Data Interpretation Lecture 2

PREFIT school, DESY (2020)

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Rationale

Rationale for New Physics

Even if we had no evidence for BSM, there would be a rationale for new physics

Rationale

Hierarchies
gauge, mass, flavor

End of the road
unitarity, triviality, stability

Symmetries and/or dynamics
New states

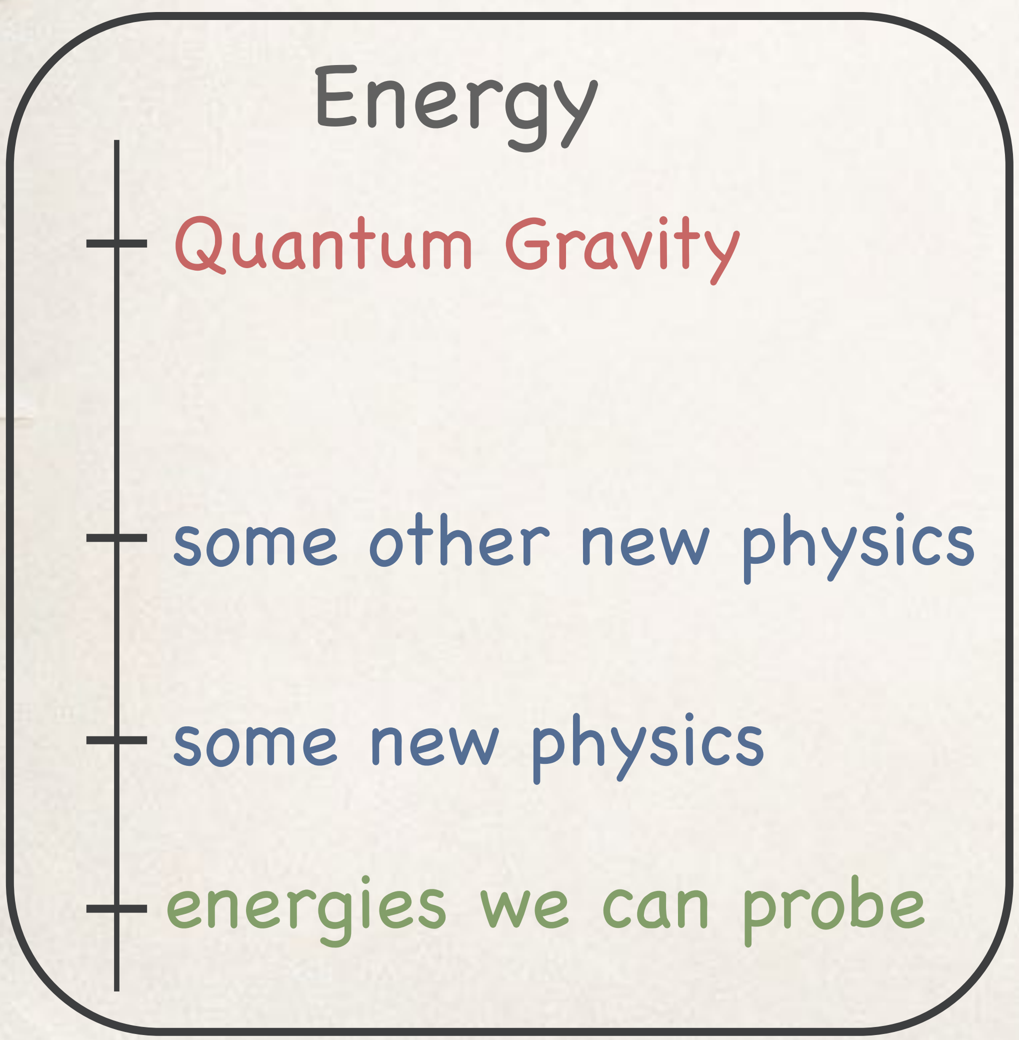
Rationale for New Physics

Example: Naturalness

Predictive theory: quantum mechanical. In QFT, physical quantities *run*

mass term in a Lagrangian, quantum corrections

$$\mathcal{L}_m = -m_\Psi \bar{\Psi}\Psi - m_\phi^2 \phi^2$$



Fermions

Massless fermion, additional symmetry

$$\Psi \to e^{-i\gamma_5 \theta}\Psi$$

if this chiral symmetry is preserved QM

$$\delta m_\Psi \propto m_\Psi \log(\mu_1/\mu_2)$$

chiral symmetry protects fermions masses from large UV corrections

Light fermions are technically natural

Rationale for New Physics

Example: Naturalness

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mass term in a Lagrangian, quantum corrections

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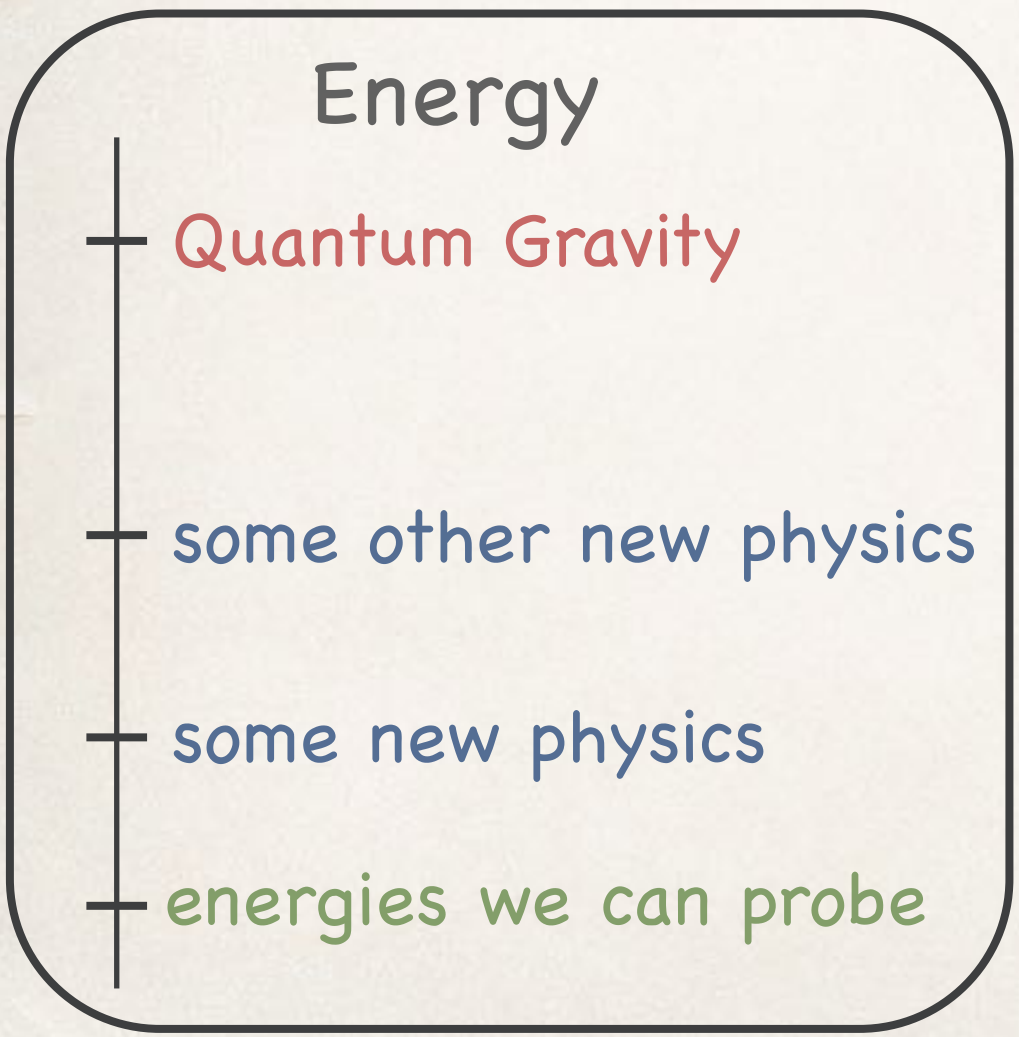


