Supersymmetry Status

Supersymmetry

Motivation: unifying matter (fermions) and interactions (mediated by bosons)

Symmetry that relates fermions and bosons

Prediction: new particles supersymmetric partners of all known fermions and bosons : differ spin 1/2

Not discovered yet

Hierarchy problem

SUSY particles (~TeV) to stabilize Higgs mass against radiative corrections → should be within reach of LHC

R-parity and dark matter

Supersymmetry

Supersymmetry transformation

$Q|\mathrm{Fermion}\rangle >= |\mathrm{Boson}\rangle$, $Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle$

$$\{Q_a^\dagger, Q_b\} = (\bar{\sigma}^\mu)_{ab} P_\mu$$

Symmetry of the Lagrangian which mixes fermions and bosons

$$\delta_\xi \phi = \sqrt{2}\xi^T c\psi$$
$$\delta_\xi \psi = \sqrt{2} i\sigma \cdot \partial\phi c \xi^*$$

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi + \psi^\dagger i\bar{\sigma} \cdot \partial\psi$$
$$\delta_\xi \mathcal{L} = 0$$

Most general renormalizable Lagrangian with chiral superfields (scalar, fermion) and vector superfields (vector, fermion)

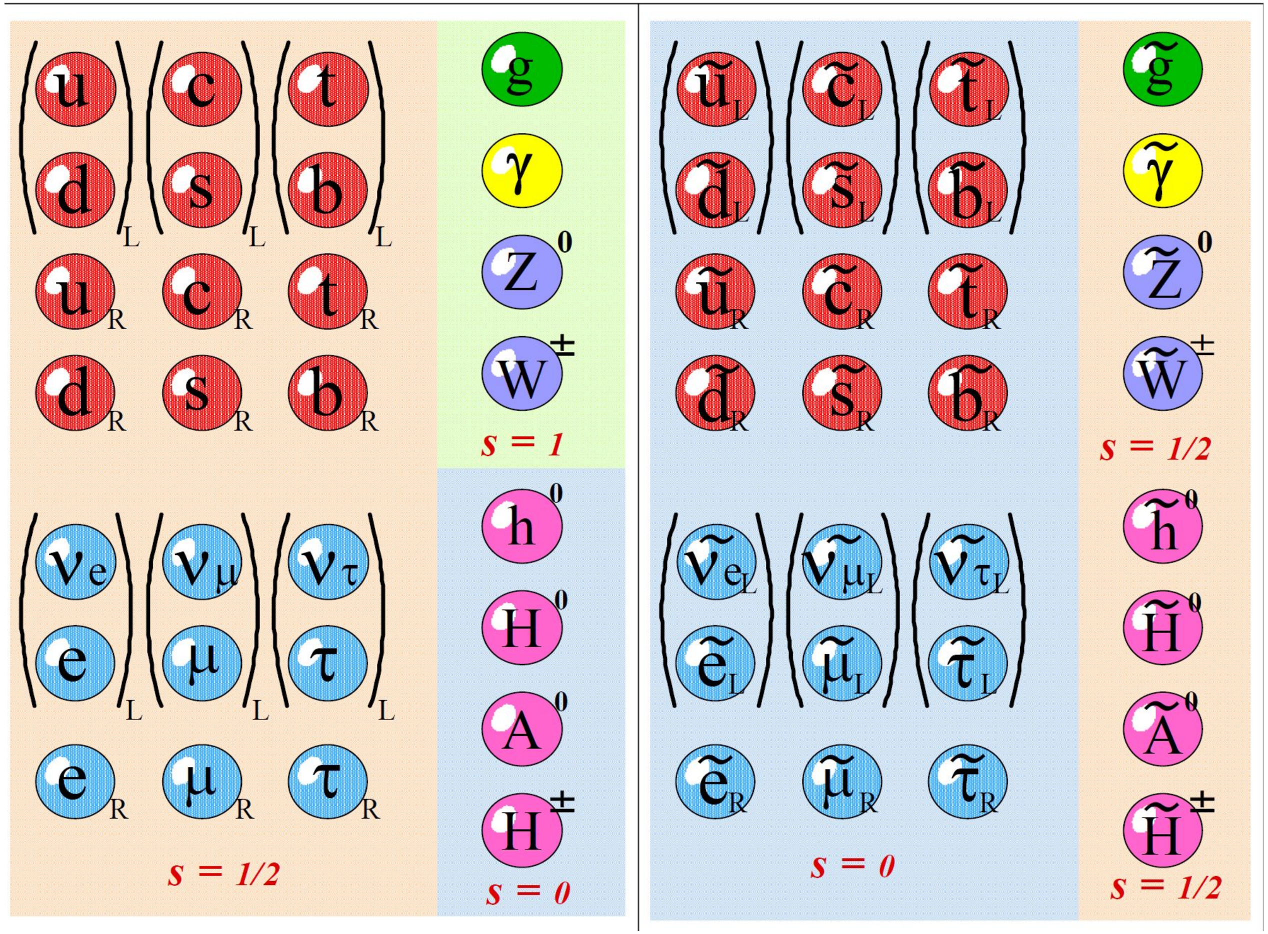
$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{kin} + \mathcal{L}_{Yukawa} + \mu h_1 h_2$$

If SUSY exact

sparticles and particles : same mass

Interactions dictated by SUSY

MSSM particles



Additional Higgs doublet

Only one additional field: Higgs doublet

H (scalar), A (pseudoscalar) H^+, H^-

Give masses to all fermions, $Y(h_2)=1/2$, $Y(h_1)=-1/2$

$$W = \lambda_u^{ij} \overline{u}^i{}_R h_2 Q_L^j + \lambda_d^{ij} \overline{d}^j_R h_1 Q_L^j + \lambda_l^{ij} \overline{e}^i_R h_1 L_L^j$$

In SM use φ and φ* but using h_2* gives a Lagrangian which is not supersymmetric

Minimal Supersymmetric Standard Model

Minimal field content: partner to SM particles (also need two Higgs doublets)

Neutralinos: neutral spin ½ partners of gauge bosons (bino, wino) and Higgs scalars (Higgsinos)

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino		
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_2^0	Higgs boson	$\tilde{H}_2^0$	higgsino		
H_3^0	Higgs boson				

Hierarchy problem

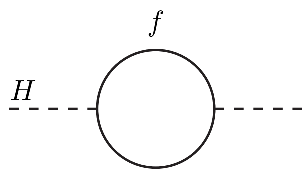
Higgs mass (~100GeV) is not stable against radiative corrections

One solution: introduce new particles

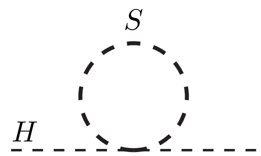
If supersymmetry is exact each SM fermion contribution is cancelled by that of two scalar partners ($\lambda_S = \lambda_F^2$)

$$-\lambda_f H \overline{f} f$$

$$-\lambda_S |H|^2 |S|^2.$$



(a)



(b)

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}^2$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\mathrm{UV}}^2\right.$$

Each increase quadratically with energy

Supersymmetry is broken (SUSY partners of SM particles not observed)

Quadratic divergences still cancelled if only soft susy breaking terms

Corrections to Higgs mass ~M_{Soft}^2 , the SUSY scale.

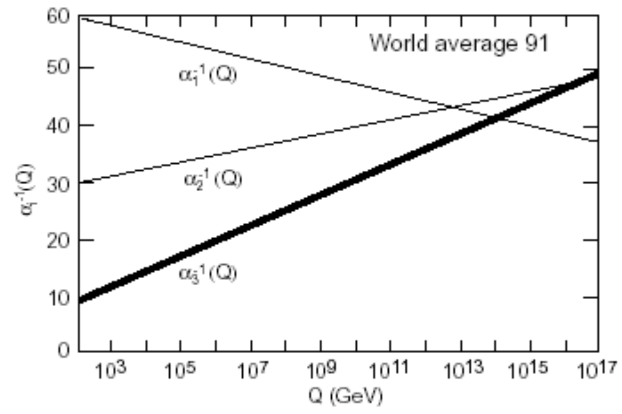
$$\Delta m_H^2 = m_{\mathrm{soft}}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda_{\mathrm{UV}}/m_{\mathrm{soft}}) + \ldots\right]$$

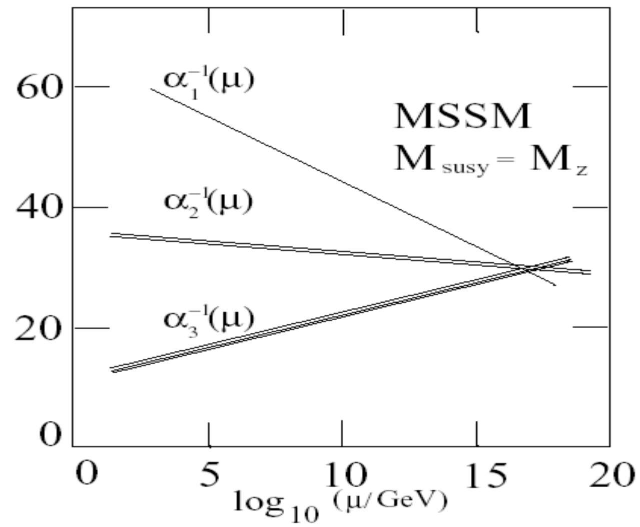
Indications of supersymmetry?

