MODERN STATUS OF SUPERSYMMETRY

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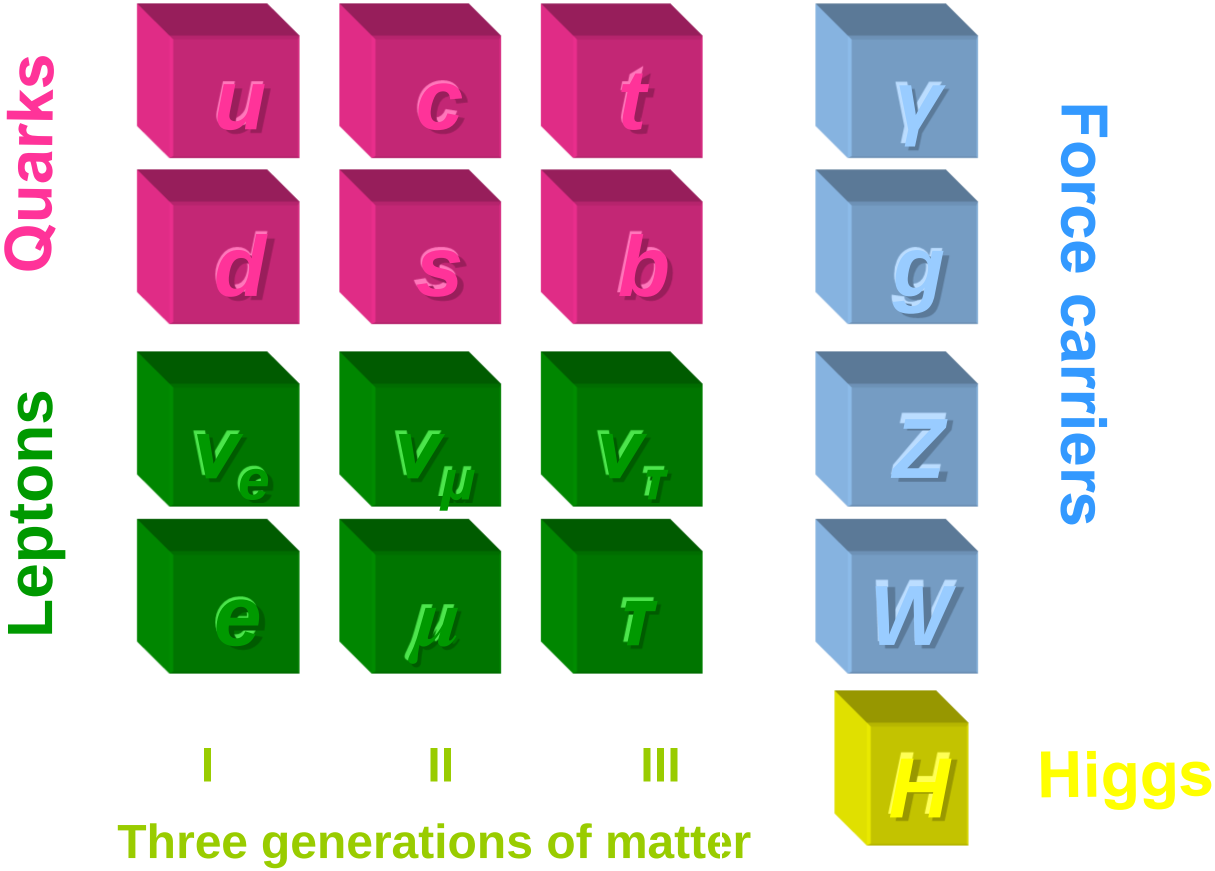
NEW TRENDS IN HIGH ENERGY PHYSICS 2016

October 3, 2016

Fundamental Particles



Quarks	u	c	t	γ	Force carriers
	d	s	b	g	
Leptons	ν_e	ν_μ	ν_τ	Z	
	e	μ	τ	W	
	I	II	III	H	Higgs

Three generations of matter

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 ?
- Why the proton charge is equal to the electron charge ?
- How can we include gravity into the theory ?

- The Standard Model has no answers

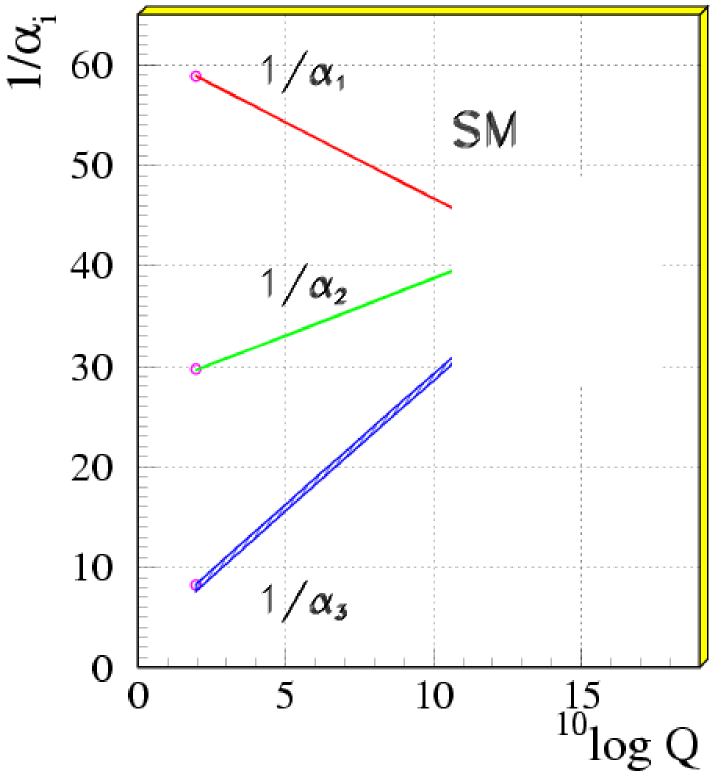
The Standard Model: what to do?

- 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)

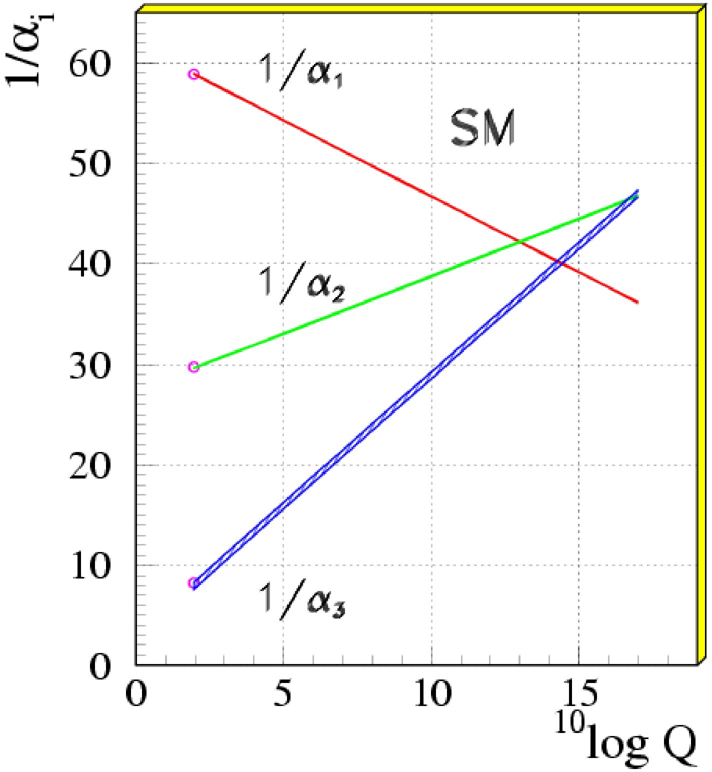
$$\frac{d\tilde{\alpha}_i}{dt} = b_i\tilde{\alpha}_i^2, \quad \tilde{\alpha}_i = \frac{\alpha_i}{4\pi} = \frac{g_i^2}{16\pi^2}, \quad t = \log\frac{Q^2}{\mu^2}$$

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

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

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)

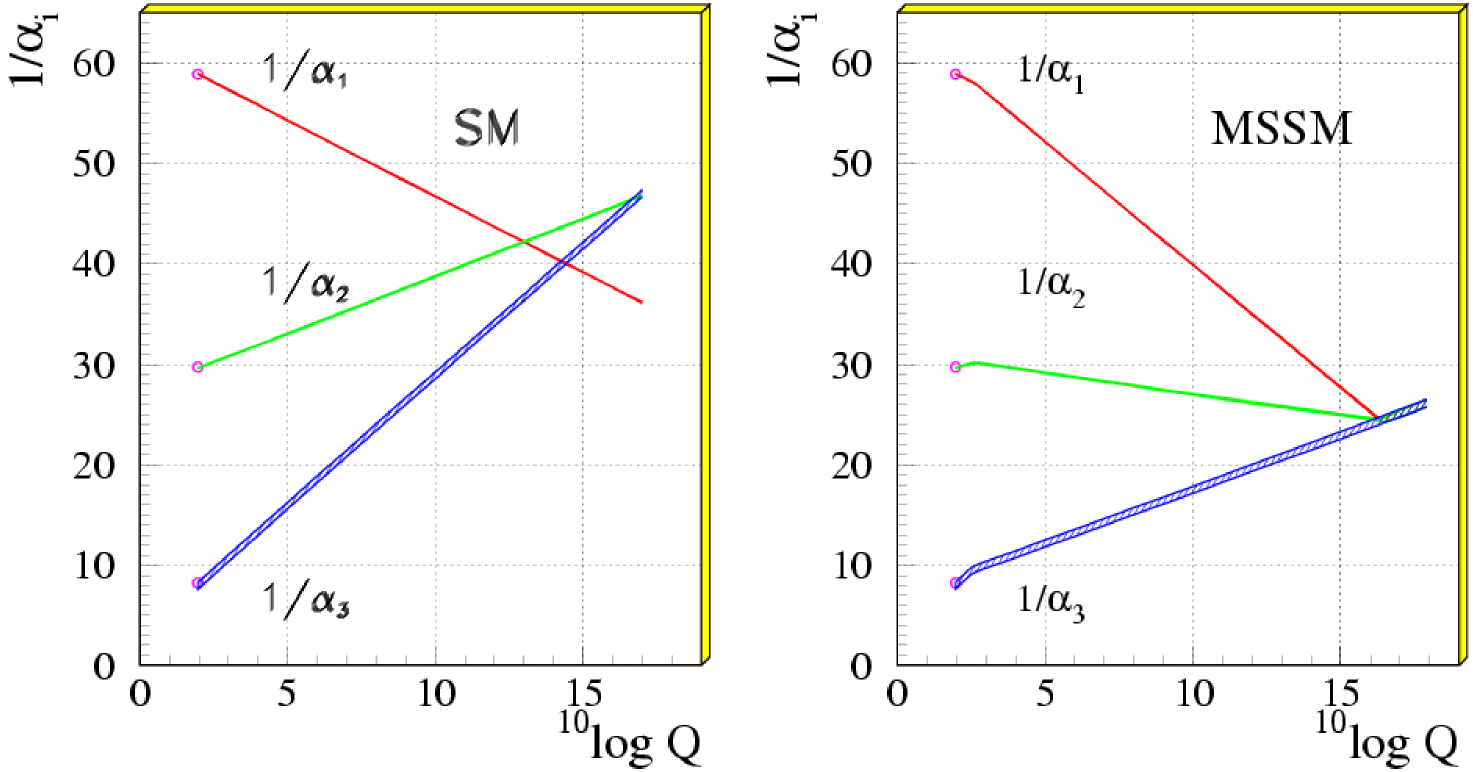
$$\frac{d\tilde{\alpha}_i}{dt} = b_i\tilde{\alpha}_i^2, \quad \tilde{\alpha}_i = \frac{\alpha_i}{4\pi} = \frac{g_i^2}{16\pi^2}, \quad t = \log\frac{Q^2}{\mu^2}$$

