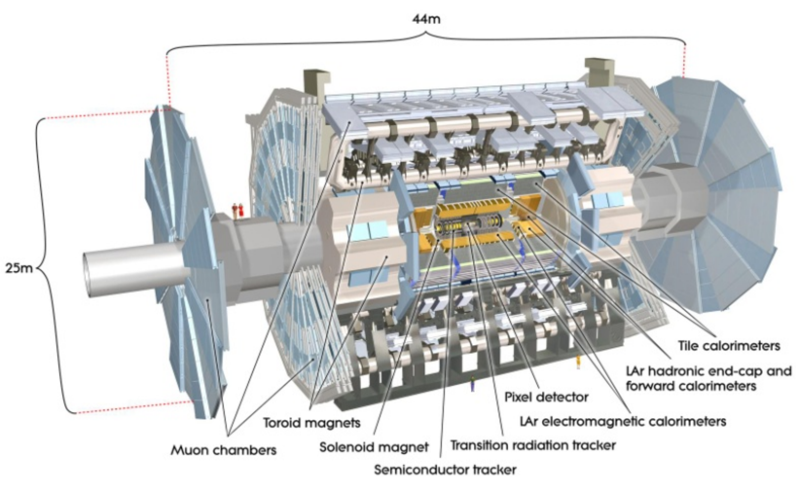
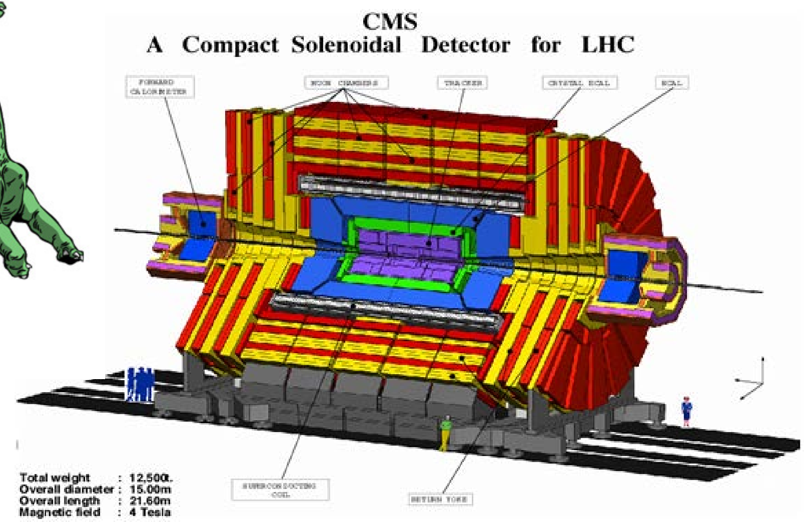
Beyond the MSSM (?)

(why think about this now & what are some of the options)





SLAC NATIONAL ACCELERATOR LABORATORY

T.G. Rizzo 5/4/2012

Searches for SUSY @ the LHC have not found any signals (yet)…

From LHC4TeV @CERN : 'the CMSSM/mSUGRA scenario has been "punched in the face" by the data'…

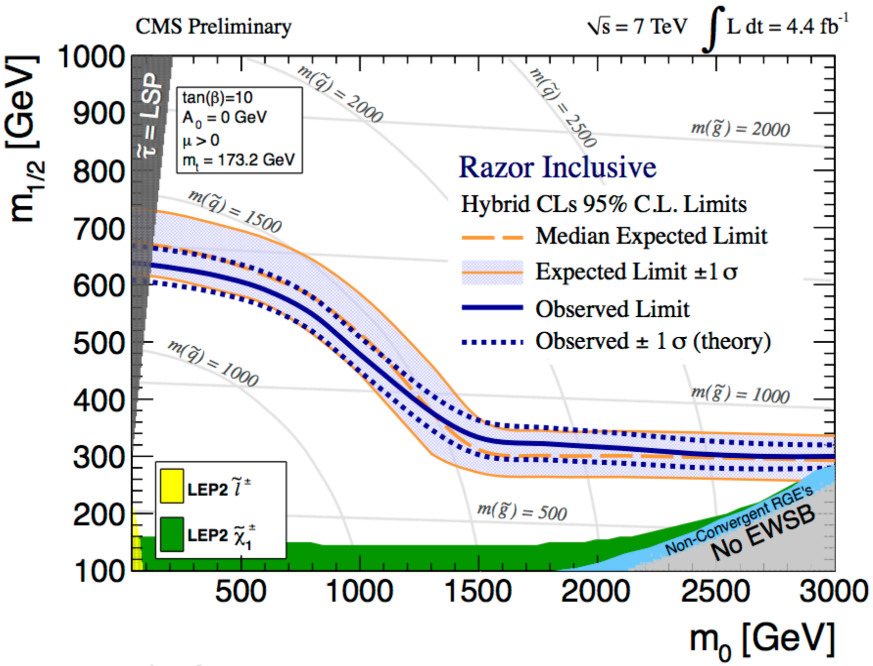
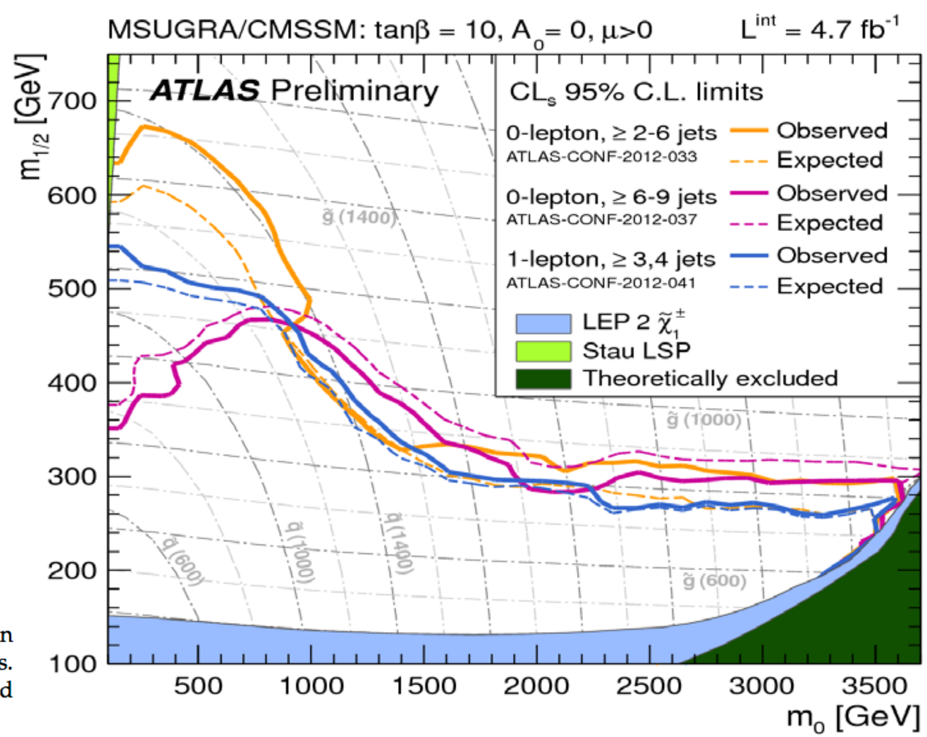


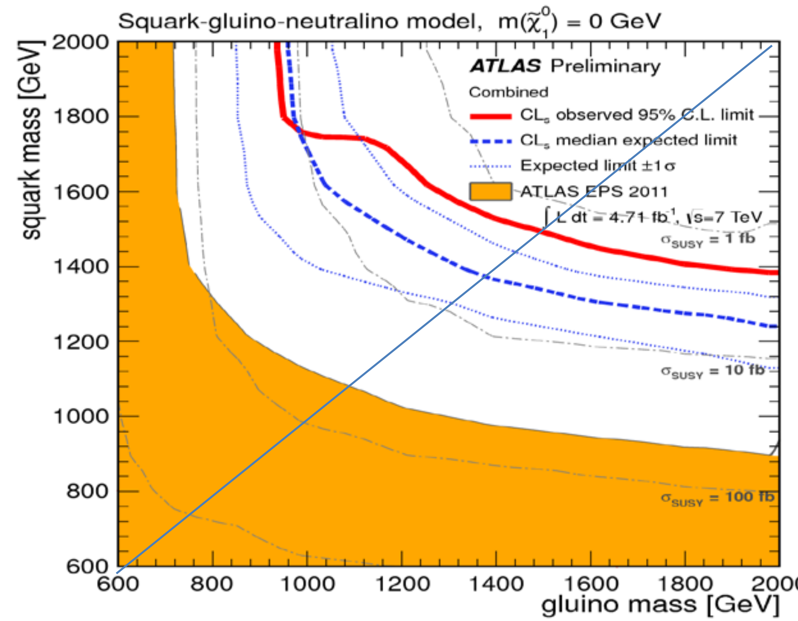
Figure 10: Observed (solid curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, $A_0 = 0$, $\text{sgn}(\mu) = +1$ from the razor analysis. The $\pm$ one standard deviation equivalent variations in the uncertainties are shown as a band around the median expected limit.



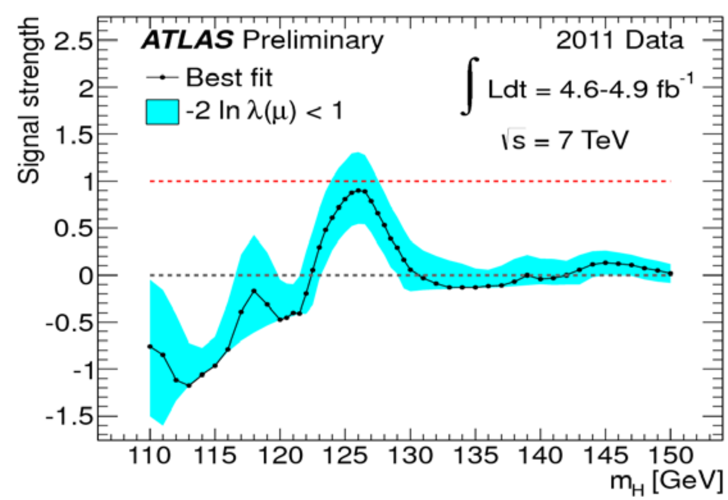
But do we need to go beyond the MSSM & if so how far ?

‘Apparent’ MSSM issues :

(i) At least at first glance, squarks of the 1st & 2nd gens & gluinos seem to be heavier than we’d have thought



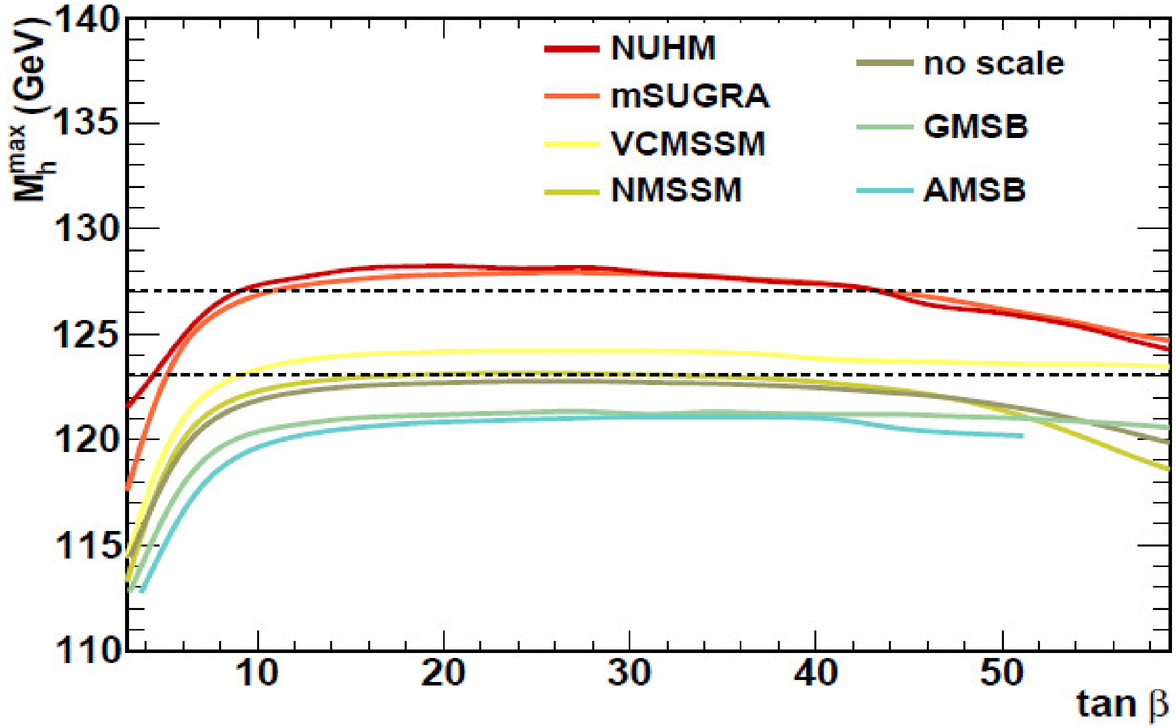
(ii) There is reasonable evidence for a SM-like Higgs at ~125± 2 GeV



(iii) The combination of these two + other inputs leads to a ‘large amount’ of fine-tuning (FT)

Are these REALLY MSSM problems?

