Modified Signals for Supersymmetry in the NMSSM with a Singlino-like LSP

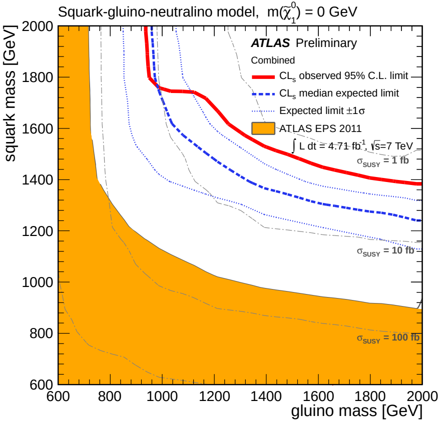
Debottam Das

Laboratoire de Physique Theorique d'Orsay

April 23, 2012

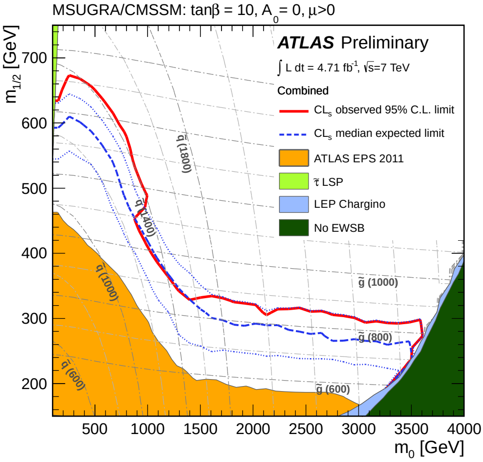
Refs: **arXiv:1202.5244 (Debottam Das, Ulrich Ellwanger, Ana M. Teixeira)** & To appear in JHEP

Status of MSSM under the lamppost of LHC:



Exclusion limits in a simplified MSSM scenario with only strong production of gluinos and first and second generation squarks, and direct decays to jets and neutralinos

Status of cMSSM under the lamppost of LHC:



Exclusion limits in a cMSSM scenario with $\tan\beta = 10$, $A_0 = 0$, and $\mu > 0$

MSSM : Superpotential

- The Lagrangian of MSSM consists of kinetic and gauge terms, also terms derived from the superpotential W, and a softly broken supersymmetry part $\mathcal{L}_{soft}$
- Superpotential:

$$W_{\mathrm{MSSM}} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d$$

  H_u, H_d, Q, L, $\overline{u}$, $\overline{d}$, $\overline{e}$ chiral superfields

  $\Rightarrow$ Provides all Yukawa interactions in SM

- The dimensionless Yukawa couplings $\mathbf{y_u}, \mathbf{y_d}, \mathbf{y_e}$ are 3×3 matrices in family space
- *No superparticle has yet been observed* $\Rightarrow$ SUSY must be broken $\Rightarrow$ we require $\mathcal{L}_{soft}$
- Soft SUSY breaking avoids quadratic divergence $\Rightarrow$ masses and coupling parameters for scalars and gauginos $\simeq$ 1 TeV $\Rightarrow$ so as to avoid the SUSY finetuning problem

μ problem in MSSM: NMSSM

- The SUSY preserving μ-term should be $<< M_P(\text{Plank scale}), \mathrm{M_G}(\text{Gut scale})$
  Similarly, $\mu > 100$ GeV (From LEP limit on chargino mass)
  $\mu \sim M_{SUSY} \sim TeV$ is required $\Rightarrow$ this is known as μ problem
- An elegant way to solve this problem is by introducing an additional singlet superfield S with a coupling $\lambda S H_u H_d$ in the superpotential $W_{NMSSM} = \lambda S H_u H_d + \frac{k}{3} S^3 + ...$ ($\mathcal{Z}_3$ invariant superpotential)

  The VEV $< s >$ of the real scalar component of $S \Rightarrow \mu_{eff} = \lambda s \Rightarrow \mu_{eff} \sim M_{SUSY}$

  Known as Next-to-Minimal Supersymmetric Standard Model (NMSSM)

  Simplest SUSY model with M_{SUSY} as the only scale in the Lagrangian

NMSSM : Spectrum

- The SM singlet scalar $S \Rightarrow$ can leave the footprints only in the Higgs sector and in the neutralino sector $\Rightarrow$
  - 3 CP-even neutral Higgs bosons H_i (H_1, H_2, H_3)
    H_1 is the lightest CP-even Higgs boson
  - 2 CP-odd neutral Higgs bosons A_1 and A_2 $(A_2 \simeq A_{MSSM})$
  - Charged Higgs boson $H^{\pm}$
  - Five neutralinos χ_i^0, $i = 1 \ldots 5$, which are mixtures of the Bino, the neutral Wino, the neutral Higgsinos and the Singlino

