A NEW PROBE OF NEUTRALINOS AT THE LHC

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May 13, 2014

Based on work in progress with Bhaskar Dutta, Yu Gao, Teruki Kamon

MITCHELL INSTITUTE
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Workshop on Collider and Dark Matter Physics

THE BIG PICTURE

From a theoretical perspective, the most well-motivated dark matter candidate is the lightest neutralino in supersymmetry (SUSY)

The detection of dark matter / supersymmetry (via large missing energy) is the LHC's main goal, and has driven theoretical and experimental efforts over the past few years

Complementary to indirect and direct detection searches

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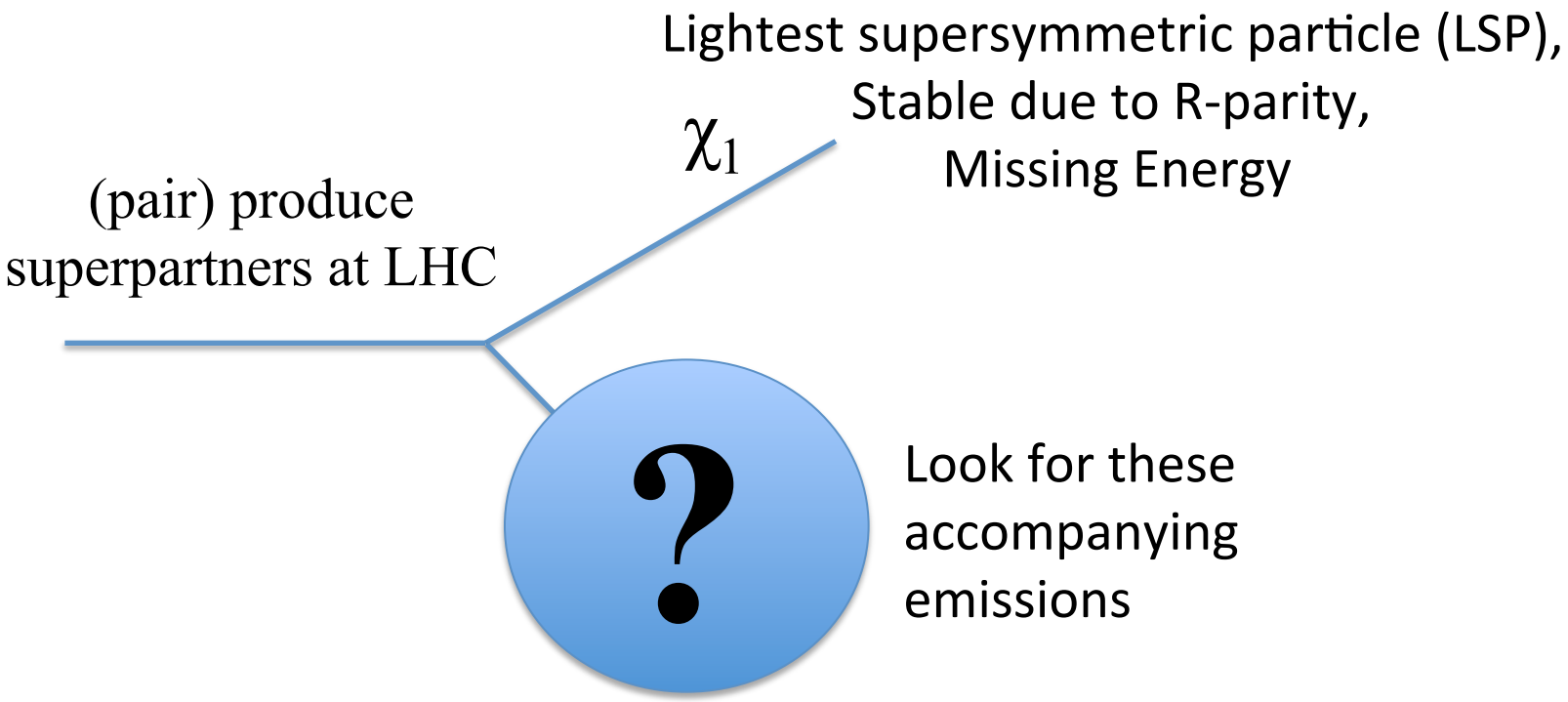
Complementary to indirect and direct detection searches