E.g. : it is a fact that some MSSM SUSY-breaking models have difficulties generating a ~125 GeV Higgs mass



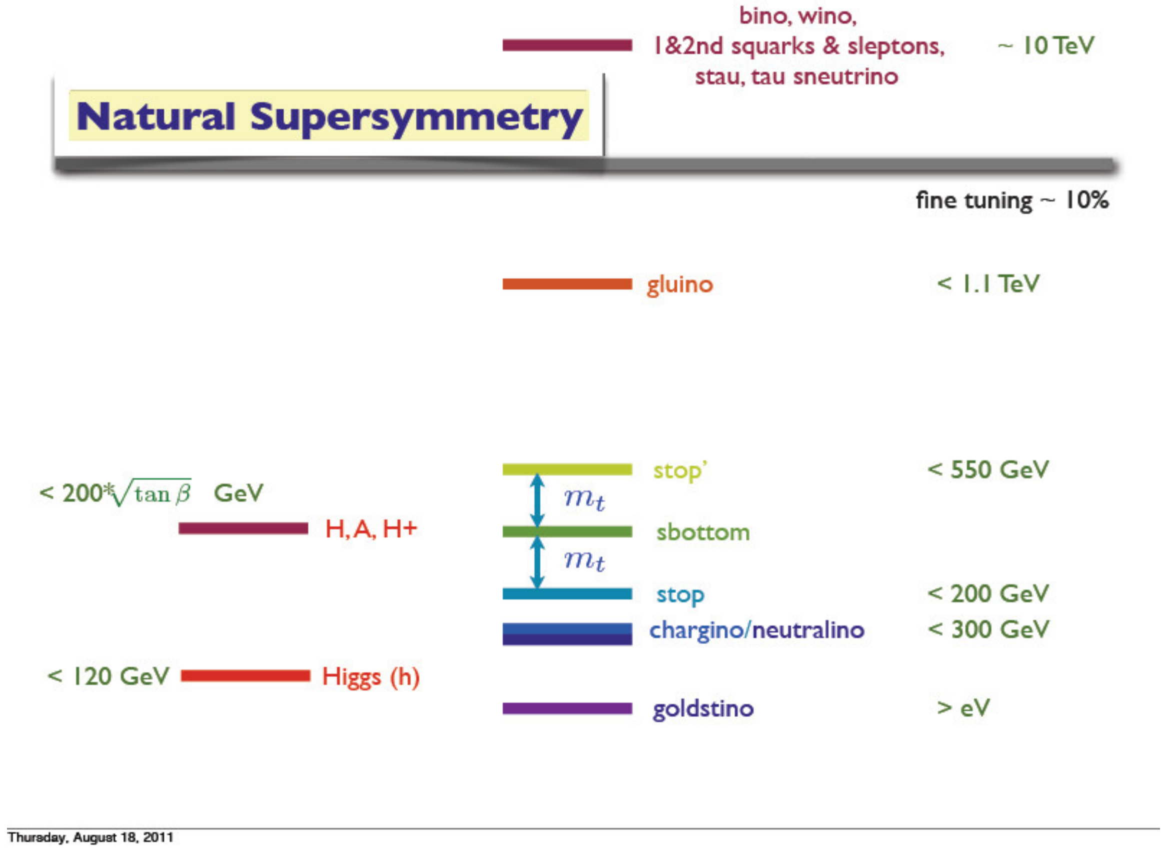
1112.3028

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
M_h^{max}	121.0	121.5	128.0	123.0	123.5	124.5	128.5

But these are NOT MSSM problems, only ones with some SUSY-breaking mechanisms

→ (However watch out for the scan ranges !)

As we know, decoupling the 1st & 2nd gens. from the 3rd can allow us to avoid issues (i)-(iii) in a ‘natural’, generalized MSSM scenario :



Barbieri, Hall,…

This requires that ‘light’ stops/sbottoms & Higgsinos should ‘soon’ be found BUT their spectra may be non-trivial making observation harder as we’ll see..

- In a general MSSM scenario, such as the 19/20-parameter pMSSM, present LHC SUSY searches are easily avoided while obtaining a Higgs mass in the ~125 GeV region.

- Furthermore, this Higgs can be reasonably ~SM-like

- However, simultaneously requiring FT values below, say, ~100 (i.e., ~1%) is somewhat more difficult to achieve

- Out of 2 sets of ~250k pMSSM models with a χ (G) LSP, requiring FT <100, a Higgs mass of 125±2 GeV , all 7 TeV MET & non-MET LHC searches satisfied leaves us only 13 (0) models ! Low FT requires a special spectrum.

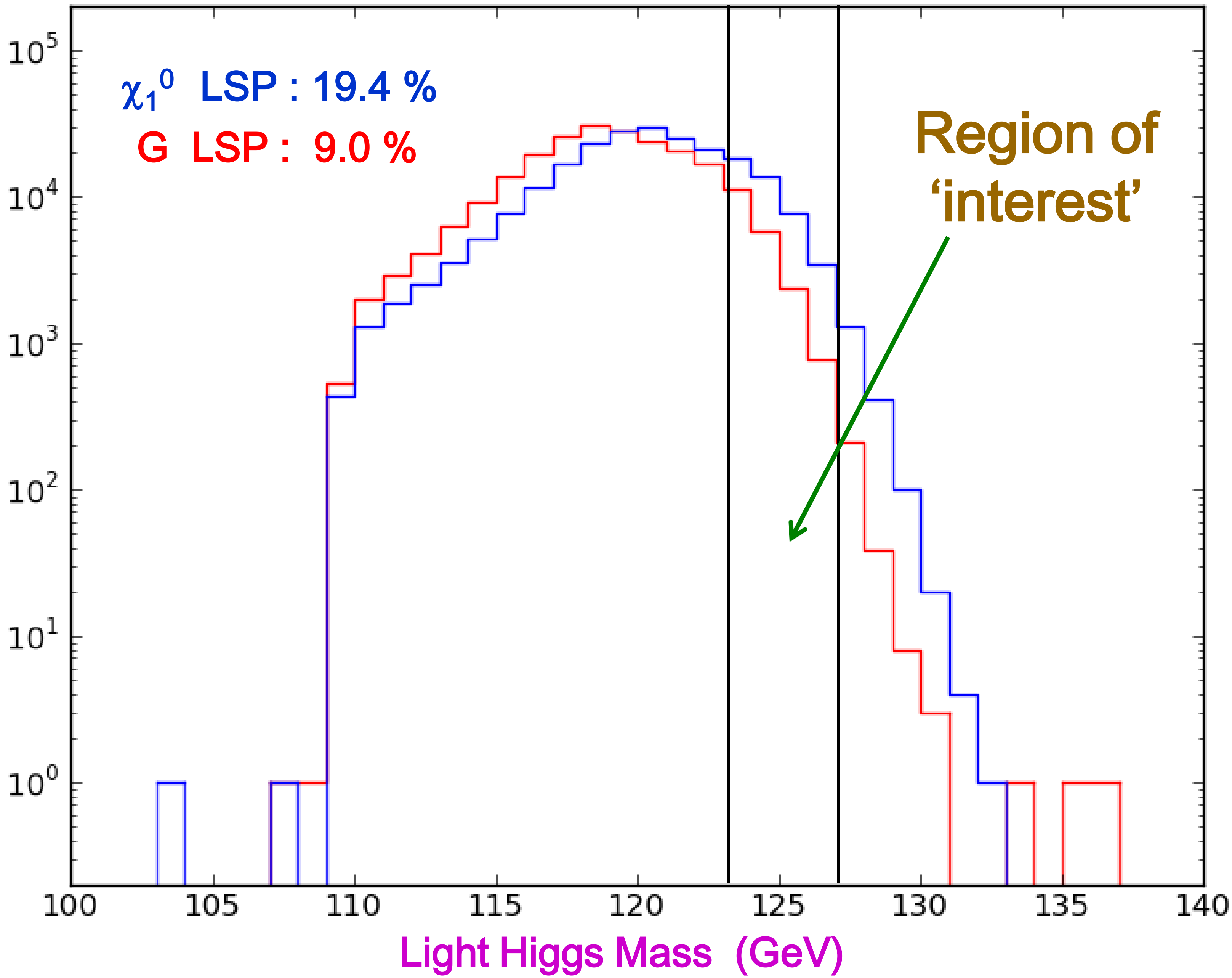
- Thus FT motivates us to look beyond the MSSM…if you're not a FT 'believer' you can settle for the pMSSM for now

ATLAS Coverage of our Neutralino LSP pMSSM Models w/ Extrapolation to 8 TeV

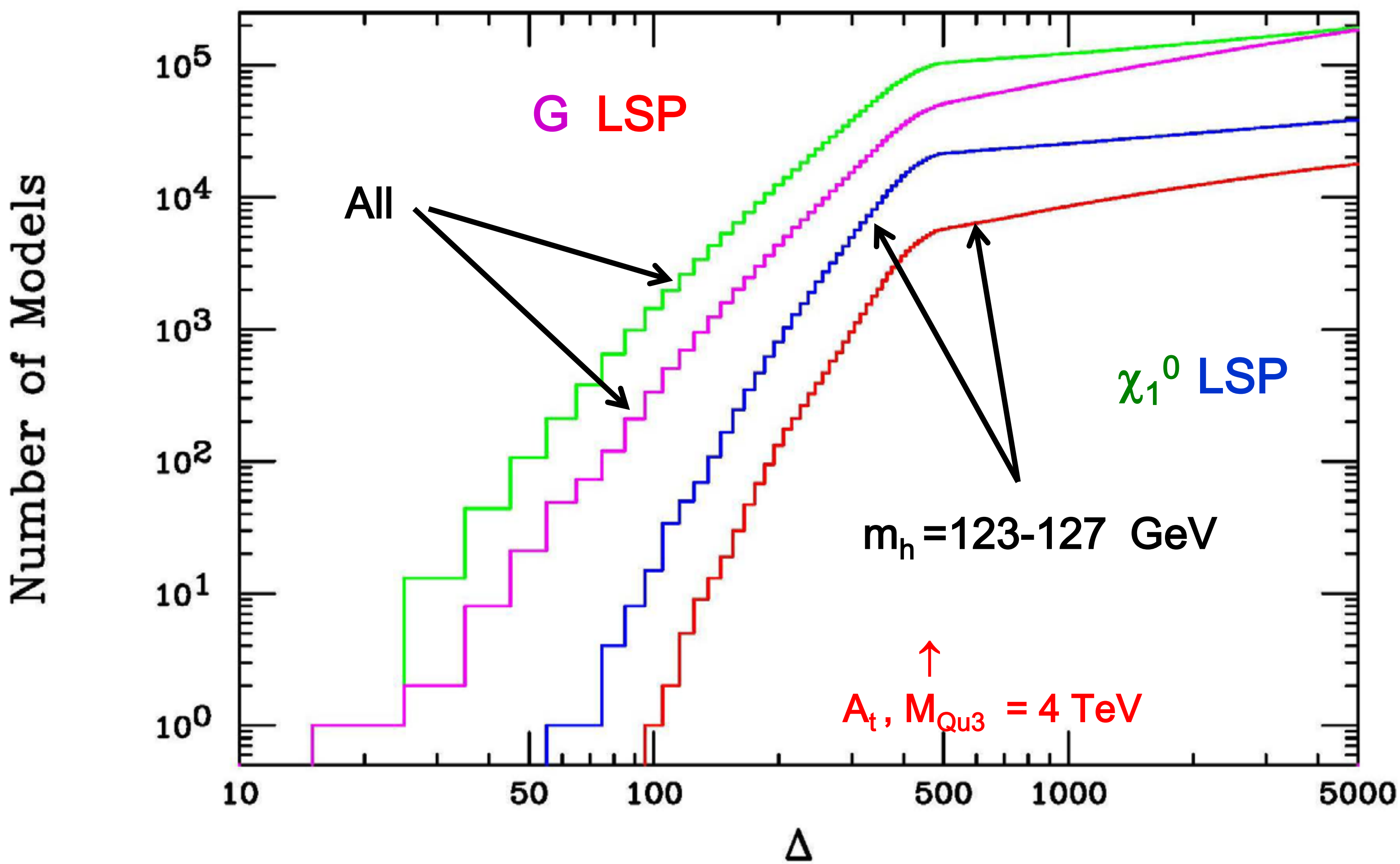
Analysis	7 TeV 1 fb^{-1}	7 TeV 4.7 fb^{-1}	8 TeV 5 fb^{-1}	8 TeV 20 fb^{-1}
Jets + MET	6.68%	23.23%	*32.70%*	*45.11%*
Many jets + MET	0.36%	1.61%	*6.26%*	*7.35%*
1 ℓ + jets + MET	0.81%	2.64%	*1.41%*	*1.53%*
2 ℓ + jets + MET	0.16%	*0.22%*	*0.35%*	*0.38%*
Remaining models	93.27%	76.72%	*67.25%*	*54.87%*

