Reinterpretations of non-resonant searches for Higgs boson pairs

HH Workshop, Fermilab

Alexandra Carvalho, Florian Goertz, Ken Mimasu,
Maxime Gouzevitch, **Anamika Aggarwal**

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Outline

- Recast of CMS and ATLAS measurements
- Model dependent interpretations of non-resonant gg-HH
  - Models which can be described with one parameter
  - Models with more than one free parameter
- VBF HH

Setup for the reinterpretations

Lagrangian specifying the Higgs couplings for GGF analysis:

$$
\begin{aligned}
\mathcal{L}_{hh} = &- \frac{m_h^2}{2v}\left(1 - \frac{3}{2}c_H + c_6\right)h^3 - \frac{m_h^2}{8v^2}\left(1 - \frac{25}{3}c_H + 6c_6\right)h^4 \\
&+ \frac{\alpha_s c_g}{4\pi}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)G^a_{\mu\nu}G_a^{\mu\nu} \\
&- \left[\frac{m_t}{v}\left(1 - \frac{c_H}{2} + c_t\right)\bar{t}_L t_R h + \frac{m_b}{v}\left(1 - \frac{c_H}{2} + c_b\right)\bar{b}_L b_R h + \text{h.c.}\right] \\
&- \left[\frac{m_t}{v^2}\left(\frac{3c_t}{2} - \frac{c_H}{2}\right)\bar{t}_L t_R h^2 + \frac{m_b}{v^2}\left(\frac{3c_b}{2} - \frac{c_H}{2}\right)\bar{b}_L b_R h^2 + \text{h.c.}\right],
\end{aligned}
$$

We base our MC in anomalous couplings => this makes it fully flexible for interpretations

Let's experiment with interpretations of EFT's matched to UV completions!
(= anomalous couplings mapped to EFTs matched to UV completions)

Recast of CMS and ATLAS measurements

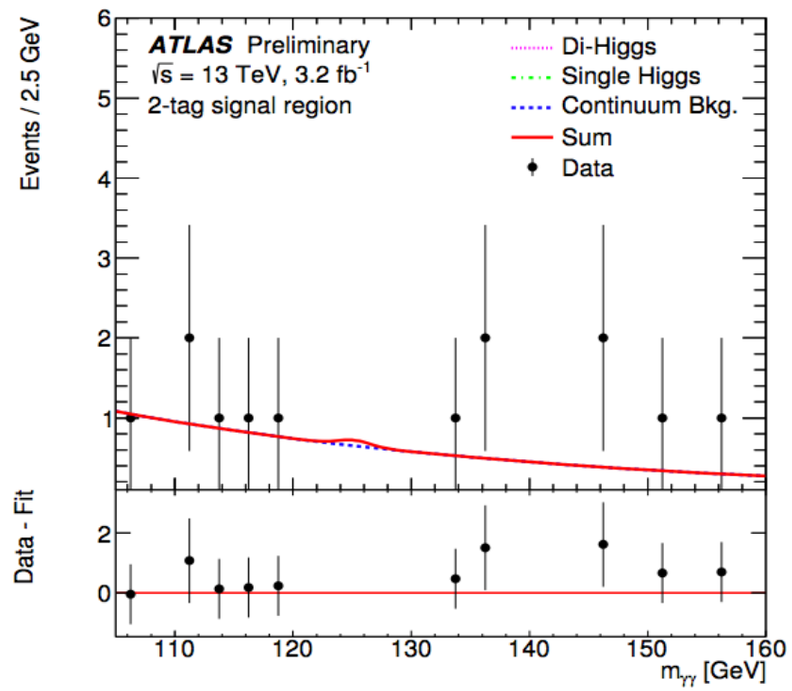
- Delphes recast of 2015 ATLAS and CMS γγbb analysis (using CMS phase II card)
- Why 2015 only? There is no MVA (our goal is exemplify reinterpretation)
- The choice of the HH → γγbb channel results from the fact that this final state is easy to simulate and to reconstruct using a parametric model of the ATLAS and CMS detectors.

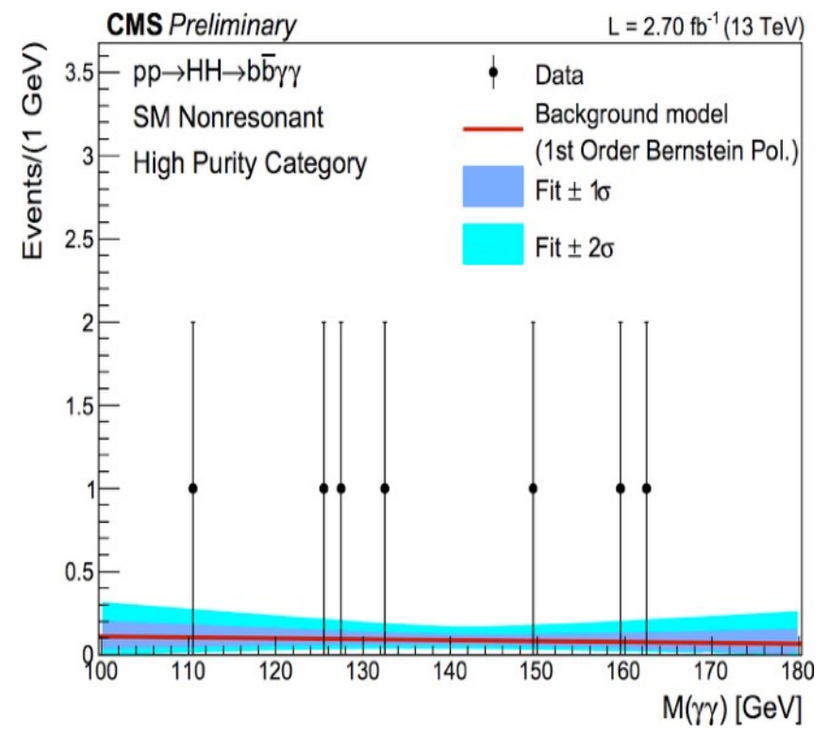
Selections used in the recast analysis

variable	ATLAS	CMS
$\lvert\eta_{max}\rvert$	2.37	2.5
Rejected fiducial region in $\lvert\eta\rvert$	[1.37, 1.52]	[1.44, 1.57]
Leading photon ($p_{T,min}$)	—	30
Subleading photon ($p_{T,min}$)	—	20
Leading photon $(p_{T,min})/M_{\gamma\gamma}$	0.35	1/3
Trailing photon $(p_{T,min})/M_{\gamma\gamma}$	1/4	
ΔR with any jet	> 0.4	
$\lvert\eta_{max,b}\rvert$	2.5	2.4
Leading b-jet $p_{T,min}$ (GeV)	55	25
Trailing b-jet $p_{T,min}$ (GeV)	35	25
$M_{\gamma\gamma}$ window (GeV)	[122, 128]	
$M_{b\bar{b}}$ window (GeV)	[95,135]	[80,200]
$M_{\gamma\gamma b\bar{b}}$ minimum (GeV)	—	350

✳ We use only the highest purity category of each experiment.
✳ A mass cut in Mgg is introduced and limits are derived based on cut-and-count

Recast of CMS and ATLAS measurements





ATLAS			CMS		
$\epsilon_{SM,D}$	ϵ_{SM}	f_{SM}	$\epsilon_{SM,D}$	ϵ_{SM}	f_{SM}
7.1%	10%	1.41	10.8%	≈ 10%	1

Moduli fudge factors (f_{SM}) the signal efficiency from recast ($\epsilon_{SM,D}$) is compatible with the ones quoted by the exp. documents (ϵ_{SM})

We also extrapolate the limits to lumi=100/fb by simple rescaling of the ~3/fb result

[19] *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*. Tech. rep. ATLAS-CONF-2016-004. Geneva: CERN, 2016. URL: http://cds.cern.ch/record/2138949.

[20] *Search for $H(bb)H(\gamma\gamma)$ decays at 13TeV*. Tech. rep. CMS-PAS-HIG-16-032. CERN, 2016. URL: http://cds.cern.ch/record/2207960.

