

XXXVI Annual Reunion  
Division of Particles and Fields

# *Vital signs of Supersymmetry*

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## *Outline*

- Motivation for Supersymmetry.
- Direct search experimental data.
- Supersymmetry, an introduction.  
pMSSM. hMSSM.
- Indirect SUSY searches from precision Higgs data.  
Higgs production.  
Higgs decays.  
DM candidate.

## Supersymmetry: a loved theory.

- EW scale is stabilized, with  $\lambda_S = |\lambda_f|^2$  then the  $\Lambda_{UV}^2$  will neatly cancel

for instance see [S.P. Martin 08, a SUSY Premier]

- Unification of gauge couplings.
- Generates DM candidates.
- Possible exotic signals of FV and  $\mathcal{CP}$  through *SUSY loops*
- Solution to hierarchy problem
- GUT: mSugra

H.Haber (1995),

S. Heinemeyer, Stal and Weiglein (2012).

*Low-energy Supersymmetry: Prospects and Challenges*, Djouadi and Quevillon (2013).

# Higgs mass renormalization, weak scale stability

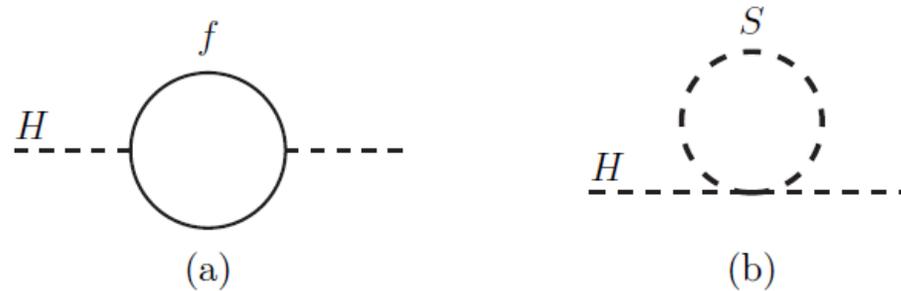


Figure 1: (a) fermionic and (b) any scalar correction to the Higgs mass

✧ Fermionic contribution to the Higgs mass

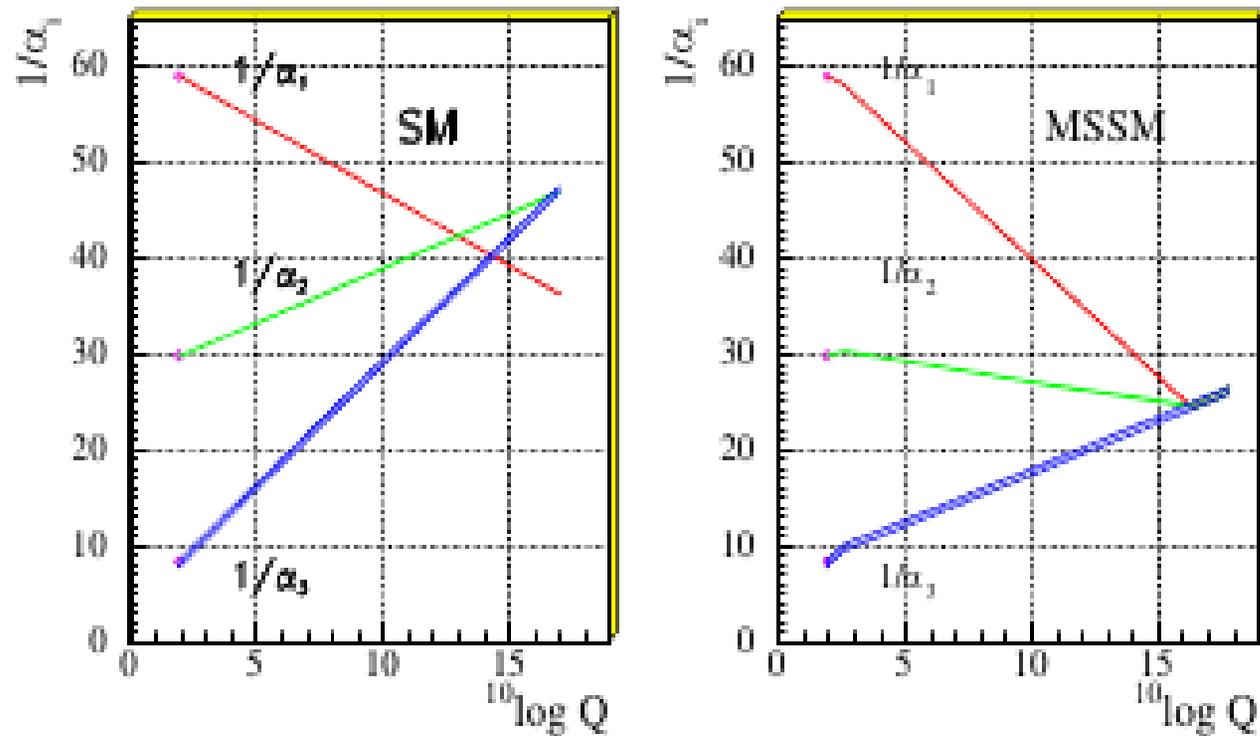
$$\Delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \dots \quad (1)$$

✧ Contribution to the Higgs mass from a scalar

$$\Delta m_h^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{UV}^2 - 2m_S^2 \log \frac{\Lambda_{UV}}{m_S} + \dots \right] \quad (2)$$

