Several topics:

1. WZ+MET (arXiv:1201.5383)
2. Wh+MET (arXiv:1201:2949)
3. natural SUSY: the new paradigm (arXiv:1203.5539)

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Hi mom!

Some recent LHC results

- m(sq)~m(gluino)>1.4 TeV
- m(sq)>>m(gluino); m(gl)>800 GeV
- mh~125? favors heavy squarks, large A0

But many theorists have long favored m(sq)>>10 TeV

Decoupling solution to SUSY flavor/CP problem;
suppress p-decay;
if linked to m(gravitino), solves gravitino problem
for m(grav)>~5 TeV

Suppose very heavy squarks: which sparticles are then produced at LHC8?

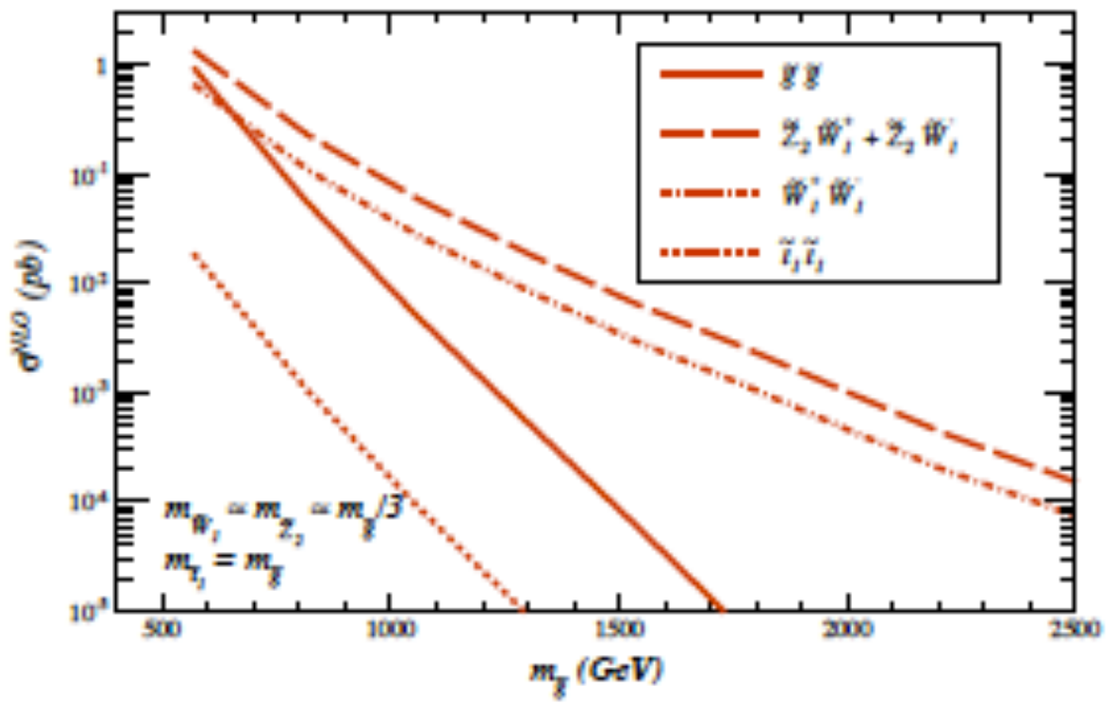


Figure 1: *Total NLO cross sections (from Prospino) for $\tilde{g}\tilde{g}$, $\tilde{W}_1^{\pm}\tilde{Z}_2$ and $\tilde{W}_1^+\tilde{W}_1^-$ production at LHC7 versus $m_{\tilde{g}}$, where $m_{\tilde{q}} = 15$ TeV and $m_{\tilde{W}_1} \approx m_{\tilde{Z}_2} \approx m_{\tilde{g}}/3$. The dotted line shows the cross section for $\tilde{t}_1\bar{\tilde{t}}_1$ production with $m_{\tilde{t}_1} = m_{\tilde{g}}$ and neglecting intra-generational squark mixing.*

In models with gaugino mass unification, EWinos dominant for m(gluino)>500 GeV!

What do they decay to?

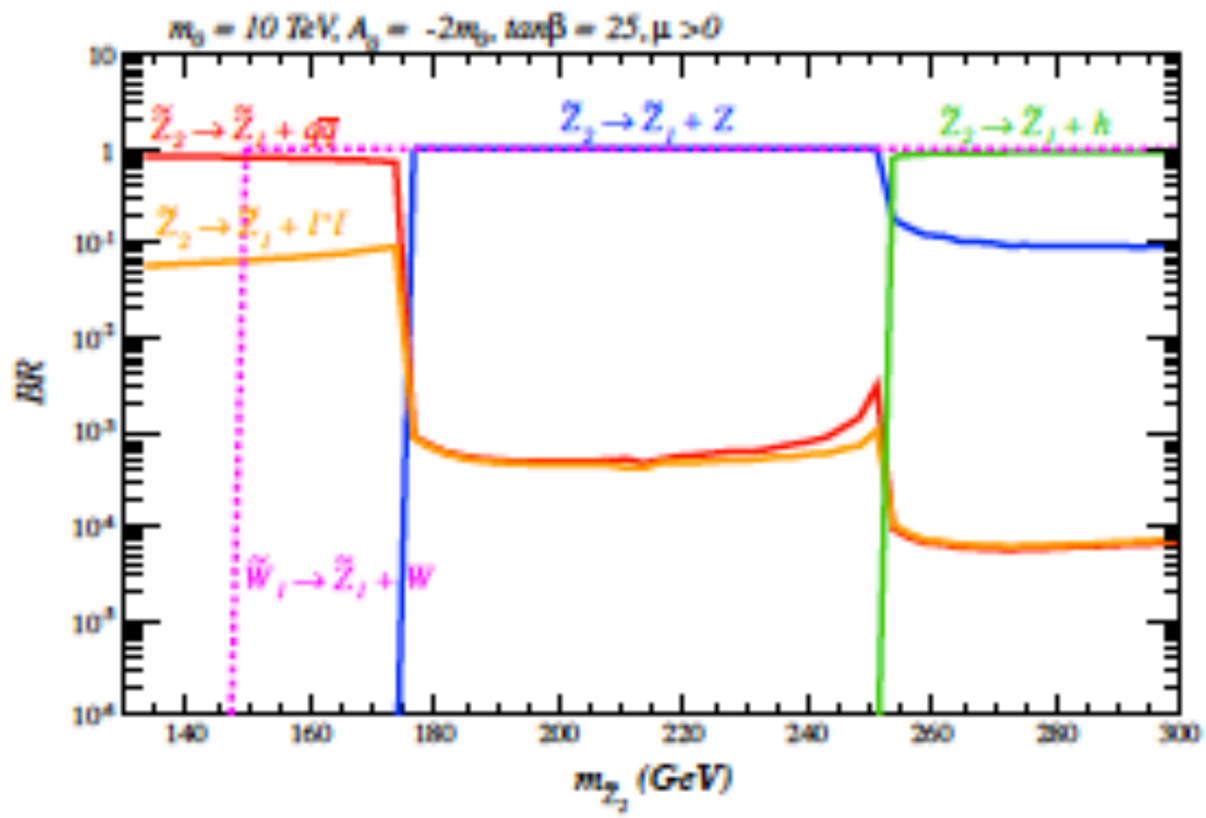
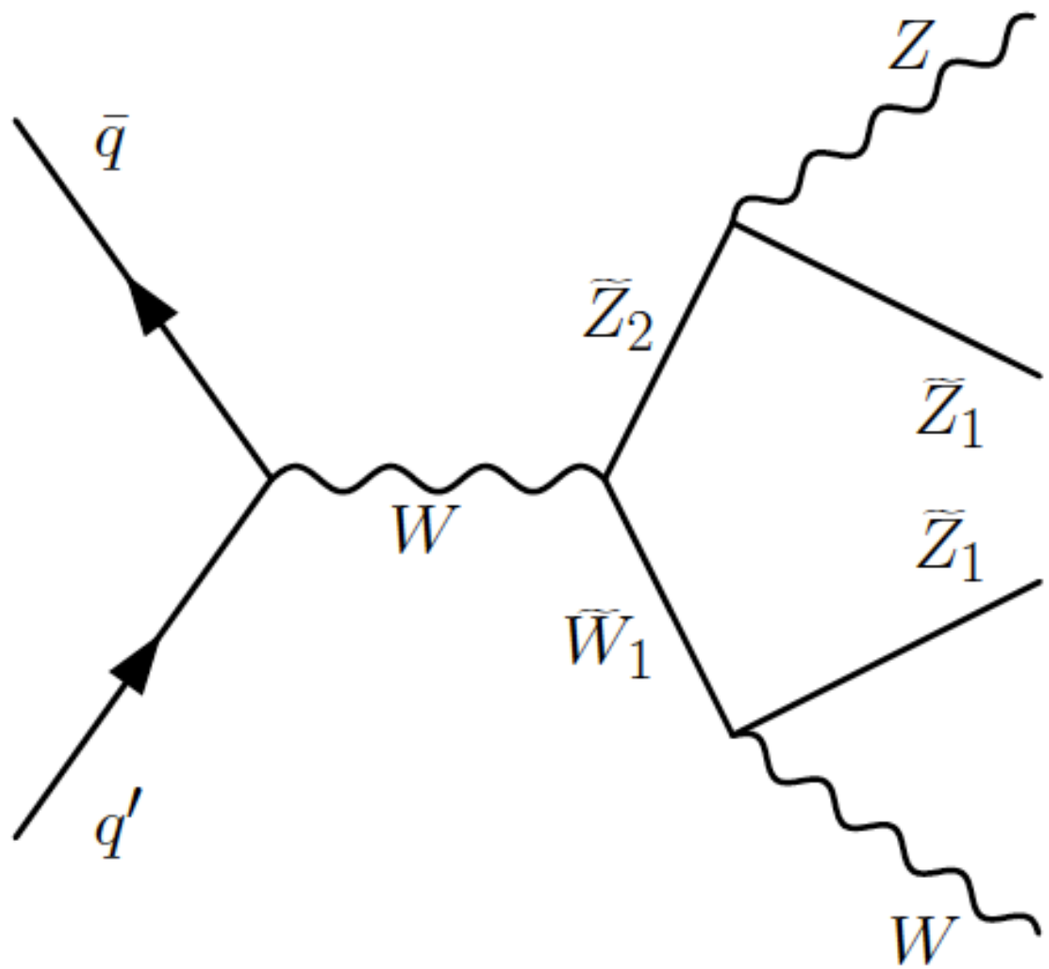