Model dependent interpretations

11 models were investigated in consideration to mapping to the EFT

Model	NP integrated out	Ref.
1	real scalar singlet with explicit Z_2 breaking	[37, 38]
2	real scalar singlet with spontaneous Z_2 breaking	[37]
3	real scalar triplet	[37, 38]
4	complex scalar triplet	[37, 38]
5	quartet scalar with $Y = 1/2$	[37, 38]
6	quartet scalar with $Y = 3/2$	[37, 38]
7	2HDM (addtl. scalars heavy + Z_2)	[39]
8	vector-like quark: T (singlet top partner)	[40]
9	vector-like lepton: E (flavor universal singlet)	[41]
10	MCHM_5	[7, 8, 42, 43]
11	MCHM_4	[7, 8, 42, 43]

Model dependent interpretations

Model	Fund. Parameters	κ_λ	κ_t	c_2
1	$\alpha, m_2, \lambda_\alpha$	$1-\frac{3}{2}t_\alpha^2+t_\alpha^2\left(\lambda_\alpha - t_\alpha\frac{m_2}{v}\right)/\lambda_{\rm SM}$	$1-\frac{t_\alpha^2}{2}$	$-\frac{t_\alpha^2}{2}$
2	α	$1-\frac{3}{2}t_\alpha^2$	$1-\frac{t_\alpha^2}{2}$	$-\frac{t_\alpha^2}{2}$
3	β, m_{H^+}, m_H	$1+4s_\beta^2\left(3+\frac{m_{H^+}^2}{v^2\lambda_{\rm SM}}\right)\frac{m_{H^+}^4}{m_H^4}$	1	$-2s_\beta^2\frac{m_{H^+}^4}{m_H^4}$
4	β, m_A, m_H	$1+2s_\beta^2\left(3+\frac{4m_A^2}{v^2\lambda_{\rm SM}}\right)\frac{m_A^4}{m_H^4}$	$1-2s_\beta^2\frac{m_A^4}{m_H^4}$	$-4s_\beta^2\frac{m_A^4}{m_H^4}$
5	β, m_A, m_H	$1+\frac{24}{7}t_\beta^2\frac{m_A^4}{m_H^2v^2\lambda_{\rm SM}}$	1	0
6	β, m_A, m_H	$1+\frac{8}{3}t_\beta^2\frac{m_A^4}{m_H^2v^2\lambda_{\rm SM}}$	1	0
7	β, Z_6, m_H	$1-\frac{3Z_6^2}{2\lambda_{\rm SM}}\frac{v^2}{m_H^2}$	$1-\frac{Z_6}{t_\beta}\frac{v^2}{m_H^2}$	$-\frac{3Z_6}{2t_\beta}\frac{v^2}{m_H^2}$
8	λ_{Tt}, M_T	1	$1-V_{tb}\frac{\lvert\lambda_{Tt}\rvert^2v^2}{2M_T^2}$	$-3V_{tb}\frac{\lvert\lambda_{Tt}\rvert^2v^2}{4M_T^2}$
9	$\lambda_{E\ell}, M_E$	$1+\frac{\lvert\lambda_{E\ell}\rvert^2v^2}{4M_E^2}$	$1+\frac{\lvert\lambda_{E\ell}\rvert^2v^2}{4M_E^2}$	0
10	ξ	$\frac{(1-2\xi)}{\sqrt{1-\xi}}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$	-2ξ
11	ξ	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$	$-\frac{\xi}{2}$

Correlations!

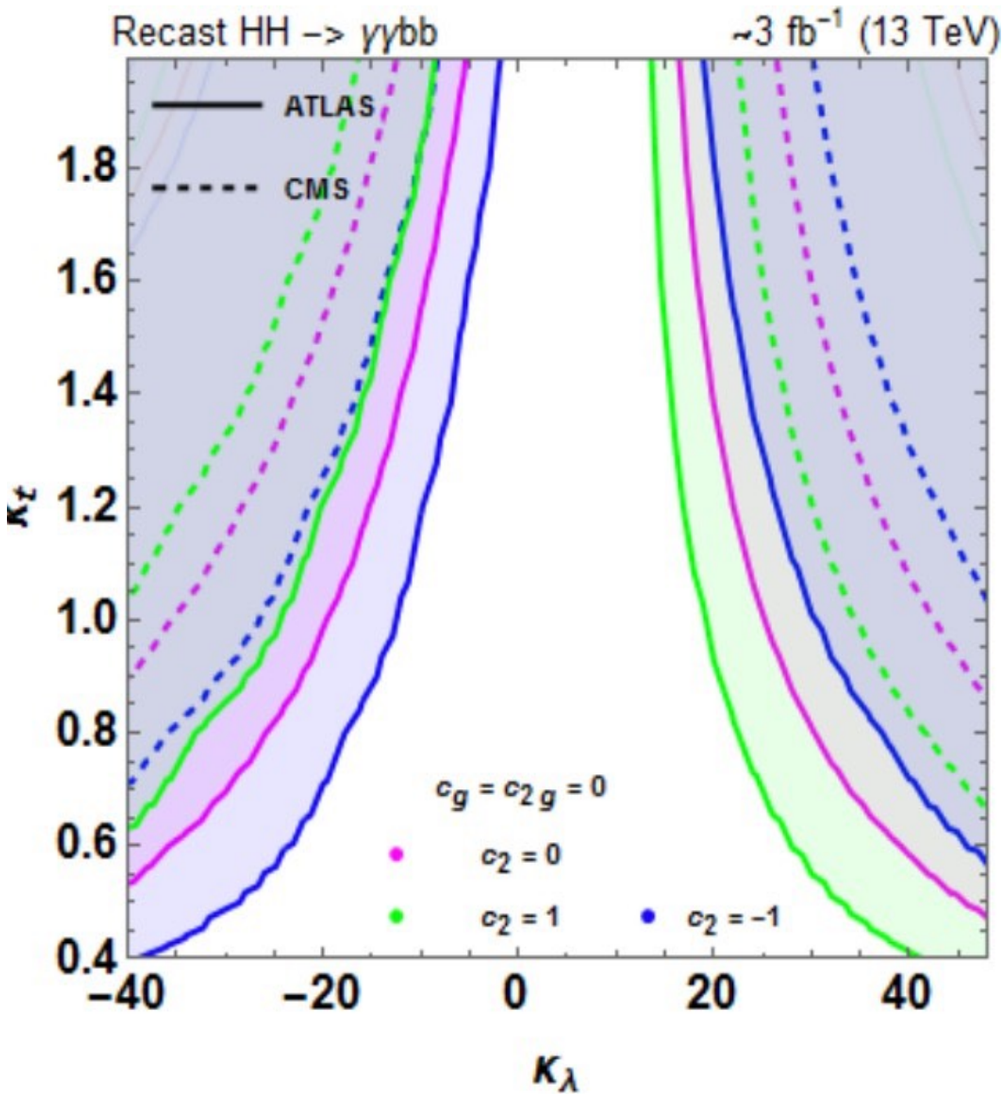
There is no cg/c2g in this table!
=> Loop level EFT is much more laborious to match to EFT by hand

Model	Free Parameters	κ_λ	κ_t	c_2
1	κ_t, κ_λ	κ_λ	κ_t	$\kappa_t - 1$
2	κ_t	$3\kappa_t - 2$	κ_t	$\kappa_t - 1$
3	κ_λ, c_2	κ_λ	1	c_2
4	κ_t, κ_λ	κ_λ	κ_t	$2\kappa_t - 2$
5	κ_λ	κ_λ	1	0
6	κ_λ	κ_λ	1	0
7	κ_t, κ_λ	κ_λ	κ_t	$3/2(\kappa_t - 1)$
8	κ_t	1	κ_t	$3/2(\kappa_t - 1)$
9	κ_t	κ_t	κ_t	0
10	κ_t	κ_t	κ_t	$\kappa_t(\kappa_t + \sqrt{\kappa_t^2 + 8})/4 - 1$
11	κ_t	κ_t	κ_t	$(\kappa_t^2 - 1)/2$