Lightest CP-odd Higgs boson A_1 in the basis (A_{MSSM}, S_I):

$$A_1 = \cos\theta_A A_{MSSM} + \sin\theta_A S_I$$

lightest pseudoscalar can be very light $\mathcal{O}(10)$ GeV

Strategy: Introduction

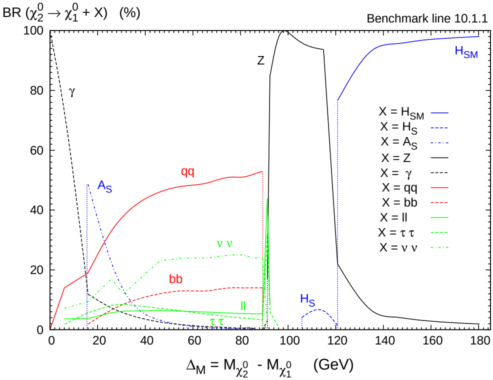
- We perform a first study of possible modifications of the signals for supersymmetric particles in the framework of a generalisation of the CMSSM towards the NMSSM
  where the singlino-like neutralino is the LSP χ_1^0
- Bino (MSSM LSP) is considered as the NLSP
- The sparticle decay cascades will evolve as in the MSSM, with an additional final decay

$$\chi_2^0 \rightarrow \chi_1^0 + X$$

- Then $\Delta_M = M_{\chi_2^0} - M_{\chi_1^0} \Rightarrow$ this additional decay of the NLSP will generally
  (i)reduce E_T^{miss}, but
  (ii)lead to more jets and/or leptons

  Affect the efficiencies in the various search channels for supersymmetry.

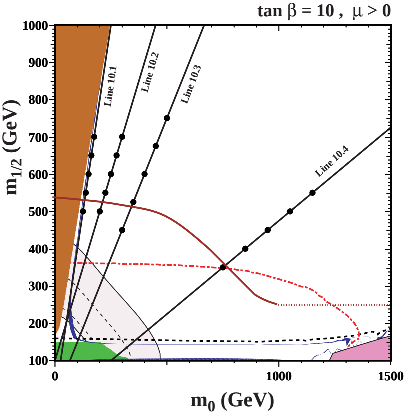
Examples for Branching fractions : BP-10.1.1



Branching fractions into the various states X in the decay $\chi_2^0 \to \chi_1^0 + X$ as function of Δ_M for the benchmark line 10.1.1

Strategy ....

- Here we confine ourselves to three benchmark points for the CMSSM, presently not excluded, but of possible future relevance for the LHC at 7 TeV c.m. energy
  Ref: S. S. AbdusSalam et al., Eur. Phys. J. C 71 (2011) 1835 [arXiv:1109.3859 [hep-ph]]



Strategy ...ATLAS Jet/Multijet channels.

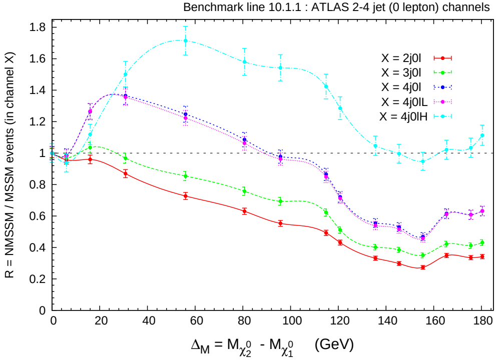
- Keeping MSSM sectors unaltered, we allow non-universal values for m_S^2, A_λ and A_κ (so-called sNMSSM) to have
  $\Rightarrow$ Singlino-like LSP χ_1^0 with largest possible range (Δ_m) compatible with constraints from LEP
  $\Rightarrow$
  Thus each BP of the CMSSM is promoted to a BL of the sNMSSM
- Then we study the ratios R of efficiencies sNMSSM/CMSSM as function of Δ_M for
  1. ATLAS jets + missing transverse momentum (0 leptons) analysis (5 search channels)
  2. ATLAS multijet + missing transverse momentum (0 leptons) analysis (4 search channels)