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

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

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)

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

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

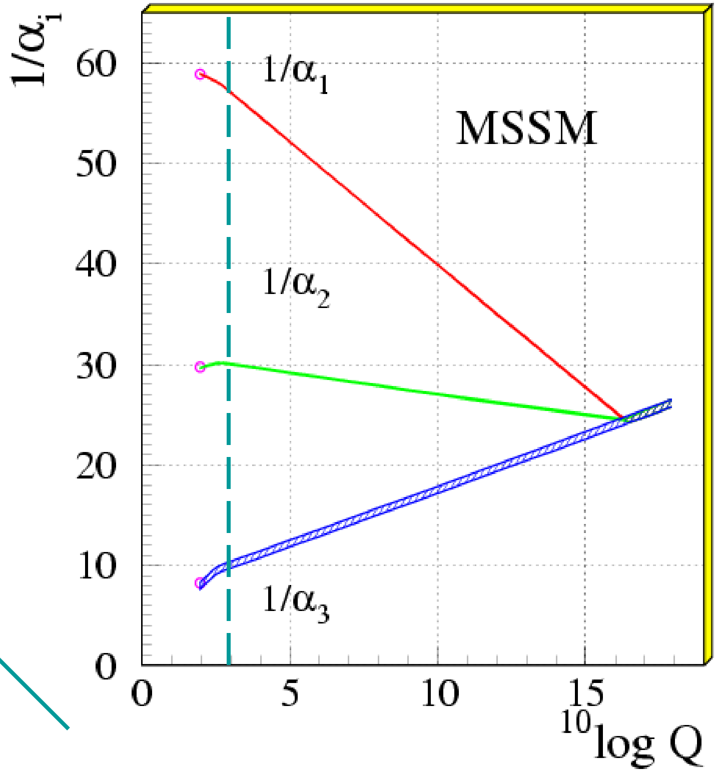
$$\alpha_s(M_Z) = 0.1184 \pm 0.0031$$

then we calculate

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

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

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



- The scale of supersymmetry breaking is $\sim 1\ TeV$

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

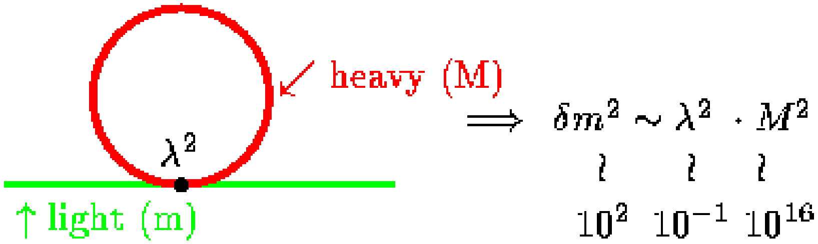
- Possible solution: to postulate the hierarchy.

  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



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

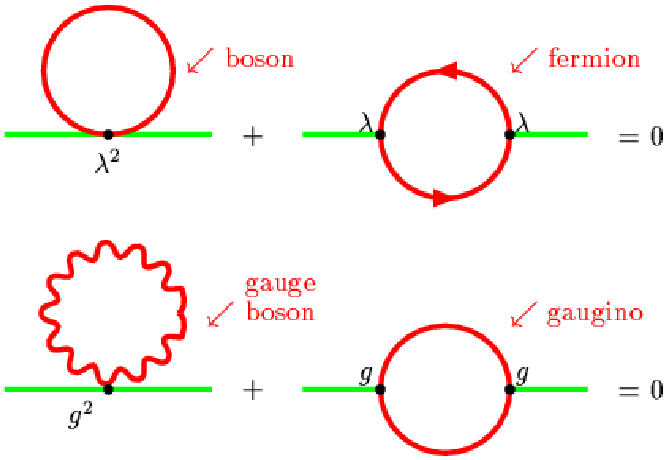
$$M_\Sigma \sim V \sim 10^{16} \; GeV$$

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.



$$m_{boson}^2 - m_{fermion}^2 = M_{SUSY}^2$$

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

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

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

Supersymmetric SM

- 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 :

$$\underset{\text{vector fields } (\gamma, Z, W^+, W^-, \text{ gluons})}{(4 + 8) \times 2} \quad + \quad \underset{\text{Higgs boson}}{2 \times 2}$$

  - 90 (96) fermionic degrees of freedom:

$$\underset{\text{quarks and charged leptons}}{(6 \times 3 + 3) \times 4} \quad + \quad \underset{\text{neutrinos}}{3 \times 2\ (4)}$$

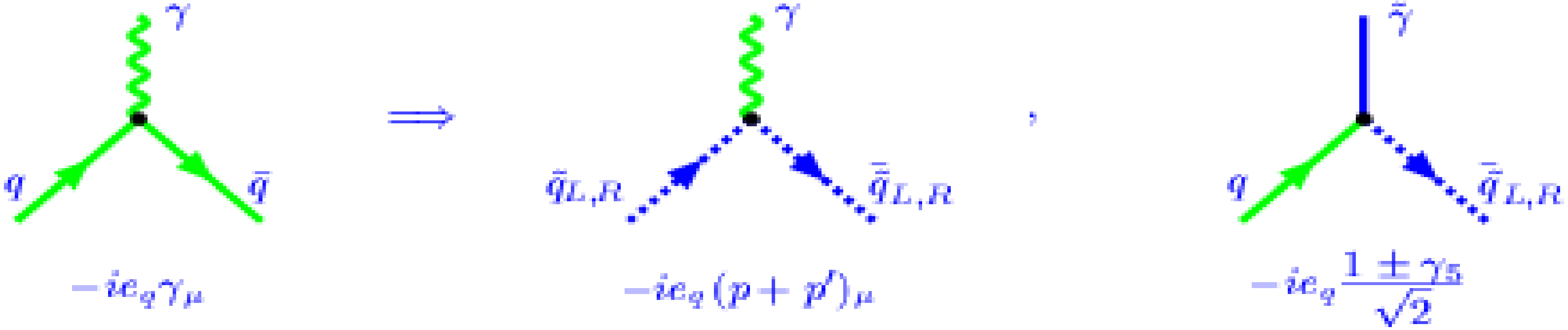
- The Standard Model is not supersymmetric

	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

	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

Minimal SUSY SM (MSSM)

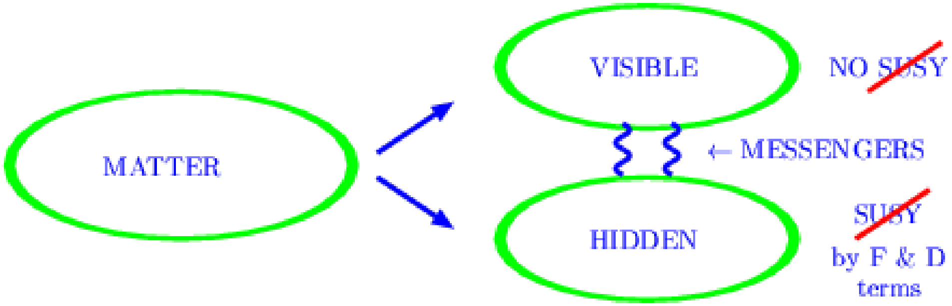
- Consequences of R-parity conservation:
  - Interactions of particles and superpartners are the same (just replace two of the particles in the interaction vertex by superpartners)



  - 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

Constrained MSSM

- Parameters of the Minimal Supersymmetric Standard Model
  - Gauge cuopling constants $\alpha_i,\ \text{i=1,2,3}$
  - 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

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

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

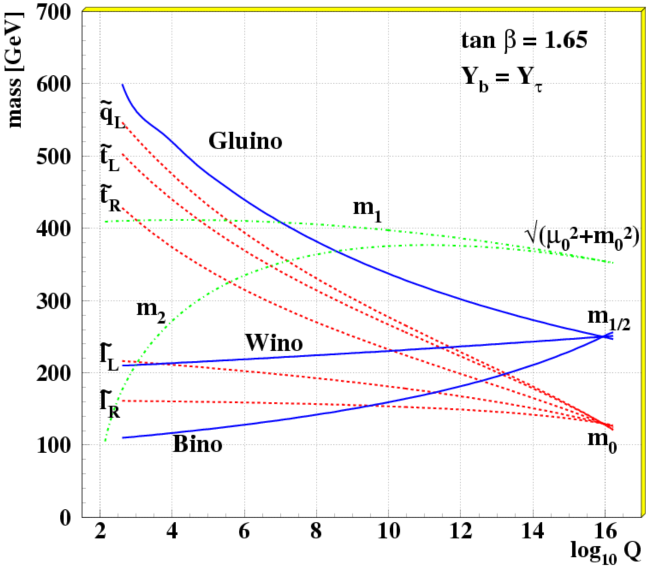
- As a result, MSSM has

  5 free parameters

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

  while the Standard Model has 2 ones

  m, λ



Constrained MSSM

- To make prediction one can choose a certain way
  - Take low-energy values of parameters (superpartners masses, mixing parameters, etc.) and then calculate observables as functions of these values.
  - Take high-energy values of parameters, then using evolution equations find their low-energy values, calculate masses, and then calculate observables. All the calculation now uses a small number of free parameters.
- “Experimental” data are sufficient to find allowed set of parameters

SUSY Dark Matter

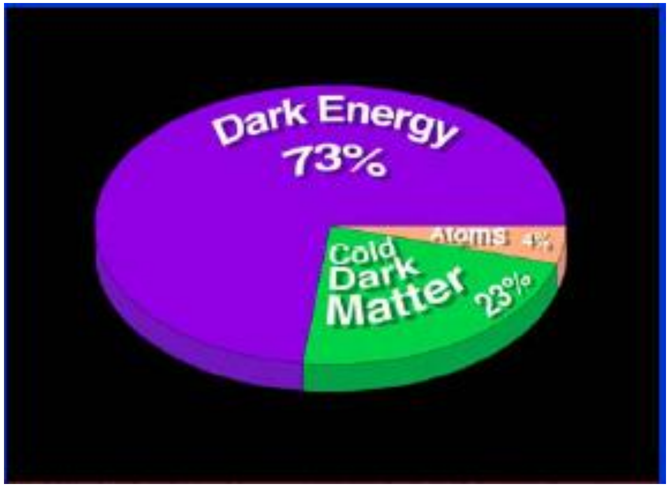
- Dark Matter in the Universe.

