An overview into Supersymmetry: Current experimental status

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Outline

1. Supersymmetry

   ⇒ What is it?
   ⇒ Motivating new physics;
   ⇒ A bit of theory. A minimal extension to the SM.

2. Direct searches and constraints

   ⇒ Gluinos/Neutralinos;
   ⇒ Squarks;
   ⇒ Charginos;
   ⇒ Sleptons.

3. Conclusions

SUSY? What is it?

$\boxed{\text{A symmetry between fermions and bosons}}$

$$Q\,|\text{Fermion}\rangle = |\text{Boson}\rangle \qquad \{Q, Q^\dagger\} = 2i\sigma^\mu P_\mu$$
$$Q\,|\text{Boson}\rangle = |\text{Fermion}\rangle \qquad \{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0$$

To every particle, we assign a superpartner $\longrightarrow$ We are essentially doubling the particle content !

With more particles, more parameters that may be introduced, which means more arbitrariness in the model. So, is it truly necessary?

Provides a potential formalism for the addition of gravity

Addresses quadratic divergences in the Higgs mass

Offers good dark matter candidates

SUSY? What is the point?

Unification of forces at high energy scales

SUSY provides a solid mathematical framework that can effectively address the main issues with the Standard Model (SM)!

These theories usually require some key ingredients not common in standard field theories, so a bit formalism …

Chiral supermultiplet

$$\mathcal{L} = i\psi^{\dagger i}\bar{\sigma}^{\mu}D_{\mu}\psi_i + D^{\mu}\phi^{*i}D_{\mu}\phi_i - W^{*i}W_i - \left(\frac{1}{2}W^{ij}\psi_i\psi_j + \text{H.c.}\right)$$

We can work out a *superpotential*

$$W = \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k \longrightarrow$$

Derivatives with respect to ϕ fields to get W_i and W^{ij}.

Vector supermultiplet

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a + i(\lambda^a)^{\dagger}\bar{\sigma}^{\mu}D_{\mu}\lambda_a + \frac{1}{2}D^aD_a$$

With $D^a = -g\phi_i^*\left[T^a\right]^{ij}\phi_j$.

$$D_{\mu}\lambda^a = \partial_{\mu}\lambda^a - gf^a{}_{bc}A^b_{\mu}\lambda^c$$

Interactions

$$\mathcal{L} = g(\phi_i^*\left[T^a\right]^{ij}\psi_j)\lambda^a + g\lambda^{a\dagger}(\psi_i^{\dagger}\left[T^a\right]^{ij}\phi_j) + g(\phi_i^*\left[T^a\right]^{ij}\phi_j)D^a$$

Interactions are imposed via an underlying gauge symmetry, encoded in a covariant derivative.

$$D_{\mu} = \partial_{\mu} - ig\frac{T_a}{2}A^a_{\mu}$$

"Standard Model" of SUSY: MSSM

Superfield	$\mathrm{SU(3)_C}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	# of generations
$\boldsymbol{W} = (W^a,\, \tilde{W}^a)$	$\mathbf{1}$	$\mathbf{3}$	0	1
$\boldsymbol{B} = (B,\, \tilde{B})$	$\mathbf{1}$	$\mathbf{1}$	0	1
$\boldsymbol{G} = (G^a,\, \tilde{G}^a)$	$\mathbf{8}$	$\mathbf{1}$	0	1

Superfield	$\mathrm{SU(3)_C}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	# of generations
$\boldsymbol{Q} = (Q,\, \tilde{Q})$	$\mathbf{3}$	$\mathbf{2}$	1/6	3
$\bar{\boldsymbol{u}}_{\boldsymbol{R}} = (u_R^\dagger,\, \tilde{u}_R^\dagger)$	$\bar{\mathbf{3}}$	$\mathbf{1}$	−2/3	3
$\bar{\boldsymbol{d}}_{\boldsymbol{R}} = (d_R^\dagger,\, \tilde{d}_R^\dagger)$	$\bar{\mathbf{3}}$	$\mathbf{1}$	1/3	3
$\boldsymbol{L} = (L,\, \tilde{L})$	$\mathbf{1}$	$\mathbf{2}$	-1/2	3
$\bar{\boldsymbol{e}}_{\boldsymbol{R}} = (e_R^\dagger,\, \tilde{e}_R^\dagger)$	$\mathbf{1}$	$\mathbf{1}$	1	3
$\boldsymbol{H_u} = (H_u,\, \tilde{H}_u)$	$\mathbf{1}$	$\mathbf{2}$	1/2	1
$\boldsymbol{H_d} = (H_d,\, \tilde{H}_d)$	$\mathbf{1}$	$\mathbf{2}$	-1/2	1

MSSM is the minimal extension to the SM, with the least amount of new states.