All sparticles are below 4 TeV

Higgs mass in the p(henomenological)SSM



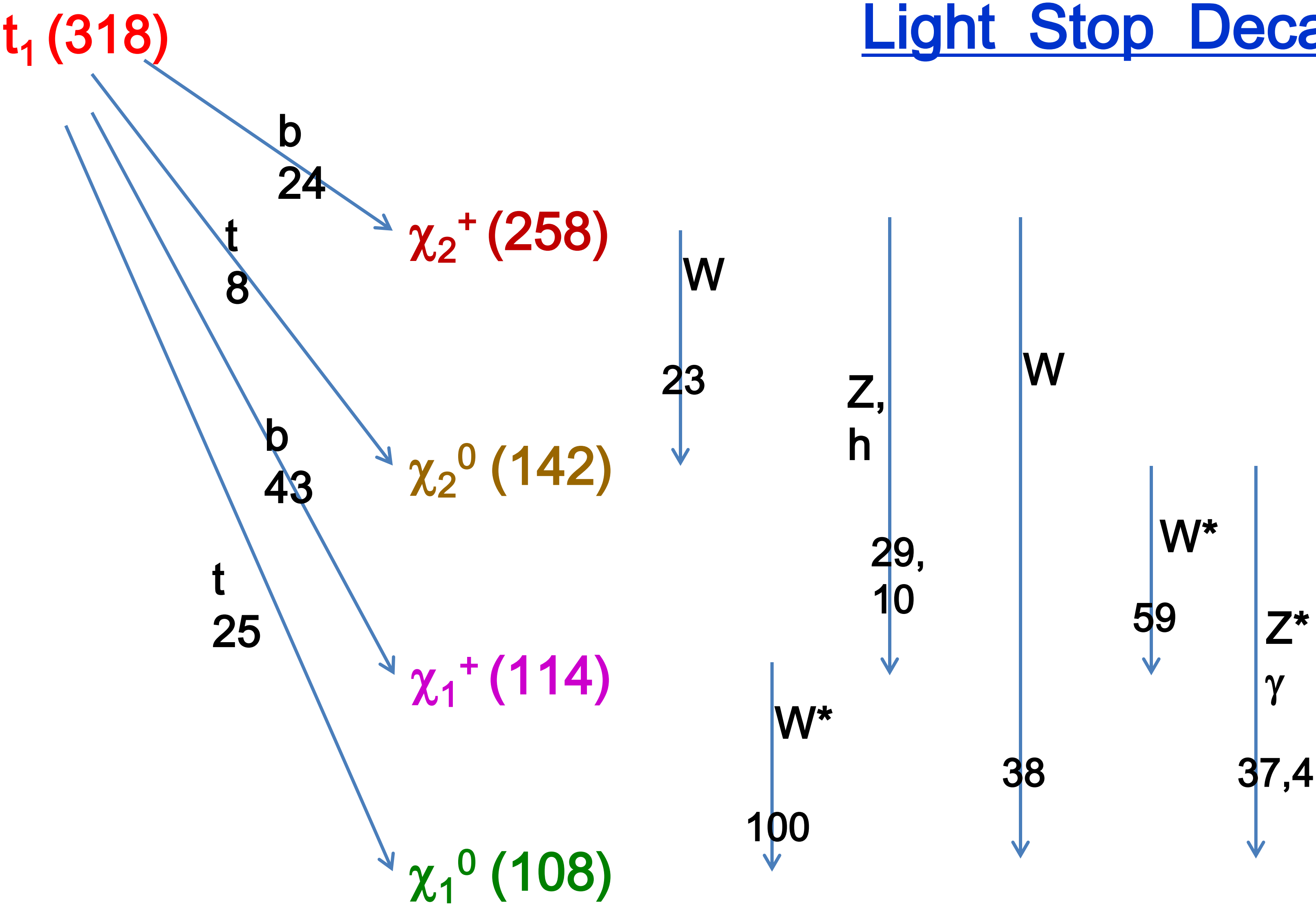
Fine-tuning in the pMSSM



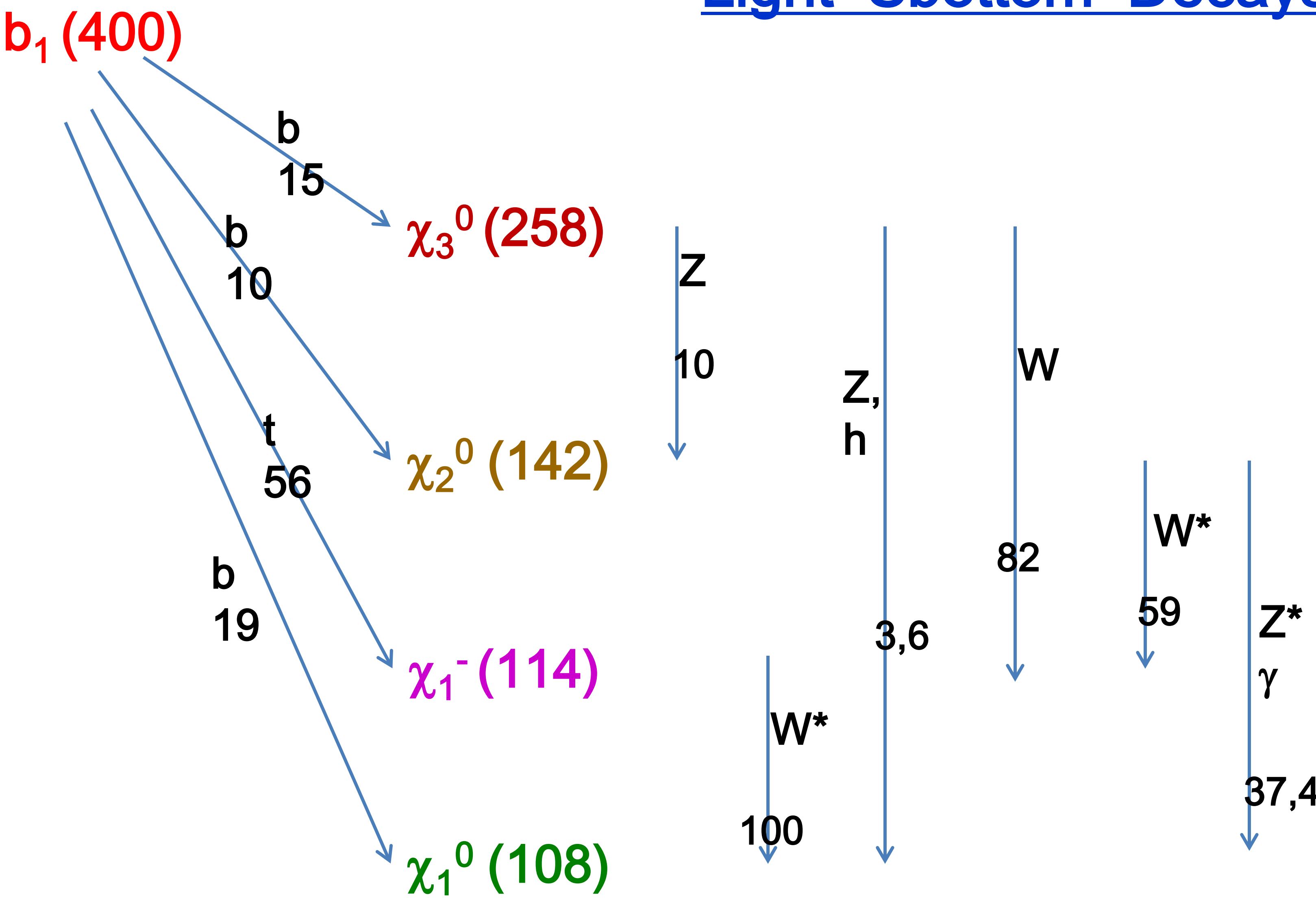
- The ~125GeV Higgs mass removes many of the models with the lowest FT values

An Example :
#178770 w/ FT=56.3

Light Stop Decays



Light Sbottom Decays



(w/ these BFs the ATLAS 2b-jet + MET search would exclude this b_1 below ~240 GeV)

Beyond the MSSM Scenarios

Grand Hotel, Stockholm

There are many choices on the menu…

Right now, it is just a question of taste.

Here we can only sample a few R-parity conserving (for DM) possibilities

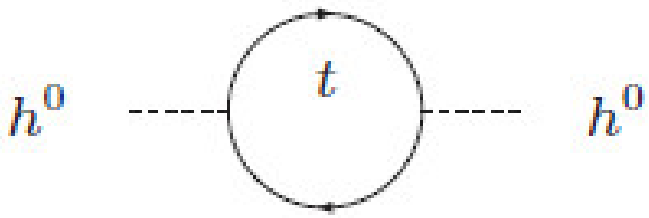
Adding More Courses

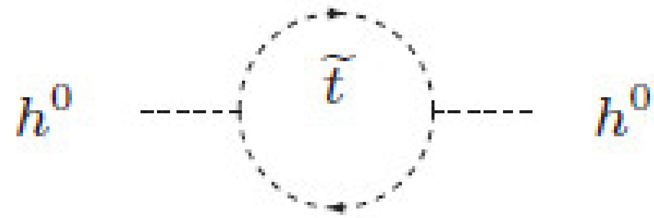
- Fields: e.g., add an extra singlet S as in the NMSSM
- Symmetries: extend the gauge sector as in the E_6 SSM
- Operators: e.g., from super & Kahler potent. a la BMSSM
- SUSY: "N=1 ½" ..make gauginos Dirac fields (SSSM)

Usually only the influence on the Higgs is considered…but how do they alter canonical SUSY searches? I'll say a few words about some of these.

- The simplest possibility & the one given the most attention is the NMSSM w/ only one new SM singlet superfield, S.

How does this help? In the MSSM, to get a ~125 GeV Higgs we need very large RCs from top/stop loops:





$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right],$$

$X_t = A_t - \mu/t_\beta$ & $M_S^2 = m_{t1}\, m_{t2}$

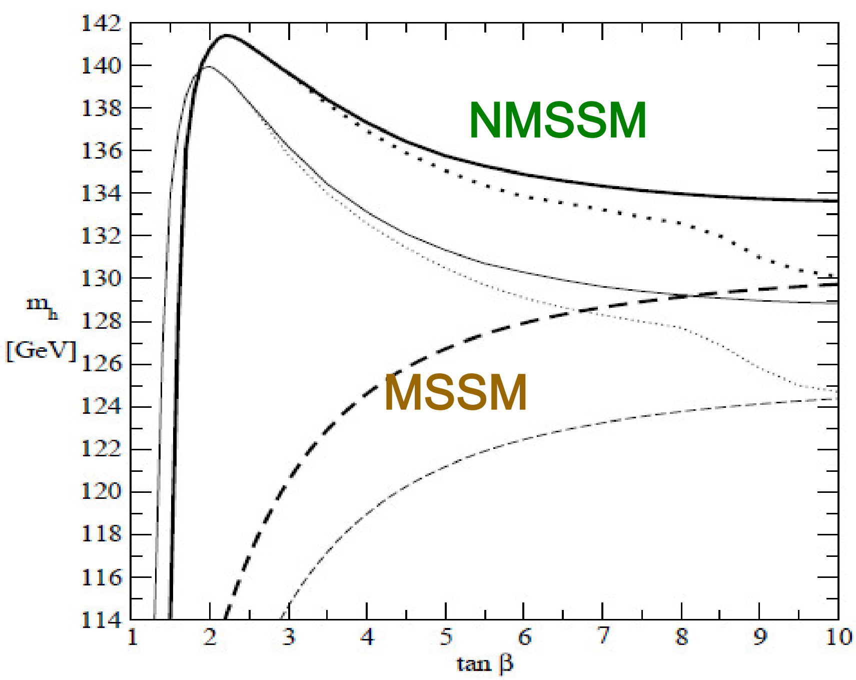
Large A-terms & stop mixing forces large FT on us

$$\Delta \sim 3[y_t(A_t, M_{Qu3})/2\pi M_Z]^2 \log \Lambda/M_S$$

• In the NMSSM the additional singlet alters the Higgs potential & thus the tree-level mass for h :

$$
\begin{aligned}
V &= V_F + V_D + V_{\rm soft} \\
&= |\lambda|^2|S|^2\left(H_u^\dagger H_u + H_d^\dagger H_d\right) + \left|\lambda(H_u^{\rm T}\epsilon H_d) + \kappa S^2\right|^2 \\
&+ \frac{1}{2}g_2^2|H_u^\dagger H_d|^2 + \frac{1}{8}(g_1^2+g_2^2)\left(H_u^\dagger H_u - H_d^\dagger H_d\right)^2 \\
&+ m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + m_S^2|S|^2 + \left(\lambda A_\lambda (H_u^{\rm T}\epsilon H_d)S + \frac{1}{3}\kappa A_\kappa S^3 + c.c.\right)
\end{aligned}
$$

