

Carla Biggio  
Università di Genova e INFN

# Bosone di Higgs o prima particella supersimmetrica scoperta?

Based on CB, Riva, Pomarol, JHEP 1302 (2013) 081

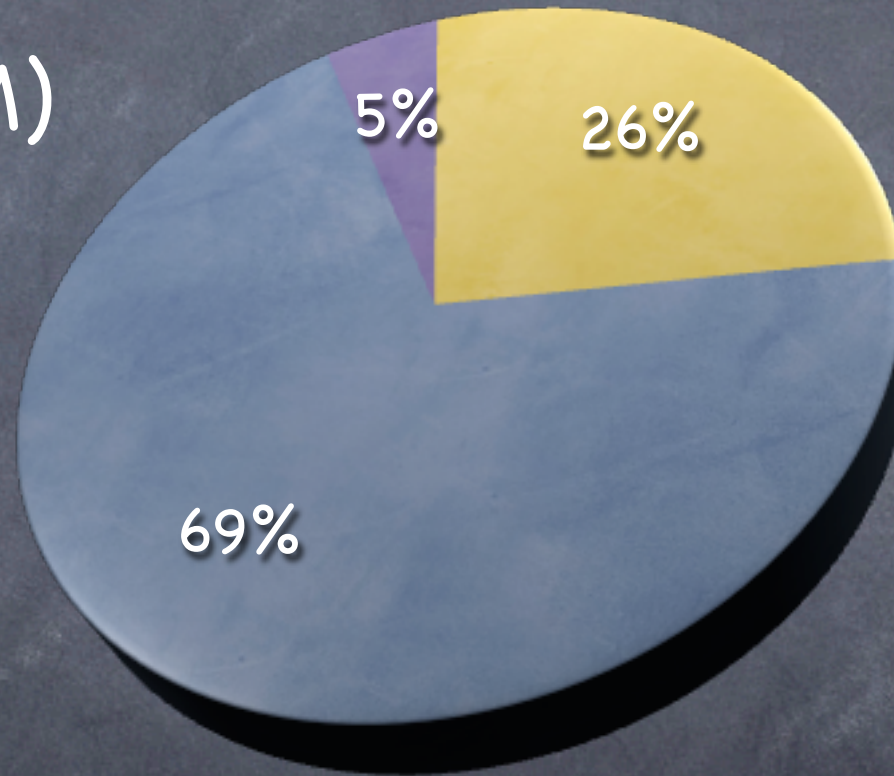
Dipartimento di Fisica, Università di Genova  
10/12/13



# The energetic balance of the universe

Ordinary matter  
its interactions are  
explained by the  
Standard Model (SM)

Dark matter: interacts  
gravitationally but not  
electromagnetically



Dark energy: correspond to the  
accelerated expansion of the universe



# The SM in one slide...

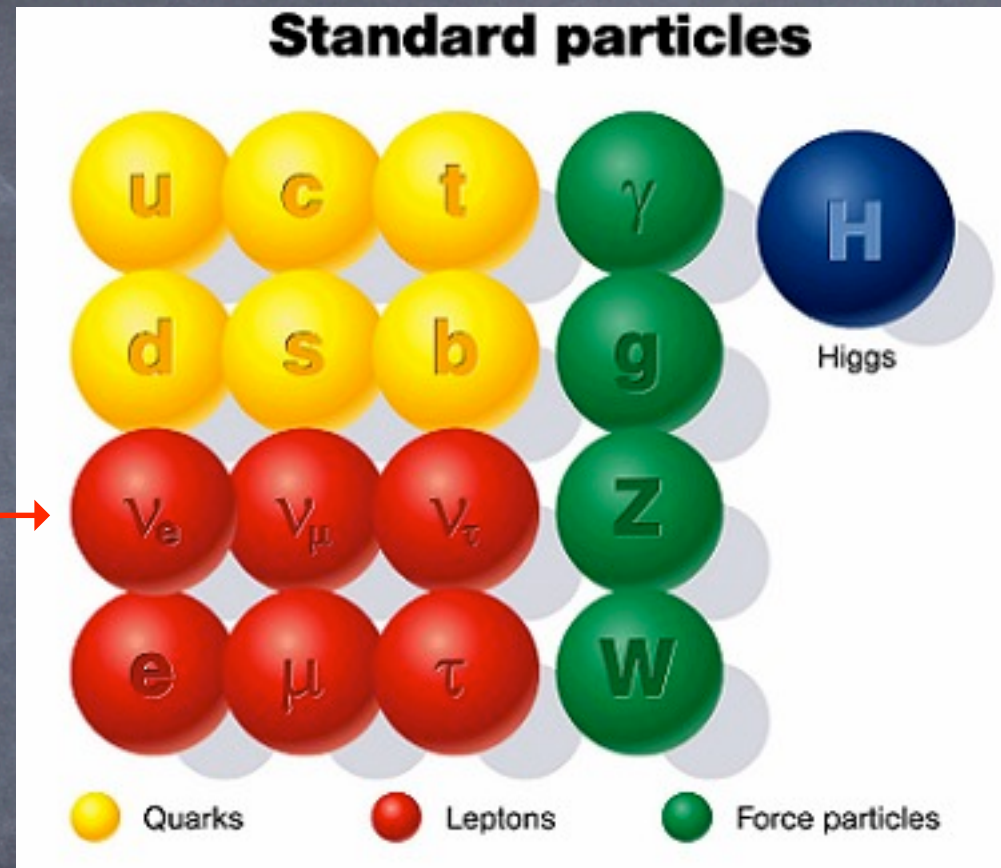
## QUARKS

EM, weak &  
strong interactions

only weak! →

## LEPTONS

EM & weak  
interactions



## Higgs boson:

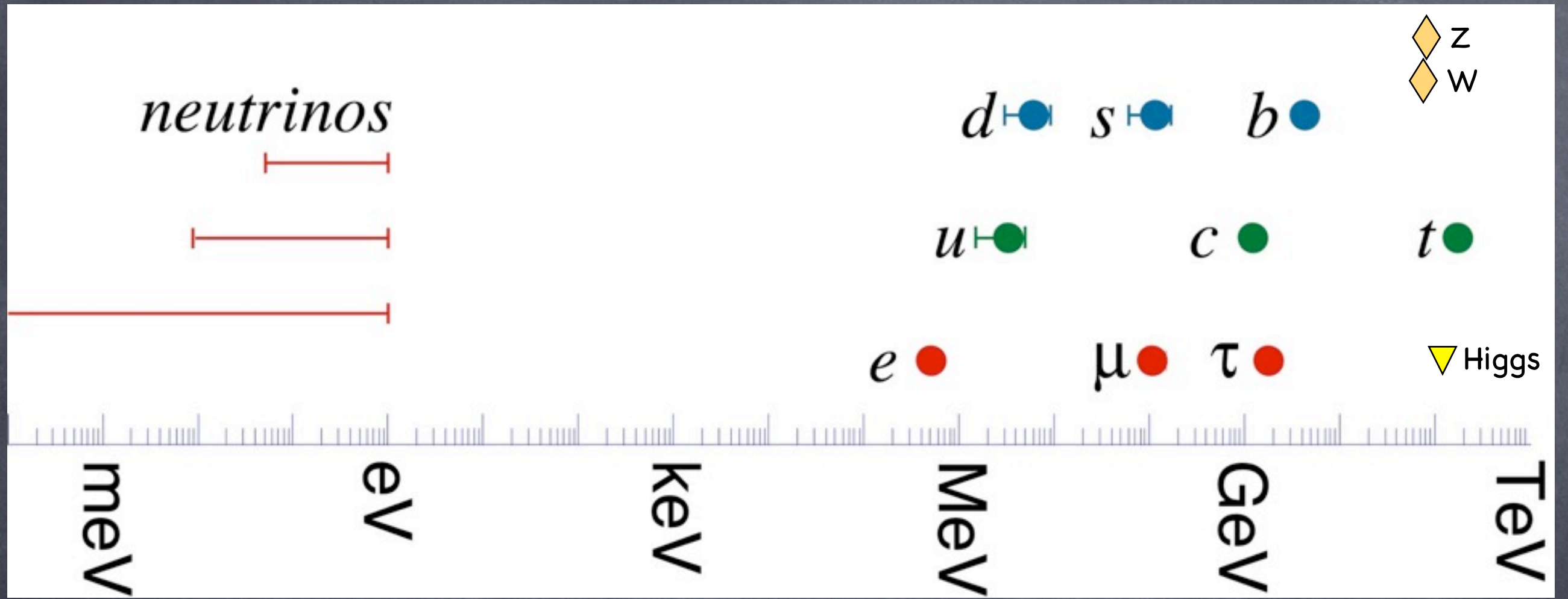
- discovered @LHC July 2012
- Nobel price 2013 Englert, Higgs responsible of EWSB and of the masses of these particles

GAUGE VECTORS BOSONS  
force mediators

Based on gauge symmetry  $SU(3) \times SU(2) \times U(1)$

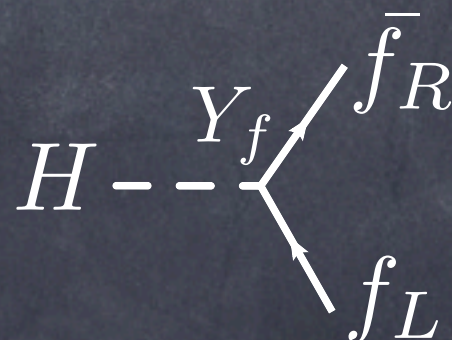


or two...



gluons and photons are massless

Fermion masses come from the interaction of the fermion and the Higgs:  
the larger the coupling  
the heavier the mass



$$m_f = Y_f \frac{v}{\sqrt{2}}$$



# Why we need to go beyond the SM?

- ✓ the SM have been tested at the ‰ level in LEP



# Why we need to go beyond the SM?

- ✓ the SM have been tested at the % level in LEP
- ✓ the last missing piece → Higgs boson have been discovered at the LHC



# Why we need to go beyond the SM?

- ✓ the SM have been tested at the % level in LEP
- ✓ the last missing piece → Higgs boson have been discovered at the LHC

However:

neutrino oscillation exps have revealed that neutrinos are massive (and veeery light) while in the SM are not.

→ Even to explain completely ordinary matter the SM must be extended



# Why we need to go beyond the SM?

- ✓ the SM have been tested at the % level in LEP
- ✓ the last missing piece → Higgs boson have been discovered at the LHC

However:

neutrino oscillation exps have revealed that neutrinos are massive (and veeery light) while in the SM are not.

→ Even to explain completely ordinary matter the SM must be extended

- simplest extension: just add  $\nu_R$  and Dirac neutrino masses
- "nicer" extension: add  $\nu_R$  with heavy Majorana mass (→ new physics scale) and get neutrinos naturally light



# Why we need to go beyond the SM?

•  $\nu$  mass



# Why we need to go beyond the SM?

•  $\nu$  mass

• Dark Matter (DM)



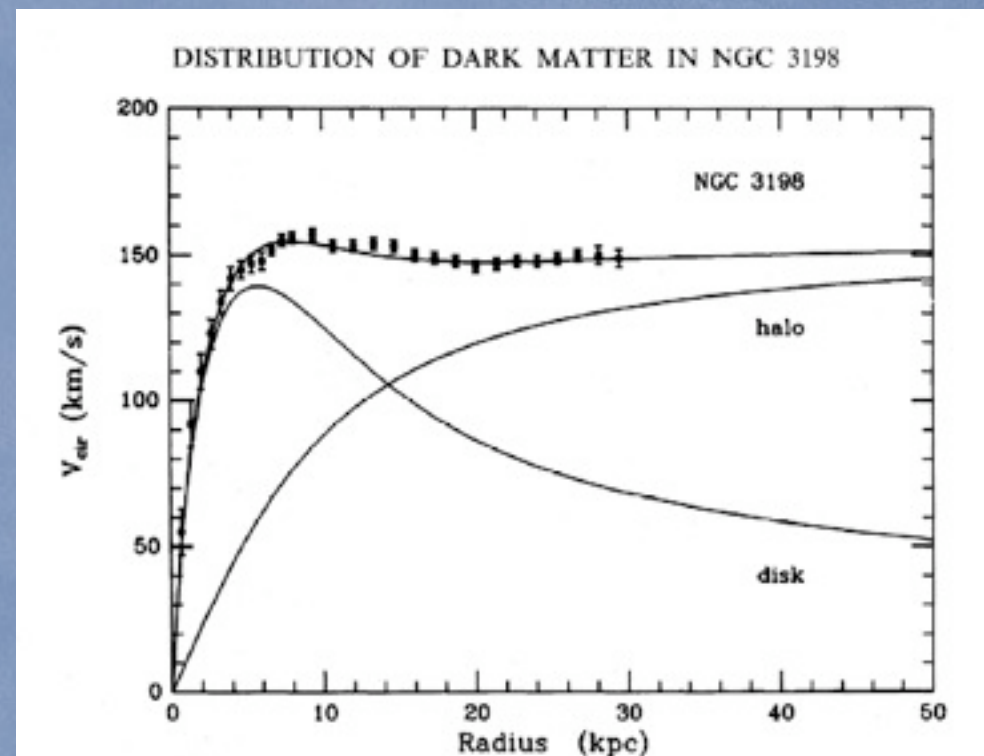
# Why we need to go beyond the SM?

• v r

Dark matter:

• Da

postulated in the 70's to explain the galaxies rotation curves:



in the galaxies there is  
more gravitational mass than visible mass



# Why we need to go beyond the SM?

- $\nu$  mass
- Dark Matter (DM)
- baryogenesis



# Why we need to go beyond the SM?

## Baryogenesis

Why the universe is made of matter and no antimatter?

Matter & antimatter are created in pairs; which mechanism generated an unbalance?

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \simeq 10^{-10}$$

Within the SM it is not possible to explain the generation of this asymmetry



# Why we need to go beyond the SM?

- $\nu$  mass
- Dark Matter (DM)
- baryogenesis
- strong CP problem



# Why we need to go beyond the SM?

- $\nu$  mass
- Dark Matter (DM)
- baryogenesis
- strong CP problem
- Dark Energy (DE)



# Why we need to go beyond the SM?

- $\nu$  mass
- Dark Matter (DM)
- baryogenesis
- strong CP problem
- Dark Energy (DE)
- (hierarchy problem) ← NOT AN EXPERIMENTAL ISSUE



# Why we need to go beyond the SM?

Hierarchy problem:

masses of scalar particles tend to be as heavy as the heaviest scale present

ex:  $M_{\text{pl}} \sim 10^{19}\text{GeV}$  gravity scale

the Higgs mass is  $\sim 126\text{GeV}$ ; why so low?



