Supersymmetry breaking in the light of LHC

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Habemus Higgs

- \bullet "h" is SU(3)_c x U(1)_{em} neutral
- \bullet "h" has S = 0 and P = 1
- "h" couplings prop. to masses

"h" singlet under custodial symmetry

The unbearable lightness of the Higgs

$$
\delta m_h^2 \sim 12 \lambda_t^2 \int \frac{k^3 dk}{8\pi^2} \frac{1}{k^2} \xrightarrow{\text{cut-off}} 12 \frac{\lambda_t^2}{(4\pi)^2} Q_{\text{max}}^2
$$

- Quadratic divergences "per se" do not mean much (e.g. disappear in dimensional regularization)
- If the SM is the ultimate (renormalizable) theory of everything: $Q_{max} \rightarrow \infty$ mathematical problem (renormalization theory)
- If the SM is the low energy limit of a more fundamental theory: $Q_{max} \rightarrow m_{NP}$ physical (calculability) problem IF m_{NP} $\gg m_H$

μ²" " parametro del potenziale di Higgs (tree level)

M2 massa O(1016 GeV) particella con accoppiamento g all'Higgs

$$
m_H^2 \sim -2 \mu^2 + \frac{g^2}{(4\pi)^2} M^2
$$

The SM can be extrapolated up to MPI

Buttazzo et al

Is SM the ultimate renormalizable theory of everything?

Experimental "problems"

Gravity

Dark matter

Baryon asymmetry

Neutrino masses

Is SM the ultimate renormalizable theory of everything?

Experimental "hints" of physics beyond the SM Neutrino masses

Quantum number unification

Unification

Y

Is SM the ultimate renormalizable theory of everything?

Theoretical puzzles of the SM

 \odot <H> \ll Mp_l

Family replication

Small Yukawa couplings, masses and mixings

Is SM the ultimate renormalizable theory of everything?

Theoretical problems of the SM

Landau poles

Strong CP problem

Naturalness problem

Cosmological constant problem

 $\overline{\theta G_{\mu\nu}\tilde{G}^{\mu\nu}}$ $\overline{D} = 4$

 $\alpha Q_{\text{max}}^2 H^{\dagger} H$ $D = 2$

 $\beta Q_{\text{max}}^4 \sqrt{g}$ *D* = 0

Naturalness problem

Due comments

1. m_{NP} is not precisely determined: any value of m_{NP} is viable as long as a cancellation of one part out of

> $\Delta \gtrsim$ $\sqrt{m_{\rm NP}}$ 0*.*5 TeV \setminus^2

is accepted.

E.g. $m_{NP} > 1.5$ TeV \leftrightarrow $\Delta > 10$ $\overline{m}_{NP} > 5$ TeV \leftrightarrow $\Delta > 100$

Due comments

2. The bound
$$
\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5 \, \text{TeV}}\right)^2
$$
 is model dependent

For example:

Supersoft theories $\delta m_h^2 \approx m_h^2$ $\sqrt{m_{\rm NP}}$ 0*.*5 TeV \setminus^2

Soft theories

$$
\delta m_h^2 \approx m_h^2 \left(\frac{m_{\rm NP}}{0.5 \,\text{TeV}}\right)^2 \times
$$

 $\times \log \left(\frac{M^2}{m_{\tau}^2} \right)$ m_NP^2 ◆

(e.g. **supersymmetry** with mediation scale M)

Due comments

3. Though general, the above argument rests on assumptions

existence of superheavy physics

the cancellation in the Higgs mass is accidental

(dynamical mechanisms? environmental selection?)

