# Prospects for BSM Higgs boson phenomenology at Run-2

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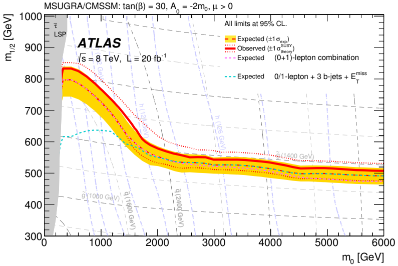
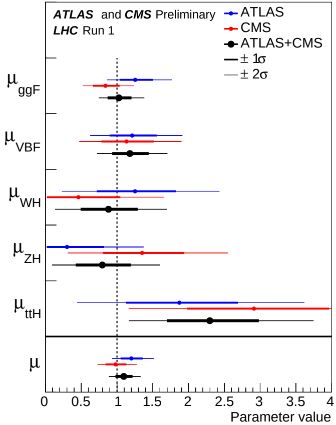
# Talk structure

# Physical motivations

- Discovery of SM-like Higgs at the LHC Run 1.
- Negative results from BSM searches so far.
- Are there any other Higgses?
- What's the room left for SUSY? Can we use the Higgs as a probe for SUSY?



# The Lagrangian of the 2HDM

- Two higgs doublets, $H_1$ and $H_2$
- Most general form of the scalar potential assuming that CP is conserved

$$V_0 = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - m_{12}^2 \left(H_1^\dagger H_2 + H_2^\dagger H_1\right) + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_1}{2}\left(H_2^\dagger H_2\right)^2$$
$$+ \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \left(H_2^\dagger H_1\right)^2\right]$$

- Both Higgs fields get non-zero v.e.v.

$$\langle H_1 \rangle_0 \equiv \langle 0 | H_1 | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad \langle H_2 \rangle_0 \equiv \langle 0 | H_2 | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

There are two important parameters in the 2HDM:

- $\tan\beta \equiv \frac{v_2}{v_1}$
- The CP-even mixing angle $\alpha$

# The Higgs sector of the 2HDM

- 5 physical states in the spectrum: two CP-even ($h$ and $H$), one CP-odd ($A$) and two charged Higgses ($H^{\pm}$).
- Modified couplings to the gauge bosons and the fermions.

| Coupling | Type I | Type II | Lepton specific | Flipped |
|---|---|---|---|---|
| $\lambda_u^h$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| $\lambda_d^h$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| $\lambda_u^H$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ |
| $\lambda_d^H$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| $\lambda_u^A$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| $\lambda_d^A$ | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\tan\beta$ |
| $\lambda_l^h$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |
| $\lambda_l^H$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ |
| $\lambda_l^A$ | $-\cot\beta$ | $\tan\beta$ | $\tan\beta$ | $-\cot\beta$ |
| $\lambda_V^h$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ |
| $\lambda_V^H$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ |
| $\lambda_V^A$ | 0 | 0 | 0 | 0 |

# The Minimal Supersymmetric Standard Model

## Chiral supermultiplets

| Name | Symbol | spin 0 | spin 1/2 | $(SU(3)_C, SU(2)_L, U(1)_Y)$ |
|---|---|---|---|---|
| squarks,quarks | $Q$ | $(\tilde{u}_L, \tilde{d}_L)$ | $(u_L, d_L)$ | $\left(\mathbf{3}, \mathbf{2}, \frac{1}{6}\right)$ |
| (×3 families) | $\bar{u}$ | $\tilde{u}_R^*$ | $u_R^\dagger$ | $\left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}\right)$ |
| | $\bar{d}$ | $\tilde{d}_R^*$ | $d_R^\dagger$ | $\left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)$ |
| sleptons,leptons | $L$ | $(\tilde{\nu}, \tilde{e}_L)$ | $(\nu, e_L)$ | $\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$ |
| (×3 families) | $\bar{e}$ | $\tilde{e}_R^*$ | $e_R^\dagger$ | $(\mathbf{1}, \mathbf{1}, 1)$ |
| Higgses, Higgsinos | $H_u$ | $(H_u^+, H_u^0)$ | $(\widetilde{H}_u^+, \widetilde{H}_u^0)$ | $\left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right)$ |
| | $H_d$ | $(H_d^0, H_d^-)$ | $(\widetilde{H}_d^0, \widetilde{H}_d^-)$ | $\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$ |

## Gauge supermultiplets

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

# Higgs mechanism in the MSSM

- Realization of type-II 2HDM. However the structure is now determined by supersymmetry.
- Tree level Higgs scalar potential ($m_1^2 = m_{H_1}^2 + |\mu|^2$ and $m_2^2 = m_{H_2}^2 + |\mu|^2$) is

$$V_0 = m_1^2 \left|H_1^0\right|^2 + m_2^2 \left|H_2^0\right|^2 + B_\mu (H_1^0 H_2^0 + \text{h.c.}) + \frac{g^2 + g'^2}{8} \left( \left|H_1^0\right|^2 - \left|H_2^0\right|^2 \right)^2$$

- Mass matrix for the scalar sector ($m_1^2$ and $m_2^1$ replaced by a combination of $m_A^2$ and $\tan\beta$)
- 

$$m_{h,H} = \frac{1}{2} \left( m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4 m_Z^2 m_A^2 \sin^2(2\beta)} \right)$$

- At tree level we have that $m_h \leq m_Z |\cos(2\beta)|$.
- Large radiative corrections allow the MSSM to survive the discovery of a 125 GeV.

