Mutlilepton signals of Gauge Mediated SUSY @ *LHC*

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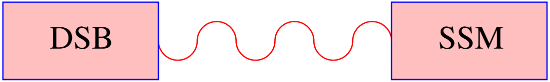
Credits:

- P. Grajek, A. Mariotti and D.R. arXiv:1303.0870 [hep-ph]
- K. De Causmaecker, J. D'Hondt, B. Fuks, A. Mariotti, K. Mawatari, C. Petersson and D. R. arXiv:1310.0018 [hep-ph]
- L. Calibbi, A. Mariotti, C. Petersson and D. R. *work in progress*

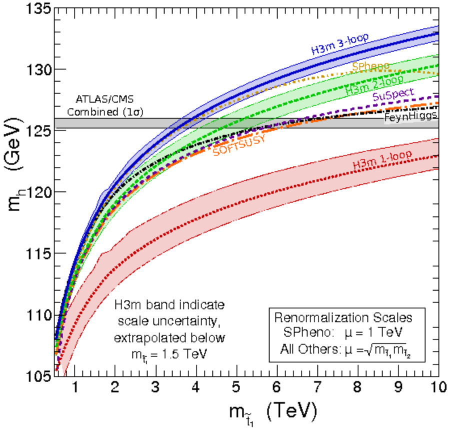
SUSY BREAKING AND GAUGE MEDIATION



- **Hidden sector:** with spontaneous (dynamical) susy breaking
- **Visible sector:** MSSM
- MSSM gauge interactions connect the two sectors:
- $G_{SM} = U(1) \times SU(2) \times SU(3)$ with gauge couplings (g_1, g_2, g_3)
- Interactions lead to susy breaking **soft terms** in the MSSM

- Predictive framework for the susy breaking terms
- Gauge interactions are flavour blind: No flavour problem

$m_h = 125$ GeV: An un-natural solution



J. L. Feng, P. Kant, S. Profumo, D. Sanford 1306.2318

Higgs mass ⇒ Heavy Stops!

MOTIVATIONS

MAP OUT ALL the regions accessible at LHC!

- The parameter space is highly constrained

  $\Rightarrow$ A complete mapping might be feasible
- Are there poorly explored regions?
- Are there extra constraints coming from model building?
- Understanding to what extent minimal SUSY can be falsifiable at LHC can be also useful for non-minimal models.

General Gauge Mediation

- Gauge mediation definition:

When $(g_1, g_2, g_3) \to 0$ No susy breaking in MSSM

- $\Rightarrow$ Soft masses in GGM

$$m_{\lambda_i} = \frac{g_i^2}{(4\pi)^2} \Lambda_{G_i} \qquad i = 1, \ldots 3$$

$$m_{sf}^2 = 2 \sum_{i=1}^{3} C_i k_i \frac{g_i^4}{(4\pi)^4} \Lambda_{S_i}^2 \; ; \qquad C_i = \text{Casimir} \qquad k_i = (3/5, 1, 1)$$

- $(\Lambda_{G_i}, \Lambda_{S_i})$ for each gauge group factor $U(1), SU(2), SU(3)$
- M_{mess} sets length of the RG-flow
- $3 + 3 + 1$ independent parameters: $(\Lambda_{G_i}, \Lambda_{S_i}, M_{mess})$
- 1 extra parameter to determine the EWSB: μ

Covers all possible models of gauge mediation

Universal properties of Gauge Mediation

- Predictive framework for soft terms
- Gravitino LSP:
  the NLSP has a two body decay to gravitino + SM partner

$$\Gamma(\tilde{Y} \to Y + \tilde{G}) = \frac{m_{\tilde{Y}}^5}{48\pi M_{planck}^2 m_{3/2}^2} \left(1 - \frac{m_Y}{m_{\tilde{Y}}}\right)^4$$

- A-terms are suppressed at the UV scale
- Phenomenology (final state in the collider) dictated by NLSP-type

General Gauge Mediation

- Model-independent parametrization of the complete parameter space of gauge mediated models
- Generic type of NLSP can be obtained
- Powerful generator of Supersymmetric Spectra
  $\Rightarrow$ Simplifed Models + Collider Signatures

An Intriguing example

GGM AFTER LHC8

- Heavy Stops $\Rightarrow$ all the squarks decoupled
- Gluino production strongly constrained: $m_{\tilde{g}} \geq 1$TeV Evans, Kats, Shih, Strassler '13
- One important question: How light the stops can be in GGM after LHC8?

