Complementarity of the mono-X and SUSY searches

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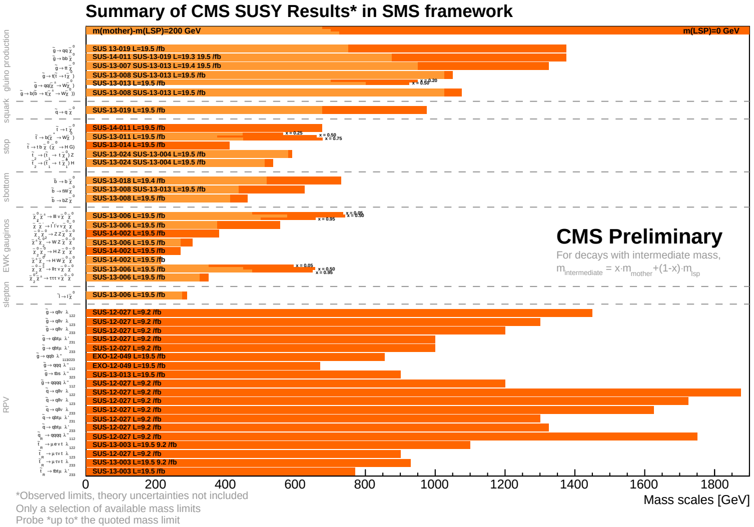
CMS overview