This avoids any novel analysis of backgrounds and systematic errors

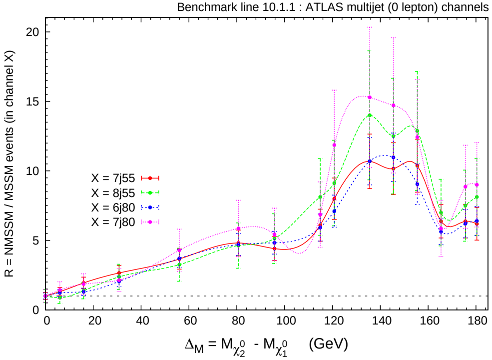
Benchmark Points in cMSSM & sNMSSM

Point:	10.1.1	10.4.1	40.2.1
$M_{1/2}$	500	350	450
m_0	125	750	550
A_0	0	0	-500
$\tan\beta$	10	10	40
$\mu_{\rm eff}$	635	465	645
M_A	720	895	710
$m_{\tilde{g}}$	1145	870	1065
$\langle m_{sq} \rangle$	1030	1040	1080
$M_{\chi_2^0}$	205	143	187
λ	10^{-3}	0.013	10^{-3}
κ	$-1.6 \cdot 10^{-4} \ldots -2 \cdot 10^{-5}$	$-2 \cdot 10^{-3} \ldots -8.7 \cdot 10^{-4}$	$1.8 \cdot 10^{-5} \ldots 1.4 \cdot 10^{-4}$
A_κ	$0.7 \ldots 1.6$	$0 \ldots 150$	$-7 \ldots -4.2$
$M_{\chi_1^0}$	$25 \ldots 205$	$50 \ldots 143$	$23 \ldots 187$
$M_{H_{SM}}$	~ 115	$115 \ldots 117$	~ 117
M_{H_S}	$25 \ldots 205$	$55 \ldots 89$	$21 \ldots 186$
M_{A_S}	$8 \ldots 20$	$5 \ldots 160$	$6 \ldots 34$
$\sigma_{\rm Tot}$	82 fb	300 fb	87 fb

Results for 10.1.1: ATLAS jets analysis



The ratios R of efficiencies in the sNMSSM w.r.t. the CMSSM point 10.1.1 in 5 different signal regions of the ATLAS jets + missing transverse momentum analysis as function of Δ_M



The ratios R of efficiencies in the sNMSSM w.r.t. the CMSSM point 10.1.1 in 4 different signal regions of the ATLAS multijet + missing transverse momentum analysis as function of Δ_M

Results for 10.1.1: Discussion

- R is always larger than 1 for the $4jH$ signal region
- $R < 1$ everywhere for the $3j$ and $2j$ signal regions, and particularly, R can drop to ~ 0.3 for $\Delta_M \sim 160$ GeV
- The dominant decay mode is $\chi_2^0 \to \chi_1^0 + H_{SM}$ with $H_{SM} \to b\bar{b}$
- These additional b jets coming from H_{SM} would mainly contribute to ATLAS multijet + missing transverse momentum (0 leptons) analysis
- For each search channel, we compare the corresponding bound in the $m_0 - M_{1/2}$ plane
- The constraints are dominated by the $2j/3j$ signal regions where R can drop to ~ 0.3

Discussion..contd

- Next question is :
  how far this decrease in efficiencies can affect the $m_0 - M_{1/2}$ plane in sNMSSM
- The cross-section roughly goes like $M_{1/2}^{-10}$
- Hence, the lower bound on $M_{1/2}$ in the sNMSSM with $\Delta_M \sim 160$ GeV is lower than in the CMSSM by a factor $(1/3)^{1/10} \sim 0.9$
- This leads to $\boxed{M_{1/2} \gtrsim 420}$ GeV instead of $M_{1/2} \gtrsim 470$ GeV

Benchmark Points in cNMSSM and cMSSM

Point:	cNMSSM.1	cNMSSM.2
$M_{1/2}$	520	600
m_0	0	0
A_0	-146.5	-171
$\tan\beta$	22.2	23.3
λ	10^{-3}	10^{-3}
κ	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
$m_{\tilde{g}}$	1190	1360
$\langle m_{sq} \rangle$	1060	1200
$M_{\chi_1^0}$	146.4	171
$M_{\tilde{\tau}_1}$	150.5	174.5
M_{H_1}	103	114.7
M_{H_2}	114.3	121
M_{A_1}	179	209
	CMSSM.1	CMSSM.2
m_0	170	194
$M_{\chi_1^0}$	214.8	249.8
$M_{\tilde{\tau}_1}$	221.6	254.1
σ_{Tot}	73 fb	28 fb

Channel:	$2j$	$3j$	$4j$	$4jL$	$4jH$
R (cNMSSM.1/CMSSM.1)	0.63	0.73	0.86	0.86	0.96
R (cNMSSM.2/CMSSM.2)	0.65	0.75	0.95	0.96	1.1

Table: Ratios R of efficiencies for two points of the cNMSSM w.r.t. the CMSSM in 5 different signal regions of the ATLAS jets + missing transverse momentum analysis.