  Knapen, D.R., Shih *work in progress*
- Any uncolored sparticle can be the NLSP in some region of the parameter space Grajek, Mariotti, D.R. '13

Focusing on EW production:

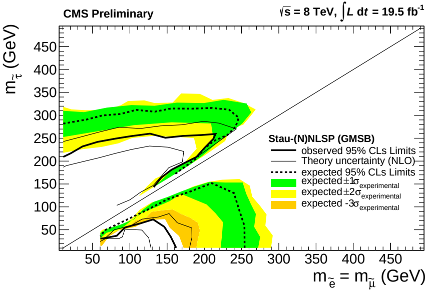
? Poorly explored SUSY spectra with interesting LHC phenomenology ?

$\Rightarrow$ Selectron/Smuon co-NLSP & simplified Models for Slepton pair prod.

CMS SUS 13 002;

D'Hont et al. '13; Calibbi, Mariotti, Petersson, D.R. to appear

Sleptons and Stau (N)NLSP in Gauge Mediation



CMS SUS 13 002

- Simplified model with only right sleptons and stau accessible at LHC
- Goldstino LSP
- Different phenomenology depending on mass hierarchy among sleptons

Three different regions:

Stau NLSP	Mass degenerate	Selectron/smuon co-NLSP
$m_{\tilde{\tau}_R} \ll m_{\tilde{\ell}_R}$	$m_{\tilde{\tau}_R} \sim m_{\tilde{\ell}_R}$	$m_{\tilde{\tau}_R} \gg m_{\tilde{\ell}_R}$

QUESTIONS:

THEORY: EMBEDDING ALL THE REGIONS OF THE SIMPLIFIED MODEL IN GGM

- Colored sector can be made independently heavy
- Stau NLSP from two distinct effects:
  1. $y_\tau \gg y_{\mu,e}$ stau mass is lowered by Yukawa RG effects.
  2. Non negligible off-diagonal term in the stau mass matrix

What about about selectron/smuon co-NLSP?

PHENO: WHAT ARE THE TYPICAL SIGNATURES AT LHC?

- We expect multileptons in final states
- Pure EW production $\Rightarrow$ Low Cross Section but clean signal
- EW production studied for LEP and Tevatron e.g.: Ruderman, Shih '10

Re-interpreting the CMS analysis

UV conditions for $m^2_{\tilde{\ell}_R} < m^2_{\tilde{\tau}_1}$

- Trace back the IR requirement on mass splitting to a UV condition
- RG equation for mass splitting

$$16\pi^2 \frac{d}{dt}(m^2_{\tilde{\tau}_R} - m^2_{\tilde{\ell}_R}) = 2X_\tau = 4|y_\tau^2|(m^2_{H_d} + m^2_{\tilde{\tau}_L} + m^2_{\tilde{\tau}_R})$$

- $\Rightarrow$ Moderate to large $\tan\beta$ to enhance y_τ

Negative X_τ :

1. GGM: $m^2_{H_d} = m^2_{E_L} \qquad \Longrightarrow \qquad (2m^2_{E_L} + m^2_{\tilde{\tau}_R}) < 0$
2. GGM+ Deflections: $m^2_{H_d} = m^2_{E_L} + \Delta^2_d \qquad \Longrightarrow \qquad \Delta^2_d < 0$

- Intuitively the presence of tachyonic scalars along the RG-flow reverse the Yukawa effects.

  $\Rightarrow m^2_{\tilde{\ell}_R} < m^2_{\tilde{\tau}_1}$ as a consequence of $y_\ell < y_\tau$.

LOW ENERGY CONSTRAINTS:

1. GGM: tachyonic sleptons
2. GGM+ Deflections: tachyonic CP-odd Higgs

$$m_A^2 = 2\mu^2 + m_{H_u}^2 + m_{H_d}^2 \simeq -m_{H_u}^2 + m_{H_d}^2 < \mu^2$$

Solutions

1.1 Gaugino Mediation

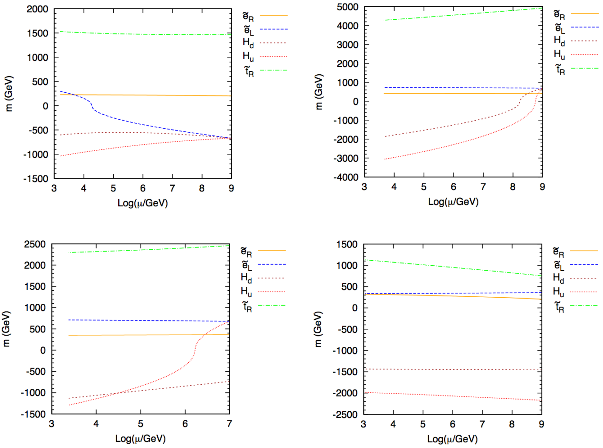
1.2 Large $\tan\beta$ regime

2.1 "at Tree-level"

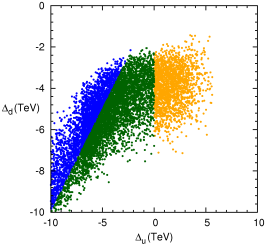
$$m_{H_u}^2 = m_{E_L}^2 + \Delta_u^2$$
$$\Longrightarrow \Delta_u^2 < 0$$

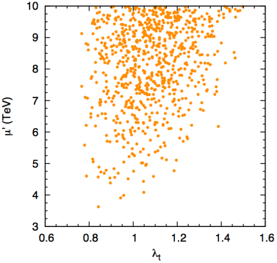
2.2 "Radiatively"

$$\frac{d}{dt}(m_{H_d}^2 - m_{H_u}^2) \simeq -3X_t$$
$$\Longrightarrow \text{Large } M_{susy} \text{ or } A_t$$



EXISTENCE PROOFS *(in progress)*





IR constraints in the scans:

- $m_{\tilde{\tau}_1} - m_{\tilde{l}_R} \geq 20$ GeV
- $m_h = 125$ GeV
- direct searches bounds on m_A CMS PAS HIGH-12-05
- Blue: tree level
  Orange: radiative
  Green: intermediate

Scan over $\Lambda_G, \Lambda_{S_{1,2}}, \Lambda_{S_3}$

- Large stops in the UV
- Long running: $M_{mess} > 10^4$ TeV

  $\Rightarrow$ Benchmarks for long-lived NLSP: $2l + 2\tau + 2$ *charged tracks* in the final states

$$W = \lambda_t Q_3 U_3 \Phi_{H_u} + \mu' \Phi_{H_u} H_d$$

$$\Rightarrow \Delta_d^2 \simeq -\mu'^2 \frac{\Lambda^2}{M_{mess}^2}$$ Evans, Ibe, Yanagida ’11

- Large A-terms in the UV
- Short running: $M_{mess} < 10^3$ TeV

  $\Rightarrow$ Benchmarks for promptly decaying NLSP: $4l + 2\tau$ in the final states
- The stops can be light and accessible

LIGHT SLEPTONS IN GAUGE MEDIATION AT LHC

- Different mass hierarchy in right-sleptons realizable in GGM (or extensions)
- From now on Sleptons $\equiv \tilde{\ell}_R = \tilde{e}_R, \tilde{\mu}_R \qquad \neq \qquad$ Stau $\equiv \tilde{\tau}_R$
- Pure EW production of sleptons/staus at LHC

NLSP BOUNDS

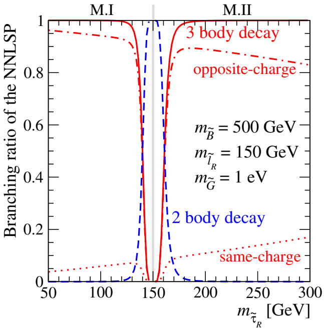
- $m_{\tilde{l}_R} \geq 230$ GeV from ATLAS and CMS 2l+MET searches
- $m_{\tilde{\tau}_R} \geq 90$ GeV from LEP

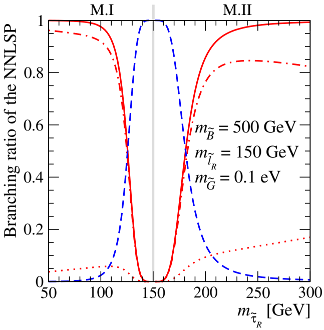
Two models of light sleptons/stau in Gauge Mediation

