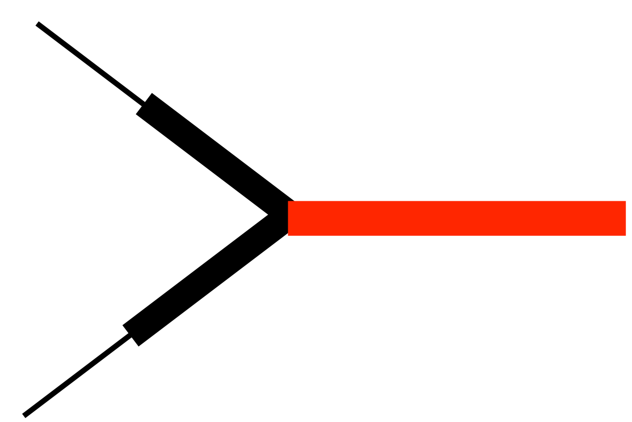
Bilinear: ETC, conformalTC

Dimopoulos, Susskind
Holdom
....
Luty, Okui

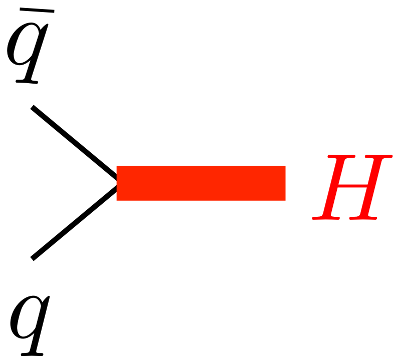


Linear: partial compositeness

D.B. Kaplan
....
Huber
RS with bulk fermions



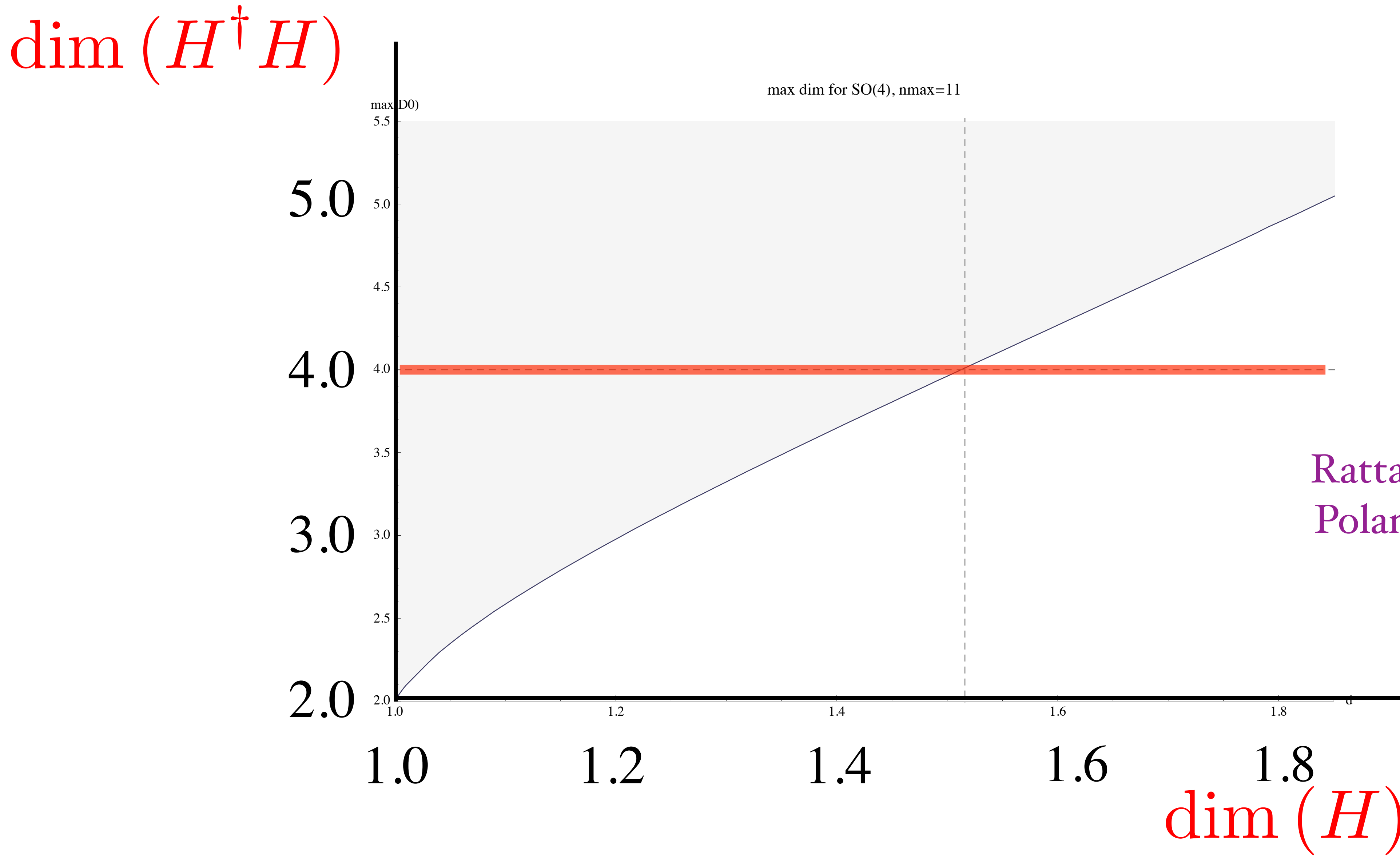
Yukawas are *irrelevants*
m_t hard to produce



$\dim(H) \equiv d_H > 1$

$\dim(\bar{q}qH) = 4 + (d_H - 1) > 4$

question: how close can I push $d_H \rightarrow 1$
without getting back the hierarchy problem?



Rattazzi, Rychkov, Tonni, Vichi ’08
Poland, Simmons-Duffin, Vichi ’11

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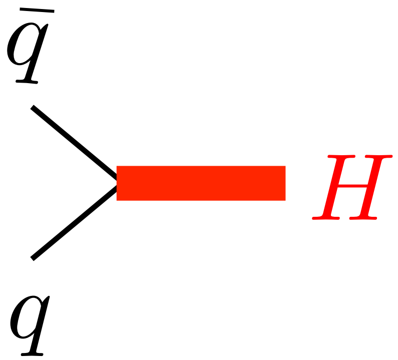

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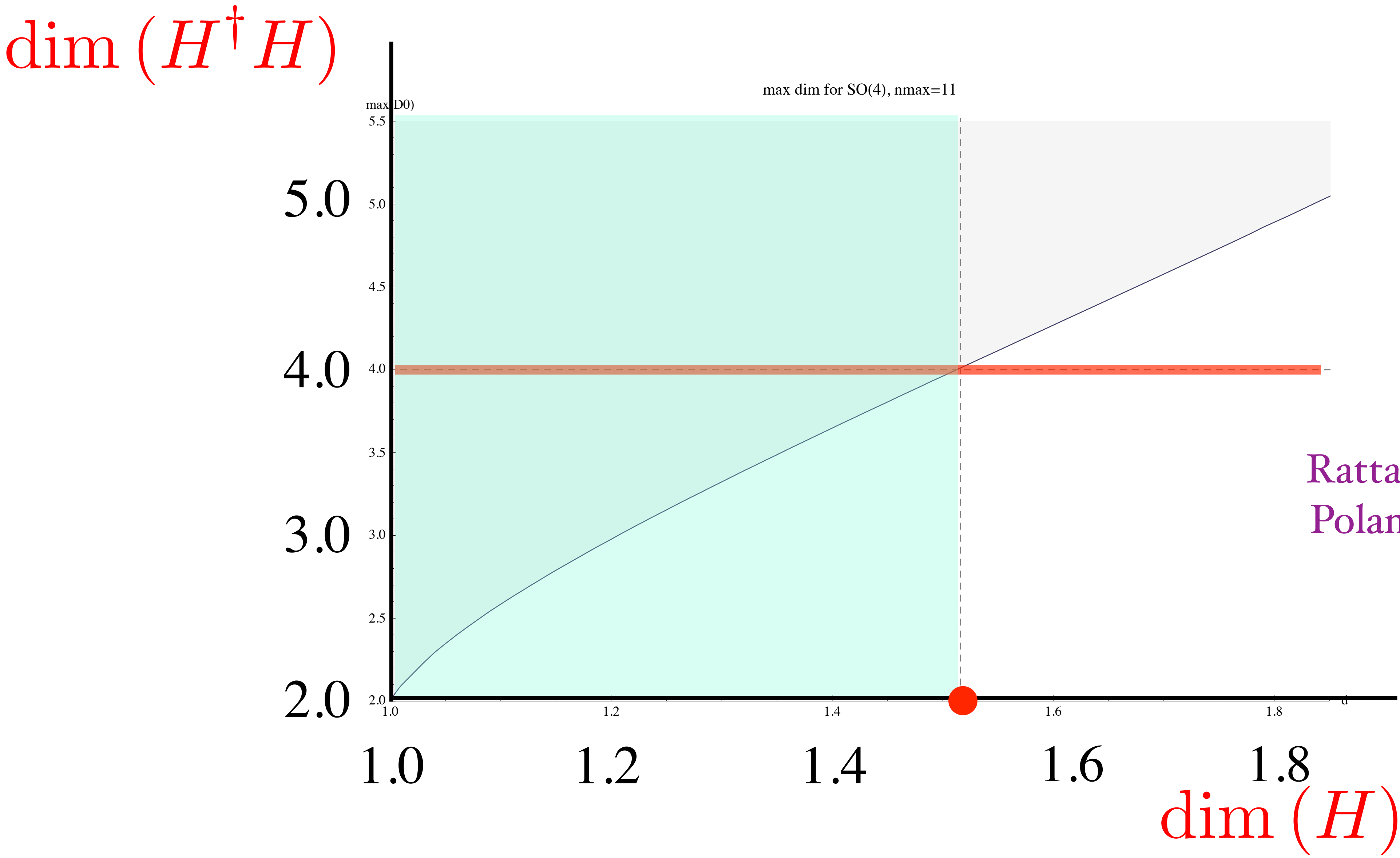
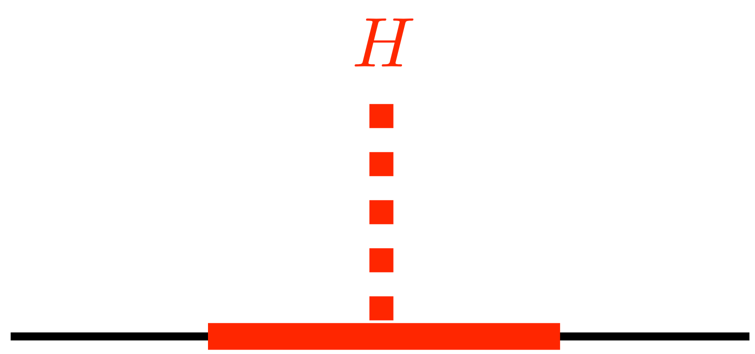


Rattazzi, Rychkov, Tonni, Vichi ’08
Poland, Simmons-Duffin, Vichi ’11

Flavor from partial compositeness

D.B. Kaplan '91
....
Huber, Shafi '00
RS with bulk fermions

$$\mathcal{L}_{Yukawa} = \epsilon_q^i q_L^i \Psi_q^i + \epsilon_u^i u_L^i \Psi_u^i + \epsilon_d^i d_L^i \Psi_d^i$$



$$Y_u^{ij} \sim \epsilon_q^i \epsilon_u^j g_*$$

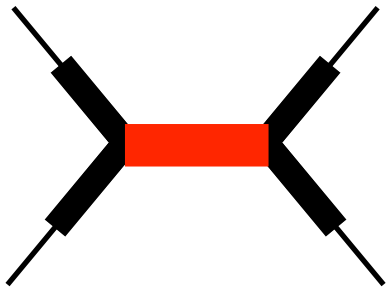
$$Y_d^{ij} \sim \epsilon_q^i \epsilon_d^j g_*$$

