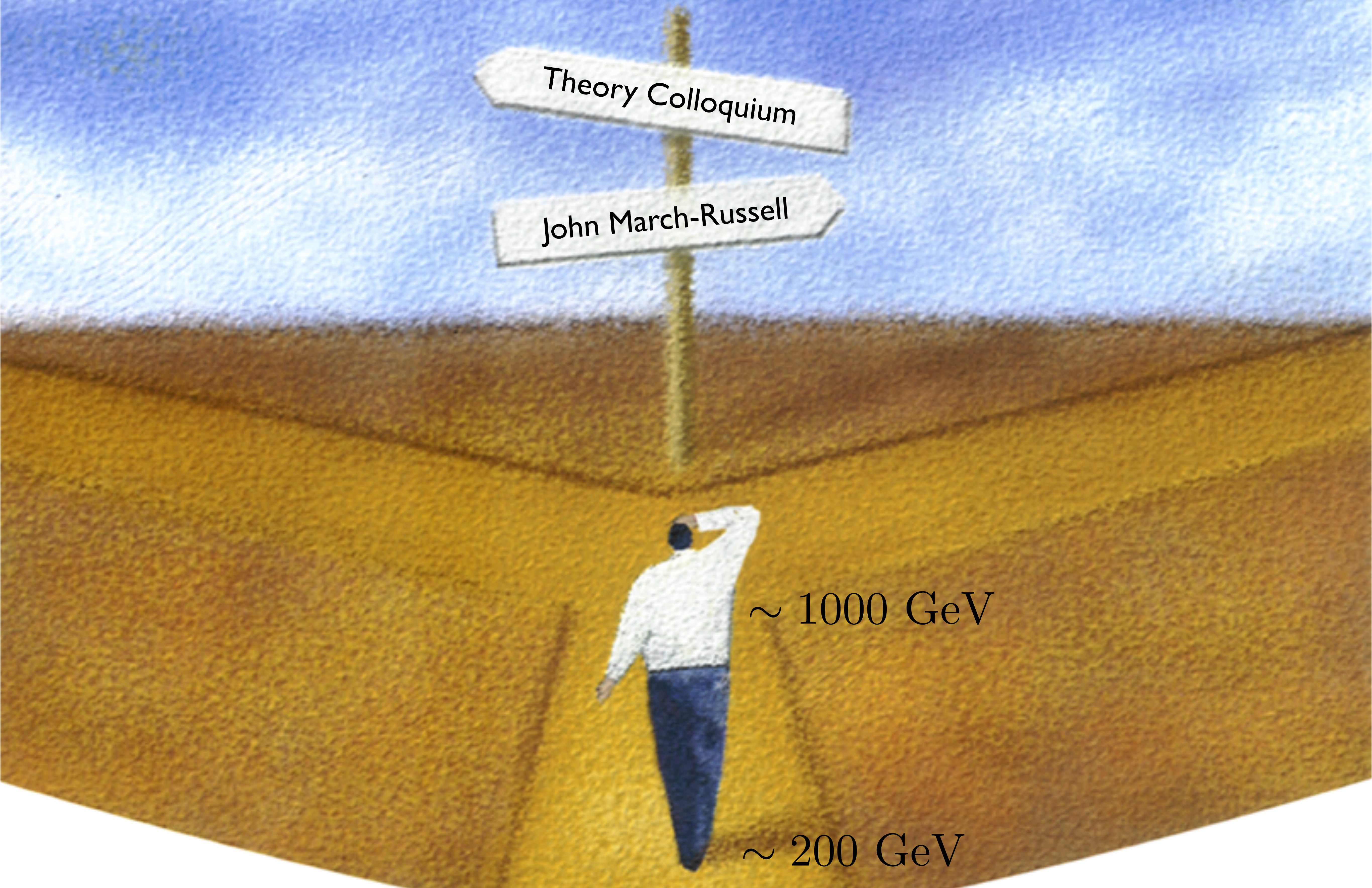
# The Higgs, The Hierarchy Problem, and the LHC

Theory Colloquium

John March-Russell



# Subject at hand...

- Mystery of the Higgs & the Weak Scale: Approaches to the “Hierarchy Problem” and what the LHC will be able to tell us
- Everything else: Dark matter? CP-violation? Strong CP problem? Inflation? Flavour-violation? Baryogenesis? Gauge unification? Family replication? 4D? Almost zero vacuum energy?...

# Subject at hand...

for this talk just

- Mystery of the Higgs & the Weak Scale: Approaches to the "Hierarchy Problem" and what the LHC will be able to tell us

- ~~Everything else: Dark matter? CP-violation? Strong CP problem? Inflation? Flavour-violation? Baryogenesis? Gauge unification? Family replication? 4D? Almost zero vacuum energy?...~~

reason: hard to understand (most) other problems w/o solution to first

# Higgs Enigma

Discovery of Higgs, h, sharpens deep mystery of Weak Scale:

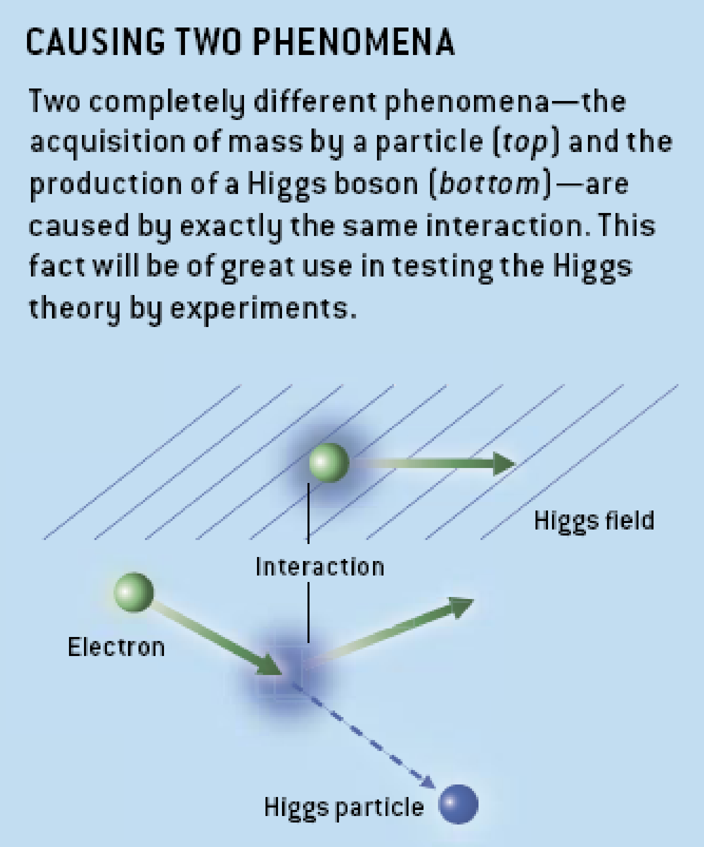
Why is Higgs mass so much less than other energy scales — in particular the scale of gravity?

$$m_h \simeq 125.5~\text{GeV} \lll M_{\text{Planck}} = 1/\sqrt{G_N} \simeq 1.2 \times 10^{19}~\text{GeV??}$$

A very closely related mystery:

We live inside an "electro-weak superconductor" where SU(2)xU(1) symmetry is broken (everywhere in the observed universe)

— similar to how inside a usual superconductor electromagnetism is broken (and photon gets a mass) due to condensate of Cooper-pairs



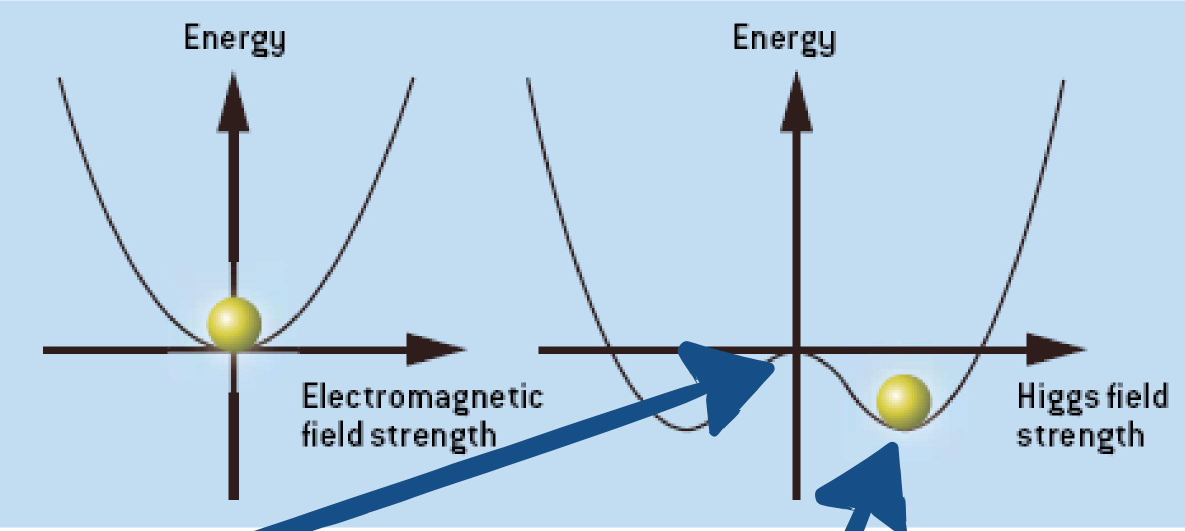
**CAUSING TWO PHENOMENA**

Two completely different phenomena—the acquisition of mass by a particle (*top*) and the production of a Higgs boson (*bottom*)—are caused by exactly the same interaction. This fact will be of great use in testing the Higgs theory by experiments.

# Higgs Enigma

Discovery of Higgs, h, sharpens deep mystery of Weak Scale:

A closely related mystery concerns the scale of "Higgs condensate" $\langle h \rangle \equiv v$



Why unstable?? — what led to -ve mass-squared, $-\mu^2$, around origin?

Why $\langle h \rangle \equiv v \simeq 246 \text{ GeV} \lll M_{\text{Planck}}$??

# Higgs Enigma

Higgs multiplet is

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1 + i\phi_2 \\ v + h + i\phi_3 \end{pmatrix}$$

A (1,2,+1/2) state under
SU(3)xSU(2)xU(1)

In terms of the appropriate Higgs-Kibble potential experimentally now know

$$V(H) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \ldots$$

$$m_h^2 = \lambda v^2/2$$

~0.52

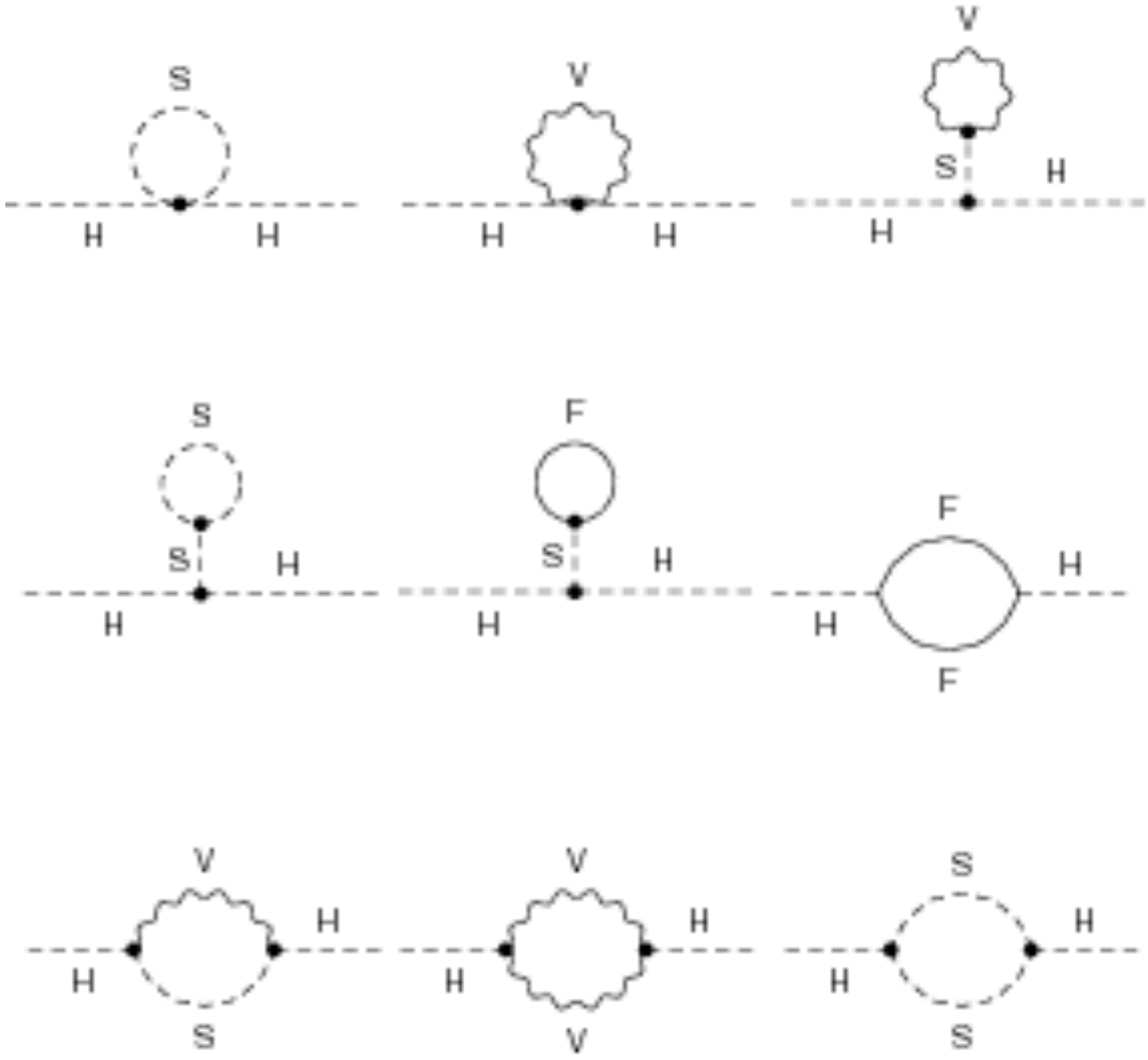
$-(89\ \mathrm{GeV})^2$

The Higgs-Englert-Brout-Kibble-Guralnik-Hagen theory does not explain these facts — just parameterises them

# Hierarchy Problem

An elementary Higgs sharpens deep mysteries:

- Absent new symmetries/dynamics, Higgs condensate and Higgs mass are unstable to quantum corrections & dragged-up to very large energy scales



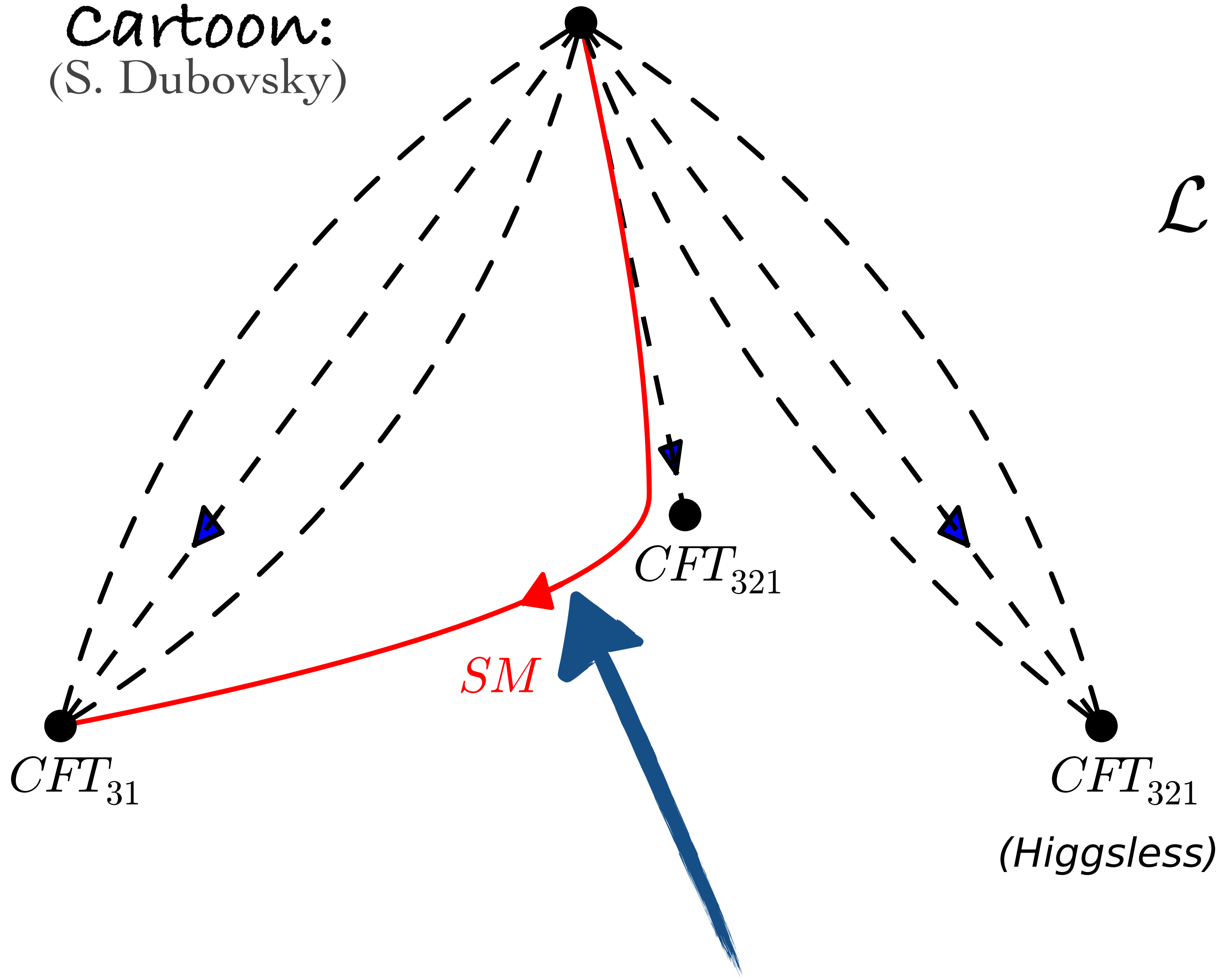
$$\frac{\delta v^2}{v^2} \simeq \sum_i \pm \frac{g_i^2}{16\pi^2}\left(\frac{M_i^2}{v^2}\right) \gg 1$$

proxy for unknown heavy mass scales (gravity, GUTs, flavour, DM,...)

