2HDM Model with FCNCs

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LIP/CFTC Meeting, 30/01/2020

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Eur. Phys. J. C (2019) 79:552

SYMMETRIES OF THE MODEL

- **The model possesses a CP SYMMETRY, such that all of its parameters are forced to be real.**
- **That is complemented with a Z_3 symmetry which affects both the quark and scalar sectors , such that, with**

$$\Phi_2 \to \omega^2 \Phi_2,$$
$$Q_{L1} \to \omega^2 Q_{L1}, \quad Q_{L2} \to \omega Q_{L2},$$
$$n_{R3} \to \omega n_{R3},$$
$$p_{R1} \to \omega p_{R1}, \quad p_{R2} \to \omega p_{R2}.$$

with $\omega = e^{2i\pi/3}$. Recall that n and p and the positive and negative quark fields (not yet rotated to their mass basis) and Γ, Δ are the 3×3 Yukawa coupling ma

$$\mathcal{L}_{\text{Yukawa}} = -\sum_{j,k=1}^{3}\sum_{a=1}^{2} \bar{Q}_{Lj}\left[\Phi_a (\Gamma_a)_{jk}\, n_{Rk} + \tilde{\Phi}_a (\Delta_a)_{jk}\, p_{Rk}\right] + \text{H.c.}$$

- **We do not address the leptonic sector in this work – it is easy to see it can be chsen to be flavour conserving, like one of the regular 2HDM types).**

SYMMETRIES OF THE MODEL

- The Z_3 symmetry **BREAKS FLAVOUR CONSERVATION** bcause it treats each generation differently. Therefore, tree-level flavour changing neutral currents (FCNC) mediated by scalars are to be expected.

- The scalar potential becomes indistinguishable from that of a Peccei-Quinn model,

$$V_{U(1),softly\,broken} = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - \left(m_{12}^2\, e^{i\theta}\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2$$

where we have **SOFTLY BROKEN** the Z_3 symmetry via the **COMPLEX** m_{12} parameter.

- The phase θ is the only source of CP violation in the model!

- But for the scalar sector, it is easy to think of this phase as vanishing through a doublet phase redefinition – it will turn out later in the fermion sector!

THEORETICAL BOUNDS ON 2HDM SCALAR PARAMETERS

Potential has to be bounded from below:

$$\lambda_1 \geq 0, \qquad \lambda_2 \geq 0,$$
$$\lambda_3 \geq -\sqrt{\lambda_1 \lambda_2}, \qquad \lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1 \lambda_2}$$

Theory must respect unitarity:

$$
\begin{aligned}
a_\pm &= \frac{3}{2}(\lambda_1 + \lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2}, \\
b_\pm &= \frac{1}{2}(\lambda_1 + \lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}, \\
c_\pm &= \frac{1}{2}(\lambda_1 + \lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_5^2}, \\
e_1 &= \lambda_3 + 2\lambda_4 - 3\lambda_5 \\
e_2 &= \lambda_3 - \lambda_5, \\
f_+ &= \lambda_3 + 2\lambda_4 + 3\lambda_5, \\
f_- &= \lambda_3 + \lambda_5, \\
f_1 &= \lambda_3 + \lambda_4,
\end{aligned}
$$

$$|a_\pm|, \ |b_\pm|, \ |c_\pm|, \ |f_\pm|, \ |e_{1,2}|, \ |f_1|, \ |p_1| < 8\pi$$

(for the current model these conditions are valid, with of course $\lambda_5 = 0$)

S. Kanemura, T. Kubota and E. Takasugi, Phys. Lett. B **313** (1993) 155 [arXiv:hep-ph/9303263].
A. G. Akeroyd, A. Arhrib and E. -M. Naimi, Phys. Lett. B **490**, 119 (2000) [hep-ph/0006035].

SPONTANEOUS SYMMETRY BREAKING:

Doublet field components:

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

Both doublets may acquire REAL vevs, v_1 and v_2, such that

$$v_1{}^2 + v_2{}^2 = v^2 = (246\ GeV)^2$$

Definition of β angle: $\tan\beta \equiv \dfrac{v_2}{v_1}$

(yes, it is unphysical in this model, in principle – call it a placeholder variable...)