  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

SUSY production at colliders

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

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

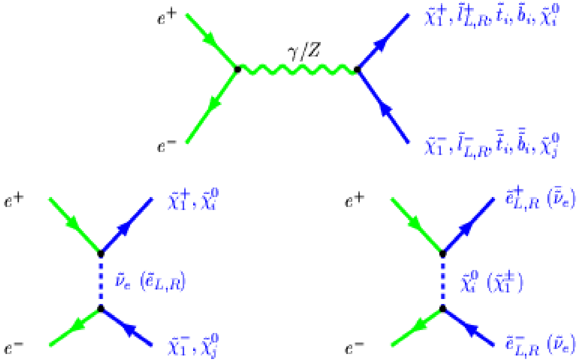
- ❑ Production and subsequent decay crucially depends on the model and the mass spectrum

- ❑ 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

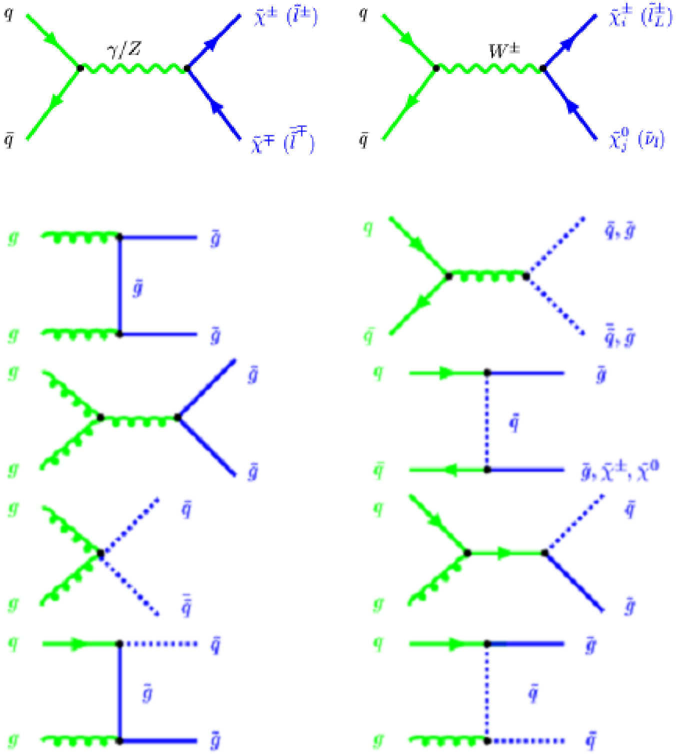
SUSY production at colliders

- ❑ Processes of creation of supersymmetric particles

- ❑ e^+e^- colliders

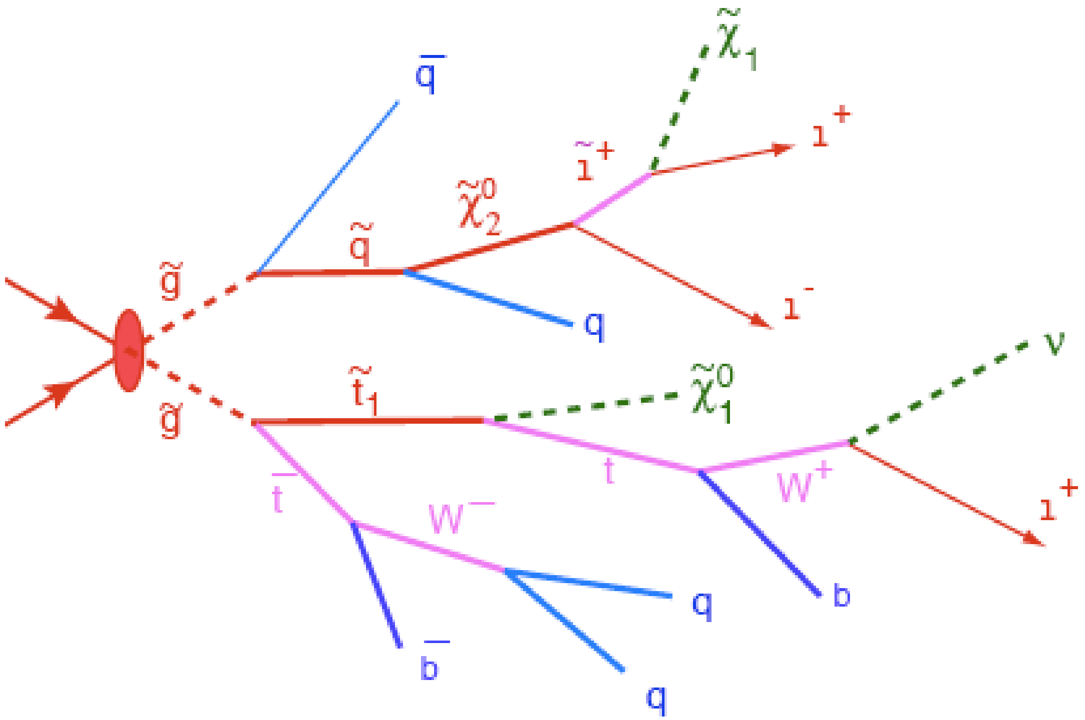


- ❑ Hadron colliders



SUSY events signatures

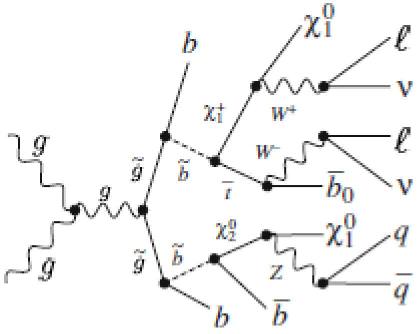
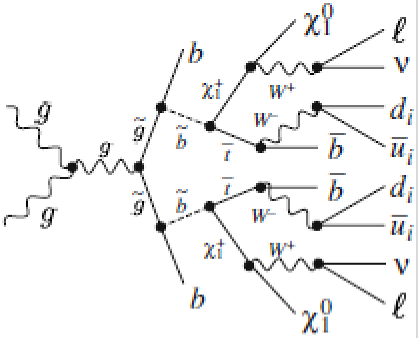
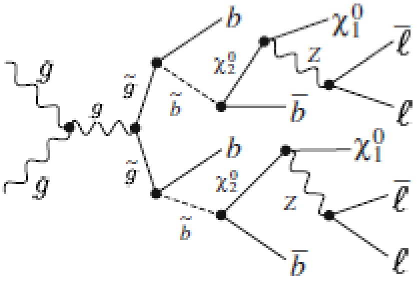
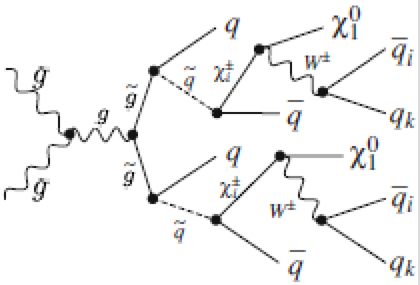
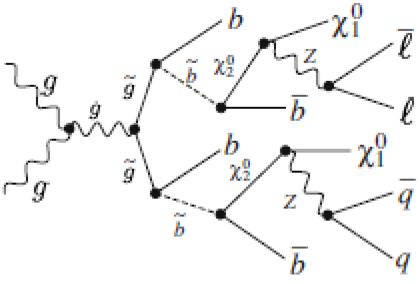
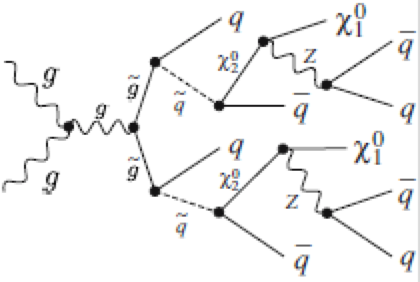
- Missing Energy: from LSP
- Multi-Jet: from cascade decay (gaugino)
- Multi-Leptons: from decay of charginos/neutralios



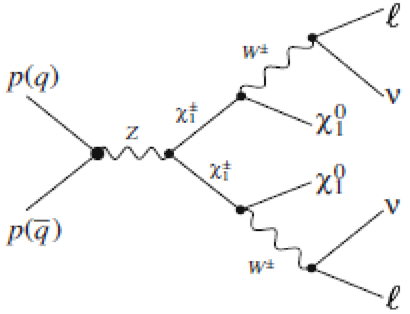
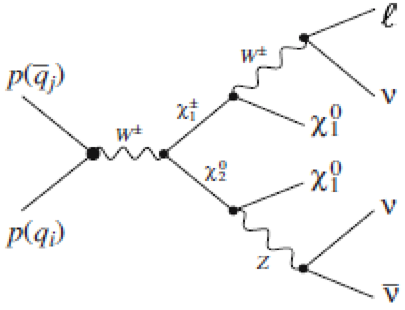
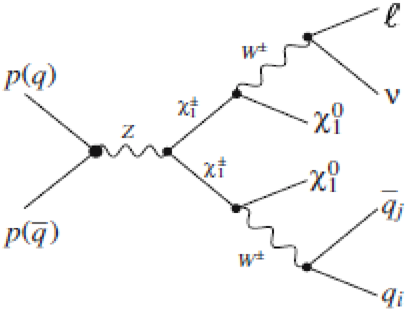
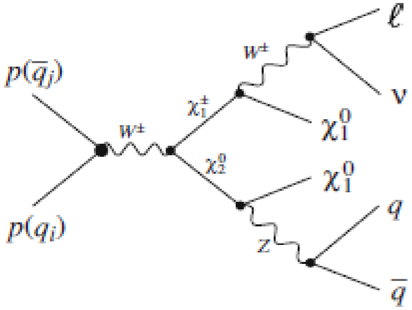
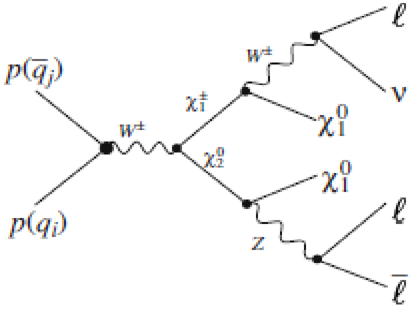
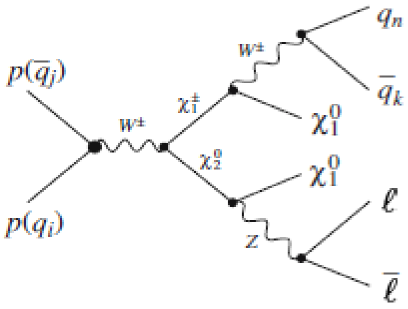
SUSY events signatures

Production	Main decay mode	Signature
$\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ q\bar{q}'\tilde{\chi}_1^\pm \\ g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$ $\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	$\not{E}_T$ + multijets (+ leptons)
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu, \tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$	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

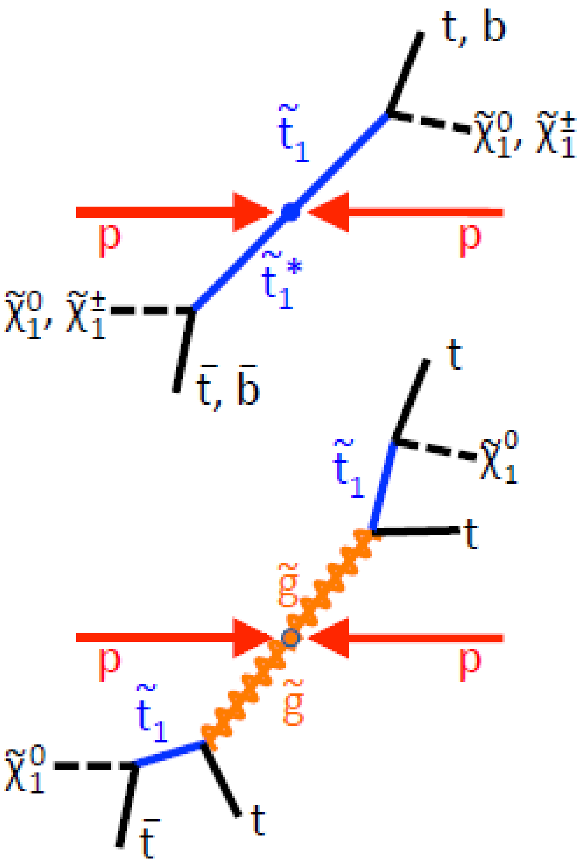
Process	Final state	Process	Final state
	2ℓ 2ν 6j $\not{E}_T$		2ℓ 2ν 8j $\not{E}_T$
	4ℓ 4j $\not{E}_T$		8j $\not{E}_T$
	2ℓ 6j $\not{E}_T$		8j $\not{E}_T$

