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 Λ^2_{UV} will neatly cancel

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

- Unification of gauge couplings.
- Generates DM candidates.
- Posisible exotic signals of FV and $\not{CP}$ 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

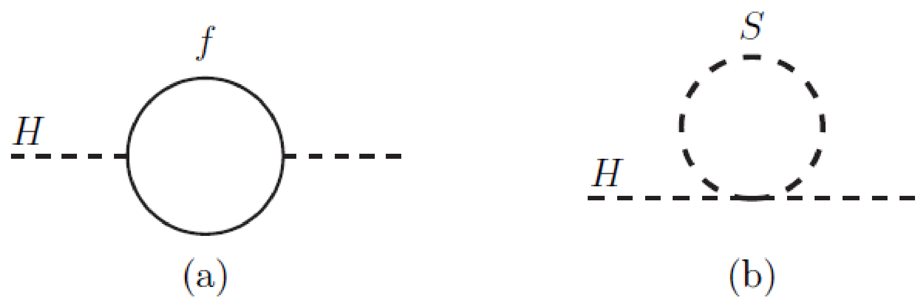


Figure 1: *(a) fermionic and (b) any scalar correction to the Higgs mass*

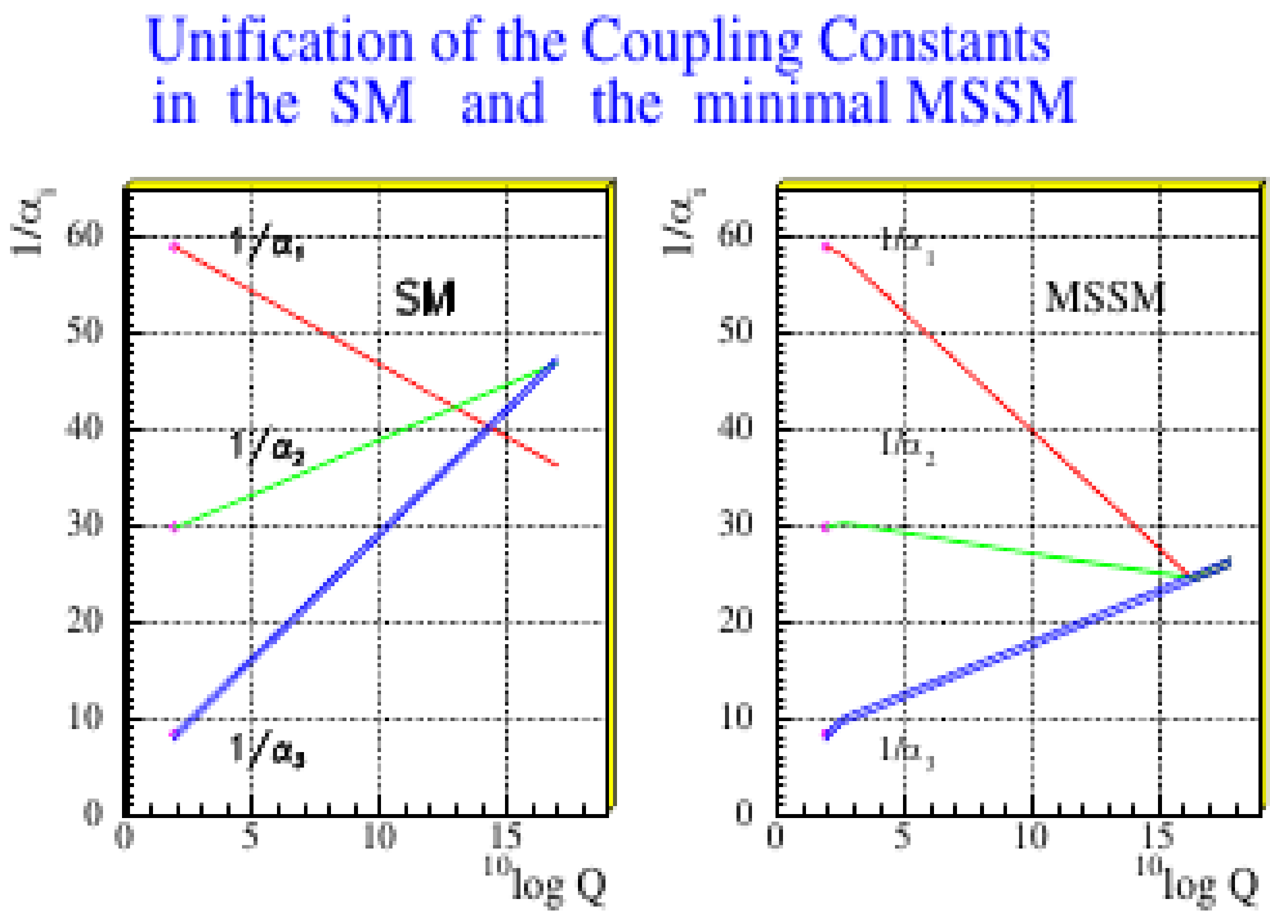
✧Fermionic contribution to the Higgs mass