Coupling constants "run" with energy

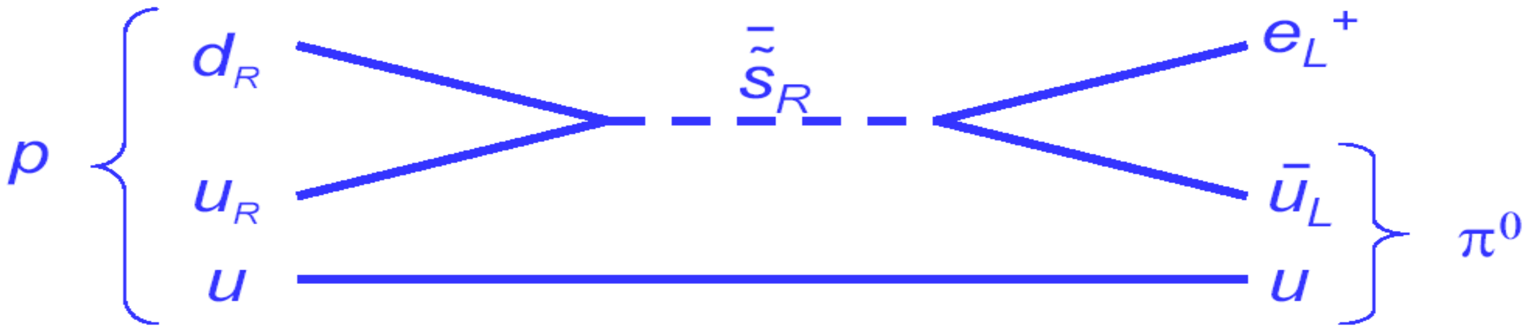
Precise measurements of coupling constants of Standard Model SU(3),SU(2),U(1) at electroweak scale (LEP) indicate that they do not unify at high scale (GUT scale)

SM coupling constants unify within MSSM





R-parity



Proton decay

To prevent this introduce R parity

$R=(-1)^{3B-3L+2S}$; R=1: SM particles R=-1 SUSY

The LSP is stable : could be a suitable DM candidate if neutral

Minimal Supersymmetric Standard Model

MSSM – Lagrangian

Full supersymmetric generalization of SM Lagrangian with chiral superfield: S,ψ + vector superfield A, λ (2 component fermion)

$$\mathcal{L}_{\rm kin} = \sum_i \left\{ (D_\mu S_i^*)(D^\mu S_i) + i\overline{\psi}_i D_\mu \gamma^\mu \psi_i \right\} + \sum_a \left\{ -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \frac{i}{2} \overline{\lambda}_a \sigma^\mu D_\mu \lambda_a \right\}$$

Interactions specified by SM and SUSY invariance, no new parameter

$$\mathcal{L}_{\rm int.\ scal-fer.-gauginos} \;=\; -\sqrt{2} \sum_{i,a} g_a \left[S_i^* T^a \overline{\psi}_{iL} \lambda_a + {\rm h.c.} \right]$$

Superpotential : scalar potential + yukawa interactions

MSSM – Lagrangian

Interaction Lagrangian z: superfields

$$\mathcal{L}_W = -\sum_i \left|\frac{\partial W}{\partial z_i}\right|^2 - \frac{1}{2}\sum_{ij}\left[\overline{\psi}_{iL}\frac{\partial^2 W}{\partial z_i \partial z_j}\psi_j + \text{h.c.}\right]$$

F-terms and D-terms contribute to scalar potential

$$V_F = \sum_i |W^i|^2 \quad \text{with } W^i = \partial W/\partial S_i \qquad V_D = \frac{1}{2}\sum_{a=1}^{3}\left(\sum_i g_a S_i^* T^a S_i\right)^2$$

Superpotential

$$W = \sum_{i,j=gen} -Y_{ij}^u\, \hat{u}_{Ri}\hat{H}_2\cdot\hat{Q}_j + Y_{ij}^d\, \hat{d}_{Ri}\hat{H}_1\cdot\hat{Q}_j + Y_{ij}^\ell\, \hat{\ell}_{Ri}\hat{H}_1\cdot\hat{L}_j + \mu\hat{H}_2\cdot\hat{H}_1$$

Exact SUSY : only one new parameter : μ

Supersymmetry must be broken : no sparticles with SM masses

MSSM – soft terms

Many possibilities for SUSY breaking instead write most general Lagrangian which violate SUSY without disturbing cancellation of quadratic divergences in scalar mass (Grisaru and Girardelo 1982)

$$-\mathcal{L}_{\rm gaugino} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a\right.$$

$$-\mathcal{L}_{\rm sfermions} = \sum_{i=gen} m^2_{\tilde{Q}_i} \tilde{Q}_i^\dagger \tilde{Q}_i + m^2_{\tilde{L}_i} \tilde{L}_i^\dagger \tilde{L}_i + m^2_{\tilde{u}_i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d}_i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{\ell}_i} |\tilde{\ell}_{R_i}|^2$$

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

$$-\mathcal{L}_{\rm tril.} = \sum_{i,j=gen} \left[A^u_{ij} Y^u_{ij} \tilde{u}^*_{R_i} H_2 \cdot \tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}^*_{R_i} H_1 \cdot \tilde{Q}_j + A^l_{ij} Y^\ell_{ij} \tilde{\ell}^*_{R_i} H_1 \cdot \tilde{L}_j \;+\; {\rm h.c.}\right]$$

Electroweak symmetry breaking

Higgs potential

$$\begin{aligned} V_{\text{Higgs}} &= (m_{H_d}^2 + \mu^2) H_d^\dagger H_d + (m_{H_u}^2 + \mu^2) H_u^\dagger H_u + B\mu (H_u \cdot H_d + \text{h.c.}) \\ &+ \frac{g_1^2 + g_2^2}{8} (H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{g_2^2}{2} (H_d^\dagger H_u)(H_u^\dagger H_d), \end{aligned}$$

Electroweak symmetry breaking: negative mass^2 for some H_u,H_d combination

$$\partial V_{\text{Higgs}} / \partial H_d^0 = \partial V_{\text{Higgs}} / \partial H_u^0 = 0$$

Minimization condition μ^2 and $B\mu$

$$\tan\beta = v_u / v_d$$

$$\begin{aligned} \mu^2 &= \frac{1}{2} \left[\tan 2\beta (m_{H_u}^2 \tan\beta - m_{H_d}^2 \cot\beta) - M_Z^2 \right] \\ B\mu &= \frac{1}{2} \sin 2\beta \left[m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 \right] \end{aligned}$$

Higgs masses

5 scalars: h,H,A,H^+,H^-

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

$$\begin{aligned} m_A^2 &= -B\mu/\sin\beta\cos\beta \\ m_{H+}^2 &= m_A^2 + m_W^2 \\ m_{h,H}^2 &= \frac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right) \end{aligned}$$

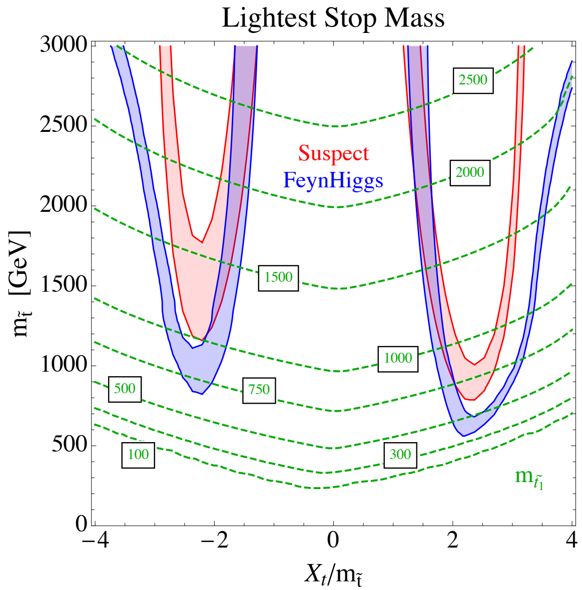
Upper bound on light Higgs mass

$$m_h < m_Z \cos 2\beta$$

Increase with radiative corrections (stops)

$$\Delta m_h^2 = \frac{3}{4\pi^2} v^2 y_t^2 \sin^4 \beta ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

Light Higgs mass



- Mass at 125 GeV
  - need large radiative corrections

$$m_h^2 \; = \; M_Z^2 \cos^2 2\beta + \delta_t^2$$

  - δ_t~85 GeV (comparable to tree-level)
  - Large stop mixing

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$X_t = A_t - \mu/\tan\beta$

The MSSM case

Fine-tuning issue

$$M_Z^2 \simeq -2\mu^2 + \frac{2(m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2)}{\tan^2\beta - 1}$$

Unless $\mu \sim O(100)$GeV (natural SUSY) need large cancellation

– implications for DM since μ determines the Higgsino component of the LSP

Fine-tuning also from radiative corrections – m_{Hu} strong dependence on parameters of stop sector

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

Fine-tuning

Barbieri-Giudici measure

$$\Delta_p \equiv \left| \frac{\partial \log m_Z^2}{\partial \log p} \right| \qquad \Delta \equiv \sqrt{\Delta_0^2 + \Delta_{\rm rad}^2}$$

In MSSM : (Δ_0 <100 if μ<700 GeV)

Casas et al, 1407.6966

Δ>100 -> %level fine-tuning

MSSM parameters

Soft Lagrangian: many new parameters ~105

Soft parameters obey RGE equations (can be quite different at weak scale and messenger scale (e.g. GUT scale or Planck scale or other intermediate scale)

If assume

- All parameters are real (no new source of CP violation) – no real justification
- All mass matrices and trilinear couplings are flavour diagonal -- want to avoid FCNC
- First and second generation are identical (constraints on rare processes, K , lepton)

MSSM : 22 new parameters

MSSM parameters

Real parameters and no flavour structure : 22 parameters

- $\tan\beta$: the ratio of the vevs of the two–Higgs doublet fields.
- $m^2_{H_u}, m^2_{H_d}$: the Higgs mass parameters squared.
- M_1, M_2, M_3: the bino, wino and gluino masses.
- $m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: the 1st/2nd generation sfermion masses
- $m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: the 3rd generation sfermion masses
- A_u, A_d, A_e: the 1st/2nd generation trilinear couplings.
- A_t, A_b, A_τ: the 3rd generation trilinear couplings.