Recent results have prompted us to reconsider the details

How to look for dark matter at the LHC



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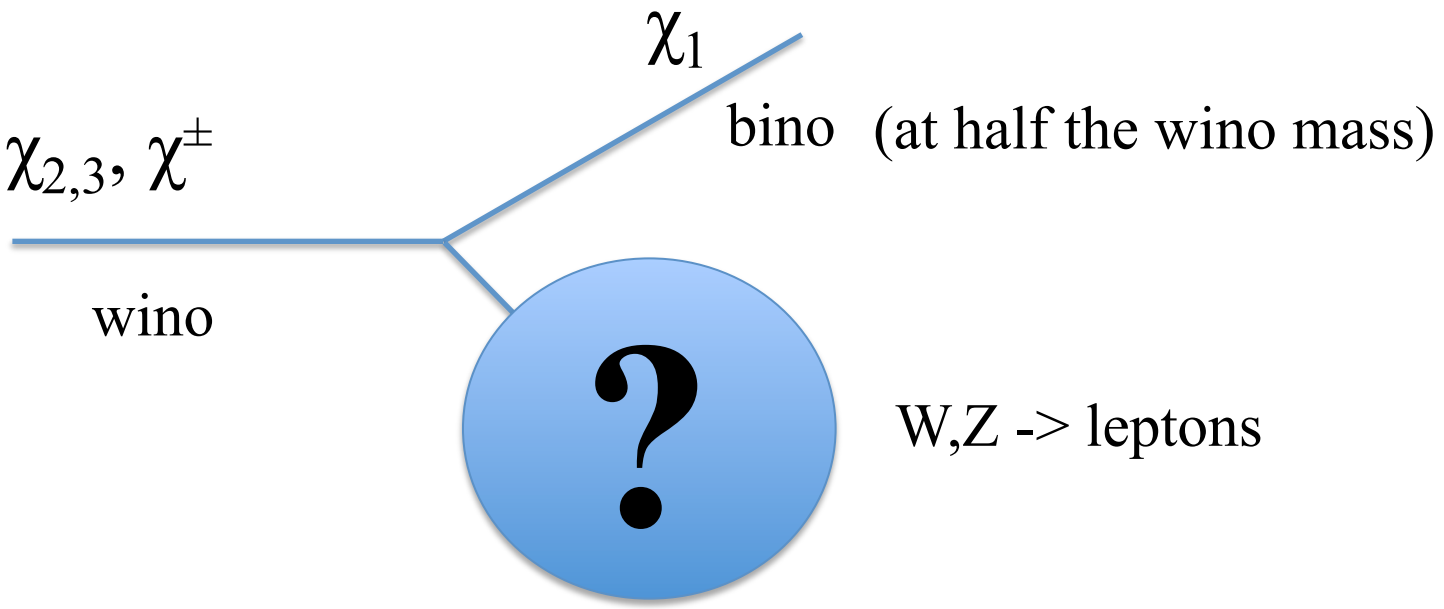

Inspired by CMSSM with gaugino mass unification

However...

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)<200$ GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta>18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)>50$ GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)>50$ GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)>220$ GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})>200$ GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)<600$ GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)<350$ GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)<400$ GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)<300$ GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)<90$ GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^\pm)=2\, m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)=55$ GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^+)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)<200$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5$ GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85$ GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)>150$ GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)+180$ GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^+\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=160$ MeV, $\tau(\tilde{\chi}_1^\pm)=0.2$ ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)=100$ GeV, 10 $\mu s<\tau(\tilde{g})<1000$ s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	$10<\tan\beta<50$	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4<\tau(\tilde{\chi}_1^0)<2$ ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	$1.5<c\tau<156$ mm, BR(μ)=1, $m(\tilde{\chi}_1^0)=108$ GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda'_{311}=0.10$, $\lambda_{132}=0.05$	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}<1$ mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)>300$ GeV, $\lambda_{121}>0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)>80$ GeV, $\lambda_{133}>0$	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)<80$ GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

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**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

However...