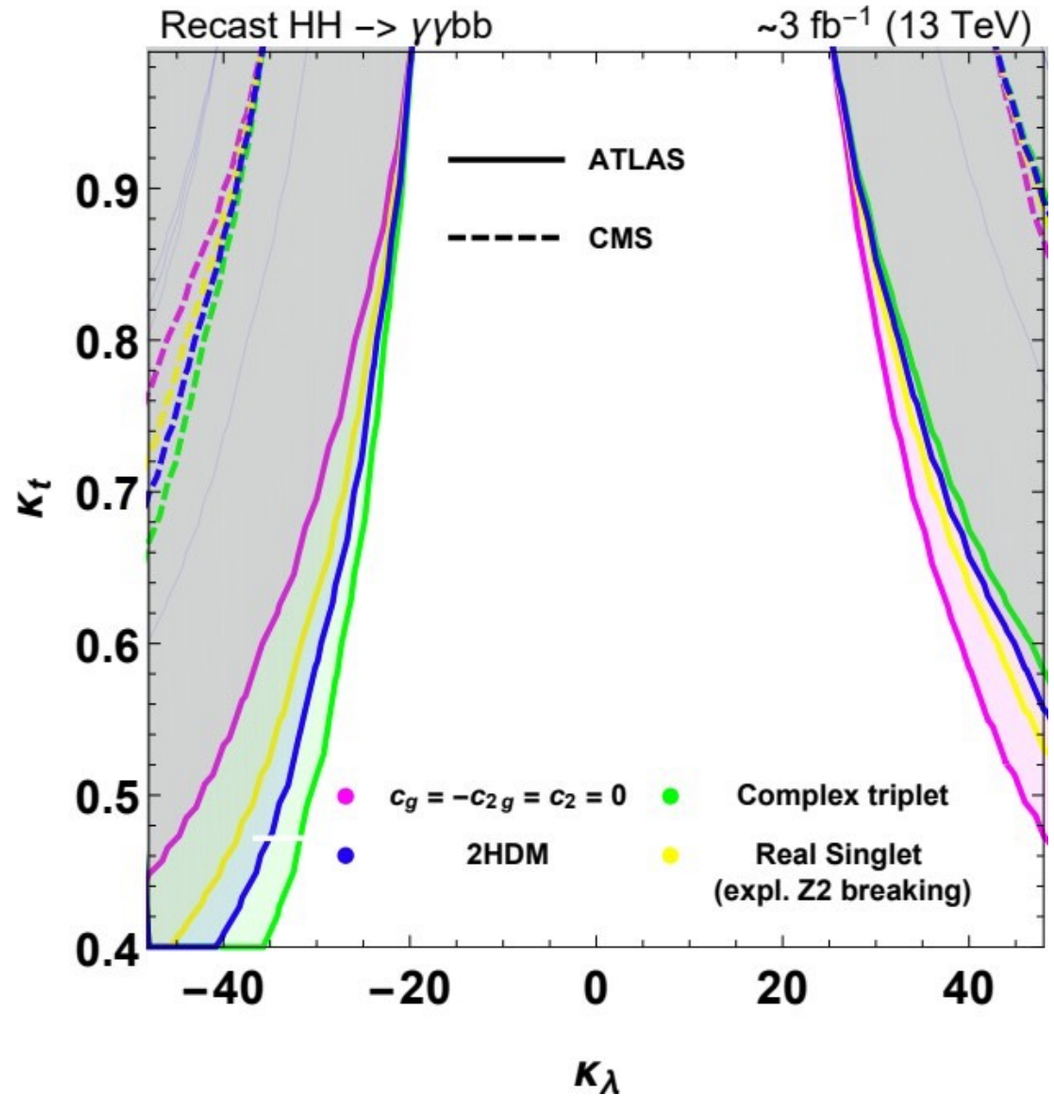
- α is the mixing angle between the two scalars,
- $\beta = \arccos(v_1/v)$ is the arccosine of the ratio of the vev of the (first) doublet and the electroweak vev $v \approx 246$ GeV.
- A common mass m_H is assumed for the heavy scalars, besides for H^+ and A in models 3-6, with masses m_{H^+}, m_A.
- m_2 is the coefficient of the triple-singlet coupling and λ_α that of the bi-quadratic scalar term.
- M_T and M_E are the masses of the heavy vector-like quark and lepton, respectively.
- $\lambda_{Tt}, \lambda_{El}$ are the coefficients of their (Yukawa-type) couplings with the SM fermions, mediated by the Higgs.
- $\xi \equiv v^2/f^2$ parametrizes the composite Higgs non-linearity, with f the Pseudo-Goldstone decay constant.

$\kappa_\lambda \kappa_t$ plane

(correlations effect)



Varying c2 freely



Considering the correlations on the models

Ignoring the modifications on the H BR that are uniquely predicted on each model

Model dependent interpretations

For indicated models, there is a non negligible effect of H BR on the limits on physical parameters

Model	NP integrated out	Ref.
1	real scalar singlet with explicit Z_2 breaking	[37, 38]
2	real scalar singlet with spontaneous Z_2 breaking	[37]
3	real scalar triplet	[37, 38]
4	complex scalar triplet	[37, 38]
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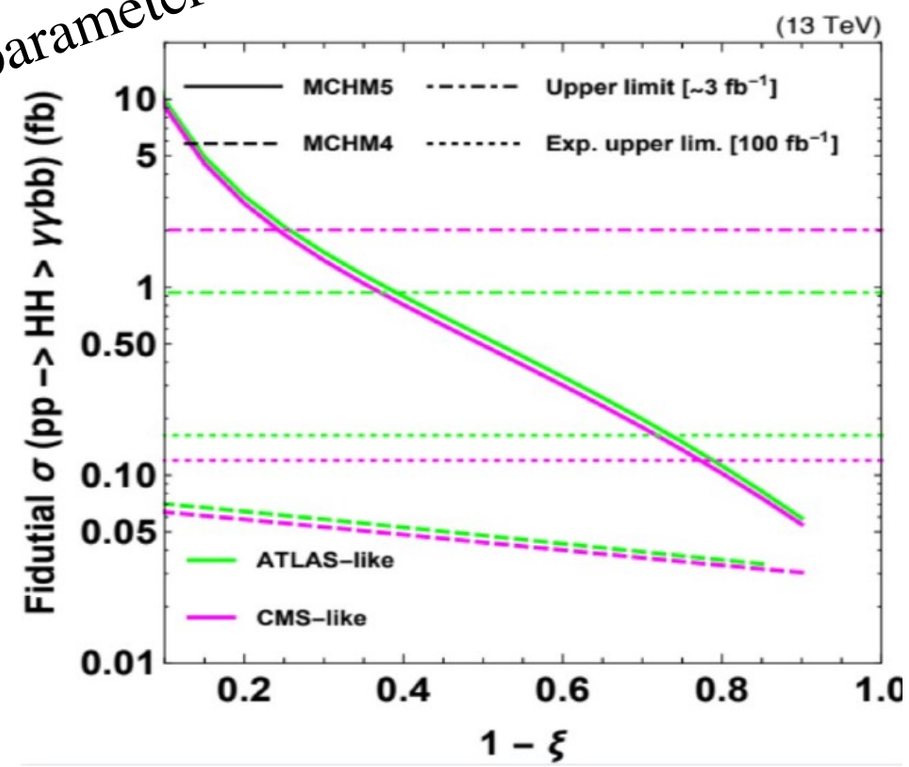
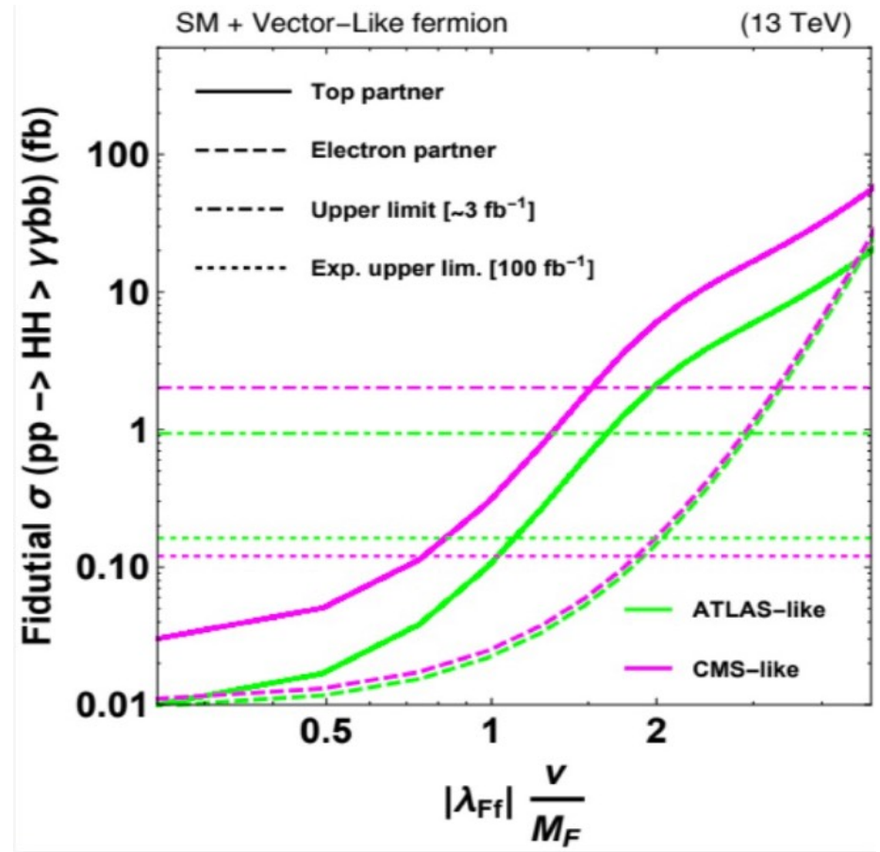
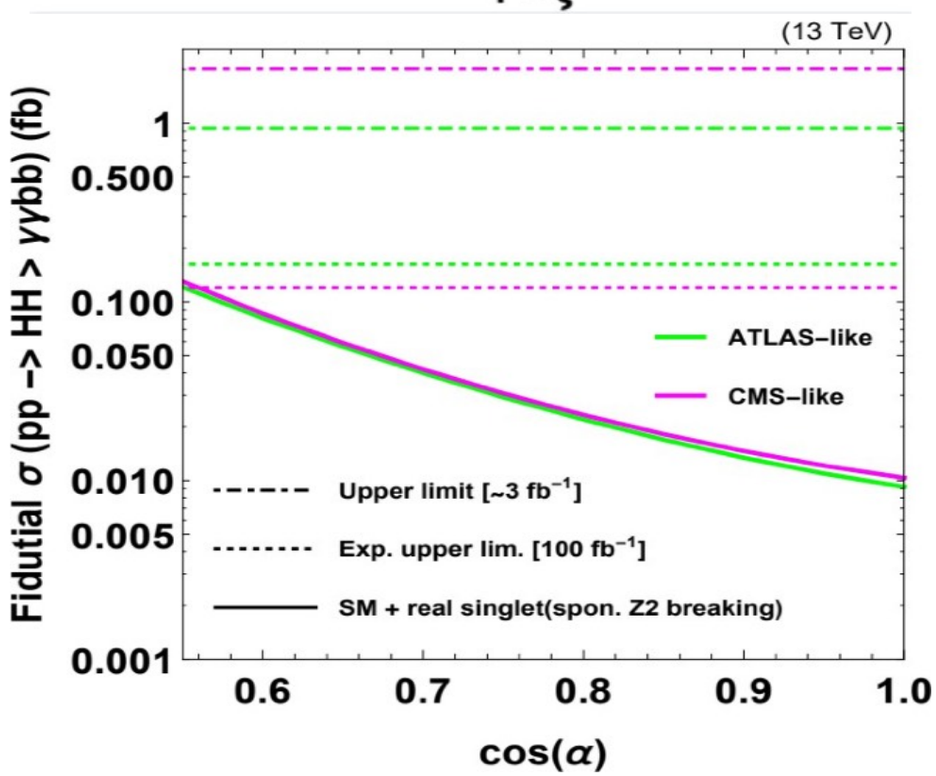
Folding interpretations on explicit model parameters

