The Supersymmetric Fat Higgs

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work with

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hep-ph/0311349

Outline

- Motivation
  - MSSM is fine-tuned, Weakly Coupled NMSSM
  - SUSY= Light Higgs ? Strongly Coupled NMSSM.
- Fat Higgs, Basic Mechanism
  - UV completion, Strong Coupling, Supersymmetric EWSB
- Model Building
  - Fermion Masses, Generating Scales, Unification
- Phenomenology
  - Higgs Spectrum, EW Precision

Motivation

The Supersymmetric Desert

In the last ~ 20 years, supersymmetry was the favorite candidate for new physics at a TeV.

- Supersymmetry stabilizes the EW scale.
- MSSM running is consistent with grand unification. $\Rightarrow$ Desert.
- Physics is weakly coupled at a TeV. Agrees with EW precision.

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- MSSM running is consistent with grand unification. $\Rightarrow$ Desert.
- Physics is weakly coupled at a TeV. Agrees with EW precision.
- Due to minimality MSSM gives a prediction- :)
  MSSM Higgs quartic is set by SUSY, $\lambda_h \propto g^2 + g'^2$.
  $\Longrightarrow m_h \sim \lambda_h v \leq m_Z$ at tree level.

The LEP II bound pushes the MSSM to fine tuning. :(

MSSM's Getting Fine Tuned

- The tension in the MSSM comes from the double role of the stop:

1. Stop loop raises higgs quartic and mass

$$m_{h^0}^2 \simeq m_Z^2 + \frac{3}{4\pi^2} h_t^4 v^2 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

Higgs above 115 GeV $\Longrightarrow$ heavy stop.

2. Stop loop triggers EWSB,

$$\Delta m_{H_u}^2 \sim -12 \frac{h_t^2}{16\pi^2} m_{\tilde{t}}^2 \log \frac{M_{UV}}{\mu_{IR}},$$

sets EW scale $\Longrightarrow$ light stop.

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The NMSSM

- Within the MSSM: Satisfy (1), Fine-tune (2).
- A possible fix beyond the MSSM:

  Add an additional quartic, increase tree level mass.
- E.g. extended gauge interactions- next talk.
- In the NMSSM we add

$$W = \lambda N H_u H_d - \frac{k}{3} N^3$$

We have new quartic $\propto \lambda^2$. Increases m_h at tree level.

Now $m_h^2 \sim \lambda^2 v^2 + O(m_z^2)$. We don't have to rely on $m_{\tilde{t}}$!

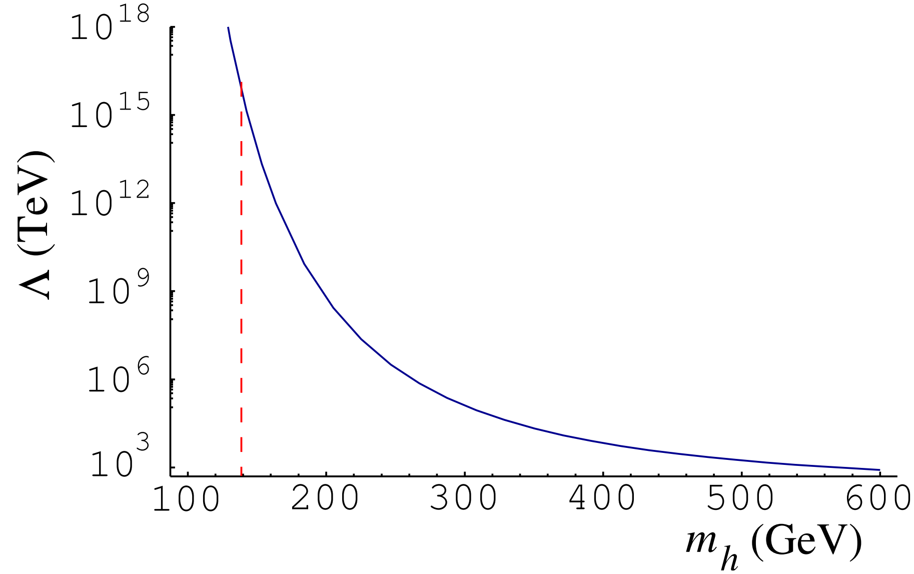
(need large $\lambda(v)$ ...)

Lore: SUSY $\Rightarrow$ Light Higgs

- λ grows in the UV. Hits a Landau pole.

  There's a relation between m_h and the Landau pole.

! But strong coupling in the middle of the desert will ruin unification!



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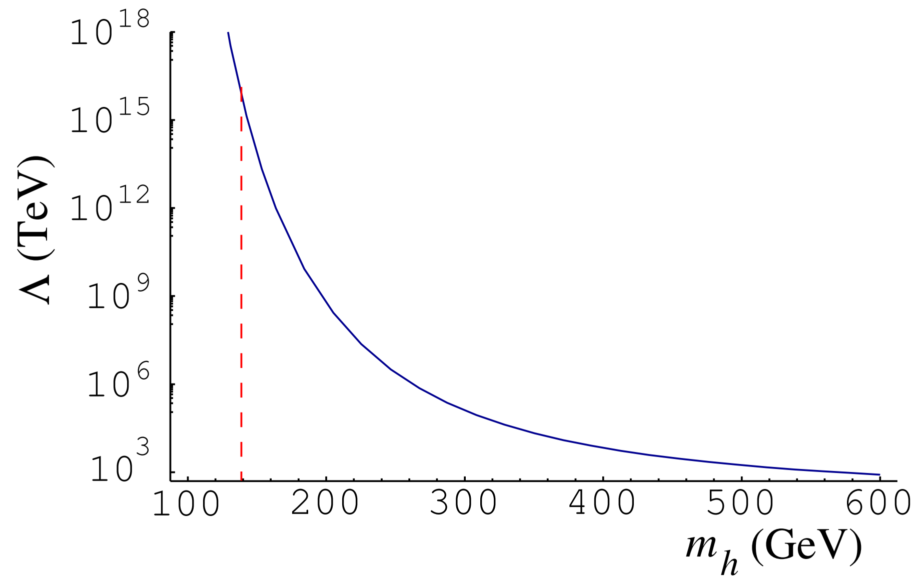


require a desert $\Longrightarrow$ $\Lambda \geq M_{GUT}$

$\Downarrow$

SUSY= light Higgs $\Longleftarrow$ $m_h \lesssim 150\text{GeV}$

e.g. Espinosa, Quiros

Effective Field Theory

- But what if we don't find a light Higgs??? Is SUSY dead?
- The requirement $\Lambda \geq M_{GUT}$ is too restrictive.
- Set the cutoff at Λ.
- The NMSSM with a heavy Higgs is a good EFT below the cutoff.
- Does not explain the apparent unification $\Rightarrow$ Nobody's perfect.
- Many non-supersymmetric models took this approach

  Kaplan-Georgi, Little Higgs

UV Completion

- Can we still hope to connect to the UV?

