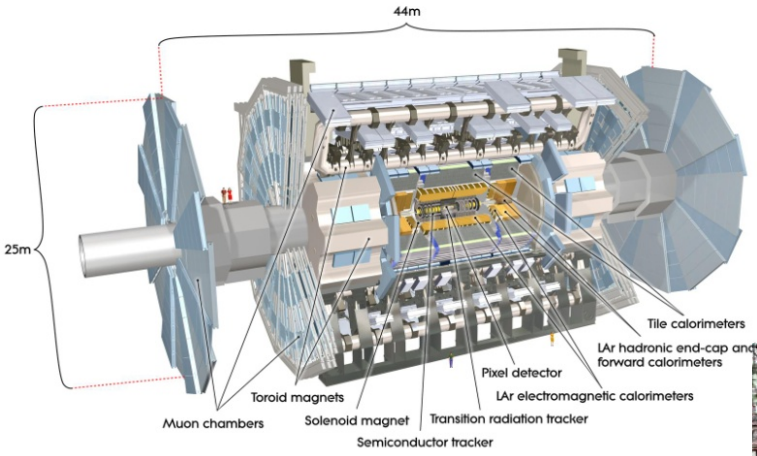
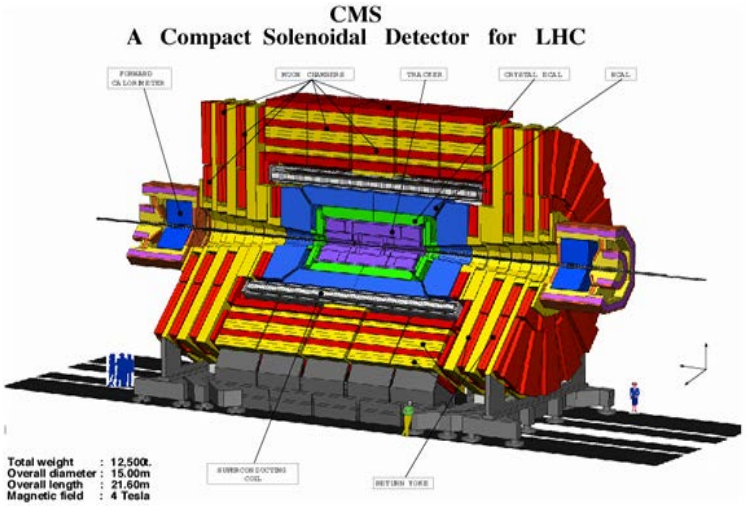
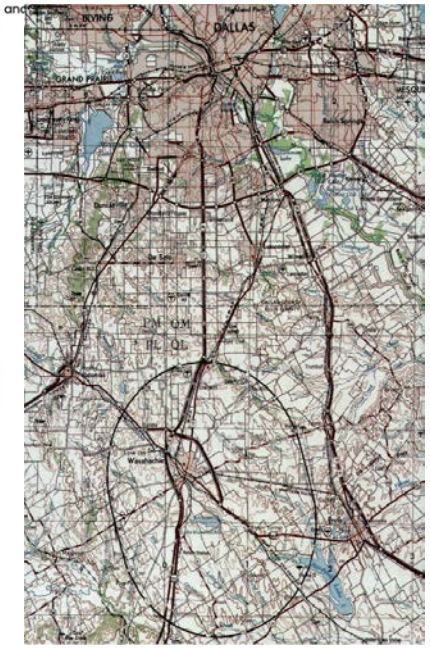
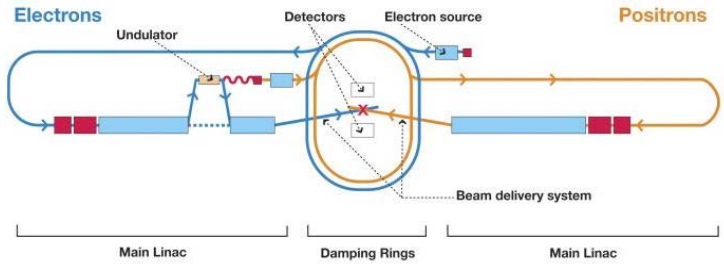
pMSSM SUSY Searches @ the LHC & Implication for the LC









1206.4321, 1206.5800, 1211.xyzt & 1211.abcd 10/23/12

SLAC NATIONAL ACCELERATOR LABORATORY
M.W. Cahill-Rowley, J.L. Hewett, S. Hoeche, A. Ismail, T.G.R.

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Barack Obama to be re-elected President in 2012

Event: 2012 Presidential Election Winner (Individual)

Lowest Ask	Highest Bid
$6.16	$6.13
128 shares	43 shares
Buy shares	Sell shares

Mitt Romney to be elected President in 2012

Event: 2012 Presidential Election Winner (Individual)

Lowest Ask	Highest Bid
$3.86	$3.84
22 shares	10 shares
Buy shares	Sell shares

Barack Obama to win the third Presidential debate (according to CNN poll)

Event: Winner of the third Presidential debate (according to CNN...

Lowest Ask	Highest Bid
$6.94	$6.70
10 shares	9 shares
Buy shares	Sell shares

Intrade Buzz

Exchange news

- New Market: What percentage of the popular vote will Gary Johnson win?
- New Market: State with the smallest winning margin (for either candidate)
- New Market: Obama vs. Romney - Winning Margin (Popular Vote)
- $4.99 p.m. for Effective "Free" Active Trading

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Forum posts

- When is the time-decay going to to kick in?
- Gay marriage ballot initiatives

Observation of the Supersymmetric Particle (2 Markets)

intrade **Supersymmetric Particle to be observed before midnight ET 31 Dec 2012**

Event: Observation of the Supersymmetric Particle

5.0% CHANCE Predict

intrade **Supersymmetric Particle to be observed before midnight ET 31 Dec 2013**

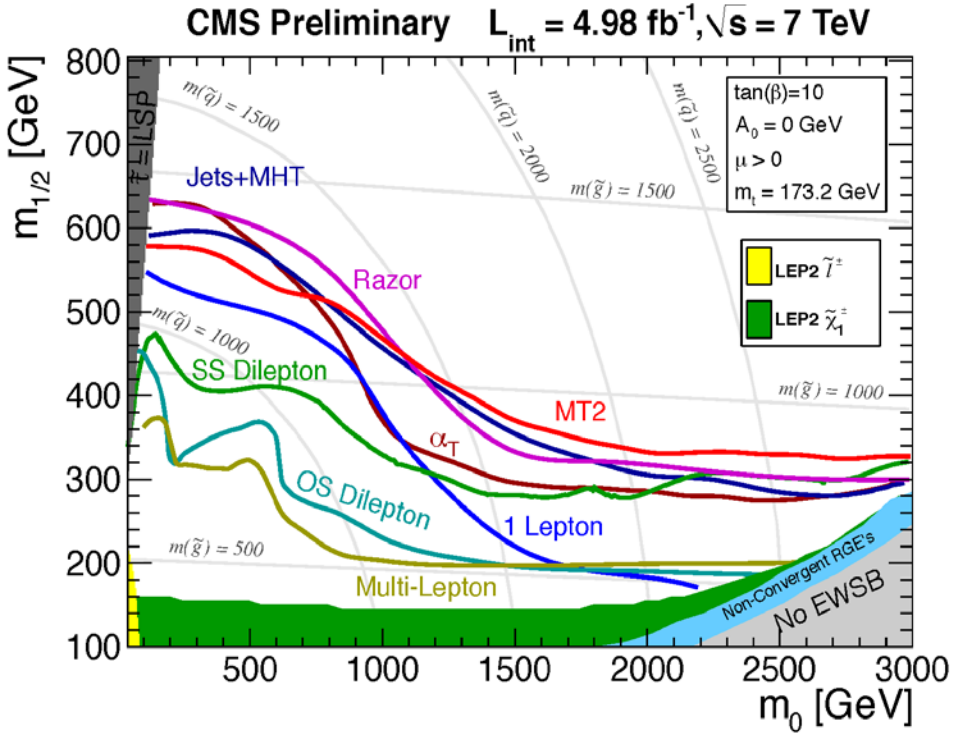
Event: Observation of the Supersymmetric Particle

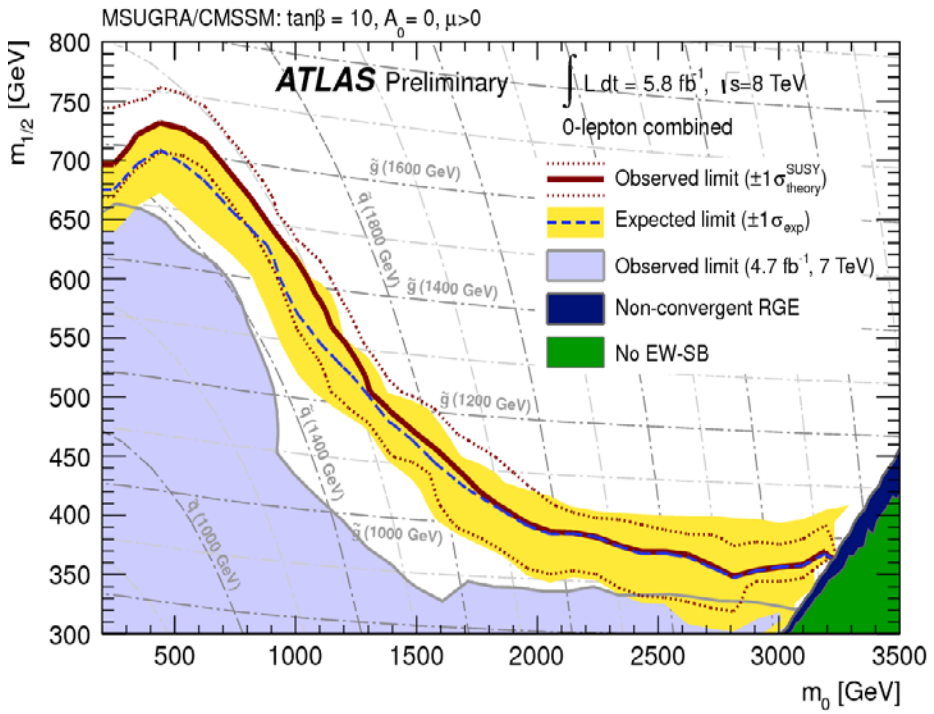
24.0% CHANCE Predict

?

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

It would be useful to go beyond, e.g., the cMSSM, to study the MSSM more generally.. but without giving up the correlations among experimental observables





Our Approach: The p(henomenological)MSSM

The MSSM has too many parameters so we make assumptions to reduce these to a reasonable level

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale (the CKM controls flavor)
- The lightest neutralino or the gravitino is the LSP.
- The first two sfermion generations are degenerate (sfermion type by sfermion type).
- The first two generations have negligible Yukawa's.
- No assumptions about SUSY-breaking or GUT

→ the pMSSM with 19/20 real, TeV/weak-scale parameters…

Choose the ranges of these parameters & how they're selected

Scan: look for ~250k points in these spaces satisfying all existing data & study their signatures @ the LHC & elsewhere.. NO FITS!

pMSSM Scans: Neutralino & Gravitino LSPs

(via SOFTSUSY +SuSpect + FeynHiggs)

$100\ \text{GeV} \leq m_{Le1,3} \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq m_{Qud1} \leq 4\ \text{TeV}$ $\quad 200\ \text{GeV} \leq m_{Qud3} \leq 4\ \text{TeV}$

$50\ \text{GeV} \leq |M_1| \leq 4\ \text{TeV}$ $\quad 100\ \text{GeV} \leq |M_2, \mu| \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq M_3 \leq 4\ \text{TeV}$ $\quad |A_{t,b,\tau}| \leq 4\ \text{TeV}$

$100\ \text{GeV} \leq M_A \leq 4\ \text{TeV}$ (flat scan)

$1 \leq \tan\beta \leq 60$

→→ For the gravitino LSP: $1\ \text{eV} \leq m_G \leq 1\ \text{TeV}$ (log scan)

- Generate points & then apply all the usual non-LHC + all LHC non-MET constraints (as of 12/1/2011) . Additional ones apply, eg, BBN , for the gravitino LSP case

ATLAS SUSY Analyses @ 7 & 8 TeV

- We (almost) exclusively follow the ATLAS analysis suite with fast MC (modified PGS/Pythia), validated using ATLAS cMSSM points & employing ATLAS backgrounds

- First, we consider the 'vanilla' MET searches

χ_1^0 LSP

(126 ± 3 GeV only)

% models excluded	7 TeV ~1 fb^{-1}	7 TeV ~5 fb^{-1}
nj0l [5/11]	6.68%	21.04%(18.53%)
multi-j [4/6]	0.36%	1.61%(1.34%)
nj1l [8/3]	0.81%	3.16% (2.80%)
(sub)total	6.73%	21.19%(18.64%)

Now there is 8 TeV data since SUSY2012:

8 TeV 5.8 fb^{-1} **

	without m_h cut	with m_h cut
nj0l [12]	26.50%	23.80%
multi-j [6]	3.31%	2.84%
nj1l [1]	3.30%	3.07%
nj2l (SS) [1]	4.88%	4.50%
total	26.90%	24.16%

(126 ± 3 GeV only)

..out of the subset of models passing the Higgs mass constraint

The Higgs mass cut doesn't change things too much but there is a 'minor' inclusive search degradation

** The corresponding analyses are

2012 Data (8 TeV)

Short Title of the CONF note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
0 leptons + >=2-6 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-109	Link
0 leptons + >=6-9 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-103	Link
1 lepton + >=4 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-104	Link
2 same-sign leptons + >=4 jets + Etmiss NEW	08/2012	8	5.8	ATLAS-CONF-2012-105	Link

Comments

- Interestingly, 1591 of the models that SURVIVED the 8 TeV analysis were ALREADY KILLED by the 7 TeV one!

Here is a valuable lesson !

- It is likely that some reasonable fraction of SUSY points will get 'by-passed' as the LHC collision energy increases due to their inability to pass stiffer selection cuts

- It certainly helps to combine analyses performed at various energies but this is no guarantee of complete coverage

Third Generation & Multi-lepton searches @ 7 TeV

- There are a huge number of searches (see next slide) & we have tried to simulate ALL of the ones that are relevant for our model sets .. Some work still remains for the gravitino models.