# GUTs

Unification of the Coupling Constants  
in the SM and the minimal MSSM

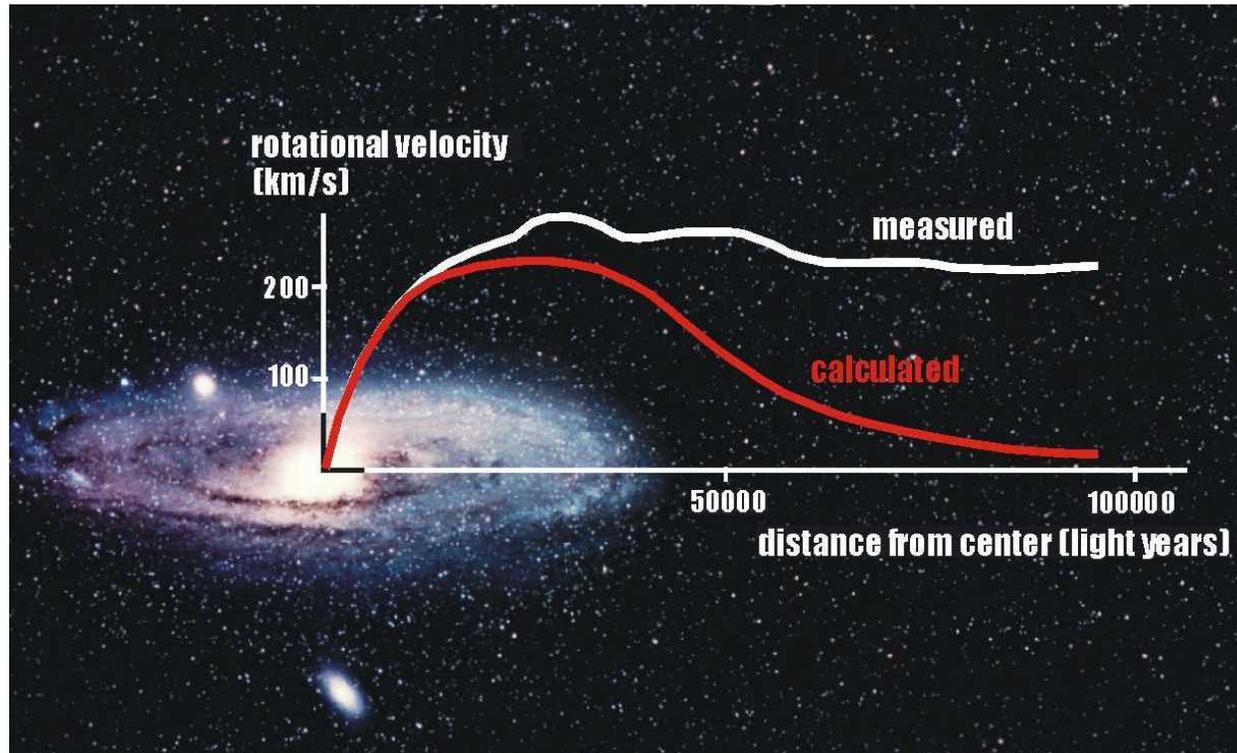


[Amaldi, de Boer, Fürstenau '92]

# Dark Matter

Vera

Rubin



# Baryogenesis

Barionic Asymmetry, difference between matter and antimatter quantification.

This early state of the universe stands in stark contrast to what we observe in the universe today. Direct observation shows that the universe around us contains no appreciable primordial antimatter. In addition, the theory of primordial nucleosynthesis allows accurate predictions of the cosmological abundances of all the light elements,  $H$ ,  ${}^3He$ ,  ${}^4He$ ,  $D$ ,  $B$  and  ${}^7Li$ , while requiring only that, defining  $n_b(\bar{b})$  to be the number density of (anti)-baryons and  $s$  to be the entropy density

$$2.6 \times 10^{-10} < \eta = \frac{n_b - n_{\bar{b}}}{s} < 6.2 \times 10^{-10} \quad (3)$$

## Some unexplained experimental signals

- ① Muon anomalous magnetic moment  $g - 2$ .
- ② New data for  $W$  mass, departing from SM value.
- ③ Neutrinos oscillations  $\rightarrow$  massive right neutrinos.
- ④ Still high experimental bounds with respect to SM values:
  - $BR^{Exp}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$
  - $BR^{Exp}(t \rightarrow ch) < 10^{-3}$ ;  $BR^{SM}(t \rightarrow ch) \simeq 10^{-14}$
  - Very tight but still a room for extra  $CP$  mixing mesones:  $B_s$ ,  $D_s$
  - Leptonic non-universality in semileptonic meson decays.

