Electroweak Symmetry Breaking

waiting for the LHC

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I. Hierarchy Problem

II. Composite Higgs

III. Supersymmetry

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II. Composite Higgs

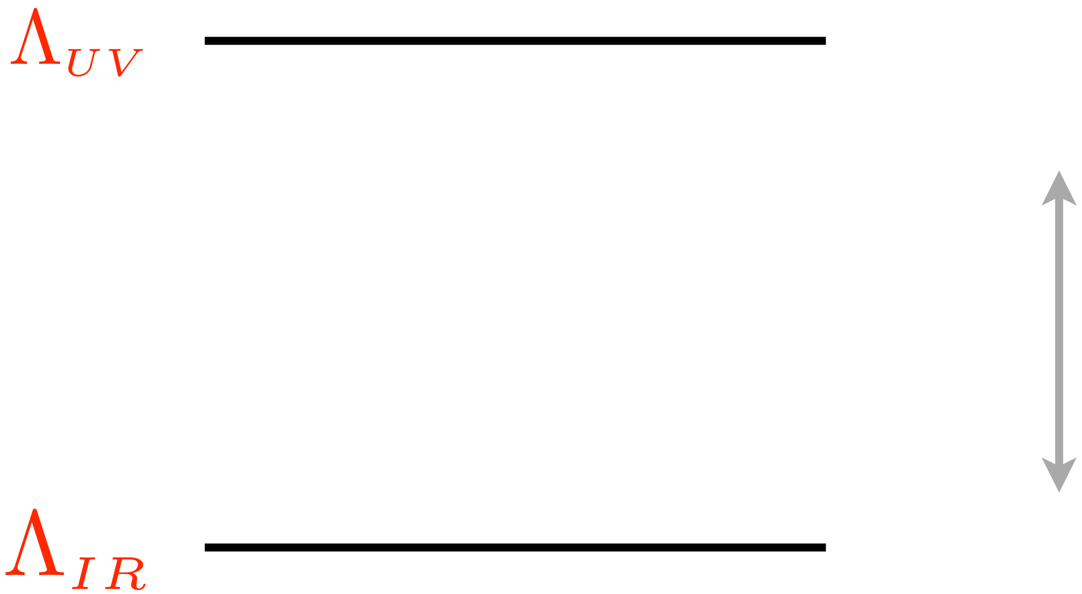
III. Supersymmetry

Λ_{UV}

$\sim$ scale invariant dynamics

$\sim$ conformal invariance

Λ_{IR}

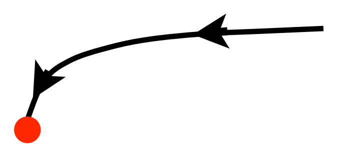


$\sim$ scale invariant dynamics

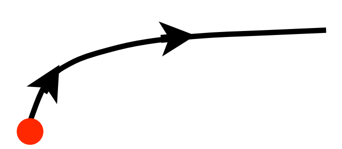
$\sim$ conformal invariance

- *stability* of $\Lambda_{IR} \ll \Lambda_{UV}$ characterized by dimensionality of *perturbations* at fixed point

$$\Delta \mathcal{L} = \lambda \mathcal{O} \qquad \lambda(E) = \lambda(\Lambda_{UV}) \left(\frac{E}{\Lambda_{UV}} \right)^{d_{\mathcal{O}}-4}$$

$d_{\mathcal{O}} - 4 > 0$ irrelevant 

$d_{\mathcal{O}} - 4 = 0$ marginal 

$d_{\mathcal{O}} - 4 < 0$ relevant 

Ex. scalar mass $\quad \lambda(E) = \left(\frac{m}{E} \right)^2$

Natural Hierarchy

Natural Hierarchy

A. There exists no strongly relevant operator

most relevant $4 - d_{\mathcal{O}} = \epsilon \ll 1$ $\lambda(E) = \lambda_0 \left(\dfrac{\Lambda_{UV}}{E} \right)^{\epsilon}$

$\Lambda_{IR} \longleftrightarrow \lambda(\Lambda_{IR}) \sim 1 \Rightarrow \Lambda_{IR} \sim \Lambda_{UV} \lambda_0^{1/\epsilon}$ exponential hierarchy

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B. Strongly relevant operators exist, but can be controlled by a symmetry

Ex.

- quark mass in QCD $d_{\mathcal{O}} = 3$ controlled by chiral symmetry
- scalar masses in MSSM $d_{\mathcal{O}} = 2$ SUSY + chiral symm

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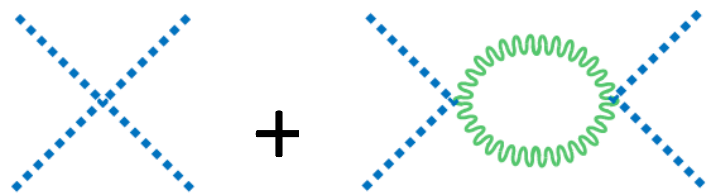
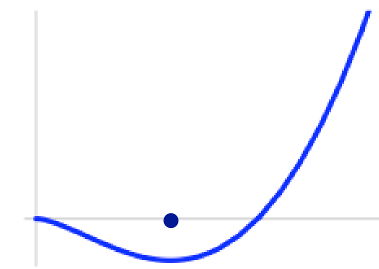
The Standard Model belongs to neither cathegory

In ordinary QFT, without supersymmetry, we cannot rely on weakly coupled scalars to naturally generate hierarchy

Ex. Coleman-Weinberg
mechanism
is not natural



$$V(\varphi) = \lambda(\varphi)\varphi^4 \; + m^2\varphi^2$$



$$\varphi_{min} = e^{-\frac{4\pi}{\alpha}}\Lambda$$

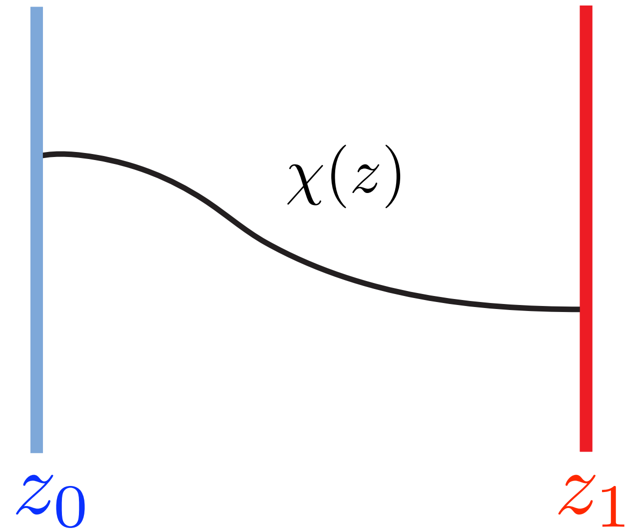
No supersymmetry
+
Natural Hierarchy

Strong Dynamics
Ex. Technicolor

Very difficult to make theoretical progress !!