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit		Reference
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	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)<200$ GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta>18$	ATLAS-CONF-2013-026
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						619 GeV	$m(\tilde{\chi}_1^0)>50$ GeV	ATLAS-CONF-2012-144
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						690 GeV	$m(\tilde{H})>200$ GeV	ATLAS-CONF-2012-152
						645 GeV	$m(\tilde{g})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen.						1.2 TeV	$m(\tilde{\chi}_1^0)<600$ GeV	ATLAS-CONF-2013-061
						1.1 TeV	$m(\tilde{\chi}_1^0)<350$ GeV	1308.1841
						1.34 TeV	$m(\tilde{\chi}_1^0)<400$ GeV	ATLAS-CONF-2013-061
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3rd gen. squarks						100-620 GeV	$m(\tilde{\chi}_1^0)<90$ GeV	1308.2631
						430 GeV	$m(\tilde{\chi}_1^\pm)=2\, m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
							$m(\tilde{\chi}_1^0)=55$ GeV	1208.4305, 1209.2102
							$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)-50$ GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
						225-525 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-065
						150-580 GeV	$m(\tilde{\chi}_1^0)<200$ GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5$ GeV	1308.2631
						200-610 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-037
						320-660 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-024
							$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85$ GeV	ATLAS-CONF-2013-068
						500 GeV	$m(\tilde{\chi}_1^0)>150$ GeV	ATLAS-CONF-2013-025
						271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)+180$ GeV	ATLAS-CONF-2013-025
EW							$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-049
						-450 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
							$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
						600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
							$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-035
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Long-lived							$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=160$ MeV, $\tau(\tilde{\chi}_1^\pm)=0.2$ ns	ATLAS-CONF-2013-069
						832 GeV	$m(\tilde{\chi}_1^0)=100$ GeV, 10 μs$<\tau(\tilde{g})<1000$ s	ATLAS-CONF-2013-057
						475 GeV	$10<\tan\beta<50$	ATLAS-CONF-2013-058
							$0.4<\tau(\tilde{\chi}_1^0)<2$ ns	1304.6310
						1.0 TeV	$1.5<c\tau<156$ mm, BR(μ)=1, $m(\tilde{\chi}_1^0)=108$ GeV	ATLAS-CONF-2013-092
RPV						1.61 TeV	$\lambda'_{311}=0.10$, $\lambda_{132}=0.05$	1212.1272
						1.1 TeV	$\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$	1212.1272
						1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}<1$ mm	ATLAS-CONF-2012-140
						760 GeV	$m(\tilde{\chi}_1^0)>300$ GeV, $\lambda_{121}>0$	ATLAS-CONF-2013-036
						GeV	$m(\tilde{\chi}_1^0)>80$ GeV, $\lambda_{133}>0$	ATLAS-CONF-2013-036
						916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
						880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon→$q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
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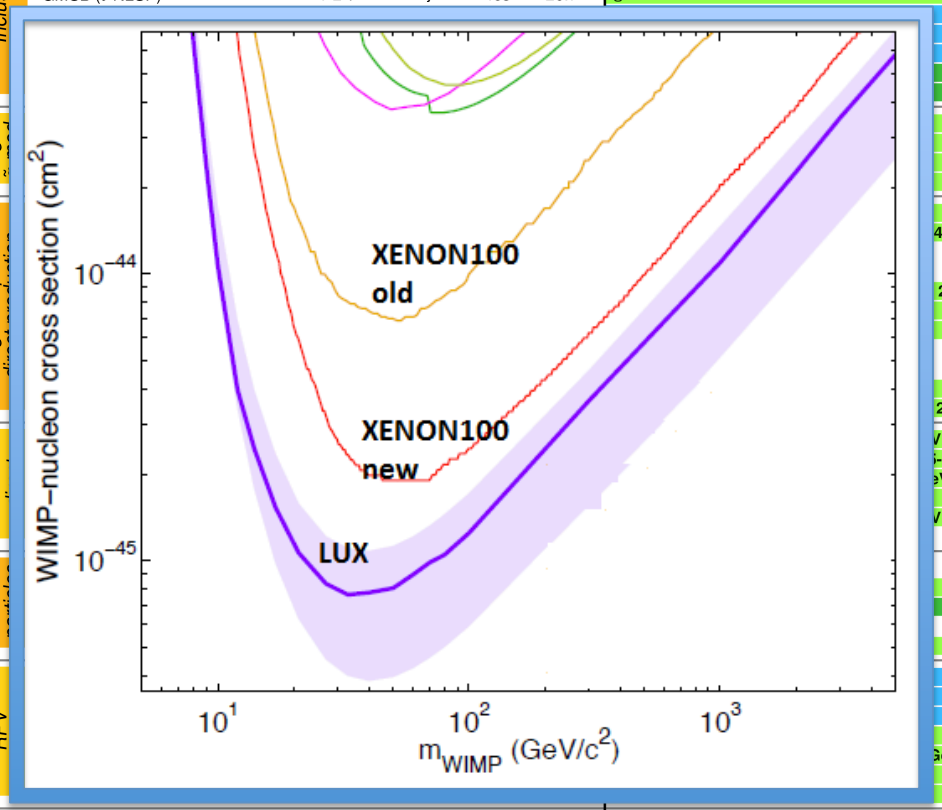

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Mass scale [TeV]

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Guiding Idea:

NATURALNESS

Tree level relation for m_Z :

$$m_Z^2 = -m_u^2 \left(1 - \frac{1}{\cos 2\beta}\right) - m_d^2 \left(1 + \frac{1}{\cos 2\beta}\right) - 2|\mu|^2$$

If terms on r.h.s. are not ~100 GeV, need cancellations to make things work. Fine-tuning !

GLUINO feeds into stop mass

STOPS feed into m_u^2

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HIGGSINOS need to be light

Need these to be light from a naturalness point of view.
Other superpartners can be heavy.

Higgsinos at the LHC

- If no other superpartners LHC-accessible (assume this is the case for this talk) (includes gluino and stops), electroweak production cross section is fairly small

- Tiny mass splitting between the two mass eigenstates, not ideal for missing energy searches

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Q: Are there any well-motivated scenarios with lighter particles that these higgsinos can decay into?

Naturalness Continued: Beyond the MSSM

- No superpartners observed so far

SM-like Higgs at 125 GeV

Naturalness Continued: Beyond the MSSM

- No superpartners observed so far

SM-like Higgs at 125 GeV

NMSSM

- Extend MSSM by a gauge singlet superfield S. Superpotential contains:

$$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- Gives additional contribution to tree level higgs mass

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

- Can get close to 125 GeV with large λ (~0.6), small tanβ (~2), only a small loop correction needed. Significantly improves fine-tuning.