# Hierarchy Problem

Can discuss hierarchy problem directly in terms of the Wilsonian RG flow of finite quantities, eg, for non-SUSY GUT theory

**Cartoon:**
(S. Dubovsky)



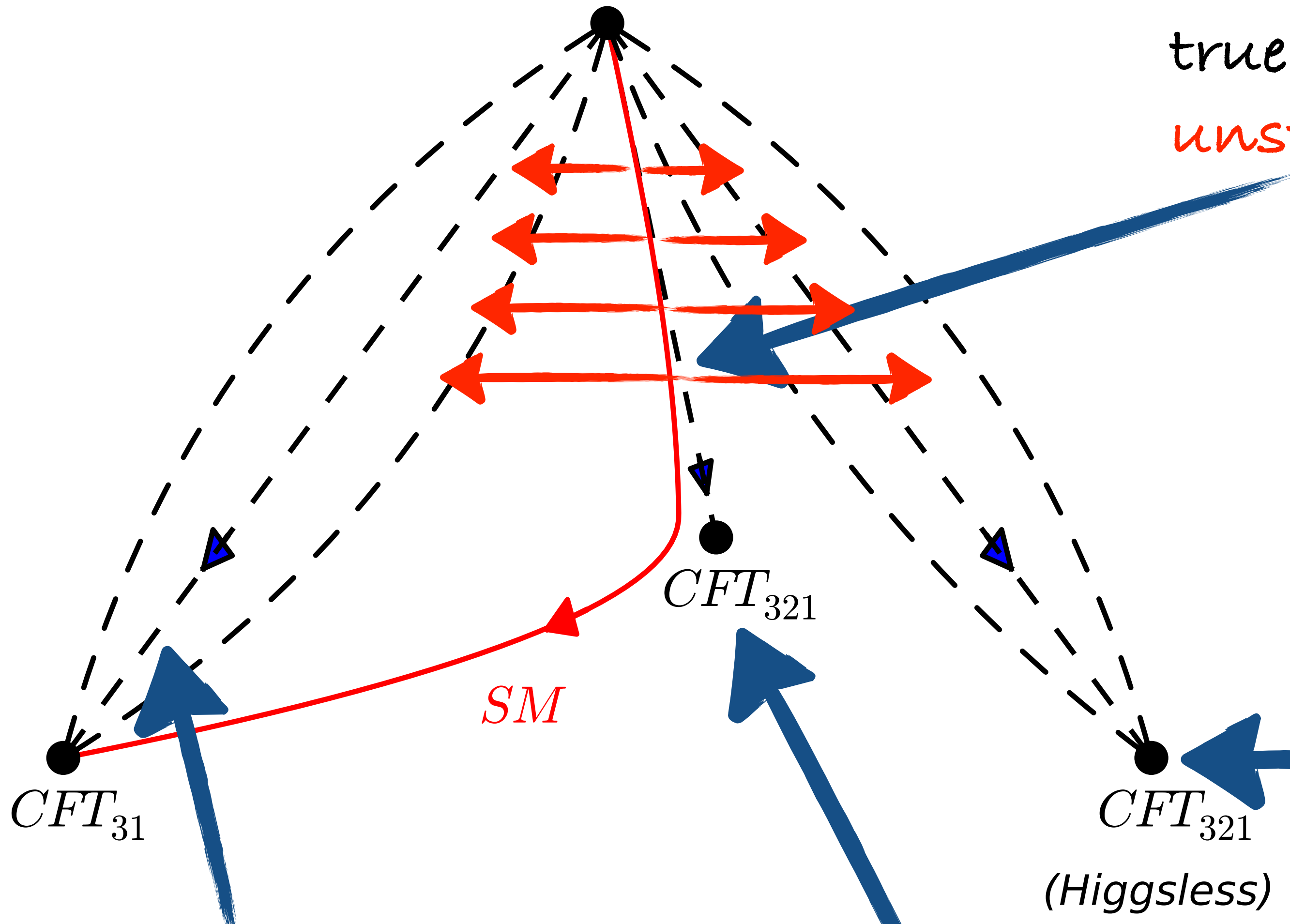
flow trajectory of theory parameters
(incl higgs mass) from UV to IR

$$\mathcal{L} = \mathcal{L}_{321} + m^2 H^\dagger H + \sum_i \frac{\mathcal{O}^{\Delta_i}}{\Lambda_{UV}^{(\Delta_i-4)}}$$

strongly relevant operator
not forbidden by symm if
SM correct

# Hierarchy Problem

Why does trajectory of SM so closely approach zero, -0.000000000000000000000000000001, Higgs mass-squared in IR when there is nothing special about trajectory in UV (if SM true up to high scales) and trajectory is unstable??



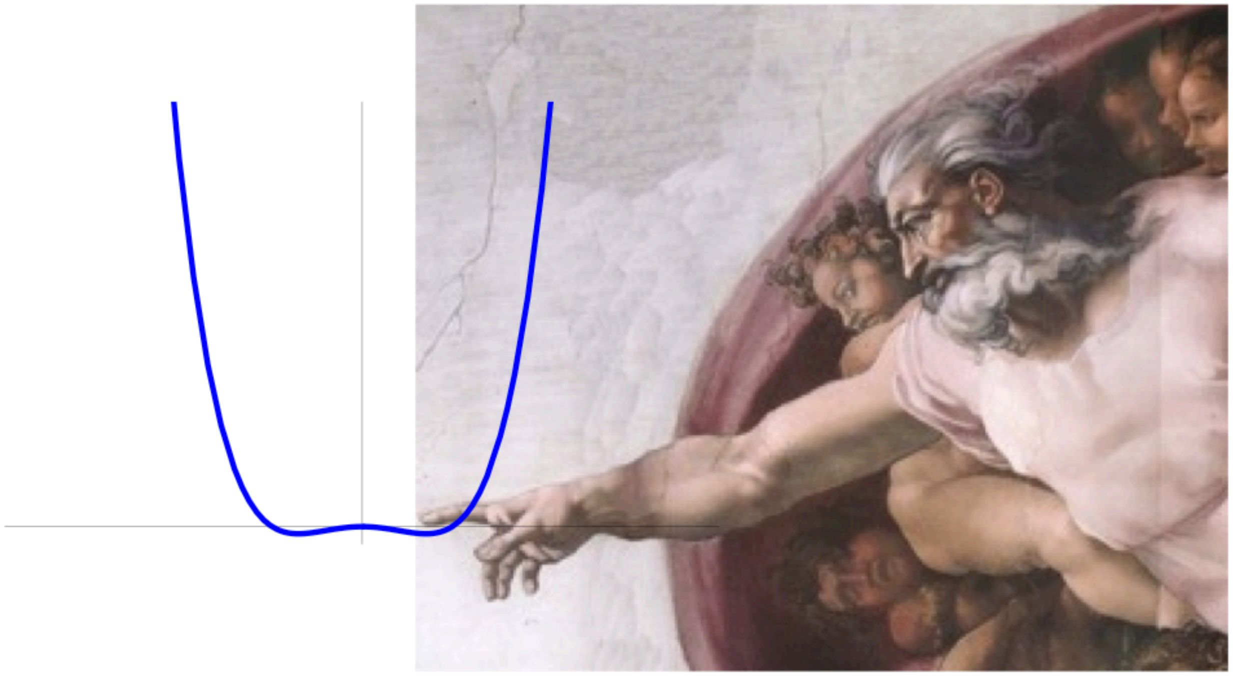
unbroken EW symm
with v. large higgs mass

broken EW symm
with v. large vev

exactly massless higgs

# Hierarchy Problem

SM situation like tuning of a phase transition to 2nd-order point — nothing *a-priori* special about 374.4 C and 217.7 atm for water — an experimentalist has to very carefully *tune* the knobs!



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

pictures courtesy R. Rattazzi & V. Rychkov
who stole them anyway

# Hierarchy Problem

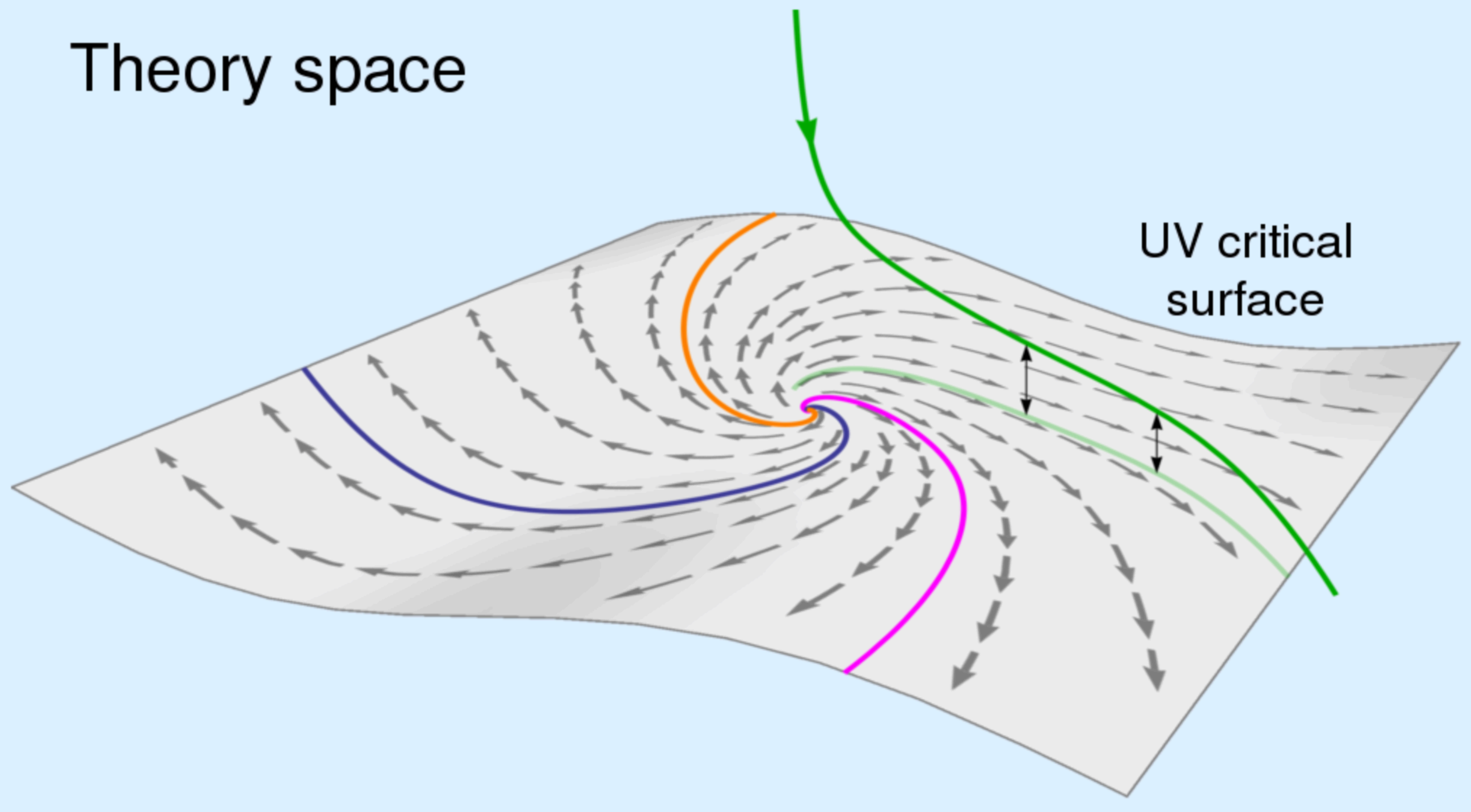
(Grand) Hierarchy Problem: what physics sets and stabilises IR value of Higgs mass parameter to

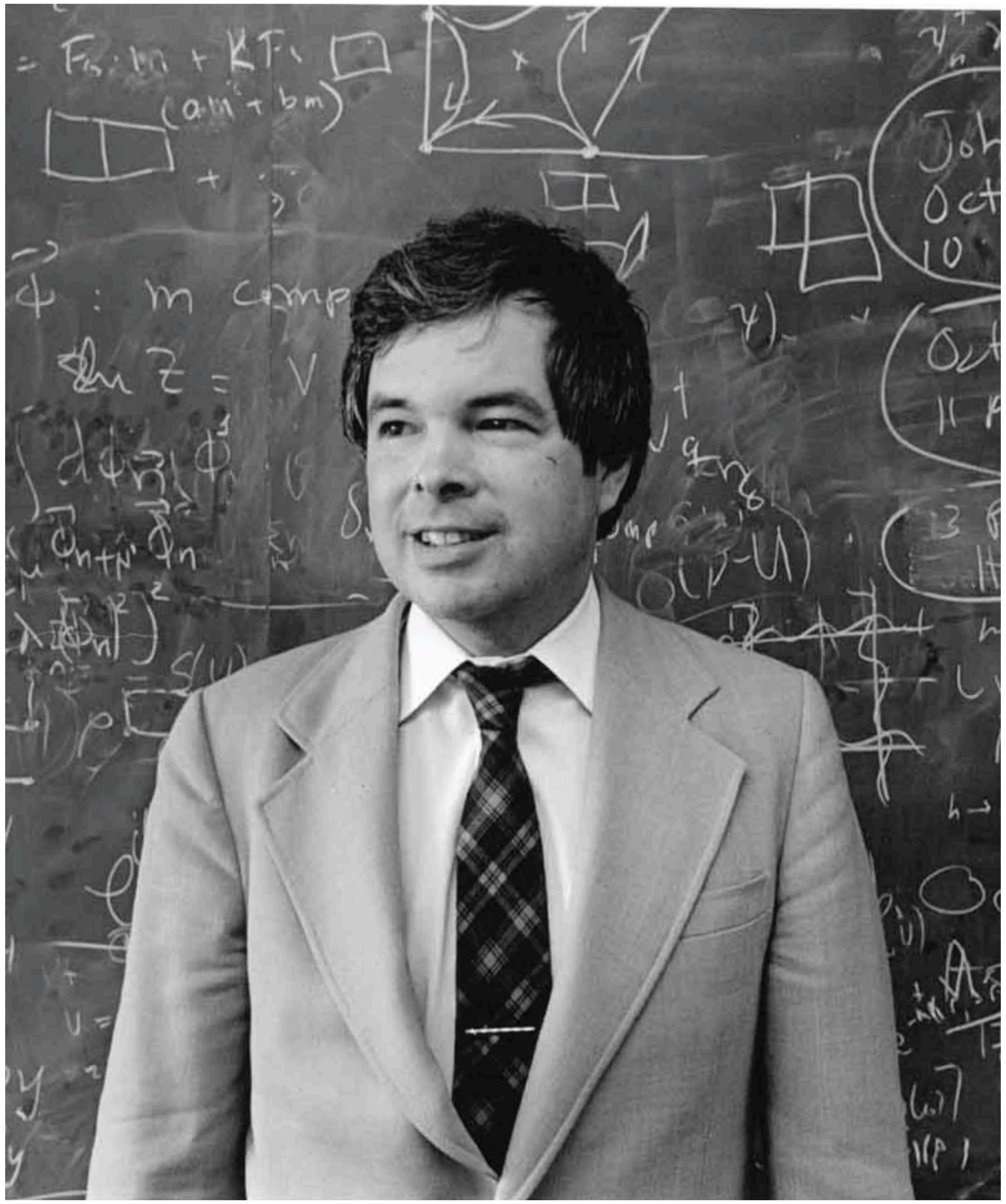
$$\left(\frac{-\mu^2}{M_{\text{Planck}}^2}\right) \sim 10^{-32}$$

Note to experts: Hierarchy problem is sharpest for theories where Higgs properties, EWSB condensate, and higgs mass, are calculable

# Hierarchy Problem

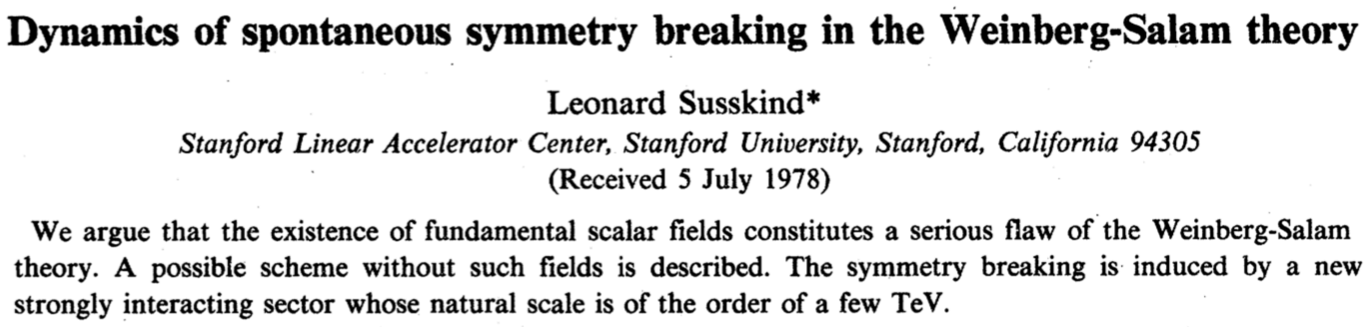
Greatest advance in QFT in the last 50yrs was Wilson's understanding of RG flow of effective FT's





# Hierarchy Problem

Greatest advance in QFT in the last 50yrs was Wilson's understanding of RG flow of effective FT's

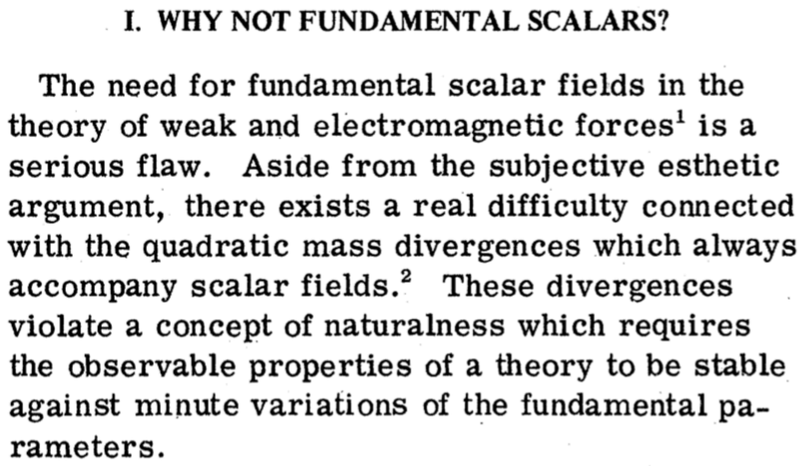


## Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory

Leonard Susskind*
*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305*

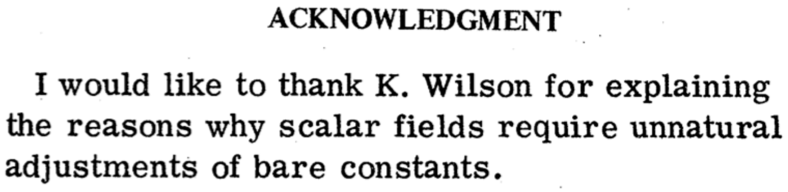
(Received 5 July 1978)

We argue that the existence of fundamental scalar fields constitutes a serious flaw of the Weinberg-Salam theory. A possible scheme without such fields is described. The symmetry breaking is induced by a new strongly interacting sector whose natural scale is of the order of a few TeV.



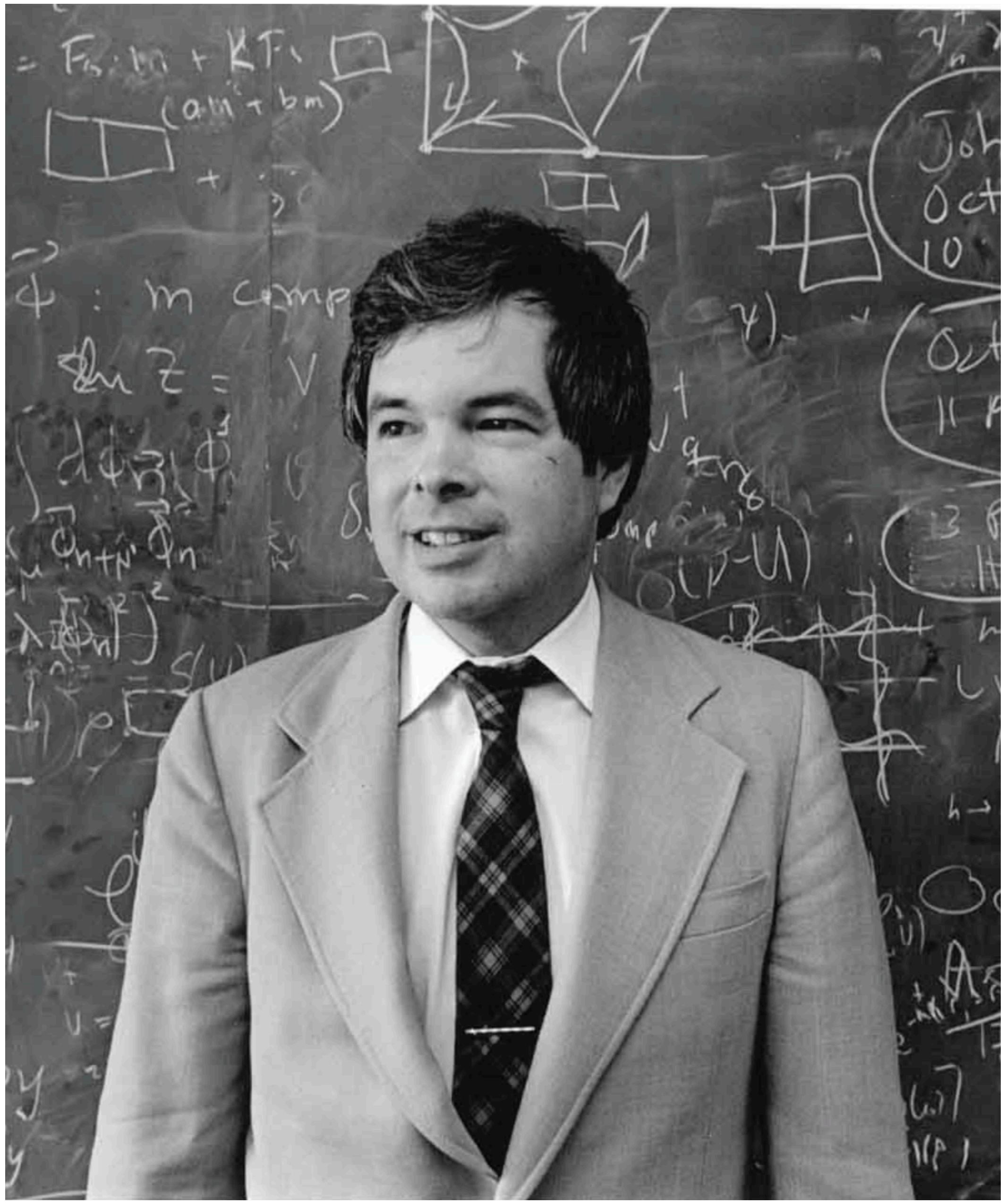
### I. WHY NOT FUNDAMENTAL SCALARS?