Figure 2: *Some prominent branching fractions for $\tilde{Z}_2$ decay in the mSUGRA model with parameters $m_0 = 10$ TeV, $A_0 = -2m_0$, $\tan\beta = 25$ and $\mu > 0$. We also show the $\tilde{W}_1 \to W + \tilde{Z}_1$ branching fraction (dotted line).*

Single production process followed by simple decays to WZ+MET



HB, Barger, Kraml, Lessa, Sreethawong, Tata, arXiv:1201.5383

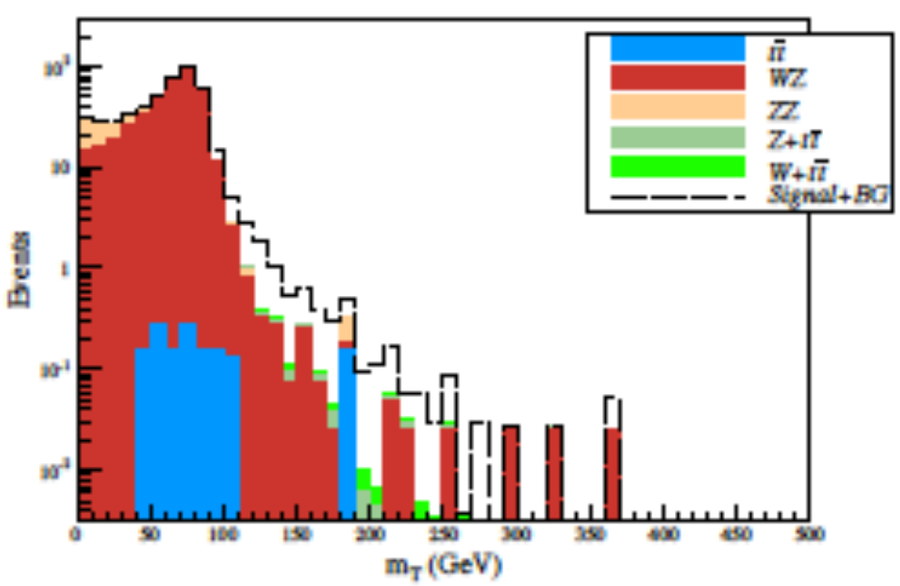
Codes used:

- Sparticle spectra: isajet
- Sparticle production: isajet, prospino
- Cascade decays: isajet
- Event generation: isajet
- Relic density, EWPO: isajet
- Toy detector: isajet
- 2->3, 2->4 processes: AlpGen/Pythia

Trileptons with m(l+l-)~MZ and mT(l,MET)>MW

	$t\bar{t}$	WZ	ZZ	$Z+t\bar{t}$	$W+t\bar{t}$	Total BG	Signal
Events Generated	5.1M	100K	194K	451K	9.5M		200K
Total σ (fb)	1.6×10^5	5.1×10^2	5.4×10^3	22.3	183	7.8×10^6	1.1×10^4
$n(b) = 0, n(l) = 3$	1.6	85.1	9.2	0.9	0.4	97.5	6.7
OS/SF pair	1.1	84.9	9.2	0.9	0.3	96.6	6.7
$m(\ell^+\ell^-)$ cut	0.3	79.1	9.1	0.66	0.06	89.5	6.6
$m_T > 125$ GeV	0.03	0.20	0.03	0.03	0.02	0.31	0.67
$\not{E}_T > 50$ GeV	0.03	0.17	0	0.03	0.02	0.25	0.64

Table 1: Number of events generated, total cross section and cross section after cuts for the dominant backgrounds in the trilepton channel and for the signal. All cross sections are in fb and the signal is from just $\widetilde{W}_1\widetilde{Z}_2$ production with $m_{\widetilde{W}_1} = 189.3$ GeV, $m_{\widetilde{Z}_2} = 187.3$ GeV and $m_{\widetilde{Z}_1} = 89.4$ GeV. The Total BG values include all processes listed in the text, including the subdominant ones not shown in the Table.