Ψ = composite with dimension $\sim \frac{5}{2}$ $\epsilon_q^i,\ \epsilon_u^i,\ \epsilon_d^i$ = dimensionless

- Hypothesis seems a bit wishful to me, but I see no other option
- Problems of minimal technicolor greatly alleviated, but not eliminated

Flavor transitions controlled by selection rules

ΔF=2



$$\epsilon_q^i \epsilon_d^j \epsilon_q^k \epsilon_d^\ell \times \frac{g_\rho^2}{m_\rho^2} \qquad (\bar{q}^i \gamma^\mu d^j)(\bar{q}^l \gamma_\mu d^\ell)$$

ΔF=1

$$\epsilon_q^i \epsilon_u^j g_\rho \times \frac{v}{m_\rho^2} \times \frac{g_\rho^2}{16\pi^2} \quad \bar{q}^i \sigma_{\mu\nu} u^j G_{\mu\nu}$$

Bounds & an intriguing hint

Davidson, Isidori, Uhlig '07
Csaki, Falkowski, Weiler '08

Keren-Zur, Lodone, Nardecchia, Pappadopulo, RR, Vecchi '12

ϵ_k	$m_\rho \gtrsim 10\ \text{TeV}$
$\epsilon'/\epsilon, \quad b \to s\gamma$	$m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (10-15)\ \text{TeV}$
d_n	$m_\rho \gtrsim \frac{g_\rho}{4\pi} \times (20-40)\ \text{TeV}$
CP violation in D decays $\Delta a_{CP} = a_{KK} - a_{\pi\pi} = -(0.67 \pm 0.16)\%$	$m_\rho \simeq \frac{g_\rho}{4\pi} \times 10\ \text{TeV}$

tuning

$$0.1\% \left(\frac{m_h}{125\,\text{GeV}}\right)^2 \left(\frac{10\,\text{TeV}}{m_\rho}\right)^2$$

- connection with weak scale not perfect
- Not crazy at all to see deviation in D's first !
- d_n should be next

$$\mu \to e\gamma \qquad\qquad \frac{\sqrt{m_\mu m_e}}{m_\rho^2}\,\bar{\mu}\sigma_{\alpha\beta}e\,F^{\alpha\beta}$$

MEG: Br($\mu \to e\,\gamma$) < 2.4 x 10^{-12} $\qquad m_\rho \gtrsim 150\ \mathrm{TeV}$

Partial compositeness clearly cannot be the full story

Must assume strong sector possesses some flavor symmetry

$U(1)_e \times U(1)_\mu \times (1)_\tau$

Range of possibilities

. . . .

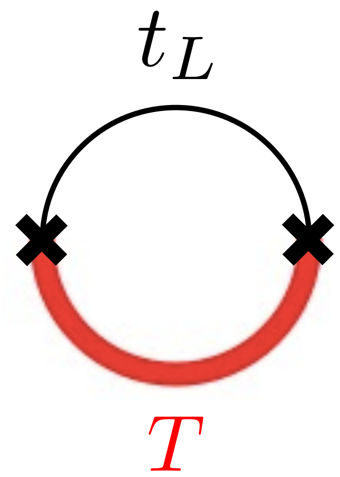
Redi, Weiler '11
Barbieri et al. '12

SU(3) x SU(3) x ...

Higgs potential, fine-tuning and expectations at the LHC

Higgs's mass versus top-partners'

$V(h) =$



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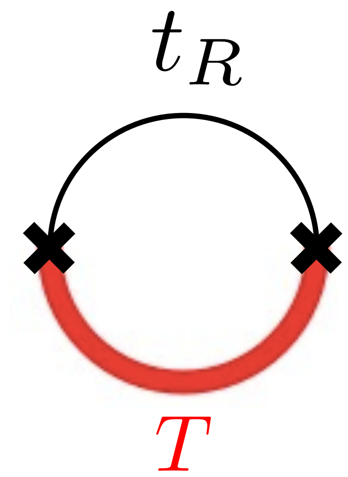

$+ \ldots$

$O(\lambda_L^2)$ $\qquad$ $O(\lambda_R^2)$

$$\boxed{\lambda_L \lambda_R \sim \lambda_t g_T}$$

$\lambda_L \sim \lambda_t$

best option $\quad t_R \quad$ is fully composite SO(5) singlet

$\lambda_R \sim g_T$

$$\boxed{V(h) = \frac{m_T^4}{g_T^2} \times \frac{\lambda_t^2}{16\pi^2} \times F(h/f)}$$

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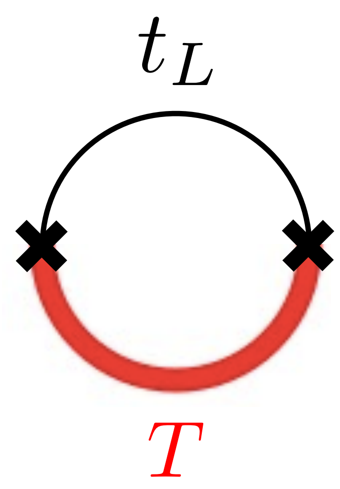
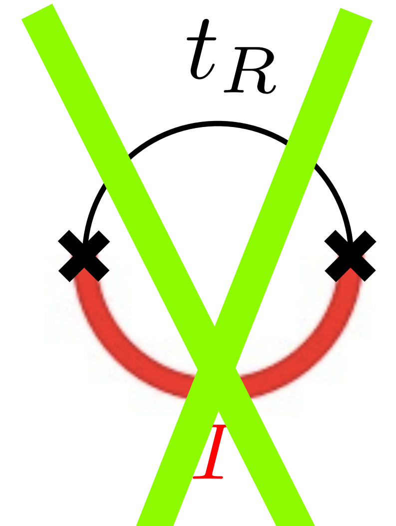
$V(h) =$ 

$+$ 

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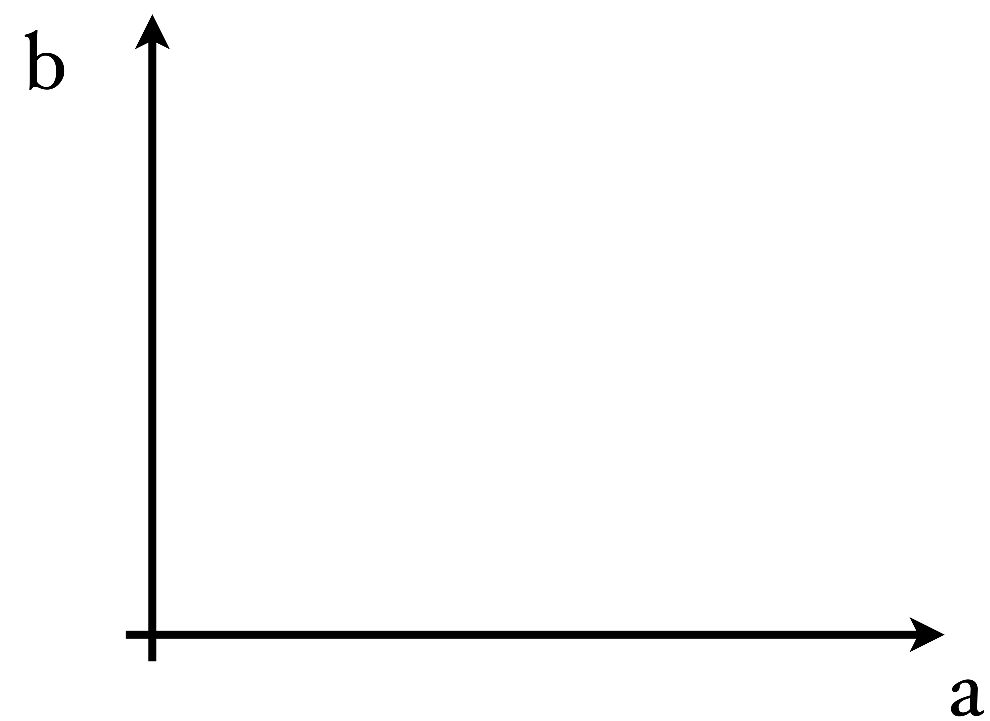
Mrazek et al, '11
Pomarol, Riva '12

$$V = \frac{3\lambda_t^2 m_T^2}{16\pi^2}\left(ah^2 + bh^4/f^2 + \dots\right)$$



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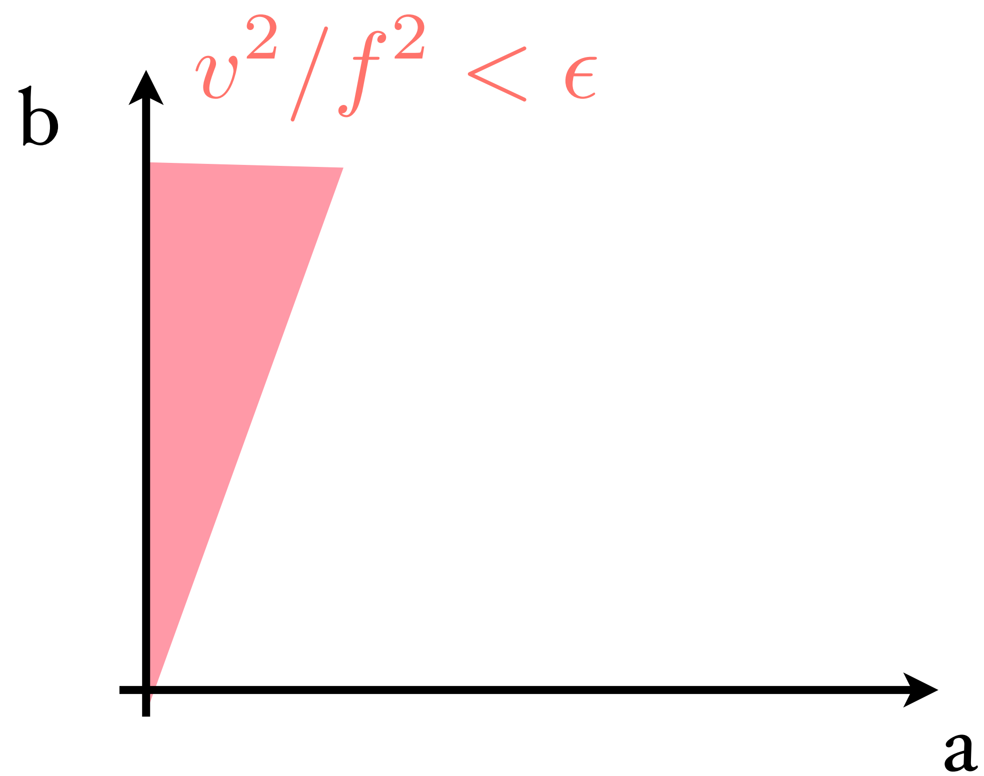