# Higgs EFT

- Alternative approach that try to be agnostic on the specific UV completion of the Standard Model.
- Extend the SM as an EFT with higher-dimensional operators.
- Leading effects from dimension-6 operator (dimension-5 violate lepton number conservation).
- All complete basis are formally equivalent (*Warsaw*, *Higgs*, *SILH*).
- Data → Fiducial cross-sections → Pseudo-observables → Model independent EFT → BSM

[LHCHXSWG-INT-2015-001]

$$\mathscr{L}_{\mathrm{SM-EFT}} = \mathscr{L}_{\mathrm{SM}} + \Delta\mathscr{L}_{\mathrm{EFT}}$$

$$\begin{aligned}\mathcal{L}_{hvff} &= \sqrt{2}g\frac{h}{v}W^+_\mu\left(\bar{u}_L\gamma_\mu\delta g_L^{hWq}d_L + \bar{u}_R\gamma_\mu\delta g_R^{hWq}d_R + \bar{\nu}_L\gamma_\mu\delta g_L^{hW\ell}e_L\right) + \text{h.c.}\\ &+ 2\frac{h}{v}\sqrt{g^2+g'^2}Z_\mu\left[\sum_{f=u,d,e,\nu}\bar{f}_L\gamma_\mu\delta g_L^{hZf}f_L + \sum_{f=u,d,e}\bar{f}_R\gamma_\mu\delta g_R^{hZf}f_R\right],\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{\mathrm{hdvff}} = &-\frac{h}{4v^2}\Bigg[g_s\sum_{f\in u,d}\bar{f}\sigma_{\mu\nu}T^a d_{hgf}fG^a_{\mu\nu} + e\sum_{f\in u,d,e}\bar{f}\sigma_{\mu\nu}d_{h\gamma f}fA_{\mu\nu} + \sqrt{g^2+g'^2}\sum_{f\in u,d,e}\bar{f}\sigma_{\mu\nu}d_{hzf}fZ_{\mu\nu}\\ &+\sqrt{2}g\left(\bar{d}\sigma_{\mu\nu}d_{hwq}uW^-_{\mu\nu} + \text{h.c.}\right) + \sqrt{2}g\left(\bar{\nu}_L\sigma_{\mu\nu}d_{hw\ell}e_RW^+_{\mu\nu} + \text{h.c.}\right)\Bigg]\\ &-\frac{1}{4v}\Bigg[g_s\sum_{f\in u,d}\bar{f}\sigma_{\mu\nu}T^a\tilde{d}_{hgf}f\widetilde{G}^a_{\mu\nu} + e\sum_{f\in u,d,e}\bar{f}\sigma_{\mu\nu}\tilde{d}_{h\gamma f}f\widetilde{A}_{\mu\nu}\\ &+\sqrt{g^2+g'^2}\sum_{f\in u,d,e}\bar{f}\sigma_{\mu\nu}\tilde{d}_{hzf}f\widetilde{Z}_{\mu\nu} + \sqrt{2}g\left(\bar{d}\sigma_{\mu\nu}\tilde{d}_{hwq}u\widetilde{W}^-_{\mu\nu} + \text{h.c.}\right)\Bigg],\end{aligned} \tag{3.11}$$

# The light Higgs mass as an observable

Considering radiative corrections to the self-energies then all MSSM particles contributes.

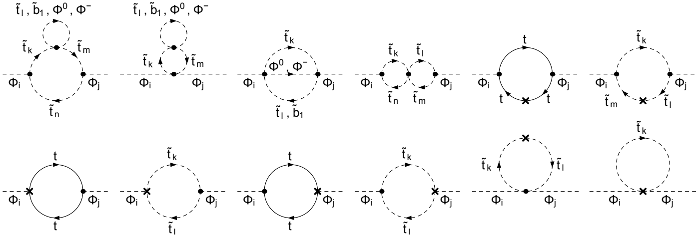
- $\hat{\Sigma}_{ij}(q^2) = \hat{\Sigma}^1_{ij}(q^2) + \hat{\Sigma}^2_{ij}(q^2) + \dots$

## Structure of radiative corrections

Only stop-top sector for simplicity

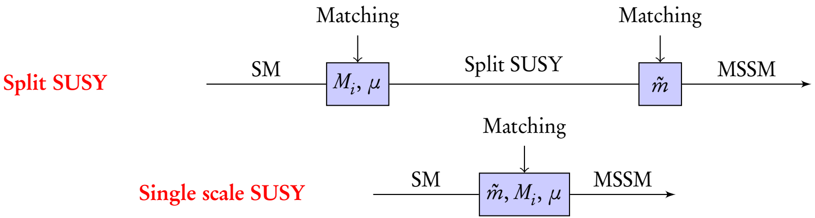
1. At one loop: $\Delta(M_h^{(1)})^2 = m_t^4[L + C^{(1)}]$ with $L = \left(\frac{m_{\tilde{t}}}{m_t}\right)$
2. At two loop: $\Delta(M_h^{(2)})^2 = m_t^2\left[m_t^2\alpha_s\left(L^2 + L + C^{(2)}\right) + m_t^4\left(L^2 + L + D^{(2)}\right)\right]$

Large logs ($\log(M_S/Q_{EW})$) if SUSY is heavy. Needs resummation.

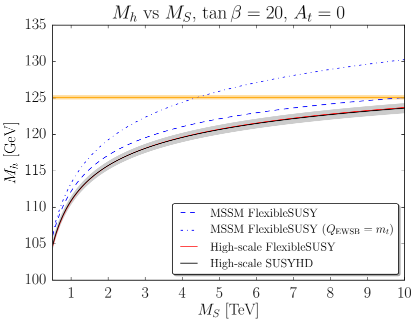


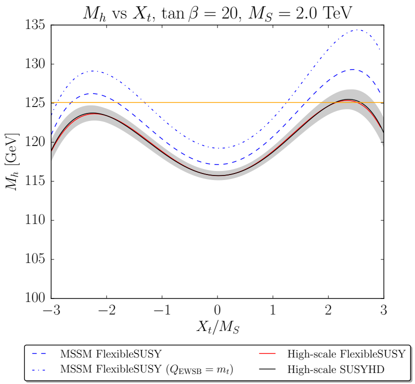
# The light Higgs mass as an observable

- Problem: mass gap in the physical spectrum makes large logs of the ratio $m_{\mathrm{ew}}/\tilde{m}$ appears in the perturbative expressions.
- Solution: For a proper computation these logs have to be resummed.
- Method: define a tower of effective field theories, where the heavy particles are integrated out, and match them at a proper scale. Use RGE to resum the large logarithms.



# The light Higgs mass as an observable




- Different region of applicability for the two approaches (low SUSY vs large SUSY masses).
- Uncertainty estimation in the intermediate, phenomenologically interesting region, not trivial.

