Light stops at the ILC in view of the latest Higgs results by LHC

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September 4, 2013

What this talk is about:

Investigating the possibility of having a $\tilde{t}$ with a mass below 600 GeV consistent with latest Higgs mass measurements and direct $\tilde{t}$ searches at the LHC (ATLAS).

What it is not about:

Considering constraints by cross sections, direct or indirect searches for other sparticles, cosmology, etc.

Outline

Beyond the Standard Model
- The picture not long ago
- Why go beyond?
- What is supersymmetry?
- What do we gain from it?

The 2012 discovery
- What does it mean for SUSY?

Scanning the parameter space
- Procedure
- 2D scans
  - Range
  - Results
- Multi-D scans
  - Range
  - Large or small mixing?

Comparison with ATLAS data

Prospects for the Linear Collider

Leptons			Quarks		
$e^{\pm}$	$\mu^{\pm}$	$\tau^{\pm}$	u	c	t
ν_e	ν_μ	ν_τ	d	s	b

Gauge bosons

γ	Z	$W^{\pm}$	
$(\ B^0$	W_3^0	$W_{1,2}^{\pm}\ )$	g
Electroweak			Strong

?

Why go beyond?

- Electroweak ✓
- Strong ✓
- Gravity ✗
- Unification of gauge couplings ✗
- Hierarchy "problem" ✗
- Fine tuning ✗
- Dark matter ✗
- Baryon asymmetry ✗
- $(g-2)_\mu$ ✗

And more...

What is supersymmetry?

Supersymmetry says:

boson $\leftrightarrow$ fermion: same quantum numbers and mass, different spin ×

Broken symmetry?

Introduce mass-like terms for sparticles $\Rightarrow$ softly break supersymmetry.

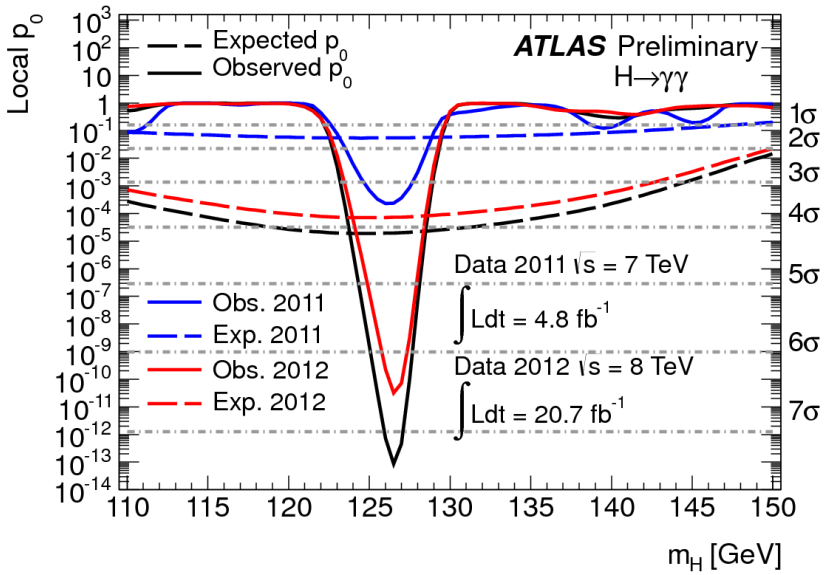
Need different basis $\Rightarrow$ mixing: $\tilde{f}_{L,R} \rightarrow \tilde{f}_{1,2} \Rightarrow$ more parameters, e.g.:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} M_{\tilde{t}_L}{}^2 + m_t^2 + D_t^1 & m_t(A_t^* - \mu \cot\beta) \\ m_t(A_t - \mu^* \cot\beta) & M_{\tilde{t}_R}{}^2 + m_t^2 + D_t^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

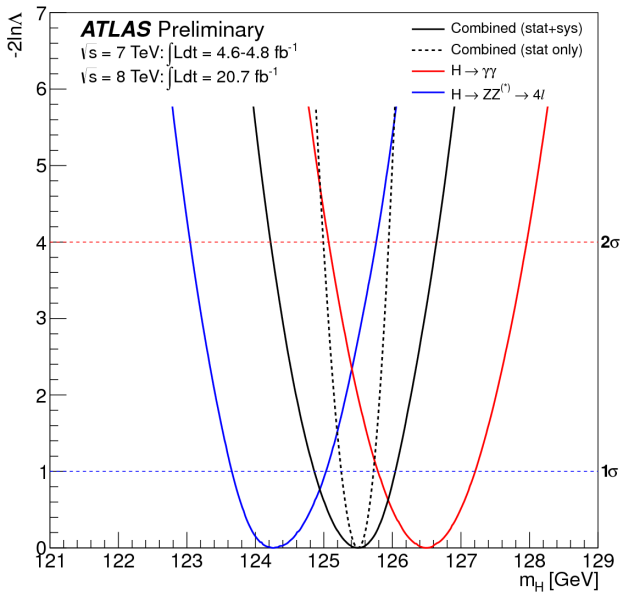
What do we gain from it?