# Supersymmetry experimental searches.

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

July 2020

ATLAS Preliminary

$\sqrt{s} = 13$  TeV

|   | Model  | Signature  | $\int \mathcal{L} dt$ [fb $^{-1}$ ] | Mass limit                  | Reference   |  |   |
|---|--|--|-------------------------------------|-----------------------------|---|--|---|
| Inclusive Searches  | $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$  | 0 $e, \mu$<br>mono-jet   | 2-6 jets<br>1-3 jets                | $E_{miss}^T$<br>36.1        | $\tilde{q}$ [10x Degen.]<br>$\tilde{q}$ [1x, 8x Degen.] | $m(\tilde{\chi}_1^0) < 400$ GeV<br>$m(\tilde{q}) - m(\tilde{\chi}_1^0) = 5$ GeV  | ATLAS-CONF-2019-040<br>1711.03301   |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$   | 0 $e, \mu$   | 2-6 jets                            | $E_{miss}^T$<br>139         | $\tilde{g}$<br>$\tilde{g}$                              | $m(\tilde{\chi}_1^0) = 0$ GeV<br>$m(\tilde{\chi}_1^0) = 1000$ GeV  | ATLAS-CONF-2019-040<br>ATLAS-CONF-2019-040  |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$  | 1 $e, \mu$   | 2-6 jets                            | $E_{miss}^T$<br>139         | $\tilde{g}$   | $m(\tilde{\chi}_1^0) < 600$ GeV  | ATLAS-CONF-2020-047   |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$                                       | $ee, \mu\mu$   | 2 jets                              | $E_{miss}^T$<br>36.1        | $\tilde{g}$   | $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 50$ GeV  | 1805.11381  |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$   | 0 $e, \mu$   | 7-11 jets                           | $E_{miss}^T$<br>139         | $\tilde{g}$   | $m(\tilde{\chi}_1^0) < 600$ GeV  | ATLAS-CONF-2020-002   |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$   | SS $e, \mu$  | 6 jets                              | $E_{miss}^T$<br>139         | $\tilde{g}$   | $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV   | 1909.08457  |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$   | 0-1 $e, \mu$<br>SS $e, \mu$  | 3 $b$<br>6 jets                     | $E_{miss}^T$<br>79.8<br>139 | $\tilde{g}$<br>$\tilde{g}$                              | $m(\tilde{\chi}_1^0) < 200$ GeV<br>$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV  | ATLAS-CONF-2018-041<br>1909.08457   |
|   | 3 <sup>rd</sup> gen. squarks direct production   | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0/\tilde{\chi}_1^\pm$ | Multiple<br>Multiple                | Multiple<br>Multiple        | 36.1<br>139   | $\tilde{b}_1$<br>$\tilde{b}_1$   | $m(\tilde{\chi}_1^0) = 300$ GeV, $BR(\tilde{b}_1\tilde{\chi}_1^0) = 1$<br>$m(\tilde{\chi}_1^0) = 200$ GeV, $m(\tilde{\chi}_1^\pm) = 300$ GeV, $BR(\tilde{b}_1\tilde{\chi}_1^\pm) = 1$ |
| $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_2^0 \rightarrow bh\tilde{\chi}_1^0$                              |  | 0 $e, \mu$<br>2 $b$  | 6 $b$<br>2 $b$                      | $E_{miss}^T$<br>139<br>139  | $\tilde{b}_1$<br>$\tilde{b}_1$                          | $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV<br>$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV | 1908.03122<br>ATLAS-CONF-2020-031   |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$   |  | 0-1 $e, \mu$   | $\geq 1$ jet                        | $E_{miss}^T$<br>139         | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 1$ GeV  | ATLAS-CONF-2020-003, 2004.14060   |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$  |  | 1 $e, \mu$   | 3 jets/1 $b$                        | $E_{miss}^T$<br>139         | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 400$ GeV  | ATLAS-CONF-2019-017   |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b\nu, \tilde{\tau}_1 \rightarrow \tau\tilde{G}$                 |  | 1 $\tau + 1 e, \mu, \tau$  | 2 jets/1 $b$                        | $E_{miss}^T$<br>36.1        | $\tilde{t}_1$   | $m(\tilde{\tau}_1) = 800$ GeV  | 1803.10178  |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0/\tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$ |  | 0 $e, \mu$   | 2 $c$                               | $E_{miss}^T$<br>36.1        | $\tilde{t}_1$<br>$\tilde{t}_1$                          | $m(\tilde{\chi}_1^0) = 0$ GeV<br>$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50$ GeV<br>$m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5$ GeV                             | 1805.01649<br>1805.01649<br>1711.03301  |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \text{mono-jet}$   |  | 0 $e, \mu$   | mono-jet                            | $E_{miss}^T$<br>36.1        | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 500$ GeV  | SUSY-2018-09  |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$           |  | 1-2 $e, \mu$   | 1-4 $b$                             | $E_{miss}^T$<br>139         | $\tilde{t}_1$   | $m(\tilde{\chi}_2^0) = 500$ GeV  | SUSY-2018-09  |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$   |  | 3 $e, \mu$   | 1 $b$                               | $E_{miss}^T$<br>139         | $\tilde{t}_2$   | $m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV   | SUSY-2018-09  |
| EW direct   |  | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ  | 3 $e, \mu$<br>$ee, \mu\mu$          | $\geq 1$ jet                | $E_{miss}^T$<br>139<br>139                              | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$<br>$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$   | $m(\tilde{\chi}_1^0) = 0$<br>$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 5$ GeV  |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ via WW  | 2 $e, \mu$   | $\geq 1$ jet                        | $E_{miss}^T$<br>139         | $\tilde{\chi}_1^\pm$                                    | $m(\tilde{\chi}_1^0) = 0$  | 1908.08215  |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh  | 0-1 $e, \mu$   | 2 $b/2 \gamma$                      | $E_{miss}^T$<br>139         | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$                   | $m(\tilde{\chi}_1^0) = 70$ GeV   | 2004.10894, 1909.09226  |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$ via $\tilde{\ell}_L/\tilde{\nu}$  | 2 $e, \mu$   | 2 $\tau$                            | $E_{miss}^T$<br>139         | $\tilde{\chi}_1^\pm$                                    | $m(\tilde{\chi}_1^0) = 0$  | 1908.08215  |
|   | $\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$  | 2 $\tau$   | 2 $\tau$                            | $E_{miss}^T$<br>139         | $\tilde{\tau}$  | $m(\tilde{\chi}_1^0) = 0$  | 1911.06660  |
|   | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$                                  | 2 $e, \mu$<br>$ee, \mu\mu$   | 0 jets<br>$\geq 1$ jet              | $E_{miss}^T$<br>139<br>139  | $\tilde{\ell}$<br>$\tilde{\ell}$                        | $m(\tilde{\chi}_1^0) = 0$<br>$m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV  | 1908.08215<br>1911.12606  |
|   | $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$  | 0 $e, \mu$<br>4 $e, \mu$   | $\geq 3 b$<br>0 jets                | $E_{miss}^T$<br>36.1<br>139 | $\tilde{H}$<br>$\tilde{H}$                              | $BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$<br>$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$   | 1806.04030<br>ATLAS-CONF-2020-040   |
|   | Long-lived particles   | Direct $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ prod., long-lived $\tilde{\chi}_1^\pm$   | Disapp. trk                         | 1 jet                       | $E_{miss}^T$<br>36.1                                    | $\tilde{\chi}_1^\pm$<br>$\tilde{\chi}_1^\pm$   | Pure Wino<br>Pure higgsino  |
| Stable $\tilde{g}$ R-hadron   |  | Multiple   | Multiple                            | 36.1                        | $\tilde{g}$   | $m(\tilde{\chi}_1^0) = 100$ GeV  | 1902.01636, 1808.04095  |
| Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$   |  | Multiple   | Multiple                            | 36.1                        | $\tilde{g}$   | $\tau(\tilde{g}) = 10$ ns, 0.2 ns  | 1710.04901, 1808.04095  |
| RPV   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow Z\ell \rightarrow \ell\ell\ell$ | 3 $e, \mu$   | Multiple                            | 139                         | $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$                   | Pure Wino  | ATLAS-CONF-2020-009   |
|   | LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu/\nu\tau$                           | $e\mu, e\tau, \mu\tau$   | Multiple                            | 3.2                         | $\tilde{\nu}_\tau$                                      | $\lambda'_{511} = 0.11, \lambda'_{132/133/233} = 0.07$   | 1607.08079  |
|   | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0 \rightarrow WW/Z\ell\ell\nu\nu$                                 | 4 $e, \mu$   | 0 jets                              | $E_{miss}^T$<br>36.1        | $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$                   | $\lambda'_{133} \neq 0, \lambda'_{124} \neq 0$<br>$m(\tilde{\chi}_1^0) = 100$ GeV  | 1804.03602  |
|   | $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$       | Multiple   | 4-5 large-R jets                    | 36.1<br>36.1                | $\tilde{g}$<br>$\tilde{g}$                              | Large $\lambda'_{112}$<br>$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like   | 1804.03568<br>ATLAS-CONF-2018-003   |
|   | $\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$                             | Multiple   | Multiple                            | 36.1                        | $\tilde{t}_1$   | $\lambda'_{123} = 2e-4, 1e-2$  | ATLAS-CONF-2018-003   |
|   | $\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow bbs$                         | $\geq 4b$  | Multiple                            | 139                         | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 200$ GeV, bino-like   | ATLAS-CONF-2018-003   |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$   | 2 jets + 2 $b$   | Multiple                            | 36.1                        | $\tilde{t}_1$   | $m(\tilde{\chi}_1^0) = 500$ GeV  | ATLAS-CONF-2020-016   |
|   | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$  | 2 $e, \mu$<br>1 $\mu$  | 2 $b$<br>DV                         | 36.1<br>136                 | $\tilde{t}_1$<br>$\tilde{t}_1$                          | $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$<br>$BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$   | 1710.07171<br>1710.05544<br>2003.11956  |