Definition of α angle (h, H: CP-even scalars):

$$h = \rho_1 \sin\alpha - \rho_2 \cos\alpha,$$
$$H = -\rho_1 \cos\alpha - \rho_2 \sin\alpha$$

(without loss of generality: $-\pi/2 \leq \alpha \leq +\pi/2$)

THE YUKAWA SECTOR

- **The Z_3 symmetry's impact on the Yukawa matrices is to reduce them to a very simple form (after rephasings),**

$$\Gamma_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & e_n \\ c_n & d_n & 0 \end{pmatrix} \quad , \quad \Gamma_2 = \begin{pmatrix} a_n & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & b_n \end{pmatrix}$$

$$\Delta_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_p & d_p \\ e_p & 0 & 0 \end{pmatrix} \quad , \quad \Delta_2 = \begin{pmatrix} 0 & a_p & 0 \\ b_p & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- **The quark mass matrices are then REAL and given by**

$$M_n = \frac{1}{\sqrt{2}}(\Gamma_1 v_1 + \Gamma_2 v_2) \quad , \quad M_p = \frac{1}{\sqrt{2}}(\Delta_1 v_1 + \Delta_2 v_2)$$

which are bi-diagonalized by matrices U_L and U_R such that

$$U_L^{n\dagger} M_n U_R^n = M_d \equiv \mathrm{diag}\,(m_d,\ m_s,\ m_b)$$

$$U_L^{p\dagger} M_p U_R^p = M_u \equiv \mathrm{diag}\,(m_u,\ m_c,\ m_t)$$

THE YUKAWA SECTOR

- **IMPORTANT**: the diagonalization matrices end up being **REAL ORTHOGONAL** matrices,

$$O_{Ln} M_n O_{Rn} = M_d, \quad O_{Lp} M_p O_{Rp} = M_u$$

which has two crucial consequences:

- The CKM matrix is given by

$$V_{CKM} = O_{Lp} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{3i\theta} & 0 \\ 0 & 0 & e^{3i\theta} \end{pmatrix} \times O^T_{Ln}$$

and therefore only through the phase θ does one obtain a complex CKM!

- The Yukawa interaction matrices,

$$N_n = \frac{1}{\sqrt{2}}(\Gamma_1 v_2 - \Gamma_2 v_1) \quad , \quad N_p = \frac{1}{\sqrt{2}}(\Delta_1 v_2 - \Delta_2 v_1)$$

are completely **REAL** in the mass basis:

$$N_d = O_{Ln} N_n O_{Rn}, \quad N_u = O_{Lp} N_p O_{Rp}$$

THE YUKAWA SECTOR

- But the matrices N_d and N_u are NOT diagonal in the quark mass basis, due to flavour violation, and therefore we have **scalar-mediated tree-level FCNC!**

$$
\begin{aligned}
\mathcal{L}_{\text{physical}} \;=\;& \frac{iA}{v}\,\bar{u}\left(N_u P_R - N_u^\dagger P_L\right) u \\
&+\frac{iA}{v}\,\bar{d}\left(N_d^\dagger P_L - N_d P_R\right) d \\
&+\frac{h}{v}\,\bar{u}\left[\left(s_{\beta-\alpha} M_u - c_{\beta-\alpha} N_u^\dagger\right) P_L + \left(s_{\beta-\alpha} M_u - c_{\beta-\alpha} N_u\right) P_R\right] u \\
&+\frac{h}{v}\,\bar{d}\left[\left(s_{\beta-\alpha} M_d - c_{\beta-\alpha} N_d^\dagger\right) P_L + \left(s_{\beta-\alpha} M_d - c_{\beta-\alpha} N_d\right) P_R\right] d \\
&+\frac{H}{v}\,\bar{u}\left[\left(c_{\beta-\alpha} M_u + s_{\beta-\alpha} N_u^\dagger\right) P_L + \left(c_{\beta-\alpha} M_u + s_{\beta-\alpha} N_u\right) P_R\right] u \\
&+\frac{H}{v}\,\bar{d}\left[\left(c_{\beta-\alpha} M_d + s_{\beta-\alpha} N_d^\dagger\right) P_L + \left(c_{\beta-\alpha} M_d + s_{\beta-\alpha} N_d\right) P_R\right] d \\
&+\frac{\sqrt{2}H^+}{v}\,\bar{u}\left(N_u^\dagger V P_L - V N_d P_R\right) d \\
&+\frac{\sqrt{2}H^-}{v}\,\bar{d}\left(V^\dagger N_u P_R - N_d^\dagger V^\dagger P_L\right) u,
\end{aligned}
$$