Scalars

Massless scalar, scale invariance

This classical symmetry is not preserved QM (is anomalous)

scalars are not protected by a symmetry, are UV sensitive, natural value for the mass is the highest scale it couples to

Light scalars are **unnatural**

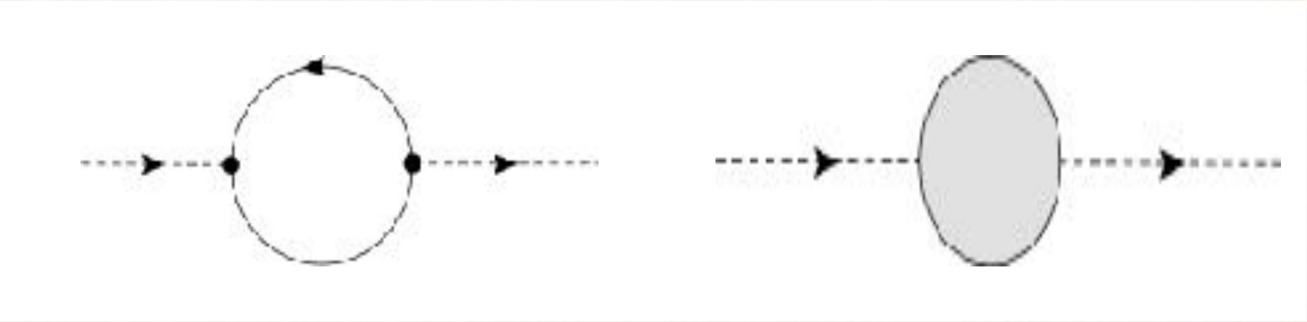
Rationale for New Physics

Example: Naturalness

Energy

- Quantum Gravity
- some other new physics
- some new physics
- energies we can probe

Quantum corrections to scalars



threshold corrections

QGrav

$$\delta m_\phi^2 \propto c_1\, \Lambda_{NP}^2 + c_2\, M_{Pl}^2$$

(Physical mass)^2 = (bare mass)^2 + (unsuppressed Qcorrections)^2

light scalar = enormous fine-tuning

The Higgs is a scalar, and there is no sight of new physics so far

Should we just live with it?

Is a tuning all there is?

Example: Naturalness

At the beginning of the EW theory, people were trying to figure out how to make sense of a gauge theory with massive W,Z

mass terms spoil renormalizability (predictivity) of the gauge theory

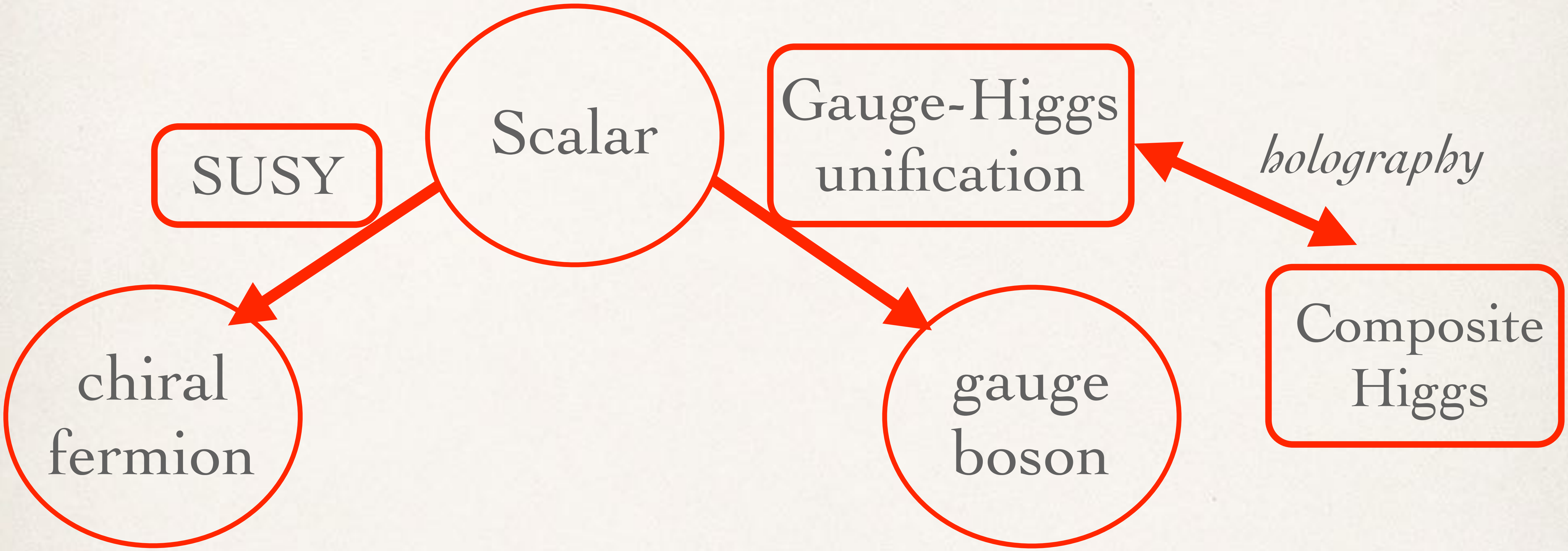
Feinberg (1958) proposed divergences were cancelled if a precise set of cancellations could happen (invoked fine-tuning)

At the end the story was more subtle
The concept of Spontaneous Symmetry Breaking
secret renormalizability

I view fine-tunings as calls for
new principles to be discovered

Light scalars

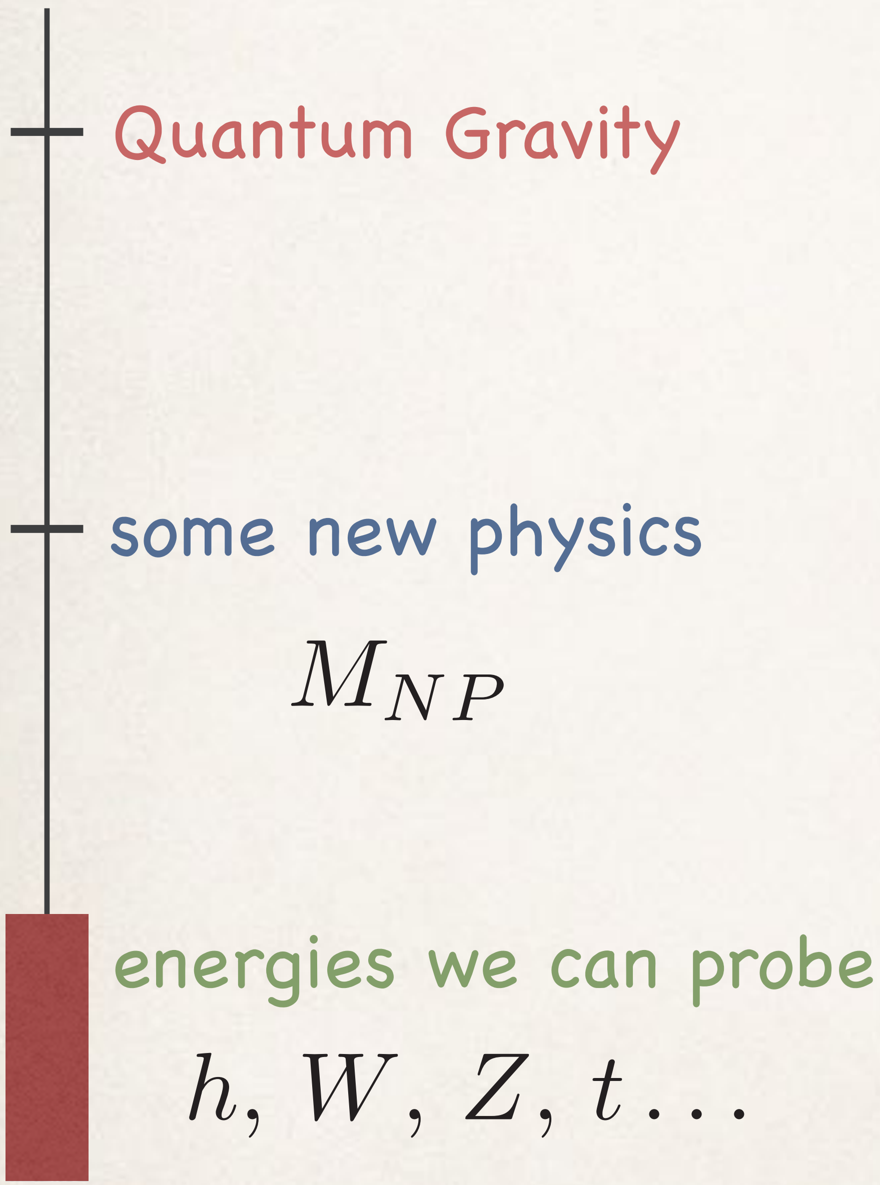
The light Higgs is a reality
symmetry/duality arguments to explain its nature