Models which can be described with one parameter





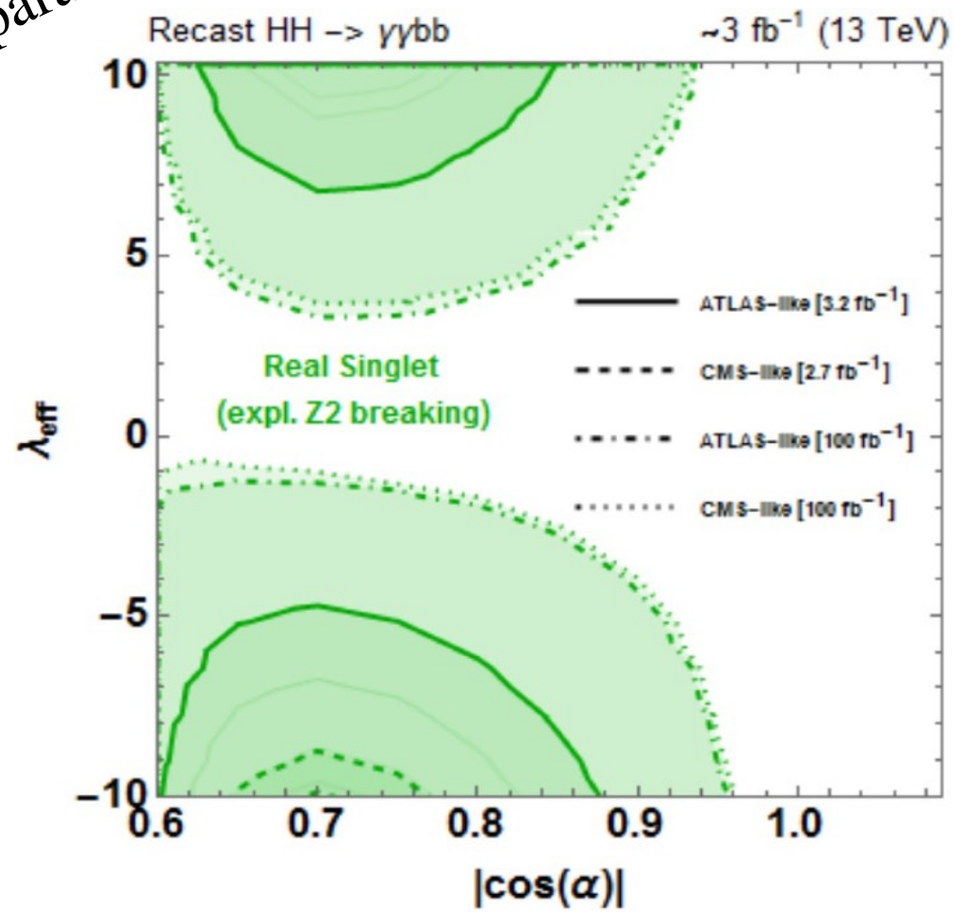


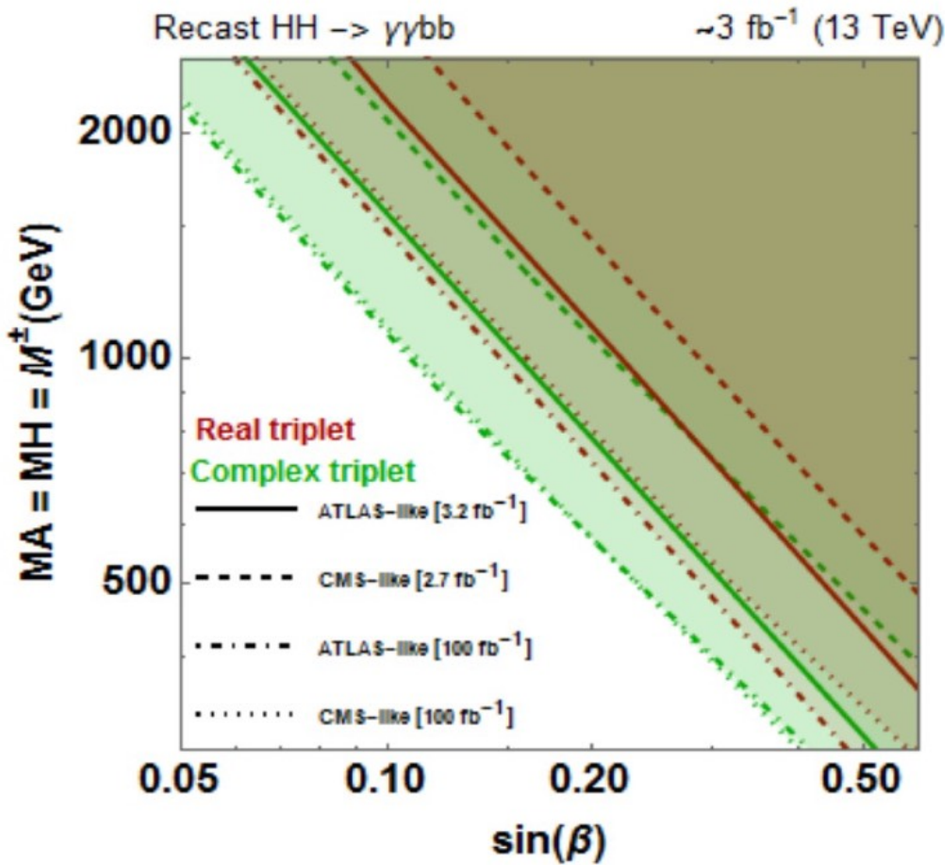
Observations:

- The current analyses are sensitive to values of ξ ~ 0.9 in the case of the $MCHM_5$ and values of ξ ~ 0.2 can be probed with 100 fb^{-1}
- no bound is obtained for the $MCHM_4$
- in the case of the singlet, the kinematics are not greatly affected and also, no bound is obtained for mixing angles cos α $\gtrsim$ 0.5

Folding interpretations on explicit model parameters

Models with more than one free parameter





Observations:

- The current constraints on the real singlet lie in regions of large λ_{eff} of order 5–10 and of sizeable mixing with the Higgs. The bounds will however improve significantly with increasing luminosity.
- For the triplets, the analyses are sensitive to large mixings for masses of a few hundred GeV while increasing the heavy scalar mass leads to an increased sensitivity, including also smaller mixing angles ß.