SUSY does not exist at the EW scale

$\downarrow$

Additional soft-breaking terms are needed.

$$W = (y_u)_{ij}\bar{\boldsymbol{u}}^i_{\boldsymbol{R}}\boldsymbol{Q}^j\boldsymbol{H_u} - (y_d)_{ij}\bar{\boldsymbol{d}}^i_{\boldsymbol{R}}\boldsymbol{Q}^j\boldsymbol{H_d} - (y_e)_{ij}\bar{\boldsymbol{e}}^i_{\boldsymbol{R}}\boldsymbol{L}^j\boldsymbol{H_u} + \mu\boldsymbol{H_u}\boldsymbol{H_d}$$

Two Higgs doublets are needed for mass generation so not to break SUSY.

Additional R-symmetry, $R = (-1)^{3(\mathrm{B-L+2S})}$, to prevent lepton and baryon violating terms.

Phenomologically important: SUSY particles must be pair-produced. The lightest SUSY particle can not decay $\longrightarrow$ **Viable Dark matter !**

Breaking of SU(2) via the Higgs mechanism $\longrightarrow$ Mass for gauge bosons (the same as the SM). Mass for **five** new Higgs scalars

SM fermions gain its mass via the same process.

Nomenclature	Mass basis	Interacting basis
Higgs	$h^0, H^0, A^0, H^\pm$	$H_u^0, H_d^0, H_d^+, H_d^-$
squarks	$(\tilde{u}_L, \tilde{u}_R)$ $(\tilde{u}_L, \tilde{d}_R)$	–
	$(\tilde{s}_L, \tilde{s}_R)$ $(\tilde{c}_L, \tilde{c}_R)$	–
	$(\tilde{t}_1, \tilde{t}_2)$ $(\tilde{b}_1, \tilde{b}_2)$	$(\tilde{t}_L, \tilde{t}_R)$ $(\tilde{b}_L, \tilde{b}_R)$
sleptons	$(\tilde{e}_L, \tilde{e}_R)$ $\tilde{\nu}_e$	–
	$(\tilde{\mu}_L, \tilde{\mu}_R)$ $\tilde{\nu}_\mu$	–
	$(\tilde{\tau}_1, \tilde{\tau}_2)$ $\tilde{\nu}_\tau$	$(\tilde{\tau}_L, \tilde{\tau}_R)$ $\tilde{\nu}_\tau$
Neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$\tilde{B}, \tilde{Z}^0, \tilde{H}_u^0, \tilde{H}_d^0$
Charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\tilde{W}^\pm, \tilde{H}_u^+, \tilde{H}_d^-$
gluino	$\tilde{g}$	–

At this point in time, no experimental observation of SUSY particles at the EW scale as been observed.

Either SUSY particles do not exist, or SUSY breaks at a higher energy scale.

$\Rightarrow$ Higher breaking scale indicates heavier states (m > 1 TeV);

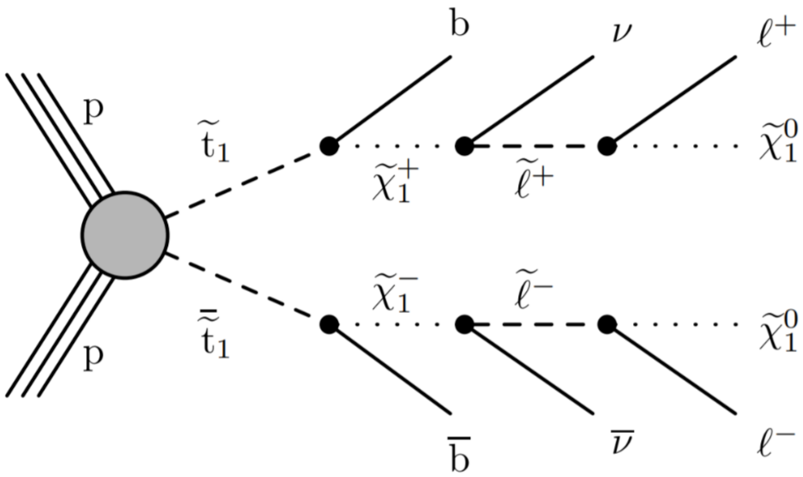
$\Rightarrow$ Production is easily achievable by current particle accelerators.