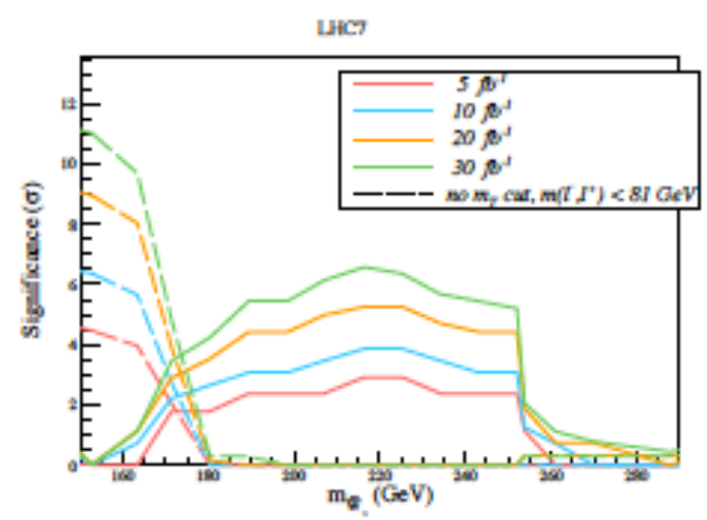


Figure 4: *Significance of $\widetilde{W}_1\widetilde{Z}_2 \to WZ + \not{E}_T \to 3\ell + \not{E}_T$ signal for various integrated luminosities at LHC7. The solid lines have all the trilepton cuts listed in Table 1, while the dashed lines do not include the m_T cut and require $M_Z - m(\ell^+\ell^-) > 10$ GeV instead.*

Simplified model analysis

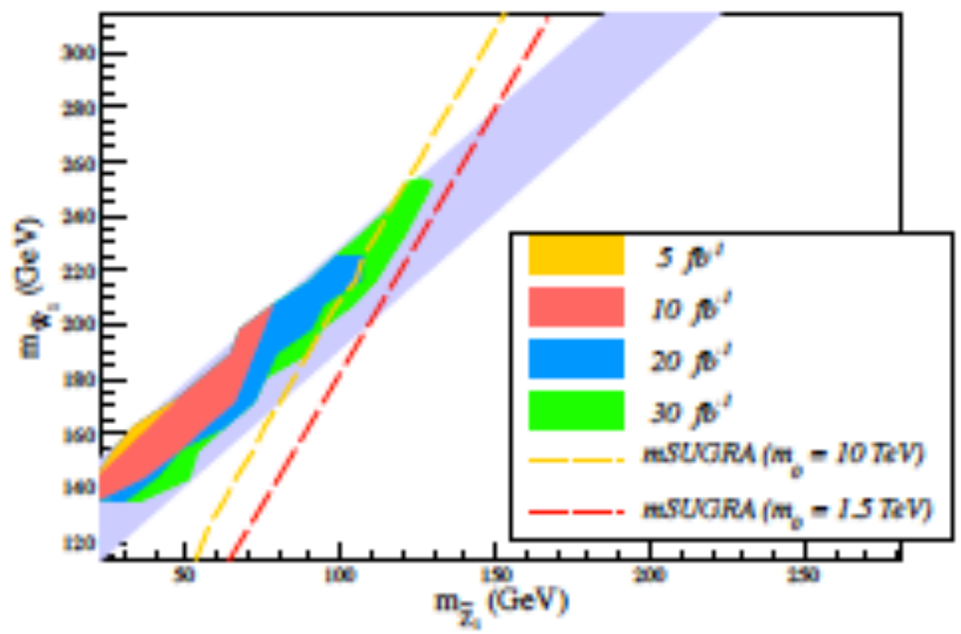


Figure 5: 5σ *discovery regions for various integrated luminosities at LHC7 in the* $m_{\widetilde{W}_1} - m_{\widetilde{Z}_1}$ *plane. We assume* $m_{\widetilde{Z}_2} = m_{\widetilde{W}_1}$ *and consider only* $\widetilde{W}_1\widetilde{Z}_2$ *production. The Higgs boson mass is assumed to be* 128.5 *GeV throughout the plane. The orange (red) line shows the mSUGRA line with* $m_0 = 10$ *TeV,* $A_0 = -2m_0$, $\tan\beta = 25$ *and* $\mu > 0$ *(*$m_0 = 1.5$ *TeV,* $A_0 = 0$, $\tan\beta = 45$ *and* $\mu > 0$*).*

Z->l+l- and W-> qqbar also possible

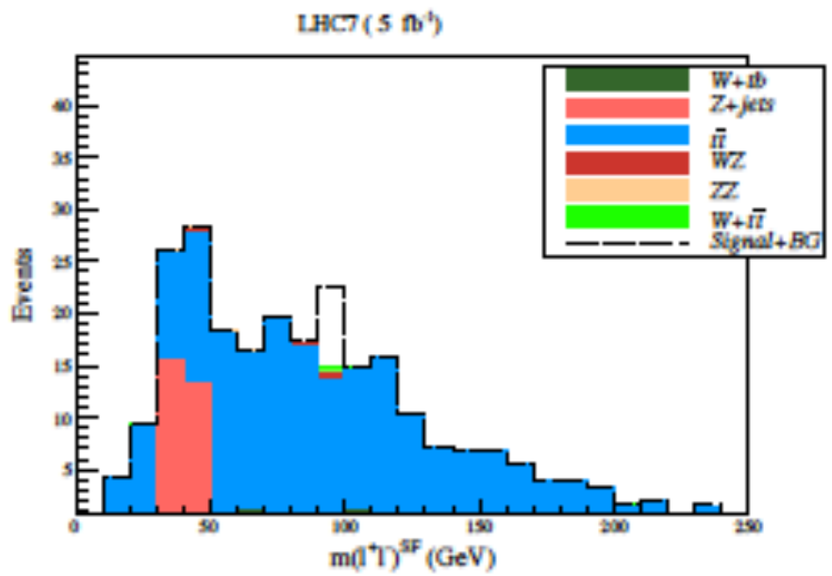


Figure 7: *Number of OS/SF dilepton events expected in 5 fb^{-1} of LHC7 data versus $m(\ell^+\ell^-)$ for various summed SM backgrounds (shaded) and signal plus BG (dashed) with $m_{\widetilde{W}_1} = 189.3$ GeV, $m_{\widetilde{Z}_2} = 187.3$ GeV and $m_{\widetilde{Z}_1} = 89.4$ GeV.*

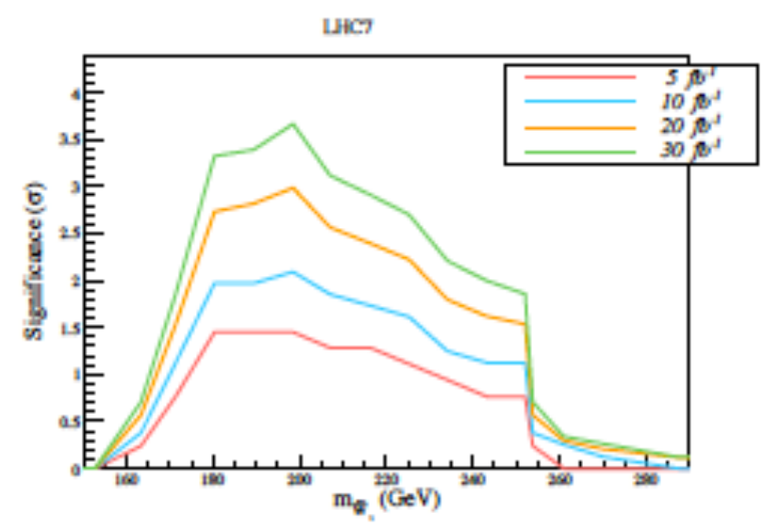


Figure 8: *Significance of $\widetilde{W}_1\widetilde{Z}_2 \to WZ + \not{E}_T \to jj + (Z \to \ell^+\ell^-) + \not{E}_T$ signal for various integrated luminosities at LHC7, after the cuts listed in Table 2 have been applied.*

At LHC14, also look at Wh+MET; dicey, but can do with ~100-1000 fb^-1; may extend LHC14 reach past gluino pair limit

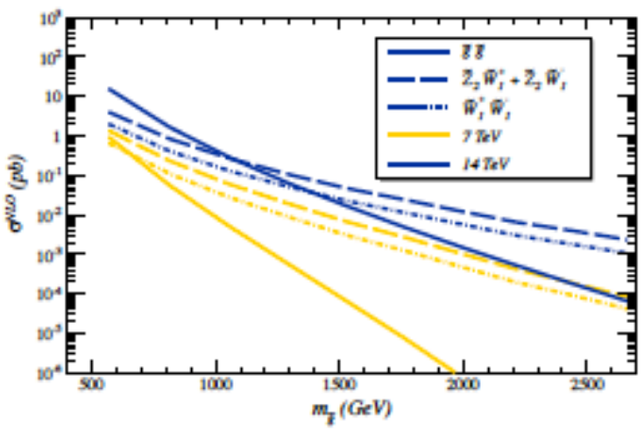


FIG. 1: Total NLO cross sections for $\tilde{g}\tilde{g}$, $\widetilde{W}_1^{\pm}\widetilde{Z}_2$ and $\widetilde{W}_1^{+}\widetilde{W}_1^{-}$ production at LHC7 (light) and LHC14 (dark), versus $m_{\tilde{g}}$, with $m_{\tilde{q}} = 15$ TeV.