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup>

1

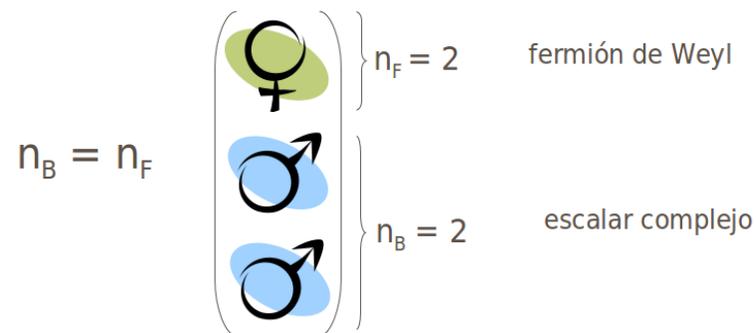
Mass scale [TeV]

# Supersymmetry

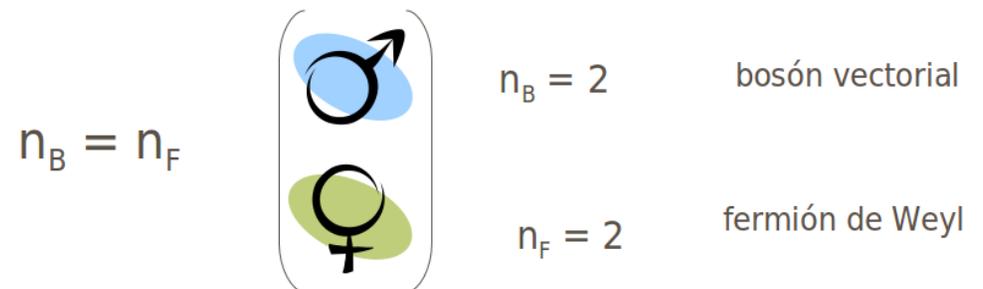
*Although present LHC studies set stringent bounds on masses of new particles, to the extent where supersymmetry (SUSY) appears now to be less "natural" than initially thought, it remains among the best benchmarks for new physics searches.*

Arbey, Battaglia, Djouadi, Mahmoudi, Muhlleitner and Spira (2021)

Supermultiplete quiral



Supermultiplete vectorial



# Supersymmetry

Symmetry relates fermions to bosons



SUSY uses superfields (chiral and vector) to describe all particles and interactions.

Straightforward phenomenological consequence



Duplicates the particle spectrum.

Superpartners for Standard Model particles

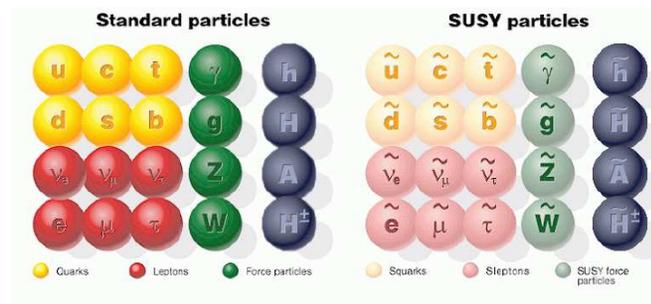


Figure 2: *Almost half of the Supersymmetry spectrum already found.*

~> **Susy must be broken introducing *Soft Susy Lagrangian.***

## *Super potential of the MSSM*

All the fields have the canonical kinetic Lagrangian with the usual  $D_\mu$  and field strengths  $F_{\mu\nu}$ .

Interactions  $\rightsquigarrow$  SUSY and Gauge invariance

The only *freedom* that one has is the choice of the *superpotential*  $\mathbf{W}$

[A .DJOUADI, The Anatomy of ElectroWeak Symmetry Breaking Tome II: The Higgs bosons in the Minimal Supersymmetric Model]

$$W_{MSSM} = \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k \quad (4)$$

where  $\phi$  are the chiral super fields.

By renormalization only bilinear and trilinear terms are permitted

[see for instance S.P. Martin 07]

# Supersymmetry field structure for fermions

## Supermultiplets:

Each of the fermion is accompanied by a complex scalar  $\rightarrow$  *chiral superfield*.

Supermultiplete quiral



*fermions and sfermions*

$$n_B = n_F \left( \begin{array}{l} \left. \begin{array}{c} \text{♀} \\ \text{♂} \end{array} \right\} n_F = 2 \quad \text{fermi3n de Weyl} \\ \left. \begin{array}{c} \text{♂} \\ \text{♂} \end{array} \right\} n_B = 2 \quad \text{escalar complejo} \end{array} \right)$$

*Higgsinos and Higgs*

Figure 3: *Quiral supermultipletes: equal fermionic and bosonic d.o.f.*

## Supersymmetry field structure for gauge bosons

### Supermultiplets:

Each of the gauge boson is accompanied by a weyl doublet  $\rightarrow$  *vectorial superfield*.

Supermultiplete vectorial



*Gauge bosons*

$$n_B = n_F \quad \left( \begin{array}{l} \text{♂} \\ \text{♀} \end{array} \right) \quad \begin{array}{l} n_B = 2 \quad \text{bosón vectorial} \\ n_F = 2 \quad \text{fermión de Weyl} \end{array}$$

*and gauginos*

Figure 4: *Vector supermultipletes: equals bosonic and fermionic d.o.f.*

Once SUSY is broken we need to add no-dynamical fields components  $F$  and  $D$  terms, in order to conserved the fermionic-bosonic degrees of freedom.