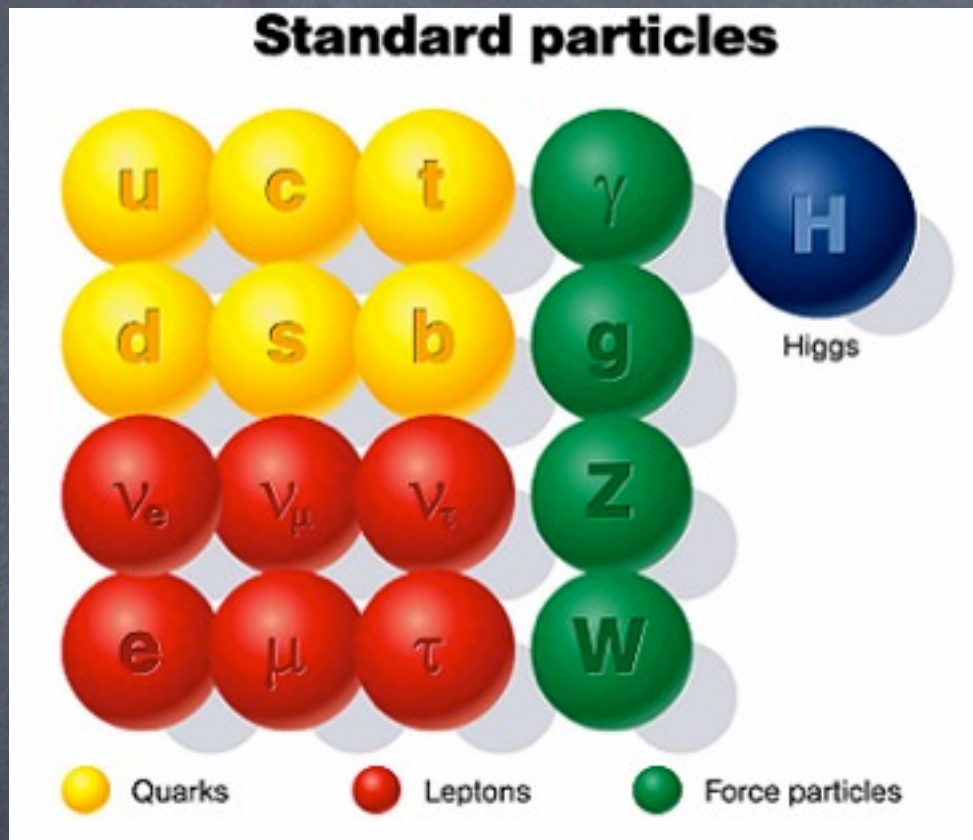
# Why we need to go beyond the SM?

- $\nu$  mass
- Dark Matter (DM)
- baryogenesis
- strong CP problem
- Dark Energy (DE)
- (hierarchy problem)



# The most studied BSM physics: SUSY

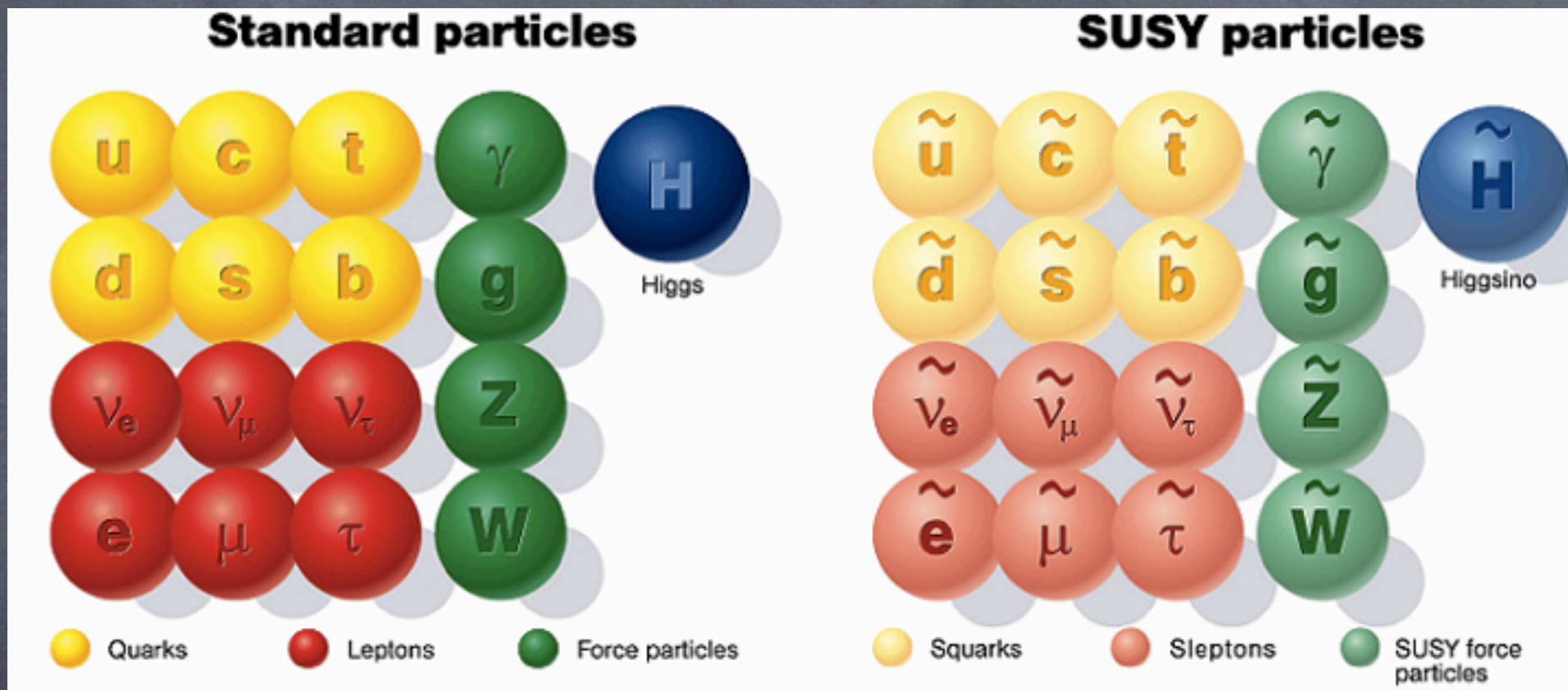
**SUPERSYMMETRY:** to each bosonic degree of freedom corresponds a fermionic one and viceversa





# The most studied BSM physics: SUSY

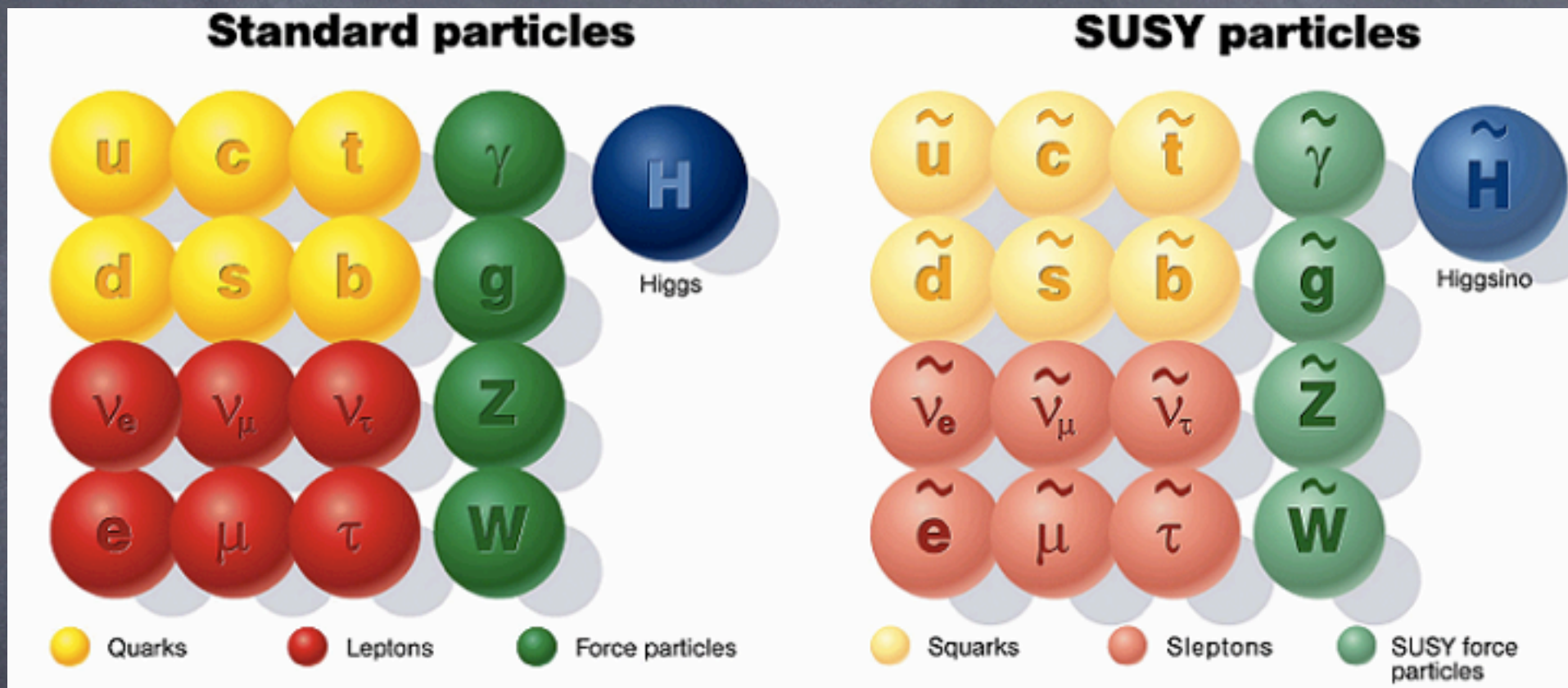
**SUPERSYMMETRY:** to each bosonic degree of freedom corresponds a fermionic one and viceversa





# The most studied BSM physics: SUSY

**SUPERSYMMETRY:** to each bosonic degree of freedom corresponds a fermionic one and viceversa



SUSY exact: mass of susy partners should be equal  
so far no SUSY particles  $\rightarrow$  SUSY must be broken

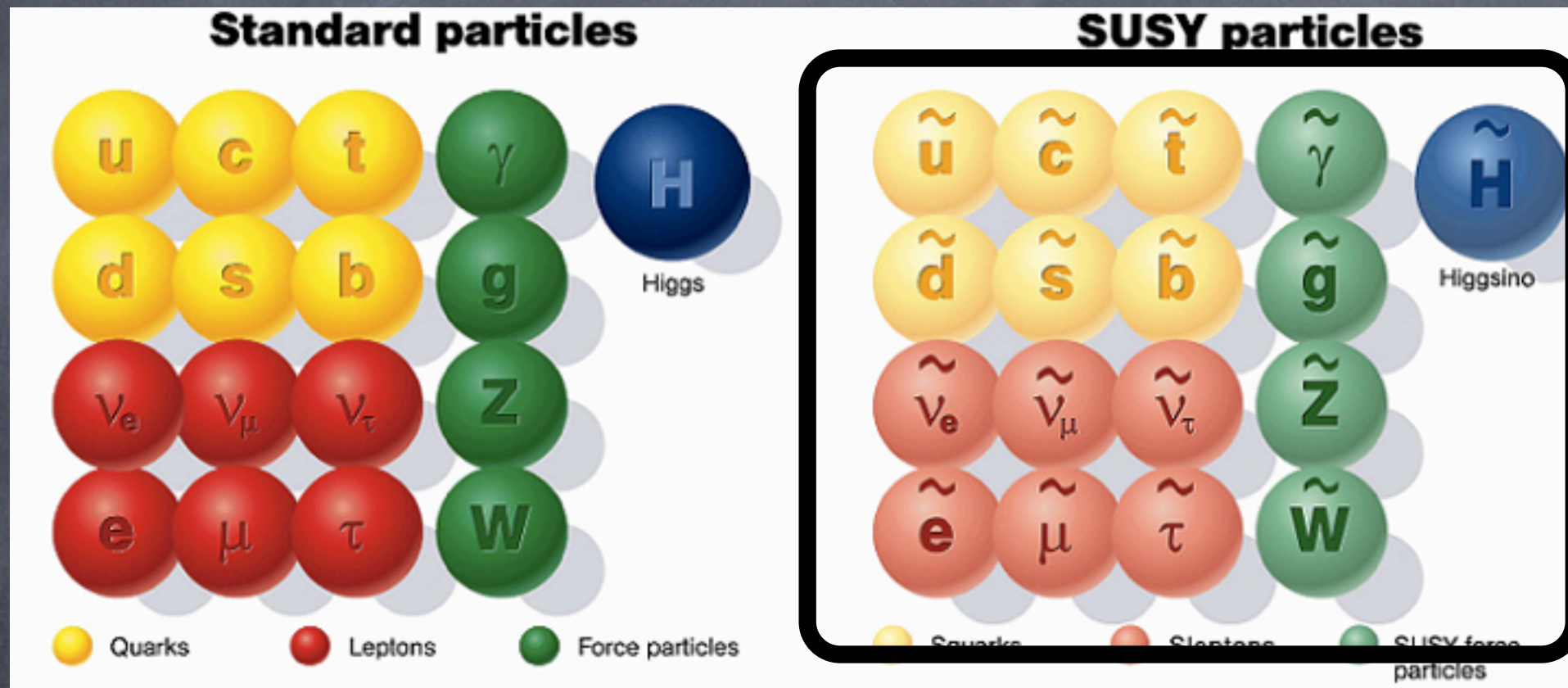
SUSY solves the hierarchy problem (if light sparticles)



# The most studied BSM physics: SUSY

Minimal Supersymmetric Standard Model (MSSM)

In order to avoid fast proton decay: R-parity



$R=1$

$R=-1$

- 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)



# The most studied BSM physics: SUSY

Introduced to solve the hierarchy problem

Moreover, for free:

- Dark Matter candidate
- baryogenesis
- gauge couplings unification

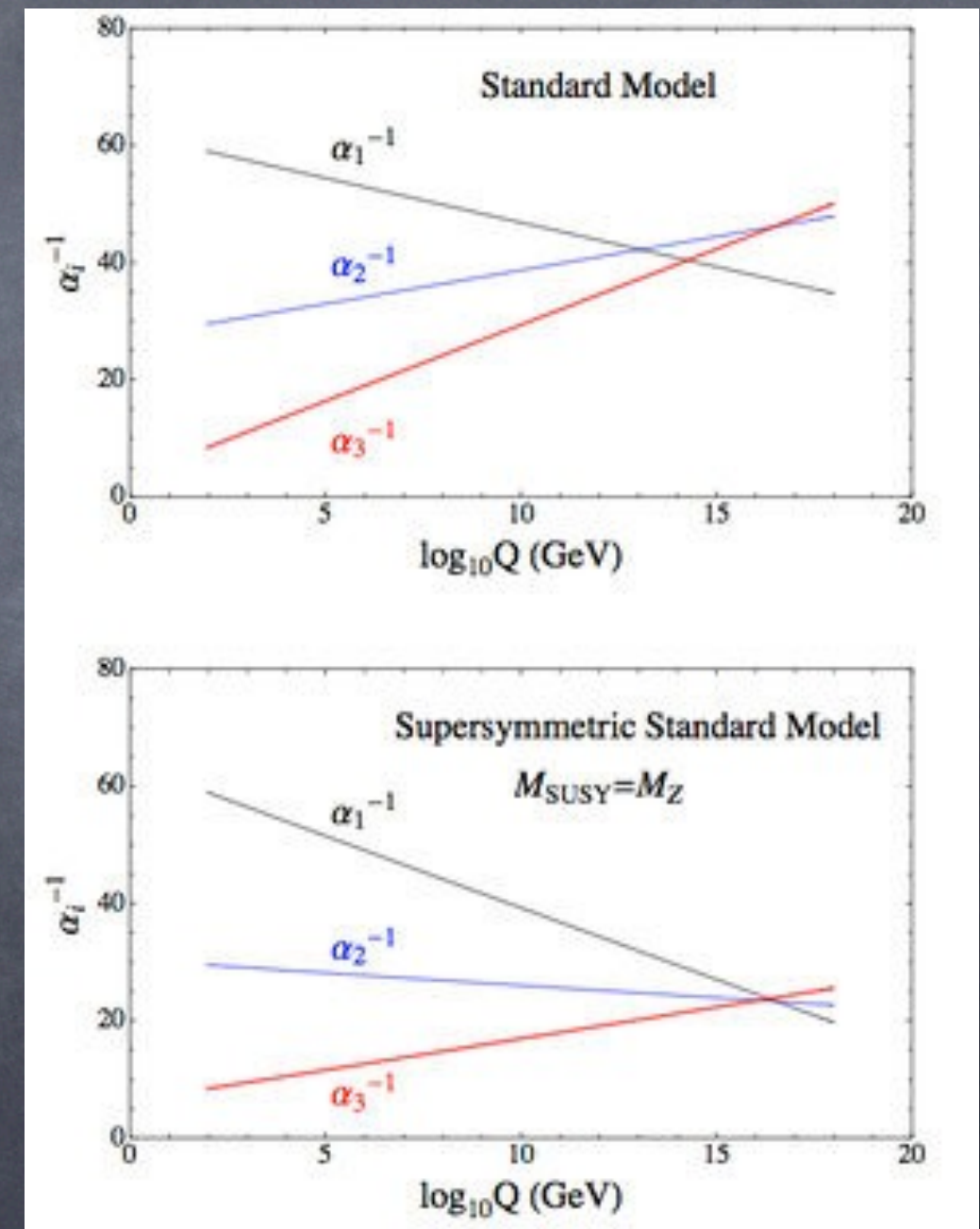


# The most studied BSM physics: SUSY

Introduced to solve the hierarchy problem

Moreover, for free:

- Dark Matter candidate
- baryogenesis
- gauge couplings unification





# The most studied BSM physics: SUSY

Introduced to solve the hierarchy problem

Moreover, for free:

- Dark Matter candidate
- baryogenesis
- gauge couplings unification

All this work (especially the solution to the hierarchy problem)

if SUSY particles are lighter than 1 TeV



# The most studied BSM physics: SUSY

Introduced to solve the hierarchy problem

Moreover, for free:

- Dark Matter candidate
- baryogenesis
- gauge couplings unification

All this work (especially the solution to the hierarchy problem)

if SUSY particles are lighter than 1 TeV

However LHC started operations...