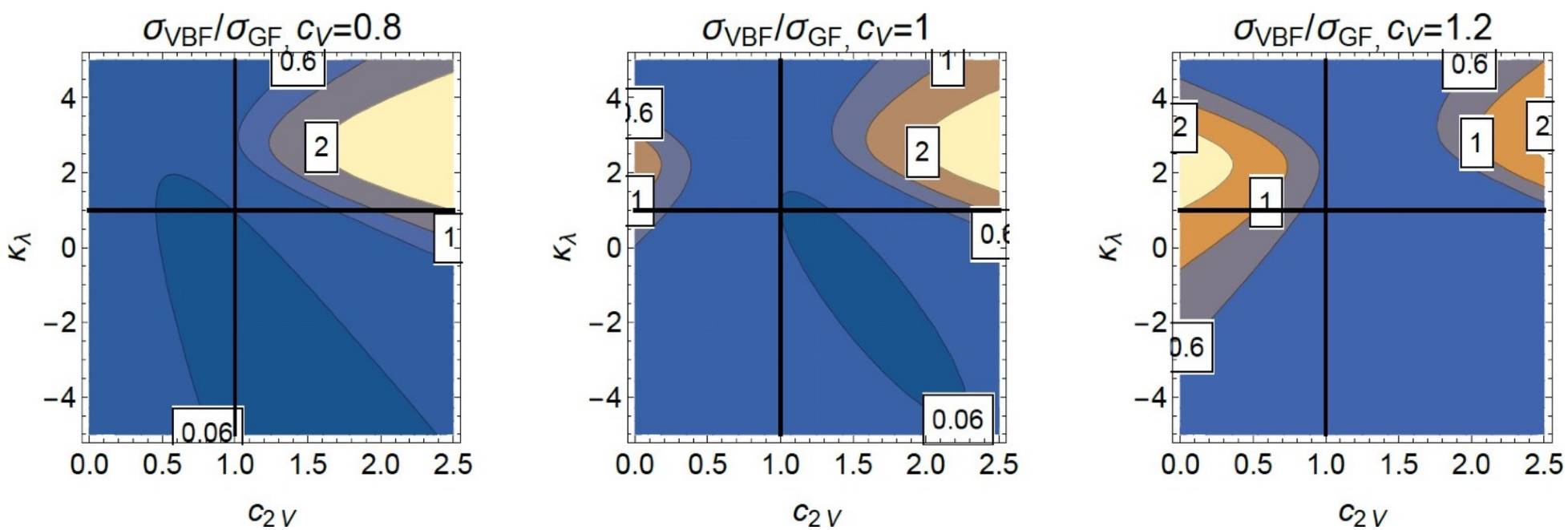
What about VBF HH?

$$\mathcal{L}_h = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4} Tr\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2} + \ldots\right)$$

with the Higgs potential $V(h)$ given by

$$V(h) = \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda v h^3 + \ldots$$

The second largest production mode of HH is the VBF mode. Though in SM case, the VBF is non-significant compared to GGF but in BSM scenario, the VBF can become quite sizeable with respect to GGF



How to construct a HH signal composed of gluon fusion and VBF components on EFT on the most model independent way possible?

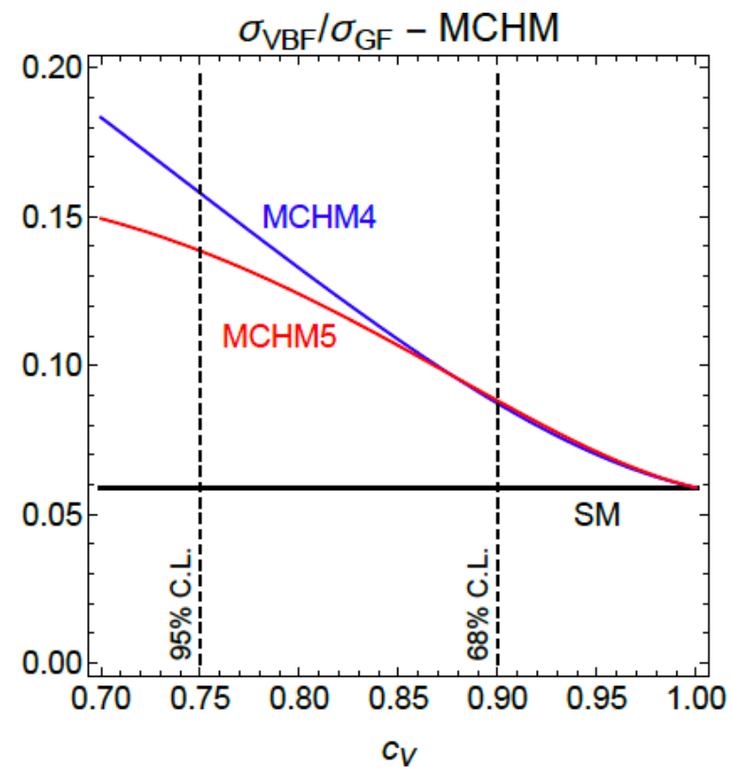
==> Up to now we just have the question but here we are looking at explicit models.

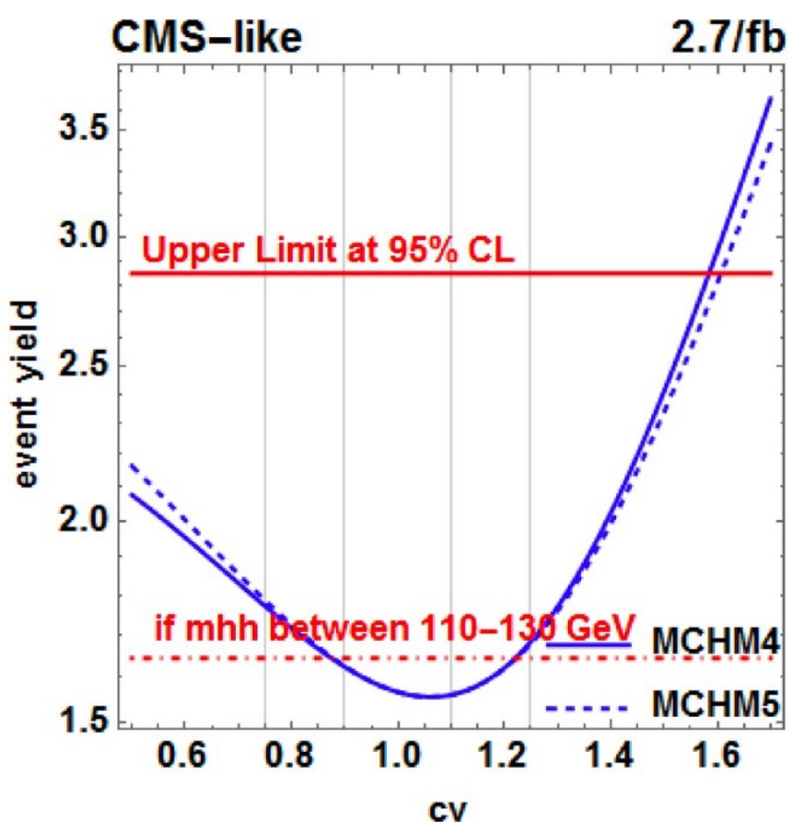
Work in progress!

