

# Sgoldstino physics and lepton flavor-violating Higgs boson decays

Sergei Demidov<sup>1</sup> Ivan Sobolev<sup>1,2</sup>

<sup>1</sup>Institute for Nuclear Research RAS

<sup>2</sup>Moscow State University

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## Motivation. LFV processes.

- Extremely suppressed in SM. In SM with non-zero neutrino masses LFV can happen but its rate is tiny

$$Br(\tau \rightarrow \mu \gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\tau i}^* U_{\mu i} \frac{m_i^2}{M^2} \right|^2 \sim 10^{-50}$$

- Due to their small probability these processes are ideal tests for physics beyond SM
- Recently a slight excess of signal events of decay  $H \rightarrow \mu\tau$  was observed by CMS group ( $2.4\sigma$ ) (hep-ex/1502.07400).

$$Br(h \rightarrow \mu\tau) = (0.84_{-0.37}^{+0.39})\% \text{ at } 95\% \text{ C.L.}$$

# Motivation. Why MSSM?

MSSM is attractive extension of SM:

- MSSM helps to solve hierarchy problem, e.g. instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale (for example in Grand Unified Theory (GUT)).
- Unification of gauge couplings in MSSM.
- MSSM provides CDM candidate.
- Local supersymmetry  $\implies$  supergravity.

# SUSY breaking and its scale.

- For phenomenological viability SUSY should be broken.
- We need hidden sector, where breaking of SUSY takes place and then transmitted to visible sector (via gauge mediation, gravity mediation,...). Chiral superfield in hidden sector  
 $\Phi = \phi + \sqrt{2}\psi\theta + F\theta^2$ .  $\langle\sqrt{F}\rangle$  – SUSY breaking scale and  
 $\phi = (s + ip)/\sqrt{2}$
- $\sqrt{F} \gg M_{EW}$  – hidden sector decouples. Conventional MSSM with soft terms.
- $\sqrt{F} \sim O(\text{TeV})$  hidden sector is not so hidden. We should include  $\phi$  and  $\psi$  particles to our effective theory.

# Model description. MSSM and sgoldstino interaction.

$$\mathcal{L}_{\Phi-MSSM} = \mathcal{L}_{Kahler} + \mathcal{L}_{superpotential} + \mathcal{L}_{\Phi}$$

$$\mathcal{L}_{Kahler} = \int d^2\theta d^2\bar{\theta} \sum_k \left(1 - \frac{m_k^2}{F^2} \Phi^\dagger \Phi\right) \Phi_k^\dagger e^{g_1 V_1 + g_2 V_2 + g_3 V_3} \Phi_k$$

$$\begin{aligned} \mathcal{L}_{superpotential} = & \int d^2\theta \left\{ \epsilon_{ij} \left( \left( \mu - \frac{B}{F} \Phi \right) H_d^i H_u^j \right) + \left( Y_{ab}^L + \frac{A_{ab}^L}{F} \Phi \right) L_a^j E_b^c H_d^i \right\} + \\ & + \left( Y_{ab}^D + \frac{A_{ab}^D}{F} \Phi \right) Q_a^j D_b^c H_d^i \right) + \left( Y_{ab}^U + \frac{A_{ab}^U}{F} \Phi \right) Q_a^j U_b^c H_u^i \right) + \\ & + \frac{1}{4} \sum_a \left( 1 + \frac{2M_a}{F} \Phi \right) Tr W^a W^a + h.c. \left. \right\} \end{aligned}$$

$$\mathcal{L}_{\Phi} = \int d^2\theta d^2\bar{\theta} (\Phi^\dagger \Phi + \tilde{K}(\Phi^\dagger, \Phi)) - \left( \int d^2\theta F \Phi + h.c. \right)$$

- We consider effective theory. It is valid at energies  $E \leq \sqrt{F}$ .
- We assume that  $\langle \phi \rangle = 0$  and that there is no CP-violation.

