Analyzing signals of compressed spectra in SUSY

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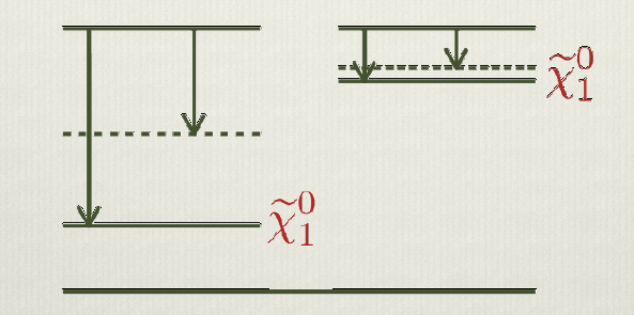
Outline

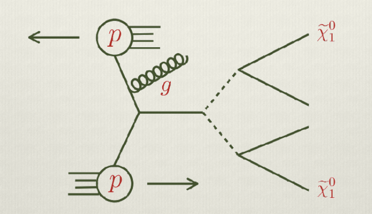
- Compressed spectra in MSSM
  - with $\widetilde{\chi}_1^0$ LSP.
  - with $\widetilde{G}$ LSP.
- Signals & Results
- Conclusions

Compressed spectra

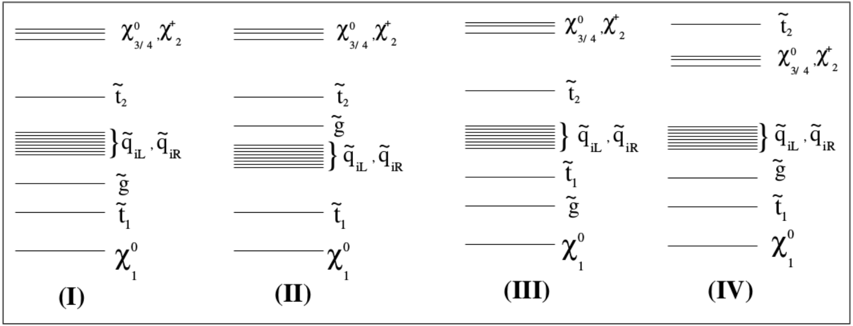
- Compressed spectra has relatively closely spaced sparticles.
- Such a spectrum produces softer jets, leptons and missing transverse energy $\rightarrow$ may not pass the signal selection criterions leading to weak bounds on such spectra.

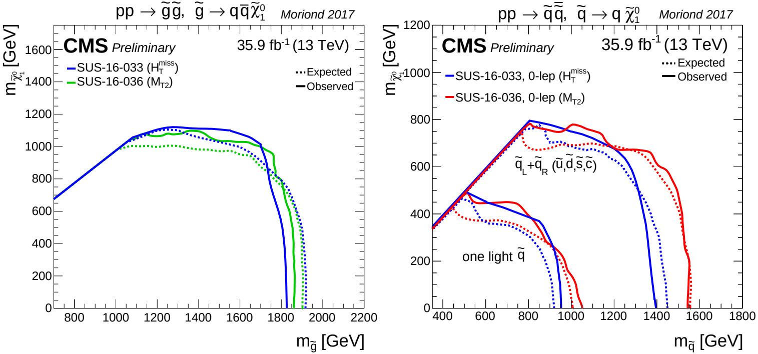


- Most studies in this direction focus on simplified models with a squark or gluino compressed with the LSP and rest of the spectrum decoupled.
- Monojet + $\not{E}_T$ $\rightarrow$ trademark channel for discovery.



Non-universal SUSY breaking at high scale could give rise to a compressed spectrum with masses of gluinos, squarks, sleptons close to the $\widetilde{\chi}_1^0$ LSP.




pp → g̃g̃, g̃ → qq̄χ̃⁰₁
Moriond 2017
CMS Preliminary
35.9 fb⁻¹ (13 TeV)
SUS-16-033 (H_T^miss)
SUS-16-036 (M_T2)
Expected
Observed
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
pp → q̃q̃̄, q̃ → q χ̃⁰₁
Moriond 2017
CMS Preliminary
35.9 fb⁻¹ (13 TeV)
Expected
Observed
SUS-16-033, 0-lep (H_T^miss)
SUS-16-036, 0-lep (M_T2)
q̃_L+q̃_R (ũ,d̃,s̃,c̃)
one light q̃
m_χ̃⁰₁ [GeV]
m_q̃ [GeV]

