(Some scalar sector) Standard Model Extensions

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Workshop on BSM Models in Vector Boson Scattering processes

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Outline

- Extensions of the scalar sector
- Some do not like VBS
- Others do
- A dark sector
- One unrelated final slide
- Conclusions

Extended Scalars

1. **Direct detection of new physics** - Motivate searches at the LHC in simple extensions of the scalar sector – benchmark models for searches.

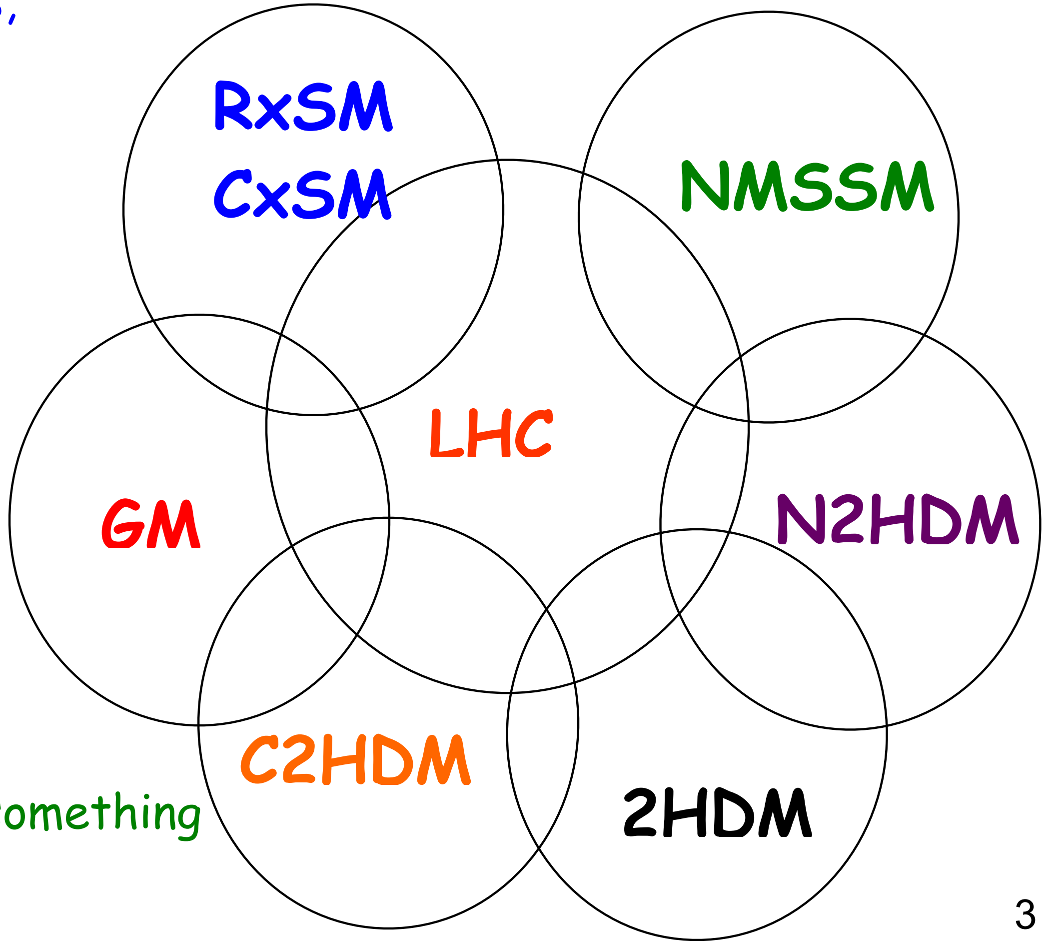
2. **Indirect detection of new physics** (via measurements of the 125 GeV Higgs couplings)

a) Mixing effects with other Higgs bosons, e.g. singlet, doublet, CP admixtures.

b) How efficiently can the parameter space of these simple extensions be constrained through measurements of Higgs properties? Focus on CP.

c) What are higher order EW corrections (of extended models) good for?

3. **Distinguishing models** - Need to find something first!



Extensions of the scalar sector

- Should contain a SM-like Higgs boson

- Electroweak ρ parameter should be close to 1

$$\rho_{exp} = 1.0004^{+0.0003}_{-0.0004}$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos\theta_W^2} = \frac{\sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

$$Q = T_3 + Y/2$$

T_i $SU(2)_L$ Isospin

Y_i Hypercharge

v_i VEV

c_i 1(1/2) for complex (real) representations

Tree-level Unitarity

In the SM the Higgs unitarises WW scattering if the Higgs mass is below 700 GeV. In extensions of the scalar sector with N_0 neutral scalar fields ϕ_n^0 with VEVs v_n^0, the same unitarity condition leads to a sum rule.

The "unitarity sum rules" are required for the cancelation of the perturbatively unitary violating high energy scattering amplitudes of weak gauge bosons and the neutral Higgs bosons at tree level.

$$WW \to WW \text{ scattering}: \qquad \sum_{n=1}^{N_0} \kappa_{WW}^{\phi_n^0} \kappa_{WW}^{\phi_n^0} = 1$$

Using all possible 2 to 2 scattering amplitudes we can constrain the parameter space of the models. For instance for the softly broken Z_2 2HDM we get

$$\begin{aligned}
a_\pm &= \frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2 + (2\lambda_3+\lambda_4)^2},\\
b_\pm &= \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2},\\
c_\pm &= \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2},\\
e_1 &= \lambda_3 + 2\lambda_4 - 3\lambda_5\\
e_2 &= \lambda_3 - \lambda_5,\\
f_+ &= \lambda_3 + 2\lambda_4 + 3\lambda_5,\\
f_- &= \lambda_3 + \lambda_5,\\
f_1 &= \lambda_3 + \lambda_4,\\
p_1 &= \lambda_3 - \lambda_4.
\end{aligned}$$

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

Many simple models with new physics

	CxSM (RxSM)	2HDM	C2HDM	N2HDM
Model	SM+Singlet	SM+Doublet	SM+Doublet	2HDM+Singlet
Scalars	$h_{1,2,(3)}$ (CP even)	$H,\ h,\ A,\ H^{\pm}$	$H_{1,2,3}$ (no CP), $H^{\pm}$	$h_{1,2,3}$ (CP-even), A, $H^{\pm}$
Motivation	DM, Baryogenesis	$+\ H^{\pm}$	+ CP violation	+ ...

