SUPERSYMMETRY
IN PARTICLE PHYSICS
and SUSY searches at LHC

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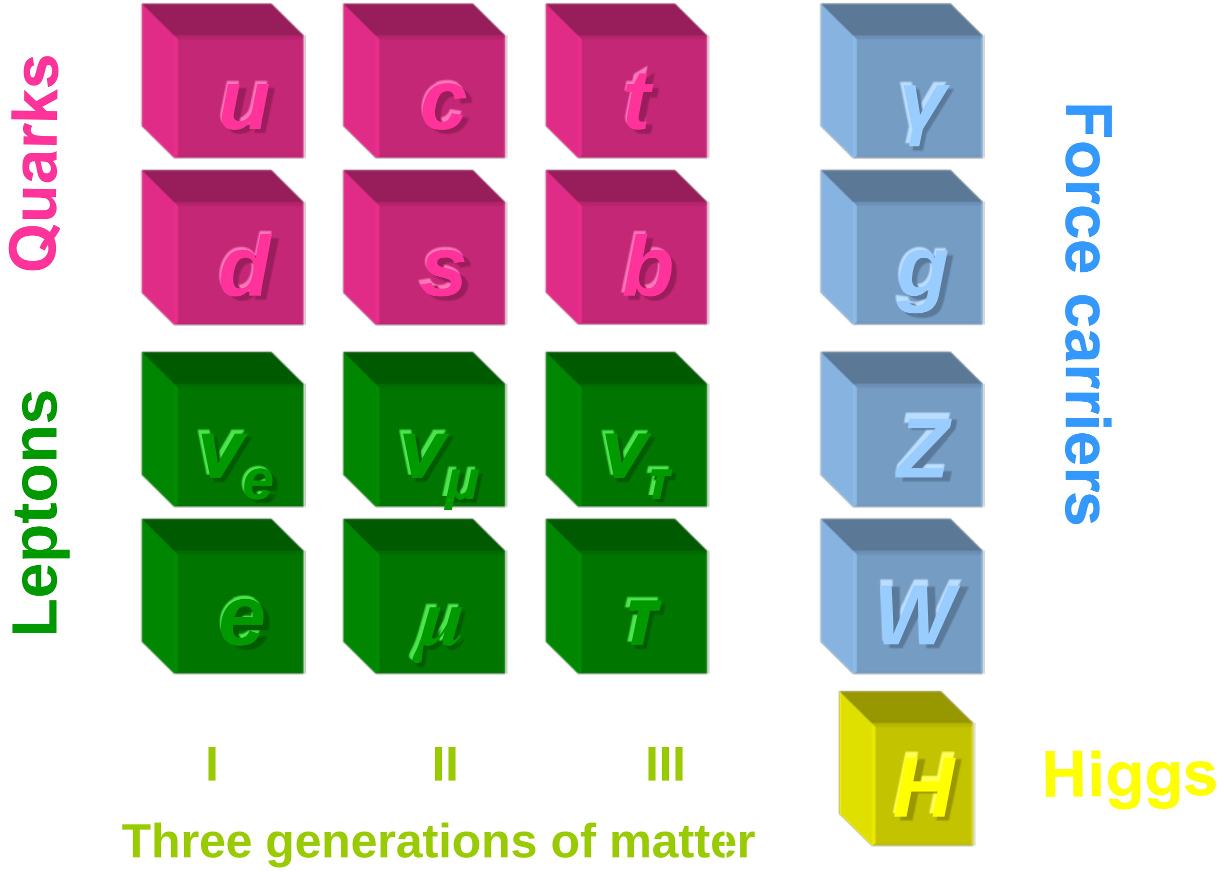
Fundamental Particles



Quarks

u c t

d s b

Leptons

ν_e ν_μ ν_τ

e μ τ

γ

g

Z

W

Force carriers

H

Higgs

I II III

Three generations of matter

The Standard Model

- Standard Model Lagrangian

$$\boxed{L = L_{gauge} + L_{Yukawa} + L_{Higgs}}$$

- Gauge interactions (kinetic terms for the gauge fields, quarks, leptons and Higgs bosons; self-interactions of the gauge fields; interactions of the gauge fields and Higgs bosons)

$$\boxed{\begin{aligned} L_{gauge} &= -\tfrac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} - \tfrac{1}{4} W^i_{\mu\nu} W^i_{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B_{\mu\nu} \\ &+ i\overline{L}_\alpha \gamma^\mu D_\mu L_\alpha + i\overline{Q}_\alpha \gamma^\mu D_\mu Q_\alpha + i\overline{E}_\alpha \gamma^\mu D_\mu E_\alpha \\ &+ i\overline{U}_\alpha \gamma^\mu D_\mu U_\alpha + i\overline{D}_\alpha \gamma^\mu D_\mu D_\alpha + (D_\mu H)^\dagger (D_\mu H) \end{aligned}}$$

The Standard Model

- Yukawa interactions (interactions of quark and leptons with the Higgs boson)

$$\boxed{L_{Yukawa} = y^{L}_{\alpha\beta}\overline{\mathrm{L}}_{\alpha}E_{\beta}H + y^{D}_{\alpha\beta}\overline{\mathrm{Q}}_{\alpha}D_{\beta}H + y^{U}_{\alpha\beta}\overline{\mathrm{Q}}_{\alpha}U_{\beta}\widetilde{H}}$$

$$\boxed{\widetilde{H} = i\tau_{2}H^{\dagger}}$$

- Scalar potential (mass term and self-interaction of the Higgs boson)

$$\boxed{L_{Higgs} = -V = m^{2}H^{\dagger}H - \tfrac{\lambda}{2}(H^{\dagger}H)^{2}}$$

The Standard Model: drawbacks

- Large number of free parameters:
  - gauge coupling constants g_s , g , g'
  - 3×3 matrices of Yukawa coupling constants
  - coupling constant of the Higgs self-interaction
  - the Higgs mass parameter
  - mixing angles and phases

How one can reduce the number of parameters ?

- The choice of the gauge group:

why there are three independent symmetry groups ?

$$SU(3)_C \times SU(2)_{EW} \times U(1)_Y$$

The Standard Model: drawbacks

- The unification of the strong and electroweak interactions is formal
- Why the «strong» interactions are strong and «weak» ones are weak ?
- Why there are 3 generations of the matter fields ?
- The origin of particle masses: why are particles massive ?
- Why the top-quark is heavy and leptons are light ?
- Is the Higgs boson a fundamental particle ?

  What is the mass of the Higgs boson ?
- Why the proton charge is equal to the elctron charge ?
- How can we include gravity into the theory ?

- The Standard Model has no answers

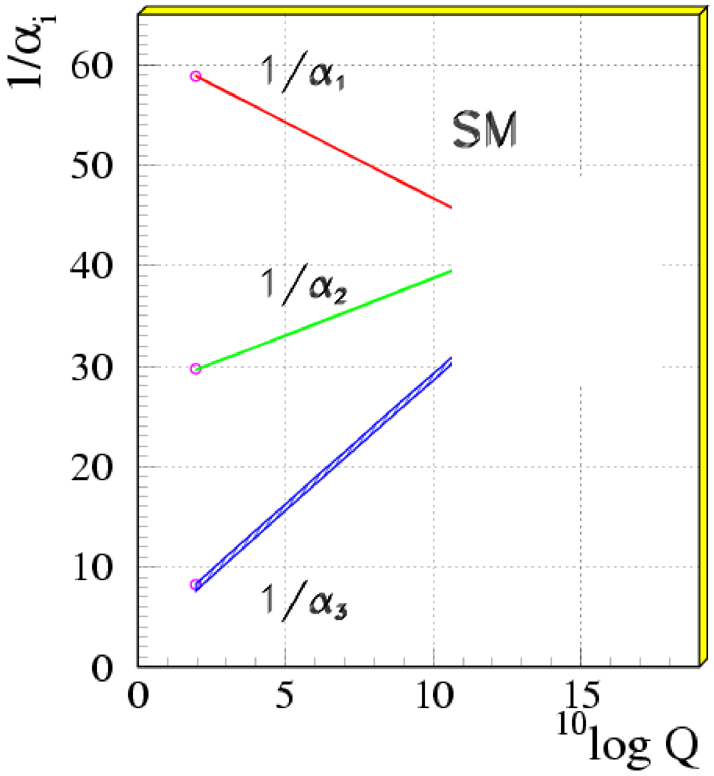
The Standard Model: what to do?

- CONCLUSION: The Standard Model is an effective theory valid within a certain approximation
- WHAT TO DO: consider *more symmetric* theories

- Examples:
  - Grand Unification Theories: The strong, weak and electromagnetic interactions are described by one symmetry group
  - Supersymmetry: Bosons and fermions are described in a common way.

Grand Unification

- The idea of unification is based on the observation that three gauge couplings tends to the same point at high energy



- Evolution equations (SM)

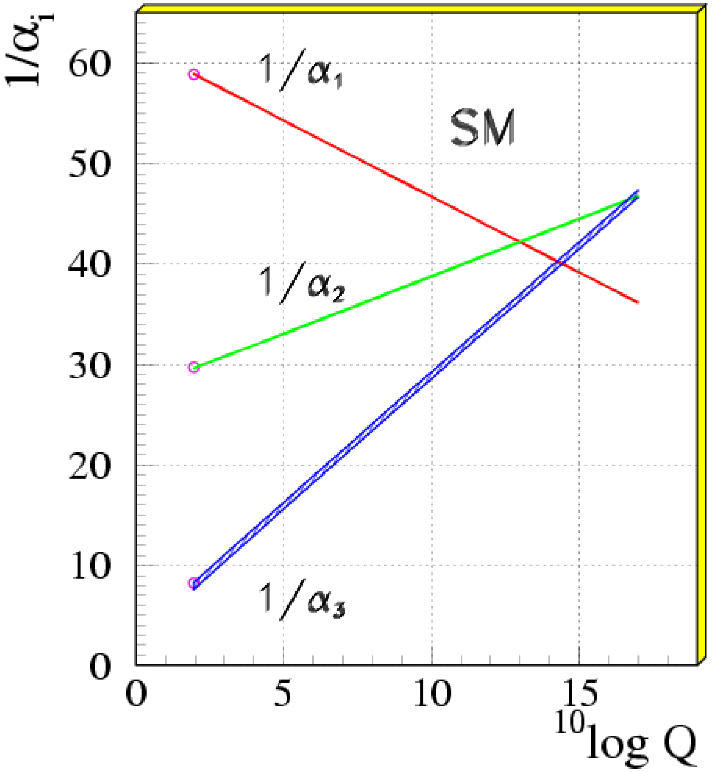
$$\frac{d\tilde{\alpha}_i}{dt} = b_i \tilde{\alpha}_i^2, \quad \tilde{\alpha}_i = \frac{\alpha_i}{4\pi} = \frac{g_i^2}{16\pi^2}, \quad t = \log \frac{Q^2}{\mu^2}$$

$$\frac{1}{\tilde{\alpha}_i} = \frac{1}{\tilde{\alpha}_{0i}} - b_i t$$

$$b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 41/10 \\ -19/6 \\ -7 \end{pmatrix}$$

Grand Unification

- ☐ However, there is no Grand Unification at high energies if we use the Standard Model evolution equations for the gauge couplings



- ☐ Evolution equations (MSSM)

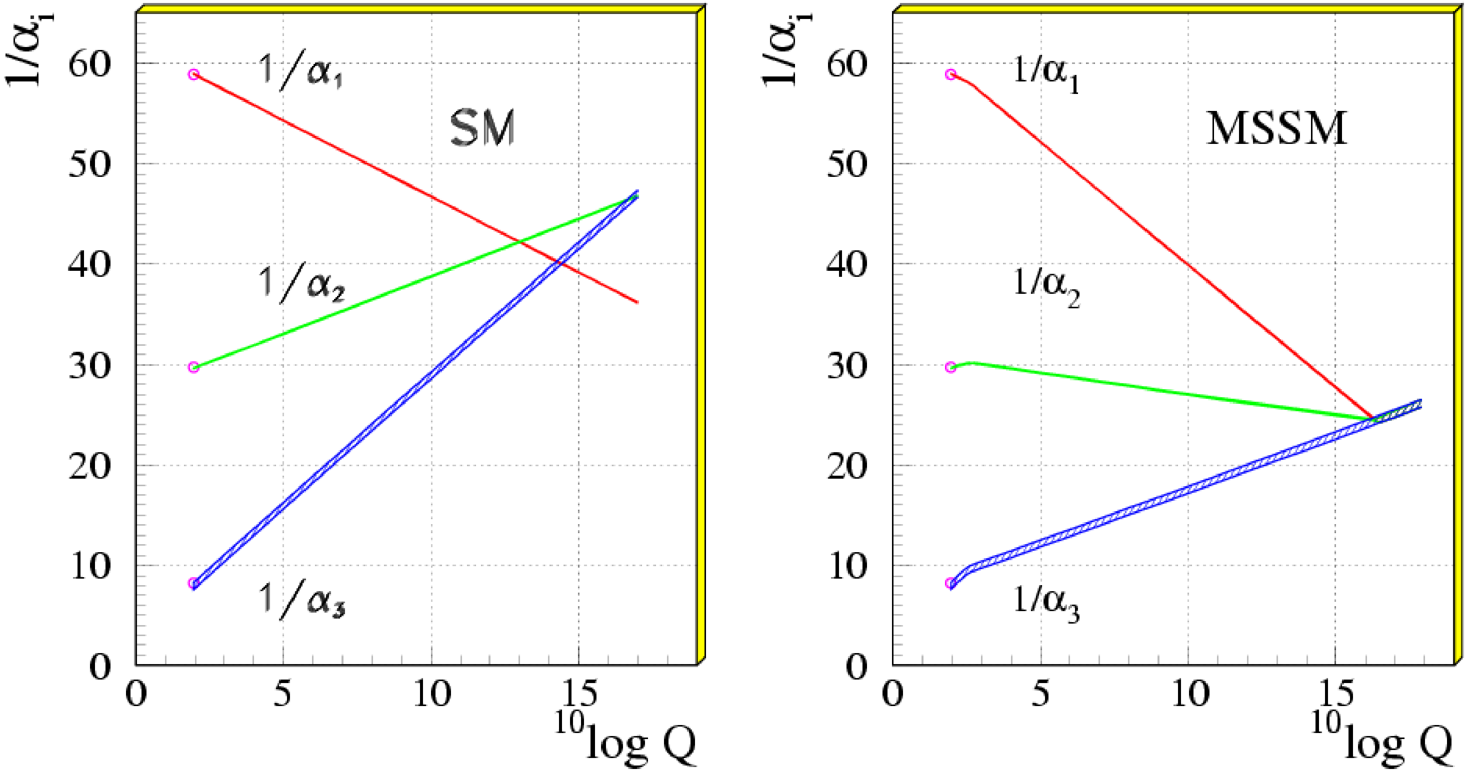
$$\frac{d\tilde{\alpha}_i}{dt} = b_i\tilde{\alpha}_i^2, \quad \tilde{\alpha}_i = \frac{\alpha_i}{4\pi} = \frac{g_i^2}{16\pi^2}, \quad t = \log\frac{Q^2}{\mu^2}$$

$$\frac{1}{\tilde{\alpha}_i} = \frac{1}{\tilde{\alpha}_{0i}} - b_i t$$

$$b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 33/5 \\ 1 \\ -3 \end{pmatrix}$$

Grand Unification

- In the Minimal supersymmetric Standard Model the gauge coupling constants do unify !



Grand Unification

- CONCLUSION: we need supersymmetry for unification

- Initial conditions at low energy are known ('93)

$$\alpha^{-1}(M_Z) = 128.978 \pm 0.027$$

$$\sin^2 \theta_{\overline{MS}} = 0.23146 \pm 0.00017$$

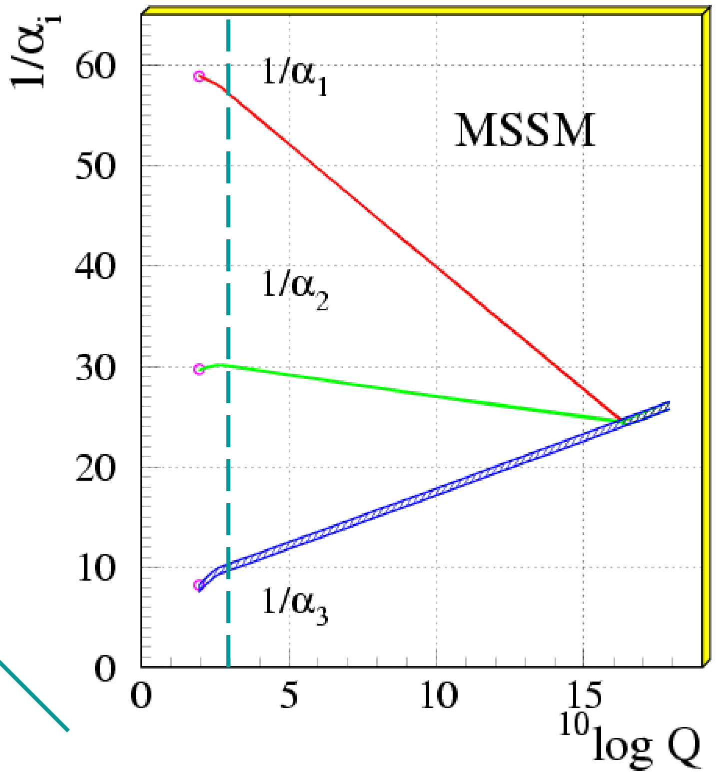
$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

then we calculate

$$M_{SUSY} = 10^{3.4\pm0.9\pm0.4} \text{ GeV}$$

$$M_{GUT} = 10^{15.8\pm0.3\pm0.1} \text{ GeV}$$

$$\alpha^{-1}_{\text{GUT}} = 26.3 \pm 1.9 \pm 1.0$$



- The scale of supersymmetry breaking is ~ *1 TeV*

Hierarchy problem

- Hierarchy problem

  Why there are very different energy scales ?

  - Electroweak symmetry breaking scale ($M_W \sim 100\ GeV$)
  - Grand Unification scale ($M_{GUT} \sim 10^{15\text{-}16}\ GeV$)

    or Plank scale ($M_{Pl} \sim 10^{19}\ GeV$)

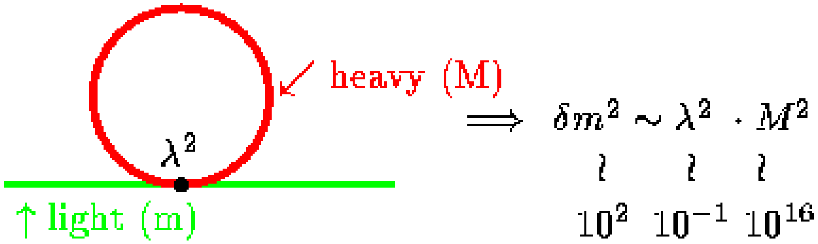
- Possible solution: to postulate the hierarchy.

  Very unnatural !

Hierarchy problem

- Another side of the problem: the hierarchy is destroyed by the radiative corrections

Consider the correction
to the light Higgs boson mass



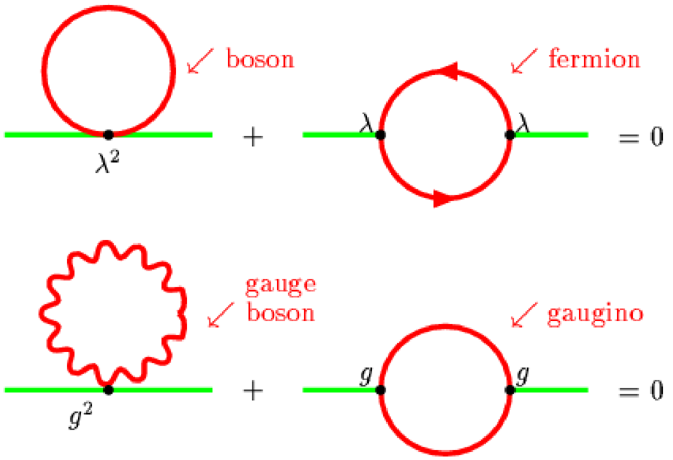
$$m_H \sim v \sim 10^2 \ GeV$$

$$M_\Sigma \sim V \sim 10^{16} \ GeV$$

Even if the hierarchy was postulated it is destroyed by radiative corrections (unless they cancel up to 10^{-14})

Hierarchy problem

- ❑ Supersymmetry can help to solve the hierarchy problem



- ❑ Let us add a «superpartner» -
  a particle with the same mass but
  with a different spin.
  Then the divergency cancells.
- ❑ The «accuracy» of cancellation is controlled by the mass-squared difference.

$$m^2_{boson} - m^2_{fermion} = M^2_{SUSY}$$

- ❑ If the correction is not larger than the mass itself then we have

$$\delta m_h^2 \sim g^2 M^2_{SUSY} \sim m_h^2 \sim 10^4 GeV \quad \Rightarrow \quad M_{SUSY} \sim 10^3 GeV$$

Supersymmetry: motivations

- Consistency of Grand Unification theory :
  unification of gauge coupling constants
- Solution to the hiearchy problem
- Supersymmetry populates «The Great Desert»: it predicts new particles and their spectrum
- Supersymmetry suggest a solution of the Dark Matter problem
- Radiative electroweak symmetry breaking.
  The Higgs boson mass is calculable.
- Supersymmetry can be tested experimentally

- SUSY is the most popular idea beyond the Standard Model

Superspace and superfields

- The simplest example is a chiral superfield, defined as

$$\bar{D}_{\dot\alpha} F(x,\theta,\bar\theta) = 0 \qquad \bar{D}_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta_{\dot\alpha}} - i(\theta\sigma^{\mu})_{\dot\alpha}\partial_{\mu}$$

- The expansion in Taylor series has the form

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y) \qquad y = x + i\theta\sigma\bar\theta$$

$$= A(x) + i\theta\sigma^{\mu}\bar\theta\partial_{\mu}A(x) + \tfrac{1}{4}\theta\theta\bar\theta\bar\theta\Box A(x)$$

$$+\sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_{\mu}\psi(x)\sigma^{\mu}\bar\theta + \theta\theta F(x)$$

- *A(x)* – complex scalar field (2 bosonic d.o.f.),

  ψ*(x)* – Weyl spinor field (2 fermionic d.o.f.)