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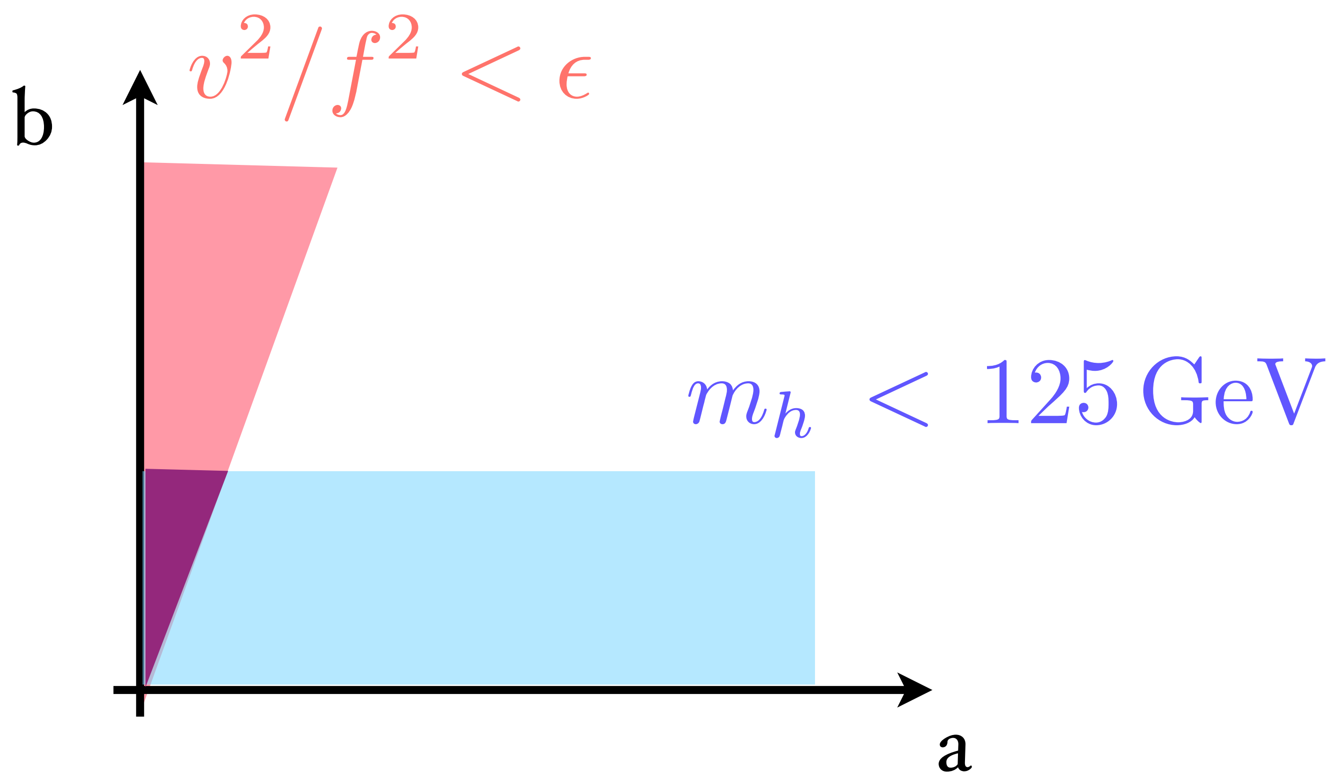


Total tuning ~ area = $\left(\frac{430\,\mathrm{GeV}}{m_T}\right)^2 \times \frac{4}{g_T^2}$

The main test of naturalness is the search for fermionic top partners

Perelstein, Pierce, Peskin '03
Contino, Servant '08
Mrazek, Wulzer '10

but how to proceed? given we do not have in our hand a truly compelling and calculable model

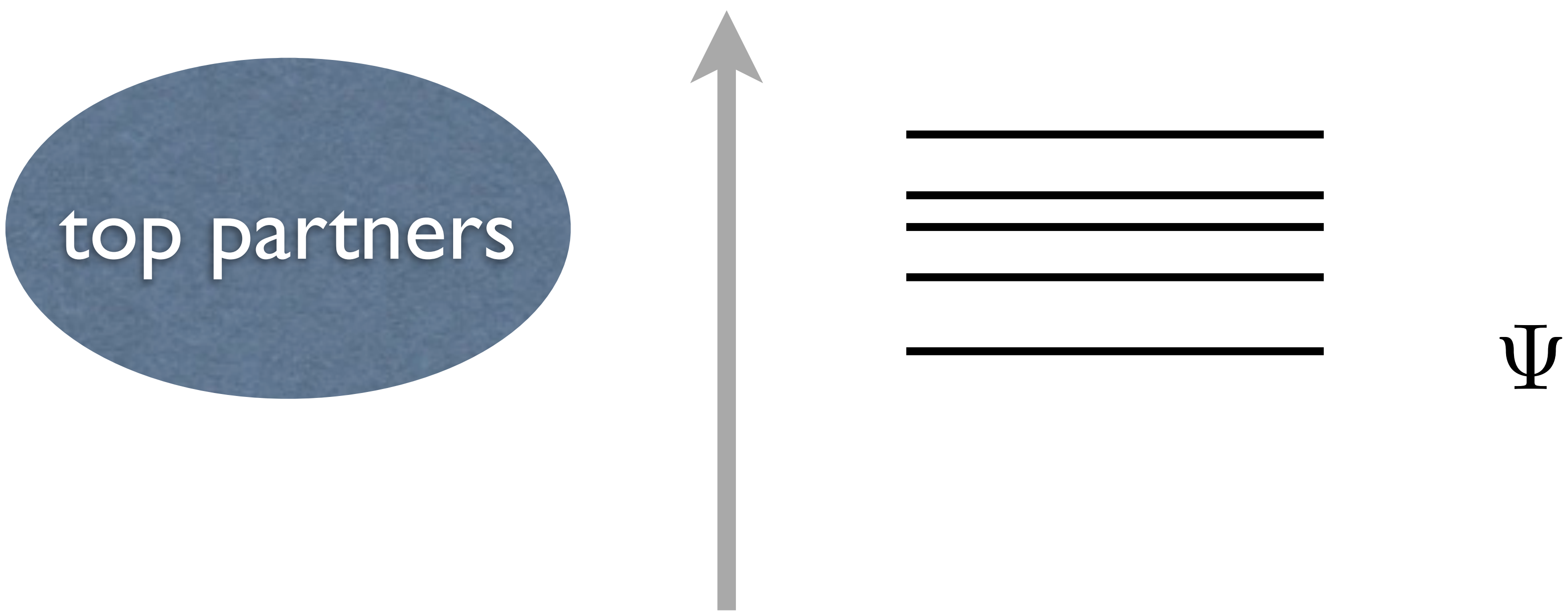
how to help our experimental colleagues to express the results of their searches in the light of more interesting scenarios than, say, a fourth family

Simplified Model Ideology

in the end model builders mistrust full fledged models

De Simone, Matsedonkyi, RR, Wulzer '12

mass



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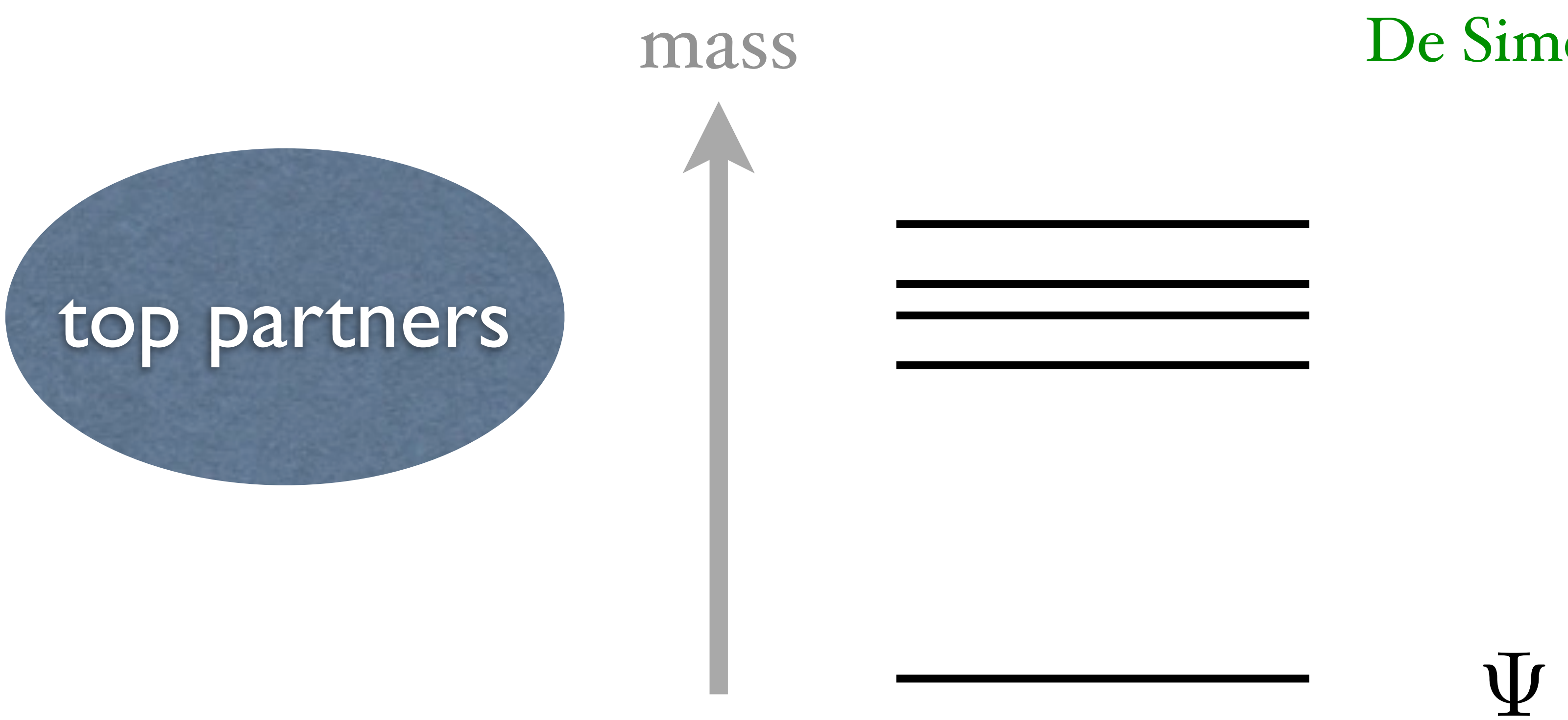


Focus on
on just Ψ

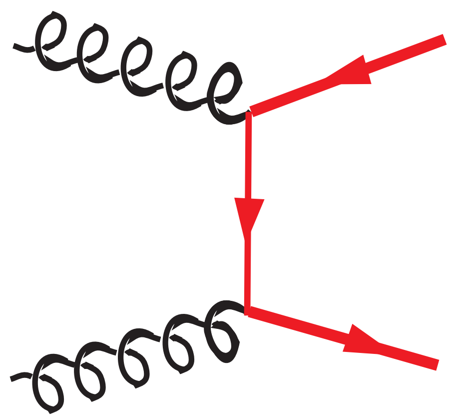
Combining
- choice for Ψ quantum numbers
- hypothesis on UV origin of λ_t