A A, Enrico Bertuzzo, Alexandra Carvalho and Florian Goertz

What about VBF HH?

We investigated Higgs portal and MCHM model for VBF HH:
For MCHM, we see that VBF HH for BSM couplings, has significant contributions





We repeat the logic we had done in GF case for MCHM, using the same type of recast (results only for the CMS case) to see the sensitivity on the anomalous couplings

Work in progress!

For Higgs portal, VBF contribution was not significant in any parameter space (in Backup)

Conclusions

- We did exercise of applying specific UV completions correlations on recast of hh analysis for both GGF and VBF.
- The objective here is to exemplify that it is necessary to quantify the effect of correlations of parameters.
- Even with early stage of analysis, we have coverage for exclusion of parameter space for some specific models.
- How to convey experimental results? Suggestions:

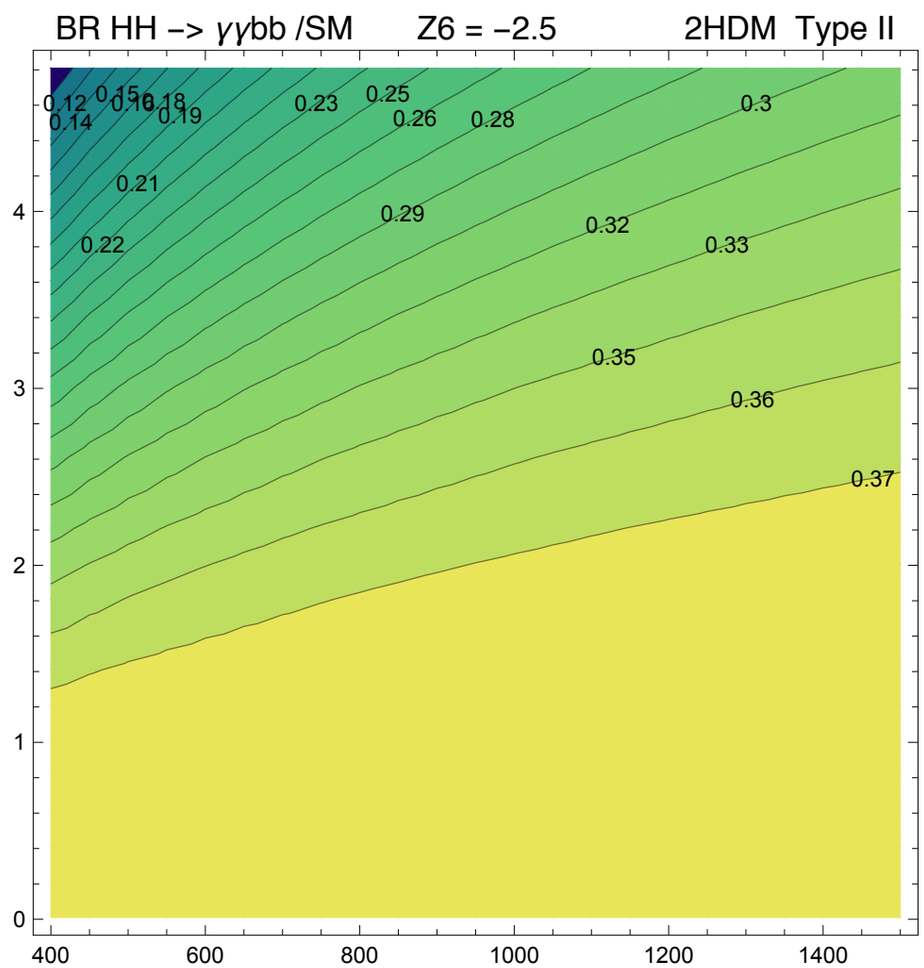
1) Some interpretations by considering explicit models as benchmarks
   - first assessment direct from exp.
   - it would act also as point of sanity check for reinterpretations

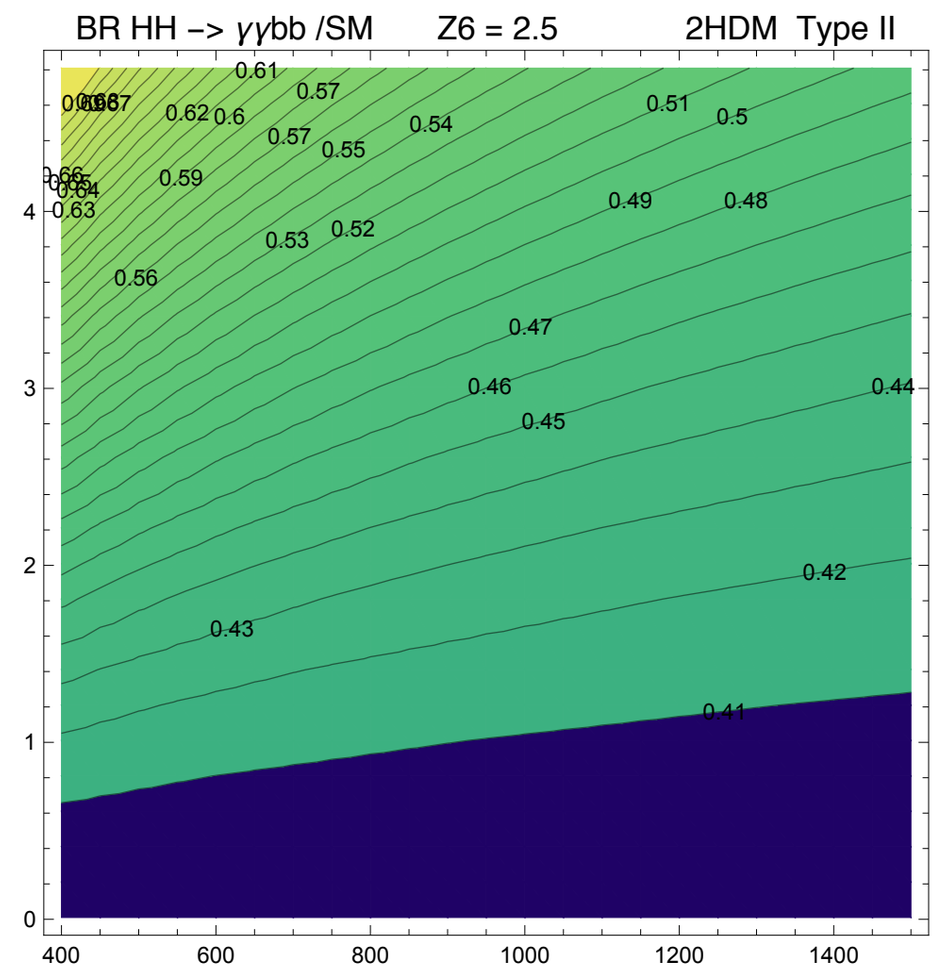
2) parallel way of allowing easy reinterpretations (necessity!) (yesterday discussion)

3) explicit scans on some 2D/3D parameters (?)