# SUSY and the LHC

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1}$   $\sqrt{s} = 7, 8 \text{ TeV}$

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference		
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{q}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^\pm \rightarrow qqW^\pm\tilde{\chi}_1^0$	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-089
	GMSB ( $\tilde{\ell}$ NLSP)	2 $e, \mu$	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau$	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta > 18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 $\gamma$	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)>220 \text{ GeV}$	1211.1167
GGM (higgsino NLSP)	2 $e, \mu (Z)$	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})>200 \text{ GeV}$	ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4} \text{ eV}$	ATLAS-CONF-2012-147	
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)<600 \text{ GeV}$	ATLAS-CONF-2013-061
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0) < 350 \text{ GeV}$	1308.1841
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^\pm$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2013-061
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^\pm$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	ATLAS-CONF-2013-061
	3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0) < 90 \text{ GeV}$
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$		2 $e, \mu$ (SS)	0-3 $b$	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^0)=2 m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-007
$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$		1-2 $e, \mu$	1-2 $b$	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)=55 \text{ GeV}$	1208.4305, 1209.2102
$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{t}_1) - m(W) - 50 \text{ GeV}, m(\tilde{t}_1) < m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^\pm$		2 $e, \mu$	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-065
$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$		0	2 $b$	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1308.2631
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$		1 $e, \mu$	1 $b$	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-037
$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^\pm$		0	2 $b$	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-024
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$		0	mono-jet/ $c$ -tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < 85 \text{ GeV}$	ATLAS-CONF-2013-068
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)		2 $e, \mu (Z)$	1 $b$	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0) > 150 \text{ GeV}$	ATLAS-CONF-2013-025
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu (Z)$	1 $b$	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180 \text{ GeV}$	ATLAS-CONF-2013-025	
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\ell\bar{\nu})$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tau\bar{\nu})$	2 $\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\ell(\ell\bar{\nu}), \tilde{\ell}\tilde{\nu}\ell\ell(\ell\bar{\nu})$	3 $e, \mu$	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 $e, \mu$	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 $e, \mu$	2 $b$	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$	ATLAS-CONF-2013-093
	Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm) = 0.2 \text{ ns}$
Stable, stopped $\tilde{g}$ R-hadron		0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$	ATLAS-CONF-2013-057
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$		1-2 $\mu$	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	$10 < \tan\beta < 50$	ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$		2 $\gamma$	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4 < \tau(\tilde{\chi}_1^0) < 2 \text{ ns}$	1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV)		1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$	ATLAS-CONF-2013-092
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda'_{311}=0.10, \lambda_{132}=0.05$	1212.1272
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda'_{311}=0.10, \lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	1 $e, \mu$	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0) > 300 \text{ GeV}, \lambda_{121} > 0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0) > 80 \text{ GeV}, \lambda_{133} > 0$	ATLAS-CONF-2013-036
	$\tilde{g} \rightarrow qq\tilde{q}$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	$\text{BR}(\tilde{t}) = \text{BR}(\tilde{b}) = \text{BR}(\tilde{c}) = 0\%$	ATLAS-CONF-2013-091
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, $s\text{gluon} \rightarrow q\tilde{q}$	0	4 jets	-	4.6	$s\text{gluon}$ 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, $s\text{gluon} \rightarrow t\tilde{t}$	2 $e, \mu$ (SS)	1 $b$	Yes	14.3	$s\text{gluon}$ 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$M^*$ scale 704 GeV	$m(\chi) < 80 \text{ GeV}, \text{limit of } < 687 \text{ GeV for D8}$	ATLAS-CONF-2012-147

$\sqrt{s} = 7 \text{ TeV}$   
full data

$\sqrt{s} = 8 \text{ TeV}$   
partial data

$\sqrt{s} = 8 \text{ TeV}$   
full data

10<sup>-1</sup>

1

Mass scale [TeV]

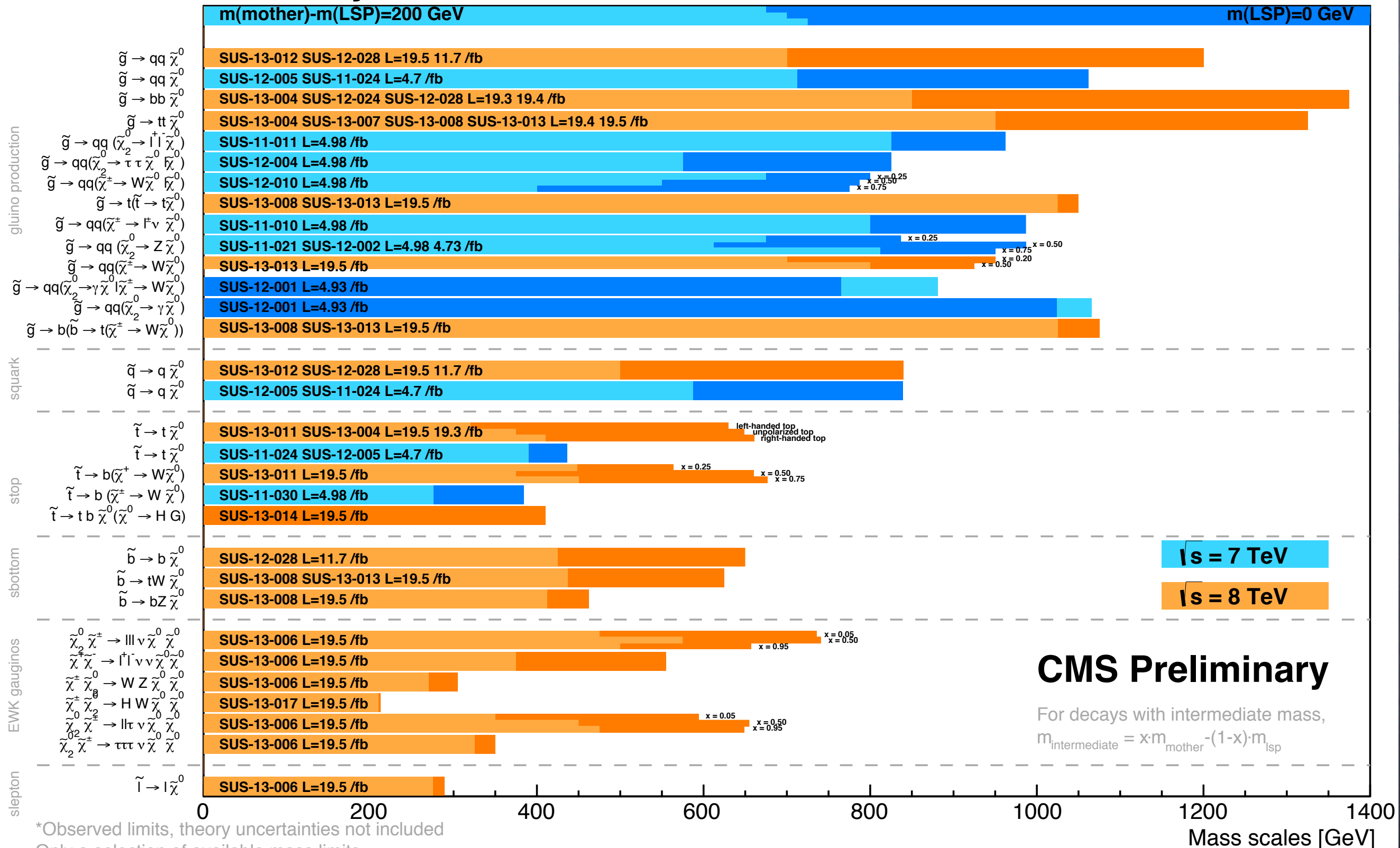
\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.



# SUSY and the LHC

## Summary of CMS SUSY Results\* in SMS framework

SUSY 2013



\*Observed limits, theory uncertainties not included  
 Only a selection of available mass limits  
 Probe \*up to\* the quoted mass limit



# SUSY and the LHC

No signal of SUSY so far  
(no signal of any BSM physics so far...)

SUSY is "in trouble":

- it can always be there at a higher scale
- but the original motivation (hierarchy problem) would be lost; at least stops must be "light"

is it possible that low scale SUSY is there but "hidden"?

→ look for alternative SUSY scenarios!



## A (new) idea

The recently discovered Higgs boson  $H$   
and the neutrino  $\nu$  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?



## A (new) idea

The recently discovered Higgs boson  $H$   
and the neutrino  $\nu$  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?