ATLAS overview

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde q, \tilde g$ 1.8 TeV	$m(\tilde q)=m(\tilde g)$	1507.05525
	$\tilde q\tilde q$, $\tilde q \to q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde q$ 850 GeV	$m(\tilde\chi_1^0)$=0 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1405.7875
	$\tilde q\tilde q$, $\tilde q \to q\tilde\chi_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde q$ 100-440 GeV	$m(\tilde q)$-$m(\tilde\chi_1^0)$<10 GeV	1507.05525
	$\tilde q\tilde q$, $\tilde q \to q(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde q$ 780 GeV	$m(\tilde\chi_1^0)$=0 GeV	1503.03290
	$\tilde g\tilde g$, $\tilde g \to q\bar q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde g$ 1.33 TeV	$m(\tilde\chi_1^0)$=0 GeV	1405.7875
	$\tilde g\tilde g$, $\tilde g \to qq\tilde\chi_1^\pm \to qqW^\pm\tilde\chi_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde g$ 1.26 TeV	$m(\tilde\chi_1^0)$<300 GeV, $m(\tilde\chi^\pm)$=0.5($m(\tilde\chi_1^0)$+$m(\tilde g)$)	1507.05525
	$\tilde g\tilde g$, $\tilde g \to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ	0-3 jets	-	20	$\tilde g$ 1.32 TeV	$m(\tilde\chi_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde\ell$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde g$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde g$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde g$ 1.3 TeV	$m(\tilde\chi_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde g$ 1.25 TeV	$m(\tilde\chi_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde g$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde G)>1.8\times10^{-4}$ eV, $m(\tilde g)=m(\tilde q)$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde g$ med.	$\tilde g\tilde g$, $\tilde g \to b\bar b\tilde\chi_1^0$	0	3 b	Yes	20.1	$\tilde g$ 1.25 TeV	$m(\tilde\chi_1^0)$<400 GeV	1407.0600
	$\tilde g\tilde g$, $\tilde g \to t\bar t\tilde\chi_1^0$	0	7-10 jets	Yes	20.3	$\tilde g$ 1.1 TeV	$m(\tilde\chi_1^0)$ <350 GeV	1308.1841
	$\tilde g\tilde g$, $\tilde g \to t\bar t\tilde\chi_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.34 TeV	$m(\tilde\chi_1^0)$<400 GeV	1407.0600
	$\tilde g\tilde g$, $\tilde g \to b\bar t\tilde\chi_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.3 TeV	$m(\tilde\chi_1^0)$<300 GeV	1407.0600
3^{rd} 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	20.3	$\tilde b_1$ 275-440 GeV	$m(\tilde\chi_1^\pm)$=2 $m(\tilde\chi_1^0)$	1404.2500
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to b\tilde\chi_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde t_1$ 110-167 GeV 230-460 GeV	$m(\tilde\chi_1^\pm)$ = 2$m(\tilde\chi_1^0)$, $m(\tilde\chi_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to Wb\tilde\chi_1^0$ or $t\tilde\chi_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde t_1$ 90-191 GeV 210-700 GeV	$m(\tilde\chi_1^0)$=1 GeV	1506.08616
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to c\tilde\chi_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde t_1$ 90-240 GeV	$m(\tilde t_1)$-$m(\tilde\chi_1^0)$<85 GeV	1407.0608
	$\tilde t_1\tilde t_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde t_1$ 150-580 GeV	$m(\tilde\chi_1^0)$>150 GeV	1403.5222
	$\tilde t_2\tilde t_2$, $\tilde t_2 \to \tilde t_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde t_2$ 290-600 GeV	$m(\tilde\chi_1^0)$<200 GeV	1403.5222
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	$\tilde\ell$ 90-325 GeV	$m(\tilde\chi_1^0)$=0 GeV	1403.5294
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+ \to \tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm$ 140-465 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi_1^\pm)$+$m(\tilde\chi_1^0)$)	1403.5294
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+ \to \tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.3	$\tilde\chi_1^\pm$ 100-350 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\tau,\tilde\nu)$=0.5($m(\tilde\chi_1^\pm)$+$m(\tilde\chi_1^0)$)	1407.0350
	$\tilde\chi_1^\pm\tilde\chi_2^0 \to \tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm, \tilde\chi_2^0$ 700 GeV	$m(\tilde\chi_1^\pm)$=$m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi_1^\pm)$+$m(\tilde\chi_1^0)$)	1402.7029
	$\tilde\chi_1^\pm\tilde\chi_2^0 \to W\tilde\chi_1^0 Z\tilde\chi_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde\chi_1^\pm, \tilde\chi_2^0$ 420 GeV	$m(\tilde\chi_1^\pm)$=$m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde\chi_1^\pm\tilde\chi_2^0 \to W\tilde\chi_1^0 h\tilde\chi_1^0$, $h \to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde\chi_1^\pm, \tilde\chi_2^0$ 250 GeV	$m(\tilde\chi_1^\pm)$=$m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde\chi_2^0\tilde\chi_3^0$, $\tilde\chi_{2,3}^0 \to \tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	$\tilde\chi_{2,3}^0$ 620 GeV	$m(\tilde\chi_2^0)$=$m(\tilde\chi_3^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)$=0.5($m(\tilde\chi_2^0)$+$m(\tilde\chi_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde W$ 124-361 GeV	$c\tau$<1 mm	1507.05493
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	1310.3675
	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde\chi_1^\pm$ 482 GeV	$m(\tilde\chi_1^\pm)$-$m(\tilde\chi_1^0)$~160 MeV, $\tau(\tilde\chi_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde g$ 832 GeV	$m(\tilde\chi_1^0)$=100 GeV, 10 μs<$\tau(\tilde g)$<1000 s	1310.6584
	Stable $\tilde g$ R-hadron	trk	-	-	19.1	$\tilde g$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde\tau$, $\tilde\chi_1^0 \to \tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde\chi_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde\chi_1^0 \to \gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	20.3	$\tilde\chi_1^0$ 435 GeV	2<$\tau(\tilde\chi_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde\chi_1^0$ 1.0 TeV	7 <$c\tau(\tilde\chi_1^0)$< 740 mm, $m(\tilde g)$=1.3 TeV	1504.05162
	GGM $\tilde g\tilde g$, $\tilde\chi_1^0 \to Z\tilde G$	displ. vtx + jets	-	-	20.3	$\tilde\chi_1^0$ 1.0 TeV	6 <$c\tau(\tilde\chi_1^0)$< 480 mm, $m(\tilde g)$=1.1 TeV	1504.05162
RPV	LFV $pp \to \tilde\nu_\tau + X$, $\tilde\nu_\tau \to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	20.3	$\tilde\nu_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde q, \tilde g$ 1.35 TeV	$m(\tilde q)=m(\tilde g)$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+ \to W\tilde\chi_1^0$, $\tilde\chi_1^0 \to ee\tilde\nu_\mu, e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.3	$\tilde\chi_1^\pm$ 750 GeV	$m(\tilde\chi_1^0)$>0.2×$m(\tilde\chi_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+ \to W\tilde\chi_1^0$, $\tilde\chi_1^0 \to \tau\tau\tilde\nu_e, e\tau\tilde\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde\chi_1^\pm$ 450 GeV	$m(\tilde\chi_1^0)$>0.2×$m(\tilde\chi_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde g\tilde g$, $\tilde g \to qqq$	0	6-7 jets	-	20.3	$\tilde g$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde g\tilde g$, $\tilde g \to q\tilde\chi_1^0$, $\tilde\chi_1^0 \to qqq$	0	6-7 jets	-	20.3	$\tilde g$ 870 GeV	$m(\tilde\chi_1^0)$=600 GeV	1502.05686
	$\tilde g\tilde g$, $\tilde g \to \tilde t_1 t$, $\tilde t_1 \to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde g$ 850 GeV		1404.250
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to bs$	0	2 jets + 2 b	-	20.3	$\tilde t_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde t_1\tilde t_1$, $\tilde t_1 \to b\ell$	2 e,μ	2 b	-	20.3	$\tilde t_1$ 0.4-1.0 TeV	BR($\tilde t_1 \to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde c \to c\tilde\chi_1^0$	0	2 c	Yes	20.3	$\tilde c$ 490 GeV	$m(\tilde\chi_1^0)$<200 GeV	1501.01325

