HIGGS SECTOR IN THE SUPERSYMMETRIC EXTENSION OF THE STANDARD MODEL WITH LIGHT SGOLDSTINOS

Sergey Demidov, Dmitry Gorbunov, **Ekaterina Kriukova**

Lomonosov Moscow State University,
Institute for Nuclear Research of RAS

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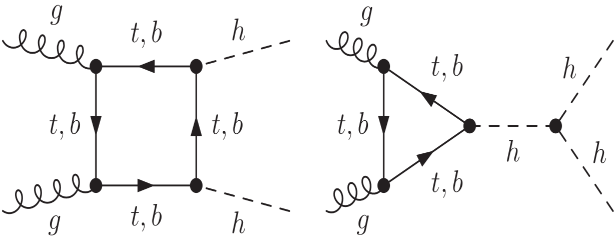
Model with sgoldstino

- Supersymmetric model with low-scale SUSY breaking in hidden sector. Goldstone theorem $\Rightarrow$ goldstino G, sgoldstino ϕ.
- Heavy fields are integrated out. Effective theory with MSSM fields, goldstino multiplet and gravitino.
- Sgoldstino can decay to SM particles (R-even). Interactions in effective lagrangian: sgg, shh, sW^+W^-, sZZ, $s\gamma\gamma$, $sZ\gamma$.
- Aim: consider the possibility of increase in di-Higgs production cross section at LHC due to processes with sgoldstino $gg \to s \to hh$.
- Main SM diagrams for di-Higgs production.



MSSM Lagrangian

- sum over all gauge superfields W_α $\rightarrow$ kinetic terms of gauge fields
$$\frac{1}{4}\sum_\alpha \int d^2\theta \mathrm{Tr} W_\alpha W^\alpha + h.c., \tag{1}$$
- Kähler potential (sum over all matter superfields Φ_k and Higgs fields)
$$\int d^2\theta d^2\bar{\theta} \sum_k \Phi_k^\dagger e^{g_1 V_1 + g_2 V_2 + g_3 V_3} \Phi_k, \tag{2}$$
- superpotential
$$\int d^2\theta \epsilon_{ij} \left(\mu H_D^i H_U^j + Y_{ab}^L L_a^j E_b^c H_D^i + \right. \\ \left. + Y_{ab}^D Q_a^j D_b^c H_D^i + Y_{ab}^U Q_a^i U_b^c H_U^j \right) + h.c. \tag{3}$$

Spontaneous SUSY breaking

Goldstone theorem $\Rightarrow$ goldstino fermion G,
its superpartner sgoldstino ϕ.

Chiral superfield

$\Phi = \phi + \sqrt{2}\theta G + F_\phi \theta^2$, where F_ϕ is an auxiliary field.
Its nonzero VEV, $\langle F_\phi \rangle \equiv F \neq 0$, breaks the supersymmetry.

The lagrangian of goldstino supermultiplet:

$$\mathcal{L}_\Phi = \int d^2\theta d^2\bar{\theta} \Phi^\dagger \Phi - \left(\int d^2\theta F \Phi + h.c. \right) \qquad (4)$$

Lagrangian of the model with SUSY breaking

$$\mathcal{L} = \mathcal{L}_K + \mathcal{L}_{superpotential} + \mathcal{L}_{gauge} + \mathcal{L}_\Phi, \tag{5}$$

$$\mathcal{L}_K = \int d^2\theta d^2\bar{\theta} \sum_k \left(1 - \frac{m_k^2}{F^2}\Phi^\dagger\Phi\right) \Phi_k^\dagger e^{g_1 V_1 + g_2 V_2 + g_3 V_3} \Phi_k, \tag{6}$$

$$\begin{aligned} \mathcal{L}_{superpotential} = \int d^2\theta \epsilon_{ij} \Bigg(\left(\mu - \frac{B}{F}\Phi\right) H_D^i H_U^j + \\ + \left(Y_{ab}^L + \frac{A_{ab}^L}{F}\Phi\right) L_a^j E_b^c H_D^i + \left(Y_{ab}^D + \frac{A_{ab}^D}{F}\Phi\right) Q_a^j D_b^c H_D^i + \\ + \left(Y_{ab}^U + \frac{A_{ab}^U}{F}\Phi\right) Q_a^i U_b^c H_U^j \Bigg) + h.c., \end{aligned} \tag{7}$$

$$\mathcal{L}_{gauge} = \frac{1}{4}\sum_\alpha \int d^2\theta \left(1 + \frac{2M_\alpha}{F}\right) \mathrm{Tr} W_\alpha W^\alpha + h.c., \tag{8}$$