- *F(x)*, the auxiliary field is unphysical and can be eliminated

Superspace and superfields

- The anti-chiral superfield is defined as

$$D_\alpha \Phi^\dagger = 0 \qquad D_\alpha = \frac{\partial}{\partial \theta_\alpha} + i(\sigma^\mu \bar{\theta})_\alpha \partial_\mu$$

- The chiral and antichiral superfields are used to describe matter

- The product of chiral (anti-chiral) superfields

$$\Phi^2, \Phi^3, \ldots \quad (\Phi^{\dagger 2}, \Phi^{\dagger 3}, \ldots)$$

  is again a chiral (anti-chiral) superfield

- The product of chiral and anti-chiral superfields $\Phi^\dagger \Phi$ is a general superfield

Superspace and superfields

- The arbitrary function of chiral superfields and its Taylor expansion has the form

$$\mathcal{W}(\Phi) = \mathcal{W}(A + \sqrt{2}\theta\psi + \theta\theta F)$$

$$= \mathcal{W}(A) + \frac{\partial \mathcal{W}}{\partial A}\sqrt{2}\theta\psi + \theta\theta(\frac{\partial \mathcal{W}}{\partial A}F - \frac{1}{2}\frac{\partial^2 \mathcal{W}}{\partial A^2}\psi\psi)$$

- This function is called a superpotential

The superpotential and the conjugated one are used for the construction of supersymmetric lagrangians.

Superspace and superfields

- To describe gauge interactions we need a real vector superfield.

$$
\begin{aligned}
V(x,\theta,\bar{\theta}) = {} & C(x) + i\theta\chi(x) - i\bar{\theta}\bar{\chi}(x) \\
& + i\theta\theta M(x) - i\bar{\theta}\bar{\theta}M^{+}(x) - \theta\sigma^{\mu}\bar{\theta}V_{\mu}(x) \\
& + i\theta\theta\bar{\theta}[\bar{\lambda}(x) + i\bar{\sigma}^{\mu}\partial_{\mu}\chi(x)] - i\bar{\theta}\bar{\theta}\theta[\lambda(x) + i\sigma^{\mu}\partial_{\mu}\bar{\chi}(x)] \\
& + \tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}[D(x) + \tfrac{1}{2}\Box C(x)]
\end{aligned}
$$

- The set of component fields in not irreducible. Choosing the particular gauge one can get rid of some of them
- One may choose the Wess-Zumino gauge, $C = \chi = M = 0$ which leaves only physical degrees of freedom (the vector and spinor fields) and an auxiliary field D

Superspace and superfields

- In the Wess-Zumino gauge one has

$$V = -\theta\sigma^{\mu}\bar{\theta}v_{\mu}(x) + i\theta\theta\bar{\theta}\bar{\lambda}(x) - i\bar{\theta}\bar{\theta}\theta\lambda(x) + \tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D(x)$$

$$V^{2} = -\tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}\, v_{\mu}(x)v^{\mu}(x)$$

$$V^{3} = 0$$

- One can define the field strength tensor (abelian case)

$$W_{\alpha} = -\frac{1}{4}\bar{D}^{2}D_{\alpha}V \qquad W_{\dot{\alpha}} = -\frac{1}{4}D^{2}D_{\dot{\alpha}}V$$

$$W_{\alpha} = -i\lambda_{\alpha} + \theta_{\alpha}D - \tfrac{i}{2}(\sigma^{\mu}\bar{\sigma}^{\nu}\theta)_{\alpha}F_{\mu\nu} + \theta^{2}\sigma^{\mu}\partial_{\mu}\bar{\lambda}$$

$$F_{\mu\nu} = \partial_{\mu}v_{\nu} - \partial_{\nu}v_{\mu}$$

Supersymmetric lagrangians

- The action is the integral over superspace

$$Action = \int d^4x \, \mathcal{L} \quad \Longrightarrow \quad \int d^4x \, d^4\theta \, \mathcal{L}$$

- SUSY invariant lagrangian

$$L = \int d^2\theta d^2\overline{\theta} \, \Phi_i^+ \Phi_i + \int d^2\theta \, (\lambda_i \Phi_i + \tfrac{1}{2} m_{ij} \Phi_i \Phi_j + \tfrac{1}{3} y_{ijk} \Phi_i \Phi_j \Phi_k) + h.c.]$$

- In components one has

$$L = i\partial_\mu \overline{\psi}_i \overline{\sigma}^\mu \psi_i + A_i^* \Box A_i - \frac{1}{2} m_{ij} \psi_i \psi_j - \frac{1}{2} m_{ij}^* \overline{\psi}_i \overline{\psi}_j$$

$$- y_{ijk} \psi_i \psi_j A_k - y_{ijk}^* \overline{\psi}_i \overline{\psi}_j A_k^* - V(A_i, A_j)$$

Supersymmetric lagrangians

- ❑ Gauge part of the lagrangian

$$L = \tfrac{1}{4}\int d^2\theta\ W^\alpha W_\alpha + \int d^2\bar{\theta}\ \overline{W}^{\dot{\alpha}}\,\overline{W}_{\dot{\alpha}} = \tfrac{1}{2}D^2 - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} - i\lambda\sigma^\mu D_\mu \bar{\lambda}$$

- ❑ Gauge and SUSY invariant lagrangian

$$\mathcal{L}_{SUSY\ \ YM} = \tfrac{1}{4}\int d^2\theta\ \mathrm{Tr}(W^\alpha W_\alpha) + \tfrac{1}{4}\int d^2\theta\ \mathrm{Tr}(\overline{W}^\alpha\,\overline{W}_\alpha)$$

$$+\int d^2\theta d^2\bar{\theta}\ \overline{\Phi}_{ia}(e^{gV})^a_b\Phi^b_i + \int d^2\theta\ \mathcal{W}(\Phi_i) + \int d^2\bar{\theta}\ \overline{\mathcal{W}}(\overline{\Phi}_i)$$

Supersymmetric lagrangians

- In components the full lagrangian reads

$$
\begin{aligned}
L_{SUSY\ YM} &= -\tfrac{1}{4} F^{a}_{\mu\nu} F^{a\mu\nu} - i\lambda^{a}\sigma^{\mu} D_{\mu}\overline{\lambda}^{a} + \tfrac{1}{2} D^{a} D^{a} \\
&+(\partial_{\mu} A_{i} - igv^{a}_{\mu} T^{a} A_{i})^{\dagger} (\partial_{\mu} A_{i} - igv^{a}_{\mu} T^{a} A_{i}) - i\overline{\psi}_{i} \overline{\sigma}^{\mu} (\partial_{\mu}\psi_{i} - igv^{a}_{\mu} T^{a}\psi_{i}) \\
&-D^{a} g A_{i}^{\dagger} T^{a} A_{i} - i\sqrt{2} g A_{i}^{\dagger} T^{a} \lambda^{a} \psi_{i} + i\sqrt{2} g \overline{\psi}_{i} T^{a} \overline{\lambda}^{a} A_{i} + F_{i}^{\dagger} F_{i} \\
&+ \frac{\partial \mathcal{W}}{\partial A_{i}} F_{i} + \frac{\partial \overline{\mathcal{W}}}{\partial A_{i}^{\dagger}} F_{i}^{\dagger} - \tfrac{1}{2} \frac{\partial^{2} \mathcal{W}}{\partial A_{i} \partial A_{j}} \psi_{i} \psi_{j} - \tfrac{1}{2} \frac{\partial^{2} \overline{\mathcal{W}}}{\partial A_{i}^{\dagger} \partial A_{j}^{\dagger}} \overline{\psi}_{i} \overline{\psi}_{j}
\end{aligned}
$$

- After eliminating auxiliary fields F and D using equations of motion one can easily reproduce the Standard Model lagrangian and kinetic terms and interactions of superpartners

Supersymmetric lagrangians

- The scalar potential
  - F-term (from SUSY invariant part of the lagrangian)
  - D-term (from gauge invariant part of the lagrangian)

$$\mathrm{V}=\tfrac{1}{2}D^a D^a + F_i^{\dagger} F \qquad D^a = -gA_i^{\dagger}T^a A_i, \quad F_i = -\frac{\partial \mathcal{W}}{\partial A_i}$$

- The scalar potential is not arbitrary, it is fixed by supersymmetry

- The lagrangian is constructed using only symmetry considerations. One has to choose matter fields and gauge fields

Supersymmetric lagrangians

- How to construct a supersymmetric model:
    - Define the matter and gauge field content
    - Using the vector superfields construct thefield strength tensor(s)
    - Using the chiral and anti-chiral superfields construct the kinetic terms and the superpotential
    - Write down the full lagrangian in terms of superfields
    - Integrate over grassmanian coordinates
    - Eliminate auxiliary fields using equations of motion
- The result is the lagrangian describing the ordinary fields, the superpartners and their interactions

Minimal SUSY SM (MSSM)

- In supersymmetric theories the number of bosonic degrees of freedom is equal to the number of fermionic degrees of freedom

- In the Standard Model we have
  - 28 bosonic degrees of freedom :

$$(4 + 8) \times 2 \quad + \quad 2 \times 2$$

vector fields Higgs boson

(γ,Z,W^+,W^-, gluons)

  - 90 (96) fermionic degrees of freedom:

$$(6 \times 3 + 3) \times 4 \; + \; 3 \times 2\ (4)$$

quarks and charged leptons neutrinos

- The Standard Model is not supersymmetric

	Bosons	Fermions	SU(3)	SU(2)	U(1)
Matter fields					
L_i		leptons $L_i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $E_i = e_R$	1	2	-1
E_i			1	1	2
Q_i		quarks $Q_i = \begin{pmatrix} u \\ d \end{pmatrix}_L$ $U_i = u_R$ $D_i = d_R$	3	2	1/3
U_i			3*	1	-4/3
D_i			3*	1	2/3
Gauge fields					
G^a	gluons g^a		8	0	0
V^k	$W^{\pm}, Z$ - bosons photon γ		1	3	0
V'			1	1	0
Higgs field					
H	Higgs boson $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$		1	2	-1

Minimal SUSY SM (MSSM)

- In order to supersymmetrize the Standard Model one has to add new particles (superpartners)
  - In the Standard Models there are no fermions with quantum numbers of gauge bosons
  - The Higgs and lepton doublets have the same quantum numbers (1,2,-1). Can they be superpartners?
- One has to add the second Higgs doublet
- Fermion masses (up and down quarks).

Yukawa interactions in the SM → superpotential in the MSSM

$$\boxed{\mathcal{L}_{Yukawa} = y^{L}_{\alpha\beta}\overline{L}_{\alpha}E_{\beta}H + y^{D}_{\alpha\beta}\overline{Q}_{\alpha}D_{\beta}H + y^{U}_{\alpha\beta}\overline{Q}_{\alpha}U_{\beta}\widetilde{H}}$$

$$\tilde{H} = i\tau_2 H^{\dagger}$$

	Bosons	Fermions	SU(3)	SU(2)	U(1)
Matter fields					
L_i	sleptons $\tilde{L}_i = \begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_L$	leptons $L_i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	1	2	-1
E_i	$\tilde{E}_i = \tilde{e}_R$	$E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = \begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L$	quarks $Q_i = \begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	1/3
U_i	$\tilde{U}_i = \tilde{u}_R$	$U_i = u_R$	3*	1	-4/3
D_i	$\tilde{D}_i = \tilde{d}_R$	$D_i = d_R$	3*	1	2/3
Gauge fields					
G^a	gluons g^a	gluino $\tilde{g}^a$	8	0	0
V^k	$W^\pm, Z$-bosons	wino $\tilde{W}^\pm$, zino $\tilde{Z}$,	1	3	0
V'	photon γ	photino $\tilde{\gamma}$	1	1	0
Higgs fields					
H_1	Higgs boson $H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}$	higgsino $\tilde{H}_1 = \begin{pmatrix} \tilde{H}_1^+ \\ \tilde{H}_1^0 \end{pmatrix}$	1	2	-1
H_2	Higgs boson $H_2 = \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix}$	higgsino $\tilde{H}_2 = \begin{pmatrix} \tilde{H}_2^0 \\ \tilde{H}_2^- \end{pmatrix}$	1	2	1

MSSM Lagrangian

- MSSM lagrangian

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{SoftBreaking}$$

- Yukawa interactions (superpotential)

$$\boxed{\mathcal{W}_R = y_U Q_L H_2 U_R + y_D Q_L H_1 D_R + y_L L_L H_1 E_R + \mu H_1 H_2}$$

- In components this will lead to the Standard Model Yukawa interactions + interactions with superpartners

MSSM Lagrangian

- Supersymmetry allow also the following terms in the superpotential

$$\boxed{\mathcal{W}_{NR} = \lambda_L L_L L_L E_R + \lambda_L^{'} L_L Q_L D_R + \mu^{'} L_L H_2 + \lambda_B U_R D_R D_R}$$

- They break baryon and lepton numbers and are absent in the Standard Model

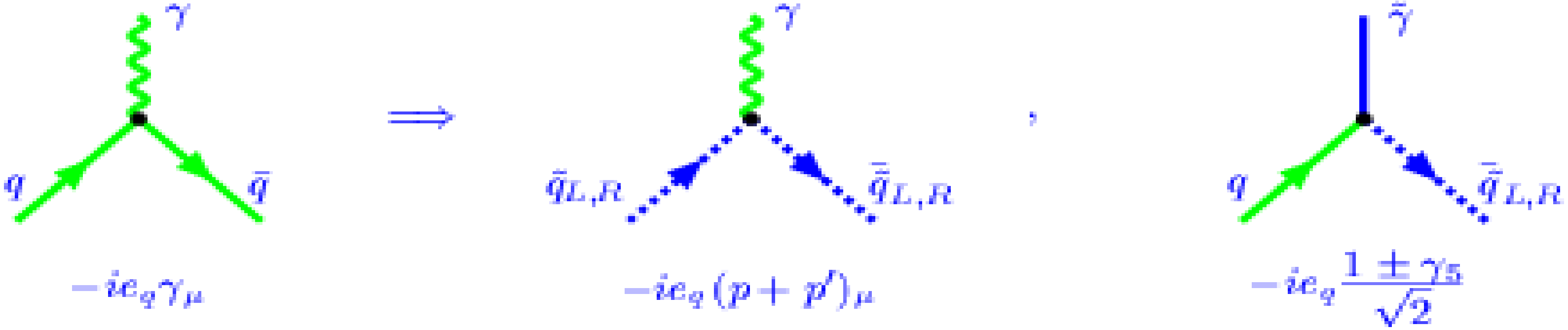
- To get rid of them one has to introduce a new symmetry – R-parity

- All the Standard Model particles have R= +1, and superpartners have R= -1.

$$\boxed{R = (-1)^{3(B-L)+2S}}$$

MSSM Lagrangian

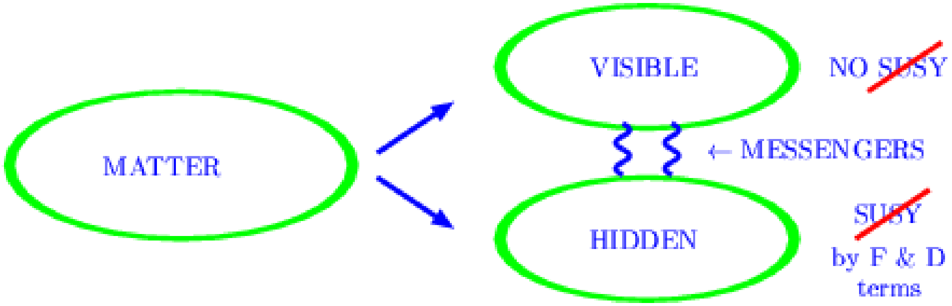
- Consequences of R-parity conservation:
  - Interactions of particles and superpartners are the same (just replace two of the particles in the interaction vertex by superpartners)



  - Superpartners are created in pairs
  - The lightest supersymmetric particle is stable !

Breaking of supersymmetry

- Since superpartners are not observed, in nature supersymmetry can be realised as broken symmetry
- In the MSSM the soft supersymmetry breaking mechanism is used.
- One assumes that breaking takes place in the hidden sector. Mediators of the supersymmetry sbreakin from the hidden sector to the visible one can be
  - Gravitons (SUGRA)
  - Gauge fields
  - Gaugino fields



(the difference is only in details)

Breaking of supersymmetry

- Soft breaking of supersymmetry can be parametrized by additional terms in the lagrangian
  - The mass terms for the scalar components of chiral superfiels $m_{ij}^2 A_i^* A_j$
  - The mass terms for the fermion components of vector superfiels $M\lambda\lambda$
  - Bilenear softsupersymetry breaking term $B_{ij}\mu_{ij}A_i A_j$
  - Trilinear soft supersymetry breaking terms $A_{ijk}\lambda_{ijk}A_i A_j A_k$

- Supersymmetry is broken since components of the same superfield have different masses

Breaking of supersymmetry

- The part of the MSSM lagrangian responsible for supersymmetry breaking reads

$$-L_{SoftBreaking} = \sum_{scalars} m_i^2 \,|\, A_i \,|^2 + \sum_{gauge} M_i (\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i)$$

$$+ A_U y_U Q_L H_2 U_R + A_U y_D Q_L H_1 D_R + A_U y_L L_L H_1 E_R + B\mu H_1 H_2$$

- Too many free parameters (more than a hundred !)

- Now one can calculate the mass spectrum of superparticles

- Later we will see how to reduce the number of parameters

Higgs bosons in the MSSM

- At the tree level the MSSM Higgs potential has the form

$$
\begin{aligned}
V_{tree}(H_1, H_2) = m_1^2 \,|H_1|^2 + m_2^2 \,|H_2|^2 - m_3^2 (H_1 H_2 + h.c.) \\
+ \frac{g^2 + g'^2}{8} (|H_1|^2 - |H_2|^2)^2 + \frac{g^2}{2} |H_1^+ H_2|^2
\end{aligned}
$$

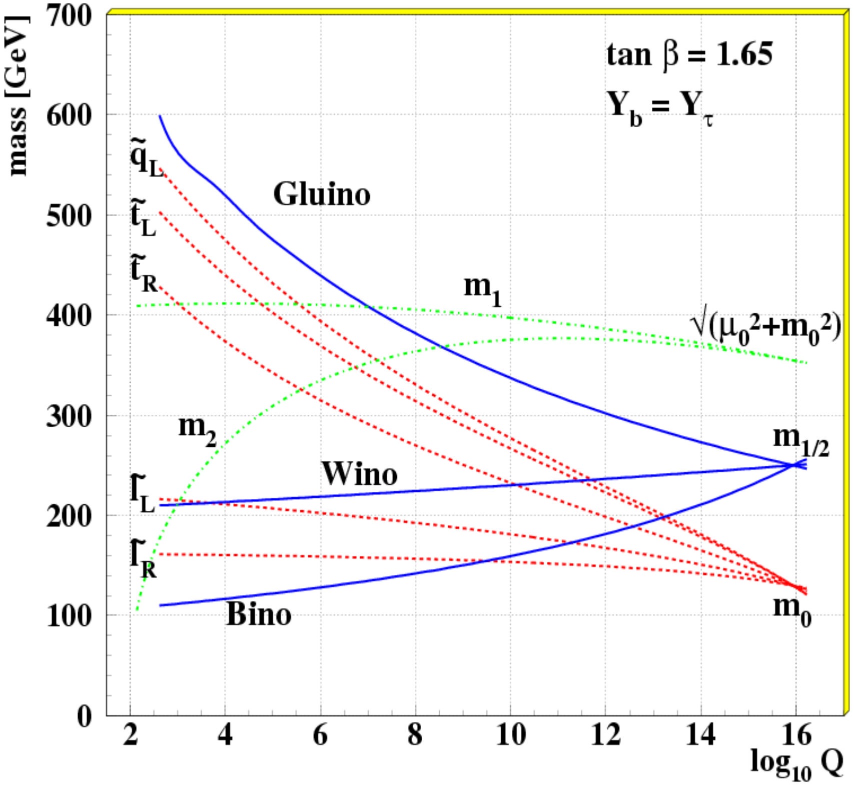
Note: the Higgs self-interaction coupling constant is fixed and is determined by the gauge interactions, this case differs from the Standard Model.