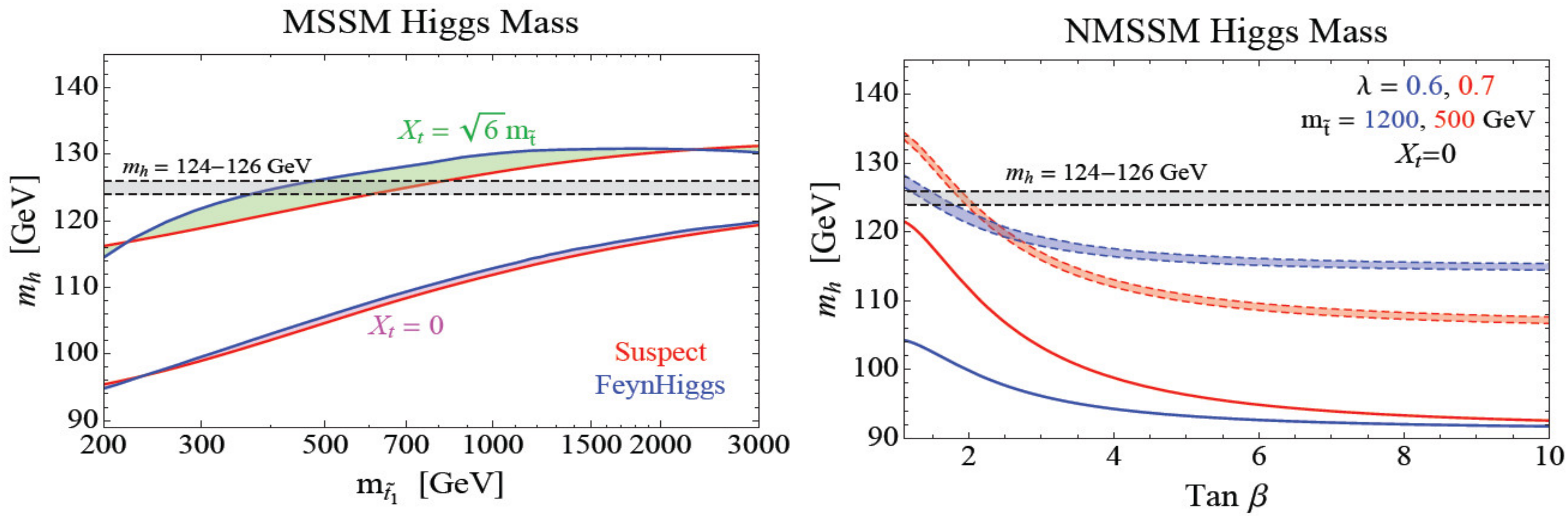
$\longrightarrow$ $$(m_{H_1}^{\rm NMSSM})^2 < m_Z^2\left(\cos^2(2\beta) + \frac{2|\lambda|^2\sin^2(2\beta)}{g_1^2+g_2^2}\right)$$ (λ must be ~0.5)



• The larger tree-level term in the NMSSM allows us to reach ~125 GeV (or larger) Higgs masses without the very large MSSM loop contributions & resulting large FT.

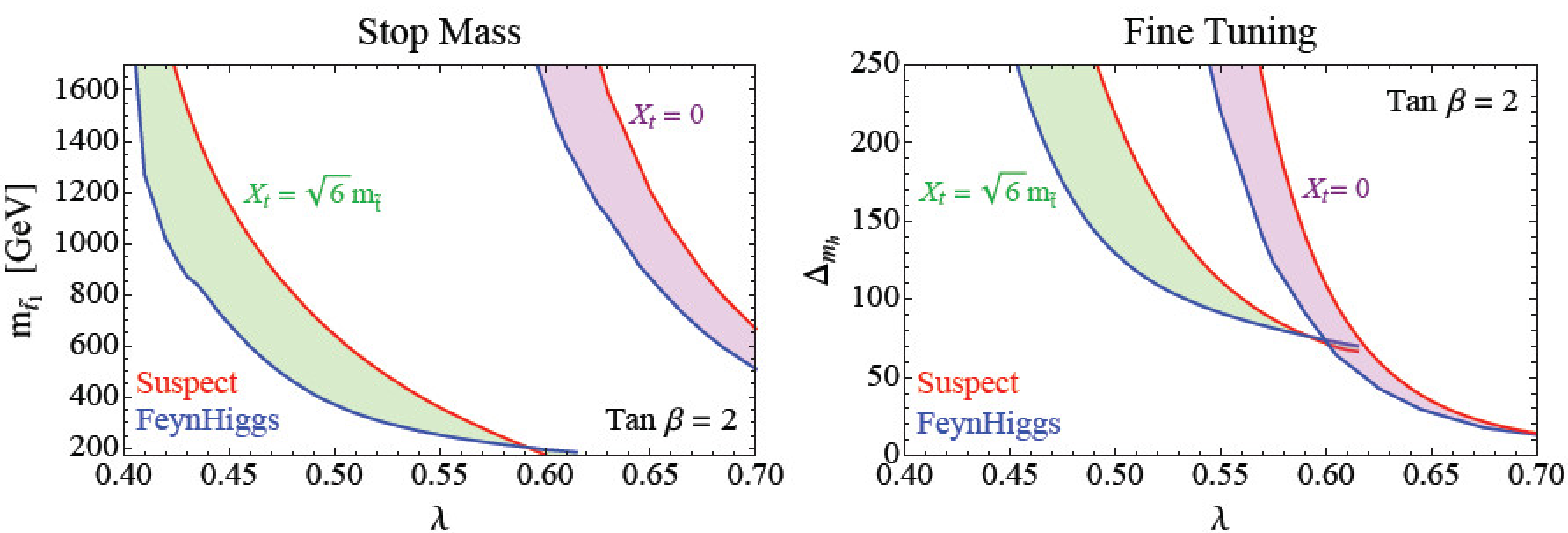
Let's compare…

Ellwanger

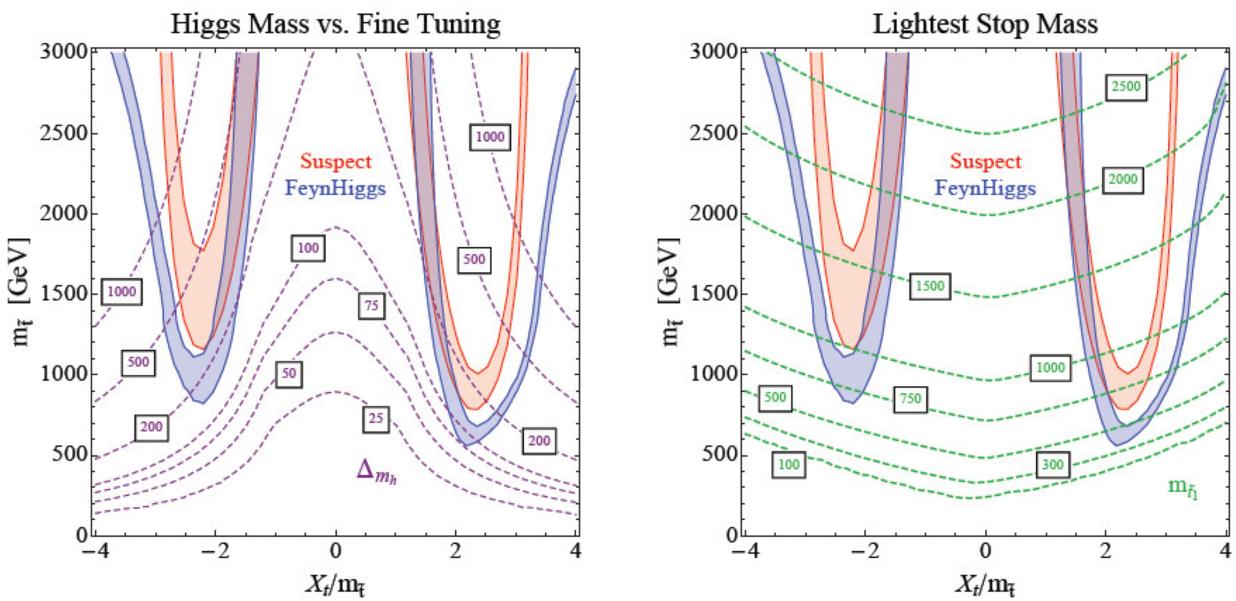


Hall etal.

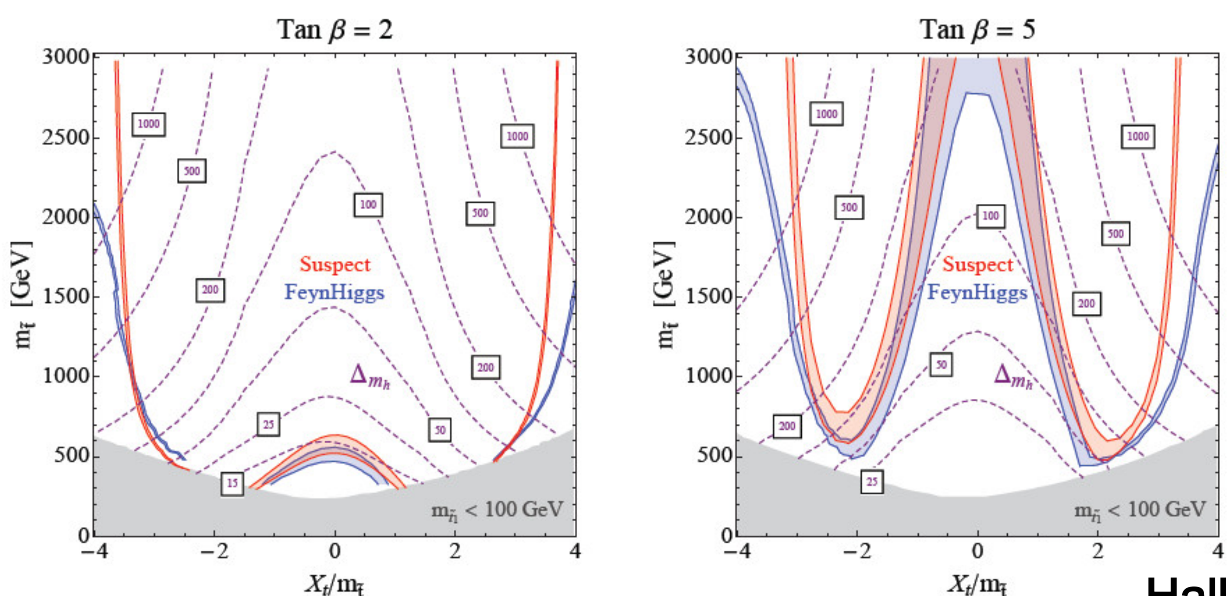
NMSSM



MSSM



NMSSM



The modified Higgs potential of the NMSSM allows one to get to ~125 GeV h masses without paying a big FT cost.

Stops/sbottoms need not be very light to achieve low FT..but Higgsinos are still light

Higgs properties can be altered by mixing with the singlet

→ The additional singlet can lengthen SUSY decay chains degrading searches

Hall etal.

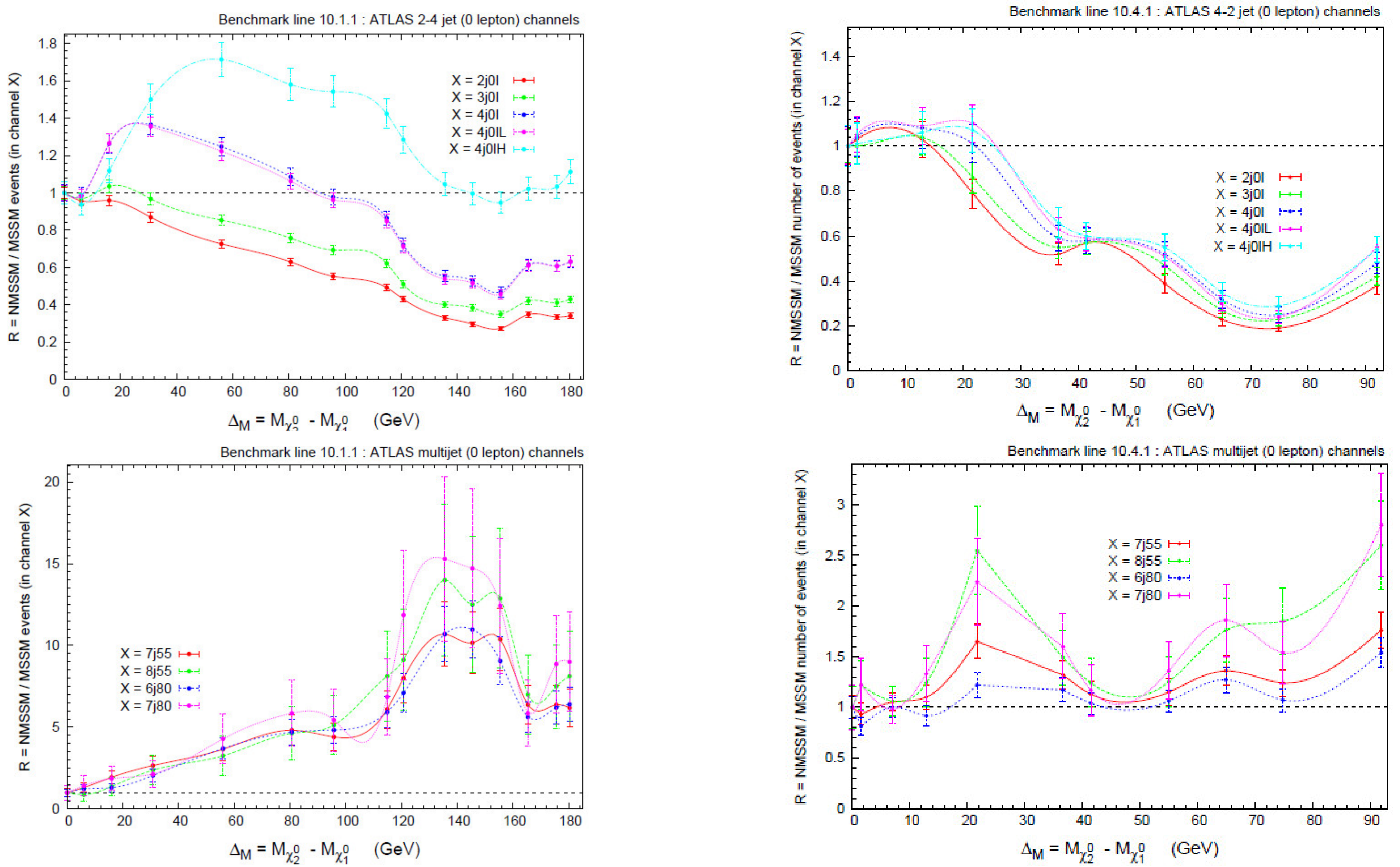
- The additional field S helps w/ the FT problem but its SUSY singlino partner may degrade MET SUSY searches if it is (mostly) the LSP. Why?