Warped compactifications based on Randall-Sundrum scenario allow for a remarkable way out of this connection

radius stabilization
a la Golberger-Wise



$$ds^2 \;=\; \frac{L^2}{z^2}\left(dx^\mu dx_\mu + dz^2\right)$$

radius stabilization
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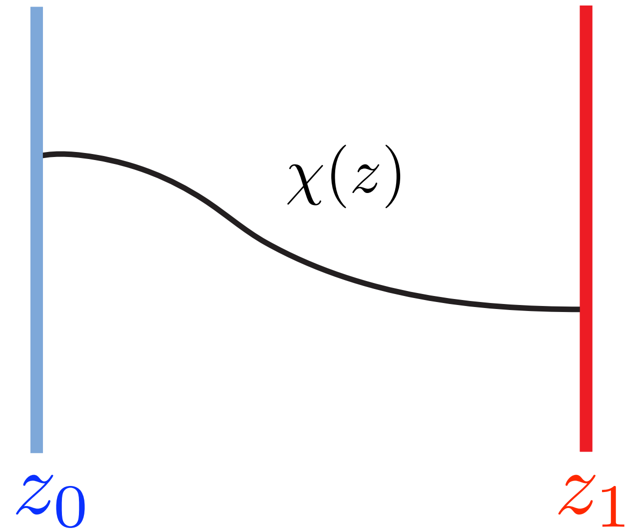

$$ds^2 = \frac{L^2}{z^2}\left(dx^\mu dx_\mu + dz^2\right)$$

equivalent to RG flow

AdS	**CFT**
χ	$\mathcal{O}$
$m_\chi^2 = -\frac{2\epsilon}{L^2}$	$d_{\mathcal{O}} - 4 = -\epsilon$
$\chi(z)$	$\lambda(E) = \lambda_0 \left(\frac{\Lambda_{UV}}{E}\right)^\epsilon$

ads radion $\quad \frac{1}{z_1} \equiv \varphi \quad$ cft dilaton

Perturbatively calculable
Effective Potential

$$V(\varphi) = \varphi^4 \left[a - b\lambda_0 (\frac{\Lambda_{UV}}{\varphi})^\epsilon \right]^2 + \ldots$$

minimized at

$$\langle\varphi\rangle \equiv \Lambda_{IR} = \Lambda_{UV} \left(\frac{b\lambda_0}{a} \right)^{\frac{1}{\epsilon}}$$

$\ll \Lambda_{UV}$
naturally

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So, where is the catch?

5D perspective: weakly coupled effective field theory valid below a cut-off

4D perspective: we can compute a lot less than in ordinary renormalizable QFT

cannot compute

- ✦ correlators of fields with arbitrary large dimension
- ✦ exclusive production of sufficiently heavy KK

However for sufficiently inclusive quantities theory can be extrapolated up to $\Lambda_{UV} \sim M_{\text{Planck}}$

Ex: inclusive production of KK's from sources on UV brane

Randall Sundrum scenario ⟷ weakly coupled alternative to SUSY with composite Higgs

unleashed
model building

Holographic resurrection of technicolor

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Technicolor ?

★ what about Flavor ?

★ what about Electroweak Precision Tests ?

Standard Model

$y_{ij}\, \underbrace{H \bar{F}_i F_j}_{\text{dim}=4}$ $\quad \Lambda_{UV} \to \infty$

- y_{ij} unaffected
- extra unwanted Flavor effects decouple

$$\frac{1}{\Lambda_{UV}^2}\, \bar{q}_i q_j \bar{q}_k q_\ell$$

very relevant operator $\Lambda_{UV}^2 H^\dagger H$

makes $\Lambda_{UV} \to \infty$ problematic

Technicolor

no relevant singlet scalar

Yukawas $\frac{y_{ij}}{\Lambda_{UV}^2} H \bar{F}_i F_j$ as relevant as $\frac{1}{\Lambda_{UV}^2}\, \bar{q}_i q_j \bar{q}_k q_\ell$

Two approaches to improve situation

I. Conformal technicolor

Luty-Okui 04

Ideal situation

- Flavor $d_H \;\to\; 1$
- Hierarchy $d_{H^\dagger H} \;\to\; 4$

but QFT theorem says $d_{H^\dagger H} \;=\; 2$ if $d_H \;=\; 1$

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- Hierarchy $d_{H^\dagger H} \rightarrow 4$

but QFT theorem says $d_{H^\dagger H} = 2$ if $d_H = 1$

How fast $d_{H^\dagger H} \rightarrow 2$ when $d_H \rightarrow 1$?

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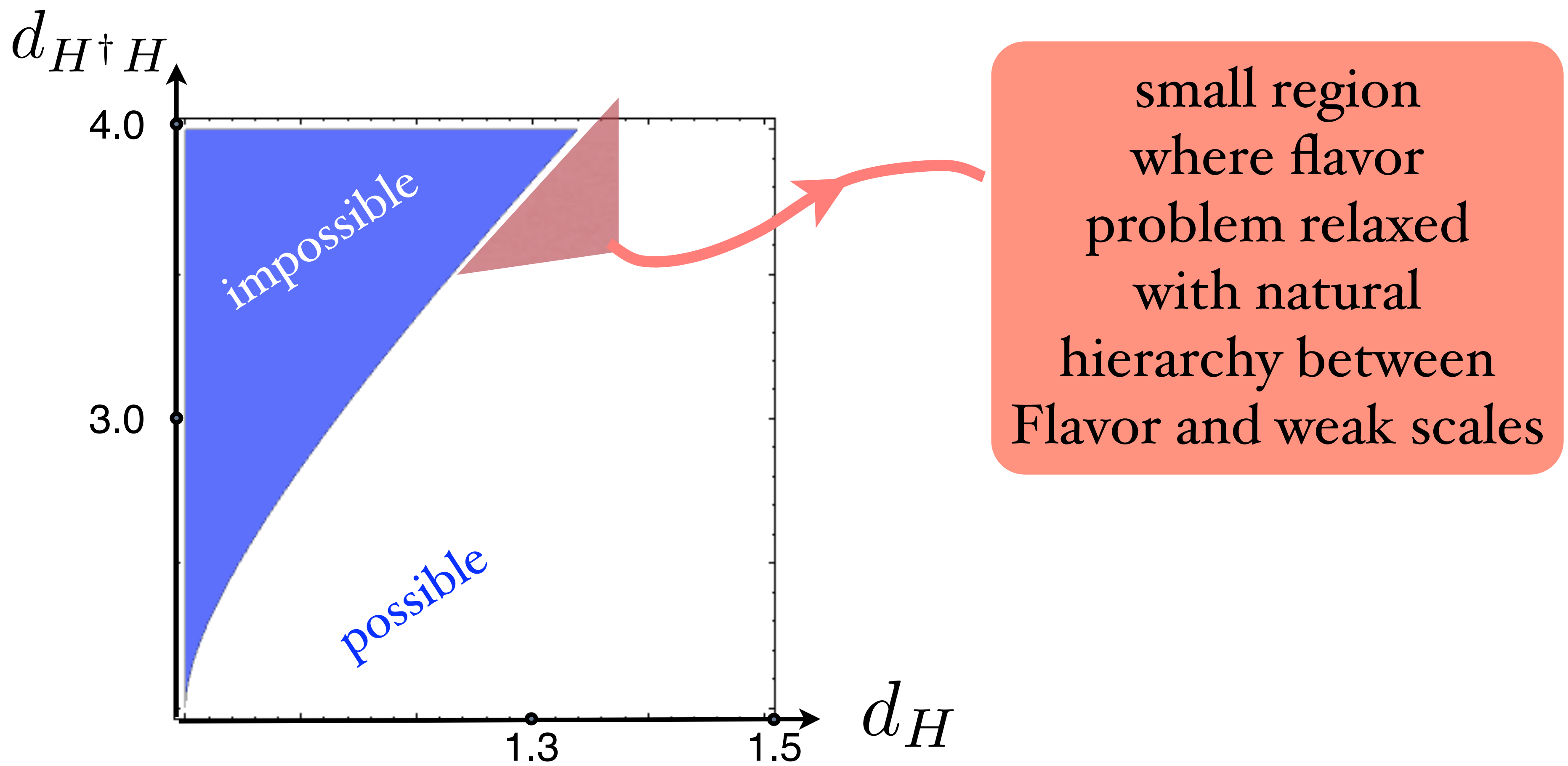
Prime principle study recently completed