Potential of scalar fields p.1

$$V = V_{11} + V_{12} + V_{21} + V_{22}, \tag{9}$$

$$V_{11} = \frac{g_1^2}{8}\left(1 + \frac{M_1}{F}(\phi + \phi^*)\right)^{-1}\left[h_d^\dagger h_d - h_u^\dagger h_u - \right.$$
$$\left. - \frac{\phi^*\phi}{F^2}\left(m_d^2 h_d^\dagger h_d - m_u^2 h_u^\dagger h_u\right)\right]^2, \tag{10}$$

$$V_{12} = \frac{g_2^2}{8}\left(1 + \frac{M_2}{F}(\phi + \phi^*)\right)^{-1}\left[h_d^\dagger \sigma_a h_d + h_u^\dagger \sigma_a h_u - \right.$$
$$\left. - \frac{\phi^*\phi}{F^2}\left(m_d^2 h_d^\dagger \sigma_a h_d + m_u^2 h_u^\dagger \sigma_a h_u\right)\right]^2. \tag{11}$$

Here g_1, g_2 are coupling constants of the groups $U(1)_Y, SU(2)_L$, M_1, M_2 are soft masses, corresponding to gauginos, $\sqrt{F}$ is a scale of supersymmetry breaking, σ_a are Pauli matrices.

Potential of scalar fields p.2

$$V_{21} = \left(1 - \frac{m_u^2}{F^2} h_u^\dagger h_u - \frac{m_d^2}{F^2} h_d^\dagger h_d - \frac{m_u^4}{F^4}\phi^*\phi h_u^\dagger h_u - \frac{m_d^4}{F^4}\phi^*\phi h_d^\dagger h_d\right)^{-1}$$
$$\left|F + \left(-h_d^0 h_u^0 + h^- h^+\right)\left(\frac{B}{F} - \frac{m_u^2 + m_d^2}{F^2}\phi^*\left(\mu - \frac{B}{F}\phi\right)\right)\right|^2, \quad (12)$$

$$V_{22} = \frac{\mu^2}{F^2}|\phi|^2\left(m_u^2 h_d^\dagger h_d + m_d^2 h_u^\dagger h_u\right) + \left|\mu - \frac{B}{F}\phi\right|^2\left(h_d^\dagger h_d + h_u^\dagger h_u\right). \quad (13)$$

Higgs doublets $h_d = \begin{pmatrix} h_d^0 \\ h^- \end{pmatrix}$, $h_u = \begin{pmatrix} h^+ \\ h_u^0 \end{pmatrix}$,

μ is a real parameter of higgsino mixing from superpotential.

Some notation

$v_u \equiv v \sin\beta$, $v_d \equiv v \cos\beta$, $v = 174$ GeV
The expansion of fields around electroweak vacuum

$$h_u^0 = v_u + \frac{1}{\sqrt{2}}(h\cos\alpha + H\sin\alpha) + \frac{i}{\sqrt{2}}A\cos\beta, \qquad (14)$$

$$h_d^0 = v_d + \frac{1}{\sqrt{2}}(-h\sin\alpha + H\cos\alpha) + \frac{i}{\sqrt{2}}A\sin\beta. \qquad (15)$$

Extract scalar s and pseudoscalar p from sgoldstino field

$$\phi = \frac{1}{\sqrt{2}}(s + ip). \qquad (16)$$

Introduce masses

$$m_Z^2 \equiv \frac{g_1^2 + g_2^2}{2}v^2, \qquad m_A^2 \equiv m_u^2 + m_d^2 + 2\mu^2. \qquad (17)$$

Trilinear couplings before mixing

sHH term.