Similar neutral Higgs sector but different underlying symmetries

- There is a 125 GeV Higgs (other scalars can be lighter and/or heavier).
- From the 2HDM on, $\tan\beta = v_2/v_1$. Also charged Higgs are present.
- Models (except singlet extensions) can be CP-violating.
- They all have $\rho=1$ at tree-level.
- You get a few more scalars (CP-odd or CP-even or with no definite CP)
- In case all neutral scalars mix there will be three mixing angles
- They can have dark matter candidates (or not)

Automatic in the 2HDM but not in all other models.

All the points presented respect: tree-level unitarity, potential is bounded from below, absolute minimum… and "most relevant" experimental constraints.

The potential(s)

Potential

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{m_S^2}{2}\Phi_S^2$$
$$+ \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2) + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger \Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger \Phi_2)\Phi_S^2$$

with fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \quad \Phi_S = v_S + \rho_S$$

magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (also CxSM)

magenta + black $\Longrightarrow$ 2HDM (also C2HDM)

magenta + black + blue + red $\Longrightarrow$ N2HDM

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not.

softly broken Z_2 : $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2$

softly broken Z_2 : $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2;\ \Phi_S \to \Phi_S$

exact Z_2' : $\Phi_1 \to \Phi_1;\ \Phi_2 \to \Phi_2;\ \Phi_S \to -\Phi_S$

- m^2_{12} and λ_5 real 2HDM
- m^2_{12} and λ_5 complex C2HDM

h_{125} couplings (gauge)

Lightest Higgs coupling modifiers (to gauge bosons)

$$g^{hVV}_{2HDM} = \sin(\beta - \alpha) g^{hVV}_{SM}$$

CP-VIOLATING 2HDM

$$g^{hVV}_{C2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

"PSEUDOSCALAR" COMPONENT (DOUBLET)

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

$$g^{hVV}_{N2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

SINGLET COMPONENT

$(a + ib)$

SM + REAL SINGLET

$$g^{hVV}_{RxSM} = \cos\alpha_1 \, g^{hVV}_{SM}$$

SM + COMPLEX SINGLET

$$g^{hVV}_{CxSM} = \cos\alpha_1 \cos\alpha_2 \, g^{hVV}_{SM}$$

REAL COMPONENT

IMAGINARY COMPONENT

h_{125} couplings (Yukawa)

How can we avoid large tree-level FCNCs?

1. **Fine tuning** - for some reason the parameters that give rise to tree-level FCNC are small

Example: Type III models CHENG, SHER (1987)

2. **Flavour alignment** - for some reason we are able to diagonalise simultaneously both the mass term and the interaction term

Example: Aligned models PICH, TUZON (2009)

$$Y_d^2 \propto Y_d^1$$ (for down type)

3. Use symmetries- Type I 2HDM Z_2 symmetries GLASHOW, WEINBERG; PASCHOS (1977) BARGER, HEWETT, PHILLIPS (1990)

Type I $\kappa_U^I = \kappa_D^I = \kappa_L^I = \frac{\cos\alpha}{\sin\beta}$

Type II $\kappa_U^{II} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^{II} = \kappa_L^{II} = -\frac{\sin\alpha}{\cos\beta}$

Type F(Y) $\kappa_U^F = \kappa_L^F = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^F = -\frac{\sin\alpha}{\cos\beta}$

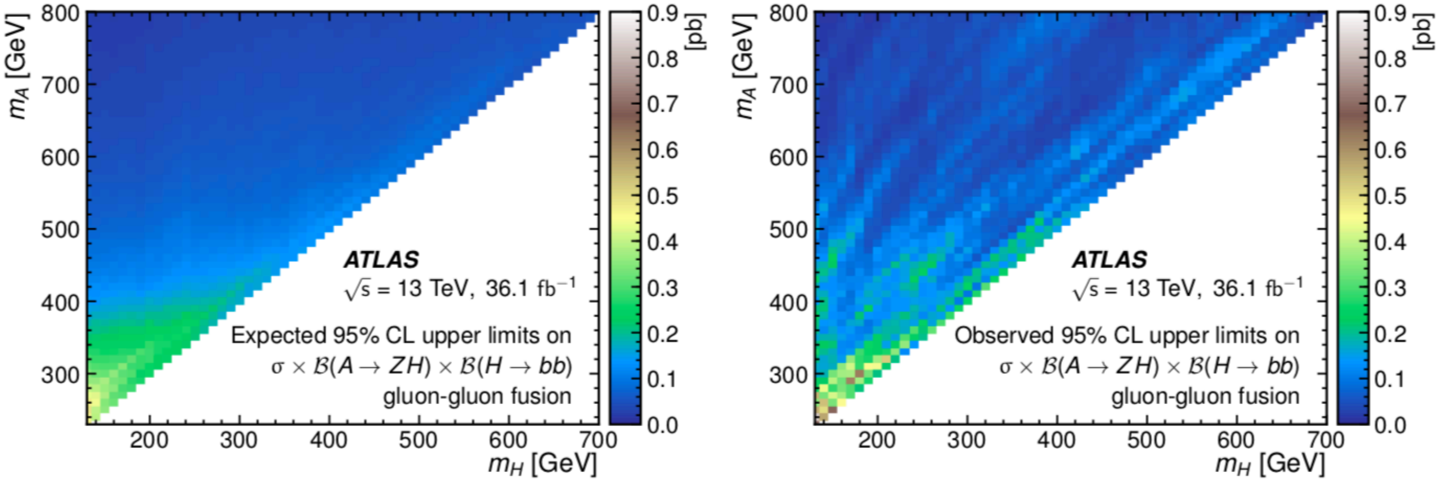
Type LS(X) $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$

$$Y_{C2HDM} = \cos\alpha_2 Y_{2HDM} \pm i\gamma_5 \sin\alpha_2 \tan\beta(1/\tan\beta)$$