Rattazzi, Rychkov, Tonni, Vichi 08

- In large N theories $d_{\mathcal{O}^2} = 2d_{\mathcal{O}} + O\left(\frac{1}{N}\right)$

- conformal technicolor requires small N
- cannot be modeled by 5D construction

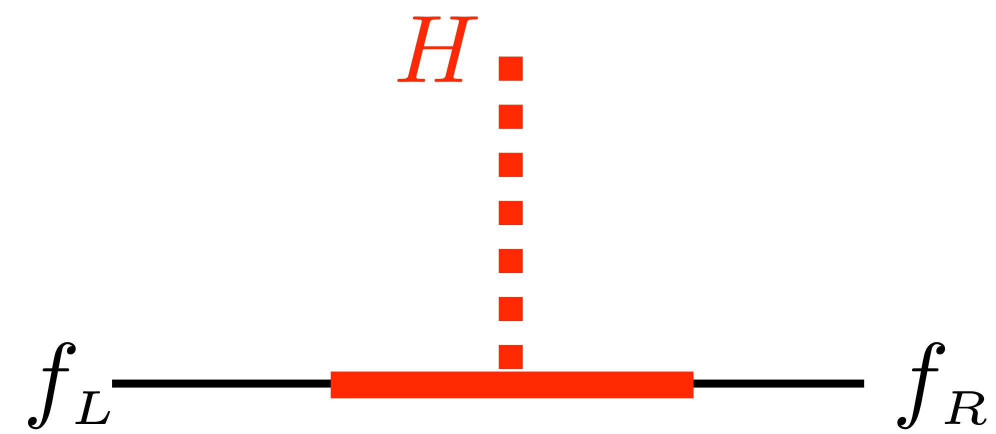
II. Fermion masses by mixing to composites

D.B. Kaplan 80's
Agashe, Contino, Pomarol 04

$$d_f \sim \frac{3}{2}$$

$$\mathcal{L}_{\rm Flavor} = \lambda_L^{ij} f_L^i \mathcal{O}_R^j + \lambda_R^{ij} f_R^i \mathcal{O}_L^j$$

$$d_{\mathcal{O}} \sim \frac{5}{2}$$

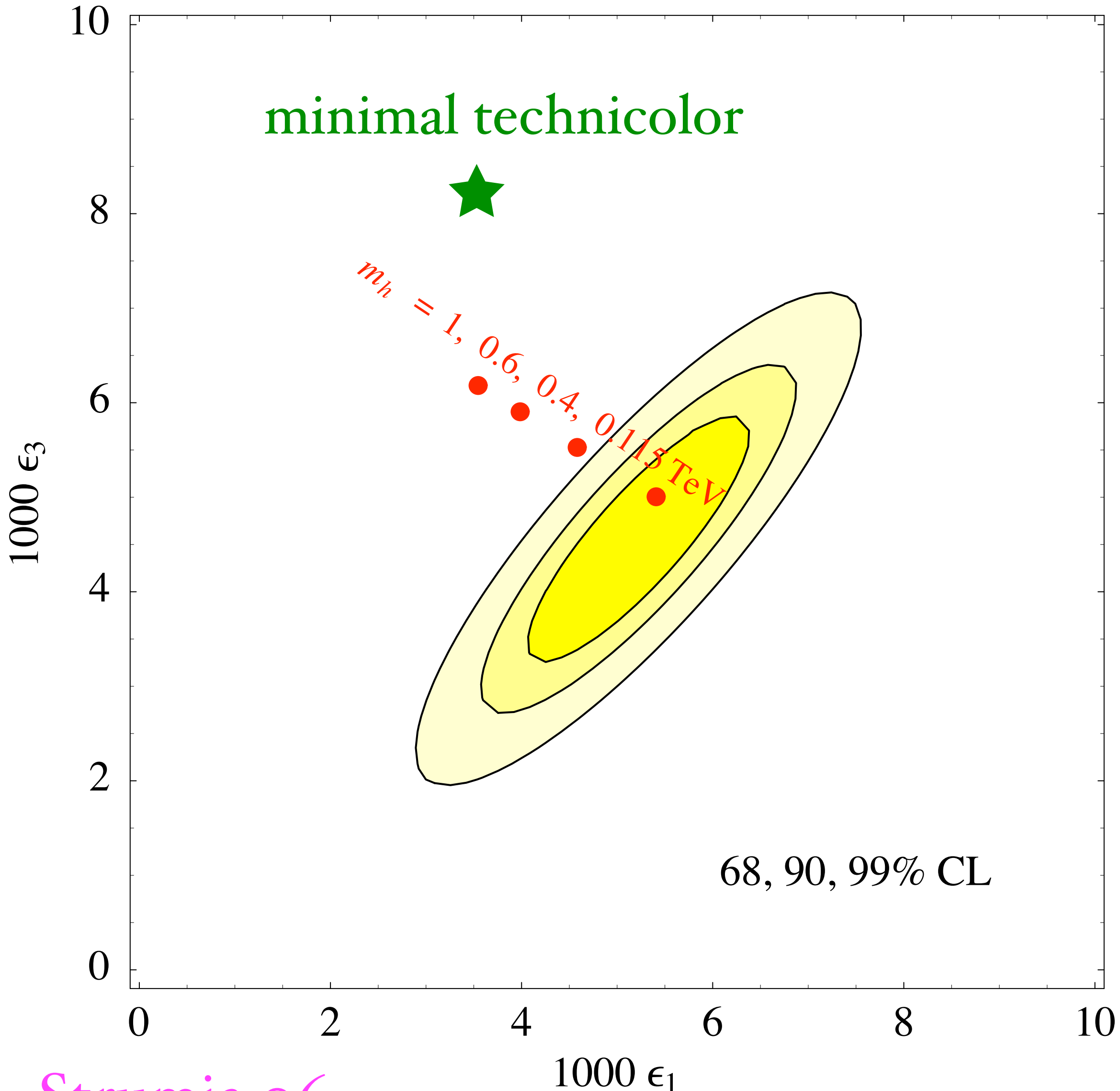


$d_\lambda \sim 0$: can decouple unwanted Flavor effets keeping λ fixed

- nicely implemented in Randall Sundrum scenario
- small differences in dimensions of λ^{ij} give plausible explanation of pattern of masses and mixings
- unwanted flavor violation at weak scale under control (some tension in ϵ_K)