Can trade scalar mass for more physical parameters : μ, M_A

Trilinear couplings of light fermions mostly irrelevant(except g-2,DD)

Constrained MSSM

- Underlying theory at high scale : relations amongst parameters at GUT scale – renormalisation group equations used to get MSSM spectrum at SUSY scale
- Heavily used in early studies – reduced number of parameters
- Unification of gaugino masses: $m_{1/2}$, scalar masses m_0, trilinear couplings A_0 at GUT scale
- Gaugino mass $M_3:M_2:M_1 = 6:2:1$
- Sfermions RH< LH $\quad m_{\tilde{q}_i}^2 \sim m_0^2 + 6m_{1/2}^2\,, \quad m_{\tilde{\ell}_L}^2 \sim m_0^2 + 0.52m_{1/2}^2\,, \quad m_{\tilde{e}_R}^2 \sim m_0^2 + 0.15m_{1/2}^2$
- Squarks heavier than sleptons
- In general $\mu >> M_1$ - bino LSP
- Focus point region (at large m0) $\mu \sim M_1$
  - Fixed point behaviour – value of Higgs mass parameters independent of boundary value (depends on top Yukawa)

Properties of supersymmetric particles

The neutralino mass matrix

$$\mathcal{M}_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & -\mu \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -\mu & 0 \end{pmatrix}$$

Mass and nature of neutralino LSP : determined by smallest mass parameter

- $M_1 < M_2, \mu$ bino
- $\mu < M_1, M_2$ Higgsino (in this case $m\chi_1 \sim m\chi_2 \sim m\chi_+$)
- $M_2 < \mu, M_1$ wino

Determine couplings of neutralino to vector bosons, scalars…

In most studied SUSY model CMSSM (or mSUGRA) the LSP is usually bino

Chargino mass matrix

$$M = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

$$M_{diag} = U M V^T$$

$$\tilde{\chi}^+ = V \tilde{\psi}^+ \quad \tilde{\chi}^- = U \tilde{\psi}^-$$

$$\tilde{\psi}^+ = (-i\tilde{w}^+, \tilde{h}_2^+)^T \quad \tilde{\psi}^- = (-i\tilde{w}^-, \tilde{h}_1^-)^T$$

Lightest chargino constrained by LEP direct searches >103GeV

M_2, μ >100GeV → restrictions on neutralino mass matrix

Additional relation $M_2=2M_1$ → lower bound on neutralino mass

Sfermion mass matrix

$$\begin{pmatrix} m^2_{\tilde{q}_{3L}} + m_t^2 + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) m_Z^2 \cos 2\beta & m_t\,(A_t - \mu\cot\beta) \\ m_t\,(A_t - \mu\cot\beta) & m^2_{\tilde{t}_R} + m_t^2 + \frac{2}{3}\sin^2\theta_W m_Z^2 \cos 2\beta \end{pmatrix}$$

$$\begin{pmatrix} m^2_{\tilde{\tau}_L} + m_\tau^2 - (\frac{1}{2} - \sin^2\theta_W) m_Z^2 \cos 2\beta & m_\tau\,(A_\tau - \mu\tan\beta) \\ m_\tau\,(A_\tau - \mu\tan\beta) & m^2_{\tilde{\tau}_R} + m_\tau^2 - \sin^2\theta_W m_Z^2 \cos 2\beta \end{pmatrix}$$

Charged fermions constrained by LEP direct searches >103GeV

L-R mixing relevant only for third generation (exception DD)

Neutralino

Neutral spin ½ *SUSY* partner of gauge bosons (Bino, Wino) and Higgs scalars (Higgsinos)

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2$$

Lightest neutralino is stable because of R-parity (also stabilizes the proton)

Neutralino is Majorana particle

Exact nature of neutralino (model dependent) will determine its annihilation properties – relevant for relic density, for indirect detection rate, for direct detection through interaction with nuclei in large detector

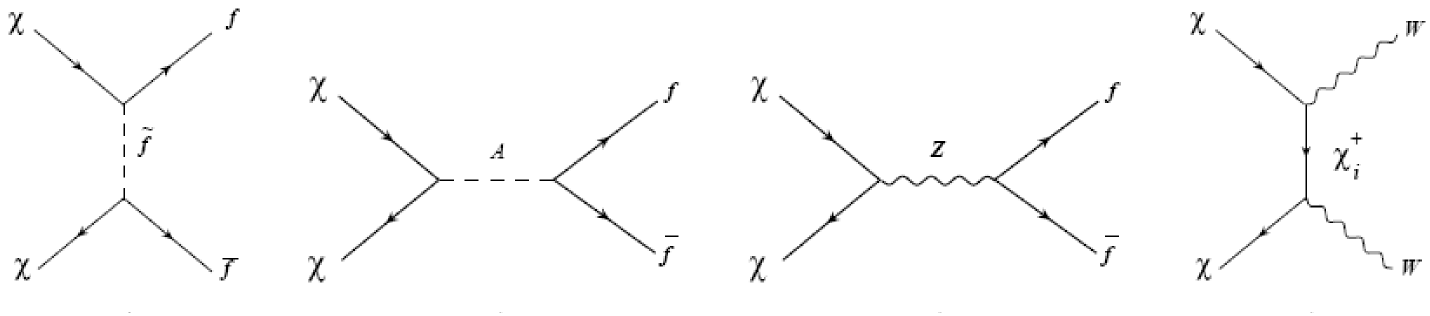
orders of magnitude variations in DM observables

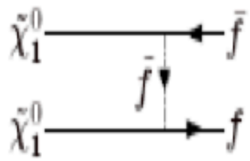
Since only SUSY particles known are SM ones : large parameter space to explore

Neutralino dark matter

Annihilation of LSP depend on parameters of model

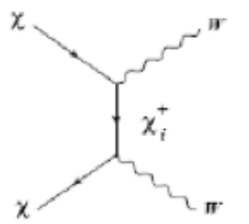
- Mass of neutralino LSP
- Couplings of LSP : whether neutralino (bino,wino, higgsino)
- Mass of sparticles exchanged
- Mass of NLSP (Stau, Neutralino2, Chargino)





- Bino: annihilates into fermions – sfermions must be light

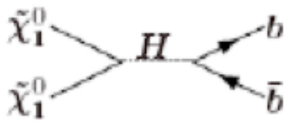
$$\sigma v \propto m_{\tilde{\chi}}^2 / m_{\tilde{l}}^4$$



- Mixed B/Higgs-ino : efficient into WW

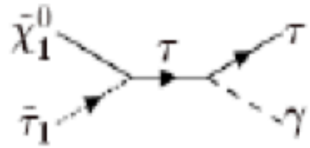
$$\sigma v \propto 1/m_{\tilde{\chi}}^2$$

- Mixed W/B/H-ino



- All (not pure bino): annihilation Higgs resonance

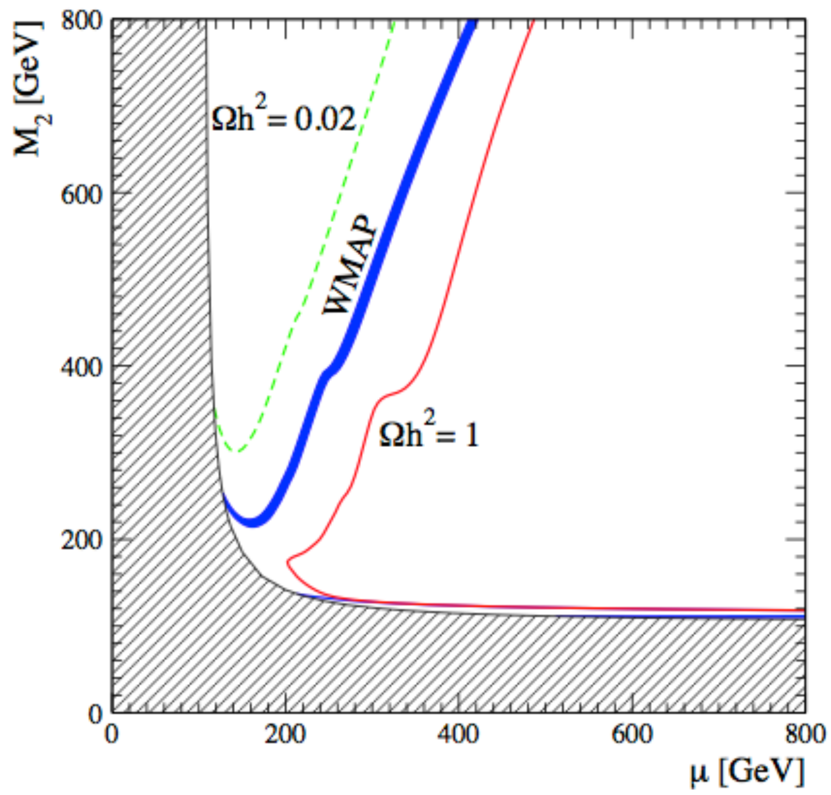
$$\sigma v \propto m_{\tilde{\chi}}^2 / (4m_{\chi}^2 - m_H^2)^2$$



- All: coannihilation possible suppression exp(-ΔM/T)