- Electroweak ✓
- Strong ✓
- Gravity ?
- Unification ✓
- Hierarchy "problem" ✓
- Fine tuning ✓
- Dark matter ✓ (?)
- Baryon asymmetry ✓ (?)
- $(g-2)_\mu$ ✓

The 2012 discovery



(a) H→ $\gamma\gamma$ [ATLAS-CONF-2013-012]



(b) Combined H→ $\gamma\gamma/ZZ^{(*)}$ [ATLAS-CONF-2013-014]

Figure 1: ATLAS Higgs results with the full 2011 and 2012 data.

What does it mean for SUSY?

In SUSY the Higgs mass is a prediction, rather than a parameter!

- Constrained models are under tension
- MSSM: If h is Standard Model-like, then $M_h \lesssim 135$ GeV ✓
  BUT has **105** parameters!! What can we do?

  Couplings of sparticles depend on Yukawa couplings of their particle partners $\Rightarrow$ largest contribution from the $\tilde{t}$ sector.

  Few parameters matter in the Higgs sector of the MSSM ✓

Seven parameters affect strongly M_h:

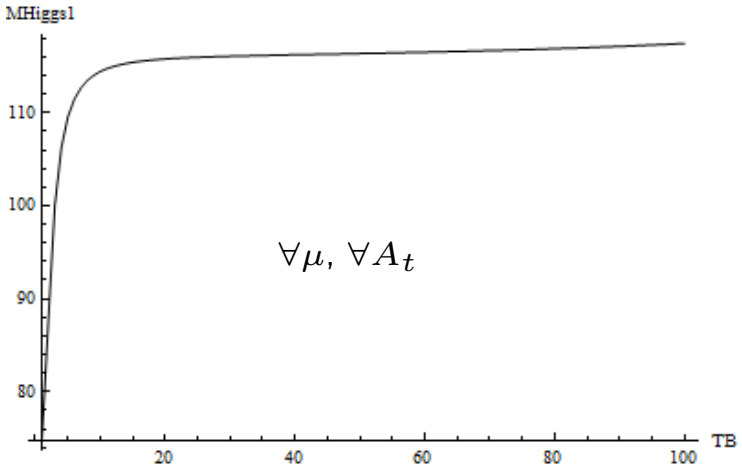
μ, $\tan\beta$, A_t, $M_{\tilde{\tau}_L}(= M_{\tilde{\tau}_R})$, $M_{\tilde{t}_L}(= M_{\tilde{t}_R})$, M_2 and M_A

Procedure (inspired by [arXiv:1211.1955])

- Use FeynHiggs [arXiv:hep-ph/9812320]
- Vary one at a time for several fixed values of the others
- Identify interesting range
- Loop over all of them simultaneously
- Compare predictions for light stops with LHC data

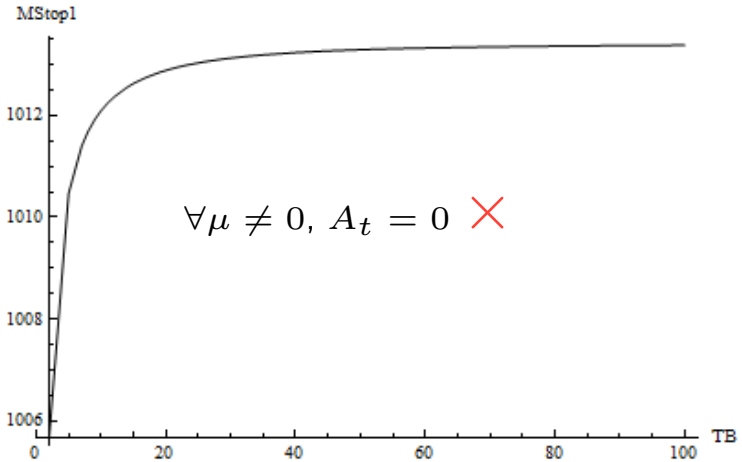
Parameter	Range*			Default value*
μ	-1500	;	1500	200
$\tan\beta$	1	;	100	5
A_t	-4500	;	4500	2000
$M_{\tilde{\tau}_L}$	0	;	1500	300
$M_{\tilde{t}_L}$	0	;	1500	1000
M_2	0	;	500	500
M_A	0	;	500	250

* $\tan\beta$ is dimentionless, all other values are in GeV.

