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Is the SM scalar the first discovered SUSY particle?

Based on JHEP 1302 (2013) 081 [arXiv: 1211.4526]

with A. Pomarol and F. Riva

Rencontres de Moriond 2014
Electroweak Interactions and Unified Theories
La Thuile, 15-22/03/2014

The recently discovered scalar particle ➠ H
and the neutrino ν have the
same gauge quantum numbers:

$$L = \begin{pmatrix} \nu \\ l_L^- \end{pmatrix} = (1,2)_{1/2} \qquad H = \begin{pmatrix} h^0 \\ h^- \end{pmatrix} = (1,2)_{1/2}$$

but L is a fermion and H is a boson...

can they be one the superpartner of the other?

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but L is a fermion and H is a boson...

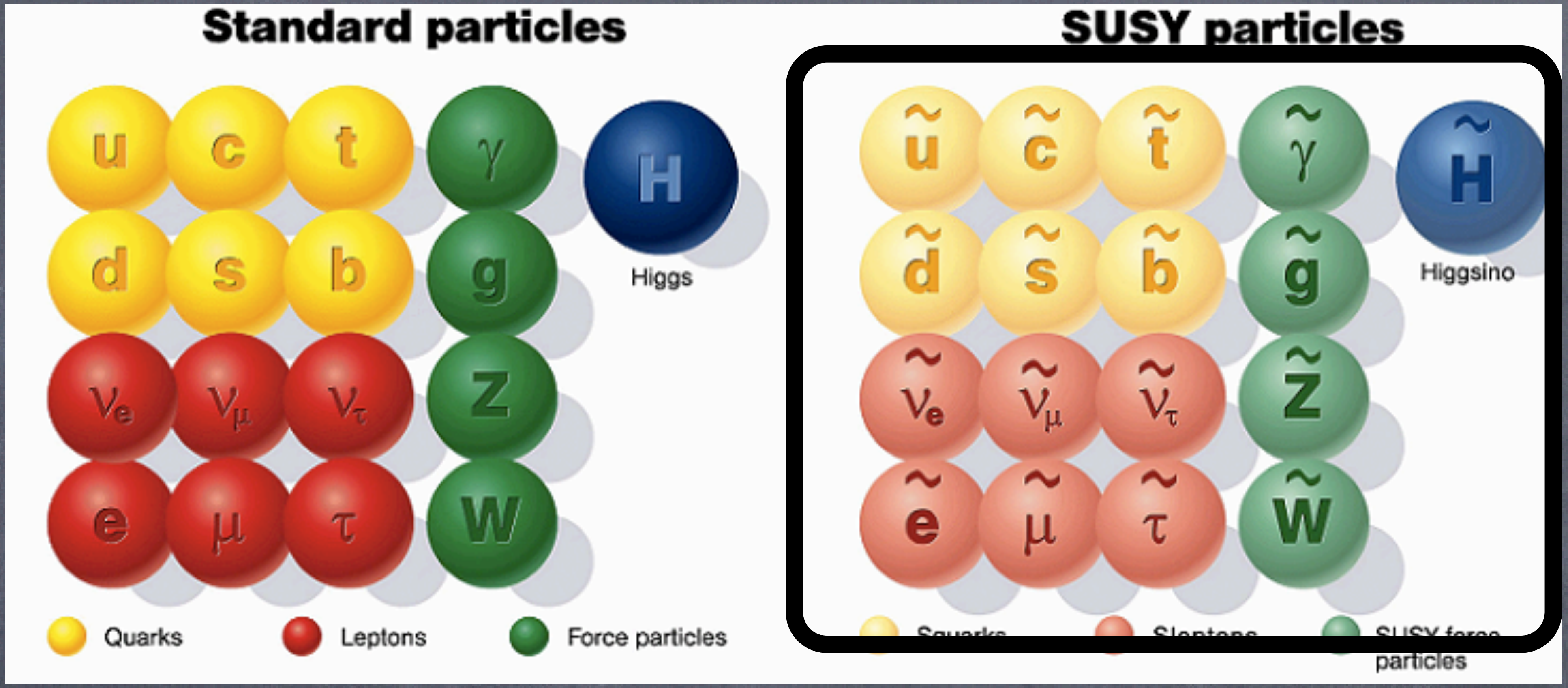
can they be one the superpartner of the other?

YES!

but not trivial: 2 conditions have to be satisfied

MSSM with R-parity

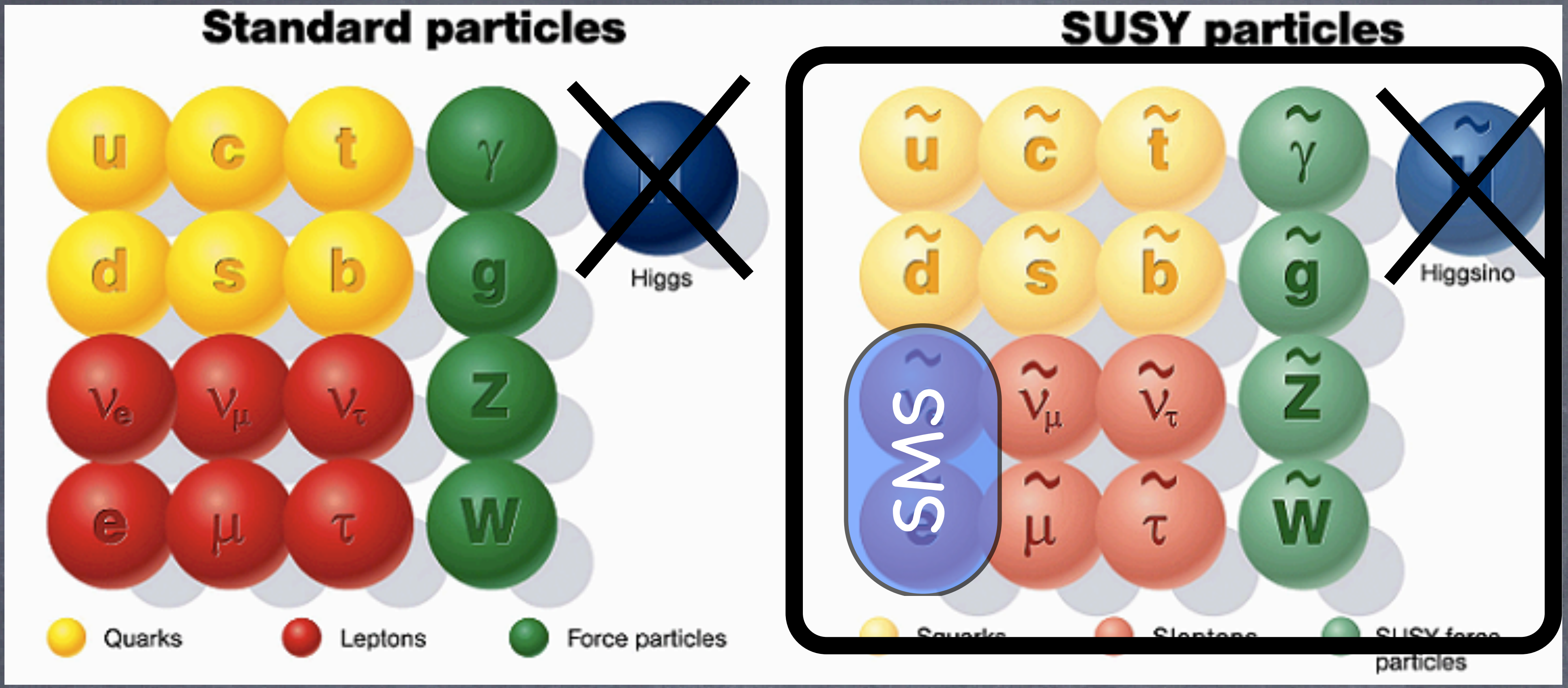
An R-parity is imposed, mainly to avoid fast proton decay



R=1 R=-1

Conseqs: 1. stable Lightest SUSY Particle (LSP): DM candidate?
2. @LHC SUSY particles produced in pairs
3. @LHC if LSP neutral, a lot of MET (missing energy)

$H \equiv \tilde{\nu}$: IS IT POSSIBLE? (1)