Neutralino Sector of the NMSSM

Basis: $\{B, W_3, H_u^0, H_d^0, S\}$

$$\begin{pmatrix} M_1 & 0 & -m_Z s_W \cos\beta & m_Z s_W \sin\beta & 0 \\ 0 & M_2 & m_Z c_W \cos\beta & -m_Z c_W \sin\beta & 0 \\ -m_Z s_W \cos\beta & m_Z c_W \cos\beta & 0 & -\mu & -\lambda v \sin\beta \\ m_Z s_W \sin\beta & -m_Z c_W \sin\beta & -\mu & 0 & -\lambda v \cos\beta \\ 0 & 0 & -\lambda v \sin\beta & -\lambda v \cos\beta & 2\frac{\kappa}{\lambda}\mu \end{pmatrix}$$

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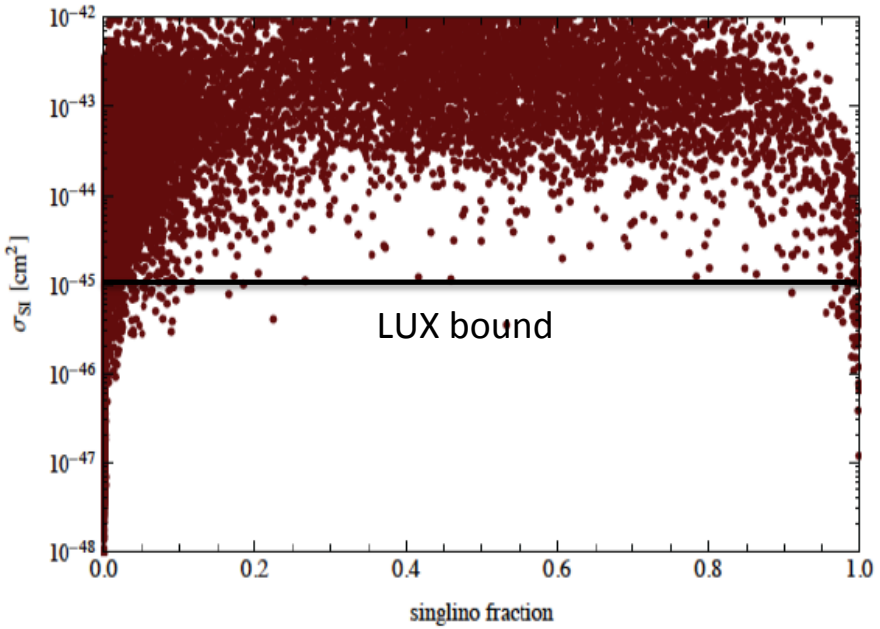
Basis: $\{B, W_3, H_u^0, H_d^0, S\}$

$$\begin{pmatrix} M_1 & 0 & -m_Z s_W \cos\beta & m_Z s_W \sin\beta & 0 \\ 0 & M_2 & m_Z c_W \cos\beta & -m_Z c_W \sin\beta & 0 \\ -m_Z s_W \cos\beta & m_Z c_W \cos\beta & 0 & -\mu & -\lambda v \sin\beta \\ m_Z s_W \sin\beta & -m_Z c_W \sin\beta & -\mu & 0 & -\lambda v \cos\beta \\ 0 & 0 & -\lambda v \sin\beta & -\lambda v \cos\beta & 2\frac{\kappa}{\lambda}\mu \end{pmatrix}$$

- New component: SINGLINO
- tied to higgsino mass scale μ
- naturalness requires large λ, so singlino is usually lighter
- higgsino can decay into singlino!

NMSSM and direct detection

Scattering with nuclei occurs through the Higgs via the $\lambda S H_u H_d$ vertex, requires LSP to have both a higgsino and singlino component



Perelstein, Shakya 1208.0833

To avoid direct detection constraints: either pure higgsino or pure singlino.

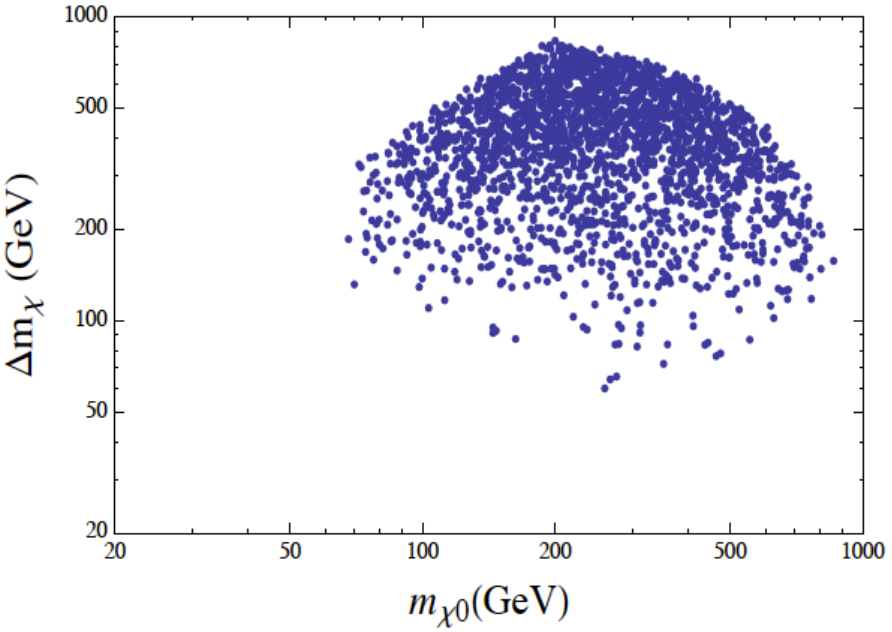
Avoiding this mixing requires separation of higgsino and singlino mass scales.