## *SUSY* $\rightarrow$ *Soft-terms of MSSM*

As SUSY is broken we add mass terms to the Lagrangian that break the symmetry  
**Soft SUSY Lagrangian:**

Kuroda 99

$$\mathcal{L}_{soft}^{MSSM} = \mathcal{L}_{gauginogluino}^{mass} - \mathcal{L}_{sfermion}^{mass} - \mathcal{L}_{Higgs} - \mathcal{L}_{trilinear} \quad (5)$$

with

$$-\mathcal{L}_{gauginogluino}^{mass} = \frac{1}{2} \left[ M_1 \tilde{B} \tilde{B} + M_2 \sum_{a=1}^3 \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^8 \tilde{G}^a \tilde{G}_a + h.c. \right] \quad (6)$$

$$-\mathcal{L}_{sfermion}^{mass} = \sum_{i=gen} m_{\tilde{Q}_i}^2 \tilde{Q}_i^\dagger \tilde{Q}_i + m_{\tilde{L}_i}^2 \tilde{L}_i^\dagger \tilde{L}_i + m_{\tilde{u}_i}^2 |\tilde{u}_{Ri}| + m_{\tilde{d}_i}^2 |\tilde{d}_{Ri}|^2 + m_{\tilde{l}_i}^2 |\tilde{l}_{Ri}|^2 \quad (7)$$

$$-\mathcal{L}_{Higgs} = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + \mu B (H_2 \cdot H_1 + h.c.) \quad (8)$$

$$-\mathcal{L}_{trilinear} = \sum_{i,j=gen} \left[ A_{ij}^u \tilde{Q}_i H_2 \tilde{u}_{Rj}^* + A_{ij}^d \tilde{Q}_i H_1 \tilde{d}_{Rj}^* + A_{ij}^l \tilde{L}_i H_1 \tilde{l}_{Rj}^* \right] \quad (9)$$

... or constraining the *MSSM* parameters

- **mSUGRA** → **cMSSM** (most common) → *gravitational SUSY breaking* in a hidden sector.  $\rightsquigarrow$  *soft SUSY breaking* parameters obey a set of universal boundary conditions at the GUT scale.
- **AMSB** → *Anomaly Mediated SUSY breaking* in a hidden sector, transmitted by the super-Weyl anomaly  $\rightsquigarrow$  *soft SUSY breaking* parameters related to the scale dependence of gauge and matter kinetic functions.
- **GMSB** → *SUSY breaking is mediated by SM gauge interactions* .  $\rightsquigarrow$  *soft SUSY breaking* parameters arise from one-loop or two-loops diagrams

## *Supersymmetry models.*

In addition there are other SUSY models which may fit the current LHC data

- NUHM1 [Buchmueller et. al. 11]
  - NMSSM [Benbrik et. al. 12]
  - Split SUSY [Arkani-Hamed and S. Dimopoulos 05]
  - High-scale SUSY [L.J. Hall and Y. Nomura 10]
- ... we may even review H. Baer and J. List 13, *Post LHC8 SUSY benchmark points for ILC physics*

## *Reducing MSSM parameters*

At tree level, the MSSM parameters could be reduced to only 2:  $m_A$  and  $\tan\beta$ , CMSSM.

Once we calculate one-loop radiative corrections we must set values to other parameters.

Most scenarios were built in order to have the least free parameters.

### **phenomenological MSSM, pMSSM**

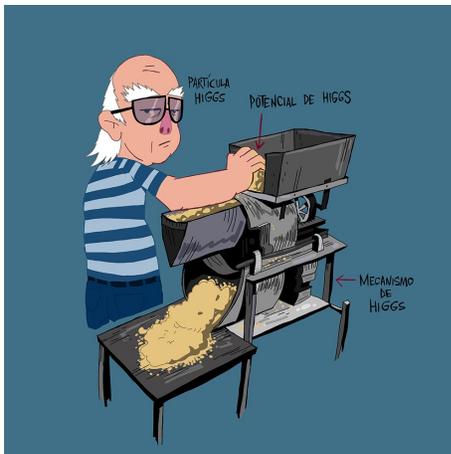
- ① CP-conserving (no extra source)
- ② no FCNC
- ③  $m_{\tilde{f}_1} \approx m_{\tilde{f}_2}$  to accomplish  $K^0 - \bar{K}^0$  mixing

# phenomenological, pMSSM

22 input parameters:

$$\begin{aligned} & \tan \beta; \\ & m_1^2, m_2^2; \\ & M_1, M_2, M_3; \\ & \tilde{m}_q, \tilde{m}_{uR}, \tilde{m}_{dR}, \tilde{m}_l, \tilde{m}_{eR}; \\ & \tilde{m}_{Qt}, \tilde{m}_{tR}, \tilde{m}_{bR}, \tilde{m}_{L\tau}, \tilde{m}_{\tau R}; \\ & A_{u,c}, A_{d,s}, A_{e,\mu}; \quad A_t, A_b, A_\tau \end{aligned}$$

The current way to analyze a supersymmetric model is to fix the Higgs mass to the experimental value, and all of the corrections adjust from there, calling this parametrization as **hMSSM**



$$m_h = 125 \text{ GeV}$$

## *Higgs sector of the MSSM*

Two complex SU(2) Higgs doublets:

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - i\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + i\chi_2) \end{pmatrix}$$

Physical Higgs particle spectrum :

$\phi_i$  ,  $CP = 1$   $\rightarrow$  two scalar fields:  $h^0, H^0$ ,

$\chi_i$  ,  $CP = -1$   $\rightarrow$  one pseudoscalar field:  $A^0$ .

and

$\phi^\pm$  ,  $\rightarrow$  two charged fields:  $H^\pm$

SSB: Assuming the scalar fields to develop nonzero vacuum expectation values that break  $SU(2)_L$

$$\langle H_1 \rangle = v_1 \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \langle H_2 \rangle = v_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (10)$$

Defining:  $\tan \beta = \frac{v_2}{v_1}$  and  $v = (v_1^2 + v_2^2)^{1/2} \approx 173 \text{ GeV}$ .

## *MSSM Higgs masses*

At tree level we have the Higgs masses are given by only two parameters. Considering the minimal set of soft-SUSY breaking parameters, supersymmetry leads to only true independent parameters  $\tan\beta$  and  $M_A$ . The relations within MSSM parameters impose, at tree level, a strong hierarchical structure on mass spectrum:  $M_h < M_Z$ ,  $M_A < M_H$  and  $M_W < M_{H^\pm}$ , which is broken by radiative corrections [Djouadi08].