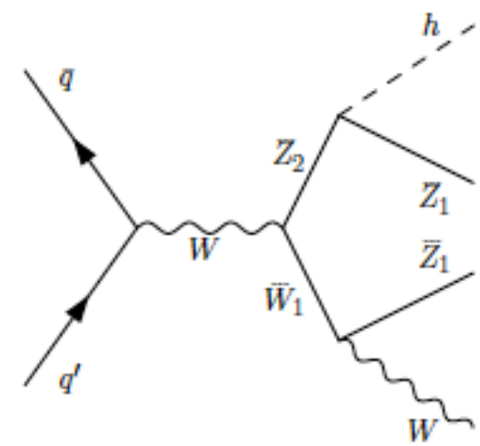


FIG. 2: Feynman diagram for $q'\bar{q} \to \widetilde{W}_1^{\pm}\widetilde{Z}_2 \to (W^{\pm}\widetilde{Z}_1) + (h\widetilde{Z}_1)$

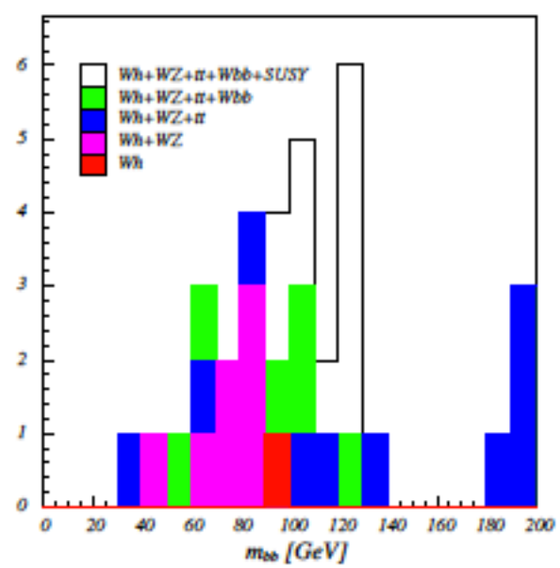


FIG. 3: Number of events expected in 100 fb^{-1} of LHC14 data versus $m(b\bar{b})$ for various summed SM backgrounds (shaded) and SUSY signal, with $m_{\widetilde{W}_1} = 620$ GeV and $m_h = 125$ GeV.

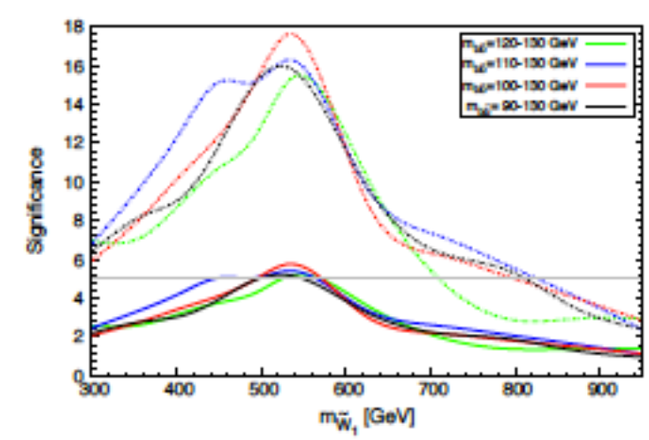


FIG. 4: Significance of signal in 100 fb^{-1} (solid) and 1000 fb^{-1} (dashes) of LHC14 data versus $m_{\widetilde{W}_1}$ for various $m(b\bar{b})$ bin sizes. The dashed gray horizontal line shows the $S/\sqrt{B} = 5$ significance level. We have checked that whenever the statistical significance exceeds 5σ the signal level exceeds 5 events. We take $m_0 = 5$ TeV and $A_0 = -1.8m_0$.

Natural SUSY

- Arkani-Hamed, Oct. 31 WG2 meeting
- Brust, Katz, Lawrence & Sundrum, arXiv:1110.6670
- Essig, Izaguirre, Kaplan & Wacker, arXiv:110.6443
- Papucci, Ruderman & Weiler, arXiv:1110.6926
- King, Muhlleitner & Nevzorov, arXiv:1201:2671
- Larsen, Nomura & Roberts, arXiv:1202.6339
- Csaki, Randall & Terning, arXiv:1201.1293
- HB, Barger, Huang & Tata, 1203.5539 (this talk)
- notify me if your paper is missing: baer@nhn.ou.edu :-)

- EWSB relation: $\frac{1}{2}M_Z^2 = \frac{(m_{H_d}^2 + \Sigma_d) - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2$

- natural if each term comparable to MZ

  - $|\mu| \lesssim 150 - 200$ GeV,
  - third generation squarks $m_{\tilde{t}_{L,R}}$, $m_{\tilde{b}_L} \lesssim 1 - 1.5$ TeV,
  - $m_{\tilde{g}} \lesssim 3 - 4$ TeV and SSB electroweak-ino masses smaller than 1-2 TeV
  - $m_A \lesssim |\mu| \tan\beta$,
  - $m_{\tilde{q}_{1,2}}$, $m_{\tilde{\ell}_{1,2}} \sim 10 - 50$ TeV,

1. decoupling sol'n to SUSY flavor/CP
2. lightest MSSM particle = higgsino
3. ~sub-TeV 3rd gen. squarks
4. evades LHC limits

Would be great to generate spectra top-down preserving SUSY/GUT etc. connections

Parameter space:

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A$$

We can also allow some degree of non-universality between $m_0(1)$ and $m_0(2)$ so long as both lie in the tens of TeV regime, and provide a decoupling solutions to SUSY FCNC and CP-violating processes (for constraints from FCNC processes, see Ref. [30]). For convenience, we will take them as degenerate.