- The MSSM Higgs potential is positively defined and has no non-trivial non-zero minimum.

Higgs bosons in the MSSM

- Running of the Higgs masses leads to the phenomena known as radiative electroweak symmetry breaking.

$$
\begin{aligned}
&V_{tree}(H_1, H_2)\\
&= m_1^2 \,|H_1|^2 - \left|m_2^2\right| |H_2|^2\\
&- m_3^2 (H_1 H_2 + h.c.)\\
&+ \frac{g^2 + g'^2}{8} (|H_1|^2 - |H_2|^2)^2
\end{aligned}
$$



- This results in the conditions for the spontaneous electroweak symmetry breaking

Higgs bosons in the MSSM

- The physical spectrum of the MSSM Higgs sector consists of 5 states:

$$\begin{aligned}
G^0 &= -\cos\beta P_1 + \sin\beta P_2 && \mathit{Goldstone\ boson} \rightarrow Z_0 \\
A &= \sin\beta P_1 + \cos\beta P_2 && \mathit{Neutral\ CP} = -1\ \mathit{Higgs} \\
G^+ &= -\cos\beta (H_1^-)^* + \sin\beta H_2^+ && \mathit{Goldstone\ boson} \rightarrow W^+ \\
H^+ &= \sin\beta (H_1^-)^* + \cos\beta H_2^+ && \mathit{Charged\ Higges} \\
h &= -\sin\alpha S_1 + \cos\alpha S_2 && \mathrm{SM}\ \mathit{Higgs\ boson\ CP} = 1 \\
H &= \cos\alpha S_1 + \sin\alpha S_2 && \mathit{Extra\ heavy\ Higgs\ boson}
\end{aligned}$$

- Compare to the Standard Model with 1 Higgs boson.

Higgs bosons in the MSSM

- One can calculate the Higgs masses diagonalizing corresponding mass matrices.

- Masses of the CP-odd and charged Higgs bosons

$$m_A^2 = m_1^2 + m_2^2$$

$$m_{H^\pm}^2 = m_A^2 + M_W^2$$

- Masses of the CP-even Higgs bosons

$$m_{h,H}^2 = \frac{1}{2}[m_A^2 + M_Z^2 \pm \sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta}]$$

- If $m_A \gg M_Z$, the lightest Higgs boson is lighter than Z-boson !

$$\boxed{m_h \approx M_Z\,|\cos 2\beta| \; < \; M_Z}$$

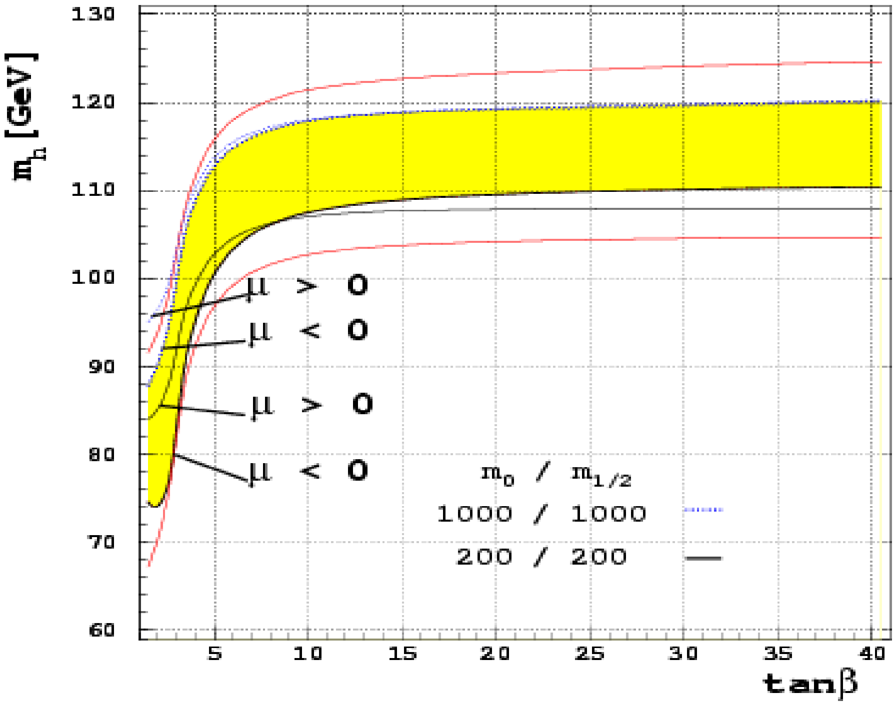
Higgs bosons in the MSSM

- The inequality $m_h \approx M_Z \,|\cos 2\beta|\, < M_Z$ is spoiled by radiative corrections

$$m_h^2 \approx M_Z^2 \cos^2 2\beta$$

$$+\frac{3g^2 m_t^4}{16\pi^2 M_W^2}\log\frac{\tilde{m}_{t_1}^2\,\tilde{m}_{t_2}^2}{m_t^4}$$

$$+2\ loops$$



- 1-loop contribution is very large and positive
- 2-loop contribution is much smaller and negative

Constrained MSSM

- ❑ Parameters of the Minimal Supersymmetric Standard Model
  - ❑ Gauge cuopling constants $\alpha_i,$ i=1,2,3
  - ❑ Yukawa coupling constants $y^k_{ab},\ k = U, D, L, (E)$
  - ❑ Higgs mixing parameter μ
  - ❑ Soft supersymmetry breaking parameters

- ❑ The Higgs self-interaction coupling is not arbitrary, it is fixed by supersymmetry.

$$\lambda = \frac{g^2 + g'^2}{8}$$

- ❑ The main uncertainty is due to the soft supersymmetry breaking parameters

Constrained MSSM

- Universality hypothesis: soft supersymmetry breaking parameters unify at the scale of Grand Unification

$$-L_{SoftBreaking} = m_0^2 \sum_{scalars} |A_i|^2 + m_{1/2} \sum_{gauge} (\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i)$$

$$+A\left(y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\right) + B\mu H_1 H_2$$

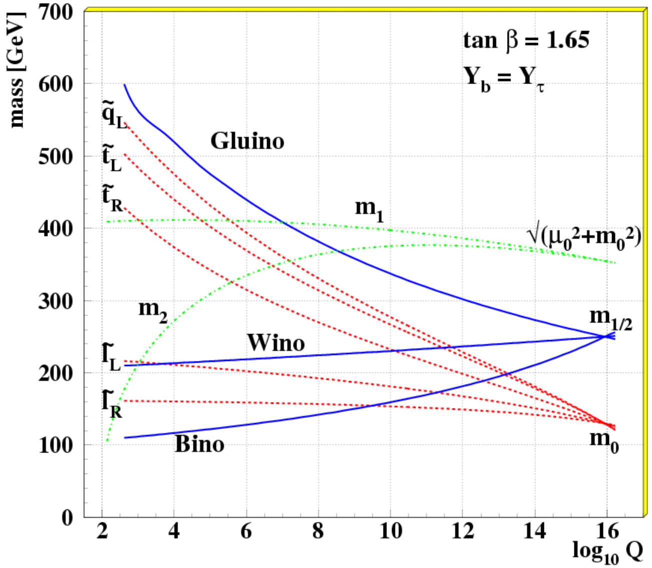
- As a result, MSSM has

  5 free parameters

  $$\mu,\ A,\ m_0,\ m_{1/2},\ B(\tan\beta)$$

  while the Standard Model has 2 ones

  $$m,\ \lambda$$



Constrained MSSM

- To make prediction one can choose a certain way
  - Take low-energy values of parameters as input (superpartners masses, mixing parameters, etc.) and then calculate observables as functions of these values.
  - Take high-energy values of parameters as input, then using evolution equations find their low-energy values, calculate the mass spectrum, and then calculate observables. All the calculation now uses a small number of free parameters.

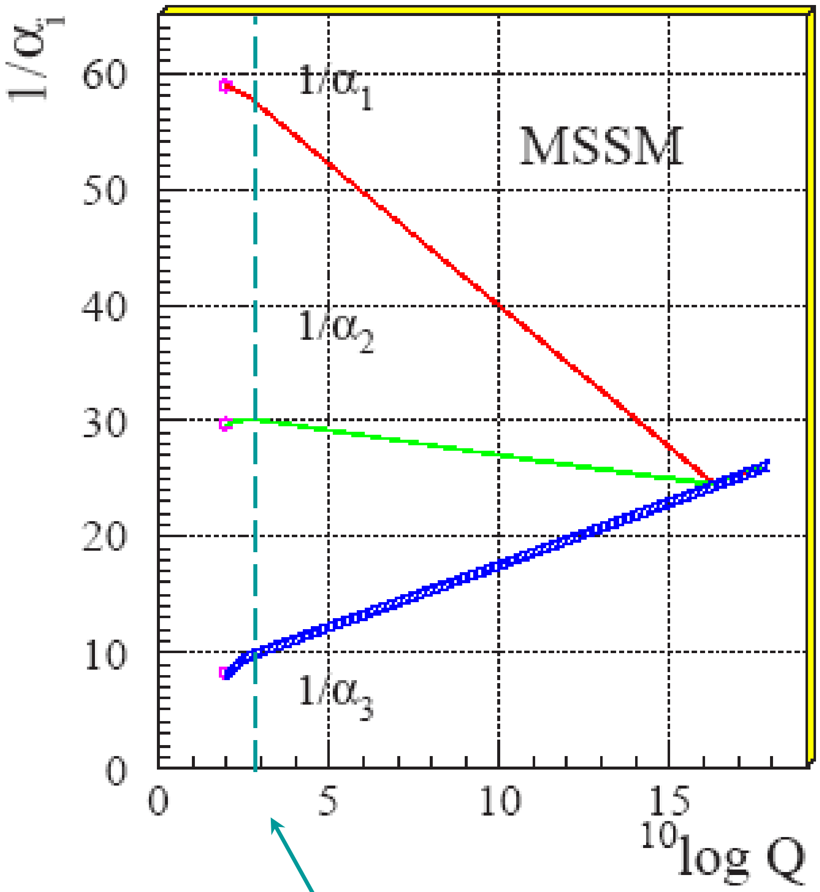
"Experimental" data are sufficient
to find allowed values of initial parameters

Constrained MSSM

- Choice of constraints

  - Unification of the gauge coupling constants
    It is one of the crucial constraints and fixes the scale of supersymmetry breaking.

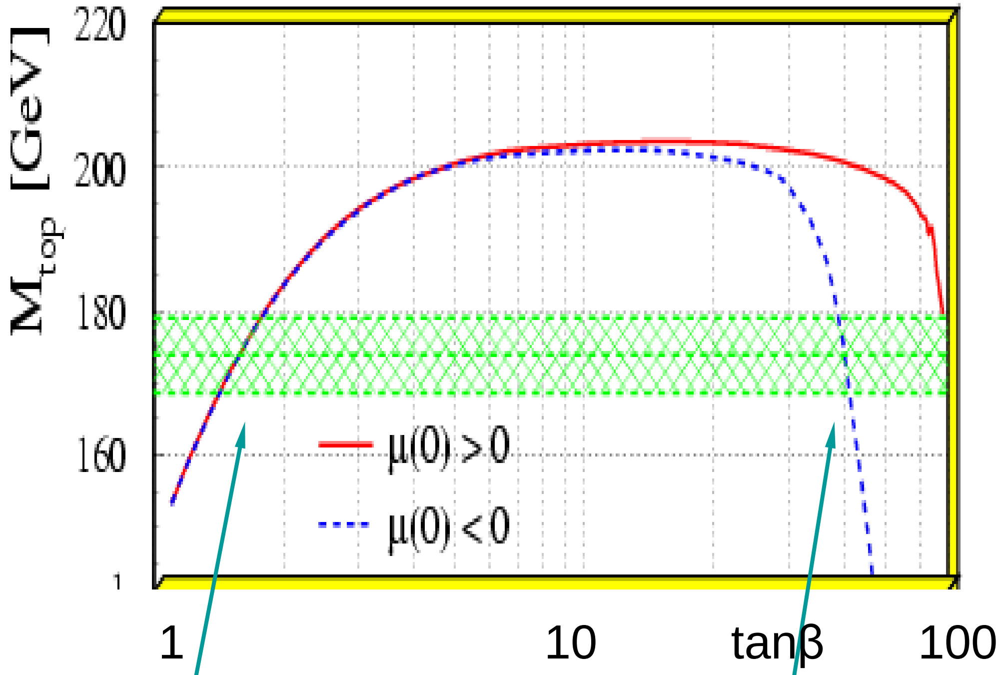
  - Masses of superpartners are in the TeV region



$M_{SUSY} \sim 1\ TeV$

Constrained MSSM

- Choice of constraints
  - Unification of the Yukawa coupling constants. Combination of b-quark and τ-lepton Yukawa couplings unification with the t-quark mass strongly constrains the tan β value.



- Small tan β scenario
- Large tan β scenario

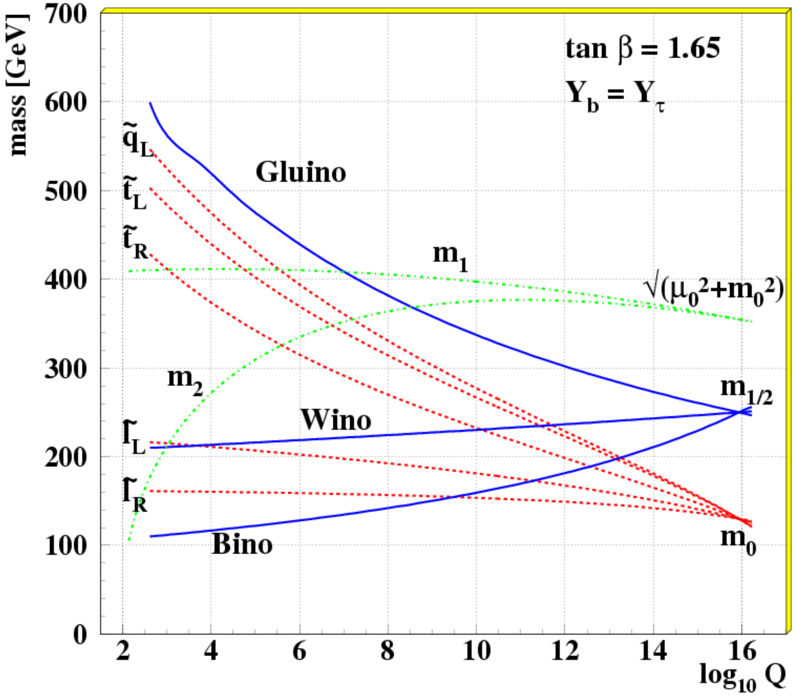
$1 < \tan\beta < 3$

$50 < \tan\beta < 70$

Constrained MSSM

- Choice of constraints
  - Radiative electroweak symmetry breaking and Z-boson mass.

    It defines the μ parameter for given values of m_0. The sign of μ is undetermined.



$$\mu^2 = \frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{M_Z^2}{2} \approx -m_{H_2}^2 - \frac{M_Z^2}{2}$$

Constrained MSSM

- Choice of constraints

- Let us fix the value of tan β
- Let us calculate the value of the μ parameter (up to the sign)
- Soft supersymmetry breaking parameter A_0 is irrelevant in most cases (A=0)

- We end up with only a pair of parameters

$$\mu,\ A,\ \underline{m_0,\ m_{1/2},}\ \tan\beta$$

- From now on we will use the $m_0 – m_{1/2}$ plane and look for allowed regions

Constrained MSSM

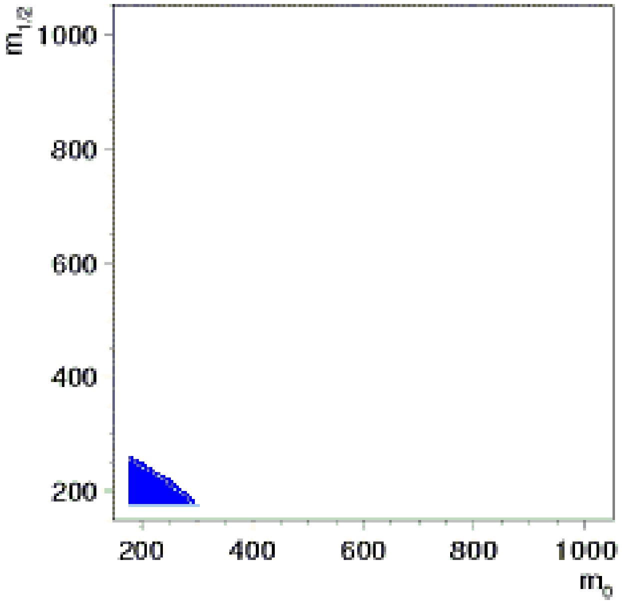
- Choice of constraints
  - Experimental bounds on the Higgs mass. The bound $m_H > 114$ GeV excludes $\tan\beta < 4$
  - Experimental bounds on superpartner masses. Non-observation of superpartners constrains their masses (that is constrains the soft supersymmetry breaking parameters)
  - Neutrality of the lightest supersymmetric particle. Consequence of R-parity conservation

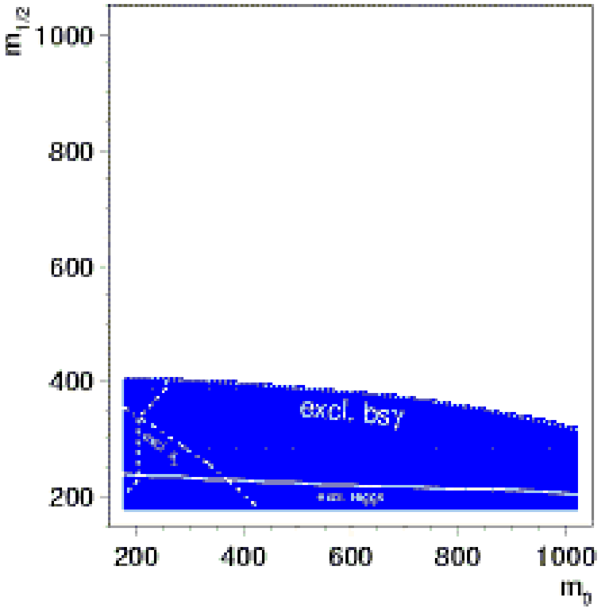
Constrained MSSM

- ❑ Choice of constraints

- ❑ Precise measurements of rare decays branching ratios. This may be influenced by radiative corrections including superpartners in loops. Example:

$$b \to s\gamma$$

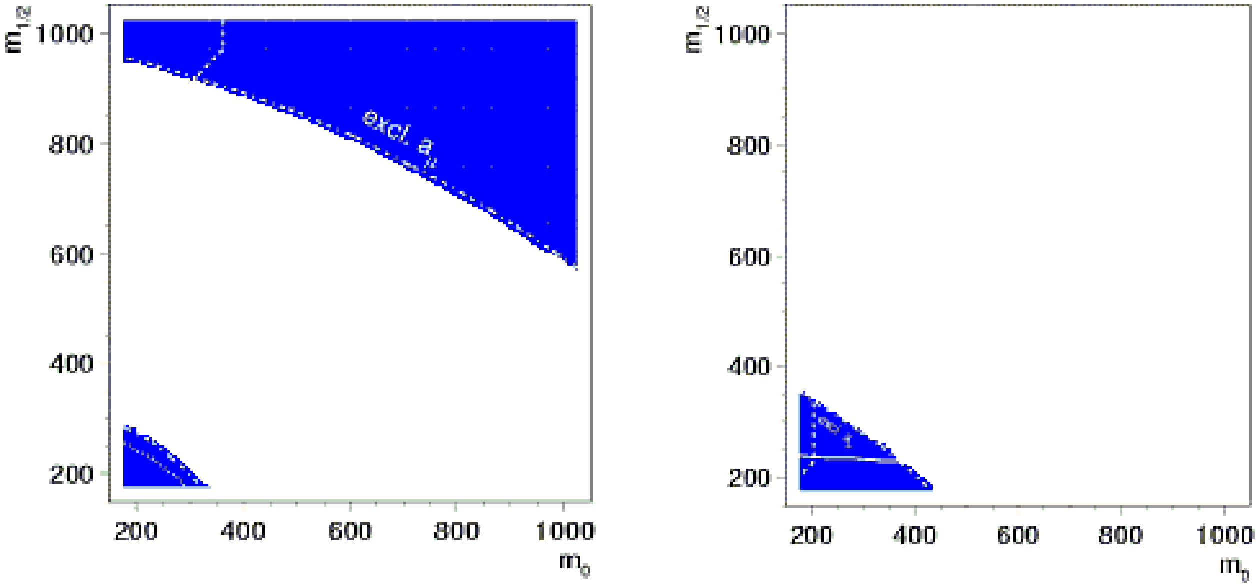




Constrained MSSM

- Choice of constraints

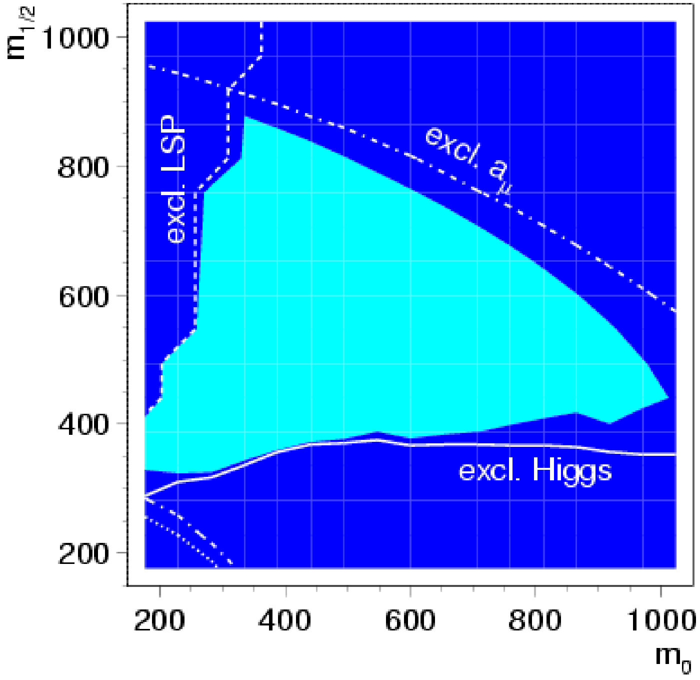
- Muon anomalous magnetic moment. Measurements point to a deviation from the SM predictions. The gap can be filled with SUSY contribution. This requires positive μ