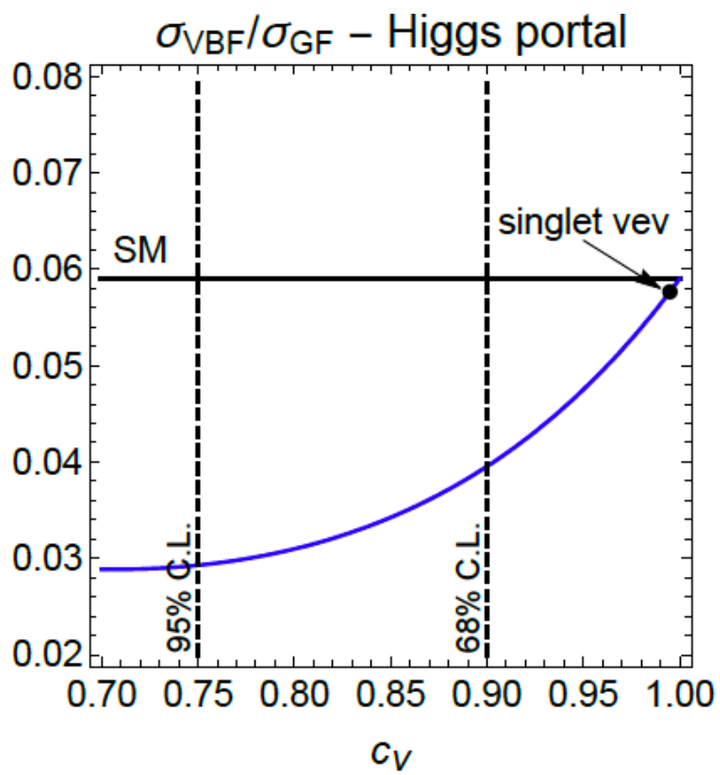
BACKUP

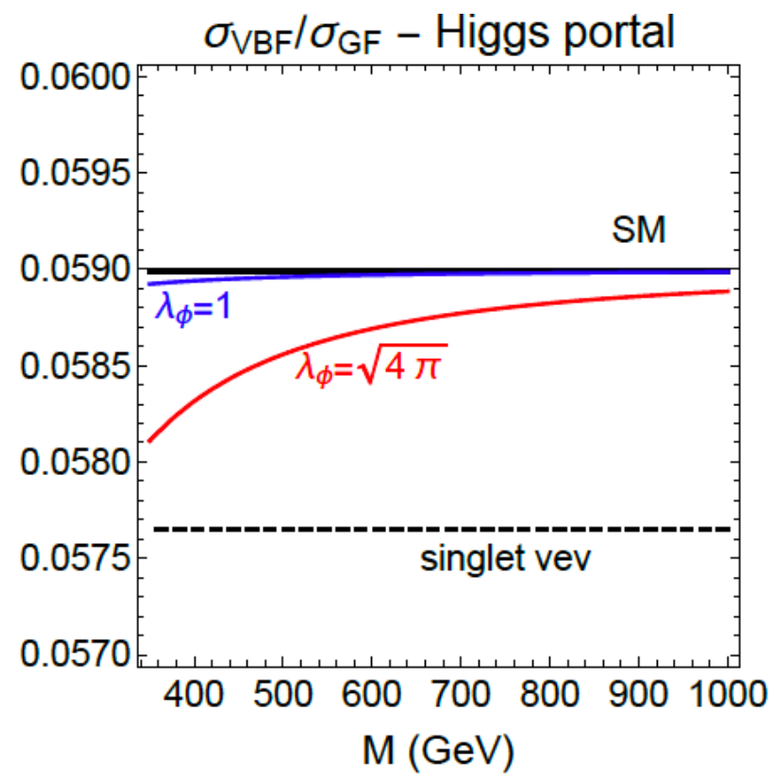
H BR effect in 2HDM model





Effect of VBF in Higgs Portal Model





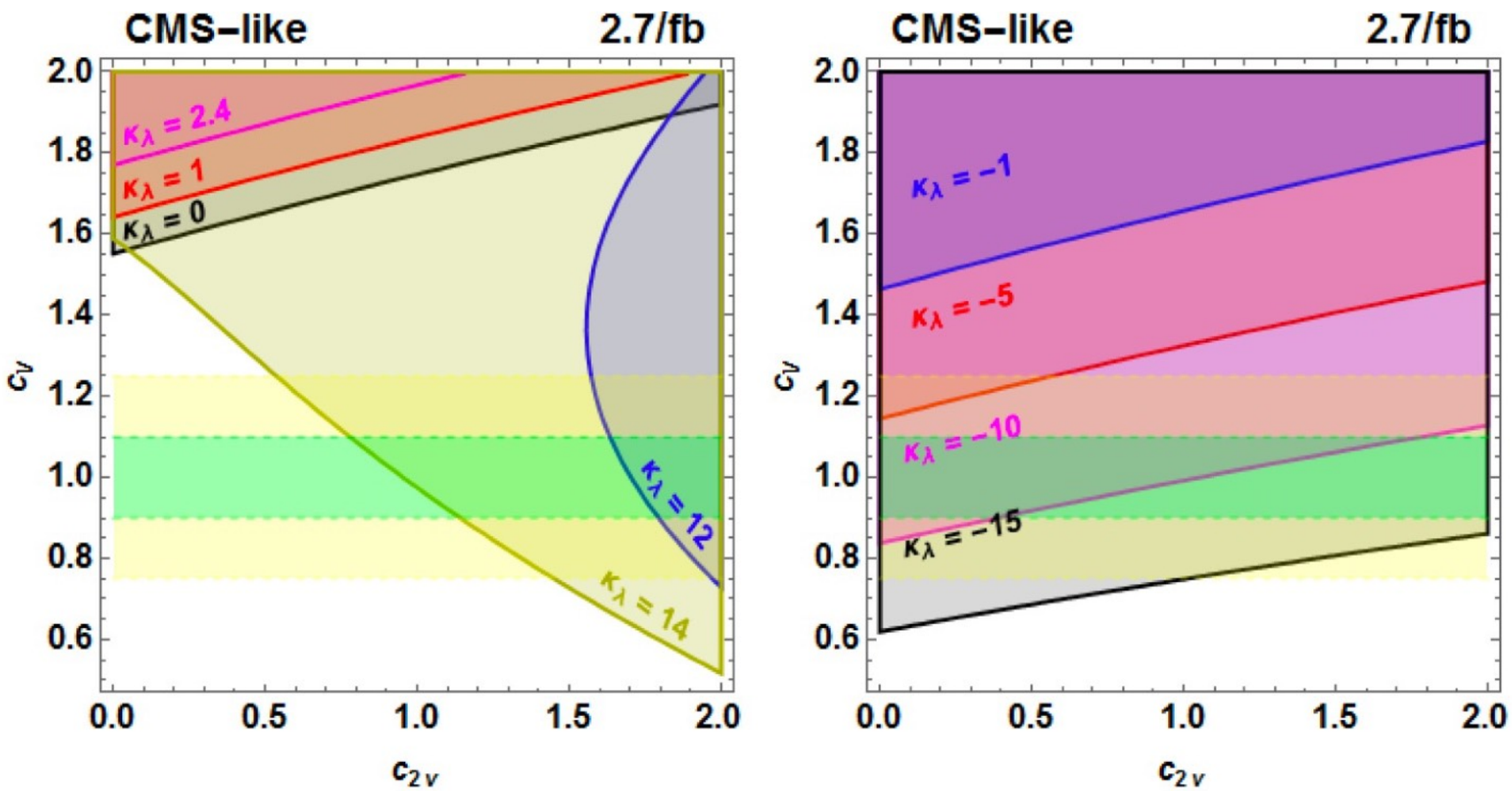
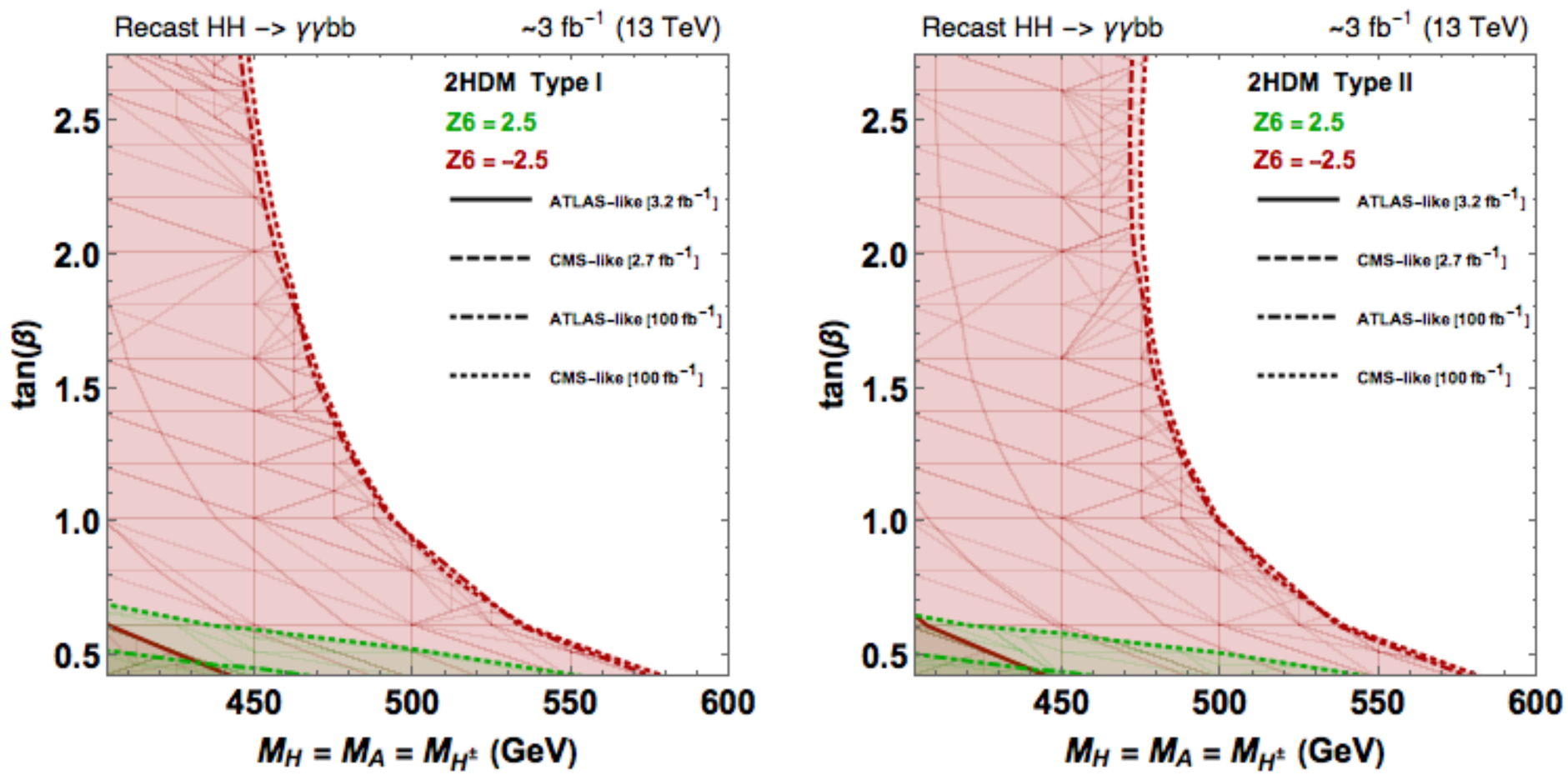