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

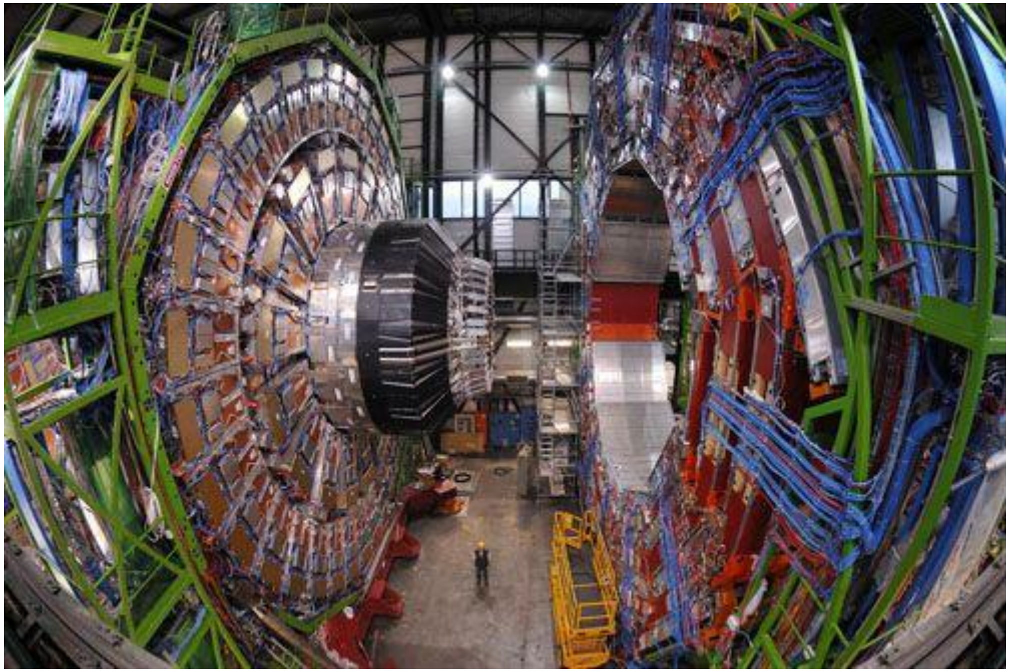


SUSY searches at CMS

- CMS is a particle detector designed to see a wide range of particles and phenomena produced in high-energy collisions in the LHC.