The *CP* – even Higgs mass matrix

$$\mathcal{M} = M_Z^2 \begin{pmatrix} c_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & s_\beta^2 \end{pmatrix} + M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + \begin{pmatrix} \Delta M_{11}^2 & \Delta M_{12}^2 \\ \Delta M_{21}^2 & \Delta M_{22}^2 \end{pmatrix} \quad (11)$$

In supersymmetry, radiative corrections are crucial. In the leading one-loop approximation, the maximal value for Higgs boson is given by

$$M_h^2 \rightarrow M_Z^2 \cos^2 2\beta + \Delta M_{22}^2 \sin^2 \beta$$

## *Ligth Higgs mass as a fixed parameter: hMSSM*

In order to accomplish for the previous simple relation of Higgs mass, the following choice of SUSY parameters:

[M. Carena (2013) ]

- ① A decoupling regime with heavy A states:  $m_A \sim \mathcal{O}(TeV)$
- ②  $\tan \beta \gtrsim 10$  to maximize tree-level contributions.
- ③ Heavy stops squarks, *i.e.* large SUSY mass scale  $M_S$ , to enhance logarithmic contributions.
- ④ Maximal mixing scenario for trilinear stop couplings:  $X_t = \sqrt{6}M_S$ , maximizing stop loops.

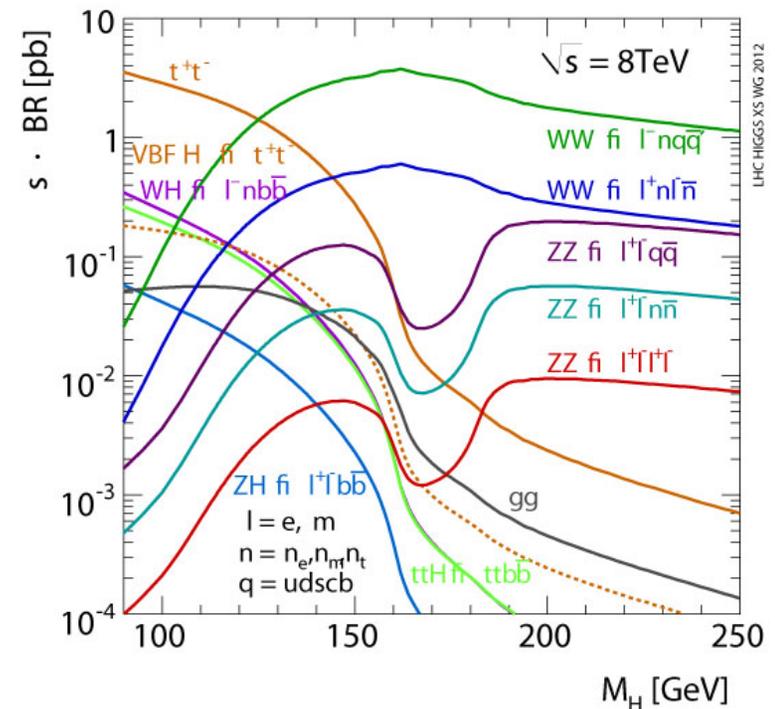
## *Higgs boson production*

Once the Higgs mass is determined, the SM Higgs properties are fixed. Any contribution from an extended Higgs sector may shift the couplings, and hence its production and decay rates.

[Arbey, Battaglia, Djouadi, Mahmoudi, Muhlleitner and Spira \(2021\)](#)

Bounds on Higgs production be precise proved by HL-LHC.

| process                    | $\sqrt{s}$ | $\sigma^{tot}$                            |
|----------------------------|------------|---|
| $gg \rightarrow h$         | 14 TeV     | $\sigma_{ggh}^{tot} \approx 50 pb$        |
| $qq \rightarrow hqq$       | 14 TeV     | $\sigma_{VBF}^{tot} \approx 4 pb$         |
| $qq \rightarrow hV$        | 14 TeV     | $\sigma_{hV}^{tot} \approx 2.5 pb$        |
| $pp \rightarrow t\bar{t}h$ | 14 TeV     | $\sigma_{t\bar{t}h}^{tot} \approx 0.6 pb$ |
| $gg \rightarrow hh$        | 14 TeV     | $\sigma_{gghh}^{tot} \approx 50 fb$       |

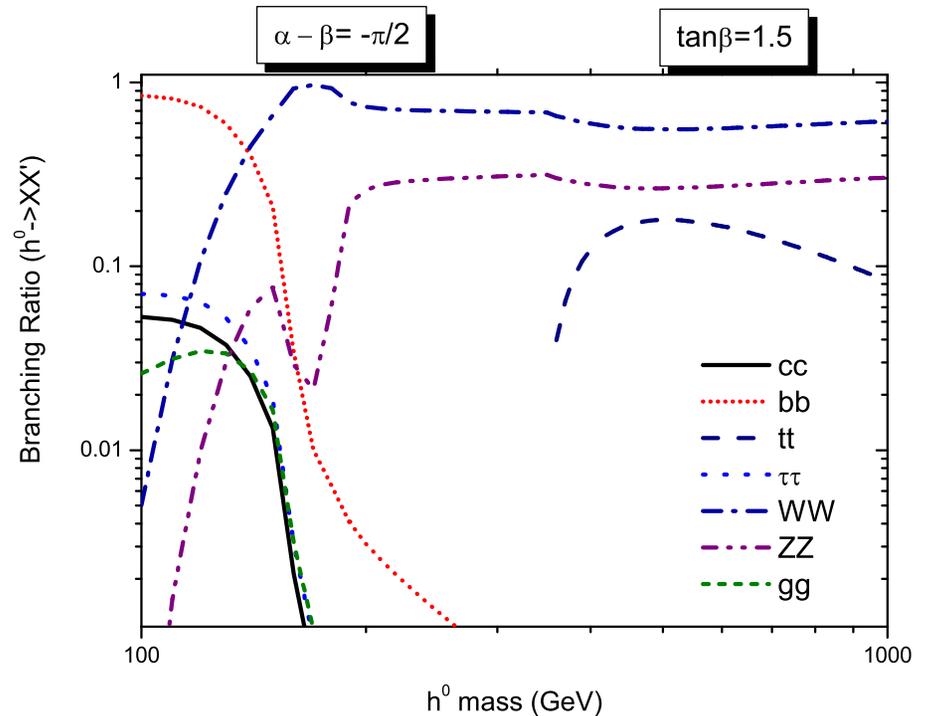


## *Higgs boson decay rates*

Analyze the production and decay rates using the defined coupling modifiers

$$\kappa_X = \frac{g_{hXX}^{MSSM}}{g_{hXX}^{SM}}$$

| process                                     | BR                 |
|---|--------------------|
| $h \rightarrow b\bar{b}$                    | over 60%           |
| $h \rightarrow W^*W^* \rightarrow ll\nu\nu$ | 20%                |
| $h \rightarrow Z^*Z^* \rightarrow llll$     | 2.5%               |
| $h \rightarrow \tau\tau$                    | $\approx 5\%$      |
| $h \rightarrow gg$                          | 8%                 |
| $h \rightarrow c\bar{c}$                    | 3%                 |
| $h \rightarrow \gamma\gamma$                | $2 \times 10^{-3}$ |
| $h \rightarrow \mu\bar{\mu}$                | $2 \times 10^{-4}$ |