Due to lack of observation, many experimental searches have been relegated to constraining SUSY.

We will be focusing in the most up-date searches at ATLAS and CMS.

ATLAS/CMS operate for pp collisions $\Rightarrow$ **Favors colored particle production!**

However, “dirtier” events are common, with backgrounds dominated by multijet events, mainly of top production origin.



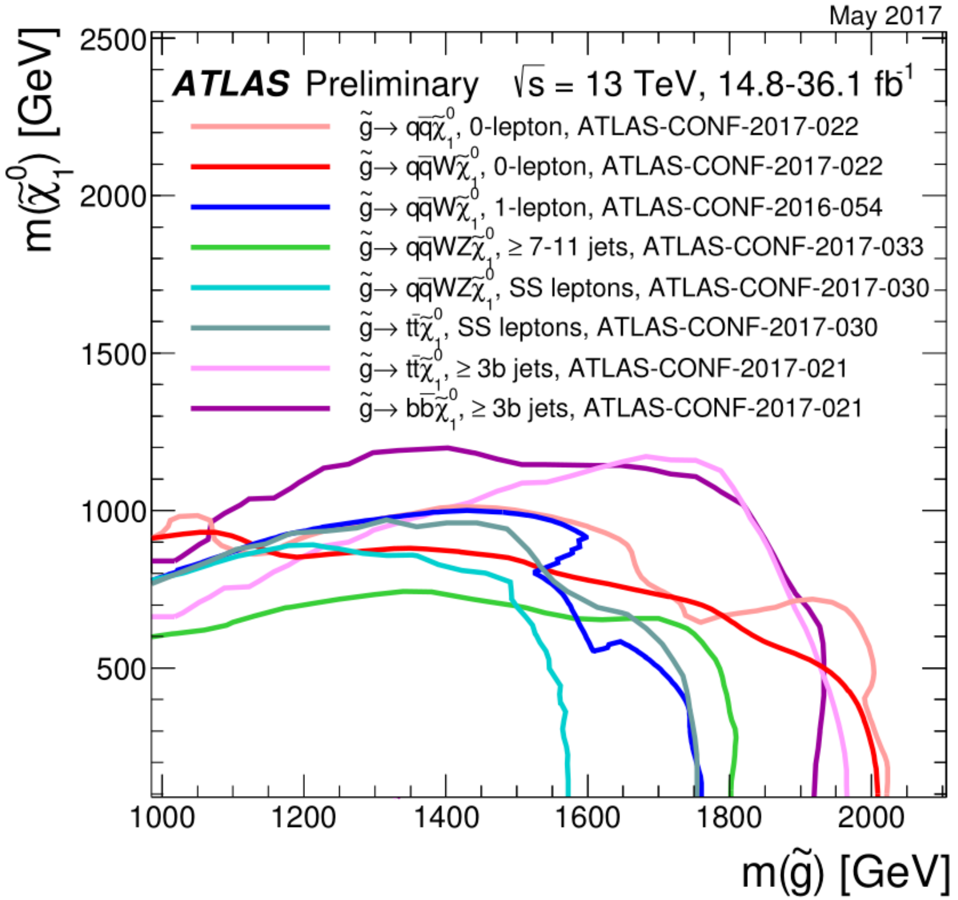
arXiv:1808.05936

$\Rightarrow$ High p_T jets and substantial $\not{E}_T$.

$\Rightarrow$ Typical variables include H_T, $\not{E}_T$ and effective mass (sum of the two).

For SM backgrounds, the effective mass is dominant for lower energies.

Most exclusions are model dependent, with constraints varying by considered assumptions



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⇒ For massless neutralinos, gluinos can be excluded for masses upwards of 2 TeV.

⇒ Weaker constraints for light neutralinos.

⇒ Stronger constraints for channels with intermediate tops.