$$\Delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \cdots \tag{1}$$

✧ Contribution to the Higgs mass from a scalar

$$\Delta m_h^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \log\frac{\Lambda_{UV}}{m_S} + \cdots\right] \tag{2}$$

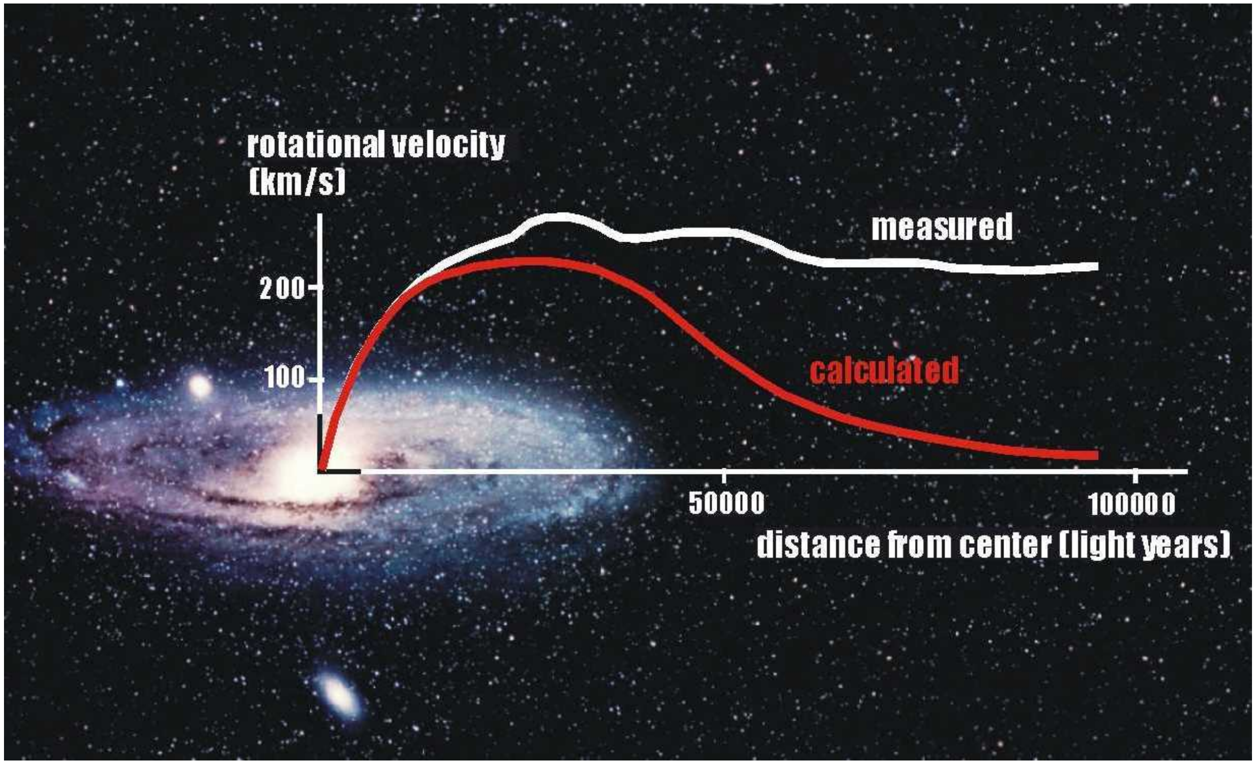
GUTs



[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

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

Some unexplained experimental signals

① Muon anomalous magnetic moment $g-2$.