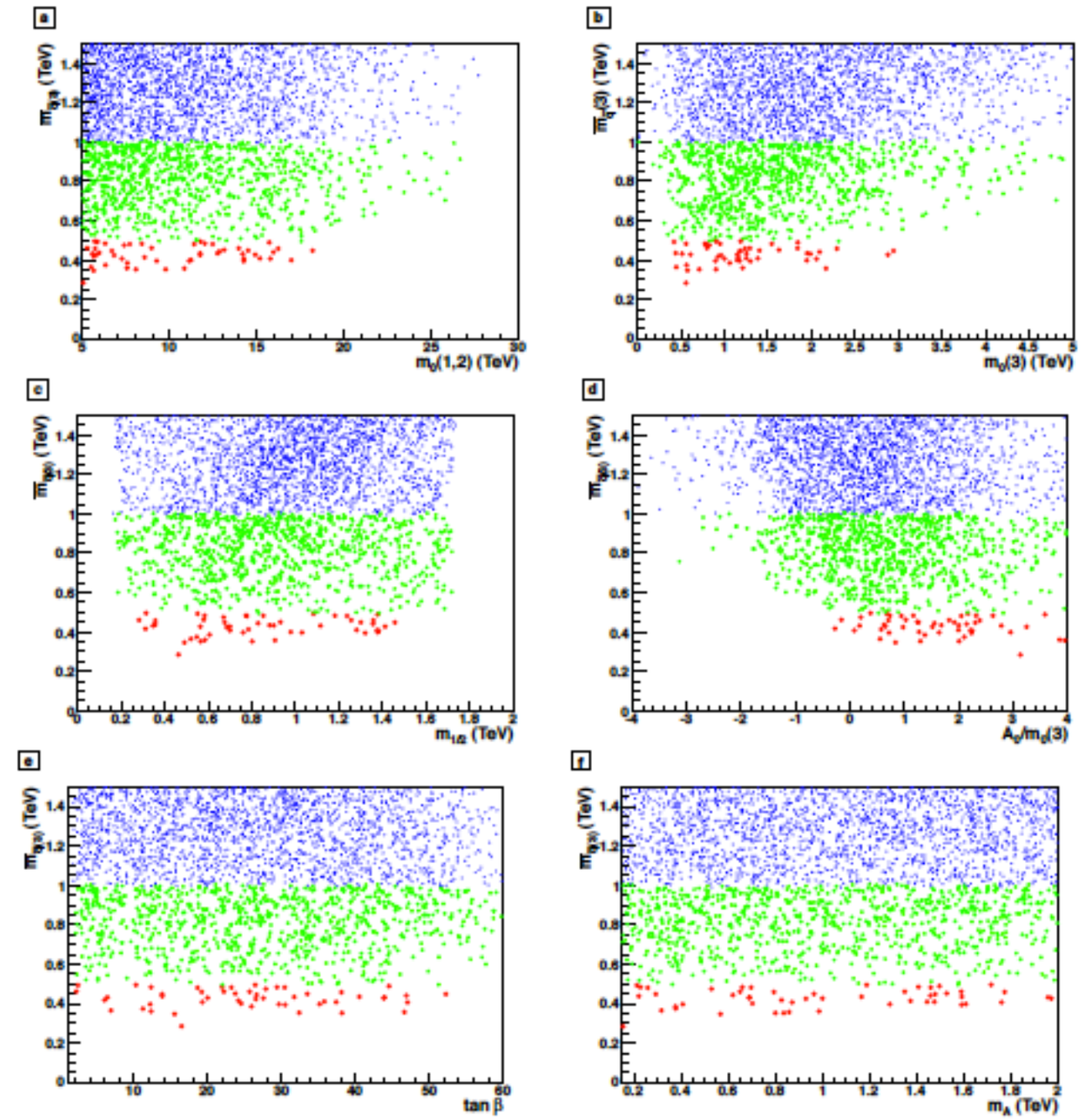


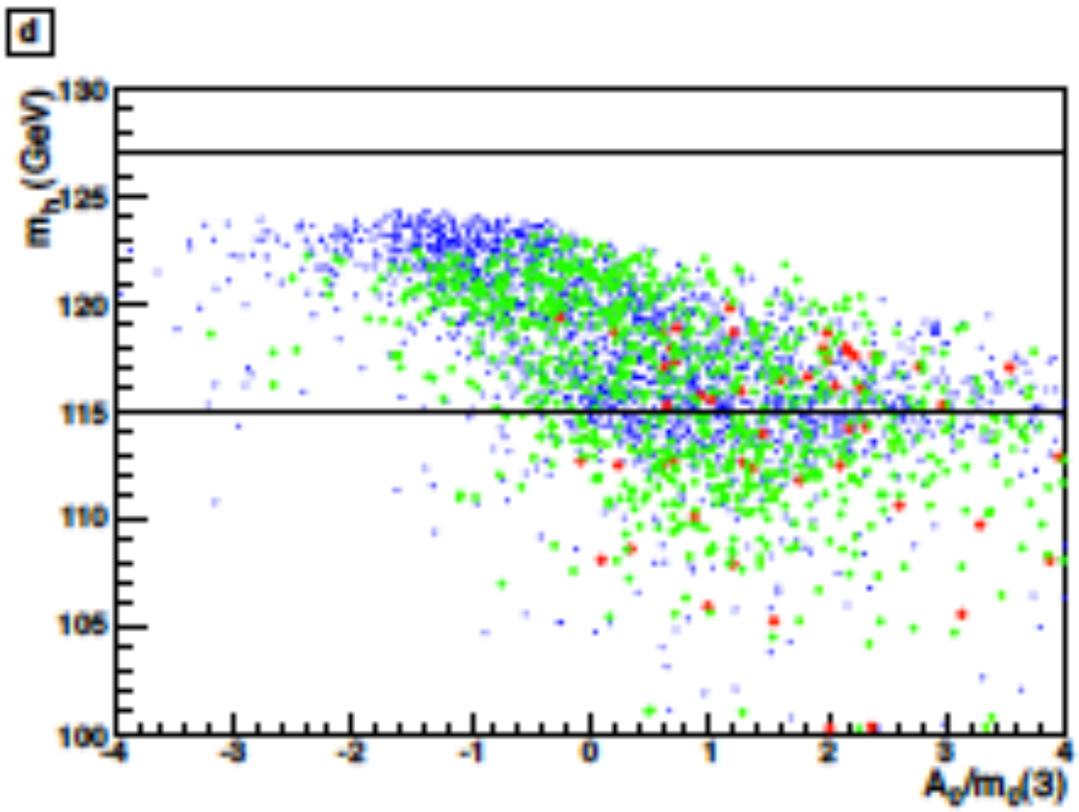
Figure 1: The value of $\overline{m}_{\tilde{q}}(3)$ versus various SUSY parameters with $\mu = 150$ GeV. The dots a colour-coded by the range of $\overline{m}_{\tilde{q}}(3)$:$\leq$ 0.5 TeV (red); 0.5-1 TeV (green); 1-1.5 TeV (blue).

The results of our scan are plotted in Fig. 1. On the y-axis, we plot the average third generation squark mass

$$\overline{m}_{\tilde{q}}(3) = (m_{\tilde{t}_1} + m_{\tilde{t}_2} + m_{\tilde{b}_1})/3 \tag{2.8}$$

while the x-axis lists the particular parameter. Blue points have $\overline{m}_{\tilde{q}}(3) < 1.5$ TeV, green points have $\overline{m}_{\tilde{q}}(3) < 1$ TeV and red points have $\overline{m}_{\tilde{q}}(3) < 0.5$ TeV.

Value of mh:
tends to be 115-121 but can be as high as 124 GeV



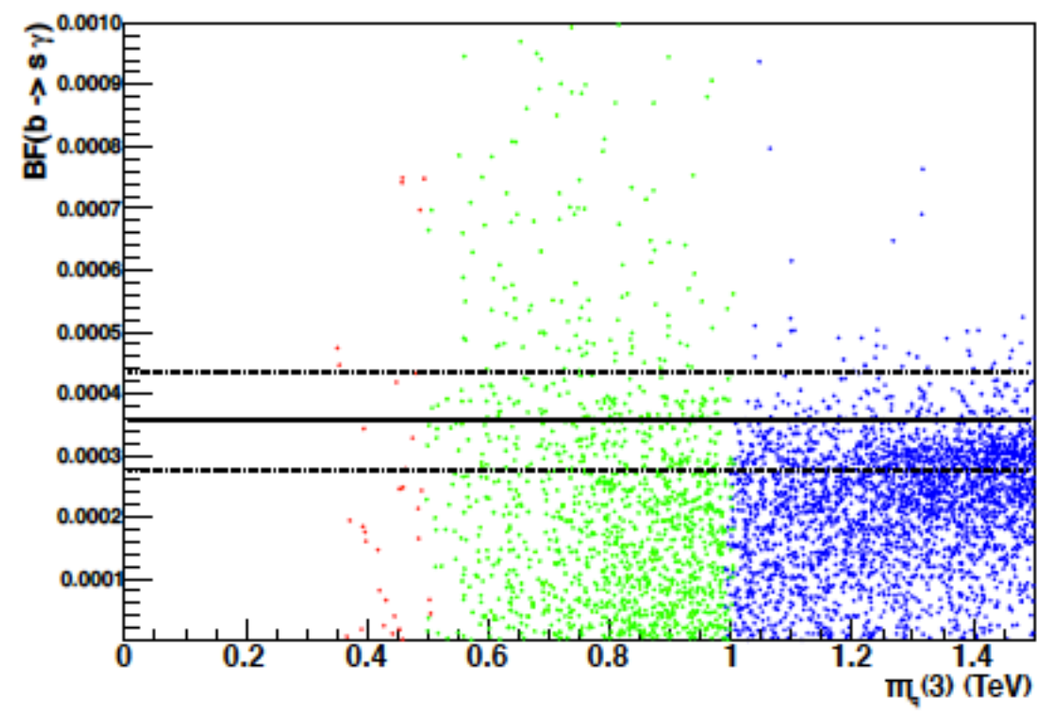


Figure 3: Predicted values of the branching fraction for $b \to s\gamma$ vs. $\overline{m}_{\tilde{q}}(3)$. We also show the experimentally determined central value $\pm 3\sigma$ band for the $BF(b \to s\gamma)$.

