Aspects of search for new physics at the LHC

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With the LHC running, the focus of experimental and theoretical high energy physics is on interpretation of the LHC data in terms of physics of electroweak symmetry breaking and possible new phenomena at the TeV scale. Review of some aspects related to models for new TeV-scale physics and their LHC signatures is presented. We also discuss possible new physics signatures and describe how they can be linked to specific models of physics beyond the Standard Model.

NUST MISiS

Lecture 1, February 2020.

Outline

- Why new physics at the multiTeV scale?

    - Gauge hierarchy problem
    - Dark matter and dark energy in the Universe
    - Baryon asymmetry of the universe

- Popular models
    - Supersymmetry
    - Extra dimensions
    - Extensions of the Higgs sector

- Reconstruction of the underlying theory

    - Model independent searches. Effective operators of higher dimensions. ATLAS - CMS combination for the Higgs boson identification. Kappa-scheme. Pseudoobservables.

    - Model dependent searches. Effective field theory at the m_{top} scale. MSSM two-doublet Higgs sector.

Standard Model (SM)

Fermions

$$\psi_L^l = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, e_R^-, \mu_R^-, \tau_R^-, \nu_R^{e,\mu,\tau}$$

$$\psi_L^q = \begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L, u_R, d_R, c_R, s_R, t_R, b_R$$

$SU(2)$ **states** d'_L, s'_L, b'_L **are related to mass states** d_L, s_L, b_L **by unitary transformation defined by CKM matrix.**

Scalars

$\varphi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}$, **where** $\varphi_1 = \varphi^+$ **charged Goldstone field,** $\varphi_2 = \varphi^0$ **neutral field.**

Gauge fields

triplet W_μ^+, W_μ^-, Z^0 **and singlet** A_μ.

$$\begin{aligned} L_{SM} = \quad & i\bar{\psi}_L^l \gamma^\mu \nabla_\mu \psi_L^l + i\bar{\psi}_R^l \gamma^\mu \nabla_\mu \psi_R^l + i\bar{\nu}_R \gamma^\mu \nabla_\mu \nu_R \\ & + i\bar{\psi}_L^q \gamma^\mu \nabla_\mu \psi_L^q + i\bar{\psi}_R^u \gamma^\mu \nabla_\mu \psi_R^u + i\bar{\psi}_R^d \gamma^\mu \nabla_\mu \psi_R^d \\ & + \nabla_\mu \varphi^+ \nabla^\mu \varphi + \mu^2 (\varphi^+ \varphi) - \frac{\lambda}{4} (\varphi^+ \varphi)^2 \\ & - \frac{1}{2} Sp\, G_{\mu\nu} G^{\mu\nu} - \frac{1}{2} Sp\, V_{\mu\nu} V^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ & - g_l^{ik} \bar{\psi}_L^{li} \psi_R^{lk} \varphi - g_l^{*ki} \bar{\psi}_R^{lk} \psi_L^{li} \varphi^+ \\ & - g_\nu \bar{\psi}_L \nu_R \varphi^c - g_\nu^* \bar{\nu}_R \psi_L \varphi^{c+} \\ & - g_d^{ik} \bar{\psi}_L^{qi} \psi_R^{dk} \varphi - g_d^{*ki} \bar{\psi}_R^{dk} \psi_L^{qi} \varphi^+ \\ & - g_u^{ik} \bar{\psi}_L^{qi} \psi_R^{uk} \varphi^c - g_u^{*ki} \bar{\psi}_R^{uk} \psi_L^{qi} \varphi^{c+} \end{aligned}$$

Problems of the Standard Model (SM)

(1) EW symmetry breaking is the main concept of the SM. Mass parameter of the Higgs boson is extremely sensitive to quantum corrections. Extrapolation of the SM to energies much greater than the EW scale lead to gauge hierarchy problem, where unnatural fine-tuning of the SM parameters is required to get correct value of the EW scale.

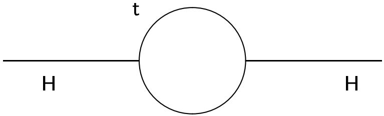
(2) The SM does not include any particle – candidate for the DM in the Universe. A new stable heavy particle weakly interacting with the SM naturally leads to correct relic density of DM through the process of thermal freeze-out in the early Universe. New weakly interacting heavy states protect the EW scale against quantum instabilities.

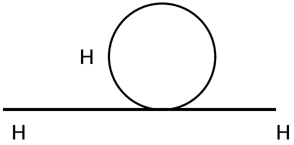
(3) The SM cannot explain the asymmetry of visible matter over antimatter. New Physics at TeV scale could give rise to this baryon asymmetry.

(4) The SM cannot explain flavor mixing and the origin of neutrino masses (neutrino oscillations).

Gauge hierarhy problem - illustration

Corrections to "bare"Higgs boson mass parameter m_O at the one loop, $m_H^2 = m_0^2 + \Sigma(m) = m_0^2 + \Delta m_H^2$ where mass operator $\Sigma(p)$ is divergent





one-loop corrections from top quark (left) and Higgs boson loop (right), $d^4p = \pi^2 p^2 dp^2$,

$$-\frac{3g_t^2}{(4\pi)^2}\int_0^{\Lambda}\frac{d^4p}{\hat{p}^2} \quad \Longrightarrow \quad \Delta m_H^2 = -\frac{3g_t^2}{(4\pi)^2}\Lambda^2 \qquad OR \quad \Delta m_H^2 = \frac{\lambda}{(4\pi)^2}\Lambda^2$$

where Λ can be up to $\sim M_{Planck} = 1/\sqrt{G} = 1.2 \cdot 10^{19}$ GeV in the natural system of units $c = \hbar = 1$.

or in the renormalized propagator $\Sigma_R(p)$ in the Pauli-Villars framework

$$\begin{aligned} &Z^{-1}\Sigma_R(k) = \Sigma(k) - \Sigma(m) - (k^2 - m^2)\Sigma'(m) \\ &Z^{-1} = 1 - \Sigma'(m), \quad m^2 = m_0^2 + \Sigma(m) \\ &G(p) = \frac{1}{k^2 - m_0^2 - \Sigma(k)}, \quad G_R(k) = \frac{1}{k^2 - m^2 - \Sigma_R(k)} \\ &G(k) = Z\, G_R(k) \end{aligned}$$

compensation of bare mass parameter m_0^2 and quadratically divergent mass operator $\Sigma(k)$ to get pole mass $m =$125 GeV is 34 orders of magnitude.

Dark matter problem

Most of the matter in the Universe is in the form of non-relativistic heavy particle species very weakly interacting with the SM particles. Most popular example: gravitational lens

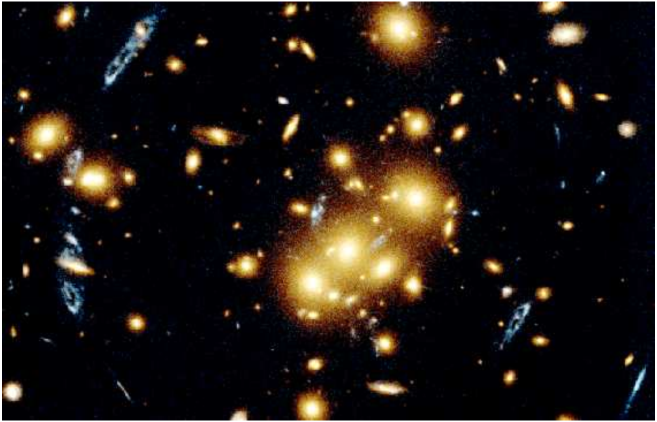


Рис.: source: J.Kneib et al, Astrophys.J. 598 (2003) 804

There is no dark matter candidate in the SM.

Dark energy problem

Let us estimate the energy density of the Universe ρ combining observables of proper dimension. Gravitational constant $\gamma = \frac{1}{M_P^2}$ GeV^{-2} is connected with Planck mass M_P =1.2·10^{19} GeV. The energy density ρ is of dimension GeV^4 (in the HEP natural units c=$\hbar$=1; in the usual units the dimension is GeV/cm^3). So the "gravitational charge" $\gamma\rho$ has the dimension GeV^2 and this quantity defines an observable expansion of the Universe caused by gravity. The same dimension GeV^2 can be provided by the Hubble constant H_0 squared[1]. Numerically $H_0 = 73$ km/(sec Mpc)[2]. Assuming that the dimensionless combination $H_0^2(\gamma\rho)^{-1}$ is of the order of 1 we get

$$\rho = \gamma^{-1} H_0^2 = M_P^2 H_0^2 = 10^{-5} \frac{GeV}{cm^3} \sim 10^{-47} GeV^4$$

From other side, the electroweak vacuum of the Standard Model has the energy density

$$\rho_{EW} \sim v^4 \sim 10^8 GeV^4.$$

So the difference between vacuum energy density estimates based on astrophysical observations and vacuum energy density of the SM which is pecisely defined by Fermi constant G_F of particle decays is 55 orders of magnitude.

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[1] **Hubble parameter $H(t) = \dot{r}(t)/r(t)$ defines relative increase of the distance in a unit of time. For small departures in the stellar objects spectrum z Hubble law is $z = H_0 r$, r is the distance to an object**

[2] **1 Mpc=10^6 pc=3.1·10^{24} cm. 1 cm = 5·10^{13} GeV-1**

Dark energy in the ΛCDM cosmological model

$\Omega_\Lambda = \rho_\Lambda / \rho_c$ – energy density fraction of the Universe provided by dark energy
$\Omega_m = \rho_M / \rho_c$ – energy density fraction of the Universe provided by dark matter
Regions consistent with observation of the CMB, supernova, and structure formation

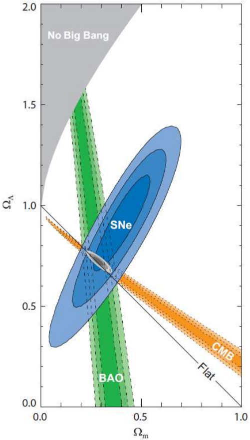


Рис.: From Kowalski et al, *Improved cosmological constraints from new, old and combined supernova datasets*, arXiv:0804.4142[astro-ph]

Baryon asymmetry problem

In the early Universe at the temperature of the order of 100 MeV-1 intensive processes of quark (positive baryon number) – antiquark (negative baryon number) creation and annihilation took place. Qualitative thermodynamics estimate

$$\frac{N_q - N_{\bar{q}}}{N_q + N_{\bar{q}}} \approx \frac{N_{baryons}}{N_{photons}} \approx 10^{-10}$$

In the process of expansion quarks annihilate with antiquarks to photons but some redundant quarks form the existing baryonic matter plus relic photons. What is the mechanism to form redundant quarks? SM does not provide sufficient CP violation to form baryon asymmetry.