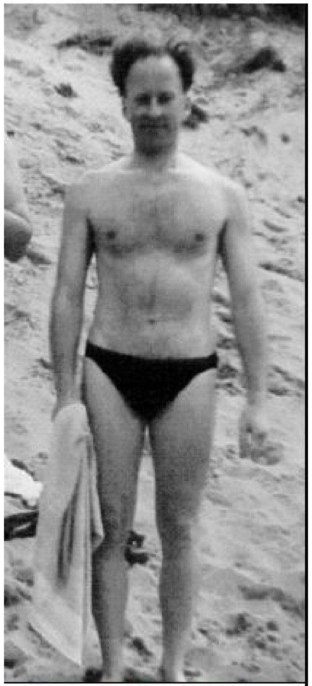
- At the scale Λ we expect a UV completion to take over.
- The NMSSM Higgs is a composite of UV d.o.f.
- Exact results in strong SUSY gauge theories.

- We found a UV completion to the NMSSM's cousin

$$W = \lambda N (H_d H_u - v_0^2) \; .$$

The Fat Higgs a.k.a. the nMSSM

The Fat Higgs



A sure sighting of a higgs... Peter Higgs on the shores of the Firth of Fourth by Prof J D Jackson, July 1960

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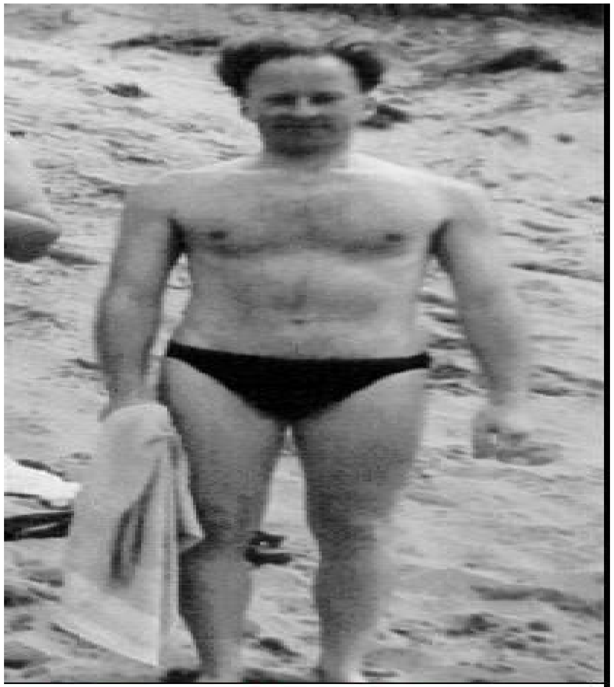

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Ingredients

- Introduce a new gauge group $SU(2)_H$.
- Matter content ($SU(2)_H \times SU(2)_L \times U(1)_Y$):

$T_{1,2}$	$(\mathbf{2},\ \mathbf{2},\ 0)$
$T_{3,4}$	$(\mathbf{2},\ \mathbf{1}, \pm\frac{1}{2})$
$T_{5,6}$	$(\mathbf{2},\ \mathbf{1},\ 0)$

An $SU(2)$ gauge theory with $N_f = 3$ $\Longleftarrow$

Gets strong at Λ_H

- Add a mass to $T_{5,6}$: $W = mT_5T_6$

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- Seiberg says: Low energy d.o.f are mesons $M_{ij} = T_iT_j$

$$W_{dyn} = \frac{\mathrm{Pf}M}{\Lambda^3}$$

Composite Higgs

- The mesons are $(SU(2)_L \times U(1))$:

$(i = 1, 2)$

$$H_u \equiv (T_4 T_i) = (\mathbf{2}, -\tfrac{1}{2})$$
$$H_d \equiv (T_3 T_i) = (\mathbf{2}, +\tfrac{1}{2})$$
$$N \equiv (T_5 T_6) = (\mathbf{1}, 0)$$
$$\vdots$$

Fat Higgses $\Longleftarrow$

- A renormalizable interaction $\quad \mathrm{Pf} M \supset N H_u H_d$
- A linear term for N $\quad m T_5 T_6 \to m N$.

Supersymmetric EWSB

- After canonical normalization

$$W = \lambda N (H_u H_d - v_0^2)$$

Electroweak symmetry is broken even in SUSY limit.

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Electroweak symmetry is broken even in SUSY limit.