10^{-1} 1 **Mass scale [TeV]**

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.

SUSY and DM complementarity

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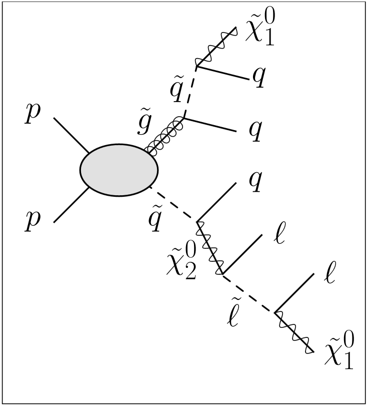
- Stuff generally (but not always) means ≥ 2 particles
- Vast majority of searches are NOT SUSY specific
    - Simply looking for a heavy state that decays to MET + ...
    - Majority of searches target decay products



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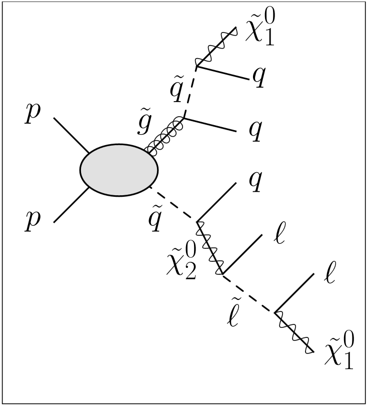


~~SUSY searches~~ $\rightarrow$ General DM searches

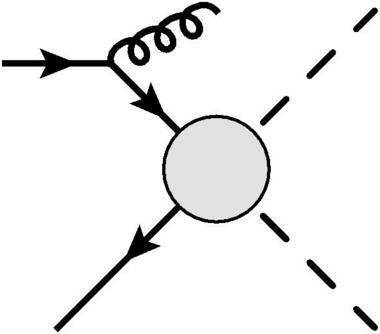
SUSY and DM complementarity

Mono-X searches $\rightarrow$ Singular stuff $+$ MET

SUSY and DM complementarity

Mono-X searches $\rightarrow$ Singular stuff + MET

- Mono-X searches are a continuation of the 'SUSY' analyses to lower multiplicity
- Jets (g, q, b, t's), $W^{\pm}$, Z^0, γ, h^0
- Difference is that searches (mostly) aim to target initial state radiation (ISR)



Quiz Question

Question: How many LHC monojet searches have there been (7, 8 and 13 TeV)?

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ANSWER: 1

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$m_{\tilde{\chi}} = 200$ GeV @ 13 TeV $p_T(j_1) > 100$ GeV	Xsec (fb)
$pp \to \tilde{\chi}\tilde{\chi}\, j \quad (+N\, j)$	0.005
$pp \to \tilde{\chi}\tilde{\chi}\, j\, j \;\; (+N\, j)\,,\;\; p_T(j_2) > 30$ GeV	0.004

- Results show that jet-vetoes should be handled with care.
  - CMS 'mono-jet' @ 13 TeV allows ANY jet multiplicity
- Only ATLAS $Z \to \ell^+\ell^-$ now has explicit jet veto
  - Kill $t\bar{t}$ background