BF(b->s gamma) also very constraining

Some benchmark points:

parameter	NS1	NS2	NS3
$m_0(1,2)$	13363.3	19542.2	7094.3
$m_0(3)$	761.1	2430.6	890.7
$m_{1/2}$	1380.2	1549.3	1202.6
A_0	-167.0	873.2	-2196.2
$\tan\beta$	22.9	22.1	19.4
μ	150	150	150
m_A	1545.6	1652.7	410.1
$m_{\tilde{g}}$	3272.2	3696.8	2809.3
$m_{\tilde{u}_L}$	13591.1	19736.2	7432.9
$m_{\tilde{u}_R}$	13599.3	19762.6	7433.4
$m_{\tilde{e}_R}$	13366.1	19537.2	7086.9
$m_{\tilde{t}_1}$	301.4	572.0	812.5
$m_{\tilde{t}_2}$	909.2	715.4	1623.2
$m_{\tilde{b}_1}$	788.1	497.3	1595.5
$m_{\tilde{b}_2}$	1256.2	1723.8	1966.7
$m_{\tilde{\tau}_1}$	430.9	2084.7	652.2
$m_{\tilde{\tau}_2}$	532.9	2189.1	1065.5
$m_{\tilde{\nu}_\tau}$	402.3	2061.8	1052.1
$m_{\widetilde{W}_2}$	1180.2	1341.2	1013.9
$m_{\widetilde{W}_1}$	155.9	156.1	156.2
$m_{\widetilde{Z}_4}$	1181.3	1340.4	1020.0
$m_{\widetilde{Z}_3}$	615.3	698.8	532.6
$m_{\widetilde{Z}_2}$	156.3	156.2	157.0
$m_{\widetilde{Z}_1}$	148.4	149.2	147.4
m_h	121.3	121.1	123.5
$\Omega^{std}_{\widetilde{Z}_1}h^2$	0.007	0.006	0.007
$BF(b\to s\gamma)$	2.8×10^{-4}	3.6×10^{-4}	2.8×10^{-4}
$\sigma^{SI}(\widetilde{Z}_1 p)$ (pb)	5.5×10^{-9}	1.8×10^{-9}	9.8×10^{-9}
$\sigma^{SD}(\widetilde{Z}_1 p)$ (pb)	3.9×10^{-5}	2.9×10^{-5}	5.7×10^{-5}
$\langle\sigma v\rangle\|_{v\to0}$ (cm^3/sec)	3.0×10^{-25}	3.1×10^{-25}	3.0×10^{-25}

Table 1: Input parameters and masses in GeV units for three Natural SUSY benchmark points, with $\mu = 150$ GeV. Also shown are the values of several non-accelerator observables.

- Light higgsinos with small mass gap very hard to see at LHC (HB, Barger, Huang, arXiv:1107:5581)

- May see light 3rd gen. squarks, but not easy

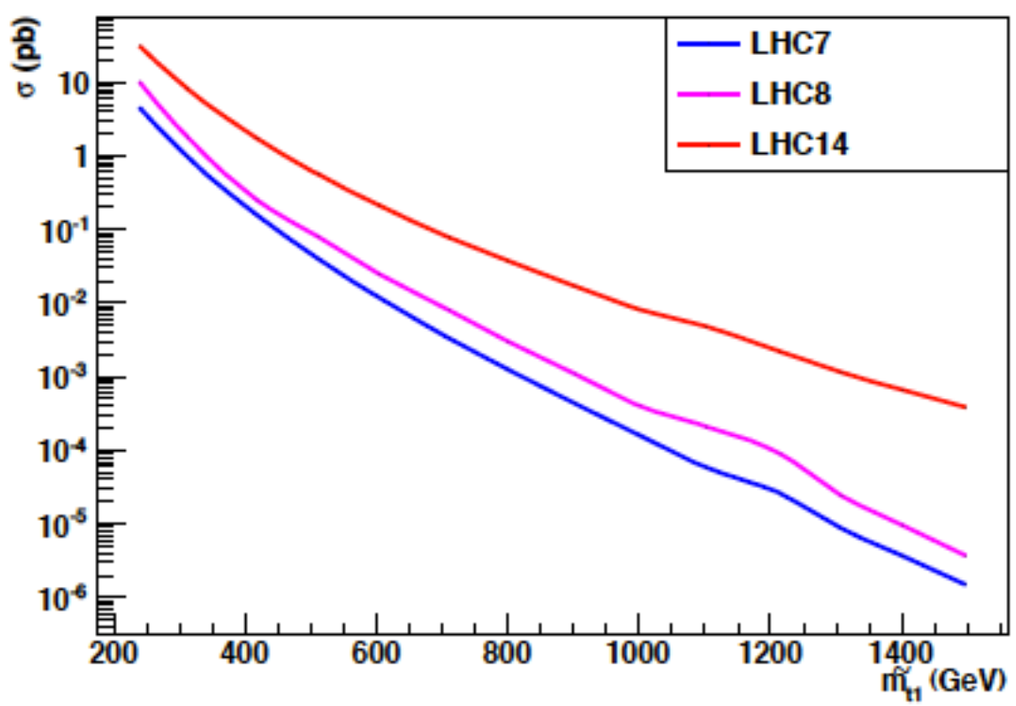


Figure 6: Top squark pair production cross sections at LHC7, LHC8 and LHC14 versus $m_{\tilde{t}_1}$. With the appropriate mass substitution these curves also represent the cross sections for pair production of $\tilde{t}_2, \tilde{b}_1$ or $\tilde{b}_2$ squarks.

parameter	NS1	NS2	NS3
$\sigma(\tilde{t}_1\tilde{t}_1)$	2000 fb	30 fb	2 fb
$BF(\tilde{t}_1 \to b\widetilde{W}_1)$	1.0	0.25	0.62
$BF(\tilde{t}_1 \to t\widetilde{Z}_1)$	–	0.42	0.08
$BF(\tilde{t}_1 \to t\widetilde{Z}_2)$	–	0.33	0.30
$\sigma(\tilde{b}_1\tilde{b}_1)$	4 fb	80 fb	0.00013 fb
$BF(\tilde{b}_1 \to b\widetilde{Z}_1)$	0.01	0.10	0.01
$BF(\tilde{b}_1 \to b\widetilde{Z}_2)$	0.01	0.09	0.01
$BF(\tilde{b}_1 \to t\widetilde{W}_1)$	0.09	0.81	0.04
$BF(\tilde{b}_1 \to W\tilde{t}_1)$	0.89	–	0.94
$\sigma(\tilde{t}_2\tilde{t}_2)$	1 fb	6 fb	0.00011 fb
$BF(\tilde{t}_2 \to b\widetilde{W}_1)$	0.09	0.29	0.05
$BF(\tilde{t}_2 \to Z\tilde{t}_1)$	0.70	0.01	0.39
$BF(\tilde{t}_2 \to h\tilde{t}_1)$	0.01	0.23	0.25
$BF(\tilde{t}_2 \to W\tilde{b}_1)$	0.03	0.16	0.26
$BF(\tilde{t}_2 \to t\widetilde{Z}_1)$	0.09	0.13	0.03
$BF(\tilde{t}_2 \to t\widetilde{Z}_2)$	0.08	0.16	0.02
$\sigma(\tilde{b}_2\tilde{b}_2)$	0.05 fb	0.0001 fb	0.00004 fb
$BF(\tilde{b}_2 \to b\widetilde{Z}_1)$	0.22	0.23	0.01
$BF(\tilde{b}_2 \to b\widetilde{Z}_2)$	0.22	0.22	0.01
$BF(\tilde{b}_2 \to b\widetilde{Z}_3)$	0.07	0.08	–
$BF(\tilde{b}_2 \to t\widetilde{W}_1)$	0.42	0.44	0.02
$BF(\tilde{b}_2 \to W\tilde{t}_1)$	0.03	0.01	–
$BF(\tilde{b}_2 \to h\tilde{b}_1)$	0.03	0.02	–
$BF(\tilde{b}_2 \to H\tilde{b}_1)$	–	–	0.23
$BF(\tilde{b}_2 \to A\tilde{b}_1)$	–	–	0.23
$BF(\tilde{b}_2 \to H^-\tilde{t}_1)$	–	–	0.41
$BF(\tilde{b}_2 \to H^-\tilde{t}_2)$	–	–	0.08