- We expect these searches to be complimentary to the more general vanilla MET searches

- Some of these results are still PRELIMINARY !

2011 Data (7 TeV)

Short Title of the Paper		Date	√s (TeV)	L (fb^{-1})	Document	Plots+Aux. Material	Journal
1-2 leptons + >=2-4 jets + Etmiss NEW	✓	08/2012	7	4.7	1208.4688	Link	Submitted to PRD
2 leptons + >=1 jet + Etmiss [Very light stop] NEW	✓	08/2012	7	4.7	1208.4305	Link	Submitted to EPJC
3 leptons + Etmiss [Direct gauginos] NEW	✓	08/2012	7	4.7	1208.3144	Link	Submitted to PLB
2 leptons + Etmiss [Direct gauginos/sleptons] NEW	✓	08/2012	7	4.7	1208.2884	Link	Submitted to PLB
1 lepton + >=4 jets (>=1 b-jet) + Etmiss [Heavy stop] NEW	✓	08/2012	7	4.7	1208.2590	Link	Submitted to PRL
0 lepton + 1-2 b-jet + 5-4 jets + Etmiss [Heavy stop] NEW	✓	08/2012	7	4.7	1208.1447	Link	Submitted to PRL
0 lepton + >=2-6 jets + Etmiss NEW	✓	08/2012	7	4.7	1208.0949	Link	Submitted to PRD
0 lepton + >=3 b-jets + >=(1-3) jets + Etmiss [Gluino med. stop/sb.]	✓	07/2012	7	4.7	1207.4686	Link	Submitted to EPJC
0 lepton + >=(6-9) jets + Etmiss	✓	06/2012	7	4.7	1206.1760	Link	JHEP 1207 (2012) 167
Electron-muon continuum [RPV]	X	05/2012	7	2.05	1205.0725	Link (inc. HEPData)	EPJC 72 (2012) 2040
Z->ll + b-jet + jets + Etmiss [Direct stop in natural GMSB]	✓	04/2012	7	2.05	1204.6736	Link (inc. HEPData)	PLB 715 (2012) 44

Short Title of the Conf. note		Date	√s (TeV)	L (fb^{-1})	Document	Plots
1-2 taus + 0-1 leptons + jets + Etmiss NEW	X	08/2012	7	4.7	ATLAS-CONF-2012-112	Link
3 leptons + jets + Etmiss NEW	✓	08/2012	7	4.7	ATLAS-CONF-2012-108	Link
2 b-jets + Etmiss [Direct sbottom] NEW	✓	08/2012	7	4.7	ATLAS-CONF-2012-106	Link
muon + displaced vertex [RPV] NEW	✓	08/2012	7	4.7	ATLAS-CONF-2012-113	Link
Disappearing track + jets + Etmiss *[Direct long-lived charginos - AMSB]* NEW	✓ ✓	08/2012	7	4.7	ATLAS-CONF-2012-111	Link
~~*2 jet pair resonances [N=1/2 scalar gluons]* NEW~~		08/2012	7	4.7	ATLAS-CONF-2012-110	Link
~~*General new phenomena search* NEW~~		08/2012	7	4.7	ATLAS-CONF-2012-107	Link
Monophoton [ADD, WIMP]		07/2012	7	4.7	ATLAS-CONF-2012-085	Link
Monojet [ADD, WIMP]		07/2012	7	4.7	ATLAS-CONF-2012-084	Link
Long-Lived Particles [R-hadron, slepton]	✓	07/2012	7	4.7	ATLAS-CONF-2012-075	Link
2 photons + Etmiss [GGM]	✓	07/2012	7	4.8	ATLAS-CONF-2012-072	Link
2 leptons + jets + Etmiss [Medium stop]	✓	07/2012	7	4.7	ATLAS-CONF-2012-071	Link
1-2 b-jets + 1-2 leptons + jets + Etmiss [Light Stop]	X	07/2012	7	4.7	ATLAS-CONF-2012-070	Link

Third Generation & Multi-lepton searches @ 7 TeV

	w/o Higgs cut	w/ Higgs cut
1207.4686	4.92%	4.54%
1208.4305	<0.01%	0
-071	0.32%	0.24%
1208.1447	3.66%	3.15%
1208.2590	1.94%	1.69%
1204.6736	<0.01%	0
-106	2.47%	2.20%
-108	1.05%	0.92%
1208.4688	4.11%	3.61%
1208.2884	0.11%	0.10%
1208.3144	0.33%	0.27%
All 3rd gen.	7.26%	6.48%
All ML	4.29%	3.78%

χ_1^0 LSP

There are a lot of searches that provide very different coverage of the pMSSM model space

These add substantially to the TOTAL coverage as they are mostly orthogonal to the jet+MET generic searches

Again Higgs mass cuts are not very influential in changing total coverage

Other non-MET 7 TeV Searches

χ_1^0 LSP	w/o Higgs cut	w/ Higgs cut
HSCP(CMS)	4.03%	4.14%
Dis. Tracks	2.59%	2.21%
$B_s \rightarrow \mu\mu$	2.71%	5.58%
$A/H \rightarrow \tau\tau$	0.01%	< 0.01%
ALL Searches	33.89%	33.45%

When all searches are combined the Higgs mass constraint has little influence on the total coverage of the pMSSM models

Gravitino LSPs

- Gravitino LSP scenarios can produce many models with detector-stable charged/colored sparticles over a very wide range of masses & species.

- Stable sparticle searches will then be a powerful means of probing these models. This additional handle will be critical as there will be reduced production of MET in decay chains that can end in HSCP. Here we follow the CMS analysis.

- These effects are visible in the model coverage

Gravitino Model Searches @ 7 TeV

	7 TeV ~5 fb^{-1}	with Higgs mass cut	
nj0l [11]	14.46%	13.09%	
multi-j [6]	3.32%	3.07%	
nj1l [3]	5.35%	4.65%	
(sub)total	16.44%	14.73%	Less MET !!!
HSCP	14.34%	12.81%	Clearly Important!!
(sub) total	30.75%	27.32%	

The subset w/ the Higgs mass cut has slightly degraded coverage

The 8 TeV 'jet + MET' search results are not yet available…jobs running now!

Third Generation & Multi-lepton searches @ 7 TeV

	w/o Higgs cut	w/ Higgs cut
1207.4686	4.57%	4.81%
1208.4305	0.02%	<0.01%
-071	5.29%	4.65%
1208.1447	3.78%	4.32%
1208.2590	2.69%	3.02%
1204.6736	0.12%	0.13%
-106	2.97%	2.98%
-108	7.17%	6.32%
1208.4688	9.93%	8.59%
1208.2884	1.44%	1.24%
1208.3144	6.71%	5.84%
sub-total	18.13%	17.46%
All Searches	38.23%	38.29%

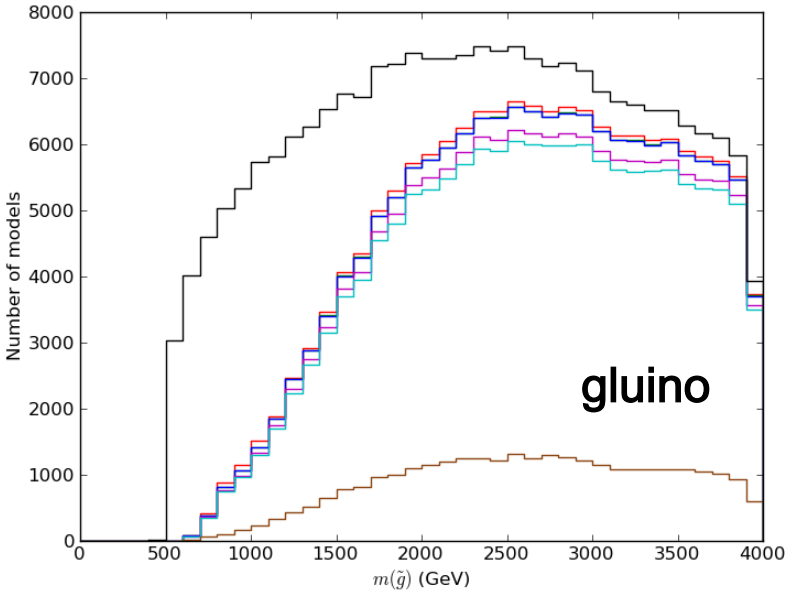
G LSP

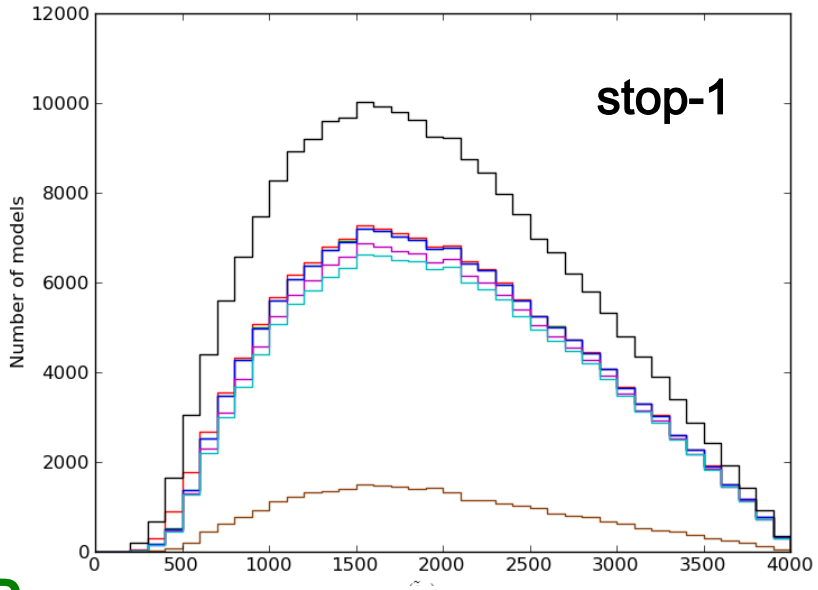
3rd gen/Multi-l searches are significantly more effective for the gravitino set.

This is due to several factors including lighter stops and sbottoms & the relatively high frequency of slepton NLSPs producing leptons & MET

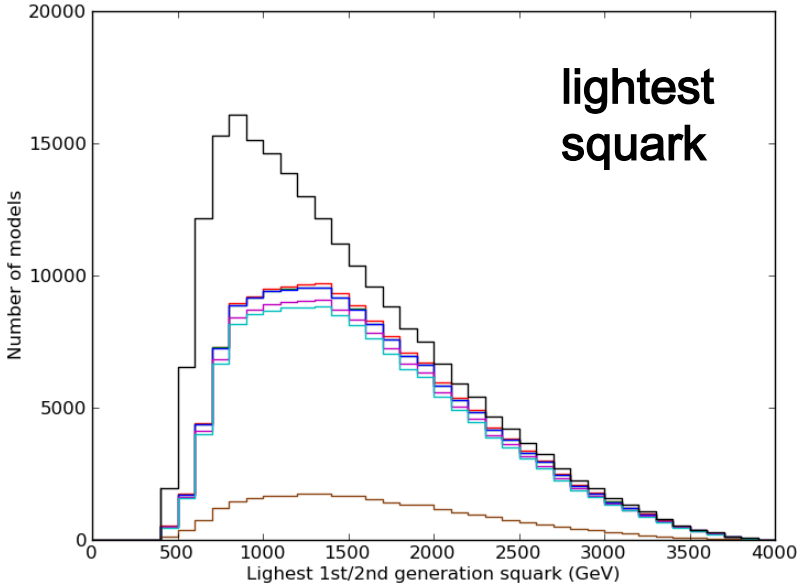
Again, OVERALL, there is little difference imposing the Higgs mass cut, but more so in individual searches

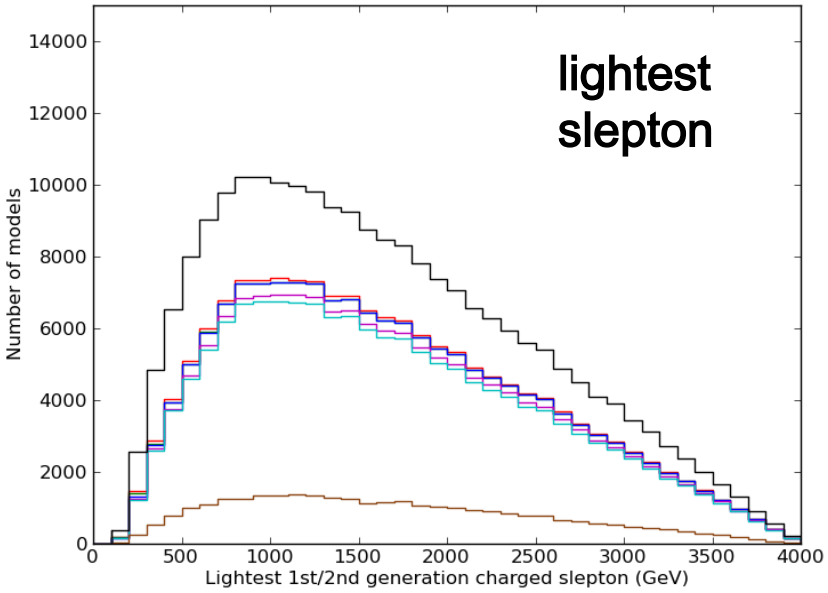
How does the pMSSM respond to negative searches ?

