Light Sgoldstinos and Higgs Sector in the Supersymmetric Extension of the Standard Model

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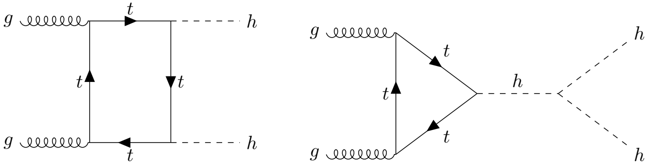
Model with sgoldstino



- Double Higgs production $\sigma_{SM}^{NLO}(pp \to hh) = 33.5$ fb
  Can be increased if there is an additional scalar particle.
- Supersymmetric model with low-scale SUSY breaking in hidden sector. Goldstone theorem $\Rightarrow$ goldstino fermion G, its superpartner sgoldstino ϕ.
  Goldstino 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.
- Fields of the hidden sector are heavy
- Sgoldstino can decay to SM particles (R-even)

The Lagrangian of the model in terms of superfields

MSSM + soft SUSY breaking terms + sgoldstino multiplet Lagrangian $\mathcal{L}_\Phi$

$$\mathcal{L} = \mathcal{L}_K + \mathcal{L}_{gauge} + \mathcal{L}_W + \mathcal{L}_\Phi$$

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

$$\mathcal{L}_{gauge} = \frac{1}{4}\sum_a \int d^2\theta \left(1 + \frac{2M_a}{F}\Phi\right) \mathrm{Tr} W_\alpha W^\alpha + h.c.$$

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

$$\mathcal{L}_\Phi = \int d^2\theta d^2\bar{\theta} \left(\Phi^\dagger\Phi - \frac{m_s^2 + m_p^2}{8F^2}(\Phi^\dagger\Phi)^2 - \right.$$
$$\left. - \frac{m_s^2 - m_p^2}{12F^2}(\Phi^\dagger\Phi^3 + \Phi^{\dagger 3}\Phi) \right) - \left(\int d^2\theta F\Phi + h.c. \right)$$

Potential of the scalar fields

1. Lagrangian in superfields $\mathcal{L}$
2. Scalar potential of the sgoldstino and Higgs sector $V(\phi, h_d, h_u)$ that depends on
   sgoldstino field ϕ, Higgs doublets $h_d = \begin{pmatrix} h_d^0 \\ H^- \end{pmatrix}$, $h_u = \begin{pmatrix} H^+ \\ h_u^0 \end{pmatrix}$
3. Expand scalar fields around **vev**

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

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

4. Mass terms, sgld-Higgs vertices in the leading order in $1/F$
   sHH, shh, shH, sAA, sH^+H^-, pAH, pAh

Sgoldstino-Higgs mixing

Mass terms of Higgs and sgoldstino fields

$$\frac{1}{2}\begin{pmatrix}H & h & s\end{pmatrix}\begin{pmatrix}m_H^2 & 0 & Y/F\\ 0 & m_h^2 & X/F\\ Y/F & X/F & m_s^2\end{pmatrix}\begin{pmatrix}H\\ h\\ s\end{pmatrix}+$$

$$+\frac{1}{2}\begin{pmatrix}A & p\end{pmatrix}\begin{pmatrix}m_A^2 & Z/F\\ Z/F & m_p^2\end{pmatrix}\begin{pmatrix}A\\ p\end{pmatrix}$$

Mixing angles ψ, θ, ϕ, ξ are assumed to be **small**.

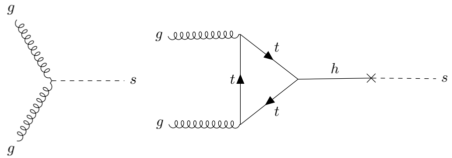
In the leading non-zero order in $1/F$

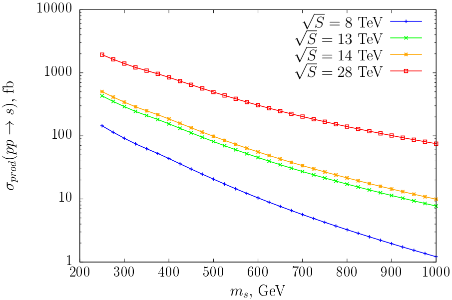
$$\psi=\frac{Y}{F(m_H^2-m_s^2)}\,,\quad \theta=\frac{X}{F(m_h^2-m_s^2)}\,,\quad \xi=\frac{Z}{F(m_A^2-m_p^2)}\,,$$