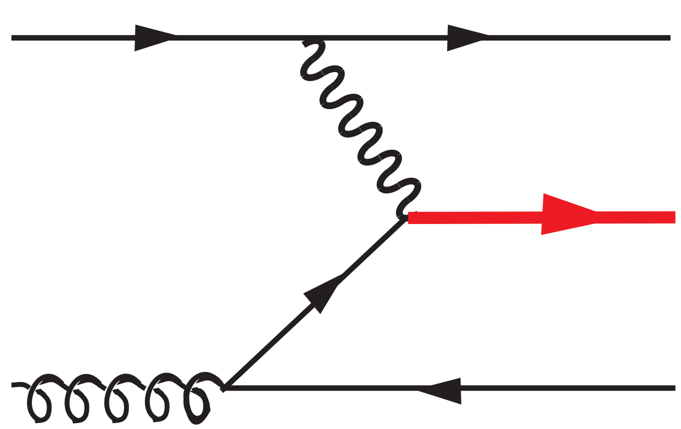
→ a handful of models

- symmetry, selection rules, power counting

→ a handful of parameters

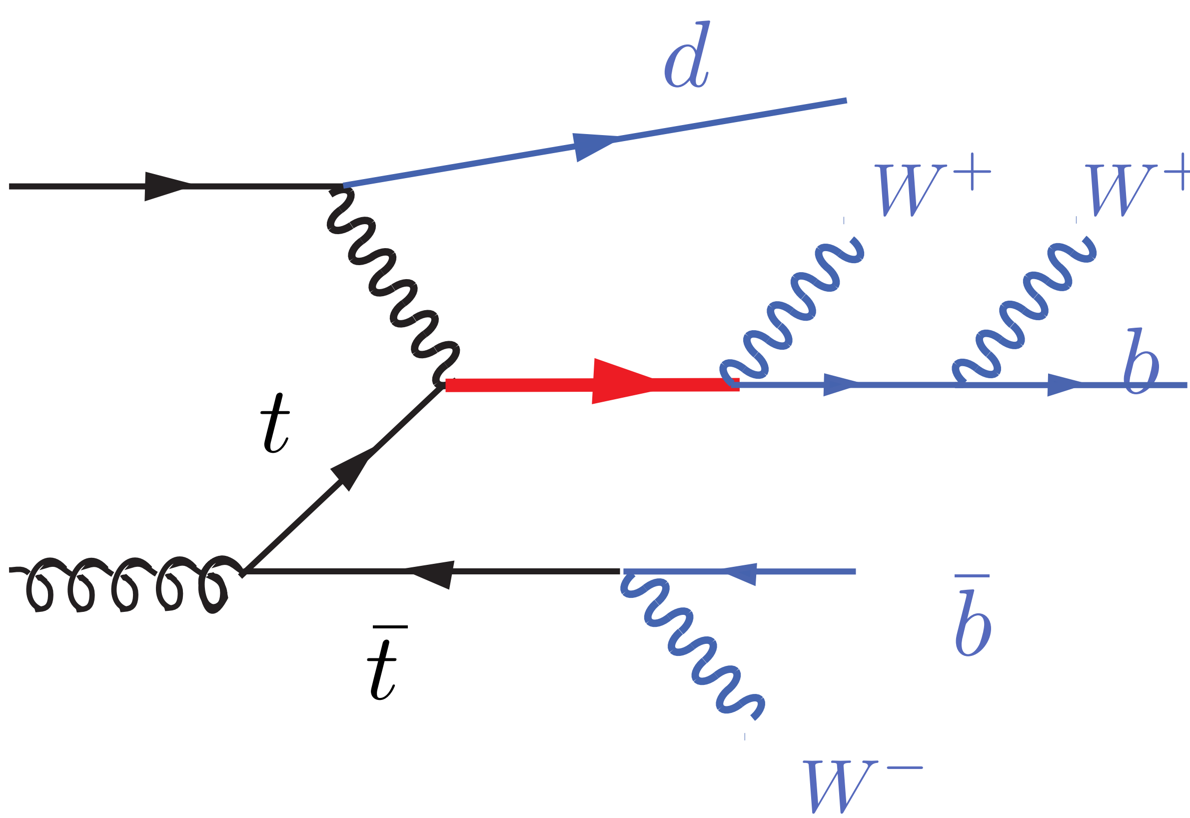
Production





Decay

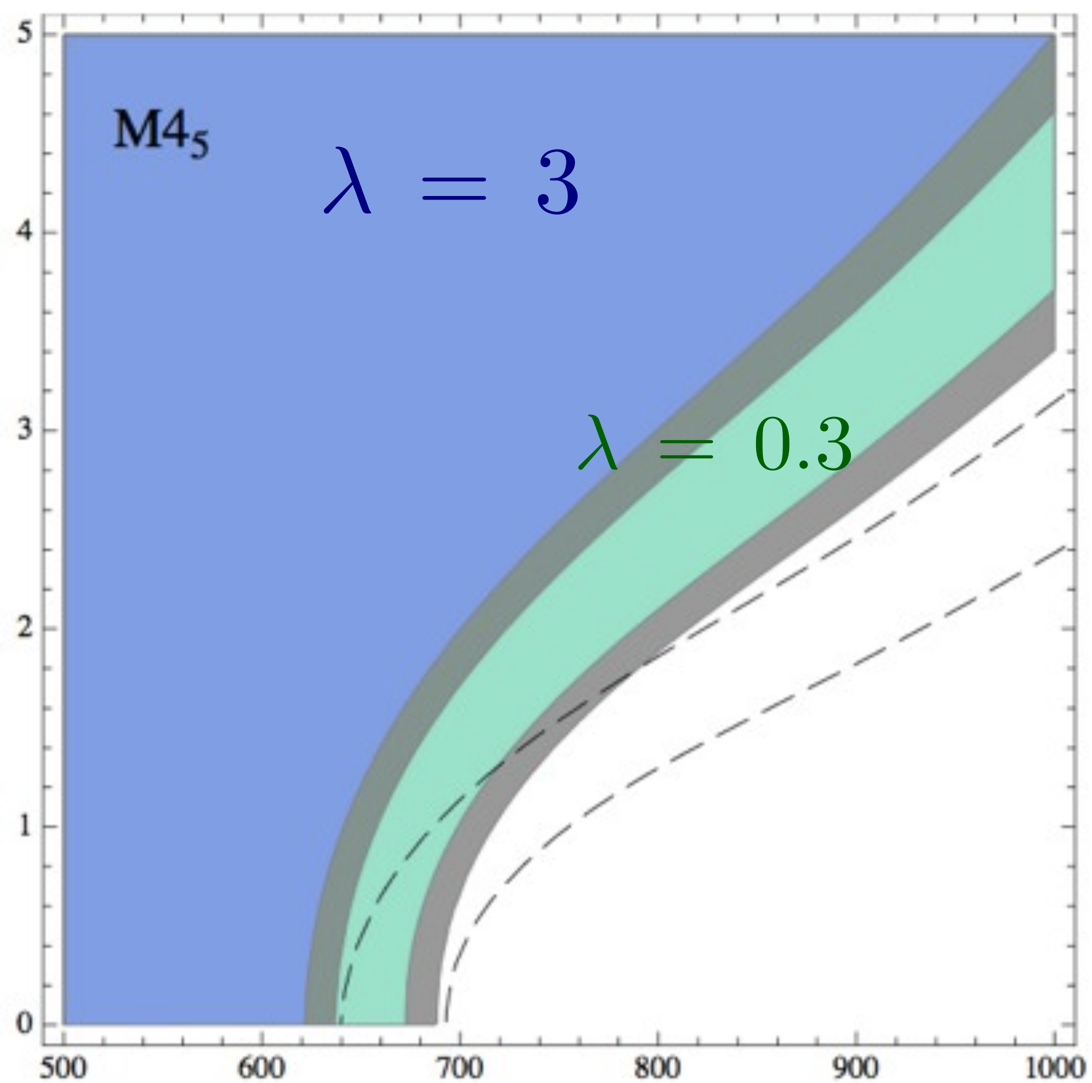
Ex.: $\Psi_{5/3} \in (\frac{1}{2}, \frac{1}{2})$



Contino, Servant 2008

$\Psi_{5/3}$ et $\Psi_{-1/3} \in (\frac{1}{2}, \frac{1}{2})$ constrained by 4th family search $b' \to Wt$

same sign dileptons (trileptons) + b + 3 (2) jets



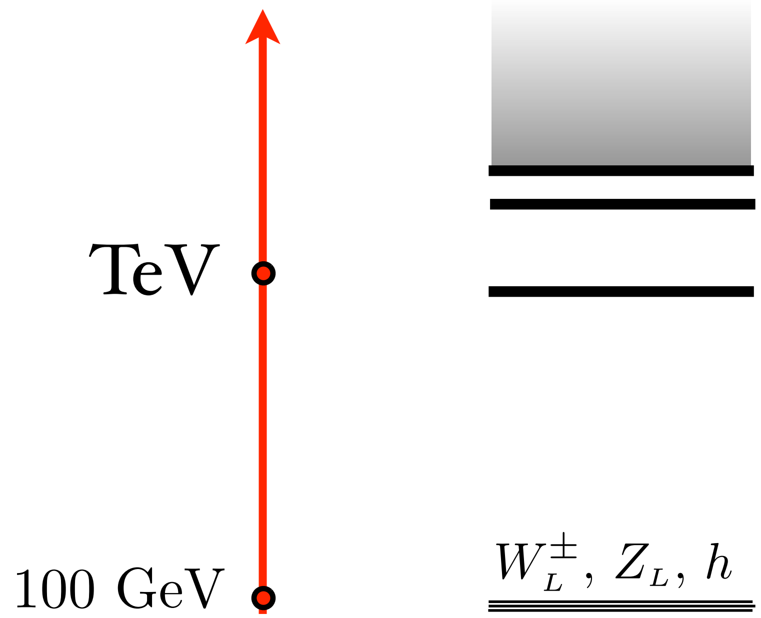
c_1

$M_{5/3}$

$$\xi \equiv \frac{v^2}{f^2} = 0.2$$

At 14 TeV with ab^{-1} , one expects a reach of up to 2 TeV mass

Mrazek, Wulzer '10



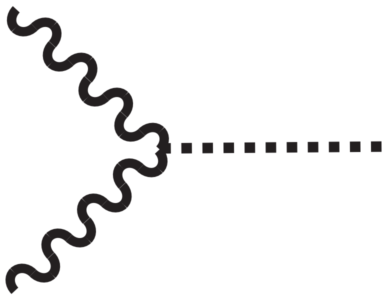
Effective Lagrangian for a composite light Higgs boson
(+ pseudo-Goldstone hypothesis)

Giudice, Grojean, Pomarol, RR, 2007

Two leading operators in effective lagrangian

$$\# \frac{1}{2f^2} \partial_\mu |H|^2 \partial^\mu |H|^2$$

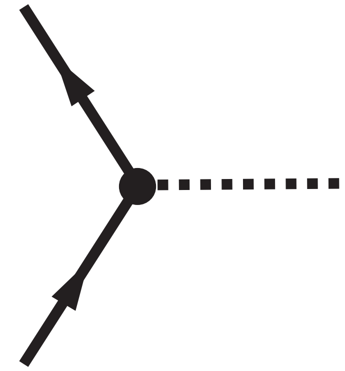
$$\# \frac{y_i}{f^2} (\bar{f}_i f_i H) |H|^2$$



$$a \times \frac{2m_V^2}{v}$$

$$a \simeq 1 - \frac{1}{2}\frac{v^2}{f^2} < 1$$

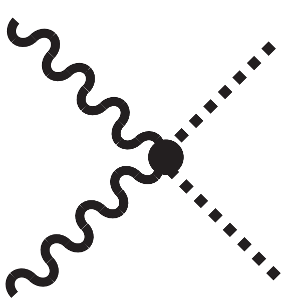
robust consequence
of coset structure



$$c_i \times \frac{m_i}{v}$$

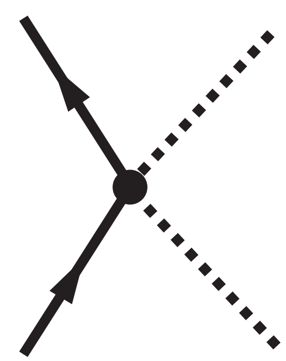
$$c_i \simeq 1 + O(\frac{v^2}{f^2}) < 1$$