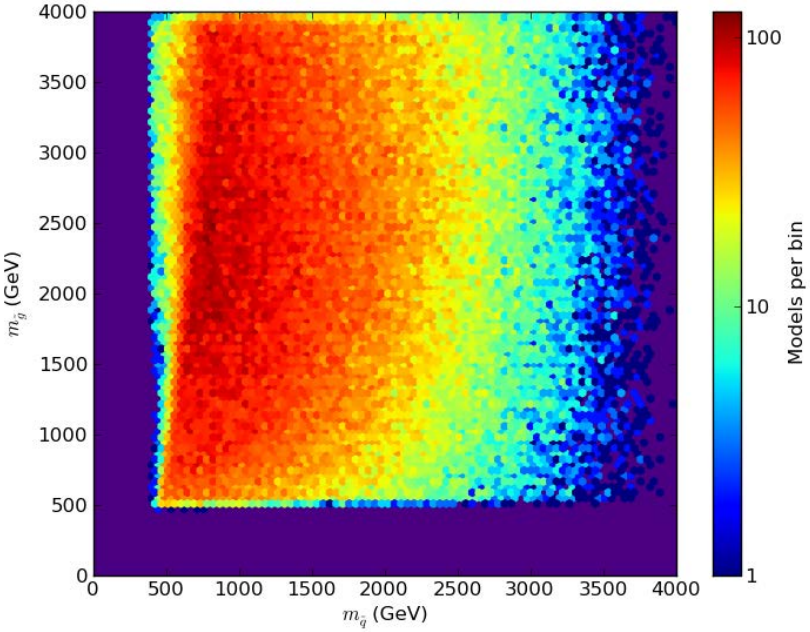


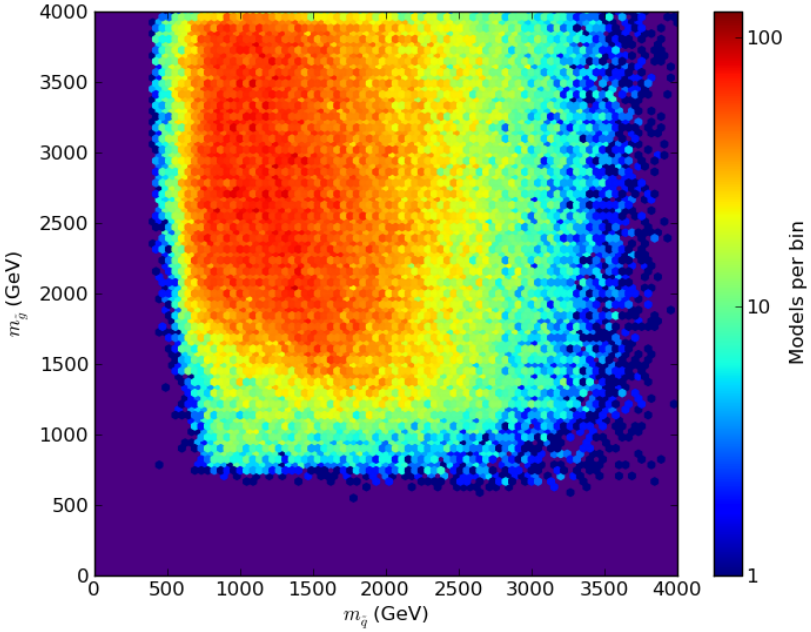


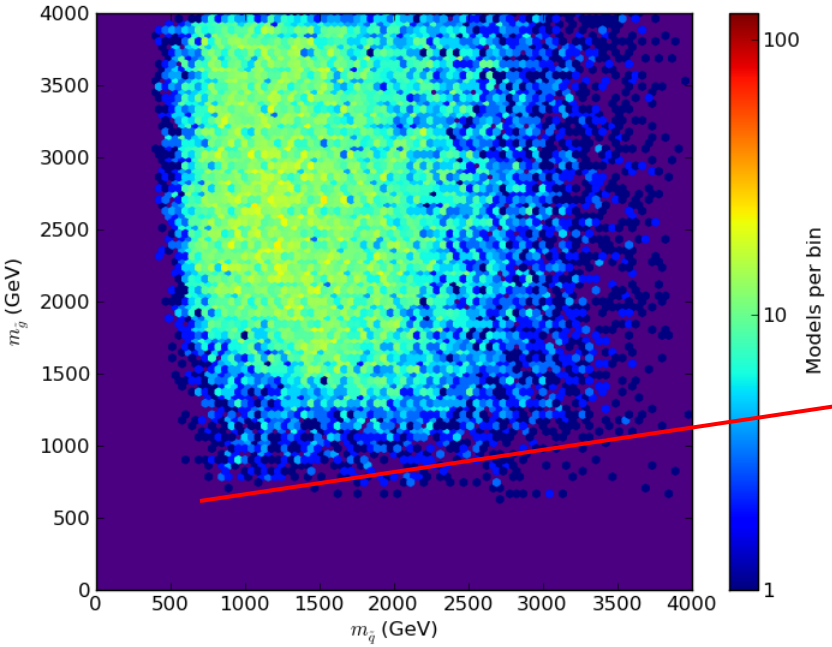
χ_1^0 LSP

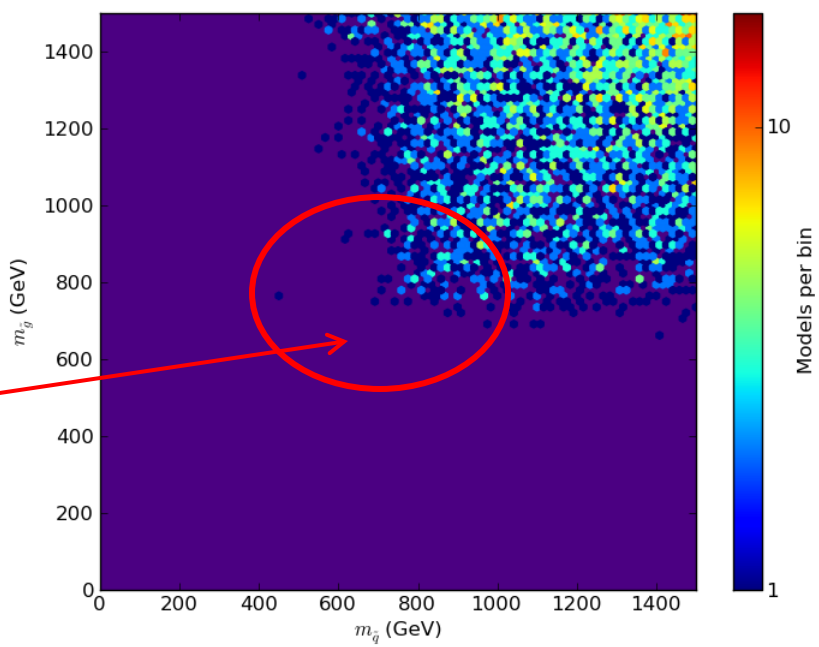


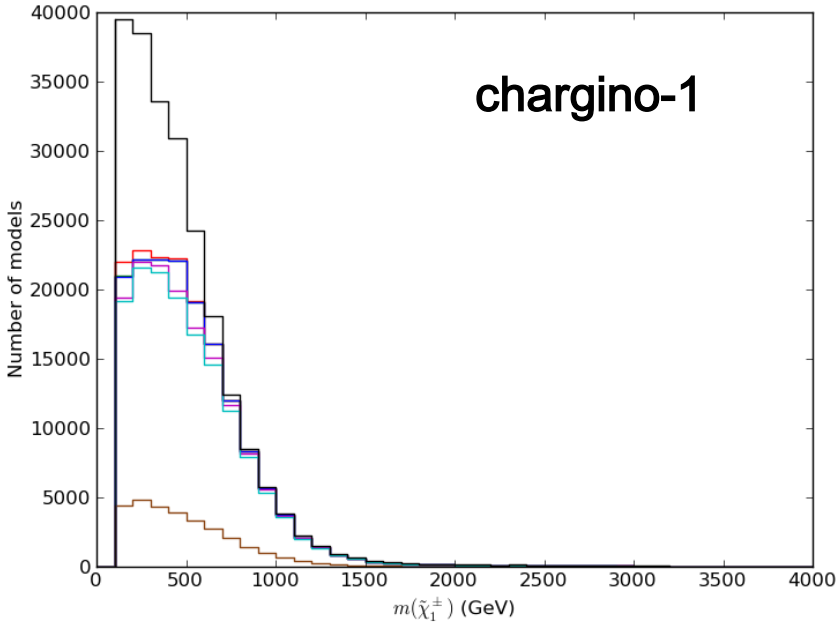


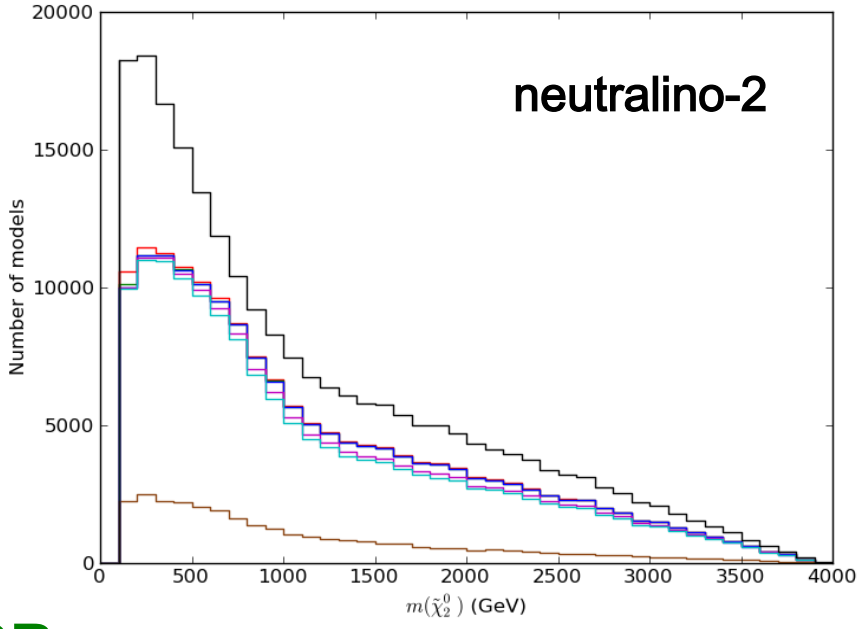

$m_{\tilde{g}}$ (GeV)
$m_{\tilde{q}}$ (GeV)
Models per bin


$m_{\tilde{g}}$ (GeV)
$m_{\tilde{q}}$ (GeV)
Models per bin

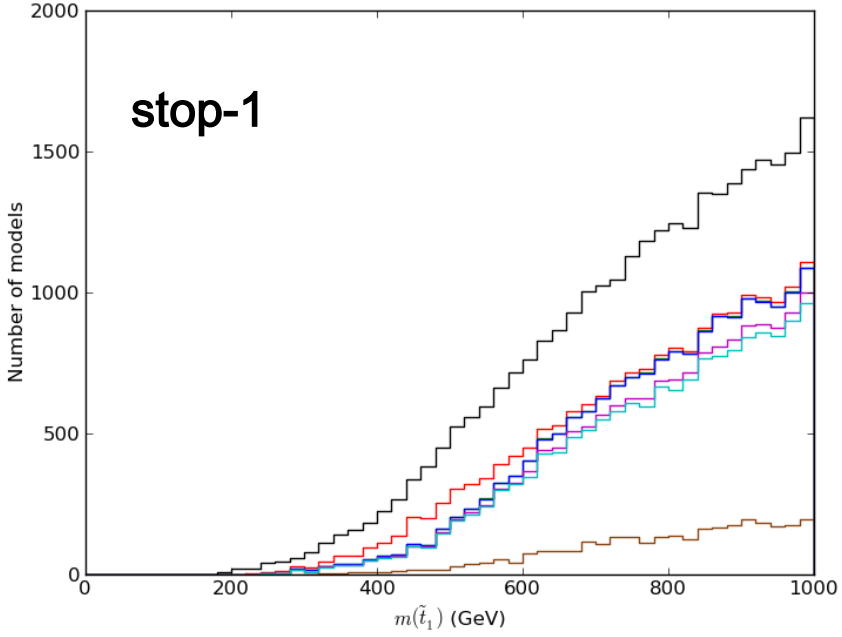

$m_{\tilde{g}}$ (GeV)
$m_{\tilde{q}}$ (GeV)
Models per bin

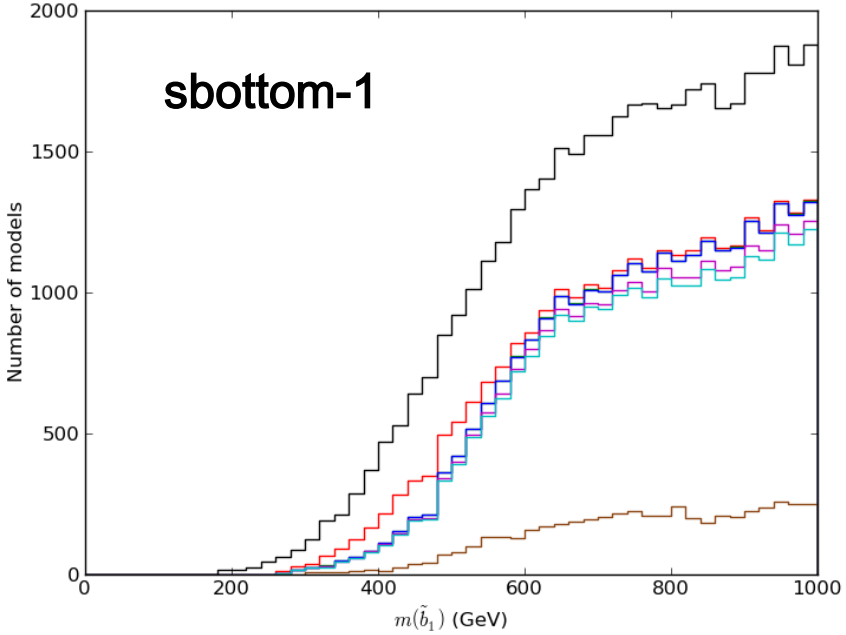

$m_{\tilde{g}}$ (GeV)
$m_{\tilde{q}}$ (GeV)
Models per bin


chargino-1
Number of models
$m(\tilde{\chi}_1^{\pm})$ (GeV)


neutralino-2
Number of models
$m(\tilde{\chi}_2^0)$ (GeV)