PHENOMENOLOGY

- The model has 7 parameters in the scalar sector, and 10 non-zero entries of the Yukawa matrices. It needs to fit the W and Z mass, the observed Higgs boson mass (and SM-like behaviour) and correctly reproduce the quark masses and CKM matrix entries. We took for the quark sector the following values:

$$\begin{aligned} m_u &= (2.2 \pm 2 \times 0.6)\,\mathrm{MeV}, \\ m_d &= (4.7 \pm 2 \times 0.5)\,\mathrm{MeV}, \\ m_s &= (96 \pm 2 \times 8)\,\mathrm{MeV}, \\ m_c &= (1.28 \pm 0.03)\,\mathrm{GeV}, \\ m_b &= (4.18 \pm 0.04)\,\mathrm{GeV}, \\ m_t &= (173.2 \pm 0.6)\,\mathrm{GeV}, \end{aligned}$$

$$\begin{aligned} |V_{us}| &= 0.2243 \pm 0.0005, \\ |V_{cb}| &= 0.0422 \pm 0.0008, \\ |V_{ub}| &= 0.00394 \pm 0.00036, \\ \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) &= (73.5 \pm 5.5)^\circ\,. \end{aligned}$$

- The Higgs boson mass was demanded to be equal to **125 GeV**, and chosen to be the lighter of the neutral scalars.

- The occurrence of FCNC means that a series of mesonic observables wil have to be looked into. Other B-physics constraints, such as $b \to s\,\gamma$, will also need to be modified to take into account the neutral scalars' contributions.

PHENOMENOLOGY

- **The FCNC interactions of the neutral scalars give tree-level contributions to observables – like neutral meson mass differences (ΔM_K, ΔM_{Bs}, ΔM_{Bd}, ΔM_D) and ε_K – whose leading SM contribution comes at one loop. This will limit the off-diagonal entries of the matrices N_d and N_u (this last one solely from ΔM_D) as well as the masses of the neutral scalars.**

- **Like in the flavour-preserving 2HDM, there are charged Higgs contributions to as $b \to s\, \gamma$, but with FCNC the neutral scalars also contribute to this observable. Nonetheless, the charged Higgs contribution is found to be the dominant one.**

- **The charged Higgs is also the main contributor to $Z \to b\, \bar{b}$, although the neutral FCNC contributions were also taken into account.**

- **The parameter space probed could include reasonable low charged and neutral masses, so the possibility of exotic top quark decays ($t \to q\, H^+$ or $t \to u\, h, \ldots$) was also considered, the latest LHC constraints used to limit its possibility**

HIGGS ALIGNMENT CUTS

- **The observed Higgs boson has been found, at the LHC, to behave ina manner quite consistent with SM expectations – so the 2HDM "h" state should be almost *aligned* with the SM Higgs.**

- **The main experimental observables concerning the 125 GeV scalar are the ratios of observed and expected (in the SM) cross section times branching ratios, for the channels $pp \rightarrow h \rightarrow XX$ (with X = $Z^0Z^0,\ W^+W^-,\ b\bar{b},\ \tau\bar{\tau},$ or $\gamma\gamma$ ...),**

$$\mu_X = \frac{\sigma\left(pp \to h\right)\, \mathrm{BR}\left(h \to X\right)}{\sigma^{\mathrm{SM}}\left(pp \to h\right)\, \mathrm{BR}^{\mathrm{SM}}\left(h \to X\right)}$$

- **Current uncertainties still allow for non-SM scalars to conform to experimental values. Requiring that μ_X does not deviate by more than 20% from 1 (exact SM behaviour) on all channels does an effective description of current experimental constraints.**

- **For a first exploration, only the gluon-gluon fusion cross section was considered. But VBF and other processes would be well described.**

