Beyond 2017 Standard Model

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Introduction

- The discovery of the Higgs boson in 2012 $\Longrightarrow$ Completed the experimental verification of the Standard Model
- Theory of the S.M. completed in 1973
- since then many ideas to go beyond:
  GUTs, Technicolor, Compositeness, SUSY, L-R symmetry, Extra-dimensions ...

But up to now NO SIGN of them in experiments

Beyond S.M.? Why? Where?

Neutrinos oscillations

Oscillations $\Longrightarrow$ Neutrinos are massive:

- Dirac mass: $\lambda_D \bar{L} H \nu_R \quad \longrightarrow \quad \lambda_D \sim 10^{-11} \quad \longrightarrow$ S.M.
- Majorana mass:
  $\lambda_M \bar{L} H \nu_R + M_R \nu_R \nu_R \quad \longrightarrow \quad M_R \gg M_Z \quad \text{and} \quad \lambda_M \sim O(1)$

See-saw $\Longrightarrow$ New Physics at M_R

Effects on Higgs can be important:

$\longrightarrow$ One-loop correction to Higgs mass and quartic coupling.

S.M. + Gravity

Need to couple S.M. to gravity $\longrightarrow$ issues:

- Naturalness of the electroweak scale (Higgs mass)
- Baryonic asymmetry
- Dark matter candidate
- Inflation (where is the inflaton?)
- Dark energy

The strong CP problem not directly related to gravity

Naturalness

Naturalness of the EW scale

Quadratic divergence of the Higgs mass parameter:

$$\delta m_H^2 = -\frac{3}{8\pi^2} h_t^2 \Lambda^2$$

where Λ is associated with:

- Gravity at $\Lambda \lesssim M_{Pl}$ $\rightarrow$ New d.o.f. appear as heavy states
- Also, some new physics can imply new heavy states at $\Lambda \ll M_{Pl}$

Then: $\Longrightarrow$ fine-tuning

Many solutions proposed.

Dimensionless theories

The idea is that M_{Pl} is an infrared generated parameter

In the UV $\longrightarrow$ dimensionless theory (need to avoid Landau poles!)

In the computations, all power divergent quantum corrections are regulated to become zero.

Gravity $\longrightarrow$ conformal gravity

Regularization $\Longrightarrow$ quadratic divergent correction to the Higgs mass $\to 0$

Up to now, progress but this idea falls short to have a realistic implementation
(Bardeen, Shaposhnikov et al., t'Hooft, Giudice-Isidori-Strumia-Slavio, ...)

Pseudo-Goldstone Higgs

Small Higgs mass is protected by a global symmetry:

- Global symmetry G $\rightarrow$ spontaneously broken to sub-group H
- $\Longrightarrow$ G/H parametrized by Goldstone bosons: Higgs.
- Shift symmetry forbids Higgs mass
- Explicit breaking by radiative effects $\rightarrow$ small Higgs mass.
- The top quark loop divergence cancelled by top partners.

$$\delta m_H^2 = -\frac{3}{8\pi^2} h_t^2 m_T^2 log(\Lambda/m_T)$$

(m_T top partner mass)

Pseudo-Goldstone Higgs: simple scenario

For the Higgs kinetic term, non-linear sigma model reads:

$$|\partial_\mu H|^2 + \frac{H^\dagger H}{f^2}|\partial_\mu H|^2 \to \frac{1}{2}(1+\frac{v^2}{f^2})\partial_\mu h^2$$

Canonically normalization → modified Higgs coupling, Ex:

$$\frac{M_Z^2}{v} h Z_\mu Z^\mu \to \frac{M_Z^2}{v}(1-\frac{v^2}{2f^2}) h Z_\mu Z^\mu$$

$\Longrightarrow$ EW precision tests $\to f \gtrsim 1.2$ TeV

The top partners have not been observed (vector like quarks) (limit ~ 3 TeV).

Vector resonances not observed (limit ~ 3 TeV).

Supersymmetry

Most popular solution: protect Higgs mass by a chiral symmetry

- SUSY $\Longrightarrow \delta m_H^2 = 0$
- Broken SUSY $\Longrightarrow \delta m_H^2 \sim \frac{3}{8\pi^2} h_t^2 m_{soft}^2 log(\Lambda/m_{soft})$

SUSY offers a technically natural fix for the hierarchy problem.