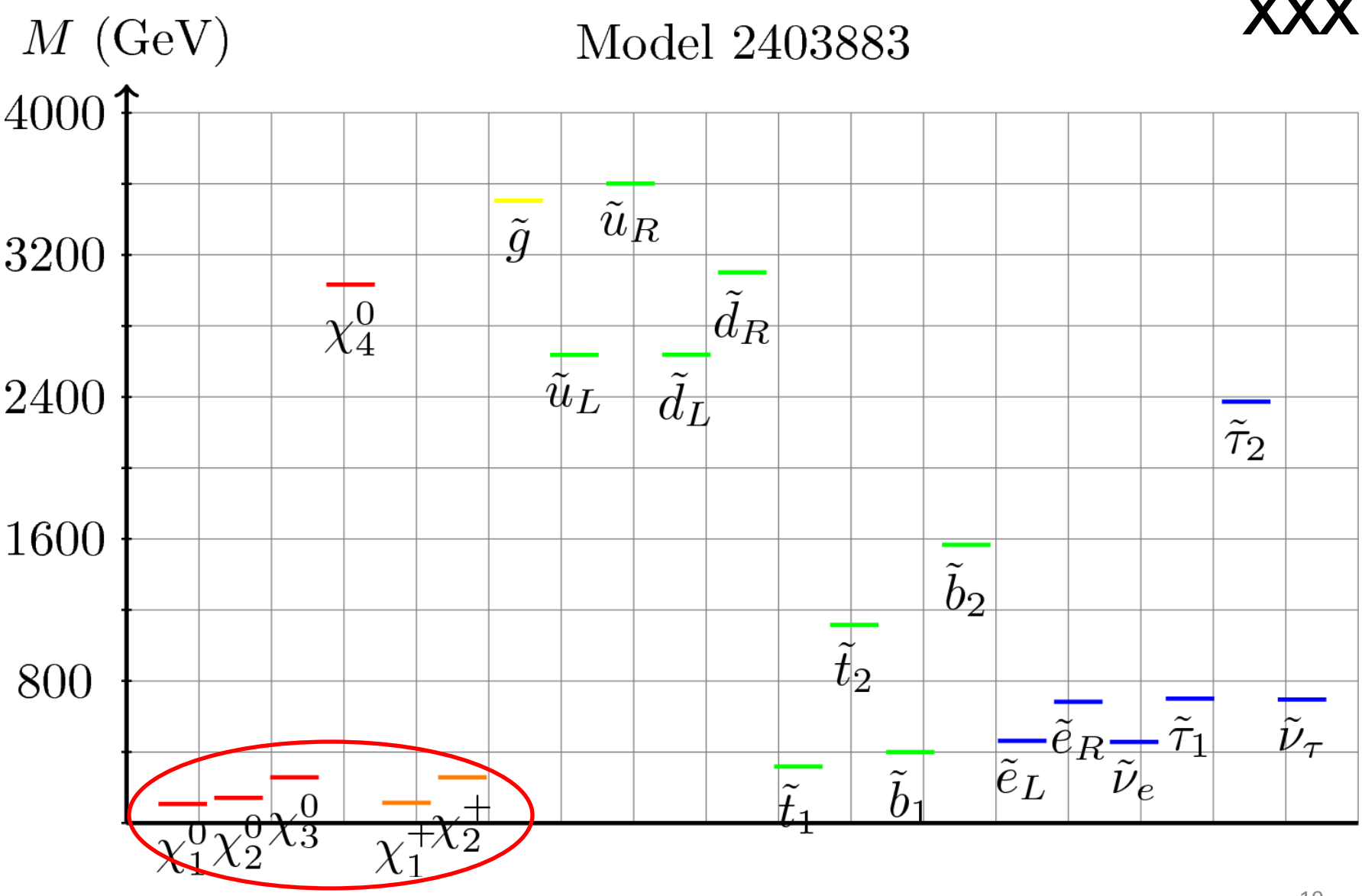
χ_1^0 LSP


stop-1
Number of models
$m(\tilde{t}_1)$ (GeV)

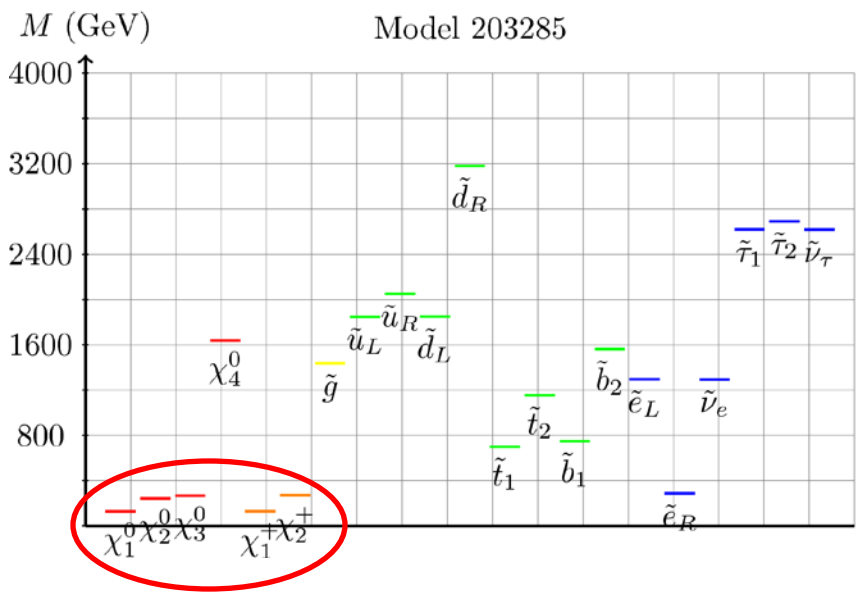

sbottom-1
Number of models
$m(\tilde{b}_1)$ (GeV)

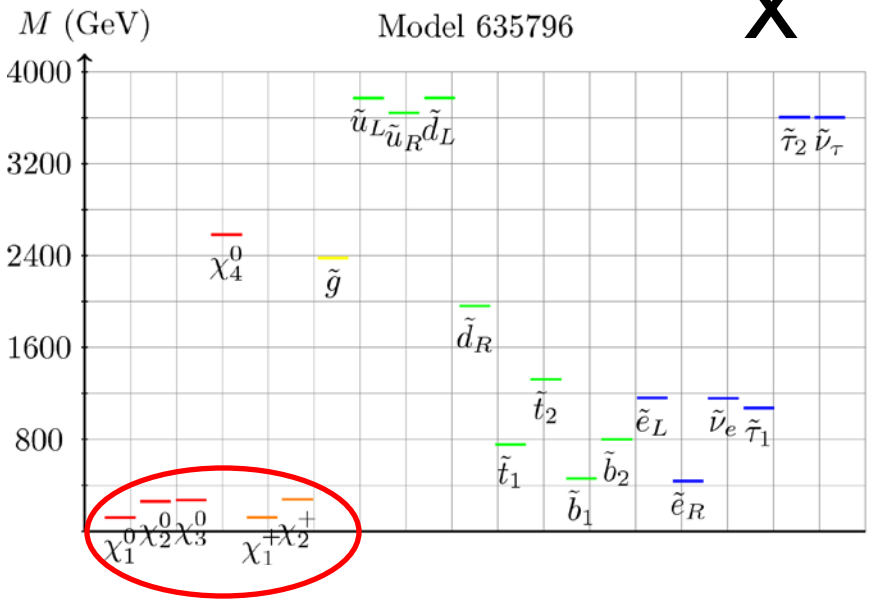
A ‘typical’ low-FT example…

XXX



The Better Models & Their Natures





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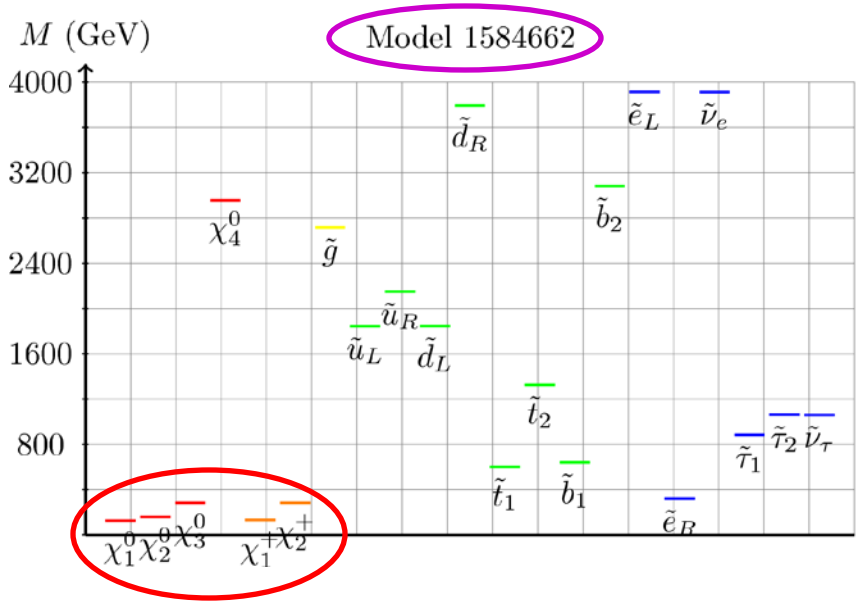
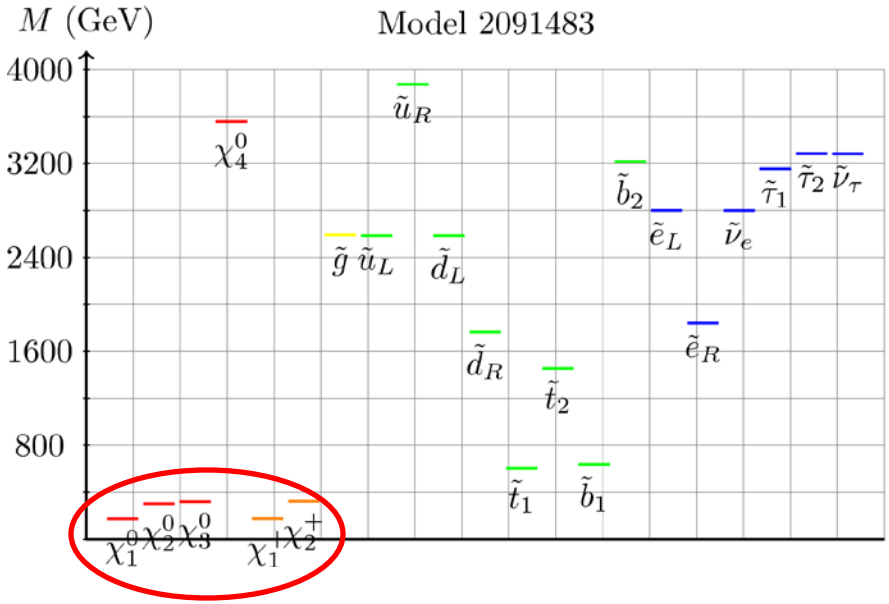
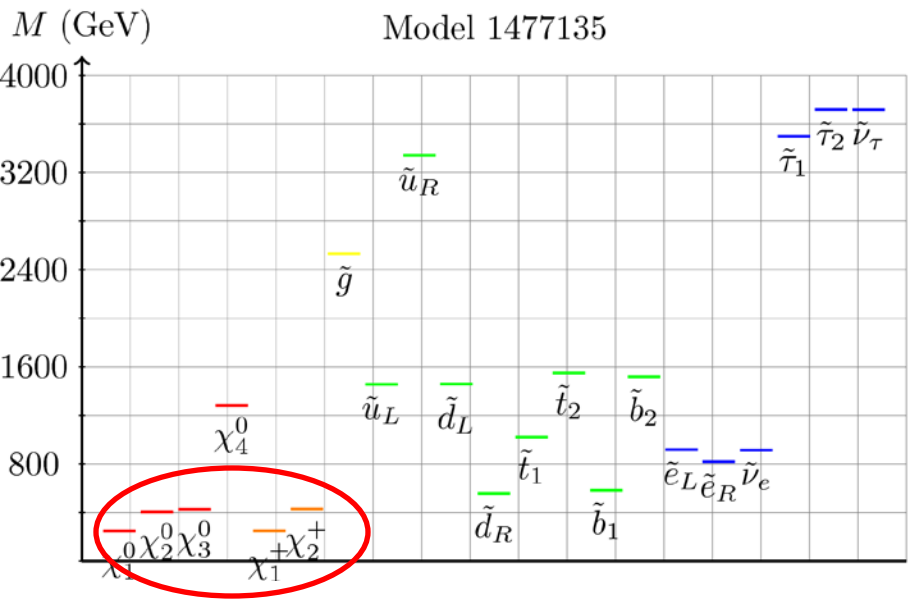
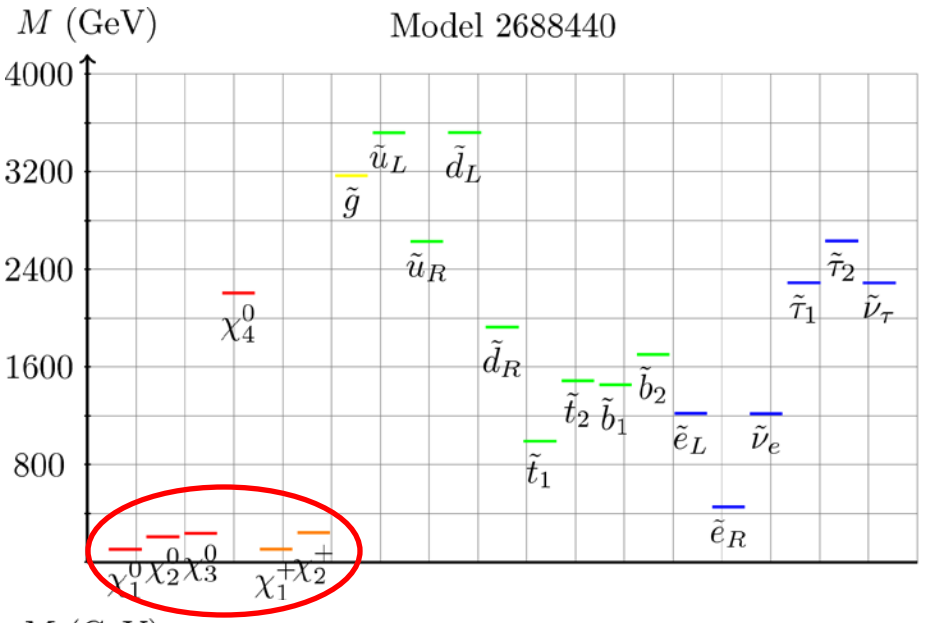
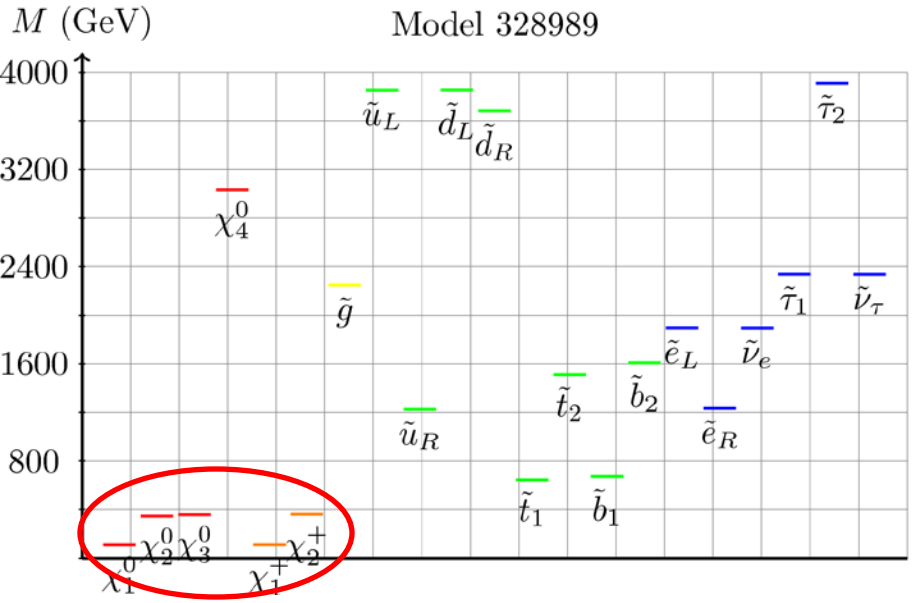