WMAP

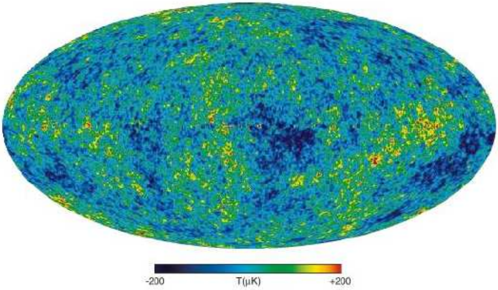


Рис.: Energy of relic photons from celestial sphere. Average termerature 2.7 K is subtracted, so the fluctuation dT/T of the relic background temperature is shown, which does not exceed 10^{-4}. Relic photons came out of primordial Big Bang plasma 400 thousand years ago. Source: G.Hinshaw et al, Three year WMAP observations..., astro-ph/060345

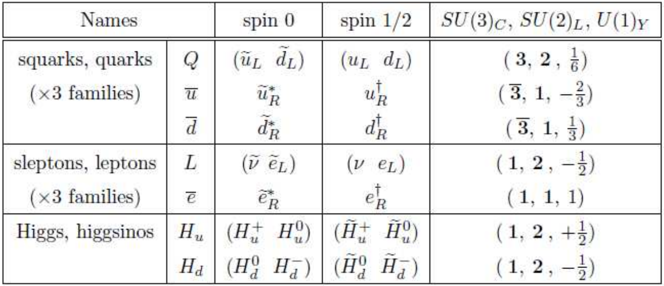
Models. General.

Experimental and theoretical shortcomings of the SM initiated increasing number of models with new physics at TeV scale. Not all of these models solve or address all of the problems, but two primary issues are focused upon (1) the mechanism of electroweak symmetry breaking (2) the observation of dark matter.

For a long time supersymmetry has been a favorite candidate for new physics beyond the Standard Model (BSM physics). Advantages
– SUSY is renormalizable perturbative field theory
– naturally accounts for the gauge hierarchy between the EW and the Planck scales
– includes consistent mechanism of EW symmetry breaking (two-doublet Higgs sector)
– includes candidates for the dark matter
– includes additional sources of CP violation to produce baryon asymmetry
– ensures unification of electromagnetic, weak and QCD couplings at the GUT scale 10^{15} GeV

Models. Supersymmetry.

In the Minimal Supersymmetric Standard Model (MSSM) all SM particles are embedded in supermultiplets. Fermions of the SM are placed in chiral multiplets.



Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

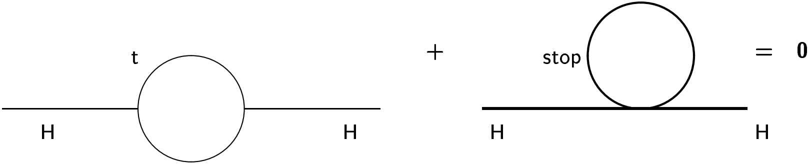
Рис.: Chiral supermultiplets in the MSSM.

Models. Supersymmetry.

Vector supermultiplets contain a SM vector field and a chiral Weyl fermion.

Names	spin 1/2	spin 1	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	(8, 1 , 0)
winos, W bosons	$\widetilde{W}^{\pm}$ $\widetilde{W}^0$	$W^{\pm}$ W^0	(1, 3 , 0)
bino, B boson	$\widetilde{B}^0$	B^0	(1, 1 , 0)

Рис.: Vector supermultiplets in the MSSM.



Cancellation of quadratic divergences in the MSSM.

MSSM. Benchmark models. Signatures.

Example of a simple model with reduced parameter space: constrained MSSM (cMSSM). Also called minimal supergravity (mSUGRA). Universal soft SUSY breaking terms are introduced at a large mass scale of the order of M_{GUT}. Parameters of soft SUSY breaking terms are taken in the form of degenerate sets
– all mass parameters of scalar superpartners are set to a common M_0
– all trilinear soft parameters are set to A
– all gaugino masses are taken to be $M_{1/2}$ at the GUT scale
– superfield mass parameter μ
– Higgs sector parameters m_A, $\tan\beta$
furter simplification in some models $M_0 = M_{1/2}$ scalar superpartners mass scale.
Rather standard useful five-dimensional parameter space
m_A, $\tan\beta$, M_S, μ, A
which defines the superpartner and the Higgs boson mass spectrum.
In such models the dark matter candidate is neutralino LSP.
Neverteless such parametrization has no convincing theoretical motivation and imposes certain constrains on the MSSM particles mass spectrum which should be consistent with LHC exclusion limits.

MSSM lagrangian - soft SUSY breaking terms

$$\mathcal{V}^{\,0} = \mathcal{V}_M + \mathcal{V}_\Gamma + \mathcal{V}_\Lambda + \mathcal{V}_{\widetilde{Q}}\,,$$

where

$$\mathcal{V}_M = (-1)^{i+j} m_{ij}^2 \Phi_i^\dagger \Phi_j + M_{\widetilde{Q}}^{\,2} \left(\widetilde{Q}^{\,\dagger} \widetilde{Q}\right) + M_{\widetilde{U}}^{\,2} \widetilde{U}^* \widetilde{U} + M_{\widetilde{D}}^{\,2} \widetilde{D}^* \widetilde{D}\,,$$

$$\mathcal{V}_\Gamma = \Gamma_i^D \left(\Phi_i^\dagger \widetilde{Q}\right) \widetilde{D} + \Gamma_i^U \left(i\Phi_i^T \sigma_2 \widetilde{Q}\right) \widetilde{U} + \overset{*}{\Gamma}{}_i^D \left(\widetilde{Q}^{\,\dagger} \Phi_i\right) \widetilde{D}^* - \overset{*}{\Gamma}{}_i^U \left(i\widetilde{Q}^{\,\dagger} \sigma_2 \Phi_i^*\right) \widetilde{U}^*\,,$$

$$\mathcal{V}_\Lambda = \Lambda_{ik}^{jl} \left(\Phi_i^\dagger \Phi_j\right) \left(\Phi_k^\dagger \Phi_l\right) + \left(\Phi_i^\dagger \Phi_j\right) \left[\Lambda_{ij}^Q \left(\widetilde{Q}^{\,\dagger} \widetilde{Q}\right) + \Lambda_{ij}^U \widetilde{U}^* \widetilde{U} + \Lambda_{ij}^D \widetilde{D}^* \widetilde{D}\right] +$$

$$+ \overline{\Lambda}{}_{ij}^{\,Q} \left(\Phi_i^\dagger \widetilde{Q}\right) \left(\widetilde{Q}^{\,\dagger} \Phi_j\right) + \frac{1}{2} \left[\Lambda \epsilon_{ij} \left(i\Phi_i^T \sigma_2 \Phi_j\right) \widetilde{D}^* \widetilde{U} + h.c.\right]\,, \quad i, j,\, k, l = 1, 2\,,$$

$\mathcal{V}_{\widetilde{Q}}$ denotes the four scalar quarks interaction terms, Pauli matrix $\sigma_2 \equiv \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}$.
The Yukawa coupligs for the third generation of scalar quarks are defined in a standard way $h_{\,t} = \frac{\sqrt{2}\, m_{\,t}}{v \sin\beta}$, $h_{\,b} = \frac{\sqrt{2}\, m_b}{v \cos\beta}$, $\Gamma_{\{1;\,2\}}^{\,U} \equiv h_U \{-\mu; A_U\}$, $\Gamma_{\{1;\,2\}}^{\,D} \equiv h_D \{A_D\,; -\mu\}$.

MSSM. Signatures.

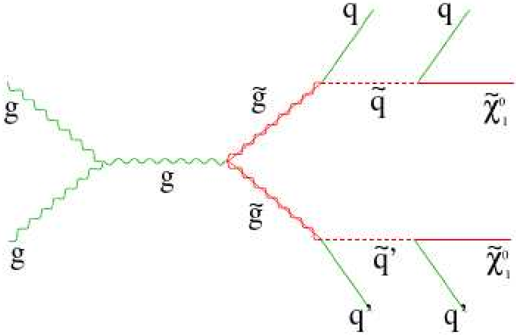


Рис.: Cascade decay with a neutralino LSP in cMSSM.

MSSM. Signatures.

Stable neutralino LSP leave the detector without generating a signal. They can be registered indirectly by measuring imbalanced momentum (e.g. sum of visible transverse momenta of particles in the event) and/or imbalanced energy

$$\vec{p}_T^{\,missing} = \sum_{visible} \vec{p}_{Ti} = - \sum_{invisible} \vec{p}_{Ti}$$

Reconstruction of the missing energy is difficult - all particle associated with the signal should be measured separating the SM backgrounds and detector properties
– missing momentum can appear due to wrong detector detector performance (energy loss)
– missing energy is easily produced in the SM backgrounds with $Z \to \nu\nu$ and $W \to e\nu$
Other specific signatures
– resonances from new heavy vector bosons
– multi-jet resonances

SM. Charged particle production.