NNLSP DECAY MODES

Two body decay to Goldstino vs Three body decay via virtual Bino

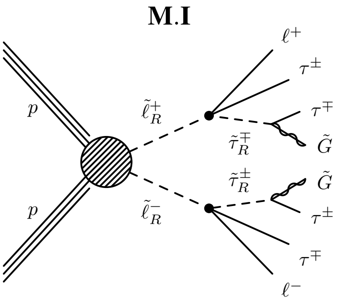
- Two representative BR plots for both **M.I** and **M.II**

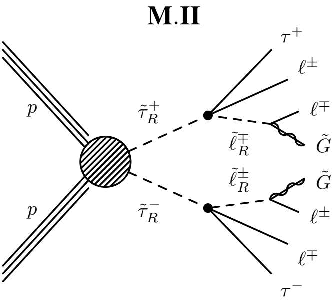




- For $m_{3/2} \geq 1$ eV three body decay dominates except in mass degenerate region where $m_{\tilde{\ell}_R} \sim m_{\tilde{\tau}_R}$
- Robust result under variations of Bino mass up to $O(\text{TeV})$

MULTILEPTON SIGNALS FROM NNLSP DECAY





- For: 1 eV $\leq m_{3/2} \leq 10$ eV
- $\Rightarrow$ NNLSP three body decay dominates
- $\Rightarrow$ Prompt NLSP decay into goldstino
- Leptons + Taus + MET in final state
- Final number of τ's and ℓ's depends on hadronic or leptonic τ decay
- $\Rightarrow$ Study multileptons in Gauge Med at 8 TeV and prospects for 13 TeV

CMS SUS-13-002

- CMS search for three or four leptons signals at $\sqrt{s} = 8$ TeV and 19.5 fb^{-1}
- Here table for

Four leptons & Small Hadronic Activity: $H_T < 200$GeV

- OSSFn indicates number of opposite sign same flavour leptons pair

Selection 4 Lepton Results		E_T^{miss}	$N(\tau_h)=0$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}=0$ obs	exp	$N(\tau_h)=0$, $N_{b-jets}\geq1$ obs	exp	$N(\tau_h)=1$, $N_{b-jets}\geq1$ obs	exp
OSSF0 $H_T < 200$	NA	(100,∞)	0	0.11 ± 0.08	0	0.17 ± 0.1	0	0.03 ± 0.04	0	0.04 ± 0.04
OSSF0 $H_T < 200$	NA	(50,100)	0	0.01 ± 0.03	2	0.7 ± 0.33	0	0 ± 0.02	0	0.28 ± 0.16
OSSF0 $H_T < 200$	NA	(0,50)	0	0.01 ± 0.02	1	0.7 ± 0.3	0	0.001 ± 0.02	0	0.13 ± 0.08
⟹ OSSF1 $H_T < 200$	off-Z	(100,∞)	0	0.06 ± 0.04	3	0.6 ± 0.24	0	0.02 ± 0.04	0	0.32 ± 0.2
OSSF1 $H_T < 200$	on-Z	(100,∞)	1	0.5 ± 0.18	2	2.5 ± 0.5	1	0.38 ± 0.2	0	0.21 ± 0.1
⟹ OSSF1 $H_T < 200$	off-Z	(50,100)	0	0.18 ± 0.06	4	2.1 ± 0.5	0	0.16 ± 0.08	1	0.45 ± 0.24
OSSF1 $H_T < 200$	on-Z	(50,100)	2	1.2 ± 0.34	9	9.6 ± 1.6	2	0.42 ± 0.23	0	0.5 ± 0.16
⟹ OSSF1 $H_T < 200$	off-Z	(0,50)	2	0.46 ± 0.18	15	7.5 ± 2	0	0.09 ± 0.06	0	0.7 ± 0.31
OSSF1 $H_T < 200$	on-Z	(0,50)	4	3 ± 0.8	41	40 ± 10	1	0.31 ± 0.15	2	1.5 ± 0.47
OSSF2 $H_T < 200$	off-Z	(100,∞)	0	0.04 ± 0.03	-	-	0	0.05 ± 0.04	-	-
OSSF2 $H_T < 200$	on-Z	(100,∞)	0	0.34 ± 0.15	-	-	0	0.46 ± 0.25	-	-
OSSF2 $H_T < 200$	off-Z	(50,100)	2	0.18 ± 0.13	-	-	0	0.02 ± 0.03	-	-
OSSF2 $H_T < 200$	on-Z	(50,100)	4	3.9 ± 2.5	-	-	0	0.5 ± 0.21	-	-
OSSF2 $H_T < 200$	off-Z	(0,50)	7	8.9 ± 2.4	-	-	1	0.23 ± 0.09	-	-
OSSF2 $H_T < 200$	on-Z	(0,50)	*156	159 ± 34	-	-	4	2.9 ± 0.8	-	-