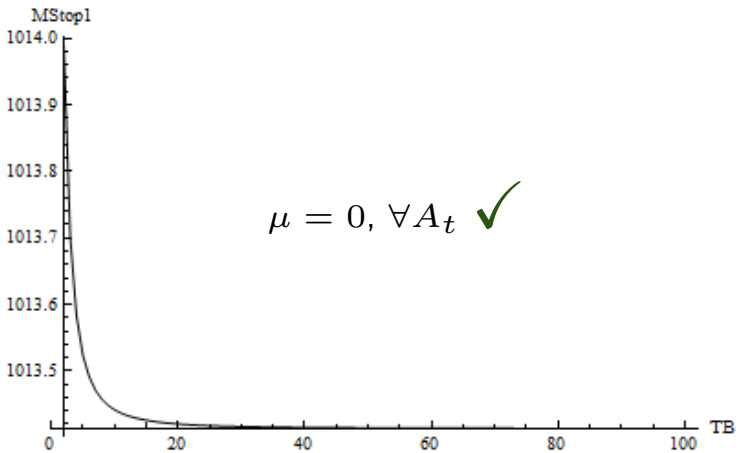


$\forall \mu,\ \forall A_t$

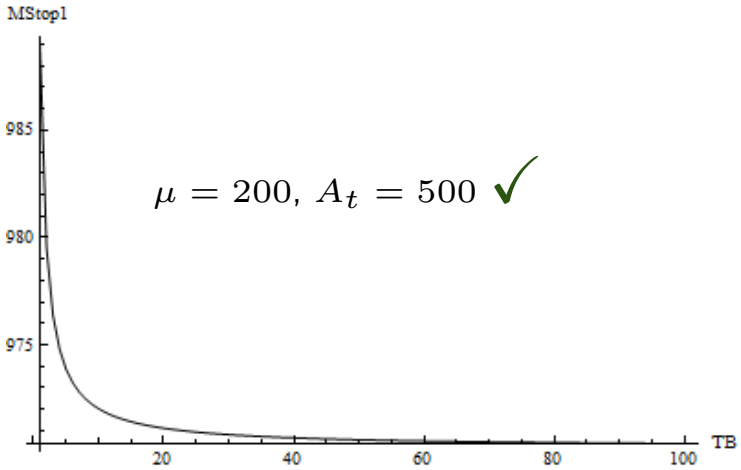
$\Rightarrow$ Need large $\tan\beta$



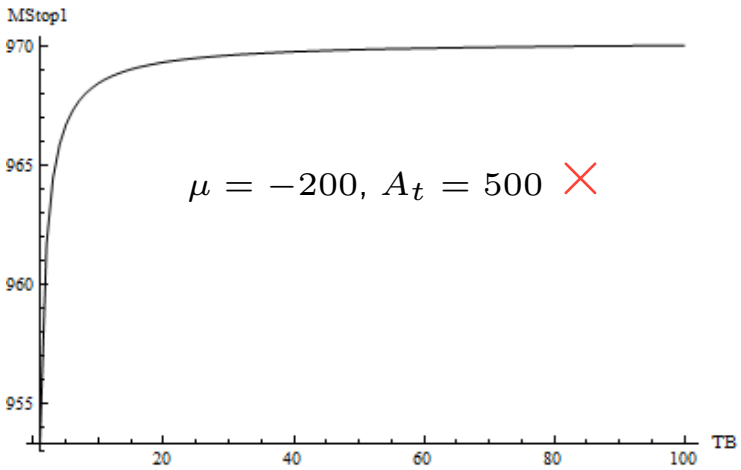
$\forall \mu \neq 0,\ A_t = 0$ ✗



$\mu = 0,\ \forall A_t$ ✓

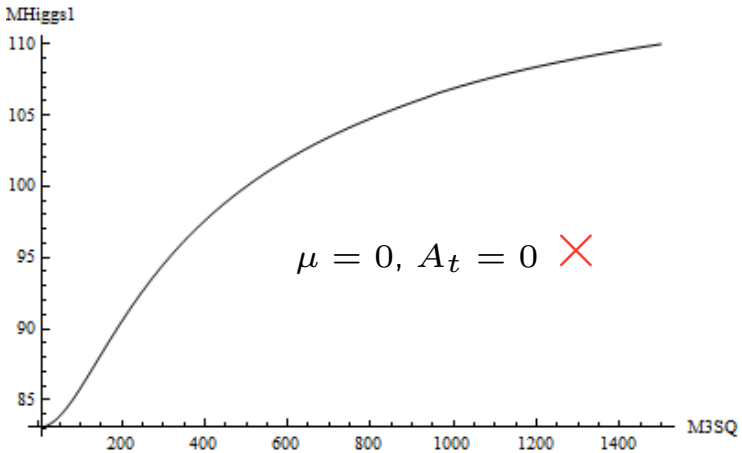


$\mu = 200,\ A_t = 500$ ✓



$\mu = -200,\ A_t = 500$ ✗

$\Rightarrow$ either $\mu = 0$ OR $A_t \neq 0$ and $\mu > 0$.