`[SusyHD 1504.05200] [FlexibleSUSY WIP] [FeynHiggs 1312.4937]`

# The hMSSM approach

- Based on using the observed Higgs mass (and not the un-observed spectrum) as an input.
- Higgs sector of the MSSM described only in terms of $m_A$,$\tan\beta$ and $m_h$ (which is now an input).
- Predictive power in the heavy Higgs mass and the mixing angle $\alpha$

$$\mathcal{M}^2_\Phi = \mathcal{M}^2_{\text{tree}} + \begin{pmatrix} \Delta\mathcal{M}^2_{11} & \Delta\mathcal{M}^2_{12} \\ \Delta\mathcal{M}^2_{12} & \Delta\mathcal{M}^2_{22} \end{pmatrix}$$

$$\tan\alpha = -\frac{(m_Z^2+m_A^2)\cos\beta\sin\beta}{m_Z^2\cos^2\beta+m_A^2\sin^2\beta-m_h^2}$$

$$m_H^2 = \frac{(m_A^2+m_Z^2-m_h^2)(m_Z^2\cos^2\beta+m_A^2\sin^2\beta)-m_A^2 m_Z^2\cos^2 2\beta}{m_Z^2\cos^2\beta+m_A^2\sin^2\beta-m_h^2}$$

Beware that it depends on the following assumptions

- The neglected stop-top corrections in $\Delta\mathcal{M}^2_{11}$ ,$\Delta\mathcal{M}^2_{12}$ scale as $\mu X_t/m^2_{\text{SUSY}}$
- SUSY sparticles do not affect the Higgs besides the effect in mass matrix (satisfied in the low-$\tan\beta$ scenarios).
- Proper approach is EFT (Lee and Wagner)

[1305.2172,1307.5205,1502.05653,LHCHXSWG-2015-002]

# Production and decay rates

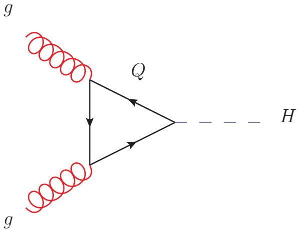
- The measured event rate is usually schematically written by

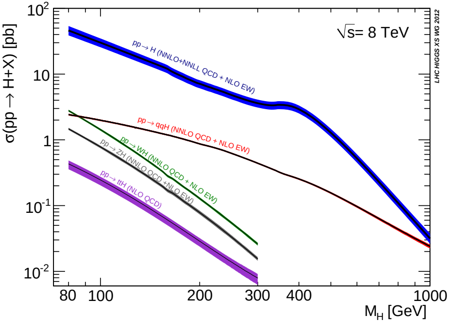
$$R_{pp\to h+X\to Y+X} = \sigma\left(pp\to h+X\right)\times \mathrm{BR}\left(h\to Y\right) = \sigma\left(pp\to h+X\right)\times \frac{\Gamma\left(h\to Y\right)}{\Gamma_{\mathrm{total}}}$$

- BSM physics can manifest itself through a modification one of these three components of the total event rate.
- The modification could be due to different couplings (e.g. in the 2HDM) or because of the presence of BSM particles in the quantum corrections.

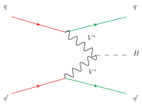
# Higgs production channels at the LHC

## Gluon fusion

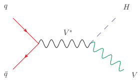


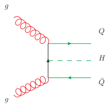

## Vector Boson Fusion (VBF)




## Higgs Strahlung




## Quark associated production

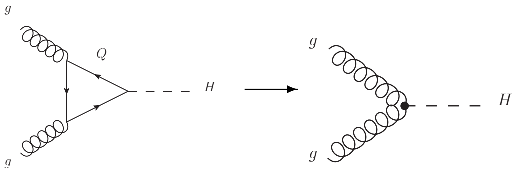


# Heavy Quark Effective Field Theory (HQEFT)

In the limit $m_{top} \to \infty$ we can construct an effective Lagrangian for the interaction of the Higgs boson with the gluons

$$\mathscr{L}_{eff} = \frac{\alpha_s}{12\pi} \frac{H}{v} (1+\Delta) \mathrm{Tr}\left[ G^a_{\mu\nu} G^a_{\mu\nu} \right]$$

In this theory the heavy quark loop shrinks to a point vertex, simplifying the calculations

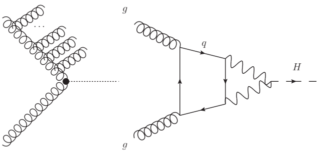


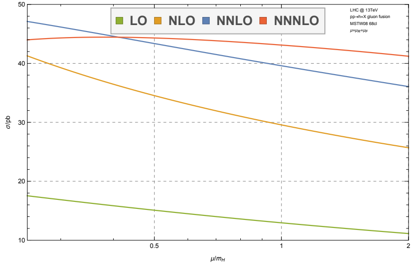

Validity conditions

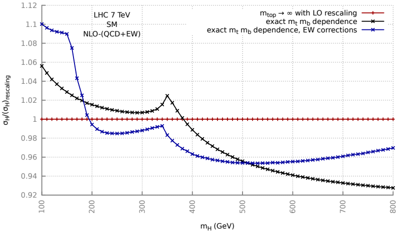
- Total cross section, $m_H < 2m_{top}$
- Kinematic variables, as $p_T^H$, less than $m_{top}$
- No strongly coupled light particles running in the loop (e.g. bottom quark in the MSSM for large $\tan\beta$)

# Gluon fusion SM

- In the HQEFT, computation now know at N3LO.
- In the SM, complete mass dependence available up to NLO.
- Estimation of the top effects at NNLO with a $m_h^2/m_t^2$ expansion.
- 2-loop EW and QCD-EW corrections known.
- NNLL-QCD threshold resummation (



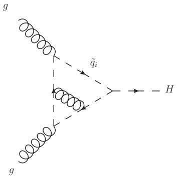



# Higgs boson production in the MSSM

Five states in the physical spectrum: two neutral CP-even scalars (h and H), one pseudoscalar (A) and two charged Higgses ($H^+$ and $H^-$)