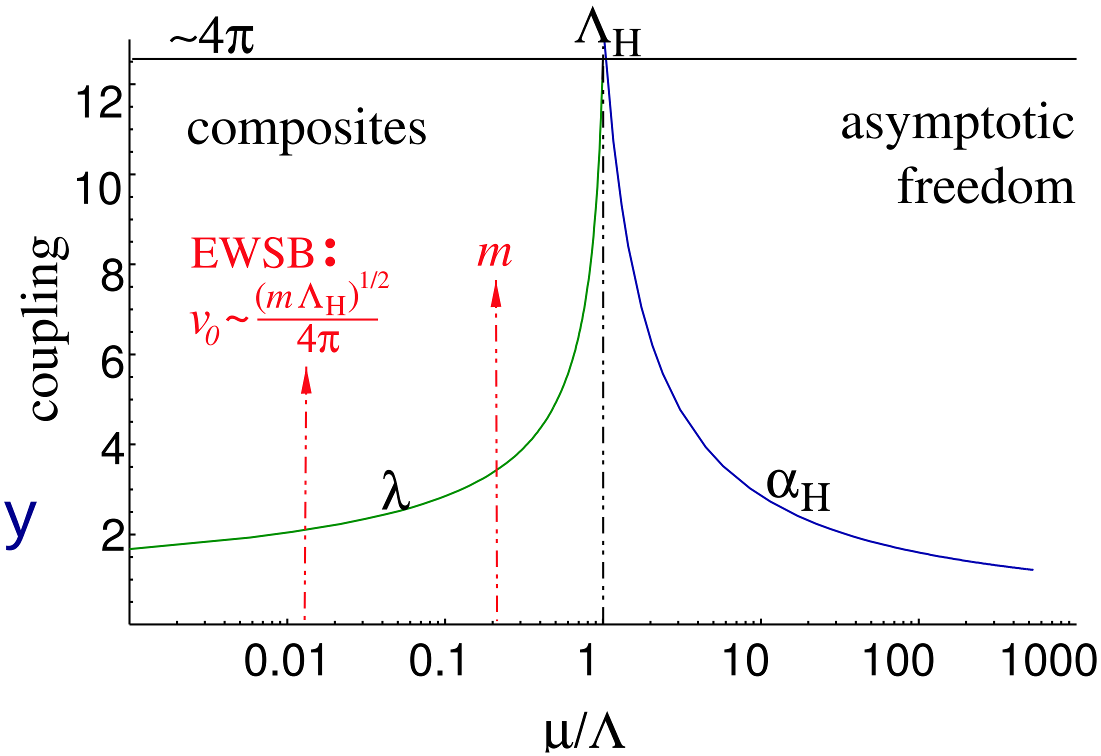
- EW scale is controlled by $\begin{cases} \text{a dynamical scale } \Lambda_H \\ \text{a SUSY mass } m \end{cases}$

In NDA we get

$$v_0^2 = \frac{m\Lambda_H}{4\pi}$$

Running

- At Λ_H, $SU(2)_H$ gauge coupling blows up.
- NDA: λ is strong at Λ_H
- λ renormalizes down quickly for $\mu < \Lambda_H$.



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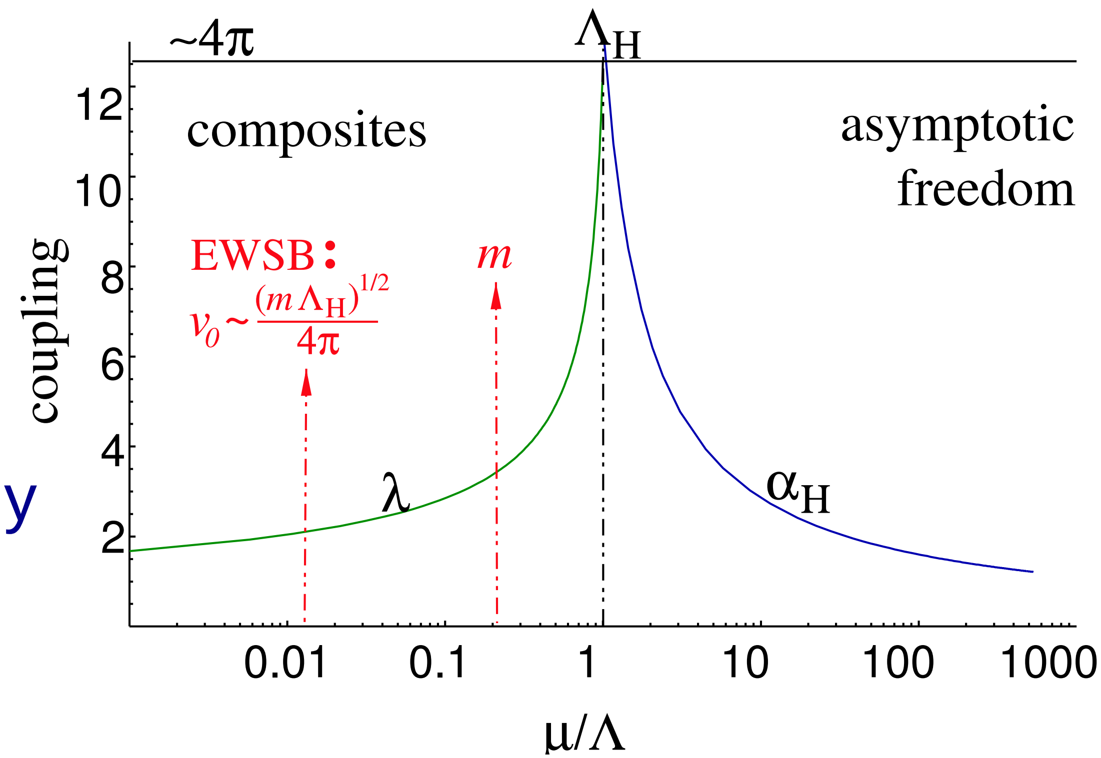

- EWSB ocurrs at weak coupling. Calculable!
- If $\lambda^2 v^2 \gg g^2 v^2$, we can neglect MSSM D-term potential. Solves MSSM fine tuning problem.

Model Building Issues

Tree Level Superpotential

- We need to guarantee EWSB ocurrs-

$$\mathrm{Pf}M \supset N M_{12} M_{34} \Longrightarrow \text{another solution} \begin{cases} M_{12} = M_{34} = v_0 \\ H_u = H_d = 0 \end{cases}$$

- Add singlets an a tree-level superpotential

$$W_s = sT_1T_2 + s'T_3T_4$$

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$$\boxed{W_s = s T_1 T_2 + s' T_3 T_4}$$

- Optional: to get minimal matter content add

$$W_{P,Q} = y(T^1, T^2) P \begin{pmatrix} T^5 \\ T^6 \end{pmatrix} + y(T^3, T^4) Q \begin{pmatrix} T^5 \\ T^6 \end{pmatrix} .$$

Symmetries

Fields	$SU(2)_L$	$SU(2)_H$	$SU(2)_R$	$SU(2)_g$	$U(1)_R$	Z_3
(T^1, T^2)	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$
(T^3, T^4)	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	0	-1
(T^5, T^6)	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	1	0
P	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	1	0
Q	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	1	0
S	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	2	$+1$
S'	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	2	-1