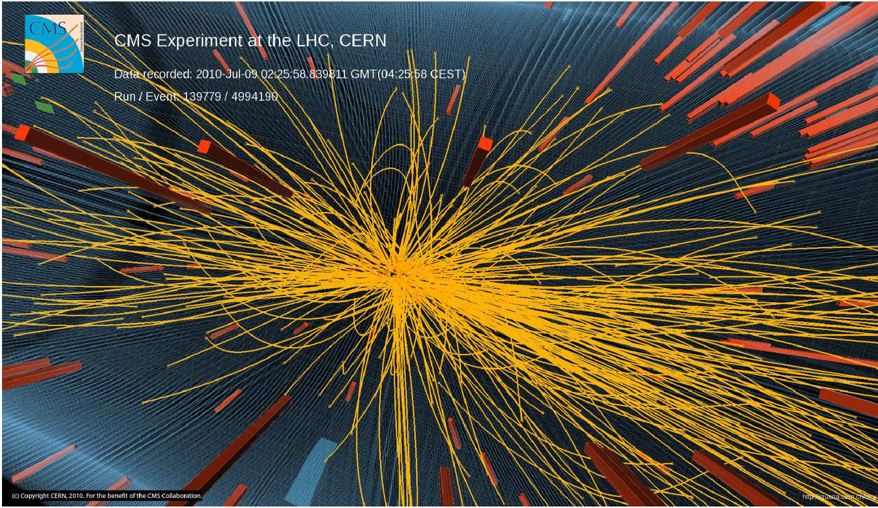
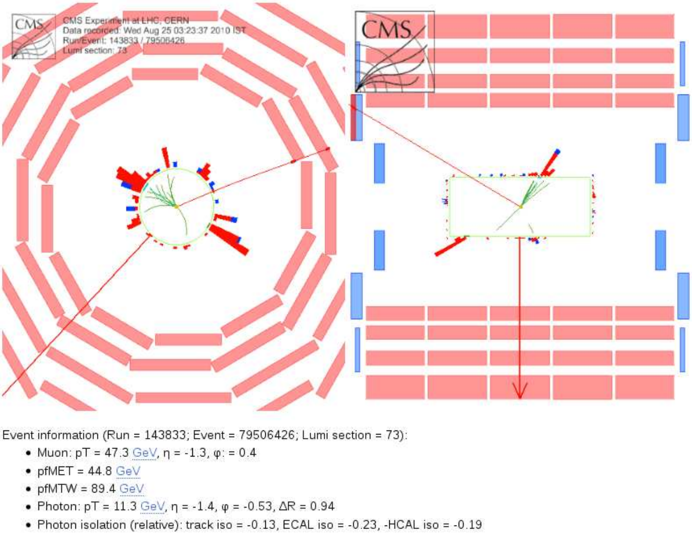


Рис.: CMS event at $\sqrt{s}$ =7 TeV

SM. Missing p_T.

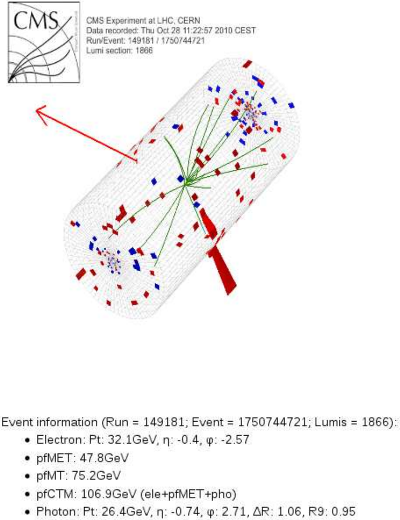


Event information (Run = 143833; Event = 79506426; Lumi section = 73):

- Muon: pT = 47.3 GeV, η = -1.3, φ: = 0.4
- pfMET = 44.8 GeV
- pfMTW = 89.4 GeV
- Photon: pT = 11.3 GeV, η = -1.4, φ = -0.53, ΔR = 0.94
- Photon isolation (relative): track iso = -0.13, ECAL iso = -0.23, -HCAL iso = -0.19

Рис.: SM event with $W \to \mu\nu\gamma$ at $\sqrt{s}$ =7 TeV

SM. Missing p_T.

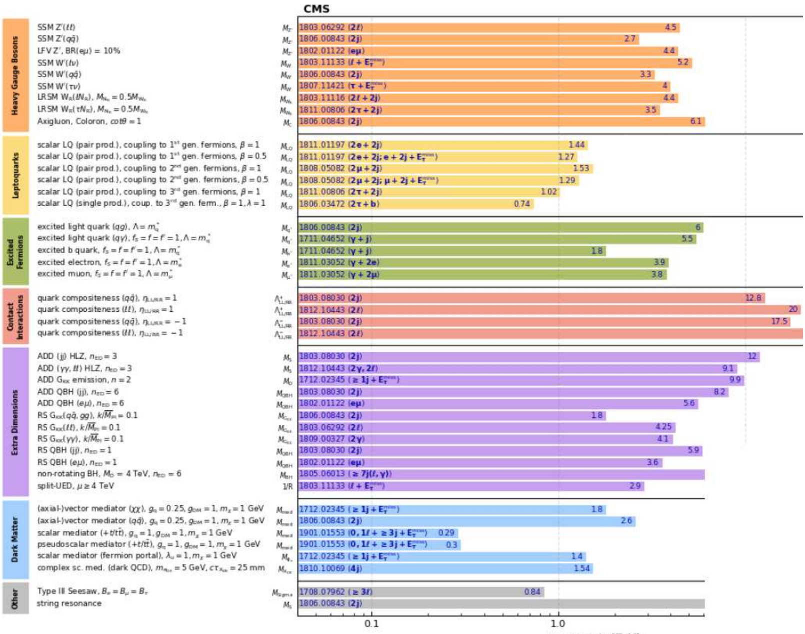


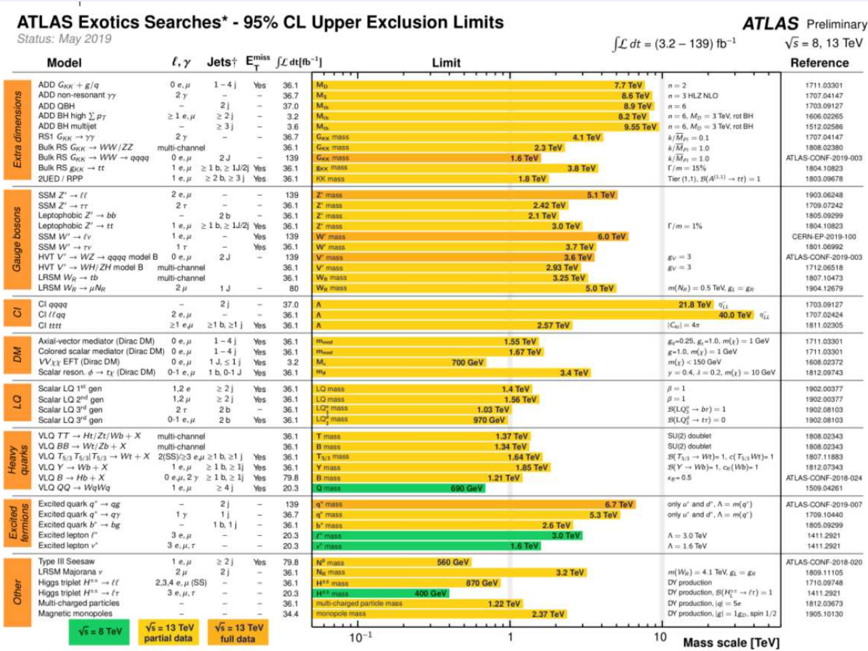
Event information (Run = 149181; Event = 1750744721; Lumis = 1866):

- Electron: Pt: 32.1GeV, η: -0.4, φ: -2.57
- pfMET: 47.8GeV
- pfMT: 75.2GeV
- pfCTM: 106.9GeV (ele+pfMET+pho)
- Photon: Pt: 26.4GeV, η: -0.74, φ: 2.71, ΔR: 1.06, R9: 0.95

Рис.: SM event with $W \to e\nu\gamma$ at $\sqrt{s}$ =7 TeV

Overview of CMS EXO results





ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)\ \text{fb}^{-1}$

$\sqrt{s} = 8, 13$ TeV

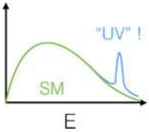
	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK}+g/q$	0 e,μ	1 − 4 j	Yes	36.1	M_D 7.7 TeV	$n=2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n=6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl}=0.1$	1707.04147
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
	Bulk RS $G_{KK}\to WW\to qqqq$	0 e,μ	2 J	–	139	G_{KK} mass 1.6 TeV	$k/\overline{M}_{Pl}=1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK}\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
Gauge bosons	SSM $Z'\to\ell\ell$	2 e,μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z'\to\tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass 3.0 TeV	$\Gamma/m=1\%$	1804.10823
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	139	W' mass 6.0 TeV		CERN-EP-2019-100
	SSM $W'\to\tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $V'\to WZ\to qqqq$ model B	0 e,μ	2 J	–	139	V' mass 3.6 TeV	$g_V=3$	ATLAS-CONF-2019-003
	HVT $V'\to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V=3$	1712.06518
	LRSM $W_R\to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R\to\mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^{-}		1703.09127
	CI $\ell\ell qq$	2 e,μ	–	–	36.1	Λ 40.0 TeV η_{LL}^{-}		1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e,μ	1 − 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)=1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e,μ	1 − 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi)=1$ GeV	1711.03301
	$VV_{\chi\chi}$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi)<150$ GeV	1608.02372
	Scalar reson. $\phi\to t\chi$ (Dirac DM)	0-1 e,μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y=0.4$, $\lambda=0.2$, $m(\chi)=10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta=1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta=1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u\to b\tau)=1$	1902.08103
	Scalar LQ 3rd gen	0-1 e,μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d\to t\tau)=0$	1902.08103
Heavy quarks	VLQ $TT\to Ht/Zt/Wb+X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y\to Wb+X$	1 e,μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B\to Hb+X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ\to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	139	q* mass 6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^*\to q\gamma$	1 γ	1 j	–	36.7	q* mass 5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	36.1	b* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e,μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert=5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV
🟨 $\sqrt{s}$ = 13 TeV partial data
🟧 $\sqrt{s}$ = 13 TeV full data

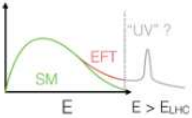
Two approaches to search for beyond the SM (BSM) physics

Let us consider the situation from theory side. How to calculate effects of new physics?

(1) Collision energy s > BSM particle production thresholds
New particles, new resonances



(2) Collision energy s < BSM particle production thresholds
New effective anomalous interactions of the top with other SM particles
New particle contributions via quantum loops → modification of SM decay widths and production cross sections, phase space distributions



Model independent searches. SM effective field theory (SMEFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

$$L_{eff}^{(n)} = L_{SM} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_k C_{nk} O_{nk}$$

c_i – dimensionless coefficients
Λ – dimensionful scale of new physics
O_i – operators constructed from SM fields preserving SM gauge invariance, and other symmetries

W. Buchmuller, D.Wyler, Nucl.Phys. B268, 621(1986)
S.Weinberg, Phys.Rev.Lett. 43, 1566 (1979)

also the "decoupling theorem"

T.Appelquist, J.Carazzone, Phys.Rev. D11, 2856 (1975)):

For any 1PI Feynman graph with external vector mesons only but containing internal fermions, when all external momenta (i.e. p^2)vare small relative to m^2, then apart from coupling constant and field strength renormalization the graph will be suppressed by some power of m relative to a graph with the same number of external vector mesons but no internal fermions.