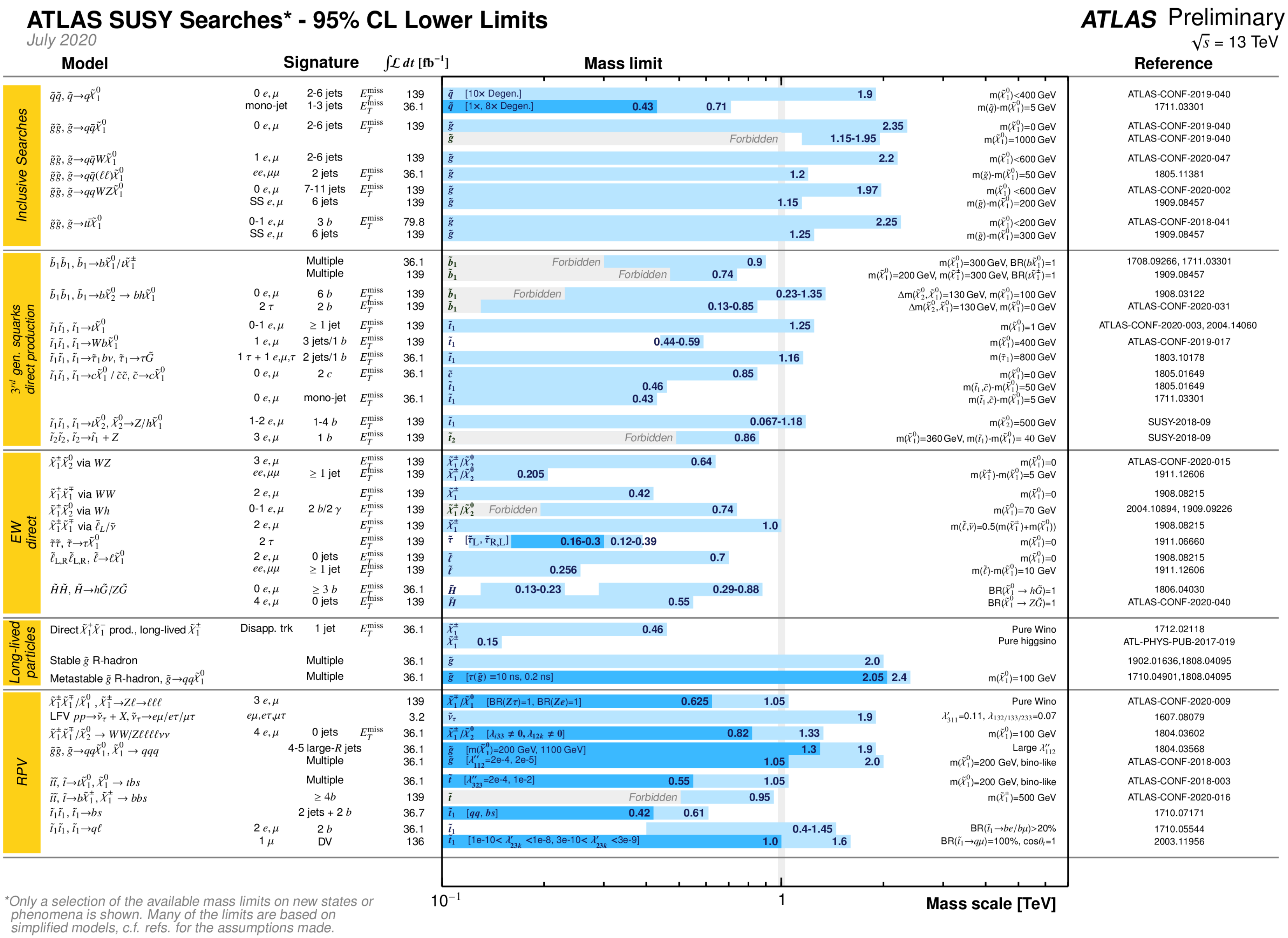
② New data for W mass, departing from SM value.

③ Neutrinos oscillations $\rightarrow$ massive right neutrinos.

④ Still high experimental bounds with respect to SM values:

- $BR^{Exp}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$
- $BR^{Exp}(t \rightarrow ch) < 10^{-3}$; $\quad BR^{SM}(t \rightarrow ch) \simeq 10^{-14}$
- Very tight but still a room for extra CP mixing mesones: Bs, Ds
- Leptonic non-universaliy in semileptonic meson decays.

Supersymmetry experimental searches.