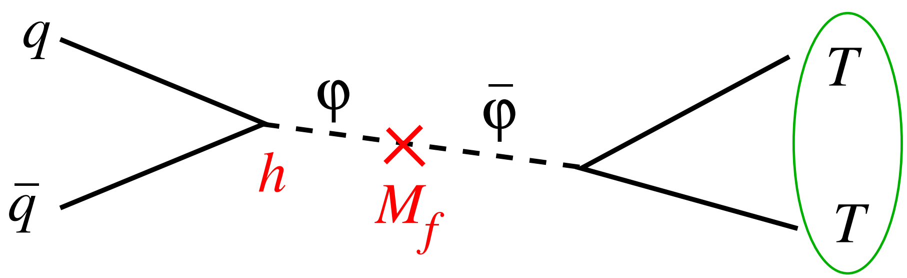
$SU(2)_R \supset U(1)_Y$ is a custodial symmetry.

Fermion Masses

- A ‘scalar ETC’ sector:

  Add heavy ‘Higgs-like’ fields that mediate EWSB

$$W_f = M_f(\varphi_u\bar{\varphi}_u + \bar{\varphi}_d\varphi_d) + \bar{\varphi}_d(TT^4) + \bar{\varphi}_u(TT^3)$$
$$+h_u^{ij}Q_iu_j\varphi_u + h_d^{ij}Q_id_j\varphi_d + h_e^{ij}L_ie_j\varphi_d.$$



$$= \frac{\Lambda_H}{4\pi}H \quad \Longrightarrow \quad \left(\frac{h}{4\pi}\frac{\Lambda_H}{M_f}\right)H\bar{q}q$$

Setting Scales

- Top Yukawa is suppressed by $\left(\frac{1}{4\pi}\frac{\Lambda_H}{M_f}\right)$.
- To prevent fine tuning, v_0 must be of order m_{SUSY}

What sets the scales Λ_H, m, M_f ?

- Add another flavor $T_{7,8}$ with a mass

$$\boxed{W = m' T_7 T_8} \qquad \text{with } m' \sim M_f$$

$N_f = 2N_c \Rightarrow$ Theory becomes superconformal at some scale, Λ_4.

Walking

- At m':