Many, many possible realizations (phenomenology)
Predict new states, to be discovered
(SUSY partners, techni-baryons and mesons, spin-two…)
AND induce deviations in the Higgs behaviour

Back to the Higgs

The Higgs is a very special creature in the SM:
a fundamental and light scalar



$$\delta m_h^2 \sim M_{NP}^2 \Rightarrow m_h^{phys} \sim M_{NP}$$

unless

1. There's *nothing* (DESERT)

2. Something *special* happens

2i.) fine-tuning (small=huge-huge)

$$m^2_{h,phys} \simeq m^2_{h,bare} + \delta m_h^2$$

2ii.) new symmetries

$$\delta m_h^2 \propto \text{ parameter breaks the symm}$$

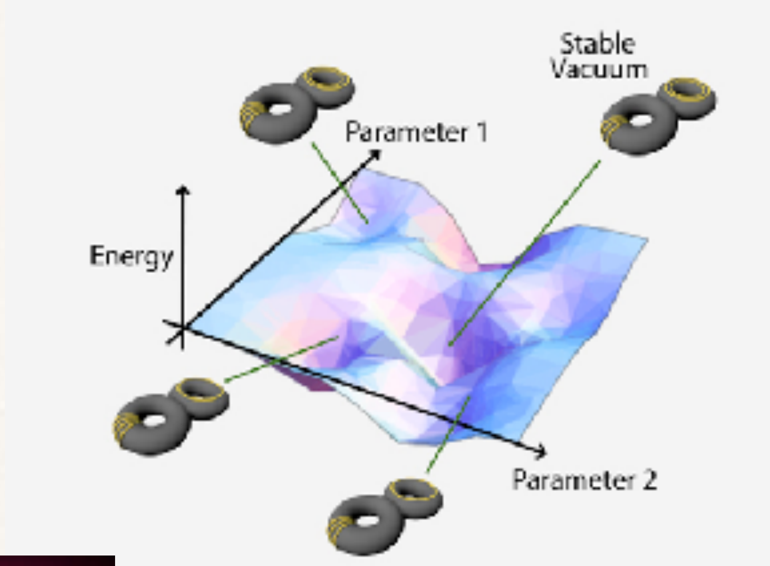
2iii.) dynamics

scalar=bound state of fermions or gauge fields

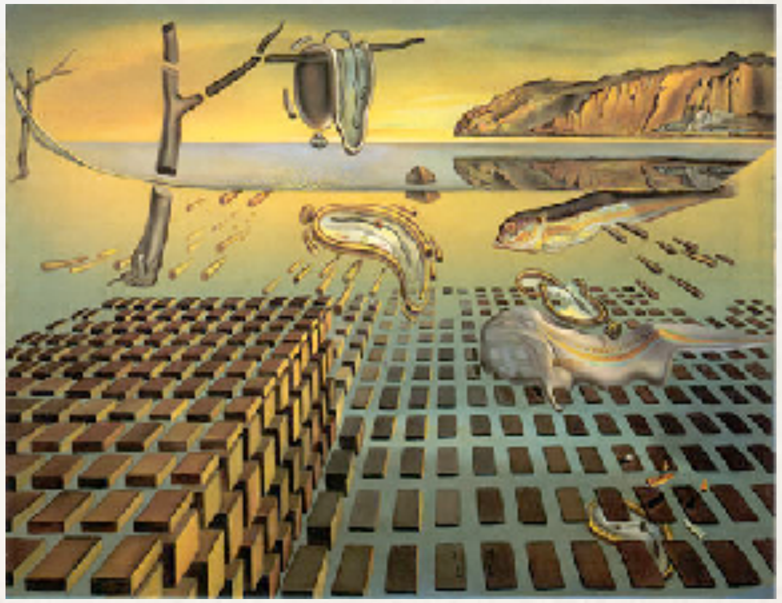
Back to the Higgs

What fundamental principle could be behind this behaviour?

Landscape of
String Theory?



Something like
Superconductivity?



New dimensions?
Supersymmetry?

Supersymmetry

Symmetries

We build field theories imposing symmetries on the action

Example s=0, 1/2, 1, 2

Klein-Gordon, Dirac, Yang-Mills, Fierz-Pauli

great ref: Landau-Lifshitz ClassFT

What is possible or not depends on whether a symmetry can be written for it

Coleman-Mandula **no-go theorem** [1962]:

Lie Algebra = Poincare $\otimes$ Internal

symmetries of S-matrix (space-time, internal)

=> internal and external (s-t) symmetries do not talk to each other

Supersymmetry (SUSY)

Supersymmetry is a way around that
abandons the Lie group framework
internal generators = > fermionic **Q**
super-Poincare algebra

<u>SUSY has important consequences</u>

Q | B > = | F >
Q | F > = | B > *

Fermions and bosons are no longer
two separate worlds

Normal field B or F -> SUSY field is both

e.g. Higgs -> SUSY Higgs $(H, \tilde{H})$ Higgs (s=0)+Higgssino (s=1/2)

All fields in superfield are *degenerate*

=> Higgs should come with a 125 GeV fermion

**being sloppy with daggers*

SUSY breaking

=> Higgs should come with a 125 GeV fermion

=> electron should come with a 0.511 GeV charged scalar

=> there should be a massless fermion (photino) force mediator

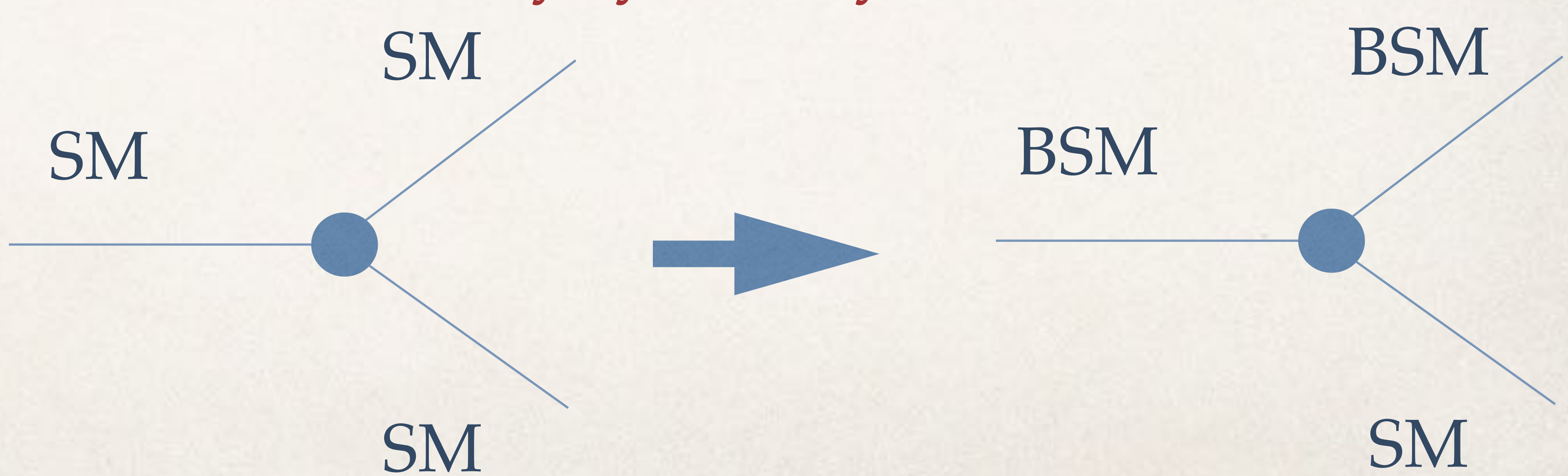
etc, etc

All that is wrong!