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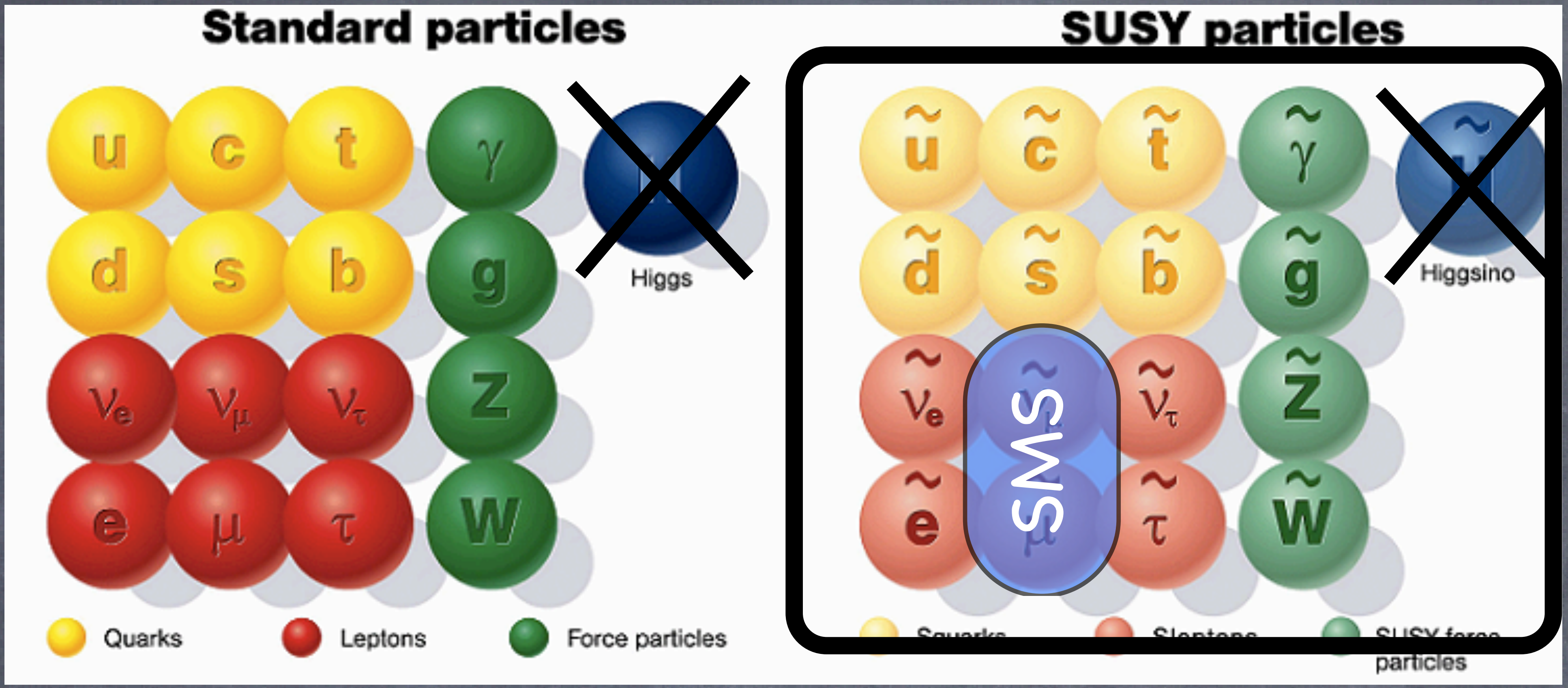

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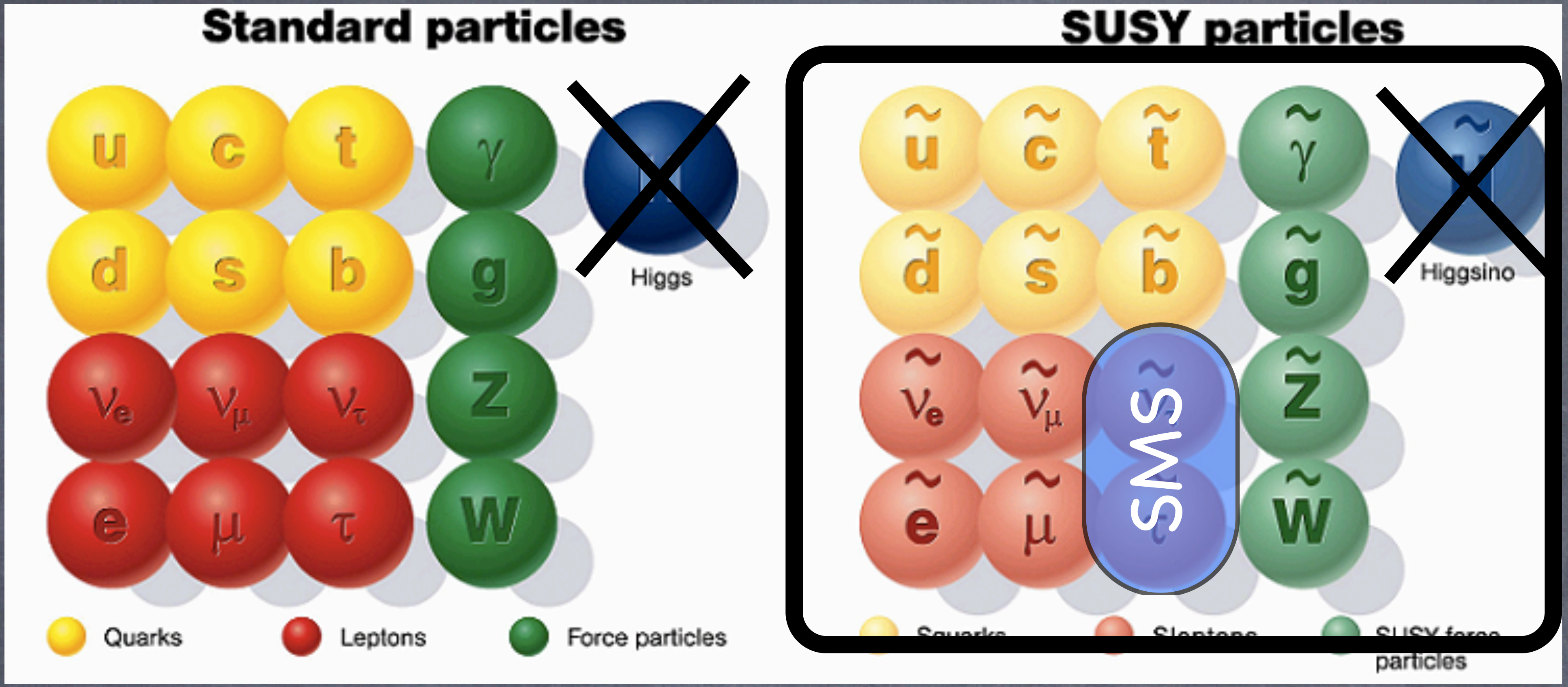

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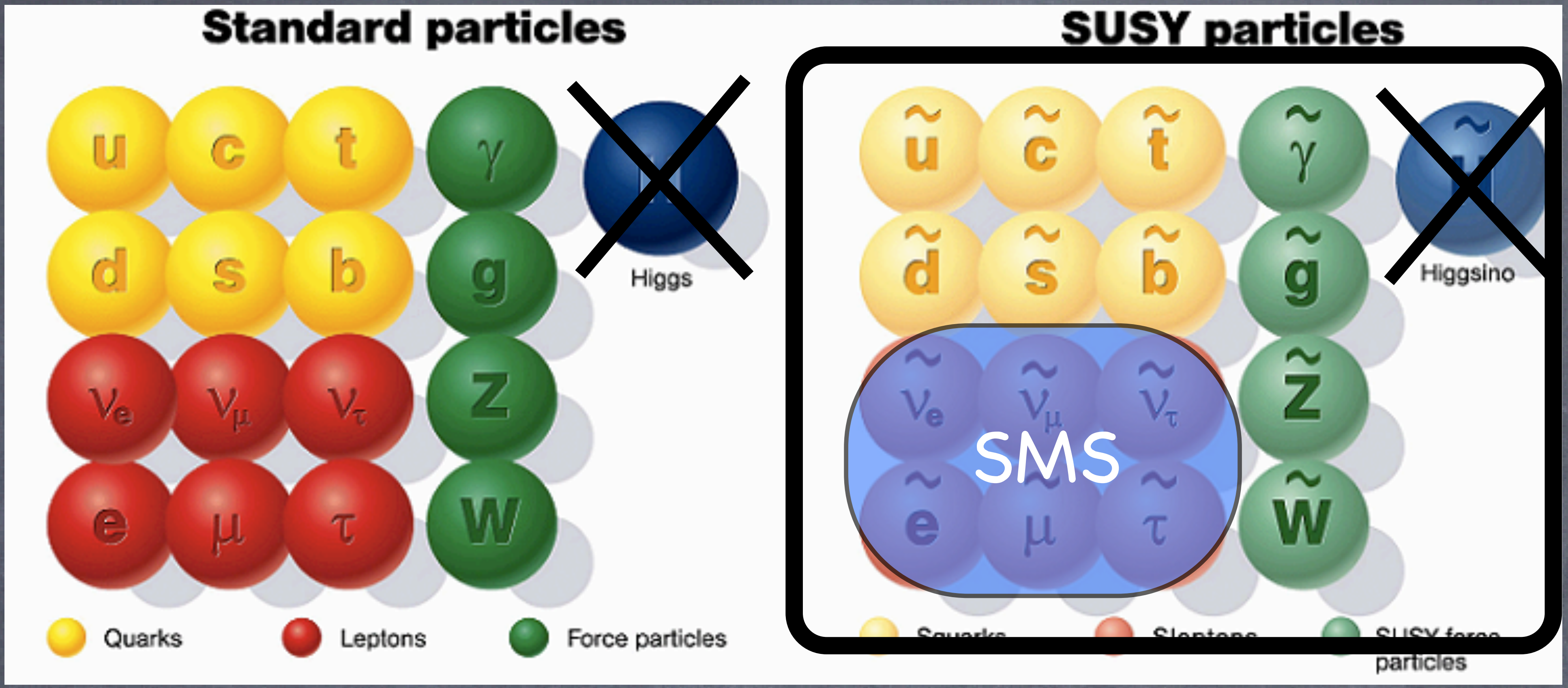