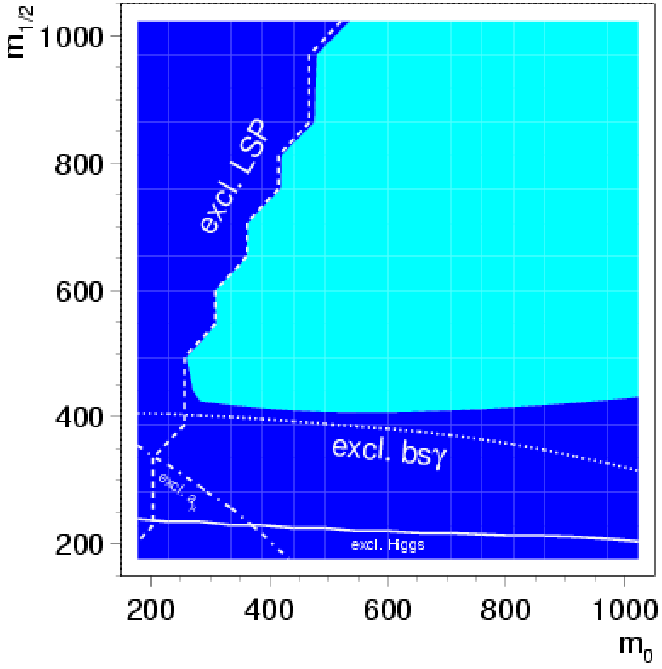


Constrained MSSM

- Choice of constraints

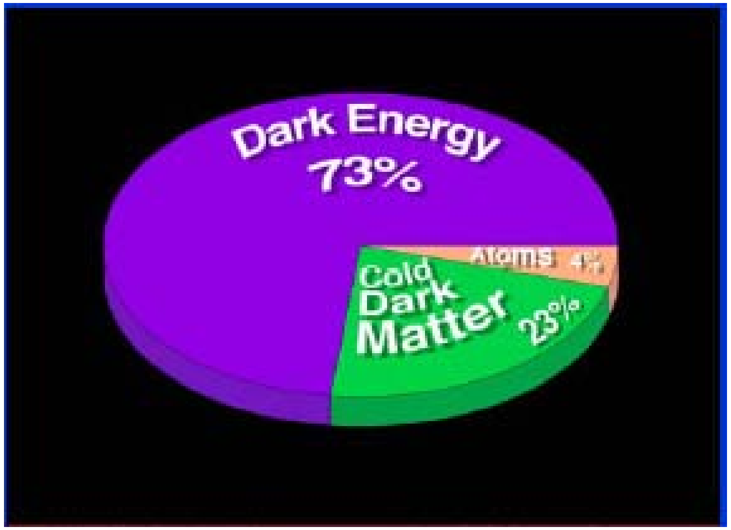
- Remarkable fact ia that all these constraints can be fulfilled simultaneously. As a result one can find optimal values of the parameters and allowed regions in the parameter space





Constrained MSSM

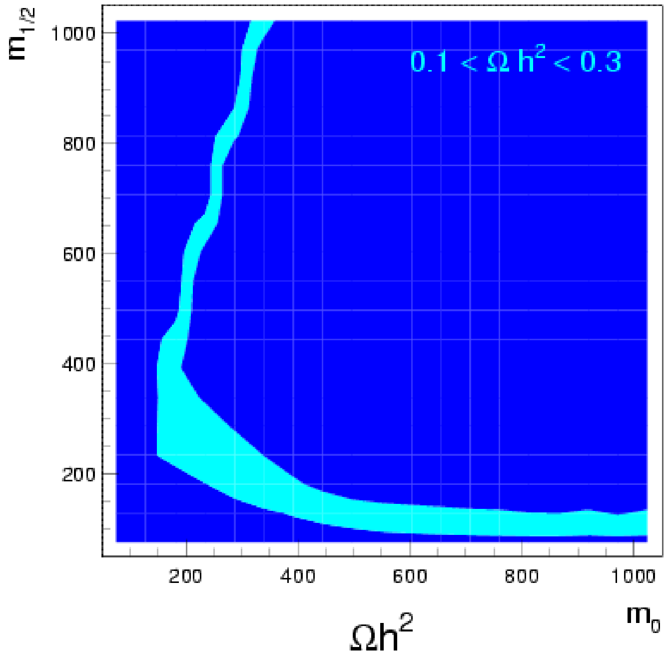
- Choice of constraints
  - Dark Matter in the Universe. MSSM has a good candidate for the WIMP – neutralino – a mixture of superpartners of photon, Z-boson and Higgses

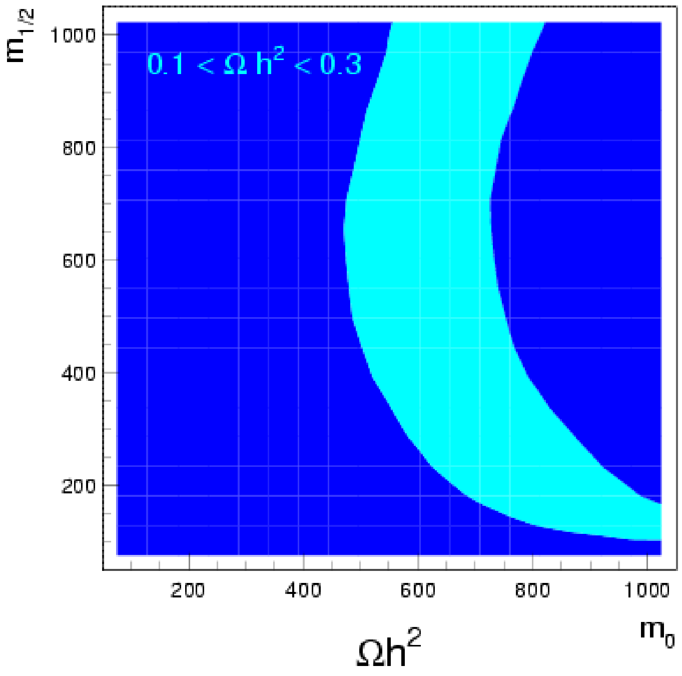


  - Neutral (no electric charge, no colour)
  - Weakly interacting (due to supersymmetry)
  - Stable (!) if R-parity is conserved
  - Heavy enough to account for cold non-baryonic dark matter

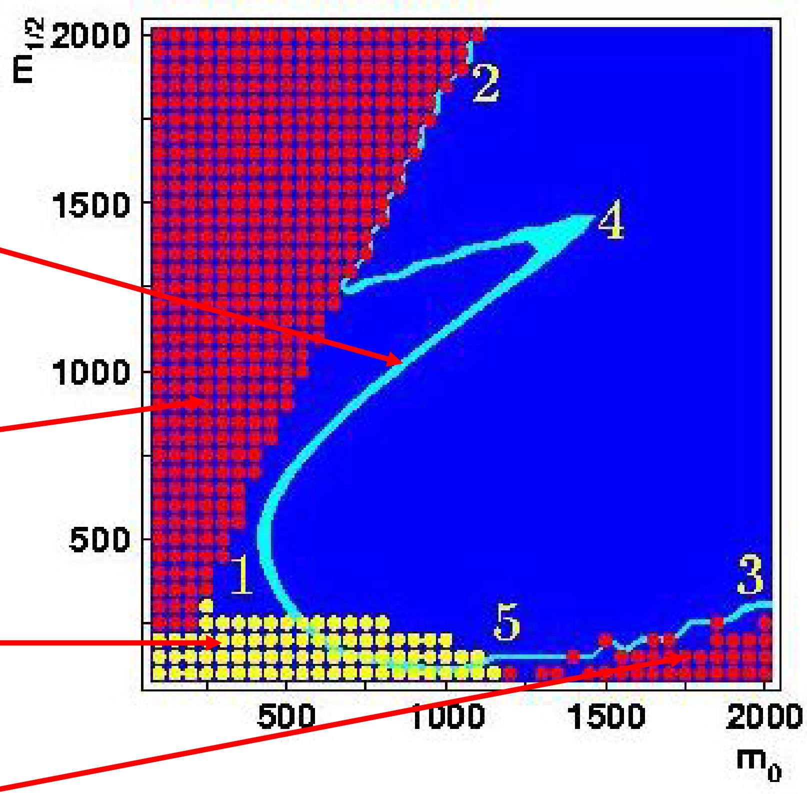
Constrained MSSM

- ❑ Regions of the MSSM parameter space consistent with the dark matter constraint (Ω = 0.1 – 0.3)





Constrained MSSM

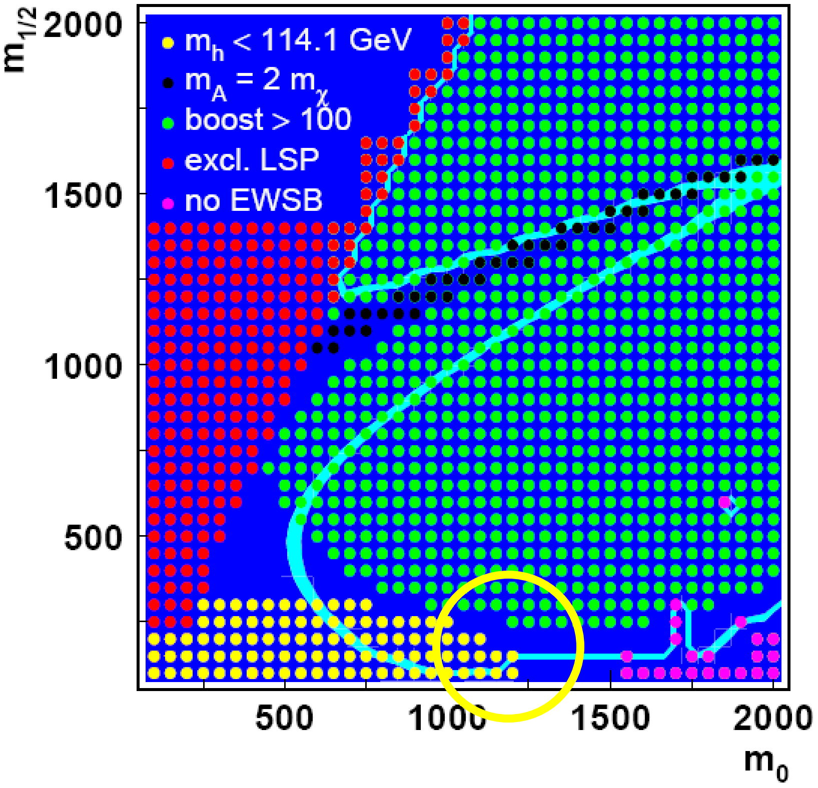


- WMAP data leave only very small allowed region which give acceptable neutralino relic density
- Excluded by LSP
- Excluded by Higgs searches at LEP2
- Excluded by REWSB

m_0 – common scalar mass
$m_{1/2}$ – common gaugino mass

Constrained MSSM

- ❑ The region compatible with all electroweak constraints as well as with WMAP and EGRET constraints are rather small



- ❑ The best fit values

  tan β = 51

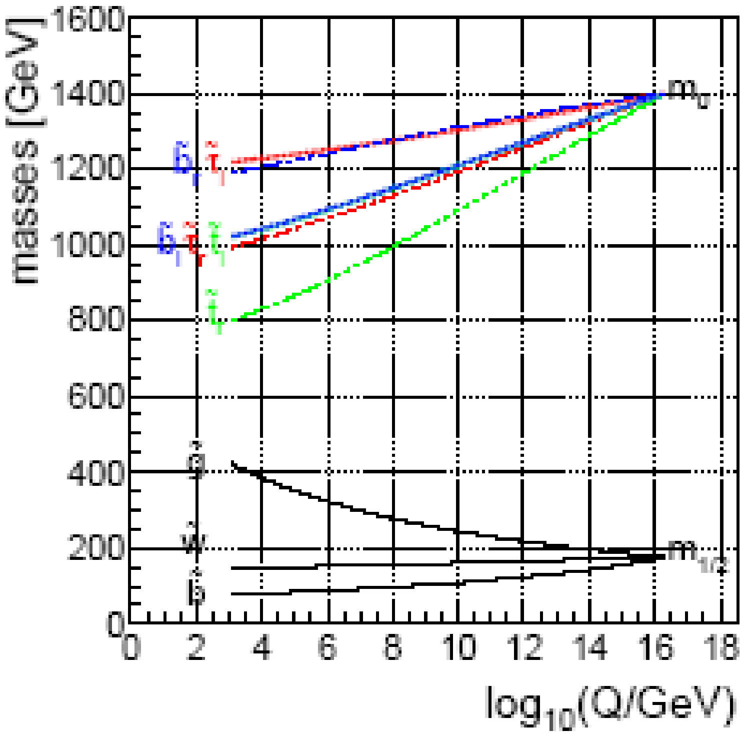
  m_0 = 1400 GeV

  $m_{1/2}$ = 180 GeV

  $A_0 = 0.5\ m_0$

Constrained MSSM

- Superparticle spectrum for m_0=1400 GeV, $m_{1/2}$=180 GeV (the region consistent with WMAP and EGRET data)

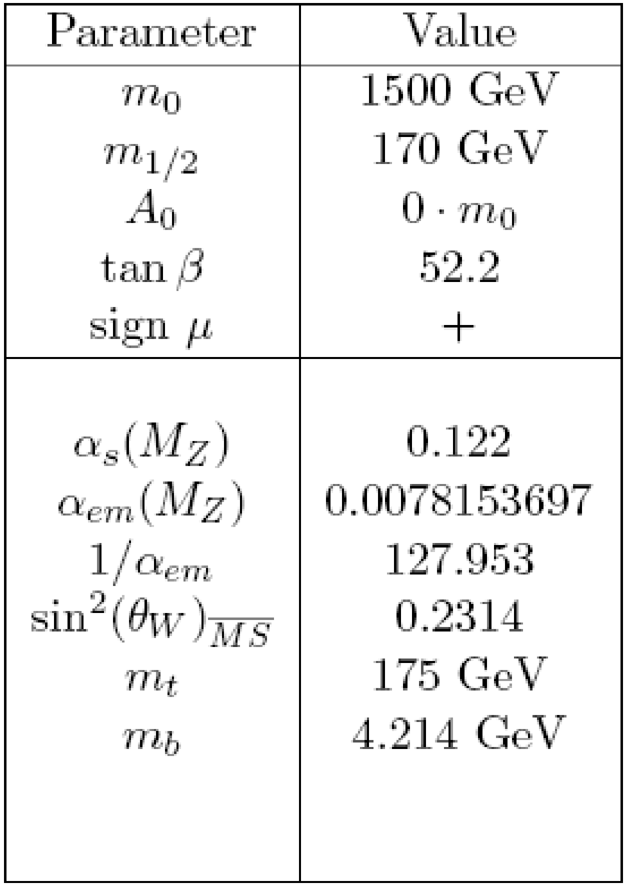


- Squarks and sleptons are heavy – their masses are around 1 TeV

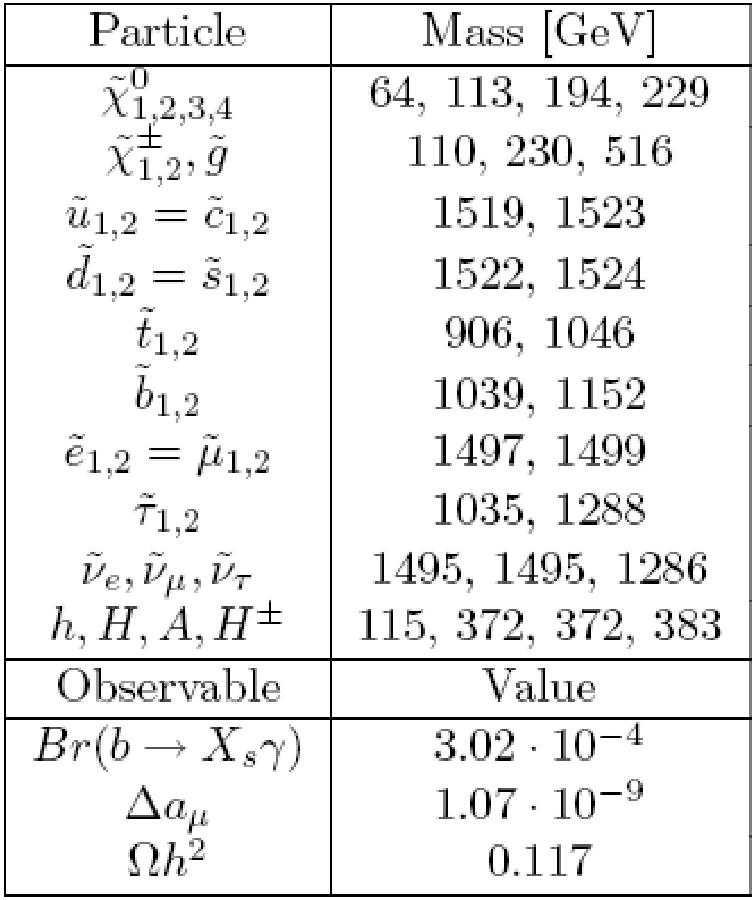
- Gluinos, charginos and neutralinos are relatively light

Constrained MSSM

- SUSY parameters and superparticle spectrum



Parameter	Value
m_0	1500 GeV
$m_{1/2}$	170 GeV
A_0	$0 \cdot m_0$
$\tan\beta$	52.2
sign μ	$+$
$\alpha_s(M_Z)$	0.122
$\alpha_{em}(M_Z)$	0.0078153697
$1/\alpha_{em}$	127.953
$\sin^2(\theta_W)_{\overline{MS}}$	0.2314
m_t	175 GeV
m_b	4.214 GeV



Particle	Mass [GeV]
$\tilde{\chi}^0_{1,2,3,4}$	64, 113, 194, 229
$\tilde{\chi}^{\pm}_{1,2}, \tilde{g}$	110, 230, 516
$\tilde{u}_{1,2} = \tilde{c}_{1,2}$	1519, 1523
$\tilde{d}_{1,2} = \tilde{s}_{1,2}$	1522, 1524
$\tilde{t}_{1,2}$	906, 1046
$\tilde{b}_{1,2}$	1039, 1152
$\tilde{e}_{1,2} = \tilde{\mu}_{1,2}$	1497, 1499
$\tilde{\tau}_{1,2}$	1035, 1288
$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	1495, 1495, 1286
$h, H, A, H^{\pm}$	115, 372, 372, 383
Observable	**Value**
$Br(b \to X_s\gamma)$	$3.02 \cdot 10^{-4}$
Δa_μ	$1.07 \cdot 10^{-9}$
Ωh^2	0.117

SUSY production at colliders

- Supersymmetric particles can be produced at collider if the energy is large enough

$$m_{sparticle} \leq \frac{\sqrt{s}}{2}$$

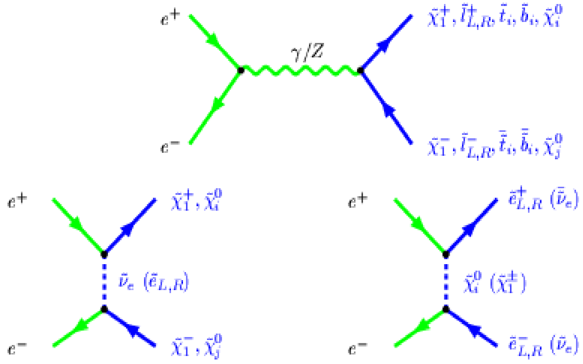
- Production and subsequent decay crucially depends on the model and the mass spectrum

- If the R-parity is conserved only lightest SUSY particles (neutralinos) remain after decays. The main feature is the missing energy taken away by LSP, since they escape detection