$$\frac{1}{F\sqrt{2}}\left(-\frac{v^2}{4}\left(g_1^2 M_1 + g_2^2 M_2\right)\left(2\cos 2\alpha \cos 2\beta - \sin 2\alpha \sin 2\beta + 1\right) + \right.$$
$$\left. + \mu \sin 2\alpha \left[\frac{m_A^2}{2}\left(1 - \frac{\sin 2\beta}{\sin 2\alpha}\right) - \mu^2\right]\right). \quad (18)$$

shh term.

$$\frac{1}{F\sqrt{2}}\left(\frac{v^2}{4}\left(g_1^2 M_1 + g_2^2 M_2\right)\left(2\cos 2\alpha \cos 2\beta - \sin 2\alpha \sin 2\beta - 1\right) - \right.$$
$$\left. - \mu \sin 2\alpha \left[\frac{m_A^2}{2}\left(1 + \frac{\sin 2\beta}{\sin 2\alpha}\right) - \mu^2\right]\right). \quad (19)$$

Other sgoldstino-Higgs vertices:
shH, sAA, sh^+h^-, pAH, pAh, ssH, ssh, ppH, pph.

Rotation towards mass basis p.1

Mass terms have the following form:

$$\frac{1}{2}\begin{pmatrix} H & h & s \end{pmatrix}\begin{pmatrix} m_H^2 & 0 & Y/F \\ 0 & m_h^2 & X/F \\ Y/F & X/F & m_s^2 \end{pmatrix}\begin{pmatrix} H \\ h \\ s \end{pmatrix} + \\ + \frac{1}{2}\begin{pmatrix} A & p \end{pmatrix}\begin{pmatrix} m_A^2 & Z/F \\ Z/F & m_p^2 \end{pmatrix}\begin{pmatrix} A \\ p \end{pmatrix}, \quad (20)$$

where

$$X = v\left(\frac{g_1^2 M_1 + g_2^2 M_2}{2} v^2 \cos 2\beta \sin(\alpha+\beta) + \mu m_A^2 \sin 2\beta \sin(\alpha-\beta) + \\ + \left(m_A^2 - 2\mu^2\right)\mu \cos(\alpha+\beta)\right) \quad (21)$$

$$Y = -v\left(\frac{g_1^2 M_1 + g_2^2 M_2}{2} v^2 \cos 2\beta \cos(\alpha+\beta) + \mu m_A^2 \sin 2\beta \cos(\alpha-\beta) + \\ + \left(2\mu^2 - m_A^2\right)\mu \sin(\alpha+\beta)\right) \quad (22)$$

$$Z = \mu v\left(m_A^2 - 2\mu^2\right). \quad (23)$$

Rotation towards mass basis p.2

Mixing angles, formulae are valid in approximation $\theta, \psi, \xi \ll 1$

$$\theta = \frac{X}{F(m_h^2 - m_s^2)}, \quad \psi = \frac{Y}{F(m_H^2 - m_s^2)}, \quad \xi = \frac{Z}{F(m_A^2 - m_p^2)}. \tag{24}$$

Old fields via new ones (mass matrix is diagonal in new basis)

$$H = \tilde{H} - \tilde{s}\frac{Y}{F(m_H^2 - m_s^2)}, \tag{25}$$

$$h = \tilde{h} - \tilde{s}\frac{X}{F(m_h^2 - m_s^2)}, \tag{26}$$

$$s = \tilde{H}\frac{Y}{F(m_H^2 - m_s^2)} + \tilde{h}\frac{X}{F(m_h^2 - m_s^2)} + \tilde{s}, \tag{27}$$

$$A = \tilde{A} - \tilde{p}\frac{Z}{F(m_A^2 - m_p^2)}, \tag{28}$$

$$p = \tilde{A}\frac{Z}{F(m_A^2 - m_p^2)} + \tilde{p}. \tag{29}$$

New trilinear couplings

Order	Vertex	Example of coefficient
0	hhh, HHH, hhH, hHH, hh^+h^-, Hh^+h^-, hAA, HAA	C_{hhh}, C_{HAA}
1	sHH, shh, shH, sAA, sh^+h^-, pAH, pAh	C_{sHH}/F, C_{pAh}/F
2	ssH, ssh, ppH, pph	C_{ssH}/F^2, C_{pph}/F^2

$$\frac{\tilde{s}\tilde{H}\tilde{H}}{F}\left(C_{sHH} - C_{hHH}\frac{X}{m_h^2 - m_s^2} - 3C_{HHH}\frac{Y}{m_H^2 - m_s^2}\right), \qquad (30)$$

$$\frac{\tilde{s}\tilde{h}\tilde{h}}{F}\left(C_{shh} - 3C_{hhh}\frac{X}{m_h^2 - m_s^2} - C_{hhH}\frac{Y}{m_H^2 - m_s^2}\right). \qquad (31)$$