Csaki et al 08

Electroweak Precision Tests



Strumia 06

$$\Delta\epsilon_3 \equiv \widehat{S} = \widehat{S}_{UV} + \frac{g^2}{96\pi^2}\ln(m_h/m_Z)$$

$$\widehat{S}_{UV} \sim \frac{g^2}{96\pi^2} N_{TF} N_{TC}$$

Peskin, Takeuchi '89

$$\Delta\epsilon_1 \equiv \widehat{T} = \widehat{T}_{UV} + \frac{3g^2\tan^2\theta_W}{32\pi^2}\ln(m_h/m_Z)$$

Minimal TC has no parameter to play with in order to reduce $\widehat{S}$

Next to minimal TC: light Higgs exists as a 4th pseudo-Goldstone boson

Georgi, Kaplan '84
Banks '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

Electroweak Precision tests are helped in two ways

- light Higgs screens IR contribution to $\widehat{S}, \widehat{T}$

- $\widehat{S}_{UV} \simeq \dfrac{g^2 N}{96\pi^2} \times \dfrac{v^2}{f^2}$

$$\begin{cases} \langle H \rangle \equiv v \\ f = \text{pseudo-Goldstone decay const.} \end{cases}$$

$\dfrac{v^2}{f^2}$ depends on extra parameters ⇨ can in principle be tuned to be a little bit smaller than 1

Compositeness scale $4\pi f$ could still be as low as a few TeV

Structure of the Models

Strong sector
H = Goldstone doublet
Ex. : $H = SO(5)/SO(4)$

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$\longleftrightarrow$

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$\Downarrow$

m_ρ mass of resonances
g_ρ coupling of resonances

$$f = \frac{m_\rho}{g_\rho}$$

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Examples

- Technicolor type $\quad g_\rho \sim \frac{4\pi}{\sqrt{N_{TC}}}$
- 5D models $\quad m_\rho \sim m_{KK} \quad g_\rho \sim g_{KK}$
- Little Higgs $\quad (m_\rho,\ g_\rho) \quad$ mass and coupling of 'regulators'

Simple Goldstone Higgs

Little Higgs

$$V(H) \sim g_{SM}^2 \left[\frac{m_\rho^2}{16\pi^2} H^2 + \frac{g_\rho^2}{16\pi^2} H^4 + \dots \right]$$

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$$v \sim \frac{m_\rho}{g_\rho} = f$$

$$v \equiv \langle H \rangle \sim \frac{m_\rho}{4\pi} = \frac{g_\rho}{4\pi} f$$

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- ✦ g_ρ as large as possible $\sim 4\pi$
- ✦ tune $\frac{v^2}{f^2}$ to ~ 0.2

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$$\hat{S} \sim \frac{g_W^2}{16\pi^2} \frac{m_T^2}{m_V^2}$$

choose $m_V \gg m_T$, $g_V \gg g_T \sim g_{SM}$

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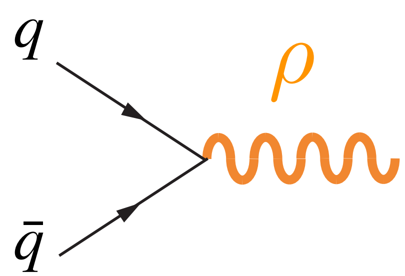
choose $\quad m_V \gg m_T$, $\quad g_V \gg g_T \sim g_{SM}$

Both scenarios prefer heavy and strongly coupled vectors

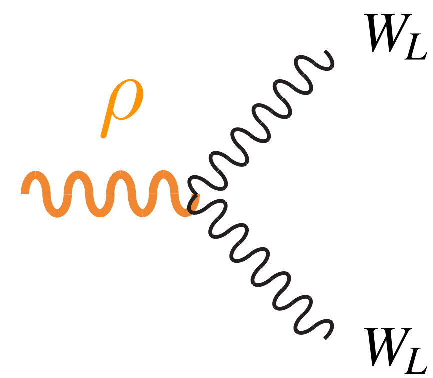
LH reduces a bit the tuning at the price of cleverness

★ new vectors are preferably

- broad & heavy
- very weakly coupled to SM fermions



$$= \frac{g_W^2}{g_\rho} \ll g_W$$



$$= g_\rho$$

$$\sigma\left(pp \to \rho_H^\pm + X\right) = \left(\frac{4\pi}{g_\rho}\right)^2 \left(\frac{3\ \mathrm{TeV}}{m_\rho}\right)^6\ 0.5\ \mathrm{fb}$$

increasingly harder to detect as $g_\rho \longrightarrow 4\pi$

★ 'top parners' can be below 1 TeV (preferably so in LH)

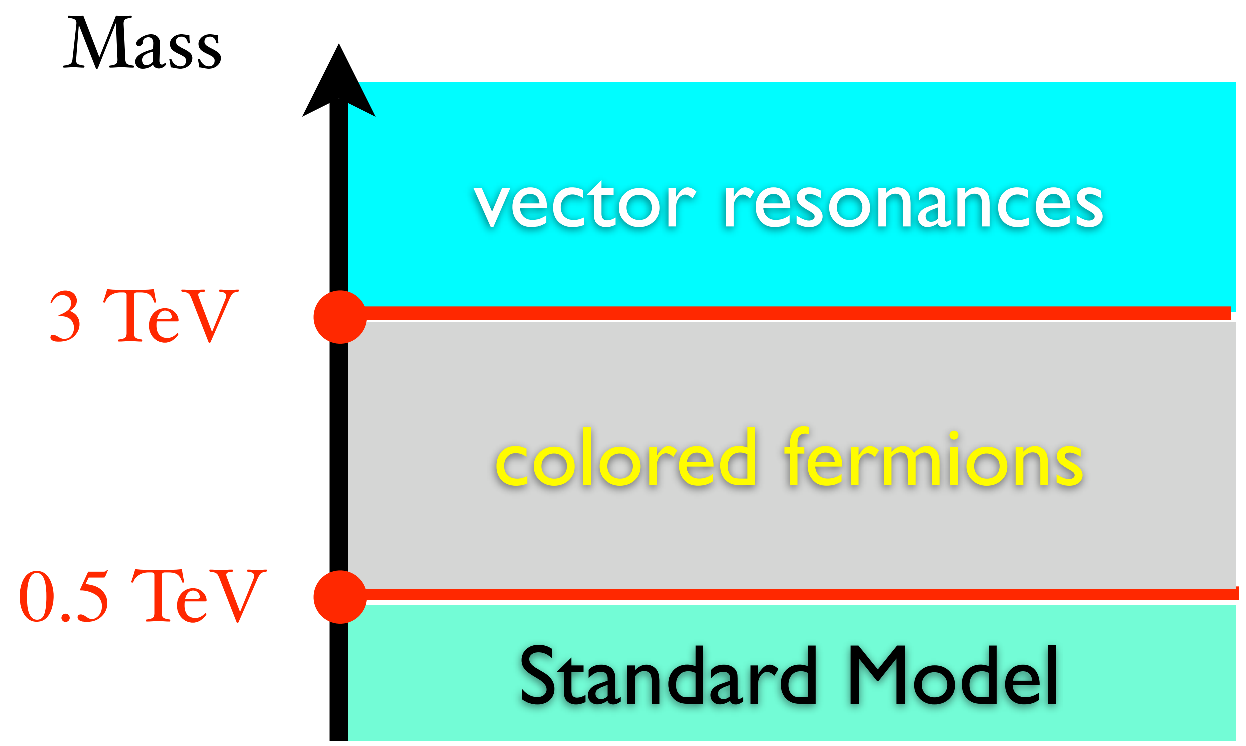
electric charges of heavy quarks $-\frac{1}{3},\quad \frac{2}{3},\quad \boxed{\frac{5}{3}}$