HIGGS ALIGNMENT CUTS

The fact that the observed 125 GeV scalar is VERY SM-like in the ZZ and WW channels has a crucial significance for the 2HDM parameters α and β,

$$\frac{iA}{v}\,\bar{u}\left(N_u P_R - N_u^\dagger P_L\right)u$$
$$+\frac{iA}{v}\,\bar{d}\left(N_d^\dagger P_L - N_d P_R\right)d$$
$$+\frac{h}{v}\,\bar{u}\left[\left(s_{\beta-\alpha}M_u - c_{\beta-\alpha}N_u^\dagger\right)P_L + \left(s_{\beta-\alpha}M_u - c_{\beta-\alpha}N_u\right)P_R\right]u$$
$$+\frac{h}{v}\,\bar{d}\left[\left(s_{\beta-\alpha}M_d - c_{\beta-\alpha}N_d^\dagger\right)P_L + \left(s_{\beta-\alpha}M_d - c_{\beta-\alpha}N_d\right)P_R\right]d$$
$$+\frac{H}{v}\,\bar{u}\left[\left(c_{\beta-\alpha}M_u + s_{\beta-\alpha}N_u^\dagger\right)P_L + \left(c_{\beta-\alpha}M_u + s_{\beta-\alpha}N_u\right)P_R\right]u$$
$$+\frac{H}{v}\,\bar{d}\left[\left(c_{\beta-\alpha}M_d + s_{\beta-\alpha}N_d^\dagger\right)P_L + \left(c_{\beta-\alpha}M_d + s_{\beta-\alpha}N_d\right)P_R\right]d$$
$$+\frac{\sqrt{2}H^+}{v}\,\bar{u}\left(N_u^\dagger V P_L - V N_d P_R\right)d$$
$$+\frac{\sqrt{2}H^-}{v}\,\bar{d}\left(V^\dagger N_u P_R - N_d^\dagger V^\dagger P_L\right)u,$$

Pseudoscalar FCNC interactions can be enhanced/suppressed by factors of tanβ

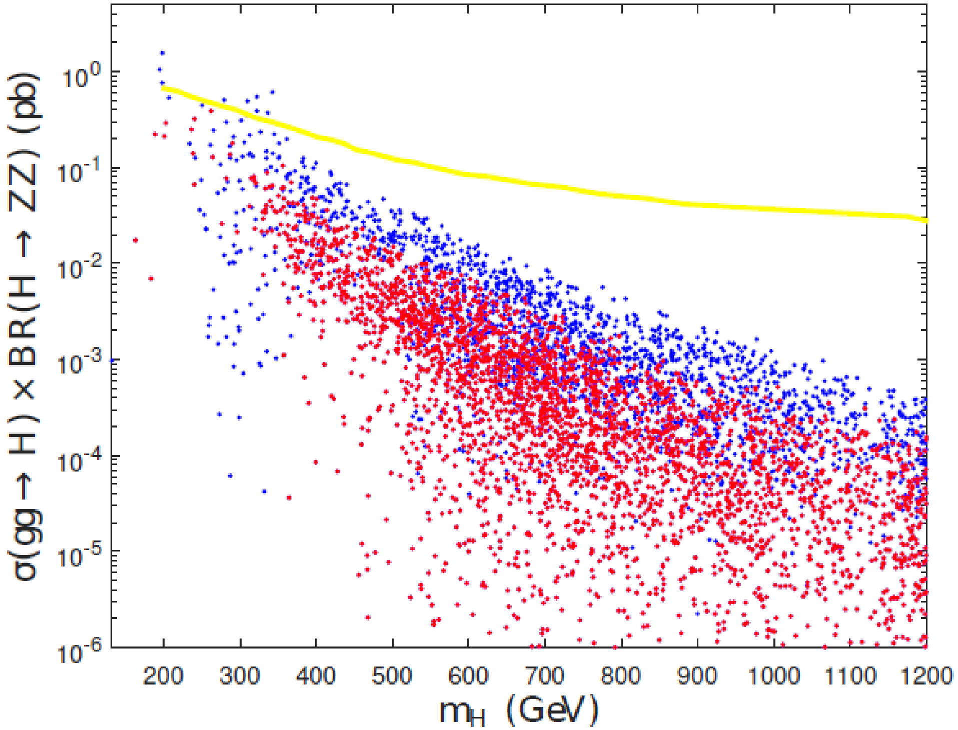
h FCNC are *suppressed* by factors of cosβ – α)

H FCNC are *"enhanced"* by factors of sin(β – α)