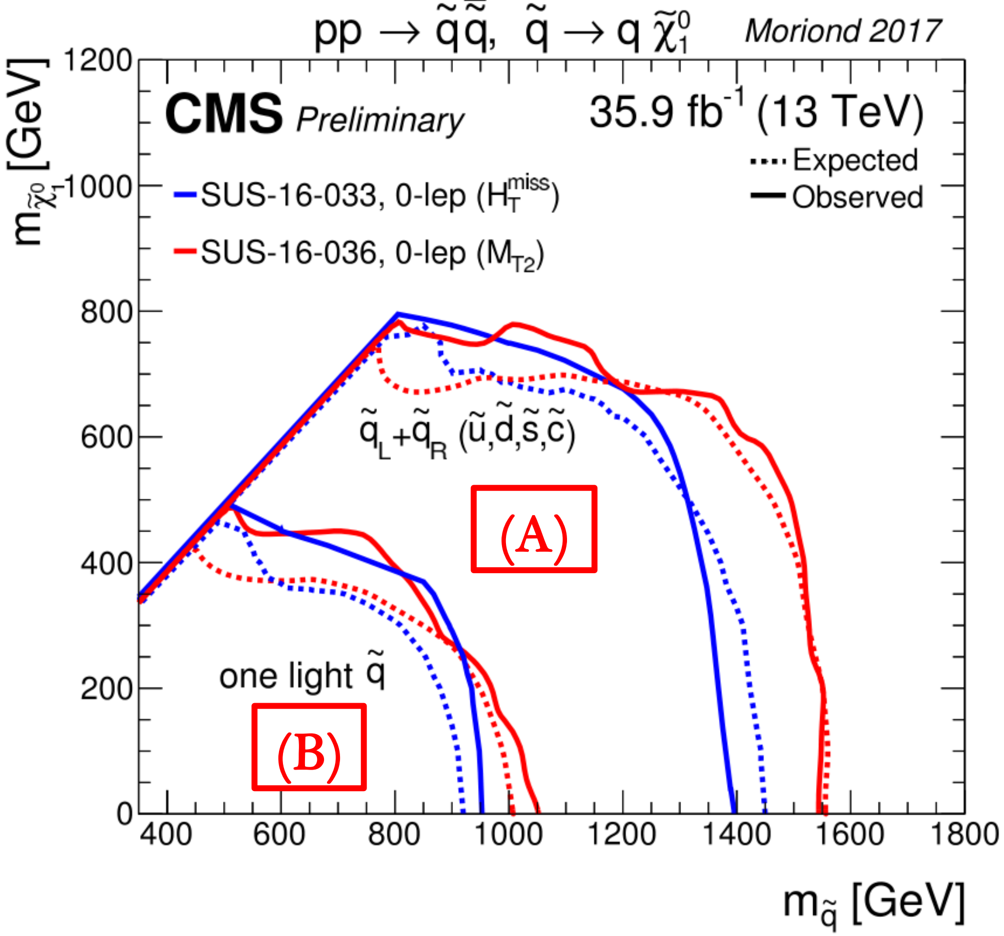
Squarks play a vital rule in stabilizing quadratic divergences in the Higgs sector.

Single decay chains $\tilde{q} \to q\tilde{\chi}_1^0$ and heavy gluinos:

(A) Constraints assuming degenerate 1st/2nd generation squarks;

(B) Looser constraints. 1st/2nd not degenerate.

SM backgrounds are dominant for looser constraints.