motivated by $Zb\bar{b}$

$\ell^-\ell^-$
$\ell^+\ell^+$ signature

Contino, Servant 08

If



A ‘precision’ study of Higgs properties would in principle help understanding the origin of the weak scale

Effective Lagrangian for composite Higgs

$$
\begin{aligned}
\mathcal{L}_{eff} = \quad & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y}{f^2}H^\dagger H\,\bar{\psi}_L H\psi_R + \text{h.c.}\right) \\
+ \quad & \frac{c_\gamma g^2}{16\pi^2 m_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g y_t^2}{16\pi^2 m_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
+ \quad & \frac{ic_W}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
+ \quad & \frac{ic_{HW}}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB}}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}
\end{aligned}
$$

$$
f = \frac{m_\rho}{g_\rho} \ll m_\rho
$$

Giudice, Grojean, Pomarol, Rattazzi 07

$$\mathcal{L}_{eff} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y}{f^2}H^\dagger H\,\bar{\psi}_L H\psi_R + \text{h.c.}\right)$$

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irrelevant

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$$+ \frac{c_\gamma g^2}{16\pi^2 m_\rho^2} H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g y_t^2}{16\pi^2 m_\rho^2} H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

$$+ \frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$+ \frac{ic_{HW}}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{ic_{HB}}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

irrelevant

$$f = \frac{m_\rho}{g_\rho} \ll m_\rho$$

Giudice, Grojean, Pomarol, Rattazzi 07

★ Higgs compositeness described by very limited set of parameters !

✦ most relevant $\quad c_H, \quad c_y, \quad c_6$

$$\frac{\delta\mathcal{A}}{\mathcal{A}_{SM}} \sim \frac{v^2}{f^2}$$

✦ relevant when fermions are ‘light’ $\quad c_\gamma, \quad c_g,$

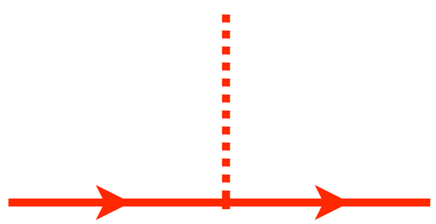
Analogues of S and T for precision Higgs physics

Effects in Higgs production & decay

all couplings rescaled by

$$c_H \quad \longrightarrow \quad \mathcal{L}_{kin} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) \partial_\mu h \partial^\mu h \qquad\qquad \frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \simeq 1 - c_H \frac{v^2}{2f^2}$$

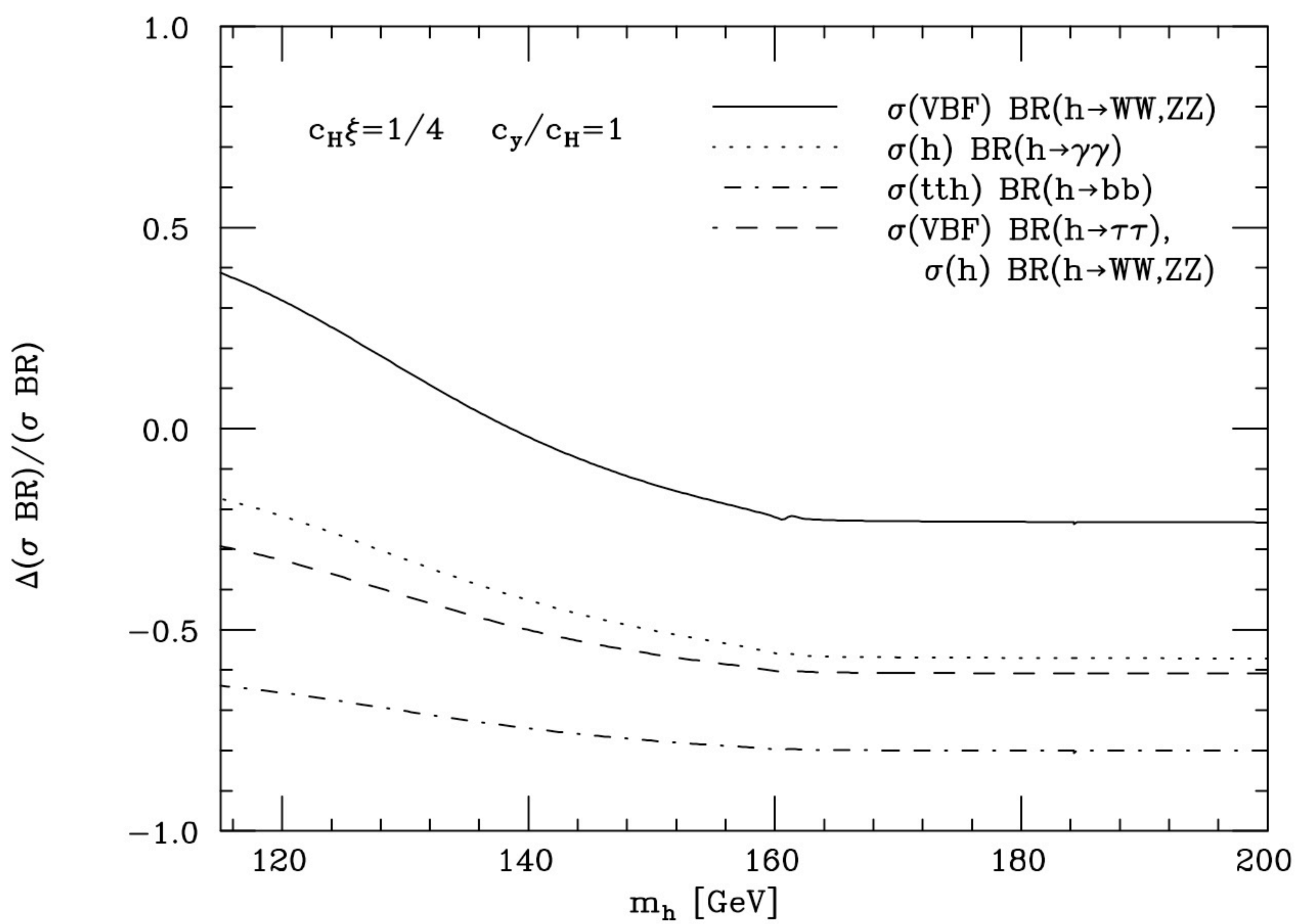
$$c_y \quad \longrightarrow$$



$$\frac{m_\psi}{v}\left(1 - c_y \frac{v^2}{f^2}\right)$$

$$\frac{\Delta\left(\sigma(\text{prod}) \times \text{Br}\right)}{\left(\sigma(\text{prod}) \times \text{Br}\right)_{SM}}$$