NMSSM and direct detection

Implications for collider searches:

higgsino-> singlino + h is possible in most of parameter space

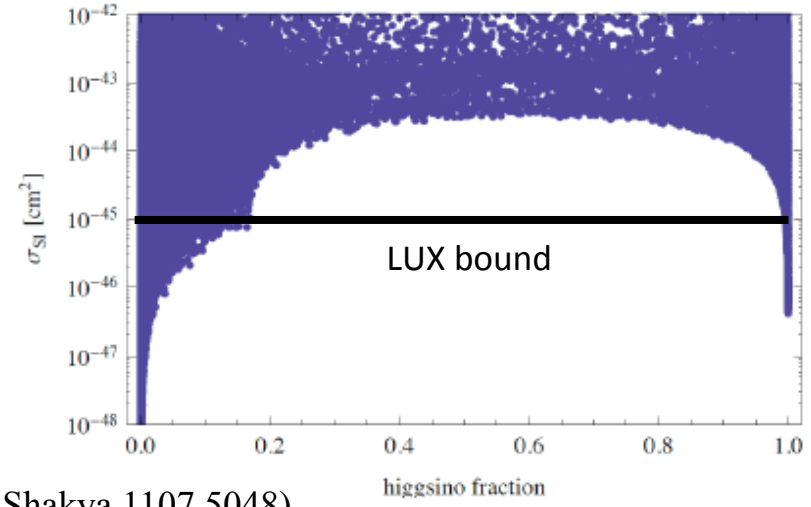
no direct coupling to Z in the pure singlino limit (will still get Zs from the goldstone component)



Similar story in the MSSM

Relic density: well tempered neutralino: bino with some higgsino mixing

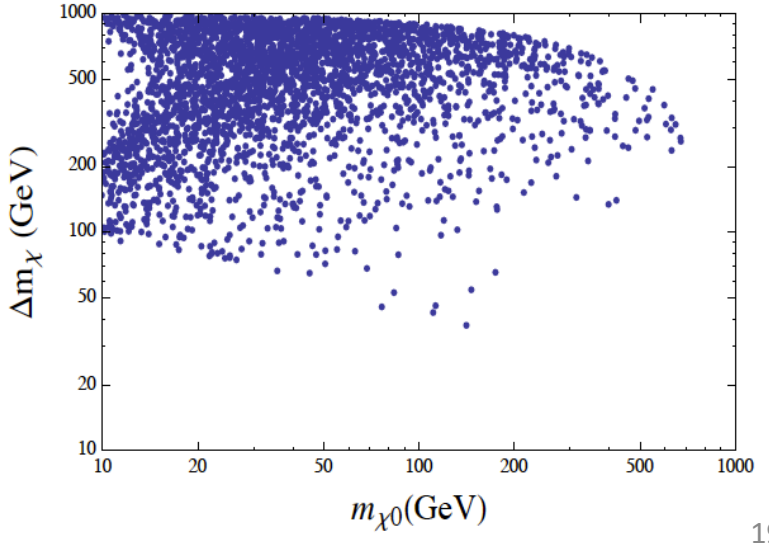
direct detection: $Bh_{u(d)}H_{u(d)}$ vertex, requires suppression of higgsino component -> separation of higgsino and bino mass scales



(Perelstein, Shakya 1107.5048)

higgsino-> bino + h is possible in most of parameter space

no direct coupling to Z in pure bino limit



So, there do exist relevant scenarios

- higgsino ➔ singlino + h (NMSSM)
- higgsino ➔ bino + h (MSSM)
- higgsino ➔ gravitino + h (scale of SUSY breaking low enough that gravitino is very light)

Most likely final state: 4b+MET
cross section is quite low

So, there do exist relevant scenarios

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Questions:

Can we detect these at the LHC?

If yes, can we glean enough information to determine which of the above we are seeing?