- SUSY predicts unification in the MSSM
- SUSY provides dark matter candidates: neutralino or gravitino

Fundamental UV theory might require SUSY: superstrings are either supersymmetric of super-ugly

The MSSM

For long times, the MSSM ruled over the SUSY land

- Belief/Hope/Dream: was that a lot of "particles" will show up at colliders !!!
- Reality: $\emptyset$ but not done with it yet ...

Strong limits of colored particles:

- Gluinos:

  $\delta m_H^2 \sim -\frac{\alpha_s}{\pi^3} h_t^2 M_3^2 log^2(\Lambda/TeV)$

  $M_3 \gtrsim 2$ TeV (1 TeV for compressed spectrum)

- Stops:

  $\delta m_H^2 \sim -\frac{3}{8\pi^2} h_t^2 m_{stop}^2 log(\Lambda/m_{soft})$

  $m_{stop} \gtrsim 1$ TeV (500 GeV for compressed spectrum)

No new particles found $\rightarrow$ about 1% tuning

What if non-SUSY

- Strong limits of colored particles → look for non-colored particles that cut-off the quadratic divergence of the Higgs mass → Neutral naturalness, Twin Higgs etc ... (Chacko, Goh, Harnik)
- Dynamical scanning of the Higgs mass parameter → the Relaxion: a scalar coupled to Higgs boson and when it takes the Higgs mass^2 parameter to negative value, the Higgs vev back-reacts and stops the relaxion evolution (Graham, Kaplan,Rajendran).

These scenarios have their own issues. They do not solve the naturalness for a UV cut-off $\sim M_{Pl}$. Need to be supplemented by something (as SUSY) at higher energies.

SUSY extended Higgs sector

Higgs sector for supersymmetry

SM $\longrightarrow$ Minimal Higgs sector: 1 Higgs doublet
MSSM $\longrightarrow$ Extended Higgs sector: 2 Higgs doublets
In general, the electroweak sector can be non minimal. But, LHC says Higgs looks like the SM one!

- Decoupling Other scalars are too heavy.
- Alignment Mass matrix of CP-even states such as the lightest eigenvalue is the one which gets a vet

Higgs alignment from N=2

Promote gauginos from Majorana fermions to Dirac fermions

- Majorana gauginos $\longrightarrow (H_u, H_d)$
- Dirac gauginos $\longrightarrow (H_u, H_d) \oplus (S, T) \oplus (R_u, R_d)$

where

S is a singlet and T an $SU(2)$ triplet. Needed

R_u, R_d, Higgs-like doublets. Needed only if R-symmetry or $SU(3)^3$ unification

Take S, T, R_u and R_d heavy $\longrightarrow$ effective two Higgs doublet model.

Higgs alignment from N=2

$$W_{\rm Higgs} = \mu\, \mathbf{H_u} \cdot \mathbf{H_d} + \lambda_S \mathbf{S}\, \mathbf{H_u} \cdot \mathbf{H_d} + 2\lambda_T\, \mathbf{H_d} \cdot \mathbf{T}\mathbf{H_u}$$

The CP-even scalars mass matrix

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} ,$$

with at tree-level:

$$Z_6 = -\frac{1}{2} s_{2\beta}\, c_{2\beta} \left[\frac{(g^2 + g'^2)}{2} - (\lambda_S^2 + \lambda_T^2) \right]$$

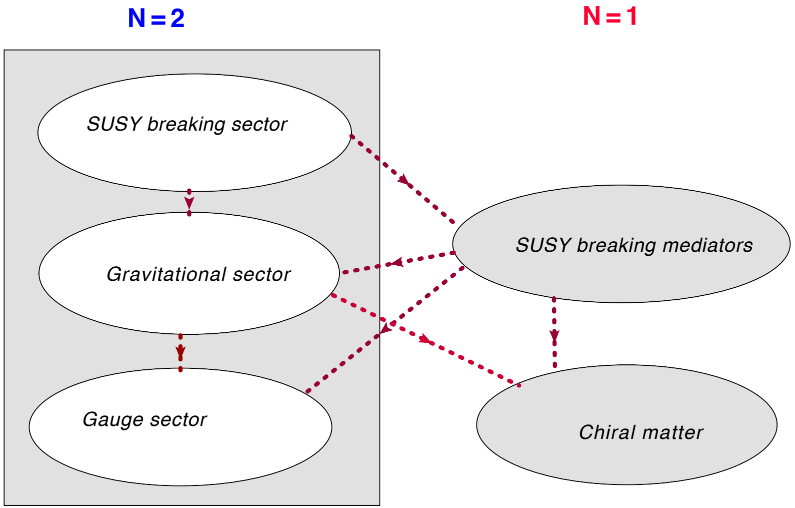
$\longrightarrow 0$ for $N = 2$ Higgs sector. Alignment