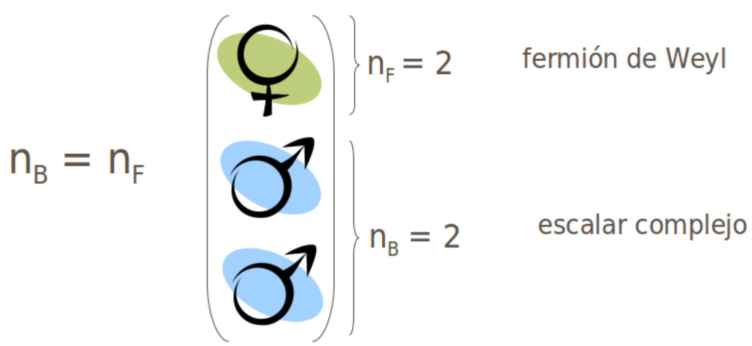


Supersymmetry

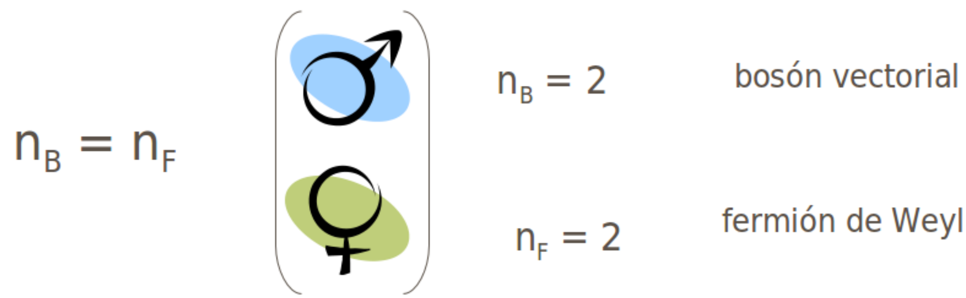
Although present LHC studies set stringent bounds on masses of new particles, to the extend where supersymmetry (SUSY) appears now to be less ”natural“ than initially thought, it remains among the best benchmarks for new physics searches.

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

Supermultiplete quiral



Supermultiplete vectorial



Supersymmetry

Symmetry relates fermions to bosons	$\rightsquigarrow$	SUSY uses superfields (chiral and vector) to describe all particles and interactions.
Straightforward phenomenological consequence	$\rightsquigarrow$	Duplicates the particle spectrum.

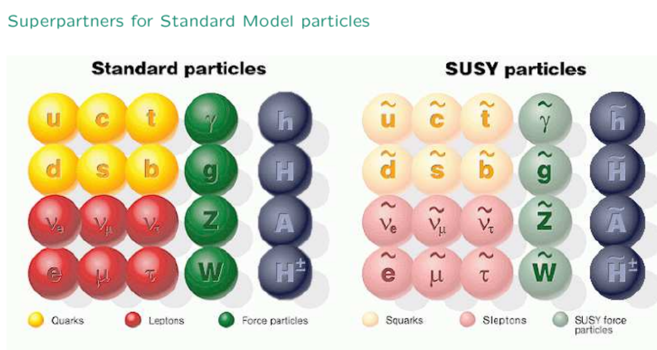


Figure 2: *Almost half of the Supersymmetry spectrum already found.*

$\rightsquigarrow$ **Susy most be broken introducing** *Soft Susy Lagrangian*.

Super potential of the MSSM

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

Interactions $\rightsquigarrow$ SUSY and Gauge invariance

The only *freedom* that one has is the choice of the *superpotential* **W**

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

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

where ϕ are the quiral super fields.

By renormalization only bilinear and trilinear terms are permited

[see for instance S.P. Martin 07]

Supersymmetry field structure for fermions

Supermultiplets:

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

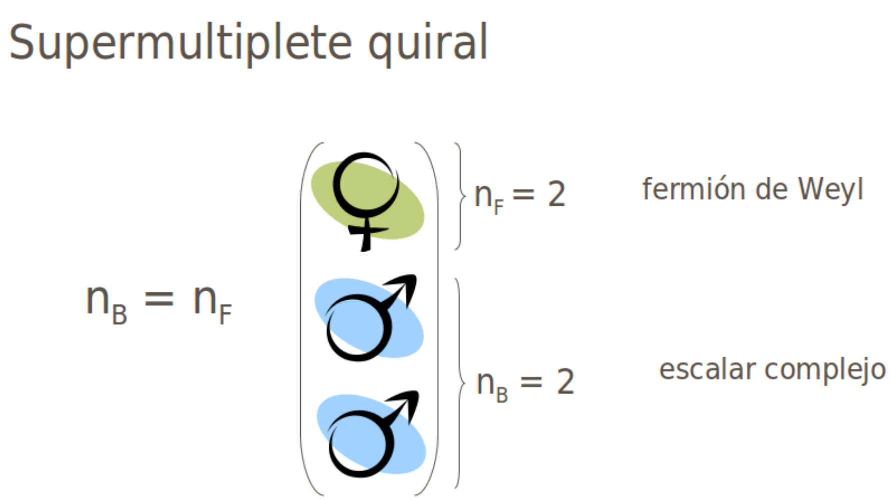


Figure 3: *Quiral supermultipletes: equal fermionic and bosonic d.o.f.*

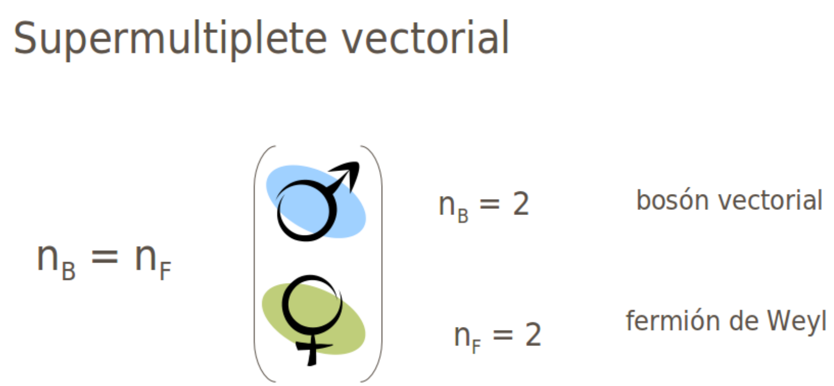
$\rightsquigarrow$ *fermions and sfermions*

Higgsinos and Higgs

Supersymmetry field structure for gauge bosons

Supermultiplets:

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



$\rightsquigarrow$ *Gauge bosons 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.

$\not{SUSY} \to$ *Soft-terms of MSSM*

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

Kuroda 99

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

with

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

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

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

$$-\mathcal{L}_{trilinear} = \sum_{i,j=gen}\left[A_{ij}^u\tilde{Q}_iH_2\tilde{u}_{Rj}^* + A_{ij}^u\tilde{Q}_iH_1\tilde{d}_{Rj}^* + A_{ij}^l\tilde{L}_iH_1\tilde{l}_{Rj}^*\right] \qquad (9)$$

... or constraining the MSSM parameters

- mSUGRA $\rightarrow$ cMSSM (most common) $\rightarrow$ *gravitational SUSY breaking* in a hidden sector. $\rightsquigarrow$ *soft SUSY breaking* parameters obey a set of universal boundary conditions at the GUT scale.

- AMSB $\rightarrow$ *Anomaly Mediated SUSY breaking* in a hidden sector, trasmited by the super-Weyl anomaly
  $\rightsquigarrow$ *soft SUSY breaking* parameters related to the scale dependance of gauge and matter kinetic functions.

- GMSB $\rightarrow$ *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]

$\cdots$ 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 most 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

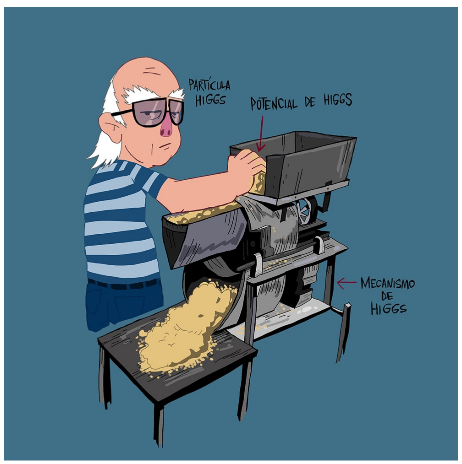
③ $m_{\tilde{f}1} \approx m_{\tilde{f}2}$ to accomplish $K^0 - \bar{K}^0$ mixing

phenomenological, pMSSM

22 input parameters:

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

The current way to analize a supersymmetric model is to fixed tha Higgs mass to the experimental value, and all of the correction adjust from there, calling this parametrization as **hMSSM**



$m_h = 125$ **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 :

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

χ_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 $SU(2)_L$

$$\langle H_1 \rangle = v_1 \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad \langle H_2 \rangle = v_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{10}$$

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

MSSM Higgs masses

At tree level we have the Higgs masses are given by only two prameters. 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 imposse, 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 correctons are crutial. In the leading one-loop aproximation, te maximal value for Higgs boson is given by

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

.

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 $\tan\beta \gtrapprox 10$ to maximize tree-level contributions.