$$Y_{N2HDM} = \cos\alpha_2 Y_{2HDM}$$

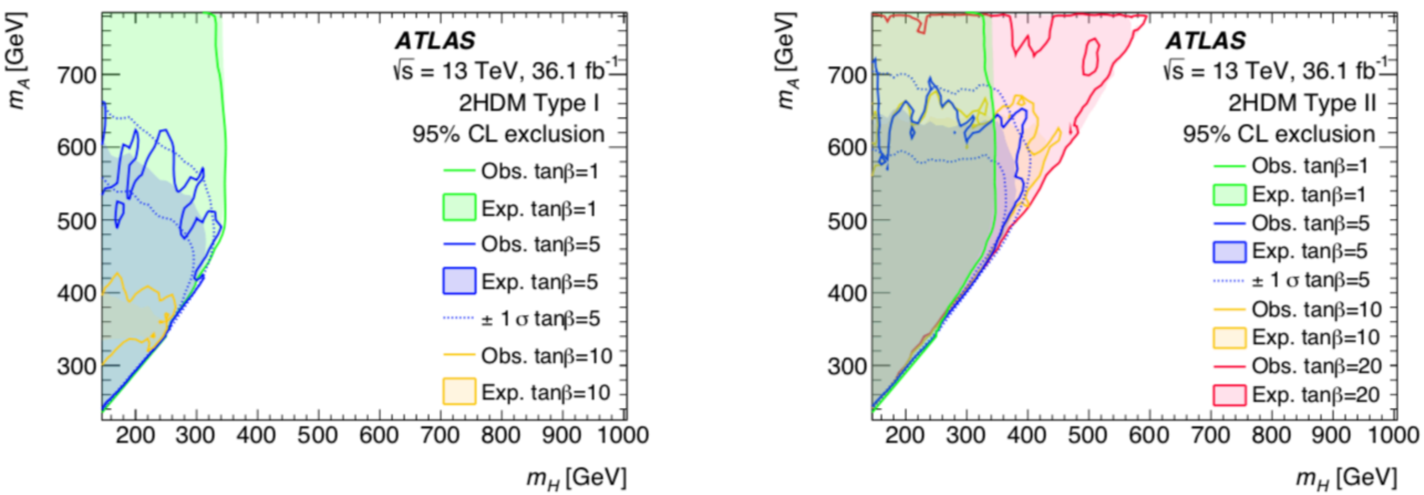
III = I' = Y = Flipped = 4... IV = II' = X = Lepton Specific= 3...

Searches - the results can easily be used for most models



Upper bounds at 95% CL on the production cross-section times the branching ratio Br(A → ZH)×Br(H → bb) in pb for gluon–gluon fusion. Left: expected; right: observed.

2HDM (CP-conserving and no tree-level FCNC)



ATLAS 1804.01126v1

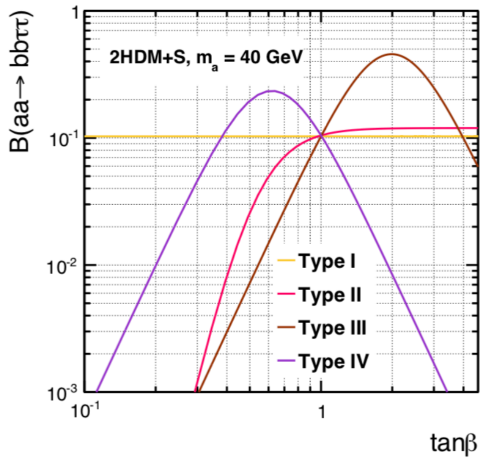
Observed and expected 95% CL exclusion regions in the (m_A,m_H) plane for various tan β values for Type I (left), and Type II (right).

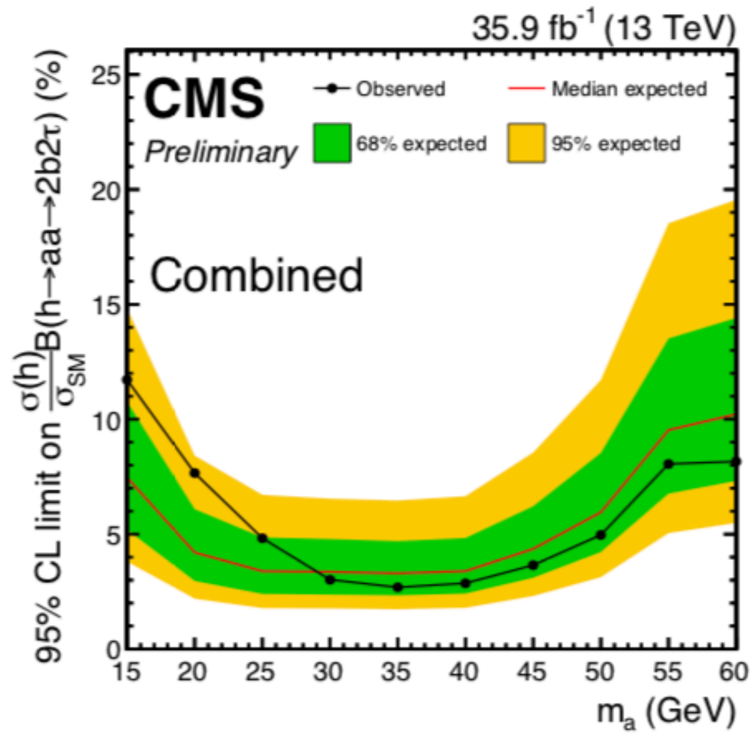
Assumptions: alignment, lightest Higgs 125 GeV, $m_{H+} = m_A$, U(1) symmetry (fixes m_{12}^2).