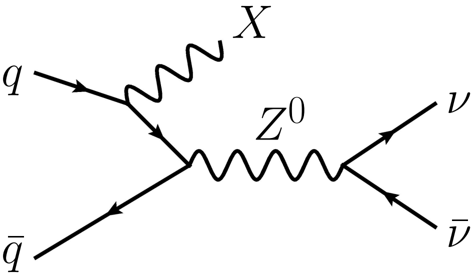
Differences

- Almost no ‘pure’ mono signatures
  - More just lower multiplicity in general
  - Very large signal region overlaps with SUSY searches
- Taking ATLAS and CMS together
  - Almost no kinematical gaps between mono-X and SUSY searches
  - One set of searches can be viewed as the continuation of the other
- Difference is more in terms of models investigated
  - ATLAS mono-jet and mono-photon are now listed under both DM and SUSY searches
  - CMS also includes mono-jet under SUSY search

Which Mono-X should we concentrate on?

Assuming ISR signal, which Mono-X is best?

- All possibilities currently targeted,
  - Jets (g, q, b, t's), W, Z, γ, h^0 ?
- Dominant background is normally X+($Z \to \nu\bar{\nu}$)



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- For γ, $S \propto g_e^2$, $B \propto g_e^2$

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- For γ, $S \propto g_e^2\,,$ $B \propto g_e^2$
- Significance, $\sigma_{\text{stat, jet}} \propto g_s\,,$ $\sigma_{\text{stat, }\gamma} \propto g_e$

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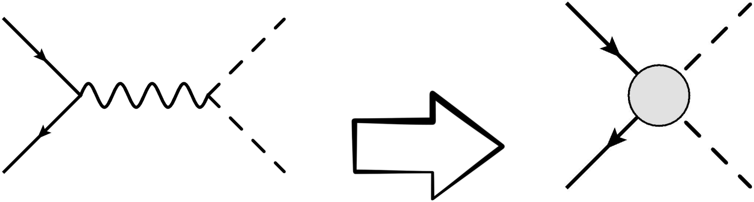
Monojet usually provides best sensitivity to ISR signal

- Constructive interference motivated mono-W
    - Models break $SU(2)_L$
      (Bell, Cai, Dent, Leane, Weiler; 2015)
      (Haisch, Kahlhoefer, Tait; 2016)
- Exceptions → Mono-X produced 'internally', via decay or heavy flavour interaction

How realistic is the ISR DM signal???

Original motivation were the effective models $\rightarrow$ integrate out heavy mediator.



$$\frac{1}{p^2 - M_\Omega^2}$$

$$-\frac{1}{M_\Omega^2}(1 + O(p^2/M_\Omega^2 + \ldots))$$

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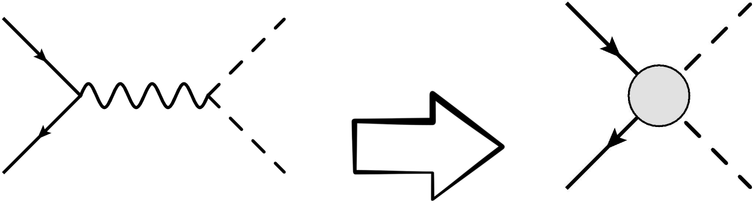


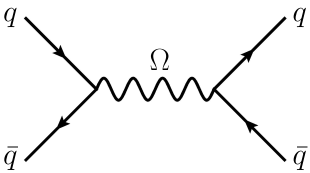
$$\frac{1}{p^2 - M_\Omega^2}$$

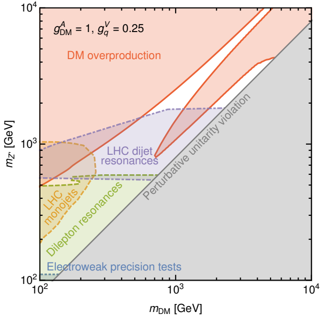
$$-\frac{1}{M_\Omega^2}\left(1 + O(p^2/M_\Omega^2 + \ldots)\right)$$

- We have an unavoidable SM interaction
- We want a model that is theoretically consistent
  - Gauge Invariance
  - Unitarity

How realistic is the ISR DM signal???