③ Heavy stops squarks, *i.e.* large SUSY mass scale M_S, to enhance logaritmic contributions.

④ Maximal mixing scenario for trilinear stop couplings: $X_t = \sqrt{6} M_S$, maximizing stop loops.

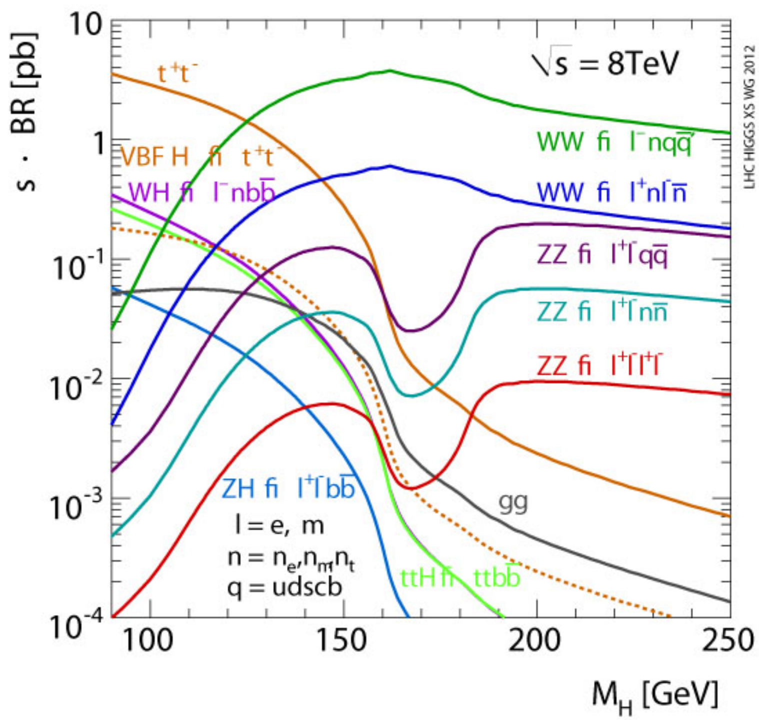
Higgs boson production

Once the Higgs mass is determined, the SM Higgs properties are fixed. Any contribution from a 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	$\sqrt{s}$	σ^{tot}
$gg \to h$	14 TeV	$\sigma^{tot}_{ggh} \approx 50pb$
$qq \to hqq$	14 TeV	$\sigma^{tot}_{VBF} \approx 4pb$
$qq \to hV$	14 TeV	$\sigma^{tot}_{hV} \approx 2.5pb$
$pp \to t\bar{t}h$	14 TeV	$\sigma^{tot}_{tth} \approx 0.6pb$
$gg \to hh$	14 TeV	$\sigma^{tot}_{gghh} \approx 50fb$

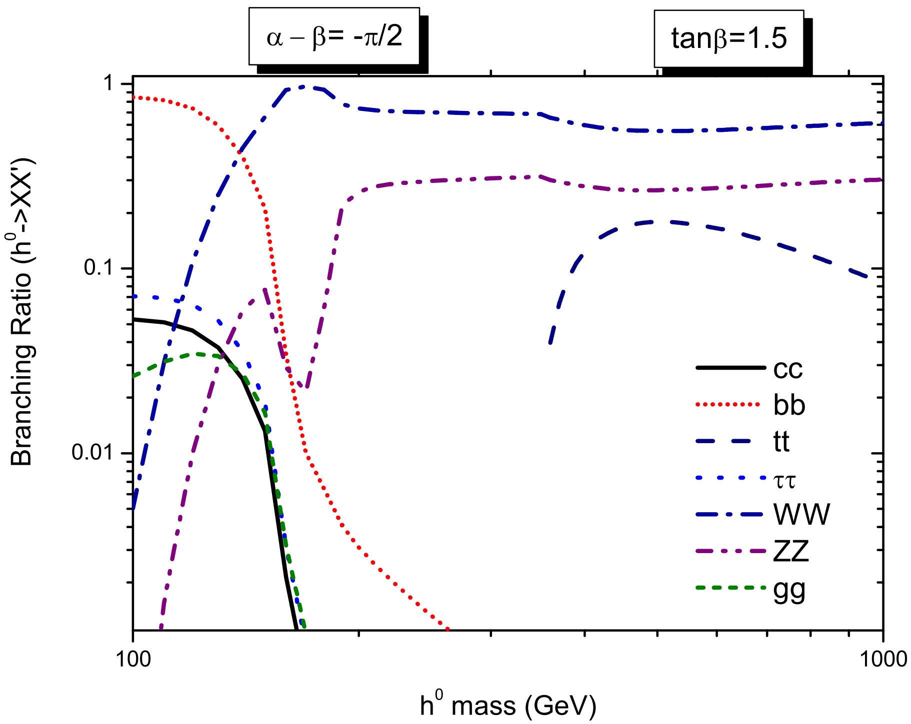


Higgs boson decay rates

Analyze the production and decay rates using the defined coupling modifiers

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

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



Beyond SM, SUSY Higgs decays, invisible.