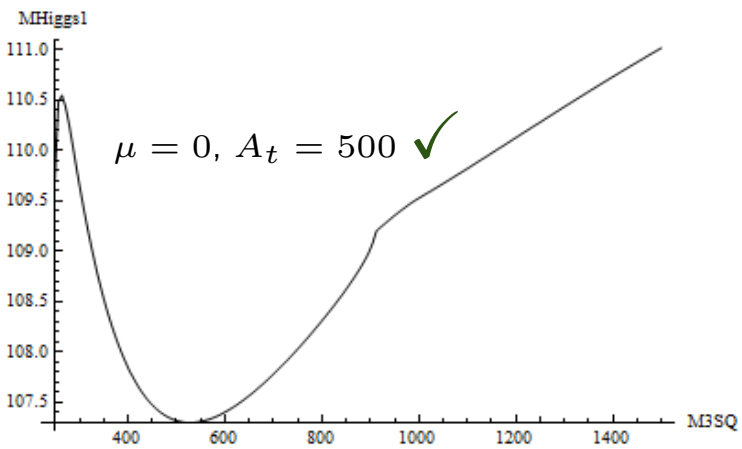


$\mu = 0,\ A_t = 0$ ✗

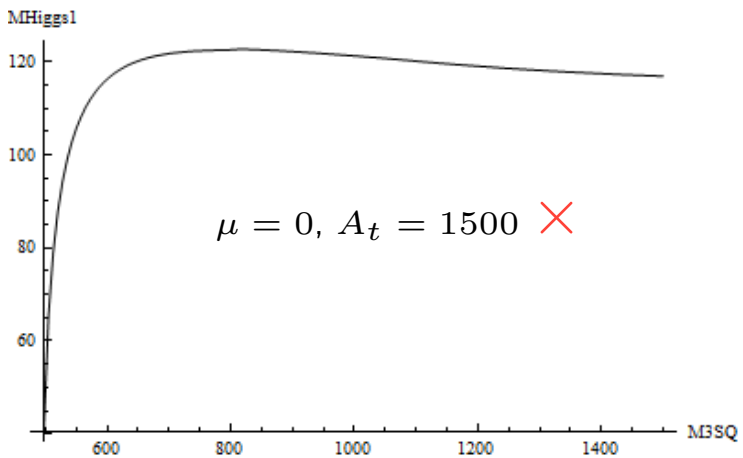
$\Rightarrow$ Need $A_t \neq 0$

But not too large!