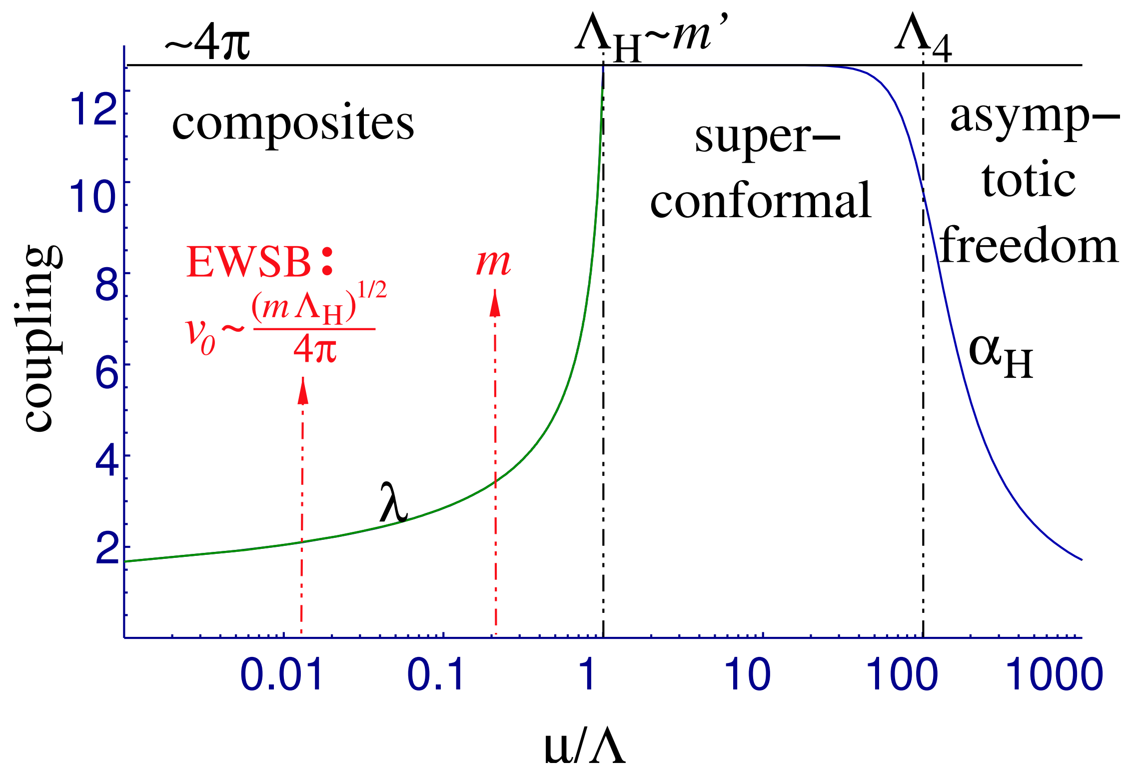
Conformal 4 flavor

$\downarrow$

3 flavor model

$\Downarrow$

$\Lambda_H \sim m'$



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↓

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⇓

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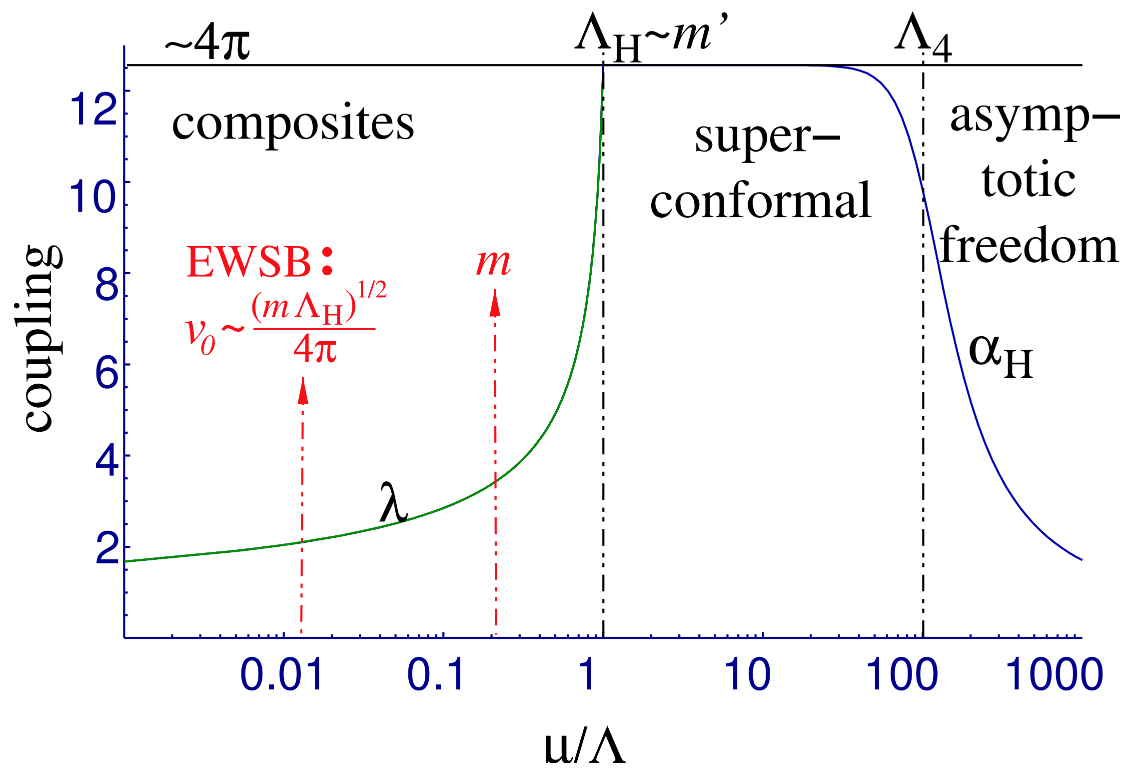

- Walking enhancement can cancel 4π in fermion masses.

- m' can be related to m_{SUSY} ala Giudice-Massierro.

Unification

- Below Λ_H the matter content is the NMSSM. Usual running.
- Exact results give us improved control at threshold.
- Above Λ_H (and Λ_4) the contributions to the β-function are:
  - $T_{1,2}$ and $T_{3,4}$ contribute like two higgs doublets of the MSSM.
  - φs, P and Q contribute like 3 more Higgs pairs.
- We can add color triplets with $Y = \pm\frac{1}{3}$ to make couplings unify.

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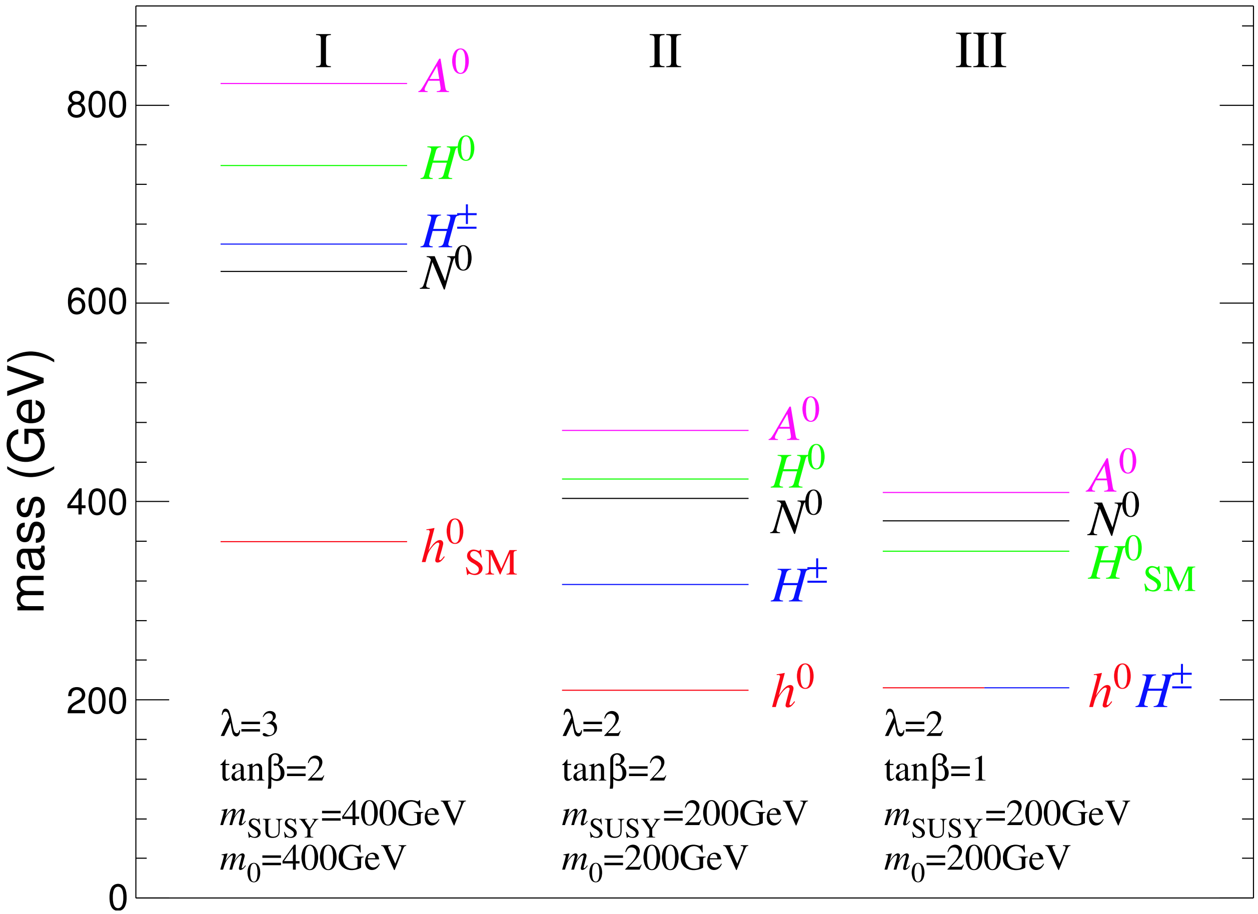
- We can add color triplets with $Y = \pm\frac{1}{3}$ to make couplings unify.
- Not a GUT-

  T, P and Q cannot be embedded into $SU(5)$ multiplets.