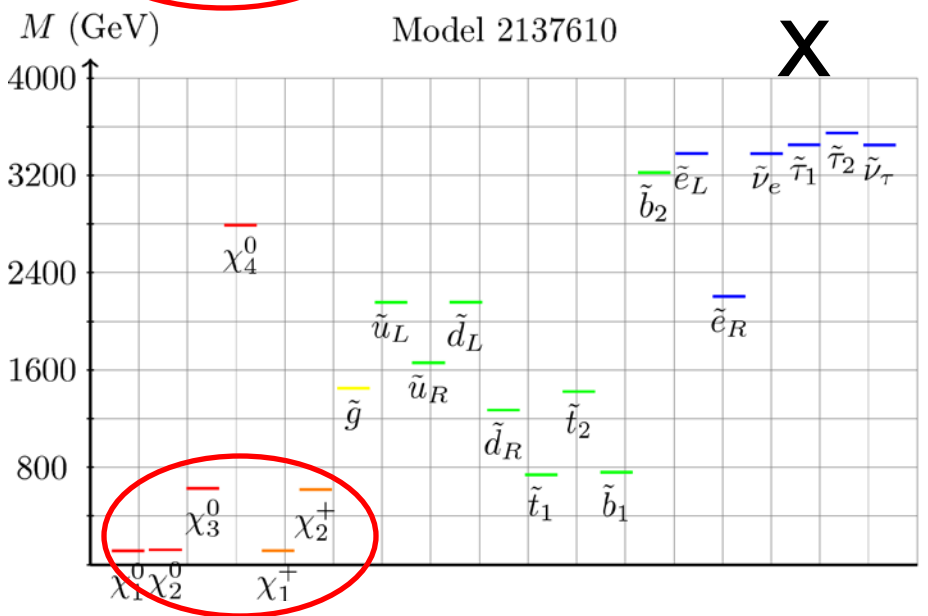


The Better Models & Their Natures II









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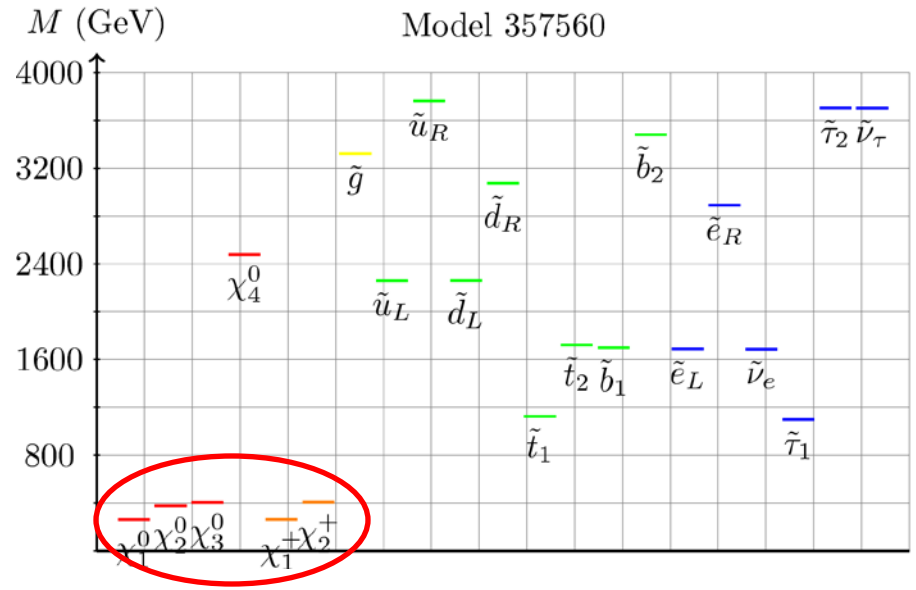
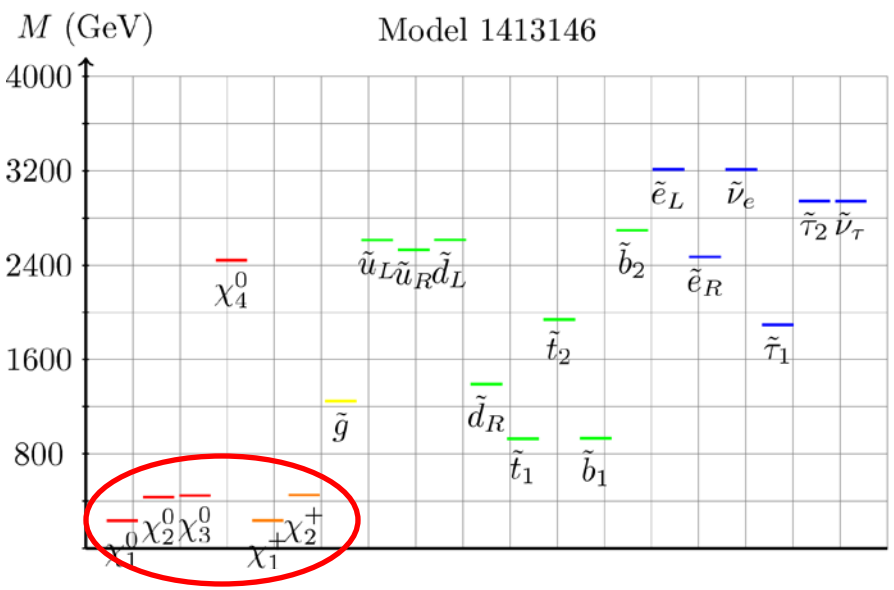
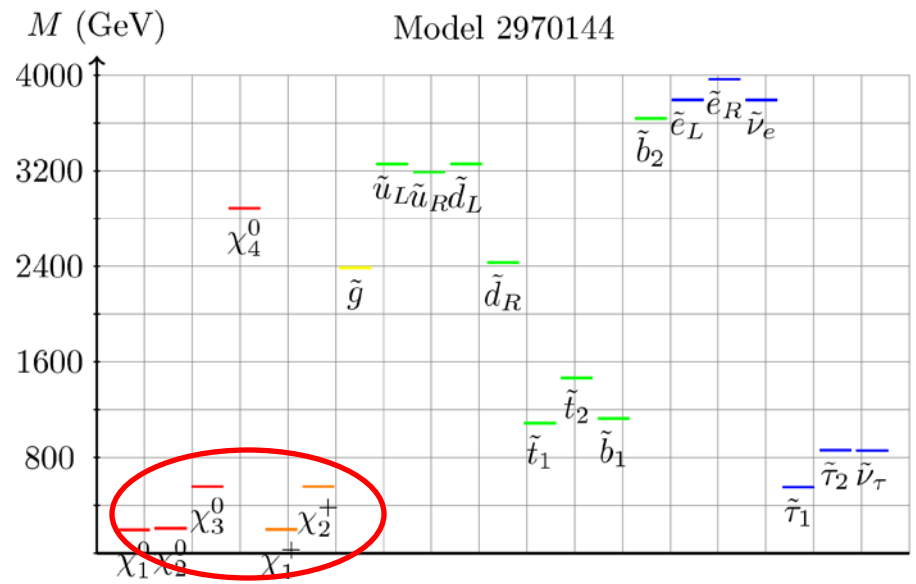
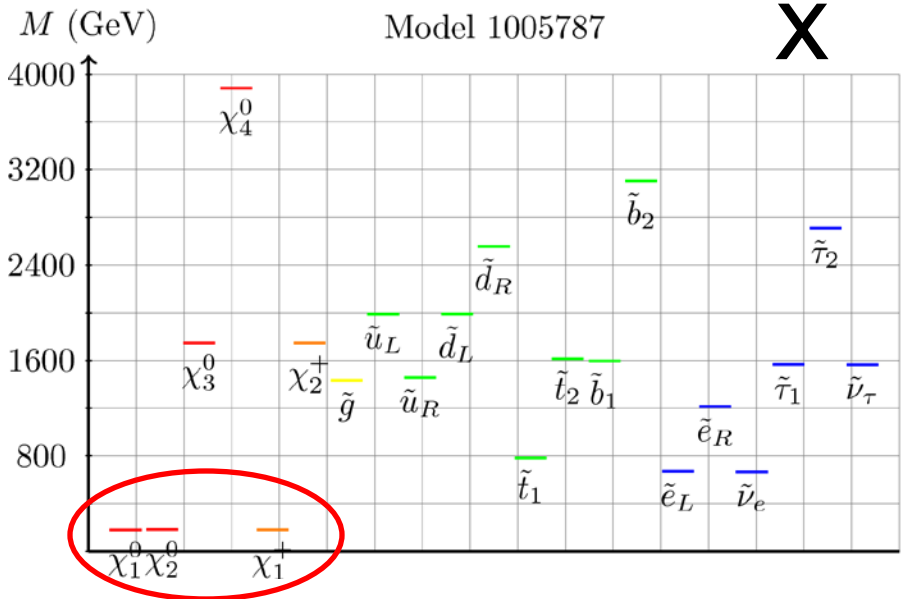
The Better Models & Their Natures III