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

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

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

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

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 $m_{\tilde{g}} \approx M_3 \geq 1 TeV$, 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 $m_{\tilde{l}}$ and decrease $m_{\tilde{\nu}}$

MSSM sfermion mass matrix

The sfermion mass matrix can be written as blocks of 3×3

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

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

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

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 Θ_N :

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

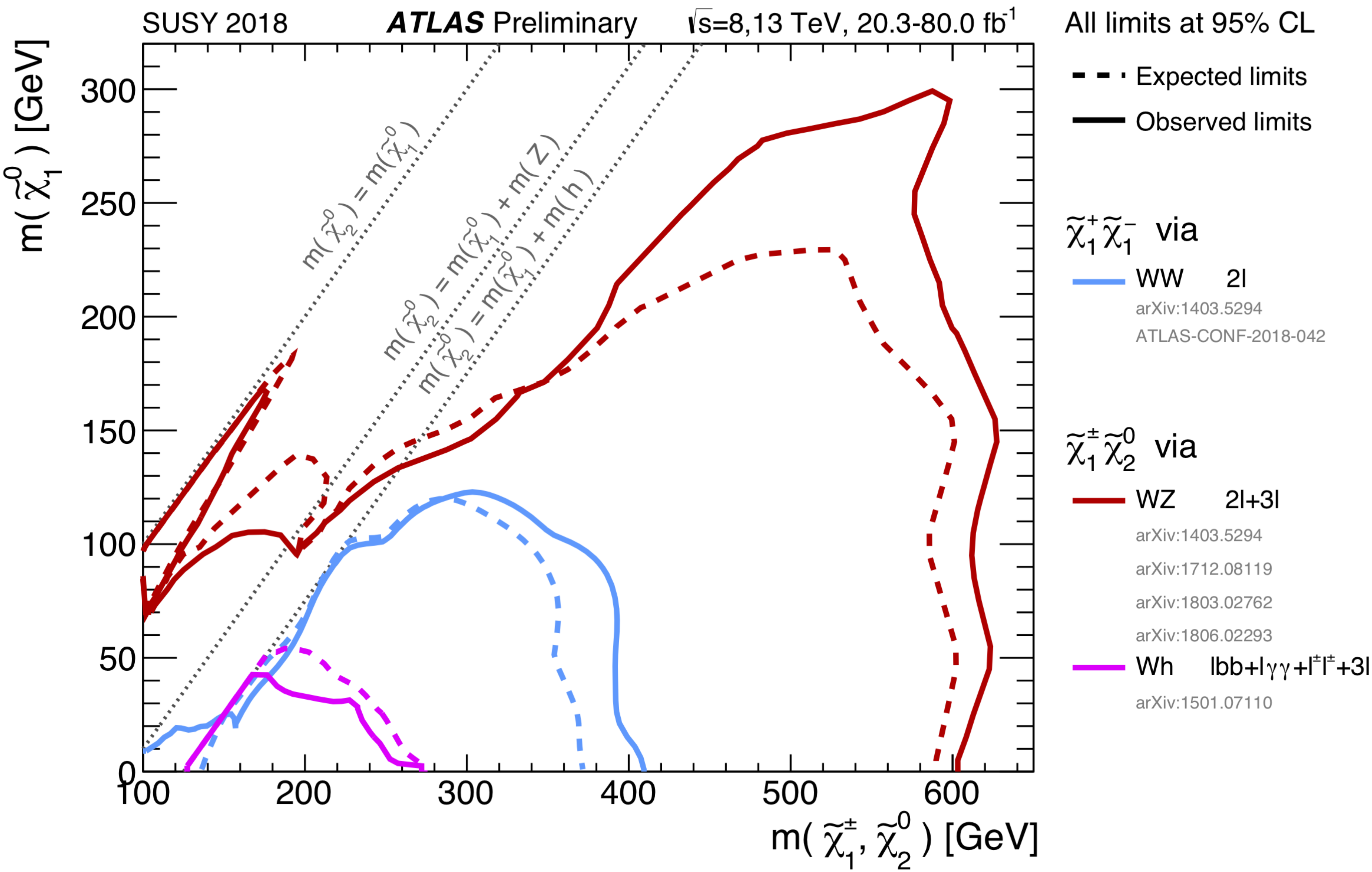
[Haber,hep-ph/9306207]

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 η_i in order to change the phase for when negative eigenvalue.