  $\Rightarrow$ Orbifold GUT?

Phenomenology

Higgs Spectrum



	λ	$\tan\beta$	m_s
I	3	2	400 GeV
II	2	2	200 GeV
III	2	1	200 GeV

Signal: $m_{H^\pm} < m_{A^0}$

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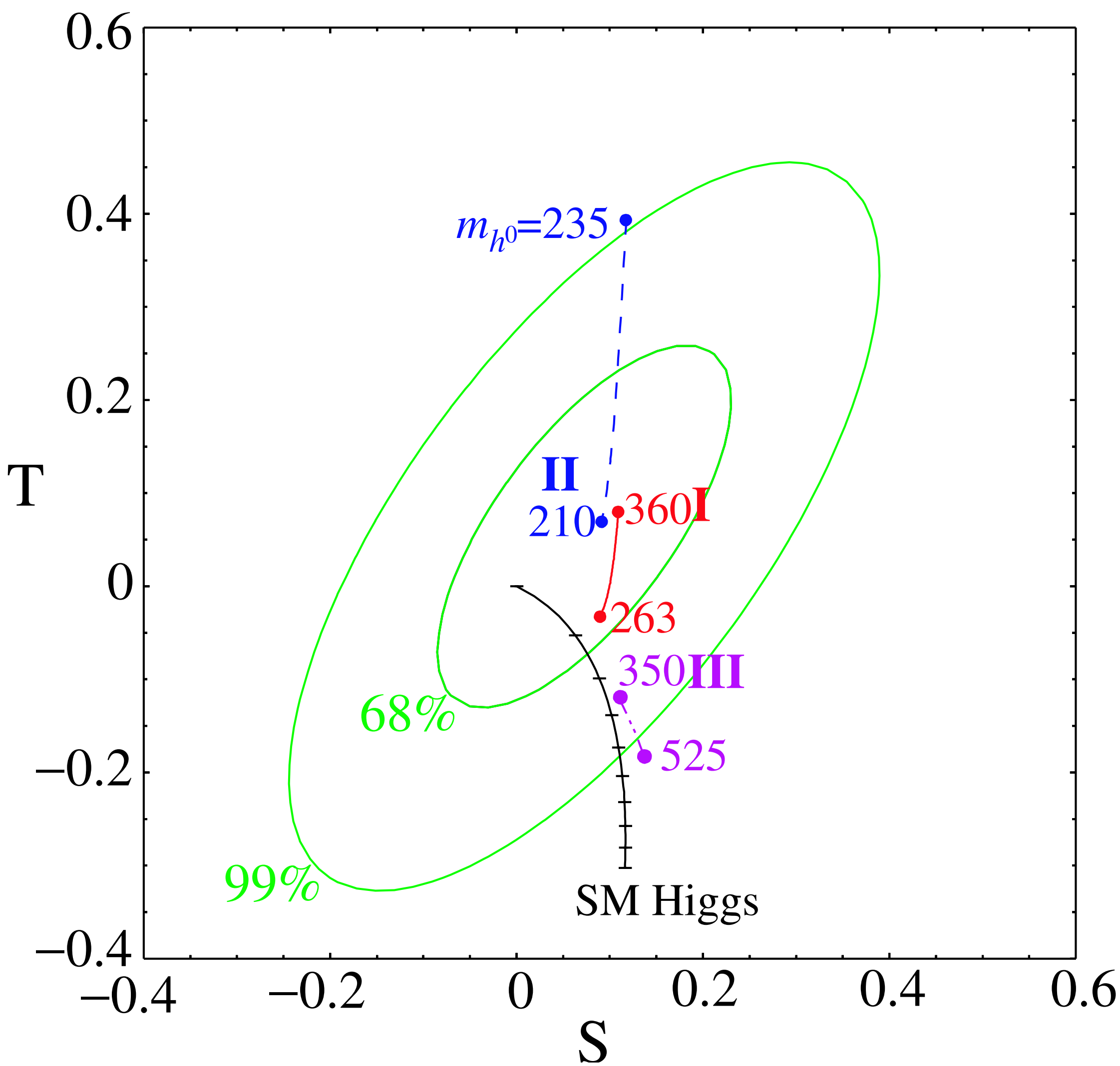
EW Precision



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Conclusions

- The MSSM is becoming uncomfortably fine-tuned.
- SUSY models have yielded light higges.

  Due to a demand of weak coupling up to M_{GUT}.
- No reason to avoid strongly coupled models.

  They are good EFTs

  Exact results in SUSY can give a simple UV completion.

Conclusions

- The Fat Higgs:

  Strong couplings at an intermidiate scale yield a composite Higgs.

  Agrees with EW precision, even though Higgs is heavy.

  UV complete, Calculable, Unifiable.

Extra sildes:

MSSM Higgs Sector

- MSSM: the top yukawa drives EWSB once SUSY is broken

$$\Delta m^2_{H_u} \sim -12 \frac{h_t^2}{16\pi^2} m^2_{\tilde{t}} \log \frac{M_{UV}}{\mu_{IR}},$$

- The Higgs quartic term is tied to the EW gauge couplings

$$V_D = \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2.$$

$\Longrightarrow$ Higgs mass is (quartic)$\times$(vev). Tied to m_Z.

$m_h \leq m_Z$ at tree level.

Fine Tuned

- The Higgs mass gets corrected by the top

$$m_{h^0}^2 \simeq m_Z^2 + \frac{3}{4\pi^2} h_t^4 v^2 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

$\Longrightarrow$ $m_{\tilde{t}} \gtrsim 500\text{GeV}.$ for $m_h \geq 115\text{GeV}$

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- But then m_{H_u} is too negative! minimizing the potential gives

$$\frac{1}{2} m_Z^2 \simeq -\mu^2 - m_{H_u}^2$$

In order to get m_Z right we need to fine tune $m_{H_u}^0$ and/or μ against Δm_{H_u}. $\Longrightarrow$ 3% fine tuning for $\Lambda_{UV} \sim 100\mathrm{TeV}.$

SUSY breaking

- SUSY will be softly broken.

$$\mathcal{L}_{soft} = m_1^2|H_d|^2 + m_2^2|H_u|^2 + \ldots$$

- Need flavor blind mediation.