generic but not a theorem



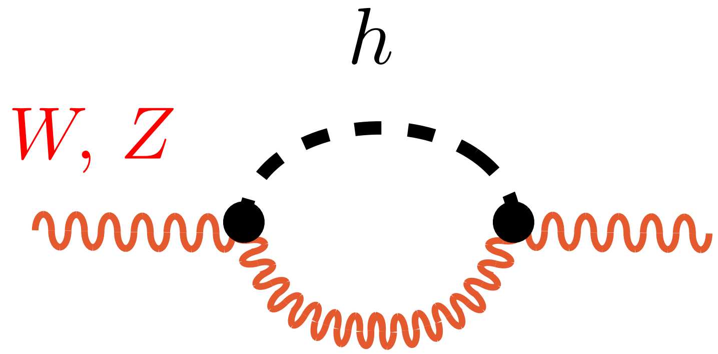
$$b \times \frac{m_V^2}{v^2}$$

$$b \simeq 1 - 2\frac{v^2}{f^2}$$



$$\propto \frac{m_i}{f^2}$$

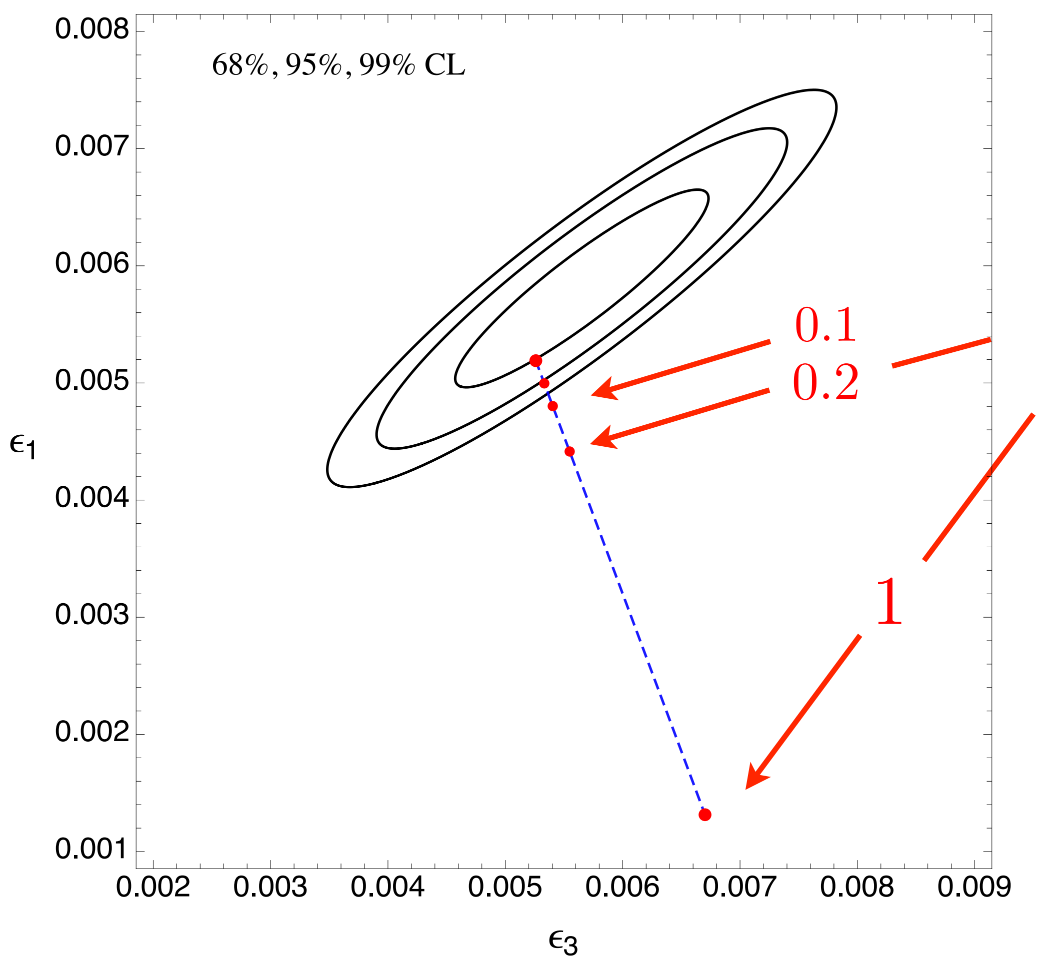
New!



(T) $$\Delta\epsilon_1 = -\frac{3g^2 \tan\theta_W^2}{32\pi^2}(1-a^2)\ln(m_\rho/m_h)$$

(S) $$\Delta\epsilon_3 = \frac{g^2}{96\pi^2}(1-a^2)\ln(m_\rho/m_h)$$

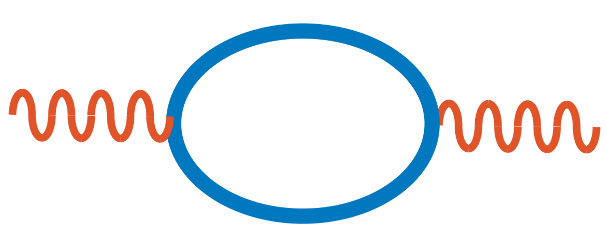
Barbieri, Bellazzini, Rychkov, Varagnolo 07



$$\frac{v^2}{f^2} = 1 - a^2$$

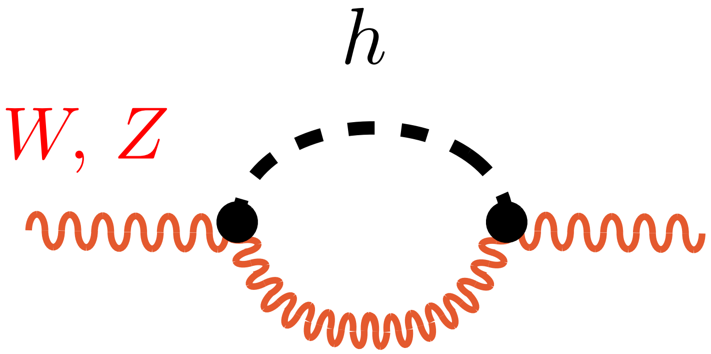
$$\boxed{\frac{v^2}{f^2} \sim 0.1 \div 0.2 \text{ is tolerable}}$$

top-partner loops



$$\Delta\epsilon_1 \gtrsim 10^{-3}$$

$$M_\Psi < 1\ \mathrm{TeV}$$



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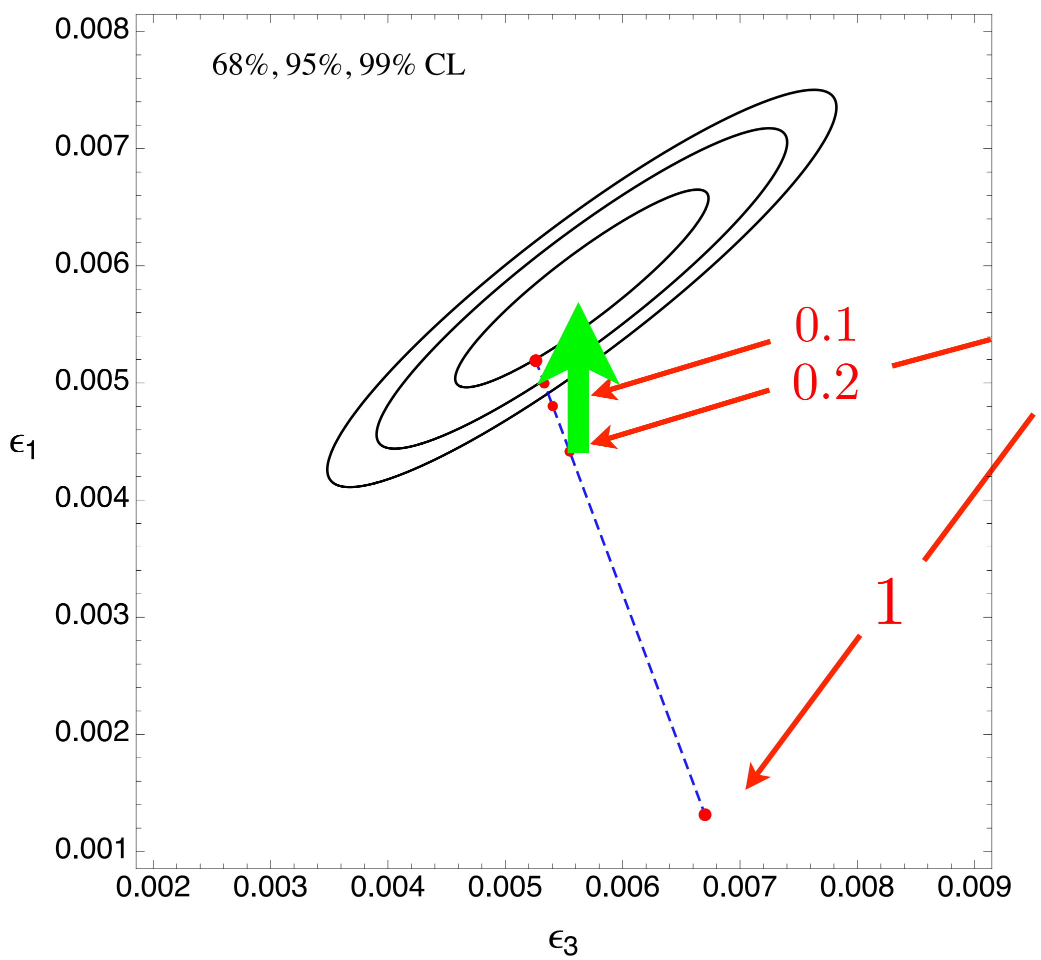

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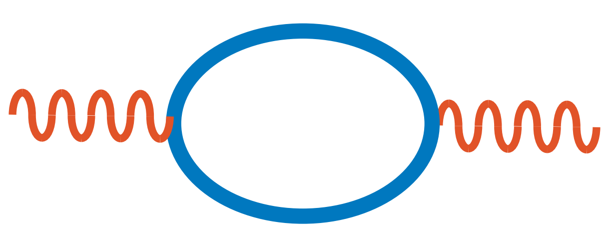

$$\Delta\epsilon_1 \gtrsim 10^{-3}$$

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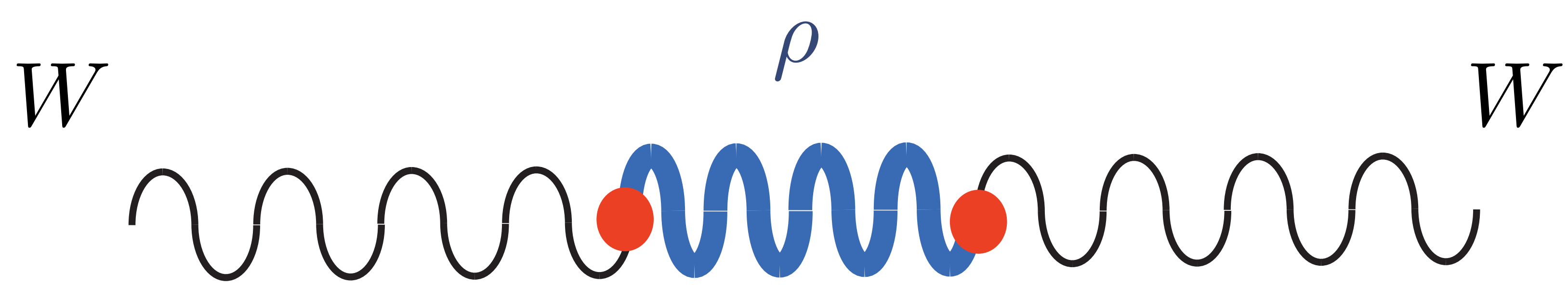
vector resonances