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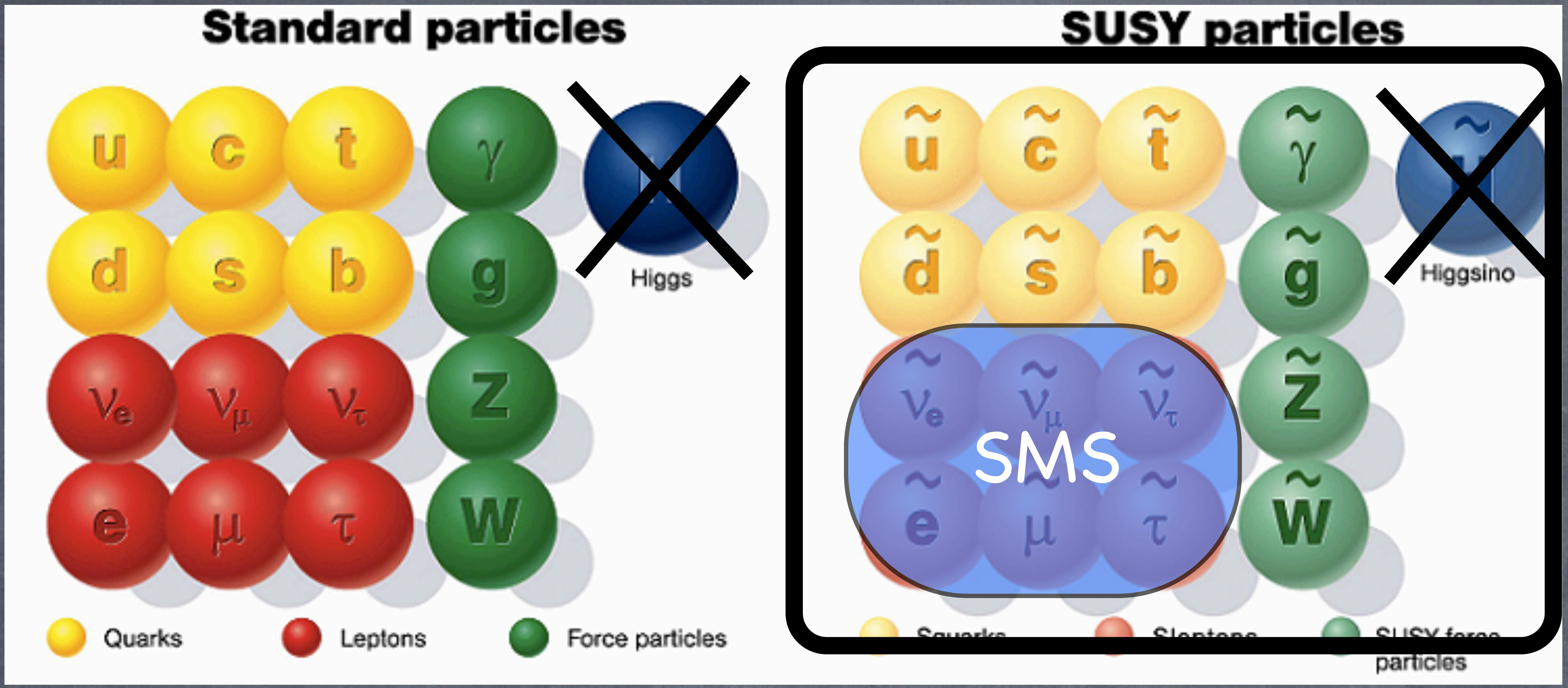


R=1

R=-1

Is R-parity still viable? *NO!*

The scalar vev breaks R-parity and L-number

→ fast proton decay

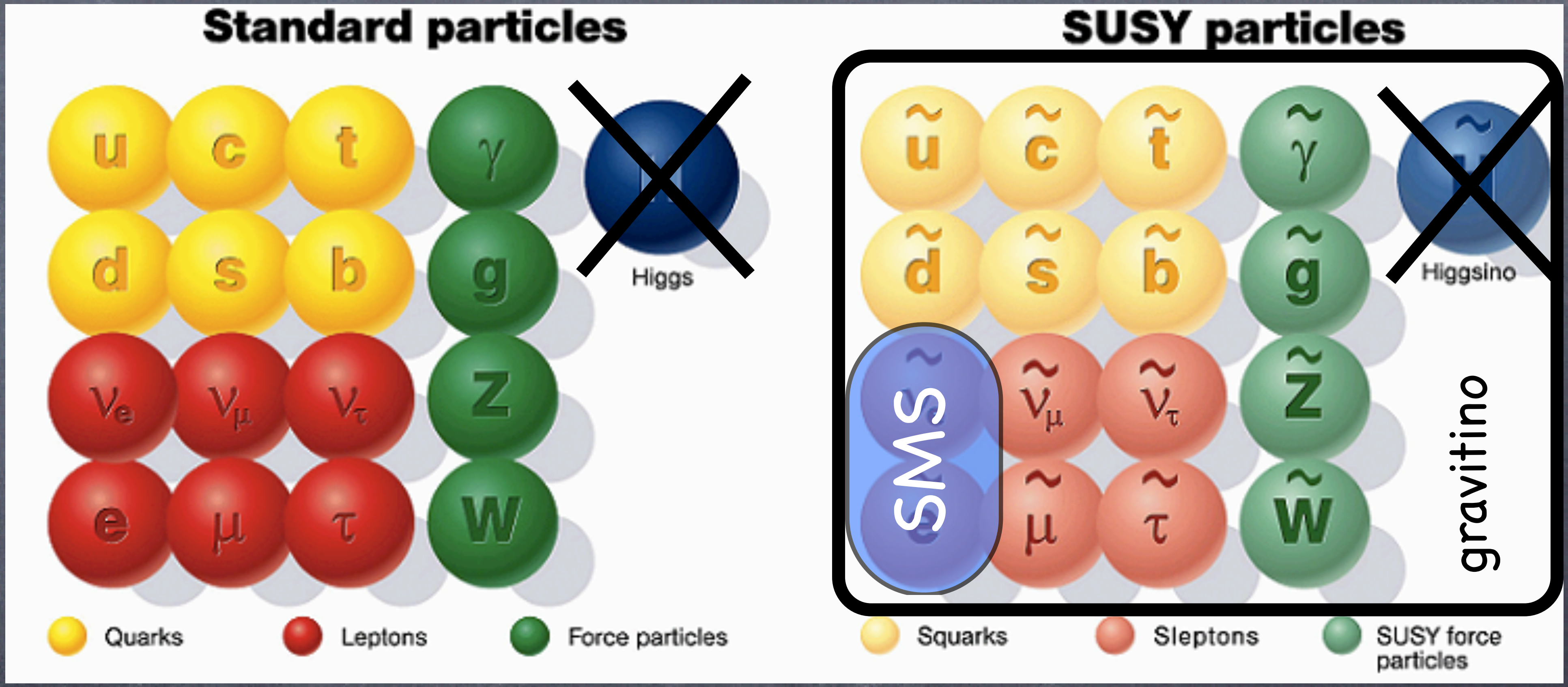
→ large neutrino masses

$H \equiv \tilde{\nu}$: IS IT POSSIBLE? (1)

1st condition:

replace R-parity with $U(1)_R$ symmetry acting as a Lepton Number

Example:



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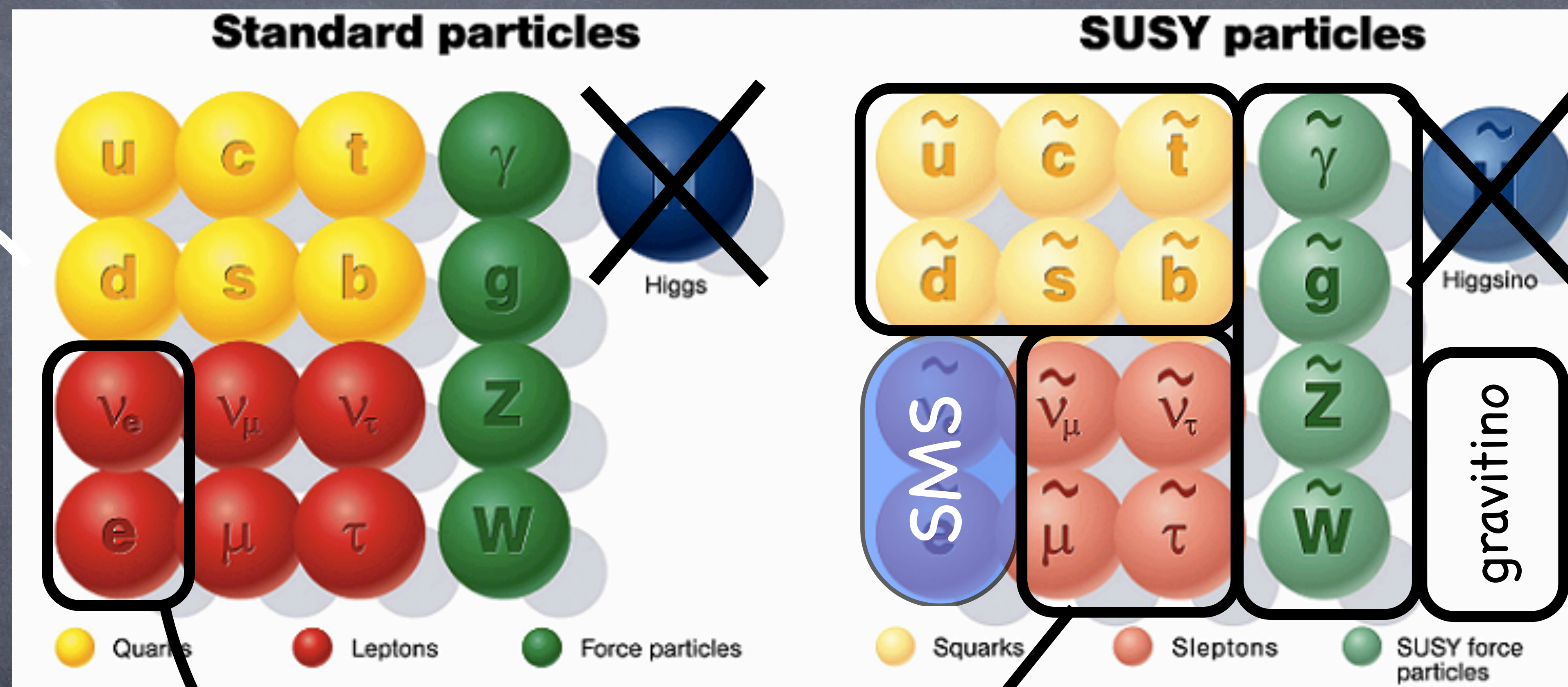


R-charge = 0

R-charge = 1

Fayet 76
Gherghetta Pomarol 03
Frugiuele Gregoire 11
Riva, CB, Pomarol 13
...