Available on the CERN CDS information server

CMS PAS SUS-13-022

CMS Physics Analysis Summary

Contact: cms-pag-conveners-susy@cern.ch

2014/02/18

Search for electroweak production of higgsinos in channels with two Higgs bosons decaying to b quarks in pp collisions at 8 TeV

The CMS Collaboration

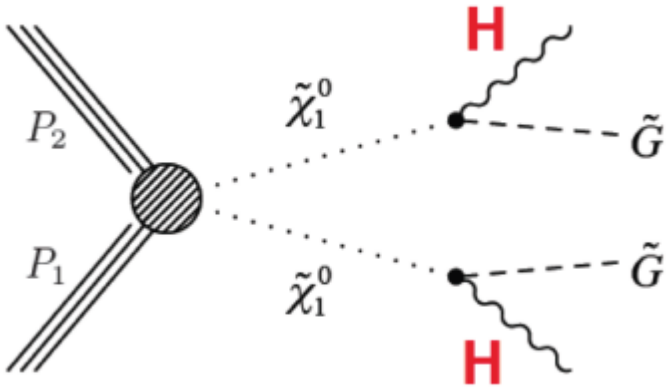
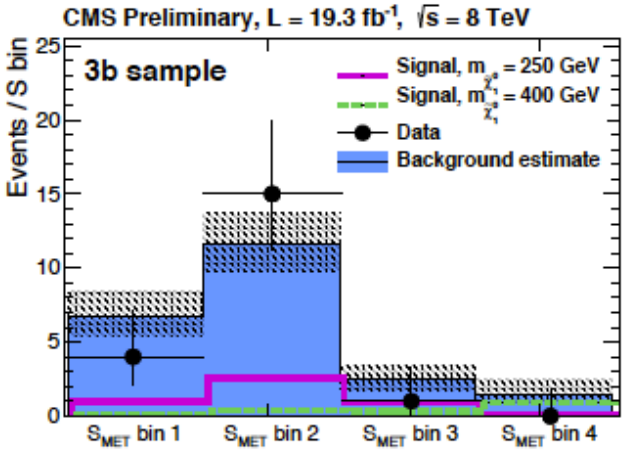
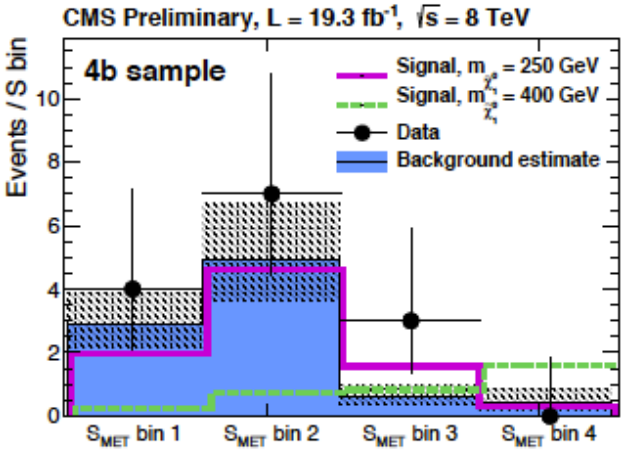


Table 4: Observed numbers of events and corresponding SM background estimates from the likelihood fit for the 3b-SIG and 4b-SIG regions. For the data, the first uncertainty is statistical and the second systematic.

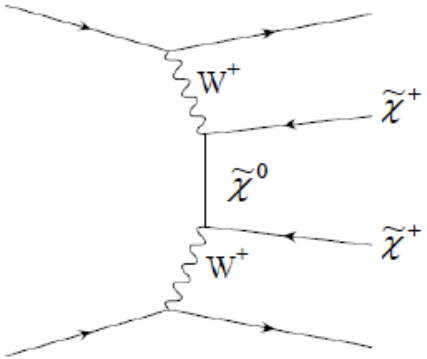
$\mathcal{S}_{\mathrm{MET}}$ bin	$\mathcal{S}_{\mathrm{MET}}$ range	SM background (3b-SIG)	Data (3b-SIG)	SM background (4b-SIG)	Data (4b-SIG)
1	$30 < \mathcal{S}_{\mathrm{MET}} < 50$	$6.7^{+1.4+1.0}_{-1.1-0.7}$	4	$2.9^{+0.8+0.5}_{-0.6-0.4}$	4
2	$50 < \mathcal{S}_{\mathrm{MET}} < 100$	$11.6^{+1.9+0.9}_{-1.6-0.7}$	15	$4.9^{+1.1+1.4}_{-0.9-0.9}$	7
3	$100 < \mathcal{S}_{\mathrm{MET}} < 150$	$2.44^{+0.84+0.56}_{-0.64-0.35}$	1	$0.59^{+0.39+0.09}_{-0.26-0.09}$	3
4	$\mathcal{S}_{\mathrm{MET}} > 150$	$1.50^{+0.82+0.64}_{-0.54-0.32}$	0	$0.40^{+0.39+0.26}_{-0.22-0.10}$	0



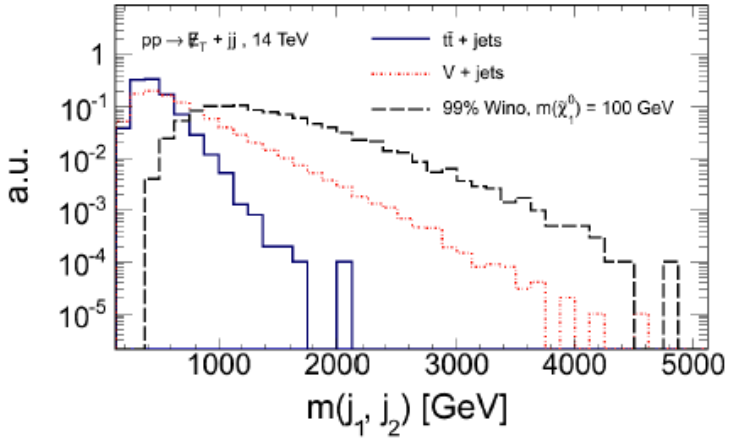


QCD background from ttbar.
Any way to get rid of it?