Numerical computation of sgoldstino production cross section

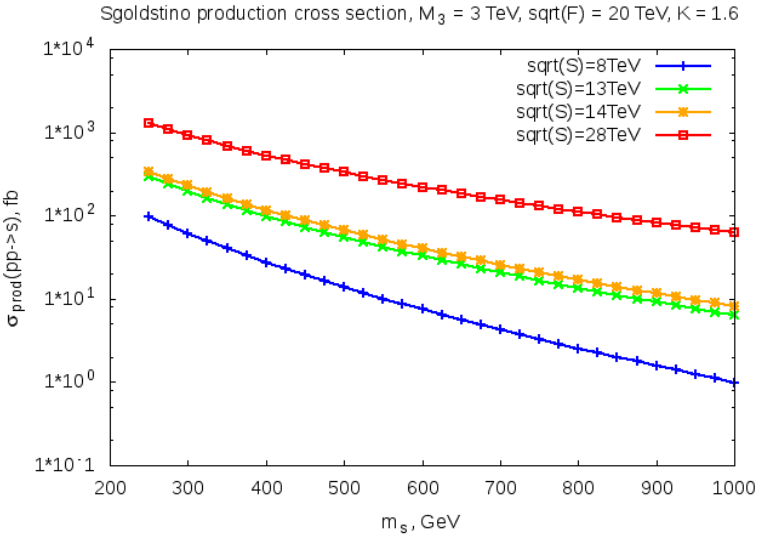
Main process is the gluon fusion, $gg \to s$. Tree-level — due to vertex sgg in sgoldstino lagrangian: $-\frac{1}{2\sqrt{2}}\frac{M_3}{F}sG^{\mu\nu}G_{\mu\nu}$.
Integrate gluon distribution functions by momentum fraction:

$$\sigma(pp \to s) = \sigma_0 \tau \int_\tau^1 \frac{\mathrm{d}x}{x} g(x, m_s^2) g(\frac{\tau}{x}, m_s^2), \qquad (32)$$

$$\sigma_0 = \frac{\pi M_3^2}{32F^2}, \qquad \tau = \frac{m_s^2}{S}, \qquad \sqrt{S} = 13 \text{ TeV}. \qquad (33)$$

Table CTEQ6L PDF for calculations in leading order.
Loop QCD contributions: K-factor $\simeq 1.6$.

Sgoldstino production cross section for different centre-of-mass energies



Numerical computation of cross section $pp \to s \to hh$

Fix $\tan\beta = 10$, μ, $m_A = 5$ TeV, $m_s = 1$ TeV, $M_1 = 1$ TeV, $M_2 = 1$ TeV, $M_3 = 3$ TeV, $\sqrt{F} = 20$ TeV.
Using them find α, m_H^2, X, Y, θ, ψ.

Small mixing angles

Consider only points of parameter space where $\theta < 0.3$, $\psi < 0.3$.

Narrow width approximation

$$\sigma\left(pp \to s \to hh\right) = \sigma_{prod}(pp \to s)Br(s \to hh), \tag{34}$$

$$Br(s \to hh) = \frac{\Gamma\left(s \to hh\right)}{\Gamma_{tot}\left(s\right)}. \tag{35}$$

Sgoldstino decay channels

$s \to hh$, $s \to gg$, $s \to WW$, $s \to ZZ$, $s \to \gamma Z$, $s \to \gamma\gamma$
Given the mixing with h, H, we compute widths and Br