Supersymmetry experimental searches for neutralinos.



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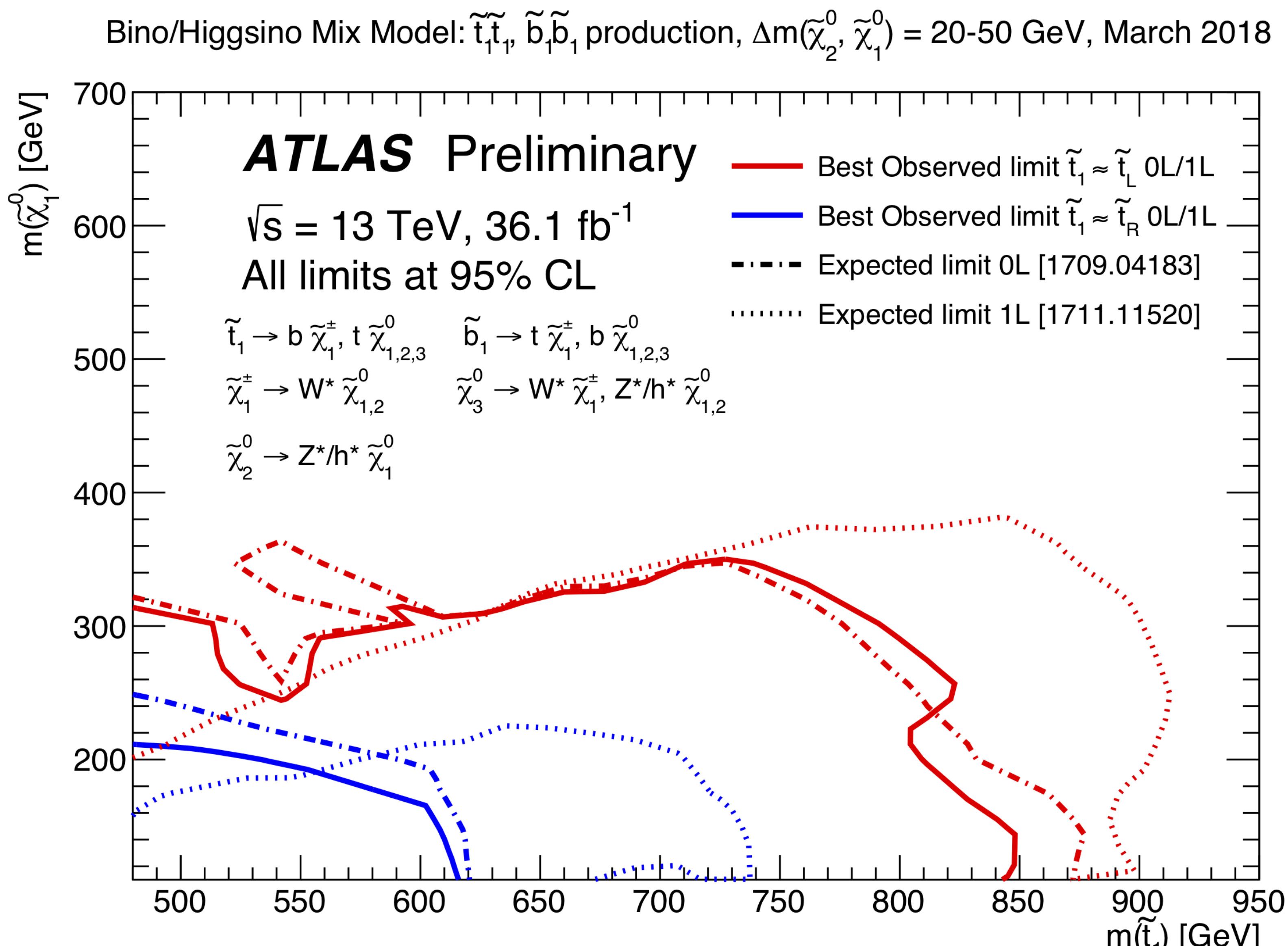

thank you!