The SMS vev does not break $U(1)_R \equiv U(1)_{LN}$

$H \equiv \tilde{\nu}$: is it possible? (1)

1st condition:

replace R-parity with U(1)$_R$ symmetry acting as a Lepton Number

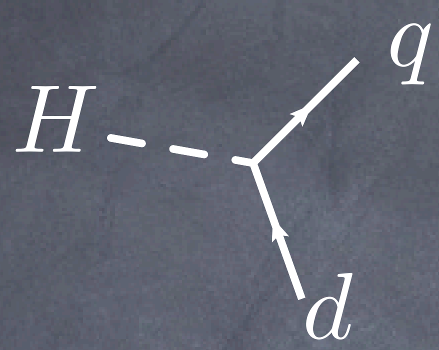
Phenomenological consequences:

- new decays @ LHC → leptoquark decays $\tilde{q} \rightarrow q\ell$
- relations among squark masses $m^2_{\tilde{b}_L} = m^2_{\tilde{t}_L} - m^2_t + m^2_b$
- Dirac gaugino masses → no same-sign dileptons
- lepton-gaugino mixing: lepton couplings modified

→ gaugino masses > TeV

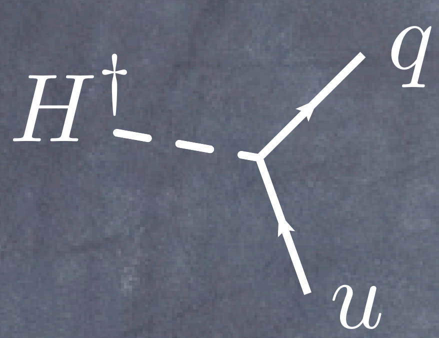
$H \equiv \tilde{\nu}$: IS IT POSSIBLE? (2)

m_d



✓ Can be supersymmetrized

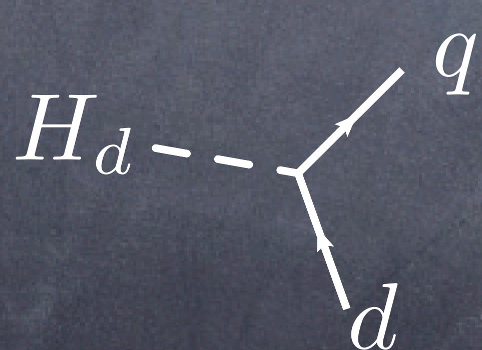
m_u



✗ Cannot be supersymmetrized:
(superpotential must be analytic)

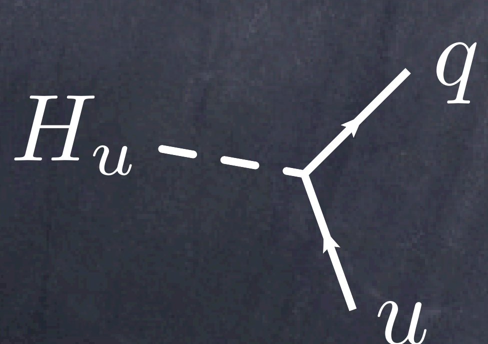
Usual solution:

m_d



✓

m_u



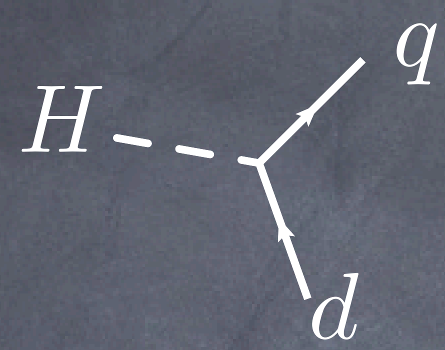
✓

Two scalar doublets:

- MSSM
- H_u + $L=H_d$ Frugiuele Gregoire 2011

$H \equiv \tilde{\nu}$: IS IT POSSIBLE? (2)

m_d



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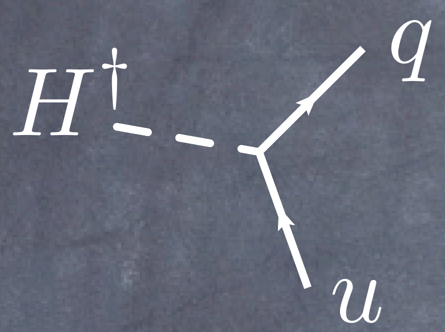

✗ Cannot be supersymmetrized:
(superpotential must be analytic)

We would like to have only 1 scalar doublet, identified with a lepton superpartner

→ 2nd condition:
the masses of the up-type quarks should come from a SUSY breaking sector

Masses from SUSY breaking sector: not a surprise!

$m_H \approx 125$GeV requires S~~USY~~ :

$$(125\text{GeV})^2 = m_Z^2 \cos^2 2\beta + \delta m^2$$

SUSY: $< (91\text{GeV})^2$

~~SUSY~~: $\gtrsim (86\text{GeV})^2$

(In the MSSM large A-terms or heavy stops)

The Higgsinoless MSSM

$$W = Y_d HQD + Y_{e\,ij} HL_i E_j$$

→ m_d

→ m_e (not for L_3)

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All the rest comes from SUSY breaking terms:

1. up-type quarks Yukawa couplings
2. L_3 Yukawa coupling
3. gaugino masses
4. Higgs quartic coupling

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1. up-type quarks Yukawa couplings

$$\int d^4\theta \; y_u \frac{X^\dagger}{M} \frac{H^\dagger QU}{\Lambda} = \int d^2\theta \; Y_u H^\dagger QU \qquad Y_u = y_u \frac{F}{M\Lambda}$$

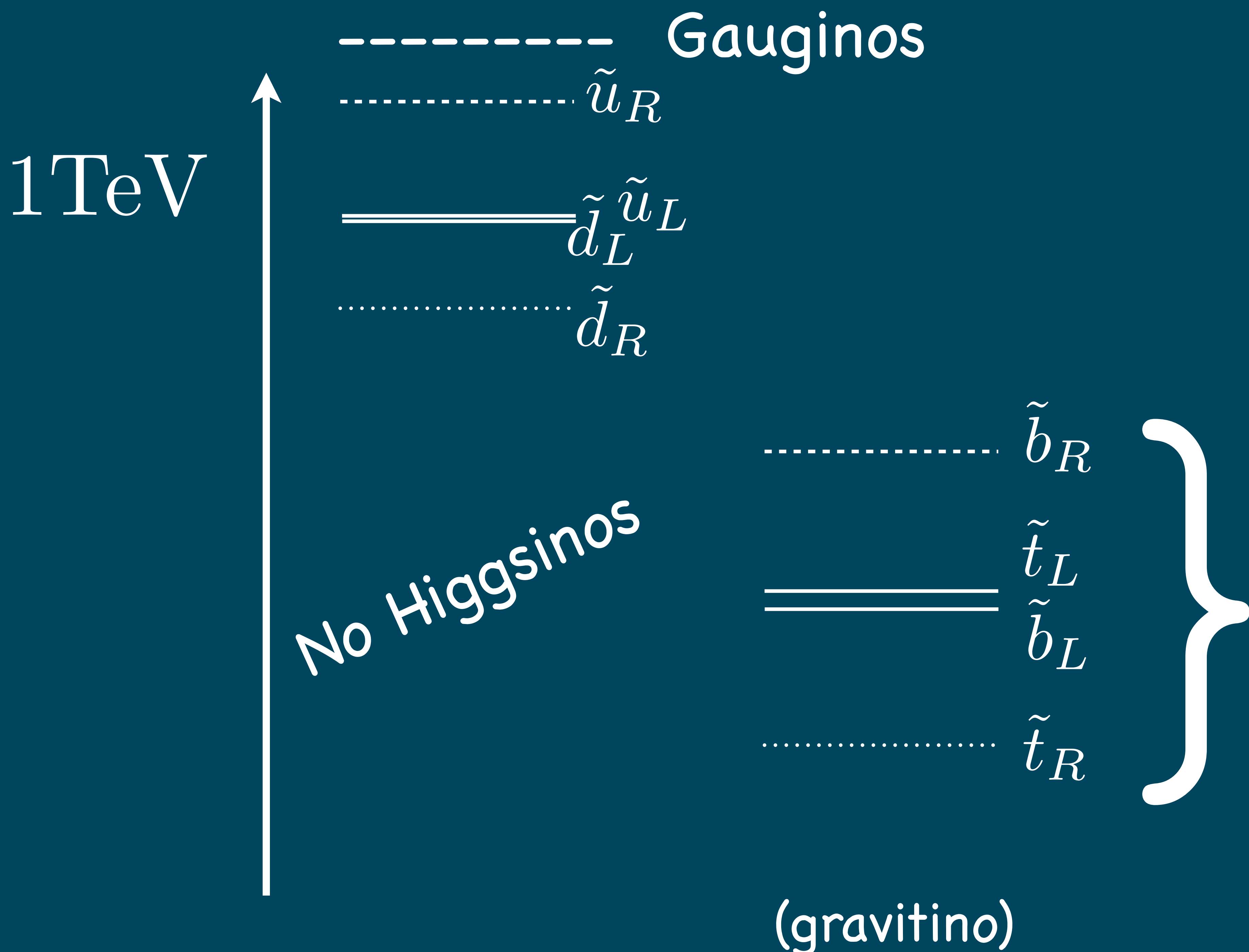
~~SUSY~~ mediation scale (M)

effective op. scale (Λ)

$$Y_u \sim 1 \Rightarrow \Lambda \sim y_u \frac{F}{M} \qquad m_{\tilde{q}} \sim \frac{F}{M} \lesssim \text{TeV} \Rightarrow \boxed{\Lambda \lesssim 4\pi \text{TeV}}$$