More jets: Worse is better!



Look at VBF processes: Tag on high ET forward jets in opposite hemispheres with large dijet invariant mass. Very efficient in getting rid of QCD background.



Probing Dark Matter at the LHC using Vector Boson Fusion Processes

Andres G. Delannoy[2], Bhaskar Dutta[1], Alfredo Gurrola[2], Will Johns[2], Teruki Kamon[1,3], Eduardo Luiggi[4], Andrew Melo[2], Paul Sheldon[2], Kuver Sinha[1], Kechen Wang[1], and Sean Wu[1]

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[2] *Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA*

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1304.7779

Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC

Bhaskar Dutta[1], Alfredo Gurrola[2], Will Johns[2], Teruki Kamon[1,3], Paul Sheldon[2], and Kuver Sinha[1]

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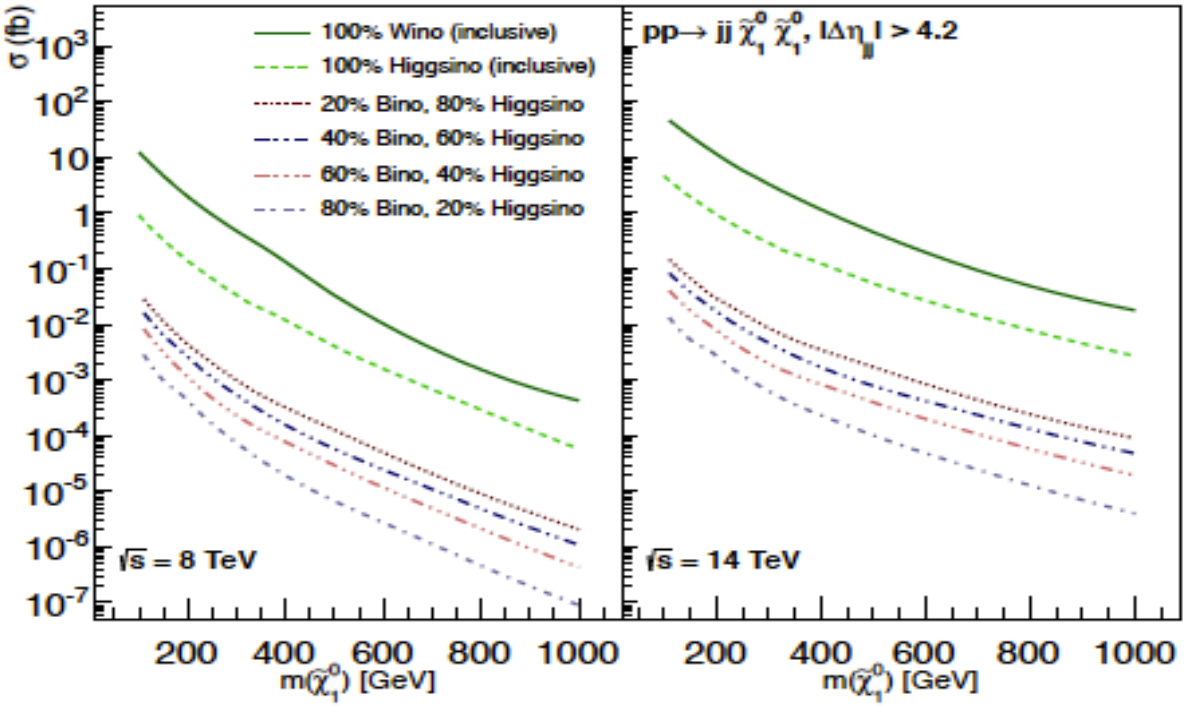
[2] *Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235*

[3] *Department of Physics, Kyungpook National University, Daegu 702-701, South Korea*

Vector boson fusion (VBF) processes offer a promising avenue to study the non-colored sectors of supersymmetric extensions of the Standard Model at the LHC. A feasibility study for searching for the chargino/neutralino system in the $R-$parity conserving Minimal Supersymmetric Standard Model is presented. The high E_T forward jets in opposite hemispheres are utilized to trigger VBF events, so that the production of the lightest chargino $\tilde{\chi}_1^{\pm}$ and the second lightest neutralino $\tilde{\chi}_2^0$ can be probed without a bias by experimental triggers. Kinematic requirements are developed to search for signals of these supersymmetric states above Standard Model backgrounds in both τ and light lepton (e and μ) final states at $\sqrt{s} = 8$ TeV.