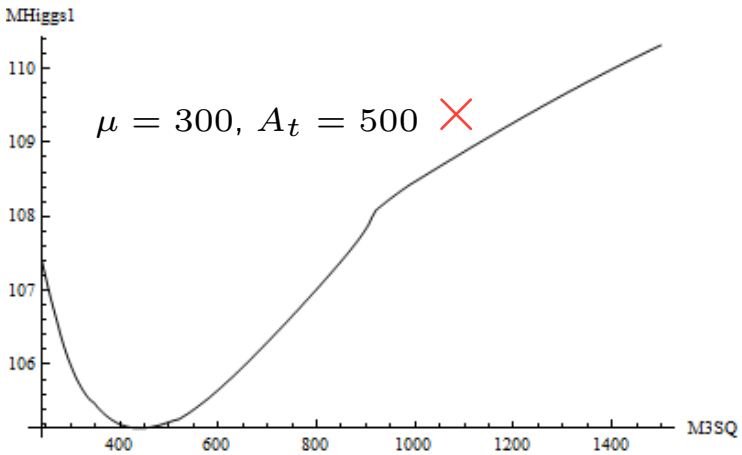
$\Uparrow$



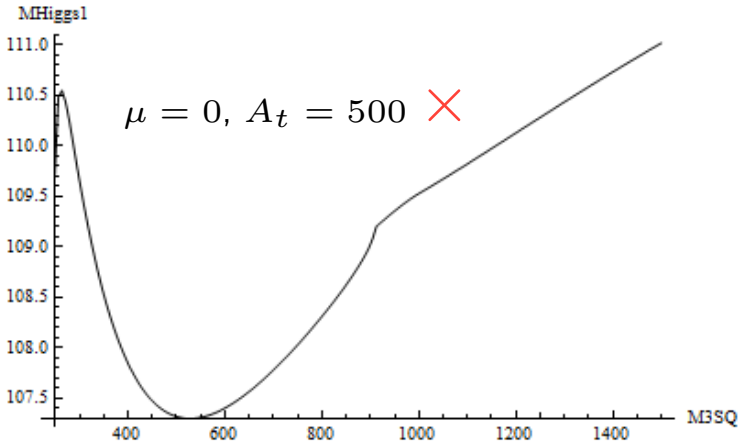
$\mu = 0,\ A_t = 500$ ✓



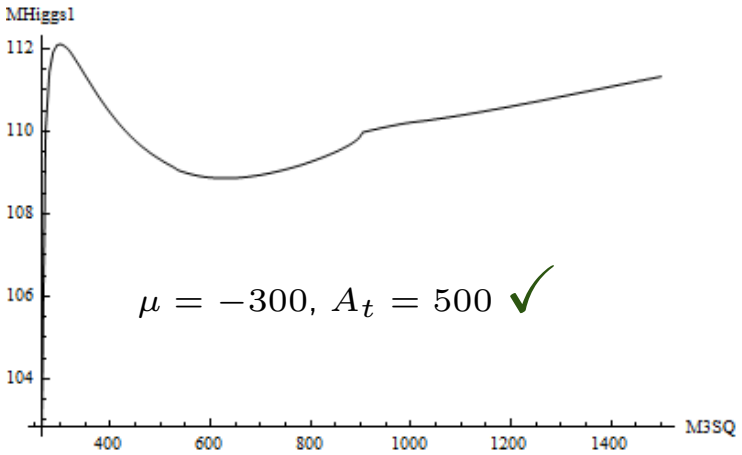
$\mu = 0,\ A_t = 1500$ ✗



$\mu = 300,\ A_t = 500$ ✗

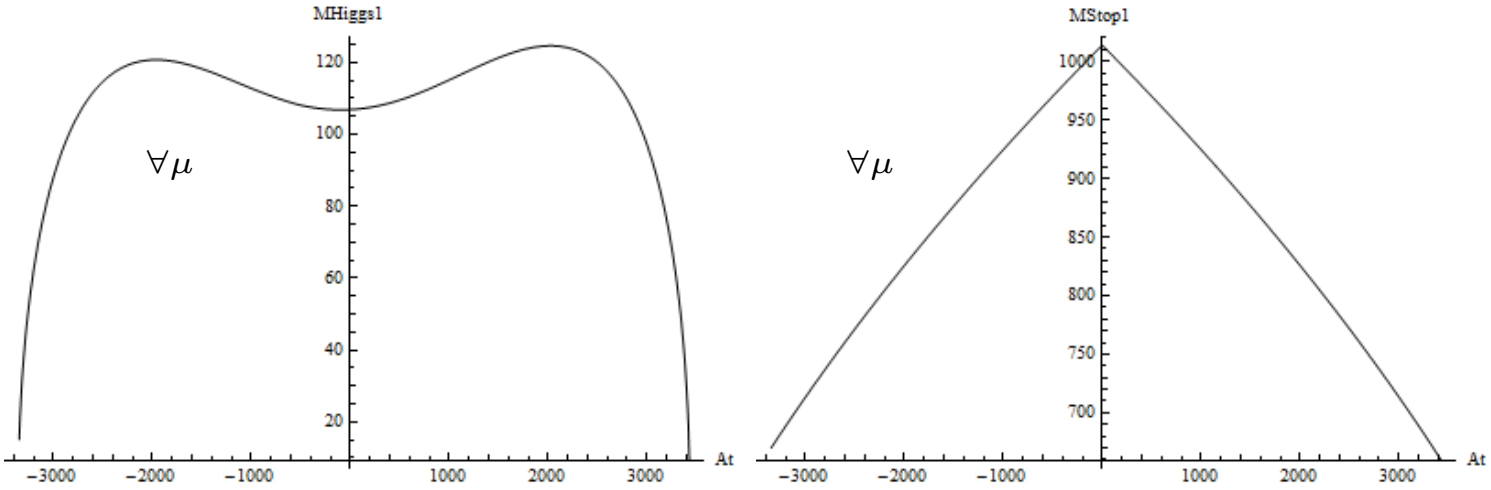


$\mu = 0,\ A_t = 500$ ✗



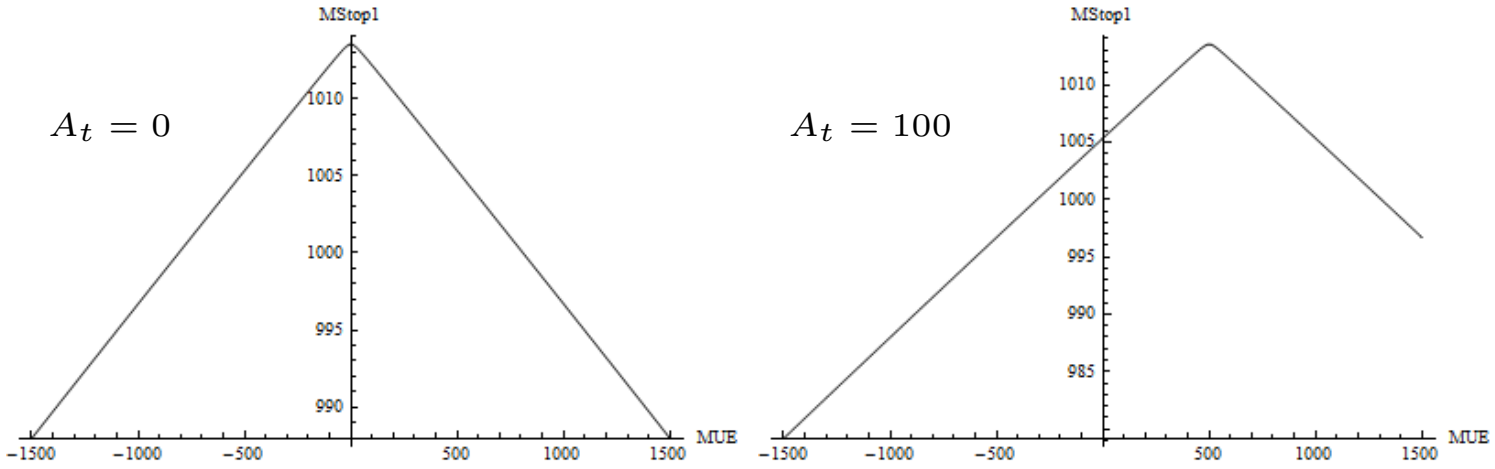
$\mu = -300,\ A_t = 500$ ✓

$\Rightarrow$ Also need $\mu < 0$



A_t is decisive for a heavy Higgs and a light $\tilde{t}_1$!