Searches - the results can easily be used for all the models

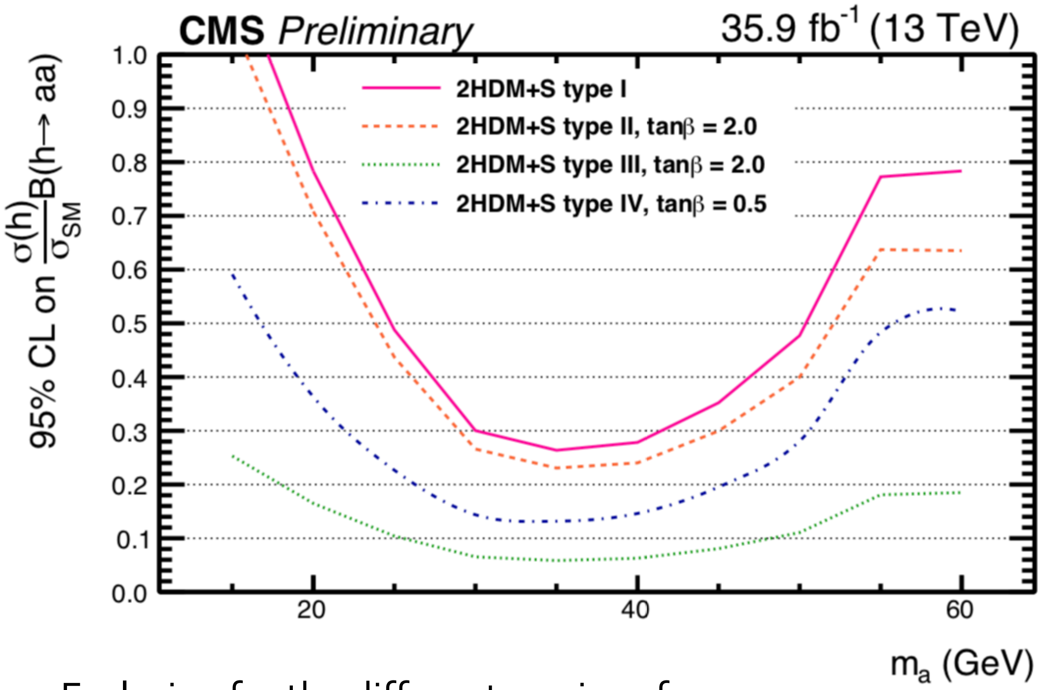
CMS PAS HIG-17-024

BRs for the 4 different versions of the model.





N2HDM (CP-conserving)



Expected and observed 95% CL limits on σ(h)B(h → aa → 2τ2b) in %. Combined eμ, eτ and μτ channels. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

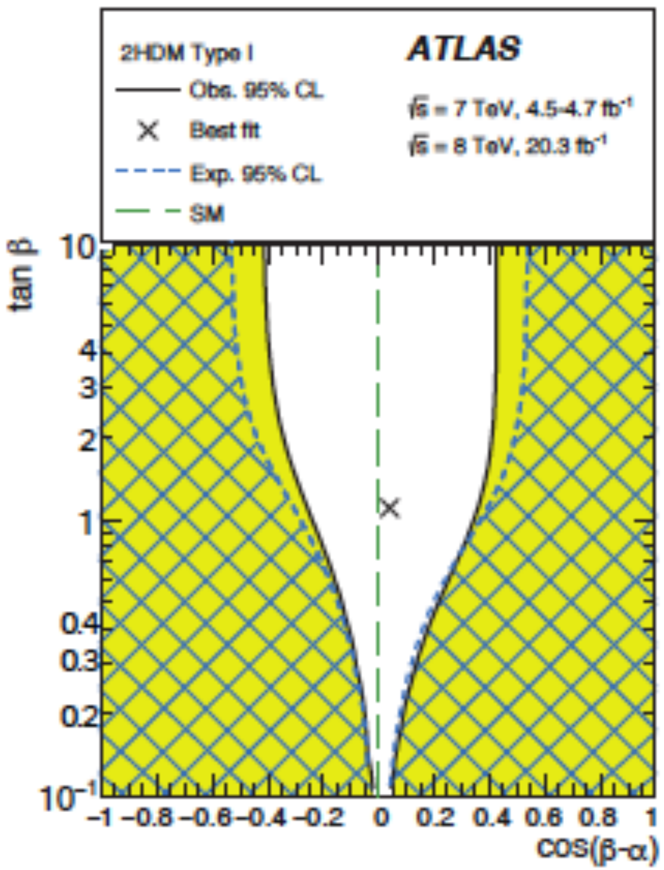
Exclusion for the different versions for 2 values of tanβ.

ATLAS, (γγjj final state),1803.11145

h_{125} couplings measurements

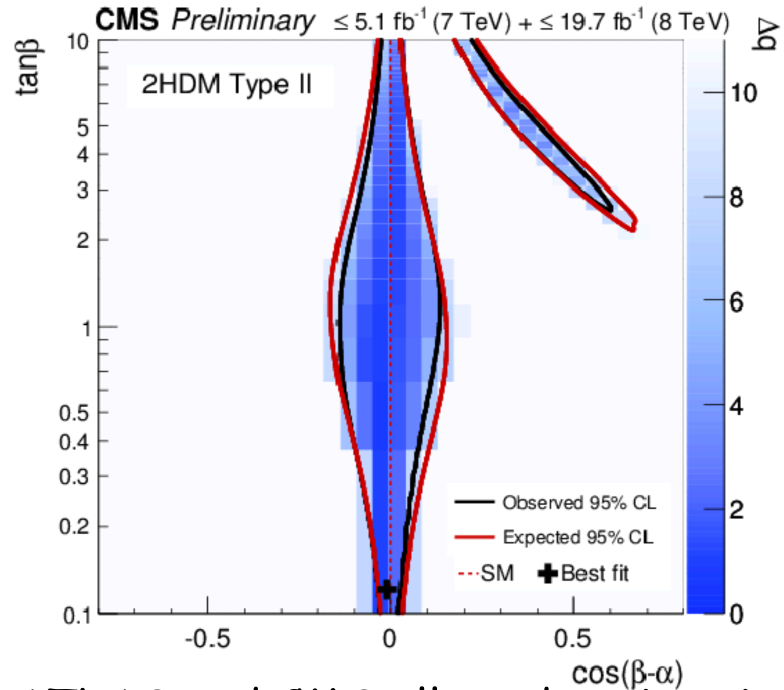
Models need couplings modifiers - simple in many extensions of the scalar sector

The 2HDM (CP-conserving and no tree-level FCNC)