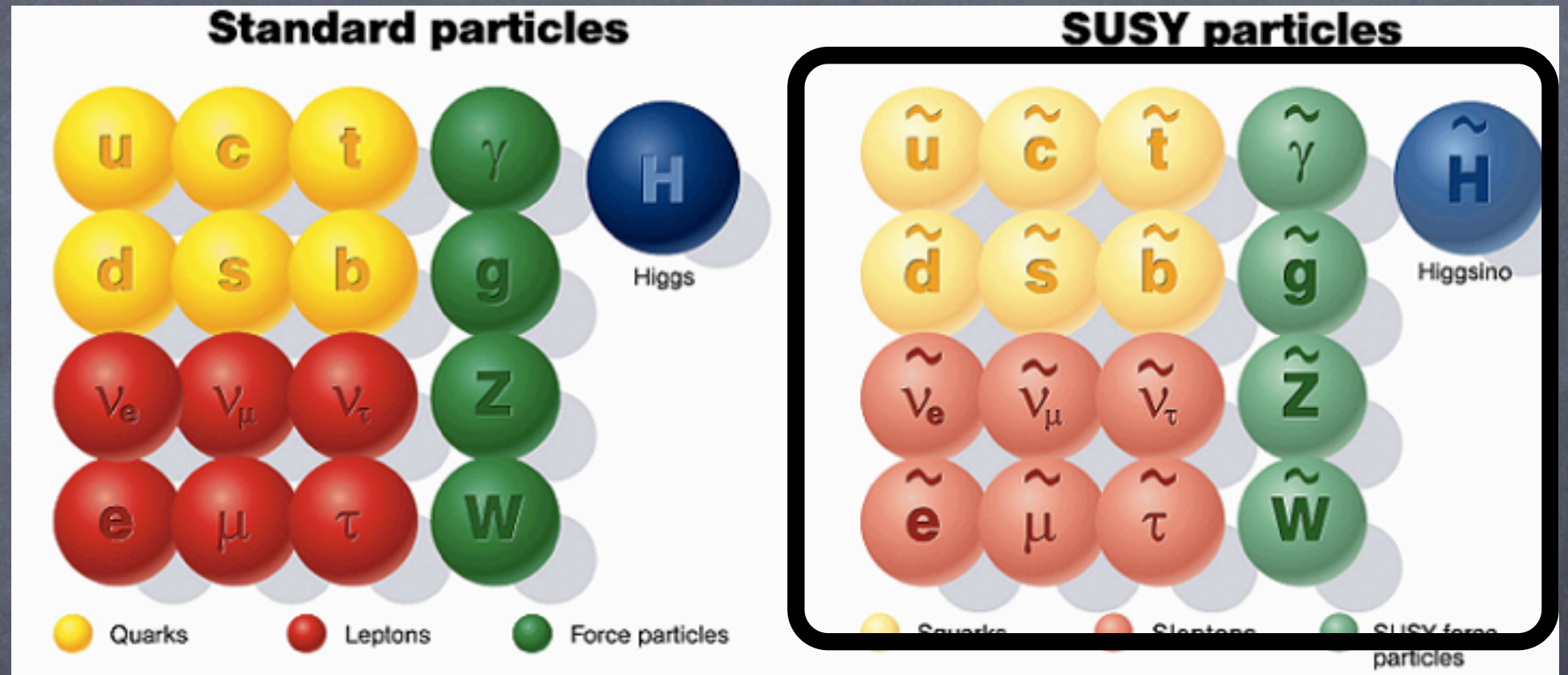
YES, but not trivial

2 conditions have to be satisfied



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

## Minimal Supersymmetric Standard Model (MSSM)



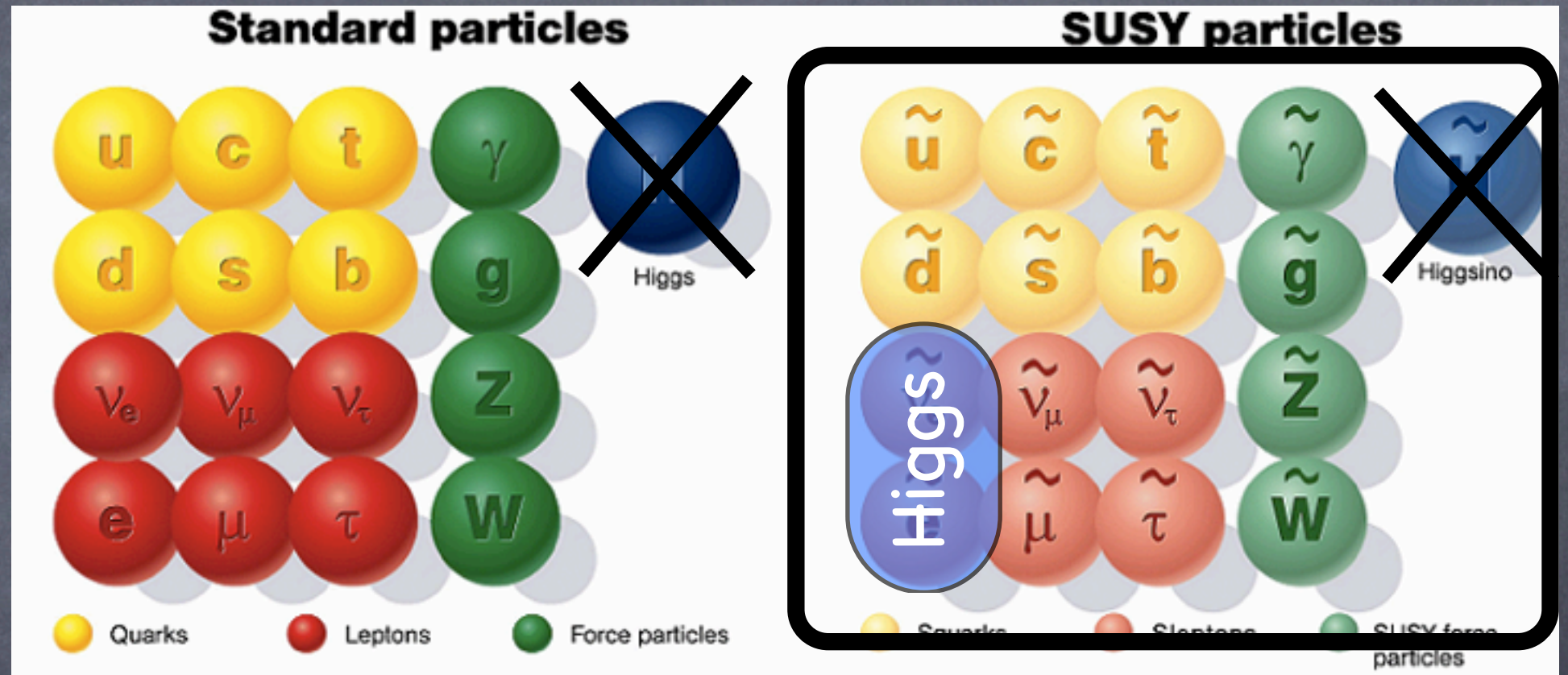
$R=1$

$R=-1$



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

Higgs as a slepton



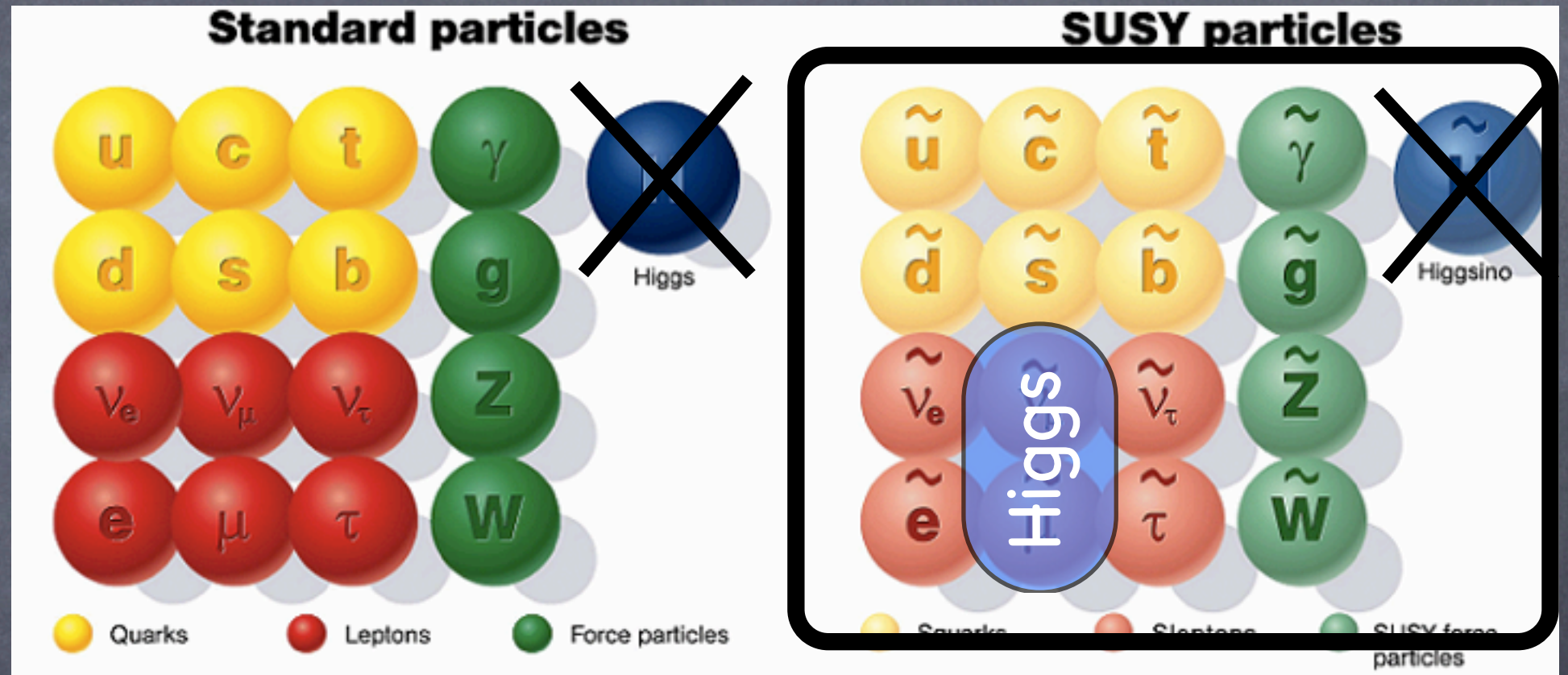
$R=1$

$R=-1$



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

Higgs as a slepton



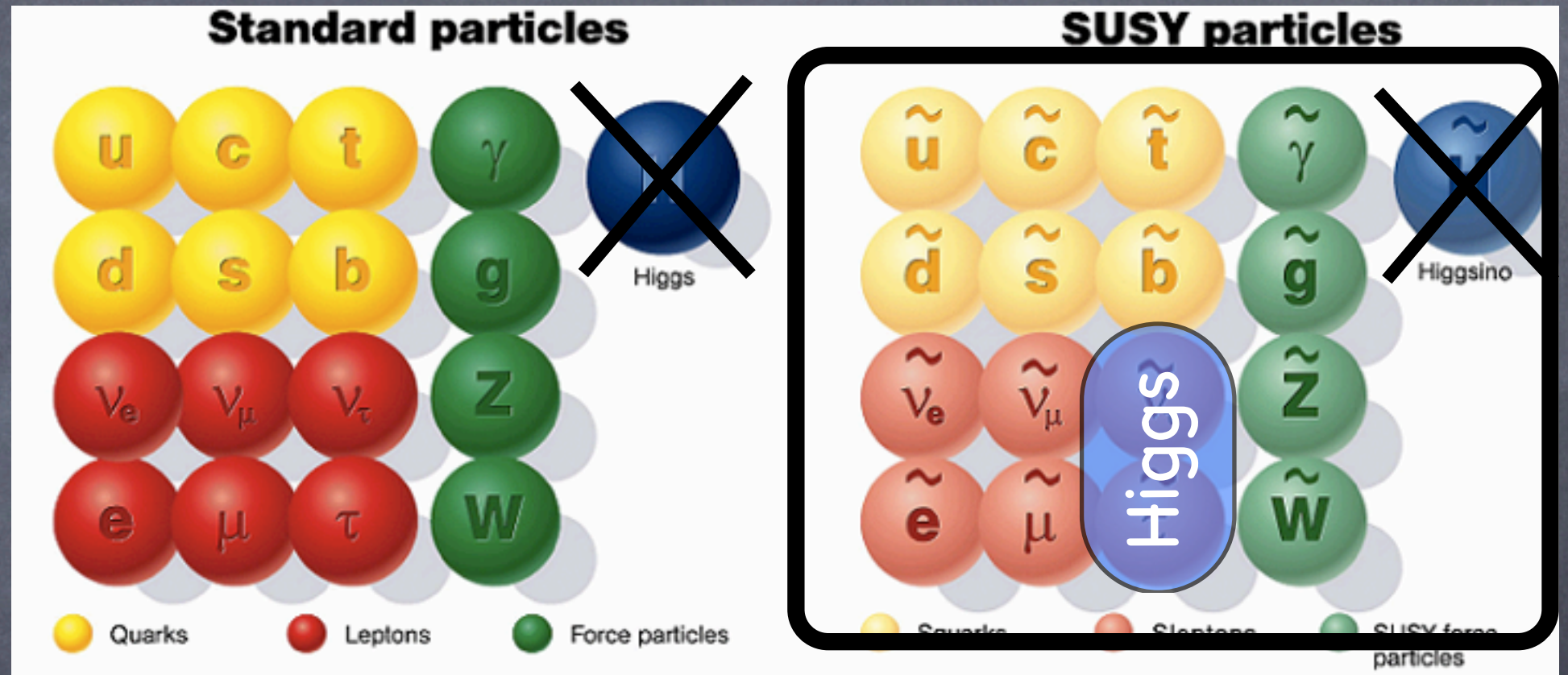
$R=1$

$R=-1$



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

Higgs as a slepton



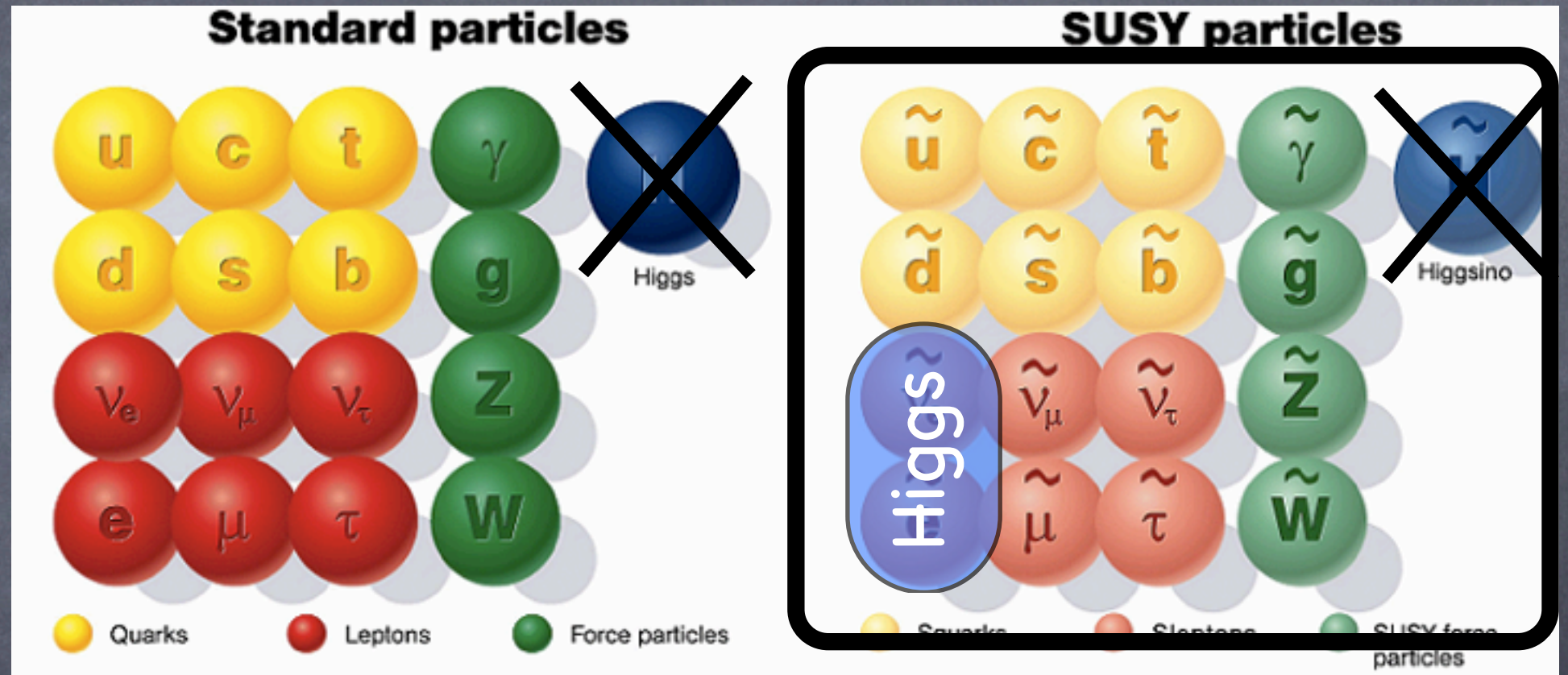
$R=1$

$R=-1$



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

Higgs as a slepton: R-parity is still viable?



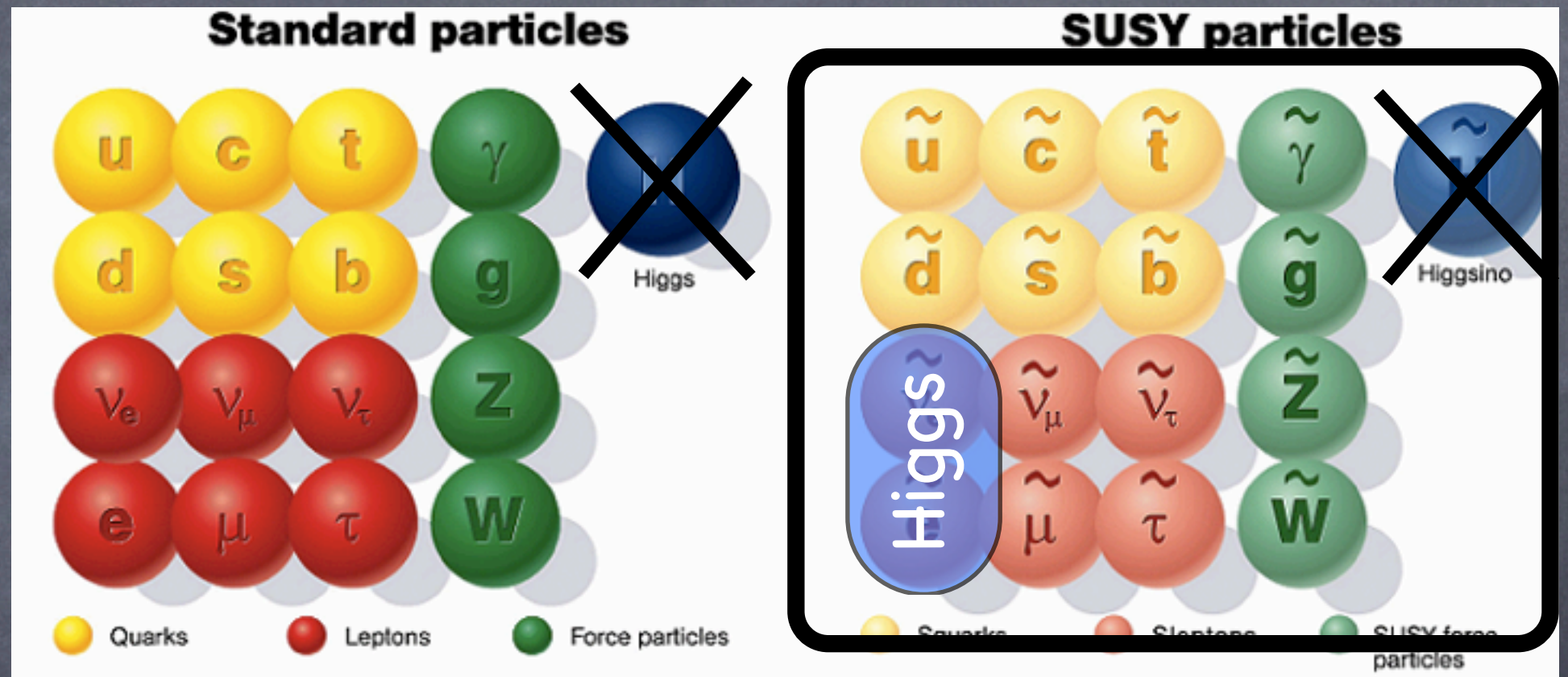
$R=1$

$R=-1$



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

Higgs as a slepton: R-parity is still viable? NO!