Need a compromise between the two (must not go to too high $|A_t|$)



$\Rightarrow$ either A_t is large and $\mu \leq 0$ OR $A_t = 0$ and $|\mu|$ is large.

For maximal M_h for minimal $M_{\tilde{t}_1}$ we also need:

- M_A and $\tan\beta$ should be large, but there is no need to go above $M_A = 250$ GeV and $\tan\beta = 10$.
- M_A only affects M_h (for $M_A < 100$ $M_h << M_Z$ and for $M_A > 150$ $M_h \approx const$) $\Rightarrow$ Put $M_A = 250$
- M_2 only affects $M_{\chi^{0,\pm}}$ (for $M_2 > 400$ $M_{\chi^{0,\pm}} \approx const$)
- $M_{\tilde{\tau}_L}$ plays very little role $\Rightarrow$ Put $M_{\tilde{\tau}_L} = 300$

$\Rightarrow$ Look at:

$$0 \leq |\mu| \leq 500,\ \ \tan\beta \approx 10,\ \ 0 < |A_t| \leq 500,\ \ 100 < M_{\tilde{t}_L} < 800,\ \ 0 \leq M_2 \leq 500$$

* $\tan\beta$ is dimentionless, all other values are in GeV.

Parameter	Range*			Number of points
μ	-650	;	650	27
$\tan\beta$	5	;	35	4
A_t	-1200	;	1200	25
$M_{\tilde{t}_L}$	100	;	1200	23
M_2	0	;	500	3

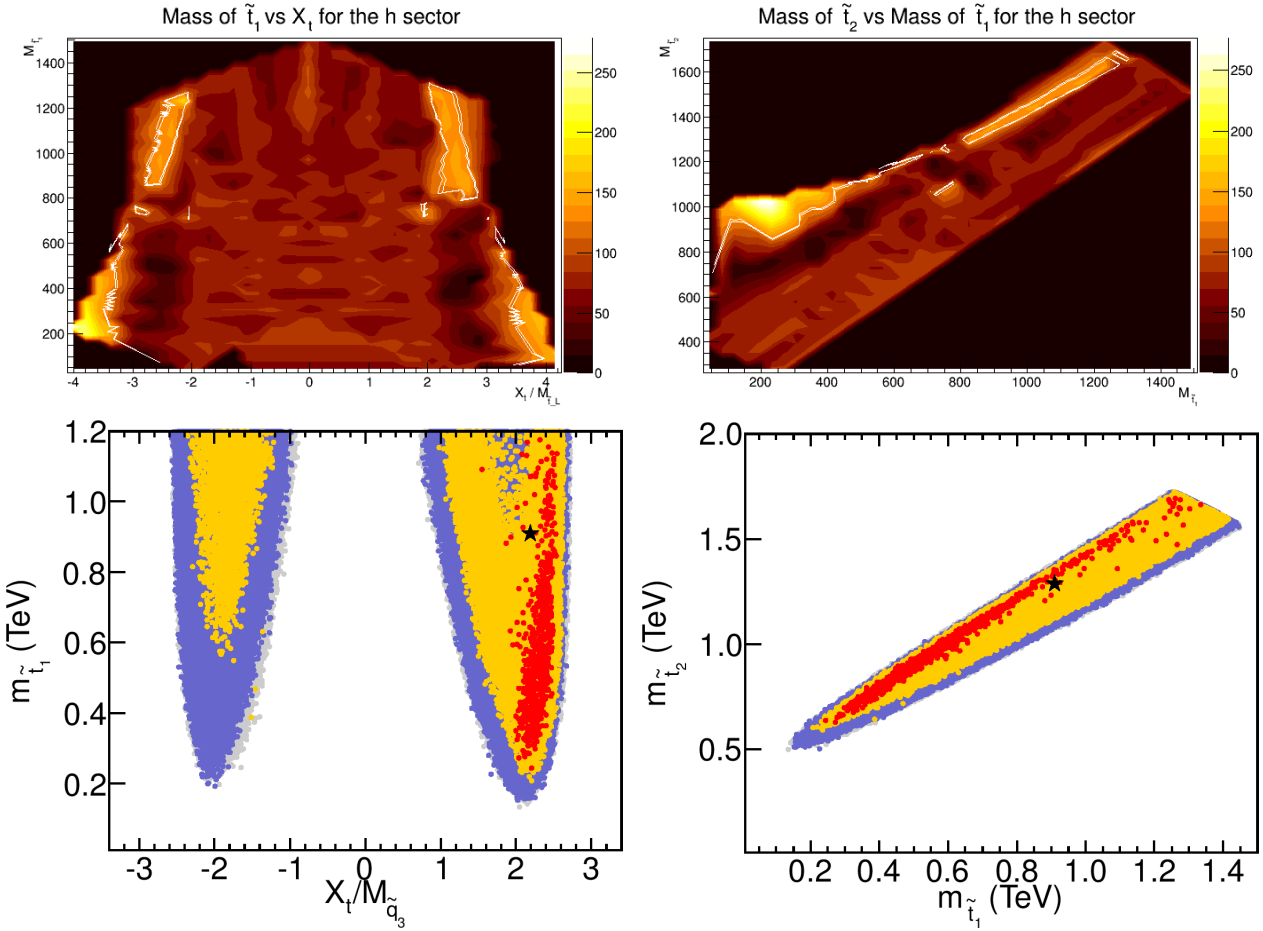
Total number of points:	186300
Number of points with no error:	148585
Number of points with $M_h \in [123.5; 127.5]$ GeV:	6956