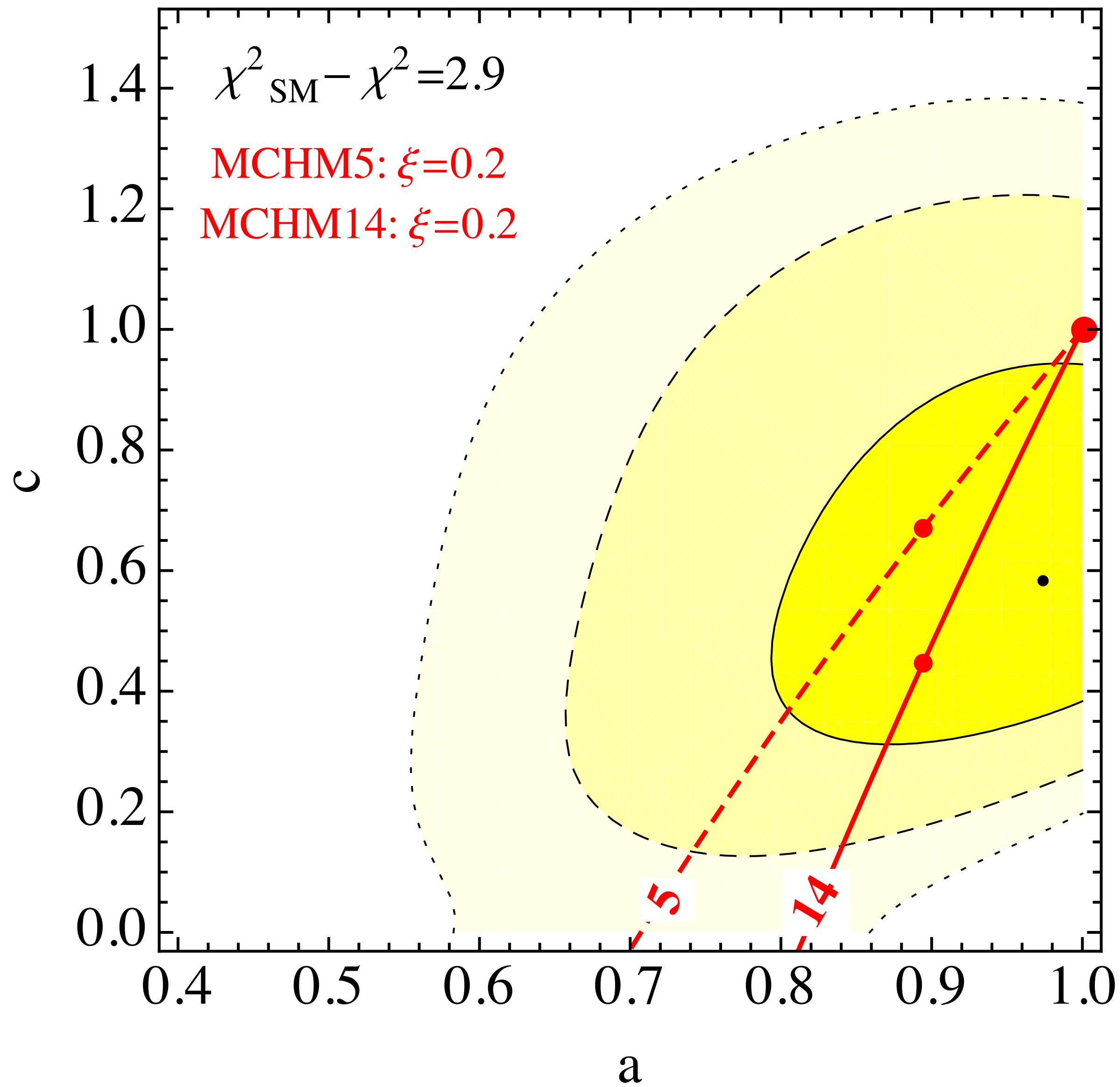


$$\Delta\epsilon_3 \sim \frac{m_W^2}{m_\rho^2}$$

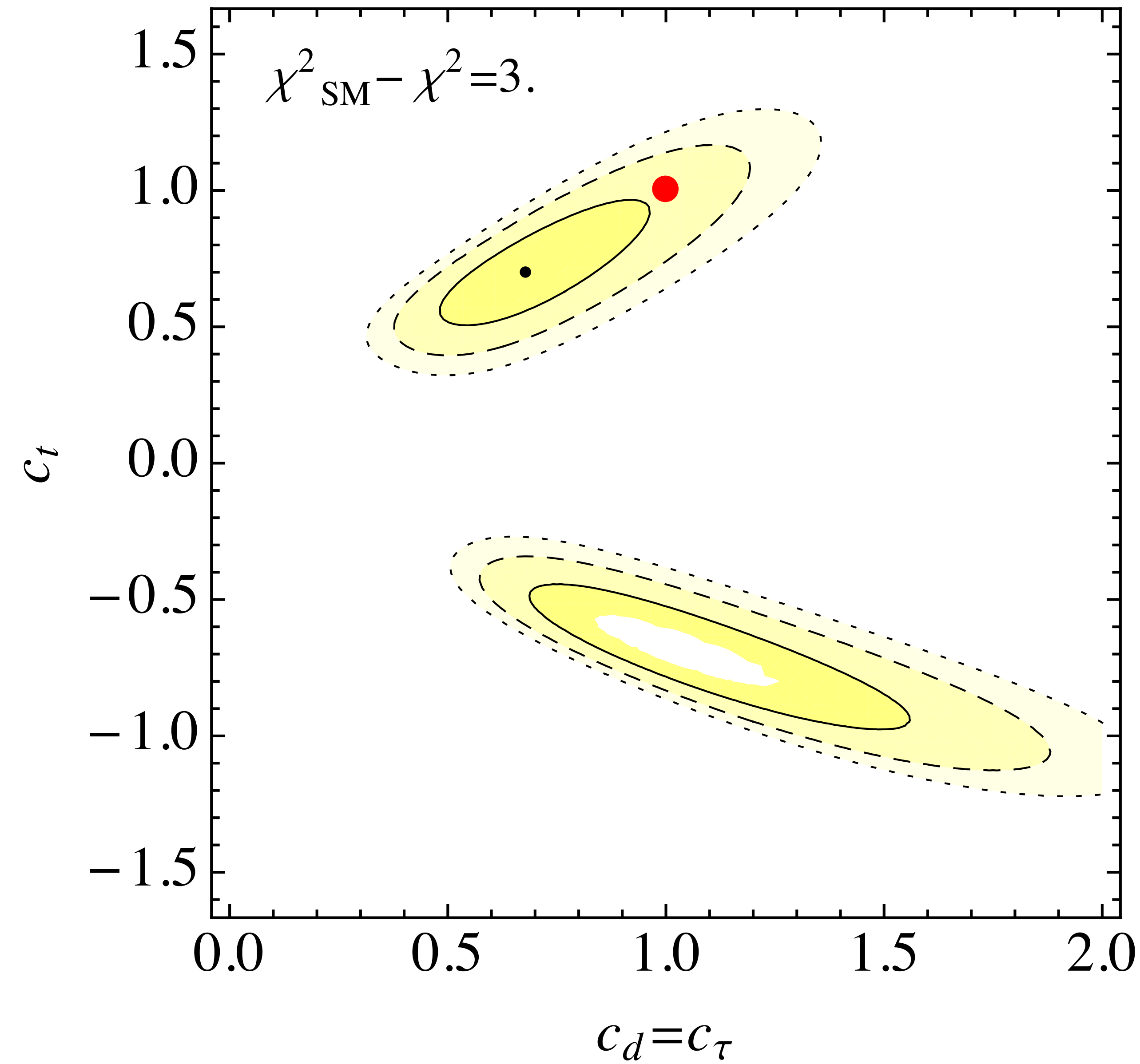
$$\Delta\epsilon_3 < 10^{-3} \qquad\qquad m_\rho > 3\,\mathrm{TeV}$$

time not ripe to search for them at LHC

CMS



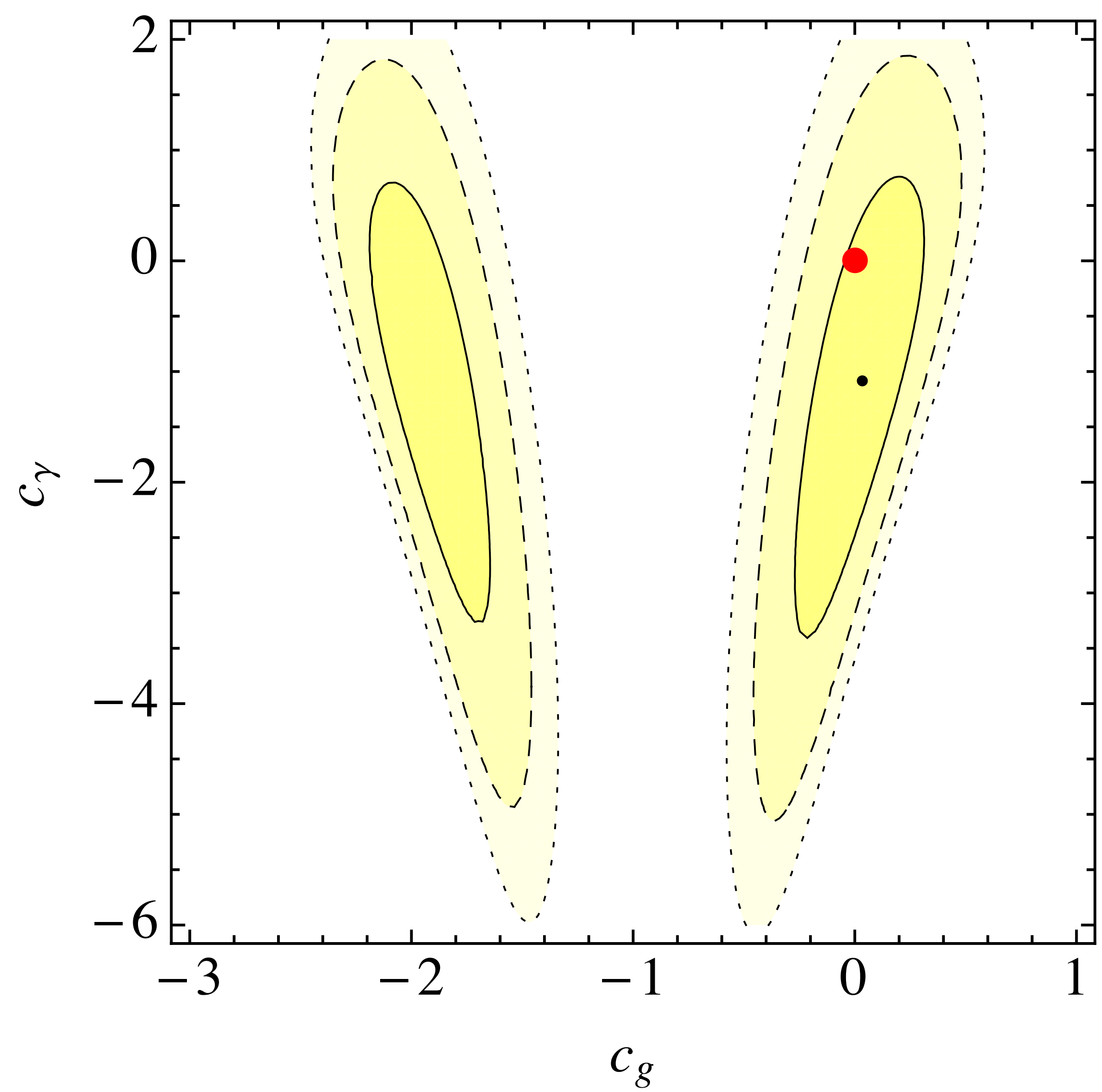
Pappadopulo '13



- overall reduction of fermion couplings is mildy favored over SM
- composite Higgs scenario not unfit
- 2HDM definitely unfit: either $c_t > 1,\ c_b < 1$ or $c_t < 1,\ c_b > 1$

Alternative lagrangian, associated with new light & weakly coupled states

$$\mathcal{L}_{eff} \;=\; c_g \frac{\alpha_s}{4\pi}\frac{h}{v} G_{\mu\nu}G^{\mu\nu} \;+\; c_\gamma \frac{\alpha}{4\pi}\frac{h}{v} F_{\mu\nu}F^{\mu\nu}$$