$R=1$

$R=-1$

The scalar vev breaks R-parity and L-number

- p-decay
- large neutrino masses



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

1<sup>st</sup> condition:

replace the R-parity with a  $U(1)_R$  symmetry



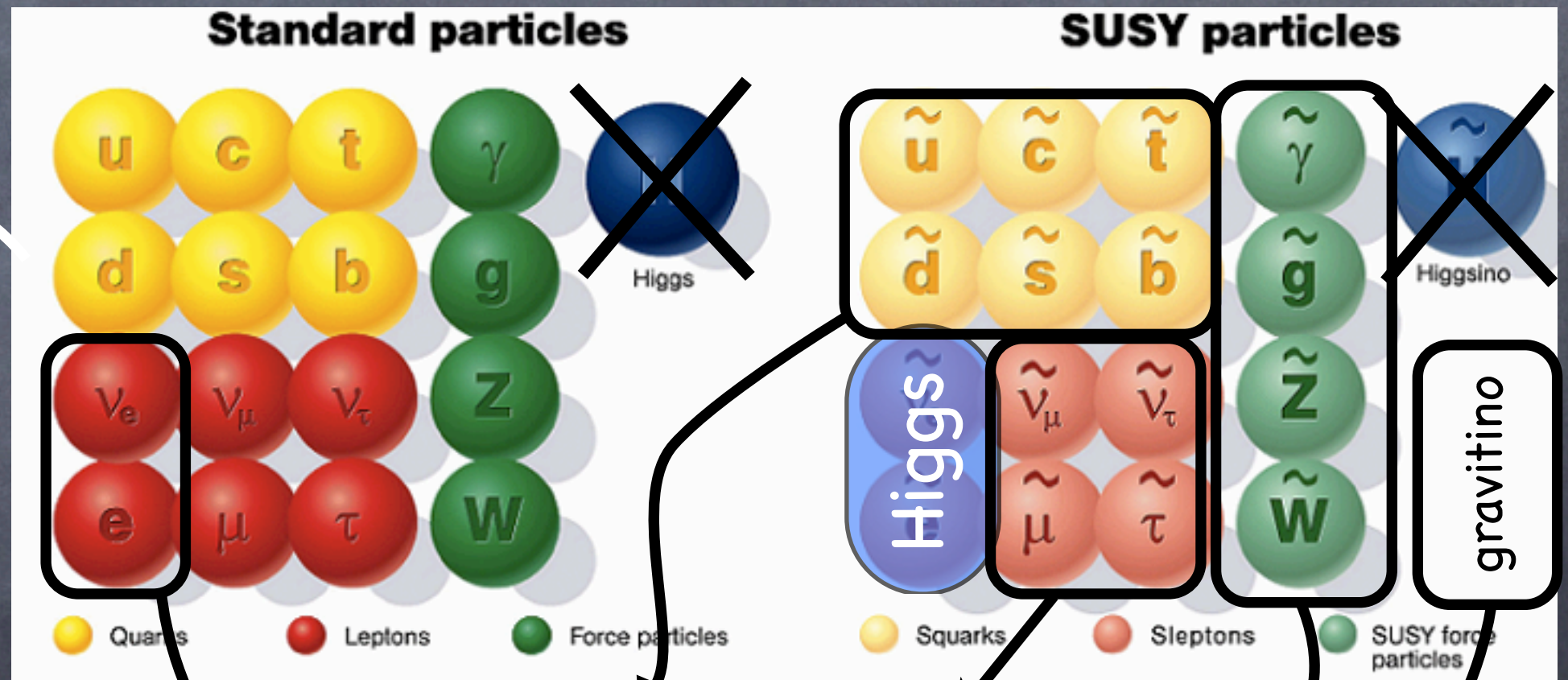
# $H \equiv \tilde{V}$ : is it possible? (1)

1<sup>st</sup> condition:

replace the R-parity with a  $U(1)_R$  symmetry

Example:

R-charge = 0



R-charge = 1

Fayet 76 - Gherghetta Pomarol 2003 - Frugiuele Gregoire 2011 - Riva, CB, Pomarol 2013 ...



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

1<sup>st</sup> condition:

replace the R-parity with a  $U(1)_R$  symmetry

Consequences:

- new decays @ LHC  $\rightarrow$  leptoquark decays  $\tilde{q} \rightarrow q\ell$



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

1<sup>st</sup> condition:

replace the R-parity with a  $U(1)_R$  symmetry

Consequences:

- new decays @ LHC  $\rightarrow$  leptoquark decays  $\tilde{q} \rightarrow q\ell$

- relations among squark masses  $m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$



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

1<sup>st</sup> condition:

replace the R-parity with a  $U(1)_R$  symmetry

Consequences:

- new decays @ LHC  $\rightarrow$  leptoquark decays  $\tilde{q} \rightarrow q\ell$
- relations among squark masses  $m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$
- Dirac gaugino masses  $\rightarrow$  no same-sign dileptons



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

1<sup>st</sup> condition:

replace the R-parity with a  $U(1)_R$  symmetry

Consequences:

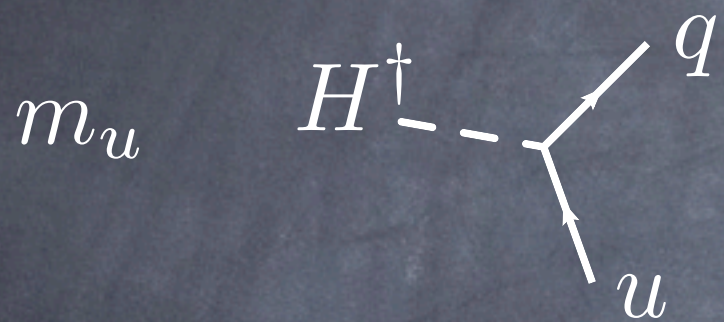
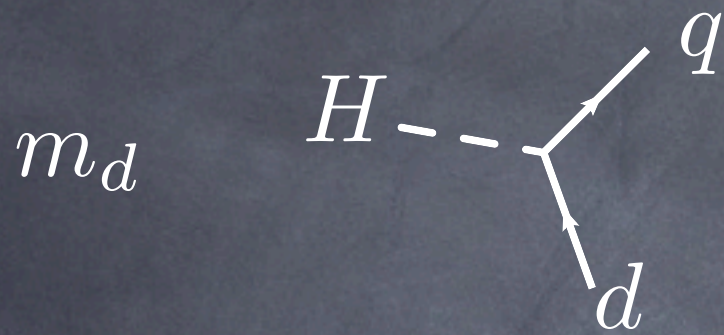
- new decays @ LHC  $\rightarrow$  leptoquark decays  $\tilde{q} \rightarrow q\ell$
- relations among squark masses  $m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$
- Dirac gaugino masses  $\rightarrow$  no same-sign dileptons
- lepton-gaugino mixing: lepton couplings modified



$\rightarrow$  gaugino masses  $>$  TeV

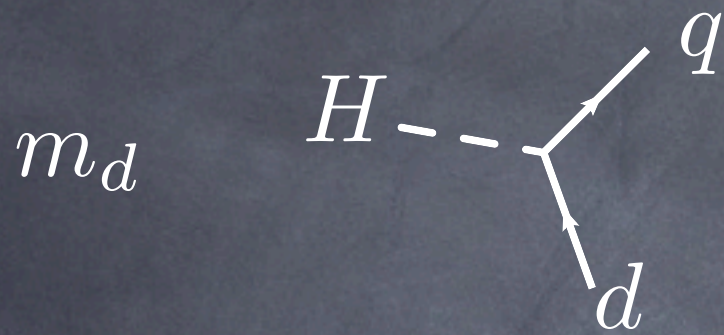


$H \equiv \tilde{V}$  : is it possible? (2)

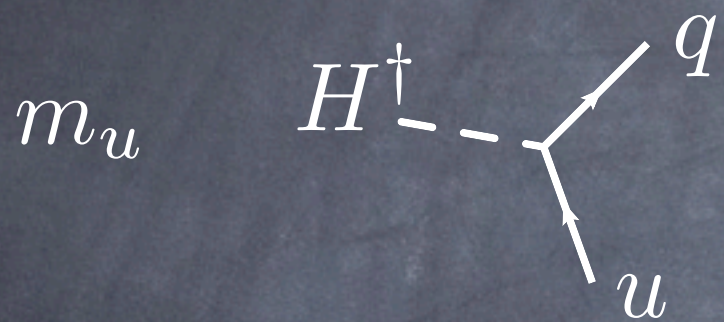




# $H \equiv \tilde{V}$ : is it possible? (2)



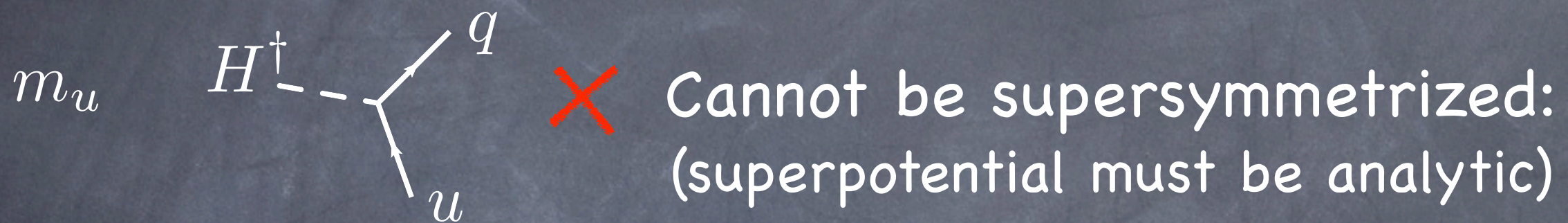
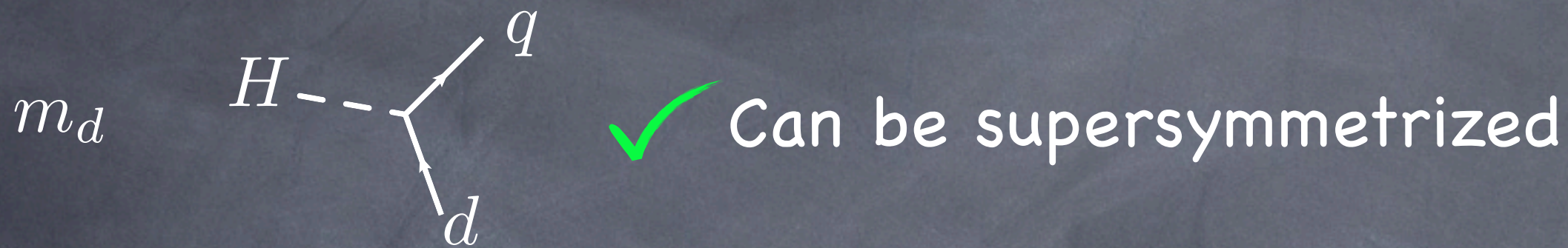
✓ Can be supersymmetrized



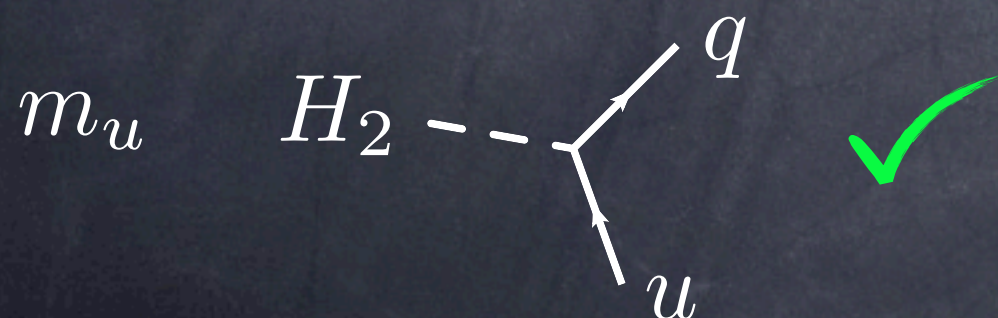
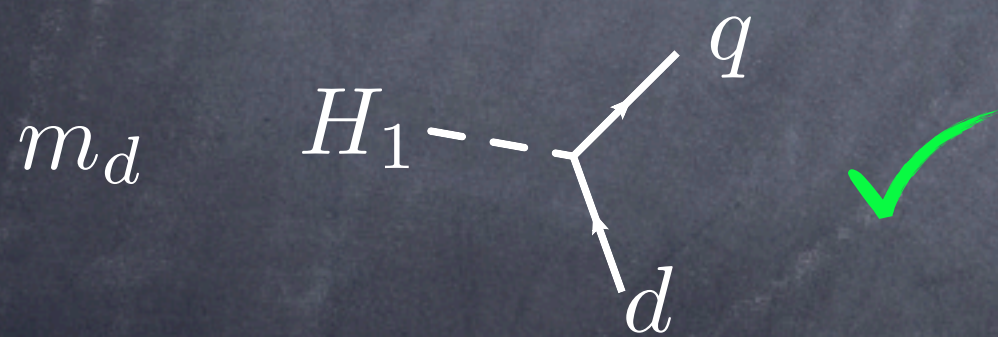
✗ Cannot be supersymmetrized:  
(superpotential must be analytic)



# $H \equiv \tilde{V}$ : is it possible? (2)



Usual solution:



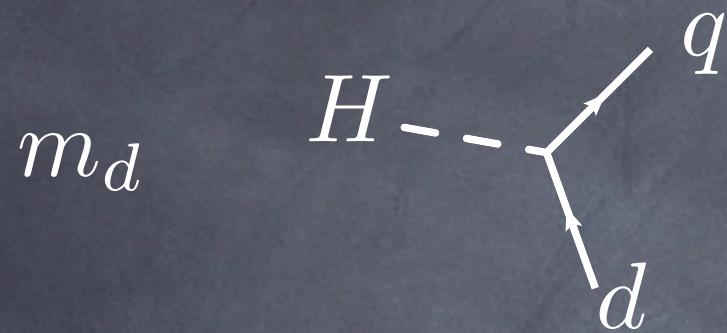
Two scalar doublets:

- MSSM

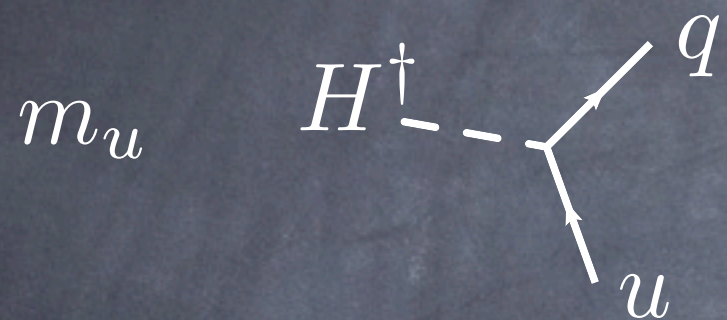
-  $H_u + L = H_d$  Frugiuele Gregoire 2011



# $H \equiv \tilde{\nu}$ : is it possible? (2)



✓ Can be supersymmetrized

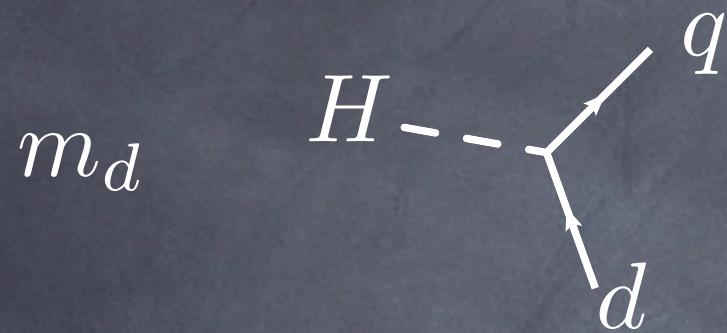


✗ Cannot be supersymmetrized:  
(superpotential must be analytic)

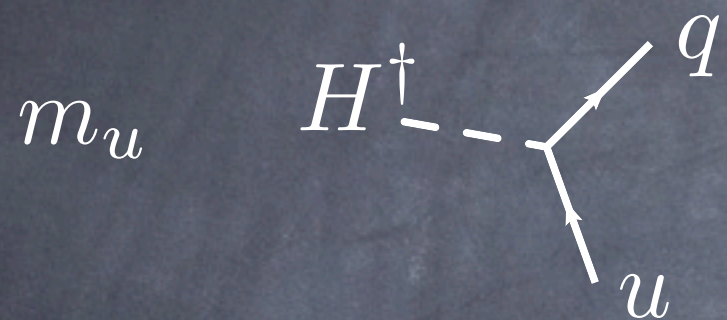
We would like to have **only 1 scalar doublet**, identified with a lepton superpartner



# $H \equiv \tilde{\nu}$ : is it possible? (2)



✓ Can be supersymmetrized



✗ Cannot be supersymmetrized:  
(superpotential must be analytic)

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

→ **2<sup>nd</sup> condition:**

the masses of the up-type quarks should come from a SUSY breaking sector



Masses from SUSY breaking sector: not a surprise!