Sgoldstino decay widths [Zwirner et al., 2000]

$$\Gamma\left(s \to gg\right) = \frac{1}{4\pi}\frac{M_3^2}{F^2}m_s^3, \qquad \Gamma\left(s \to hh\right) = \frac{1}{8\pi m_s}\frac{C_{\tilde{s}\tilde{h}\tilde{h}}}{F^2}, \tag{36}$$

$$\Gamma\left(s \to \gamma\gamma\right) = \frac{1}{32\pi}\frac{1}{F^2}\left(M_1\cos^2\theta_W + M_2\sin^2\theta_W\right)^2 m_s^3, \tag{37}$$

$$\Gamma\left(s \to \gamma Z\right) = \frac{1}{16\pi}\frac{\left(M_2 - M_1\right)^2}{F^2}\cos^2\theta_W\sin^2\theta_W m_s^3\left(1 - \frac{m_Z^2}{m_s^2}\right)^3. \tag{38}$$

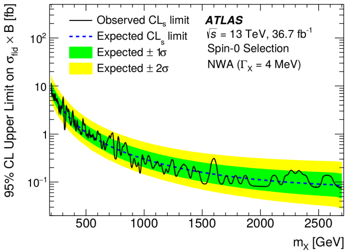
$$C_{sWW_T} = -M_2, \quad C_{sZZ_T} = -M_1\sin^2\theta_W - M_2\cos^2\theta_W, \tag{39}$$

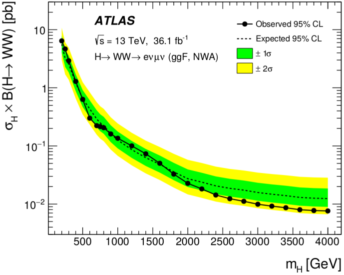
$$C_{\tilde{s}WW_L} = -\frac{\sqrt{2}}{v}\sin(\beta - \alpha) - \frac{\sqrt{2}}{v}\cos(\beta - \alpha) = 2C_{\tilde{s}ZZ_L}, \tag{40}$$

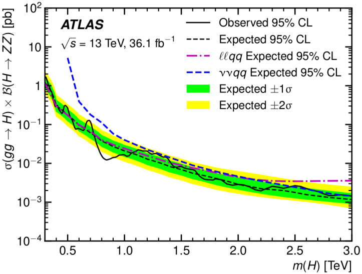
$$\Gamma\left(s \to WW\right) = \frac{1}{16\pi}\frac{m_W^4}{m_s}\left[\frac{C_{sWW_T}^2}{F^2}\left(6 - 4\frac{m_s^2}{m_W^2} + \frac{m_s^4}{m_W^4}\right) - 6\sqrt{2}\frac{C_{sWW_T}}{F}C_{\tilde{s}WW_L}\times\right.$$
$$\left.\times\left(1 - \frac{m_s^2}{2m_W^2}\right) + C_{\tilde{s}WW_L}^2\left(3 - \frac{m_s^2}{m_W^2} + \frac{m_s^4}{4m_W^4}\right)\right]\sqrt{1 - \frac{4m_W^2}{m_s^2}}, \tag{41}$$

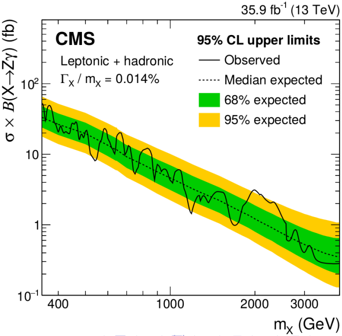
$$\Gamma\left(s \to ZZ\right) = \frac{1}{8\pi}\frac{m_Z^4}{m_s}\left[\frac{C_{sZZ_T}^2}{4F^2}\left(6 - 4\frac{m_s^2}{m_Z^2} + \frac{m_s^4}{m_Z^4}\right) - 3\sqrt{2}\frac{C_{sZZ_T}}{F}C_{\tilde{s}ZZ_L}\times\right.$$
$$\left.\times\left(1 - \frac{m_s^2}{2m_Z^2}\right) + C_{\tilde{s}ZZ_L}^2\left(3 - \frac{m_s^2}{m_Z^2} + \frac{m_s^4}{4m_Z^4}\right)\right]\sqrt{1 - \frac{4m_Z^2}{m_s^2}}. \tag{42}$$