- Gauge Invariance
  - Dilepton resonance searches
  - Electroweak precision observables
- Relatively small regions of parameter space where,
  - Relic abundance is satisfied
  - LHC monojet search is most constraining
- t-channel models
  - This is essentially SUSY!!!!
- Is the monojet actually worth looking at?





Kahlhoefer, Schmidt-Hoberg, Schwetz, Vogl; 2015

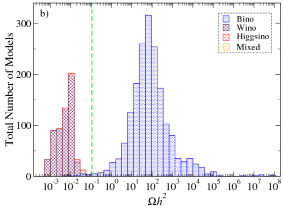
Co-annihilation

SUSY $\rightarrow$ Bino has small g_1 coupling

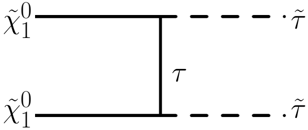
- Small annihilation cross-section
- Generically predicts DM over-abundance
- Co-annihilation is one mechanism to reduce this
- Requires small mass splitting between co-annihilating states

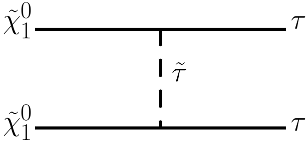
Model independent $\rightarrow$ Co-annihilation codex (Joachim tomorrow)

Baker, Brod, Hedri, Kaminska, Kopp, Liu, Thamm, de Vries, Wang, Yu, Zurita; 2015



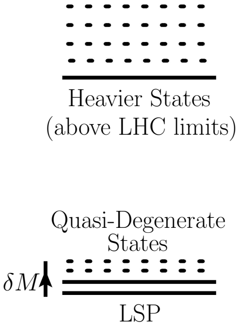
Baer, Choi, Kim, Roszkowski; 2014

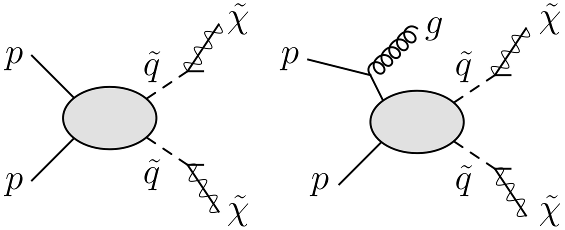




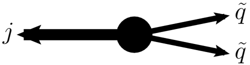
Compressed Spectra

- Co-annihilating particle may have far larger LHC cross section
- Small mass splitting means that visible particles are soft
- Natural to ask whether ISR helps





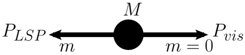
Is this a Monojet signal?



Do the visible decay products stay soft under ISR boost?

In rest frame of decaying particle,

$$P_{LSP} = P_{vis} = \frac{M^2 - m^2}{2M}$$

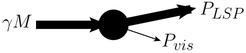


As a function of mass difference, $\delta M = M - m$,

$$P_{LSP} = P_{vis} = \delta M - \frac{\delta M^2}{2M}$$

In boosted frame, $E = \gamma M$ for decaying particle,

$$P'_{LSP} \sim \gamma \delta M \pm \gamma \beta m, \quad P'_{vis} \sim \gamma \delta M \pm \gamma \beta \delta M$$

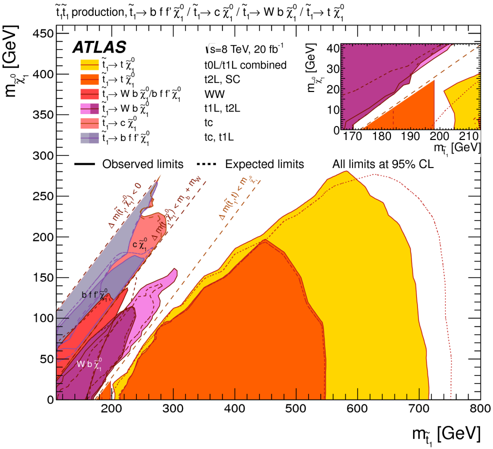


Boosts only act multiplicatively on soft particle momenta $\rightarrow$ Monojet has potential