General remark

- Bino(U(1)): annihilation into fermion pairs, usually relic too large unless light sfermion and/or coannihilation
- Higgsino – annihilation into W pairs, large cross section, relic density too small unless DM mass >1 TeV
- Mixed state (bino/higgsino and/or wino) : adjust coupling for correct relic density
- Possibility of annihilation through resonance: if mLSP~mh/2 coupling can be very small

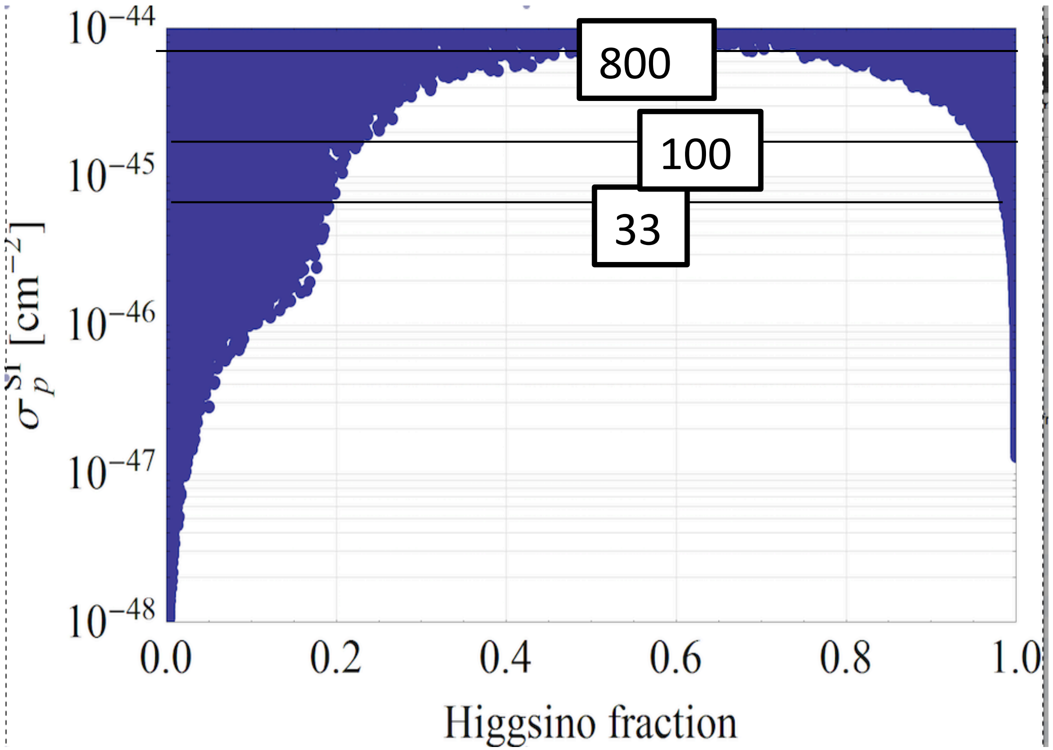


$M_2=2M_1$

Direct detection

- Coupling of neutralino to Higgs maximal for a mixed state

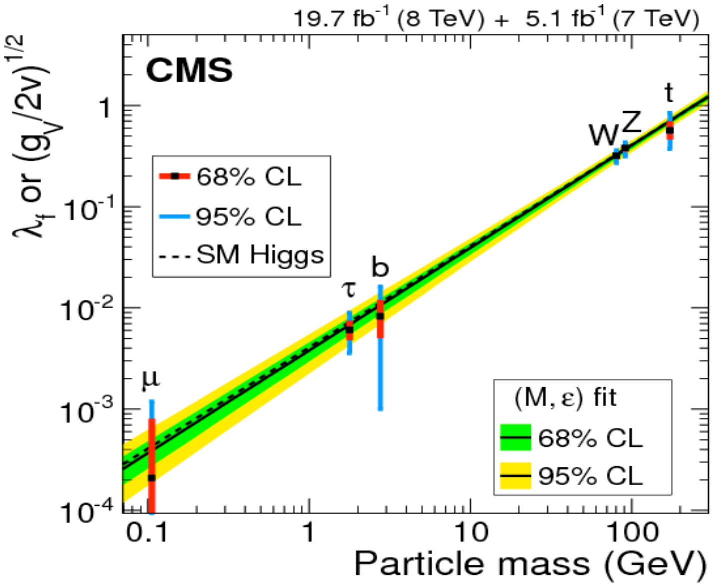
$$g_{h\chi\chi} = g(N_{\chi 2} - t_W N_{\chi 1})(N_{\chi 3}\sin\alpha + N_{\chi 4}\cos\alpha)\,.$$

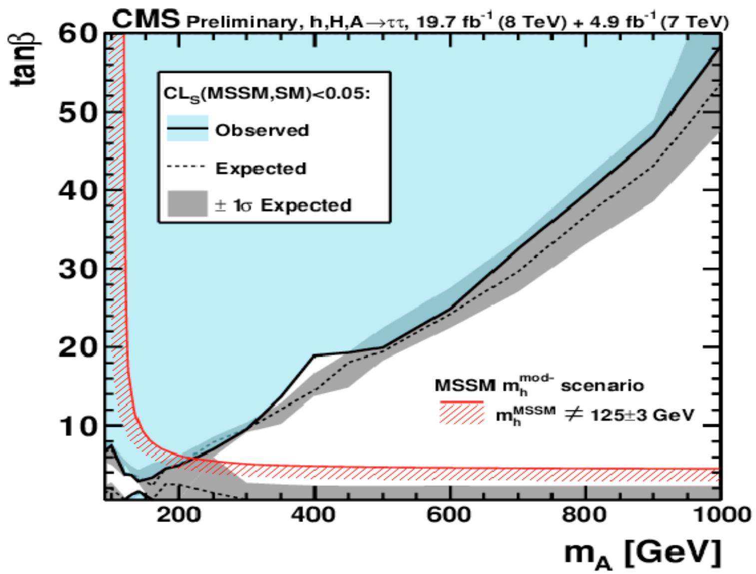


Constraints from DD (LUX) on Neutralinos that naturally Reproduce measured relic density

LHC - Higgs

- Discovery of SM-like Higgs with mass of 125 GeV impose strong constraint on supersymmetric models
- Need large enough corrections to tree-level mass (bounded by MZ) – constrain stop sector
- Higgs couplings are SM-like – decoupling limit – large M_A
- No large contribution from susy in loops + small invisible width

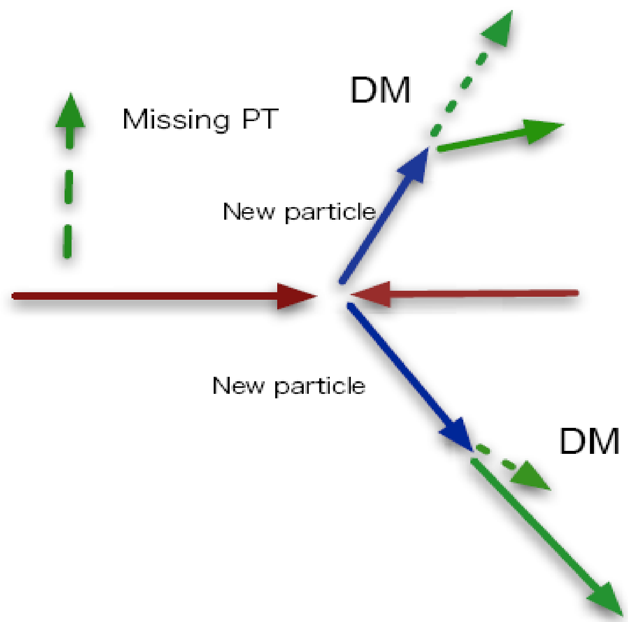




SUSY production at LHC

- pp collider 10-14TeV
- Direct production : missing energy no trigger
- Production of coloured particles: DM in decay chain