# Higgs-sgoldstino mixing.

CP-even higgs-sgoldstino mass matrix (in  $h, H$  and  $s$  basis)

$$\mathcal{M}_s^2 = \begin{pmatrix} m_H^2 & 0 & \frac{Y}{F} \\ 0 & m_h^2 & \frac{X}{F} \\ \frac{Y}{F} & \frac{X}{F} & m_s^2 \end{pmatrix}$$

where the relevant off-diagonal terms are

$$X = 2\mu^3 v \sin 2\beta + \frac{v^3}{2} (g_1^2 M_1 + g_2^2 M_2) \cos^2 2\beta$$

$$Y = \mu v (m_A^2 - 2\mu^2) + \frac{1}{4} (g_1^2 M_1 + g_2^2 M_2) \sin(4\beta)$$

and we work in decoupling limit of MSSM

$$m_A \gg m_h$$

Higgs-sgoldstino mixing angle

$$\tan 2\theta = \frac{2X}{F(m_s^2 - m_h^2)}$$

Mass states

$$\begin{pmatrix} \tilde{h} \\ \tilde{s} \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

# Modified Higgs interaction with leptons.

After the EWSB the interaction between Higgs and leptons

$$\mathcal{L} \supset (v_d \bar{l}'_R Y^L l'_L + h.c.) + \left( v_d \bar{l}'_R \left( \frac{Y^L}{\sqrt{2}v} \cos \theta + \frac{A^L}{\sqrt{2}F} \sin \theta \right) l'_L \tilde{h} + h.c. \right)$$

Using double unitary transformation we diagonalize  $Y^L$  matrix and in fermion mass basis

$$\mathcal{L} \supset -m_a \bar{l}^a l^a - (\bar{l}_L^a l_R^b Y_{ab} \tilde{h} + h.c.),$$

where

$$Y_{ab} = \frac{m_a \delta_{ab} \cos \theta}{\sqrt{2}v} - \frac{v_d (V_L (A^L)^\dagger V_R^\dagger)_{ab} \sin \theta}{\sqrt{2}F}$$

Decay width of LFV process

$$\Gamma(\tilde{h} \rightarrow l_a l_b) = \frac{\tilde{m}_h v_d^2 \sin^2 \theta}{16\pi F^2} (|\tilde{A}_{ab}|^2 + |\tilde{A}_{ba}|^2),$$

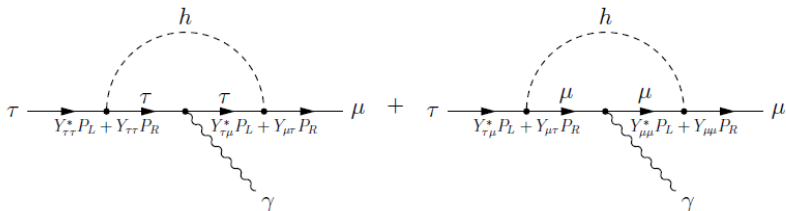
where

$$\tilde{A}_{ab} = (V_L (A^L)^\dagger V_R^\dagger)_{ab}$$



# $\tau$ flavour-violating decay mediated by Higgs.

hep-ph/1304.2783:  $\Gamma(\tau \rightarrow \mu \gamma) = \frac{\alpha m_\tau^5}{64\pi^4} (|c_L|^2 + |c_R|^2)$



$$\Gamma(\tau \rightarrow \mu \gamma) : \sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 1.6 \cdot 10^{-2}$$

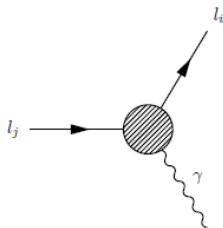
$$\text{CMS: } \sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 3.6 \cdot 10^{-3}$$

Constraint is weak!

# Flavour violating in slepton sector.

Flavour violating occurs in slepton sector and then is transmitted to lepton sector via loop diagrams. The branching ratio (hep-ph/1304.2783)

$$BR(\tau \rightarrow \mu\gamma) = \frac{\alpha\alpha_2^2}{4} \left(\frac{v}{48\pi}\right)^2 \frac{m_\tau^3}{\Gamma_\tau} \left(\frac{M_1 \cos\beta}{m_{\tilde{L}} m_{L_2} m_{L_3}}\right)^2 (|\tilde{A}_{\mu\tau}|^2 + |\tilde{A}_{\tau\mu}|^2)$$



For simplicity we assume that only  $\tilde{A}_{\mu\tau}$  constants are non-zero.

# Constraints on off-diagonal Yukawa couplings. Modified couplings.

Effective lagrangian for Higgs boson in SM:

$$\begin{aligned}\mathcal{L}_h^{\text{eff}} = & \frac{2m_W^2}{\sqrt{2}v} h W_{\mu\nu}^+ W^{\mu\nu-} + \frac{2m_Z^2}{\sqrt{2}v} h Z_{\mu\nu}^+ Z^{\mu\nu-} - \\ & - \frac{m_b}{\sqrt{2}v} h \bar{b} b + g_{h\gamma\gamma} h F_{\mu\nu} F^{\mu\nu} + g_{hgg} h \text{tr} G_{\mu\nu} G^{\mu\nu}\end{aligned}$$