## Gluon fusion




- SUSY-QCD contributions relevant for light sparticles
- Relevant role of the bottom quark in some region of the parameter space

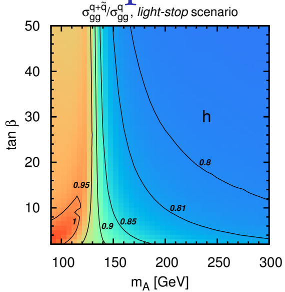
## Bottom annihilation

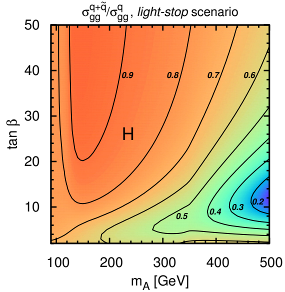
- Coupling to the bottom is $\tan\beta$ enhanced
- Dominant in sizable region of the MSSM parameter space for $H$ and $A$

$$\lambda_b^{h,MSSM} = -\frac{\sin\alpha}{\cos\beta}$$
$$\lambda_b^{H,MSSM} = \frac{\cos\alpha}{\cos\beta}$$
$$\lambda_b^{A,MSSM} = \tan\beta$$

A complete study of the MSSM production rates should include the two processes.

# The gluon fusion production process



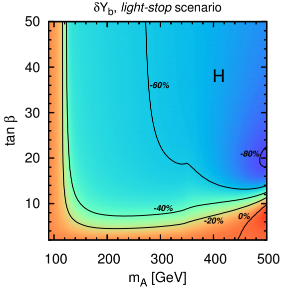



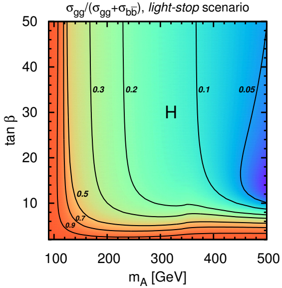

- Light squarks can produce a suppression/enhancement of production cross section even relatively into the decoupling limit (e.g. `lightstop scenario`)
- Stop effect depends on the mass hierarchy: $\delta A^{\tilde{t}} \sim \frac{m_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{m_Q^2}\right)$
- Interplay with effects in the Higgs to di-photon decay rate.

[1404.0327]

# Theoretical uncertainties

- One can compute the cross section either by extracting the bottom Yukawa from $M_b$ (the pole mass) or from the $\overline{\text{MS}}$-mass $m_b(\mu_R = m_\phi/2)$
- $\delta Y_b$ is the relative variation of the cross section with $\overline{\text{MS}}$ over the standard one with the pole mass
- Great sensitivity in some region (uncertainty up to 80%), though these are the same parameter space points where the bottom annihilation process is dominant
- Bottom annihilation very sensitive to PDF uncertainty.



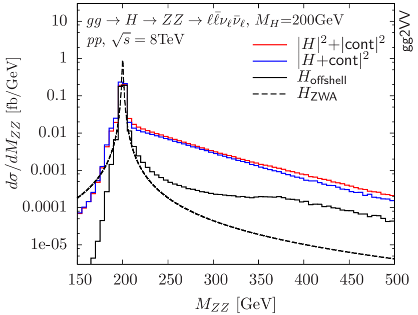

$$\mathscr{A}_b^{2\ell}(\tau) \;\propto\; C_F\left[\mathscr{F}_{C_F}(\tau) + \mathscr{F}_{1/2}^{1\ell}(\tau)\left(1 - \frac{3}{4}\ln\frac{m_b^2}{\mu_b^2}\right)\right] + C_A\,\mathscr{F}_{C_A}(\tau)$$

[1404.0327]

# Off-shell production

- Light higgs production at large virtuality.
- Top threshold effects.
- At high virtuality, larger than 1 TeV, suppressed by PDF.
- Inadequacy of the narrow width approximation.
- Need to consider the interference with the background for a precise prediction.

[1206.4803,1307.4935,1509.06734]



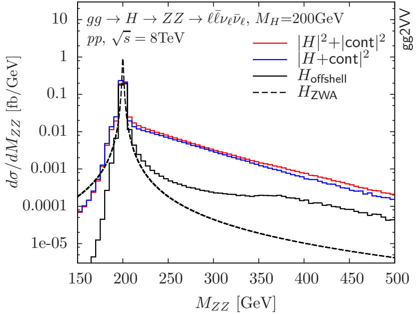
# Probing the Higgs width with off-shell production

- Close to the mass peak: $\frac{d\sigma_{i\to h\to f}}{dM^2_{ZZ}} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$
- In the tail: $\frac{d\sigma_{i\to h\to f}}{dM^2_{ZZ}} \sim \frac{g_i^2 g_f^2}{(M^2_{ZZ}-m_h^2)}$
- Parameterize the (small) deviations from the SM as: $g_{i,f} = \xi g_{i,f,SM}$, $\Gamma_H \xi^4 \Gamma_{H,SM}$

We can rewrite:

$$N^{off}_{obs} \sim g_i^2 g_f^2 = \xi^4 g^2_{i,SM} g^2_{f,SM} = \xi^4 N^{off}_{SM} = \frac{\Gamma_h}{\Gamma_{h,SM}} N^{off}_{SM}$$

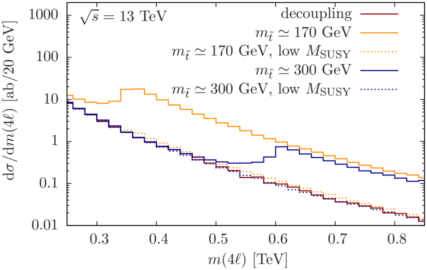
[1206.4803,1307.4935]

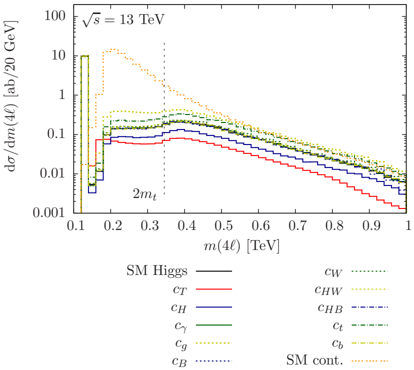


# BSM effects in in off-shell production

BSM physics can manifest itself in different ways.