(a) Type I

ATLAS 1509.00672



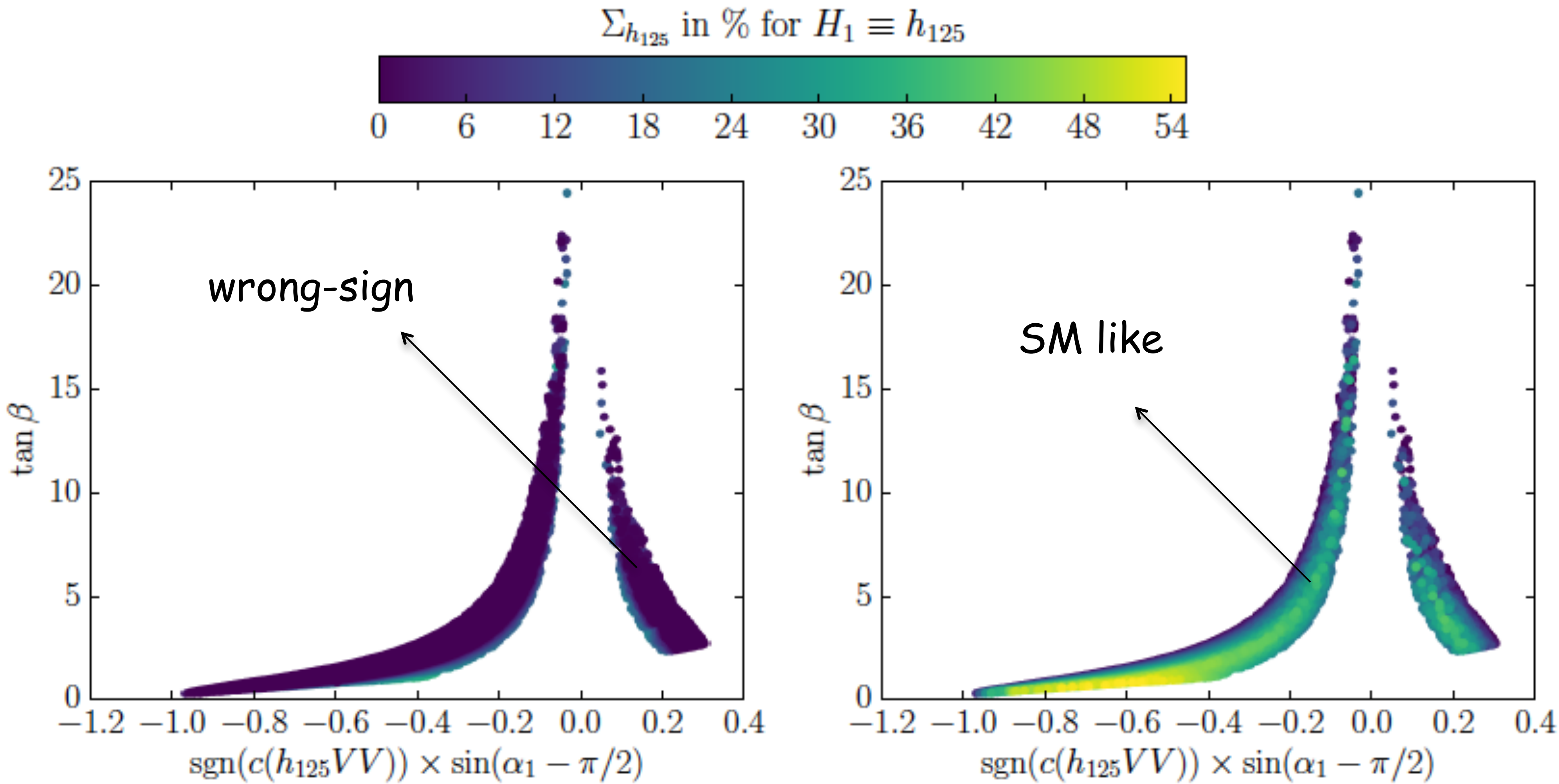
CMS-PAS-HIG-16-007

ATLAS and CMS allowed regions in type I and type II for the CP-conserving 2HDM. The central region is the SM-like limit (or alignment) where the Higgs couplings to the other SM particles are just the SM ones.

The extra leg on the right has the wrong sign in the b/tau couplings relative to SM ones.

h_{125} couplings measurements

$\Sigma_i^{\text{N2HDM}} = (R_{i3})^2$ singlet admixture of H_i (measure the singlet weight of H_i)



SM-like and wrong-sign regions in the N2HDM type II – the interesting fact is that in the alignment region the singlet admixture can go up to 54 %.

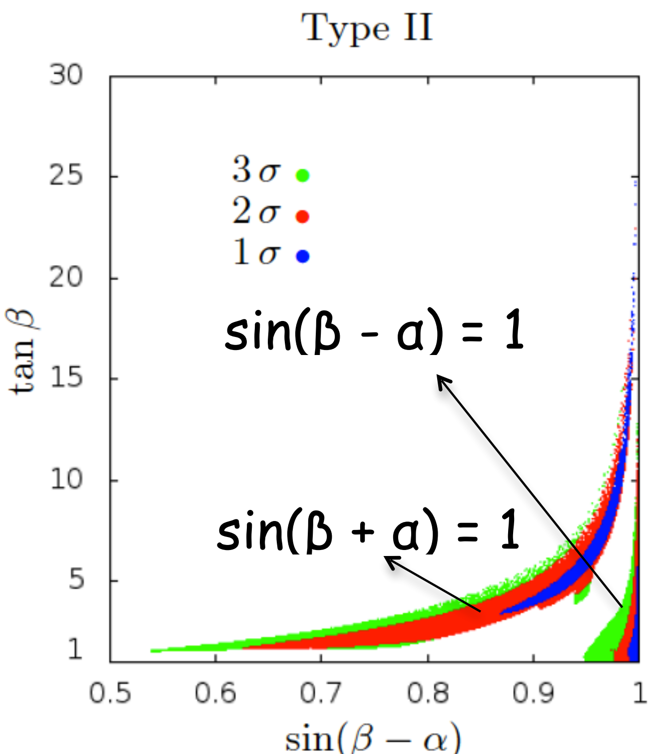
Mühlleitner, Sampaio, RS, Wittbrodt, JHEP 1703 (2017) 094