The need for fundamental scalar fields in the theory of weak and electromagnetic forces[1] is a serious flaw. Aside from the subjective esthetic argument, there exists a real difficulty connected with the quadratic mass divergences which always accompany scalar fields.[2] These divergences violate a concept of naturalness which requires the observable properties of a theory to be stable against minute variations of the fundamental parameters.

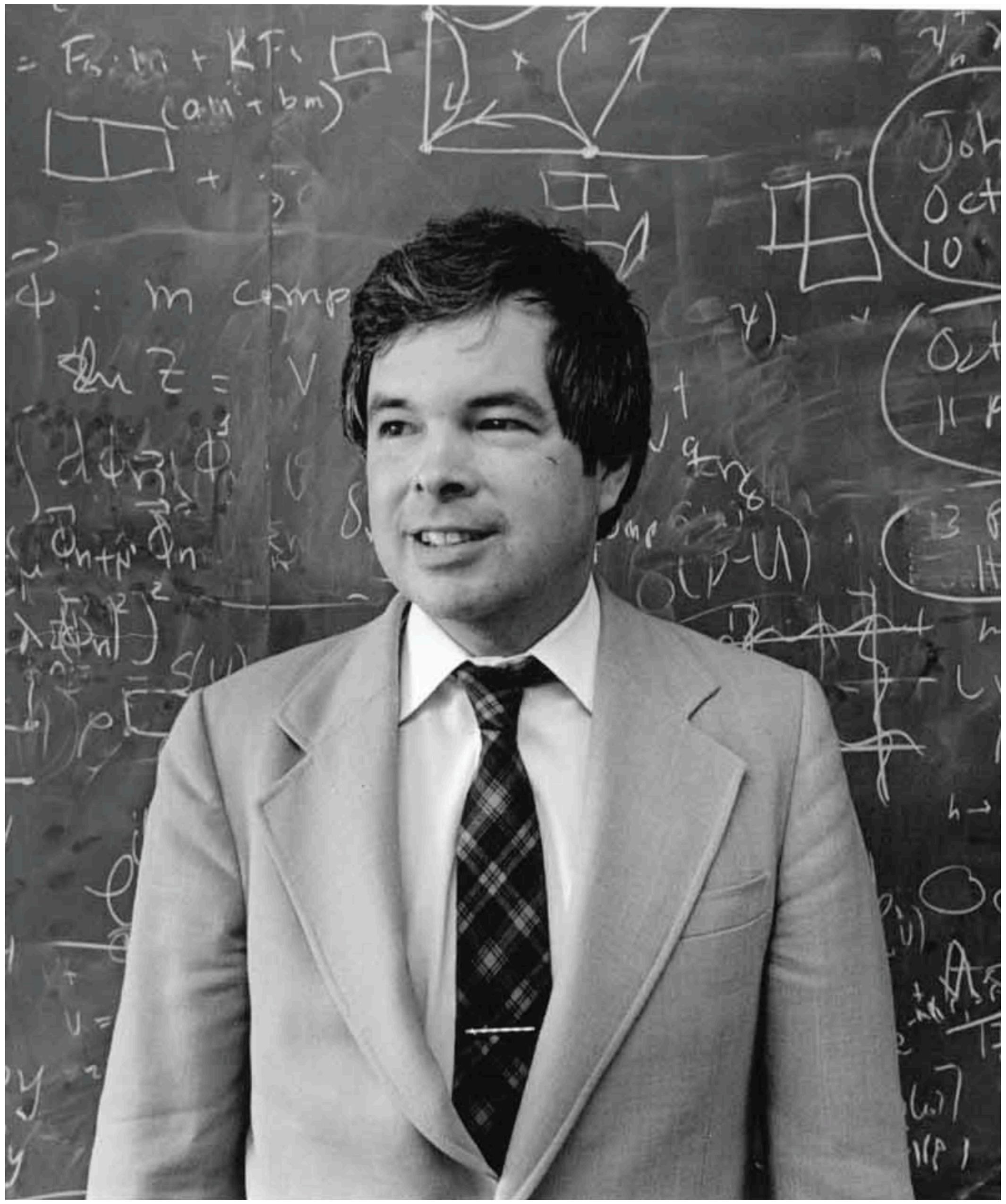


### ACKNOWLEDGMENT

I would like to thank K. Wilson for explaining the reasons why scalar fields require unnatural adjustments of bare constants.



# Hierarchy Problem



Unless there is a solution to the HP at < (few TeV) energies we almost certainly violate the Wilsonian understanding of QFT

Get estimate of maximal mass scale M of new physics from one-loop tuning arising from top-loop

$$\Delta m_h^2 \sim -\frac{3y_t^2}{4\pi^2}M^2 \longrightarrow M < \left(\frac{10\%}{\text{tuning}}\right) 1\ \text{TeV}$$

Past successes of Wilsonian reasoning

# Naturalness aka Dynamics

| Problem | Solution | |
|---|---|---|
| Hydrogen binding energy | QM $E_b = \frac{1}{2}\frac{e^4}{(4\pi)^2} m_e$ | ✓ |
| Electron mass | Chiral Symmetry | ✓ |
| $\pi^+$ - $\pi^o$ mass difference | Symmetry/Dynamics | ✓ |
| Kaon mixing | Flavour Symmetry | ✓ |
| QCD scale | Dimensional Transmutation | ✓ |

(each step v. non-trivial, ~20+yrs, with qualitatively new dynamics/symmetry)

# Hierarchy Problem

Dynamics/Naturalness at scale now being explored by LHC is *by far* best bet

# Higgs Enigma

Common misconceptions:

$$V(H) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \ldots$$

-(89 GeV)$^2$

~0.52

#1 Apart from existence of h itself these 2 numbers are all that LHC data have told us about Higgs?!

# Higgs Enigma

Common misconceptions:

$$V(H) = \underset{\overset{\nearrow}{-(89\ \mathrm{GeV})^2}}{-\mu^2} H^\dagger H + \underset{\overset{\nwarrow}{\sim 0.52}}{\frac{\lambda}{4}} (H^\dagger H)^2 + \dots$$

#1 Apart from existence of h itself these 2 numbers are all that LHC data have told us about Higgs?!

In fact we know (& are still learning) vastly more...

# Higgs Enigma

In addition to leading potential terms

$$V(H) = -\mu^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \ldots$$

have rest of usual SM terms

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i\not{D}\, \psi$$

$$- \left[ H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.} \right]$$

$$\widetilde{H}_j = \epsilon_{jk} H^{\dagger k}$$

LHC now measuring these Yukawa couplings for the first time

(this will be important)

# Higgs Enigma

In addition now measuring or constraining the couplings of these 11 further terms in Lagrangian

| $2 : H^6$ | |
|---|---|
| $Q_H$ | $(H^\dagger H)^3$ |

| $3 : H^4 D^2$ | |
|---|---|
| $Q_{H\Box}$ | $(H^\dagger H)\Box(H^\dagger H)$ |
| $Q_{HD}$ | $\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$ |

| $4 : X^2 H^2$ | |
|---|---|
| $Q_{HG}$ | $H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$ |
| $Q_{H\widetilde{G}}$ | $H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$ |
| $Q_{HW}$ | $H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$ |
| $Q_{H\widetilde{W}}$ | $H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$ |
| $Q_{HB}$ | $H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$ |
| $Q_{H\widetilde{B}}$ | $H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$ |
| $Q_{HWB}$ | $H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$ |
| $Q_{H\widetilde{W}B}$ | $H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$ |

# Higgs Enigma

Not done yet as also have these further 19 terms involving leptons or quarks

| $5:\psi^2H^3+\text{h.c.}$ | |
|---|---|
| $Q_{eH}$ | $(H^\dagger H)(\bar{l}_p e_r H)$ |
| $Q_{uH}$ | $(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$ |
| $Q_{dH}$ | $(H^\dagger H)(\bar{q}_p d_r H)$ |

| $6:\psi^2XH+\text{h.c.}$ | |
|---|---|
| $Q_{eW}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$ |
| $Q_{eB}$ | $(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$ |
| $Q_{uG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$ |
| $Q_{uW}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$ |
| $Q_{uB}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$ |
| $Q_{dG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$ |
| $Q_{dW}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$ |
| $Q_{dB}$ | $(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$ |

| $7:\psi^2H^2D$ | |
|---|---|
| $Q_{Hl}^{(1)}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$ |
| $Q_{Hl}^{(3)}$ | $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$ |
| $Q_{He}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$ |
| $Q_{Hq}^{(1)}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$ |
| $Q_{Hq}^{(3)}$ | $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$ |
| $Q_{Hu}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$ |
| $Q_{Hd}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$ |
| $Q_{Hud}+\text{h.c.}$ | $i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$ |

# Higgs Enigma

Also have strong constraints on couplings of many of these non-Higgs terms

(this will also be important...)

| $1:X^3$ | |
|---|---|
| $Q_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ |
| $Q_{\widetilde{G}}$ | $f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ |
| $Q_W$ | $\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ |
| $Q_{\widetilde{W}}$ | $\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ |

| $8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$ | |
|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$ |

| $8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$ | |
|---|---|
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$ |

| $8:(\bar{L}L)(\bar{L}L)$ | |
|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ |

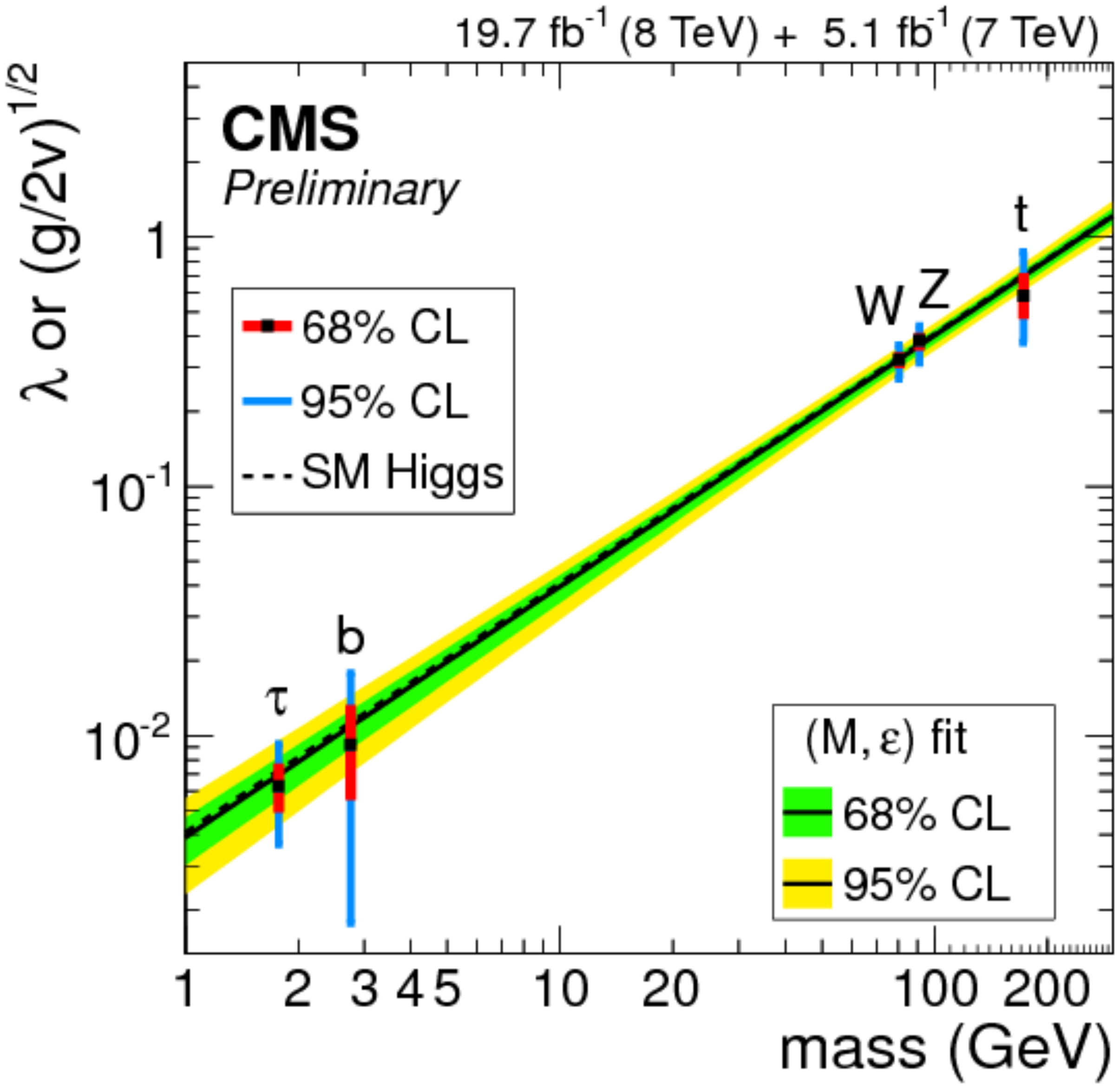
| $8:(\bar{R}R)(\bar{R}R)$ | |
|---|---|
| $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $8:(\bar{L}L)(\bar{R}R)$ | |
|---|---|
| $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

# Higgs Enigma

Higgs appears to be our very first (pseudo-?)elementary scalar:

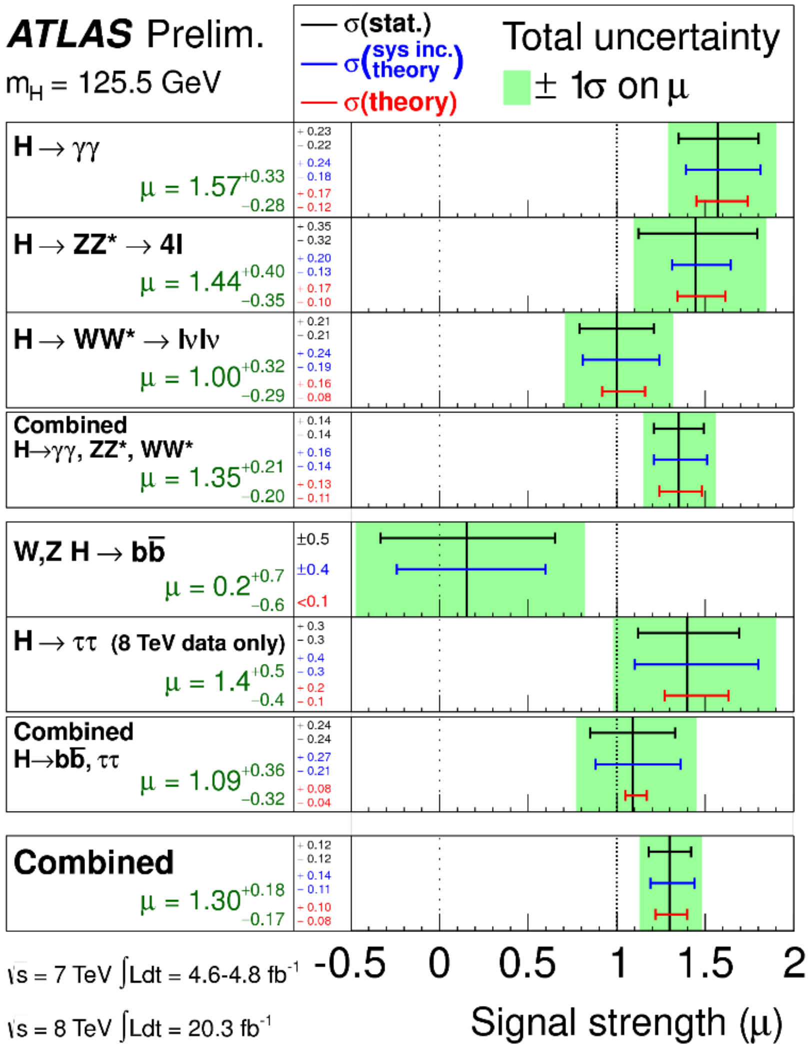
- Data indicate Higgs well-described as a spin 0 scalar, with non-derivative couplings to W/Z and Standard Model (SM) fermions roughly in-line with SM expectations

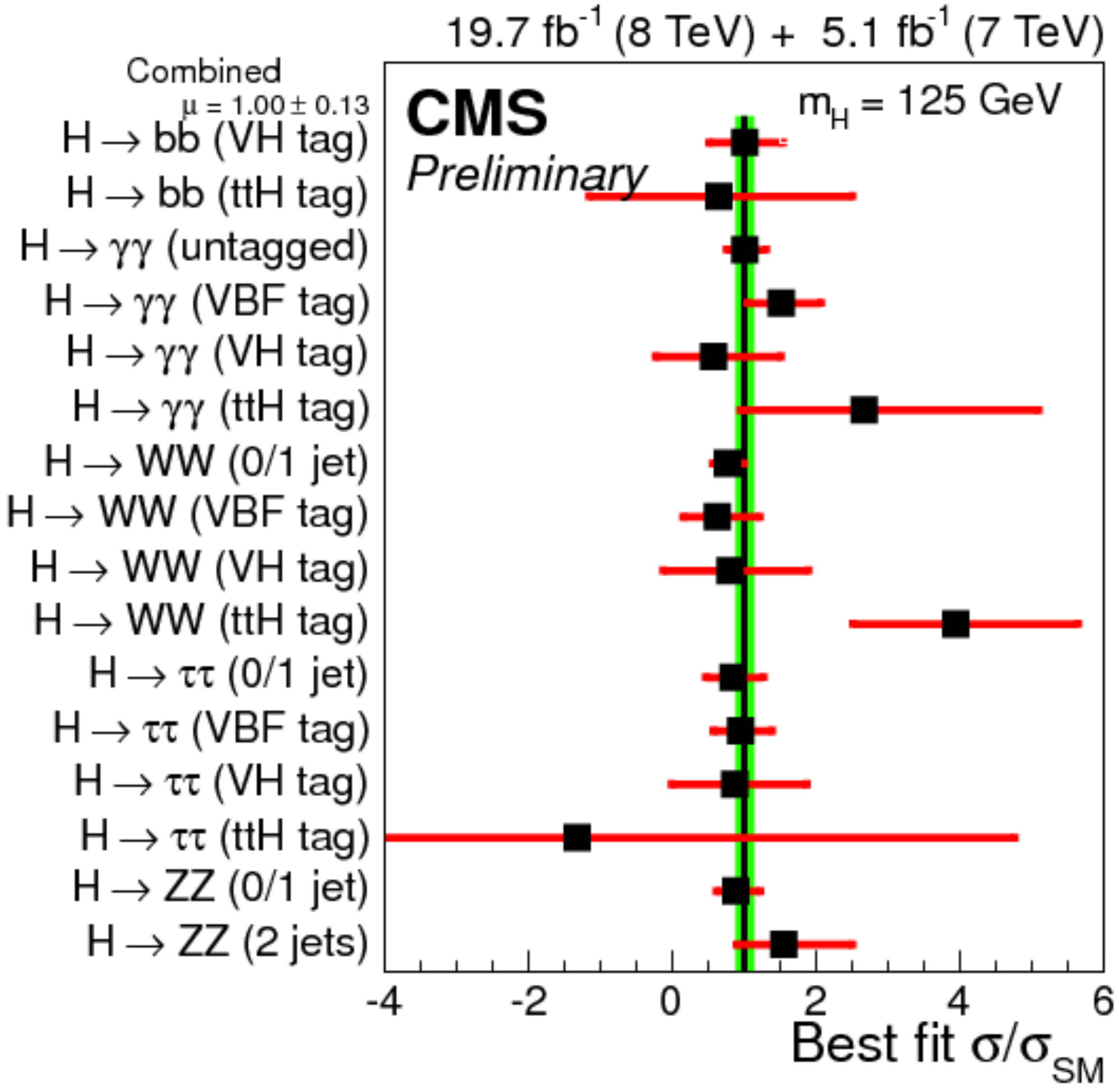


tests of tree-level couplings to fermions and vector bosons

# Higgs Enigma

Higgs appears to be our very first (pseudo-?)elementary scalar:



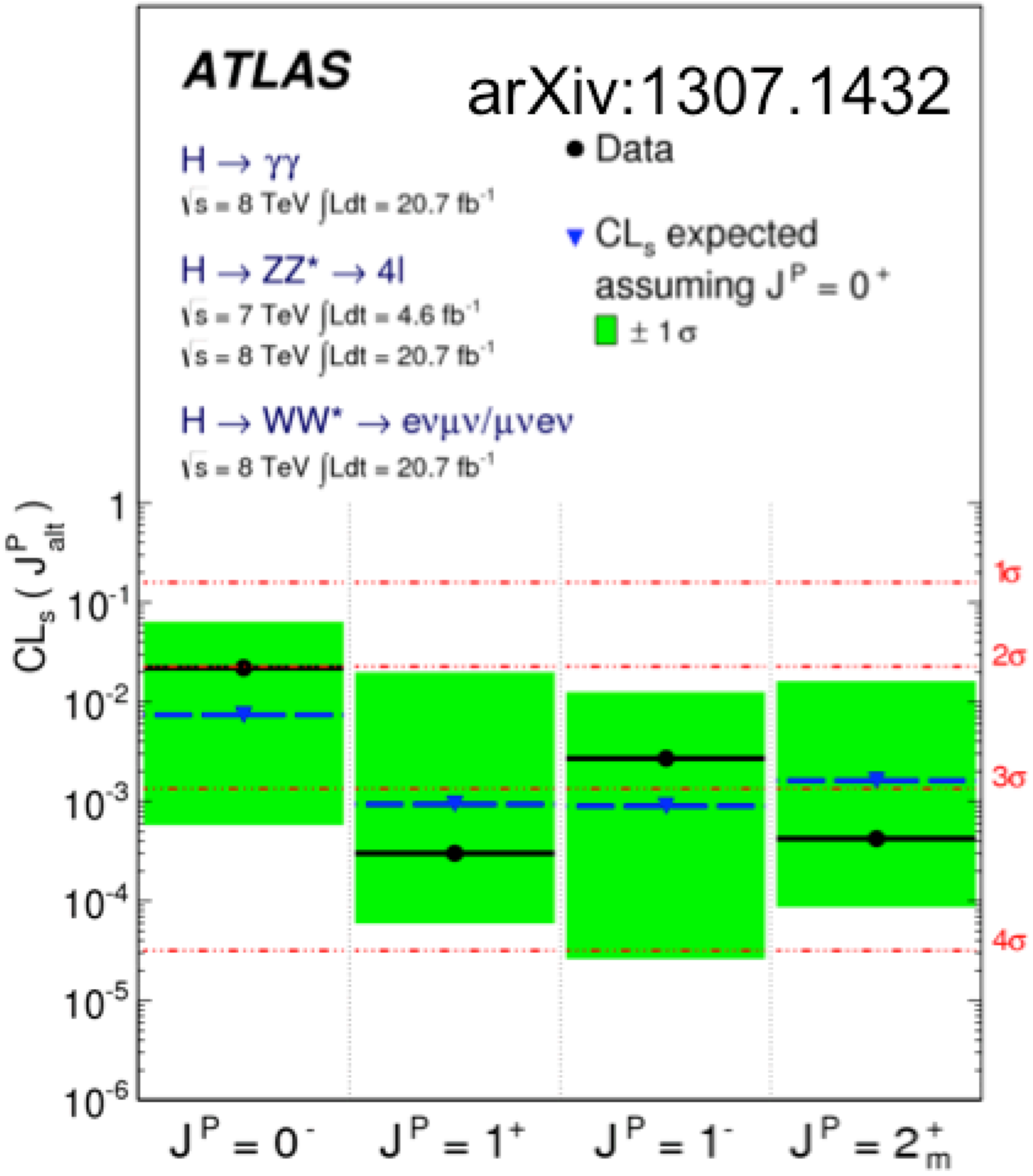


tests of tree-level couplings to fermions and vector bosons

# Higgs Enigma

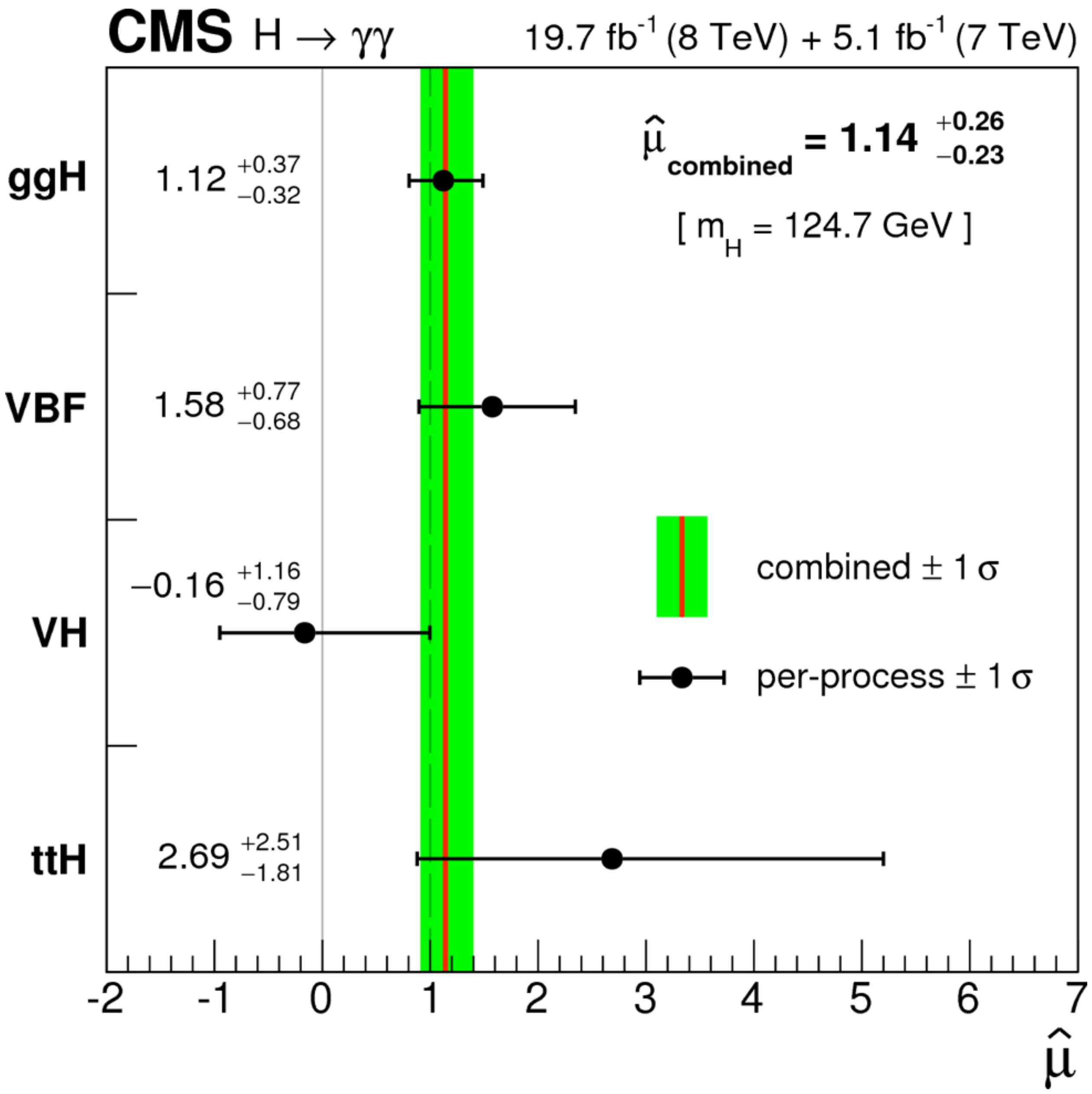
Higgs appears to be our very first (pseudo-?)elementary scalar:

Spin-parity 0+ is strongly favoured.



# Higgs Enigma

Higgs appears to be our very first (pseudo-?)elementary scalar:

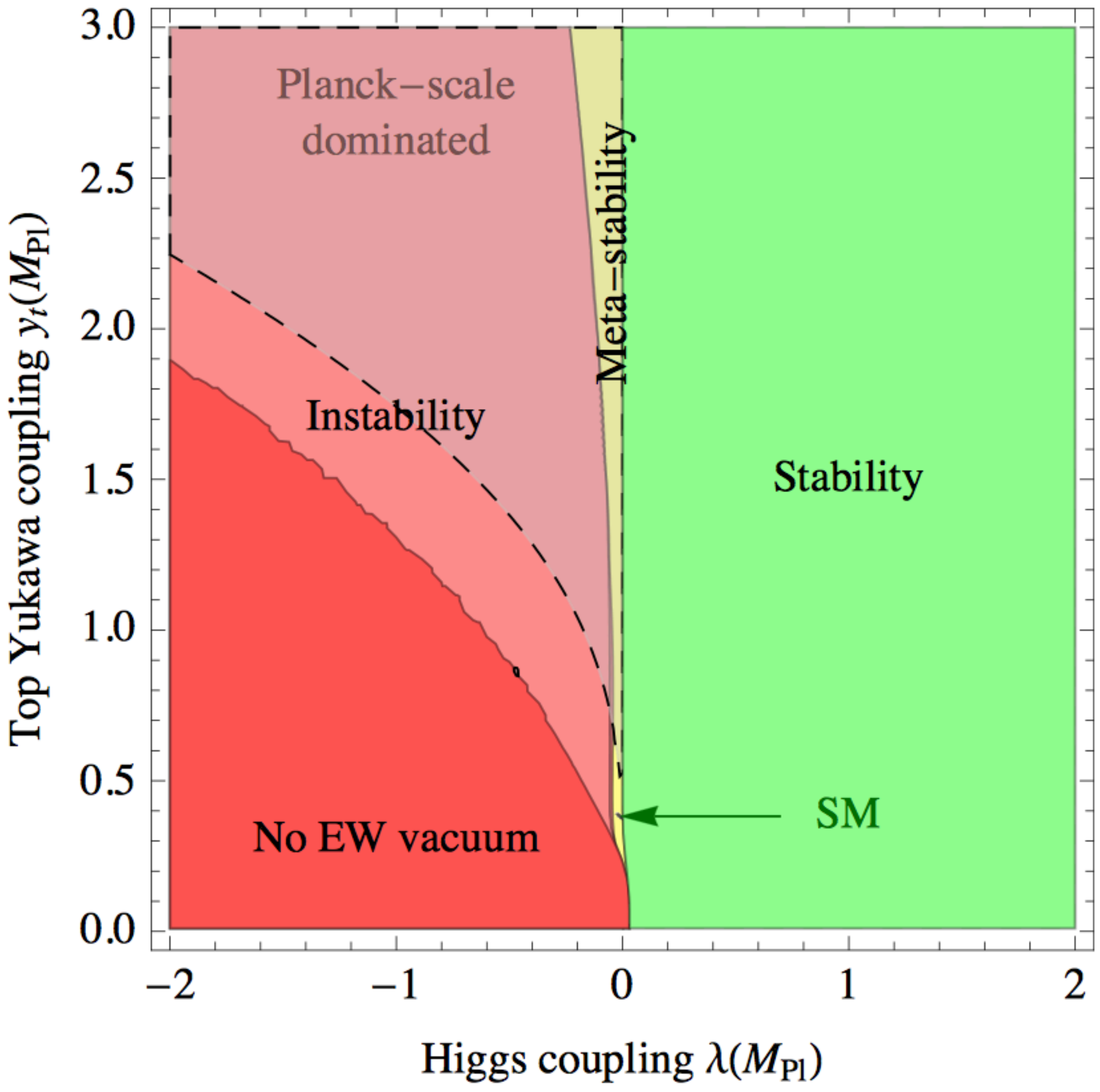


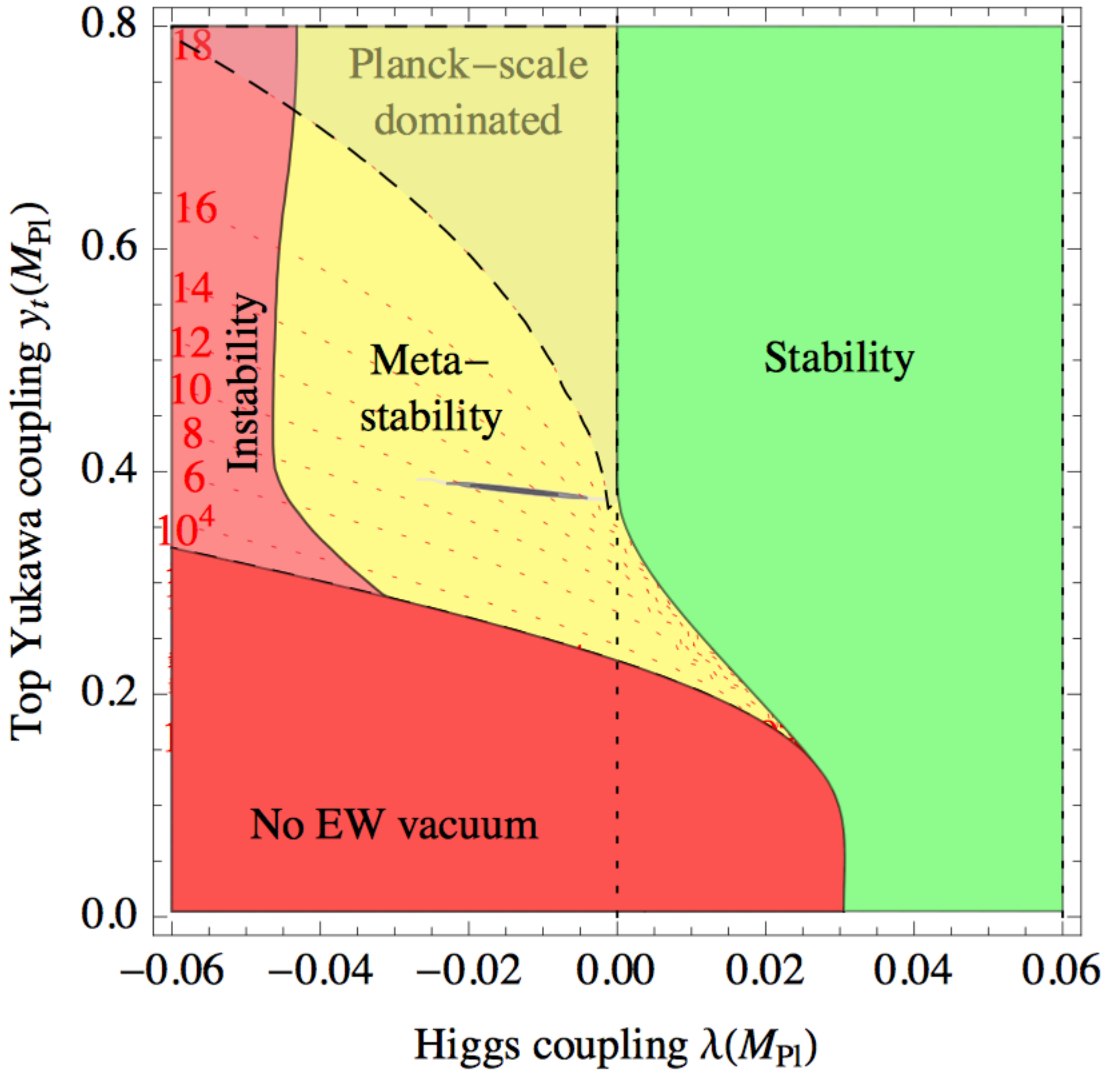
loop-level couplings?

# Stability of SM all the way up?

Sher, Giudice, Strumia,…

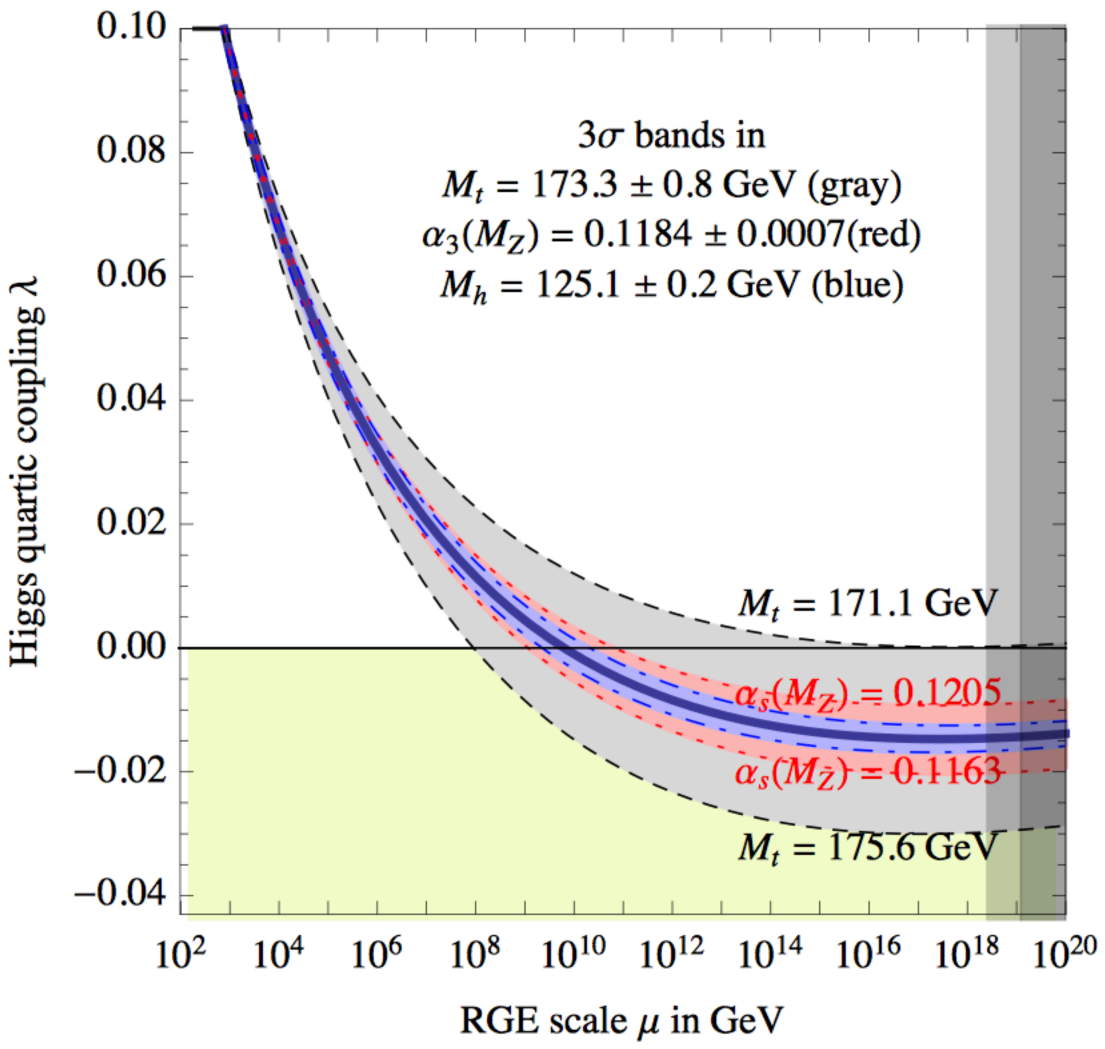
An intriguing feature of measured values of Higgs coupling and top Yukawa extrapolated to $M_{pl}$ assuming SM all the way up:

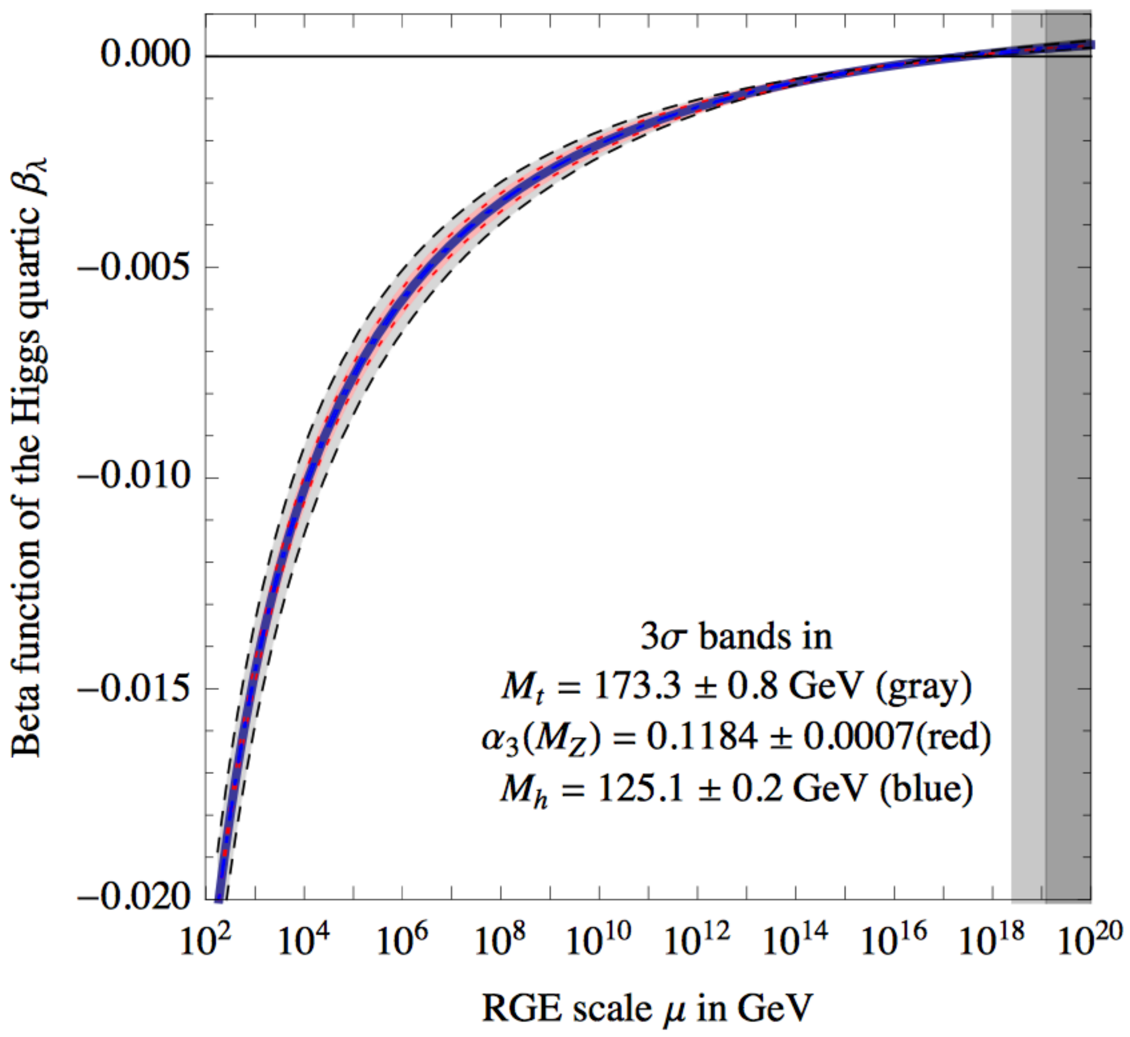




# Stability of SM all the way up?

Scale evolution of Higgs self-coupling and beta-function





is this significant??

# Higgs Enigma

## Common misconceptions:

#2 Higgs boson, and thus electro-weak superconductivity, “EWSB,” is just a bigger, better version of normal superconductivity with some form of Cooper-pair

# Higgs Enigma

Common misconceptions:

#2 Higgs boson, and thus electro-weak superconductivity, “EWSB,” is just a bigger, better version of normal superconductivity with some form of Cooper-pair

This appears to be strongly disfavoured by data

(unless there exists new form of 4D strong-coupling dynamics!)

# World without the Higgs?

Naively no EWSB but this is incorrect as
QCD dynamics leads to chiral condensate

$$\langle \bar{q}_L q_R \rangle = -f_\pi^2 B_0 \sim -(200\ \mathrm{MeV})^3$$

transforms as (1,2,+1/2) multiplet under SM gauge group — SAME as Higgs

The “Higgs” dof would then be a QCD composite state (note NOT pion) of mass

$$\sim 4\pi f_\pi \sim 1\ \mathrm{GeV}$$

(the 3 exactly massless pions of broken chiral symmetry get eaten by W's & Z, giving ~100MeV mass to these states)

and EW symmetry would be broken at scale ~200 MeV

# QCD-like EWSB?

Susskind, Wilson, Weinberg, Dimopoulos, Lane,…

Leads to the idea of "Technicolor" where we say EWSB driven by similar non-perturbative condensate

$$\langle \bar{\Psi}_L \Psi_R \rangle \simeq -\Lambda_{TC}^3 \sim -(200\ \mathrm{GeV})^3$$

note now scaled-up

Now in some SU(N) theory (with $N_f$ flavours)

Great advantage — "dimensional transmutation" explains exponential smallness and stability of weak scale

$$\Lambda_{TC} \simeq M \exp\left(-8\pi^2/b_1 g_{TC}^2\right)$$

Problem: QCD-like strong coupling solution decisively excluded by data!

# QCD-like EWSB?

Problems:

The Higgs state, h, would be heavy ~TeV

The Higgs state would not be pseudo-elementary (big form factor -> large coeffs of higher derivative operators involving h)

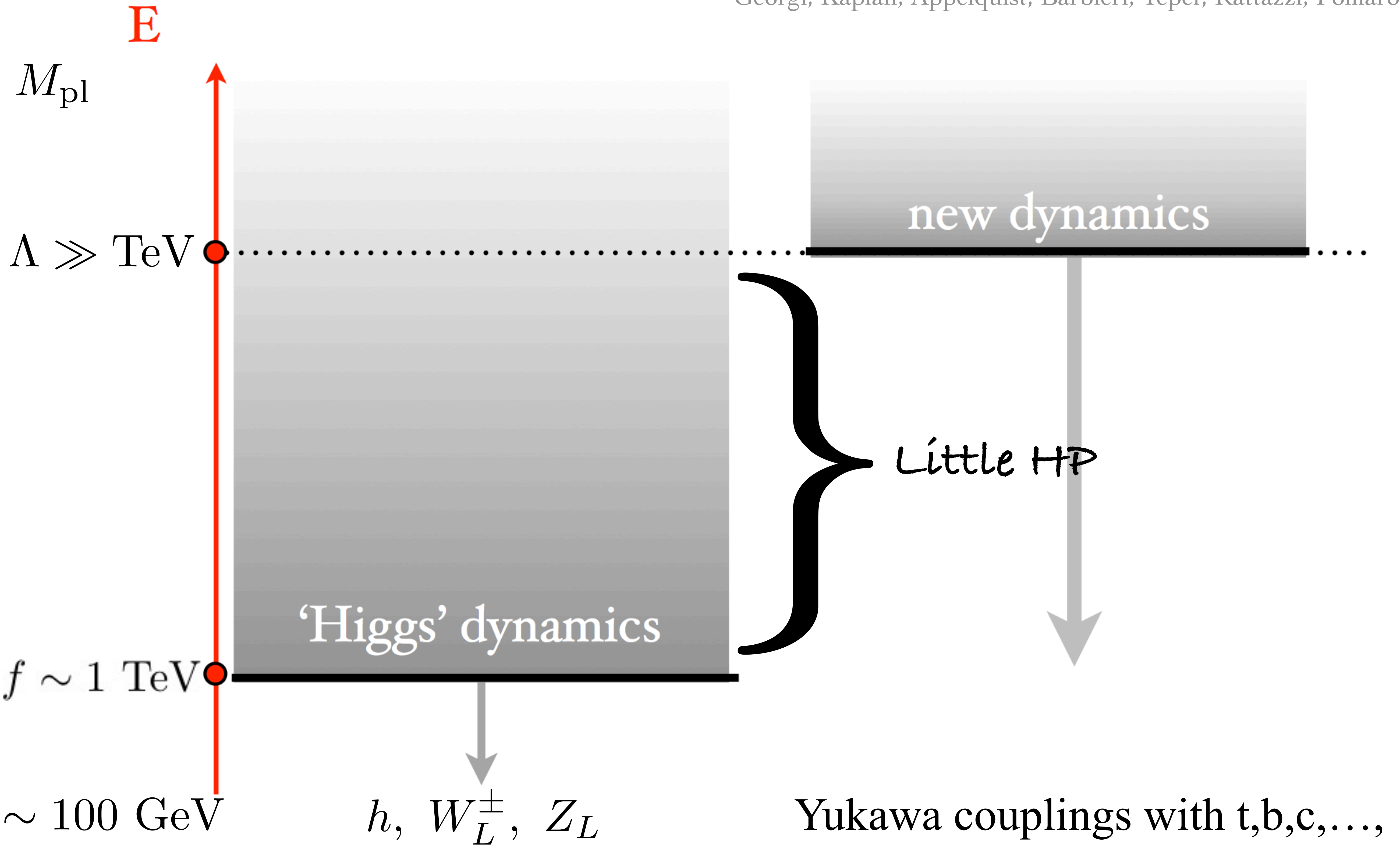
Fermion masses would have to arise from dim=6 4-fermion operators with large coeffs -> huge, insurmountable, problems with rare flavour processes

The longitudinal dof of the W,Z bosons would have significant compositeness (big form factor -> large coeffs of higher derivative operators)

dead as an ex-parrot

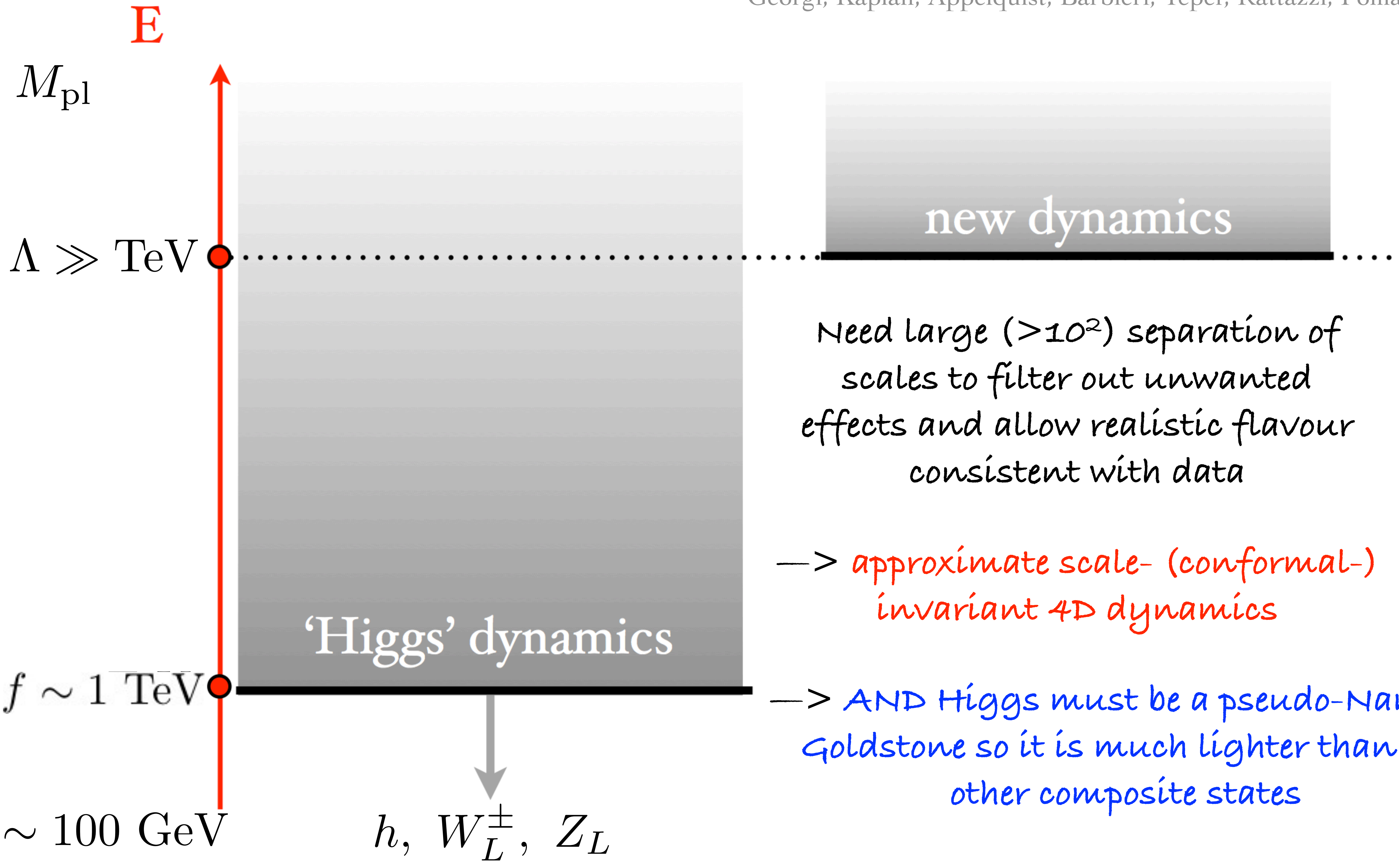
# (non-QCD-like) Composite EWSB?

Georgi, Kaplan, Appelquist, Barbieri, Teper, Rattazzi, Pomarol,….



# (non-QCD-like) Composite EWSB?

Georgi, Kaplan, Appelquist, Barbieri, Teper, Rattazzi, Pomarol,….



Need large ($>10^2$) separation of scales to filter out unwanted effects and allow realistic flavour consistent with data

—> approximate scale- (conformal-) invariant 4D dynamics

—> AND Higgs must be a pseudo-Nambu-Goldstone so it is much lighter than all other composite states

# (non-QCD-like) Composite EWSB?

Higgs if it is to be so light compared to other scales must be a pseudo-Nambu-Goldstone

Georgi, Kaplan

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ h + i\phi_3 \end{pmatrix}$$

all 4 components
must be pNGBs

QCD-like-compositeness had global symm structure SO(4)/SO(3) → 3 NGB and higgs was massive

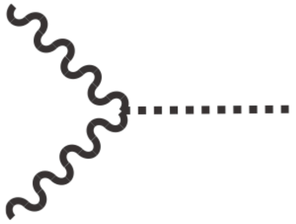
Generalise to SO(5)/SO(4) → 4 NGBs and higgs is automatically light

# (non-QCD-like) Composite EWSB?

Effective Lagrangian for a composite light pseudo-NG Higgs boson: 2 leading operators

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

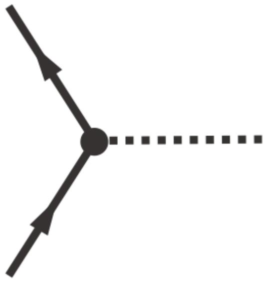
$$\# \, \frac{y_i}{f^2}\,(\bar{f}_i f_i H)\,|H|^2$$



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

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

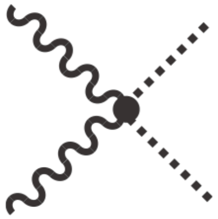
robust consequence
of coset structure



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

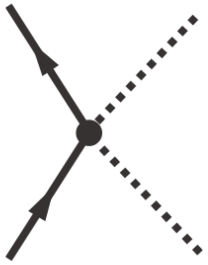
$$c_i \simeq 1 + O\left(\frac{v^2}{f^2}\right) < 1$$

generic but not a theorem



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

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

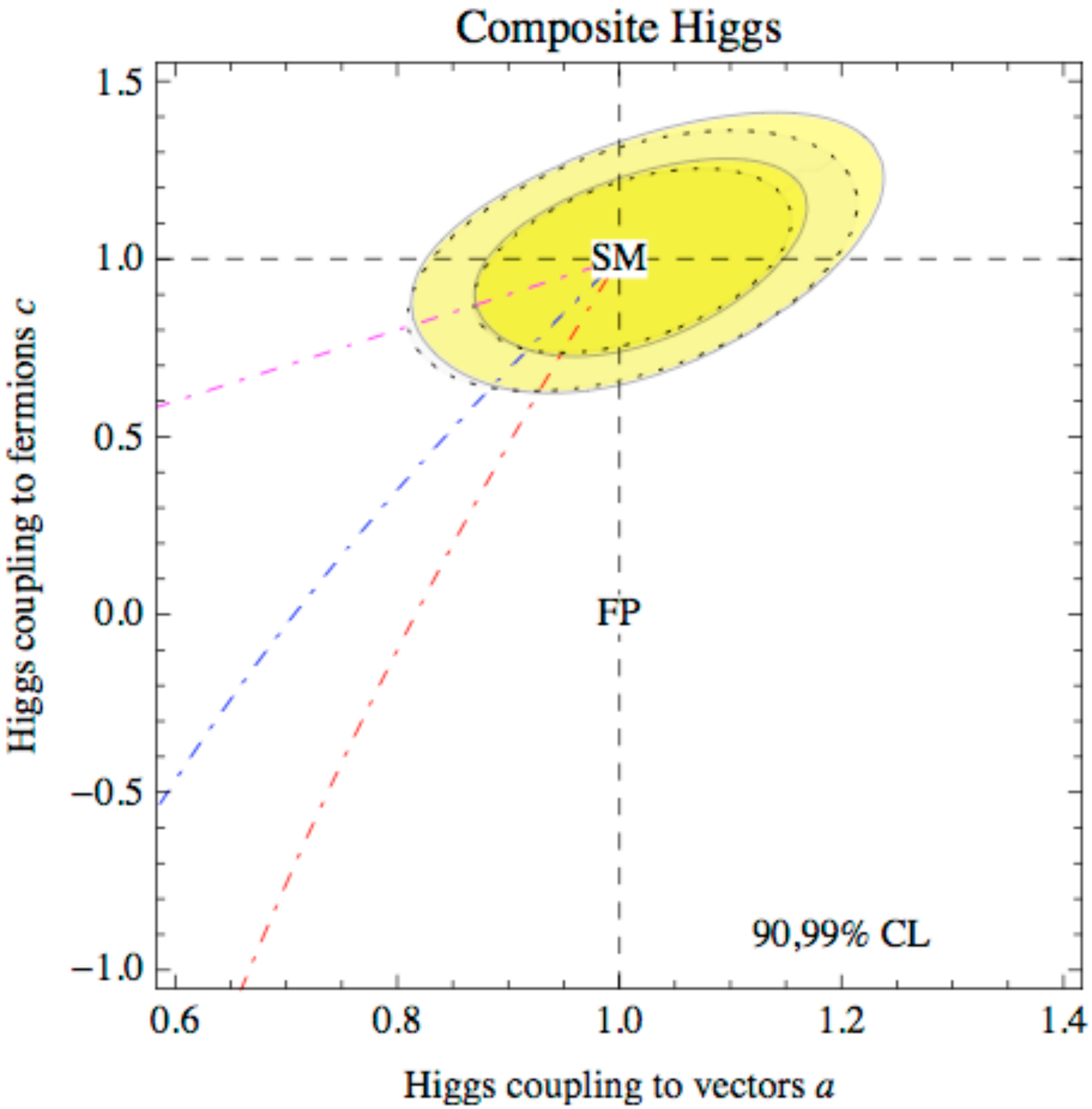


$$\propto \frac{m_i}{f^2}$$

New!