* $\tan\beta$ is dimentionless, all other values are in GeV.

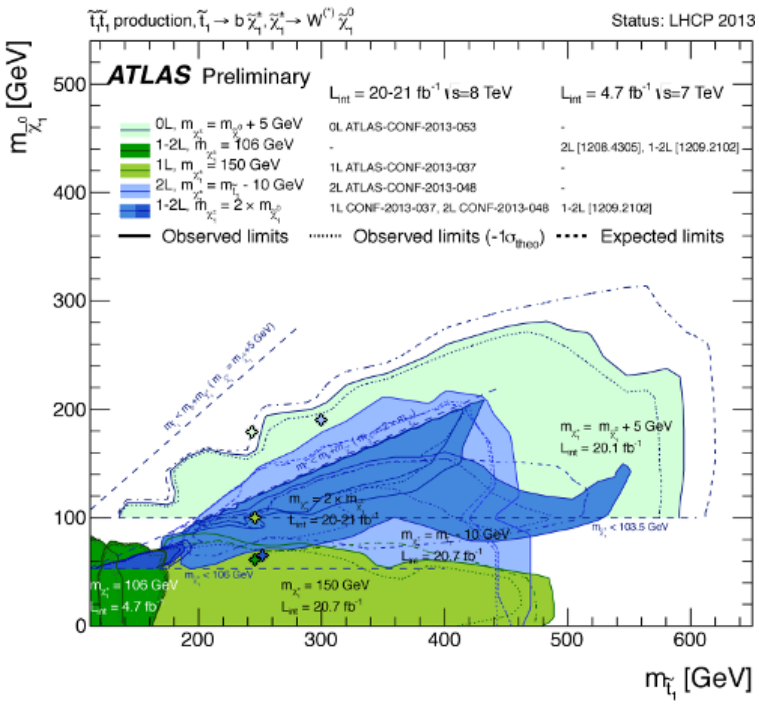
No χ^2 fit

With χ^2 fit

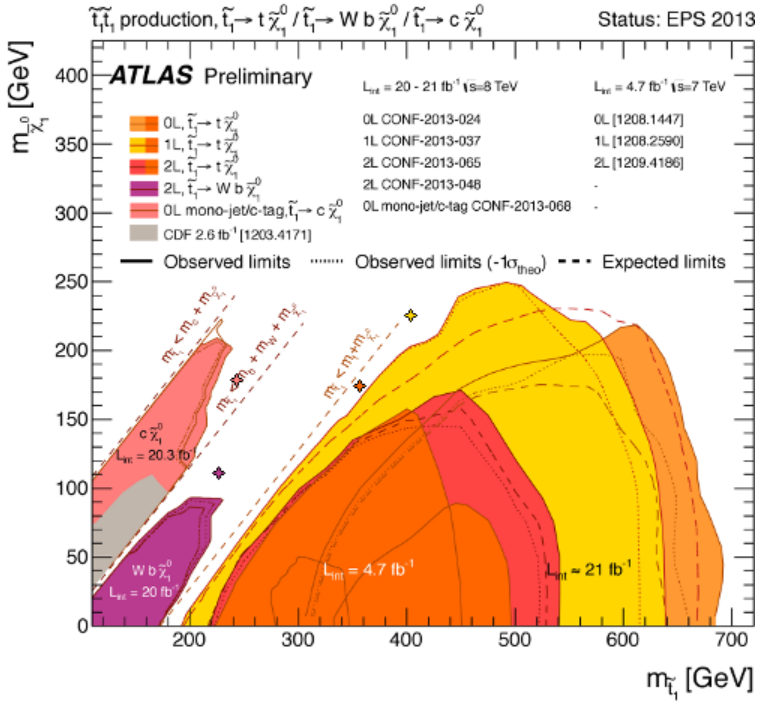
[arXiv:1211.1955]



Comparison with ATLAS data



(a) $\tilde{t} \to b\chi^{\pm}$



(b) $\tilde{t} \to t\chi^0$, $\tilde{t} \to Wb\chi^0$, $\tilde{t} \to c\chi^0$

Figure 2: ATLAS exclusion plots `[ATLAS Public, Combined Summary Plots]` + our selections.