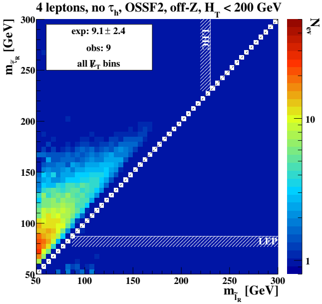
Anomalous number of events in $N(\tau) = 1$, $N_{b-jets} = 0$, off-Z category

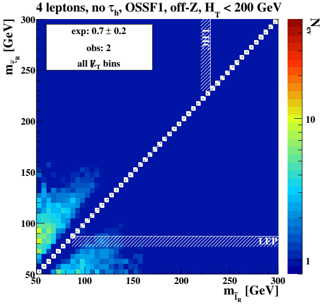
Observed 22; Expected 10.2 ± 2.1

SIGNIFICATIVE REGIONS FOR THE SIGNAL

- Three (leptons+taus) channels has large background compared to our signal
- $\Rightarrow$ We populate only the Four (leptons+taus) channel
- We populate only bins with $H_T < 200$ GeV and at least one OSSF

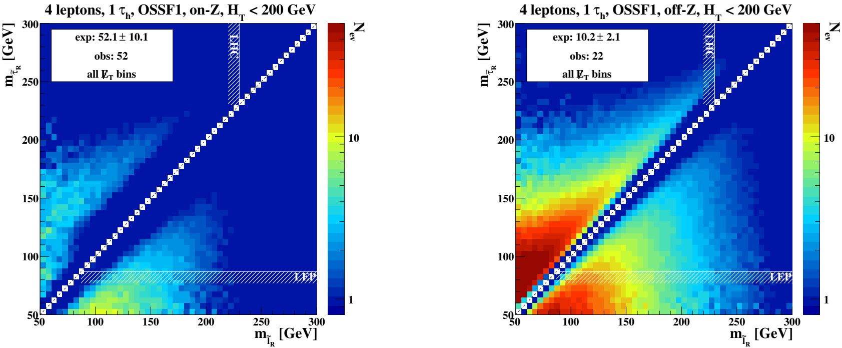
4 LEPTONS, $N(\tau) = 0$ RESULTS





- Lower half plane **M.I**, upper half plane **M.II**
- Agreement with data provided $m_{\tilde{\tau}_R} \geq 150$ GeV in **M.II**

4 Leptons, $N(\tau) = 1$ results



- Agreement with data in *on-Z* channels (left panel)
- Both models **M.I** and **M.II** can accommodate the CMS excess in *off-Z* bin (right panel)

- Most interesting region of **M.II** excluded by direct searches
- Preferred point in **M.I** to fit data is at the border of excluded $m_{\tilde{\tau}_R}$ region

$$m_{\tilde{\ell}_R} \simeq 145 \text{ GeV} \qquad m_{\tilde{\tau}_R} \simeq 90 \text{ GeV}$$

Comments on the results

From Theory:

- Both $\mathbf{M.I}$ and $\mathbf{M.II}$ can be realized in gauge mediation.
- The flavor hierarchies are induced by the hierarchies in the Yukawa coupling. $\Rightarrow$ No new constraints from flavor!
- $\mathbf{M.I}/\mathbf{M.II}$ is obtained in the absence/presence of tachyons at high-energy.
- To have promptly decaying NLSP in $\mathbf{M.II}$ deflections are needed.

From Collider:

- The best point of $\mathbf{M.I}$ is not constrained by other searches:
  - RPV multi lepton CMS search CMS SUS-13-010
  - ATLAS RPV search ATLAS CONF-2013-036
  - ATLAS di-tau search ATLAS CONF-2013-028
- Prospects for multi-lepton events
  - $\mathbf{M.I}$ gives many events with 2 hadronicaly decaying tau's and 2 leptons
  - ATLAS analogous multi-lepton search ?
  - Important to improve the mass bound on the EW produced NLSP $\tilde{\tau}_R$

Thank you!