Then SUSY must be *broken*=> splitting between partners in the superfield of order the SUSY breaking scale

if SUSY is broken, does any symmetry survive?

yes, R-parity



SUSY breaking

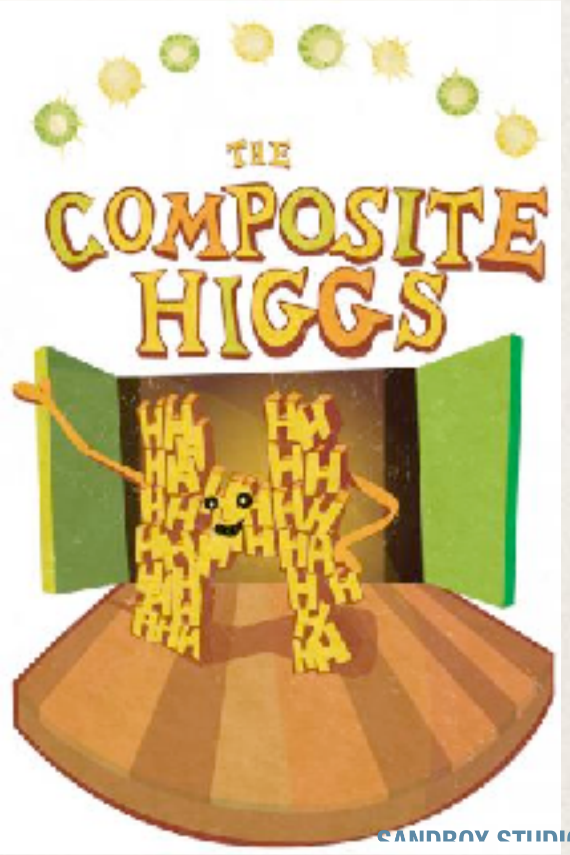
if SUSY is broken, does any symmetry survive?

yes, SUSY is still a good symmetry above SUSY breaking scale
Higgsino : chiral fermion -> protected by chiral symmetry
Higgs -> protected by chiral symmetry at high-energies

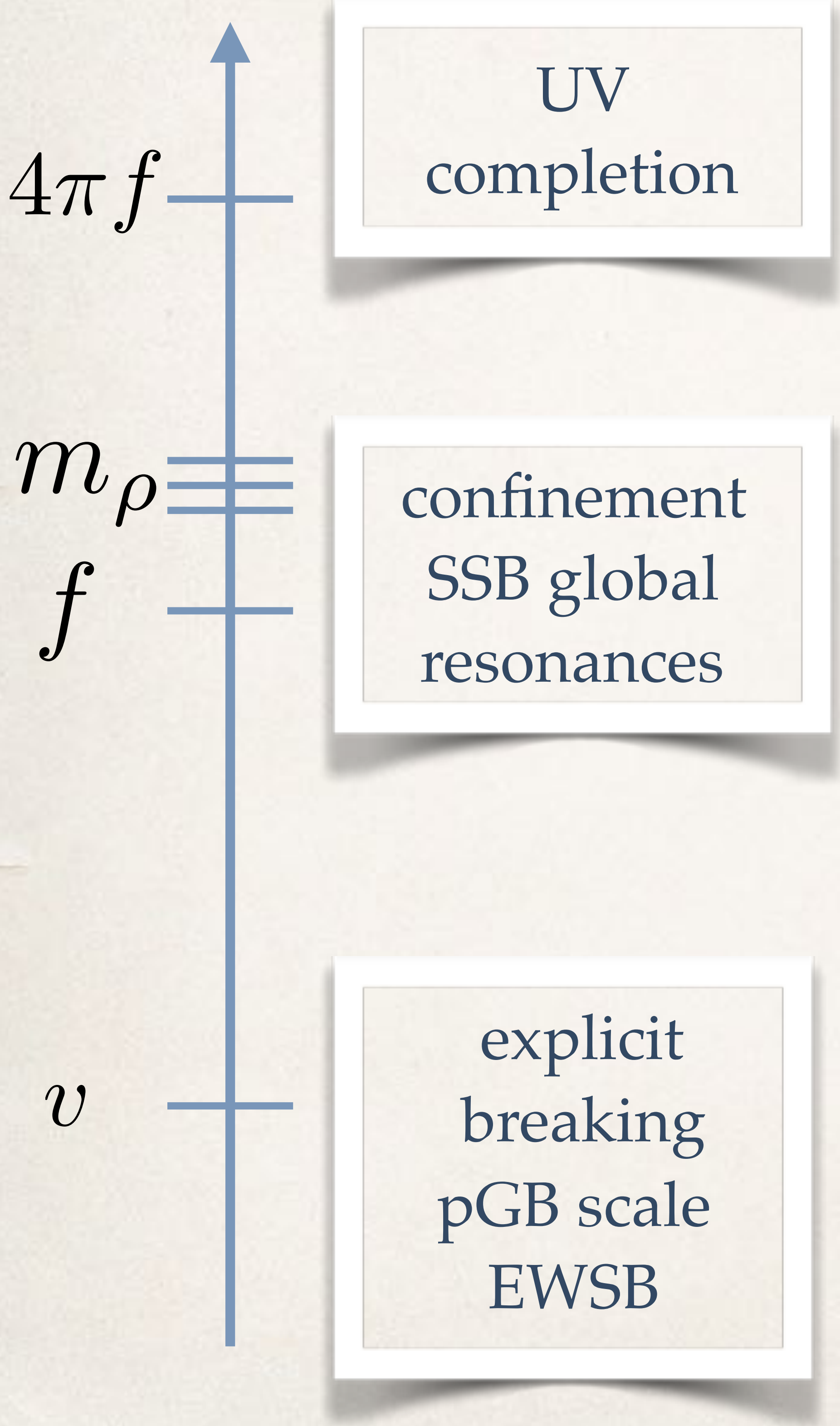
$$\delta m_h^2 \propto \text{ parameter breaks the symm } \sim m_{soft}^2 \sim (TeV)^2$$

Higgs is *naturally light* in SUSY
as long as the SUSY particles are not too far from the EW scale
Naturalness in SUSY => light SUSY particles

Compositeness



Composite Higgs in a nutshell



As pions in QCD:
light Higgs as a pseudo-GB from spontaneous breaking of a global symmetry

Contrary to pions in QCD:
the Higgs has

1. CP-even properties
2. its potential needs to trigger EWSB
3. it should couple as mass

Contrary to the SM Higgs:
EWSB can be non-linearly realized,
Higgs could be a singlet (not doublet)