Effective lagrangian for sgoldstino:

$$\begin{aligned}\mathcal{L}_s^{\text{eff}} = & -\frac{M_2}{\sqrt{2}F} s W_{\mu\nu} W^{\mu\nu*} - \frac{M_{ZZ}}{2\sqrt{2}} s Z^{\mu\nu} Z_{\mu\nu} - \\ & - \frac{M_{\gamma\gamma}}{2\sqrt{2}} s F_{\mu\nu} F^{\mu\nu} - \frac{M_3}{2\sqrt{2}F} s \text{tr} G_{\mu\nu} G^{\mu\nu}\end{aligned}$$

$$M_{ZZ} = M_1 \sin^2 \theta_W + M_2 \cos^2 \theta_W$$

$$M_{\gamma\gamma} = M_1 \cos^2 \theta_W + M_2 \sin^2 \theta_W$$

# Constraints on off-diagonal Yukawa couplings. Modified couplings.

$$g_{\tilde{h}\gamma\gamma} = g_{h\gamma\gamma} \cos \theta + \frac{M_{\gamma\gamma}}{2\sqrt{2}F} \sin \theta$$

$$g_{\tilde{h}gg} = g_{hgg} \cos \theta + \frac{M_3}{2\sqrt{2}F} \sin \theta$$

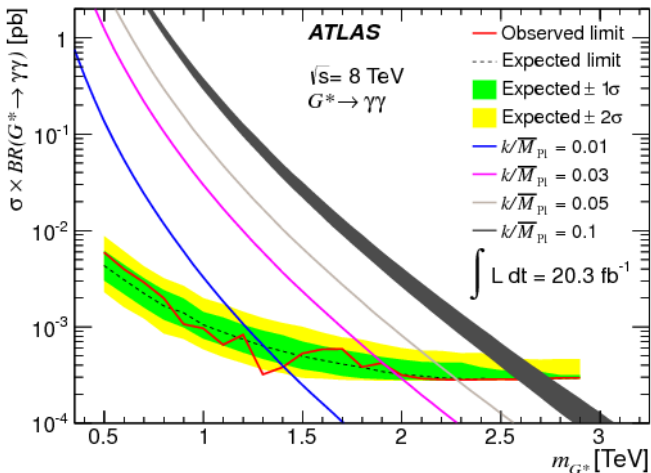
$$g_{\tilde{h}ZZ} = g_{hZZ} \cos \theta + \frac{M_{ZZ}}{\sqrt{2}F} ((k_{Z_1}, k_{Z_2})\eta^{\mu\nu} - k^{Z_2\mu} k^{Z_1\nu}) \sin \theta$$

$$g_{\tilde{h}ZZ} = g_{hW^+W^-} \cos \theta + \frac{M_2}{\sqrt{2}F} ((k_{W^+}, k_{W^-})\eta^{\mu\nu} - k^{W^+\mu} k^{W^-\nu}) \sin \theta$$

$$g_{\tilde{h}bb} = g_{hbb} \cos \theta$$

Effective coupling constants for sgoldstino-like state  $\tilde{s}$  can be obtained from those above by the replacement  $\cos \theta \rightarrow \sin \theta$  and  $\sin \theta \rightarrow -\cos \theta$ .

# Constraints on off-diagonal Yukawa couplings. Diphoton resonances. hep-ex/1504.05511

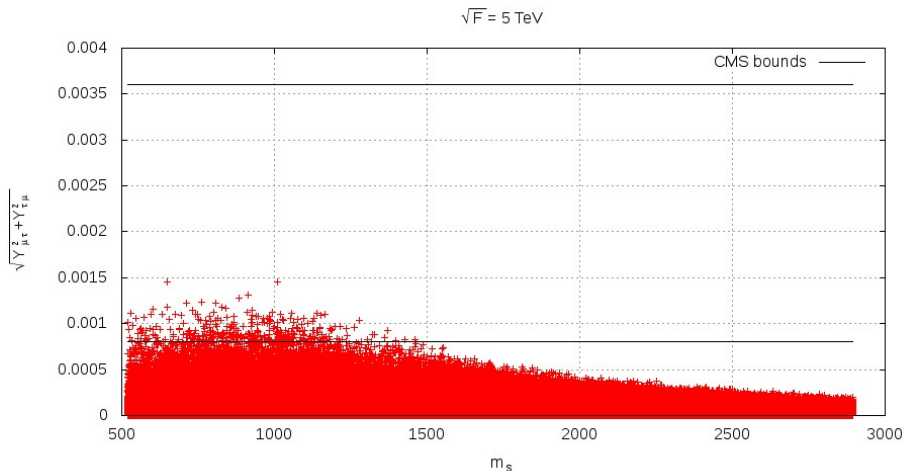


$\tan \beta$	1.5 ... 50.5
$\mu$	100 ... 2000.0 GeV
$A_{\mu\tau}$	$0.1\sqrt{F} \dots \sqrt{F}$
$M_1$	100.0 ... $\sqrt{F}$ GeV
$M_2$	200.0 ... $\sqrt{F}$ GeV
$M_3$	1.5 ... 4.0 TeV
$\tilde{m}_{sl}$	300.0 GeV ... $\sqrt{F}$