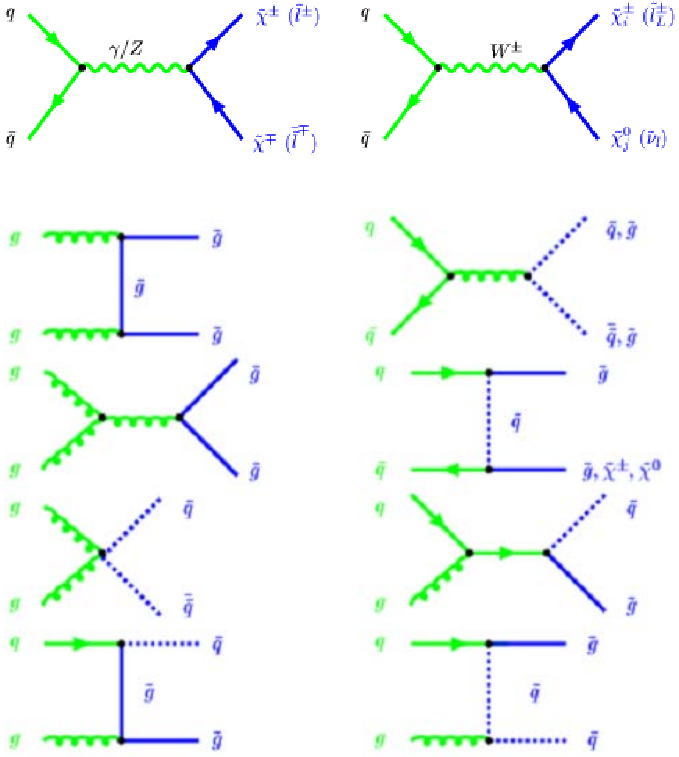
SUSY production at colliders

- Processes of creation of supersymmetric particles

- e^+e^- colliders

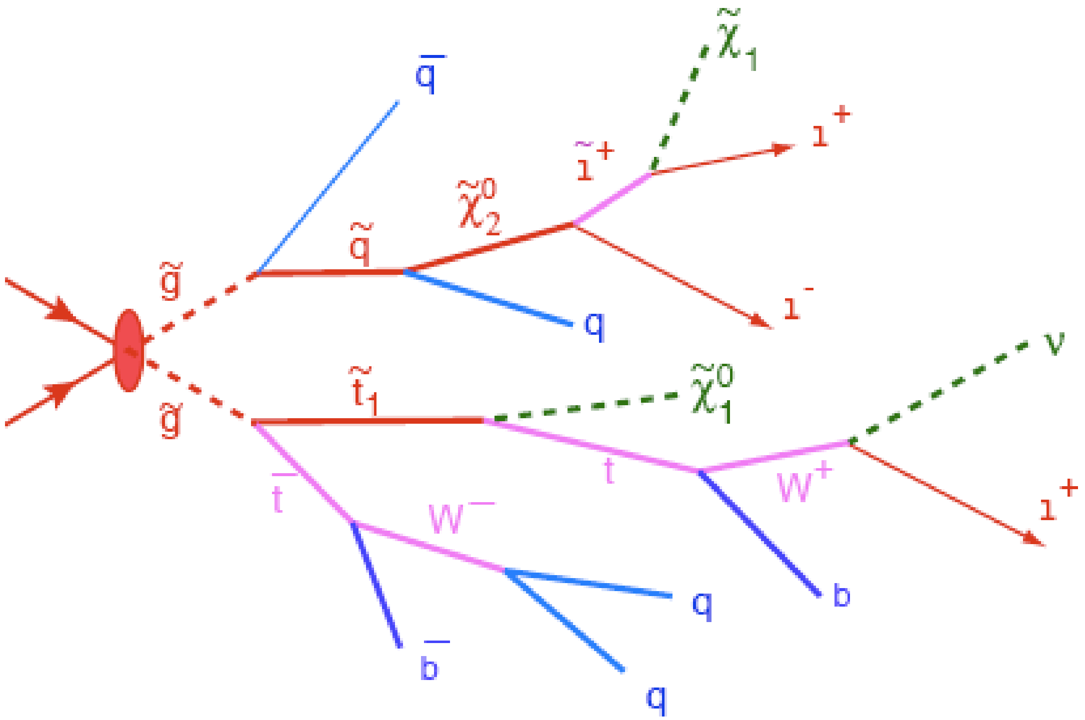


- Hadron colliders



SUSY events signatures

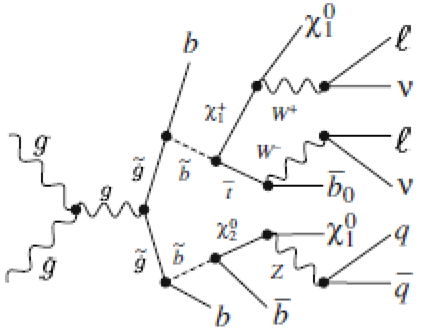
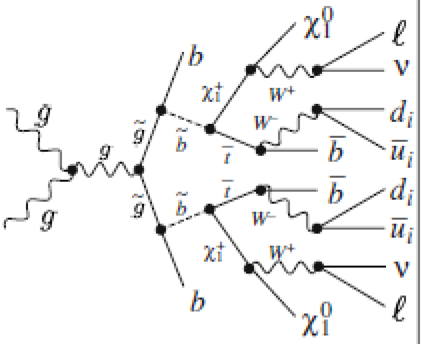
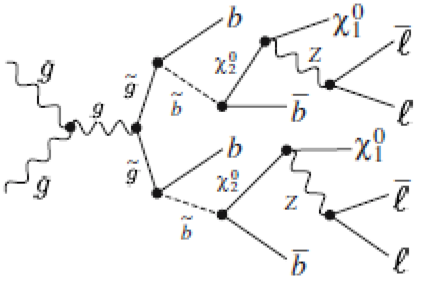
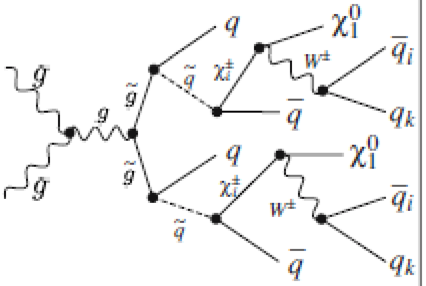
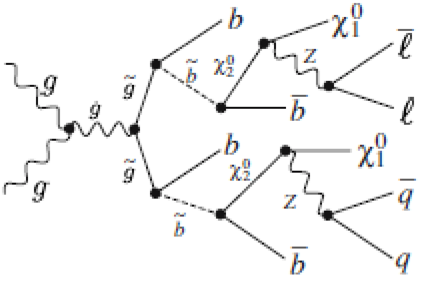
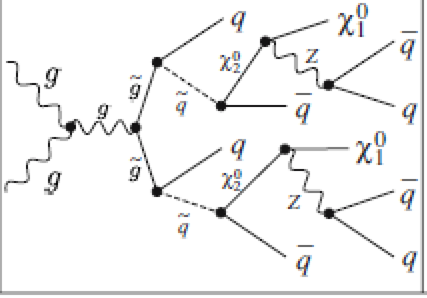
- Missing Energy: from LSP
- Multi-Jet: from cascade decay (gaugino)
- Multi-Leptons: from decay of charginos/neutralios



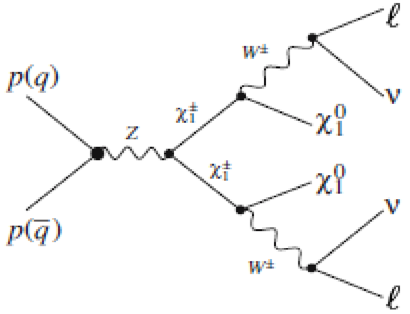
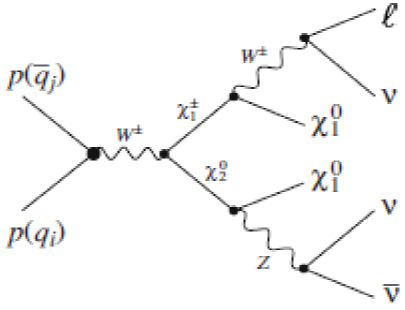
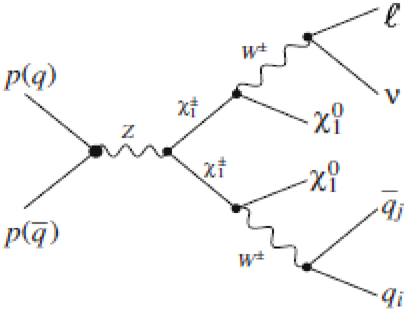
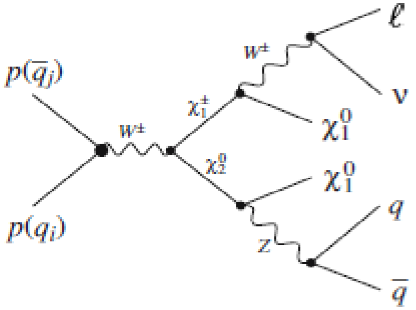
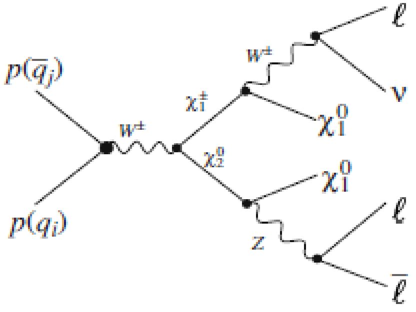
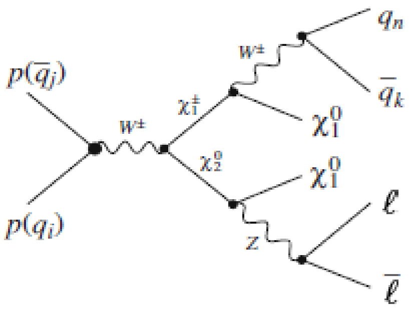
SUSY events signatures

Production	Main decay mode	Signature
$\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ q\bar{q}'\tilde{\chi}_1^\pm \\ g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$	$\not{E}_T$ + multijets (+ leptons)
	$\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$	Trilepton + $\not{E}_T$
	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$	Dileptons + jet + $\not{E}_T$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \to \ell\tilde{\chi}_1^0\ell^\pm\nu$	Dilepton + $\not{E}_T$
$\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	Dilepton + jet + $\not{E}_T$
$\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	Two noncollinear jets + $\not{E}_T$
	$\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$	Single lepton + $\not{E}_T$ + $b's$
	$\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$	Dilepton + $\not{E}_T$ + $b's$
$\tilde{\ell}\tilde{\ell}, \tilde{\ell}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{\ell}^\pm \to \ell^\pm\tilde{\chi}_i^0, \tilde{\ell}^\pm \to \nu_\ell\tilde{\chi}_i^\pm$	Dilepton + $\not{E}_T$
	$\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Single lepton + $\not{E}_T$

SUSY events signatures

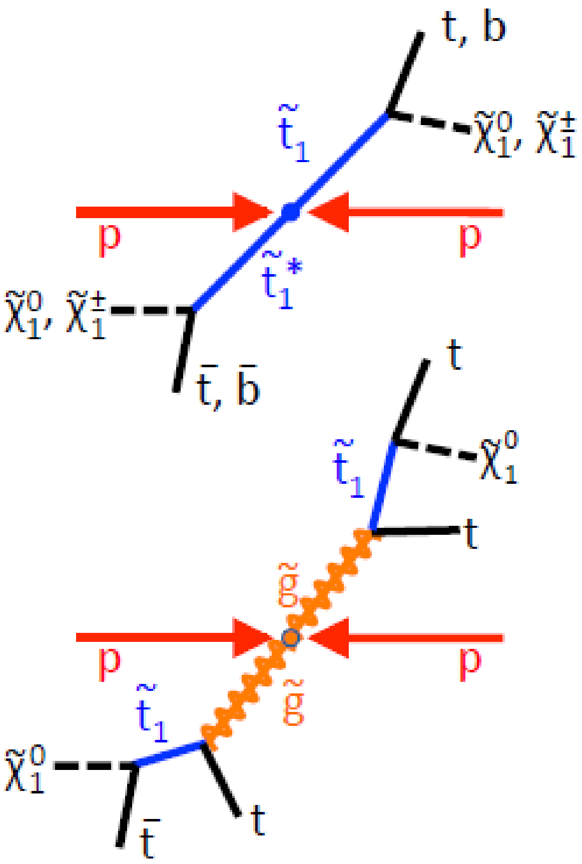
Process	Final state	Process	Final state
	2ℓ 2ν $6j$ $\not{E}_T$		2ℓ 2ν $8j$ $\not{E}_T$
	4ℓ $4j$ $\not{E}_T$		$8j$ $\not{E}_T$
	2ℓ $6j$ $\not{E}_T$		$8j$ $\not{E}_T$

SUSY events signatures

Process	Final states	Process	Final states
	2ℓ 2ν $\not{E}_T$		ℓ 3ν $\not{E}_T$
	ℓ ν $2j$ $\not{E}_T$		ℓ ν $2j$ $\not{E}_T$
	3ℓ ν $\not{E}_T$		2ℓ $2j$ $\not{E}_T$

Stop production

- Top squarks can be produced at LHC by either direct production or gluino mediated production
- Final state with several top or bottom quarks and neutralinos
- Signature: b-jets, E_T, one or several leptons, light jets



(ATLAS-CONF-2012-003)

Summary of SUSY searches

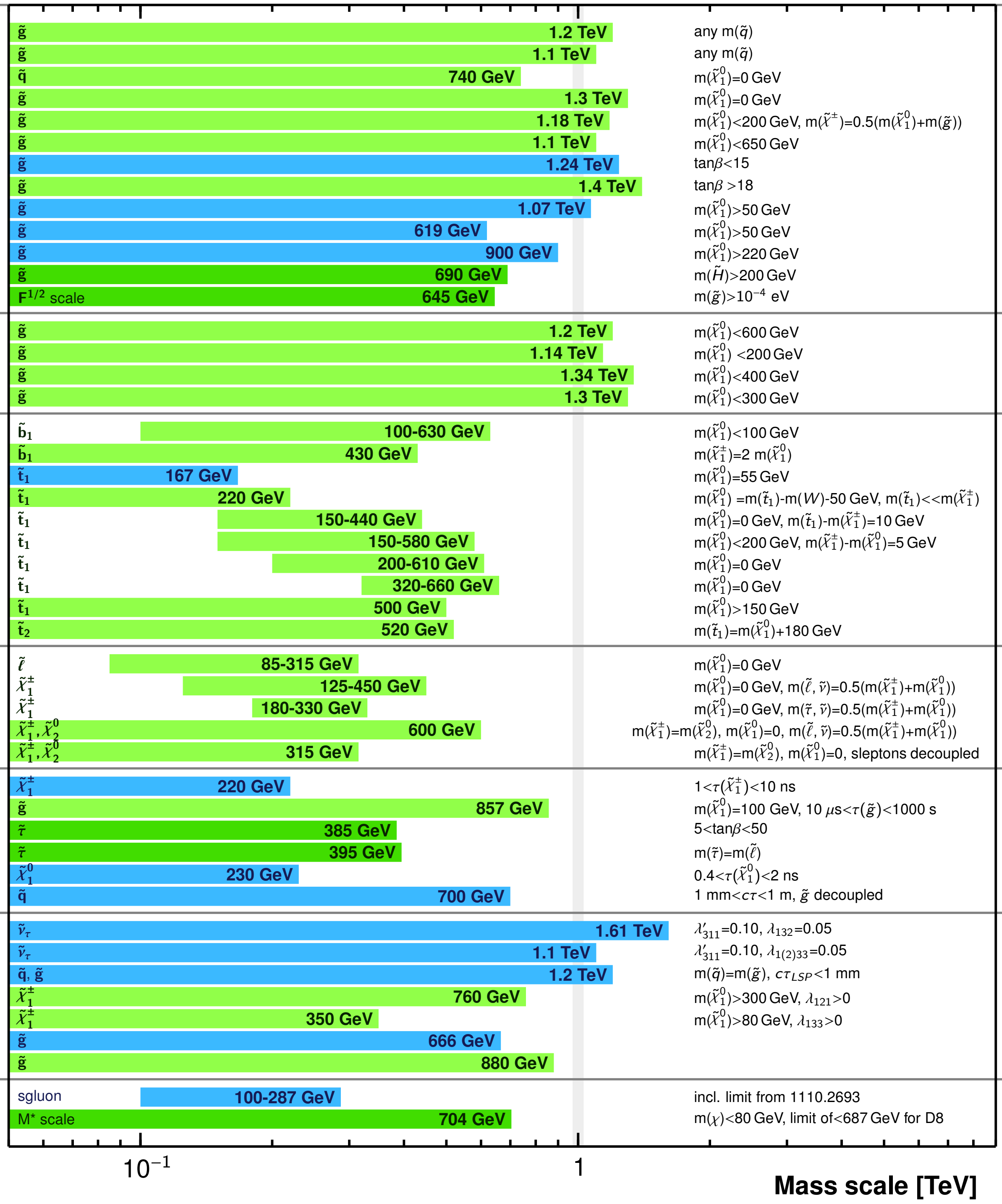
- A broad range of searches for SUSY with different final states have been performed by ATLAS and CMS collaborations
- Most recent results can be found at
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- No excess over the SM expectation was found for $L \sim 20\ \mathrm{fb}^{-1}$ of data
- Limits on the masses of the sparticles in a various SUSY scenarios have been obtained
- Around 30 fb^{-1} data is available due to LHC operation in 2010/2012
- Although no evidence for SUSY was found, more data is available for evaluation.

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LP 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt = (4.4 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV



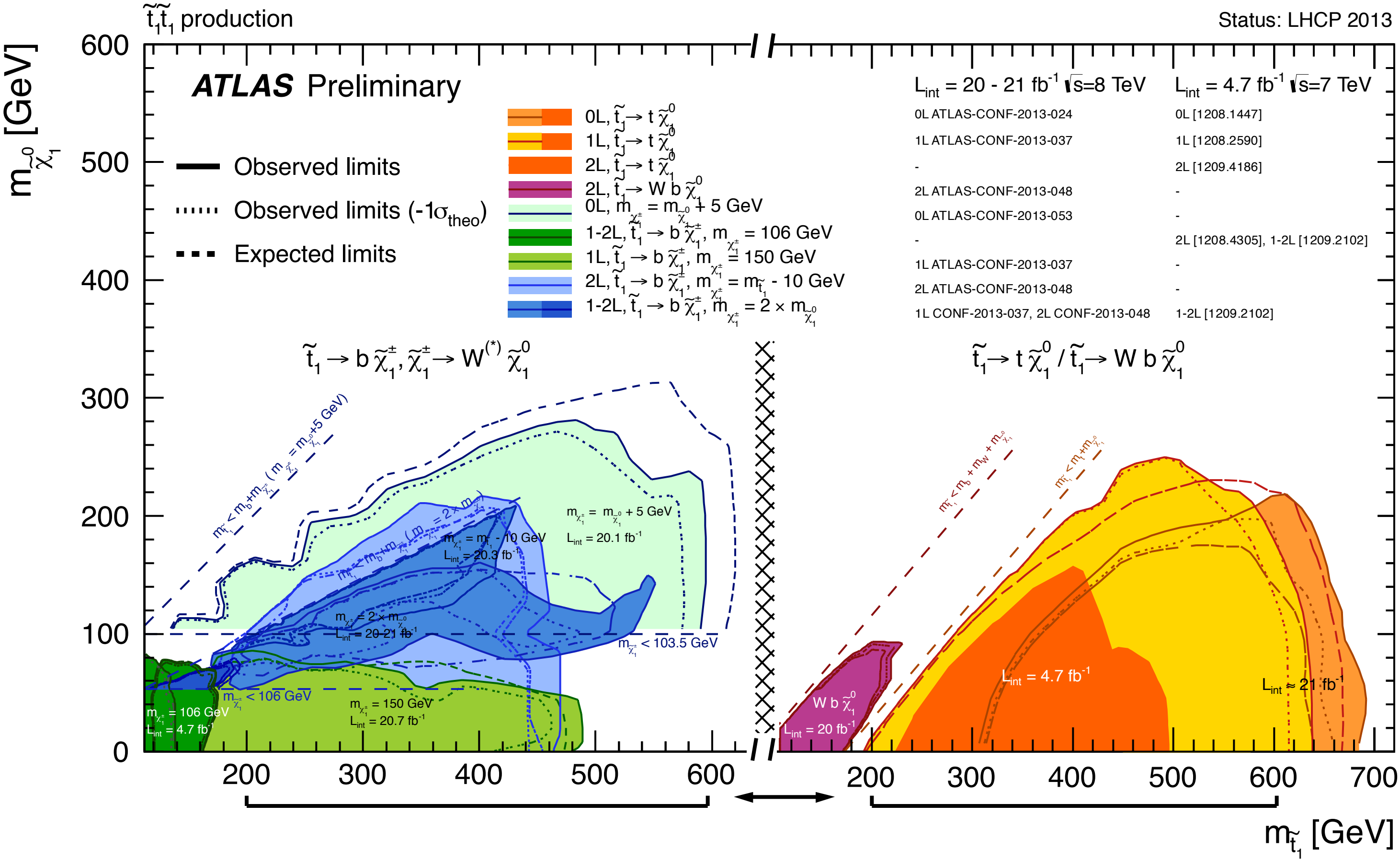
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)=0 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, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}\rightarrow qqqq\ell\ell(\ell\ell)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$)<650 GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$	1.07 TeV	m($\tilde{\chi}_1^0$)>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$\mathrm{F}^{1/2}$ scale	645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.14 TeV	m($\tilde{\chi}_1^0$) <200 GeV	ATLAS-CONF-2013-054
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} 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	$\tilde{b}_1$	100-630 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	430 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	220 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	150-440 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^{\pm}$)=10 GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(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 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	m($\tilde{\chi}_1^0$)>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	520 GeV	m($\tilde{t}_1$)=m($\tilde{\chi}_1^0$)+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	125-450 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$	180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e, μ	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W^*\tilde{\chi}_1^0Z^*\tilde{\chi}_1^0$	3 e, μ	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, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^{\pm}$	220 GeV	1<$\tau(\tilde{\chi}_1^{\pm})$<10 ns	1210.2852
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	857 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$	1-2 μ	0	-	15.9	$\tilde{\tau}$	385 GeV	5<tanβ<50	ATLAS-CONF-2013-058
	Direct $\tilde{\tau}\tilde{\tau}$ prod., stable $\tilde{\tau}$ or $\tilde{\ell}$	1-2 μ	0	-	15.9	$\tilde{\tau}$	395 GeV	m($\tilde{\tau}$)=m($\tilde{\ell}$)	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{g}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ	0	Yes	4.4	$\tilde{q}$	700 GeV	1 mm<$c\tau$<1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\rightarrow e + \mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	0	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}$, $\tilde{g}$	1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\rightarrow qqq$	0	6 jets	-	4.6	$\tilde{g}$	666 GeV		1210.4813
	$\tilde{g}\rightarrow\tilde{t}_1 t$, $\tilde{t}_1\rightarrow bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