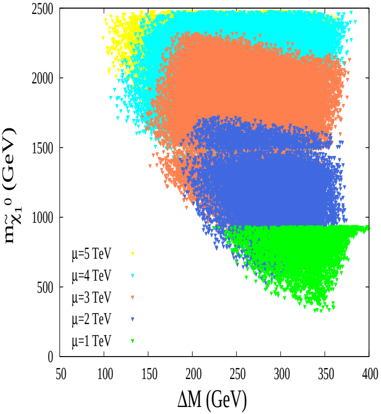
- At 1-loop order, the lightest CP-even Higgs mass is:

$$m_h^2 = m_z^2 cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2} \ln\left(\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^2}\right)$$

  where $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, $X_t = A_t - \mu \cot\beta$

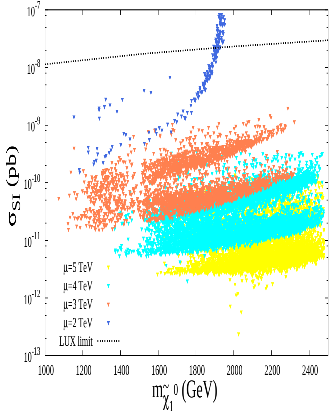
  Require atleast one heavy stop as well as large mixing X_t in the stop sector to fit $122 < m_h < 128$ GeV.

- LEP lower bound on the lightest chargino mass, i.e, $m_{\tilde{\chi}_{\pm}^1} > 103.5$ GeV.
- Constraints from branching ratios of rare decays such as $BR(b \to s\gamma)$ and $BR(B_s \to \mu\mu)$.
- For parameter scans, we have considered only the upper bound on dark matter relic density, i.e, $\Omega h^2 < 0.138$.
- Constraints from direct detection cross-sections (σ_{SI}) from LUX data.



$$\Delta M = m_S - m_{\widetilde{\chi}_1^0},$$
$$S \in [\widetilde{g}, \widetilde{t}_2, \widetilde{b}_2, \widetilde{\tau}_2, \widetilde{\chi}_2^0, \widetilde{\chi}_1^\pm]$$

Heavy spectra and large μ parameter facilitates compression (ΔM) in the spectra.

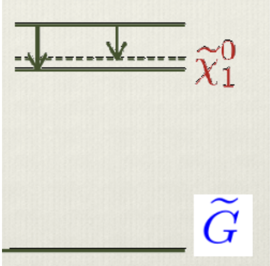


$\tilde{\chi}_1^0$ LSP and cold dark matter candidate, satisfies observed thermal relic density.

Low μ values, ($\sim$ 2 TeV) strongly constrained from direct detection cross-section data from LUX due to large bino-higgsino mixing.

Case II: Compression in MSSM + $\widetilde{G}$ LSP

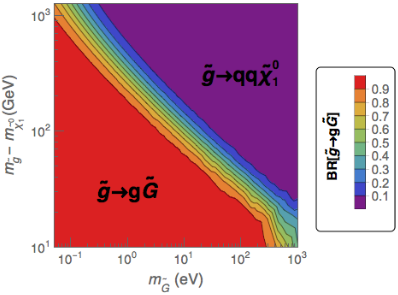
- We focus on a compressed MSSM spectra with a bino-like $\widetilde{\chi}_1^0$ NLSP extended with a keV gravitino LSP.



- Presence of light $\widetilde{G}$ relaxes DM constraints on $\widetilde{\chi}_1^0$.

Branching ratios of $\widetilde{g}$

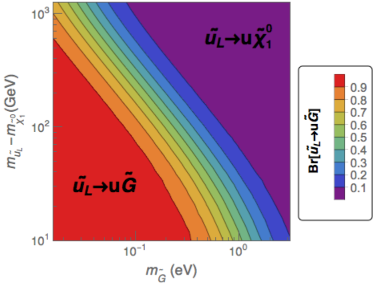
- $\Gamma(\widetilde{g} \to g\widetilde{G}) \propto m_{\widetilde{g}}^5 m_{\widetilde{G}}^{-2}$
- Competing decay modes: $\widetilde{g} \to g\widetilde{G}$, $\widetilde{g} \to q\bar{q}\widetilde{\chi}_1^0$



- Small compression ($\Delta M \sim 50$ GeV) and $m_{\widetilde{G}} \sim 1$ keV : BR($\widetilde{g} \to q\bar{q}\widetilde{\chi}_1^0$) $>$ BR($\widetilde{g} \to g\widetilde{G}$).
- Large compression ($\Delta M \sim 10$ GeV) and $m_{\widetilde{G}} \sim 1$ keV: BR($\widetilde{g} \to q\bar{q}\widetilde{\chi}_1^0$) $<$ BR($\widetilde{g} \to g\widetilde{G}$).
- For sub-keV $\widetilde{G}$: BR($\widetilde{g} \to g\widetilde{G}$) dominant.