$$\phi=\frac{XY}{F^2(m_h^2-m_s^2)(m_H^2-m_h^2)}.$$

Sgoldstino production in proton-proton collisions

Gluon fusion

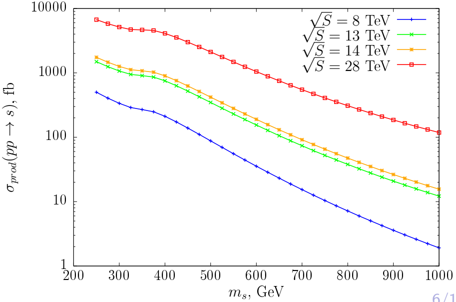




LO production cross section

$$\sigma_0 \tau \int_\tau^1 \frac{\mathrm{d}x}{x} g\left(x, m_s^2\right) g\left(\frac{\tau}{x}, m_s^2\right),$$

$$\sigma_0 = \frac{\pi}{32}\left|\frac{M_3}{F} + \frac{\alpha_s(m_s)\theta}{6\pi v} A\left(\frac{4m_t^2}{m_s^2}\right)\right|^2$$



QCD corrections: NLO K-factor $K_p = 2.0$

Top: $\theta = 0.02$, bottom: $\theta = 0.2$,

$M_3 = 3$ TeV, $\sqrt{F} = 20$ TeV

Sgoldstino decays

Interactions of the scalar sgoldstino s with SM vector bosons

$$\mathcal{L}_s^{eff} = -\frac{M_2}{\sqrt{2}F} sW^{\mu\nu *}W_{\mu\nu} - \frac{M_{ZZ}}{2\sqrt{2}F} sZ^{\mu\nu}Z_{\mu\nu} - \frac{M_{Z\gamma}}{\sqrt{2}F} sF^{\mu\nu}Z_{\mu\nu}$$
$$-\frac{M_{\gamma\gamma}}{2\sqrt{2}F} sF^{\mu\nu}F_{\mu\nu} - \frac{M_3}{2\sqrt{2}F} s\ G^{a\mu\nu}G^a_{\mu\nu}$$

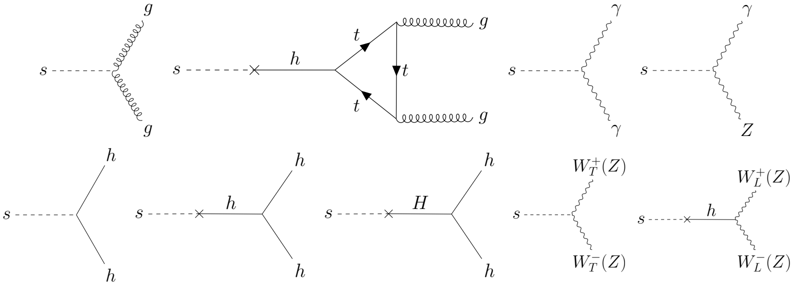
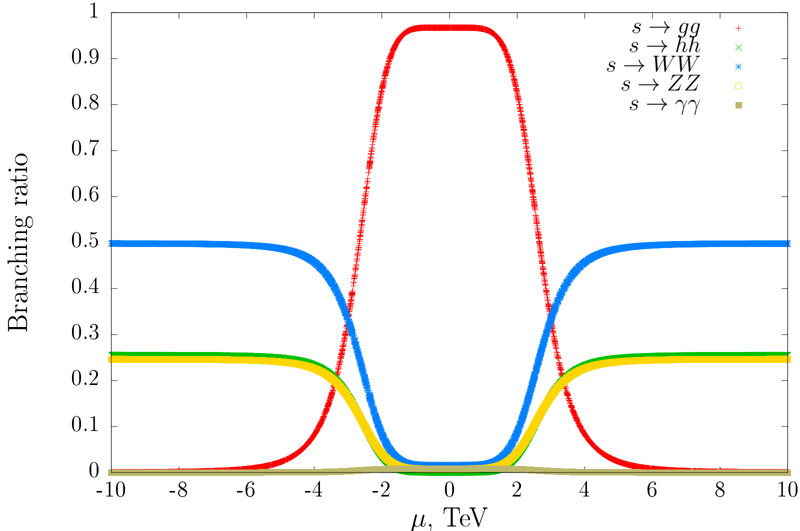


Figure: Feynman diagrams for main sgoldstino decay channels.