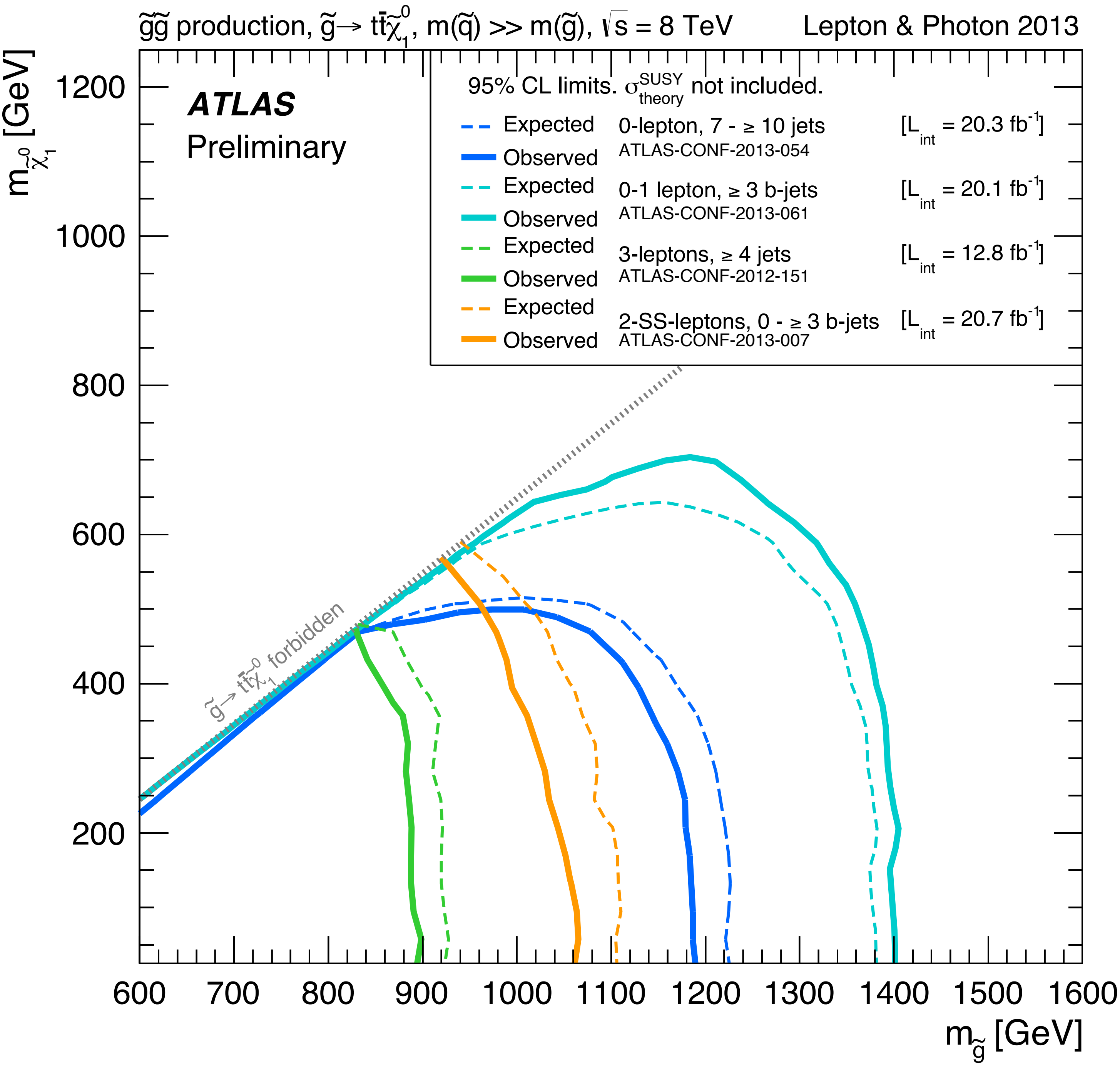
🟦 **$\sqrt{s}$ = 7 TeV full data**

🟩 **$\sqrt{s}$ = 8 TeV partial data**

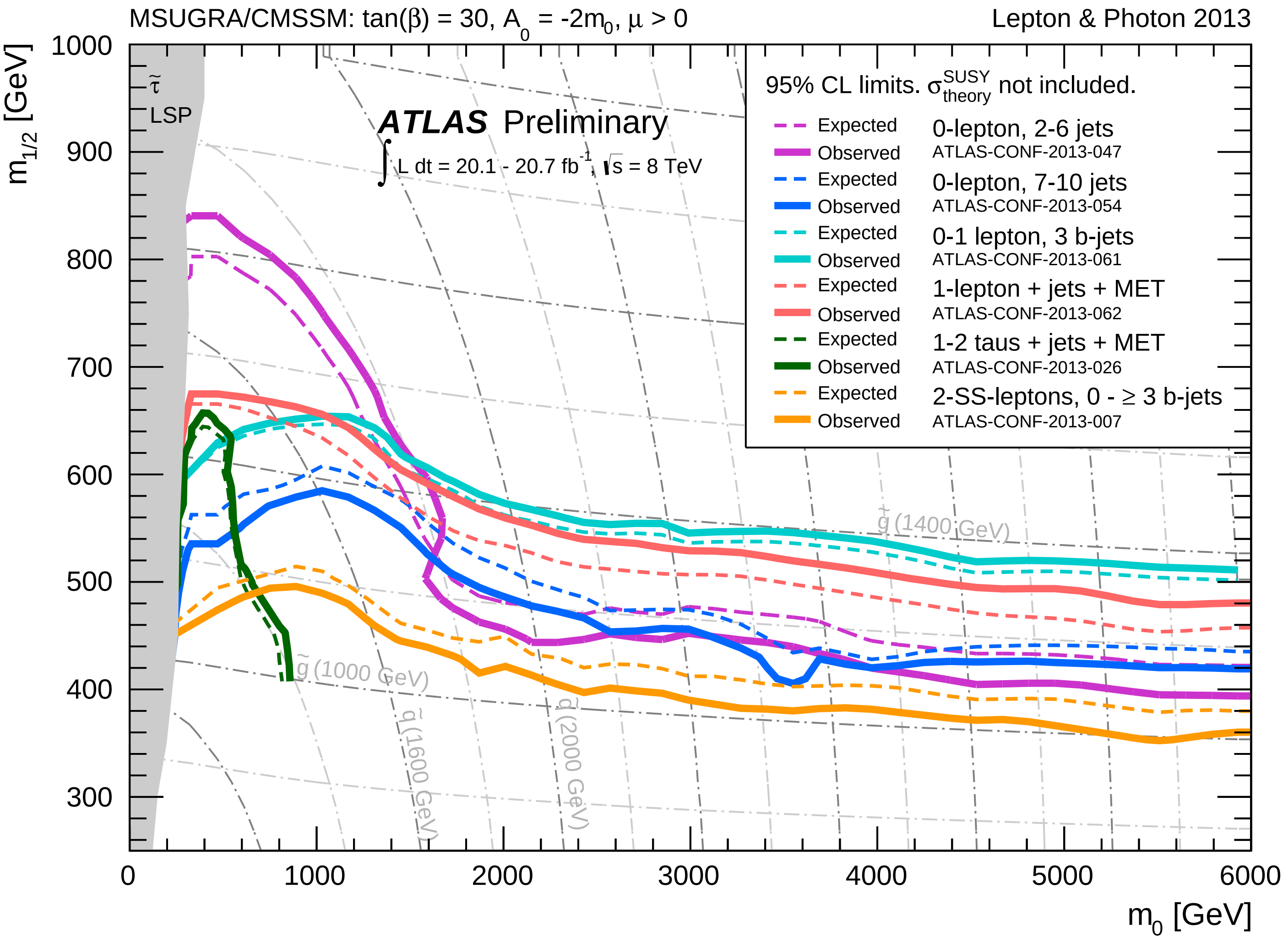
🟩 **$\sqrt{s}$ = 8 TeV full data**

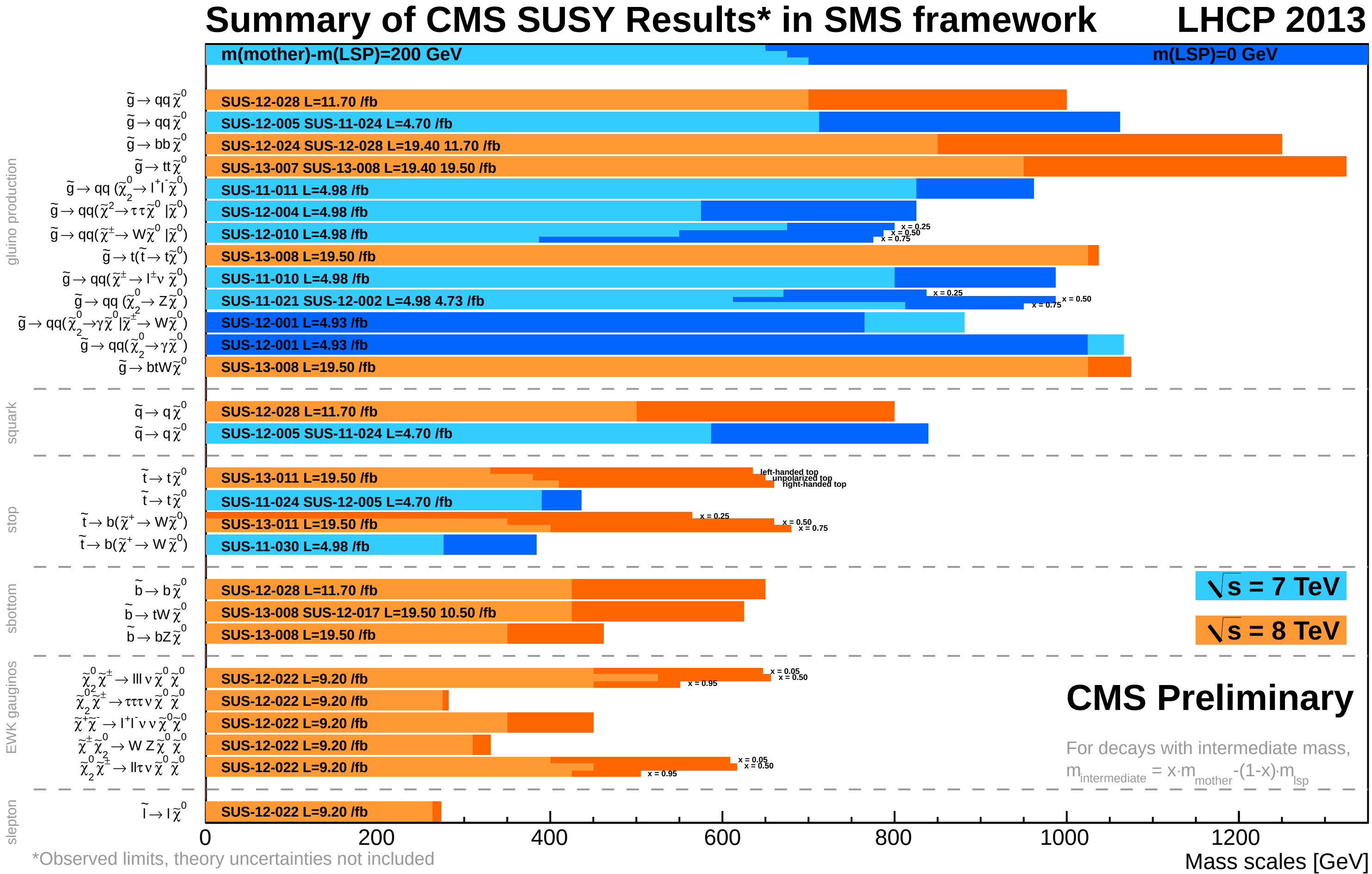
**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*


$\tilde{t}_1\tilde{t}_1$ production
Status: LHCP 2013
ATLAS Preliminary
Observed limits
Observed limits ($-1\sigma_{theo}$)
Expected limits
0L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
1L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
0L, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 5$ GeV
1-2L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 106$ GeV
1L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 150$ GeV
2L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} - 10$ GeV
1-2L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
0L ATLAS-CONF-2013-024
1L ATLAS-CONF-2013-037
-
2L ATLAS-CONF-2013-048
0L ATLAS-CONF-2013-053
-
1L ATLAS-CONF-2013-037
2L ATLAS-CONF-2013-048
1L CONF-2013-037, 2L CONF-2013-048
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
-
2L [1208.4305], 1-2L [1209.2102]
-
-
1-2L [1209.2102]
$\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \rightarrow W^{(*)}\,\tilde{\chi}_1^0$
$\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ ($m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$+5 GeV)
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ ($m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 5$ GeV
L_{int} = 20.1 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} - 10$ GeV
L_{int} = 20.3 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 20-21 fb^{-1}
$m_{\tilde{\chi}_1^\pm} < 103.5$ GeV
$m_{\tilde{\chi}_1^\pm} < 106$ GeV
$m_{\tilde{\chi}_1^\pm} = 106$ GeV
L_{int} = 4.7 fb^{-1}
$m_{\tilde{\chi}_1^\pm} = 150$ GeV
L_{int} = 20.7 fb^{-1}
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
W b $\tilde{\chi}_1^0$
L_{int} = 20 fb^{-1}
L_{int} = 4.7 fb^{-1}
$L_{int} \approx 21$ fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
500
600
200
300
400
500
600
200
300
400
500
600
700
$m_{\tilde{t}_1}$ [GeV]



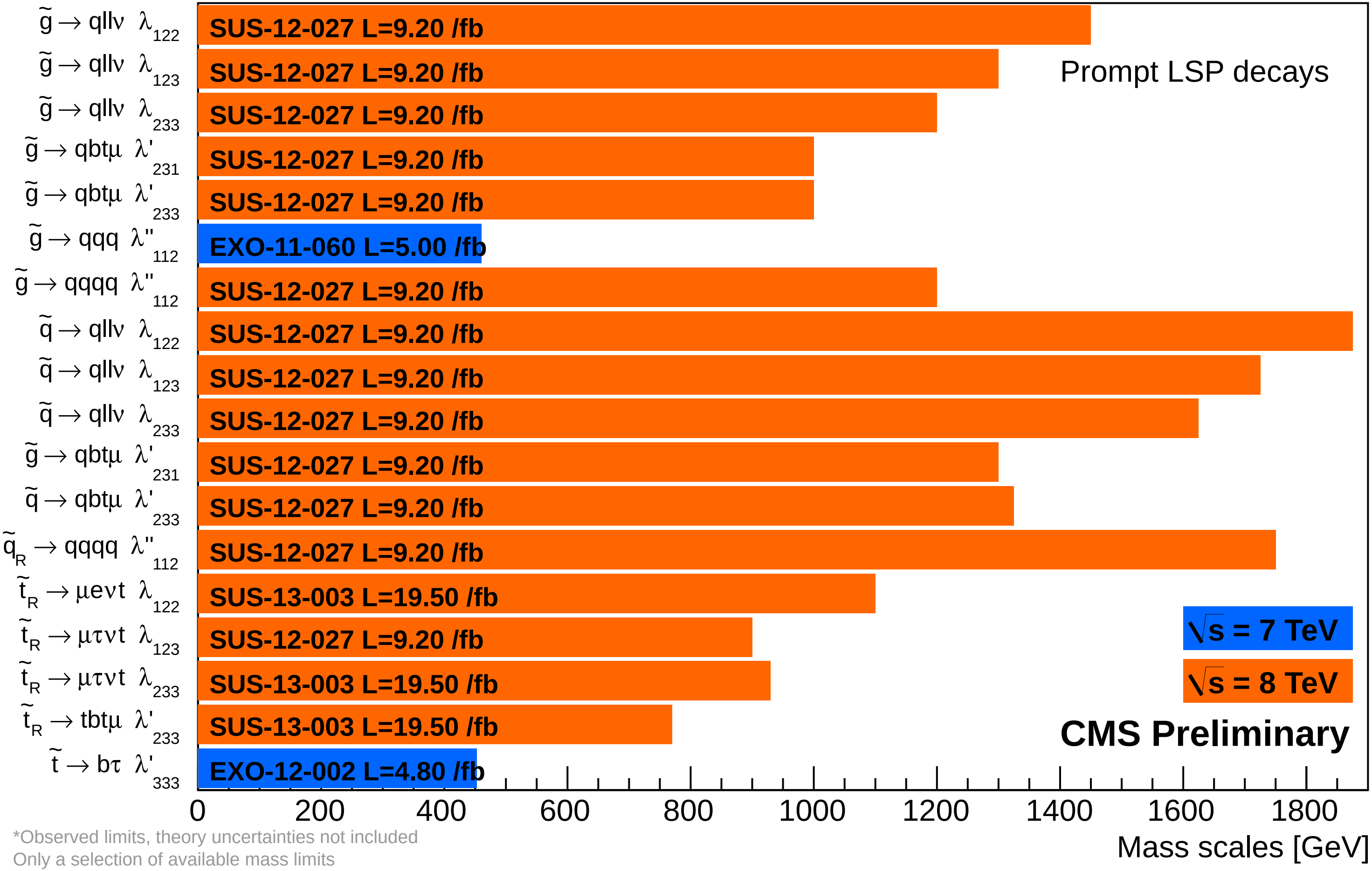
$\tilde{g}\tilde{g}$ production, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$, $m(\tilde{q}) >> m(\tilde{g})$, $\sqrt{s}$ = 8 TeV
Lepton & Photon 2013
ATLAS
Preliminary
95% CL limits. σ^{SUSY}_{theory} not included.
Expected
Observed
0-lepton, 7 - ≥ 10 jets
ATLAS-CONF-2013-054
$[L_{int} = 20.3\ fb^{-1}]$
Expected
Observed
0-1 lepton, ≥ 3 b-jets
ATLAS-CONF-2013-061
$[L_{int} = 20.1\ fb^{-1}]$
Expected
Observed
3-leptons, ≥ 4 jets
ATLAS-CONF-2012-151
$[L_{int} = 12.8\ fb^{-1}]$
Expected
Observed
2-SS-leptons, 0 - ≥ 3 b-jets
ATLAS-CONF-2013-007
$[L_{int} = 20.7\ fb^{-1}]$
$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$ forbidden
$m_{\tilde{\chi}_1^0}$ [GeV]
1200
1000
800
600
400
200
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
$m_{\tilde{g}}$ [GeV]


MSUGRA/CMSSM: tan(β) = 30, A_0 = -2m_0, μ > 0
Lepton & Photon 2013
ATLAS Preliminary
$\int L\,dt$ = 20.1 - 20.7 fb^{-1}, $\sqrt{s}$ = 8 TeV
95% CL limits. σ^{SUSY}_{theory} not included.
Expected
Observed
0-lepton, 2-6 jets
ATLAS-CONF-2013-047
Expected
Observed
0-lepton, 7-10 jets
ATLAS-CONF-2013-054
Expected
Observed
0-1 lepton, 3 b-jets
ATLAS-CONF-2013-061
Expected
Observed
1-lepton + jets + MET
ATLAS-CONF-2013-062
Expected
Observed
1-2 taus + jets + MET
ATLAS-CONF-2013-026
Expected
Observed
2-SS-leptons, 0 - ≥ 3 b-jets
ATLAS-CONF-2013-007
$\tilde{\tau}$ LSP
$\tilde{g}$ (1000 GeV)
$\tilde{g}$ (1400 GeV)
$\tilde{q}$ (1600 GeV)
$\tilde{q}$ (2000 GeV)
$m_{1/2}$ [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000
m_0 [GeV]