- The singlino's couplings to other fields are typically small as they occur only via mixing. Except for the NLSP, sparticles don't like to decay into it

- Cascades will typically end with an NLSP to singlino + X decay Depending on the mass splitting, Δ, & the identity of X, the MET search efficiencies will be modified (for better or worse) The NMSSM NLSP is commonly a bino-like object.

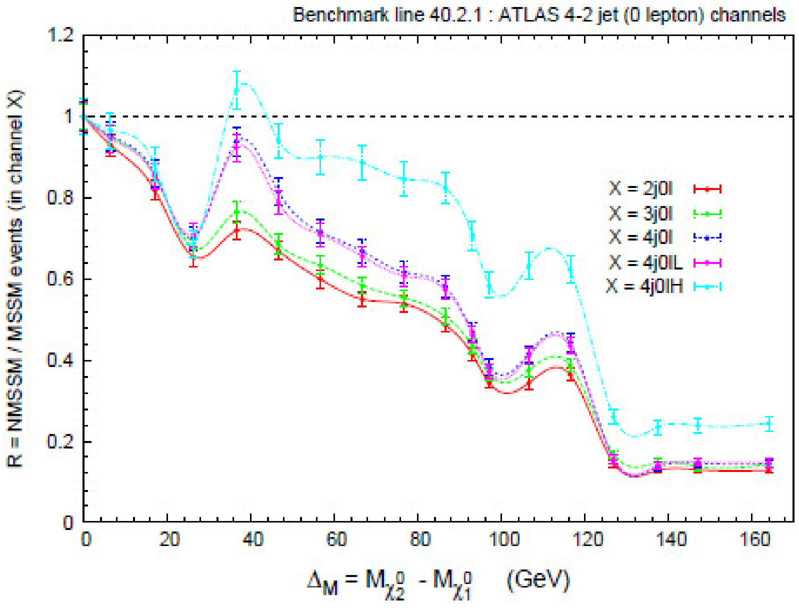
A comparison of a few cMSSM & cNMSSM benchmarks with similar spectra & input parameters is instructive in this case as the value of Δ is varied

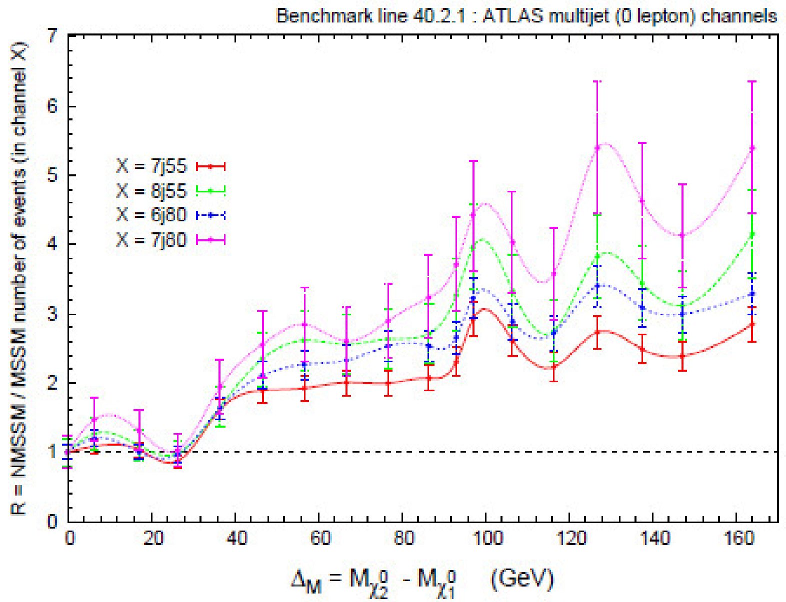
Das etal., 1202.5244



Das etal., 1202.5244

- Comparison of NMSSM/CMSSM signal rates for various ATLAS searches: nj0l degrades for large Δ but multi-j is enhanced. This is a common feature across the model parameter space…





- The 'X' in the NLSP decay mostly produces extra jets that feed into the multi-j searches at large Δ. But overall MET is reduced in the same parameter range

- Generally, the n(=2,3)j0l search carries the bulk of the 'weight' in much of the parameter space & which is not off-set by the multi-j search gains.

- A more general study of the SUSY signatures in the NMSSM is clearly warranted

Das etal., 1202.5244

- A more *radical* departure from the MSSM occurs with an extended gauge sector that likely requires additional matter superfields for anomaly cancellation & is usually formulated within a GUT framework.

- Some examples: U(1)SSM, BLMSSM, LRSSM, E6SSM, …

In the E_6 case, matter is in the 27 =16 + 10 +1 of SO(10) & the superpotential allows for different B & L assignments for the additional fields

$$W = W_0 + W_1 + W_2 + W_3 \,,$$

$$W_0 = \lambda_1 H^c Q u^c + \lambda_2 H Q d^c + \lambda_3 H L e^c + \lambda_4 H^c H S^c + \lambda_5 h h^c S^c \,,$$

$$W_1 = \lambda_6 h u^c e^c + \lambda_7 L h^c Q + \lambda_8 \nu^c h d^c \,, \qquad W_2 = \lambda_9 h Q Q + \lambda_{10} h^c u^c d^c \,, \qquad W_3 = \lambda_{11} H^c L \nu^c$$

- The augmented NMSSM-like Higgs sector plus the additional D-terms allows us to get a ~125 GeV Higgs w/o large FT

$$
\begin{aligned}
V &= V_F + V_D + V_{soft} + \Delta V\,, \\
V_F &= \lambda^2|S|^2(|H_d|^2 + |H_u|^2) + \lambda^2|(H_d H_u)|^2\,, \\
V_D &= \frac{g_2^2}{8}\left(H_d^\dagger \sigma_a H_d + H_u^\dagger \sigma_a H_u\right)^2 + \frac{g'^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_1'^2}{2}\left(\tilde{Q}_1|H_d|^2 + \tilde{Q}_2|H_u|^2 + \tilde{Q}_S|S|^2\right)^2\,, \\
V_{soft} &= m_S^2|S|^2 + m_1^2|H_d|^2 + m_2^2|H_u|^2 + \left[\lambda A_\lambda S(H_u H_d) + h.c.\right]\,,
\end{aligned}
$$

1109.6373

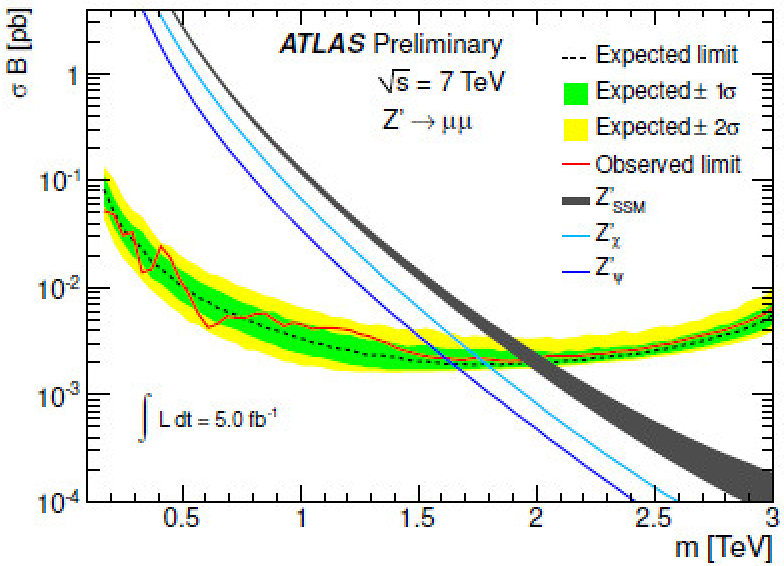
- Most pheno studies of these models have focused on the new matter (Higgs) fields &/or gauge boson sectors as they are the true hallmarks of these scenarios..

- Due to the extended matter content, RGE running leads to sfermions mostly being heavy while all gauginos are lighter

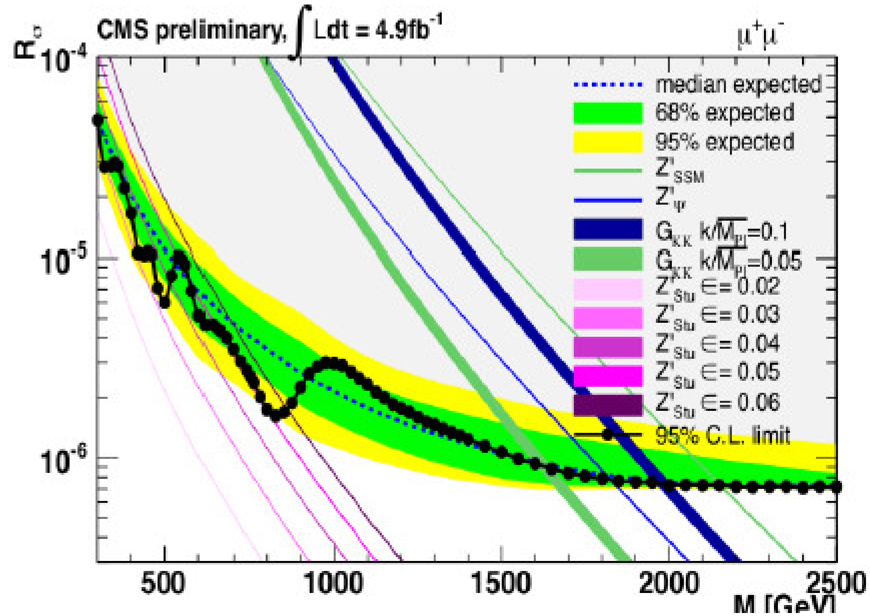
1102.4363

New Z' gauge bosons are one of the E_6SSM hallmarks…

ATLAS-CONF-2012-007



CMS EXO11019



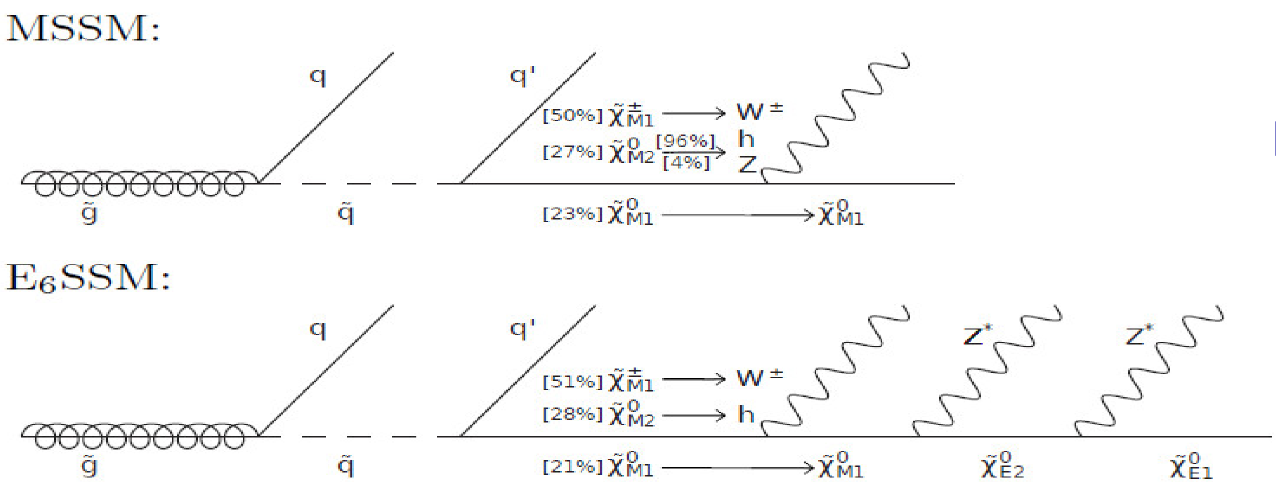
Present limits exceed ~1.5 TeV depending on couplings & decay scenarios

- A very novel feature is that the Z' decay itself can lead to sparticle production depending upon model details. This can produce resonance-enhanced rates for EWK-inos.