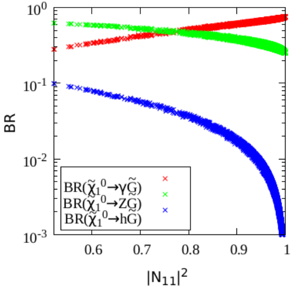
Branching Ratios of $\widetilde{q}_L$, $\widetilde{q_R}$

- $\Gamma(\widetilde{q} \to q\widetilde{G}) \propto m_{\widetilde{q}}^5 m_{\widetilde{G}}^{-2}$
- Competing decay modes: $\widetilde{q} \to q\widetilde{G}$, $\widetilde{q} \to q\widetilde{\chi}_1^0$



- Small compression and $m_{\widetilde{G}} > 1$ eV : BR$(\widetilde{q} \to q\widetilde{\chi}_1^0) >$ BR $(\widetilde{q} \to q\widetilde{G})$.
- Large compression and $m_{\widetilde{G}} > 1$ eV: BR$(\widetilde{q} \to q\widetilde{\chi}_1^0) <$ BR$(\widetilde{q} \to q\widetilde{G})$.
- For sub-eV $\widetilde{G}$: BR$(\widetilde{q} \to q\widetilde{G})$ dominant.

- The bino-like $\widetilde{\chi}_1^0$ NLSP decays dominantly to γ and $\widetilde{G}$ and a small fraction to $Z + \widetilde{G}$. This leads to extremely hard photons and large $\not{E}_T$.



- These hard photon associated signals can be very effective to probe a heavy compressed SUSY spectra with a light gravitino as there would be rarely any Standard Model events with such hard photons.

Signals & Results (for MSSM spectra with $\widetilde{\chi}_1^0$ LSP)

We consider the following signals at $\sqrt{s} = 13$ TeV for our study :

- Monojet + $\not{E}_T$
- Multijets ($\geq$ 2 j) + $\not{E}_T$

Simulation Details

SUSY signal: $\tilde{q}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{q}^*$, $\tilde{g}\tilde{g}$ $+ \leq 2$ partons.

- Spectrum Generator: SPheno
- Madgraph5 $\rightarrow$ Pythia6 $\rightarrow$ Delphes-v3 for event generation, showering and detector simulation.
- MLM matching with showerKT performed duly with QCUT $=$ 120 GeV (SUSY), 30$-$50 GeV (SM).

Background:

- MSSM: Z $+ \leq$ 4j, W $+ \leq$ 4j, QCD ($\leq$ 4j), $t\bar{t}+\leq 2j$, $t+\leq 3j$, $ZZ+\leq 2j$, $WZ+\leq 2j$.
- MSSM$+\tilde{G}$: from existing ATLAS study, i.e. ATLAS-CONF-2016-066.

Signal cross-sections computed at NLO (NLO+NLL) for MSSM (MSSM$+\tilde{G}$) using Prospino (NLL-Fast). Background cross-section upto NLO (using Madgraph5) for MSSM.

Benchmarks

Parameters	BP1	BP2
A_t	-1535.1	2300.0
μ	3000.0	3000.0
$\tan\beta$	23.9	20.0
$m_{\tilde{g}}$	1497.4	1534.7
$m_{\tilde{q}_L}$	1452.3	1524.5
$m_{\tilde{q}_R}$	1451.3	1520.8
$m_{\tilde{t}_1}$	1330.6	1507.6
$m_{\tilde{t}_2}$	1509.0	1686.6
$m_{\tilde{b}_1}$	1407.4	1521.9
$m_{\tilde{b}_2}$	1494.5	1619.5
$m_{\tilde{\chi}_1^0}$	1323.9	1496.3
$m_{\tilde{\chi}_2^0}$	1342.9	1559.0
$m_{\tilde{\chi}_1^\pm}$	1342.9	1559.1
m_h	122.5	122.4
Ωh^2	0.113	0.105
$\sigma_{SI} \times 10^{11}$ (pb)	4.65	0.13
ΔM_i (GeV)	173.5	38.4