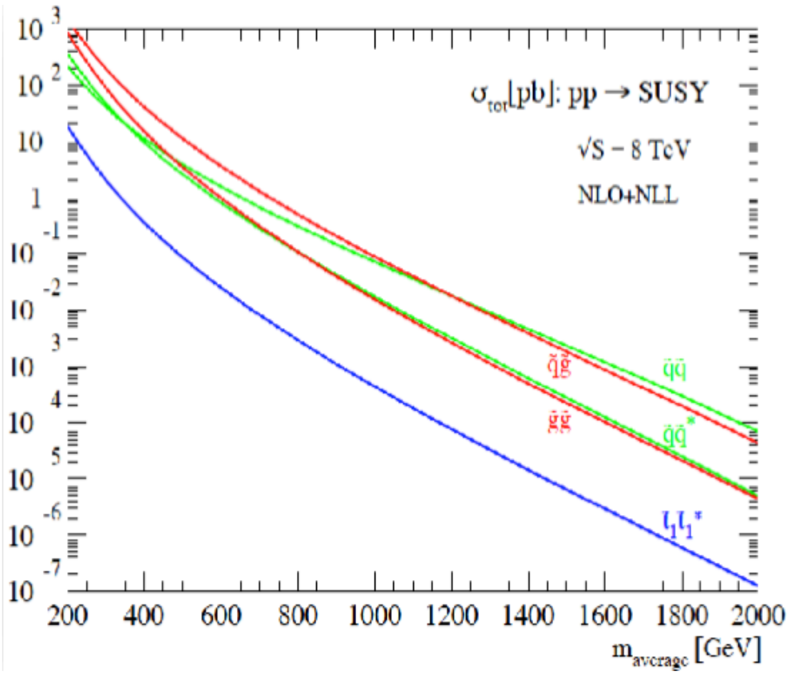
- Signatures include Missing E_T

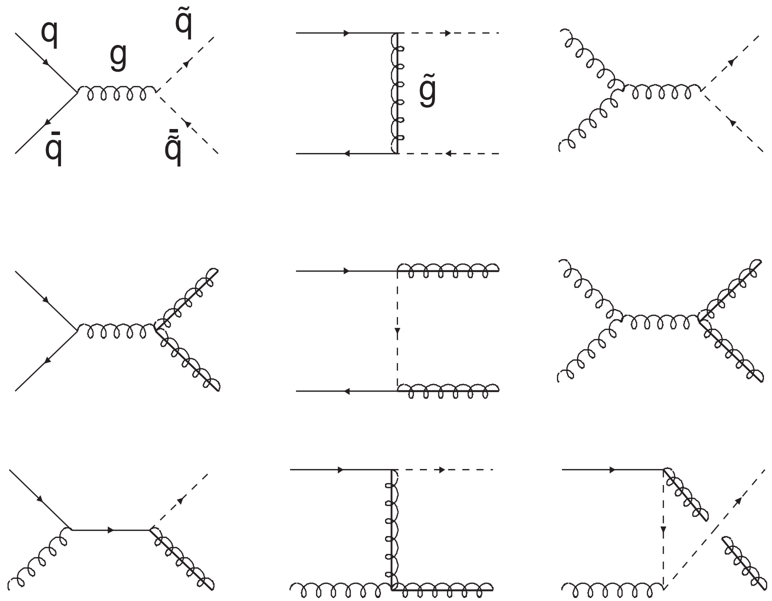


- For direct DM production : gluon or radiation from initial state

LHC – SUSY

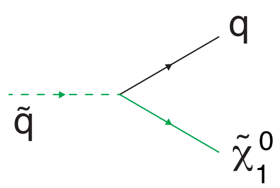
Standard susy searches : coloured particles

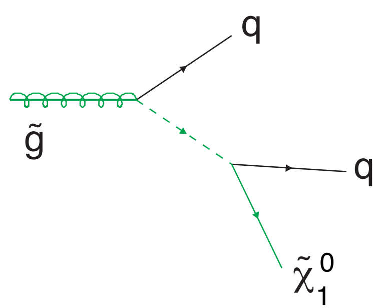




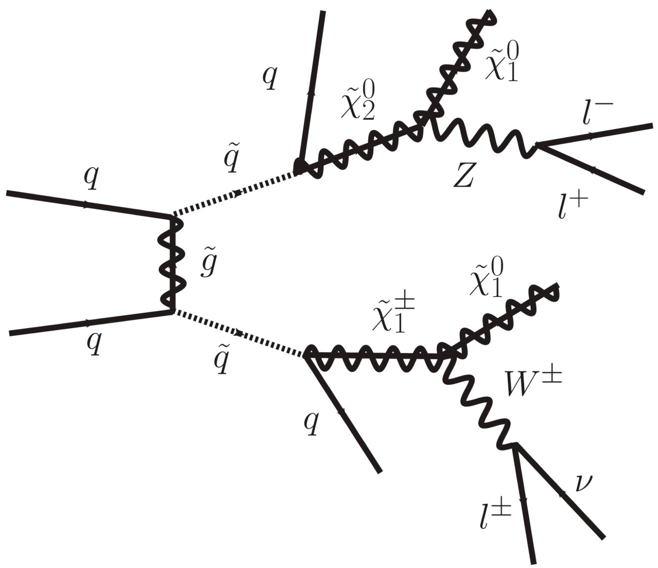
LHC – SUSY

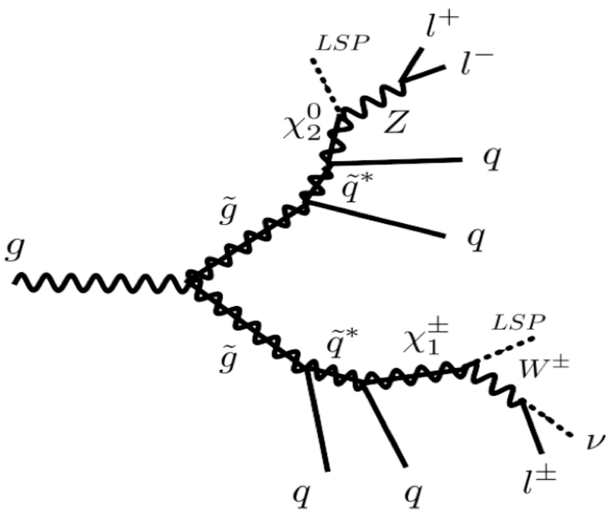
- Signatures of squarks and gluinos : jets+MET





- Jets+MET +Leptons



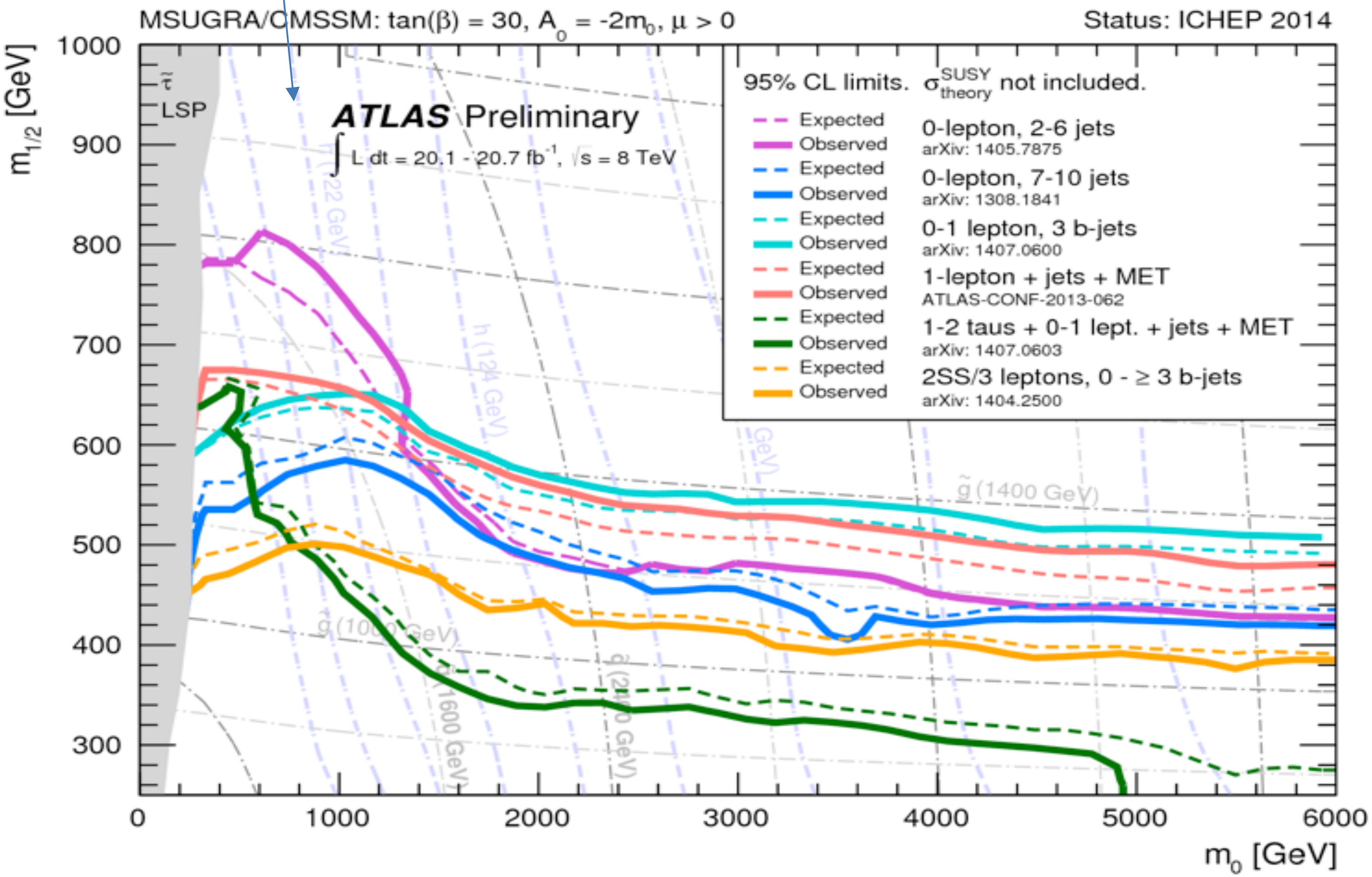


Neutralino in CMSSM

- Traditionally predictions in context of CMSSM (scenario with parameters defined at unification scale) full spectrum predictable from handful of parameters
- Neutralino is generally bino U(1) (too much dark matter unless m ~100GeV) or bino/higgsino
- Relations between masses of particles – e.g. m_{gluino}~6 m_{LSP}
- LHC has put strong constraints on this model – because m_h=125GeV with SM-like couplings, no squarks and/or gluino discovered , no evidence of SUSY in B physics