Operator basis

Operator basis is composed from all operators allowed by the symmetries and then reduced using equations of motion, integration by parts identities, and Fierz transformations

At dimension 5 there exists only a single, lepton number violating operator (Weinberg operator, Phys. Rev. Lett. 43, 1566 (1979)), whose Wilson coefficient is heavily suppressed

$$(\bar{L}^c_{L\alpha}\tilde{H}^*)(\tilde{H}^\dagger L_{L\beta}) + h.c.$$

,

$$L_L = (\nu_L, l_L)^T, \quad \tilde{H} = i\sigma_2 H^*$$

At dimension 6 there are 59 independent operators (Warsaw basis) for one generation of fermions excluding baryon number violating operators (there are about 80 operators in the original Buchmuller – Wyler basis)

B.Grzadkowski, M.Iskrzynski, M.Misiak, J.Rosiek, JHEP 10 (2010) 085

For the three generations, there exist 2499 dimension 6 operators. So global SMEFT fit should explore a huge parameter space with potentially large number of flat directions.

R. Alonso, E. E. Jenkins, A. V. Manohar, M. Trott, JHEP 04 (2014) 159

Instructive example: massless φ^4 model

Lagrangian $L = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{\lambda}{4}\varphi^4$

Equation of motion $\partial_\mu\partial^\mu\varphi + \lambda\varphi^3 = 0$

Three possible dimension 6 operators $\varphi^6; \quad (\partial_\mu\partial^\mu\varphi)^2; \quad \varphi^2(\partial_\mu\varphi\partial^\mu\varphi)^2$

Instructive example: massless φ^4 model

Lagrangian $L = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{\lambda}{4}\varphi^4$

Equation of motion $\partial_\mu\partial^\mu\varphi + \lambda\varphi^3 = 0$

Possible dimension 6 operators $\varphi^6; \quad (\partial_\mu\partial^\mu\varphi)^2; \quad \varphi^2(\partial_\mu\varphi\partial^\mu\varphi)$

Independent operators: how many?

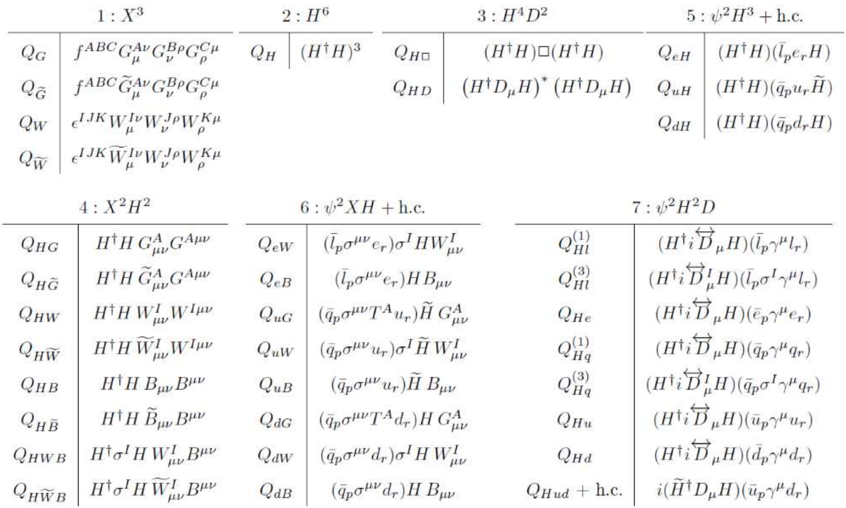
$(\partial_\mu\partial^\mu\varphi)^2 - \lambda^2\varphi^6 = (\partial_\mu\partial^\mu\varphi - \lambda\varphi^3)(\partial_\mu\partial^\mu\varphi + \lambda\varphi^3) = 0$ on the equation of motion

$\partial_\mu(\varphi\varphi^2\partial^\mu\varphi) = 0 = \varphi^2(\partial^\mu\varphi)^2 + \varphi\partial_\mu(\varphi^2\partial^\mu\varphi) = 3\varphi^2(\partial^\mu\varphi)^2 + \varphi^3(\partial_\mu\partial^\mu\varphi) =$
$3\varphi^2(\partial^\mu\varphi)^2 - \lambda\varphi^6$

So on the equations of motion $(\partial_\mu\partial^\mu\varphi)^2; \quad \varphi^2(\partial_\mu\varphi\partial^\mu\varphi)$ are equivalent to φ^6.
Only one independent operator remains.

"Warsaw" operator basis

15 4-boson operators; 19 2-boson&2-fermion operators



1 : X^3	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

2 : H^6	
Q_H	$(H^\dagger H)^3$

3 : $H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

5 : $\psi^2 H^3$ + h.c.	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

4 : $X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

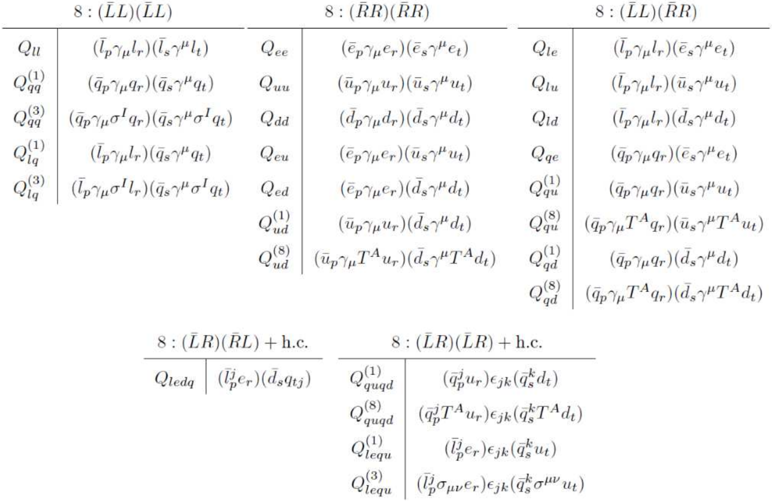
6 : $\psi^2 X H$ + h.c.	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

7 : $\psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \sigma^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \sigma^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Рис.: source:B.Grzadkowski, V.Iskrzynski, M.Misiak, J.Rosiek, JHEP 10 (2010) 085

"Warsaw" operator basis

25 4-fermion operators



$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\sigma^I q_r)(\bar{q}_s\gamma^\mu\sigma^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\sigma^I l_r)(\bar{q}_s\gamma^\mu\sigma^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

How to separate $(1/\Lambda^2)^2$ contributions?

$$L^{eff} = L^{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + ...$$

$$\sigma = \sigma^{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6)\cdot SM} + \sum_{ij} \frac{c_i^{(6)} \, c_j^{(6)*}}{\Lambda^2} \sigma_{ij}^{(6)\cdot(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \sigma_i^{(8)\cdot SM} + h.c. + ...$$

- –in order to calculate the full $1/\Lambda^4$ contribution, operator basis of dimension 8 is necessary
- – in some cases the $\sigma_i^{(6)\cdot SM}$ interference term is small (for example, FCNC processes), then the main new contribution appears al the level of squared anomalous diagrams. So the yield of dimension 8 should be considered as theoretical uncertainty and carefully estimated.

Correction to $H->\gamma\gamma$ in SMEFT

$$\mathcal{R}_{h\to\gamma\gamma} = \frac{\Gamma(\mathrm{SMEFT}, h\to\gamma\gamma)}{\Gamma(\mathrm{SM}, h\to\gamma\gamma)} \equiv 1 + \delta\mathcal{R}_{h\to\gamma\gamma}$$

$$\Gamma(\mathrm{SM}, h\to\gamma\gamma) = \frac{G_F\,\alpha_{\mathrm{EM}}^2\,M_h^3}{128\sqrt{2}\pi^3}\,|I_{\gamma\gamma}|^2 \qquad I_{\gamma\gamma} \equiv I_{\gamma\gamma}(r_f, r_W) = \sum_f Q_f^2 N_{c,f} A_{1/2}(r_f) - A_1(r_W)$$

$$A_{1/2}(r_f) = 2r_f[1 + (1 - r_f)f(r_f)]\,, \qquad A_1(r_W) = 2 + 3r_W[1 + (2 - r_W)f(r_W)]$$

$$f(r) = \begin{cases} \arcsin^2\left(\frac{1}{\sqrt{r}}\right), & r \geq 1\,, \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-r}}{1-\sqrt{1-r}}\right) - i\pi\right]^2, & r \leq 1 \end{cases} \qquad r_f \equiv \frac{4m_f^2}{M_h^2}\,, \qquad r_W \equiv \frac{4M_W^2}{M_h^2}$$

$$\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} = \sum_{i=1}^{6} \delta\mathcal{R}^{(i)}_{h\to\gamma\gamma} &\simeq 0.06\left(\frac{C^{\ell\ell}_{1221} - C^{\varphi\ell(3)}_{11} - C^{\varphi\ell(3)}_{22}}{\Lambda^2}\right) + 0.12\left(\frac{C^{\varphi\Box} - \frac{1}{4}C^{\varphi D}}{\Lambda^2}\right) \\
&- 0.01\left(\frac{C^{e\varphi}_{22} + 4C^{e\varphi}_{33} + 5C^{u\varphi}_{22} + 2C^{d\varphi}_{33} - 3C^{u\varphi}_{33}}{\Lambda^2}\right) \\
&- \left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}}{\Lambda^2} - \left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}}{\Lambda^2} \\
&+ \left[26.62 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}}{\Lambda^2} \\
&+ \left[0.16 - 0.22\log\frac{\mu^2}{M_W^2}\right]\frac{C^{W}}{\Lambda^2} \\
&+ \left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}}{\Lambda^2} + \left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}}{\Lambda^2} \\
&- \left[0.03 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{22}}{\Lambda^2} - \left[0.01 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{22}}{\Lambda^2} \\
&+ \left[0.03 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C^{dB}_{33}}{\Lambda^2} - \left[0.02 + 0.01\log\frac{\mu^2}{M_W^2}\right]\frac{C^{dW}_{33}}{\Lambda^2} \\
&+ \left[0.02 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C^{eB}_{33}}{\Lambda^2} - \left[0.01 + 0.00\log\frac{\mu^2}{M_W^2}\right]\frac{C^{eW}_{33}}{\Lambda^2} + \ldots\,,
\end{aligned}$$

$$\mu = M_W$$

Largest corrections and strongest limits for the operators appeared at tree level