courtesy of R. Rattazzi

# (non-QCD-like) Composite EWSB?



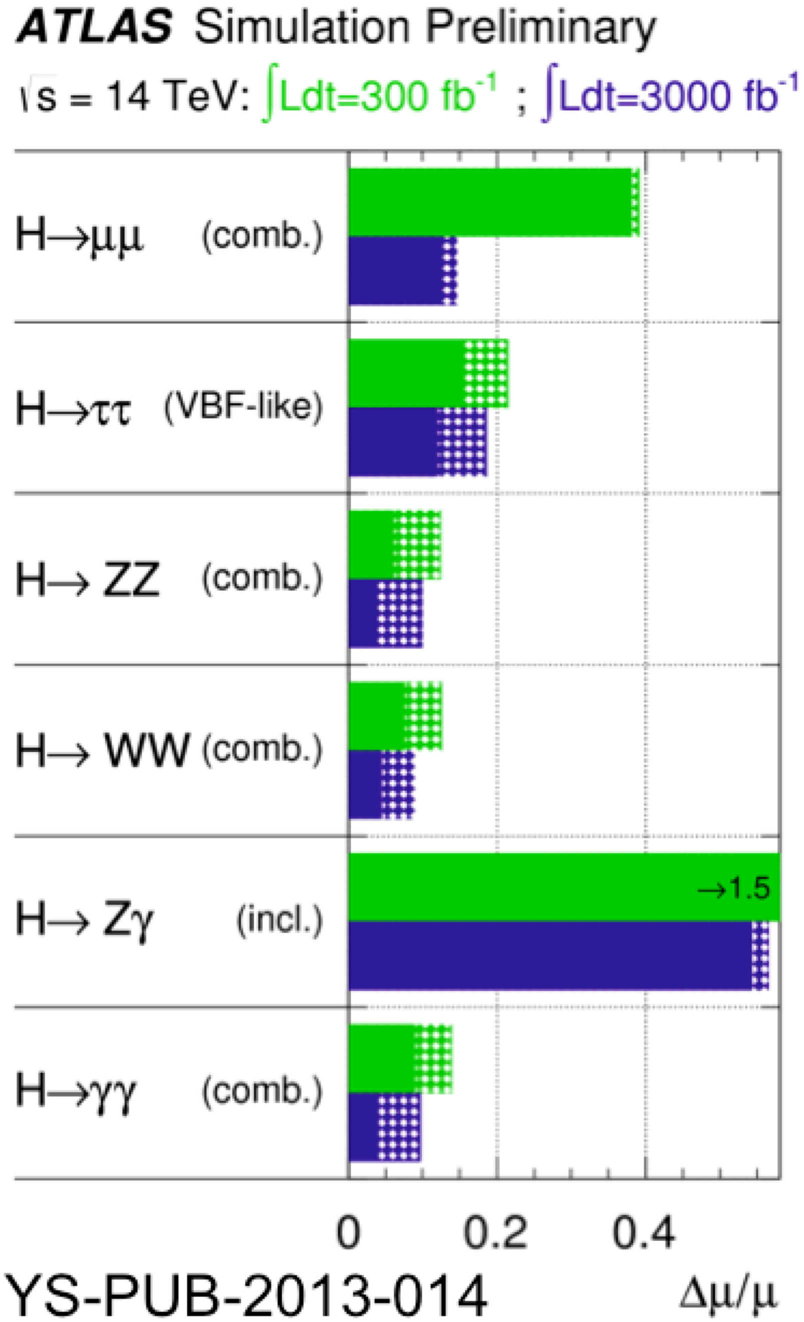
# Prospects for H(125) measurements

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

| Model | $\kappa_V$ | $\kappa_b$ | $\kappa_\gamma$ |
|---|---|---|---|
| Singlet Mixing | $\sim 6\%$ | $\sim 6\%$ | $\sim 6\%$ |
| 2HDM | $\sim 1\%$ | $\sim 10\%$ | $\sim 1\%$ |
| Decoupling MSSM | $\sim -0.0013\%$ | $\sim 1.6\%$ | $\sim -.4\%$ |
| Composite | $\sim -3\%$ | $\sim -(3-9)\%$ | $\sim -9\%$ |
| Top Partner | $\sim -2\%$ | $\sim -2\%$ | $\sim +1\%$ |

Future LHC data: measure H couplings at 2-8% level (cf 20-50% today), and to access rare decays such as H→μμ



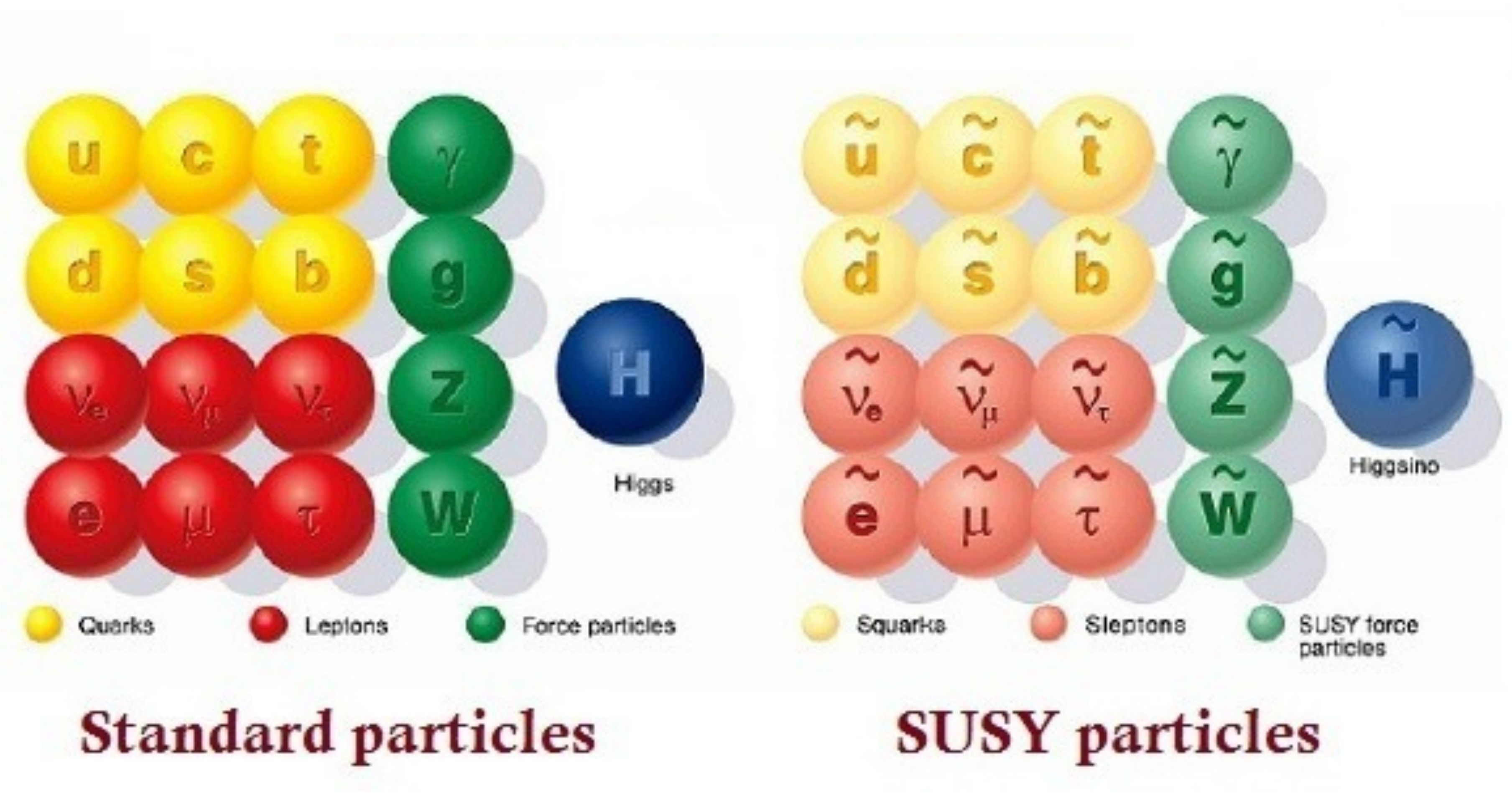
ATL-PHYS-PUB-2013-014

CMS projections for coupling precision (arXiv:1307.7135)

| L (fb$^{-1}$) | $\kappa_\gamma$ | $\kappa_W$ | $\kappa_Z$ | $\kappa_g$ | $\kappa_b$ | $\kappa_t$ | $\kappa_\tau$ | $\kappa_{Z\gamma}$ | $\kappa_{\mu\mu}$ | $BR_{SM}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 300 | [5, 7] | [4, 6] | [4, 6] | [6, 8] | [10, 13] | [14, 15] | [6, 8] | [41, 41] | [23, 23] | [14, 18] |
| 3000 | [2, 5] | [2, 5] | [2, 4] | [3, 5] | [4, 7] | [7, 10] | [2, 5] | [10, 12] | [8, 8] | [7, 11] |

Best option:

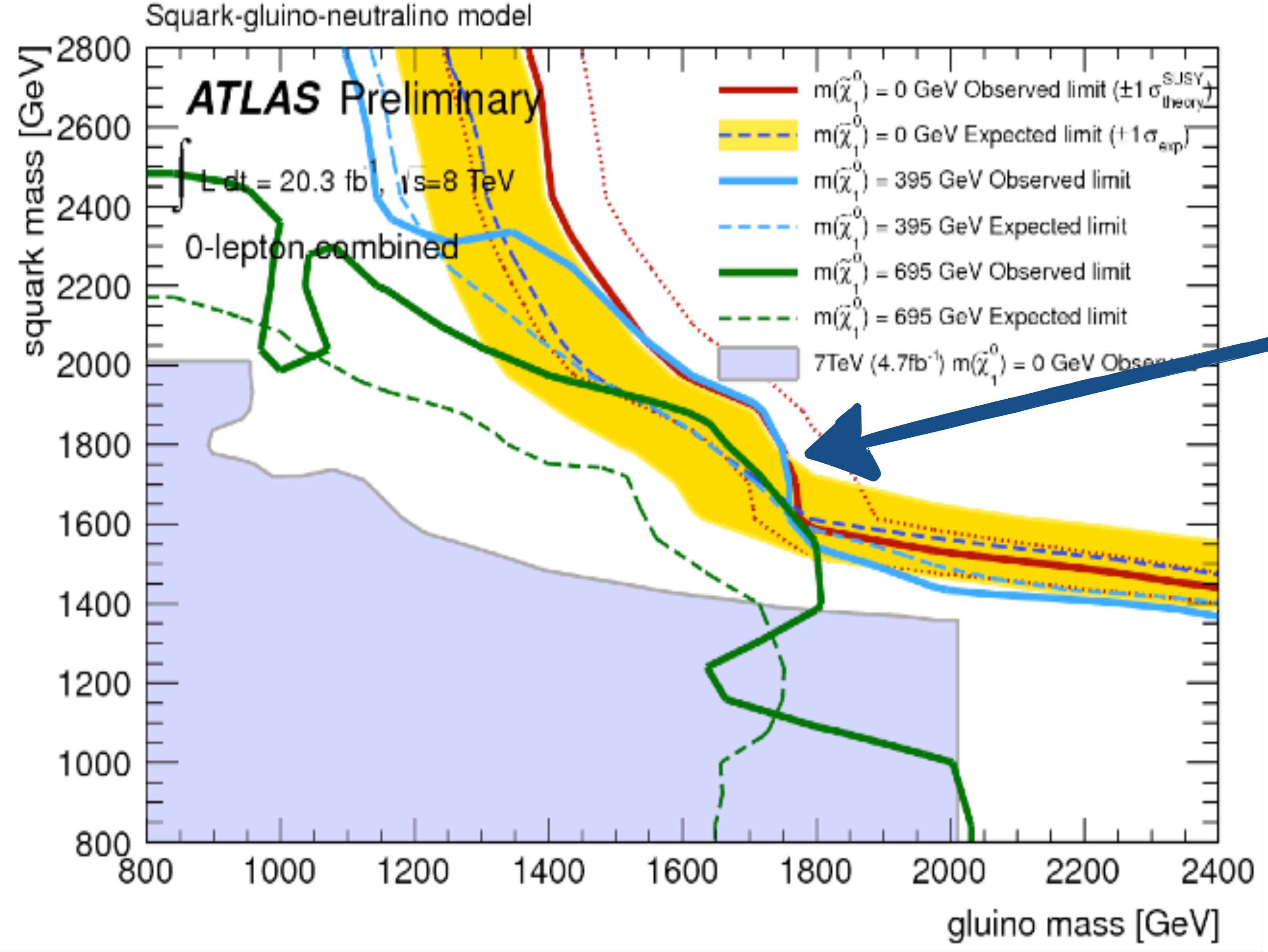
# Supersymmetry



BIG advantages:
1) SUSY automatically includes elementary scalar Higgs
2) Precision gauge-coupling unification: prediction of $\sin^2\theta_w \simeq 0.2315$
3) Flavour much easier to deal with as weakly-coupled theory

(Note:dimensional transmutation secretly sits behind generation of large hierarchy)

# Supersymmetry



lots of assumptions go into such limits and translation into amount of tuning of EWSB

SUSY tuning still much, much better than SM but…

a fully natural theory requires abandoning (parts of) traditional structure of supersymmetry

# MSSM Fine-Tuning Problem

Successful EWSB requires
$$\frac{m_Z^2}{2} \simeq -m_{H_u}^2 - |\mu|^2 \qquad (\tan\beta >> 1)$$

Sole source of higgsino mass
$\Longrightarrow$ some tree level tuning

At 1-loop Higgs soft mass gets large corrections

$$\Delta m_{H_u}^2 \sim -\frac{3|y_t|^2}{4\pi^2}\left(m_{\tilde{t}}^2 + |A_t|^2/2\right)\log\left(\frac{\Lambda}{\tilde{m}}\right)$$

$\Longrightarrow$ large loop-level tuning if stop mass & A-term not small

mediation scale of SUSY breaking

$\log \sim 35$ gravity

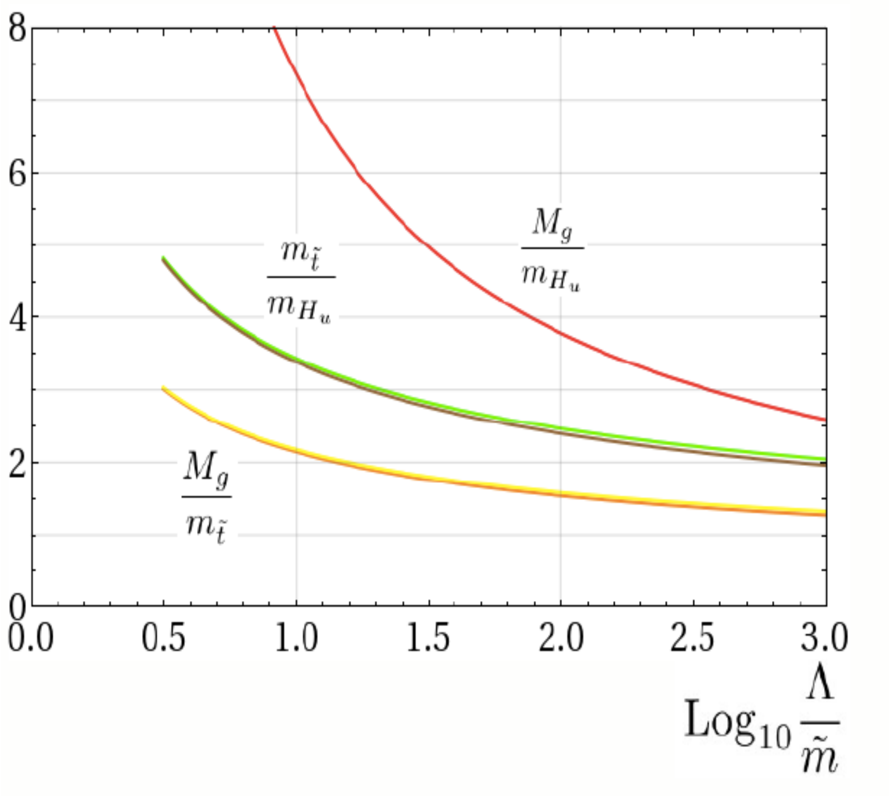
$\log \sim 6$ gauge

# The Gluino Sucks Problem

WORSE: Log RG evolution quickly pulls up stop mass, and thus EW scale, to gluino mass

$$\Delta m_{\tilde{t}}^2 \sim \frac{8\alpha_s}{3\pi} M_3^2 \log\left(\frac{\Lambda}{\tilde{m}}\right)$$

$$\Delta m_{H_u}^2 \sim -\frac{3|y_t|^2}{4\pi^2}(m_{\tilde{t}}^2 + |A_t|^2/2) \log\left(\frac{\Lambda}{\tilde{m}}\right)$$

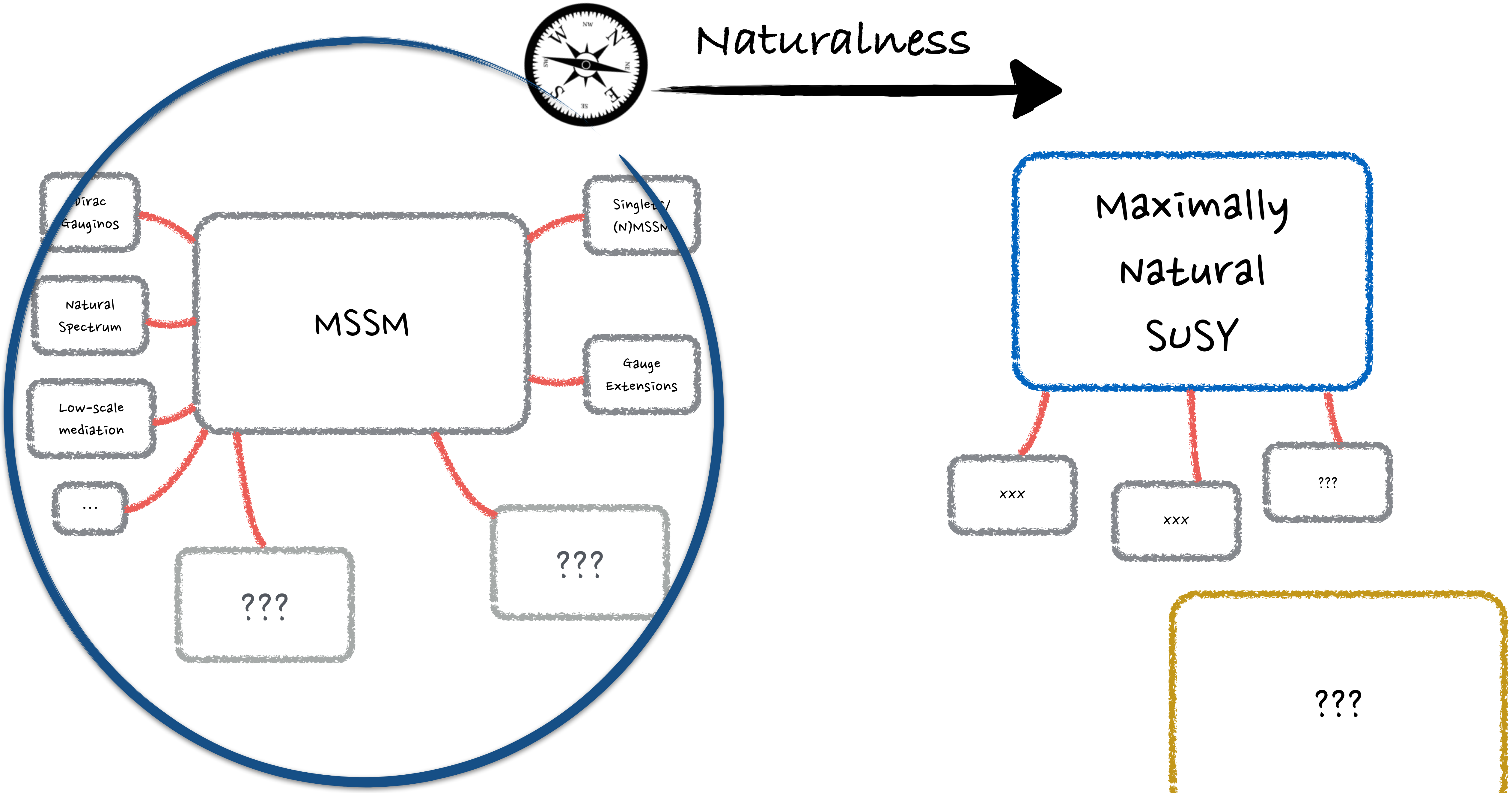


Gluino bounds constrain all MSSM-like scenarios to ~1% tuning..