$m_H \approx 125 \text{ GeV}$  requires ~~SUSY~~ :

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

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



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

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



# The Higgsinoless MSSM

$$W = Y_d H Q D + Y_e^{ij} H L_i E_j$$

→  $m_d$

→  $m_e$  (not for  $L_3$ )



# The Higgsinoless MSSM

$$W = Y_d H Q D + Y_e^{ij} H L_i E_j$$

→  $m_d$

→  $m_e$  (not for  $L_3$ )

All the rest comes from SUSY breaking terms:



# The Higgsinoless MSSM

$$W = Y_d H Q D + Y_{eij} H L_i E_j$$

→  $m_d$

→  $m_e$  (not for  $L_3$ )

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



# The Higgsinoless MSSM

$$W = Y_d H Q D + Y_e^{ij} H L_i E_j$$

→  $m_d$

→  $m_e$  (not for  $L_3$ )

All the rest comes from SUSY breaking terms:

## 1. up-type quarks Yukawa couplings

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

~~SUSY~~ mediation scale ↙

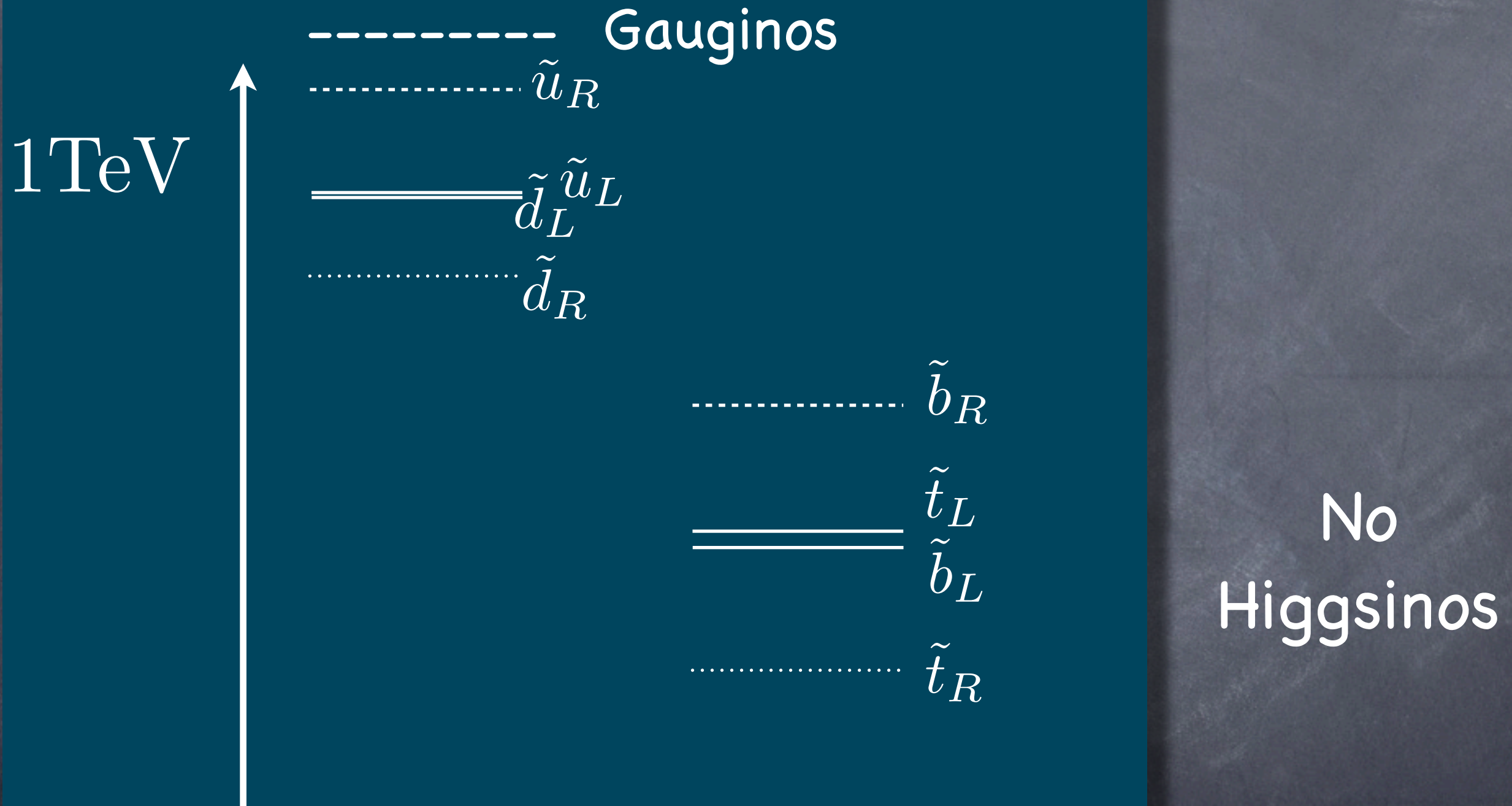
↘ effective op. scale

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

This model is an effective theory valid up to  $\sim 10$  TeV



# Typical Spectrum



Hierarchy problem still solved, natural "splitted" spectrum



# Phenomenology: the Higgs

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

Possible deviations from:

1. modification of couplings from loops mediated by stops
2. higher dimensional operators
3. invisible decays



# Phenomenology: the Higgs

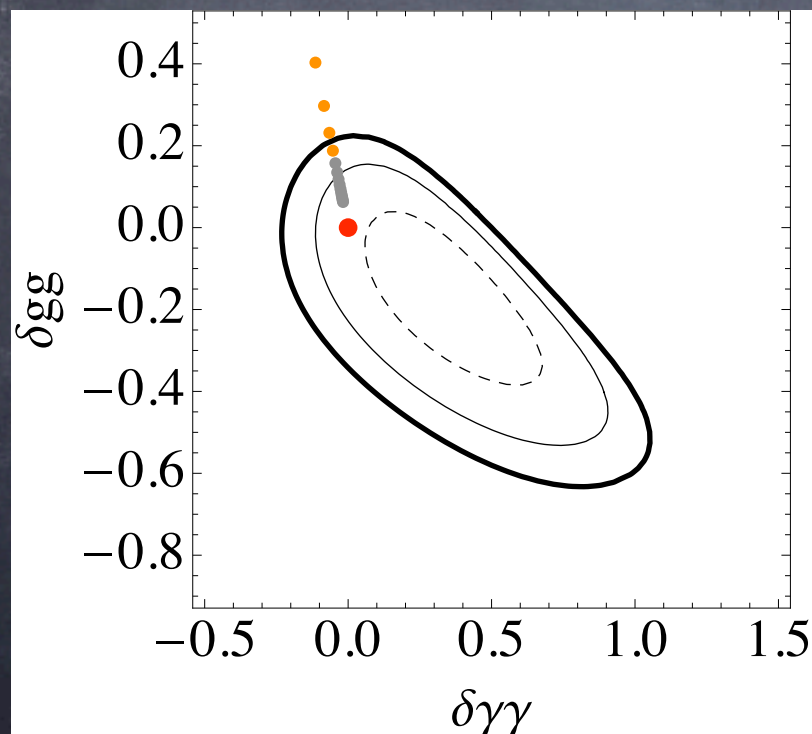
Only 1 scalar, tree-level couplings as in the SM.

Possible deviations from:

## 1. loops mediated by stops

$g_{H\Upsilon\Upsilon} \rightarrow \Gamma(H \rightarrow \Upsilon\Upsilon)$  modified  $\leftarrow$  small effect

$g_{Hgg} \rightarrow \Gamma(H \rightarrow gg)$  and  $\sigma_{\text{prod}}$  modified  $\leftarrow$  sizable effect



Fit to Higgs data:

heavier stops are favored...



# Phenomenology: the Higgs

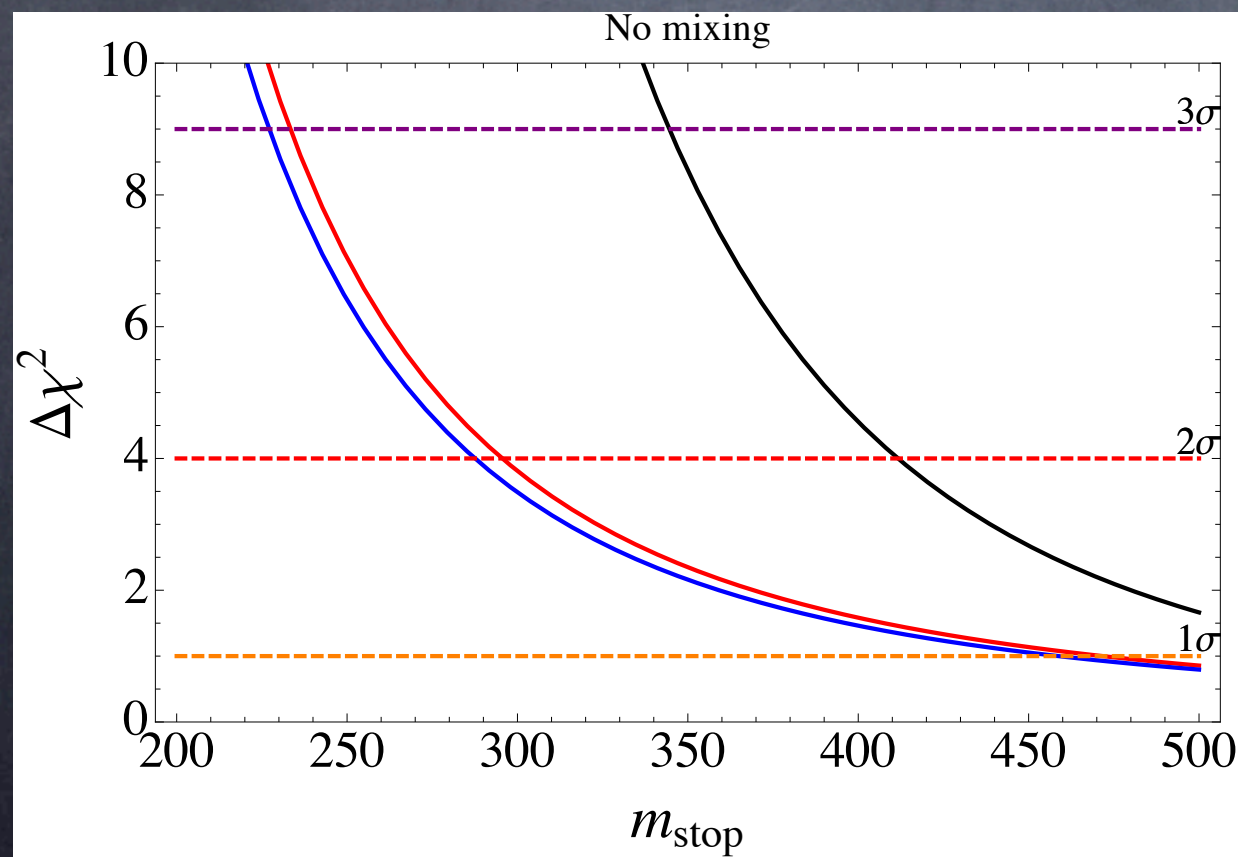
Only 1 scalar, tree-level couplings as in the SM.

Possible deviations from:

## 1. loops mediated by stops

$g_{H\Upsilon\Upsilon} \rightarrow \Gamma(H \rightarrow \Upsilon\Upsilon)$  modified  $\leftarrow$  small effect

$g_{Hgg} \rightarrow \Gamma(H \rightarrow gg)$  and  $\sigma_{\text{prod}}$  modified  $\leftarrow$  sizable effect



$m_{tR} \ll m_{tL}$	$m > 280$ GeV
$m_{tL} \ll m_{tR}$	$m > 290$ GeV
$m_{tL} = m_{tR}$	$m > 420$ GeV

Stops lighter than tops seem to be excluded in our model from Higgs data fit



# Phenomenology: the Higgs

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

Possible deviations from:

## 3. invisible decays

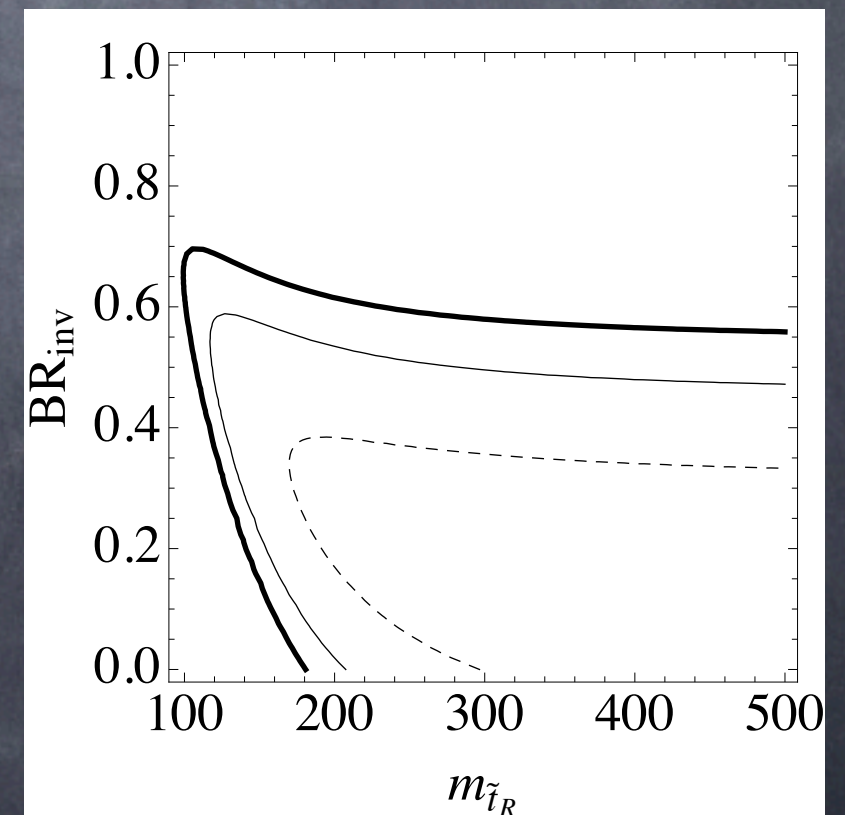
H and  $\nu$  superpartners  $\rightarrow$  interact with goldstino