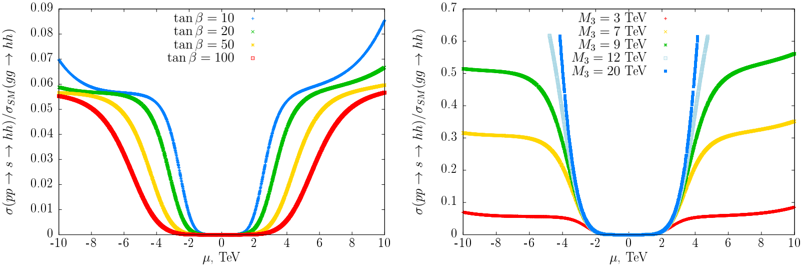
Br for main sgoldstino decay channels

Small $|\mu| \Rightarrow$ gluon domination, large $|\mu| \Rightarrow$ regime 1:2:1

$\tan\beta = 10$, $m_s = 1$ TeV, $m_A = 5$ TeV, $M_1 = M_2 = 1$ TeV, $M_3 = 3$ TeV, $\sqrt{F} = 20$ TeV, K-factor for gg channel $K_d = 1.6$



Resonant double Higgs production ($pp \to s \to hh$)



$m_s = 1$ TeV, $m_A = 5$ TeV, $M_1 = M_2 = 1$ TeV, $\sqrt{F} = 20$ TeV, $K_p = 2$, $K_d = 1.6$. Left panel: $\tan\beta$ varies from 10 to 100, $M_3 = 3$ TeV, right panel: M_3 varies from 3 TeV to 20 TeV, $\tan\beta = 10$.

Critical angles

Sgoldstino (s) decays dominantly to vector bosons if $|\theta| \gg \theta_{cr}$,
s is produced mostly due to mixing with Higgs boson if $|\theta| \gg \theta'_{cr}$,

$$\theta_{cr} \equiv 2\sqrt{2}\frac{M_3 v}{F}, \quad \theta'_{cr} \equiv 6\pi v M_3/(\alpha_s A_t F).$$

Constraints on model parameters

For $\theta_{cr} \ll |\theta| \ll \theta'_{cr}$ sgoldstino production cross section σ_{prod} depends only on the combination M_3/F and
$Br(s \to hh) = Br(s \to ZZ) = 0.25$, $Br(s \to WW) = 0.5$.