- The Z' also allows for regions where RH-sneutrinos are the LSP altering cascade structures

Porod etal.

- The additional charginos & neutralinos from the extended gauge sector can further lengthen cascade decay chains. E.g., less MET but more leptons or jets



1203.2495

Comparison of a typical gluino initiated cascades in the MSSM & E_6SSM for the same parent mass & σ @ 8 TeV

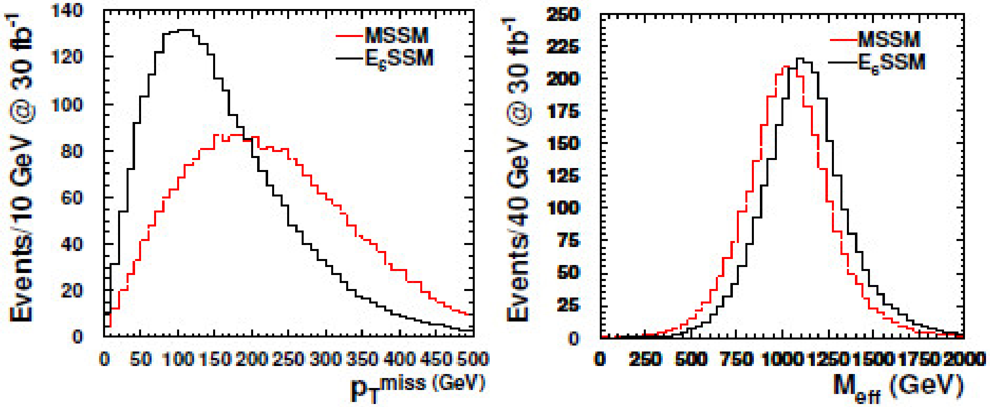


FIG. 4. Missing transverse momentum and the effective mass before cuts.

Here the increase of the number of jets & leptons generally more than compensates the MET reduction

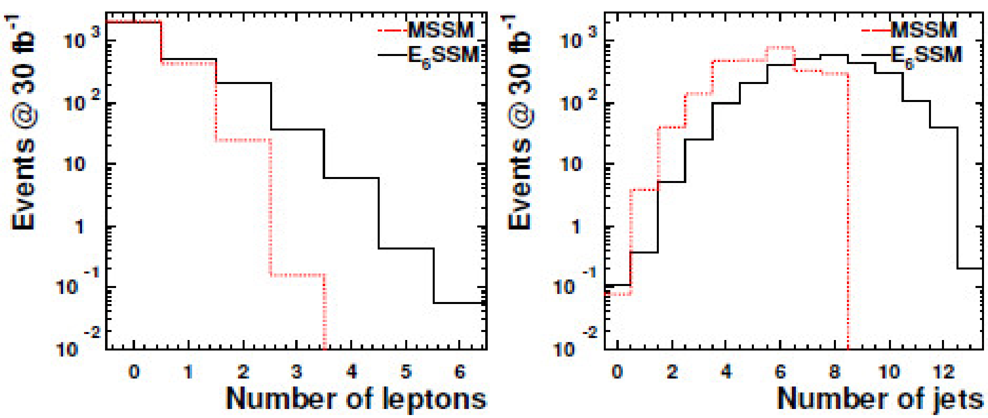


FIG. 5. Lepton multiplicity and jet multiplicity, requiring $p_T > 10$ GeV, $|\eta| < 2.5$ and $\Delta R(\text{lepton, jet}) > 0.5$ for leptons and $p_T > 20$ GeV and $|\eta| < 4.5$ for jets.

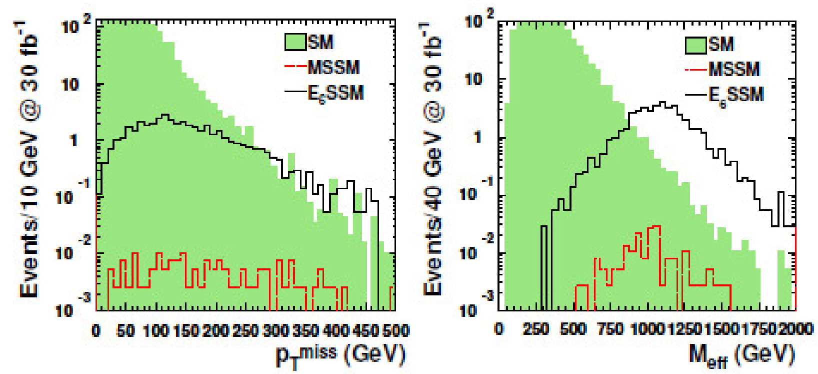


FIG. 6. Missing transverse momentum and effective mass after requiring three leptons, one with $p_T > 20$ GeV and two with $p_T > 10$ GeV. When applying a cut on the missing transverse momentum an estimation of the deviation from the SM can be made. For $\not{p}_T > 275$ GeV we expect $B = 3.24$ SM events and $S = 4.4$ events from the E_6SSM gluinos, which implies a 1.9σ excess. When instead applying a cut on the effective mass $M_{\text{eff}} > 900$ GeV we expect $S = 36.4$ events from the E_6SSM and $B = 5.0$ events from the SM, which implies a 8σ excess.

1203.2495

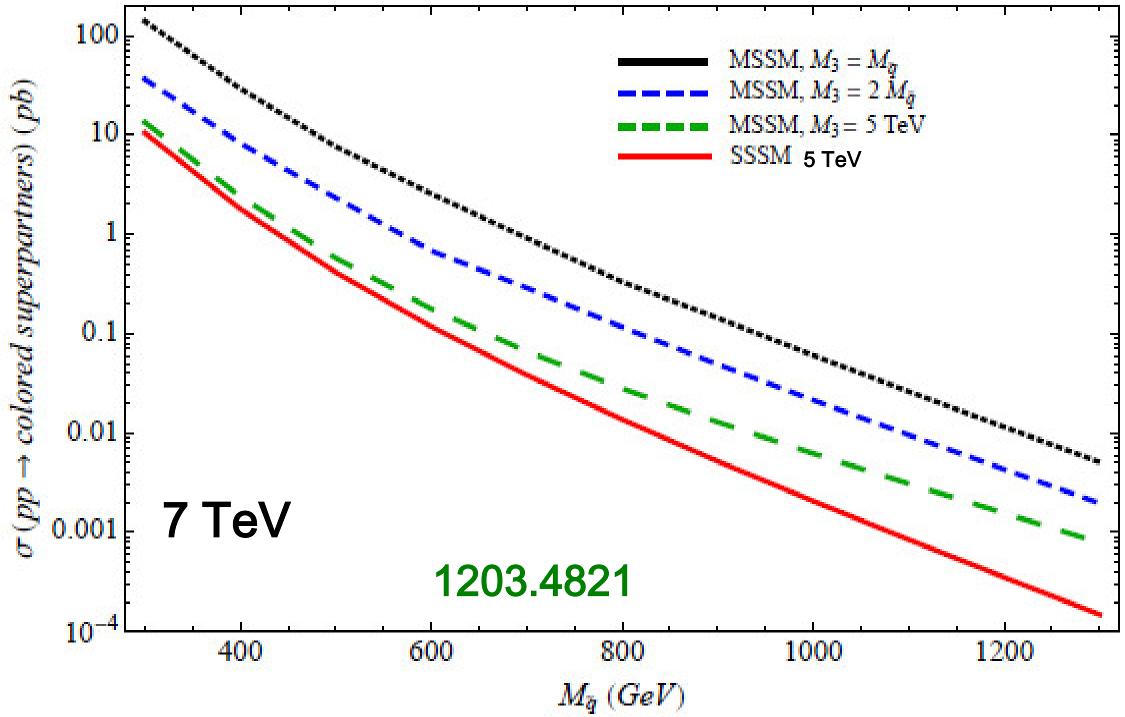
- A somewhat different extension to the MSSM occurs when additional adjoint matter fields are added & pair up with the usual vector ones turning, e.g., Majorana gluinos into Dirac fields (an N=1 ½ SUSY 'hybrid'). Note: if there is full N=2 SUSY in the gaugino sector there are also spin-0 sgluons !

- This changes the MSSM Feynman rules, hence, σ's & BF's In particular, the clean 'like-sign' dilepton signature is lost since it is the result of having Majorana gauginos.

- Specifically, valence quark initiated squark production is suppressed, i.e., $\tilde{q}_{L(R)}\ \tilde{q}_{L(R)}$ is now absent & $\tilde{q}_L\tilde{q}_R$ / $\tilde{q}_L^*\ \tilde{q}_R^*$ are both suppressed by an additional power of the gluino mass

hep-ph/0206096
0911.1951
1005.0818
1203.4821

- Some Simplified Models show this…



There is a considerable reduction in the colored sparticle cross section in the case of Dirac gluinos in comparison to the MSSM

- This paper examines in some detail how specific ATLAS & CMS jets+ MET analyses will be degraded by changing from M $\rightarrow$ D gluinos on a SR by SR basis via fast MC (Delphes)

- A direct comparison of an SSSM & three MSSM benchmarks was performed

Kribs & Martin 1203.4821

(Aside: for DM annihilation, Majorana vs Dirac LSPs can be critical)

search channel	SSSM ($M_3 = 5$ TeV)	"equal MSSM" ($\tilde{M}_3 = M_{\tilde{q}}$)	"intermediate MSSM" ($\tilde{M}_3 = 2 \times M_{\tilde{q}}$)	"heavy MSSM" ($\tilde{M}_3 = 5$ TeV)
ATLAS jets + $\not{E}_T$ 4.7 fb^{-1}				
SRA (2j) medium	737 GeV	1245 GeV	1096 GeV	890 GeV
SRA (2j) tight	634 GeV	**1453 GeV**	**1305 GeV**	**1063 GeV**
SRA′ (2j) tight	**748 GeV**	1189 GeV	1061 GeV	861 GeV
SRB (3j) tight	537 GeV	1342 GeV	1202 GeV	848 GeV
SRC (4j) loose	566 GeV	973 GeV	770 GeV	584 GeV
SRC (4j) medium	634 GeV	1095 GeV	894 GeV	670 GeV
SRC (4j) tight	**	1082 GeV	831 GeV	431 GeV
SRD (5j) tight	383 GeV	1076 GeV	803 GeV	484 GeV
SRE (6j) loose	**	731 GeV	500 GeV	328 GeV
SRE (6j) medium	491 GeV	979 GeV	712 GeV	521 GeV
SRE (6j) tight	**	933 GeV	634 GeV	388 GeV
CMS α_T 1.14 fb^{-1}				
$H_T \in [275, 325)$ GeV	396 GeV	528 GeV	489 GeV	399 GeV
$H_T \in [325, 375)$ GeV	454 GeV	594 GeV	533 GeV	473 GeV
$H_T \in [375, 475)$ GeV	509 GeV	698 GeV	631 GeV	548 GeV
$H_T \in [475, 575)$ GeV	**540 GeV**	786 GeV	694 GeV	**570 GeV**
$H_T \in [575, 675)$ GeV	487 GeV	859 GeV	770 GeV	565 GeV
$H_T \in [675, 775)$ GeV	373 GeV	932 GeV	833 GeV	460 GeV
$H_T \in [775, 875)$ GeV	**	960 GeV	806 GeV	**
$H_T \geq 875$ GeV	**	**1160 GeV**	**968 GeV**	**
combined	684 GeV	1178 GeV	1032 GeV	786 GeV
CMS jets + MHT 1.1 fb^{-1}				
$\not{E}_T > 350$ GeV, $H_T > 500$ GeV	**593 GeV**	989 GeV	844 GeV	648 GeV
$H_T > 500$ GeV	500 GeV	989 GeV	799 GeV	563 GeV
$\not{E}_T > 500$ GeV, $H_T > 800$ GeV	416 GeV	**1154 GeV**	**981 GeV**	**661 GeV**
CMS *razor*, 4.4 fb^{-1}				
$0\ \ell$, S1	**	639 GeV	**	**
$0\ \ell$, S2	**	**	**	**
$0\ \ell$, S3	**	960 GeV	783 GeV	434 GeV
$0\ \ell$, S4	**	**1082 GeV**	**898 GeV**	349 GeV
$0\ \ell$, S5	485 GeV	779 GeV	653 GeV	514 GeV
$0\ \ell$, S6	**505 GeV**	794 GeV	690 GeV	**556 GeV**
combined	588 GeV	1137 GeV	961 GeV	677 GeV

1203.4821

A serious reduction in the squark mass reach is clearly observed in the SSSM case…more studies would be very useful

Summary & Outlook

- The MSSM is certainly compatible with the Higgs evidence, the lack of a SUSY signal @ 7 TeV & the 'requirement' of low FT but the data selects a very 'special' type of sparticle spectrum that is likely to be accessible at 8 TeV w/ 20+ fb^{-1}.

- However, going beyond the MSSM menu allows for a much greater flexibility but requires the addition of more 'courses'

- Adding 'courses' not only modifies the Higgs sector but can lead to an overall modification in conventional SUSY rates & signals (e.g., like-sign leptons) BUT is also sometimes accompanied by new signatures, e.g., a Z'

- We look forward to the 8 TeV results in July… Down Under!

I want to thank the organizers & especially our BNL hosts for arranging this great workshop !

