MSSM scenarios with a light CP-odd Higgs boson

Elena Fedotova
in collaboration with M.N. Dubinin

SINP MSU

QFTHEP-2019

September 25, 2019
Sochi

BSM: many reasons but no direct evidence has yet been found at the LHC
SUSY, many free parameters (i.e. infinite parameter sets) $\rightarrow$ benchmark scenarios or BPs for the LHC searches
Though experimental information puts strong indirect constraints on BSM physics, new data are needed to constrain parameter space

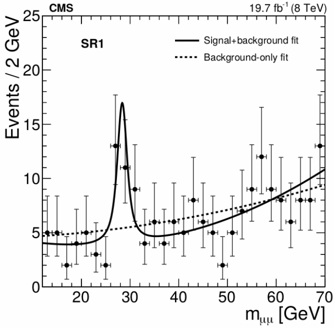
Some hints exist

CMS [2]

- $pp \rightarrow bj\mu^+\mu^-$
- $\sqrt{s}$= 8 and 13 TeV
- 19.7 and 35.9 fb^{-1}
- $m_{\mu\mu}$ ≈28 GeV, Γ ≈1.9 GeV

ATLAS[1] no excess
ALEPH (LEP)

- $Z \rightarrow b\bar{b}\mu\mu$
- $m_{\mu\mu}$=30.40 ± 0.46 GeV
- 2.6σ (5σ)



4.2σ (SR1) and 2.9σ (SR2)

1610.06536 [hep-ex]

ATLAS[1], CMS[2], LHCb[3] and LEP[4] do not exclude the existence of light (pseudo)scalar bosons

Such an excess could

- explain the deviation of the measured $(g-2)_\mu$ [5],
- be a CP-odd Higgs boson of the NMSSM[6]

The possibility of the MSSM CP-odd Higgs boson is excluded in MSSM benchmark scenarios exploited in LHC searches (the SM-like Higgs is in decoupling limit, i.e. $m_h \ll m_{H,A,H^\pm}$)
but at the low scale the MSSM is effective 2HDM, so non-renormalizable operators should be included

Let us discuss the possibility of identification the excess as a CP-odd Higgs boson in MSSM extended by dimension-six operators

[1] ATLAS-CONF-2019-036, JINST 3 (2008) S08003
[2] JHEP 11 (2018) 161, arXiv: 1808.01890[hep-ex], JINST 3 (2008) S08004
[3] JINST 3 (2008) S08005
[4] Nucl. Instrum. Meth. A294 (1990) 121
[5] Godunov, Novikov, Vysotsky, Zhemchugov, JETP Lett. 109, 358 (2019)
[6] Beskidt, Boer, Kazakov, Phys. Lett. B 782, 69 (2018)

$$U_{\text{eff}} = U + U^{(6)} + U^{(8)} + ... \tag{1}$$

$$\begin{aligned} U &= -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - [\mu_{12}^2(\Phi_1^\dagger\Phi_2) + h.c.] \\ &+ \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ [\lambda_5/2(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.] \end{aligned} \tag{2}$$

$$\begin{aligned} U^{(6)} &= \kappa_1(\Phi_1^\dagger\Phi_1)^3 + \kappa_2(\Phi_2^\dagger\Phi_2)^3 + \kappa_3(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2) + \kappa_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2 + \\ &+ \kappa_5(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \kappa_6(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ &+ [\kappa_7(\Phi_1^\dagger\Phi_2)^3 + \kappa_8(\Phi_1^\dagger\Phi_1)^2(\Phi_1^\dagger\Phi_2) + \kappa_9(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)^2 + \\ &+ \kappa_{10}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2) + \kappa_{11}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_1) + \kappa_{12}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2)^2 + \\ &+ \kappa_{13}(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2) + h.c.] \end{aligned} \tag{3}$$

$$U_{\text{eff}} = U + U^{(6)} + U^{(8)} + ... \quad (1)$$

$$\begin{aligned} U &= -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - [\mu_{12}^2(\Phi_1^\dagger\Phi_2) + h.c.] \quad (2) \\ &+ \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ [\lambda_5/2(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.] \end{aligned}$$

$$\begin{aligned} U^{(6)} &= \kappa_1(\Phi_1^\dagger\Phi_1)^3 + \kappa_2(\Phi_2^\dagger\Phi_2)^3 + \kappa_3(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2) + \kappa_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2 + \\ &+ \kappa_5(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \kappa_6(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ &+ [\kappa_7(\Phi_1^\dagger\Phi_2)^3 + \kappa_8(\Phi_1^\dagger\Phi_1)^2(\Phi_1^\dagger\Phi_2) + \kappa_9(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)^2 + \\ &+ \kappa_{10}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2) + \kappa_{11}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_1) + \kappa_{12}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2)^2 + \\ &+ \kappa_{13}(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2) + h.c.] \quad (3) \end{aligned}$$