Supersymmetry

 \bullet SUSY: fermion \leftrightarrow scalars; SUSY partners much heavier

 $H₂$ e V_1 u d μ ν2 $|c|$ $\texttt{s}~\bigl|~\texttt{b}~\bigr|~\bigl|~\texttt{g}~\bigr|~\bigl|~\tilde{\texttt{d}}~\bigr|~\bigl|~\tilde{\texttt{s}}~\bigr|~\bigl|~\tilde{\texttt{b}}$ τ W e ν3 †) (γ) (ũ) (č) (ĩ $|Z|$ H \sqrt{v}_1 \tilde{e} || $\tilde{\mu}$ || $\tilde{\tau}$ $\tilde{\bm{\mathsf{V}}}_{1}$ $\left[\begin{array}{c} \tilde{\bm{\mathsf{V}}}_{2} \end{array}\right]\left[\begin{array}{c} \tilde{\bm{\mathsf{V}}}% _{1} \end{array}\right]$ $\lceil \tilde{\tau} \rceil$ \tilde{V}_3 Ii. W \tilde{z} $\tilde{\mathsf{Y}}$ \tilde{g} $H₂$ $H₁$ $\tilde{\lambda}$ $\bf \tilde{\bf V}$

- Theoretical motivations
	- Unification of fermions and bosons (we do have a boson after all) \odot
	- Local supersymmetry = supergravity + crucial in string theory \odot
	- Completes the list of possible symmetries of S (under hypotheses) \odot
	- Powerful technical tool

Phenomenological motivations \circledcirc

Solves (the bulk of) the hierarchy problem

$$
\text{Calculability} \qquad \qquad \frac{3}{4\pi^2}\lambda_t^2Q^2 \to \frac{3}{4\pi^2}\lambda_t^2\tilde{m}^2\log\frac{Q^2}{\tilde{m}^2} \qquad \tilde{m}\lesssim \text{few TeV?}
$$

In contrast, the mass of homogeneous of homogeneous of homogeneous \mathbf{r} , one finds at tree-level \mathbf{r} The cancellation of quadratic divergences holds at all orders in perturbation theory

Can be extrapolated up to the Planck scale

Unification

+ M_{GUT} prediction: Λ_B < M_{GUT} < M_{PI}

inflation scale?

 $Q(GeV)$

However

Not chiral (explicit, supersymmetric mass term for the Higgsinos) ➥ Giudice-Masiero, NMSSM

Correct symmetry breaking not guaranteed (CCLB minima)"" ➥ radiative EWSB

- L, B not accidental symmetries anymore
	- \rightarrow R-parity
		- \rightarrow Lightest Supersymmetric Particle (LSP) is stable (DM, missing E_T)
		- SUSY corrections to SM processes only via loops

Trouble with supersymmetry breaking

Supersymmetry breaking

Supersymmetry predicts $m = \tilde{m}$

Needs to be broken, hopefully spontaneously \circ

Effective description in terms of O(100) parameters \odot

$$
-\mathcal{L}_{\text{soft}} = A_{ij}^{U} \tilde{u}_{i}^{c} \tilde{q}_{j} h_{u} + A_{ij}^{D} \tilde{d}_{i}^{c} \tilde{q}_{j} h_{d} + A_{ij}^{E} \tilde{e}_{i}^{c} \tilde{l}_{j} h_{d} + m_{ud}^{2} h_{u} h_{d} + \text{h.c.}
$$

+ $(\tilde{m}_{q}^{2})_{ij} \tilde{q}_{i}^{\dagger} \tilde{q}_{j} + (\tilde{m}_{u}^{2})_{ij} (\tilde{u}_{i}^{c})^{\dagger} \tilde{u}_{j}^{c} + (\tilde{m}_{d}^{2})_{ij} (\tilde{d}_{i}^{c})^{\dagger} \tilde{d}_{j}^{c} + (\tilde{m}_{l}^{2})_{ij} \tilde{l}_{i}^{\dagger} \tilde{l}_{j} + (\tilde{m}_{e}^{2})_{ij} (\tilde{e}_{i}^{c})^{\dagger} \tilde{e}_{j}^{c} + m_{h_{u}}^{2} h_{u}^{\dagger} h_{u} + m_{h_{d}}^{2} h_{d}^{\dagger} h_{d}$
+ $\frac{M_{3}}{2} \tilde{g}_{A} \tilde{g}_{A} + \frac{M_{2}}{2} \tilde{W}_{a} \tilde{W}_{a} + \frac{M_{1}}{2} \tilde{B} \tilde{B} + \text{h.c.}$

(Vanilla) direct experimental constraints

- Based on missing E_T \odot
- First family squarks \circ
- One slice of the par space

How bad is it?