(Arvanitaki, etal, 2013)

# Supersymmetric Theory Space

There exist qualitatively different ways of implementing SUSY than MSSM



99.5% of all SUSY papers

# Fully Natural Supersymmetry?

There exist qualitatively different ways of implementing SUSY

Crucial ingredients:

1) Eliminate the bad log enhancement in feed-in to Higgs mass parameter

$$\tilde{m}^2 \sim \frac{g^2}{16\pi^2}(\text{TeV})^2 \xcancel{\ln\frac{\Lambda^2}{\text{TeV}^2}}$$

100 TeV : ~12

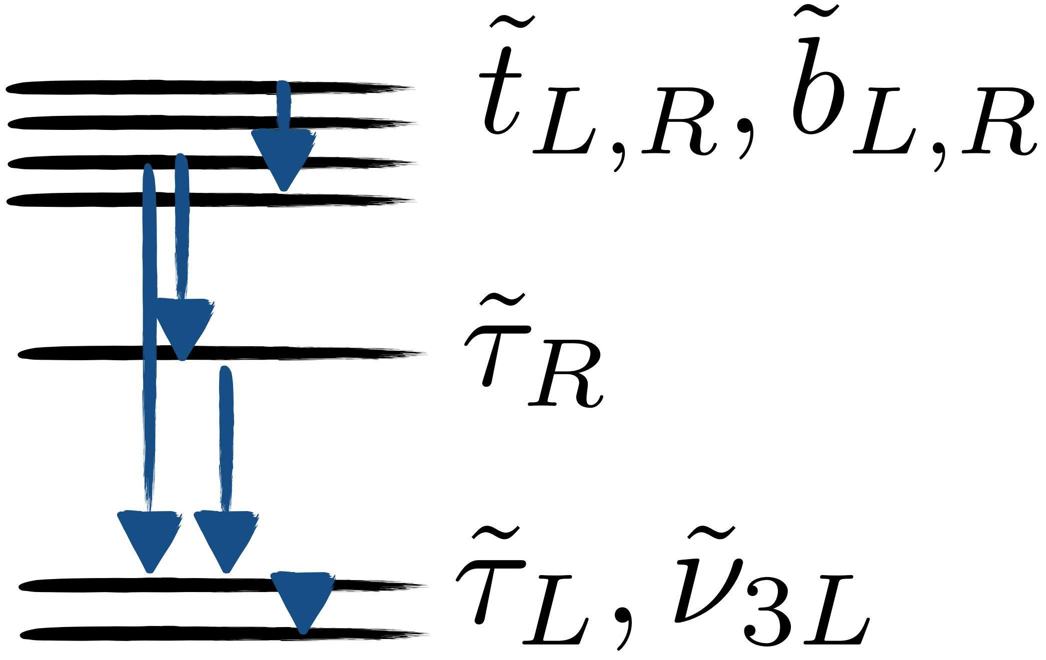
$M_{gut}$ : ~70

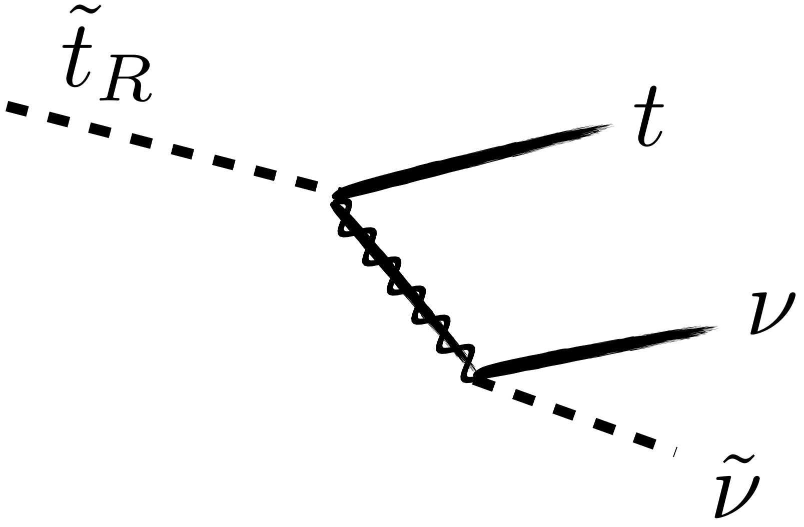
2) Eliminate the gluino sucks problem so gluino can be heavy

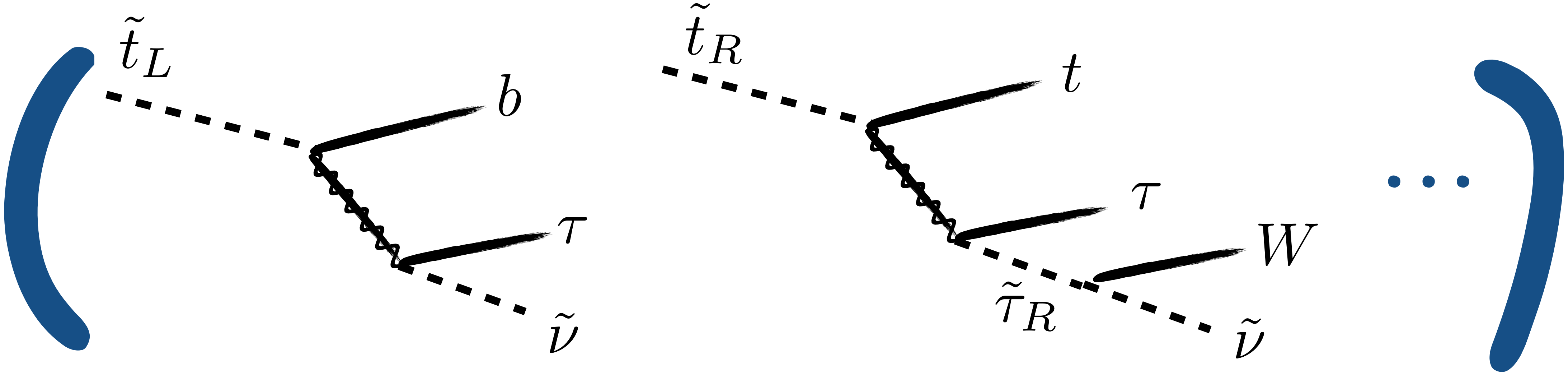
follow from enhanced symmetry structure (surviving $Z_{(N>2)R}$, $U(1)_R$, and/or N=2 structure in gauge/Higgs) or locality

bottom line: there exist SUSY theories untuned at present LHC limits

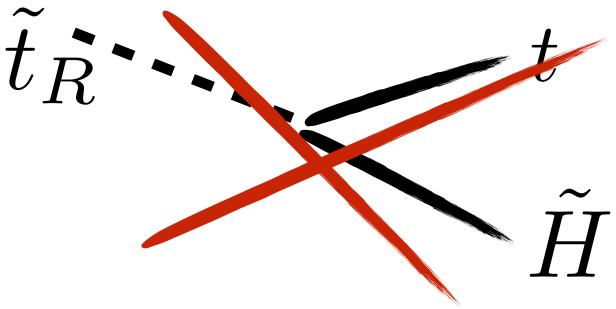
# $\tilde{\nu}_3$ LSP: New Signatures of Naturalness?







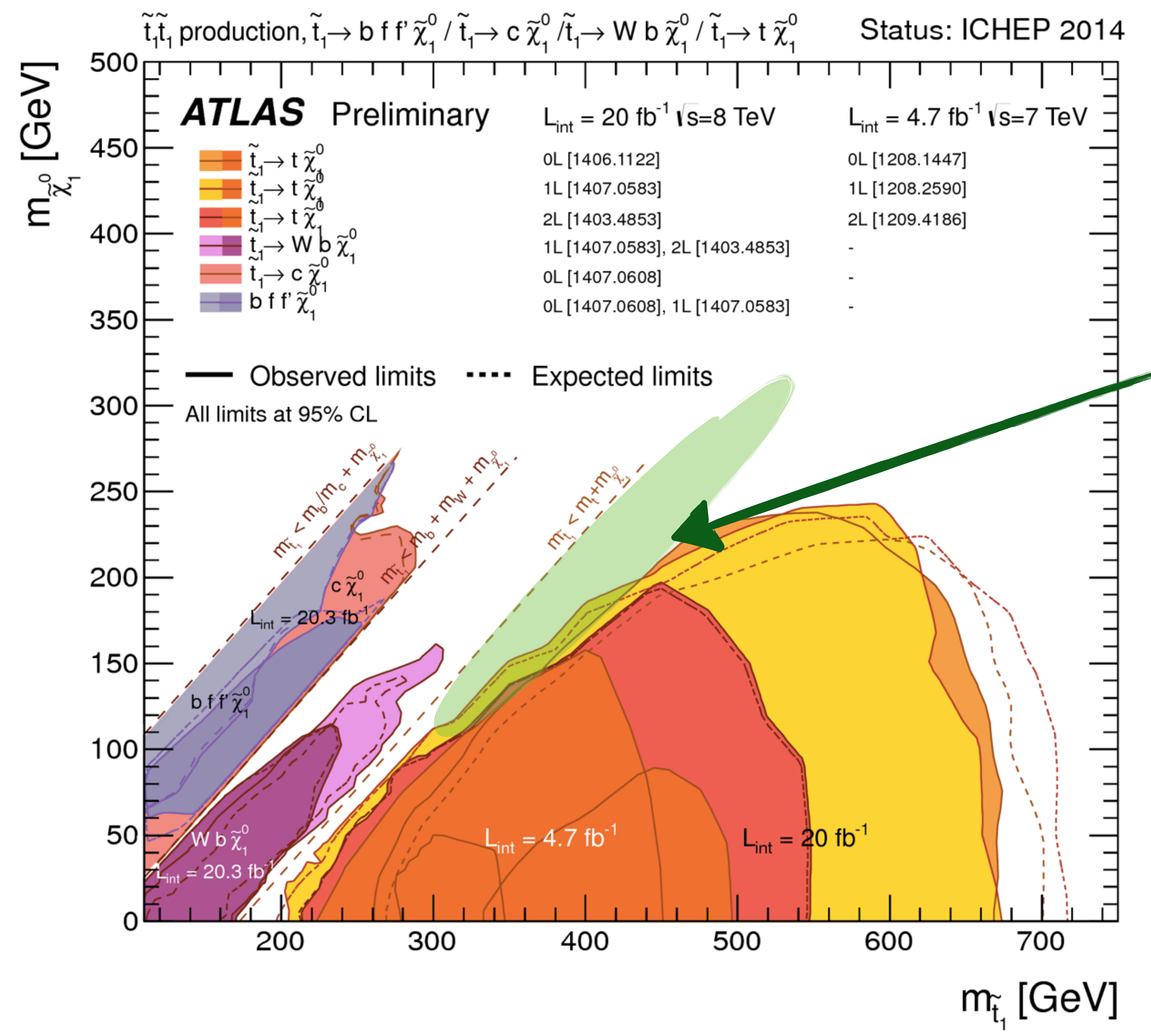
3-body Kinematics, taus + b's final states, ...



Reduced MET

ATLAS-CONF-2014-014
ATLAS-CONF-2013-026

# Auto-Concealment of SUSY ?

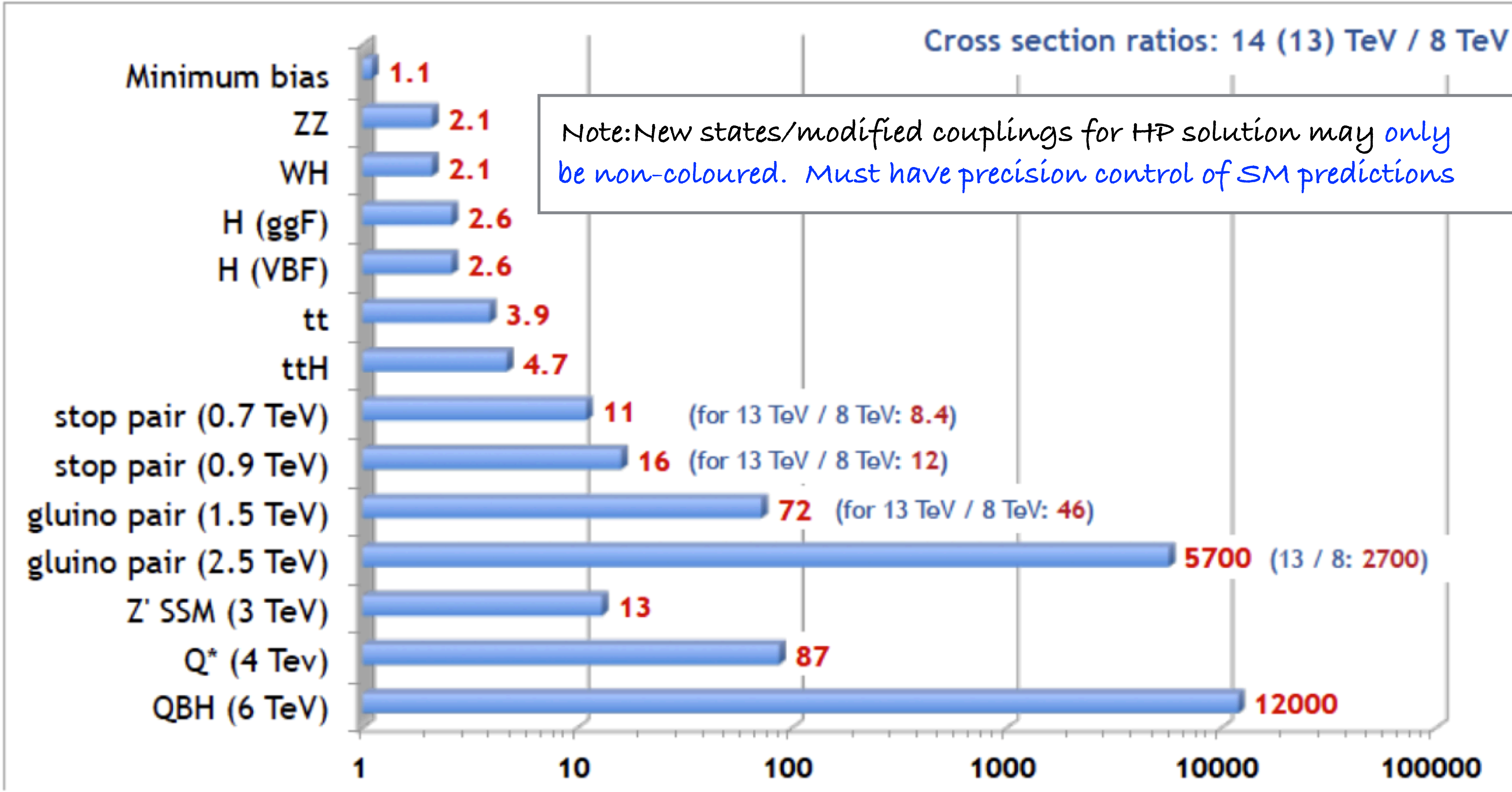


susy theories can
dynamically
sit in this region

need precision
understanding
of SM to pull
signal from
background

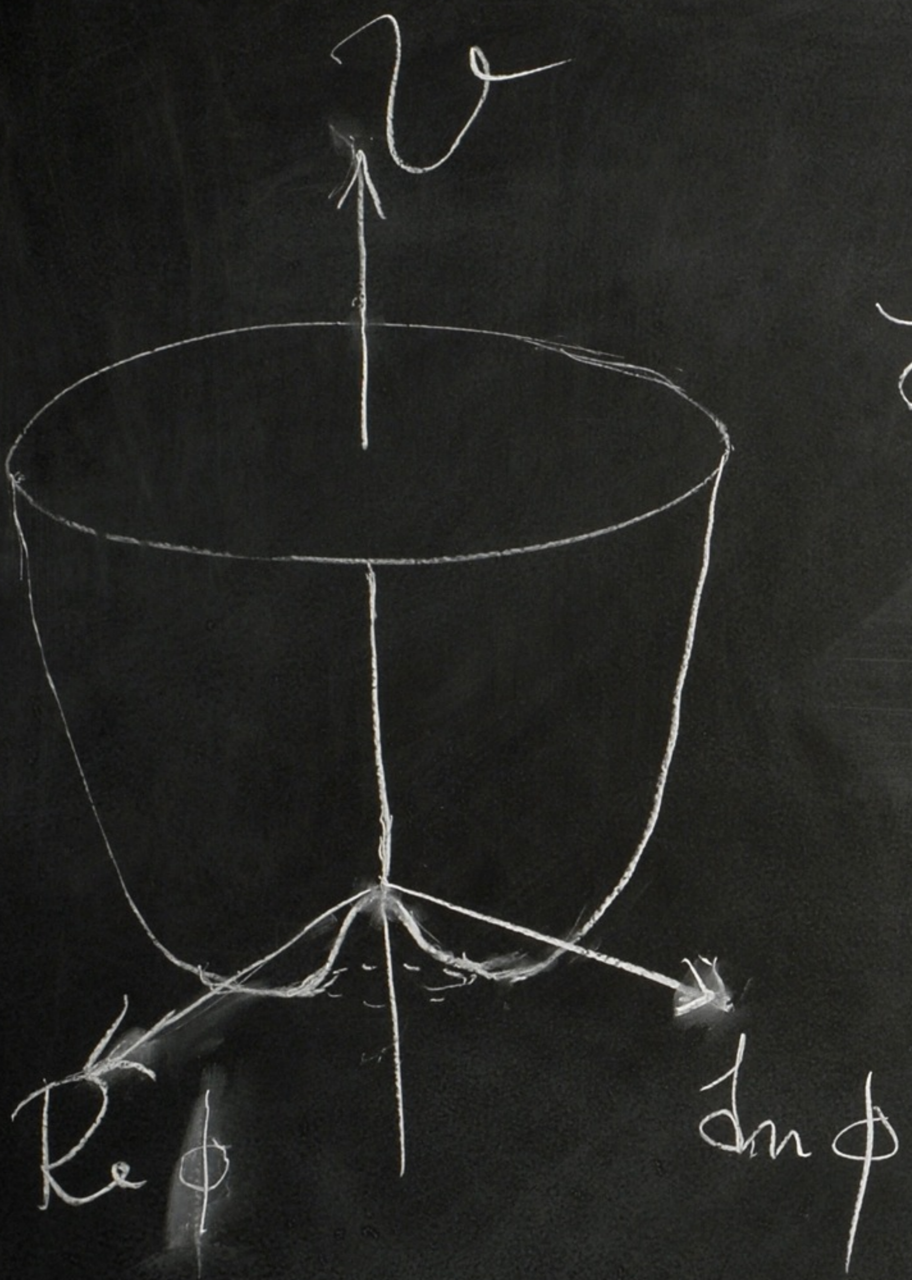
# Prospects for Run2

Hugely increased potential for discovery of heavy particles at 13~14 TeV



Note: New states/modified couplings for HP solution may only be non-coloured. Must have precision control of SM predictions

# Questions?



$$\mathcal{L} = (D_\mu\phi)^* D^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F$$

$$D_\mu\phi = \partial_\mu\phi - ieA_\mu\phi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$V(\phi) = \alpha\phi^*\phi + \beta(\phi^*\phi)^2$$

$$\alpha < 0 \quad , \quad \beta > 0$$

Peter Higgs

back-up slides

# HP & “Physical Naturalness”?

Bardeen, Foot, Shaposhnikov, Lykken,…

Some say another way of addressing HP — “it doesn’t exist”

Basically claim that there might be no higher mass scales feeding into H:

In principle gravity might be UV completed with no new particles so not affecting the Higgs mass (we know of no such construction)

AND suppose there are no other mass scales (eg, from origin of flavour; unification; dark matter;…) coupling to H either

Is this a “no-tuning” solution to hierarchy problem with
no low-energy consequences??