- $R \sim 0.6 - 1.1$, the differences between the cNMSSM and the CMSSM are not spectacular

Strategy...Multilepton channels.

- We also study CMS multilepton analysis for the sNMSSM and cNMSSM

1. we give estimates for absolute signal cross sections (production cross sections $\times$ efficiencies) for those values of Δ_M which correspond to the largest efficiencies

2. we sum over all leptons including (hadronically decaying) τ leptons, and distinguish only the search channels MET3, MET4, HT3 and HT4

   $\Rightarrow$ MET refers E_T^{miss}

   $\Rightarrow$ H_T is the scalar sum of the transverse jet energies for all jets with $E_T > 40$ GeV

   $\Rightarrow$ the numbers behind MET or HT denote the numbers of leptons including τ's

Strategy...2τ channels

- We also study 2τ search channels as analysed by CMS
- This is particularly interesting for CNMSSM where $\tilde{\tau}_1$ is the NLSP
- τs from the sparticle $\rightarrow \tilde{\tau}_1$ decay constitute a visible particular feature of the cNMSSM
  1. The 2τ search by the CMS collaboration can be categorized into three signal regions
  2. The first two require a lepton and a hadronically decaying τ lepton $e/\mu\,\tau_h$ while the other requires $\tau_h\tau_h$ where both decays hadronically

Multilepton analysis

- Benchmark Point : 10.1.1 The largest efficiencies can be found in the region $\Delta_M \sim 180$ GeV corresponding to $M_{\chi_1^0} \sim 25$ GeV

Channel:	MET3	MET4	HT3	HT4
σ [fb]	1.61 ± 0.09	0.29 ± 0.04	1.63 ± 0.09	0.31 ± 0.04

- Benchmark Point : cNMSSM

Channel:	MET3	MET4	HT3	HT4
σ [fb] (cNMSSM.1)	4.4 ± 0.2	0.7 ± 0.1	2.7 ± 0.1	0.41 ± 0.05
σ [fb] (cNMSSM.2)	1.63 ± 0.06	0.36 ± 0.03	0.94 ± 0.04	0.18 ± 0.02

For the corresponding cMSSM points cMSSM.1 and cMSSM.2, these signal cross sections are smaller by about a factor 1/20

- No significant excesses are expected within the cNMSSM at present, but these search channels can become sensitive to the cNMSSM in the future

CMS 2τ analysis

Channel:	$e/\mu\,\tau_h$ high E_T^{miss}	$e/\mu\,\tau_h$ high H_T	$\tau_h\,\tau_h$
σ [fb] (cNMSSM.1)	2.2 ± 0.1	2.4 ± 0.1	0.65 ± 0.05
σ [fb] (cNMSSM.2)	0.77 ± 0.03	0.81 ± 0.03	0.19 ± 0.01

- It was estimated that only the LHC at 14 TeV c.m. energy would become sensitive to the cNMSSM
  Ref: Ulrich Ellwanger, Alice Florent, Dirk Zerwas-JHEP 1101:103,2011 [arXiv:1011.0931 [hep-ph]]
- However, combining multilepton and $2\,\tau$ search channels and increasing the integrated luminosity to ~ 20 fb^{-1}, the LHC with 7 TeV c.m. energy could become sensitive to the low $M_{1/2}$ regime of the cNMSSM in the future

Conclusion

- As discussed, the additional cascade bino-singlino will reduce the missing energy, but provide additional jets or leptons
- We find that the efficiencies can drop by a factor $\sim 1/3$ to $\sim 1/7$ with respect to the MSSM in the most relevant 2/3 jet + missing energy search channels
- It reduces the present lower bounds on $M_{1/2}$ by a factor $\sim 0.9 - 0.83$ compared to cMSSM when bino-singlino mass difference is large
- Finally, the signal cross sections in the multilepton and 2τ search channels could give hints for the cNMSSM at the LHC with 7 TeV c.m. energy for more integrated luminosities