Experimental searches for scalar resonances









Br for main sgoldstino decay channels

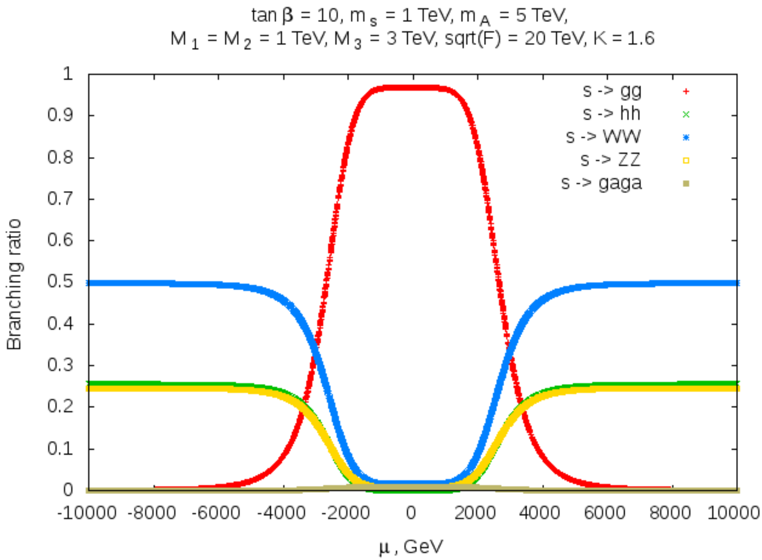
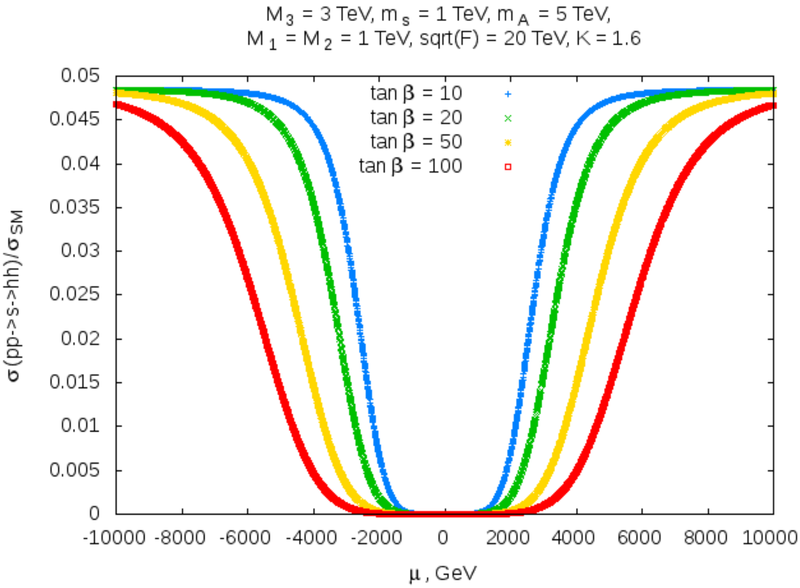
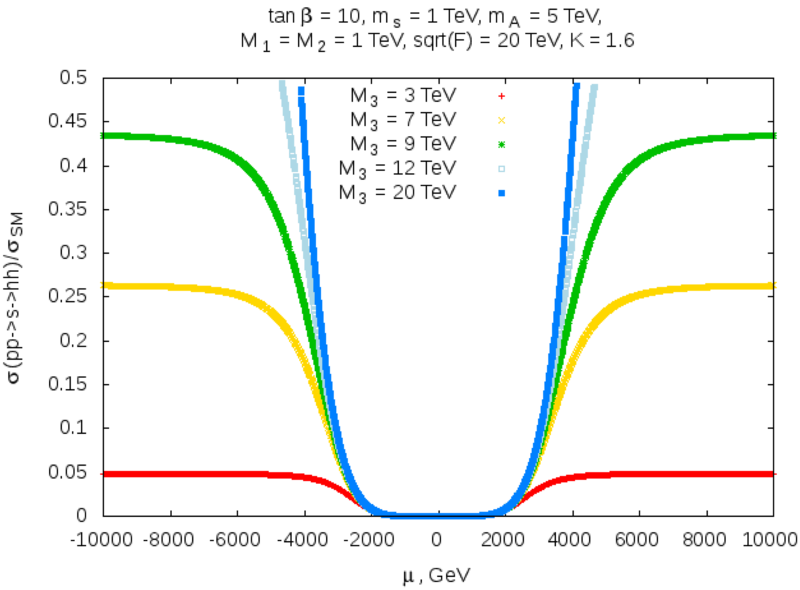


Figure: Branching ratio of sgoldstino.