This model is an effective theory valid up to ~ 10 TeV

Typical Spectrum



Naturally light: loop corrections suppressed

Hierarchy problem still solved, natural "splitted" spectrum

Phenomenology: the SMS

- Only 1 scalar, tree-level couplings as in the SM

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- Possible deviations:

1. modification of couplings from loops mediated by stops

$g_{H\gamma\gamma}$ ➛ $\Gamma(H\to\gamma\gamma)$ modified ← small effect
g_{Hgg} ➛ $\Gamma(H\to gg)$ and σ_{prod} modified ← sizable effect

2. interaction with goldstinos (H and ν are superpartners)

if the gravitino is light (LSP): $H \to \tilde{G}\,\nu$

➛ invisible Br up to 10%

$\tilde{t}_R$, $\tilde{b}_L$ Pheno: stops and sbottoms

$$\tilde{t}_R \to t_L \nu_L$$
$$\tilde{t}_R \to t_R \tilde{G}$$

$$\tilde{b}_L \to b_R \bar{\nu}_L$$
$$\tilde{b}_L \to b_L \tilde{G}$$

$\tilde{t}_R$ and $\tilde{b}_L$ decay only into top/bottom + MET

⇒ MSSM searches can be adapted

> from $\tilde{b} \to b\chi_0$ with $m_{\tilde{\chi}^0} = 0:$ $m_{\tilde{b}_L} > 650$ GeV

$$m^2_{\tilde{b}_L} = m^2_{\tilde{t}_L} - m^2_t + m^2_b$$

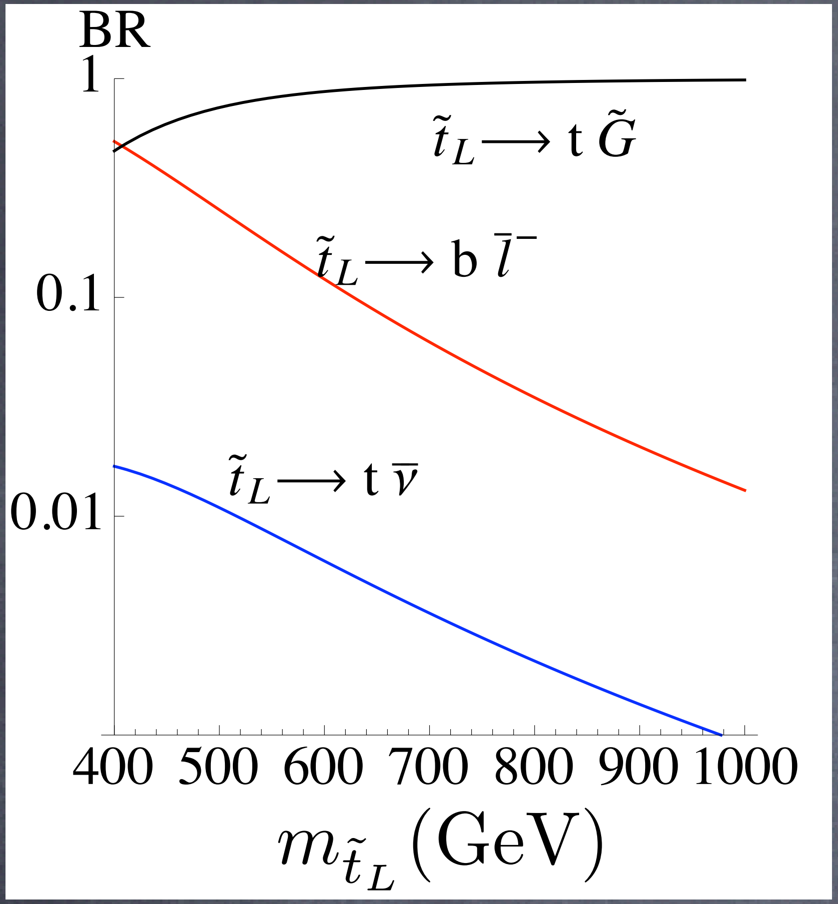
$$m_{\tilde{t}_L} > 670 \text{ GeV}$$

> from $\tilde{t} \to t\chi_0$ with $m_{\tilde{\chi}^0} = 0$: $m_{\tilde{t}_R} > 685$ GeV

stops lighter than tops in principle still allowed:

$$150 \text{ GeV} < m_{\tilde{t}_R} < 190 \text{ GeV}$$

$\tilde{t}_L$ Pheno: stops and sbottoms

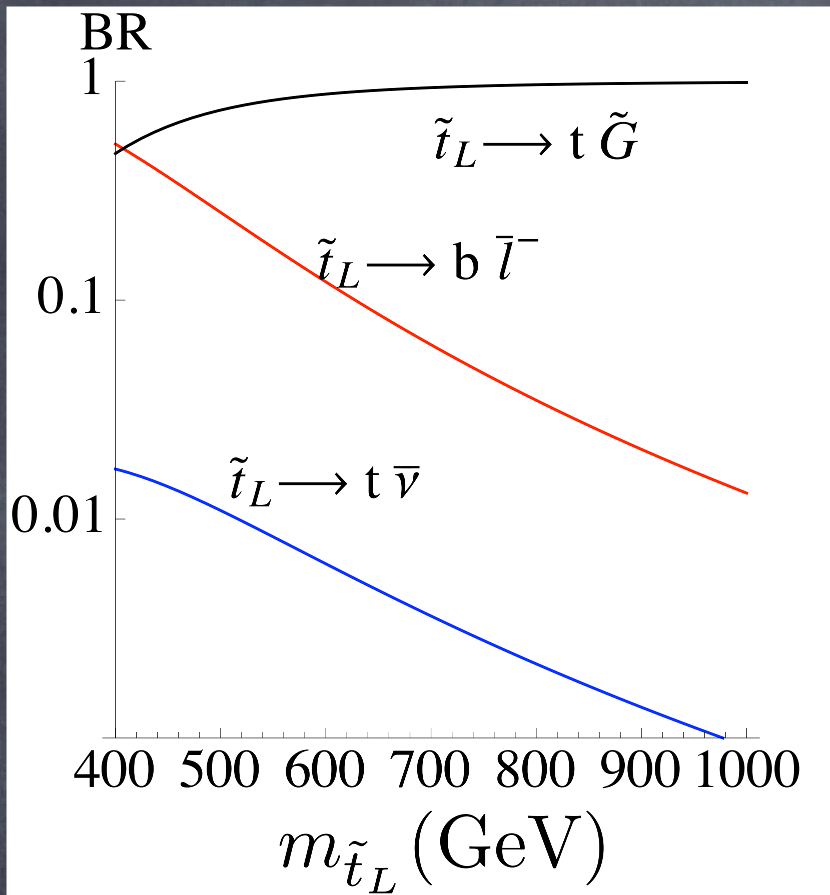


← light gravitino

adopt MSSM searches
on jets + MET:

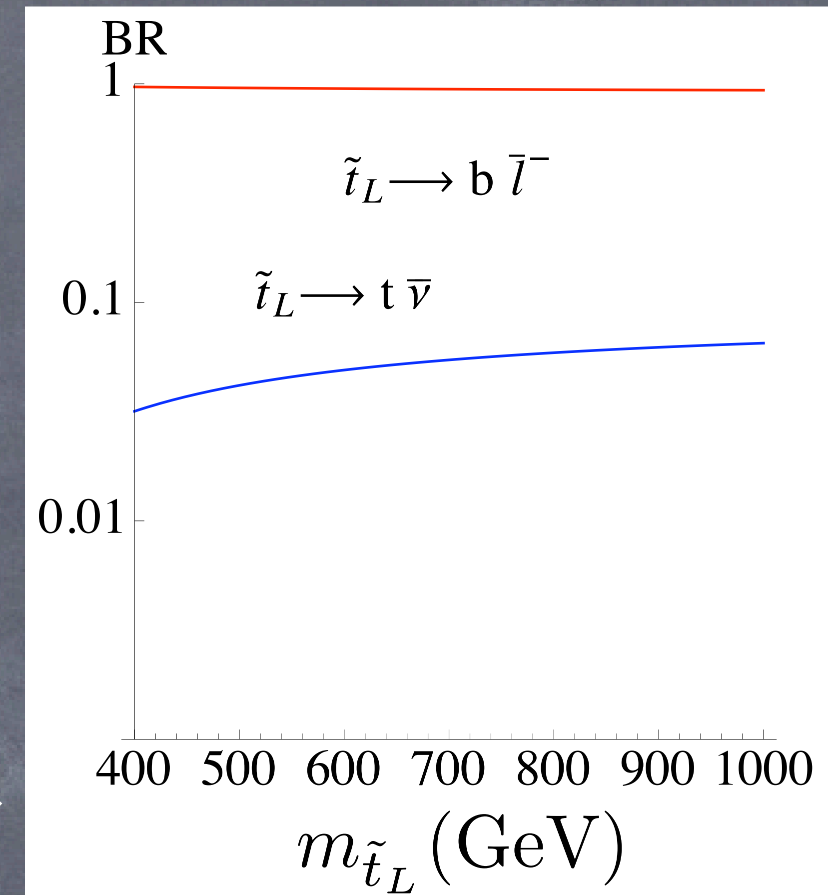
$$m_{\tilde{t}_L} > 685\ \text{GeV}$$

$\tilde{t}_L$ Pheno: stops and sbottoms



← light gravitino

heavy gravitino →



adopt MSSM searches on jets + MET:

$m_{\tilde{t}_L} > 685$ GeV

use searches for leptoquarks:

jet+e $m_{\tilde{t}_L} > 660$ GeV

jet+μ $m_{\tilde{t}_L} > 1070$ GeV

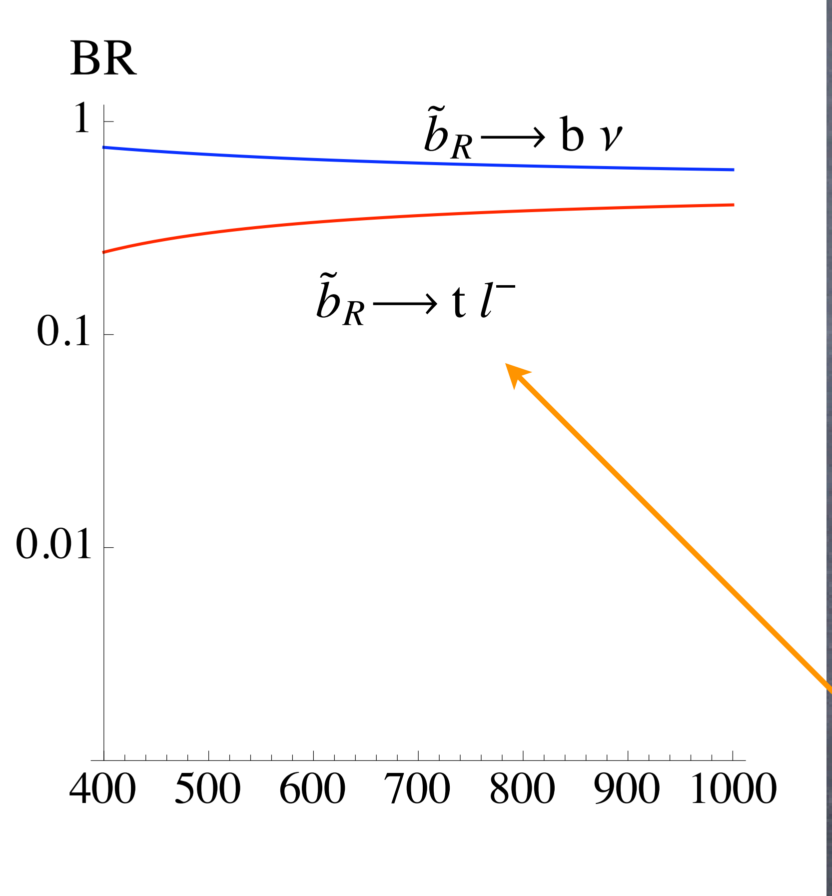
jet+τ $m_{\tilde{t}_L} > 534$ GeV

Look for b-jet + e/μ !!!

$\tilde{b}_R$

Pheno: stops and sbottoms

Light gravitino: $\tilde{b}_R \to b\ \tilde{G}$ dominates (factor ~10); otherwise:



Similar Br, both controlled by Y_b, bounds from MSSM searches for b-jets+MET

$$m_{\tilde{b}_R} > 650\ \mathrm{GeV}$$

Look for top + leptons!!!

LHC search strategy
(an example of how to distinguish from MSSM)

- b-jet + MET observed:
  - it's our $\tilde{b}_R$ only if observe also leptoquark decays @ same mass
  - it can be $\tilde{b}_L$ if observe $\tilde{t}_L$ @ slightly heavier mass
- t + MET observed:
  - it's our $\tilde{t}_L$ if observe also b+l decays
  - it can be $\tilde{t}_R$; look at top helicity

LHC search strategy

(an example of how to distinguish from MSSM)

- b-jet + MET observed:
  - it's our $\tilde{b}_R$ only
  - it can be $\tilde{b}_L$ if
- t + MET obser
  - it's our $\tilde{t}_L$ if ob
  - it can be $\tilde{t}_R$; lo

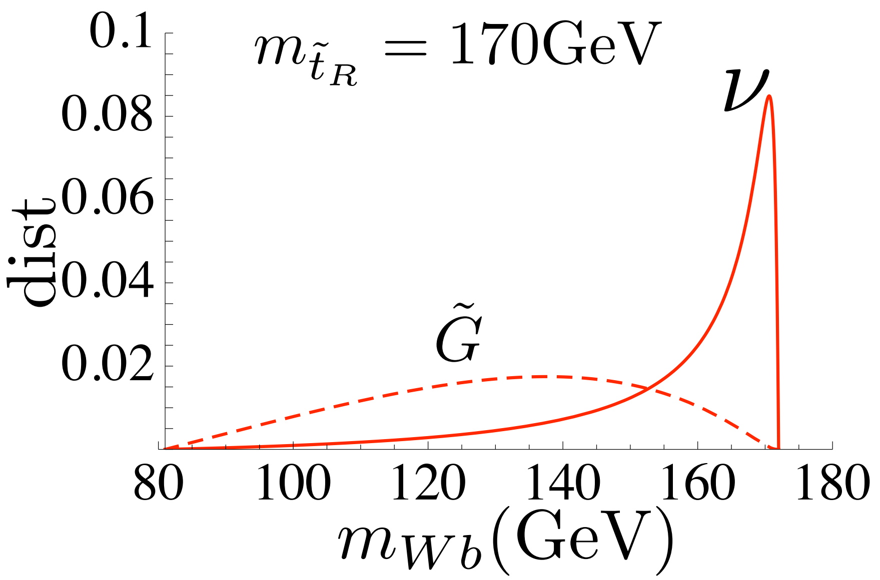
Top helicity:

- $m_{\tilde{t}_R} \gg m_t$

$$\tilde{t}_R \to t_R \bar{\tilde{G}} \quad \text{as MSSM}$$

$$\tilde{t}_R \to t_L \nu_L$$

- $m_{\tilde{t}_R} < m_t$



PHENO: 1^{ST} AND 2^{ND} GEN. SQUARKS

- light gravitino (and $F \approx TeV^2$)

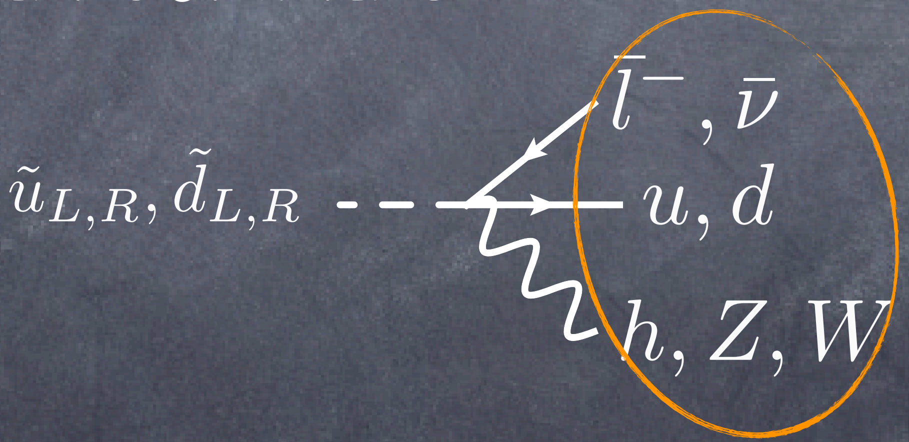
  $\tilde{q} \to q\tilde{G}$ ⤳ jets + MET   m>830GeV

- heavy gravitino (or $F \gg TeV^2$)

  2-body decays can be suppressed by small Yukawas

  ⇒ 3-body decays can dominate

$M_{\tilde{W}} \gtrsim 2\text{TeV}$



jet (no b-jets) + W/Z/h + MET/lepton   ← Look for them!!!

Pheno: sleptons

- light gravitino (and $F \approx TeV^2$)

  $\tilde{l} \to l\tilde{G}$ ⤳ leptons + MET m>270GeV

  $\tilde{\nu} \to \nu\tilde{G}$ ⤳ MET ; monojet, dijet+MET

- heavy gravitino (or $F >> TeV^2$)

  3-body decays can dominate

$\tilde{e}_L \to \nu_e + \bar{\nu}_L + W^-$	$\tilde{\mu}_L \to \nu_\mu + \bar{\nu}_L + W^-$	$\tilde{\tau}_L \to \tau + \bar{\nu}_L$
$\tilde{e}_R \to e + l_L^- + W^+$	$\tilde{\mu}_R \to \mu + \nu_L$ (50%) $\to \nu_\mu + l_L^-$ (50%)	$\tilde{\tau}_R \to \tau + \nu_L$ (50%) $\to \nu_\tau + l_L^-$ (50%)
$\tilde{\nu}_e \to e + \bar{l}_L^- + Z$	$\tilde{\nu}_\mu \to \mu + Z + \bar{l}_L^-$	$\tilde{\nu}_\tau \to \tau + \bar{l}_L^-$

↖ Look for these channels!!!