Supersymmetry is a soft theory

$$
\begin{array}{ccc}\n\delta m_h^2 & \approx & m_h^2 \left(\frac{m_{\rm NP}}{0.5 \,\mathrm{TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right) \\
& \approx & m_h^2 \left(\frac{m_{\rm NP}}{0.5 \,\mathrm{TeV}/\sqrt{\log}}\right)^2\n\end{array}
$$

M = mediation scale

E.g. in supergravity $M = M_{Pl}$

A tale of naturalness

- **Supergravity (unavoidable mediation mechanism):** $\Lambda_{NP} = M = M_{Planck}$
- \circ log = $O(70) \implies$ natural expectation: m_{NP} around Mz!

Lower M: how low?

Where does FT come from?

$$
m_Z^2 \approx -2m_{H_u}^2 - 2|\mu|^2
$$
 + experimental constraints
+ indirect bounds from m_H

$$
\delta m_{H_u}^2 \sim -12 \frac{\lambda_t^2}{(4\pi)^2} \tilde{m}_t^2 \log \frac{M}{\tilde{m}_t}
$$

$$
\delta \tilde{m}_t^2 = \frac{32}{3} \frac{g_3^2}{(4\pi)^2} M_3^2 \log \frac{M}{M_3}
$$

Ways out

- Dirac gluinos
- Weakly constrained regions

 $from m_H$

 \bullet Give up E_T-miss signature

Give up naturalness

How light can the stop be?

How light can the stop be?

"Light" stops and $m_H = 126$ GeV

In the MSSM (only SM superpartners)

$$
m_h^2 \le M_Z^2 \cos^2 2\beta \quad \text{(tree level)}
$$

$$
m_h^2 = M_Z^2 \cos^2 2\beta + 12 \frac{h_t^2 m_t^2}{(4\pi)^2} \left[\log \frac{\tilde{m}_t^2}{m_t^2} + \dots \right] \quad \text{(one loop)}
$$

Hall Pinner Rudeman 1112.2703 Hall Pinner Rudeman 1112.2703

"Light" stops and $m_H = 126$ GeV: NMSSM

Minimal extension: λSHuHd (symmetries forbid μHuHd)

harmless (unification OK)

 \bullet welcome $(\mu = \lambda \langle S \rangle \approx \text{susy scale})$

 $m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loops}$

"Natural" values of sparticle masses

M > 10 TeV + tuning < 10%: (less un)"natural SUSY"

 \circ $\mu \le 200$ GeV $\boxed{\circ}$ m_{stop} \leq 500 GeV \odot M₃ \leq 1.4 TeV

Need

 $(m_3)^2 \ll (m_{1,2})^2$ (by a factor about 5-10) MSSM → NMSSM

A motivated framework

O NMSSM

With supersymmetry mediated at a low scale M

And lighter $(m_3)^2 \ll (m_{1,2})^2$ (by a factor about 5–10)

Realizing natural susy?

Tree-level extra U(1) gauge mediation for families 1,2

[Nardecchia R Ziegler]

[Anomalous case: e.g. Barbieri Ferrara Nanopoulos Dvali Pomarol]

↑ Z^{\dagger} Z Q^{\dagger} $\mathsf Q$ V

massive vector of a spontaneously broken non-anomalous U(1) $G \supset G_{SM} \times U(1)$

 $Q_{1,2}$ charged under $U(1)$ Q3 H NOT charged

 $\tilde{m}^2_{1,2} = q_{1,2} \, \tilde{m}^2$

third family, Higgs are loop suppressed

 $M \approx M_V$ scale of U(1) breaking

◎ Ren. Kähler + tree level + $Tr(T_a) = 0 \rightarrow 5$ tr M² = 0

Supergravity: non-renormalizable Kähler: Str \neq 0 FCNC ?