Dependence of di-Higgs production cross section on $\tan\beta$

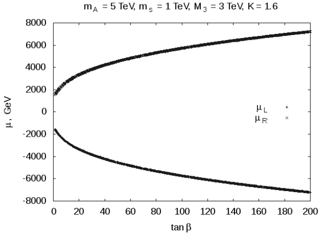


Dependence of di-Higgs production cross section on M_3

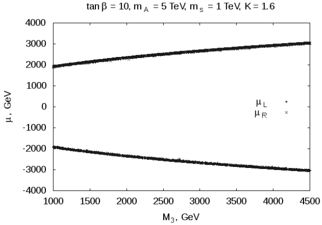


Curves $Br(s \to hh) = 0.125$

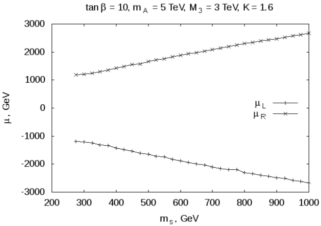
Fixed parameter values $M_1 = M_2 = 1$ TeV, $\sqrt{F} = 20$ TeV.



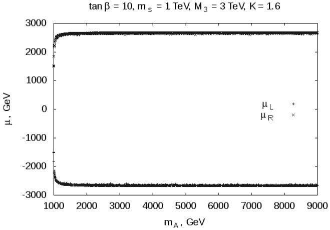
(a) Curves in plane $(\tan\beta, \mu)$



(b) Curves in plane (M_3, μ)



(c) Curves in plane (m_s, μ)



(d) Curves in plane (m_A, μ)

Upper limit on M_3/F from experimental data

Regime 1:2:1

$Br(s \to hh) = Br(s \to ZZ) = 0.25$, $Br(s \to WW) = 0.5$.

For fixed m_s

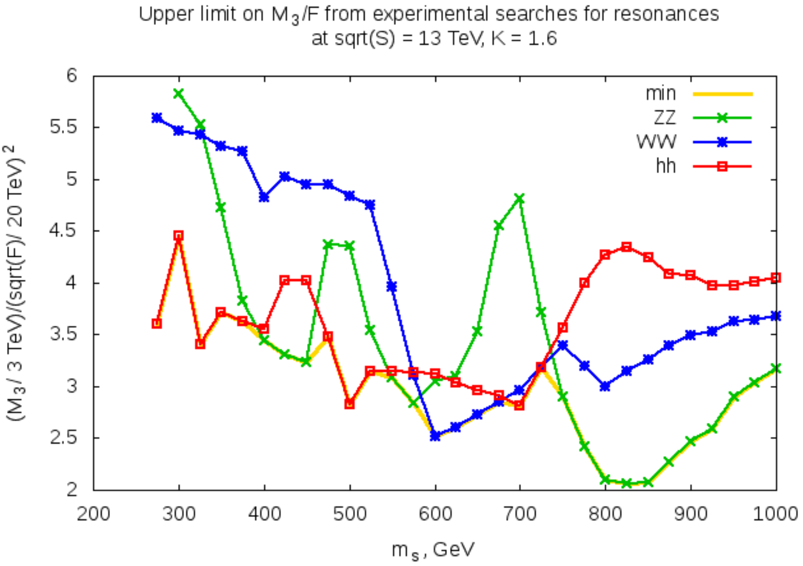
σ^{max}_{hh}, σ^{max}_{WW}, σ^{max}_{ZZ} are upper limits on hh, WW, ZZ production cross section in resonant scalar decays.

Then $\sigma_{prod} < \sigma^{max}_{hh}/Br(s \to hh)$ etc.