$$U_{\text{eff}} = U + U^{(6)} + U^{(8)} + ... \tag{1}$$

$$\begin{aligned} U \;=\; & -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - [\mu_{12}^2(\Phi_1^\dagger\Phi_2) + h.c.] \\ +\; & \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ +\; & [\lambda_5/2(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.] \end{aligned} \tag{2}$$

$$\begin{aligned} U^{(6)} \;=\; & \kappa_1(\Phi_1^\dagger\Phi_1)^3 + \kappa_2(\Phi_2^\dagger\Phi_2)^3 + \kappa_3(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2) + \kappa_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2 + \\ +\; & \kappa_5(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \kappa_6(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ +\; & [\kappa_7(\Phi_1^\dagger\Phi_2)^3 + \kappa_8(\Phi_1^\dagger\Phi_1)^2(\Phi_1^\dagger\Phi_2) + \kappa_9(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)^2 + \\ +\; & \kappa_{10}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2) + \kappa_{11}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_1) + \kappa_{12}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2)^2 + \\ +\; & \kappa_{13}(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2) + h.c.] \end{aligned} \tag{3}$$

$$U_{\text{eff}} = U + U^{(6)} + U^{(8)} + ... \tag{4}$$

$$\begin{aligned} U &= -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - [\mu_{12}^2(\Phi_1^\dagger\Phi_2) + h.c.] \\ &+ \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ [\lambda_5/2(\Phi_1^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.] \end{aligned} \tag{5}$$

$$\begin{aligned} U^{(6)} &= \kappa_1(\Phi_1^\dagger\Phi_1)^3 + \kappa_2(\Phi_2^\dagger\Phi_2)^3 + \kappa_3(\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2) + \kappa_4(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2 + \\ &+ \kappa_5(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \kappa_6(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \\ &+ [\kappa_7(\Phi_1^\dagger\Phi_2)^3 + \kappa_8(\Phi_1^\dagger\Phi_1)^2(\Phi_1^\dagger\Phi_2) + \kappa_9(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)^2 + \\ &+ \kappa_{10}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_2) + \kappa_{11}(\Phi_1^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_1) + \kappa_{12}(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2)^2 + \\ &+ \kappa_{13}(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2) + h.c.] \end{aligned} \tag{6}$$

Different methods, codes, assumptions

... to dimension-four operators[7]

$$\begin{aligned}\Delta\lambda_4^{2-\mathrm{loop}} &= \frac{3}{8\pi^2}h_t^2h_b^2\frac{1}{16\pi^2}(h_b^2+h_t^2-8g_S^2)(X_{tb}l+l^2)\\ &- \frac{3}{96\pi^2}h_t^4\frac{1}{16\pi^2}\frac{|\mu|^2}{M_{\mathrm{SUSY}}^2}(3-\frac{|A_t|^2}{M_{\mathrm{SUSY}}^2})(6h_t^2-2h_b^2-16g_S^2)l\\ &- \frac{3}{96\pi^2}h_b^4\frac{1}{16\pi^2}\frac{|\mu|^2}{M_{\mathrm{SUSY}}^2}(3-\frac{|A_b|^2}{M_{\mathrm{SUSY}}^2})(6h_b^2-2h_t^2-16g_S^2)l, \qquad l=\log(M_S^2/m_t^2) \qquad (7)\end{aligned}$$

... to dimension-six operators[8]

$$\begin{aligned}\Delta\kappa_1^{\mathrm{thr}} &= \frac{h_b^6}{32M_S^2\pi^2}\left(2-\frac{3|A_b|^2}{M_S^2}+\frac{|A_b|^4}{M_S^4}-\frac{|A_b|^6}{10M_S^6}\right)\\ &- h_b^4\frac{g_1^2+g_2^2}{128M_S^2\pi^2}\left(3-3\frac{|A_b|^2}{M_S^2}+\frac{|A_b|^4}{2M_S^4}\right)+\frac{h_b^2}{512M_S^2\pi^2}\\ &\times \left(\frac{5}{3}g_1^4+2g_1^2g_2^2+3g_2^4\right)\left(1-\frac{|A_b|^2}{2M_S^2}\right)-h_t^6\frac{|\mu|^6}{320M_S^8\pi^2}+h_t^4\frac{(g_1^2+g_2^2)|\mu|^4}{256M_S^6\pi^2}\\ &- h_t^2\frac{(17g_1^4-6g_1^2g_2^2+9g_2^4)|\mu|^2}{3072M_S^4\pi^2}+\frac{g_1^2}{1024M_S^2\pi^2}(g_1^4-g_2^4), \qquad (8)\end{aligned}$$