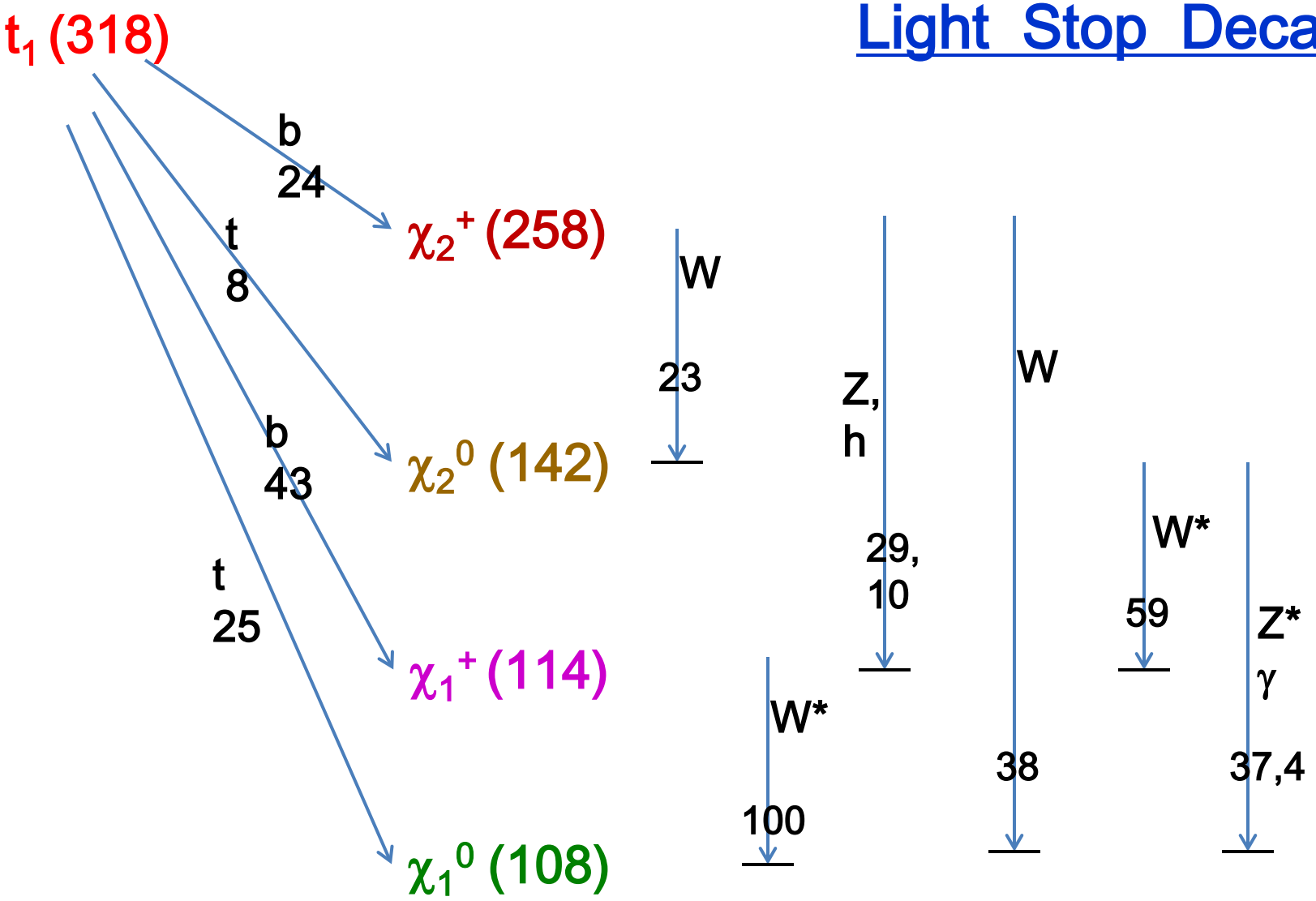




X

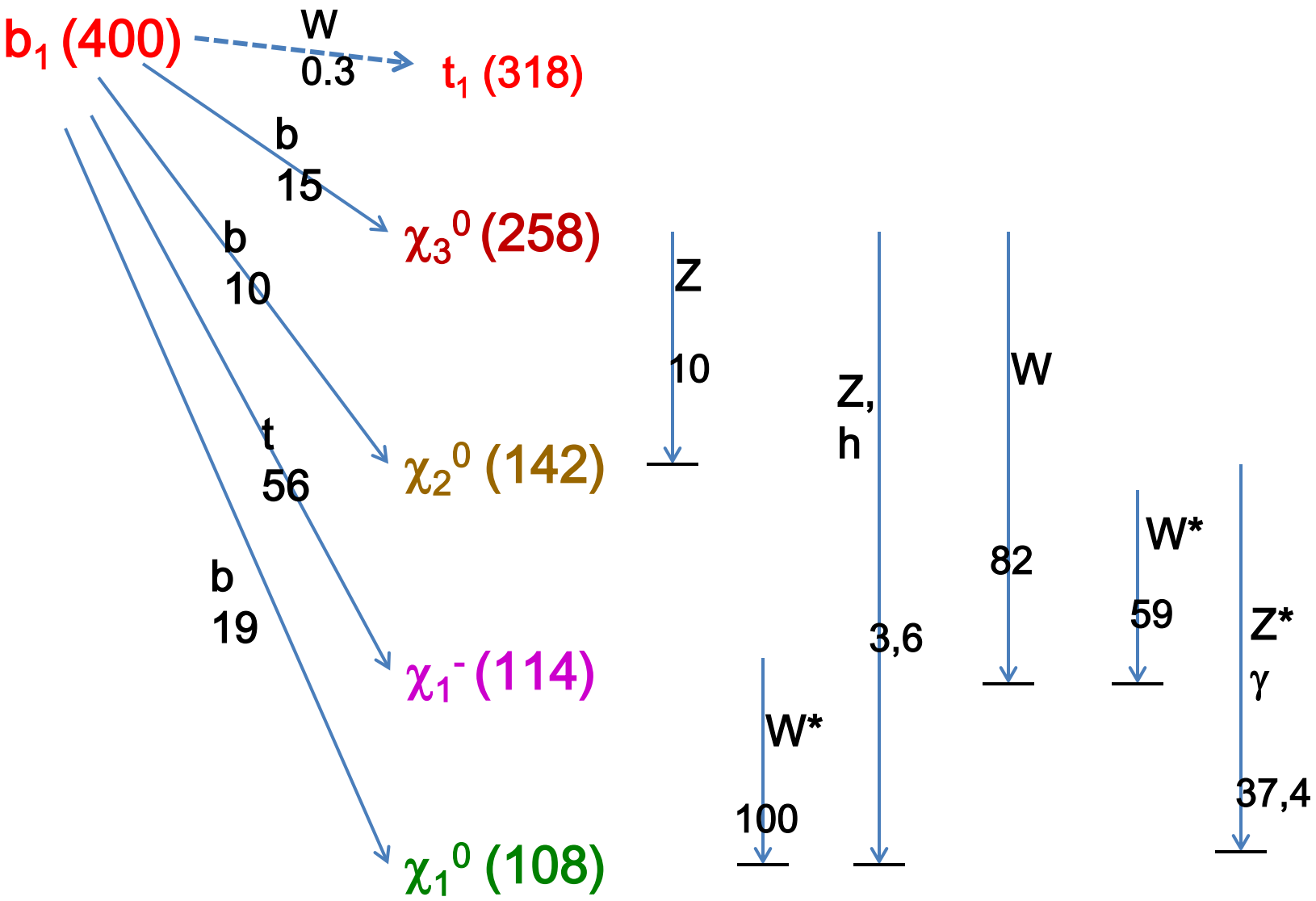
A typical but 'easy' example :
#2403883 w/ FT=56.3

Light Stop Decays

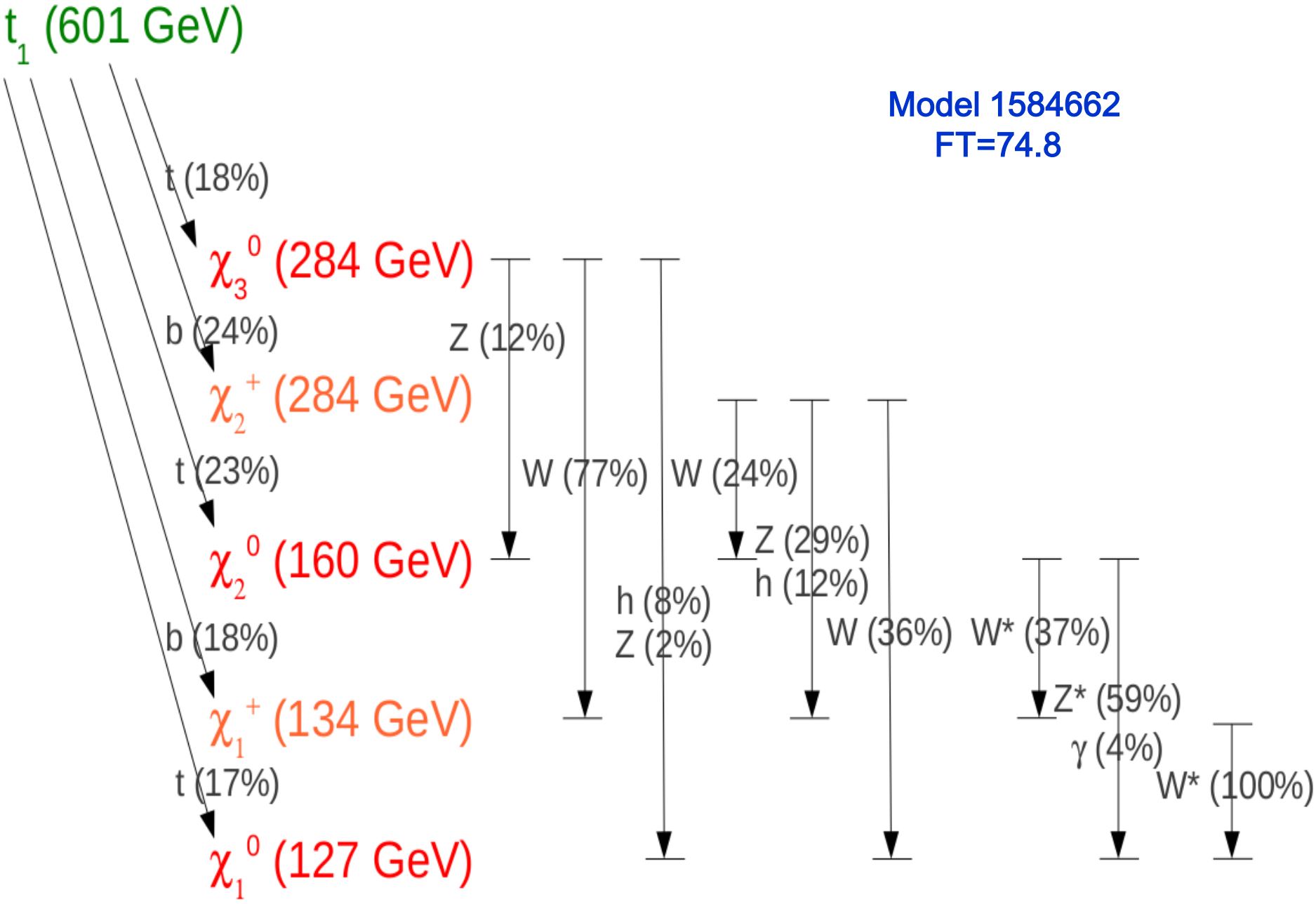


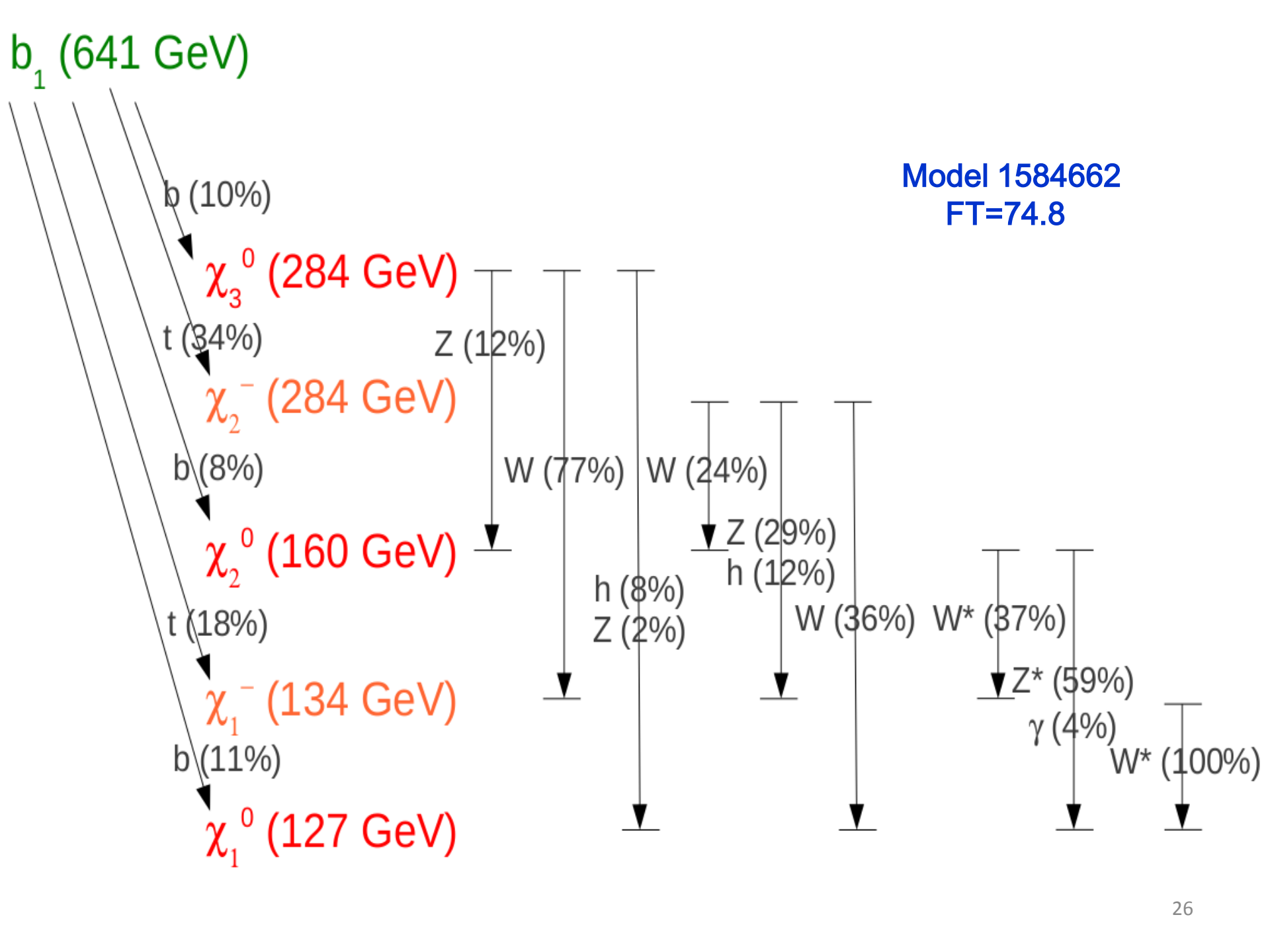
Multiple decay paths make LHC searches more difficult

Light Sbottom Decays



This model was killed by multiple searches


t_1 (601 GeV)
Model 1584662
FT=74.8
t (18%)
χ_3^0 (284 GeV)
b (24%)
Z (12%)
χ_2^+ (284 GeV)
t (23%)
W (77%)
W (24%)
χ_2^0 (160 GeV)
Z (29%)
h (12%)
h (8%)
Z (2%)
b (18%)
W (36%)
W* (37%)
χ_1^+ (134 GeV)
Z* (59%)
γ (4%)
t (17%)
W* (100%)
χ_1^0 (127 GeV)


b1 (641 GeV)
b (10%)
χ3 0 (284 GeV)
t (34%)
Z (12%)
χ2 − (284 GeV)
b (8%)
W (77%)
W (24%)
χ2 0 (160 GeV)
Z (29%)
h (12%)
h (8%)
Z (2%)
t (18%)
W (36%)
W* (37%)
χ1 − (134 GeV)
Z* (59%)
γ (4%)
b (11%)
W* (100%)
χ1 0 (127 GeV)
Model 1584662
FT=74.8

What Fraction of Models Have LC Accessible SUSY?