Can convert benchmark points into BM slopes or planes:

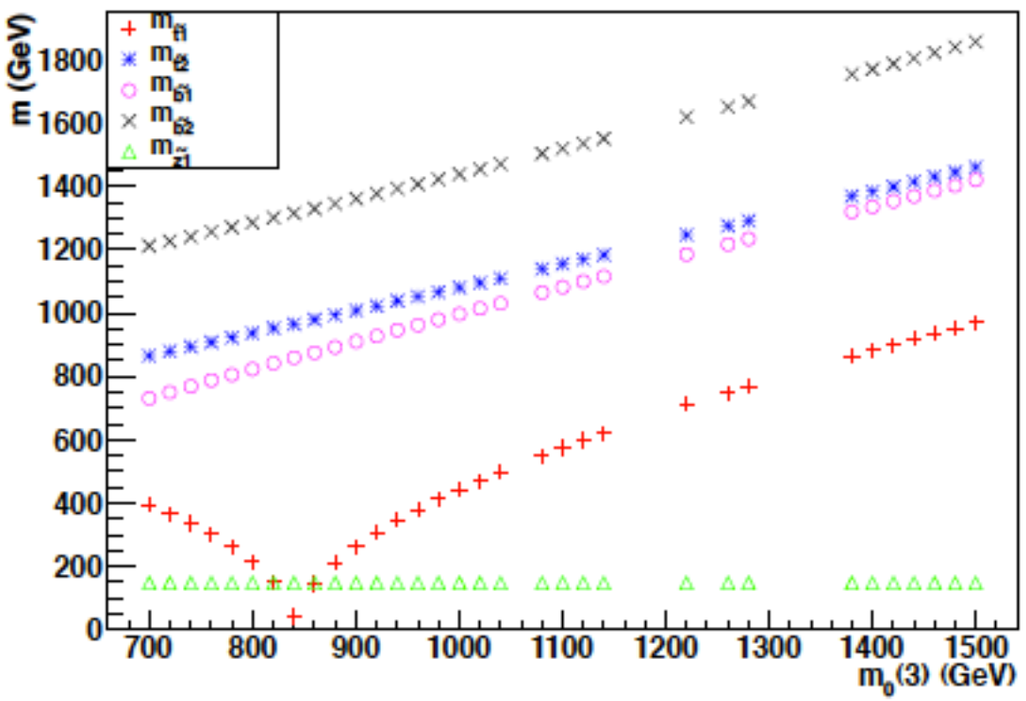


Figure 4: Plot of third generation squark masses together with the lightest neutralino mass versus variation in $m_0(3)$, with other parameters fixed as for the benchmark point NS1.

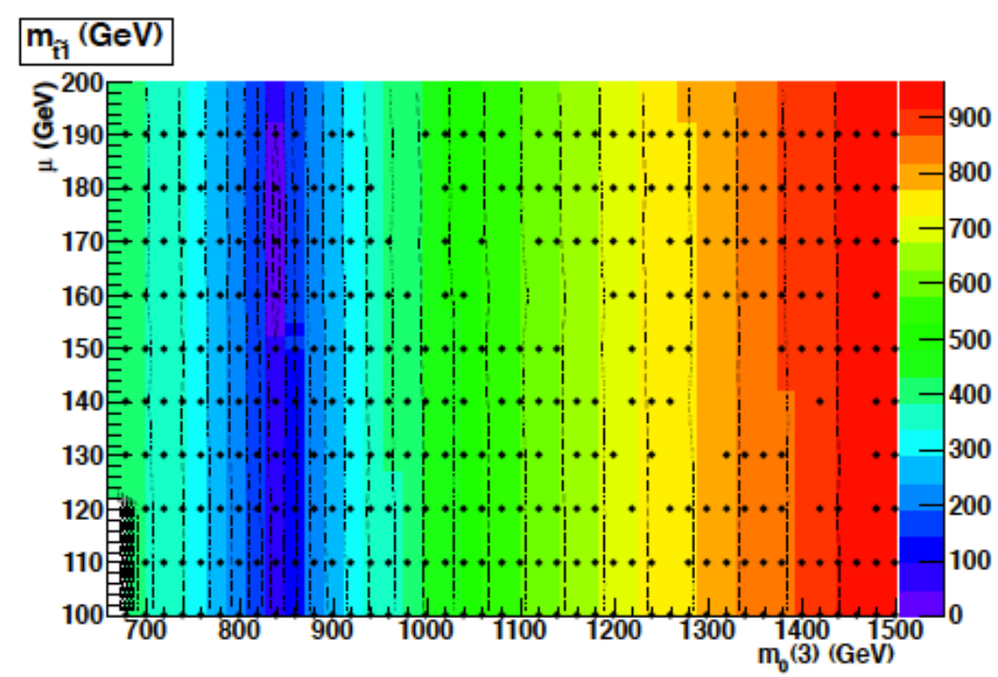


Figure 5: The top squark mass $m_{\tilde{t}_1}$ in the μ *vs.* $m_0(3)$ plane, with other parameters as for benchmark point NS1.

ILC/CLIC: a higgsino factory?