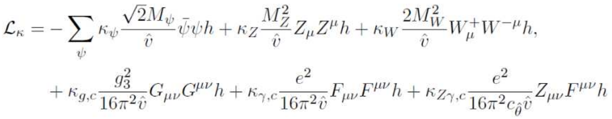
$$\frac{|C^{\varphi B}|}{\Lambda^2} \lesssim \frac{0.003}{(1\ \mathrm{TeV})^2}\,, \qquad \frac{|C^{\varphi W}|}{\Lambda^2} \lesssim \frac{0.011}{(1\ \mathrm{TeV})^2}\,, \qquad \frac{|C^{\varphi WB}|}{\Lambda^2} \lesssim \frac{0.006}{(1\ \mathrm{TeV})^2}\,,$$

$$\frac{|C^{uB}_{33}|}{\Lambda^2} \lesssim \frac{0.071}{(1\ \mathrm{TeV})^2}\,, \qquad \frac{|C^{uW}_{33}|}{\Lambda^2} \lesssim \frac{0.133}{(1\ \mathrm{TeV})^2}\,.$$

Weaker limits for the operators appeared at loop level

Рис.: source: Dedes et al, arXiv:1805.00302[hep-ph]

LHC kappa-scheme or κ - framework for the SM Higgs boson production



$$\mathcal{L}_\kappa = -\sum_\psi \kappa_\psi \frac{\sqrt{2}M_\psi}{\hat{v}}\bar{\psi}\psi h + \kappa_Z \frac{M_Z^2}{\hat{v}} Z_\mu Z^\mu h + \kappa_W \frac{2M_W^2}{\hat{v}} W_\mu^+ W^{-\mu} h,$$

$$+ \kappa_{g,c}\frac{g_3^2}{16\pi^2\hat{v}}G_{\mu\nu}G^{\mu\nu}h + \kappa_{\gamma,c}\frac{e^2}{16\pi^2\hat{v}}F_{\mu\nu}F^{\mu\nu}h + \kappa_{Z\gamma,c}\frac{e^2}{16\pi^2 c_{\hat{\theta}}\hat{v}}Z_{\mu\nu}F^{\mu\nu}h$$

Рис.: κ - framework lagrangian

- in the infinitely small width approximation of H any H production process

  $\sigma(in \to H \to out) = \sigma_{in} \times Br_{out} = \sigma_{in} \times \frac{\Gamma_{out}}{\Gamma_{tot}}$
- vertex sctucture of H BSM is not different from the CM, H CP-even scalar.
- in each H vertex κ_i factor is inserted, then

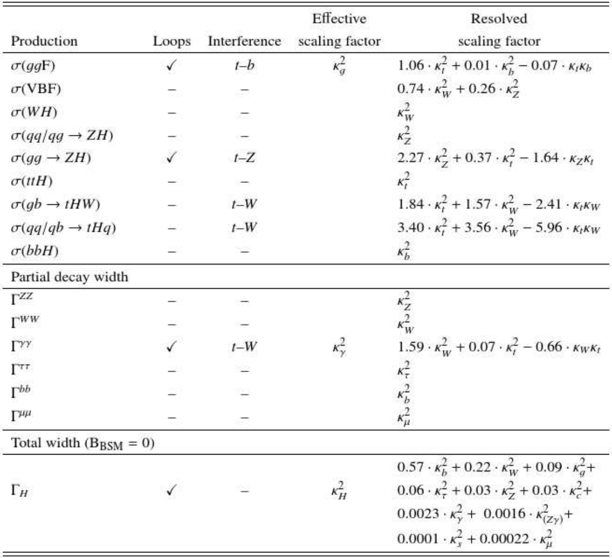
  $\sigma_{in} \times Br_{out} = [\sigma_{in} \times Br_{out}]_{SM} \cdot \frac{\kappa_{in}^2 \cdot \kappa_{out}^2}{\kappa_H^2}$
- if the signal strength for production and decay

  $\mu_{in} = \frac{\sigma_{in}}{(\sigma_{in})_{SM}} \qquad \mu_{out} = \frac{Br_{out}}{(Br_{out})_{SM}}$

  then the signal strength for a production process

  $\mu = \mu_{in}\,\mu_{out} = \frac{\kappa_{in}^2 \cdot \kappa_{out}^2}{\kappa_H^2}$

  This scheme is obviously not gauge invariant. Radiative corrections are not avaliable.



Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Рис.: Production mechanisms and their κ -modifiers including the one-loop and the interfering mechanisms. No BSM decay channels. Source: Combined ATLAS-CMS analysis, arXiv:1606.02266

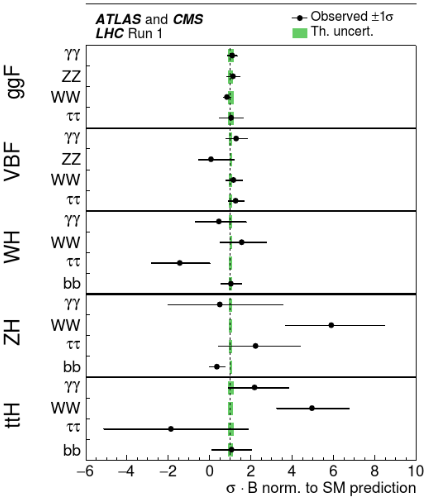


Рис.: Signal strength and its statistical error for different production mechanisms from: Combined ATLAS-CMS analysis, arXiv:1606.02266

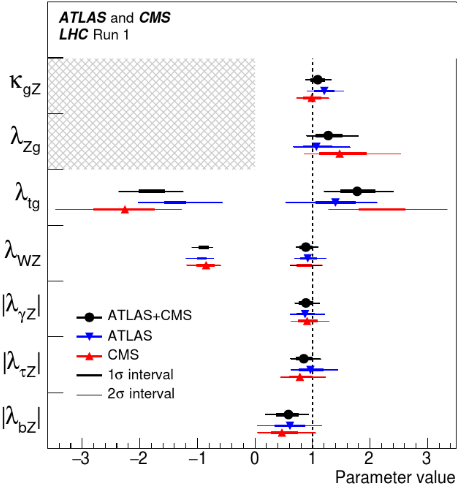


Рис.: Ratios of κ-modifiers, $\kappa_{gZ} = \kappa_g\,\kappa_Z$, $\lambda_{Zg} = \kappa_Z/\kappa_g$ and so on. Source: Combined ATLAS-CMS analysis, arXiv:1606.02266

Model dependent searches. How to construct EFT of the MSSM Higgs sector at the m_{top} scale.

Sequence of steps

- Write out soft SUSY breaking terms and reduce the MSSM parameter space to an acceptable dimension (dim3 - dim5).
- Fix the mass scales hierarchy and typical scale intervals – "MSSM scenario" .
- Check phenomenological consistency of the superpartner mass spectrum using exclusions from ATLAS, CMS, LHCb and other experiments.
- Fix gauge invariant two-doublet Higgs potential (discrete symmeties imposed or not, etc). Rotate $SU(2)$ scalar eigenstates to the mass eigenstates and transform the two-doublet Higgs potential to the mass basis. Express potential parameters through masses of scalars and mixing angles of $SU(2)$ eigenstates.
- Integrate out particles (in soft SUSY breaking terms multiplets) at high mass scale – effective potential method, covariant derivative expansion or analogous. Express potential parameters through soft SUSY parameters.
- Extract appropriate regions of the parameter space consistent with m_h =125 GeV, SM-like h couplings, decoupling of other scalar states H, A, $H^{\pm}$ and consistency with the LHC exclusions, if data available.
- Check cosmological consequences – DM candidates

Model dependent searches. EFT for the MSSM two-doublet Higgs sector

$$\mathcal{V}^{\,0} = \mathcal{V}_M + \mathcal{V}_\Gamma + \mathcal{V}_\Lambda + \mathcal{V}_{\widetilde{Q}}\,,$$

where

$$\mathcal{V}_M = (-1)^{i+j} m_{ij}^2 \Phi_i^\dagger \Phi_j + M_{\widetilde{Q}}^{\,2}\left(\widetilde{Q}^{\,\dagger}\widetilde{Q}\right) + M_{\widetilde{U}}^{\,2}\widetilde{U}^*\widetilde{U} + M_{\widetilde{D}}^{\,2}\widetilde{D}^*\widetilde{D}\,,$$

$$\mathcal{V}_\Gamma = \Gamma_i^D\left(\Phi_i^\dagger\widetilde{Q}\right)\widetilde{D} + \Gamma_i^U\left(i\Phi_i^T\sigma_2\widetilde{Q}\right)\widetilde{U} + \overset{*}{\Gamma}{}_i^D\left(\widetilde{Q}^{\,\dagger}\Phi_i\right)\widetilde{D}^* - \overset{*}{\Gamma}{}_i^U\left(i\widetilde{Q}^{\,\dagger}\sigma_2\Phi_i^*\right)\widetilde{U}^*\,,$$

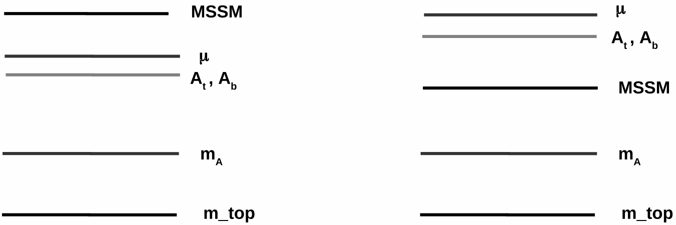
$$\mathcal{V}_\Lambda = \Lambda_{ik}^{jl}\left(\Phi_i^\dagger\Phi_j\right)\left(\Phi_k^\dagger\Phi_l\right) + \left(\Phi_i^\dagger\Phi_j\right)\left[\Lambda_{ij}^Q\left(\widetilde{Q}^{\,\dagger}\widetilde{Q}\right) + \Lambda_{ij}^U\widetilde{U}^*\widetilde{U} + \Lambda_{ij}^D\widetilde{D}^*\widetilde{D}\right] +$$

$$+\overline{\Lambda}{}_{ij}^{\,Q}\left(\Phi_i^\dagger\widetilde{Q}\right)\left(\widetilde{Q}^{\,\dagger}\Phi_j\right) + \frac{1}{2}\left[\Lambda\epsilon_{ij}\left(i\Phi_i^T\sigma_2\Phi_j\right)\widetilde{D}^*\widetilde{U} + h.c.\right]\,,\quad i,j,\,k,l = 1,2\,,$$

$\mathcal{V}_{\widetilde{Q}}$ denotes the four scalar quarks interaction terms, Pauli matrix $\sigma_2 \equiv \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix}$.
The Yukawa coupligs for the third generation of scalar quarks are defined in a standard way $h_{\,t} = \frac{\sqrt{2}\,m_{\,t}}{v\sin\beta}$, $h_{\,b} = \frac{\sqrt{2}\,m_b}{v\cos\beta}$, $\Gamma_{\{1;\,2\}}^{\,U} \equiv h_U\,\{-\mu; A_U\}$, $\Gamma_{\{1;\,2\}}^{D} \equiv h_D\,\{A_D\,;-\mu\}$.