Composite Higgs: Quantum numbers

$\mathcal{G} \to \mathcal{H}$

pGBs from SSB

$$\Sigma(x) = \exp(i\sqrt{2}h^a(x)X^a/f)\Sigma_0$$

The CP properties of the resulting pGBs depend on the CP properties of the strong sector

A. **Coupling to gauge**
part of the global sym H is weakly gauged
depends on the embedding

$$\Pi_1(p^2)\Sigma^T A_\mu A_\nu \Sigma$$

B. **Coupling to fermions**
many options for fermion rep

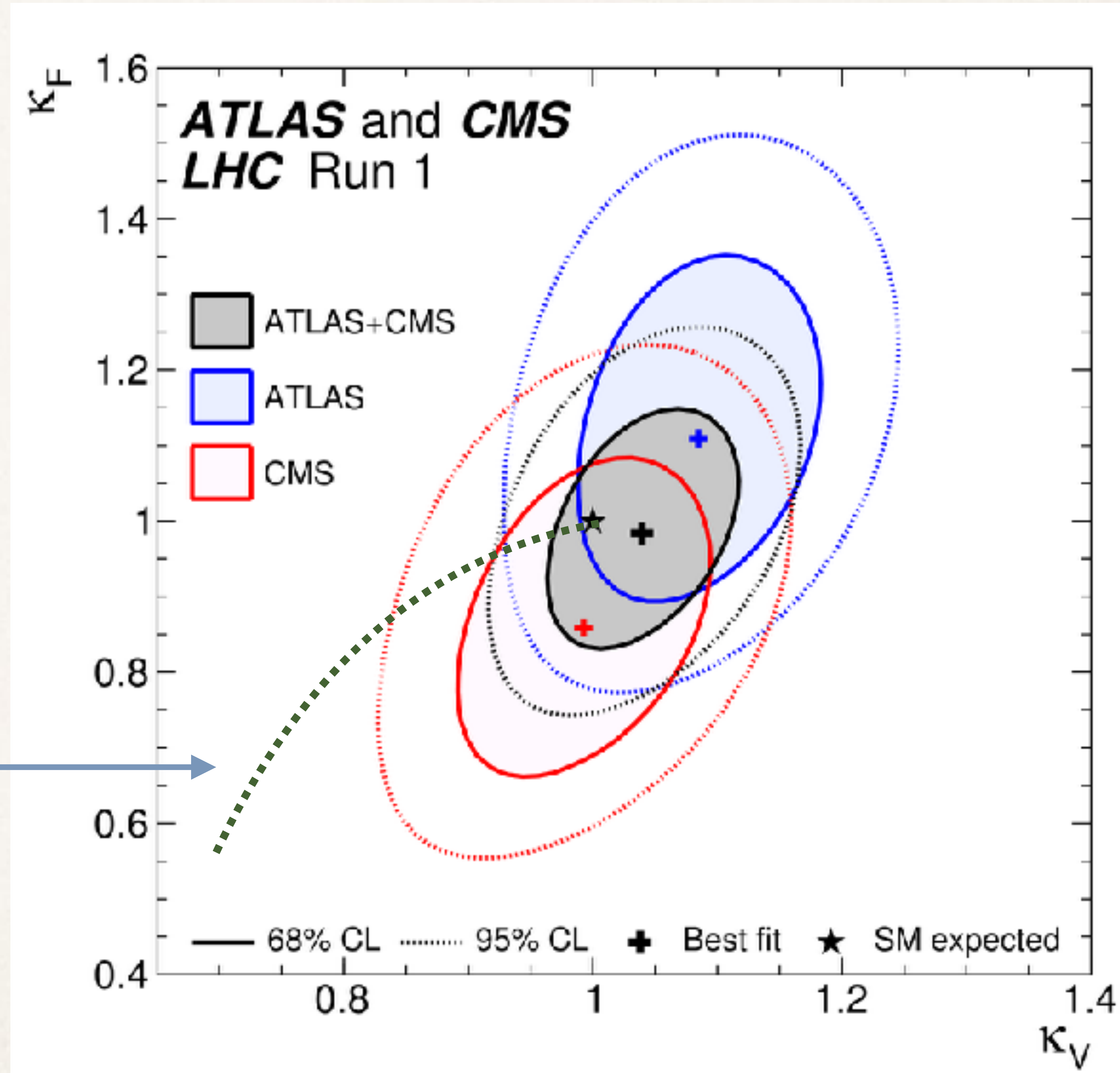
$$\overline{\Psi}\Gamma^i\Sigma_i\Psi$$

choice of global breaking and embedding: **CP-even scalar doublet**

pheno: Non-linear realization, Higgs couplings deviations

Composite Higgs: Quantum numbers

coupling to fermions



coupling to vectors

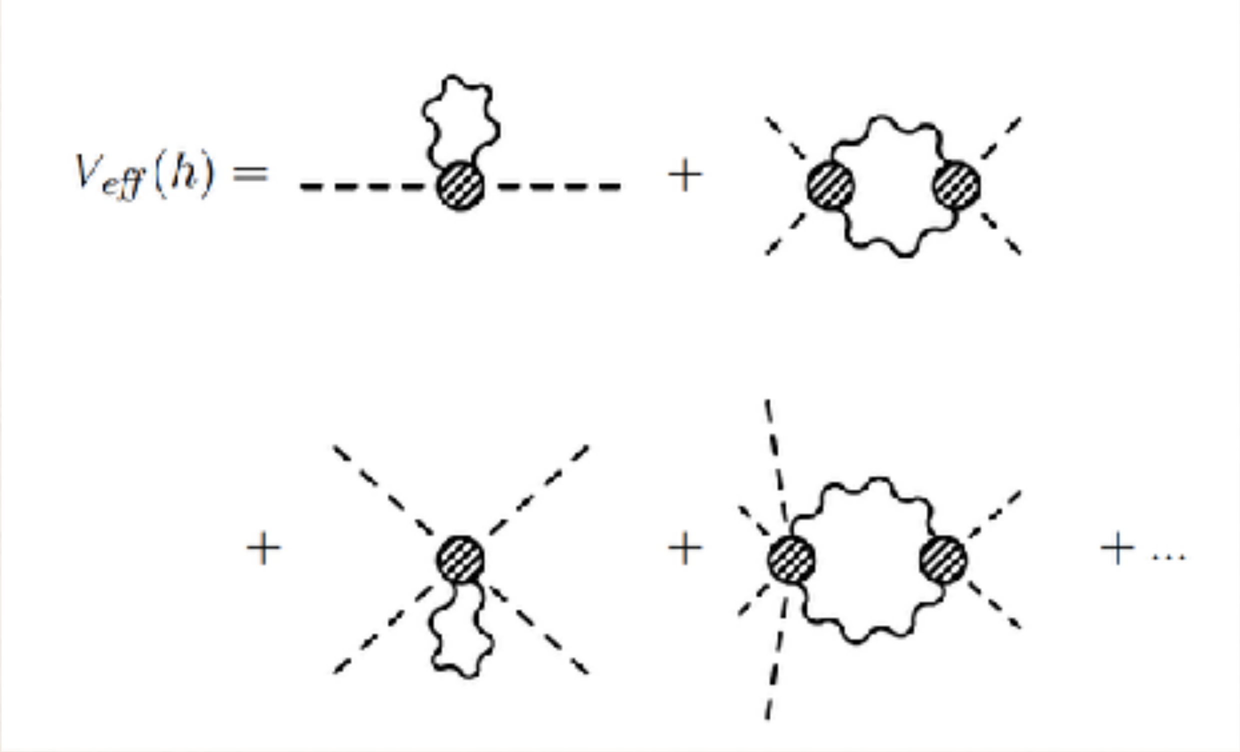
different CHMs correspond to different lines
the effect decreases as