 \bullet "Loop" gauge-mediation: loop-induced: Str \neq 0 FCNC OK

Anomalous $U(1)$'s: $Tr(T_a) \neq 0$: Str $\neq 0$ FCNC OK

 \odot Tree-level gauge mediation: Str = 0

FCNC OK

Need of extra heavy (through U(1) breaking) fields

Masses2 (before EWSB)

 $STr = 0$

• Play the role of gauge mediation messengers

Stop, gluino, and Higgs mass get a (suppressed) mass

Light Yukawas break U(1): understanding of SM flavour

A simple and viable complete model

Natural susy helps... to some extent

Where does FT come from?

$$
n_Z^2 \approx -2m_{H_u}^2 - 2|\mu|^2
$$
 + experimental constraints
+ indirect bounds from m_H

$$
\delta m_{H_u}^2 \sim -12 \frac{\lambda_t^2}{(4\pi)^2} \tilde{m}_t^2 \log \frac{M}{\tilde{m}_t}
$$

$$
\delta \tilde{m}_t^2 = \frac{32}{3} \frac{g_3^2}{(4\pi)^2} M_3^2 \log \frac{M}{M_3}
$$

Ways out

Lower M

Decouple stop from sup, scharm

m

8 NMSSM

Dirac gluinos

Weakly constrained regions

 $from m_H$

 \bullet Give up E_T-miss signature

Dirac gauginos

$$
m_Z^2 \approx -2m_{H_u}^2 - 2|\mu|^2
$$

\n
$$
\delta m_{H_u}^2 \sim -12 \frac{\lambda_t^2}{(4\pi)^2} \tilde{m}_t^2 \log \frac{M}{\tilde{m}_t}
$$

\n
$$
\delta \tilde{m}_t^2 = \frac{32}{3} \frac{g_3^2}{(4\pi)^2} M_3^2 \log \frac{M}{\tilde{M}_3}
$$

- Sfermion masses super-soft (larger natural M3)
- Suppress flavour violation
- R-symmetry conserved (useful for theory of susy breaking)
- From N=2 in gauge sector

<u>D-terms do not break and they cannot break and they cannot contribute to Majorana gauginos.</u> In our framework, D-terms can be the only source of supersymmetry breaking. We will source of supersymmetry br 2.2 Other supersoft operators

including those from top loops, which become very important in this scenario.

↵ *D*

$$
\int d^2\theta \sqrt{2} \frac{W_{\alpha}' W_{j}^{\alpha} A_j}{M} \ m_D \sim \frac{\alpha}{4\pi} \frac{D}{M} \qquad \qquad \int d^2\theta \frac{W_{\alpha}' W}{M^2}
$$

If MPL, this term will be subdominant to anomaly mediated soft masses, which masses, while in gauge in gauge in

mediated models it actually contributes negatively to sfermion masses squared [20]. Since

assume the presence of an hidden sector U(1)! which acquires a D-component vev.⁵ With the

 $A\rightarrow 2.3$ we shortly in section 2.3, this operator is supersoft, in that it does not give α

log divergent radiative contributions to other soft parameters, as would, e.g., a Majorana

additional fields from the gauge extension, we can add the operator \mathcal{A}

gaugino mass. Including this operator, the Lagrangian contains the terms

 $\frac{1}{2}$

 \mathcal{L}

$$
\int d^2\theta \frac{W'_\alpha W'^\alpha}{M^2}A_j^2
$$

As we will discuss shortly, there are the usual one-loop contributions to the quartic coupling,

 W the extended field content and the U(1) μ the U(1) μ the U(1) μ there is one other supersoft operator supersoft operator supersoft operator supersoft operator μ

 W is for the ESP fields, this term can be written for any real representation for any real representation for any α

of a gauge group. This term splits the scalar and pseudoscalar masses squared by equal

amounts, leaving some component with a negative contribution to its mass squared. If the its mass squared α

expect that it would give a logarithmically divergent "gaugino mediated" contribution to the

scalar masses squared. However, from a general argument, we can see that this is not the

$$
\frac{2}{j}\left|\ \delta\tilde{m}^2_A\sim\pm\frac{\alpha}{4\pi}\left(\frac{D}{M}\right)\right|
$$