[7] Carena, Ellis, Pilaftsis, Wagner, Nucl. Phys. B 586, 92 (2000), etc
[8] Dubinin, Petrova, Phys. Rev. D 95, 055021 (2017)

1. h, H, A, H^+, H^- in CP-conserving limit
2. only 3d generation of squarks are important and have a common mass scale M_S
3. all other SUSY particles are integrated out
4. free parameters: $\tan\beta, M_S, A_{t,b}, \mu$ and m_A
5. the Higgs-boson couplings to the heavier SM particles are SM-like (alignment limit)
6. perturbative unitarity[9] $|\mathrm{Re}(x_i)| < 1$
7. vacuum stability ('heuristic' bound[10])

$$\frac{\max(A_{t,b}, \mu)}{\min(m_{Q_3,U_3})} \leq 3 \tag{9}$$

Selection of model parameters

Let us fix

1. m_A=28 GeV
2. M_S and $\tan\beta$ and ajust A, μ in such a way that $m_{h/H}$=125 GeV in alignment limit ($0 < A_{t,b},\ \mu < 10$ TeV)

---

[9] Kanemura, Yagyu, Phys. Lett. B751 (2015)

[10] Hollik, Weiglein, Wittbrodt, JHEP 1903 (2019) 109

$\tan\beta$	dim	M_S (GeV) 600	1000	2000	3500	5000
1	four	h^{125}, H^{125}	h^{125}, H^{125}	h^{125}	h^{125}	–
	six	–	h^{125}, H^{125}	h^{125}, H^{125}	–	–
2	four	h^{125}	h^{125}	h^{125}	–	–
	six	h^{125}, H^{125}	h^{125}, H^{125}	h_{al}^{125}, H^{125}	H^{125}	H^{125}
3	four	h^{125}	h^{125}	H^{125}	–	–
	six	h^{125}, H^{125}	h^{125}, H^{125}	h_{al}^{125}, H^{125}	H^{125}	–
5	four	h^{125}	h^{125}	h^{125}	–	–
	six	h^{125}, H^{125}	h_{al}^{125}, H^{125}	h_{al}^{125}, H^{125}	H^{125}	–
15	four	h^{125}	h^{125}	h^{125}	h^{125}	–
	six	h^{125}	h^{125}	h^{125}	h^{125}	–
20	four	h^{125}	h^{125}	h^{125}	h^{125}	–
	six	h^{125}	h^{125}	h^{125}	h^{125}	–

Appropriate parameter sets

BPs	$\tan\beta$	M_S, GeV	$A_{t,b}$, GeV	μ, GeV
1	2	2000	8800	5320
2	3	2000	7820	6450
3	5	1000	3385	5040
4	5	2000	6690	7960

Model predictions

BPs	m_H, GeV	$m_{H^\pm}$, GeV	$\max\lvert x_i\rvert$	Γ_A, GeV
1	134.4	129.7	2.1	0.01
2	132.3	130.0	1.6	0.01
3	127.7	127.3	6.6	0.03
4	130.4	131.3	1.9	0.03

– non-decoupling limit

– at the limit of fulfillment of the vacuum stability and perturbative unitarity conditions

Appropriate parameter sets

BPs	$\tan\beta$	M_S, GeV	$A_{t,b}$, GeV	μ, GeV
1	2	2000	8800	5320
2	3	2000	7820	6450
3	5	1000	3385	5040
4	5	2000	6690	7960

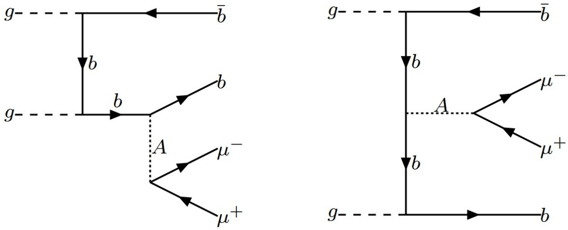
Model predictions

BPs	m_H, GeV	$m_{H^\pm}$, GeV	$\max\lvert x_i\rvert$	Γ_A, GeV
1	134.4	129.7	2.1	0.01
2	132.3	130.0	1.6	0.01
3	127.7	127.3	6.6	0.03
4	130.4	131.3	1.9	0.03

– non-decoupling limit

– at the limit of fulfillment of the vacuum stability and perturbative unitarity conditions

Cross sections



Cuts

Muons	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.1$, $m_{\mu\mu} > 12$ GeV
b-jet	$p_T >$30 GeV, $\eta \leq 2.4$
$\bar{b}$-jet	$p_T >$30 GeV, $2.4 \leq \lvert\eta\rvert \leq 4.7$ (SR1), $\eta \leq 2.4$ (SR2)