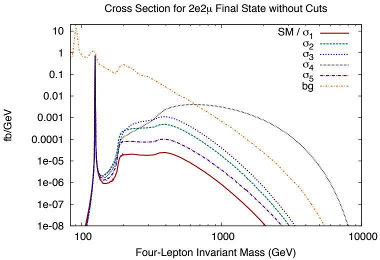
- Interference with of the off-shelf light Higgs with a heavier resonance.
- Thresholds effect in the Higgs boson line-shape due to other particles, e.g. stops.
- Effect of non-resonant contributions parameterized in terms of EFT.

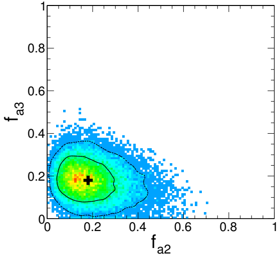


# Anomalous HZZ couplings

- Effect of EFT HZZ operators on the shape of the $M_{ZZ}$ distribution.
  - $\mathcal{O}_4 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$
  - $\mathcal{O}_6 = -\frac{M_Z^2}{M_h^2 v} Z_\mu Z^\mu \partial^2 H$
- Other operators affect the lepton angular distributions
  - $\mathcal{O}_2 = -\frac{1}{2v} H Z_{\mu\nu} Z^{\mu\nu}$
  - $\mathcal{I}_4 = \frac{2}{v} H Z_\mu \partial^2 Z^\mu$
- Good control at the HL-LHC.

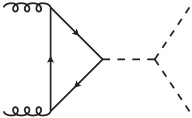


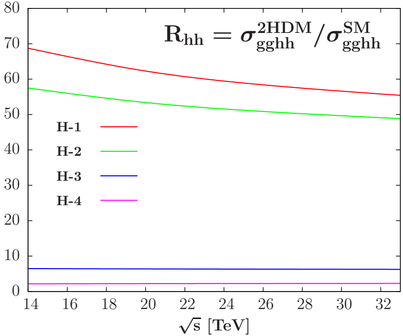




[1309.4819,1403.4951]

# Double/Triple Higgs production

- In the SM, production rates are very low, challenging if not impossible to probe at the LHC.
- Possible enhancement in BSM models (2HDM, SUSY etc.)
- Current results constraint triple light-higgs couplings. However one can enhance the triple heavy-light-light Higgs vertex.



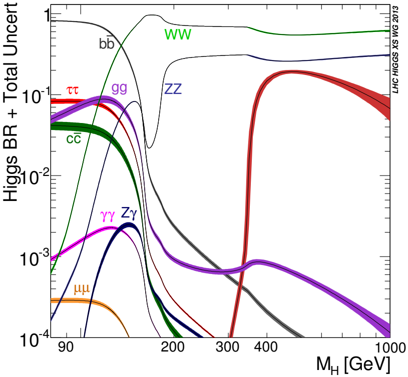



| | $\tan\beta$ | $(\beta-\alpha)/\pi$ | $m_H$ [GeV] | $m_A$ [GeV] | $m_{H^\pm}$ [GeV] | $m^2_{12}$ [GeV$^2$] |
|---|---|---|---|---|---|---|
| H-1 | 1.75 | 0.522 | 300 | 441 | 442 | 38300 |
| H-2 | 2.00 | 0.525 | 340 | 470 | 471 | 44400 |
| H-3 | 4.26 | 0.519 | 450 | 546 | 548 | 43200 |
| H-4 | 4.28 | 0.513 | 600 | 658 | 591 | 76900 |

[1403.1264,1502.00539]

# Higgs decay channels

- Higgs SM-like, with $m_h = 125$ GeV we can test a large variety of decay for the compatibility with the SM.
- Bounds from $h \to$ invis.
- Different final states from non-SM like heavier Higgses.



# The Higgs golden ratio

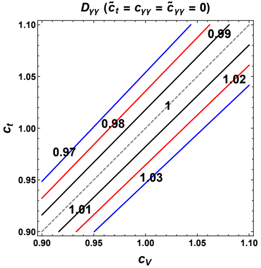
- Consider the ratio of two very clean channels, namely $\gamma\gamma$ and $ZZ$.
- Separately, theoretical uncertainty of $\mathcal{O}(10\%)$, however they cancel in the ratio (e.g. theoretical uncertainty on the production cross section).
- 

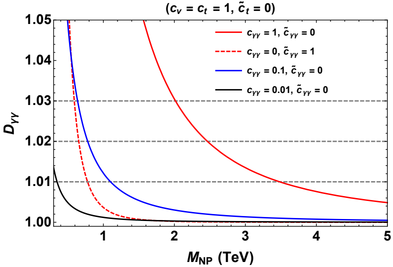
$$D_{\gamma\gamma} = \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(pp \to H \to ZZ^*)} = \frac{\sigma(pp \to H) \times \mathrm{BR}(H \to \gamma\gamma)}{\sigma(pp \to H) \times \mathrm{BR}(H \to ZZ^*)}$$

$$f = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to ZZ^*)} \propto \frac{c_\gamma^2}{c_Z^2}$$

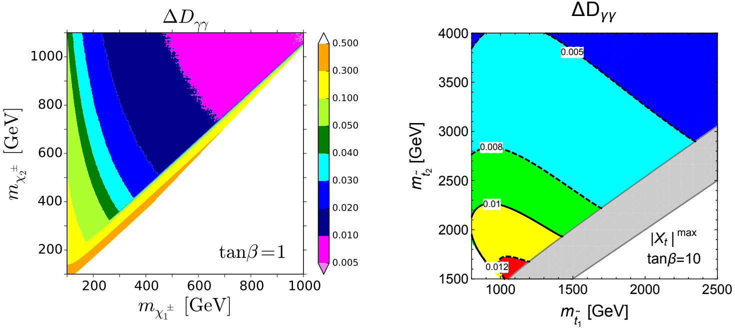
- Can parameterize the effect in terms of EFT.