- Sfermion masses super-soft $($ larger natural M₃)
	- Suppress flavour violation, prod. superpotential term, in order to prevent color and charge breaking. $\frac{1}{2}$ although there is no symmetry which allows the terms in $\frac{1}{2}$
- R-symmetry conserved (useful onserved (aserar + and an arrived theory of susy breaking)
- From N=2 in gauge sector *M, a is the complex scalar component* of α

fields charged under the group G^j . Notice that the gaugino now has a Dirac mass with

the ESP fermion $\mathcal{L}_\mathcal{A}$ is designed to designate fields which are R-parity of the R-parity of the R-parity of

masses were considered previously in the orientation of the possibility in the possibility \mathbb{R}^n . The possibility \mathbb{R}^n

- fermion masses super-soft $\bullet\quad$ μ/β µ-like issue reintroduces a arger natural M₃) is the pseudoscalar and a log(loop) enhancement
	- Tachyons?
- -symmetry conserved (useful and virification prediction spoiled
- Higgs quartic forbidden (extra \odot model-building needed) Below the scale M, where (2.4) is generated, the gaugino has a mass, so we would naively

Weakly constrained regions of parameter space

Compressed spectra

m

reduced activity (small phase space)

- LSP back to back
- theory?

Giving up the E_T -miss signature: RPV

Baryonic RPV + Leptonic RPV = proton decay

Leptonic RPV well constrained

Giving up the E_T -miss signature: RPV

- \bullet Use baryonic RPV Forbid leptonic RPV
- Need also \odot

 $m_{3/2}$ > 1 GeV (p-decay) and $m_{3/2}$ < 10 GeV (flavour) \circledcirc δ λ'' < 10⁻⁵ (Δ B = 2) and λ'' > 10⁻⁷ (prompt decay)

$$
\bullet \hspace{0.1cm} \textsf{Need} \hspace{0.1cm} W_{\text{eff}}^{\text{ren}} = W_{\text{MSSM}} + \lambda_{ijk}^{\prime\prime} u_{i}^{c} d_{j}^{c} d_{k}^{c},
$$

Unification? where ⌅⇥⇥ *ijk* is antisymmetric in the flavour indices *j, k*. $\Lambda_{ijk} \, \overline{5}_i \overline{5}_j 10_k$ \bullet Unification? $10_i \overline{5}_j \overline{5}_k = u^c_i d^c_j d^{c6}_k + Q_i d^c_j L_k + Q_i L_j d^c_k + E^c_i L_j L_k$ forms leptons into baryons (preserving *B L* in the min- $\frac{1}{\sqrt{2}}$ or $\frac{1}{\sqrt{2}}$ of $\frac{1}{\sqrt{2}}$ or $\frac{1}{\sqrt{2}}$ of $\frac{1}{\sqrt{2}}$ or $\frac{1}{\sqrt{2}}$ ication? $10_i 5_j 5_k = u^c_i d^c_j d^c_k + Q_i d^c_j L_k + Q_i L_j d^c_k$ sible *a*16*a*16 10 and *ab*16*a*16*b*10 terms are not allowed as they would give rise to *q d^cl* operators. On the other \overline{H} **h** \overline{C} \overline{I} \overline{I} E_{i} L_{j} L_{k}

as it generically also generates lepton number violating

ublets developing the EW-symmetry-breaking VEV .
ere latter into ω 10, solution inf6O(10)he standbared rb6 \oplus 16 \oplus 10 is violated through baryon-number-violating interactions lated, s
L $\frac{1}{\alpha}$ due to $\frac{1}{\alpha}$ $rac{1}{\omega}$ $\frac{1}{2}$ kawa s imal case of SU(5)), one would expect that operator to they depend on the embedding of the Higgs $V_{\rm LPLV}$ *ijkqid^c* \mathbf{e} 2–3 splitting (see e.g. [49, 50]), while the *ⁱ* and *lⁱ* are $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ are in $\frac{1}{2}$ and $\frac{1}{2}$ *ⁱ* , *e^c ⁱ* are unified in a 10*ⁱ* and the y_{max} that depend on the exploding lated, since they depend on the embedding of the Higgs ublets developing the EW-symmetry-breaking VEV. ences for the $2-3$ splitting (see e.g. $[49, 50]$), while the

$$
W_Y = y_{ij} 16_i 16 \overline{W_1} = \lambda 16 16 10 + \alpha_a \overline{16} 45_H 16_a + \beta_a 16_H 16_a 10 + M_{16} \overline{16} 16
$$

 $t_{\rm b}$ $\mathbf{D}\mathbf{e}$ ans than at least 10¹⁰ for any value of *i, j, k* and for sube discussed in detail in Sect. IV A.
It is important to stross that the model specified is The Sect. IV A.