Mass scales

The lightest CP-even MSSM Higgs boson mass $m_h \sim 125$ ГэВ
Five MSSM Higgs bosons: $h,\ H, A, H^{\pm},$ [3]



Low-energy effective field theory at the scale higher than $m_{\rm top}$ is THDM. Higgsinos, gluino and EW gauginos are very heavy and decouple. Main correctons are due to squarks.

Five-dimensional parameter space: $m_A, \tan\beta, M_{\rm SUSY}, A_t = A_b, \mu$

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[3] Haber,Hempfling,PR D48 4280 (1993); Sasaki,Carena,Wagner, NP B381 66 (1992); Akhmetzyanova,Dolgopolov,M.D. PR D71 075008 (2005); Phys.Part.Nucl. 37, 677 (2006); Lee,Wagner, PR D92, 075032 (2015) Carena,Haber,Low,Shah,Wagner PR D91 035003 (2015)

THDM in the mass basis

Radiatively corrected Higgs sector of the MSSM is a THDM

$$\Phi_i = \begin{pmatrix} -i\omega_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + \eta_i + i\chi_i) \end{pmatrix}, \qquad \langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix}, \qquad i = 1, 2$$

$$\tan\beta = \frac{v_2}{v_1}, \qquad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}$$

where $SU(2)$ states are related to mass states by means of two orthogonal rotations

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \mathcal{O}_\alpha \begin{pmatrix} h \\ H \end{pmatrix}, \qquad \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} G^0 \\ A \end{pmatrix}, \qquad \begin{pmatrix} \omega_1^{\pm} \\ \omega_2^{\pm} \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} G^{\pm} \\ H^{\pm} \end{pmatrix}$$

where rotation matrix

$$\mathcal{O}_X = \begin{pmatrix} \cos X & -\sin X \\ \sin X & \cos X \end{pmatrix}, \qquad X = \alpha, \beta.$$

THDM Higgs potential in a generic basis

$$U_{eff}(\Phi_1,\Phi_2) = -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - {\mu_{12}}^2(\Phi_1^\dagger\Phi_2) - ({\mu_{12}}^2)^*(\Phi_2^\dagger\Phi_1)$$
$$+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \frac{{\lambda_5}^*}{2}(\Phi_2^\dagger\Phi_1)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + {\lambda_6}^*(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)$$
$$+\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + {\lambda_7}^*(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

can be reduced to the potential in the mass basis ($\lambda_{5,6,7}$ and μ_{12}^2 real)

$$U(h,H,A,H^\pm,G^0,G^\pm) = \frac{m_h^2}{2}h^2 + \frac{m_H^2}{2}H^2 + \frac{m_A^2}{2}A^2 + m_{H^\pm}^2 H^+H^- + I(3) + I(4)$$

by means of explicit symbolic transformation for $\lambda_1, ...\lambda_7$ in terms of mixing angles and pole masses[4]

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[4] M.D.,Semenov, EJP C28, 223 (2003); Boudjema,Semenov, Phys.Rev. D66 095007 (2002), Gunion,Haber, PR D67 075019 (2003)

$$\begin{aligned}
\lambda_1 &= \frac{1}{2v^2}[(\frac{s_\alpha}{c_\beta})^2 m_h^2 + (\frac{c_\alpha}{c_\beta})^2 m_H^2 - \frac{s_\beta}{c_\beta^3}\mu_{12}^2] + \frac{1}{4}(\lambda_7 \texttt{tan}^3\beta - 3\lambda_6 \texttt{tan}\beta),\\
\lambda_2 &= \frac{1}{2v^2}[(\frac{c_\alpha}{s_\beta})^2 m_h^2 + (\frac{s_\alpha}{s_\beta})^2 m_H^2 - \frac{c_\beta}{s_\beta^3}\mu_{12}^2] + \frac{1}{4}(\lambda_6 \texttt{cot}^3\beta - 3\lambda_7 \texttt{cot}\beta),\\
\lambda_3 &= \frac{1}{v^2}[2m_{H\pm}^2 - \frac{\mu_{12}^2}{s_\beta c_\beta} + \frac{s_{2\alpha}}{s_{2\beta}}(m_H^2 - m_h^2)] - \frac{1}{2}(\lambda_6 \texttt{cot}\beta + \lambda_7 \texttt{tan}\beta),\\
\lambda_4 &= \frac{1}{v^2}(\frac{\mu_{12}^2}{s_\beta c_\beta} + m_A^2 - 2m_{H\pm}^2) - \frac{1}{2}(\lambda_6 \texttt{cot}\beta + \lambda_7 \texttt{tan}\beta),\\
\lambda_5 &= \frac{1}{v^2}(\frac{\mu_{12}^2}{s_\beta c_\beta} - m_A^2) - \frac{1}{2}(\lambda_6 \texttt{cot}\beta + \lambda_7 \texttt{tan}\beta),
\end{aligned}$$

massless goldstone G^0 is ensured by

$$\texttt{Re}\mu_{12}^2 = s_\beta c_\beta \left(m_A^2 + \frac{v^2}{2}(2\texttt{Re}\lambda_5 + \texttt{Re}\lambda_6 \cot\beta + \texttt{Re}\lambda_7 \tan\beta) \right)$$

Inverse transformation for pole masses in terms of λ_i

MSSM
$M_{\texttt{SUSY}}$:
$m_{\texttt{top}}$:

$$\lambda_{1,2}^{\texttt{SUSY}} = \frac{g_1^2 + g_2^2}{8}, \qquad \lambda_3^{\texttt{SUSY}} = \frac{g_2^2 - g_1^2}{4}, \qquad \lambda_4^{\texttt{SUSY}} = -\frac{g_2^2}{2}, \qquad \lambda_{5,6,7}^{\texttt{SUSY}} = 0.$$

$$\lambda_i = \lambda_i^{\texttt{SUSY}} - \Delta\lambda_i \qquad \Delta\lambda_i = \Delta\lambda_i^{\texttt{thr}} + \Delta\lambda_k^{\texttt{LL}} \ (i = 1, .., 7, k = 1, .., 4)$$

$\Delta\lambda^{\texttt{wfr}}_{F,D}$ scenario

Set of corrections:

– 1-loop resummed threshold, wave-function renormalization
– non-leading D-terms
– 2-loop electroweak and QCD[5]
– Yukawa

For example,

$$\begin{aligned}\lambda_1 \quad = \quad & \frac{g_2^2+g_1^2}{8} + \frac{3}{32\pi^2}\Big[h_b^4\frac{|A_b|^2}{M_{\rm SUSY}^2}\left(2-\frac{|A_b|^2}{6M_{\rm SUSY}^2}\right) - h_t^4\frac{|\,\mu|^4}{6M_{\rm SUSY}^4} \; + \\ & + 2h_b^4 l + \frac{g_2^2+g_1^2}{4\,M_{\rm SUSY}^2}(h_t^2|\,\mu|^2 - h_b^2|A_b|^2)\Big] + \Delta\,\lambda_1^{\rm wfr} \; + \\ & + \frac{1}{768\pi^2}\,\left(11g_1^4 + 9g_2^4 - 36\,(g_1^2+g_2^2)\,h_b^2\right) l \; - \; \Delta\lambda_1[2-\texttt{loop}],\end{aligned}$$

where $l = log(M^2_{SUSY}/\sigma^2)$ and $\Delta\,\lambda_1^{\rm wfr}$, $\Delta\lambda_1[2-\texttt{loop}]$ are

---

[5] Haber,Hempfling,Hoang, ZP C75 539 (1997); Carena,Espinosa,Quiros,Wagner PL B355 209 (1995); Heinemeyer,Hollik,Weiglein, EPJC C9 343 (1999); Pilaftsis,Wagner, NP B553 3 (1999)

`wfr` terms

$$\Delta\,\lambda_1^{\rm wfr} = \frac{1}{2}(g_1^2+g_2^2)A'_{11}, \qquad \Delta\,\lambda_2^{\rm wfr} = \frac{1}{2}(g_1^2+g_2^2)A'_{22},$$

$$\Delta\,\lambda_3^{\rm wfr} = -\frac{1}{4}(g_1^2-g_2^2)(A'_{11}+A'_{22}), \quad \Delta\,\lambda_4^{\rm wfr} = -\frac{1}{2}g_2^2(A'_{11}+A'_{22}), \quad \Delta\,\lambda_5^{\rm field} = 0,$$

$$\Delta\,\lambda_6^{\rm wfr} = \frac{1}{8}(g_1^2+g_2^2)(A'_{12}-{A'_{21}}^*) = 0, \quad \Delta\,\lambda_7^{\rm wfr} = \frac{1}{8}(g_1^2+g_2^2)(A'_{21}-{A'_{12}}^*) = 0,$$

where A'

$$A'_{ij} = -\frac{3}{96\,\pi^2\,M^{\,2}_{SUSY}}\left(h_t^2\begin{bmatrix} |\mu|^2 & -\mu^* A_t^* \\ -\mu A_t & |A_t|^2 \end{bmatrix} + \,h_b^2\begin{bmatrix} |A_b|^2 & -\mu^* A_b^* \\ -\mu A_b & |\mu|^2 \end{bmatrix}\right) \times$$

$$\times\left(1-\,\frac{1}{2}\,l\right)\,.$$

two-loop terms

$$\Delta\lambda_1[2-\texttt{loop}] = -\frac{3}{16\pi^2}h_b^4\,\frac{1}{16\pi^2}(\frac{3}{2}h_b^2+\frac{1}{2}h_t^2-8g_{\rm S}^2)(X_b l+l^2)+$$

$$+\frac{3}{192\pi^2}h_t^4\,\frac{1}{16\pi^2}\,\frac{|\mu|^4}{M_{\rm SUSY}^4}(9h_t^2-5h_b^2-16g_{\rm S}^2)l$$

m_h dependence on $A = A_{t,b}$ in $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.