*Beyond SM, SUSY Higgs decays, invisible.*

LEP experimental Data has already set bounds for some susy particles:

$$m_{\tilde{l}} > 100\text{GeV} > \frac{1}{2}M_h$$

$$m_{\tilde{\chi}_{1,2}^{\pm}} > 100\text{GeV} > \frac{1}{2}M_h$$

$$m_{\tilde{\chi}_{2,3}^0} > 100\text{GeV} > \frac{1}{2}M_h$$

- $h \rightarrow \tilde{q}\tilde{q}$  already kinematically excluded,  $m_{\tilde{q}} \gg \frac{1}{2}M_h$
- $h \rightarrow \tilde{g}\tilde{g}$  already kinematically excluded,  $m_{\tilde{g}} \gg \frac{1}{2}M_h$

## *Beyond SM, SUSY Higgs decays, invisible.*

In the not constrained MSSM, soft susy breaking parameters are not related  $M_1, M_2, M_3$  and  $m_{\tilde{g}} \approx M_3 \geq 1TeV$ , the following invisible susy Higgs decays may occur

- $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$  kinematically allowed, as  $\tilde{\chi}_1^0$  is the LSP.
- $h \rightarrow \tilde{\nu} \tilde{\nu}$  kinematically allowed, if  $m_{\tilde{\nu}} < m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}$

D-terms increase  $m_{\tilde{t}}$  and decrease  $m_{\tilde{\nu}}$

## *MSSM sfermion mass matrix*

The sfermion mass matrix can be written as blocks of  $3 \times 3$

$$\tilde{M}_f^2 = \begin{pmatrix} M_{LL}^2 & M_{LR}^2 \\ M_{LR}^{2\dagger} & M_{RR}^2 \end{pmatrix} \quad (12)$$

The elements of this matrix decomposed on the different terms of the MSSM Lagrangian are given by,

$$\tilde{M}_f^2 = \begin{pmatrix} m_{f,LL}^2 + F_{f,LL} + D_{f,LL} & m_{f,LR}^2 + F_{f,LR} \\ (m_{f,LR}^2 + F_{f,LR})^\dagger & m_{f,RR}^2 + F_{f,RR} + D_{f,RR} \end{pmatrix} \quad (13)$$

For charged leptons, we will have

$$\mathbf{M}_l^2 = \begin{pmatrix} m_{slL}^2 + m_l^2 + M_Z^2 \cos 2\beta (I_3^l - Q_l s_w^2) & m_l X_l \\ m_l X_l & m_{slR}^2 + m_l^2 + M_Z^2 \cos 2\beta Q_l s_w^2 \end{pmatrix}, \quad (14)$$

with  $X_l = A_l - \mu \tan \beta$ , and we assume  $m_{sfR}^2 \simeq m_{sfL}^2 \simeq \tilde{m}_0^2$

## Neutralino mass matrix

Neutralinos are a mixing of the neutral higgsinos ( $\tilde{H}_1^0, \tilde{H}_2^0$ ) and gauginos gauginos neutros ( $\tilde{B}^0, \tilde{W}^0$ ), which have spin 1/2.

In the interaction basis, the neutralino mass matrix is given as

$$M_N = \begin{pmatrix} M_1 & 0 & -M_Z \sin \theta_W \cos \beta & M_Z \sin \theta_W \sin \beta \\ * & M_2 & M_Z \cos \theta_W \cos \beta & -M_Z \cos \theta_W \sin \beta \\ * & * & 0 & -\mu \\ * & * & * & 0 \end{pmatrix}$$

Diagonalizing the neutralino symmetric mass matrix  $M_N$  with  $\Theta_N$  :

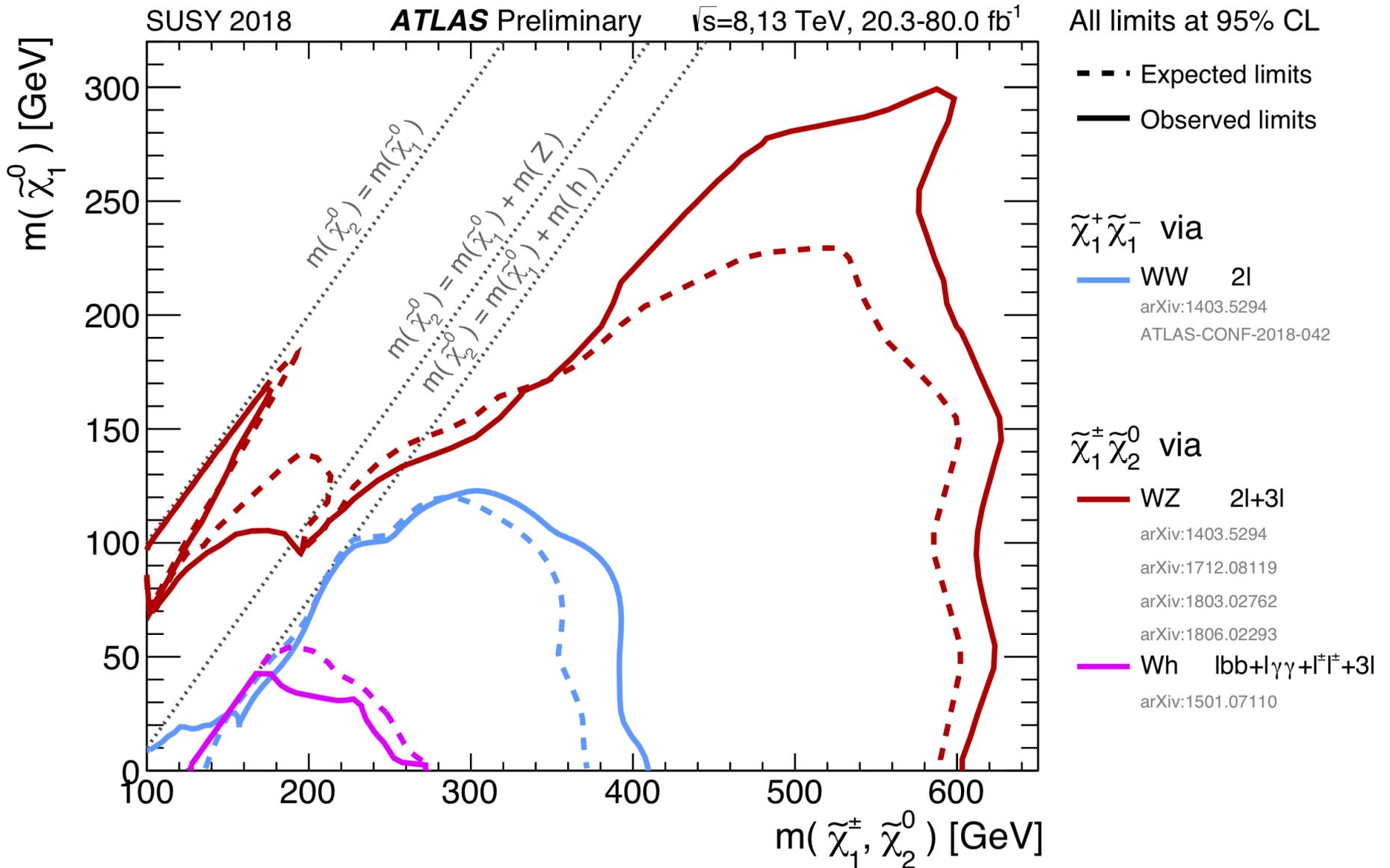
$$\Theta_N M_N \Theta_N^T = \text{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}) \quad (15)$$