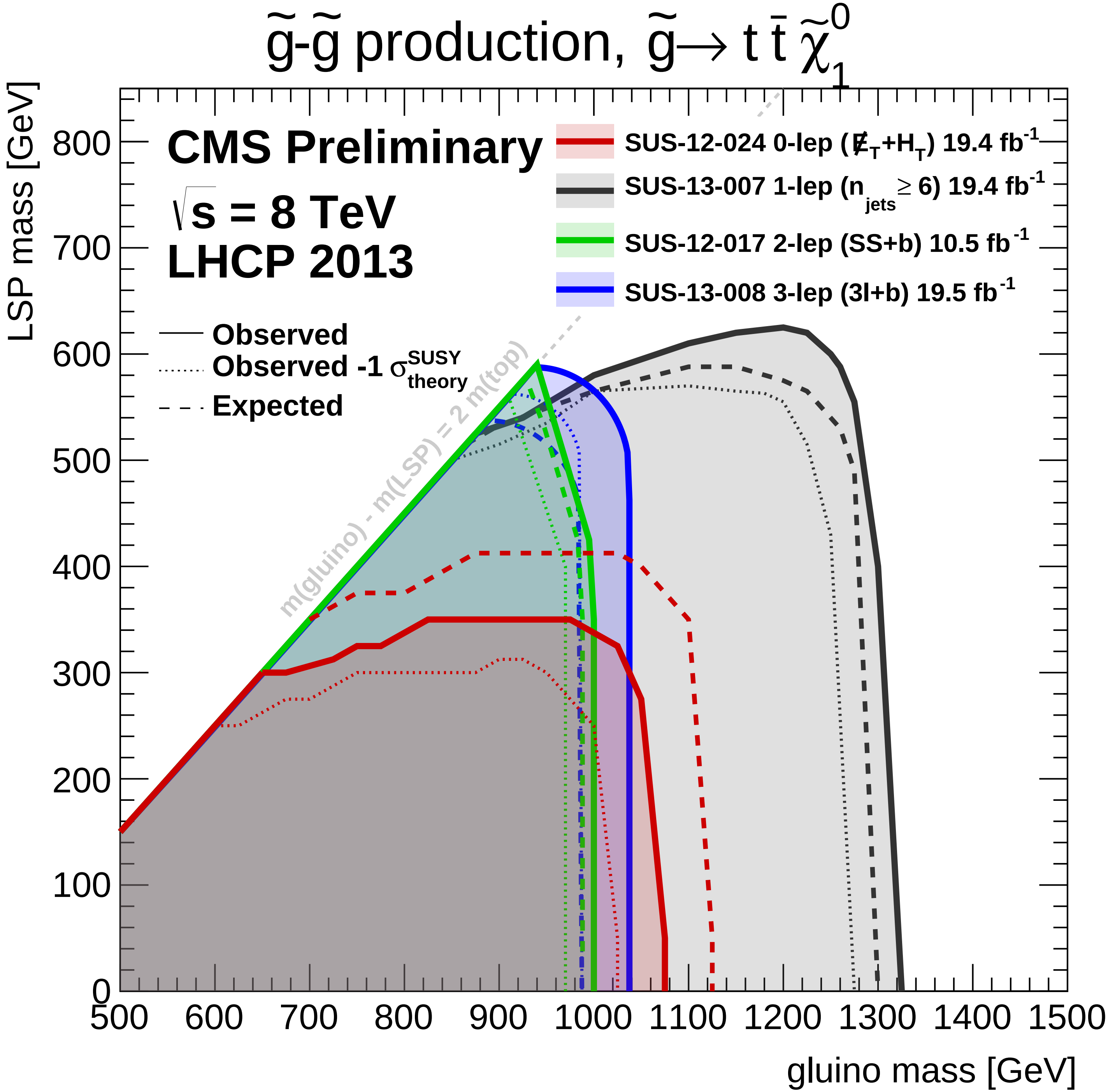


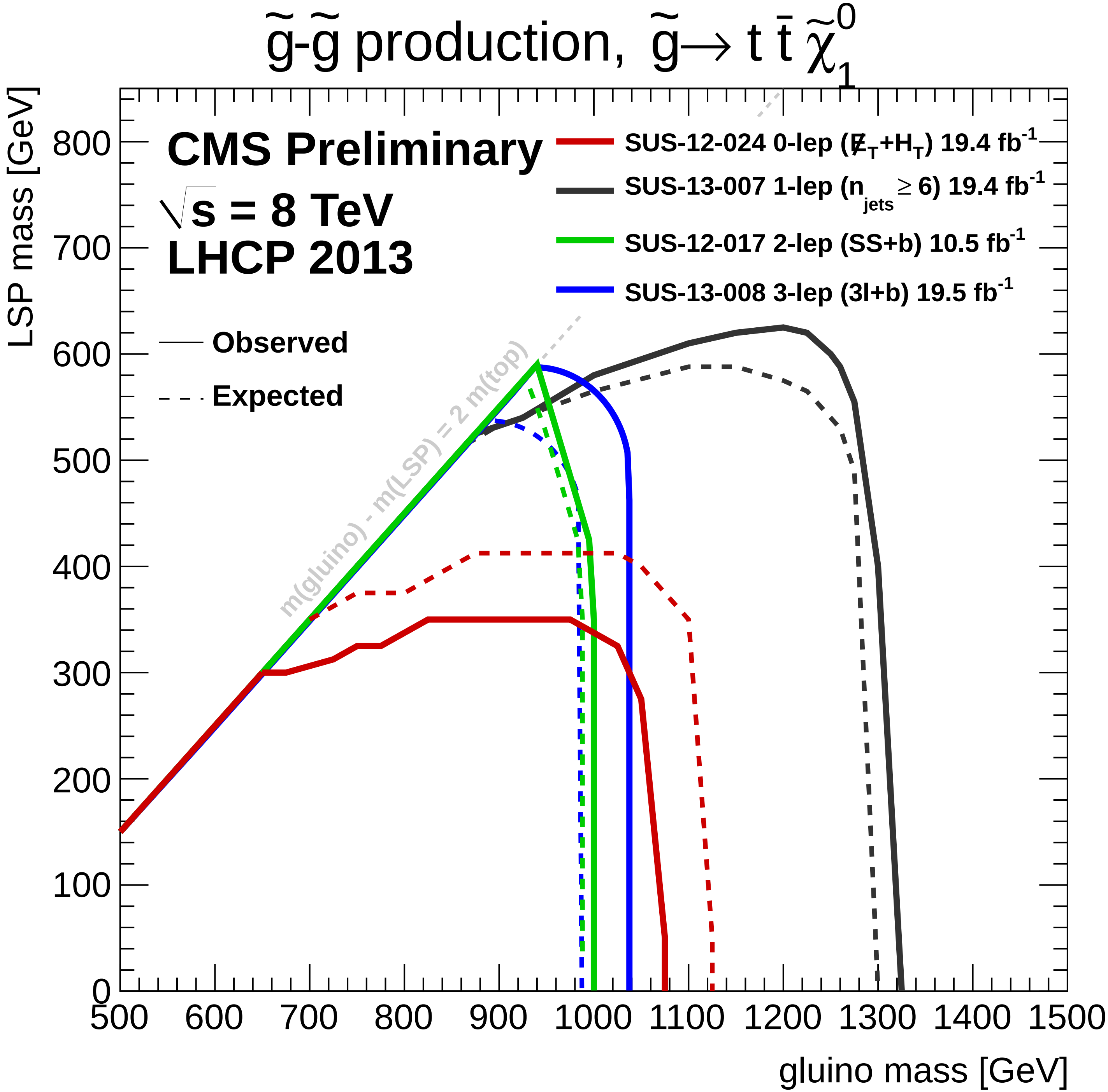
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

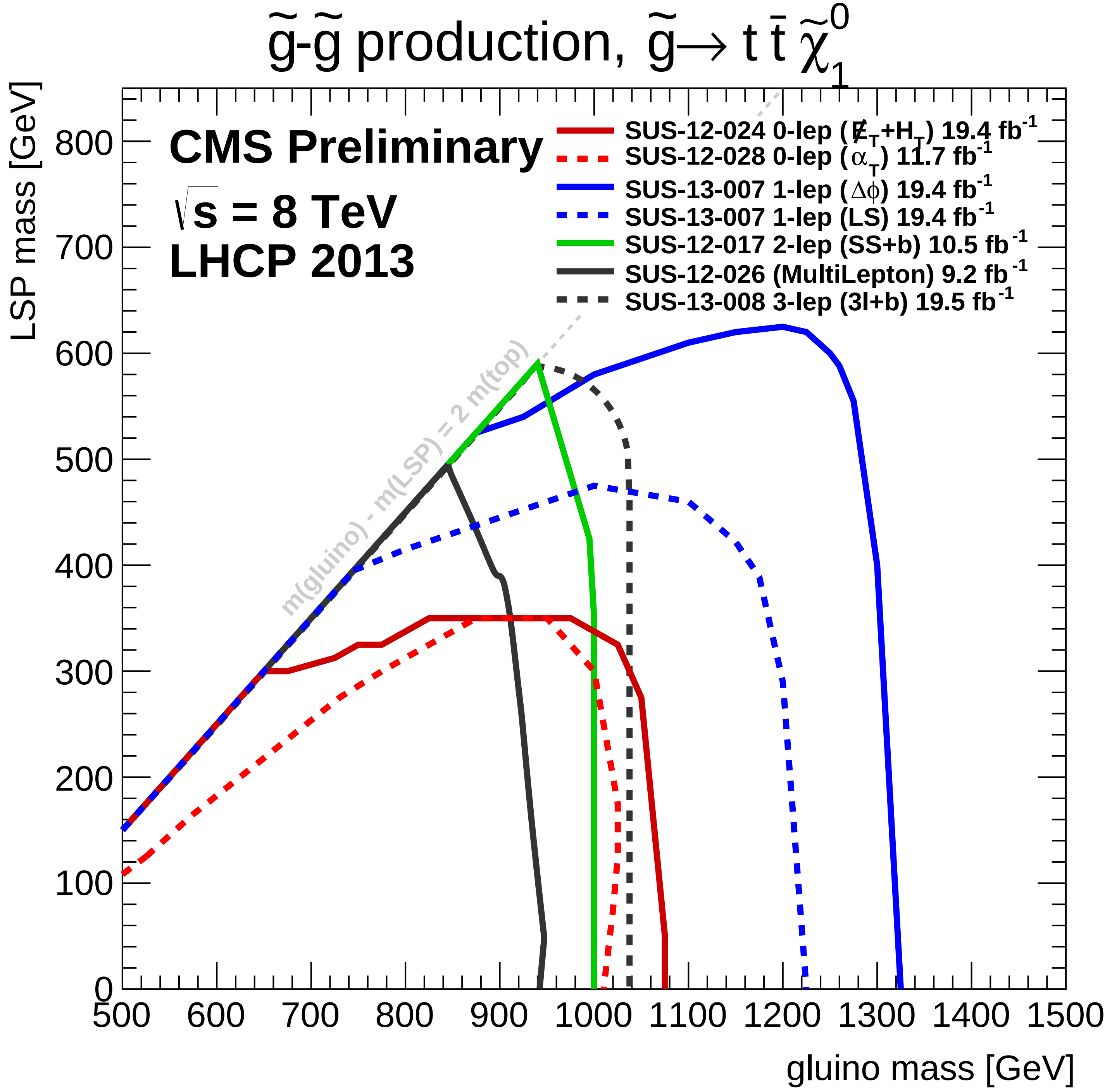
Summary of CMS RPV SUSY Results* LHCP 2013



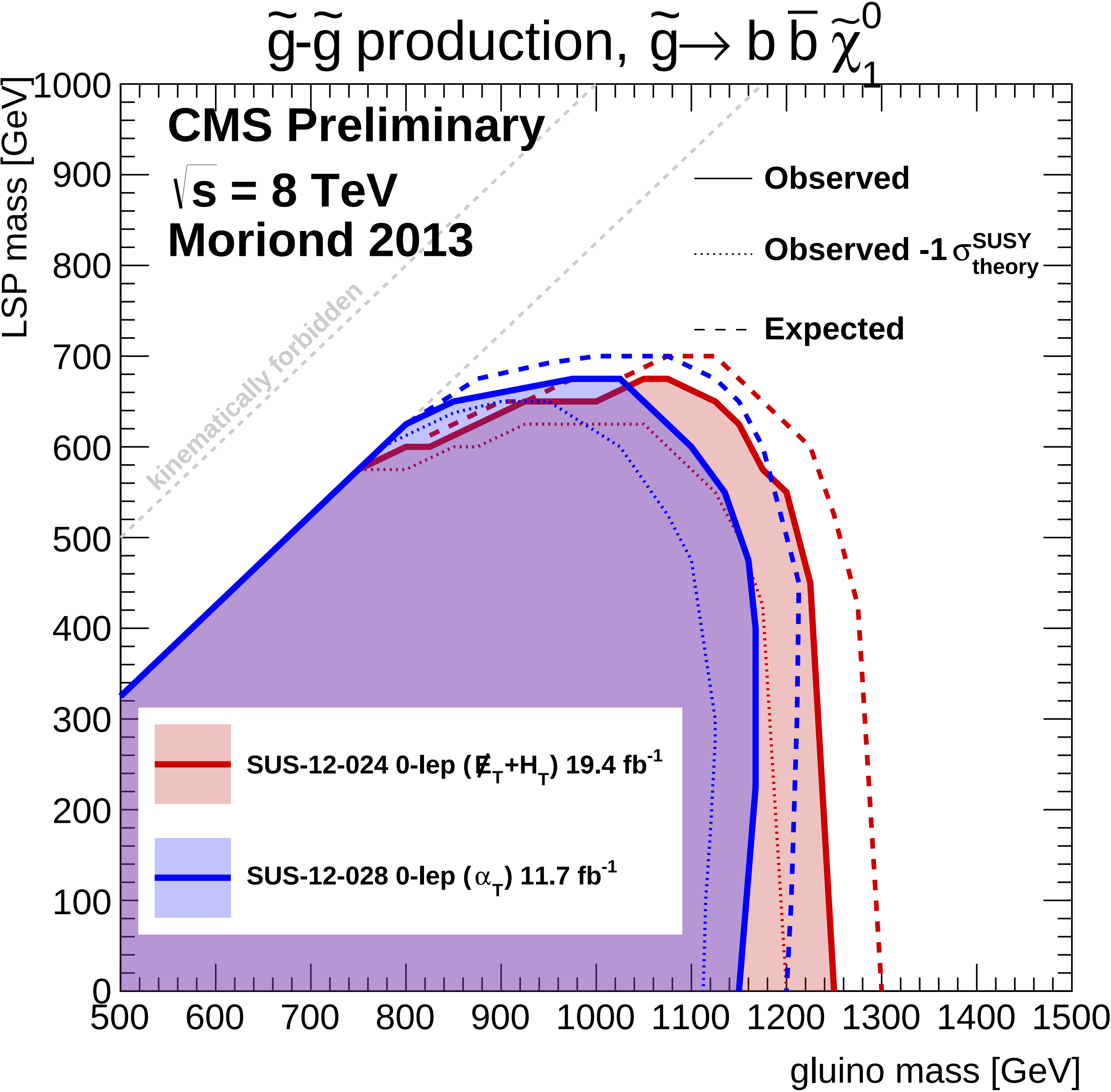
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

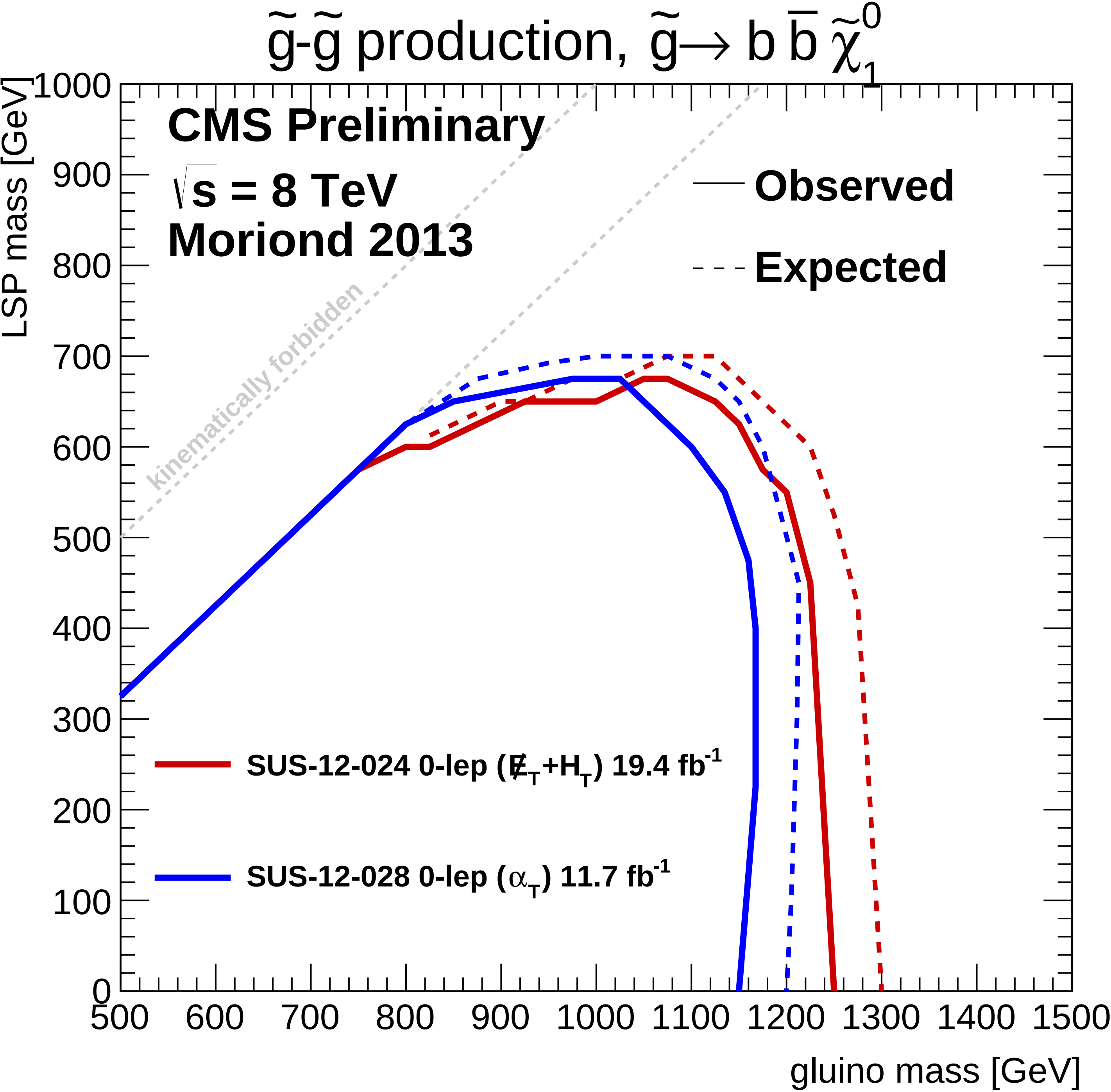

$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
LHCP 2013
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-13-007 1-lep ($n_{jets} \geq 6$) 19.4 fb^{-1}
SUS-12-017 2-lep (SS+b) 10.5 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
Observed
Observed -1 σ^{SUSY}_{theory}
Expected
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
0
100
200
300
400
500
600
700
800
500
600
700
800
900
1000
1100
1200
1300
1400
1500
gluino mass [GeV]