Cut-A: all background diagrams are omitted, $\bar{b}$ for SR1 event category

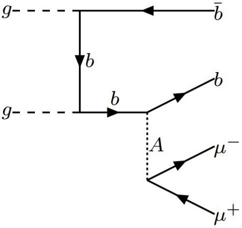
Cut-B: all background diagrams are omitted, $\bar{b}$ for SR2 event category, 25 GeV$\leq m_{\mu\mu} \leq$ 32 GeV

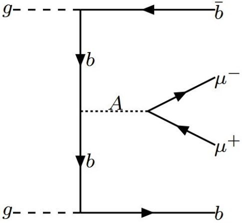
Cut-C: SR1 event category

Cut-D: SR2 event category

Cut-E: SR2 event category, 25 GeV $\leq m_{\mu\mu} \leq$ 32 GeV

Cross sections





Cuts

Muons	$p_T > 25$ GeV, $\lvert\eta\rvert < 2.1$, $m_{\mu\mu} > 12$ GeV
b-jet	$p_T >$30 GeV, $\eta \leq 2.4$
$\bar{b}$-jet	$p_T >$30 GeV, $2.4 \leq \lvert\eta\rvert \leq 4.7$ (SR1), $\eta \leq 2.4$ (SR2)

Cut-A: all background diagrams are omitted, $\bar{b}$ for SR1 event category

Cut-B: all background diagrams are omitted, $\bar{b}$ for SR2 event category, 25 GeV$\leq m_{\mu\mu} \leq$ 32 GeV

Cut-C: SR1 event category

Cut-D: SR2 event category

Cut-E: SR2 event category, 25 GeV $\leq m_{\mu\mu} \leq$ 32 GeV

$\sigma(gg \to b\bar{b}A) \times BR(A \to \mu^+\mu^-)$

Table: $\sigma(gg \to b\bar{b}A) \times BR(A \to \mu^+\mu^-)$ (fb), where BR$(A \to \mu^+\mu^-) = 1.6 \cdot 10^{-4}$. Cut-A and Cut-B are imposed on $b, \bar{b}$ jets for SR1 and SR2 event categories, correspondingly.

$\sqrt{s}$ TeV	$\tan\beta$	SR1 $\sigma(gg \to bbA)$ (fb)	SR1 $\sigma \times BR$ (fb)	SR2 $\sigma(gg \to bbA)$ (fb)	SR2 $\sigma \times BR$ (fb)
8	2	56.63	0.009	386.27	0.062
	3	127.19	0.020	870.73	0.139
	5	355.90	0.057	2423.10	0.388
13	2	165.68	0.026	904.65	0.145
	3	370.38	0.059	2021.10	0.323
	5	1040.88	0.167	5640.90	0.903

$\sqrt{s}$	8 TeV		13 TeV	
Event category	SR1	SR2	SR1	SR2
CMS σ_{fid} (fb)	4.1 ± 1.4	4.2 ± 1.7	1.4 ± 0.9	-1.5 ± 1.0

Table: $\sigma(gg \to \mu^+\mu^- b\bar{b})$ (fb) for SR1 and SR2 categories.

		SR1		SR2		
$\sqrt{s}$	BP	Cut-A	Cut-C	Cut-B	Cut-D	Cut-E
8 TeV	1	0.009	10.094	0.065	267.240	0.730
	2	0.020	13.242	0.134	236.750	0.742
	3	0.056	8.814	0.384	270.810	0.758
	4	0.057	9.800	0.387	223.870	0.769
13 TeV	1	0.027	55.994	0.148	571.790	1.887
	2	0.058	48.692	0.310	609.650	1.903
	3	0.165	53.642	0.902	610.500	1.972
	4	0.191	31.760	0.905	587.320	1.970

Conclusions

- light pseudoscalar with the mass m_A =28 GeV can be embedded in the two-doublet MSSM Higgs sector extended by dimension-six effective operators respecting the alignment limit for h(125 GeV) state in a rather specific range of parameter space, when the superparticle mass scale is around 1–2 TeV, $\tan\beta \sim$ 2–5 and soft SUSY breaking parameters $A_{t,b}, \mu$ are large, from 3 TeV to 9 TeV;
- such range of the MSSM parameter space is at the limit of fulfillment of the vacuum stability and perturbative unitarity conditions;
- cross section calculations at the tree level for the partonic level signal in $pp \to \mu^+\mu^- b\bar{b}$ at the energies $\sqrt{s}$ =8 and 13 TeV give signal cross sections by a factor of 2–5 smaller than the experimentally obtained cross section of a few fb;
- numerical estimations based on charged Higgs boson production due to top quark decay are in agreement with current LHC constraints