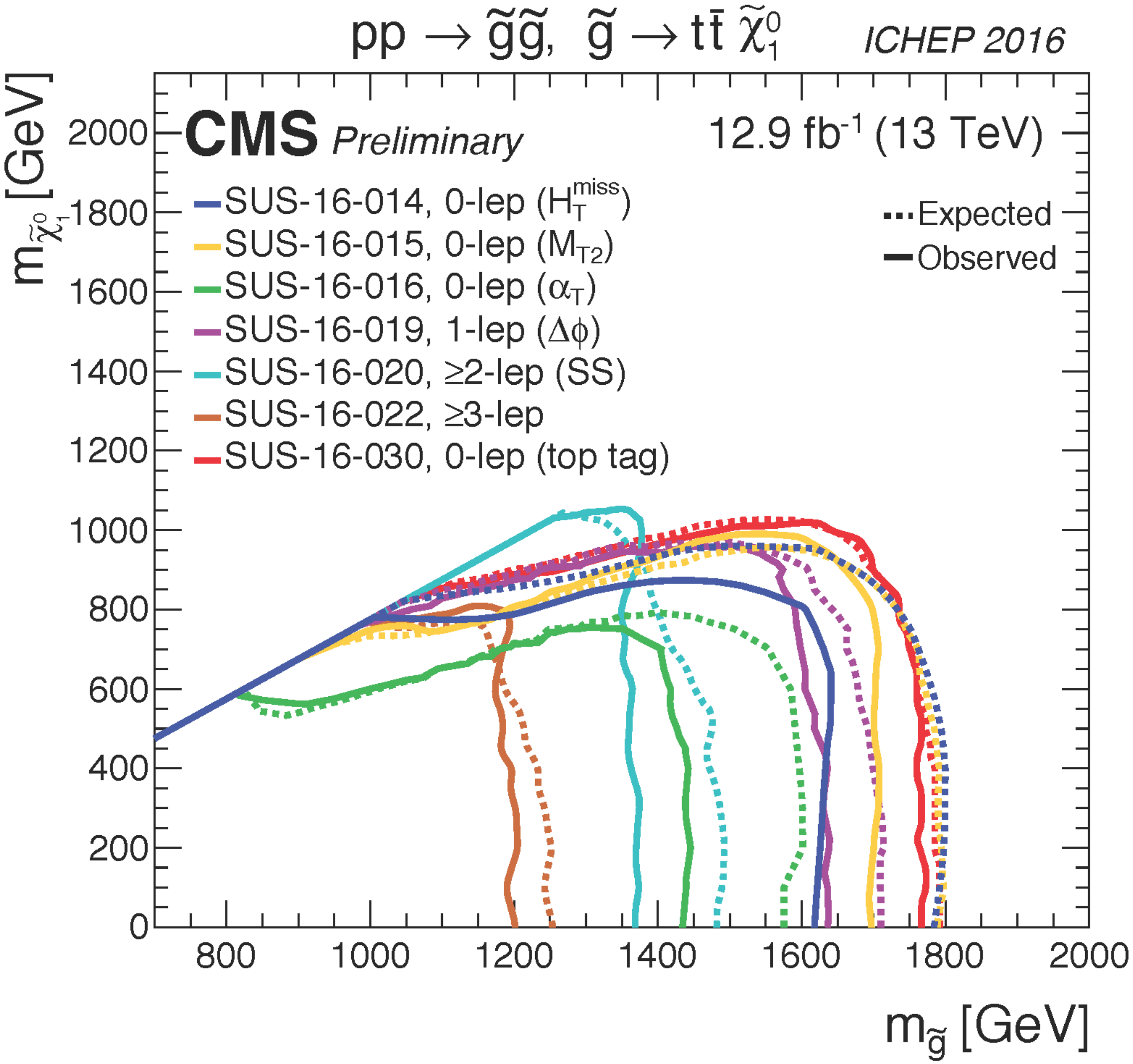
CMS

Compact Muon Solenoid



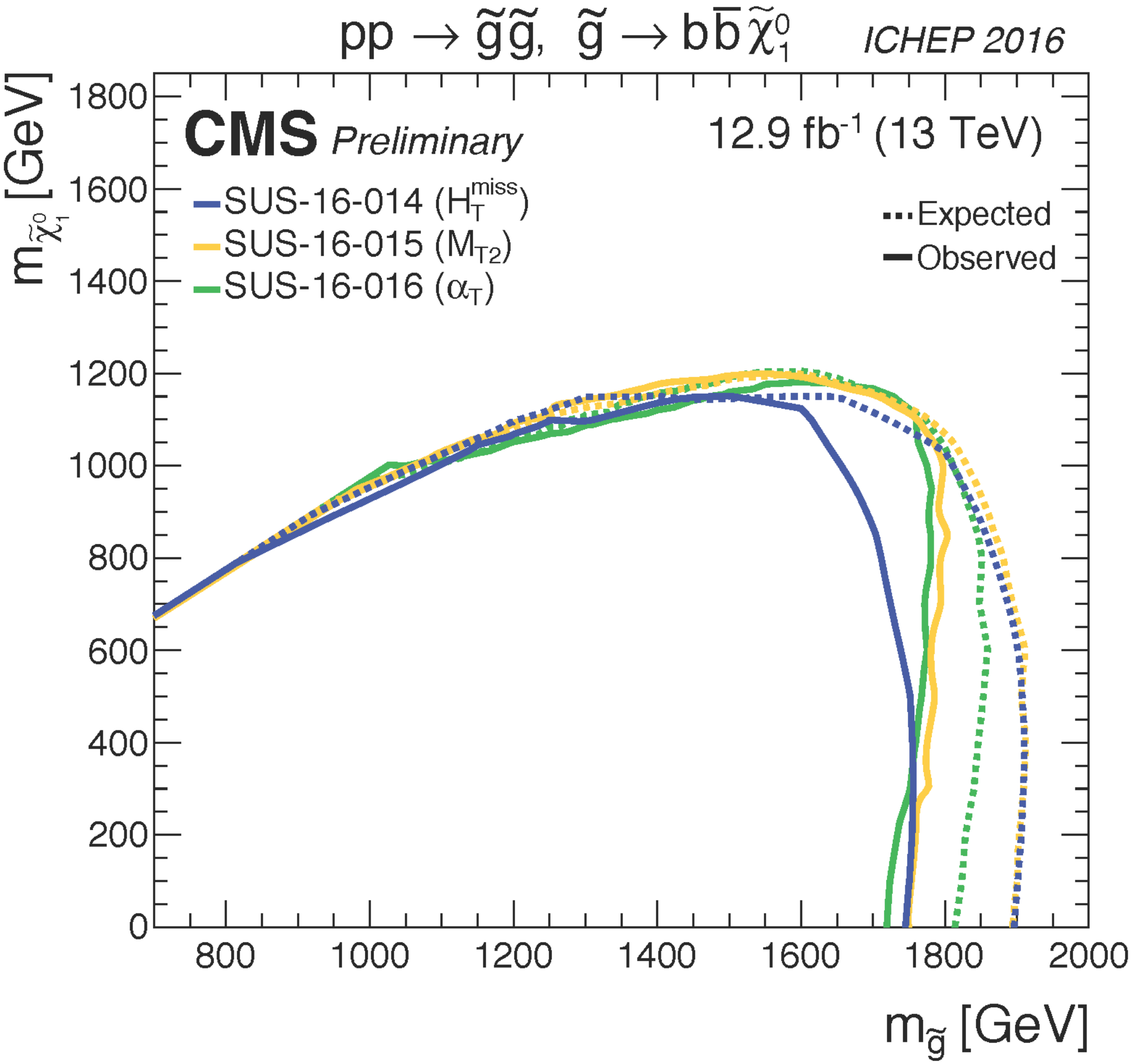
SUSY searches at CMS

- Limits on gluino pairs to 4 tops



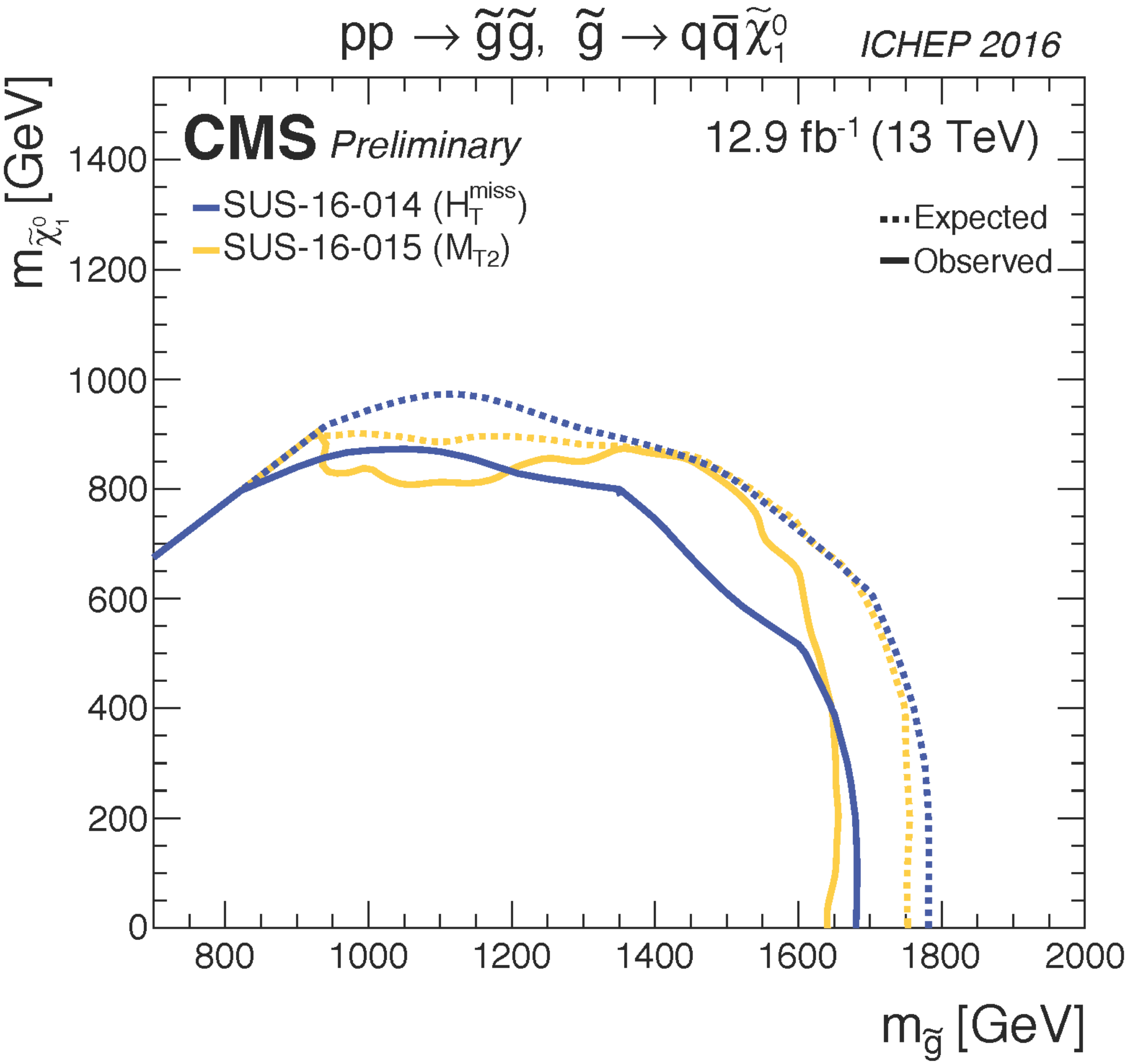
SUSY searches at CMS

- Limits on gluino pairs to 4 b



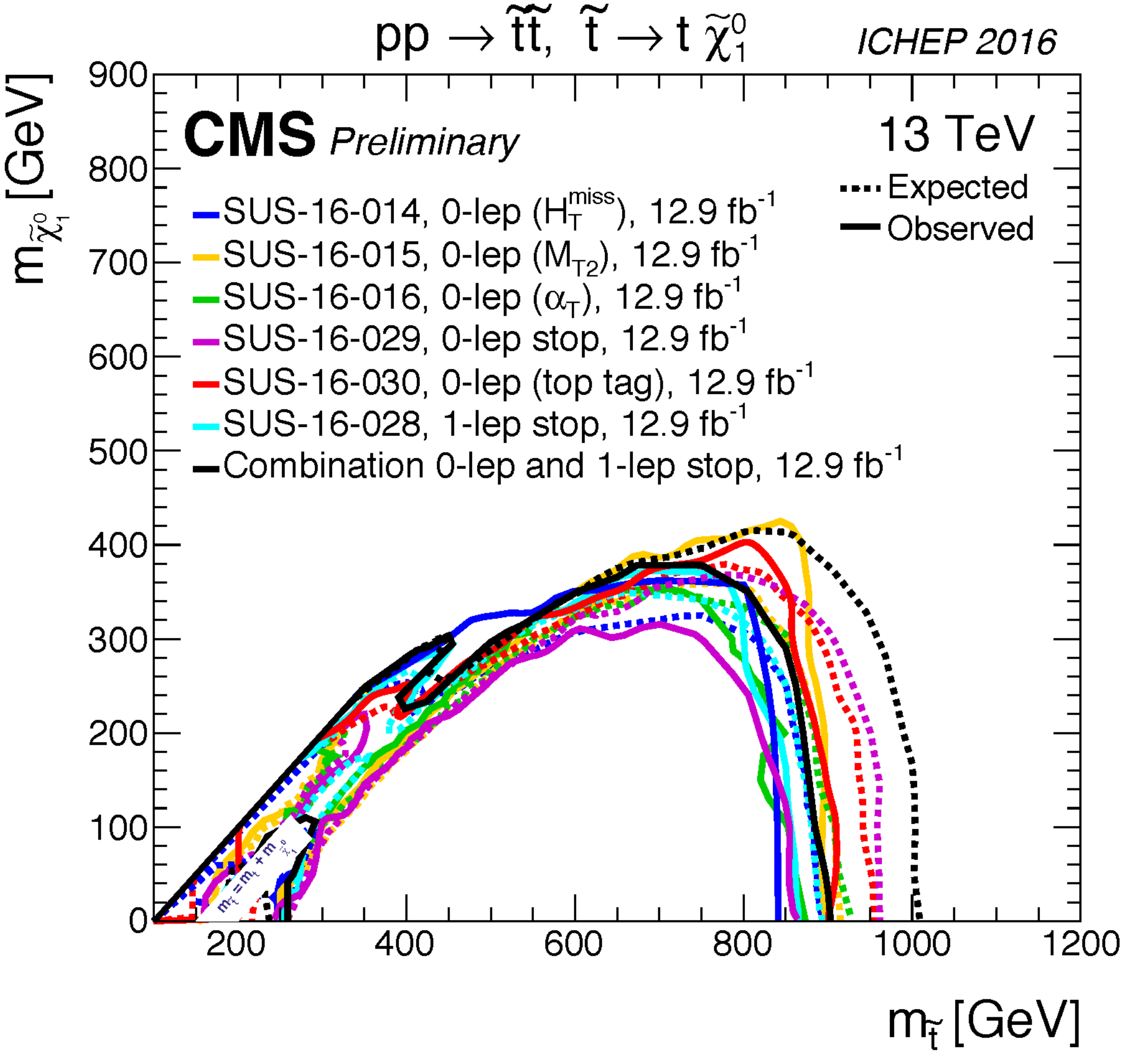
SUSY searches at CMS

- Limits on gluino pairs to light q



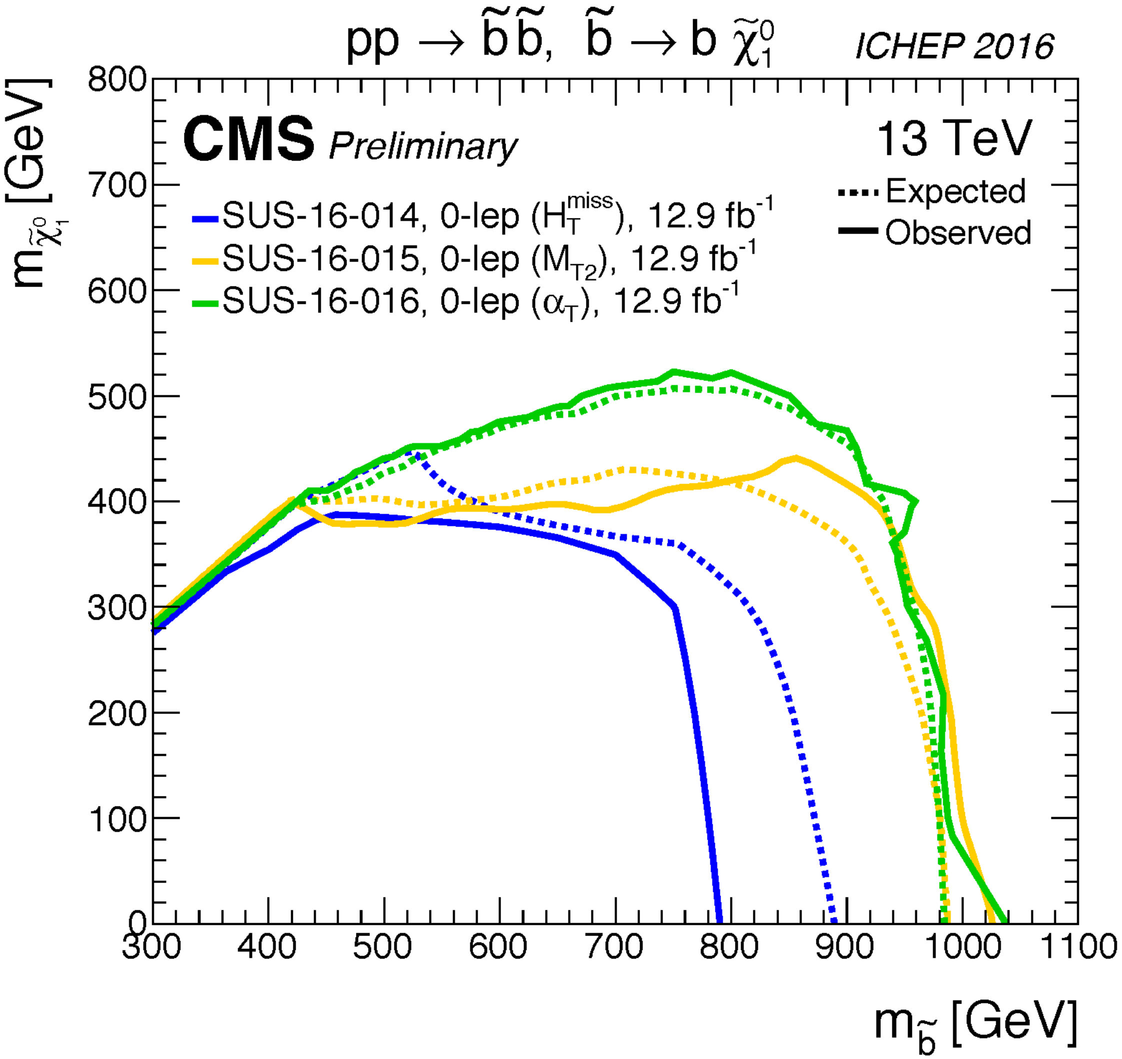
SUSY searches at CMS

- Limits on stop pairs to 2 tops



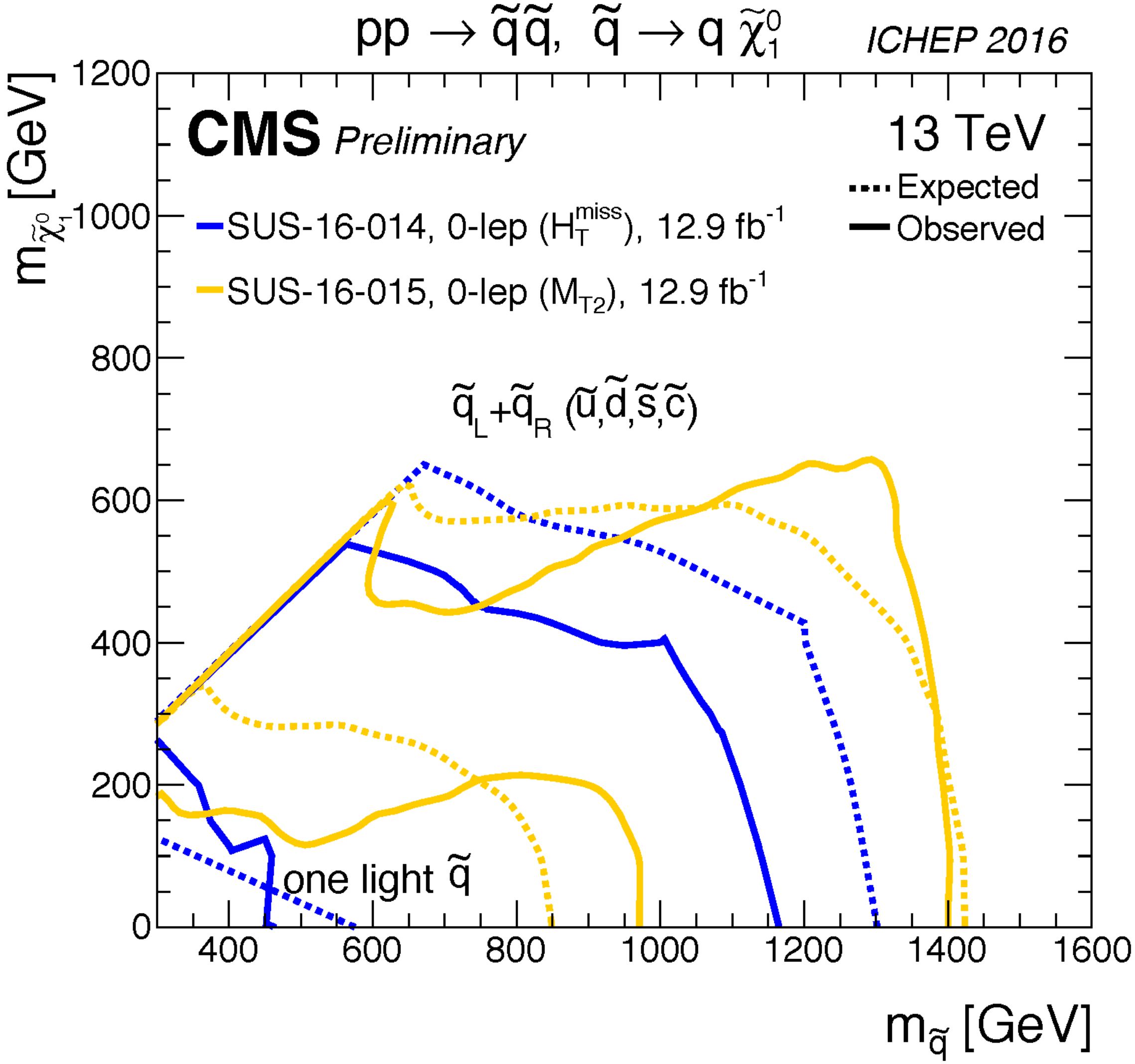