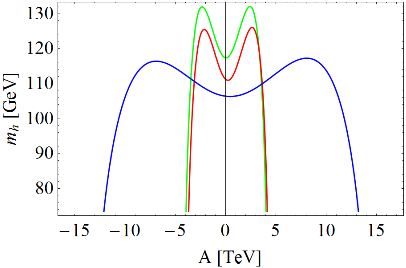


Рис.: m_h dependence on $A = A_{t,b}$ at m_A =300 GeV, μ =1 TeV for the tree sets (1) M_{SUSY} =3 TeV, $\tan\beta$ =2.5 (blue); (2) M_{SUSY} =1.5 TeV, $\tan\beta$ =5 (red); (3) M_{SUSY} =1 TeV, $\tan\beta$ =30 (green). With a limited set of $\Delta\lambda^a_i$ corrections curves have the same shape, but are 5-10 GeV lower.

Domains of m_h in the μ,A plane for $A_{t,b}$ =2 TeV and μ =1.5 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.

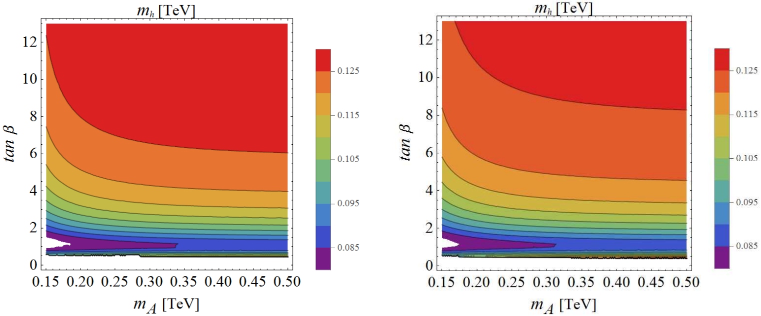


Рис.: M_{SUSY} =1 TeV (left) and 1.25 TeV (right).

Domains of m_h in the μ,A plane for $A_{t,b}$ =2 TeV and μ =1.5 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.

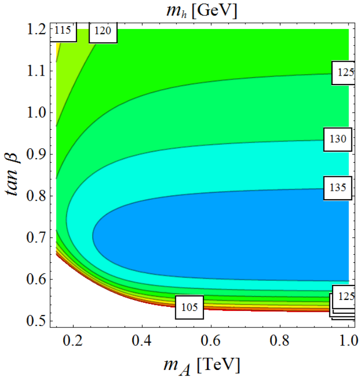


Рис.: Low $\tan\beta$ domain (see previous Fig (right)).

3D surfaces of m_h =125 GeV at low and high $\tan\beta$ in M^{SUSY},μ,A space for m_A =0.3 TeV and m_A =1 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.

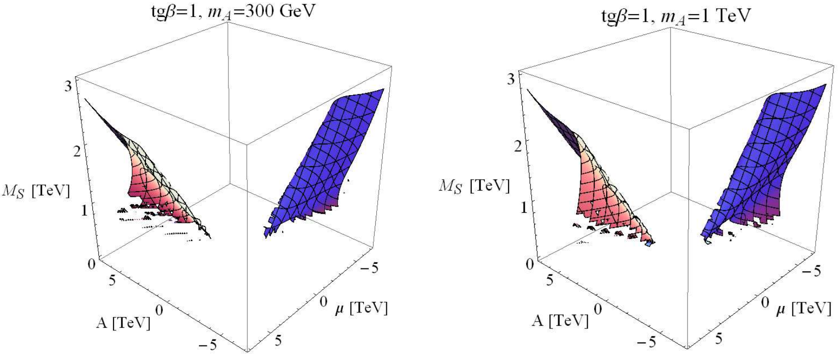


Рис.: Surface of m_h = 125 GeV, $\tan\beta$ =1, m_A =300 GeV (left) and 1 TeV (right)

Unusual MSSM scenarios

Still a number of MSSM scenarios with unusual mass spectrum of scalars and superpartner mass hierarchy are not completely excluded. They attract some attention in connection with CMS data in the channel $pp \to \mu^+\mu^-\bar{b}b$.

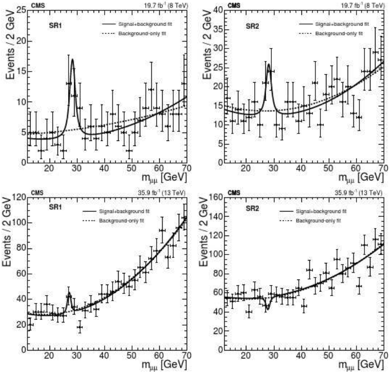


Figure 2: Upper row: the $12 < m_{\mu\mu} < 70$ GeV range in SR1 (left) and SR2 (right) in the 8 TeV analysis. Lower row: the $12 < m_{\mu\mu} < 70$ GeV range in SR1 (left) and SR2 (right) in the 13 TeV analysis. The results of an unbinned maximum likelihood fit for the signal-plus-background (solid lines) and background-only (dashed lines) hypotheses are superimposed.

Рис.: CMS Collaboration, Search for resonances in the mass spectrum of muon pairs produced in association with b-quark jets in proton-proton collisions at sqrts = 8 and 13 TeV, arXiv:1808.01890 [hep-ex], see also M.D., E.Fedotova, arXiv:1908.05223[hep-ph]

Summary

– in addition to the new $h(125\text{ GeV})$ resonance which looks like a Higgs boson of the Standard Model, no new signals have been detected at the LHC.

– at the same time, invaluable results were obtained. New data allows one to impose limits on the scales and couplings of the new physics.

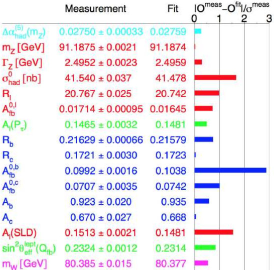
BACKUP SLIDES

Каппа-модификаторы – пример псевдонаблюдаемых.

Псевдонаблюдаемые – величины-посредники между экспериментальными наблюдаемыми и вычисленными теоретически параметрами. Предоставляют возможности анализа в рамках нестандартных моделей, позволяющего избежать трудоемкой реконструкции (начиная от datasets) и одновременно позволяют исполнять разные теоретические интерпретации измеряемых эффектов.

Появились при анализе данных LEP. Примеры: ширины векторных бозонов Γ_l, Γ_q и парциальные вероятности их распадов после процедуры исключения (deconvolution) излучения фотонов из начального состояния и вычитания интерферирующего/неинтерферирующего фона. Асимметрии вперед-назад. После фитирования псевдонаблюдаемых LEP2 составлялась комбинация четырех коллабораций ADLO, известная под названием Electroweak Precision Data (EWPD).

Псевдонаблюдаемые БАК определяются на уровне амплитуд процессов из-за сложной ситуации с фонами и исключения PDF, а также множества возможных теоретических моделей.



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377

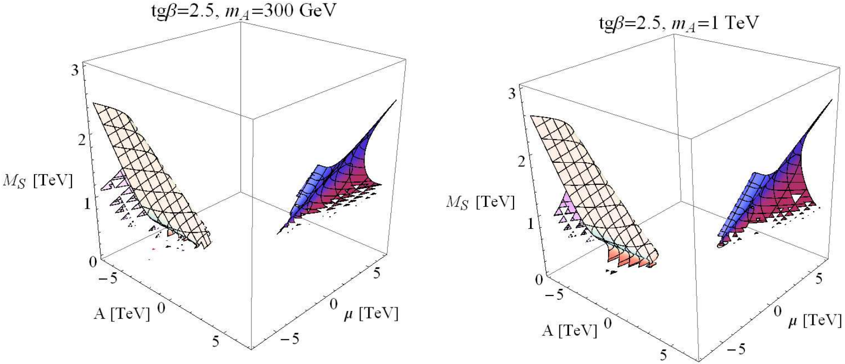
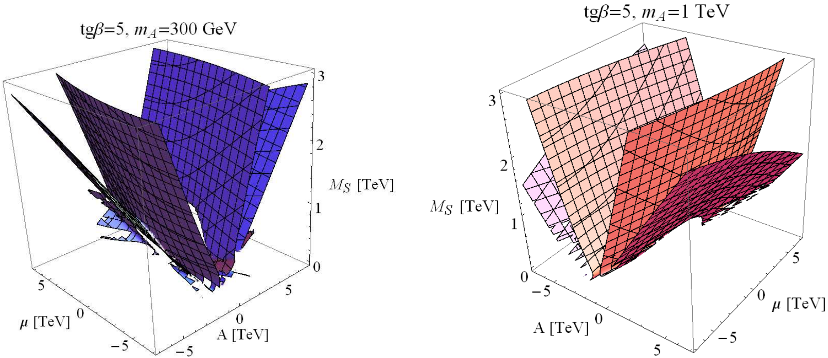


Рис.: Surface of $m_h = 125$ GeV, $\tan\beta$ =2.5, m_A =300 GeV (left) and 1 TeV (right)



tgβ=5, m_A=300 GeV

tgβ=5, m_A=1 TeV

Рис.: Surface of $m_h = 125$ GeV, $\tan\beta$ =5, m_A =300 GeV (left) and 1 TeV (right). Right 3D plot is rotated 90 degrees.

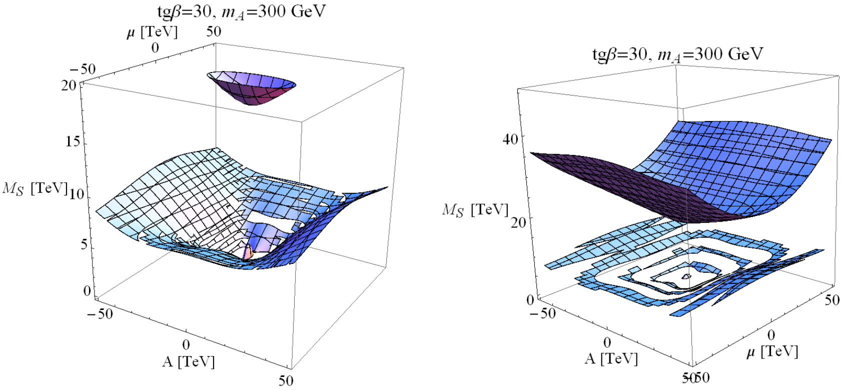
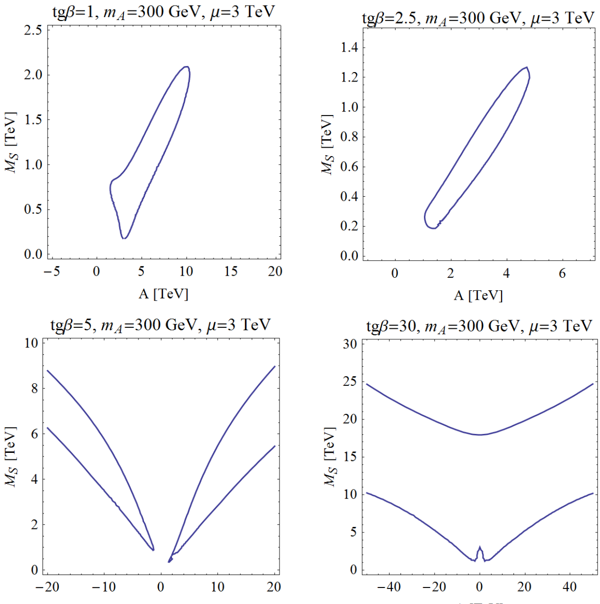
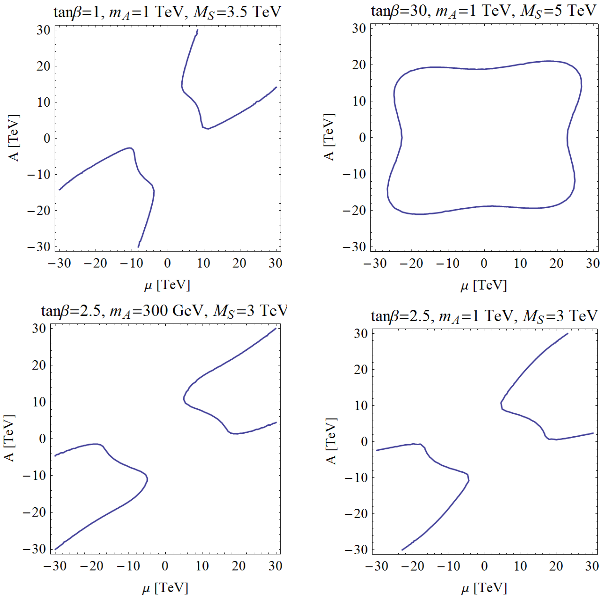