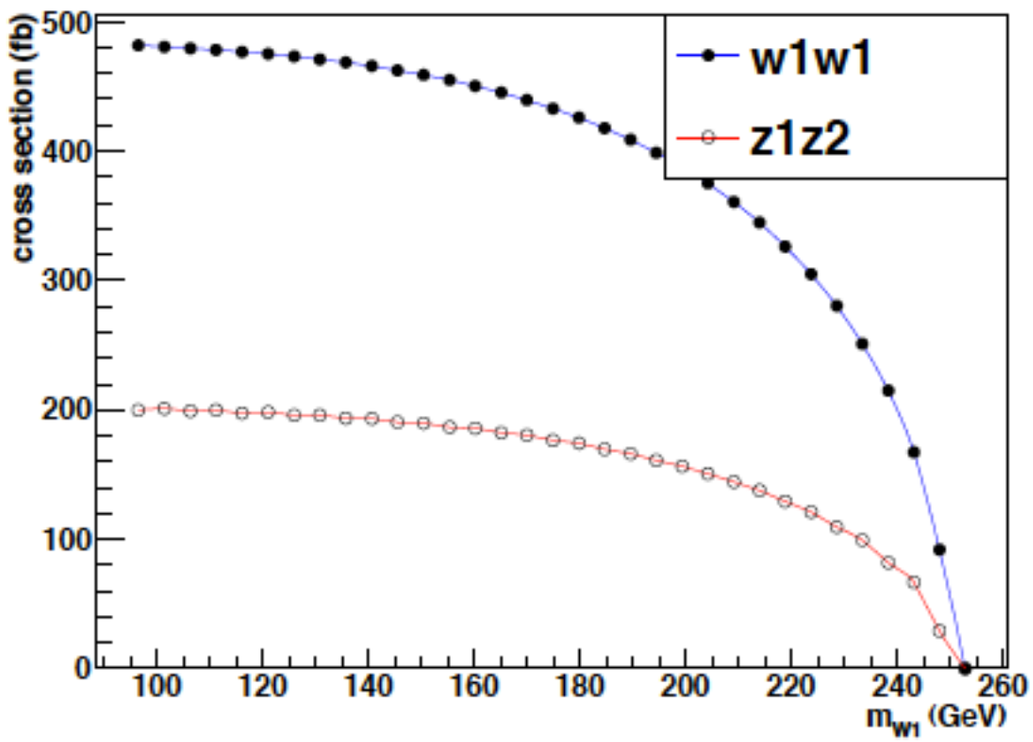


Figure 10: Cross sections for chargino pair production and neutralino pair production versus $m_{\widetilde{W}_1}$ at a $\sqrt{s} = 500$ GeV ILC or MC collider. We take SUSY parameters as in Fig. 7, and vary μ to give variation in $m_{\widetilde{W}_1}$.

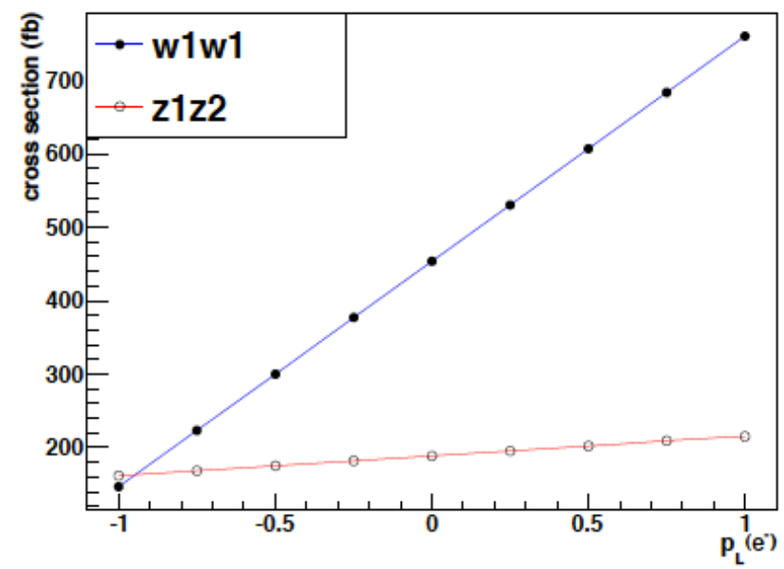


Figure 11: Cross sections for chargino pair production and neutralino pair production versus $P_L(e^-)$ at a $\sqrt{s} = 500$ GeV ILC collider. We take SUSY parameters as in HW1, with $\mu = 150$ GeV.

Maybe see also light 3rd generation squarks and sleptons

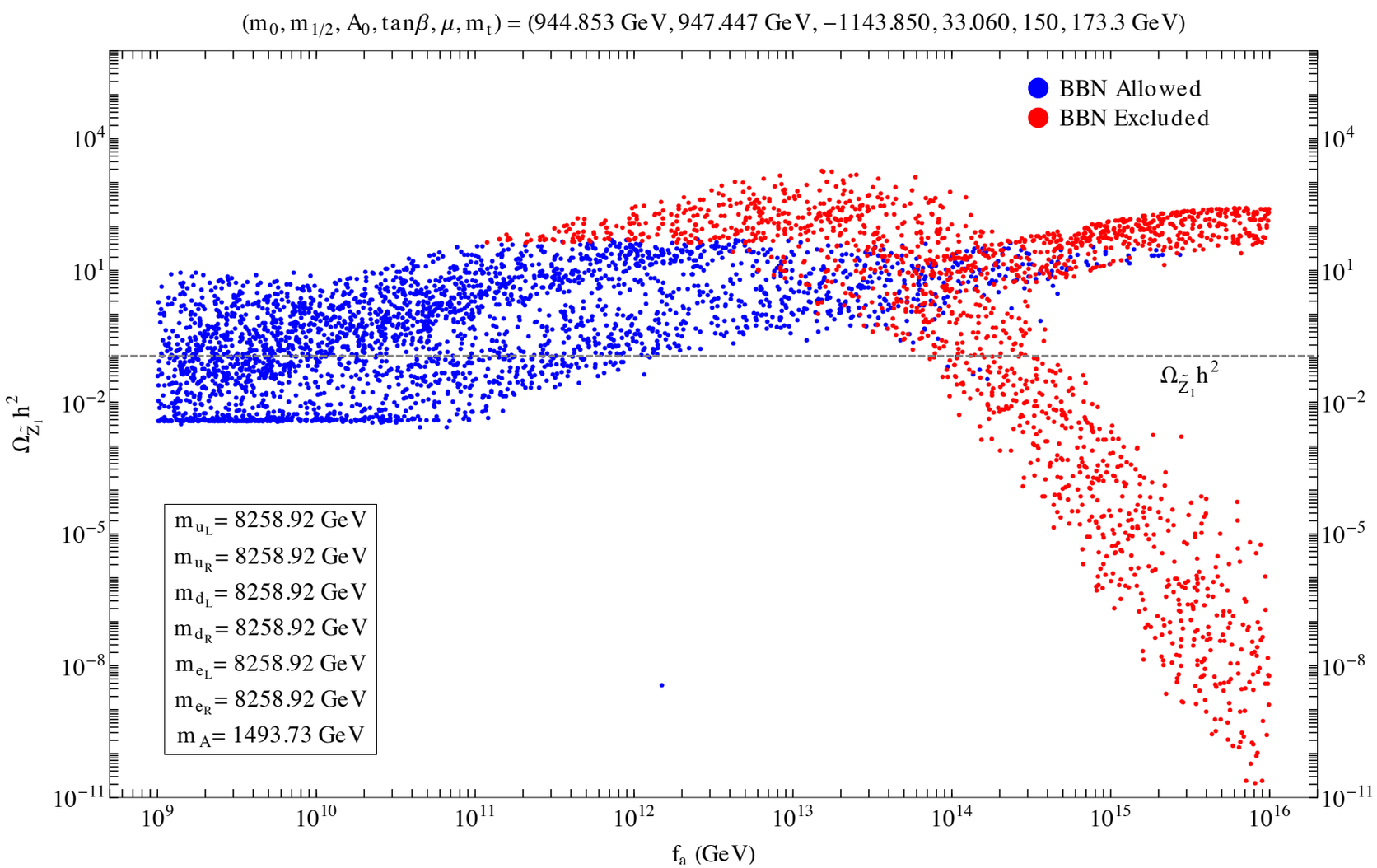
Dark matter in Natural SUSY:
LMSSMP=higgsino;
underabundance of thermal higgsinos
(by factor of ~16)

Some possibilities:

1. Add PQ sector so mixed axion/higgsino =CDM; thermally produced axinos decay and augment higgsino abundance

2. Add light (multi-TeV) moduli field; production and late decay again augments higgsino abundance

Higgsino abundance in Natural SUSY with PQ sector



DM abundance may be either higgsino or axion dominated

Conclusions:

- Models with large m(sq) and gaugino mass unification: W1Z2-> WZ+MET-> 3l+MET seems fruitful search channel for LHC8
- At LHC14, W1Z2-> Wh+MET alternative SUSY search channel; may extend LHC reach
- Natural SUSY (NS) models: new paradigm to replace mSUGRA/CMSSM
- NS hard to see at LHC but ILC is higgsino factory
- Dark matter compatible if MSSM augmented by multi-TeV moduli or PQ (axion) sector