(Antoniadis-K.B.-Delgado-Quiros, Ellis-Quevillon-Sanz, K.B.-Williamson...)

At one-loop, correction from $N = 1$ sector, from S, T fields etc ...

$\Longrightarrow$ some mis-alignment.

Hybrid SUSY



N=2/N=1 sectors.

Higgs mis-alignment from N=2 to N=1

The misalignment due to runnings of λ_S and g', and λ_T and g:

$$\left[2\lambda_S^2 - g'^2\right]_{\Lambda_{N=1}} = -\frac{2g'^2}{16\pi^2}\left[3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2 - 10g'^2\right]\log\left(\frac{\Lambda_{N=2}}{\Lambda_{N=1}}\right),$$

$$\left[2\lambda_T^2 - g^2\right]_{\Lambda_{N=1}} = -\frac{2g^2}{16\pi^2}\left[3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2 - 6g^2\right]\log\left(\frac{\Lambda_{N=2}}{\Lambda_{N=1}}\right).$$

Minimize misalignment by lowering $\Lambda_{N=2}$.

Alignment $\rightarrow$ lowering the string scale?

(K.B.-Williamson...)

High scale SUSY

What if SUSY at high scale?

What if SUSY scale is higher?

- Assumption 1: SUSY does not solve the hierarchy problem.
- Assumption 2: SUSY might be part of the solution of he hierarchy problem: takes over at some scale, or just a UV symmetry.

Questions:

- How can SUSY impacts the Higgs mass?
- Will SUSY provide a Dark matter candidate?

Higgs mass in SUSY

- Within a SUSY model , the lightest Higgs mass is computable
- In the MSSM, quartic coupling λ is not arbitrary.
  At the SUSY scale M_S, the quartic Higgs self-coupling is given by the D-term:
  $$\lambda = \frac{1}{4}\left[g^2 + g'^2\right]\cos 2\beta + \Delta\lambda$$
  For a given M_S, is there a value of β corresponding to M_h?

The Higgs quartic coupling evolution

The various contributions to β_λ at one-loop can be roughly classified as:

$$\beta_\lambda = \frac{1}{16\pi^2}\Bigg[\underbrace{12\lambda^2 + \lambda(12y_t^2 + (\cdots\tilde{g}^2\cdots) - (\cdots g^2\cdots))}_{\equiv\ \beta_{\text{quartic}}}$$

$$+\underbrace{(\cdots g\cdots)^4}_{\equiv\ \beta_g}\underbrace{-(\cdots\tilde{g}\cdots)^4}_{\equiv\ \beta_{\tilde{g}}}\underbrace{-12y_t^4}_{\equiv\ \beta_t}\Bigg] \ ,$$

where $(\cdots g\cdots)$ contains gauges contributions, $(\cdots\tilde{g}\cdots)$ contains contributions from Higgs-higgsinos-gauginos couplings.
SUSY fixes λ at M_S and evolve it down to the electroweak scale, positive contributions tend to bring λ towards lower values while negative contributions increases the final tree level Higgs mass.