$$\xi = v^2/f^2$$

Composite Higgs: Potential and EWSB

Usual paradigm:
potential generated via **Coleman-Weinberg** contributions

e.g. GAUGE



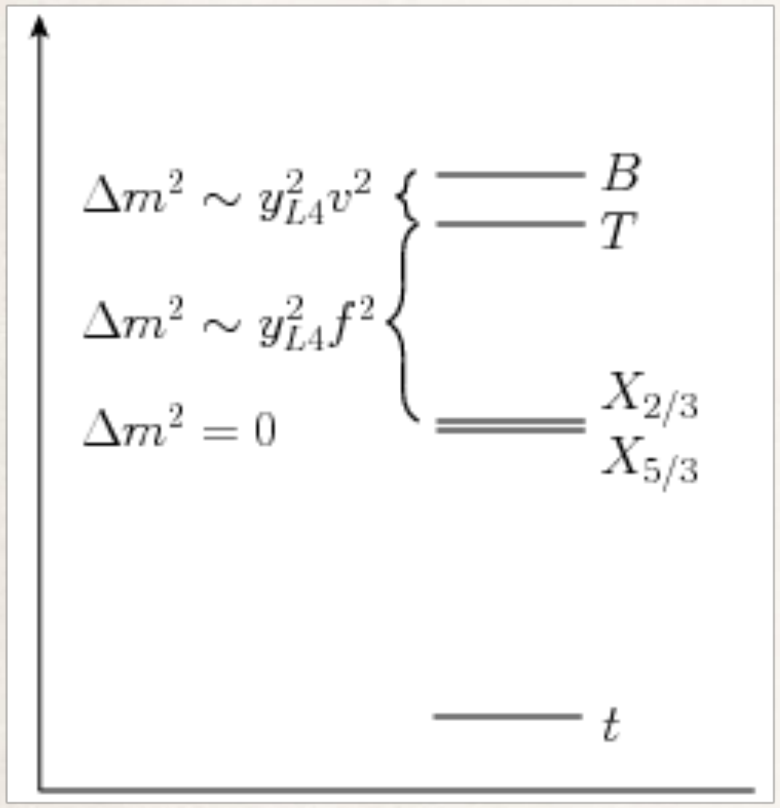
Georgi-Kaplan (80's)
gauge-top *does not* trigger EWSB
need new fermionic resonances
TOP-PARTNERS

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

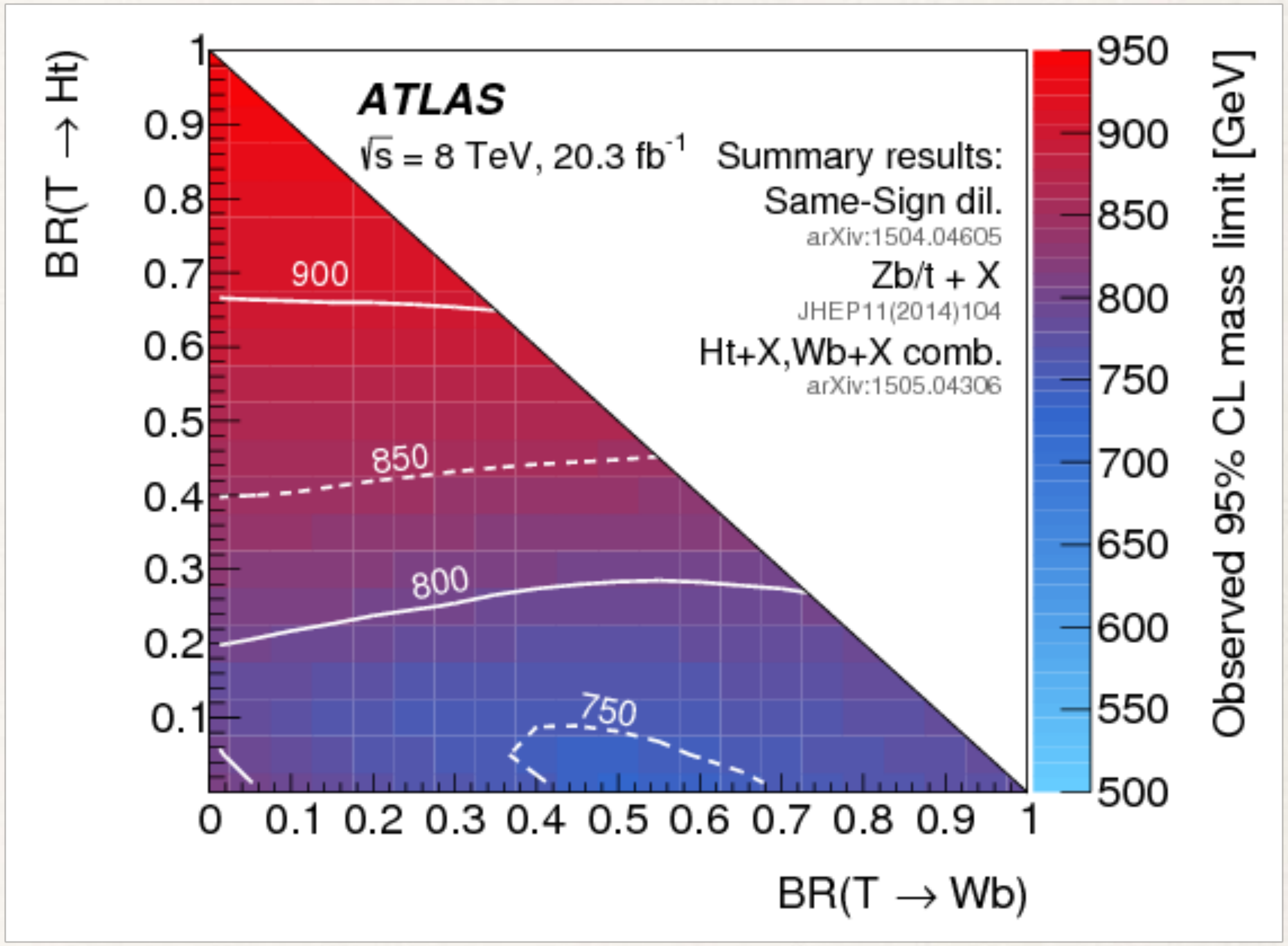
pheno: New, light (below TeV) techni-baryons
should couple to the Higgs, W, Z

Composite Higgs: Potential and EWSB

typical distribution of top-partners



Panico et al. 2016

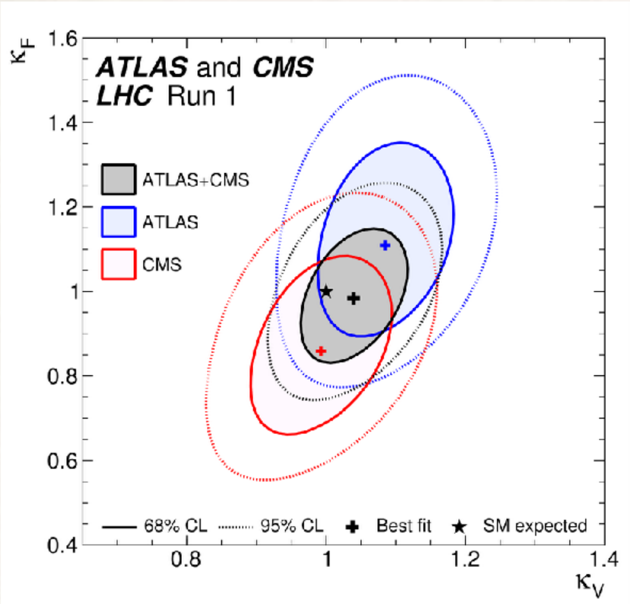


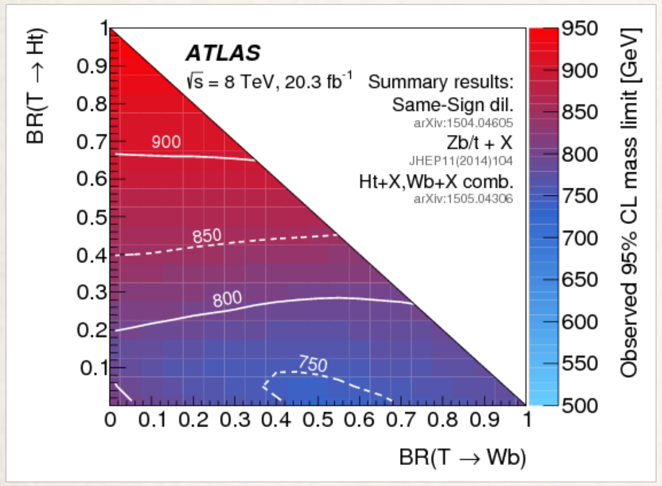
resonances below ~ 800 GeV are excluded

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

tuning in the Higgs potential severe

Status in model-building





Given the experimental constraints,
lack of deviations in the Higgs behaviour and
absence for new composite fermions
interest in more natural (non-minimal) models

e.g. new ways to trigger EWSB and fermion mass generation, measure of tuning of the theory, un-coloured fermion resonances…

examples:

EWSB triggered by other scalars: see-saw CH

VS, SETFORD. 1508.06133

new symmetries in the global sector: Maximally symmetric CH

CSAKI, MA, SHU. 1702.00405

Additional material (Exercises)

Gauge Coupling Unification and Split Supersymmetry

1 Unification

There are various arguments as to why a Supersymmetric extension of the Standard Model may be of interest for understanding TeV scale physics such as we will probed at the Large Hadron Collider. One motivation people often give is that SUSY 'predicts a unification of gauge couplings'. In this question, we'll see what this means...

We write the renormalisation group equation for the gauge couplings g_3, g_2, g_1 of the Standard Model group $SU(3) \times SU(2) \times U(1)$ as

$$\mu \frac{dg_i}{d\mu} = \frac{\beta_i}{16\pi^2} g_i^3 \qquad \text{(no sum on } i\text{)} \tag{1}$$

where μ here is the renormalisation scale, and β_i are the one-loop beta-function coefficients (real constants).

For $SU(N)$ gauge groups, we calculated the β_i coefficients in the Standard Model course:

$$\beta_i = -\frac{11N}{3} + \frac{2}{3}\sum_f T_R(f) + \frac{1}{3}\sum_s T_R(s) \ , \tag{2}$$

where f denotes a 2-component Weyl fermion and s a complex scalar. T_R is the Dynkin Index of the appropriate representation of $SU(N)$ corresponding to the field f or s; explicitly, this is 1/2 for the fundamental rep[1] and N for the adjoint rep.

For $U(1)$ we have

$$\beta_1 = \frac{2}{3}\sum_f Y_f^2 + \frac{1}{3}\sum_s Y_s^2 \tag{3}$$

where $Y_{f,s}$ is the hypercharge of a (2-component) fermion or complex scalar respectively.

[1] This choice is just a convention — once fixed, all the other T_R values follow.

In tutorial 3 we saw that for the Standard Model, at one-loop order,

$$\beta_1 = \frac{41}{6} \qquad \beta_2 = -\frac{19}{6} \qquad \beta_3 = -7\,,$$

whereas for the MSSM

$$\beta_1 = 11 \qquad \beta_2 = 1 \qquad \beta_3 = -3\,. \tag{4}$$

a) Defining $\alpha_i(\mu) = \frac{g_i^2(\mu)}{4\pi}$, solve the RG equation (1) to find a relationship between $\alpha_i(M_Z)$ and $\alpha_i(\mu_0)$ for a general scale μ_0.
Hint: Equation (1) takes the simplest form when written in terms of α^{-1}.

b) Grand Unified Theories predict that at some scale $\mu_0 = M_{GUT}$,

$$\frac{5}{3}\alpha_1(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_3(M_{GUT}). \tag{5}$$

Assuming this, derive

$$\alpha_3(M_Z)^{-1} = \alpha_2(M_Z)^{-1} + \frac{\beta_3 - \beta_2}{3\beta_1/5 - \beta_2}\left[\frac{3}{5}\alpha_1^{-1}(M_Z) - \alpha_2^{-1}(M_Z)\right]. \tag{6}$$

c) Taking the (rough) experimental values $g_1(M_Z) = 0.357$ and $g_2(M_Z) = 0.652$, and assuming all the Standard Model couplings unify at M_{GUT}, what value of $g_3(M_Z)$ do we predict from equation (6)? Does the MSSM do any better, if we assume that SUSY is broken just above the electroweak scale?

d) Show that if we introduce the fine-structure constant $\alpha = \frac{e^2}{4\pi}$, with $e = g_2 \sin\theta_W$ and $\tan\theta_W = \frac{g_1}{g_2}$, then equation (6) can be recast as

$$\alpha_3(M_Z)^{-1} = \alpha^{-1}\left[\sin^2\theta_W + \frac{3 - 8\sin^2\theta_W}{5}\,\frac{b_3 - b_2}{b_1 - b_2}\right], \tag{7}$$

where $b_3 = \beta_3$, $b_2 = \beta_2$ and $b_1 = \frac{3}{5}\beta_1$. Furthermore, show that the unification scale is given by

$$\log\left(\frac{M_{GUT}}{M_Z}\right) = \frac{2\pi\,(3 - 8\sin^2\theta_W)}{5\alpha\,(b_1 - b_2)}, \tag{8}$$

and that at the unification scale, the value of the coupling is

$$\alpha_{GUT} = \frac{5\alpha\,(b_1 - b_2)}{5\sin^2\theta_W\, b_1 - 3\cos^2\theta_W\, b_2}. \tag{9}$$

e) What is the Unification scale and value of the coupling at M_{GUT} predicted by:

(i) the Standard Model?

(ii) the MSSM?

2 Split Supersymmetry

The idea of Split Supersymmetry is to forget using SUSY as a solution to the hierarchy problem, but to still require that it leads the unification of gauge couplings and provides a dark matter candidate. We'll look at this idea, following reference [1]; their starting point was to note that the beta-function coefficients, b_i, can be written as

$$b_3 = \frac{1}{3}\left(4N_g - 33 + N_3\right) \tag{10a}$$

$$b_2 = \frac{1}{3}\left(4N_g - 22 + \frac{n_H}{2} + N_2\right) \tag{10b}$$

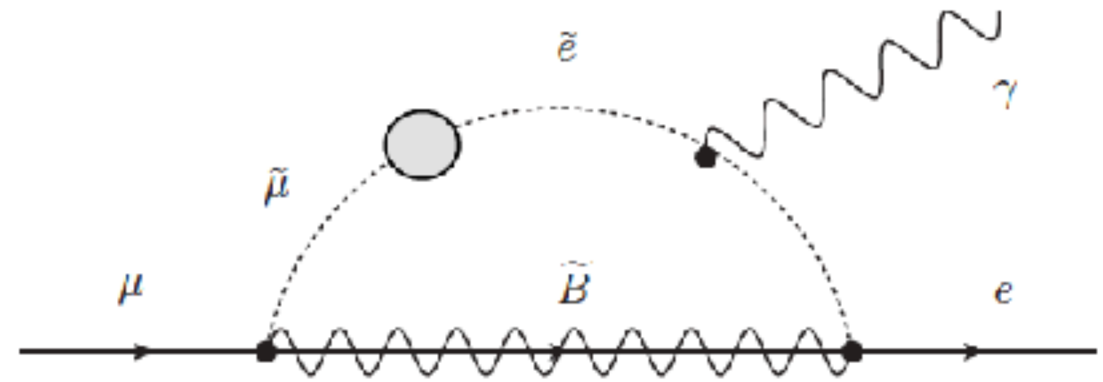
$$b_1 = \frac{1}{3}\left(4N_g + \frac{3n_H}{10} + N_1\right) \tag{10c}$$

where N_g counts the contribution to the β-functions from complete SU(5) irreps, and it is normalized such that the 3 families of SM quarks and leptons give $N_g = 3$.[2] For the MSSM one can easily show that $N_g = \frac{9}{2}$. The number of Higgs doublets is n_H, and N_i $(i = 1, 2, 3)$ give the contributions from matter in incomplete GUT multiplets (for example, in the MSSM, this includes contributions from the gauginos and higgsinos).