Supersymmetric scenarios without R-parity have re-

ceived a renewed interest after the negative results of

SUSY searches at the LHC [1–6]. R-parity accounts

for the stability of the lightest supersymmetric particle

 $\mathcal{L}(\mathcal{L})$

prototypical supersymmetry signal: missing energy. R-

parity violation (RPV) may allow supersymmetric par-

 $t_{\rm max}$

lar, it has been argued that scenarios in which R-parity

In order for baryon number violating RPV operators

 $\frac{10}{16}$ is 11 $\mathrm{E}^1[\mathrm{G}/\mathrm{L}\mathrm{G}^\prime]$ ${\rm\thinspace hie}$ ve tl R-parity was originally introduced in order to obtain (acperfect that the model specified in the TeV such a time is only "took" [Di Luzio p_i is p_i or p_i if p_i is p_i if p_i is single the theorem in p_i is single the theorem in p_i is single the theorem in p_i is p_i is p_i in p_i is p_i in p_i is p_i is p_i is p_i is p_i is p_i is p_i hieve the splittings within the GUT multiplets, without Hence, obtaining size able to the presence of vanishing σ in the presence of vanishing and presence of vanishing It is important to stress that the model specified in \mathbf{q}_5 , (29) – (30) , although entirely realistic, is only "tech- $\mathcal{L}_{\text{ca}}^{\text{S}}(G) = (30)$, although entirely realistic, is only "tech-
cally $\frac{1}{10}$ $\frac{1}{10}$ fine-tuning the parameters of the superpotential, one has •Possibility to fit the mass texture of quarks and charged leptons at the ess that the model specified in **the terms** [Di Luzio N Prf_i^{tr} term Prf_i^{tr} the singlet Prf_i^{tr} for $\text{Prf}_i^{\text{$

[Di Luzio Nardecchia R] generated. The two vectors ↵*^a* and *^a* need to be linearly i chia κ j κ

*yab*16*a*16*b*10*H*. Doublet-triplet splitting should be ac-

counted for separately, but all the ingredients for the

Dimopoulos-Wilczek mechanism are available [50, 56–

16*H*, 16*H*, 45*^H* to two matter fields, as anticipated. A

mass term in the form 1616*^a* can be eliminated by a SU(4)

rotation of the four spinorials 16, 16*a*, *a* = 1*,* 2*,* 3. Pos-

 $T_{\rm eff}$ is associated to the following to the foll

The RPV operator arises from 16*a*16 10 because of

the mixing between 16*a,* 16*,* 10 induced by the terms

↵*a*16 45*H*16*^a* and 16*H*1610 after SO(10) breaking. The

light lepton and quark doublets are fully contained in the

16*a*, so that no lepton number violating operators can be

 $T_{\rm eff}$ in principle accommodated be in princi

in the 10, 16³ and 16 (in the basis in which ↵1*,*² = 0)

and doublet-triplet splitting achieved for free if = 0.

+ 16*H*1610 + 16*H*1610 + *M*161616 *.* (10)

lowing superpotential

*W*² = *a*16*a*16 10 + ↵*a*16 45*H*16*^a*

In Eq. (9) we have included only interactions coupling

Giving up the E_T -miss signature: stealth susy

 \odot R_p is conserved

Lightest Visible Supersymmetric Particle decays into a "hidden sector" singlet with small splitting $\widetilde{\mathsf{S}} \to \mathsf{S}$ + LSP (gravitino)

 \bullet Small E_T-miss because of small Δm

How does SUSY compares with competitors?