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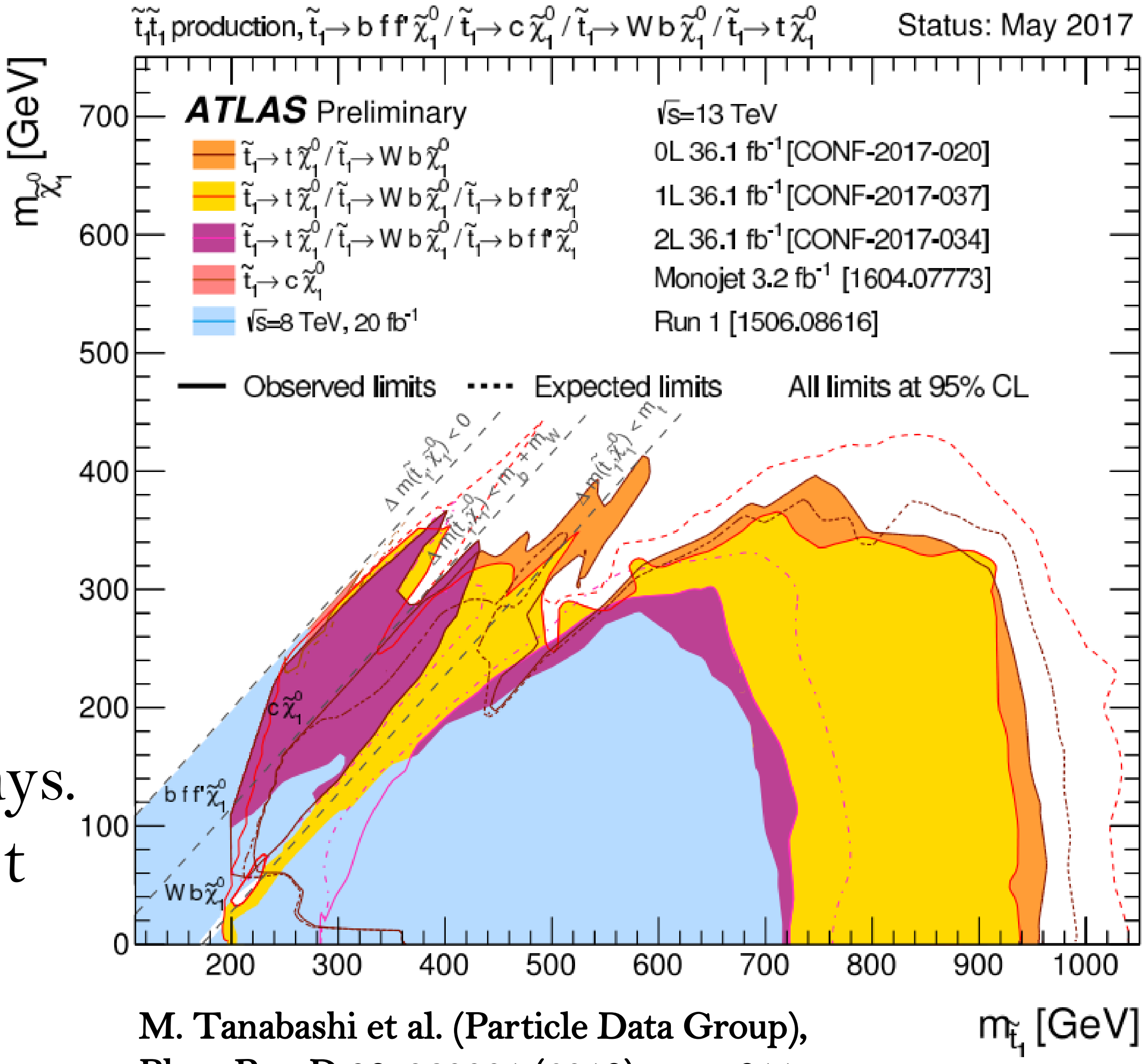
Big interlay between $t\bar{t}H$ coupling and 3rd generation squark masses.

Decays depend on SUSY spectrum:

$$\Rightarrow \tilde{t} \to t\tilde{\chi}^0 \;\text{ for }\; m_{\tilde{t}} - m_{\tilde{\chi}^0} > m_t\,;$$

$$\Rightarrow \tilde{t} \to b\tilde{\chi}^\pm \;\text{ for }\; m_{\tilde{t}} - m_{\tilde{\chi}^\pm} > m_b\,.$$

Stronger constraints from the above decays. Constraints loosen if other channels start to open up.