Monojet searches for SUSY

For compressed SUSY spectra, monojet is the most constraining

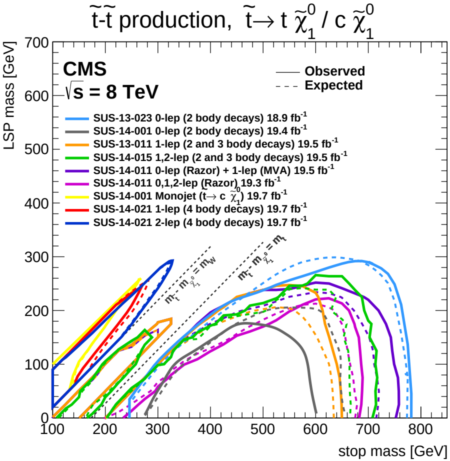
ATLAS Stop Search (Phys. Rev. D. 90, 052008 (2014))



Monojet searches for SUSY

For compressed SUSY spectra, monojet is the most constraining

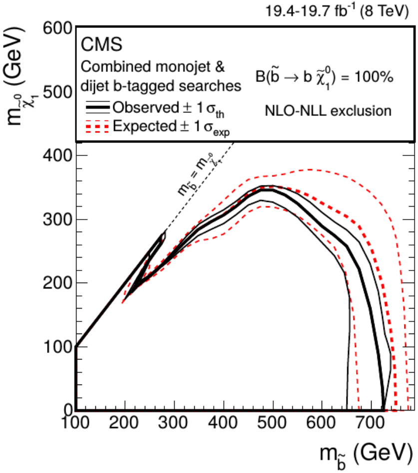
CMS Stop Search (JHEP 06 (2015) 116)



Monojet searches for SUSY

For compressed SUSY spectra, monojet is the most constraining

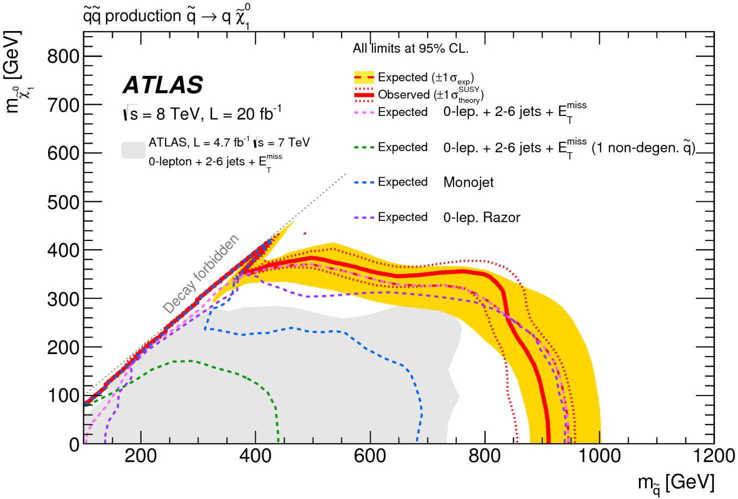
CMS Sbottom Search (JHEP 06 (2015) 116)



Monojet searches for SUSY

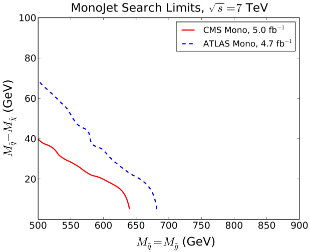
For compressed SUSY spectra, monojet is the most constraining

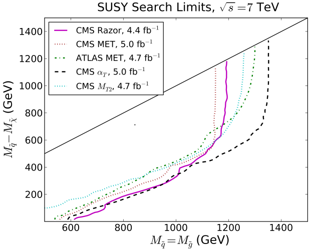
ATLAS Squark Search (JHEP 10 (2015) 054)



Monojet searches for SUSY

- These are the only SUSY monojet studies so far (+ ATLAS sbottom)
- My opinion,
  - All compressed (but prompt) scenarios will be most constrained by monojet
  - As mass scale increases, sensitivity of multijet susy search and monojet will converge
- Once again emphasise that this is not SUSY specific!