Prospects for the Linear Collider

At the e^+e^- linear collider:

- Leptonic interactions $\Rightarrow$ clean environment, known $E_{T,miss}$ $\Rightarrow$ good particle identification
- Linear $\Rightarrow$ **polarized beams** $\Rightarrow$ **asymmetric observables** (e.g. $\cos\theta_{\tilde{t}}$)

$\Rightarrow$ we can look at the asymmetry associated with different beam polarisations to determine the mixing angle between $\tilde{t}_L$ and $\tilde{t}_R$!!

For all selected points:

$$-350 \leq \mu \leq 200, \quad 15 \leq \tan\beta \leq 35, \quad 800 \leq A_t \leq 1200, \quad 400 \leq M_{\tilde{t}_L} \leq 550, \quad 135 < M_2 \leq 500$$

$M_{\tilde{t}_1}$ / GeV	$\sqrt{s}$ / GeV	$\cos\theta_{\tilde{t}}$	σ_{+-} / fb	σ_{-+} / fb	A_{LR}
237	500	-0.766	9.08	3.30	-0.467
237	600	-0.766	44.9	16.5	-0.463
240	600	-0.772	41.3	16.0	-0.442
297	1000	-0.767	36.7	13.5	-0.462
247	600	-0.774	36.6	13.4	-0.464
354	1000	-0.757	24.3	9.39	-0.443
401	1000	-0.767	15.0	5.48	-0.465
220	500	-0.781	29.4	11.6	-0.434
220	600	-0.781	59.7	23.7	-0.432

Prospects for the Linear Collider

Several regions with:

- $M_{\tilde{t}_1} < 300$ - accessible energy scale! ✓
- $\sigma \sim 40$ to 60 fb - good production cross sections! ✓

$\Rightarrow$ produce stop pairs; with enough integrated luminosity get cross section measurement and error and then...

get errors on the mass and mixing angle $\rightarrow$ propagate to uncertainty in SUSY parameters.

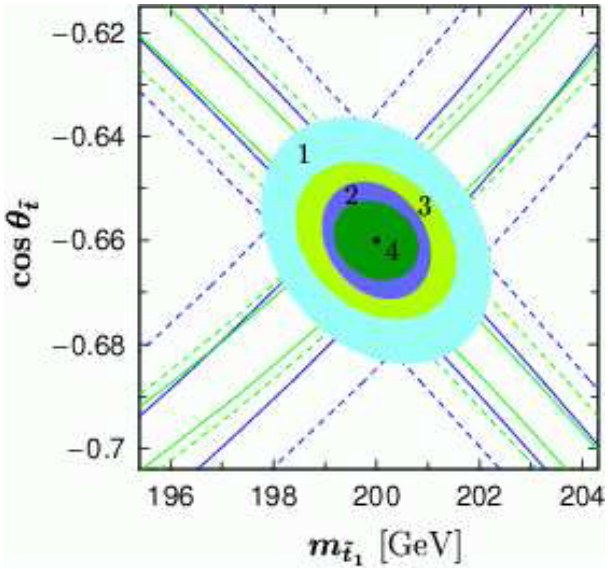


Figure 3: Production cross section error bands in $\cos\theta$-A_{LR} plane [arXiv:hep-ph/0507011].

Questions?

Backup slides

Parameter values for each nine points are shown below:

μ	$\tan\beta$	A_t	$M_{\tilde{t}_L}$	M_2	$M_{\tilde{t}_1}$	M_{χ^0}	$M_{\chi^\pm}$	M_h
$\tilde{t} \to b\chi^\pm$:								
-200	35	1000	450	500	237	178	195	124
200	20	915	432	136	240	60.1	109	124
200	20	915	432	227	240	99.4	159	124
-300	20	963	479	409	297	189	283	124
-350	20	868	432	136	247	64.7	131	124
$\tilde{t} \to t\chi^0$:								
200	15	1200	550	500	353.7	174	192	125
300	15	1000	550	500	401	224	287	124

μ	$\tan\beta$	A_t	$M_{\tilde{t}_L}$	M_2	$M_{\tilde{t}_1}$	M_{χ^0}	$M_{\chi^\pm}$	M_h
$\tilde{t} \to Wb\chi^0$:								
-200	35	800	400	250	220	111	172	124
$\tilde{t} \to c\chi^0$:								
-200	35	1000	450	500	237	178	195	124

Note:

- For all points: decay to $c\chi^0$ and $b\chi^\pm$ channel is also open.
- For all but point 1 in the $b\chi^\pm$ channel: decay to $Wb\chi^0$ channel is open.