## *Neutralinos mass eigenstates*

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix} = \begin{pmatrix} \eta_1 & 0 & 0 & 0 \\ 0 & \eta_2 & 0 & 0 \\ 0 & 0 & \eta_3 & 0 \\ 0 & 0 & 0 & \eta_4 \end{pmatrix} (\Theta_N) \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^0 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

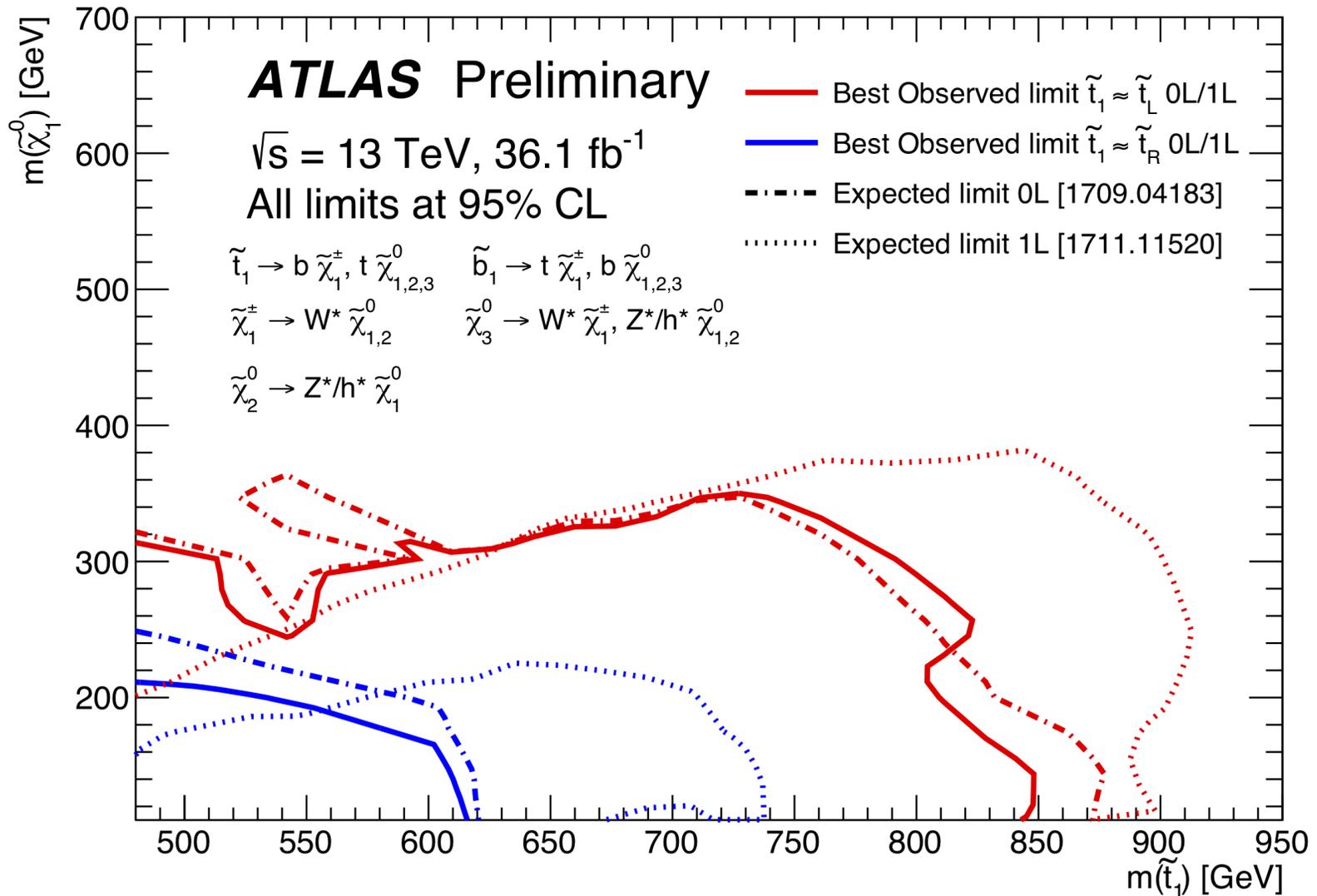
where we use  $\eta_i$  in order to change the phase for when negative eigenvalue.

# Supersymmetry experimental searches for neutralinos.



# Supersymmetry experimental searches for neutralinos.

Bino/Higgsino Mix Model:  $\tilde{t}_1, \tilde{t}_1, \tilde{b}_1, \tilde{b}_1$  production,  $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 20-50$  GeV, March 2018



*thank you!*