$\Delta M_i = m_S - m_{\tilde{\chi}_1^0}$, where $S \in [\tilde{q}, \tilde{g}]$

Employing optimal cuts on various kinematical observables (i.e, $\not{E}_T$, M_{Eff},..) for multijet and monojet searches at LHC:

Signal		Cross-section after cuts (fb)				
Benchmark Points	Production cross-section(fb)	Preselection	M_{Eff} > 800 GeV	$\not{E}_T$ > 160 GeV	$\not{E}_T/\sqrt{H_T}$ > 15GeV$^{1/2}$	$\not{E}_T/M_{Eff}$ > 0.35
BP1	126.93	59.72	20.74	19.84	9.99	9.93
BP2	95.58	12.45	6.34	6.24	4.72	4.68
SM Background	2.0E+08	253042	2833	8.85	1.36	1.35

Multijets + $\not{E}_T$ cross-section for signal and background (at NLO).

(Preselection: $p_T(j_1) > 130$ GeV, $p_T(j_2) > 80$ GeV, $\Delta\phi(j_{1/2}, \not{E}_T) > 0.4$)

Signal		Cross-section after cuts (fb)		
Benchmark Points	Production cross-section(fb)	Preselection	$\not{E}_T$ >160 GeV	M_{Eff} >800 GeV
BP1	126.93	12.06	8.22	0.88
BP2	95.58	7.48	6.20	1.63
SM background	2×10^8	46254	2602	0.938

Monojet + $\not{E}_T$ cross-section for signal and background (at NLO).

(Preselection: $p_T(j_1) > 130$ GeV, $\Delta\phi(j_1, \not{E}_T) > 1, p_T(j_2) < 80$ GeV, $\Delta\phi(j_2, \not{E}_T) > 1$)

	Luminosity (in fb^{-1}) for 3σ excess	
Signal	BP1	BP2
Multijets (≥ 2 j) + $\not{E}_T$	123	558
Monojet + $\not{E}_T$	10926	3204

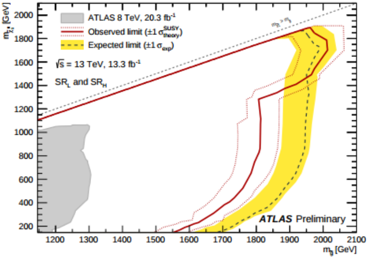
- Multijet + met searches still more efficient to look for compressed scenarios than traditional monojet + met channels.
- However both are viable modes of discovery for compressed spectra at the Run 2 of LHC.

Signals and Results
(for MSSM extended with a $\widetilde{G}$ LSP)

We consider the following signal:

- $\geq 1\gamma + > 2j + \not{E}_T$

Experimental collaborations (ATLAS−CONF−2016−66) consider signal events coming from gluino pair production only, assuming rest of the sparticles decoupled, ruling out $m_{\tilde{g}} \leq 1.95$ TeV for $m_{\widetilde{\chi}_1^0} \sim 1.8$ TeV.



- However for a compressed spectra, presence of closely spaced sparticles lead to added contributions to the same final state.
- Thus, the limits on sparticles are stronger for a compressed spectra.

Using the ATLAS analysis for $\geq 1\gamma + > 2$ jets $+ \not{E}_T$ and SM background estimates at 13.3 fb^{-1}, mass bounds significantly increase for a compressed spectra, i.e, $m_{\tilde{g}/\tilde{q}} \geq 2.5$ TeV.

Hard photons are a characteristic feature of both compressed and uncompressed spectra.

Benchmarks

	Compressed spectra		Uncompressed spectra
Parameters	**C4**	**C5**	**U2**
A_t	-3750	-3197	2895
μ	4000	3500	3000
$\tan\beta$	6	25	15
M_A	1800	2500	2500
$m_{\tilde{g}}$	2783	2562	2102
$m_{\tilde{q}_L}$	2753	2571	4721
$m_{\tilde{q}_R}$	2751	2574	4742
$m_{\tilde{t}_1}$	2625	2532	4678
$m_{\tilde{t}_2}$	2863	2718	4765
$m_{\tilde{b}_1}$	2778	2594	4558
$m_{\tilde{b}_2}$	2846	2677	4744
$m_{\tilde{\chi}_1^0}$	2585	2526	1191
$m_{\tilde{\chi}_2^0}$	2724	2619	2383
$m_{\tilde{\chi}_1^\pm}$	2724	2619	2382
m_h	124	125	125
ΔM_i	198	48	911