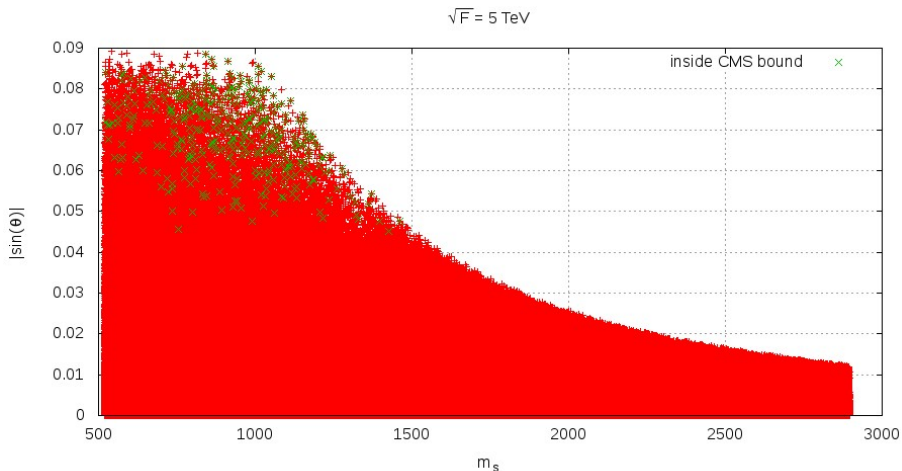
Table : Parameter space

- 1 We have assumed that  $m_{\tilde{L}_i} = m_{\tilde{E}_i} \equiv \tilde{m}_{sl}$ .
- 2 Sgoldstino mass parameter  $500\text{ GeV} < m_s < 3000\text{ GeV}$
- 3 Calculate signal strength  $\frac{\sigma(pp \rightarrow \tilde{h}) \cdot Br(\tilde{h})}{\sigma(pp \rightarrow h) \cdot Br(h)_{SM}}$  for every final state ( $\gamma\gamma$ , bb,  $\tau\tau$ , WW, ZZ)
- 4  $\sigma(pp \rightarrow s) \cdot Br(s \rightarrow \gamma\gamma)$
- 5 Slepton mass matrix must be positive definite.
- 6  $BR(\tau \rightarrow \mu\gamma) < 4.4 \cdot 10^{-8}$