[1509.03913]



# The Higgs golden ratio




- This ratio is affected in the MSSM by loops of electroweakly interacting particles (squarks, sleptons, electroweakinos).
- Contribution from charginos maximal when $\tan\beta = 1$ the two states are equal admixture of higgsinos and gauginos.
- Stops provide largest contribution to the $h \to \gamma\gamma$ vertex. For heavy stops and LSP, stronger limits than from direct detection.

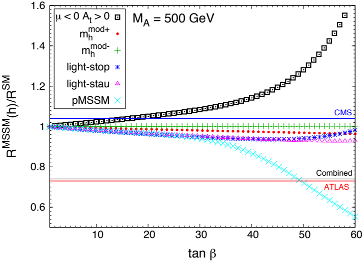
[1509.03913]

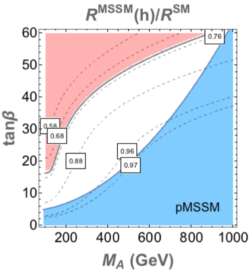
# The ratio $h \to b\bar{b}/h \to \tau\bar{\tau}$

- The ratio $R = \frac{\mathrm{BR}(h\to b\bar{b})}{\mathrm{BR}(h\to\tau^+\tau^-)} = 3\frac{m_b^2(Q)}{m_\tau^2(Q)}$ at LO is the same in the SM, 2HDM and MSSM.
- Radiative corrections can alter the decay modes $h \to b\bar{b}$ and $h \to \tau\bar{\tau}$.
- $g_{hb\bar{b},h\tau\bar{\tau}} = -\frac{m_{b,\tau}\sin\alpha}{v\cos\beta(1+\Delta_{b,\tau})}\left(1 - \frac{\Delta_{b,\tau}}{\tan\beta\tan\alpha}\right)$

Very interesting both theoretically and experimentally since

- Systematic effects cancel in the ratio, besides $\tau$- and $b$ tagging efficiencies.
- Independent on the production process and the total width.

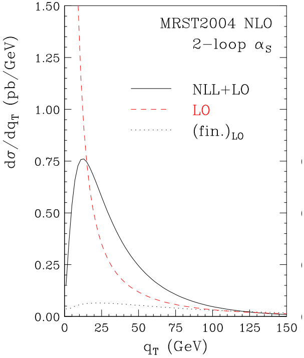



[1506.08462v2]

# The $p_T^H$ distribution

- The Higgs acquires a transverse momentum due to the recoil against QCD radiation.
- At fixed order, the $p_T^H$ distribution diverges in the limit $p_T^H \to 0$.
- The physical behavior is restored by resumming the divergent $\log\left(\frac{p_T^H}{m_H}\right)$ terms, either analytically or numerically (i.e. through a Parton Shower).
- problem: match the resummed and fixed order calculation.
- Uncertainty estimation in this procedure is important for precision phenomenology.

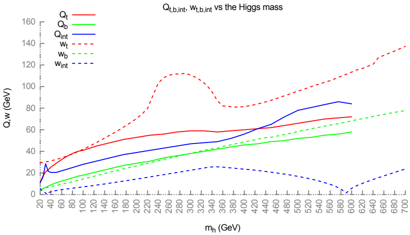


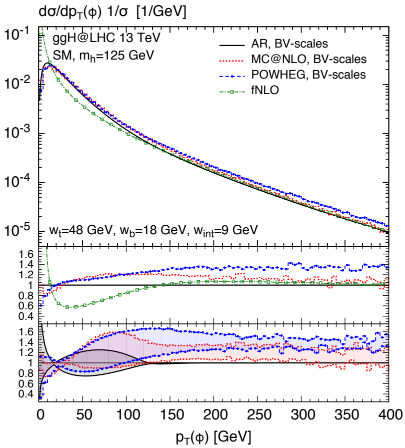

Available resummation frameworks

- **Analytic resummation** (Catani, Grazzini). Dependence on the unphysical resummation scale can be used to probe the missing higher-order terms.
- **NLO+PS,** `MC@NLO` (Frixione, Webber). Variation of the shower scale used to probe the matching uncertainty.
- **NLO+PS,** `POWHEG` (Frixione, Nason, Oleari). The damping factor $D_h$ can control higher-order terms in the matching procedure.

# Theoretical uncertainties

- Low-$p_T$ region affected by matching uncertainties.
- It's important to estimate them by varying the matching parameters.
- How to determine the matching scales? Two prescriptions on the market.




[1306.4581,1409.0531,1505.00735,1510.08850]

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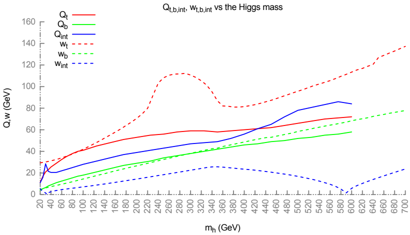


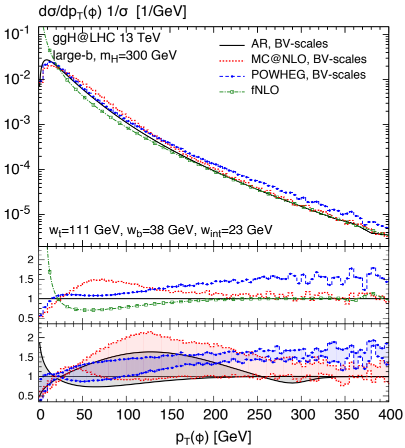


[1306.4581,1409.0531,1505.00735,1510.08850]