The important observation is that N_g actually cancels out in the equations (7) and (8), and so doesn't enter into the predictions for α_s or M_{GUT}. Split SUSY makes use of this fact: All *scalars* in the MSSM can be very heavy, except one Higgs, and unification can still take place.[3] We still need the gauginos ($\widetilde{g}$, $\widetilde{W}$ and $\widetilde{B}$) and Higgsinos $\widetilde{h}_{u,d}$ to have masses of order the TeV scale in order to retain the nice features of unification, and to also have interesting dark matter candidates.

a) If we send the scale of SUSY to the GUT scale, what are the natural values for the squark and slepton masses? What about the fermionic superpartners (gauginos and higgsinos)?

b) Another interesting feature of split SUSY is that pushing the scalar masses to high scales alleviates the most pressing bounds from flavor-changing neutral currents (FCNCs), CP violation, proton decay and so on. The reason is that all those dangerous bounds are based on calculating a diagram that is suppressed by a factor of the scalar masses. For example, let's look at the M_{scalar} dependence of the $\mu \to e\gamma$ bound: the SUSY particles typically contribute to this process through a diagram of the type:



where the mass insertion (grey blob) comes from a flavor-violating, soft SUSY-breaking term of the form $-m^2_{\tilde{e}\tilde{\mu}}\,\tilde{e}\,\tilde{\mu}$. One can use naïve dimensional analysis (NDA) to estimate the size of this contribution to the branching ratio to be

$$\mathrm{BR}(\mu \to e\,\gamma) \approx \frac{g'^2\,e^2}{16\pi^2}\left(\frac{m^2_{\tilde{e}\tilde{\mu}}}{m^2_{\tilde{\ell}}}\right)^2 \frac{v^2}{m^2_{\tilde{\ell}}}\,\frac{v^2}{m^2_{\widetilde{B}}} \tag{11}$$

where $m_{\tilde{\ell}}$ is the slepton mass, and we have used the fact that μ decays are dominated by $\mu \to e\,\nu_\mu \overline{\nu}_e$, which goes as G_F^2. Is this formula dimensionally correct?

c) Assume $m^2_{\tilde{e}\tilde{\mu}} \approx m^2_{\tilde{\ell}}$ (no flavor hierarchy) and $m_{\widetilde{B}} \approx v$. Find the experimental constraint on the $\mathrm{BR}(\mu \to e\gamma)$ and use it to derive a lower bound on $m_{\tilde{\ell}}$.

d) In split SUSY, gluinos (gluini?!) are lighter than squarks, so it is interesting to think about how gluinos decay. Use NDA to estimate the decay width $\Gamma_{\tilde{g}}$, and hence the decay length, $c\tau$, of the gluino as a function of $m_{\tilde{g}}$ and $m_{\tilde{q}}$ (assuming that $m_{\tilde{g}} \gg m_{\mathrm{LSP}}$, so there *are* SUSY particles for $\tilde{g}$ to decay into).

Long lived gluinos are a 'smoking gun' feature of split SUSY. The LHC is looking for them by keeping the detectors on when there are no collisions; as gluinos carry color charge, if they hang around long enough they end up getting bound up into R-hadrons (hadrons with non-trivial charge under R-parity) that can potentially be brought to rest by all the material in the detector. If the beams are colliding, the detector is too busy detecting other things to notice the intermittent decays of these R-hadrons, but when there are no collisions, one would only expect to register cosmic rays, and *possibly* the decay of interesting stuff trapped in the detector.

References

[1] G. F. Giudice and A. Romanino, "Split supersymmetry," Nucl. Phys. B 699 (2004) 65 [Erratum-ibid. B 706 (2005) 65] [arXiv:hep-ph/0406088].

1 Goldstone Bosons

According to Goldstone's theorem, whenever a global symmetry group G is spontaneously broken down to a smaller one H, it gives rise to $\dim(G) - \dim(H)$ massless bosons known as *Goldstone bosons*.

Today we're going to look at what happens when we spontaneously break a global symmetry:

$$\mathrm{SU}(N) \longrightarrow \mathrm{SU}(N-1)\ . \tag{1}$$

a) How many Goldstone bosons (GBs) are generated by this breaking?

There are many ways to parameterise the GB fields, but we will try to be smart and choose a representation which clearly shows how all the fields transform under SU(N) and SU($N-1$).

b) Explain how the $N \times N$ matrix

$$U_{N-1} \equiv \begin{pmatrix} \hat{U}_{N-1} & 0 \\ 0 & 1 \end{pmatrix} \qquad \text{with} \quad \hat{U}_{N-1} \ \text{an} \ (N-1)\times(N-1) \ \text{matrix} \tag{2}$$

provides a represention of the unbroken symmetry transformations.

Let's represent the GBs by introducing an $N \times N$ matrix Π in the following way

$$\phi(x) = e^{i\Pi(x)/f}\,\phi_0(x) \tag{3}$$

where

$$\Pi(x) = \begin{pmatrix} 0_{(N-1)\times(N-1)} & \vec{\pi}(x) \\ \vec{\pi}^\dagger(x) & 0 \end{pmatrix} \qquad \vec{\pi}(x) = \begin{pmatrix} \pi_1(x) \\ \vdots \\ \pi_{N-1}(x) \end{pmatrix} \in \mathbb{C}^{N-1} \tag{4}$$

$$\phi_0(x) = \frac{f}{\sqrt{2}} \begin{pmatrix} 0 \\ \vdots \\ 0 \\ \pi_0(x) \end{pmatrix} \qquad \pi_0(x) \in \mathbb{R} \tag{5}$$

c) How does ϕ transform under the unbroken symmetries?

d) Does ϕ contain the right number of degrees of freedom?

e) We would like to see how ϕ transforms under the *broken* symmetries. We will first represent the broken symmetries by the transformation:

$$U_{\text{broken}} = \exp\left\{ i \begin{pmatrix} 0 & \vec{\alpha} \\ \vec{\alpha}^{\dagger} & 0 \end{pmatrix} \right\} \qquad \vec{\alpha} \in \mathbb{C}^{N-1} \tag{6}$$

Show that ϕ transforms as

$$\phi \to U_{\text{broken}}\, e^{i\Pi/f} \phi_0 = e^{i\Pi'/f} \phi_0 \tag{7}$$

to first order in $\vec{\alpha}$, where

(i) The $\vec{\pi}$ field shifts linearly:

$$\vec{\pi}' = \vec{\pi} + f\,\vec{\alpha}. \tag{8}$$

(ii) The field ϕ_0 is invariant under SU($N - 1$) transformations.

f) Although one says that the SU(N) symmetry has been spontaneously broken down to SU($N-1$) what really happens is that the broken part of the symmetry is realized in a way that is different from the unbroken parts. To see this more clearly compare how the fields transform under a broken symmetry vs. how they transform under the unbroken ones. For the broken generators one says that the symmetries are "non-linearly" realized. Thus for infinitesimal tranformations involving the broken generators one requires that the shifts in (8) are symmetries. Show that this statement is consistent with the statement of Goldstone's theorem that the GBs are massless.

g) This shift symmetry also implies that no potential is generated (no quartic coupling, no term made up of powers of the field) and only derivative interactions are allowed. To see this explicitly, expand the GB kinetic term

$$\partial_\mu \phi^\dagger\, \partial^\mu \phi \tag{9}$$

up to quartic order in the fields.