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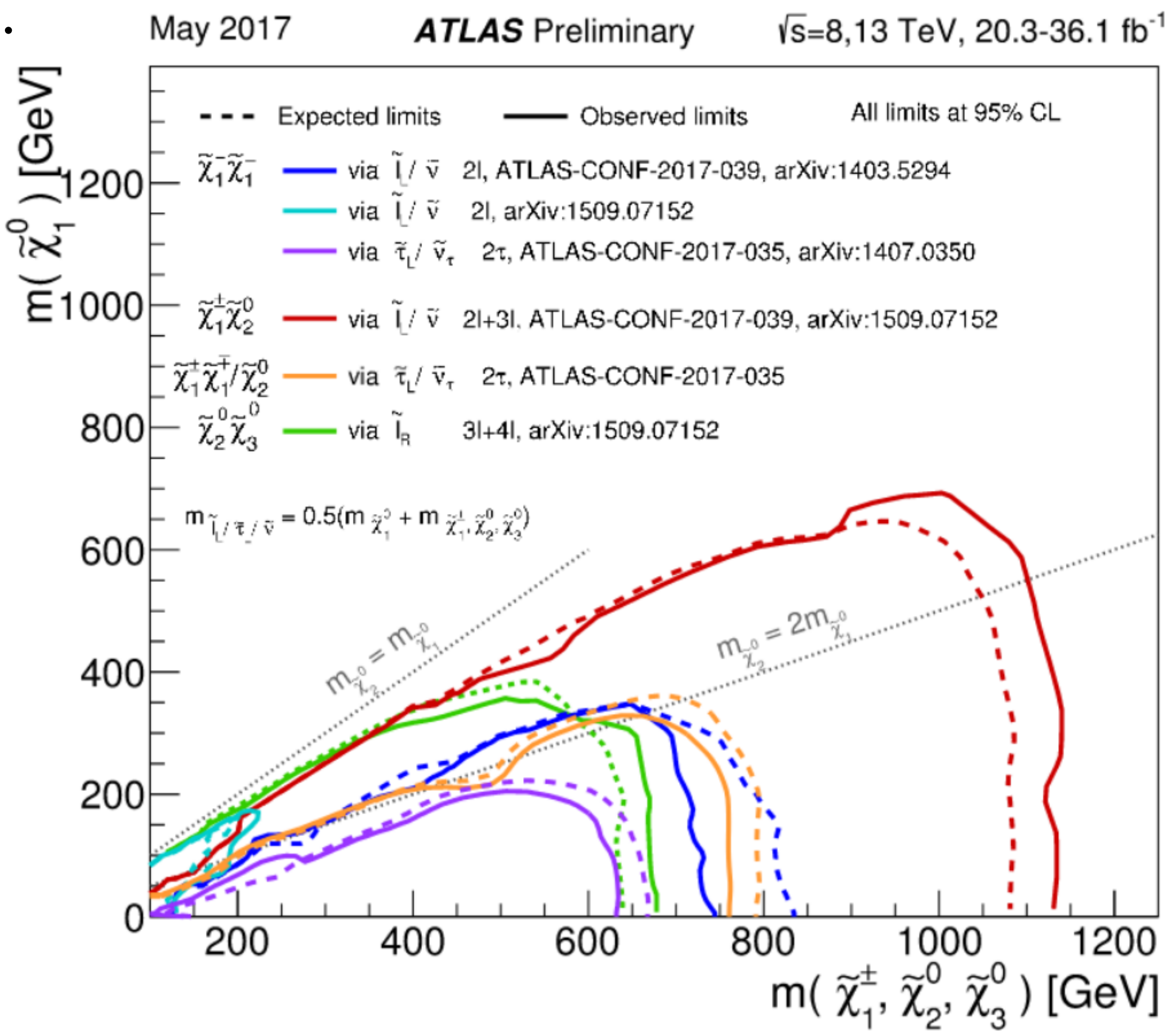
Mixtures of winos and charged Higgsinos.

Looking at channels with light sleptons as mediators of the decays:

- $\Rightarrow$ Dilepton: Up to 800 GeV for charginos. No constraints for $m_{\tilde{\chi}_1^0} > 350$ GeV.
- $\Rightarrow$ Stronger limits from trilepton channel.

Looser constraints for scenarios with heavy sleptons.