# Results. $\sqrt{F} = 5$ TeV. Yukawa couplings

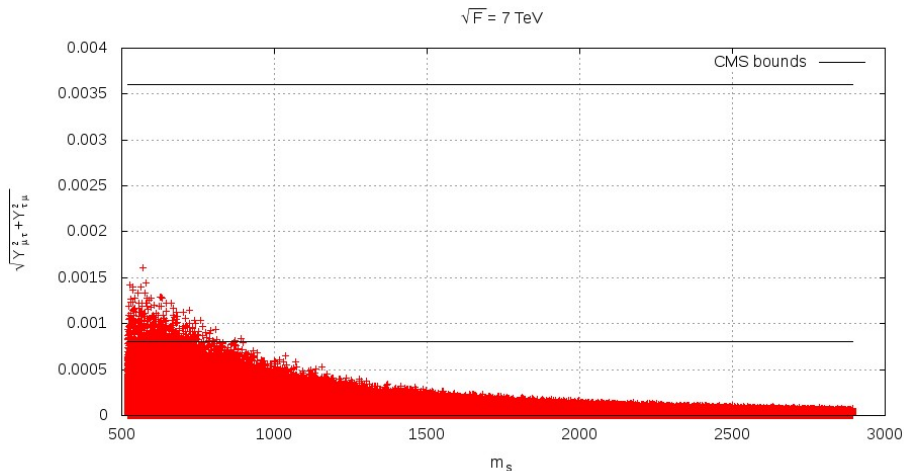


# Results. $\sqrt{F} = 5$ TeV. Mixing angle.

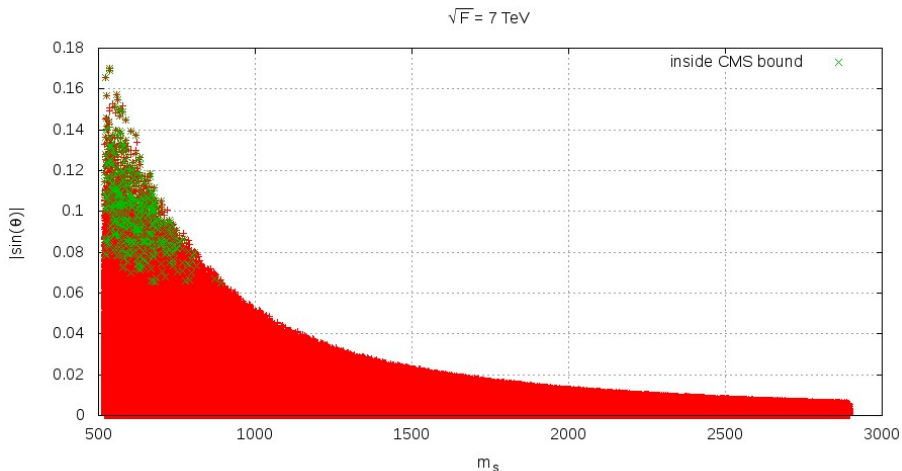




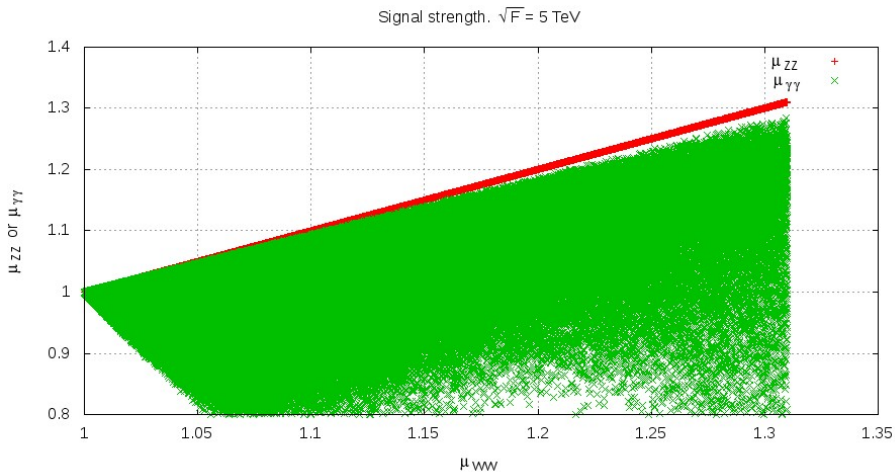
# Results. $\sqrt{F} = 7$ TeV. Yukawa couplings.



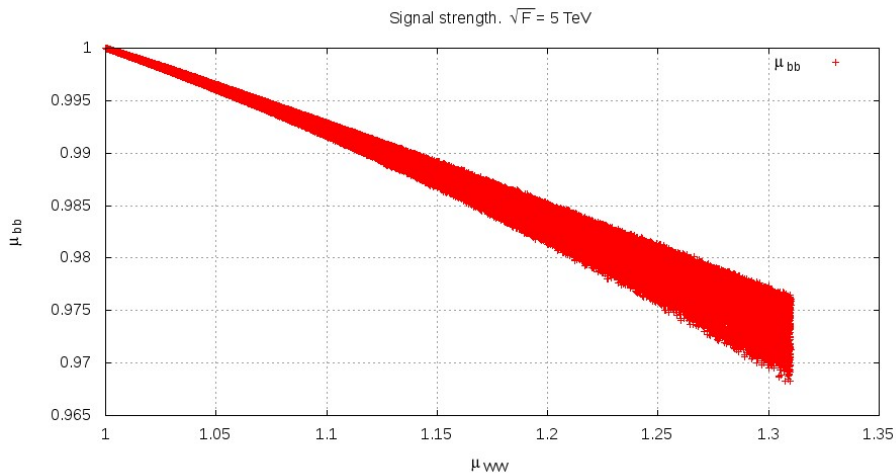
# Results. $\sqrt{F} = 7 \text{ TeV}$ . Mixing angle.



# Results. $\sqrt{F} = 5$ TeV. Signal strength.



# Results. $\sqrt{F} = 5$ TeV. Signal strength.



# Conclusions.

- Low scale supersymmetry – sgoldstinos can mix with Higgs bosons.
- Flavour violating processes can be possible.
- This scenario can be probed at the LHC.

Thank you!