For the 2HDM the results obtained by ATLAS and CMS can be understood in terms of the Higgs couplings in the Alignment and Wrong-sign Yukawa limits

The Alignment (SM-like) limit – all tree-level couplings to fermions and gauge bosons are the SM ones.

$$\sin(\beta-\alpha)=1 \quad \Rightarrow \quad \kappa_D=1; \quad \kappa_U=1; \quad \kappa_W=1$$

Wrong-sign Yukawa coupling – at least one of the couplings of h to down-type and up-type fermion pairs is opposite in sign to the corresponding coupling of h to VV (in contrast with SM).



$$\kappa_D\kappa_W<0 \quad \text{or} \quad \kappa_U\kappa_W<0$$

$$\kappa_i=\frac{g_{2HDM}}{g_{SM}}$$

at tree-level

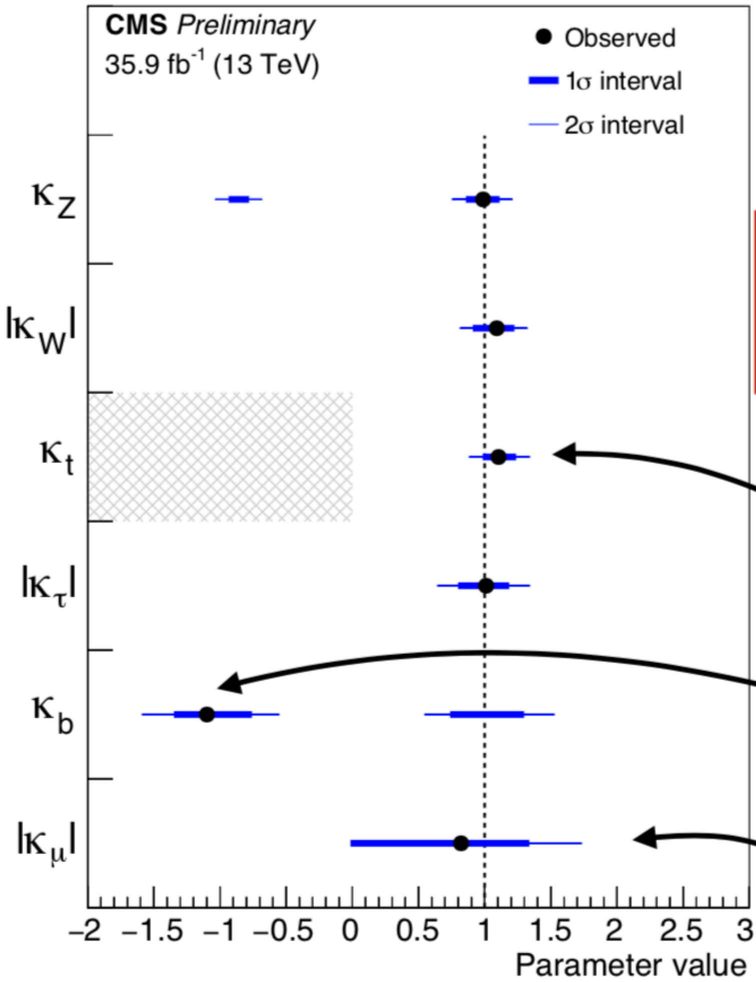
$$\kappa_i^2=\frac{\Gamma^{2HDM}(h\to i)}{\Gamma^{SM}(h\to i)}$$

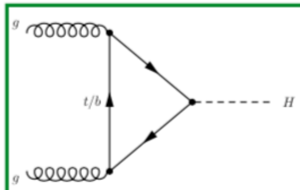
The actual sign of each κ_i depends on the chosen range for the angles.

Ferreira, Gunion, Haber, RS, PRD89 (2014) 11, 115003

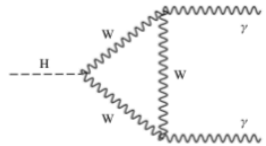
Ferreira, Guedes, Sampaio, RS, JHEP 1412 (2014) 067

The wrong-sign strikes back!





$$\kappa_g^2 = 1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$$



$$\kappa_\gamma^2 = 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$$

~ 25% stronger constraint compared to effective loop model (κ_t from ttH alone)

Mild preference for $\kappa_b < 0$ from b-t interference in gluon fusion production

Include H→μμ search for constraint on κ_μ

Type II

$$\kappa_D = \kappa_L = -\frac{\sin\alpha}{\cos\beta} = -\sin(\beta+\alpha) + \cos(\beta+\alpha)\tan\beta$$

$$\sin(\beta+\alpha) = 1 \implies \kappa_D = \kappa_L = -1$$

$$\sin(\beta-\alpha) = \frac{\tan^2\beta - 1}{\tan^2\beta + 1} \implies \kappa_V \geq 0 \text{ if } \tan\beta \geq 1$$

Constraints on $\tan\beta$ OK!