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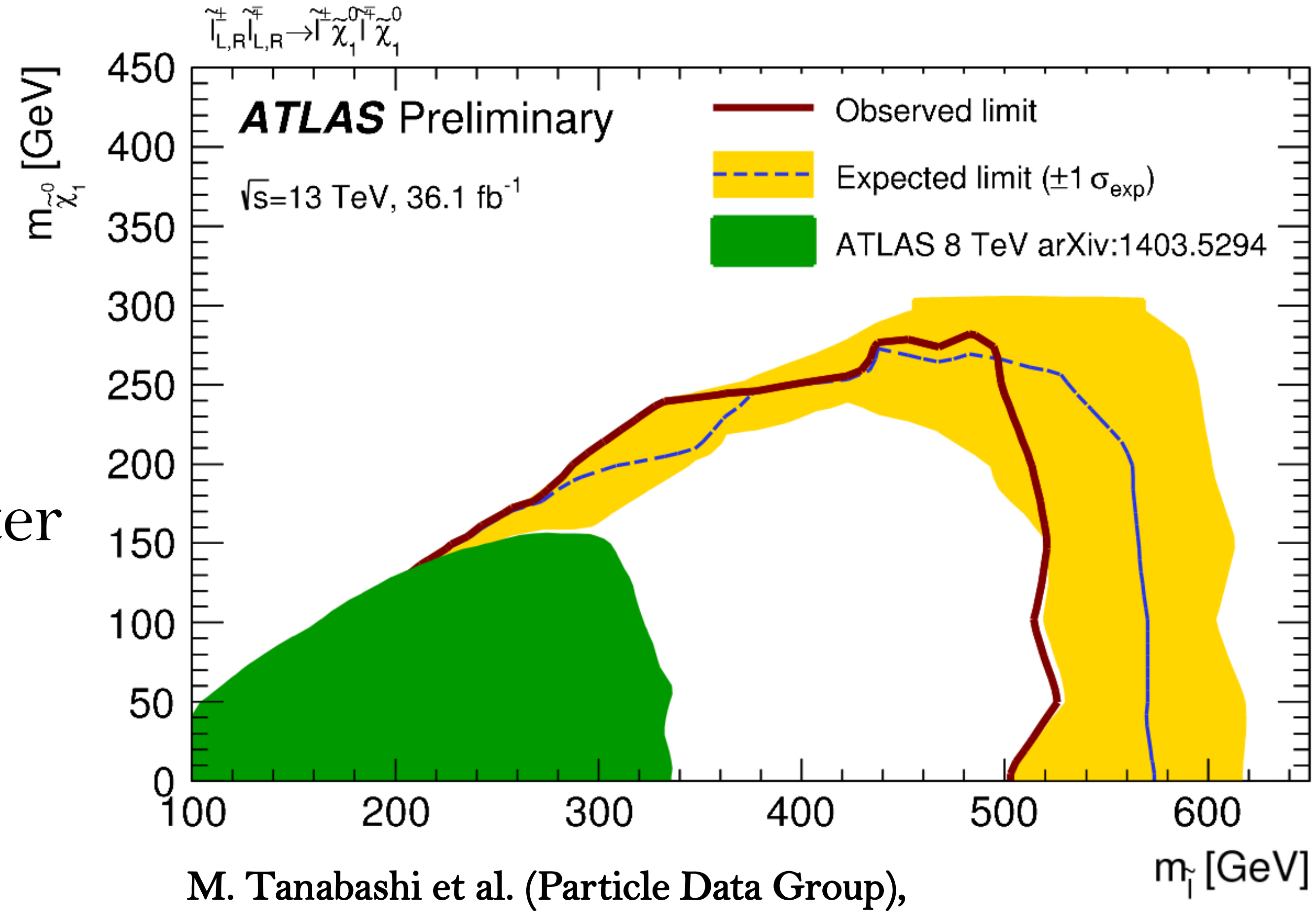
Production of sleptons is not favored $\Rightarrow$ Cross sections 2 times lower than colored SUSY particles

Assuming degenerate 1st/2nd generation sleptons

$\Rightarrow$ Looser constraints. With masses up to 600 GeV.

Low limits for neutralino mass greater than 300 GeV

$\Rightarrow$ Low lepton momentum and missing energy.



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So, what's next?

- Evidently, SUSY is not observable at and above the EW scale. If they do indeed exist, they must be at around a scale of new physics.

- While it was only discussed direct collider searches, indirect searches heavly constraint SUSY (such as proton decay limits and flavour violating processes, in models with R parity violation).

- A higher energy scale is not experimentally friendly. Higher scale requires higher energy colliders. And if it is around Planck scale, then no chance for direct observation

So, what's next?

- Indirect tests can be made for SUSY models at around a GUT scale, by analysing its low energy limit.

- GUT models naturally predict new states, such as vector-like fermions, massive Majorana neutrinos, new vector bosons and more at achievable energies at particle colliders.

$\Rightarrow$ Constraining these states, further constraints SUSY!

- With the upcoming run III of the LHC, we are surely to further restric the parameter space for SUSY!

Thank you for your attention

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