Conclusions

- We have investigated the viability of a SUSY model where no chiral Higgs superfield is needed:
  the role of the SMS is played by a (comb. of) sneutrino(s)

- Natural splitted spectrum:
  no Higgsinos, only light stops and sbottoms, heavy gauginos

- Interesting LHC pheno to test model and distinguish from MSSM

  - leptoquark decays
  - SM scalar invisible width
  - 3-body decays

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  > leptoquark decays
  > SM scalar invisible width
  > 3-body decays

Thanks!

If you think SUSY is not here 'cause you don't see it,
do not desperate...
maybe we've already discovered it, just need a confirmation!

BACK-UP SLIDES

The Higgsinoless MSSM

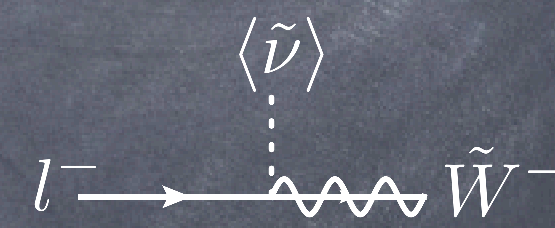
$$W = Y_d HQD + Y_{e\,ij} HL_iE_j$$

→ m_d
→ m_e (not for L_3)

All the rest comes from SUSY breaking terms:

3. gaugino masses : $\int d^2\theta \, \frac{D^\alpha X}{M} W^a_\alpha \Phi_a$ $\quad m \sim \frac{F}{M}$

Constraints on gaugino masses:
> after EWSB winos mix with leptons



g_{Zll} modified ⇒ $$M_{\tilde{W}} \gtrsim \begin{cases} 2.5\,\text{TeV} & l^-_L = e_L \\ 2\,\text{TeV} & l^-_L = \mu_L \\ 1.8\,\text{TeV} & l^-_L = \tau_L \end{cases}$$ ⇒ $\frac{F}{M} \sim \text{TeV}$

(From universality constraints: $M_{\tilde{B}} \gtrsim 500$ GeV)

The Higgsinoless MSSM

$$W = Y_d HQD + Y_{e\,ij} HL_i E_j$$

→ m_d

→ m_e (not for L_3)

All the rest comes from SUSY breaking terms:

4. ~~SUSY~~ quartic coupl. : $$\int d^4\theta \; \lambda_H \frac{X^\dagger X}{M^2} \frac{|H|^4}{\Lambda^2} = \delta\lambda_h h^4 + \dots$$

$U(1)_R$ forbids A-terms; light stop masses

⇒ additional quartic required to get $m_H \approx 125$GeV

$$\delta\lambda_h \sim 0.015$$

$H \equiv \tilde{\nu}$: advantages & consequences

- no Higgsinos ⤳ HiggsinolessMSSM

- NO μ-problem: scalar mass entirely arises from ~~SUSY~~ terms
- NO anomalies: the only extra fermions are in the adjoint (for gaugino masses, see later)

minimal model with
natural low energy SUSY spectrum

Moreover: No R-parity ⇒ no large MET in final states at the LHC

new final states at the LHC

$U(1)_R$ BREAKING

$U(1)_R$ is broken by gravitino mass:

$$m_{3/2} \sim \frac{F}{M_{Pl}} \sim 10^{-3}\mathrm{eV}\left(\frac{\sqrt{F}}{2\mathrm{TeV}}\right)^2$$

Majorana ν mass ~ $m_{3/2}$ can be generated

– if other SUSY sources are present gravitinos can be heavy:

⇒ 2 scenarios: - gravitino L(R-charged)P

- neutrino L(R-charged)P

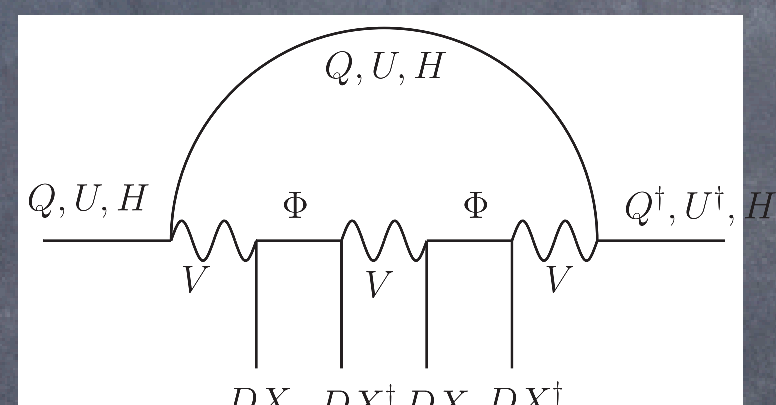
A NATURAL SPECTRUM

The presence of ~~SUSY~~ operators generates at the loop level other ~~SUSY~~ terms:

- is m_H OK?
- soft masses for scalars?

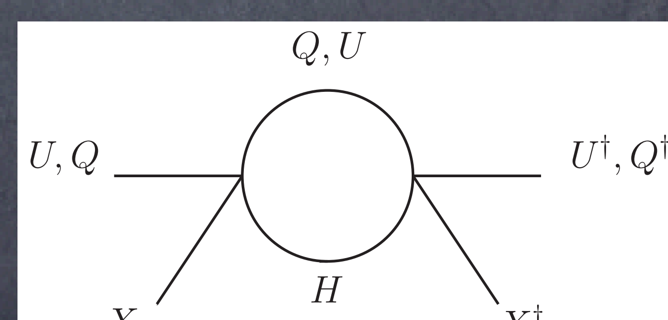
$$\int d^4\theta \; \left\{ g_Q \frac{X^\dagger X}{M^2} Q^\dagger Q + g_U \frac{X^\dagger X}{M^2} U^\dagger U + g_H \frac{X^\dagger X}{M^2} H^\dagger H \right\}$$

Squarks:



Finite contrib.

(SuperSoft SUSY breaking)
Fox, Nelson, Weiner 02



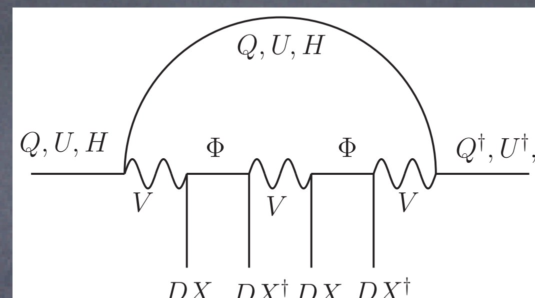
$\propto \Lambda^2$

Low cutoff

A natural spectrum

Higgs

(SuperSoft SUSY breaking)
Fox, Nelson, Weiner 02



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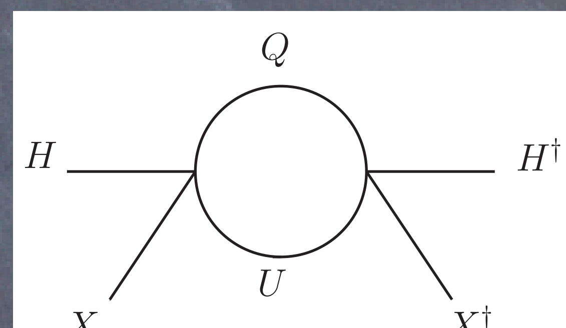
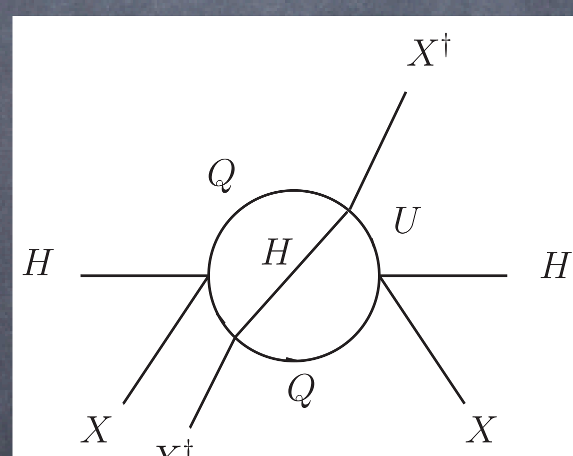


vanishes



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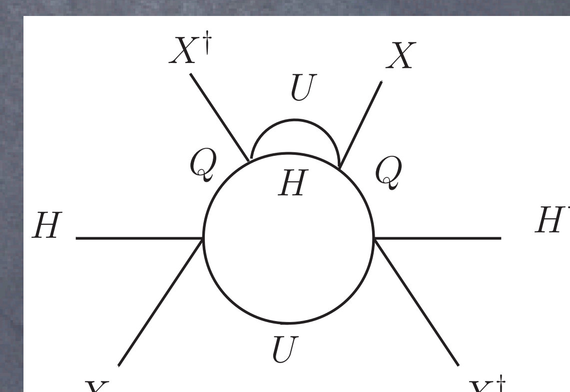
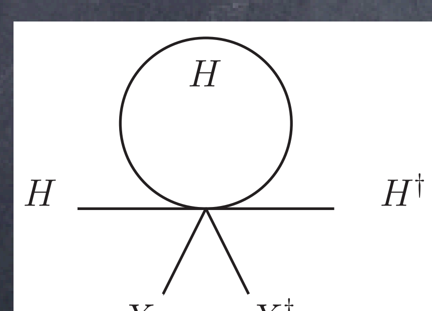