BACKUPS

Some Common Model Properties :

- Gluinos & 1st/2nd gen. squarks all lie above 1.25 TeV
- Wino/Higgsino LSPs only w/ a chargino below 270 GeV in all cases. Binos are all above 1.3 TeV
- Lightest stop (sbottom) between 300 & 1100 (400 & 1700)GeV
- Sleptons all over the place
- FT mostly driven almost entirely by μ & A_t

% models excluded	7 TeV ~1 fb^{-1}	7 TeV ~5 fb^{-1}
nj0l [5/11]	6.68%	23.23%
multi-j [4/6]	0.36%	1.61%
nj1l [8/3]	0.81%	2.64%
nj2l [5]	0.16%	0.22%***
flavor	(in progress)	(ditto)
(sub)total	6.73%	23.28%

→ nj0l is by far dominant in these searches

*** In this case, we extrapolated to ~5 fb^{-1}, since results have not yet been released. We assumed that the number of events observed equals the expected backgrounds & that the analysis cuts are exactly the same as at ~1 fb^{-1}

- Our analyses can be updated when more data is available

(Preliminary) Extrapolation to $\sqrt{s}$ = 8 TeV

- The extrapolation here is greater than for ~1 → ~5 fb^{-1} @ 7 TeV
- First pass: assume the cuts & analyses are as for 7 TeV & the number of observed events equals the expected backgrounds in each SR.
- However, we need to know the backgrounds for 8 TeV !
- Rescale ATLAS 7 TeV backgrounds? How? Use MC to determine the RATIOS of the expected backgrounds in each signal region at 7 & 8 TeV and use them as transfer factors
- When low statistics becomes an issue we closely follow ATLAS' approach using the sideband 'ABCD' method & then rescale the control regions
- Of course we still need to generate the relevant SM MC backgrounds

SM Background Generation @$\sqrt{s}$=7 & 8 TeV

- $Z/W^{\pm}$ + (0-4) j
- WW/ZZ + (0-2)j
- tt-bar + (0-1)j
- single t +(0-2)j
- QCD up to 6 jets

↔ ME + PS, weighted evts

~ 1 TB

w/ Sherpa

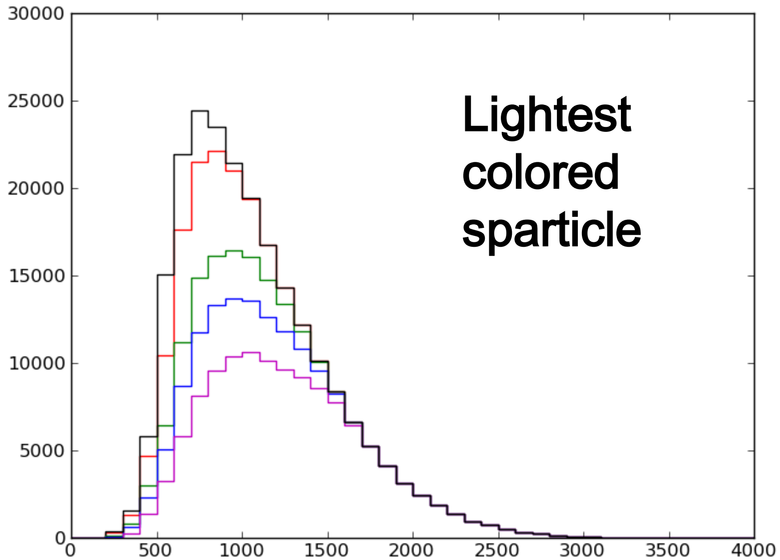
- Not too surprisingly, the gain in pMSSM coverage going to 8 TeV is substantial due to the increases in σ's. nj0l continues to dominate :

	8 TeV 5 fb^{-1}	8 TeV 20 fb^{-1}
nj0l**	32.70%	45.11%
multi-j**	6.26%	7.35%
nj1l**	1.41%	1.53%
nj2l++	0.35%	0.38%
flavor	(in progress)	(ditto)
(sub)total	32.75%	45.13%

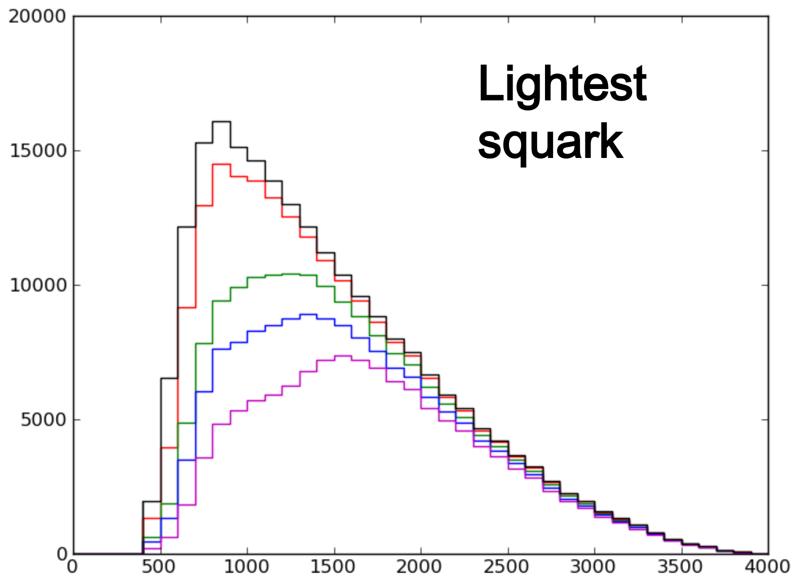
** extrapolated from ~5 fb^{-1} analysis ++ extrapolated from ~1 fb^{-1} analysis

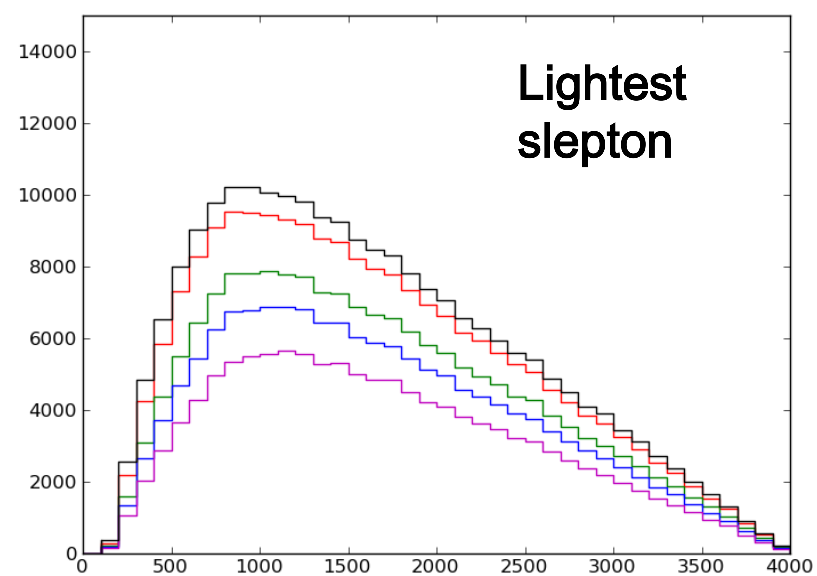
- $\sqrt{s}$=13-14TeV is needed for more complete coverage

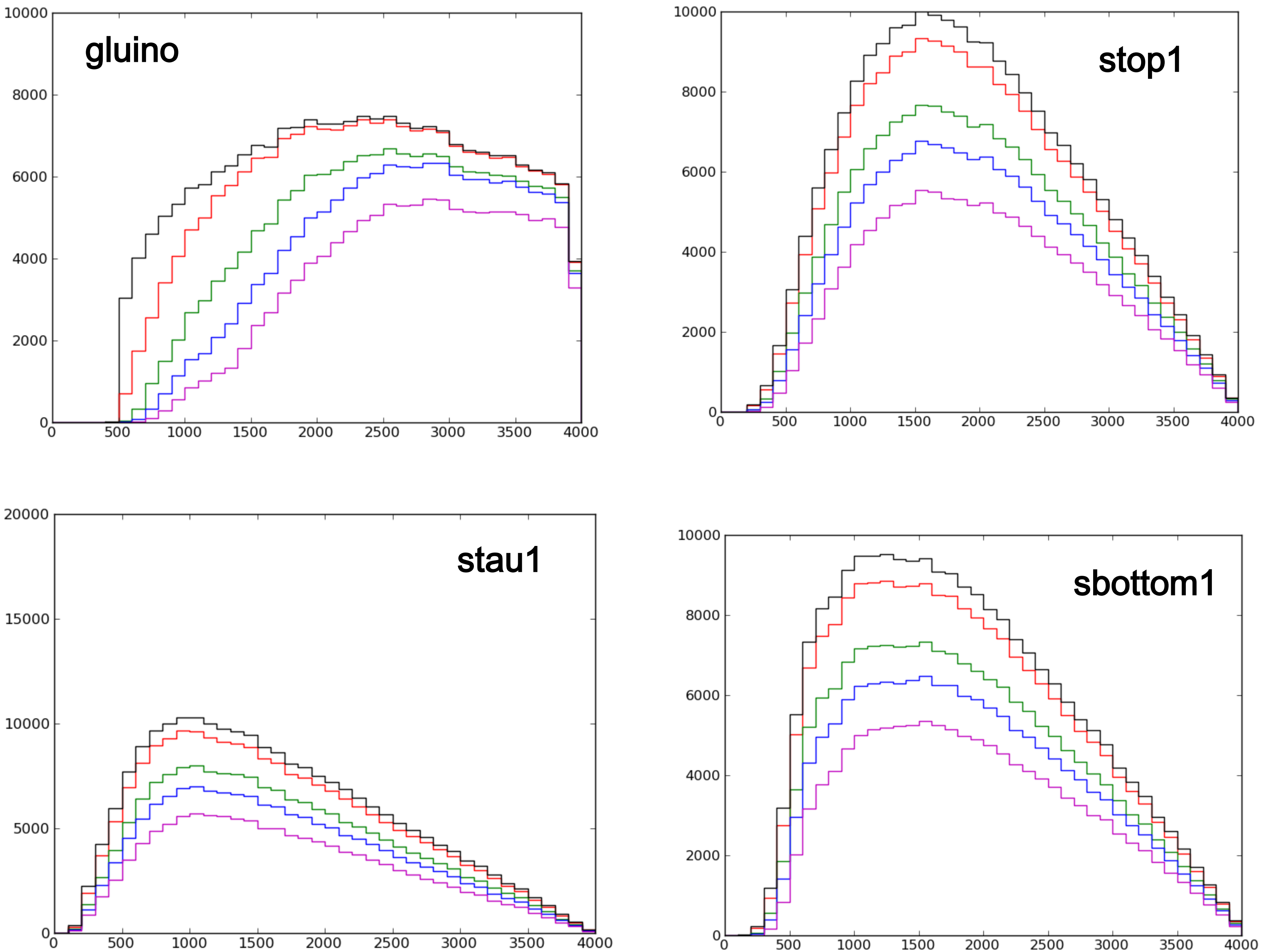
How does the pMSSM respond to negative searches ?



Note that colored sparticles get heavier, i.e., the distributions peak at higher masses as the searches progress but color singlets distributions are just rescaled downward