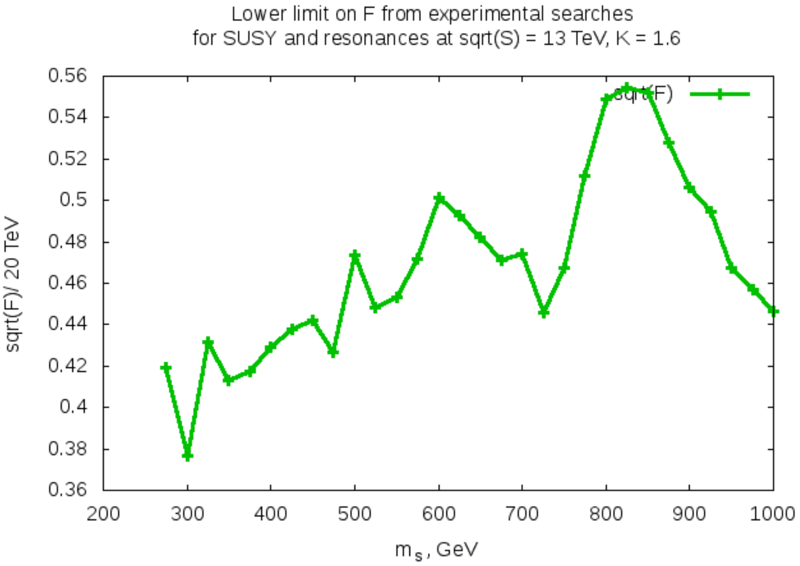
$\sigma_{prod} \sim M_3^2/F^2 \Rightarrow$

$$\left[\frac{M_3/3\ \text{TeV}}{(\sqrt{F}/20\ \text{TeV})^2}\right]^{max} = \sqrt{\frac{\sigma^{max}_{prod}}{\sigma'_{prod}}} \leq \sqrt{\frac{\sigma^{max}_{XX}}{\sigma'_{prod} Br(s \to XX)}}. \quad (43)$$

Upper limit on M_3/F from experimental data at 95%CL



Lower limit on $\sqrt{F}$ assuming $M_3 \geq 1.9$ TeV



Comparison with numerical results

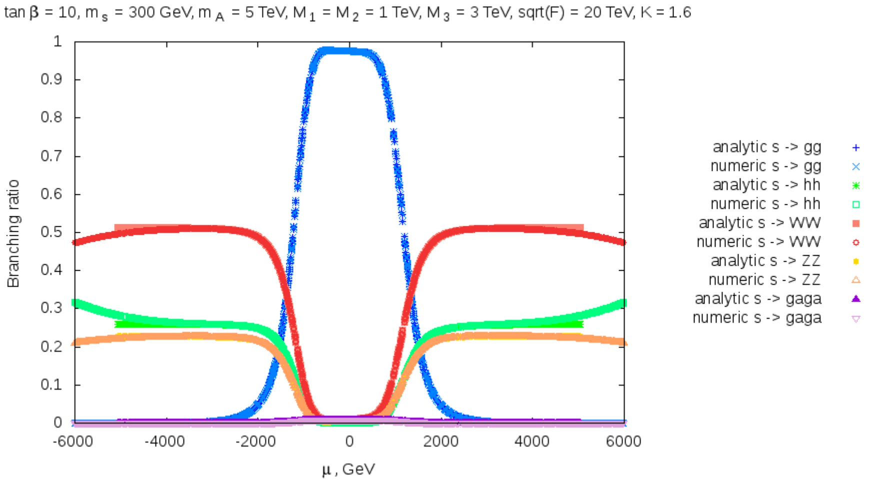


Figure: Analytically and numerically obtained branchings.

Results

- Found trilinear couplings for vertices with sgoldstino and Higgses
- Analytically made rotation towards mass basis and checked that formulae for mixing angles agree with numerical results
- Numerically obtained the sgoldstino production cross section
- Wrote program for computing sgoldstino decay widths and Br, di-Higgs production cross section
- Studied the dependence of cross section on model parameters
- Found borders of gluino dominating region
- Put upper limit at 95% CL on M_3/F in regime 1:2:1

Increase in di-Higgs production up to about $0.25\,\sigma_{prod}(pp \to s)$ is possible in the found parameter region of μ, $\tan\beta$, M_3, m_s, m_A.