LHC limits on CMSSM

mh>122 GeV

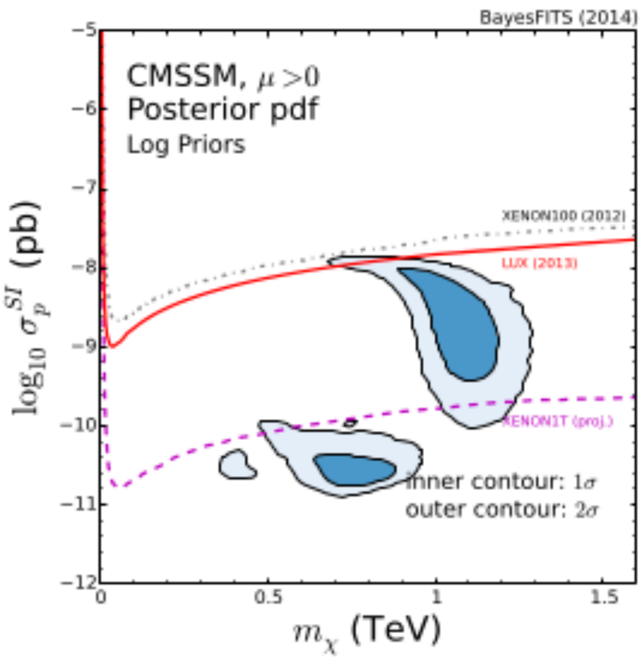


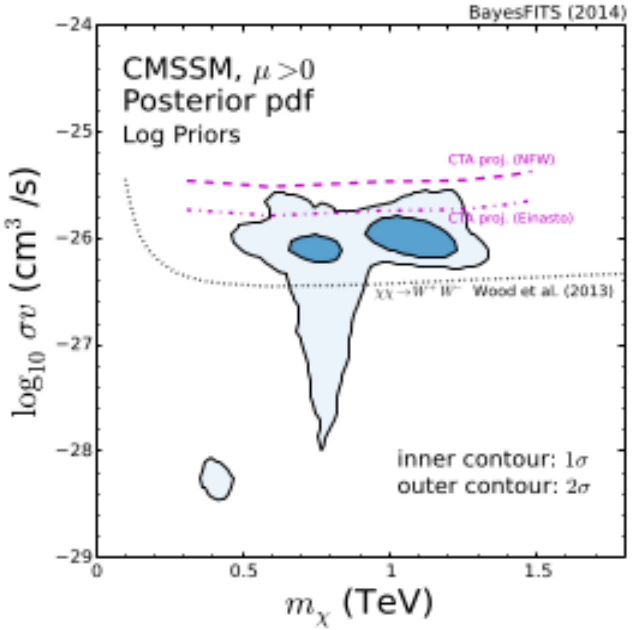
- Gluino>1.4TeV, squark > 1.7 TeV

What's left?

After fit to all observables (relic,LUX,flavour,LHC)

L. Roszkowski 1405.4289



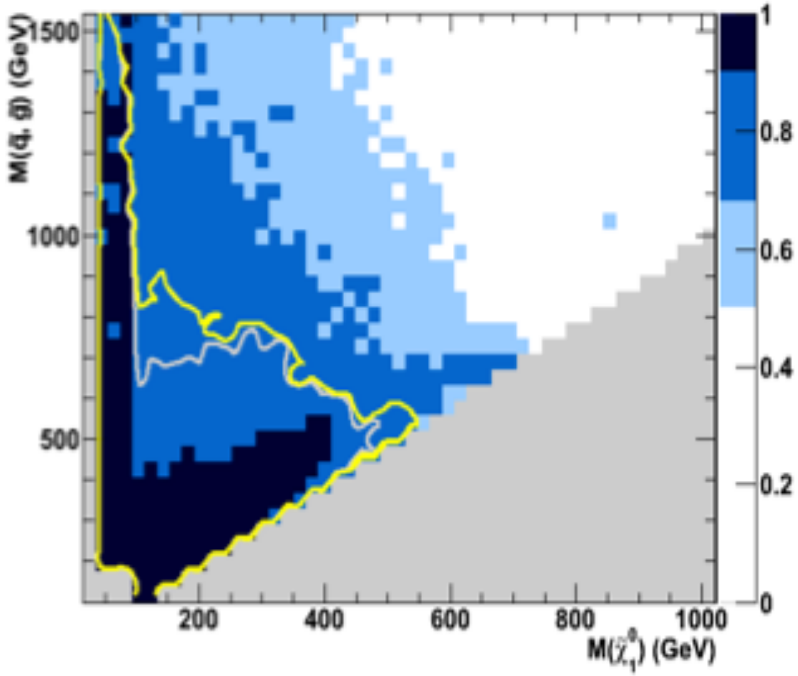


- Indirect detection : annihilation into bb and WW are usually dominant, annihilation into light fermions are suppressed at small v

Neutralino in pMSSM

- Constrained model too restrictive
- pMSSM : phenomenological MSSM – EW scale input parameters ~19 with few assumptions
- Decouple strong and electroweak sector
- LHC bounds from electroweak-ino searches (much weaker)
- Include all particle physics constraints, Higgs, flavour, LHC-susy+monojet
- Only upper bound on relic density

Arbey, Battaglia, Mahmoudi, 1311.7641



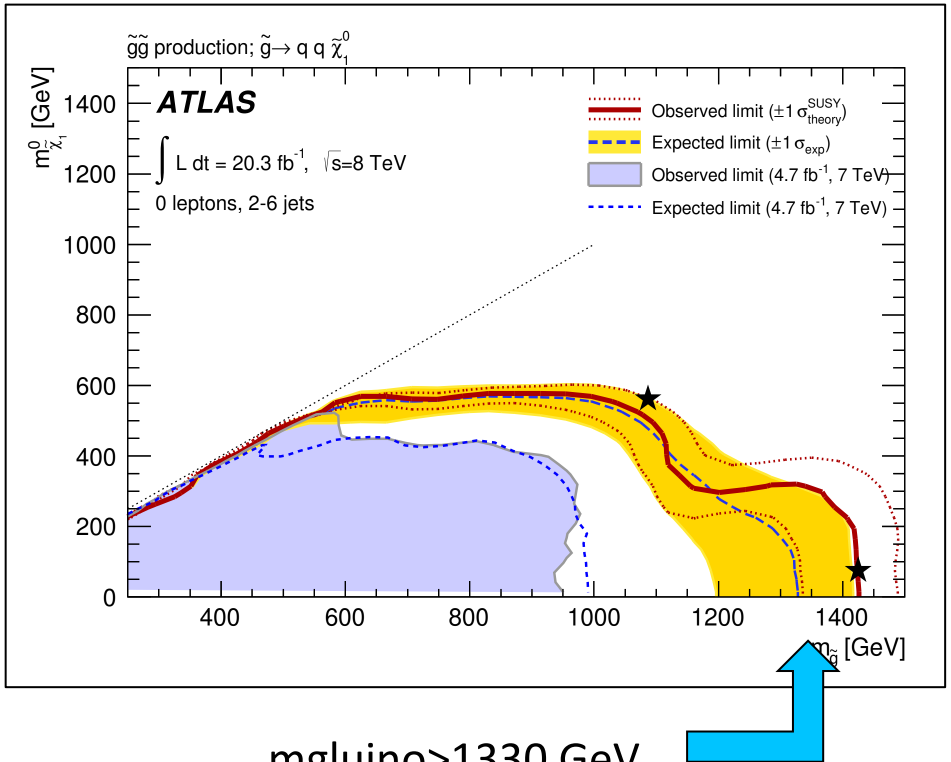
Any mass for neutralino above 30 GeV still allowed

SUSY search channels

- 0lepton + jets
- Third generation
- Monojet
- Disappearing or charged tracks

0lepton+ 2-6jets+MET

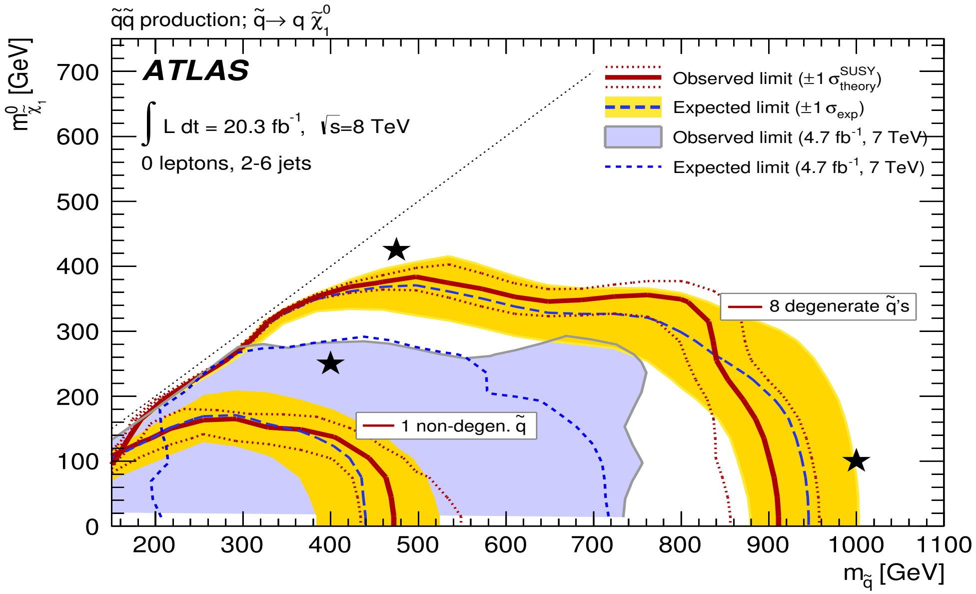
- Wide ranging sensitivity to strong particle production with squark-> q+LSP and gluino-> qq+LSP + various cascade decays
- High (low) multiplicity : gluinos (squarks)