Charged FCNC interactions can be enhanced/suppressed by factors of tanβ

PROPERTIES OF THE EXTRA SCALAR

The heavier CP-even H boson has ZZ decays well below the current experimental limit:

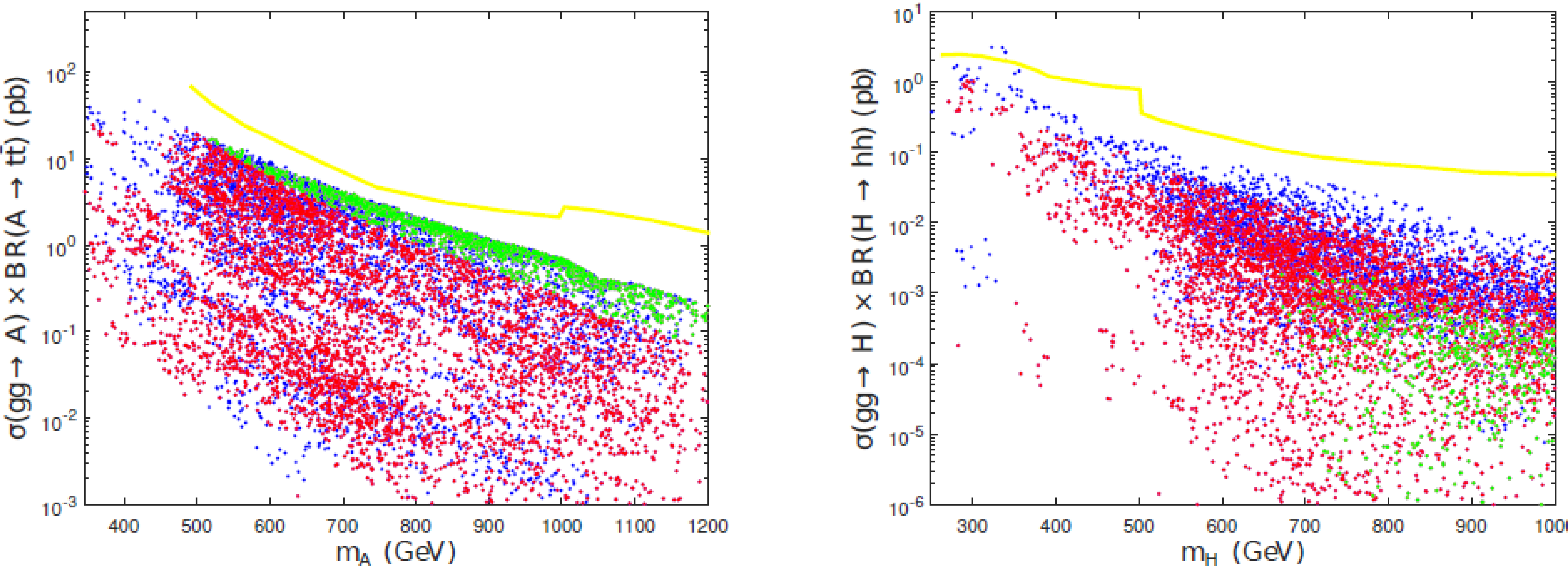


The yellow line is the upper 2σ limit from ATLAS. Blue (red) points have a cut on the Higgs rates μ_X of 20% (10%).

ATLAS Collaboration, *Search for heavy ZZ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using proton–proton collisions at $\sqrt{s} = 13\,TeV$ with the ATLAS detector*, ATLAS-CONF-2017-058.

PROPERTIES OF THE EXTRA SCALAR

Likewise for current limits from tt or hh searches.