SUSY searches at CMS

- Limits on sbottom pairs to 2 bottoms



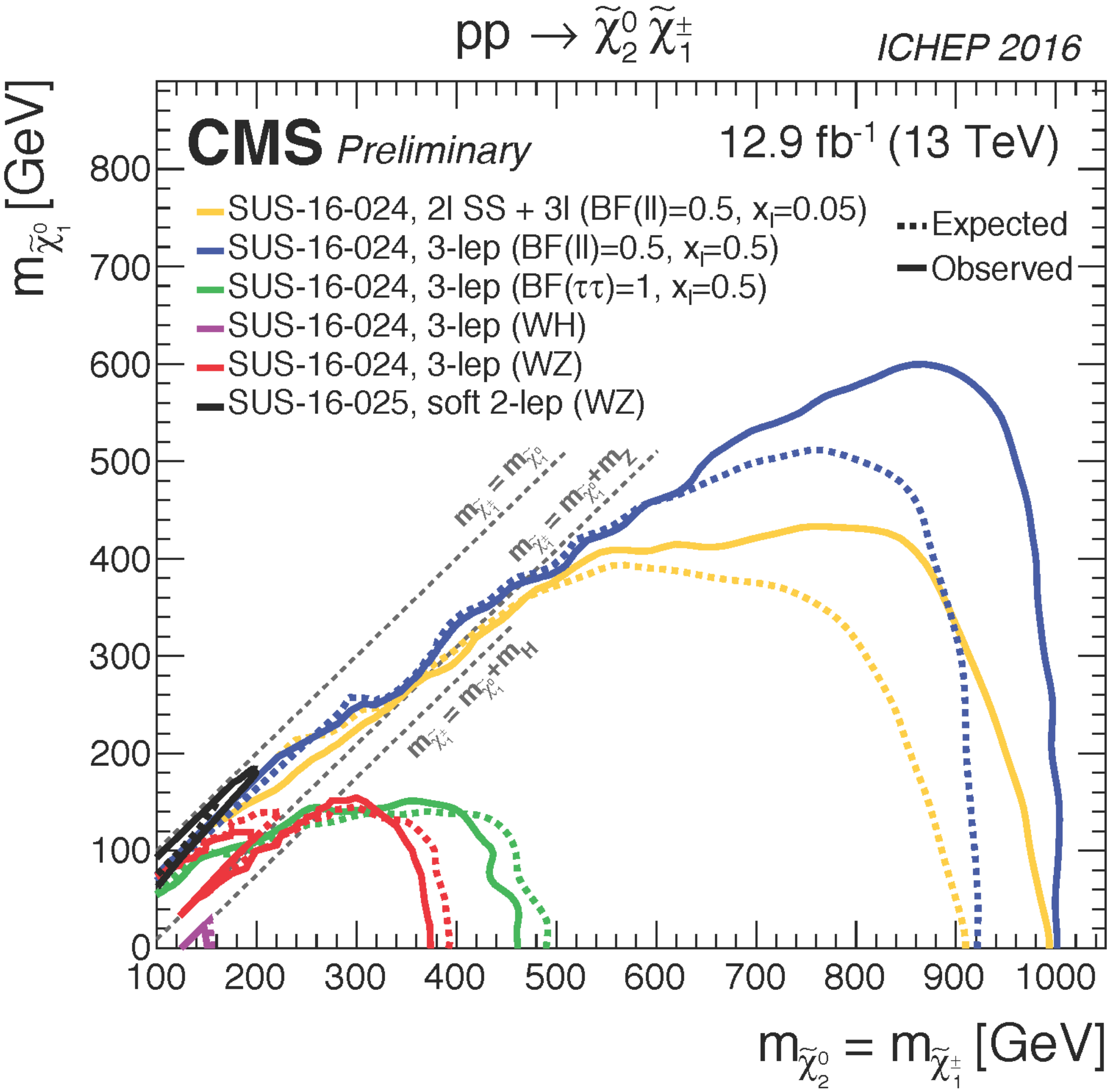
SUSY searches at CMS

- Limits on squark pairs to 2 quarks



SUSY searches at CMS

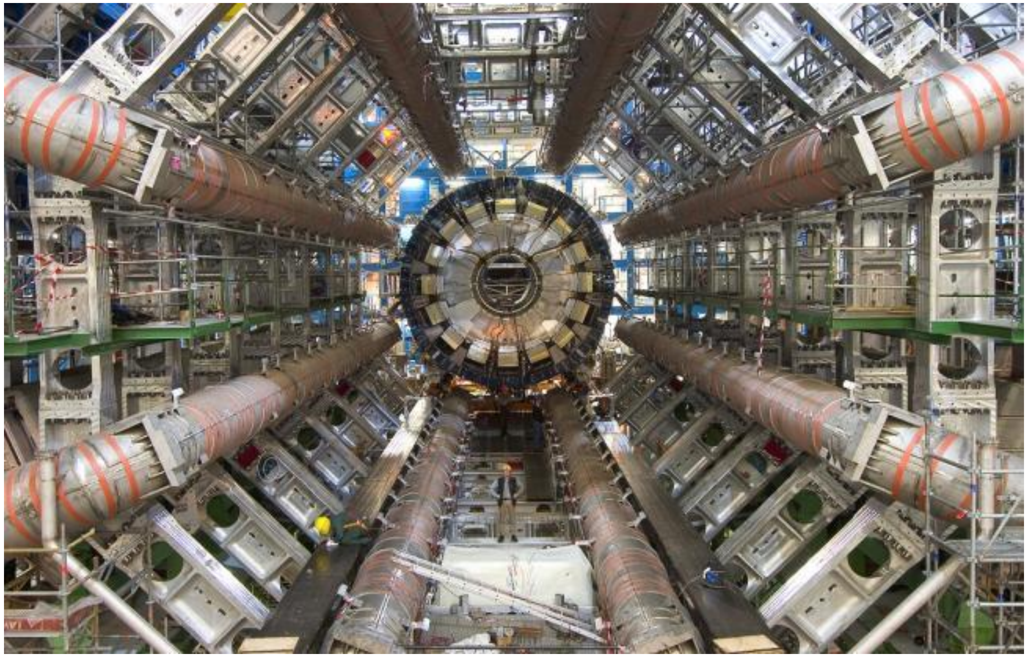
- Limits on ewk-ino production



SUSY searches at ATLAS

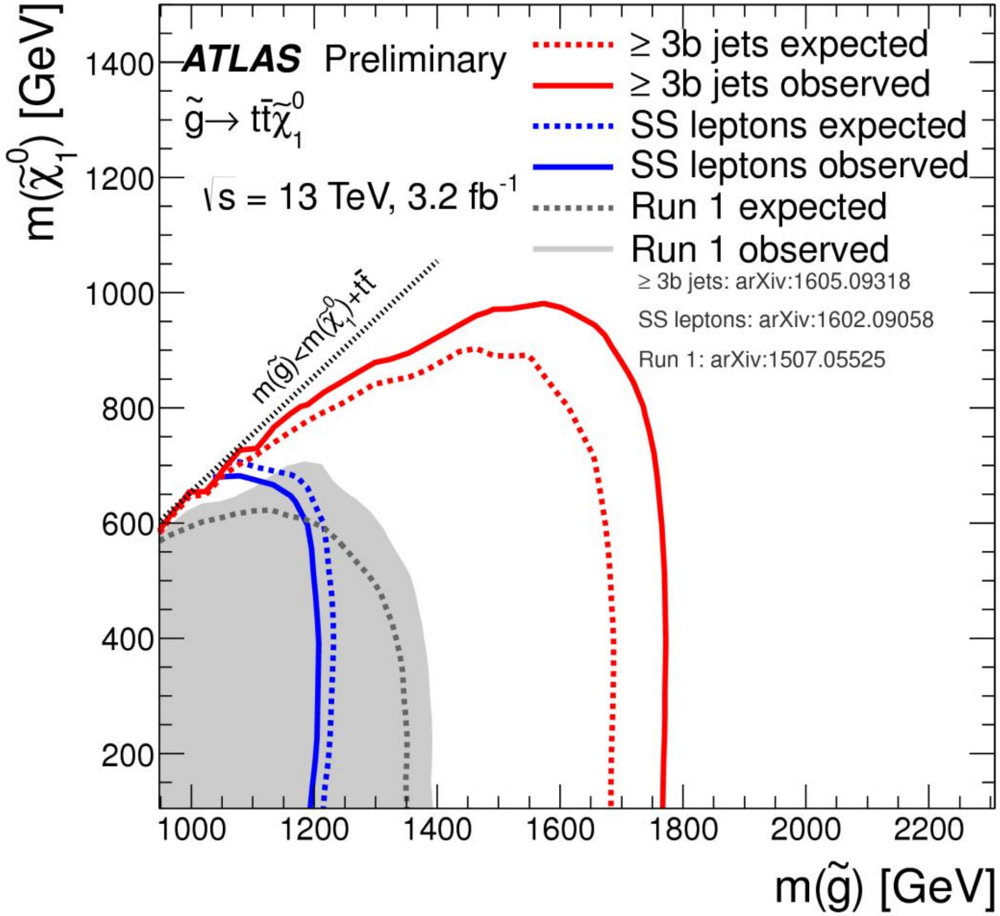
- ATLAS is one of general-purpose detectors at the LHC. It studies a wide range of physics, from the search for the Higgs boson to extra dimensions and particles that could make up dark matter.