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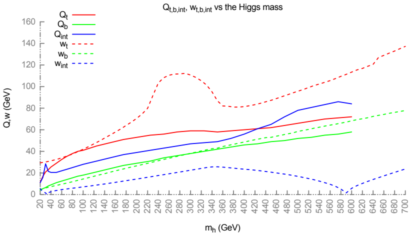
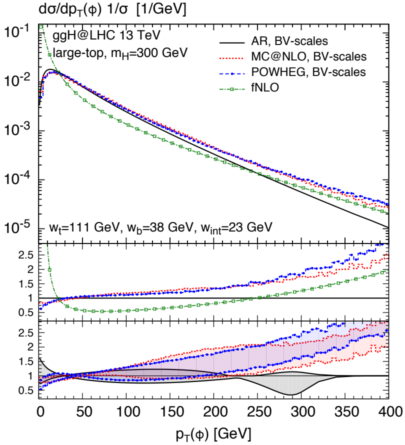
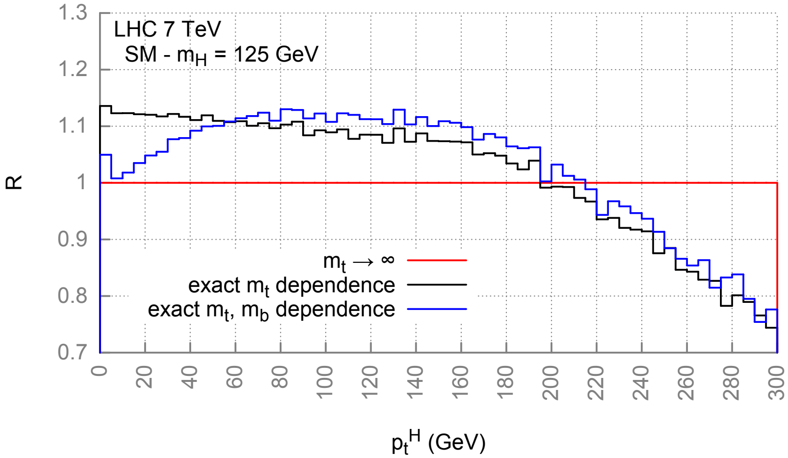



[1306.4581,1409.0531,1505.00735,1510.08850]

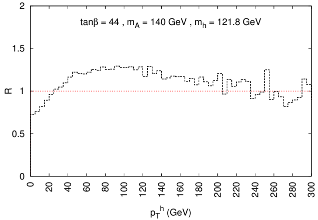
# Theoretical uncertainties

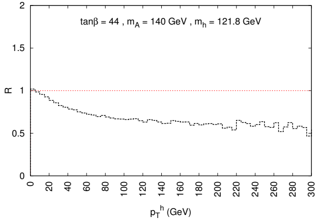



- High-$p_T$ region inaccurate if HQEFT used.
- Top-mass effect sizable, quickly greater than 50% suppression as soon as $p_T > m_t$.
- H+1@NLO not available in the SM, H+2 jets tree level.

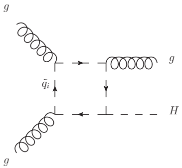
# Probing new physics with $p_T^h$

- Exactly as one can have an effect on total rates due to the presence of additional BSM particles in the gluon fusion loops, one can have effects on the shape of the $p_T^h$ distribution.
- Change in the relative weight of the Yukawa couplings to top and bottom can affect the shape too.
- High-$p_T^h$ events probe relatively large mass scales.



# Higgs $p_T^H$ distribution in the MSSM




In the MSSM the matrix element squared for the $gg \to gH$ channel is given by

$$\mathcal{M}(gg \to gH)|^2 = |\mathcal{M}_t + \mathcal{M}_b + \mathcal{M}_{\tilde{q}}|^2 =$$
$$= |\mathcal{M}_t|^2 + 2\mathrm{Re}(\mathcal{M}_t \mathcal{M}_b^\dagger) + |\mathcal{M}_b|^2 + 2\mathrm{Re}(\mathcal{M}_t \mathcal{M}_{\tilde{q}}^\dagger) + 2\mathrm{Re}(\mathcal{M}_b \mathcal{M}_{\tilde{q}}^\dagger) + |\mathcal{M}_{\tilde{q}}|^2$$

- The bottom contribution could be boosted (i.e. $\tan\beta$ enhancement).
- This in turn could make the contribution of the interference between the bottom and the squarks relevant.
- Exact treatment of mass effects could not be neglected.

# Top Yukawa from the high-$p_T$ tail

- Parameterize the couplings of the Higgs to the top and the gluons as

$$\mathscr{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$

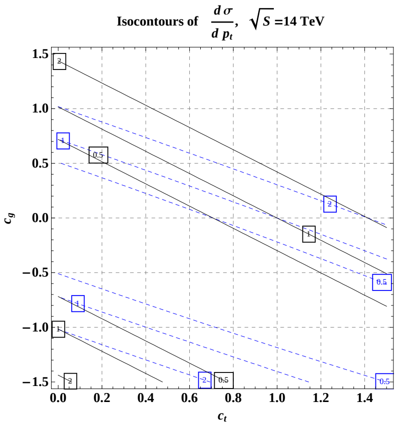
- Study of the high-pt tail allow for the disentangling of the two couplings.

$$\frac{d\sigma}{dp_T} = \sum_i \varkappa_i |f^i(p_T) c_t + c_g|^2$$

$$\left(\frac{d\sigma^{SM}(m_t)}{dp_T}\right) / \left(\frac{d\sigma^{SM}(m_t)}{dp_T}\right)$$

$$= \frac{\sum_i \varkappa_i f^i(p_T)^2}{\sum_i \varkappa_i}$$

[1309.5273]



# Top Yukawa from the high-$p_T$ tail

Divide the spectrum in two bins

$$\sigma^-(p_T < P_T) = \int_{p_T^{min}}^{P_T} \frac{d\sigma}{dp_T} dp_T, \quad N^- = \sigma^- \times \text{Luminosity}$$