Figure 2: The exclusion limits in the cv c2v plane for different values of c3. The Green and Yellow bands mark respectivelly the 68% and 95% CL allowed region in the cv parameter from single Higgs searches. The other shaded regions are 95% CL excluded regions due the CMS-like analysis. **In the CMS one I added the cut mgg between**

Folding interpretations on explicit model parameters

(including H BR modification effect)

Models with more than one free parameter



- The only thing that makes them different is the predicted effect on H BR.
- Here, the sensitivity to scalar masses in the TeV region is only possible for small tanß.

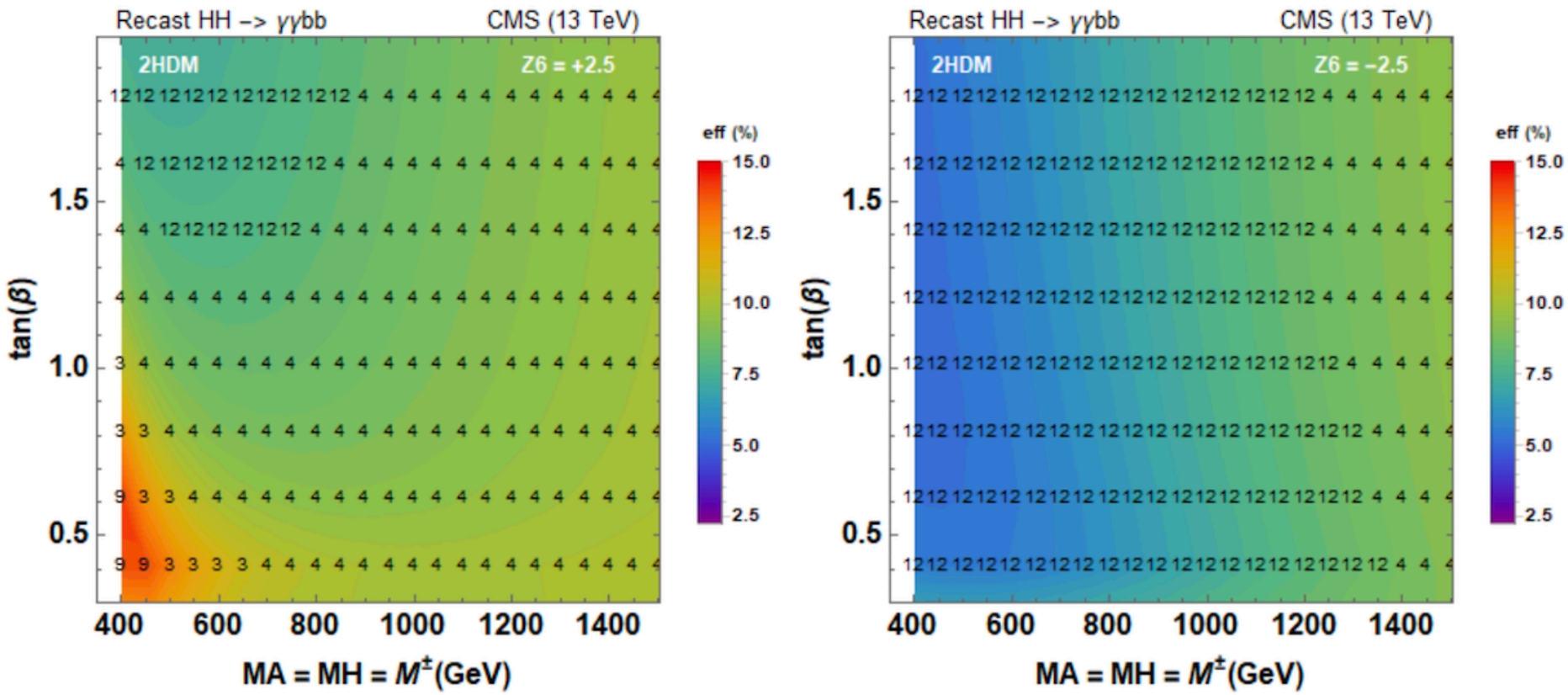


Figure 9: Efficiency maps for the signal region of the CMS-like analysis to the 2HDM benchmarks we consider. The markers superimposed correspond to the closest shape benchmark. Details in the text.

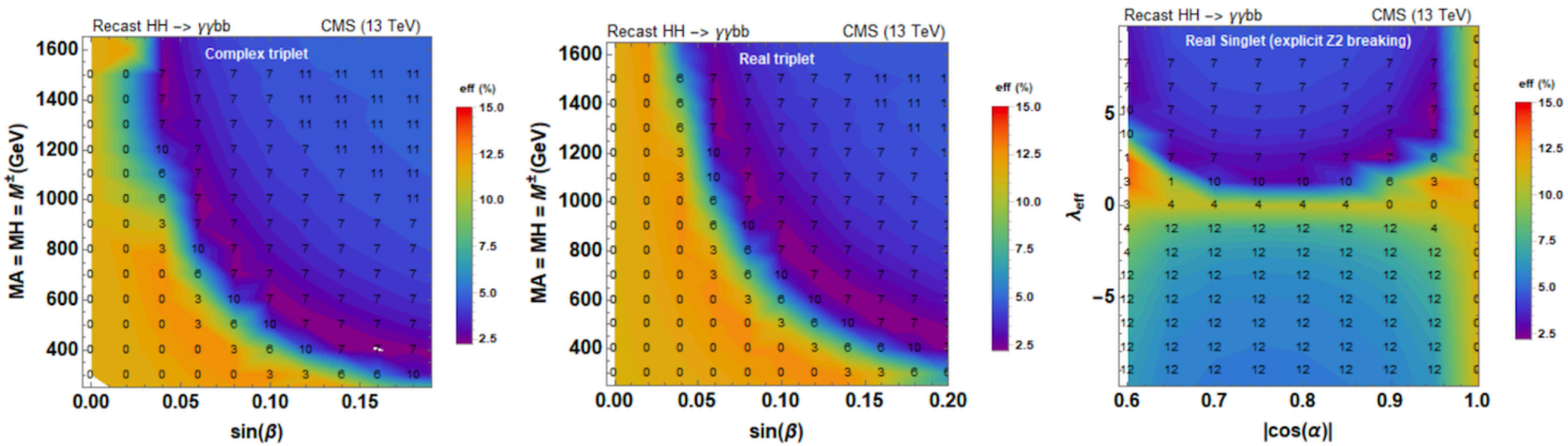


Figure 10: Efficiency maps for the signal region of the CMS-like analysis to the triplet and singlet benchmarks we consider. The markers superimposed correspond to the closest shape benchmark. Details in the text.

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ggHH

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VBF HH

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