$$= \# c_H \frac{v^2}{f^2} + \# c_y \frac{v^2}{f^2}$$



- At ILC one would test $\frac{v^2}{f^2}$ at % level

Coupling	$M_H = 120$ GeV	140 GeV
g_{HWW}	$\pm$ 0.012	$\pm$ 0.020
g_{HZZ}	$\pm$ 0.012	$\pm$ 0.013
g_{Htt}	$\pm$ 0.030	$\pm$ 0.061
g_{Hbb}	$\pm$ 0.022	$\pm$ 0.022
g_{Hcc}	$\pm$ 0.037	$\pm$ 0.102
$g_{H\tau\tau}$	$\pm$ 0.033	$\pm$ 0.048
g_{HWW}/g_{HZZ}	$\pm$ 0.017	$\pm$ 0.024
g_{Htt}/g_{HWW}	$\pm$ 0.029	$\pm$ 0.052
g_{Hbb}/g_{HWW}	$\pm$ 0.012	$\pm$ 0.022
$g_{H\tau\tau}/g_{HWW}$	$\pm$ 0.033	$\pm$ 0.041
g_{Htt}/g_{Hbb}	$\pm$ 0.026	$\pm$ 0.057
g_{Hcc}/g_{Hbb}	$\pm$ 0.041	$\pm$ 0.100
$g_{H\tau\tau}/g_{Hbb}$	$\pm$ 0.027	$\pm$ 0.042

Barger, Han,Langacker,
McElrath,Zerwas 03

J.A. Aguilar Saavedra et al.
[ECFA/DESY LC Physics WG]

ILC can rule out Higgs compositeness scale $4\pi f$ below 30 TeV

I. Hierarchy Problem

II. Composite Higgs

III. Supersymmetry

☹ **μ-problem** $\langle H \rangle \leftrightarrows m_{soft}$ $\sim$ SUSY breaking

- ❖ $V(H)$ depends crucially on supersymmetric higgsino mass μ
- ❖ need extra 'structure' to relate μ to m_{soft}

Ex. Giudice-Masiero
'mechanism'

ok in SUGRA

problematic in gauge med
gaugino med
……

$$\mu \sim \alpha \frac{F_X}{X}$$

$$B\mu \sim \alpha \frac{F_X^2}{X^2} \gg \mu^2$$

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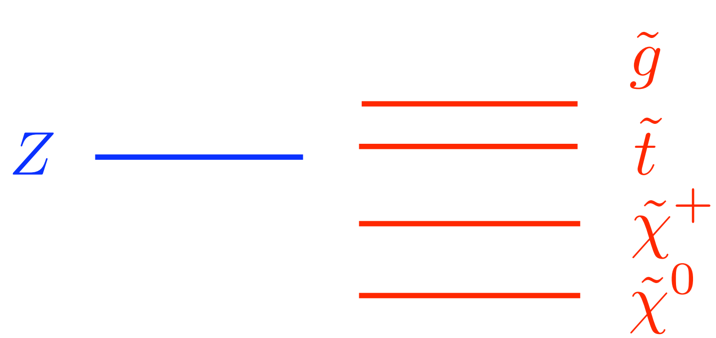
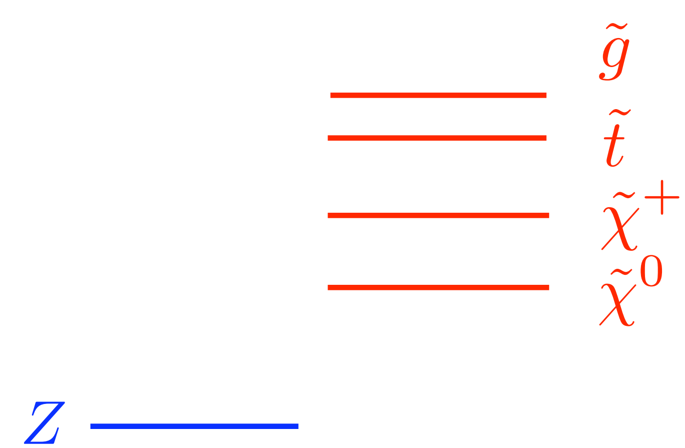
lack of direct signals at LEP and Tevatron

natural expectation before LEP



...after LEP



SUSY is tuned

Example N. 1

Barbieri, Hall, Nomura, Rychkov 06

NMSSM at large trilinear:
λSUSY

$$\lambda\, S H_1 H_2 \qquad \lambda \gg g_W$$

$$m_Z^2 \sim \frac{g_W^2}{\lambda^2}\, m_{SUSY}^2$$

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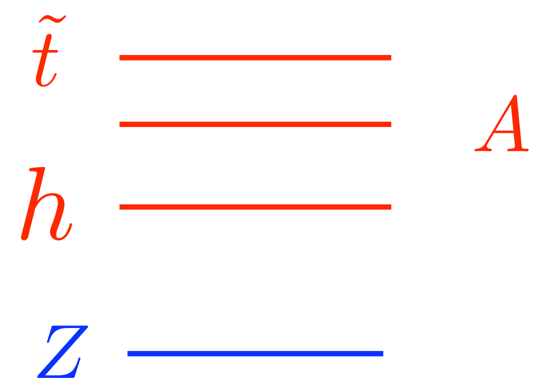

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Barbieri, Hall, Nomura, Rychkov 06