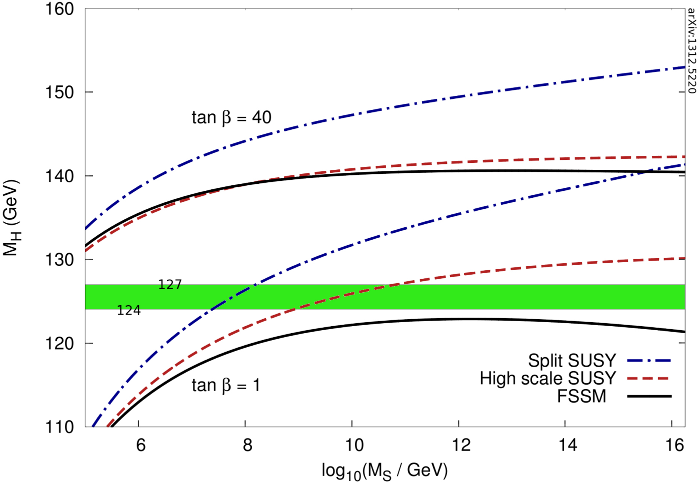
Getting arbitrarily high M_S

Want high scale SUSY. Hierarchy problem solved by something else like relaxion.

- In the MSSM λ increases monotonically when running from the UV to the IR.
- Even starting with the lowest value, $\lambda = 0$, it can reach unacceptably high values at the electroweak scale.

- Solution: change the RGE of λ
- Easiest model : the F(ake)Split SM (K.B.-Darmé-Goodsell-Slavich) One swaps the higgsinos for "fake higgsinos " to switch off the higgsinos Yukawa couplings.
- Low energy signature: gluiness and (fake)-higgsinos
- Pure High Scale SUSY difficult beyond 10^{11} GeV.

Higgs mass with high scale SUSY



$M_{\tilde{g}'} = \mu = 2$ TeV and $\tan\beta = 1$ or 40

Dark Matter

Gravitino as Dark Matter

Assumptions

- $T_{RH} < M_{SUSY} \longrightarrow$ Particles not produced after inflation ,
- $m_{3/2} \ll M_{SUSY} \longrightarrow$ Not gravity mediation SUSY breaking

Light states= SM + gravitino + $\cdots$
where $\cdots$ not super-particles and not dark matter

Gravitinos produced by the SM scattering in the thermal bath.

Gravitinos never in thermal equilibrium!

(K.B.-Chen-Dudas-Mambrini)

Gravitino as Dark Matter

Scattering described by the longitudinal modes (Goldstinos) through dim-8 operators, as

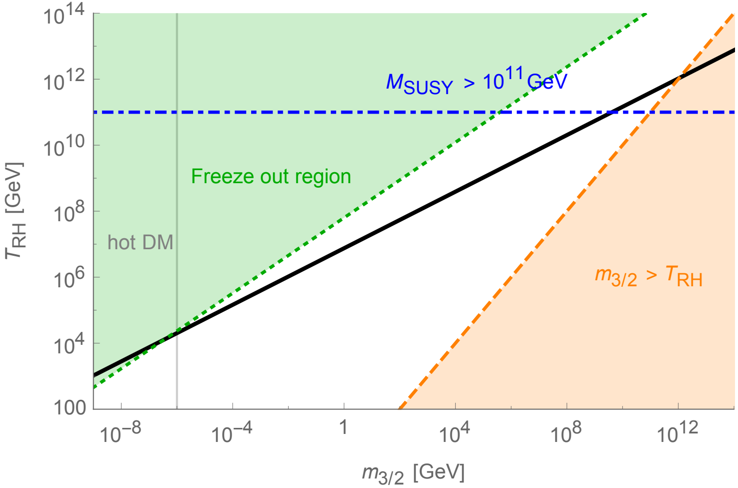
$$\frac{i}{2M_{Pl}^2 m_{3/2}^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\nu H\partial_\mu H^\dagger),$$

Leads to

$$\Omega_{3/2}h^2 \simeq 0.11\left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)^3\left(\frac{T_{\mathrm{RH}}}{5.4\times10^7\ \mathrm{GeV}}\right)^7$$

Therefore T_{RH} not very sensitive to the number of d.o.f's in the Universe.
SUSY provides the gravitino as the DM candidate

T_{RH} vs gravitino mass



Lowest allowed SUSY scale is of order 10 TeV

Conclusion

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- Theoretical indication for experiments: many models guided by the hierarchy problem
- No experimental sign (monitor LHCb) for deviations from SM
- Big theorists disappointment but still too early to abandon hope: SUSY hidden around the corner?

Conclusion

Thank you!