Type I

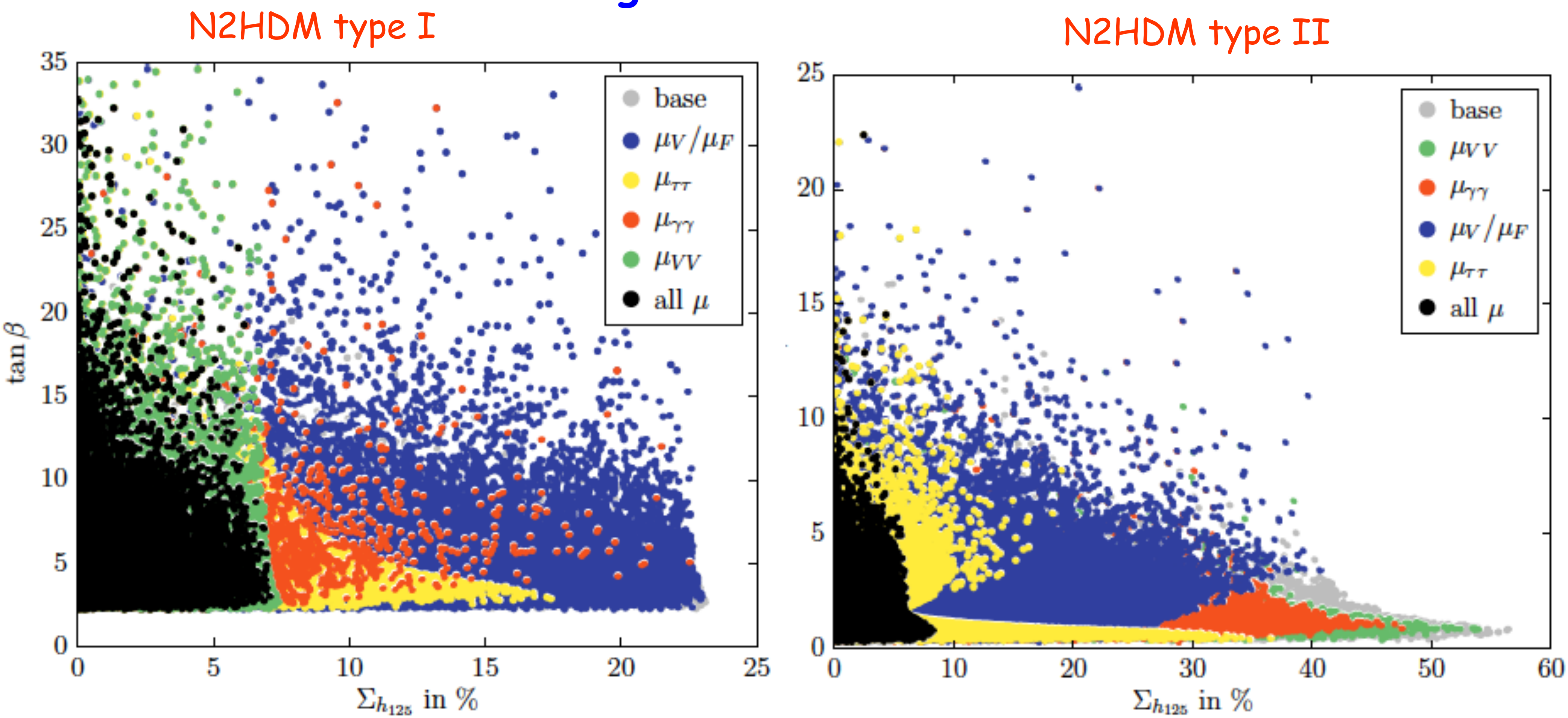
$$\kappa_U = \kappa_D = \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta$$

$$\sin(\beta+\alpha) = 1 \Rightarrow \kappa_U = 1 \quad (\kappa_D = 1)$$

$$\sin(\beta-\alpha) = \frac{\tan^2\beta - 1}{\tan^2\beta + 1} \Rightarrow \kappa_V \leq 0 \text{ if } \tan\beta \leq 1$$

Because constraints force tanβ to be order 1 or larger, "there is no wrong-sign Yukawa coupling" in Type I.

Singlet admixture



MÜHLLEITNER, SAMPAIO, RS, WITTBRODT, JHEP 1703 (2017) 094

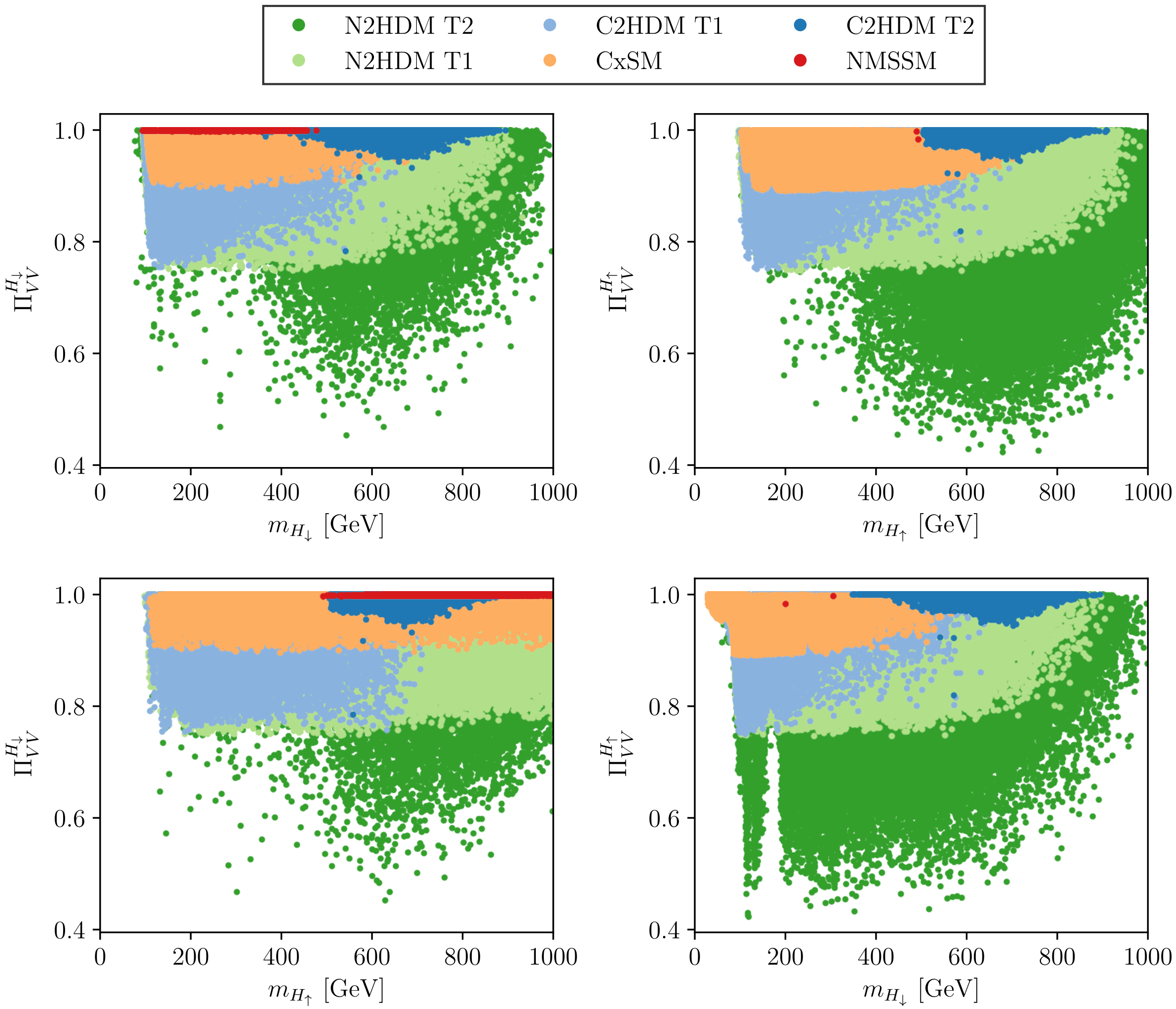
tanβ as a function of the singlet admixture for type I N2HDM (left) and type II N2HDM (right) – in grey all points with constraints; the remaining colours denote μ values measured within 5 % of the SM. In black all μ's. Singlet admixture slightly below 10 % almost independently of tanβ.