Upper bound on M_3/F

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

Searches for heavy neutral scalar by ATLAS and CMS

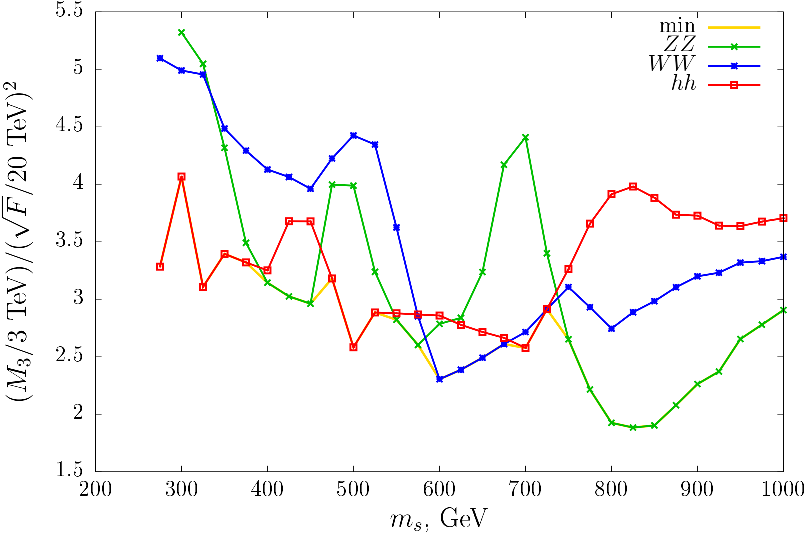
Lower bound on F

$$F(m_s) \geq \frac{(M_3)_{LB}}{(M_3/F)_{UB}(m_s)}$$

Searches for gauge-mediated supersymmetry by ATLAS and CMS

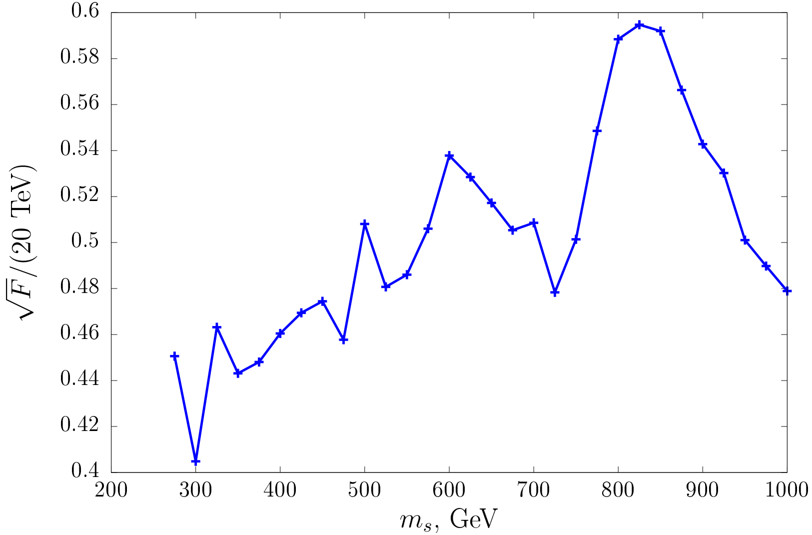
Upper bound on M_3/F from experimental data at 95%CL

for $\sqrt{S} = 13$ TeV, $K_p = 2.0$



Lower bound on $\sqrt{F}$ from experimental data

for $\sqrt{S} = 13$ TeV, $K_p = 2.0$, conservative lower bound $M_3 \geq 2$ TeV



Conclusions

- Model signature: simultaneous production of hh, WW and ZZ in a fixed ratio 1:2:1.
- Results from HL LHC $\Rightarrow$ some constraints?
- Estimate of lower bound on $\sqrt{F} \sim$ scale of SUSY breaking can be useful for further consideration.

Thank you for your attention!

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Backup slides

Potential of scalar fields p.1

$$V = V_{11} + V_{12} + V_{21} + V_{22}, \tag{1}$$

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

$$\left. - \frac{\phi^*\phi}{F^2}\left(m_d^2 h_d^\dagger h_d - m_u^2 h_u^\dagger h_u\right)\right]^2,$$

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

$$\left. - \frac{\phi^*\phi}{F^2}\left(m_d^2 h_d^\dagger \sigma_a h_d + m_u^2 h_u^\dagger \sigma_a h_u\right)\right]^2.$$

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

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

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

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.

Sgoldstino production in LO

$$\sigma_{prod}(pp \to s) = \sigma_0 \tau \int_\tau^1 \frac{\mathrm{d}x}{x} g\left(x, m_s^2\right) g\left(\frac{\tau}{x}, m_s^2\right),$$

$$\sigma_0 = \frac{\pi}{32} \left| \frac{M_3}{F} + \frac{\alpha_s(m_s)\theta}{6\pi v} A\left(\frac{4m_t^2}{m_s^2}\right) \right|^2, \qquad \tau = \frac{m_s^2}{S}.$$