- $m_{SUSY} \ll \Lambda_H$. Exact Results still hold. Arkani-Hamed, Rattazzi

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- m_{SUSY} enters the EW scale: $v^2 \sim \lambda^2 v_0^2 - m_{SUSY}^2$.
  - $m_{SUSY} \ll \lambda v_0$ is experimentally excluded.
  - $m_{SUSY} \gg \lambda v_0$ is fine tuned.

$\Longrightarrow$ need $m_{SUSY} \sim \lambda v_0$, or

$$m \sim \frac{(4\pi m_{SUSY})^2}{\Lambda_H}$$

See-saw

Combination of the see-saw and Guidice-Massiero mechanisms:

- Imagine m' is set by a flavor breaking scale.
- Flavor forbids mT_5T_6
- generate 'μ-term' via GM $m_{SUSY}(T_5T_8 + T_6T_7)$

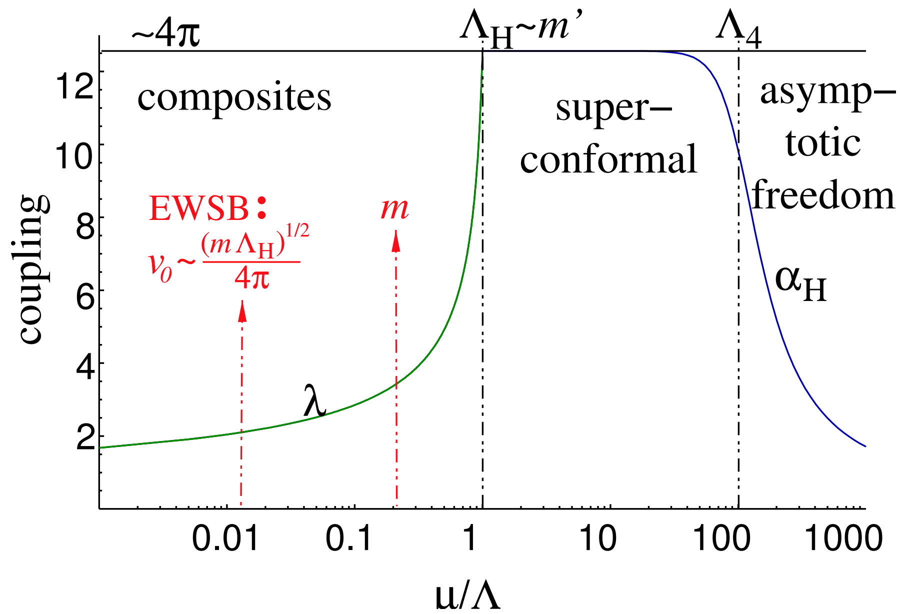
  yields a mass matrix $\begin{pmatrix} 0 & m_{SUSY} \\ m_{SUSY} & m' \end{pmatrix}$

$$\Longrightarrow \quad \boxed{m \sim \frac{m_{SUSY}^2}{m'}}$$

- Walking can give 4π enhancement (calculable!).

Matching

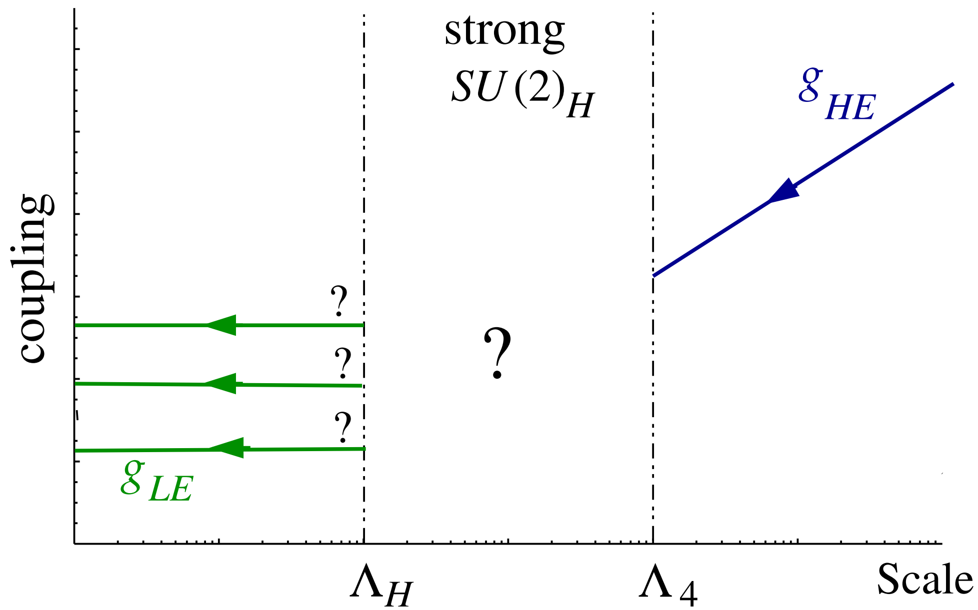
- The $SU(2)_H$ coupling blew up. How are 3-2-1 couplins affected?



- The matching between High and low energy runnigs is constrained by holomorphy and symmetries.