Future perspective on Higgs couplings

LHC 3 ab^{-1}: Single Higgs production

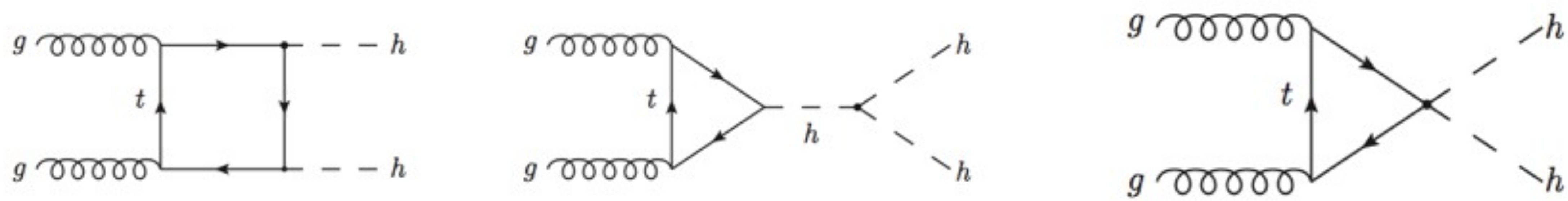
$$\Delta a = 3\%$$
$$\Delta c_f = 5\%$$

$$\frac{v^2}{f^2} \sim 0.05$$

Eupean Strategy Group docs
Crakow talk by Grojean

LHC ab^{-1}: Double Higgs production

$$\frac{v^2}{f^2} \sim 0.1$$



Grober, Muhlleitner 2010
Contino, Ghezzi, Moretti, Panico, Piccinini, Wulzer 2012

Linear Collider ab^{-1}: single Higgs production

$$\frac{v^2}{f^2} \sim 0.01$$

CLIC and beyond the Infinite

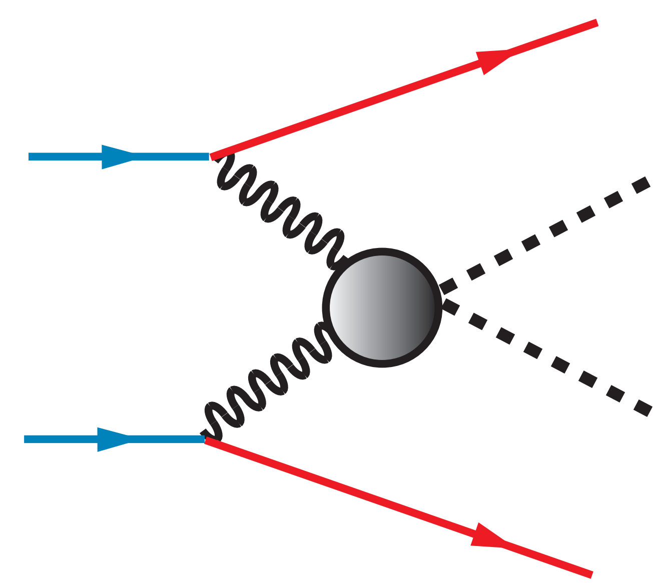
Composite h fails to fully unitarize VV scattering

$$\mathcal{A}(VV \to VV) = \frac{s}{v^2}(1-a^2) \overset{\text{Goldstone}}{=} \frac{s}{f^2}$$

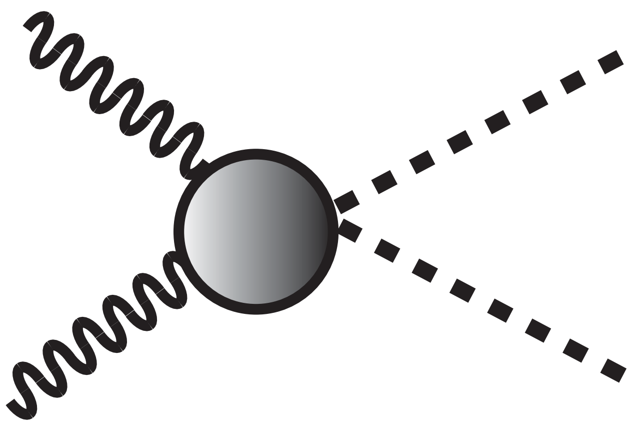
$$\mathcal{A}(VV \to hh) = \frac{s}{v^2}(a^2-b) = \frac{s}{f^2}$$

LHC ab^{-1} : sensitive to $\frac{v^2}{f^2} \gtrsim 0.3$

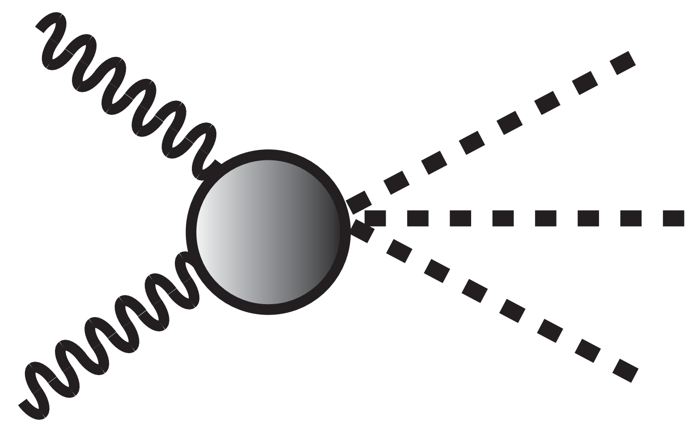
CLIC at 3TeV and 1 ab^{-1} : $\frac{v^2}{f^2} \gtrsim 0.01$



Contino, Grojean, Pappadopulo, RR, Thamm in preparation for $\quad \frac{v^2}{f^2} \gtrsim 0.1 \quad$ can test coset structure by cosidering



versus



symmetric coset
homogeneous space

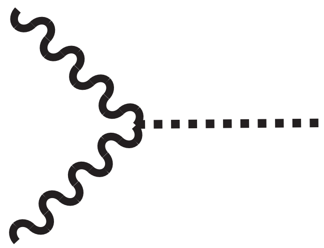
$\pi \to -\pi$ unbroken around any point

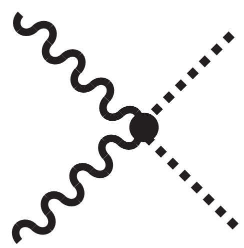
Processes with odd number of legs are suppressed

Notice: in effective lagrangian non trivial correlation of dim 6 and 8 operator coefficients