mgluino>1330 GeV

0lepton+ 2-6jets+MET

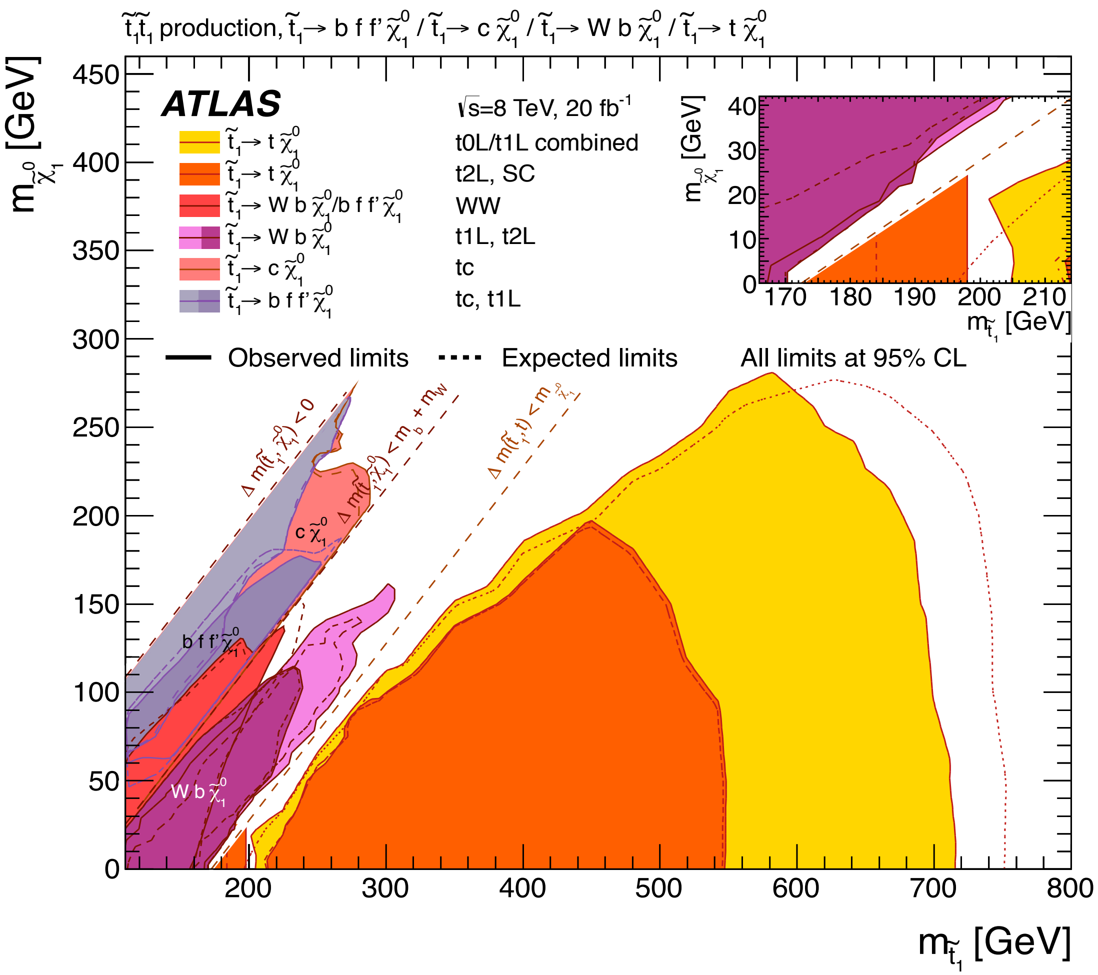
- Wide ranging sensitivity to strong particle production with squark-> q+LSP and gluino-> qq+LSP + various cascade decays
- High (low) multiplicity : gluinos (squarks)



Msquark>850 GeV

3rd generation

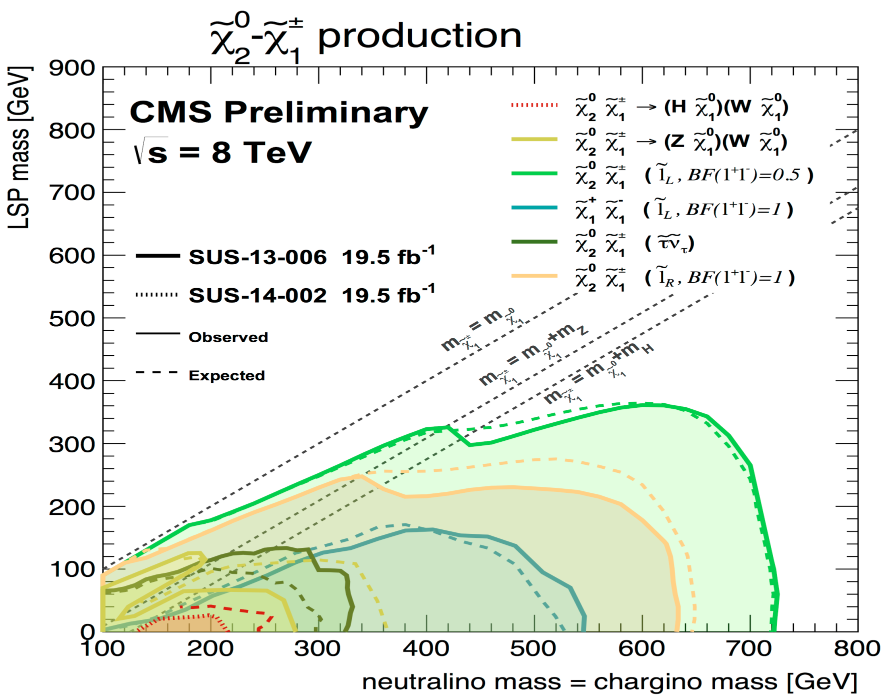
- Simplified models, Stops -> t+LSP, + …

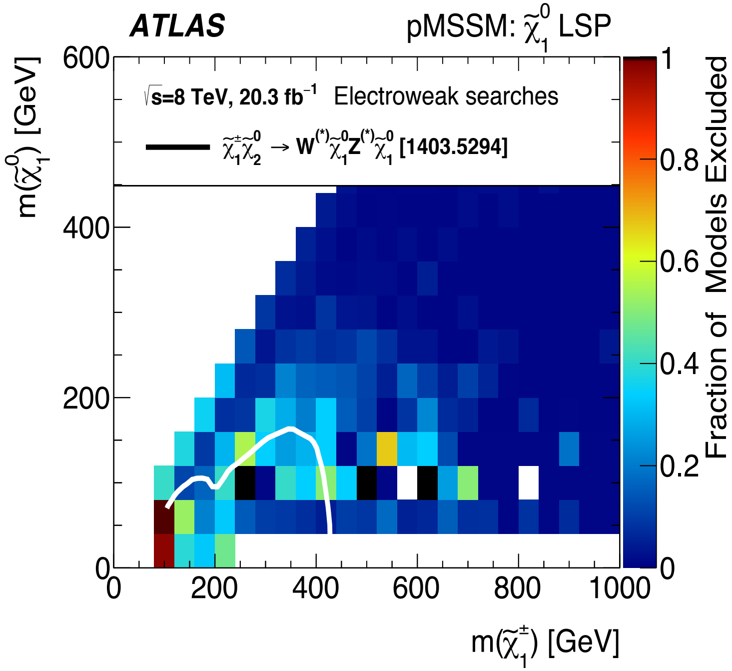


ATLAS 1508.08616

Electroweak-inos

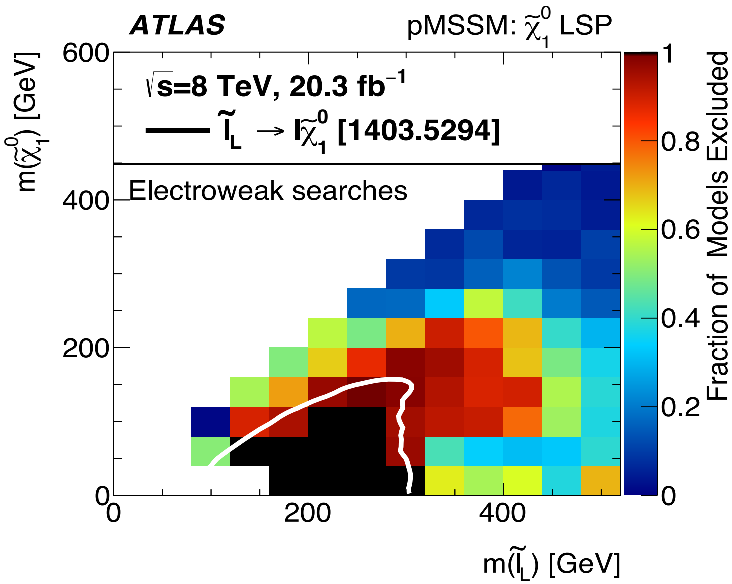
- Direct connection with dark matter (neutralino sector)
- Reach dependent on search channel (here simplified model)
- Weak constraints on charginos which decay into gauge bosons





Sleptons

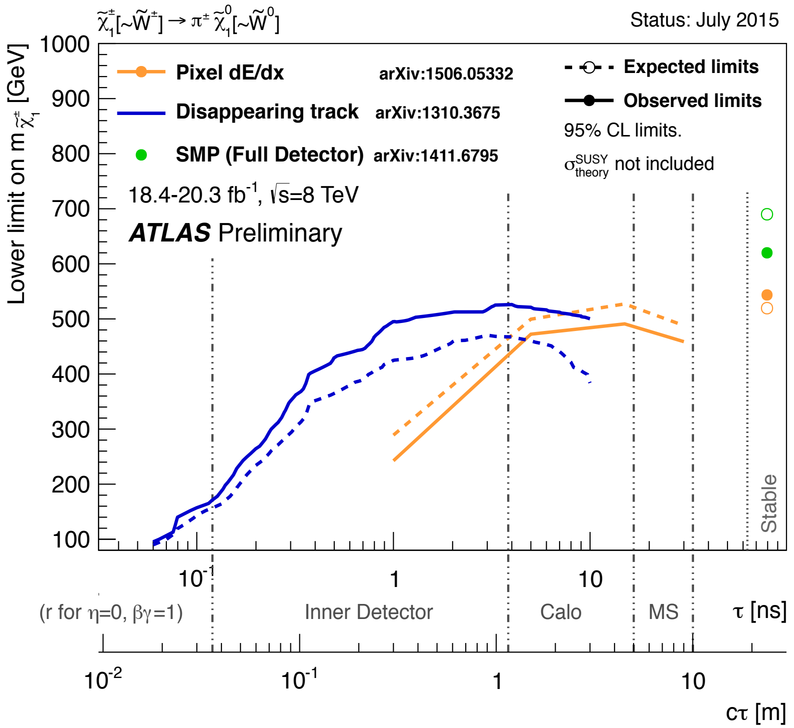
- Weak constraints, especially when small mass splitting with LSP