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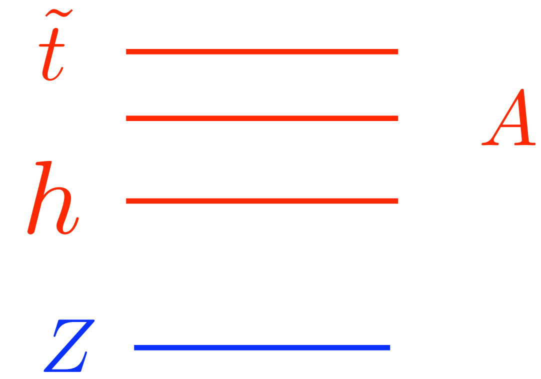
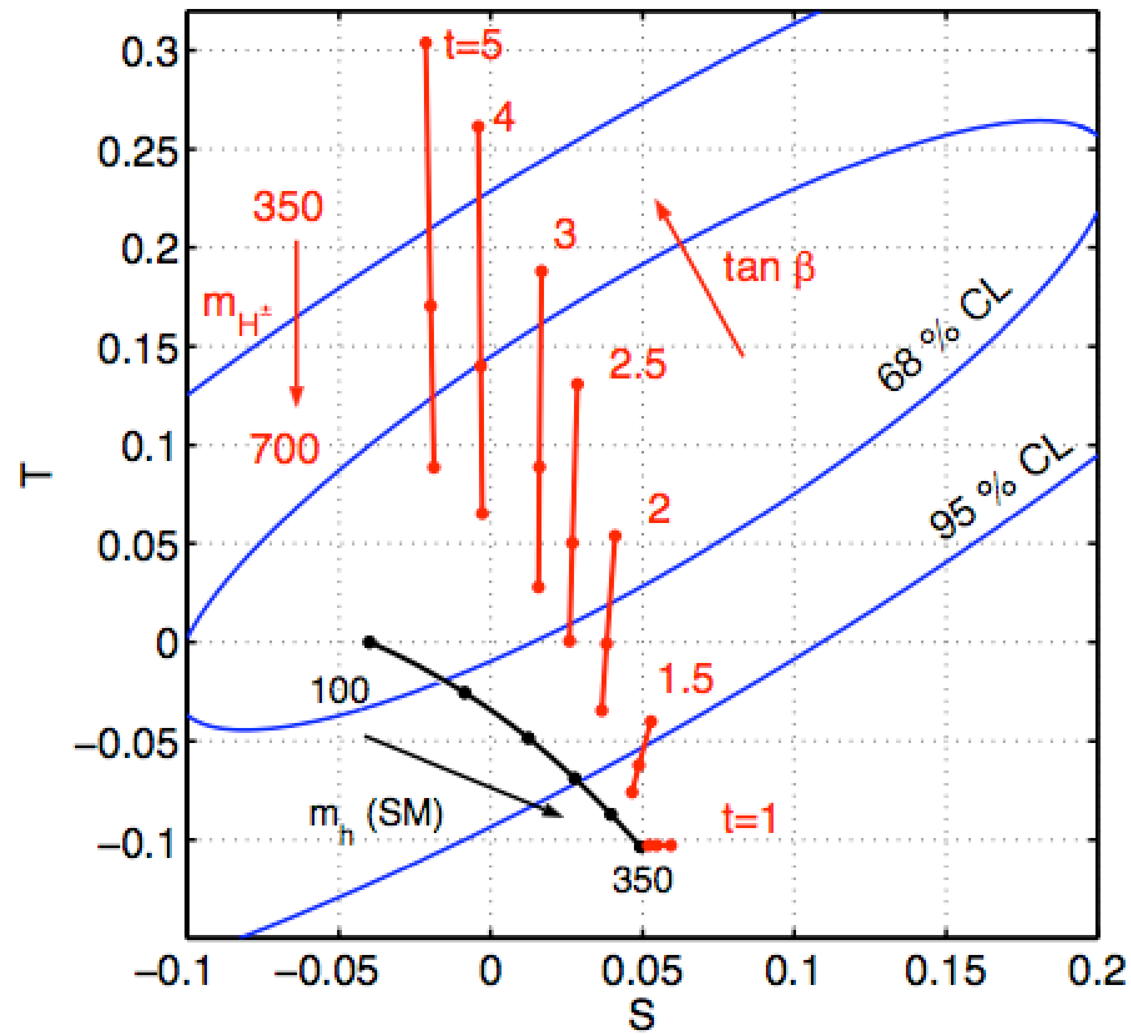


$m_h \sim 300\,\mathrm{GeV}$
can be compatible with
electroweak precision tests
thanks to compensating loop effects
(due to large splittings within Higgs
and Higgsino doublets)



- Natural mass range

$$200\,\mathrm{GeV} < m_{\mathrm{Higgses}} < 700\,\mathrm{GeV}$$
$$500\,\mathrm{GeV} < m_{\mathrm{sparticles}} < 2\,\mathrm{TeV}$$

- Higgs spectrum in λSUSY $m_h < m_{H^+} < m_H < m_A$

while in MSSM $m_h < m_A < m_{H^+}, m_H$

- Theoretical ***price*** of λSUSY: λ becomes strong just above 10 TeV
  - must complete theory above this scale
  - what about gauge unification?
  - is the Higgs composite above 10 TeV?

Example N. 2

Buying both μ and little hierarchy and paying just once

Csaki, Falkowsky, Nomura, Volansky 08

- Simplest model for μ in gauge mediation

Dvali, Giudice, Pomarol 96

$$\mu \sim \lambda_1 \lambda_2 \frac{M_S}{16\pi^2}$$

$$\hat{M}^2 \sim \begin{pmatrix} \lambda_1^2 & \lambda_1\lambda_2 \\ \lambda_1\lambda_2 & \lambda_2^2 \end{pmatrix} \frac{M_S^2}{16\pi^2}$$

- in 'old days' considered problematic

$$\mu^2 \sim m_{\tilde{f}}^2 \sim 2\,\text{loops} \ll 1\,\text{loop} \sim \hat{M}^2 \sim m_Z^2$$

- in the age of little tuning we can content ourself by choosing

$$\frac{\lambda_{1,2}^2}{16\pi^2} \sim \left(\frac{g_s^2}{16\pi^2}\right)^2$$

$$m_Z^2 \ll m_A^2 \sim m_{\tilde{t}}^2 \sim m_{\tilde{g}}^2$$

$$\mu \sim \frac{\lambda_1\lambda_2}{16\pi^2} M_S \sim \frac{g_s^2}{16\pi^2} m_{\tilde{g}}$$