Рис.: Surface of $m_h = 125$ GeV, $\tan\beta$ =30, m_A =300 GeV (left), A, μ formally extended beyond a perturbative calculation framework

Contours of m_h =125 GeV at low and high $\tan\beta$ in M^{SUSY}, A plane for m_A =0.3 TeV and m_A =1 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.



Contours of m_h =125 GeV at low and high $\tan\beta$ in μ,A plane for m_A =0.3 TeV and m_A =1 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.



tanβ=1, m_A=1 TeV, M_S=3.5 TeV

tanβ=30, m_A=1 TeV, M_S=5 TeV

tanβ=2.5, m_A=300 GeV, M_S=3 TeV

tanβ=2.5, m_A=1 TeV, M_S=3 TeV

Contours of m_h =125 GeV at low and high $\tan\beta$ in μ, A plane for m_A =0.3 TeV and m_A =1 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.

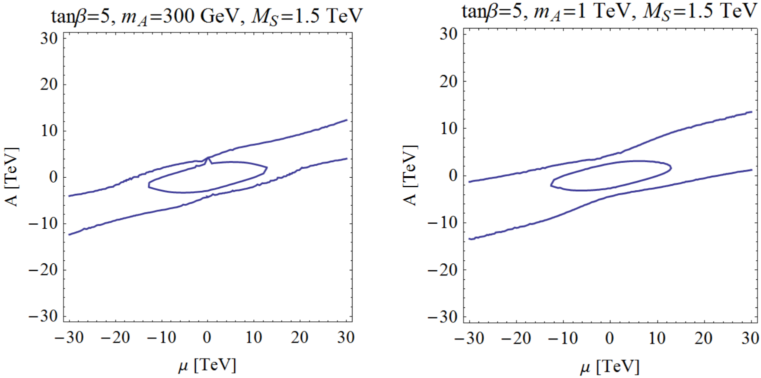


Рис.: Contours of m_h = 125 GeV, m_A =300 GeV (left) and m_A =1 TeV (right)

Domains of m_h in the μ,A plane for $A_{t,b}$ =2 TeV and μ =1.5 TeV. $\Delta\lambda^{\mathtt{wfr}}_{F,D}$ scenario.

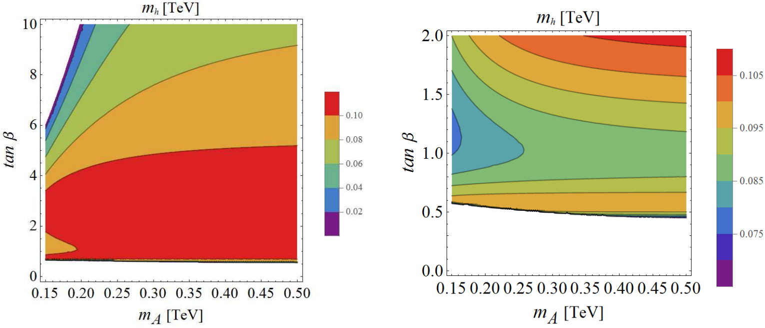


Рис.: M_{SUSY} =500 GeV (left) and 750 GeV (right).

4. Heavy CP-even H branchng ratios for m_h^{alt} and $m_h^{\text{mod+}}$ parameter sets

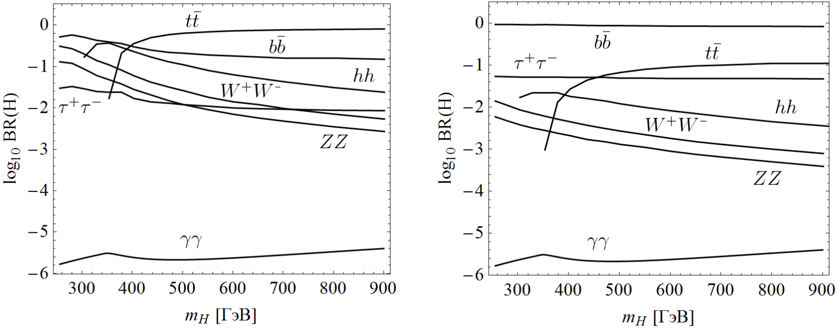


Рис.: $m_h = 124 - 126$ GeV, $M_{\text{SUSY}} = 1.5$ TeV and $\mu = 200$ GeV or 1 TeV. Left panels: $\tan\beta = 4$, $A = 2.45 M_{\text{SUSY}}$ (m_h^{alt} scenario); right panels $\tan\beta = 10$, $A = 1.5 M_{\text{SUSY}}$ ($m_h^{\text{mod+}}$ scenario). Results are stable with respect to Higgs superfield parameter μ variation.

Isocontours for CP-even H boson mass and CP-odd A boson mass

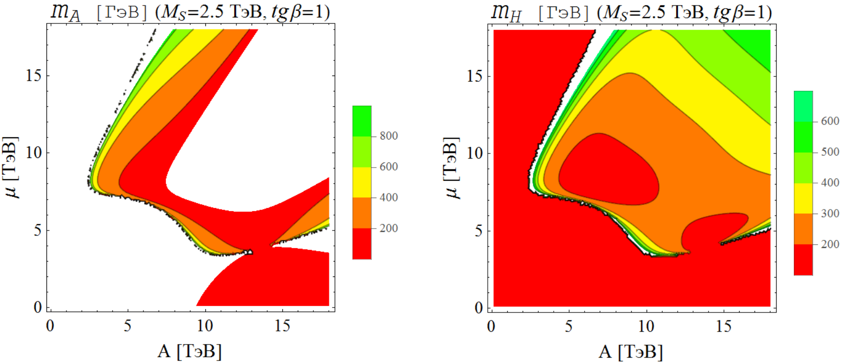


Рис.: m_h =125 GeV, $M_{\text{SUSY}} = 2.5$ TeV and $\tan\beta$ =1. m_A domains (left panel) and m_H domains (right panel).

Isocontours of mass for CP-even state A and charged state $m_{H^\pm}$.

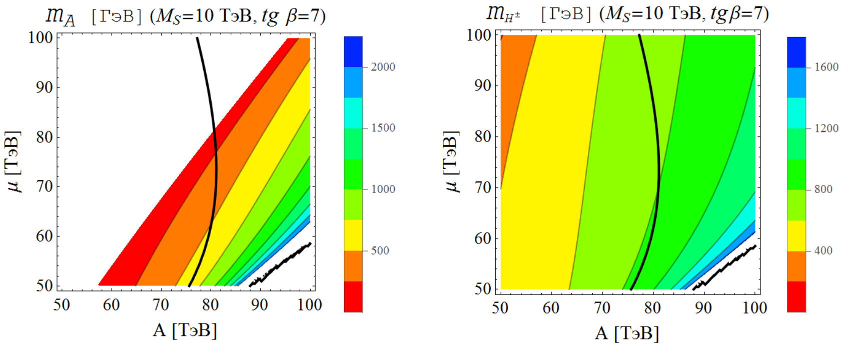


Рис.: m_h =125 GeV, $M_{\text{SUSY}} = 10$ TeV and $\tan\beta$ =7. Along the black solid line m_H =750 GeV.

Summary

- Чувствительность результатов по отношению к радиационным поправкам высока. Редукция пятимерного пространства МССМ не соответствует какому-либо массовому базису для состояний общей двухдублетной модели.
- Тем не менее редуцированные сценарии (hMSSM, FeynHiggs based) достаточно точно воспроизводят спектр масс скаляров при достаточно больших m_A, m_H более 200 ГэВ и малых $\tan\beta$. Поведение угла смешивания CP-четных состояний описывается не вполне удовлетворительно.
- На масштабе M_{SUSY} более 1 ТэВ есть узкая допустимая область $\tan\beta \sim 1$. Для малых $\tan\beta \leq 3$ масштаб масс суперпартнеров M_{SUSY} ограничен сверху на уровне (3–4) ТэВ. Основная мода $H \to t\bar{t}$. Пространство μ, A очень сильно ограничено, $m_H \sim m_A$.
- Для больших $\tan\beta \geq 30$ появляется неоднозначность масштаба масс суперпартнеров M_{SUSY}: допустимы массы как порядка нескольких ТэВ, так и порядка десятков (20–30 ТэВ). Большие $\tan\beta \sim$ 30–40 при $m_{H^\pm} \leq 400$ GeV закрыты ограничением на $t\bar{t} \to H^\pm \to$ 6 jets (Теватрон). Основная мода $H \to b\bar{b}$.
- Предположение m_H порядка 750 ГэВ одновременно с $m_h = 125$ ГэВ практически исключает малые $\tan\beta$, приводит к M_{SUSY} более 5 ТэВ и очень большим μ, A более 20 ТэВ (условия $2|m_{top}A, \mu| < M_{SUSY}$ для оправданности разложения эффективного потенциала в базисе операторов размерности 4 выполняются).