• if the gravitino is light (LSP):

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

$$\sqrt{F} \approx 1 \text{ TeV} \rightarrow \text{BR}_{\text{inv}} \approx 10\%$$

$\text{BR}_{\text{inv}} \neq 0$  lighter stops still allowed





# Pheno: stops and sbottoms

No A-terms  $\Rightarrow$  prediction:  $m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$



# Pheno: stops and sbottoms

No A-terms  $\Rightarrow$  prediction:

$$m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$$

Decay	Interaction
$\tilde{t}_L \rightarrow b_R \bar{l}_L^-$	$Y_d H Q D  _{\theta^2}$
$\tilde{t}_L \rightarrow t_R \bar{\nu}_L$	$\frac{1}{\Lambda^2}  H ^2  Q ^2  _{\theta^4}$
$\tilde{t}_L \rightarrow t_L \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_L}^2}{F} \tilde{t}_L^* \tilde{G} t_L$
$\tilde{b}_L \rightarrow b_R \bar{\nu}_L$	$Y_d Q H D  _{\theta^2}$
$\tilde{b}_L \rightarrow b_L \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_L}^2}{F} \tilde{b}_L^* \tilde{G} b_L$

Decay	Interaction
$\tilde{t}_R \rightarrow t_L \nu_L$	$\frac{1}{\Lambda^2}  H ^2  U ^2  _{\theta^4}$
$\tilde{t}_R \rightarrow t_R \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_R}^2}{F} \tilde{t}_R^* \tilde{G} \bar{t}_L$
$\tilde{b}_R \rightarrow b_L \nu_L$	$Y_d Q H D  _{\theta^2}$
$\tilde{b}_R \rightarrow t_L l_L^-$	$Y_d Q H D  _{\theta^2}$
$\tilde{b}_R \rightarrow b_R \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_R}^2}{F} \tilde{b}_R^* \tilde{G} \bar{b}_L$



# Pheno: stops and sbottoms

No A-terms  $\Rightarrow$  prediction:

$$m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$$

Decay	Interaction
$\tilde{t}_L \rightarrow b_R \bar{l}_L^-$	$Y_d HQD _{\theta^2}$
$\tilde{t}_L \rightarrow t_R \bar{\nu}_L$	$\frac{1}{\Lambda^2}  H ^2  Q ^2  _{\theta^4}$
$\tilde{t}_L \rightarrow t_L \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_L}^2}{F} \tilde{t}_L^* \tilde{G} t_L$
$\tilde{b}_L \rightarrow b_R \bar{\nu}_L$	$Y_d QHD _{\theta^2}$
$\tilde{b}_L \rightarrow b_L \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_L}^2}{F} \tilde{b}_L^* \tilde{G} b_L$

Decay	Interaction
$\tilde{t}_R \rightarrow t_L \nu_L$	$\frac{1}{\Lambda^2}  H ^2  U ^2  _{\theta^4}$
$\tilde{t}_R \rightarrow t_R \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_R}^2}{F} \tilde{t}_R^* \tilde{G} \bar{t}_L$
$\tilde{b}_R \rightarrow b_L \nu_L$	$Y_d QHD _{\theta^2}$
$\tilde{b}_R \rightarrow t_L \bar{l}_L^-$	$Y_d QHD _{\theta^2}$
$\tilde{b}_R \rightarrow b_R \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_R}^2}{F} \tilde{b}_R^* \tilde{G} \bar{b}_L$

Only jets + MET



# Pheno: stops and sbottoms

No A-terms  $\Rightarrow$  prediction:

$$m_{\tilde{b}_L}^2 = m_{\tilde{t}_L}^2 - m_t^2 + m_b^2$$

Decay	Interaction
$\tilde{t}_L \rightarrow b_R \bar{l}_L^-$	$Y_d HQD _{\theta^2}$
$\tilde{t}_L \rightarrow t_R \bar{\nu}_L$	$\frac{1}{\Lambda^2}  H ^2  Q ^2  _{\theta^4}$
$\tilde{t}_L \rightarrow t_L \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_L}^2}{F} \tilde{t}_L^* \tilde{G} t_L$
$\tilde{b}_L \rightarrow b_R \bar{\nu}_L$	$Y_d QHD _{\theta^2}$
$\tilde{b}_L \rightarrow b_L \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_L}^2}{F} \tilde{b}_L^* \tilde{G} b_L$

Decay	Interaction
$\tilde{t}_R \rightarrow t_L \nu_L$	$\frac{1}{\Lambda^2}  H ^2  U ^2  _{\theta^4}$
$\tilde{t}_R \rightarrow t_R \tilde{G}$	$\frac{m_t^2 - m_{\tilde{t}_R}^2}{F} \tilde{t}_R^* \tilde{G} \bar{t}_L$
$\tilde{b}_R \rightarrow b_L \nu_L$	$Y_d QHD _{\theta^2}$
$\tilde{b}_R \rightarrow t_L l_L^-$	$Y_d QHD _{\theta^2}$
$\tilde{b}_R \rightarrow b_R \tilde{G}$	$\frac{m_b^2 - m_{\tilde{b}_R}^2}{F} \tilde{b}_R^* \tilde{G} \bar{b}_L$

Only jets + MET

Both jets + MET  
and leptoquark decays



# Pheno: stops and sbottoms

$\tilde{t}_R$  and  $\tilde{b}_L$  decay only into top/bottom + MET  
 $\Rightarrow$  MSSM searches can be adapted

from  $\tilde{b} \rightarrow b\chi_0$  with massless neutralino:

$$m_{\tilde{b}_L} > 650 \text{ GeV}$$



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

from  $\tilde{t} \rightarrow t\chi_0$  with massless neutralino:

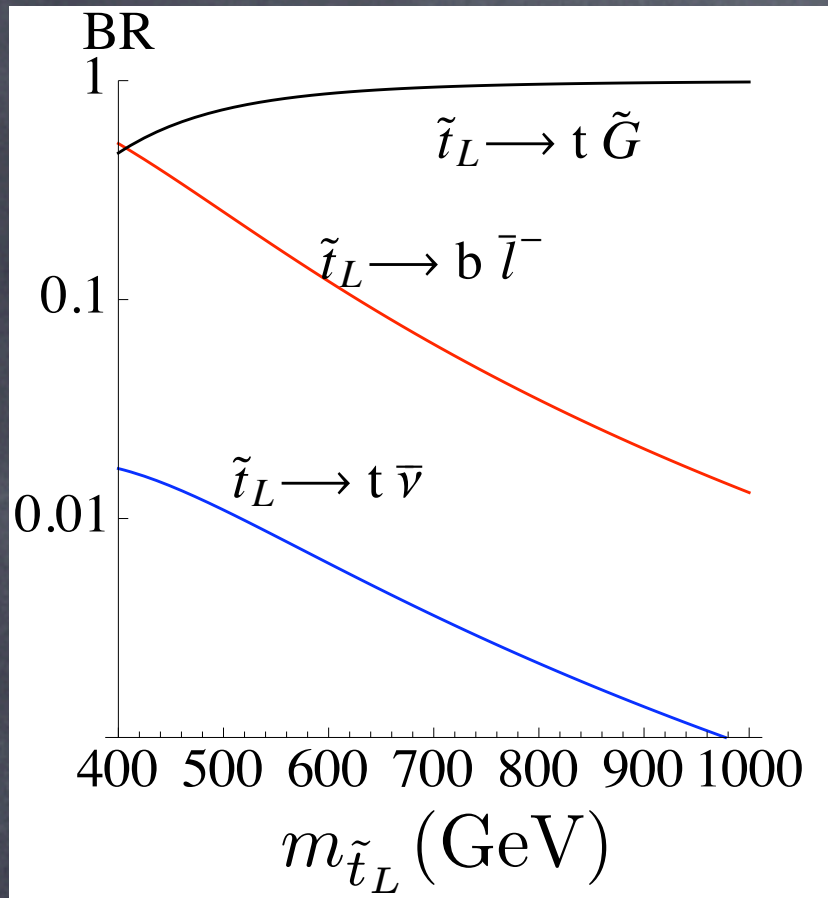
$$190 \text{ GeV} < m_{\tilde{t}_R} < 685 \text{ GeV}$$

stops lighter than tops in principle still allowed ( $m_{\tilde{t}_R} > 150 \text{ GeV}$ )