Generic composite Higgs is supersoft

$$
m_h^2 = \delta m_h^2 \approx m_h^2 \left(\frac{m_{\rm NP}}{0.5 \, {\rm TeV}} \right)^2
$$

if m_{NP} = mass of first resonances \approx compositeness scale, as expected

- Compositeness scale > 5 TeV
	- ➥ 1% fine-tuning (comparable with natural susy)

$$
\bullet \quad \textsf{But} \ m_h^2 = \delta m_h^2 \quad \textsf{needs} \ (\textsf{m}_{\textsf{NP}})^2 \ll (\textsf{5TeV})^2
$$

- \rightarrow soft, with M = compositeness scale (better)
- \rightarrow tension moves to smallness of $(m_{NP})^2$

Is the naturalness criterium really relevant?

Though general, the naturalness argument rests on assumptions

- the cancellation in the Higgs mass is accidental \odot
	- environmental selection
	- only understanding available for cosmological constant

existence of superheavy physics \odot

- **The maybe there are no dofs much heavier than TeV**
- then quadratic corrections do not matter

No superheavy physics?

Neutrino mass models add extra particles with mass *M*

Leptogenesis is compatible with FN only in type I.

Axion and LHC usually are like fish and bicycle because $f_a \gtrsim 10^9$ GeV. Axion models can satisfy FN, e.g. KSVZ models employ heavy quarks with mass *M*

$$
M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74 \text{ TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5 \text{ TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1 \text{ TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}
$$

Inflation does not need big scales and anyhow flatness implies small couplings. Absolute gravitational limit on H_I and on any mass [Arvinataki, Dimopoulos..]

$$
\delta m^2 \sim \frac{y_t^2 M^6}{M_{\rm Pl}^4 (4\pi)^6}
$$
 so $M \lesssim \Delta^{1/6} \times 10^{14} \text{ GeV}$

Dark Matter: extra scalars/fermions with/without weak gauge interactions.

- What about gravity? \rightarrow Adimensional gravity \circledcirc
	- renormalizable gravity + no mass scale inducing physical quadratic corrections \circledcirc
	- (but a ghost) \bullet r \approx 1.3

Strumia

Giving up naturalness: Split Supersymmetry

[Arkani-Hamed Dimopoulos Giudice R Arkani-Hamed Dimopoulos Giudice R]

E

SM

 $SUSY + R/$

– MPl

– SUSY

 $\langle H \rangle = 174$ GeV

 m^2 _h « δm^2 _h accidentally or because of unspeakable reasons

Dark matter and unification keep part of spectrum near TeV \odot

An (almost) troubleless MSSM

Issues $\ddot{\odot}$

- Potentially > 100 parameters (CMSSM)
- FCNCs and CP-violation in particular EDMs \bullet (SUSY breaking mechanism, symmetries)
- Proton decay from dimension 5 operators \odot (non minimal models)
- Gravitino and moduli problem (low reheating T)
- Fine-tuning (NMSSM) \circledcirc
- Successes of the MSSM \odot
	- Gauge coupling unification
	- Natural dark matter candidate (with R-parity)

scalars

fermions

Back to the MSSM

Sfermion (stop) masses from $m_H = 126$ GeV

Arvanitaki Craig Dimopoulos Villadoro

Tree-level extra U(1) gauge mediation for ALL families

[Nardecchia R Ziegler]

[Anomalous case: e.g. Barbieri Ferrara Nanopoulos Dvali Pomarol]

↑ Z^{\dagger} Z Q^+ Ω V

massive vector of a spontaneously broken non-anomalous U(1) $G \supset G_{SM} \times U(1)$

 $\tilde{m}_f^2 = q_f \, \tilde{m}^2$

 $M_g \sim$ α 4π *k h F M*

 $M \approx M_V$ scale of U(1) breaking

Expectations and constraints

In conclusion

Maybe Nature is telling us something about NP and SUSY in particular...

At least, NP is not vanilla supersymmetry

Perhaps NP is not natural

Hopefully, unlike the Higgs, is unexpected

 \bullet Looking forward to 8 TeV \rightarrow 13/14 TeV