ATLAS
EXPERIMENT



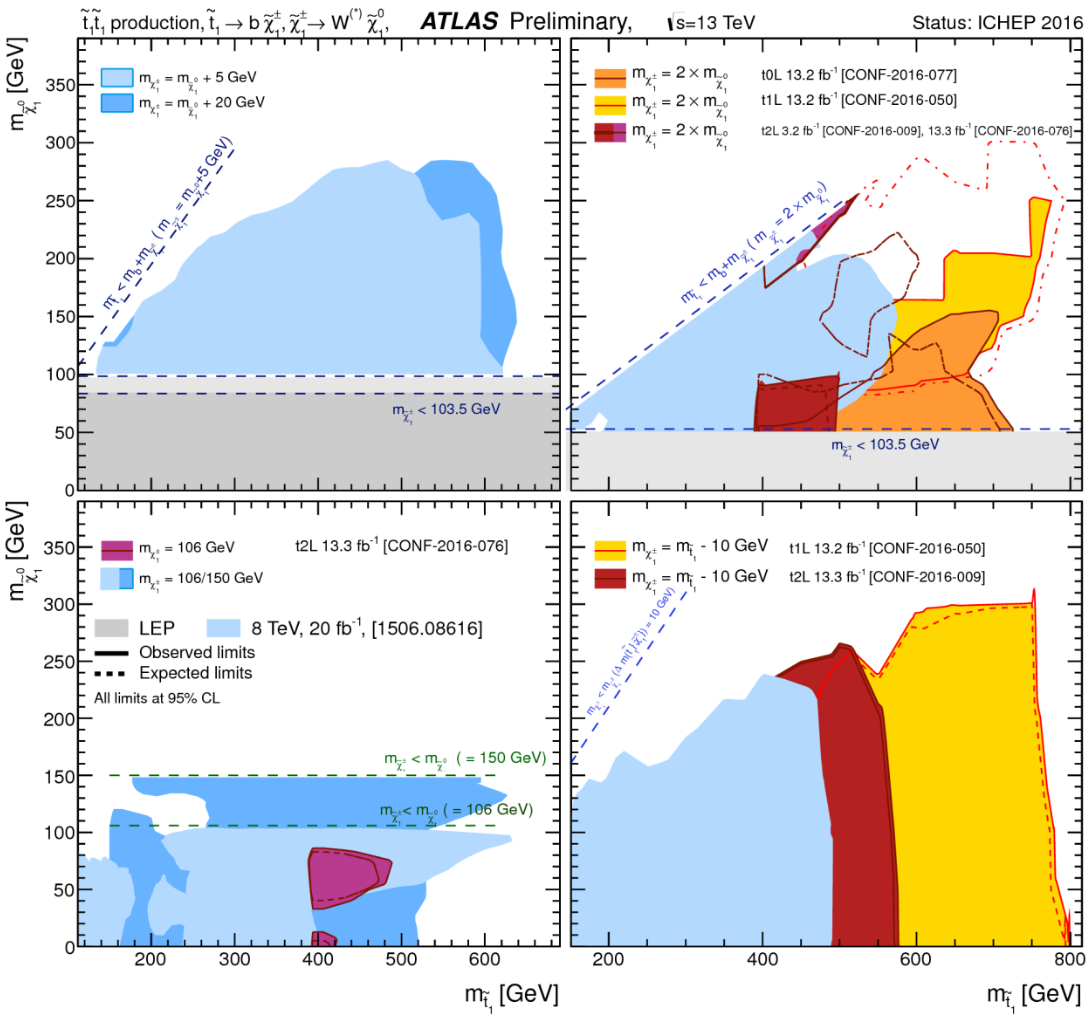
SUSY searches at ATLAS

- 95% CL exclusion limits for 13 TeV for the Gtt simplified model where gluinos decay via off-shell top squarks to four top quarks and two lightest neutralinos.



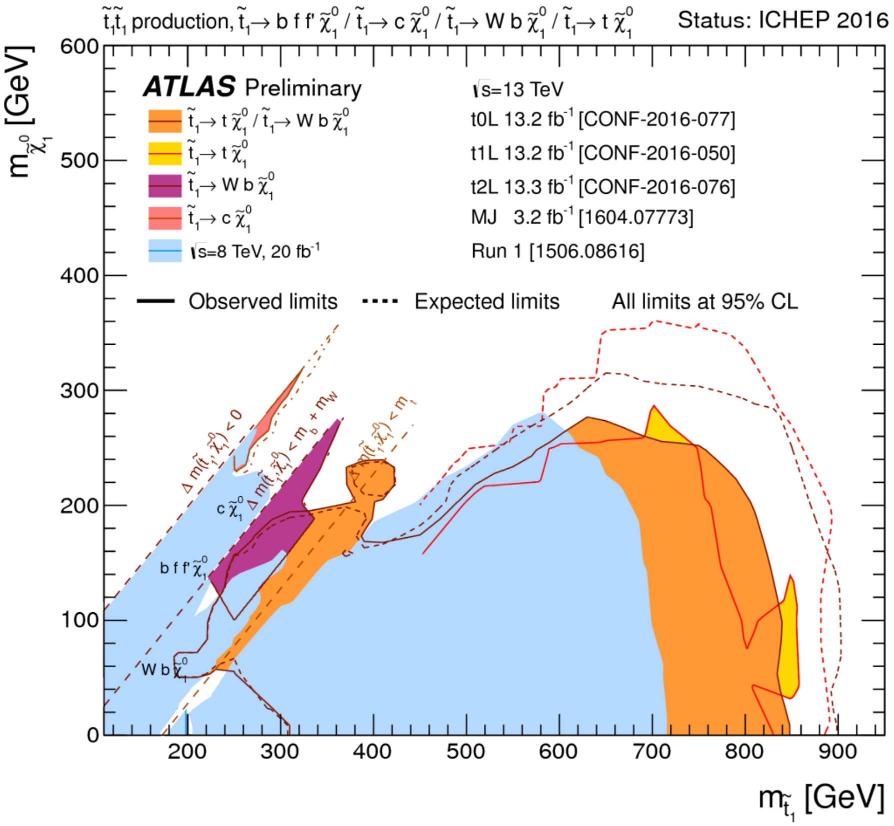
SUSY searches at ATLAS

- 95% CL exclusion limits for stop pair production based on 13 fb^{-1} data taken at $\sqrt{s}$ = 13 TeV. The mode stop1 → b+C1 is assumed with 100% BR. Various hypotheses on the stop1, C1 and N1 mass hierarchy are used. Contours show different channels, masses, and simplified scenarios.



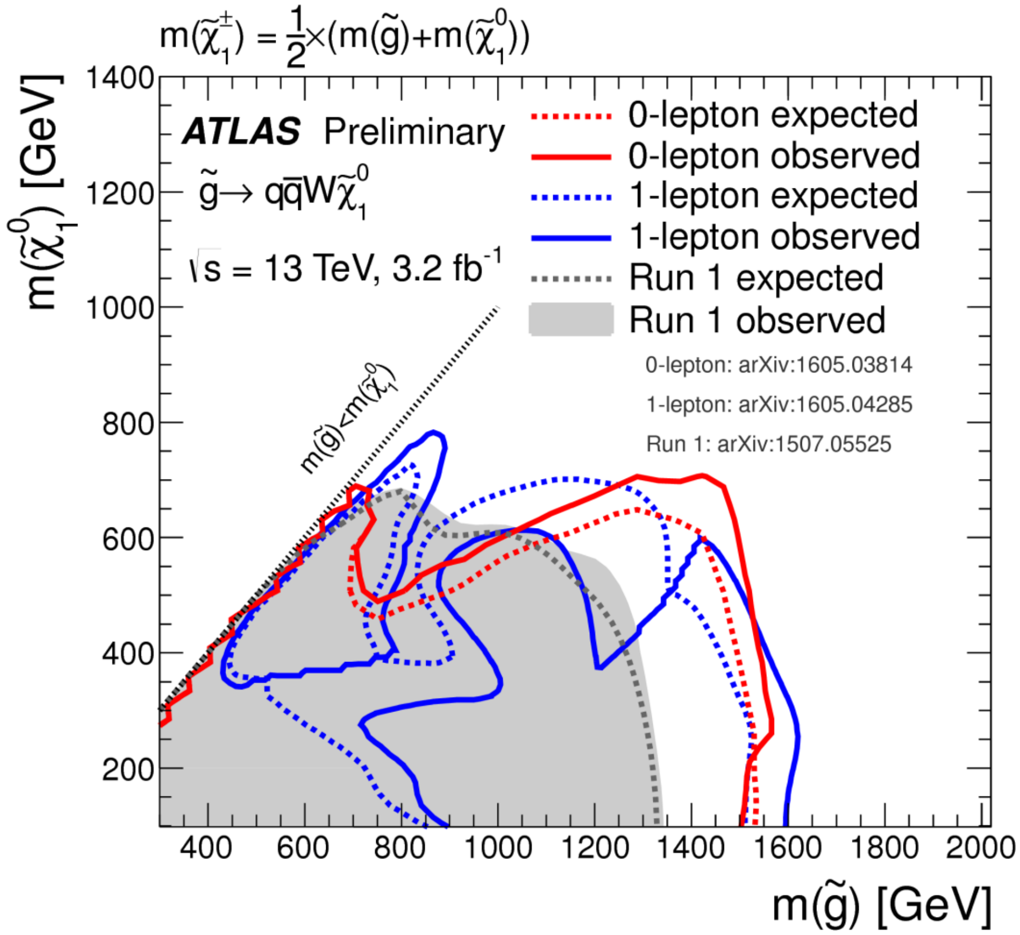
SUSY searches at ATLAS

- 95% CL exclusion limits for stop pair production based on 13 fb^{-1} data taken at $\sqrt{s}$ = 13 TeV. Four decay modes are considered with 100% BR: stop → t+neutralino1, stop → W+b+neutralino1, stop → c + neutralino1 and stop → f+f'+b+neutralino1. Contours belong to different channels, mass hierarchies, and simplified scenarios.