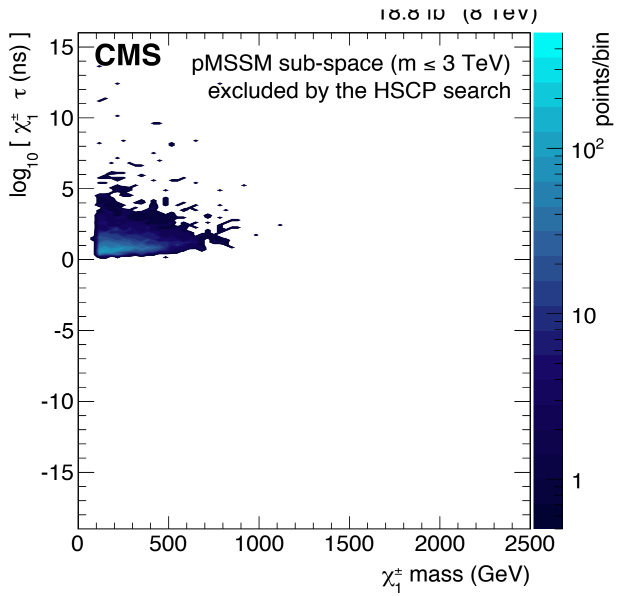
ATLAS 1508.06608

Long-lived particles

- In SUSY, charged/neutral winos have very small mass splitting (<3GeV) -> displaced vertex or stable
- But cannot explain all DM



ATLAS 1506.05332



CMS 1502.02522

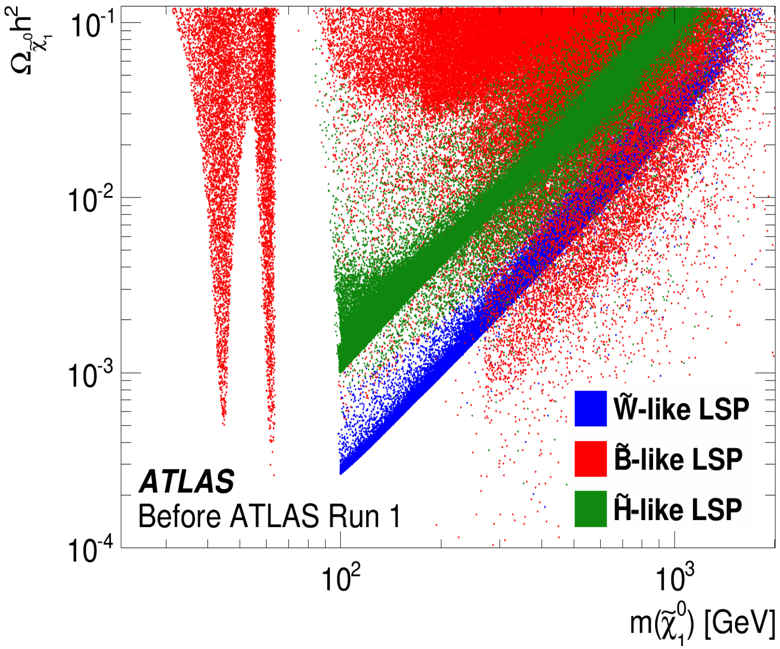
What's left after LHC

production of DM + jet from ISR and/or compressed spectra

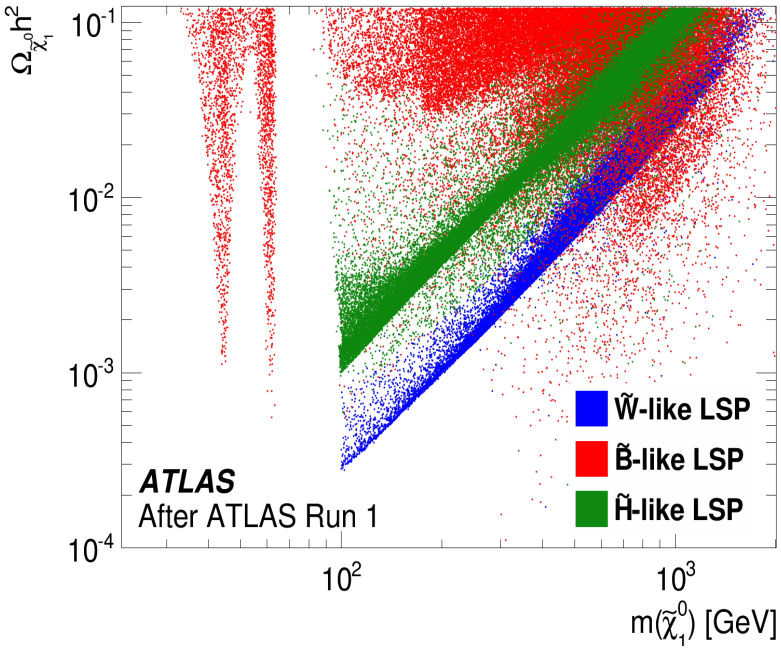
Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
$tb+E_T^{miss}$, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

ATLAS 1508.06608

What's left after LHC



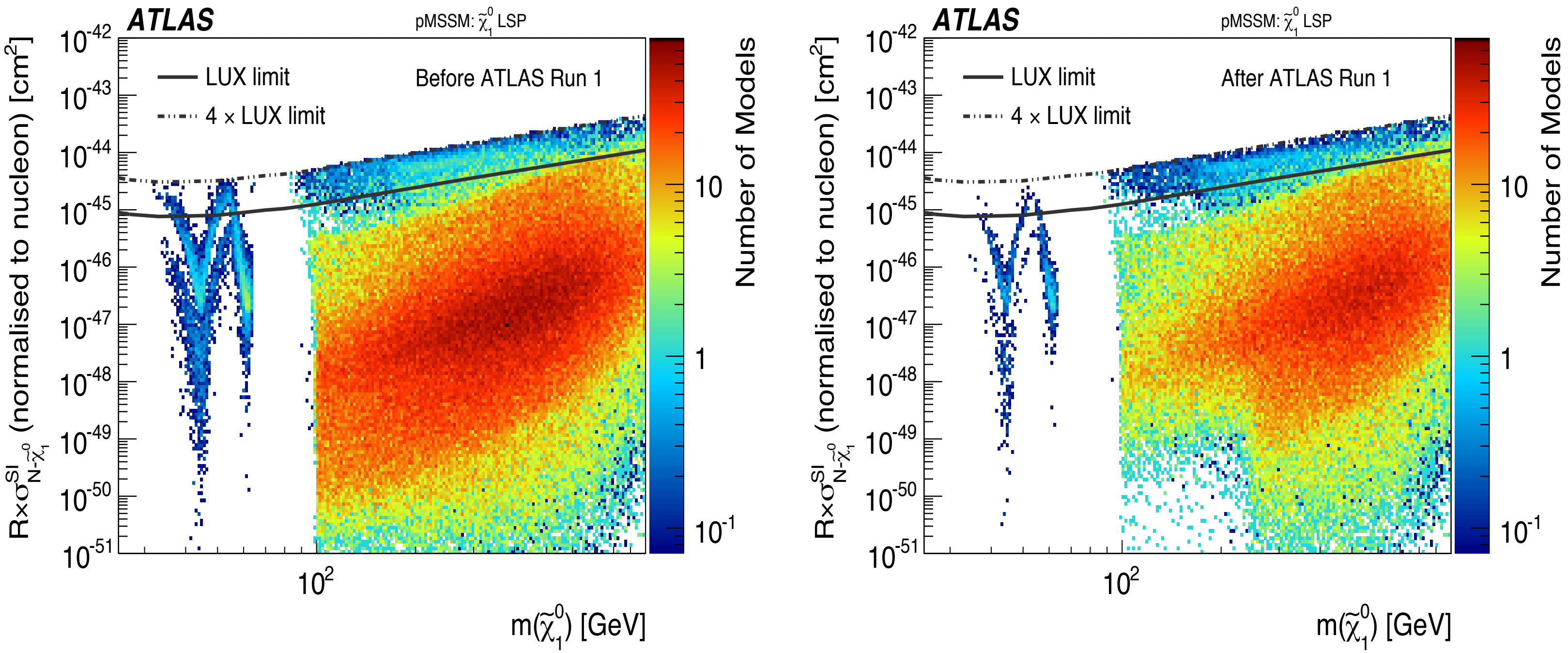
(a) Before ATLAS Run 1



(b) After ATLAS Run 1

ATLAS 1508.06608

What's left after LHC



ATLAS 1508.06608

Summary MSSM+DM

- Higgs mass → fine-tuning issue with MSSM, heavily mixed stops
- Coloured sector under pressure by LHC if below TeV -> more at 13 TeV
- Electroweak sector still wide open
- Higgs decays -> constrain light LSP (more later)
- Flavour physics : constrain large tanbeta
- Neutralino as a single DM component under pressure
    - Bino : constrained Higgs + direct search
    - Mixed higgsino/gaugino : constrain by LUX
    - Pure higgsino or pure wino : not enough relic + long-lived particles