χ_1^0 LSP ~30.0k

Sparticle	√s=250 GeV	500 GeV	1 TeV	2 TeV
LSP	3.4%	23.2%	58.9%	94.9%
Chargino-1	3.1%	22.7%	58.3%	93.8%
Neutralino-2	1.4%	11.7%	30.9%	58.4%
Selectron-L		0.1%	2.3%	12.7%
Selectron-R		0.3%	3.3%	14.6%
Stau-1		0.4%	4.9%	24.8%
Sbottom-1			0.8%	16.8%
Stop-1			0.3%	10.2%
Neutralino-3		0.8%	7.5%	26.1%
Sneutrino		0.1%	2.4%	12.9%
τ-Sneutrino		0.2%	2.5%	13.4%
Chargino-2		0.2%	5.0%	19.5%

Clearly, electroweakinos are the most likely targets for LC500 study - a conclusion reinforced by low-FT model considerations

What Fraction of Models Have LC Accessible SUSY?

G LSP ~12.5k

Sparticle	√s=250 GeV	500 GeV	1 TeV	2 TeV
Neutralino-1	2.8%	12.1%	29.9%	59.9%
Chargino-1	1.3%	8.3%	22.2%	48.3%
Neutralino-2	0.5%	4.1%	12.5%	32.7%
Selectron-L	0.1%	1.9%	9.2%	22.1%
Selectron-R		0.6%	4.9%	17.6%
Stau-1	0.1%	2.5%	13.6%	35.9%
Sbottom-1			1.0%	19.5%
Stop-1			0.5%	17.2%
Neutralino-3		0.3%	3.2%	13.3%
Sneutrino	0.2%	2.2%	9.3%	22.2%
τ-Sneutrino	0.1%	2.0%	8.9%	21.9%
Chargino-2		0.2%	1.8%	8.7%

Searches do a much different job shaping the surviving sparticle spectra

- With access to the lightest chargino & the 2 (or 3?) lightest neutralinos can the electroweak gaugino soft parameters be determined in a model-independent way ??

- This has been studied to a limited extent at the LC at various levels of sophistication including input from LHC searches, e.g.,

S.Y. Choi et.al., hep-ph/0108117

K. Desch et.al ., hep-ph/0312069

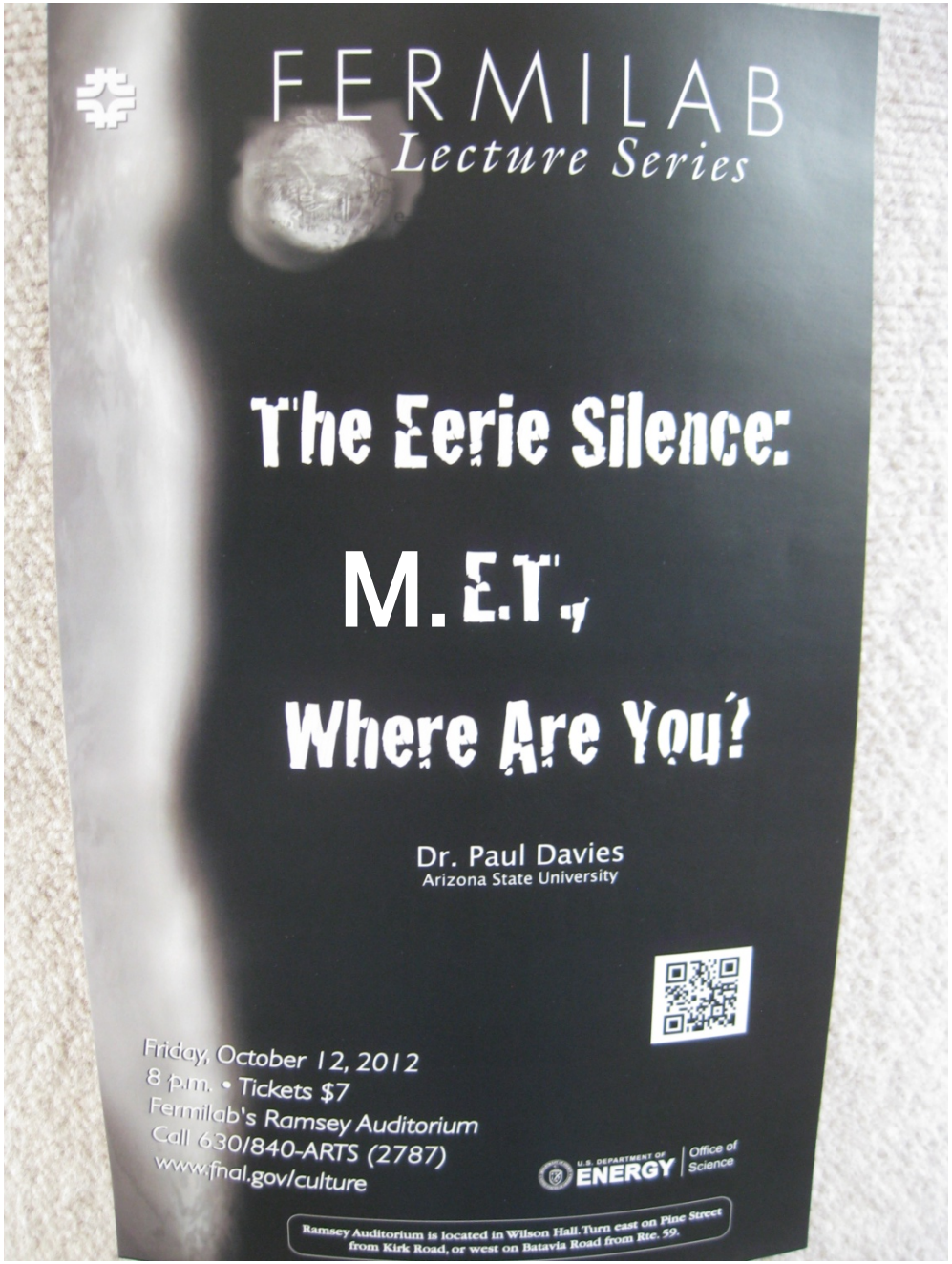
A. Bharucha et.al., 1208.1521

- More of these studies need to be done for multiple parameter space points to test their generality !

Summary & Conclusions

- The pMSSM with either neutralino or gravitino LSPs shows a wide range of very interesting properties.
- Present SUSY analyses have taken a bite out of both model sets but most of the parameter space still remains…we need √13-4 TeV data!
- Non-MET searches play a very important complementary role (as will the Higgs' properties)
- Searches + Naturalness indicate that light gauginos may be the most likely LC pMSSM SUSY targets w/ stops/sbottoms also possible at $\sqrt{s} >\sim 1$ TeV. **More studies are necessary!**

BACKUPS


FERMILAB
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The Eerie Silence:
M.E.T.,
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Dr. Paul Davies
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Friday, October 12, 2012
8 p.m. • Tickets $7
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Call 630/840-ARTS (2787)
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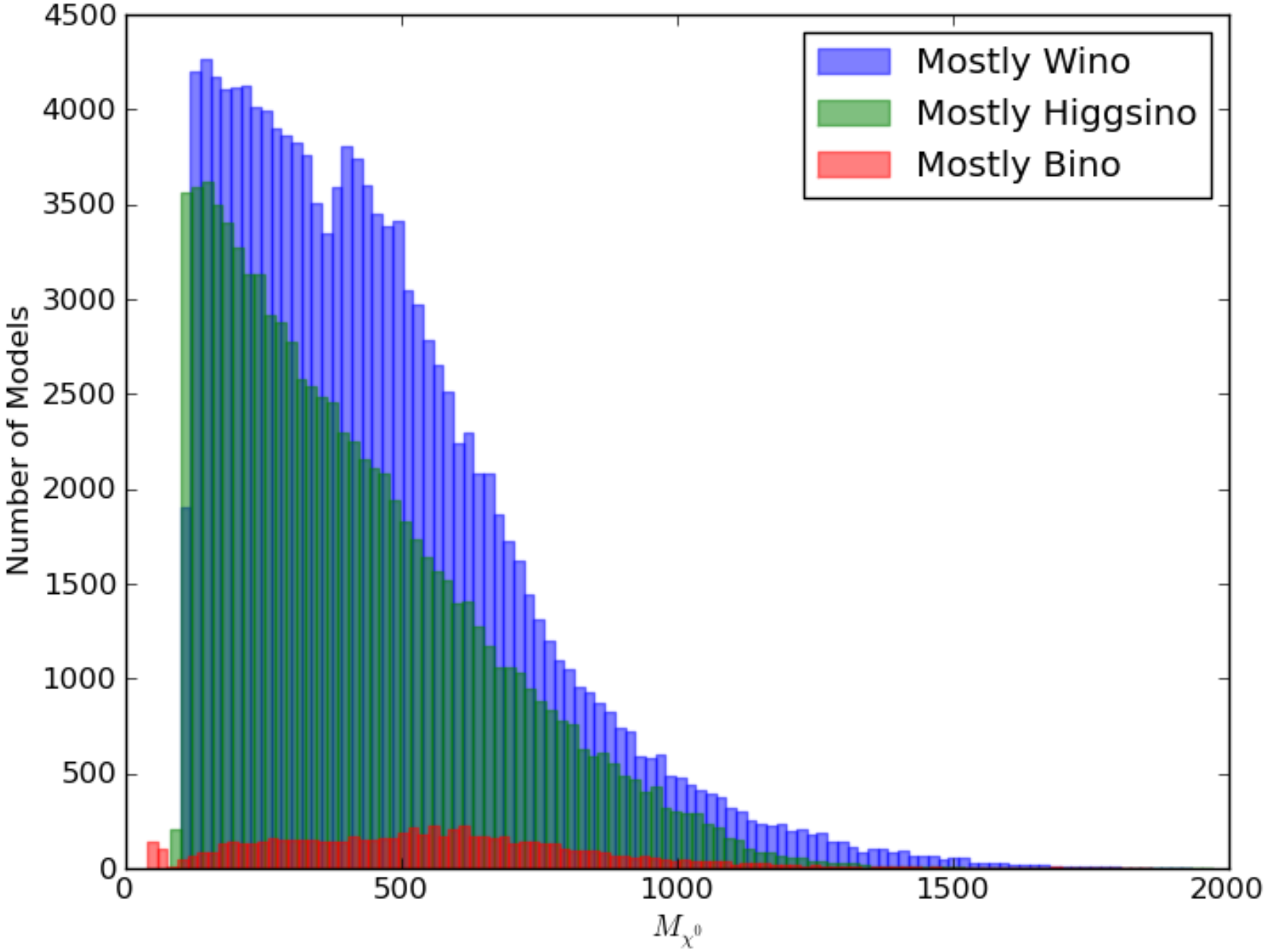
U.S. DEPARTMENT OF ENERGY | Office of Science
Ramsey Auditorium is located in Wilson Hall. Turn east on Pine Street from Kirk Road, or west on Batavia Road from Rte. 59.


Mostly Wino
Mostly Higgsino
Mostly Bino
Number of Models
0
500
1000
1500
2000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
M_{χ^0}

The 19(20) Parameter pMSSM

10 sfermion masses: m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}

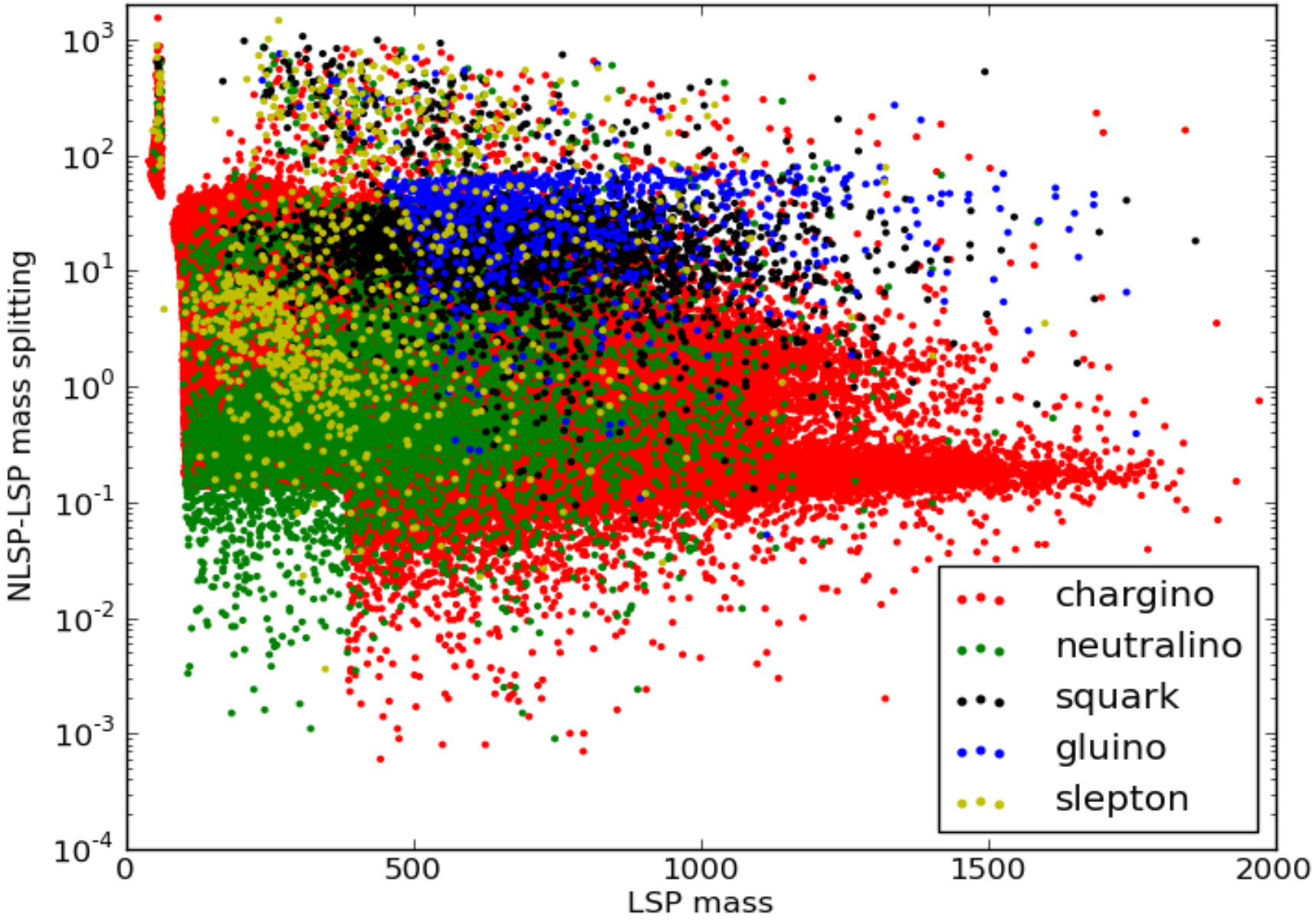
3 gaugino masses: M_1, M_2, M_3

3 tri-linear couplings: A_b, A_t, A_τ

3 Higgs/Higgsino: μ, M_A, $\tan\beta$

$\rightarrow\rightarrow$ (+ 1 gravitino mass : $m_{3/2}$)