Dreiner, Kraemer, JT; 2012

ISR searches for electroweak SUSY

Of particular interest is the neutralino/chargino system

- Neutralinos, $\mathcal{L} = -\frac{1}{2}\tilde{N}^{0\,T}\mathbf{M}_{\tilde{N}^0}\tilde{N}^0 + \text{h.c.}$

$$\mathbf{M}_{\tilde{N}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

- Charginos, $\mathcal{L} = -\frac{1}{2}(\tilde{C}^{+\,T}\mathbf{X}^T \cdot \tilde{C}^- + \tilde{C}^{-\,T}\mathbf{X}\tilde{C}^+) + \text{h.c.}$

$$\mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2}s_\beta m_W \\ \sqrt{2}c_\beta m_w & \mu \end{pmatrix}$$

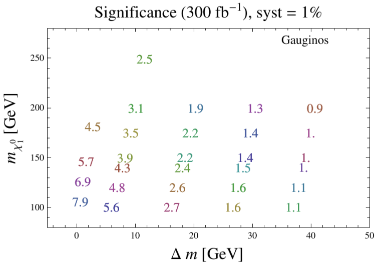
Compressed if,

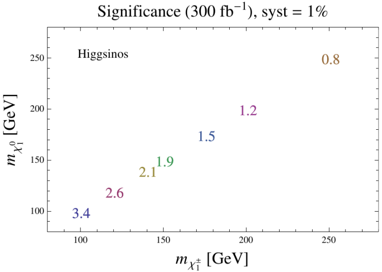
- $\mu \ll M_1, M_2$ (Higgsino)
- $M_2 \ll M_1, \mu$ (Wino)
- $M_1 \sim M_2$ (mixed)

LHC limits?

Monojet,

- Cross-sections are too small to go beyond LEP with collected data
- At 300 fb^{-1} LHC,
  - Gaugino < 200 GeV, Higgsino < 150 GeV
  - Assuming 1% systematic (using data driven $Z \to \nu\nu$)



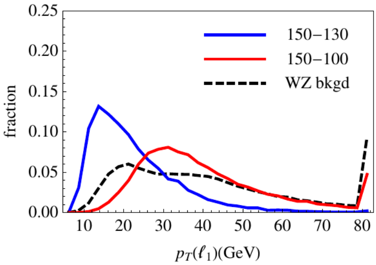


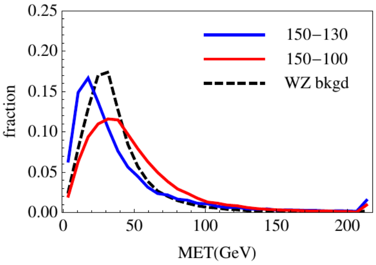
(Schwaller, Zurita; 2013)

Improvements?

Improving the LHC reach for SUSY gauginos has received significant attention

- Can we target the soft decay products?
- Looking at distributions, this seems very challenging
  - MET softer than SM background
  - Leptons softer than SM background

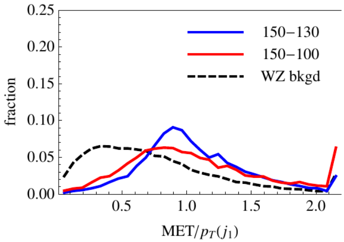


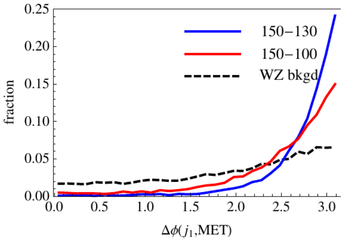


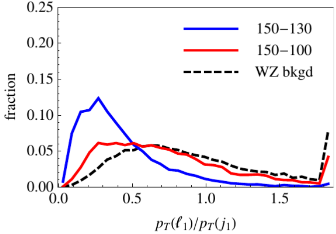
(Gori, Jung, Wang; 2013)

Improvements?

Use hard ISR to trigger and transform distributions
(Gori, Jung, Wang; 2013)

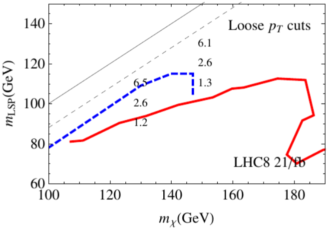




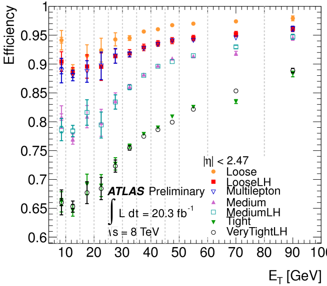


Problem Solved?