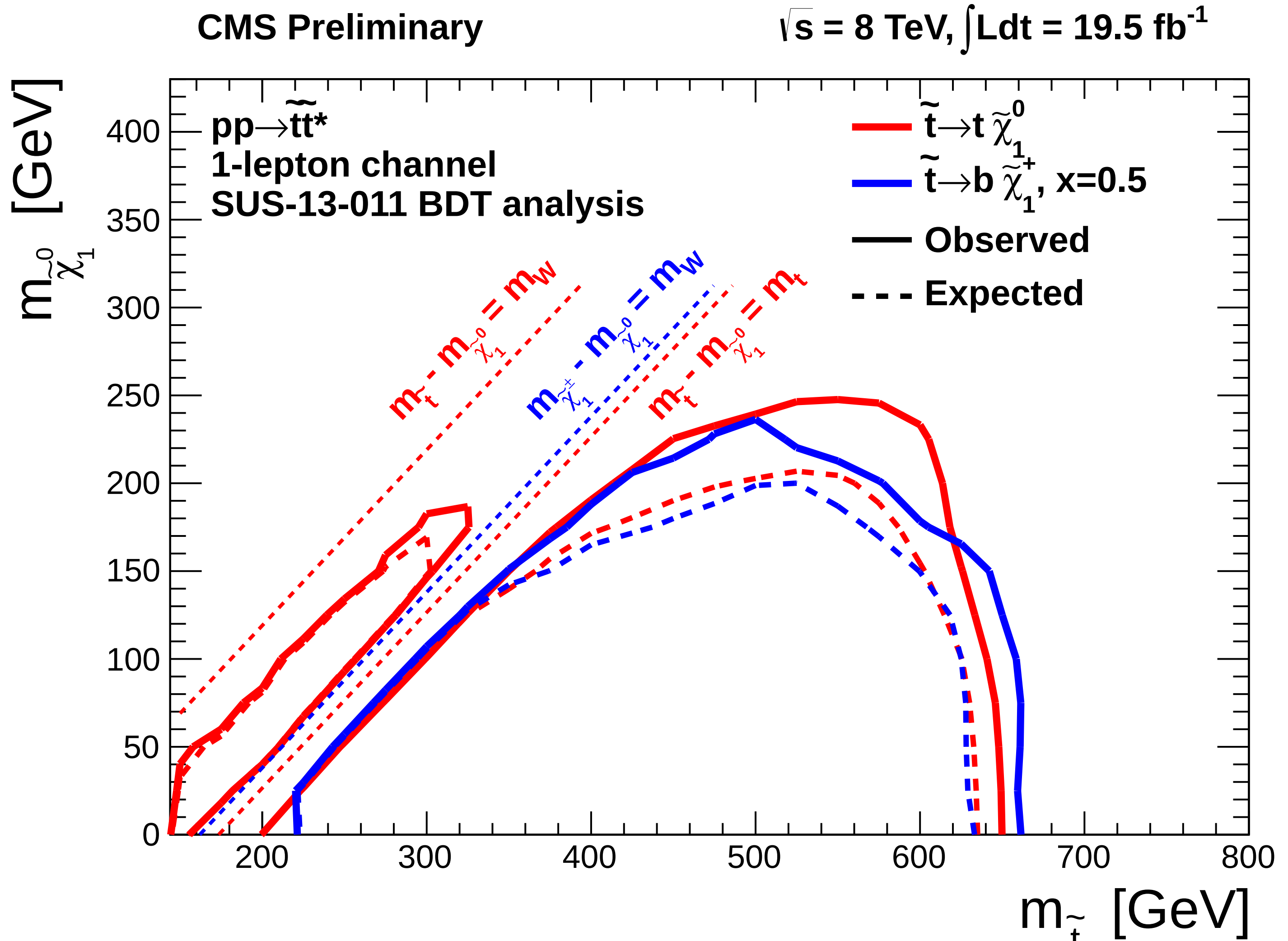

$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
LHCP 2013
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-13-007 1-lep ($n_{jets} \geq 6$) 19.4 fb^{-1}
SUS-12-017 2-lep (SS+b) 10.5 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
Observed
Expected
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
500
600
700
800
900
1000
1100
1200
1300
1400
1500

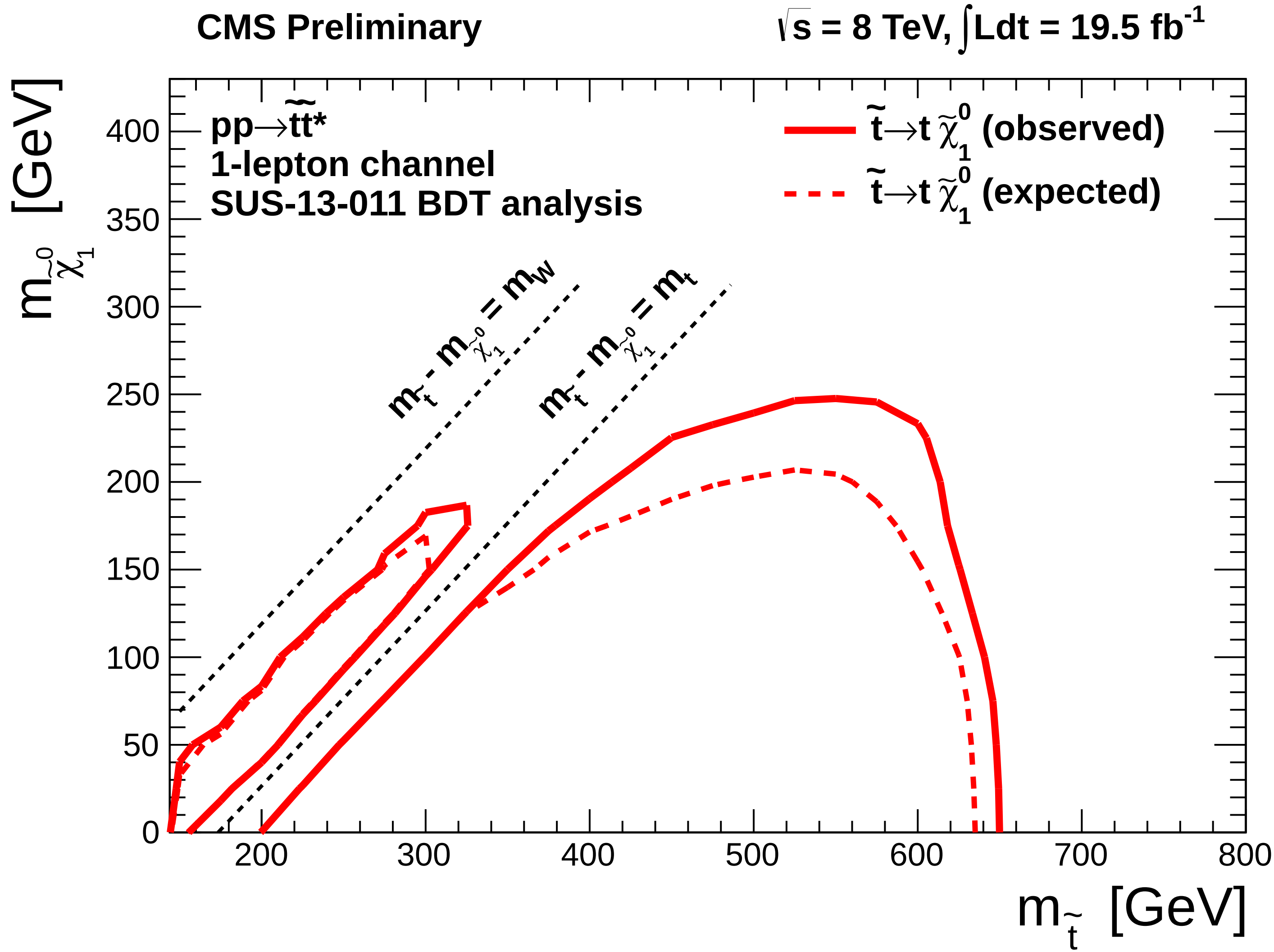


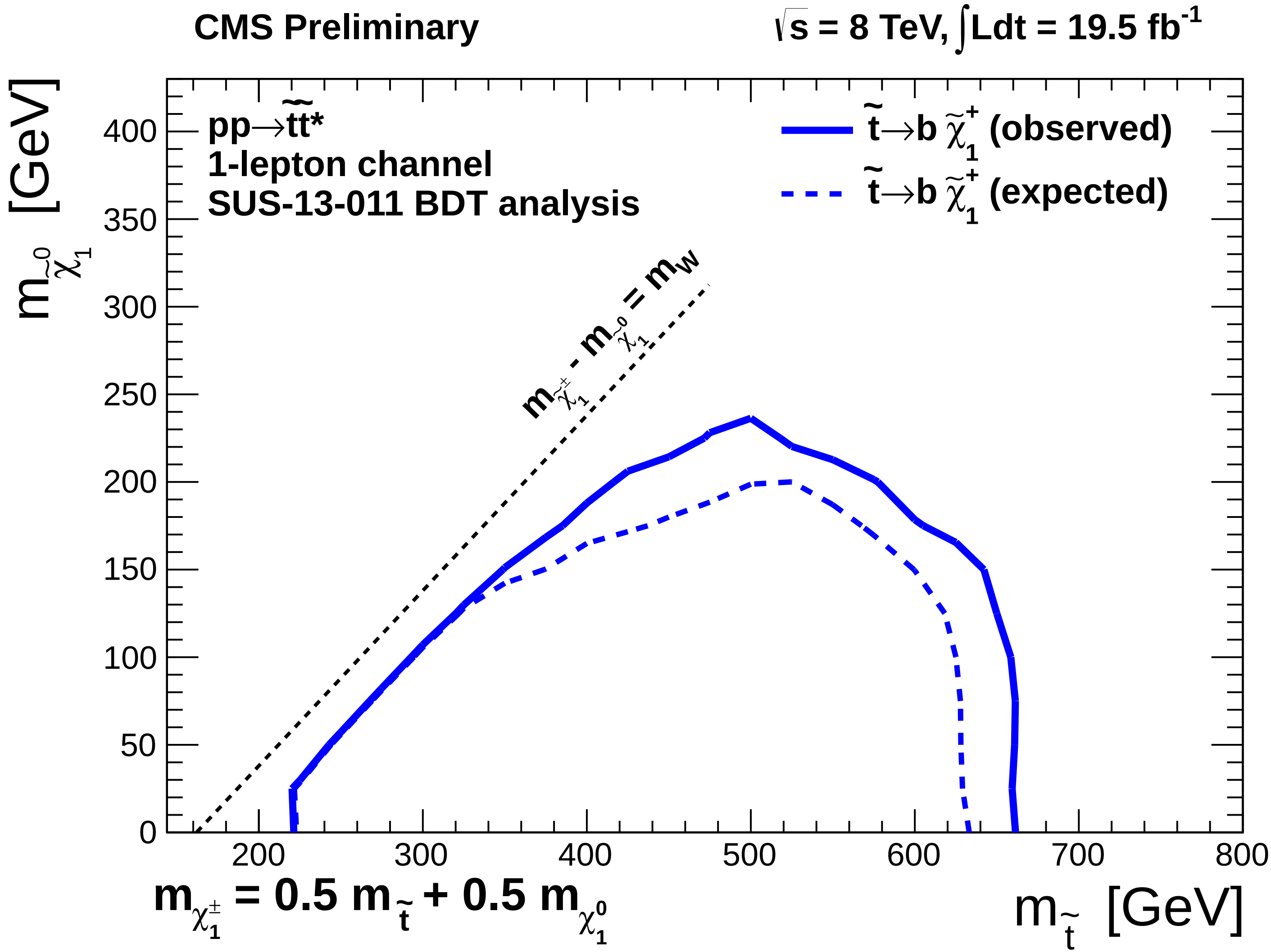
$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}_1^0$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
LHCP 2013
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-12-028 0-lep (α_T) 11.7 fb^{-1}
SUS-13-007 1-lep ($\Delta\phi$) 19.4 fb^{-1}
SUS-13-007 1-lep (LS) 19.4 fb^{-1}
SUS-12-017 2-lep (SS+b) 10.5 fb^{-1}
SUS-12-026 (MultiLepton) 9.2 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
0
100
200
300
400
500
600
700
800
gluino mass [GeV]
500
600
700
800
900
1000
1100
1200
1300
1400
1500


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow b\,\bar{b}\,\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
Moriond 2013
Observed
Observed -1 σ^{SUSY}_{theory}
Expected
kinematically forbidden
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-12-028 0-lep (α_T) 11.7 fb^{-1}
LSP mass [GeV]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
900
1000
500
600
700
800
900
1000
1100
1200
1300
1400
1500


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow b\,\bar{b}\,\tilde{\chi}_1^0$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
Moriond 2013
Observed
Expected
kinematically forbidden
SUS-12-024 0-lep ($\not{E}_T$+H_T) 19.4 fb^{-1}
SUS-12-028 0-lep (α_T) 11.7 fb^{-1}
LSP mass [GeV]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
900
1000
500
600
700
800
900
1000
1100
1200
1300
1400
1500

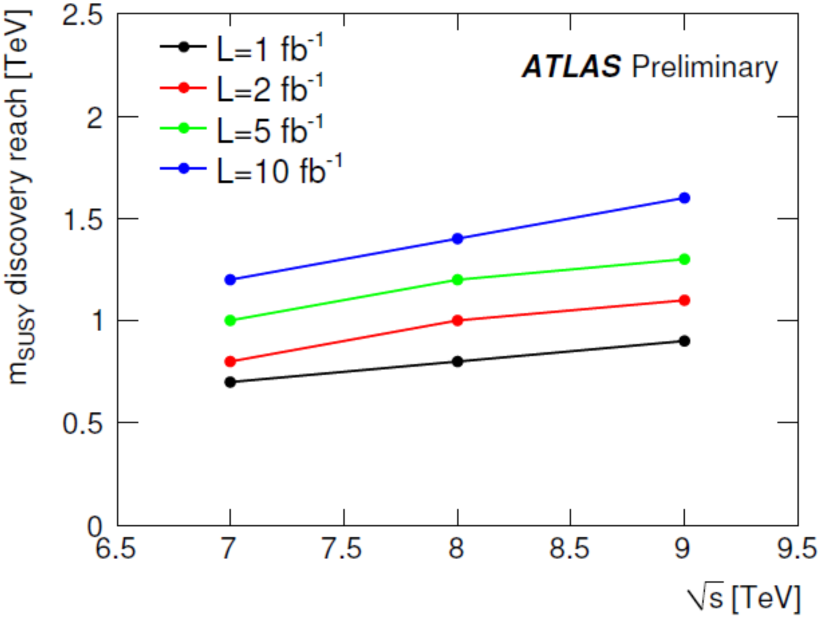

CMS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$Ldt = 19.5 fb^{-1}
pp→$\tilde{t}\tilde{t}$*
1-lepton channel
SUS-13-011 BDT analysis
$\tilde{t}\rightarrow t\,\tilde{\chi}^0_1$
$\tilde{t}\rightarrow b\,\tilde{\chi}^+_1$, x=0.5
Observed
Expected
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_t$
$m_{\tilde{\chi}^0_1}$ [GeV]
0
50
100
150
200
250
300
350
400
200
300
400
500
600
700
800
$m_{\tilde{t}}$ [GeV]

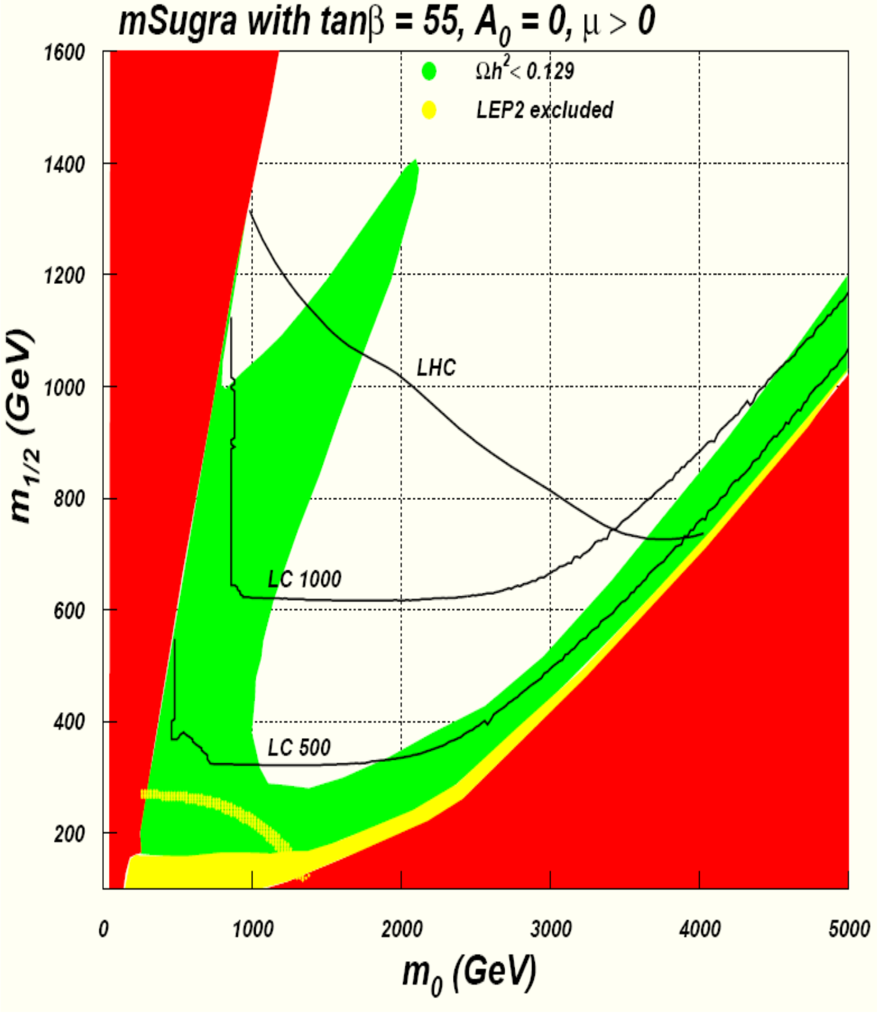

CMS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$Ldt = 19.5 fb^{-1}
pp→$\tilde{t}\tilde{t}$*
1-lepton channel
SUS-13-011 BDT analysis
$\tilde{t}\to t\,\tilde{\chi}^0_1$ (observed)
$\tilde{t}\to t\,\tilde{\chi}^0_1$ (expected)
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_t$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}}$ [GeV]
0
50
100
150
200
250
300
350
400
200
300
400
500
600
700
800


CMS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$Ldt = 19.5 fb^{-1}
pp→$\tilde{t}\tilde{t}$*
1-lepton channel
SUS-13-011 BDT analysis
$\tilde{t}\rightarrow b\,\tilde{\chi}_1^+$ (observed)
$\tilde{t}\rightarrow b\,\tilde{\chi}_1^+$ (expected)
$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = m_W$
$m_{\tilde{\chi}_1^0}$ [GeV]
0
50
100
150
200
250
300
350
400
200
300
400
500
600
700
800
$m_{\tilde{t}}$ [GeV]
$m_{\chi_1^\pm} = 0.5\, m_{\tilde{t}} + 0.5\, m_{\chi_1^0}$

SUSY perspective

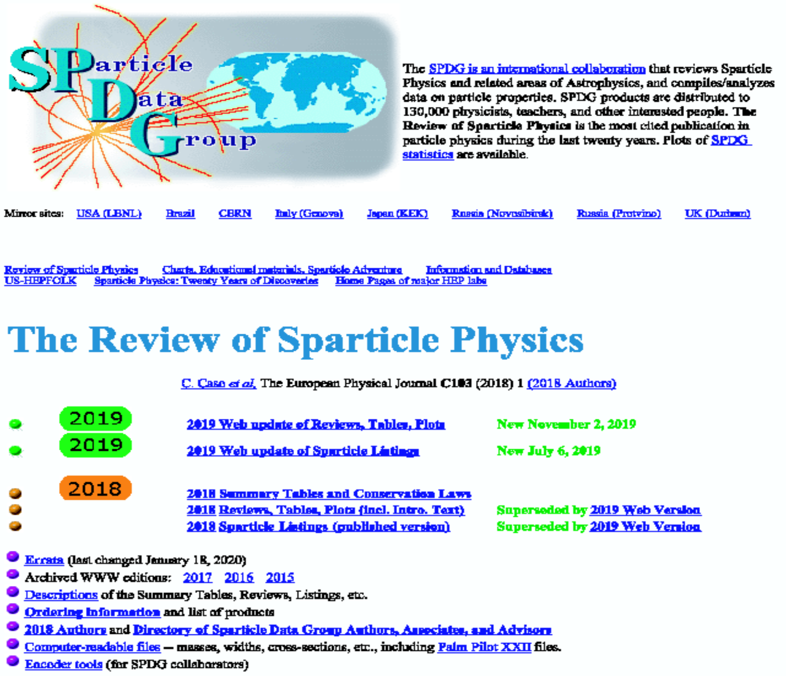
- SUSY 5σ discovery reach in TeV for different scenarios of mass-energy





Sparticle physics

- ☐ Supersymmetry is the most popular idea beyond the Standard Model
- ☐ The new physics is expected at the TeV scale
- ☐ No hints of supersymmetry so far... but the quest continues
- ☐ If we are right, the new discoveries are waiting for, and the table of fundamental particles has to be updated



The SPDG is an international collaboration that reviews Sparticle Physics and related areas of Astrophysics, and compiles/analyzes data on particle properties. SPDG products are distributed to 130,000 physicists, teachers, and other interested people. The Review of Sparticle Physics is the most cited publication in particle physics during the last twenty years. Plots of SPDG statistics are available.

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Review of Sparticle Physics Charts, Educational materials, Sparticle Adventure Information and Databases
US-HEPFOLK Sparticle Physics: Twenty Years of Discoveries Home Pages of major HEP labs

The Review of Sparticle Physics

C. Caso *et al.* The European Physical Journal C103 (2018) 1 (2018 Authors)

- 2019 — 2019 Web update of Reviews, Tables, Plots — New November 2, 2019
- 2019 — 2019 Web update of Sparticle Listings — New July 6, 2019
- 2018 — 2018 Summary Tables and Conservation Laws
- 2018 Reviews, Tables, Plots (incl. Intro. Text) — Superseded by 2019 Web Version
- 2018 Sparticle Listings (published version) — Superseded by 2019 Web Version

- Errata (last changed January 18, 2020)
- Archived WWW editions: 2017 2016 2015
- Descriptions of the Summary Tables, Reviews, Listings, etc.
- Ordering information and list of products
- 2018 Authors and Directory of Sparticle Data Group Authors, Associates, and Advisors
- Computer-readable files — masses, widths, cross-sections, etc., including Palm Pilot XXII files.
- Encoder tools (for SPDG collaborators)