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stau1
sbottom1
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2000
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3000
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4000
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6000
8000
10000
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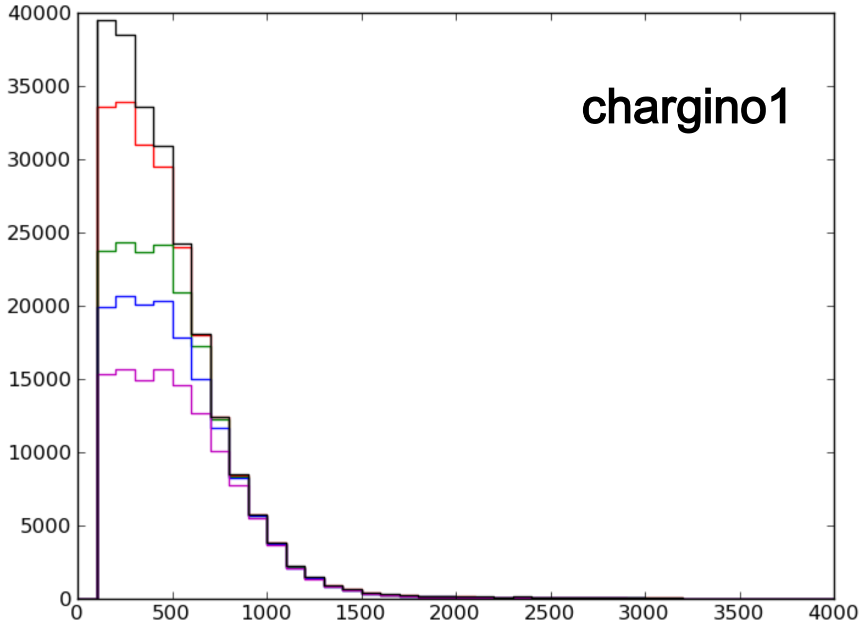
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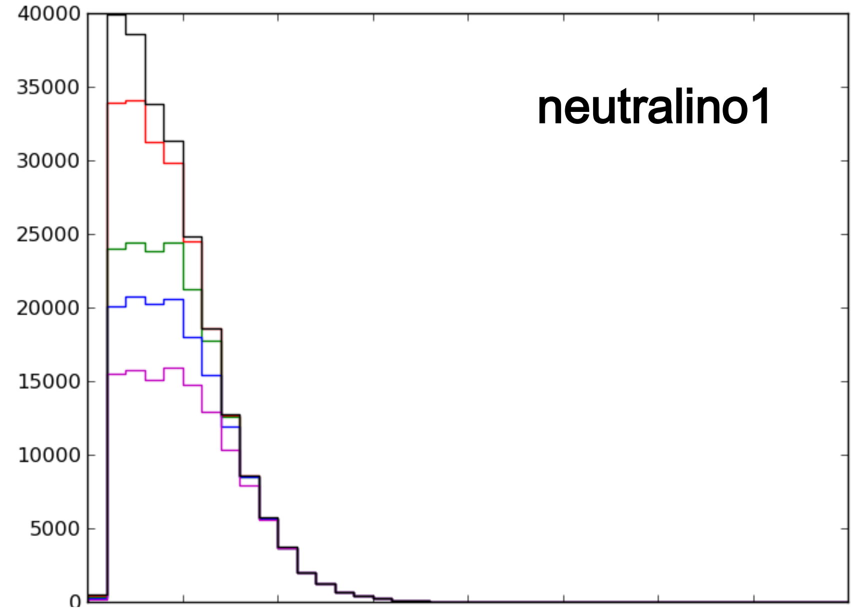
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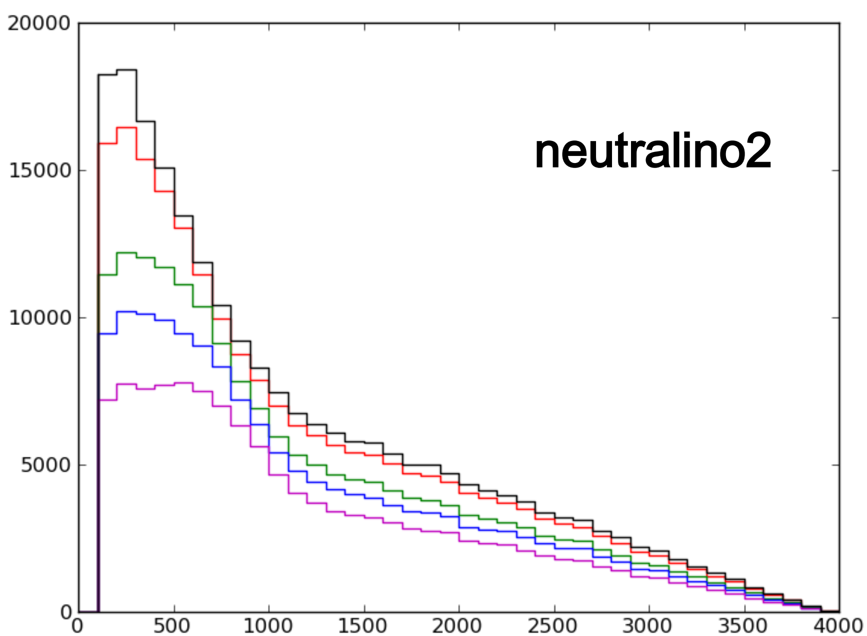
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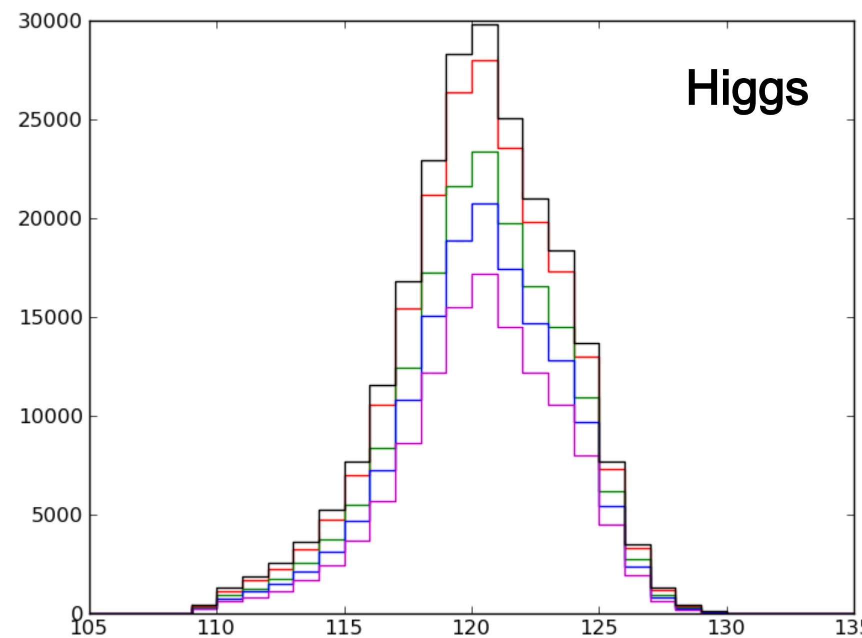
4000


Higgs
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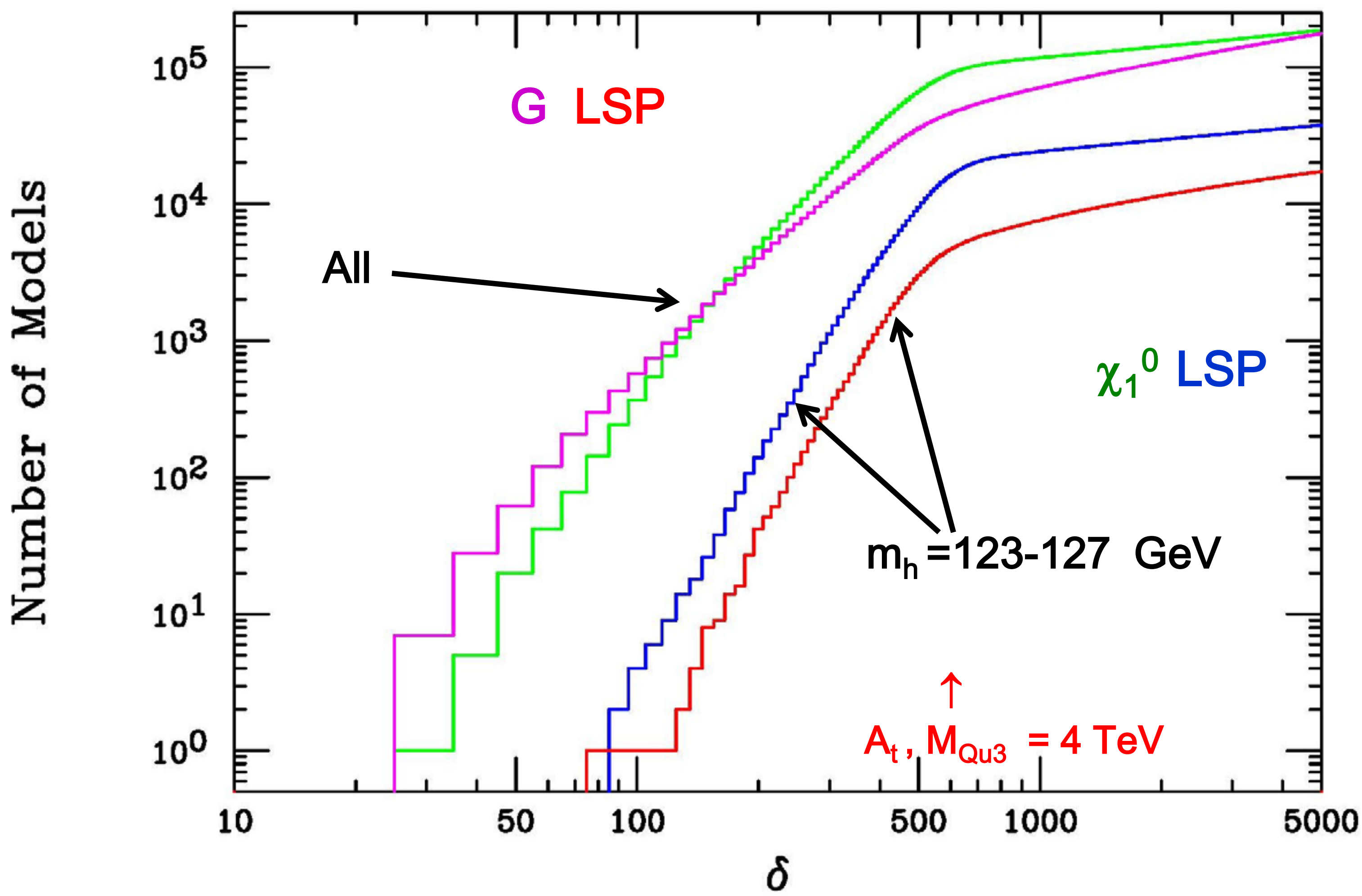
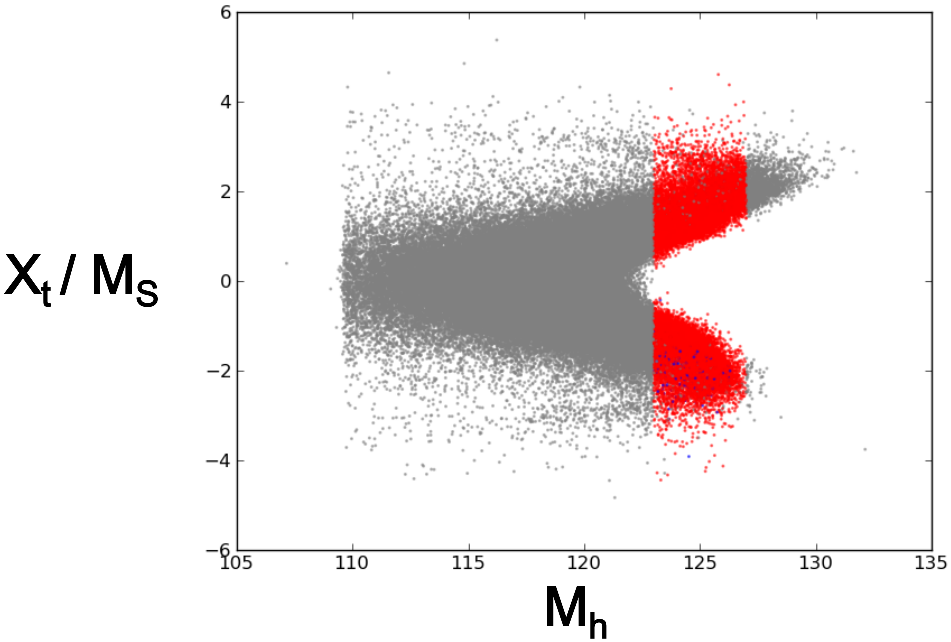
30000
105
110
115
120
125
130
135

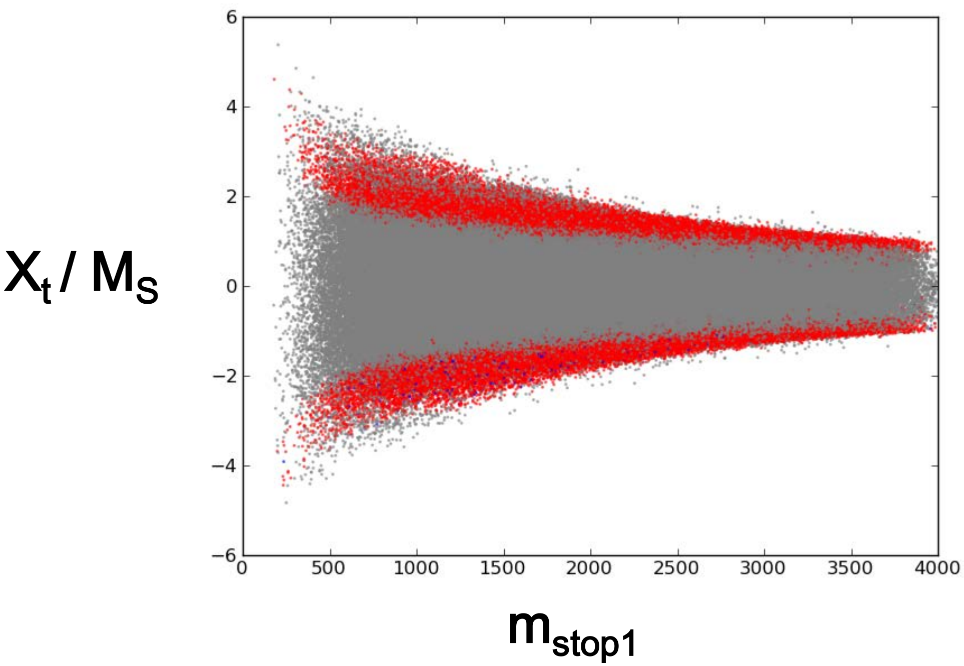
pMSSM Fine-Tuning v2.0





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

$M_S^2 = m_{stop1} \cdot m_{stop2}$



In the pMSSM:

$stop_1$ masses as low as ~250 GeV are still found for large X_t/M_s values for either model set