Precision versus energy frontier

indirect
and
semi-direct

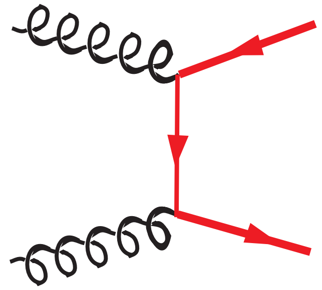




sensitive to $$\frac{1}{f^2} \sim \frac{g_\rho^2}{m_\rho^2}$$

	HL-LHC	ILC	
	5%	1%	factor 2 in f

direct



	HL-LHC	ILC	
	13 TeV	33TeV	factor 2 in m_ρ

The most amazing thing about the Standard Model Higgs boson

Being Elementary and Lonely

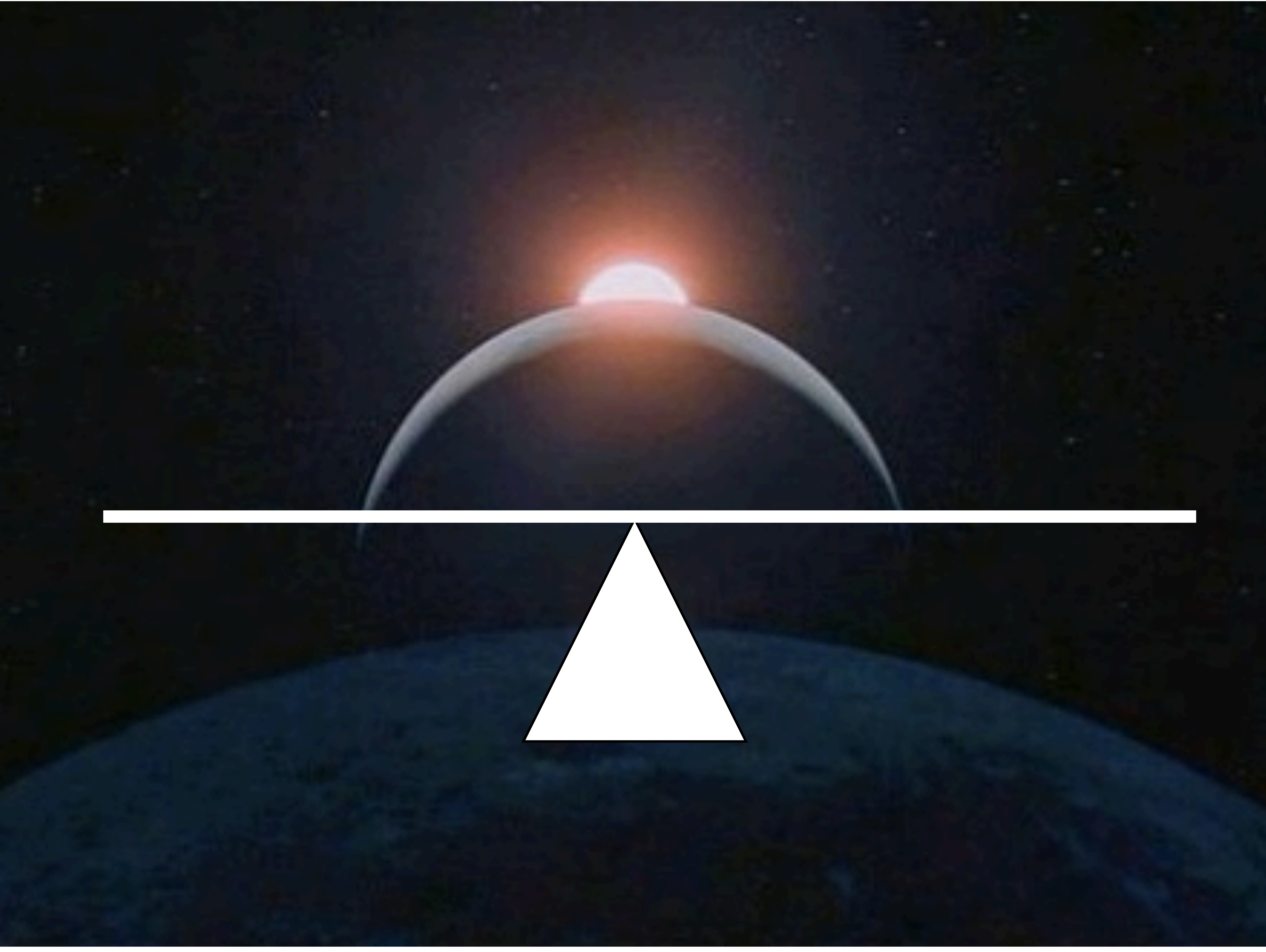
I

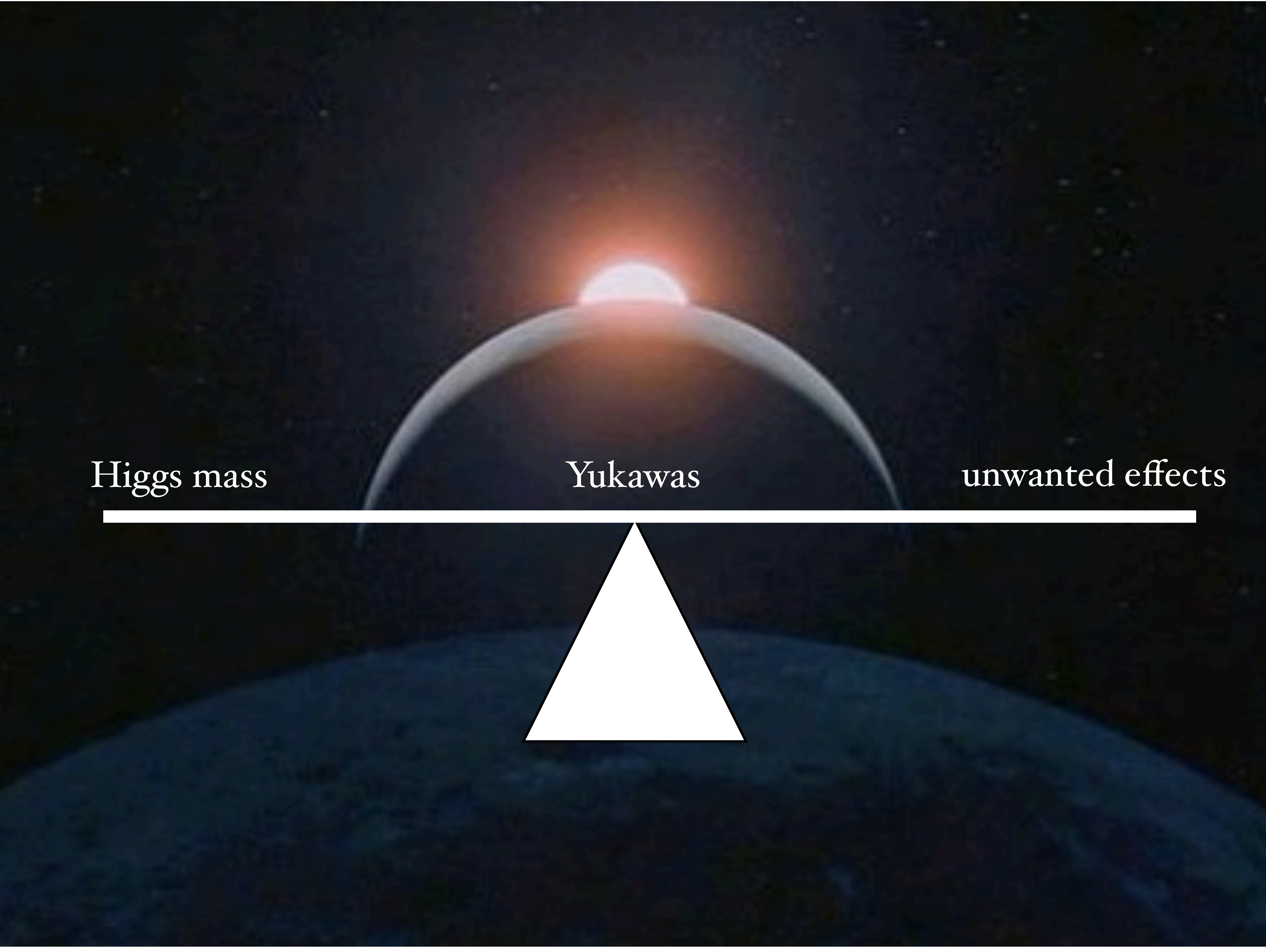
- Baryon & Lepton number conservation
- Natural Flavor Conservation (CKM)
- custodial symmetry

emergent accidents of effective theory

II

the apparent tuning of its mass parameter




Higgs mass
Yukawas
unwanted effects

✦ Flavor demands a rich spectrum of composite fermion operators, with non trivial quantum numbers under color, electroweak and flavor symmetry

✦ In UV $\dim(\Psi) \sim 5/2$, mimicking $\dim(Hq) \simeq 5/2$ in SM

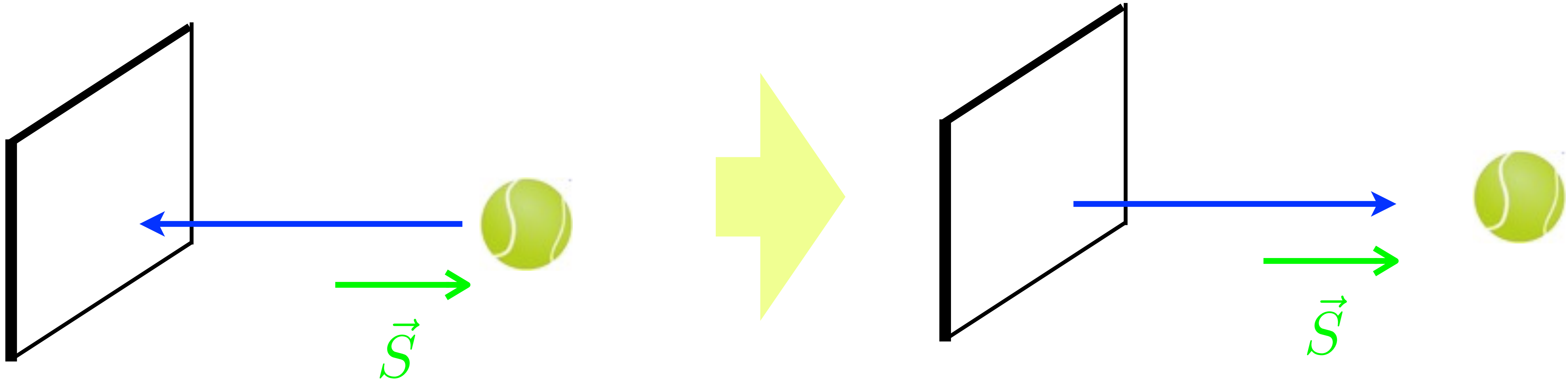
✦ Bosonic resonances: EW precision data want them heavy and strongly coupled. $m_\rho > 3\,\mathrm{TeV}$ with g_ρ as big as possible

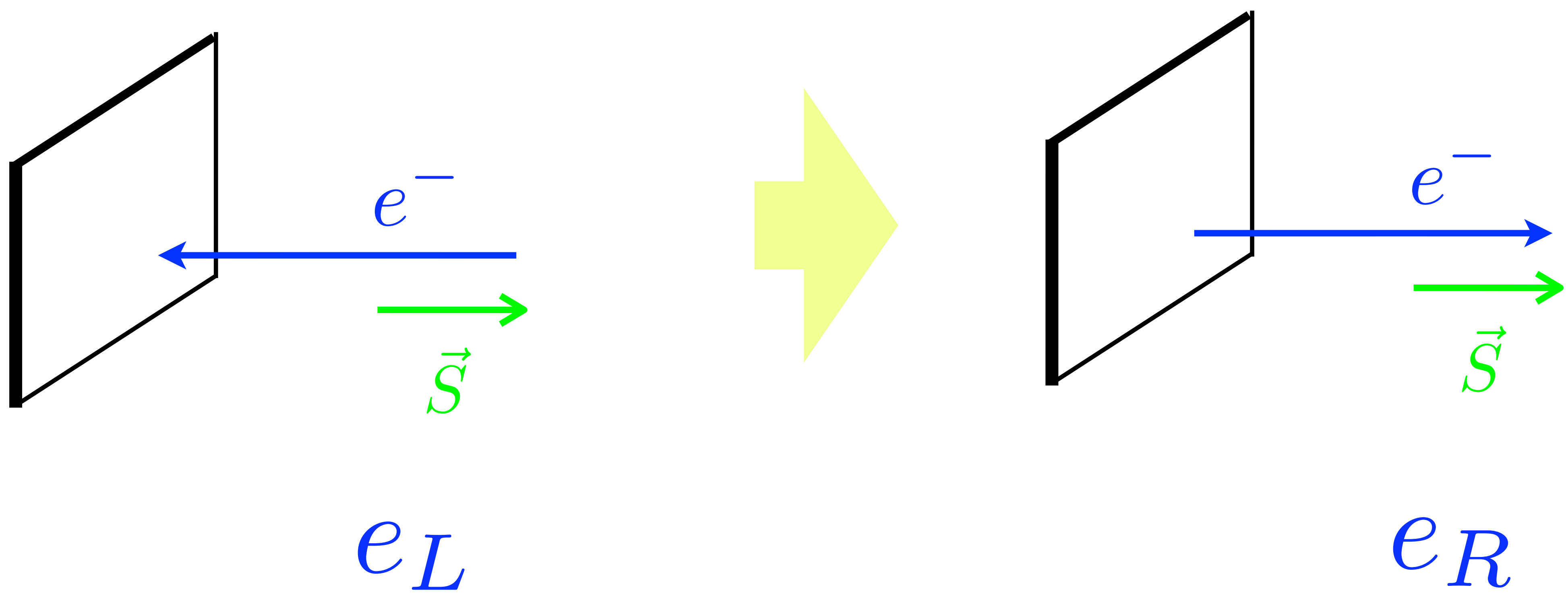
✦ Fermionic top partners: Naturalness wants them below 1 TeV, while m_h = 125 wants them more weakly coupled

If the scenario of Composite Higgs is realized in Nature it rather clear the underlying theory must be significantly more complex than a generic rescaled version of QCD !!

Scherzo

Gauge Invariance and Mass

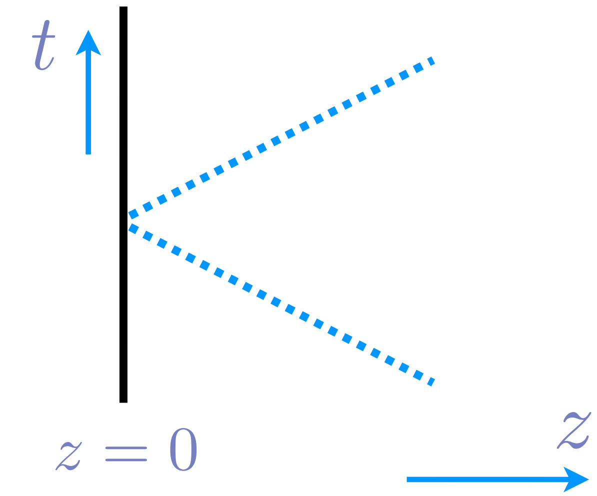

$\vec{S}$
$\vec{S}$

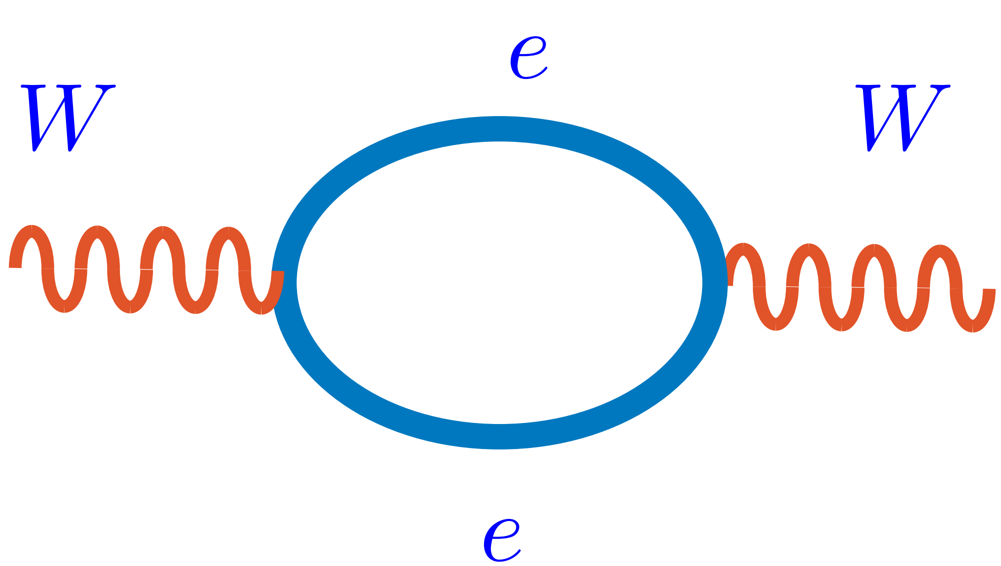

e^-
$\vec{S}$
e_L
e^-
$\vec{S}$
e_R

Higgsless Standard Model in AdS4

✤ AdS has 2+1 *boundary* which is reached in finite coordinate time by lightlike geodesics

$$ds^2 = \frac{L^2}{z^2}\left(-dt^2 + dx^2 + dy^2 + dz^2\right)$$





$$m_W^2 \propto \frac{\alpha}{4\pi}\frac{1}{L^2}$$

Rattazzi, Redi 09

- eaten Goldstone is electron-antielectron two particle state
- theory weakly coupled
- no Higgs boson