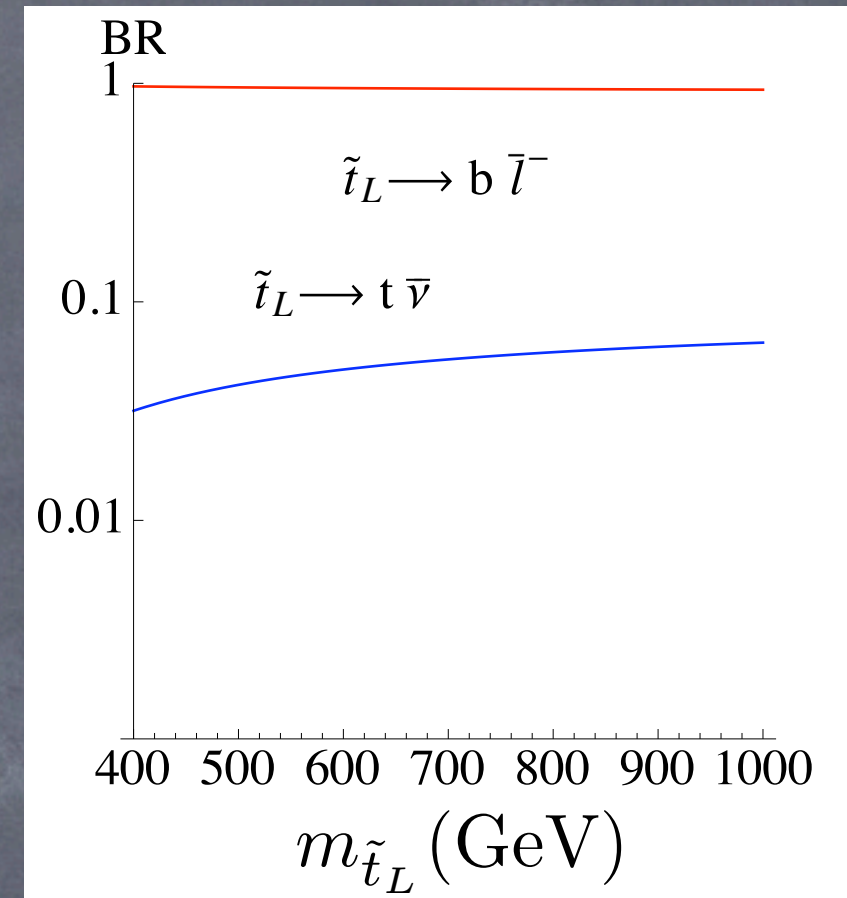
$\tilde{t}_L$ 

# Pheno: stops and sbottoms



← light gravitino  
or small F

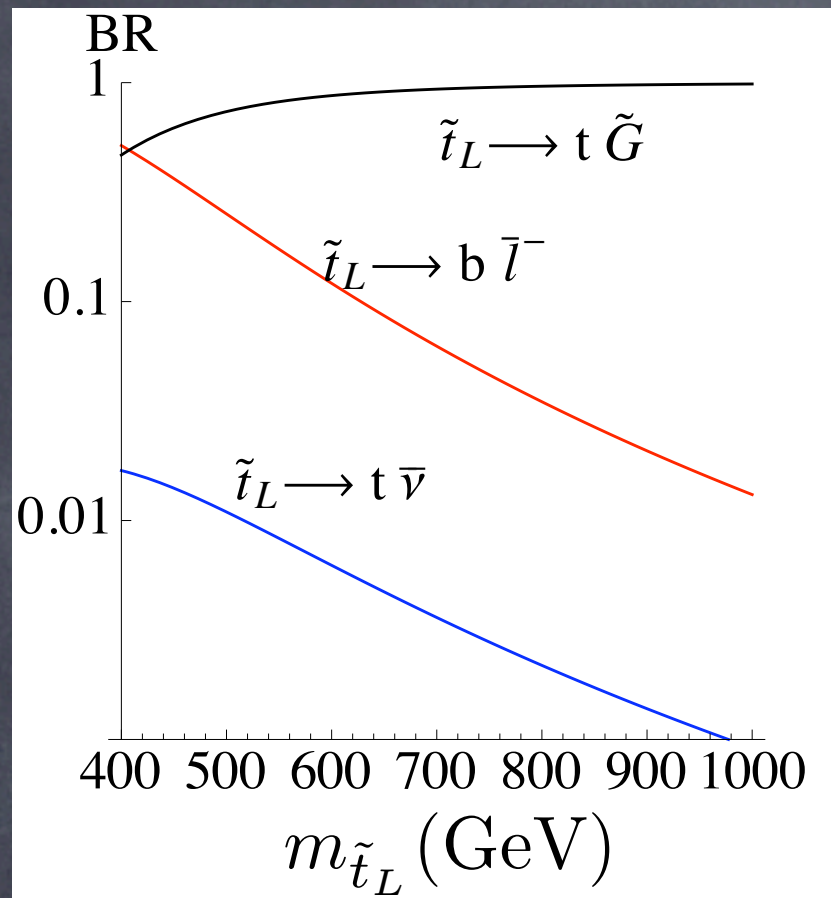
heavy gravitino  
or large F





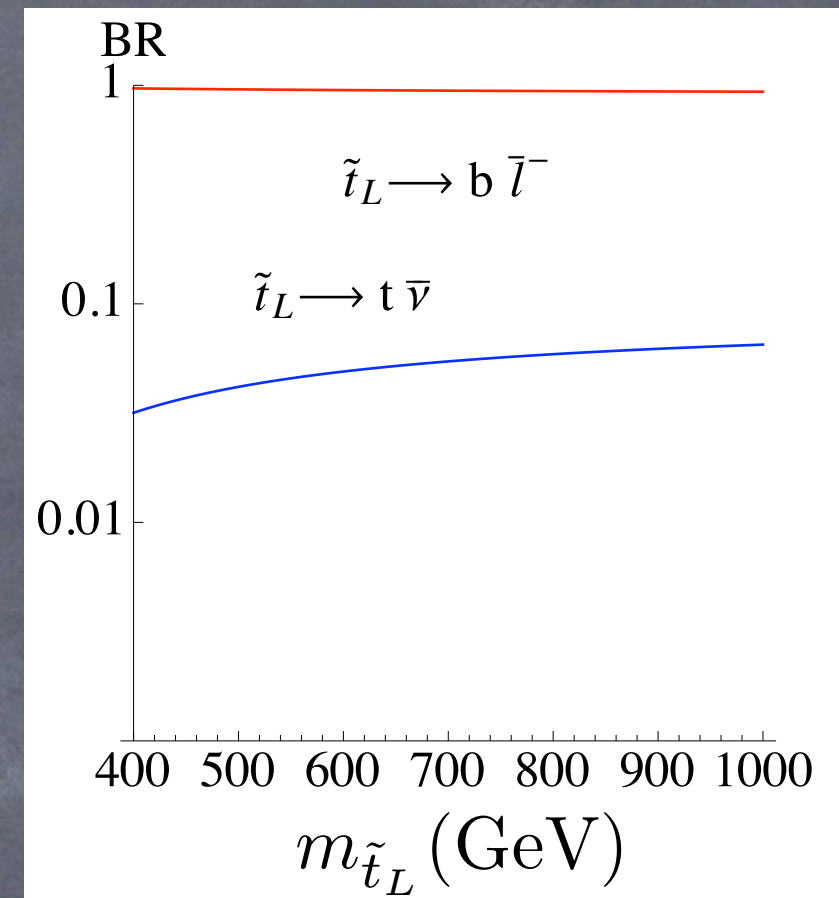
$\tilde{t}_L$ 

# Pheno: stops and sbottoms



← light gravitino  
or small F

heavy gravitino  
or large F



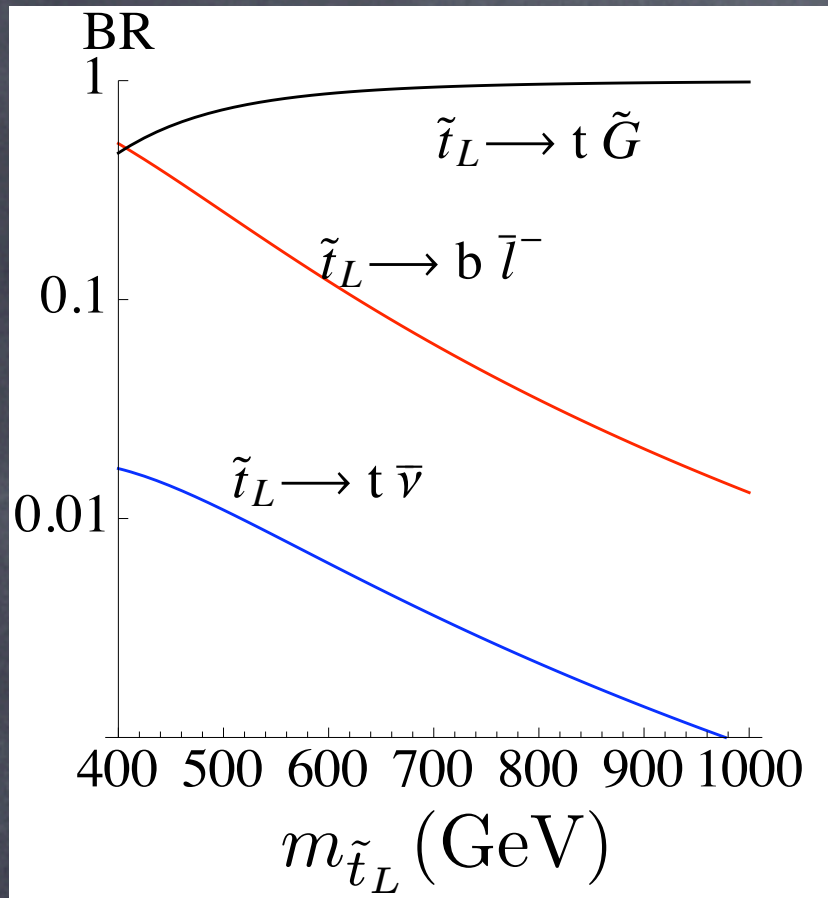
searches jets + MET:

$$190 \text{ GeV} < m_{\tilde{t}_L} < 685 \text{ GeV}$$



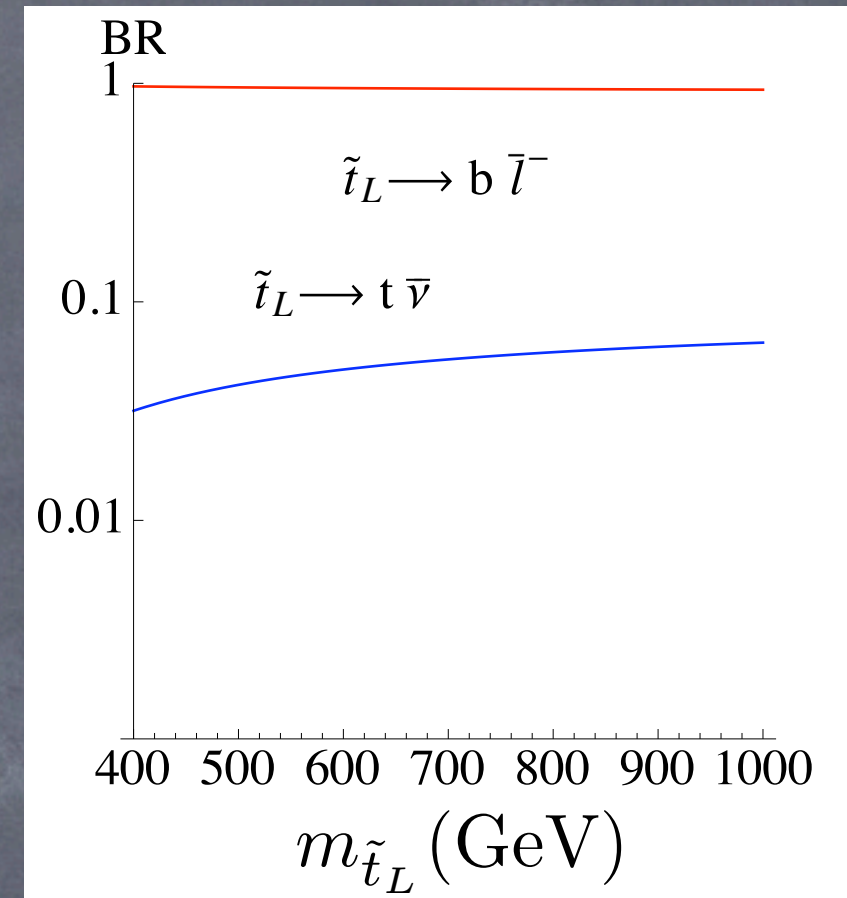
$\tilde{t}_L$ 

# Pheno: stops and sbottoms



← light gravitino  
or small F

heavy gravitino  
or large F →



searches jets + MET:

$$190 \text{ GeV} < m_{\tilde{t}_L} < 685 \text{ GeV}$$

Look for b-jet + e/ $\mu$  !!!

searches leptoquarks:

jet+e

$$m_{\tilde{t}_L} > 660 \text{ GeV}$$

jet+ $\mu$

$$m_{\tilde{t}_L} > 1070 \text{ GeV}$$

jet+ $\tau$

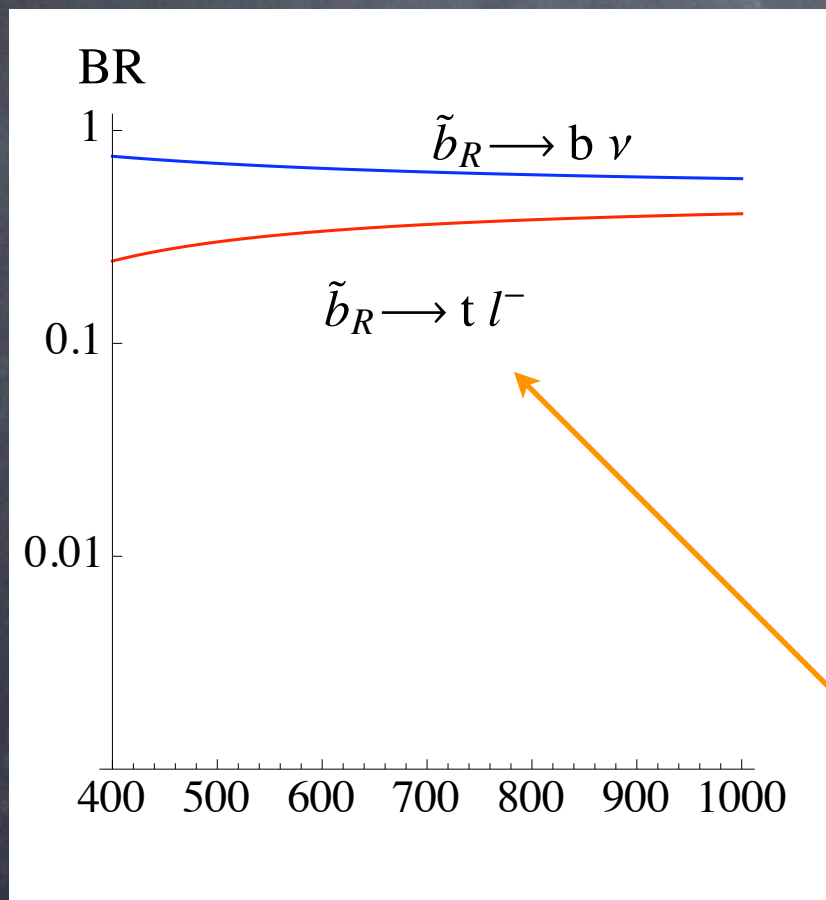
$$m_{\tilde{t}_L} > 534 \text{ GeV}$$



$\tilde{b}_R$ 

# Pheno: stops and sbottoms

Light gravitino:  $b + \text{MET}$  dominates (factor  $\sim 10$ );  
otherwise:



Similar Br, both controlled by  $Y_b$ ,  
bounds from  $b\text{-jets} + \text{MET}$

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

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

Top helicity:

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

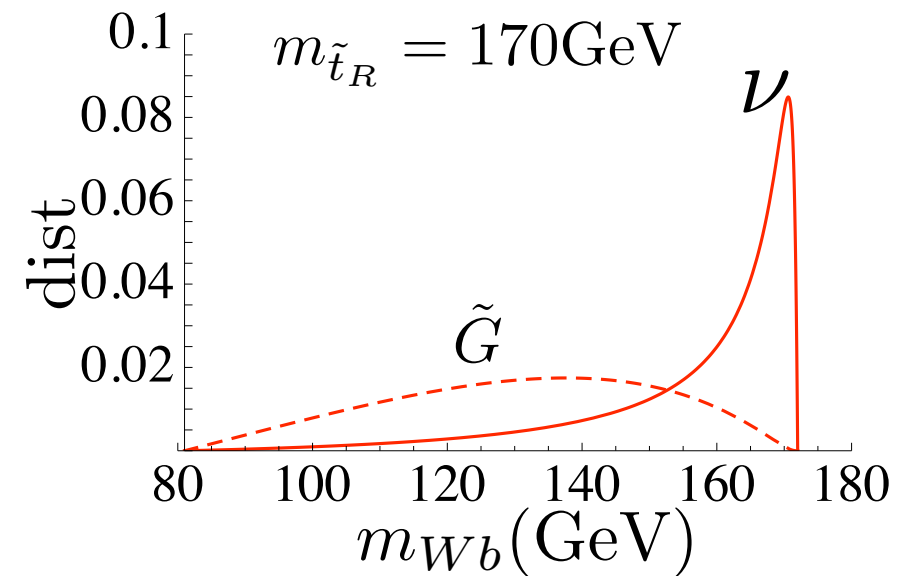
$\tilde{t}_R \rightarrow t_R \tilde{G}$  as MSSM

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

> t + MET observed:

- it's our  $\tilde{t}_L$  if
- it can be  $\tilde{t}_R$ ;

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





# Pheno: 1<sup>st</sup> and 2<sup>nd</sup> gen. squarks

• light gravitino (and  $F \approx \text{TeV}^2$ )

$\tilde{q} \rightarrow q\tilde{G} \rightsquigarrow$  jets + MET  $m > 830 \text{ GeV}$



# Pheno: 1<sup>st</sup> and 2<sup>nd</sup> gen. squarks

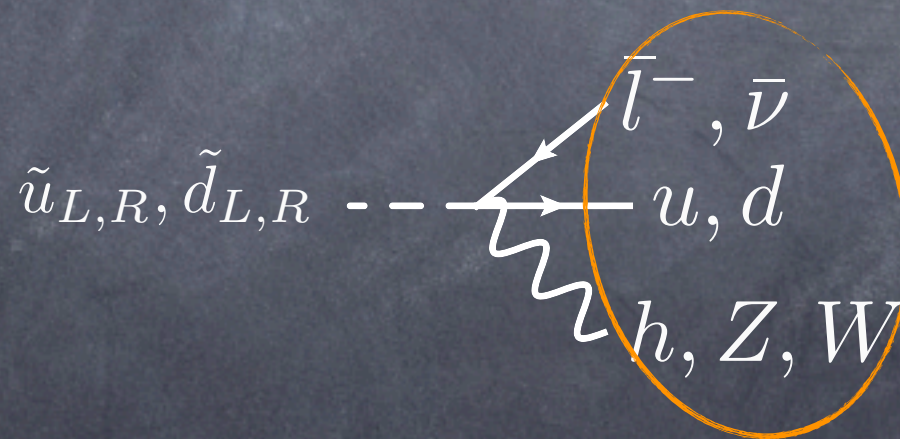
- light gravitino (and  $F \approx \text{TeV}^2$ )

$$\tilde{q} \rightarrow q\tilde{G} \rightsquigarrow \text{jets} + \text{MET} \quad m > 830 \text{ GeV}$$

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

2-body decays suppressed by small Yukawas  
 $\Rightarrow$  3-body decays can dominate

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



jet (no b-jets) + W/Z + MET/lepton  $\leftarrow$  Look for them!!!



# Pheno: sleptons

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

$$\tilde{l} \rightarrow l \tilde{G} \rightsquigarrow \text{leptons} + \text{MET} \quad m > 270 \text{ GeV}$$

$$\tilde{\nu} \rightarrow \nu \tilde{G} \rightsquigarrow \text{MET} ; \text{monojet, dijet+MET}$$

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

3-body decays can dominate

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

↖ Look for these channels!!!



# Conclusions and outlook

- The SM should be extended



# Conclusions and outlook

- The SM should be extended
- One appealing possibility: SUSY



# Conclusions and outlook

- The SM should be extended
- One appealing possibility: SUSY
- LHC is putting SUSY in a corner



# Conclusions and outlook

- The SM should be extended
- One appealing possibility: SUSY
- LHC is putting SUSY in a corner
- However SUSY could be already here, if the Higgs is the SUSY partner of the neutrino



# Conclusions and outlook

- The SM should be extended
- One appealing possibility: SUSY
- LHC is putting SUSY in a corner
- However SUSY could be already here, if the Higgs is the SUSY partner of the neutrino
- Under certain conditions this could be realized



# Conclusions and outlook

- The SM should be extended
- One appealing possibility: SUSY
- LHC is putting SUSY in a corner
- However SUSY could be already here, if the Higgs is the SUSY partner of the neutrino
- Under certain conditions this could be realized
- This model shows an interesting spectrum (only light stops and sbottoms) and interesting signatures @ LHC



# Conclusions and outlook

- 👁 The SM should be extended
- 👁 One appealing possibility: SUSY
- 👁 LHC is putting SUSY in a corner
- 👁 However SUSY could be already here, if the Higgs is the SUSY partner of the neutrino
- 👁 Under certain conditions this could be realized
- 👁 This model shows an interesting spectrum (only light stops and sbottoms) and interesting signatures @ LHC
- 👁 Even if at present SUSY seems to be disfavoured, do not desperate,  
maybe we are already in the SUSY era!



# Conclusions and outlook

- 👁 The SM should be extended
- 👁 One appealing possibility: SUSY
- 👁 LHC is putting SUSY in a corner
- 👁 However SUSY could be already here, if the Higgs is the SUSY partner of the neutrino
- 👁 Under certain conditions this could be realized
- 👁 This model shows an interesting spectrum (only light stops and sbottoms) and interesting signatures @ LHC
- 👁 Even if at present SUSY seems to be disfavoured, do not desperate,  
maybe we are already in the SUSY era!

Grazie! :)