- Reach is improved but compression hole still not filled
  - Relies on soft leptons $7 < p_T(\ell) < 50$ GeV
  - Invariant mass $12 < m_{\ell\ell} < \Delta m_{\tilde{\chi}_2 - \tilde{\chi}_1}$
- How realistic are these cuts?
  - No ATLAS or CMS analysis with 2ℓ, $p_T < 10$ GeV
  - ISR associated topology not investigated so far



(Gori, Jung, Wang; 2013)



Go even further?

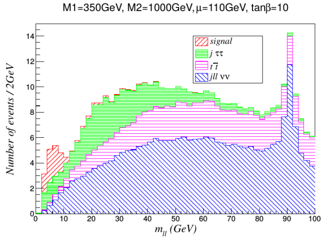
Why is this difficult,

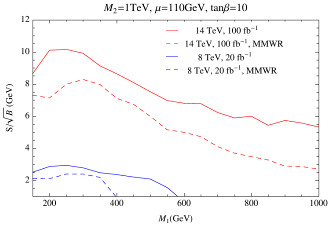
- Reconstruction of soft leptons
- Meson (J/ψ, Υ) backgrounds for $m_{\ell\ell} < 12$ GeV
- Jet fakes???
- Double parton scattering

Theory study (Higgsinos) (Han, Kribs, Martin, Menon; 2014)

- None seem to be a showstopper
- Interesting to look at soft $m_{\ell\ell}$

This is a refining of the original monojet idea





Further compression

As we go to very compressed scenarios < 2 GeV, decays are no longer prompt

Signatures include,

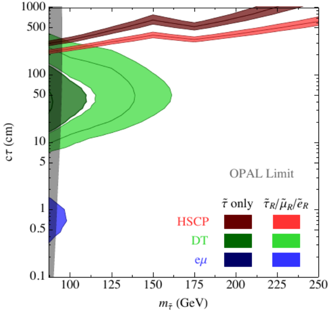
- Displaced vertices
- Disappearing tracks
- Charged tracks
- Stopped heavy particles

Neither mono-X nor exclusively SUSY but I think should be considered more in a general DM context.

Example: Stau Co-annihilation

Stau co-annihilation is well known from the CMSSM (mSUGRA).

- Lifetime of stau varies with compression
- Different lifetimes sensitive to different searches
- No displaced vertex search for solitary same flavour leptons ($e\mu$ is CMS)
- Moving away from SUSY, are we missing potential signatures?
  - Soft leptons, jets, photons
- Can displaced vertex be improved in combination with monojet?
  - Disappearing track uses a jet trigger



(Evans, Shelton; 2016)
HSCP: (CMS; JHEP01 (2015) 068)
DT: (CMS; JHEP01 (2015) 096)
$e\mu$: (CMS; PRL.114.061801)

Motivation for other mono-X

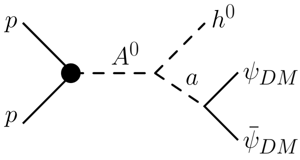
If monojets are most sensitive for ISR, are other mono signatures still motivated?

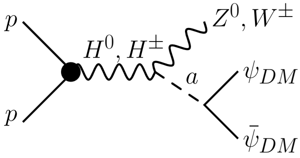
- Higgs portal models heavily investgated
    - Simplest realisation difficult for LHC when $m_{DM} > \frac{1}{2} m_{h^0}$
- Extend to a Two Higgs Doublet Model
    - Resonant production of s-channel heavy Higgs
    - Example here is pseudo-scalar Higgs portal

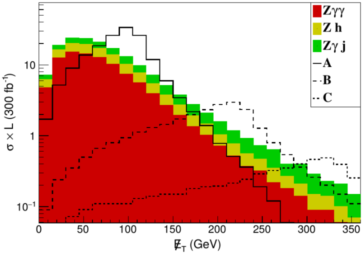
(Nomura, Thaler; 2009), (No; 2015)

Many other examples

- Best choice for experimental interpretation?







Conclusion

Mono-X and SUSY searches are clearly very complementary

- One is essentially a continuation of the other
- Both search strategies could be classed as 'General DM searches'

Nice if more SUSY signatures are investigated

More importantly $\rightarrow$ are we missing potential signals?

- ISR + soft stuff
  - Experimentally very challenging
- Long lived states?

All Mono-X states should be investigated

- Is the effective ISR interpretation always so useful?
- Perhaps other interpretations (and focus) are better for non monojet signals?