Using the existing ATLAS analysis cuts (using hard cuts on photon p_T and $\not{E}_T$) and SM background estimates at 13.3 fb^{-1} for the same final state:

Signal		Cross-section (in fb) after cuts					
Benchmark Points	Production cross-section(fb)	$p_T(\gamma_1) > 400$	$N_j > 2$ $N_l = 0$	$\Delta\phi(j_{1/2}, \not{E}_T) > 0.4$	$\Delta\phi(\gamma_1, \not{E}_T) > 0.4$	$\not{E}_T > 400$	$M_{Eff} > 2000$
C4	0.21	0.15	0.12	0.08	0.08	0.08	0.07
C5	0.49	0.34	0.15	0.13	0.13	0.12	0.11
U2	0.20	0.13	0.12	0.10	0.09	0.08	0.08

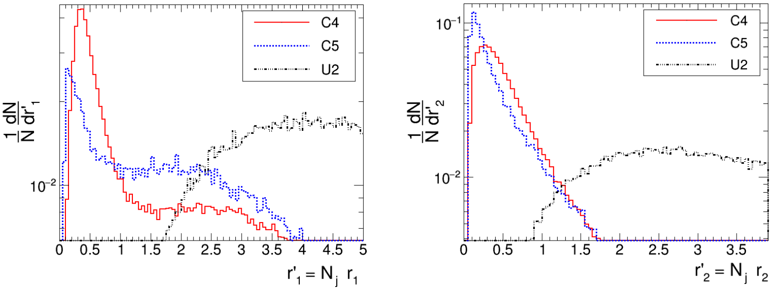
we compute the required luminosity for some benchmarks:

Signal	Luminosity $\mathcal{L}$ (in fb^{-1}) for	
	$\mathcal{S} = 3\sigma$	$\mathcal{S} = 5\sigma$
C4	176	489
C5	79	219
U2	139	385

Using $p_T(\gamma)$, $p_T(j)$ and N_j, a set of new kinematic variables identified which act as a discriminant for a compressed and uncompressed spectra with similar event rates:

$$r'_1 = N_j r_1, \;\; r'_2 = N_j r_2, \;\; \text{where } r_1 = \frac{p_T(j_1)}{p_T(\gamma_1)}, r_2 = \frac{p_T(j_2)}{p_T(\gamma_1)}$$

For **C4**, **C5**: $r'_1 \sim 0.2 - 0.5$, $r'_2 \sim 0.1 - 0.3$ while for **U2**: $r'_1 \sim 4$, $r'_2 \sim 2.5$.



Conclusions

- Compressed spectra in MSSM with $\widetilde{\chi}_1^0$ LSP gives rise to multiple jets and $\not{E}_T$ which fare better over traditional monojet and $\not{E}_T$ signal.
- We further extend the MSSM spectra with a light $\widetilde{G}$. Presence of a light $\widetilde{G}$ relaxes DM constraints on the MSSM part of the spectrum.
- With existing data, exclusion limits on colored sparticles improve significantly for a compressed spectra in photonic channels.
- Hard photons are a characteristic feature of both compressed and uncompressed spectra. Simlar event rates may be obtained for compressed and uncompressed spectra.
- Difference in compression reflected in kinematic variables involving hardness of photons, jet and jet multiplicity to distinguish such spectra.
- For sub-keV gravitinos, $\widetilde{G}$ associated decay mode of the sparticles become relevant and alternate channels of interest are multi-jets and missing energy signals requiring $\sim 1000\, fb^{-1}$ for observing a 3σ excess at LHC.

Thank You

Backup

Parameters	Ranges
M_1, M_2, M_3	(100, 2500) GeV
A_t	(-3000, 3000) GeV
tanβ	(2, 50)
$M_L = M_R$	$(M_1, M_1 + 200)$ GeV(if $M_1 < M_2$)
	$(M_2, M_2 + 200)$ GeV(if $M_2 < M_1$)

Table : Ranges of the relevant parameters for the scan. M_1, M_2, M_3 are the gaugino mass parameters, varied in the same range but independent of each other. M_L and M_R are the left-handed and the right-handed soft mass parameters of squarks and sleptons.

Differential distributions of kinematic variables