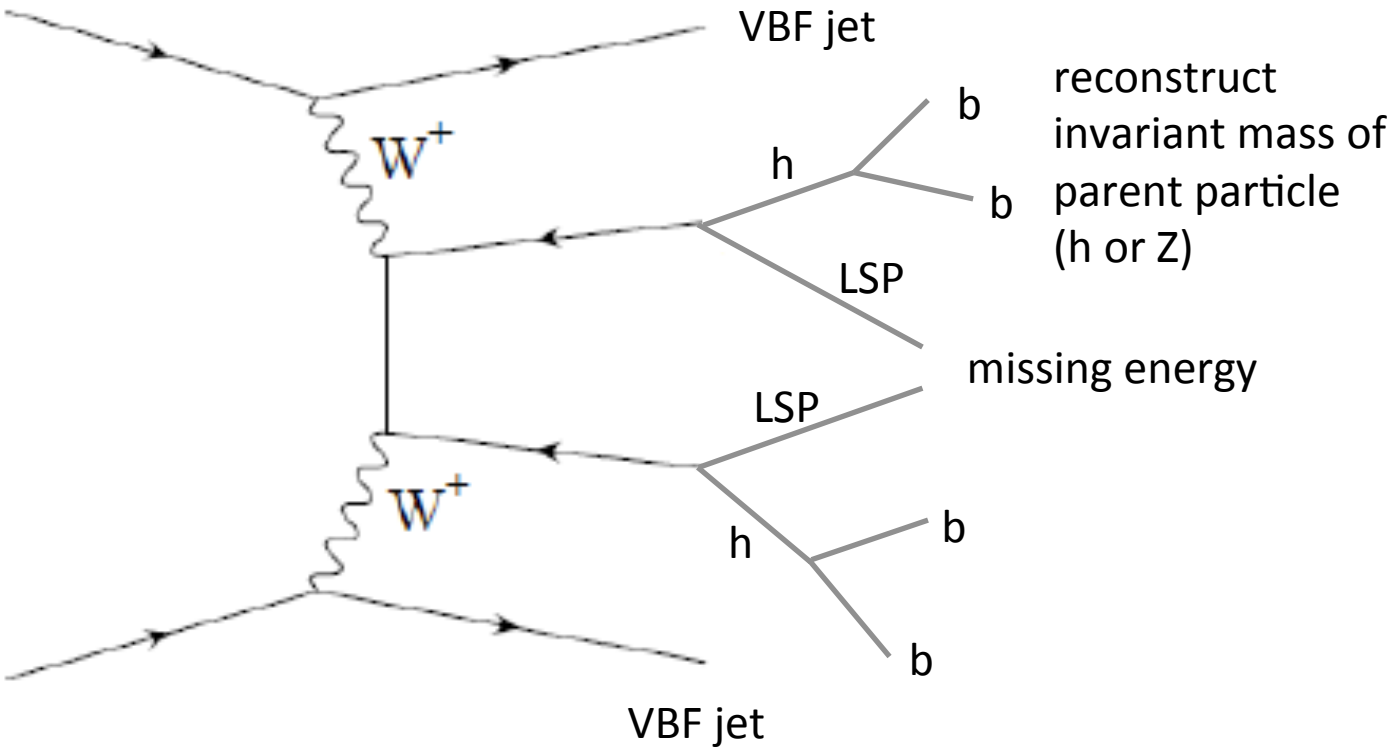
1210.0964



from 1304.7779

FIG. 1: Production cross section as a function of $m_{\tilde{\chi}_1^0}$ after requiring $|\Delta\eta(j_1, j_2)| > 4.2$, at LHC8 and LHC14. For the pure Wino and Higgsino cases, inclusive $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, and $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ production cross sections are displayed.

What we would like to look for (there is some order to this chaos!)



(Note: would also work in other scenarios with similar topologies e.g. wino decaying into higgsino)

A sample point from the NMSSM:

355 GeV Higgsinos, 192 GeV singlino

cut (efficiency)	σ [fb] (w/o BRs)
VBF cuts (25%)	0.34
$\not{E}_T > 200$GeV (35%)	**0.12**
3 isolated b parton (35%)	0.04
4 isolated b parton (45%)	0.05
3^+ tagged b (67%)	0.05
—	σ [fb] (w BRs)
3^+ tagged b	0.004

VERY Preliminary Impressions:

- Should be essentially background free
- Looks like some events should be possible at 300fb^-1
- Should be able to probe higgsinos beyond 400 GeV

Can we use measurements of these events to differentiate between models? e.g. are we seeing the MSSM or NMSSM?

the vertices are different:

MSSM: $g\ B\ h_{u(d)}H_{u(d)}$

NMSSM: $\lambda S H_u H_d$

In principle, can probably tell the difference by looking at e.g. ratio of Z/h events
(but would require many events + constraints from other measurements...)

work in progress...

SUMMARY

- Well motivated scenarios for higgsinos decaying into lighter particles (singlino, bino, gravitino)
- Main decay process: higgsino➔ higgs(➔bbar)+LSP. Cross section is low, need to make the most out of all events!
- QCD background, can be improved with VBF jets +large MET cut
- Reach might be competitive with / higher than other search strategies
- Will be able to tell you more soon!