Matching

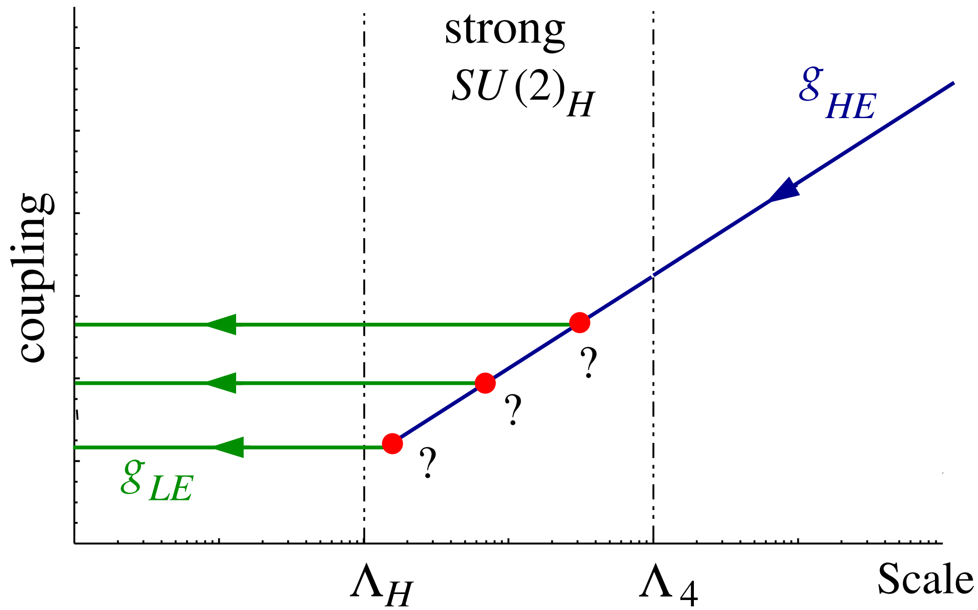
- Start with a certain bare coupling in the UV.



Which low energy trajectory do we match on to ?

Matching

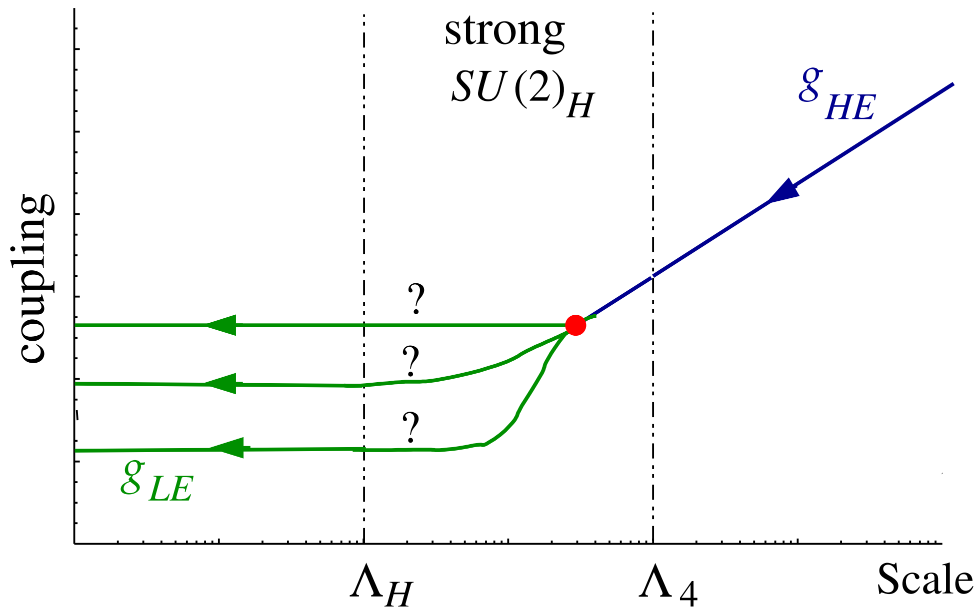
- Ideally we match the couplings at the scale $m_{match} = m(m)$.



But we do not control $m(\mu)$.

Matching

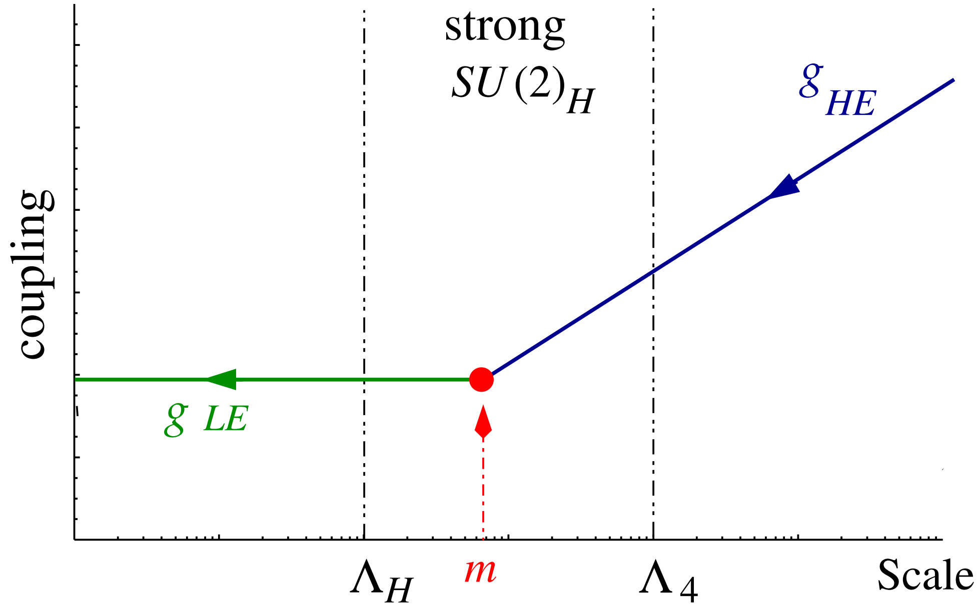
- Even if we set the matching scale . . .



How does the coupling run when $SU(2)_H$ is strong?

Matching

- These two uncertainties cancel one another!



- Holomorphy: Matching depends on bare couplings.

e.g. $\frac{8\pi^2}{g_{LE}^2} = \frac{8\pi^2}{g_{HE}^2} - \log \frac{m_0}{\Lambda_{UV}} = \frac{8\pi^2}{g_{HE}^2} - \log Z - \log \frac{Z^{-1} m_0}{\Lambda_{UV}}$

Arkani-Hamed, Murayama

Outlook

More avenues for research:

- Low compositeness scale. May Yield intersting phenomenology- 'The Fattest Higgs' (work in progress).

- SUSY Breaking:

  AMSB with D-terms works well- Kitano, Kribs, Murayama.

  Other mediation mechanisms?

  Soft terms for composites may be non-calculable.

- Model building: Dynamical solution to alignment ? Constructing a GUT ? etc.