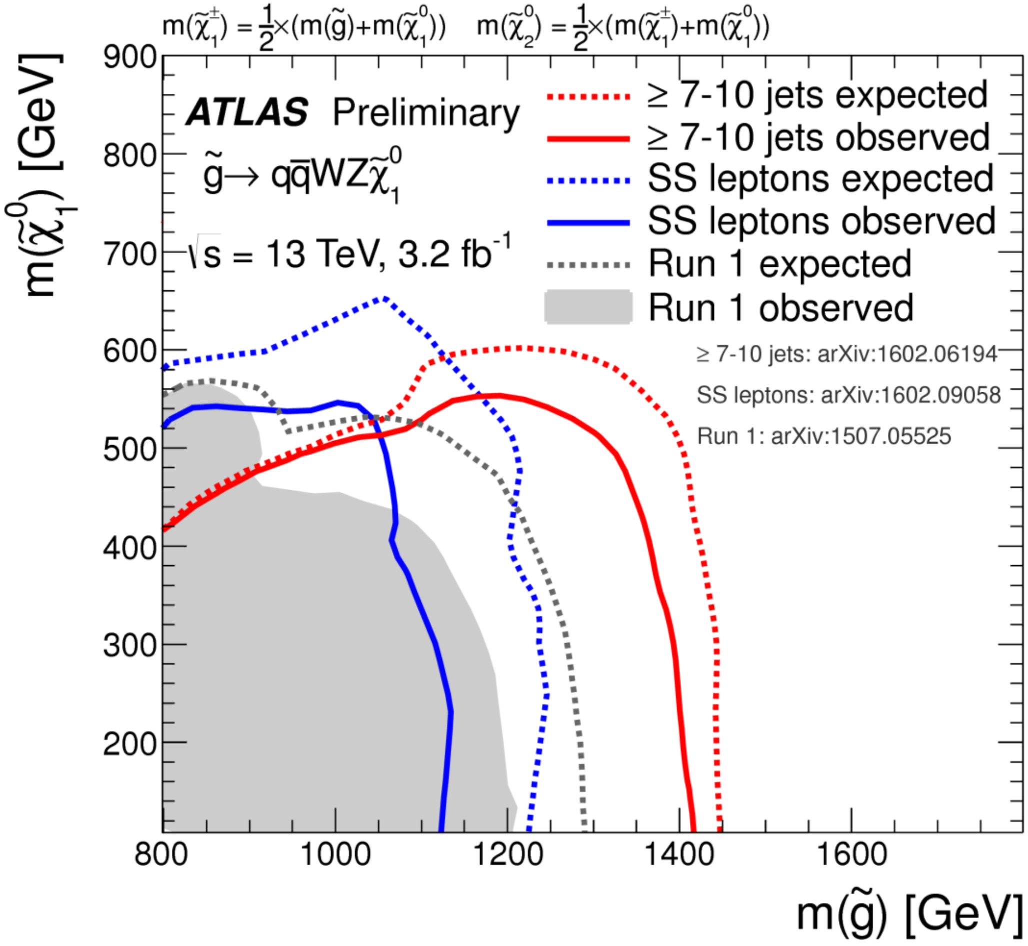
SUSY searches at ATLAS

- 95% CL exclusion limits for 13 TeV for the simplified model where a pair of gluinos are produced, and each decays via an on-shell chargino to a pair of quarks, a W boson, and the lightest neutralino. The chargino mass is assumed to be between the gluino and neutralino mass.



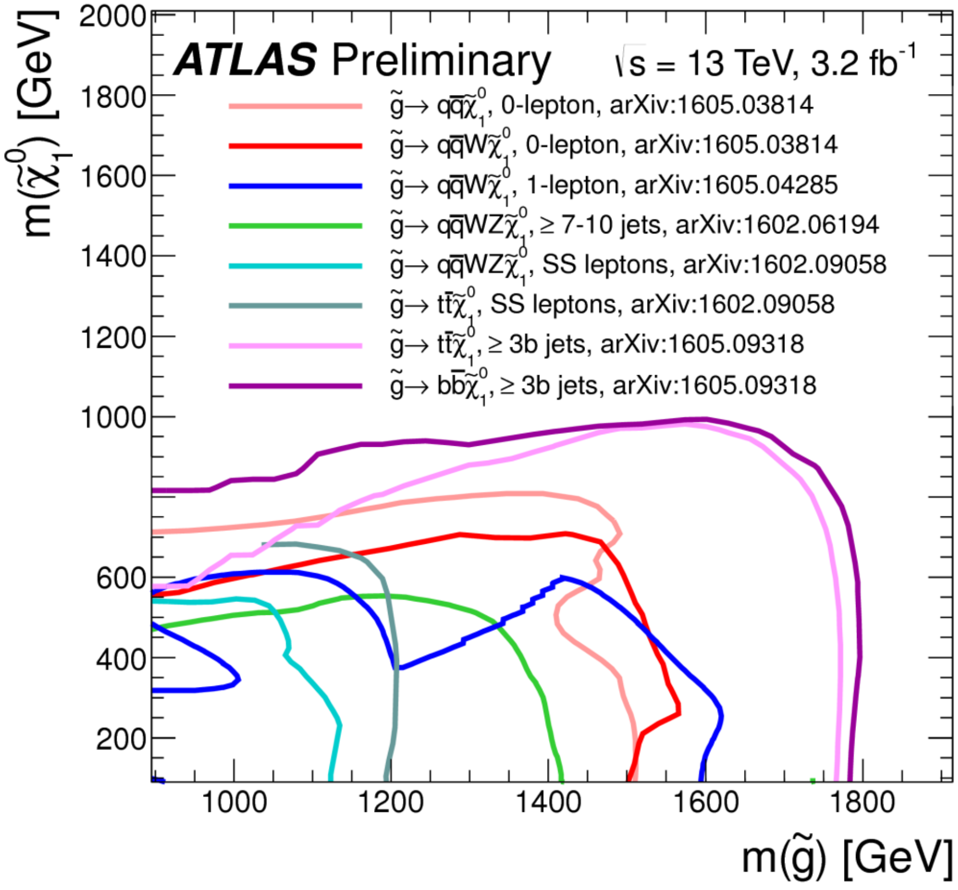
SUSY searches at ATLAS

- 95% CL exclusion limits for 13 TeV for the simplified model where a pair of gluinos are produced, and each decays promptly via the lightest chargino and the NLSP to a pair of q, a W, a Z, and the LSP.



SUSY searches at ATLAS

- 95% CL exclusion limits for 13 TeV for simplified models featuring the decay of the gluino to the LSP either directly or through a cascade chain. For each line, the gluino decay mode is assumed to proceed with 100% BR. The limits depend on additional assumptions on the mass of the intermediate states.

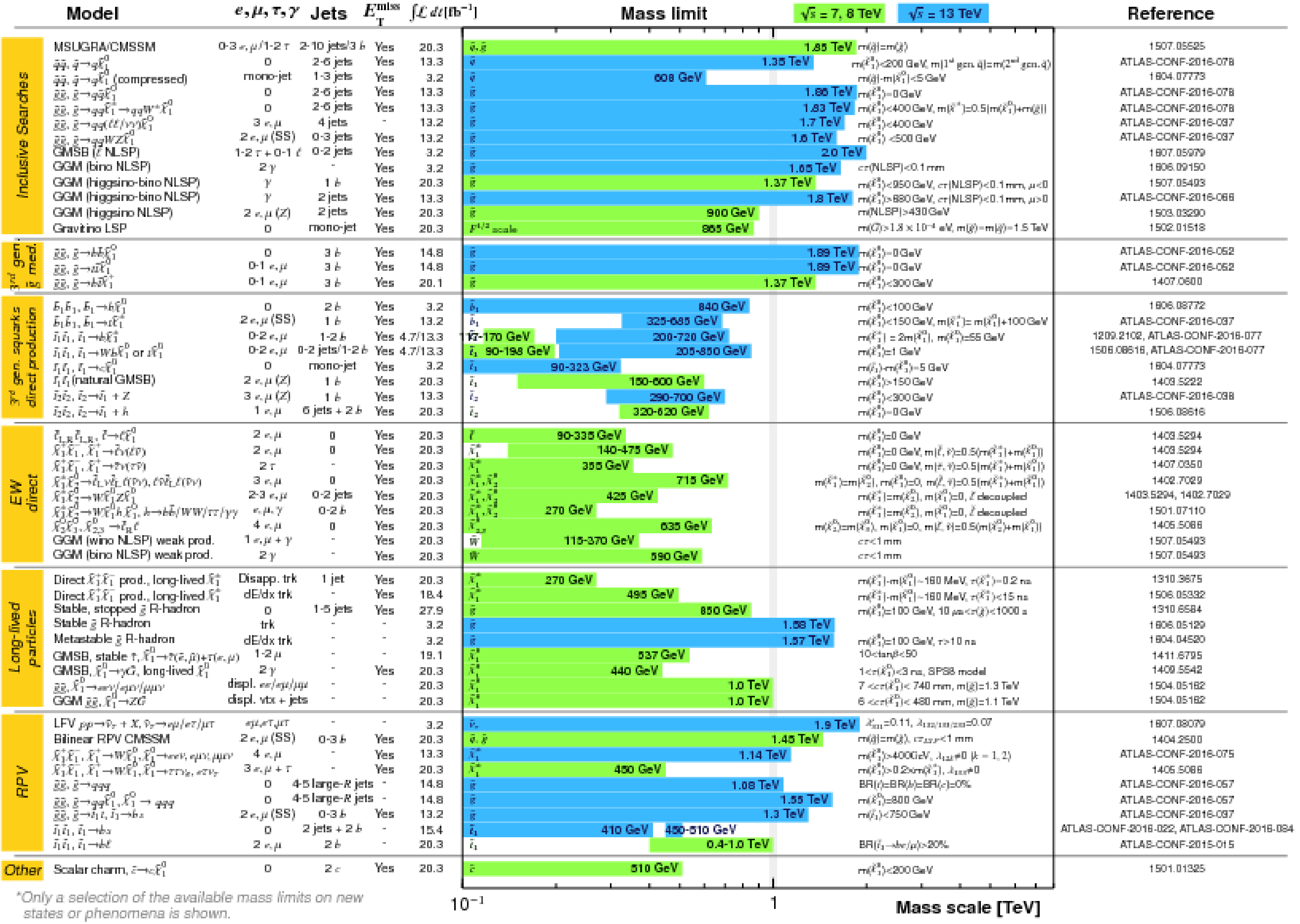


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{q}$ 1.35 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.86 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	$\tilde{g}$ 1.83 TeV	$m(\tilde{\chi}_1^0)$<400 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	$\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	14.8	$\tilde{g}$ 1.89 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$ 325-685 GeV	$m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^{\pm})$= $m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV 200-720 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 90-198 GeV 205-850 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 90-323 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	13.3	$\tilde{t}_2$ 290-700 GeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1 e,μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$ 320-620 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-335 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-475 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 355 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 715 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 425 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 635 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 495 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$ 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	13.2	$\tilde{g}$ 1.3 TeV	$m(\tilde{t}_1)$<750 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown.

Summary of SUSY searches

- A broad range of searches for SUSY have been performed by CMS and ATLAS for increased sensitivity with partial 2016 data set

- Experiments performed a large set of analyses almost synchronously with data taking

- The mass limits pushed up to 1.9 TeV (gluinos) and 900 GeV (stops)

- Much larger data sets will be available at the end of 2016 and during the rest of Run2, and we are looking forward to seeing first significant deviations from SM predictions!