# Consequences of “Physical Naturalness”

All BSM states carrying SM gauge quantum number must be below a few TeV (so no high scale gauge unification)

Yukawa coupled particles can be heavier, $M_{\nu R} < 10^7$ GeV

Gravitationally coupled particles less than $10^{12}$ GeV? (requires a 3 loop calculation not yet performed)

# Problems of “Physical Naturalness”

Must do all physics with previous constraints:

Still must explain why $M_{pl} >> v$

Family quantum numbers

Dark matter

Neutrino masses

Baryogenesis

Inflation

Flavour

$\sin^2\theta_W$...

and avoid all Landau Poles in a controllable way

looks very tough!

# Problems of "Physical Naturalness"

Arvanitaki, Dimopoulos, Dubovsky, Strumia, Villadoro

Need to expand gauge group at the TeV scale, eg, to SU(4)xSU(2)xSU(2), or $SU(3)^3$ to solve U(1) Landau pole

Add further states to avoid Higgs quartic Landau pole

And do all the rest of physics at low scales or with mysterious quantum gravity effects...

attempts so far failed even at first stages

(& even if this program worked there is generically new physics accessible by LHC/other experiments)

# Naturalness aka Dynamics

Partially tuned dynamics??

Deuteron Binding Energy!?

$$2 \text{ MeV} \ll \Lambda_{QCD} \simeq 200 \text{ MeV}$$

Often stated that involves <1% tune compared to natural nuclear scales (so justifying similar state of affairs for Weak Scale?)

# Naturalness aka Dynamics

~~Partially tuned~~ dynamics??

Deuteron Binding Energy!?

$$2 \text{ MeV} \ll \Lambda_{QCD} \simeq 200 \text{ MeV}$$

cf. saturated nuclear binding energy of 8 MeV per nucleon in whole range of larger nuclei

~~Often stated that involves <1% tune compared to natural nuclear scales (so justifying similar state of affairs for Weak Scale?)~~

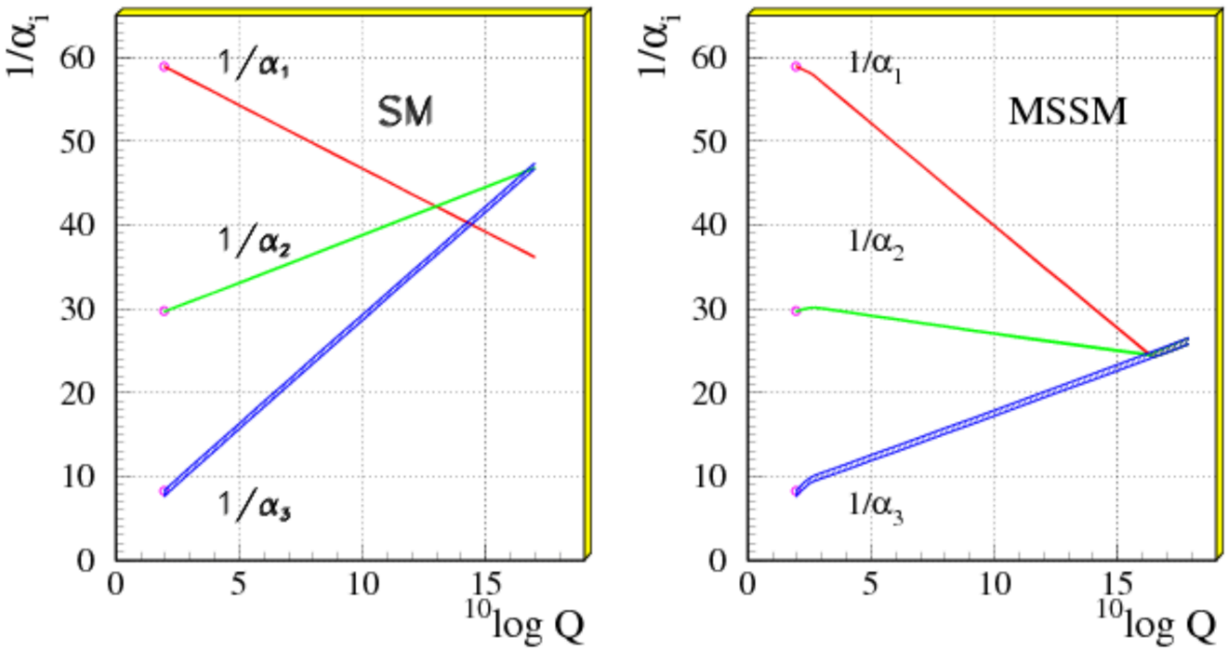
$$E_b \approx \frac{1}{2} \frac{1}{(4\pi)^2} \frac{m_N}{2}$$

$$\approx 2 \text{ MeV}$$

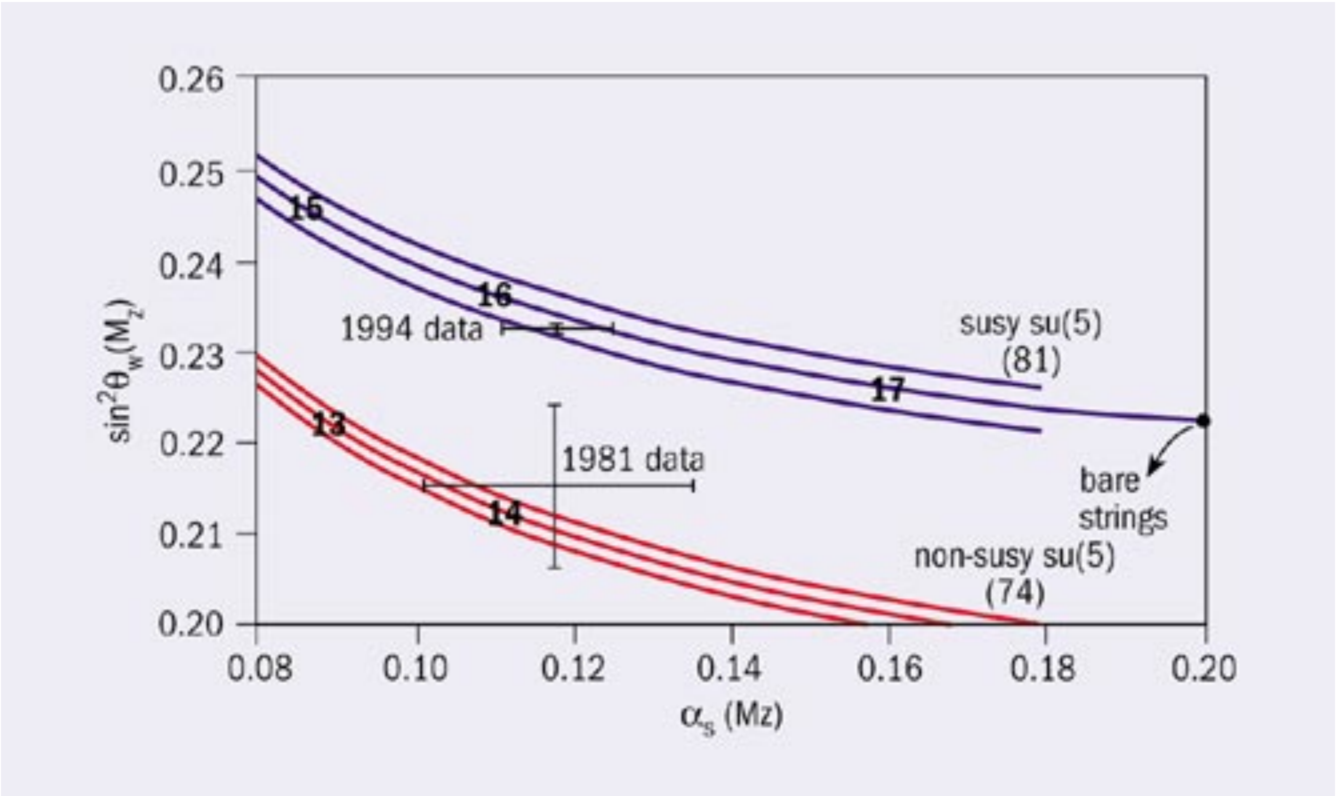
fully natural

(full argument developed by Arvanitaki, Dimopoulos, & Villadoro)

# Supersymmetry

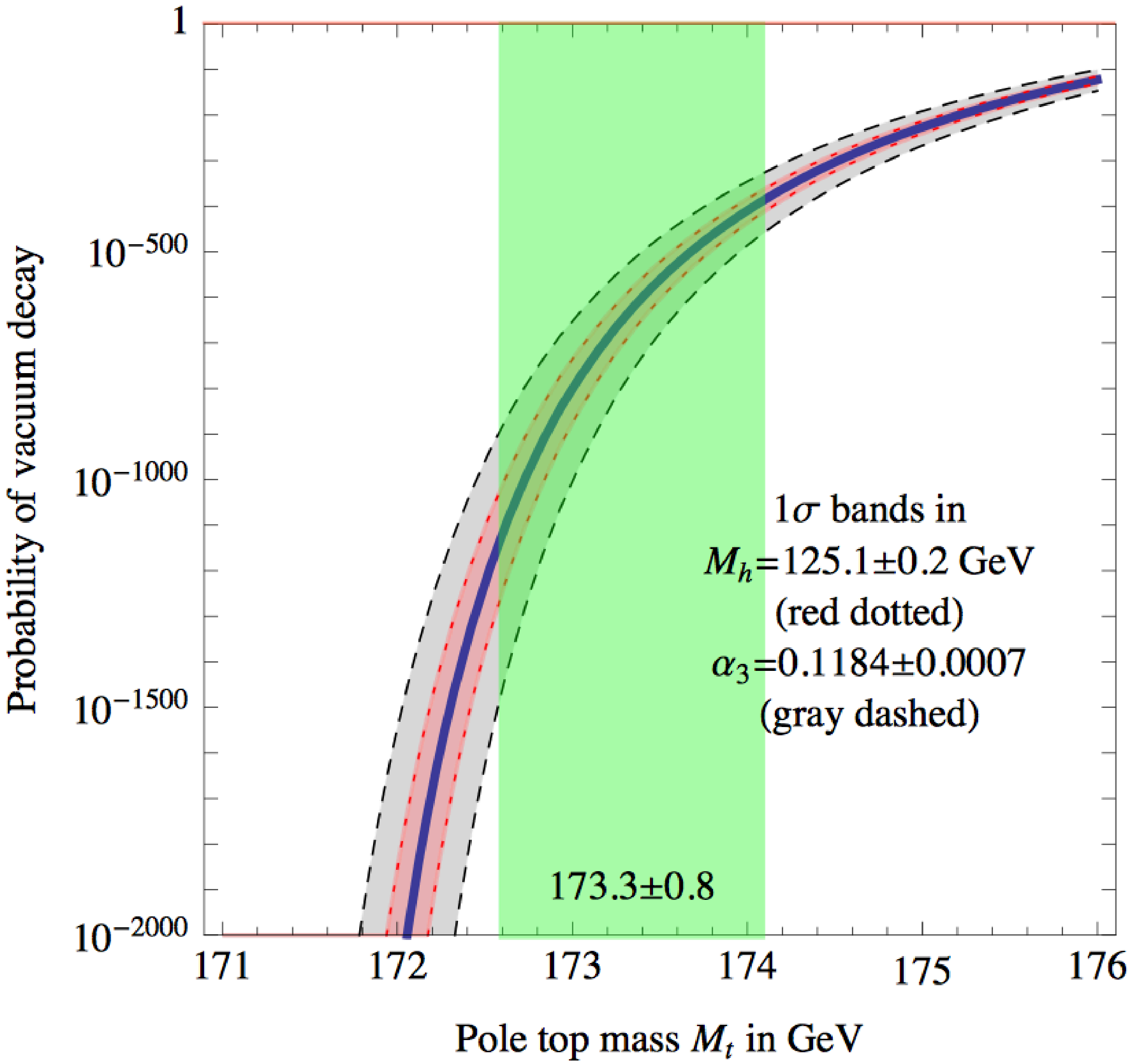


Unification of the Coupling Constants in the SM and the minimal MSSM



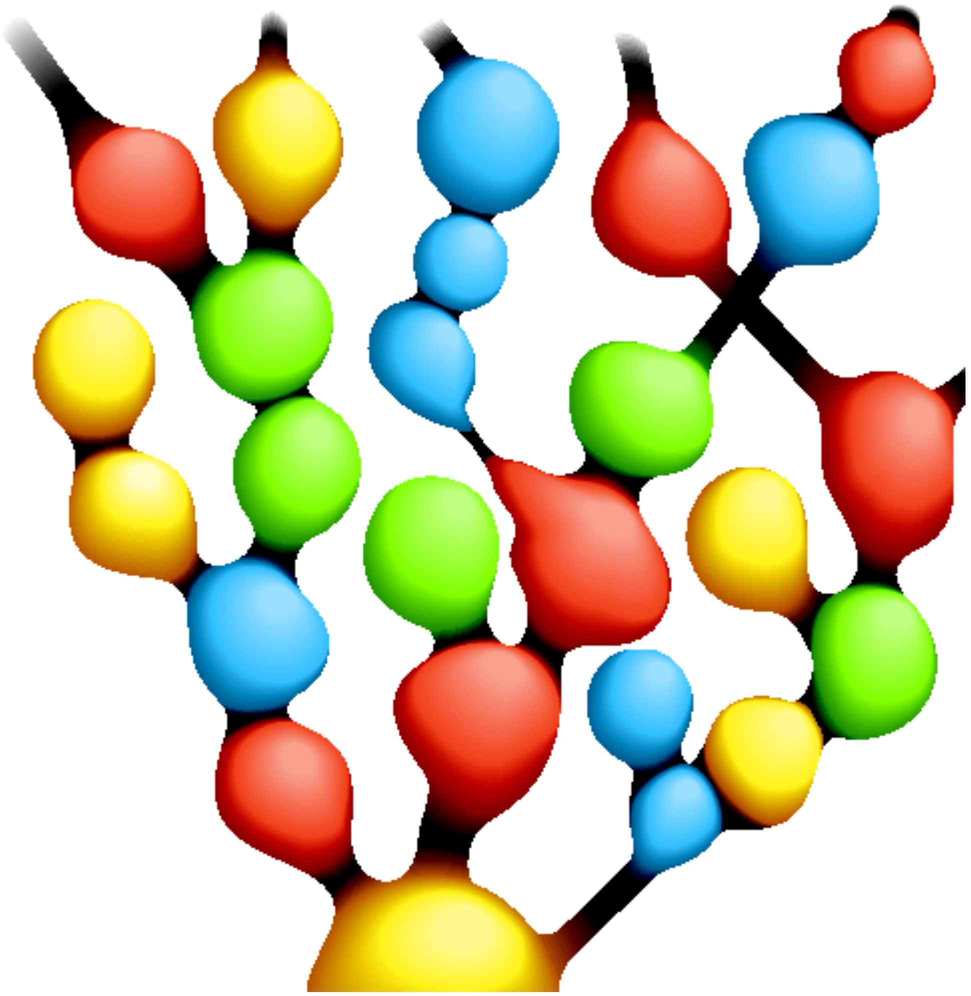
# Stability of SM all the way up?

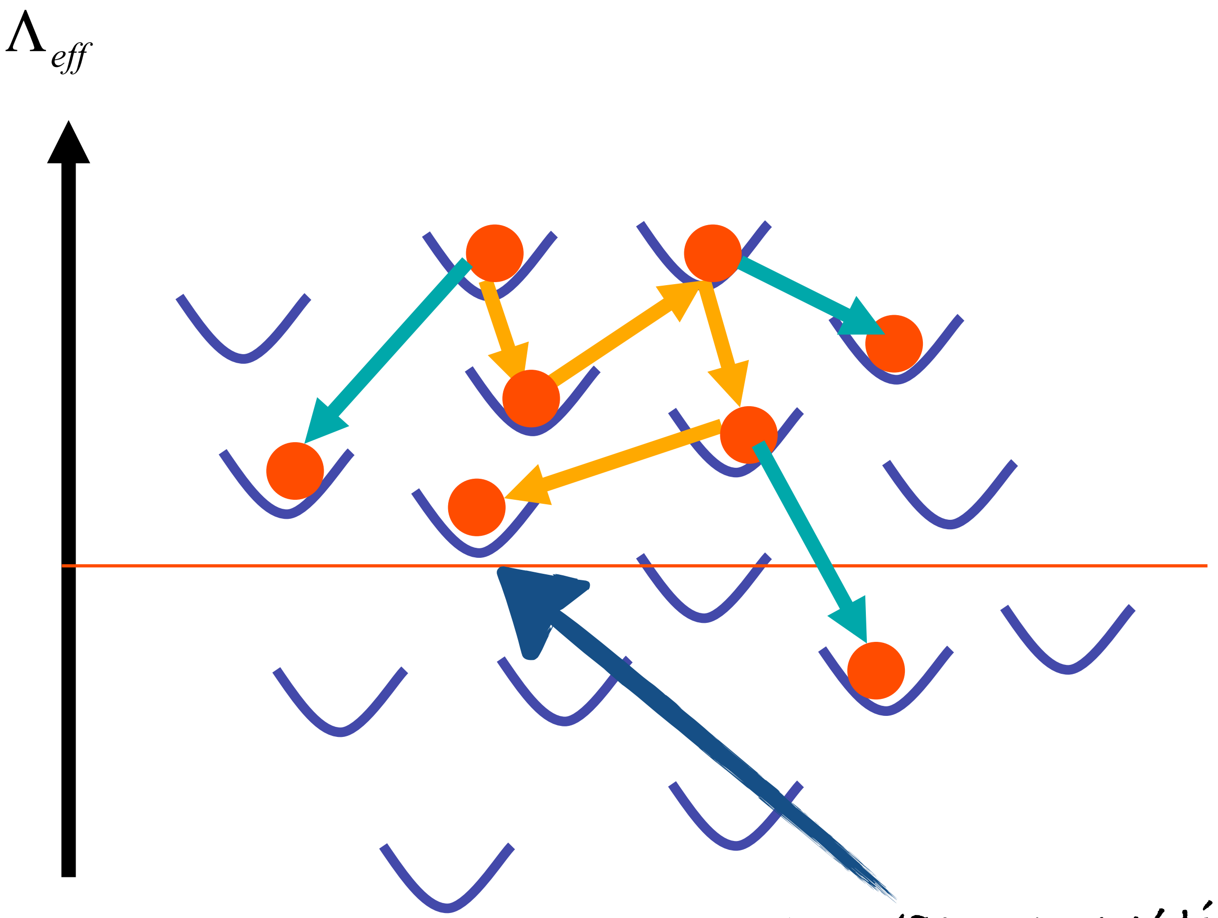
How metastable?



# Hierarchy Problem

A recent trend (?fad?) has been to say it is tuning — the Multiverse





our vacuum w/ tiny vacuum energy and 246 GeV higgs condensate

huge number of possible metastable vacua — we have to exist in the one compatible with a long-lived universe with properties we see — *"environmental selection"* or *"anthropic selection"*

# Anthropic Selection?

useful to recall some history...

| Problem | Solution |
|---|---|
| Earth-Sun Distance | Anthropic Selection $10^{22}$ suns ✓ |
| Cosmological Constant | Anthropic Selection $10^{500}$ universes??? |
| 7 eV line of $^{229}$Th nucleus | "Look-elsewhere" effect (ie, many possible lines) |
| Solar Eclipse & moon's size | Plain luck! |

Many flaw(s):

How many vacua? Distribution of stable vacua? Which parameters scan and how? With what correlations? What properties should we select on and how detailed? ("existence of atoms" "existence of life" "my name is John"?) What do probabilities mean in this multiverse anyway…

"Successes/hints":

Weinberg's `prediction' of order-of-magnitude of cosmo constant. We have no other idea why CC so tiny. Some properties of light quark masses and QCD/EM energies do seem delicately arranged. Claims that many vacua fits well with inflation & also string theory dynamics.

# Higgs Enigma

Higgs appears to be our very first (pseudo-?)elementary scalar:

Tests of SM Higgs spin-parity (0+ in yellow) against other hypotheses (all shown in blue).

Compatibility with each hypothesis measured by the amount of the curve lying to the right of the arrow.

Spin-parity 0+ is strongly favoured.