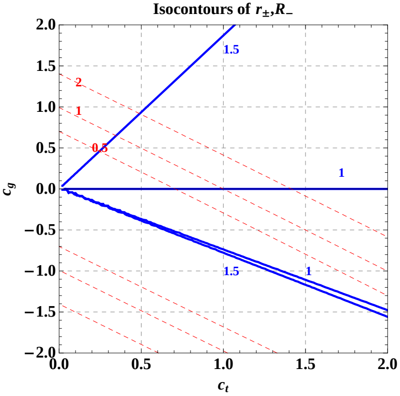
$$\sigma^+(p_T > P_T) = \int_{P_T}^{p_T^{max}} \frac{d\sigma}{dp_T} dp_T, \quad N^+ = \sigma^+ \times \text{Luminosity}$$

and define the ratios

$$R_+ = \frac{\sigma^+}{\sigma^+_{SM}} \text{ and } R_- = \frac{\sigma^-}{\sigma^-_{SM}}$$

and

$$r_\pm = \frac{R_+}{R_-}$$




fo

discriminating $p_T = 300$ GeV

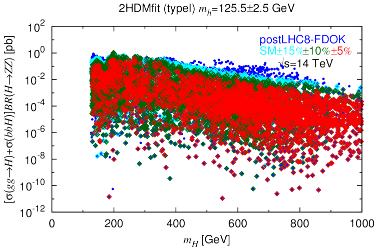
# Higgs production in the 2HDM

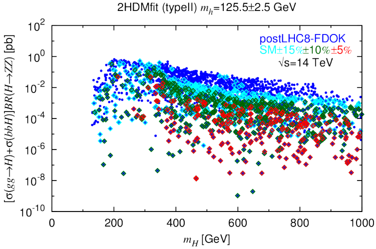
- Systematic study of THDM models after LHC run 1.
- Respecting the constraints from the light Higgs measurements, still possibility of discovery for H/A in ZZ (only for H), $\tau^+\tau^-$,$t\bar{t}$,$\mu\bar{\mu}$ and and $\gamma\gamma$.
- If we allow for the Higgs at 125.5 GeV to be the heaviest, there is a viable possibility of detection for $A$ and the lightest $h$.

Cconstraints from charged Higgs contributions to $h\gamma\gamma$ and $H\gamma\gamma$ if light higgs rates SM-like at 5%

- Remove all but a few of THDM Type-I models.
- Exclude all the THDM Type-2 models.

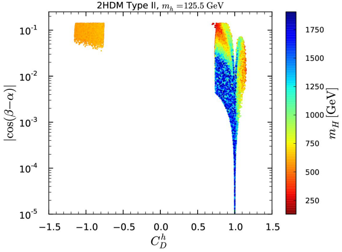
[1405.3584v2]

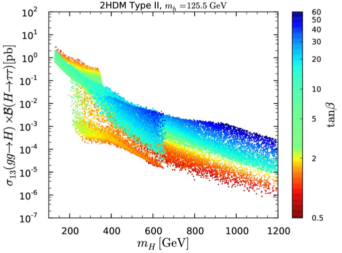


# Alignment without decoupling

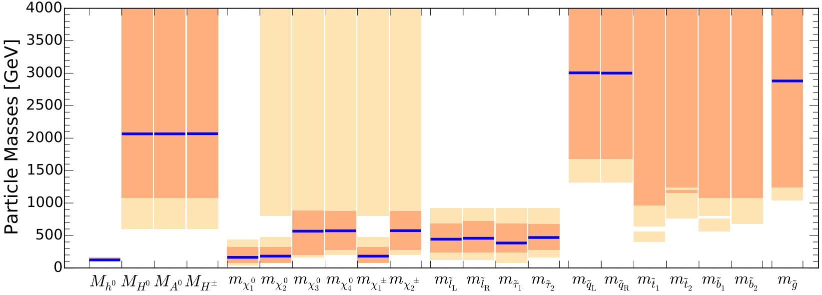
- Suppose now that we are in the alignment limit ($|\cos(\beta-\alpha)| \to 0$) of the 2HDM but without decoupling.
- Coupling of the observed Higgs boson constrained to be SM-like at 1%.
- Heavy Higgs with a mass less than 600 GeV.
- $C_D^h \simeq 0.70$-$1.15$ still allowed even for $|\cos(\beta-\alpha)| \sim 10^{-2}$. Large values are associated with light $H$ and $A$. Even region $|C_D^h| \simeq -1 \pm 0.2$.
- For $\tan\beta \sim 1$, lower bound for $gg \to H/A \to \tau^+\tau^-$ of 0.1 fb for $m_A \sim 500$ GeV. It should be probable at Run 2.




[1507.00933]

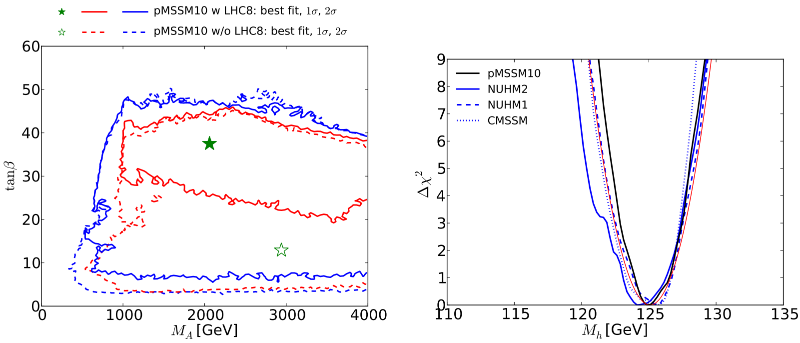
# pMSSM10 mass spectrum




- Poor determination of the mass of colored sparticles (only lower bound from LHC searches).
- Larger freedom allow to fullfill the $(g-2)_\mu$ constraint without being in tension with the LHC searches.
- Improved fit with respect to the GUT models.

[1504.03260] MasterCode collaboration

# The Higgs sector in the pMSSM10




- pMSSM10 likelihood is very similar to the experimental value smeared by the theoretical uncertainty as given by `FeynHiggs`.
- Lower value of $\tan\beta$ are disfavored at the 68% CL by $\mathrm{LHC8}_{EWK}$, $(g-2)_\mu$ and DM constraints
- The constraints interplay with the choice of a single soft SUSY-breaking mass-parameter for the sleptons.

[1504.03260] MasterCode collaboration

# Conclusions and outlook

- Discussed only a few of the possible ways the Higgs could be modified by BSM physics, in the 2HDM and MSSM.
- Global parameter space of the models effectively constrained by the LHC Run 1.
- Rich phenomenology both for total rates (modification of production and decay).
- More difficult but effects are also visible in differential observables