negative

$\propto \log\Lambda^2$



$\propto \Lambda^2$

A NATURAL SPECTRUM

- $$m^2_{Q,U} \simeq (400\ \mathrm{GeV})^2 \left[\left(\frac{M_{\tilde g}}{2\ \mathrm{TeV}} \right)^2 \ln \frac{M^2_{\Phi_{\tilde g}}}{M^2_{\tilde g}} + (0.15, 0.3) \left(\frac{\Lambda}{2\ \mathrm{TeV}} \right)^2 \right]$$

  naturally "light" 3rd gen. squarks

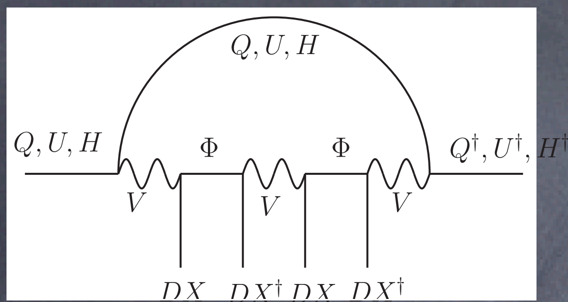
- $$m^2_H \simeq -(100\ \mathrm{GeV})^2 \left[4.3 \left(\frac{m_Q}{600\ \mathrm{GeV}} \right)^2 \frac{\ln \frac{\Lambda}{m_Q}}{\ln 5} - 3.2 \left(\frac{M_{\tilde W}}{2\ \mathrm{TeV}} \right)^2 \ln \frac{M^2_{\Phi_{\tilde W}}}{M^2_{\tilde W}} - \left(\frac{\delta\lambda}{0.015} \right) \left(\frac{\Lambda}{2\ \mathrm{TeV}} \right)^2 \right]$$

  EWSB can occur naturally

- other sparticles: at least as heavier as the above
  (they get masses at least from the gaugino loop and maybe also from ~~SUSY~~ operators, if there; in this case they can be heavier)

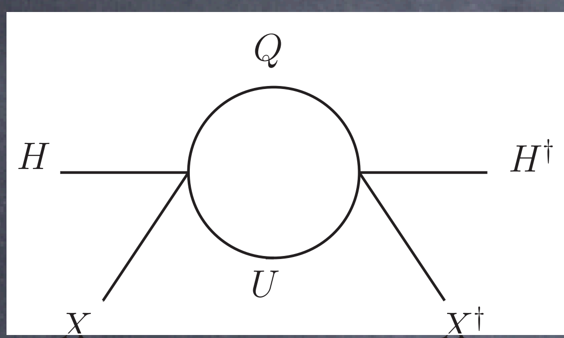
Most minimal low-energy SUSY model:
only stops & sbottoms (gravitinos) below the TeV

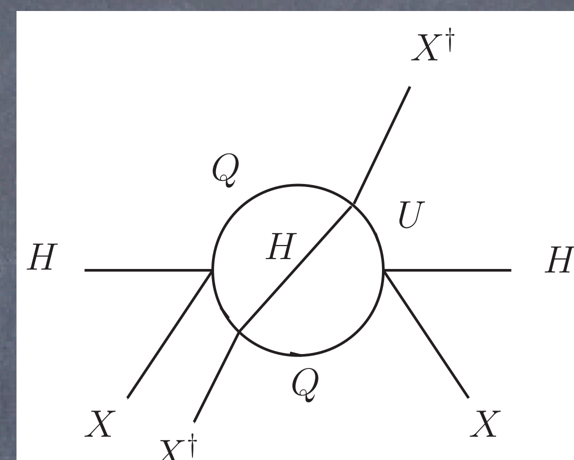
Loop contribution to M_H

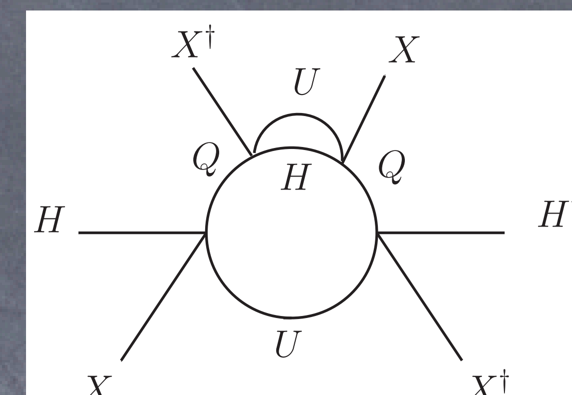


SuperSoft SUSY breaking: Dirac gauginos only induce finite contributions

Fox, Nelson, Weiner 02







Eq. (3) is induced. Interestingly, the equivalent one-loop contribution for the Higgs soft-mass, the first diagram of fig. 3, vanishes. This can be understood as follows. If we are interested only in the scalar component of H, we can neglect the θ-dependent part of H and write the top Yukawa coupling as $\int d^2\theta \; Y_u H^\dagger Q U = Y_u H^\dagger \int d^2\theta \, QU$ that is supersymmetric and then cannot generate soft-breaking terms. At the two-loop level, however, where the full Higgs superfield H can propagate (see fig. 3), we do expect a nonzero Higgs soft-mass to be induced. Surprisingly, we find that the contribution arising from the second diagram of fig. 3 vanishes, and only the third diagram induces a nonzero m_H^2. The latter is proportional to the squark masses, and, as in the MSSM, diverges logarithmically:

Possible UV completions

- this model + H_u + R_d (Frugiuele Gregoire 2011)

  $\mu H_u R_d$ → mass for Higgsinos

  $y_u H_u Q U$ → mass for up-type quarks

  $B_\mu R_d H^+ X^+ / M$

  $\mu \gg v$ integrate out H_u & R_d

$$\int d^4\theta \, y_u \frac{X^\dagger}{M} \frac{H^\dagger Q U}{\Lambda} = \int d^2\theta \, Y_u H^\dagger Q U$$

$Y_u = y_u F / \mu M$

also a soft mass for H @ tree-level

$m_H \sim F/M$ → $Y_u \sim 1$ → $y_u \sim \mu / m_H > 1$

strong dynamics above the TeV?

(composite Higgs or top)

Possible UV completions

- top (L or R) partly arising from vector superfields

example: $V_\pm \sim (3,2)+(\bar{3},2)$

$M_V^2 V_+ V_- + g_V V_- X^\dagger Q + g_V V^+ H^\dagger U$

integrate out V:

$$\int d^4\theta \; y_u \frac{X^\dagger}{M} \frac{H^\dagger QU}{\Lambda} = \int d^2\theta \; Y_u H^\dagger QU$$

$y_u = g_V^2 \quad \Lambda \sim M \sim M_V$

also soft mass for Q @ tree-level

again $g_V > 1$ to have $m_Q < M_V$

again strong dynamics above the TeV?

V can be a massive gauge boson

Ex. coming from SU(5) Cai, Cheng, Terning 2008

Phenomenology: the SMS

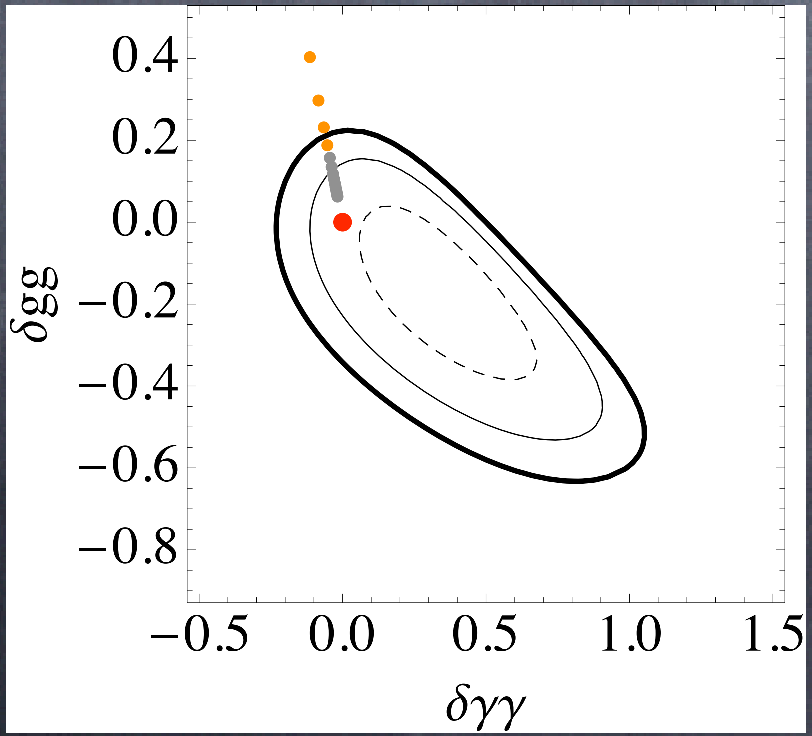
Only 1 scalar, tree-level couplings as in the SM

Possible deviations from:

1. modification of couplings from loops mediated by stops

$g_{H\gamma\gamma}$ ➛ $\Gamma(H\to\gamma\gamma)$ modified ← small effect

g_{Hgg} ➛ $\Gamma(H\to gg)$ and σ_{prod} modified ← sizable effect



Fit to Higgs data:

heavier stops are favored...

Phenomenology: the SMS

Only 1 scalar, tree-level couplings as in the SM

Possible deviations from:

2. interaction with goldstinos (H and ν are superpartners)

if the gravitino is light (LSP)

➛ invisible decays into gravitino

$$\Gamma(h \to \tilde{G}\nu_L) \simeq \frac{1}{16\pi}\frac{m_h^5}{F^2}$$

$\sqrt{F} \approx 1$ TeV → $Br_{inv} \approx 10\%$

$Br_{inv} \neq 0$ lighter stops still allowed