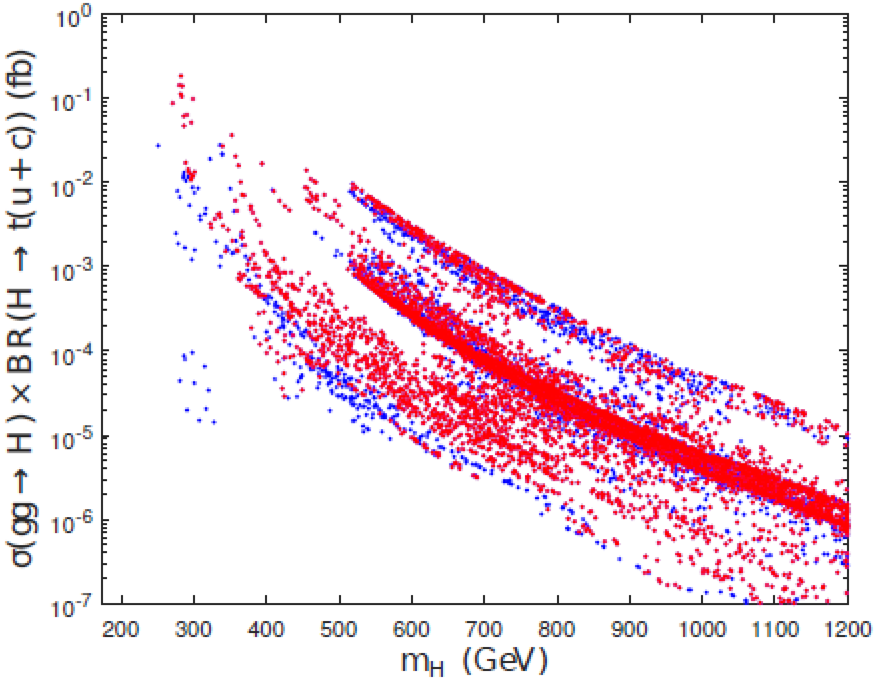


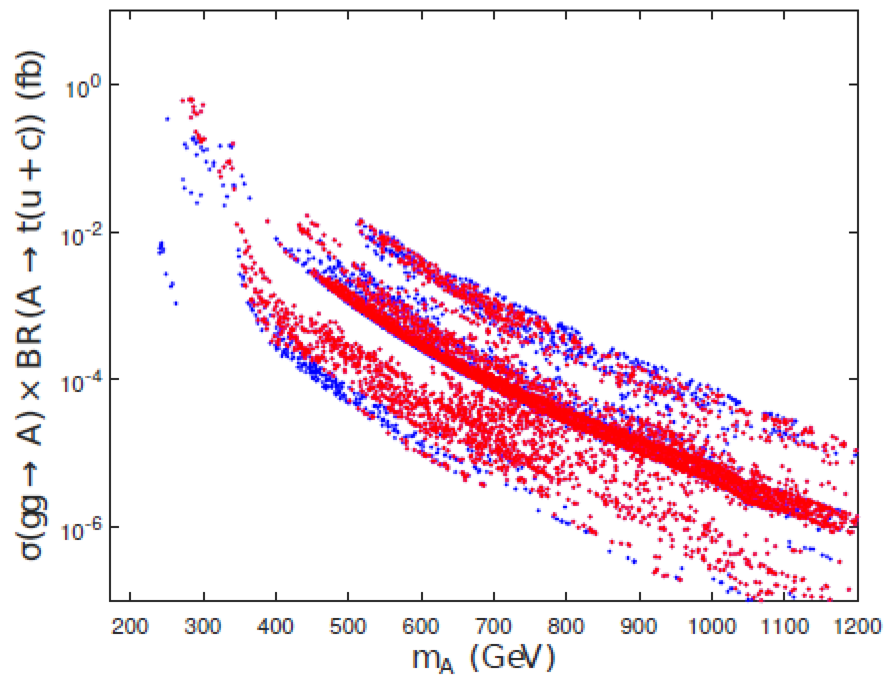
The yellow line is the upper 2σ limit from ATLAS. Blue (red) points have a cut on the Higgs rates μ_X of 20% (10%). The green points are a subset of the red ones, for which the width of the scalar is larger than 10% its mass.

G. Aad *et al.* [ATLAS Collaboration], *Searches for Higgs boson pair production in the $hh \to bb\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma bb$, $bbbb$ channels with the ATLAS detector*, Phys. Rev. D **92** (2015) 092004 [arXiv:1509.04670 [hep-ex]].

ATLAS Collaboration, *Search for Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state using pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2016-004.

WHAT ABOUT THE FCNC INTERACTIONS?





Blue (red) points have a cut on the Higgs rates μ_X of 20% (10%).

- **The extra neutral scalars, H and A, will also have FCNC decays, which might yield interesting phenomenology (single top FCNC decays!). However, those decays are also quite constrained.**

- **WHAT ARE THE CURRENT BOUNDS ON TOP + JET????**