Here $\sqrt{S}$ is the center-of-mass energy in *pp* collisions and $A\left(\frac{4m_t^2}{m_s^2}\right)$ is the loop factor

$$A(\tau_q) = \frac{3}{2}\tau_q \left(1 + (1 - \tau_q) f(\tau_q)\right),$$

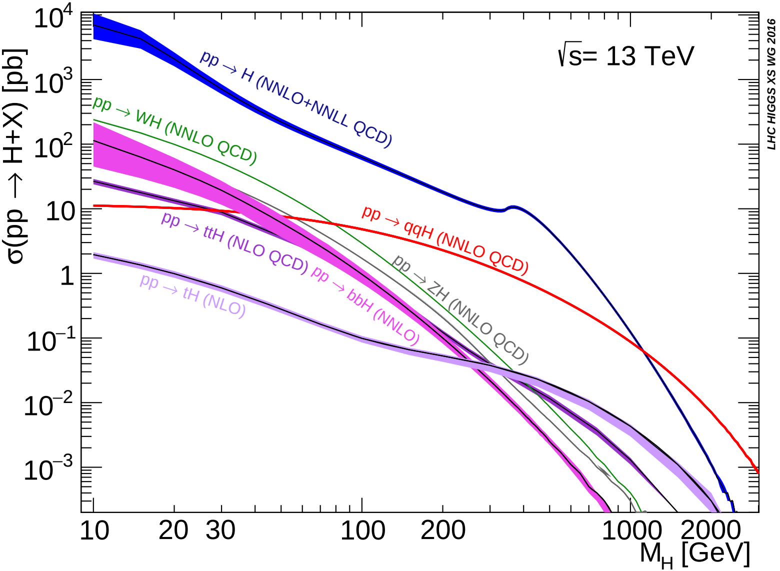
$$f(\tau_q) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau_q}}, & \text{if } \tau_q \geq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau_q}}{1-\sqrt{1-\tau_q}} - i\pi\right]^2, & \text{if } \tau_q < 1. \end{cases}$$

QCD corrections

- NLO K-factor: $K = \sigma_{NLO}/\sigma_{LO}$
- We choose NLO K-factor for sgoldstino production (K_p) using the results of
  C. Anastasiou, C. Duhr, F. Dulat, E. Furlan, T. Gehrmann, F. Herzog, A. Lazopoulos and B. Mistlberger, "CP-even scalar boson production via gluon fusion at the LHC," JHEP **1609**, 037 (2016) [arXiv:1605.05761 [hep-ph]].
- NLO K-factor for sgoldstino decays (K_d) was chosen according to M. Spira, "QCD effects in Higgs physics," Fortsch. Phys. **46**, 203 (1998) [hep-ph/9705337].

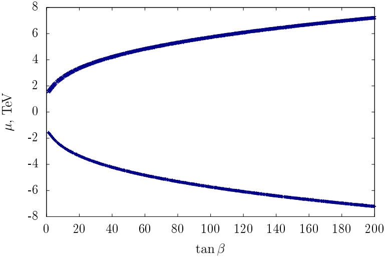
Why gluon fusion?

D. de Florian *et al.* [LHC Higgs Cross Section Working Group], arXiv:1610.07922 [hep-ph].

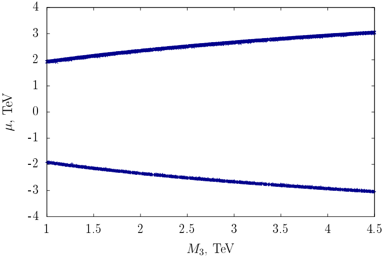


Slices $Br(s \to hh) = 0.125$

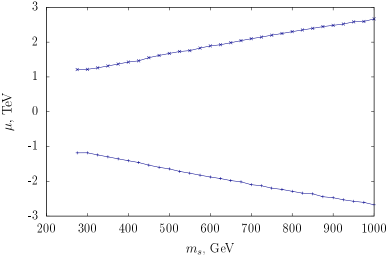
Fixed parameter values $M_1 = M_2 = 1$ TeV, $\sqrt{F} = 20$ TeV.



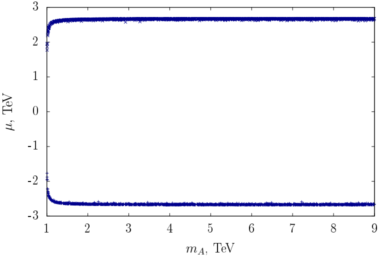
(a) ($\tan\beta, \mu$)



(b) (M_3, μ)



(c) (m_s, μ)



(d) (m_A, μ)