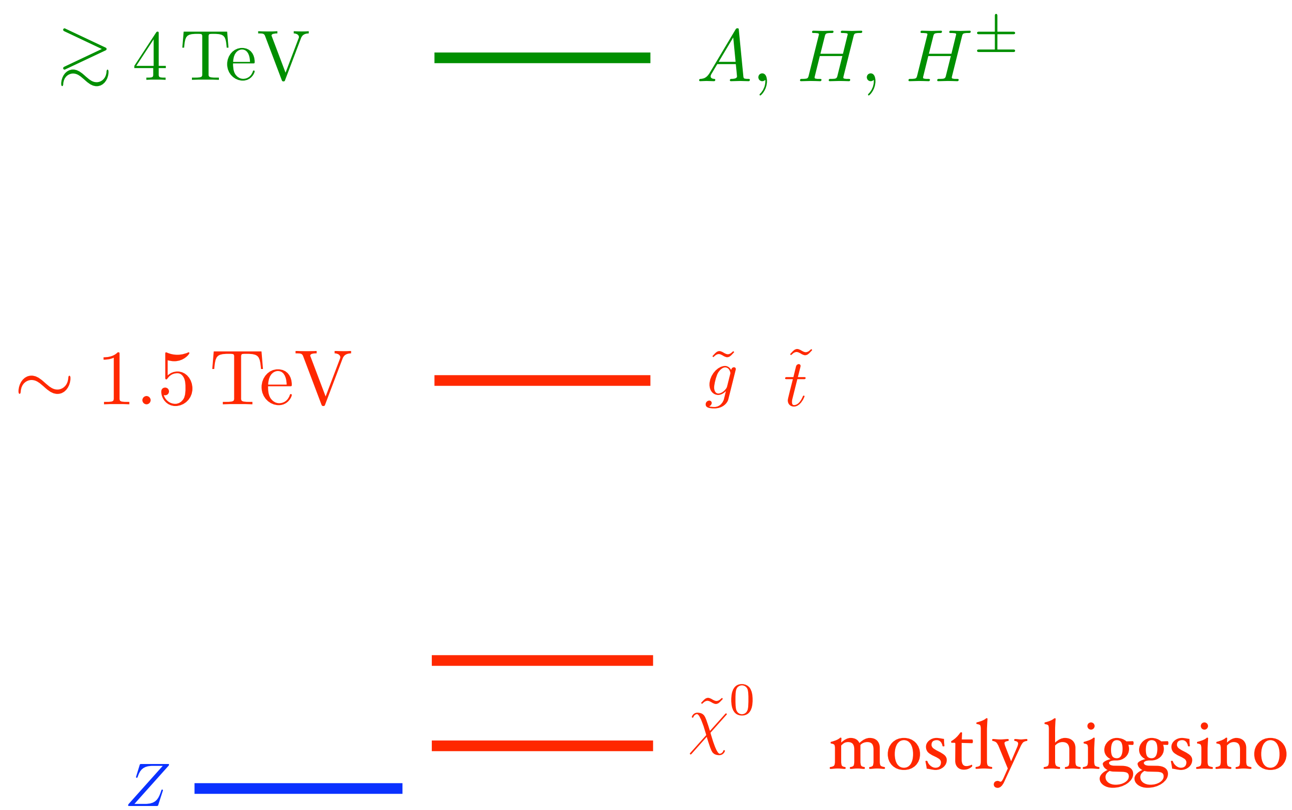
$$m_{\tilde{g}} \gtrsim 3 - 4\,\text{TeV}$$

enough to satisfy lower bound on chargino

Situation even slightly better by choosing $\lambda_1 \gg \lambda_2$ to boost chargino above bound (tuning minimized)

'ideal' situation $\longrightarrow$ $$\frac{\lambda_1^2}{16\pi^2} \gtrsim \frac{m_Z^2}{m_{\tilde{t}}^2}$$ makes obviously sense only in the presence of little hierarchy

definite prediction on the spectrum !



Example N. 3

Scalar Sequestering

Murayama, Nomura, Poland 07
Perez, Roy, Schmaltz 08

assume non-trivial fixed-point scaling in SUSY breaking sector

$$d_2 > 2d_1$$

$$\mathcal{L}_{soft} = \int d^4\theta \, Q^\dagger Q \left(\frac{X}{M_*^{d_1}} + \frac{X^\dagger X}{M_*^{d_2}} \right) \qquad \mathcal{L}_\mu = \int d^4\theta \, H_1 H_2 \left(\frac{X}{M_*^{d_1}} + \frac{X^\dagger X}{M_*^{d_2}} \right)$$

Example N. 3

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Boundary conditions
at SUSY breaking scale M_S

$$m_{1/2} \sim \mu \sim A \quad \sim \quad M_S \left(\frac{M_S}{M_*} \right)^{d_1}$$

$$m_{\tilde{f}}^2 \sim B\mu \sim m_{1,2}^2 + \mu^2 \quad \sim \quad M_S \left(\frac{M_S}{M_*} \right)^{d_2} \sim 0$$

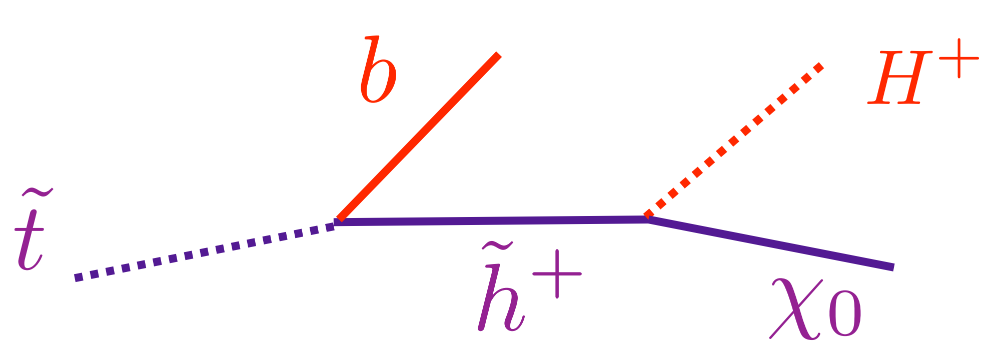
Higgs mass matrix vanishes even though $\mu \neq 0$

- correct EW vacuum obtained only for large M_s
- m_A not tightly related to μ
- even after RG evolution the relation $m_A \gg \mu$ is preserved

sample spectrum

Input	$\tan\beta$		10	
	$\hat{\mu}$		1.00	
	$M_{\rm int}$		10^{15} GeV	
Output	M_1	273 GeV	m_{Q_1}	1243 GeV
	M_2	510 GeV	m_{u_1}	1192 GeV
	M_3	1412 GeV	m_{d_1}	1186 GeV
	μ	1246 GeV	m_{t_1}	1113 GeV
	B_μ	$(115\ \mathrm{GeV})^2$	m_{t_2}	1277 GeV
	m_h	115 GeV	m_{b_1}	1279 GeV
	m_A	365 GeV	m_{b_2}	1226 GeV
	m_{H^0}	377 GeV	m_{L_1}	389 GeV
	$m_{H^\pm}$	374 GeV	m_{E_1}	204 GeV
	a_t	-906 GeV	m_{τ_1}	206 GeV
			m_{τ_2}	397 GeV

possibility to produce SUSY Higgses in cascade decays



Summary

- 30 years of speculations on the origin of the weak scale are coming to an end

- The *sentiment* never seemed more uncertain
  - supersymmetry ?
  - strong dynamics ?
  - just SM Higgs ?

- Important to learn to profit as much as possible of the LHC rain of data
  - studying the specific signatures of many classes of models is one way to train ourselves
  - but model independent approaches should be attempted whenever possible and meaningful

☑ Example: effective Lagrangian description of composite light Higgs

3 leading operators

$$\frac{c_H}{2f^2}\left[\partial_\mu\left(H^\dagger H\right)\right]^2 \qquad \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 \qquad \frac{c_y y_{ij}}{f^2} H^\dagger H\, \bar{\psi}_L^i H \psi_R^j$$

Most analyses focus instead on $H^\dagger H\, F_{\mu\nu}F^{\mu\nu}$ Manohar, Wise 06

- Single Higgs production with 300 fb^-1 $\longrightarrow$ $\frac{v^2}{f^2} \lesssim 0.2$
- $W_L W_L$ scattering emerges as a relevant process to study even in the presence of a light Higgs
- $W_L W_L \to hh$
- ILC, with 500 fb^-1 and $\sqrt{s} = 500\,\mathrm{GeV}$ $\longrightarrow$ $\frac{v^2}{f^2} \lesssim 10^{-2}$

$$4\pi f \gtrsim 30\,\mathrm{TeV}$$