χ_1^0 LSP


NLSP-LSP mass splitting
LSP mass
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
500
1000
1500
2000
chargino
neutralino
squark
gluino
slepton

Some Constraints

- $\Delta\rho$ / W-mass
- $b \to s\,\gamma$
- $\Delta(g-2)_\mu$
- $\Gamma(Z \to \text{invisible})$
- Meson-Antimeson Mixing
- $B \to \tau\nu$
- $B_s \to \mu\mu$

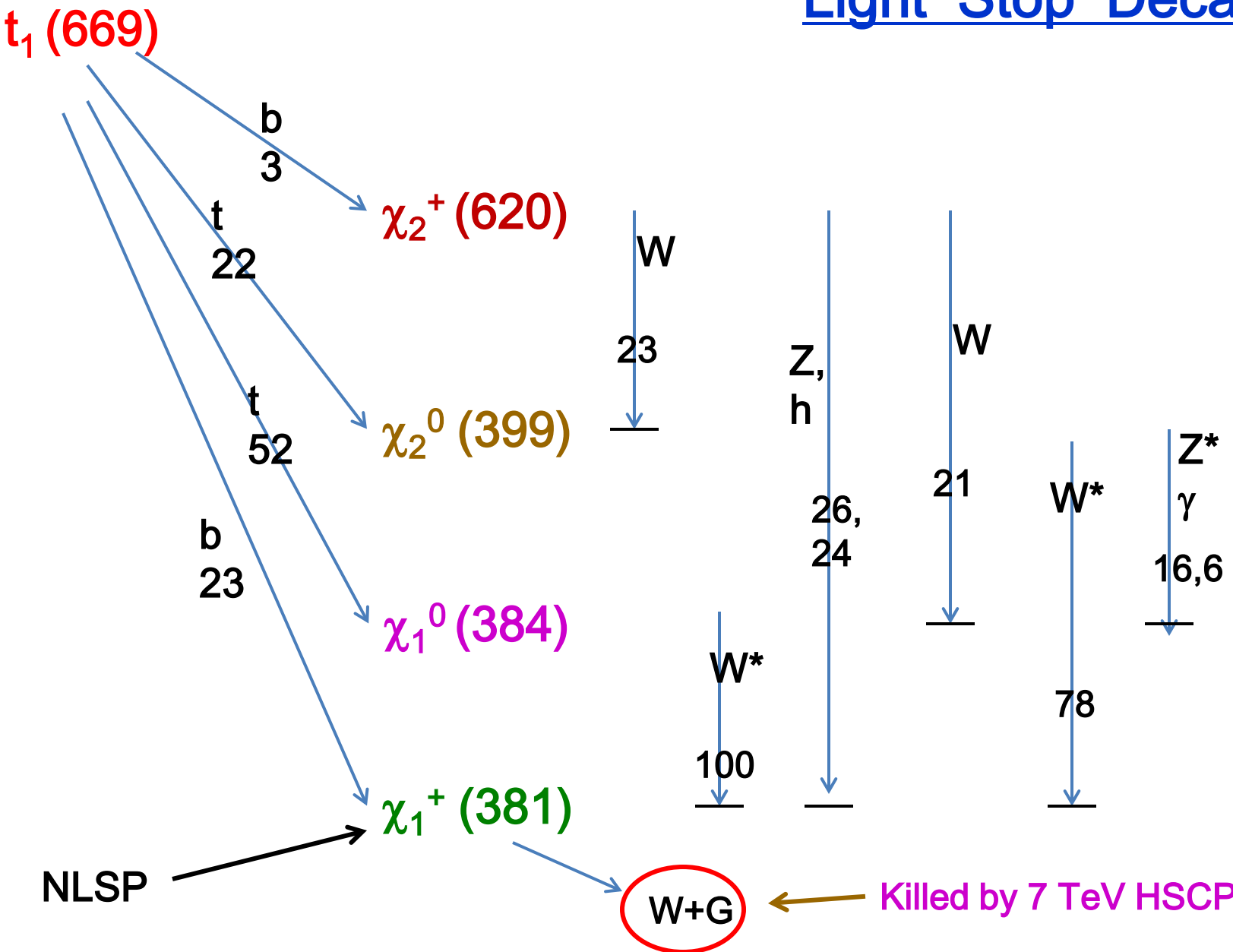
- Direct Detection of Dark Matter (SI & SD)
- WMAP Dark Matter density upper bound
- LEP and Tevatron Direct Higgs & SUSY searches
- LHC stable sparticle searches

- BBN energy deposition for gravitinos
- Relic ν's & diffuse photon bounds

- No tachyons or color/charge breaking minima
- Stable vacua only

An Example :
#146314G w/ FT=95.9

Light Stop Decays



Extrapolating:

8 TeV & 25 fb^{-1}

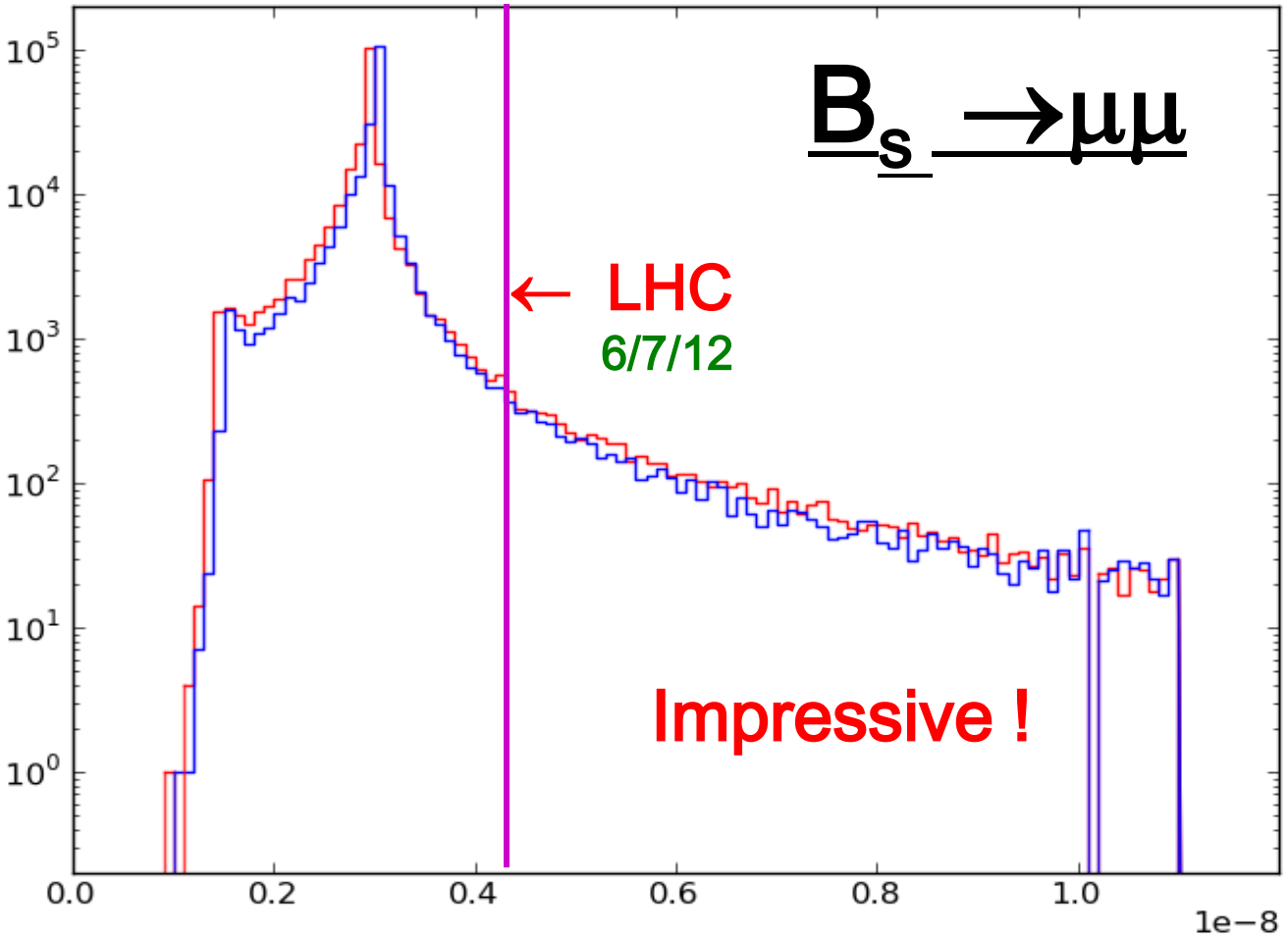
	without(with) m_h cut
nj0l [12]	25.27(22.68)%
multi-j [6]	3.31(2.84)%
nj1l [1]	3.83(3.57)%
nj2l (SS) [1]	7.45(6.96)%
total	26.05(23.49)%

Assuming identical analyses

- Note that the most important nj0l analysis takes a hit when we compare w/ the lower lumi result !

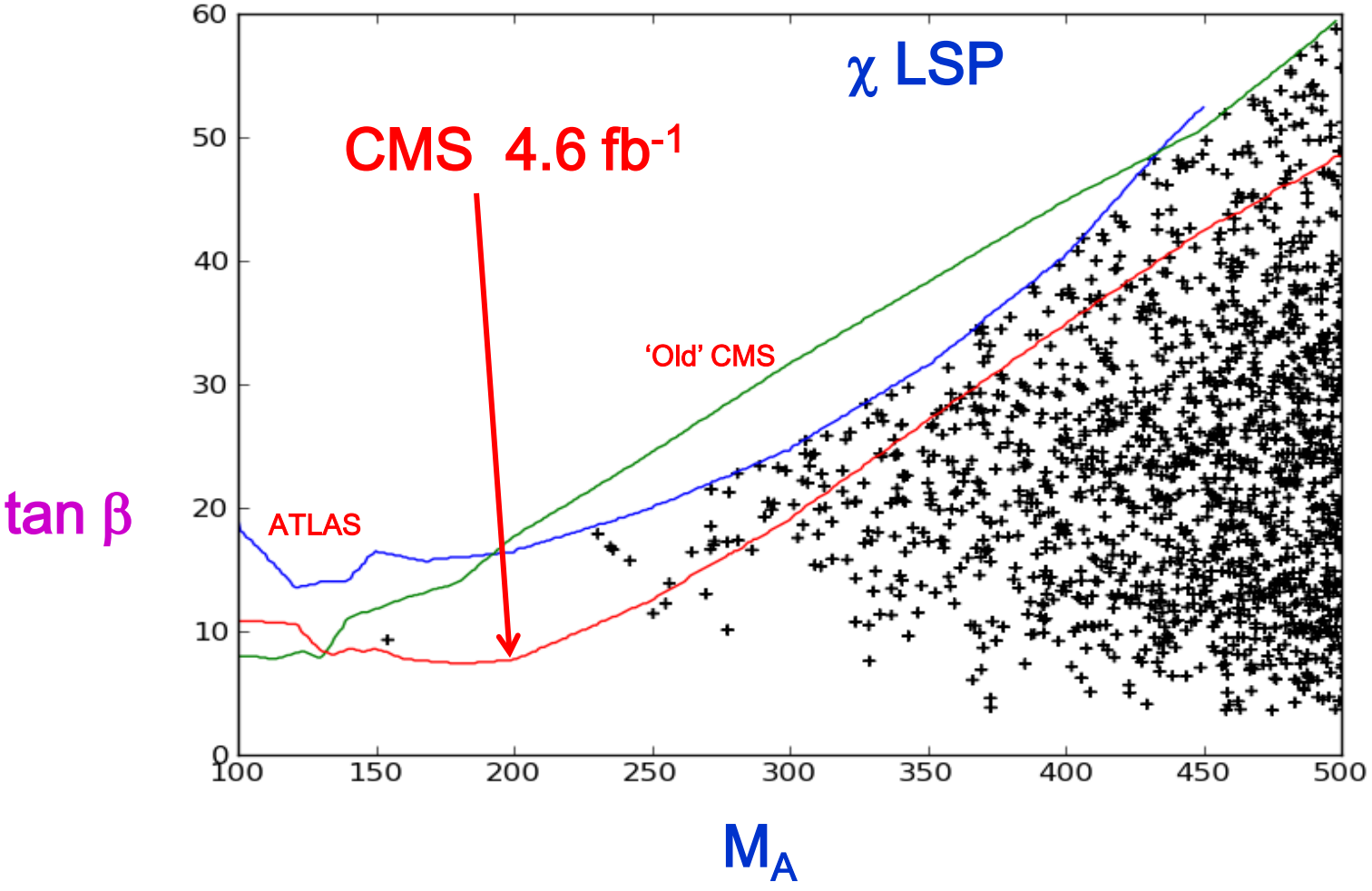
- ATLAS saw fewer events than expected in nj0l w/ 5.8 fb^{-1}. BUT we have to conservatively assume that the number of events seen equals the background values when we extrapolate

- Thus: small changes in both S & B can make substantial changes in the extrapolated pMSSM coverage



- The LHC result removes a total of 6035 (7147) models in the neutralino (G) LSP model set … The soon to be expected observation of this mode will have a very substantial impact
- non-MET searches REALLY ARE important !

Impact of A,H $\rightarrow\tau\tau$ Searches



As in the case of $B_s \rightarrow\mu\mu$, improvement in non-MET searches impact the pMSSM analyses… 160(164) models removed from the χ (G) LSP set…