The plot shows how far we can go in the measurement of the singlet component of the Higgs.

We can now sum the squared couplings of the Higgs (we found another one). Deviations from 1 will mean no 2HDM or MSSM.

$\Pi^{(3)}_{VV} = 1$ for the CxSM, N2HDM, NMSSM and C2HDM

$\Pi^{(2)}_{VV} = 1$ for the CP-conserving 2HDM and MSSM

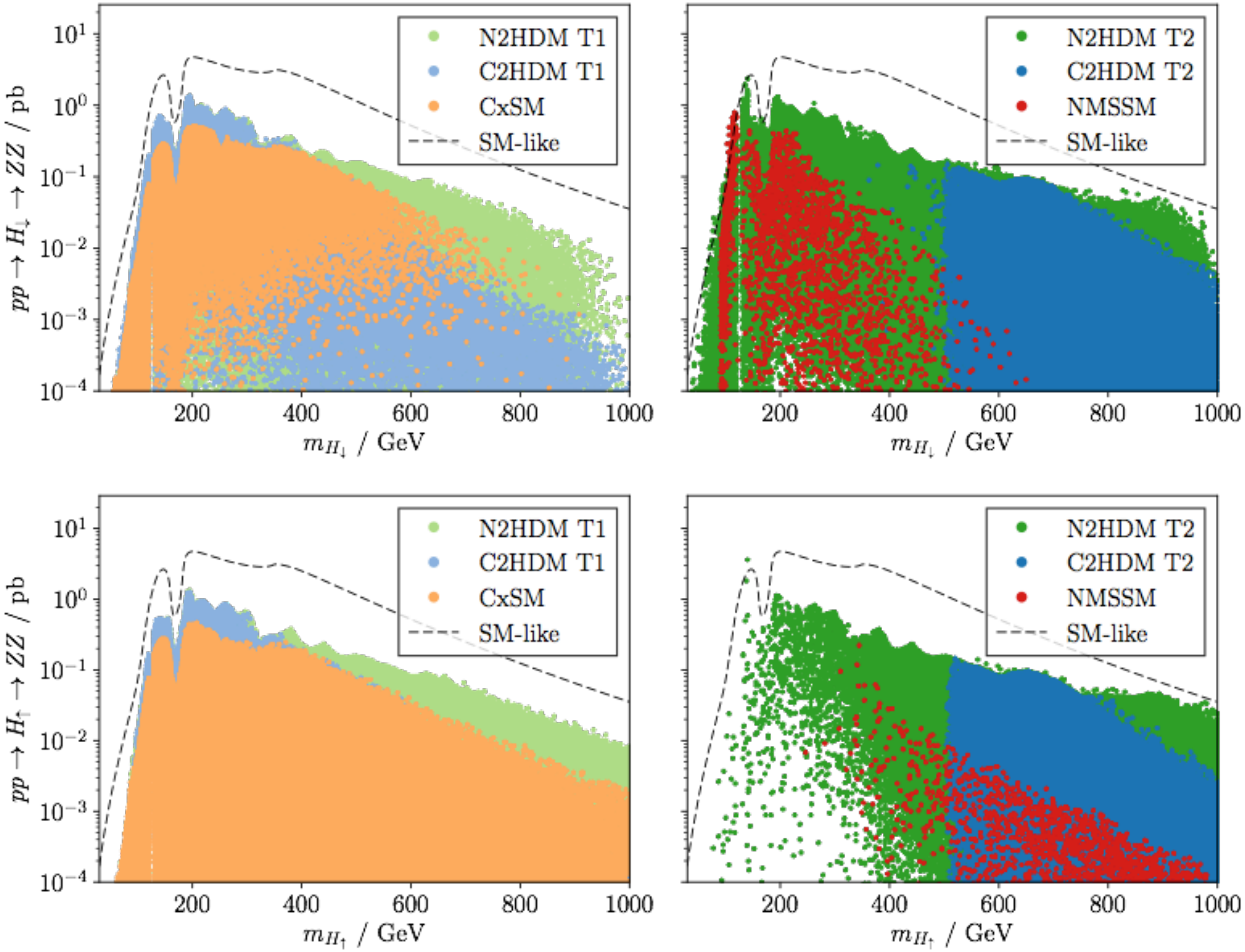


Besides h_{125} only one additional CP-even (or, for the C2HDM, CP-mixed) Higgs boson has been discovered and we sum over two instead of three Higgs bosons. In the left column, we assume that the additionally discovered Higgs boson is the $H_\downarrow$, and in the right one, it is assumed to be the $H_\uparrow$. All the points respect main constraints.

$\Pi^{(2)}$ cannot drop below about 0.9 in the CxSM. This is a consequence of enforcing $c^2(h V V) > 0.9$ or equivalently $\Pi^{(2)} > 0.9$.

The decays to gauge bosons show what to expect in VBS (relative to a SM-like Higgs)

Dashed line is the "SM".



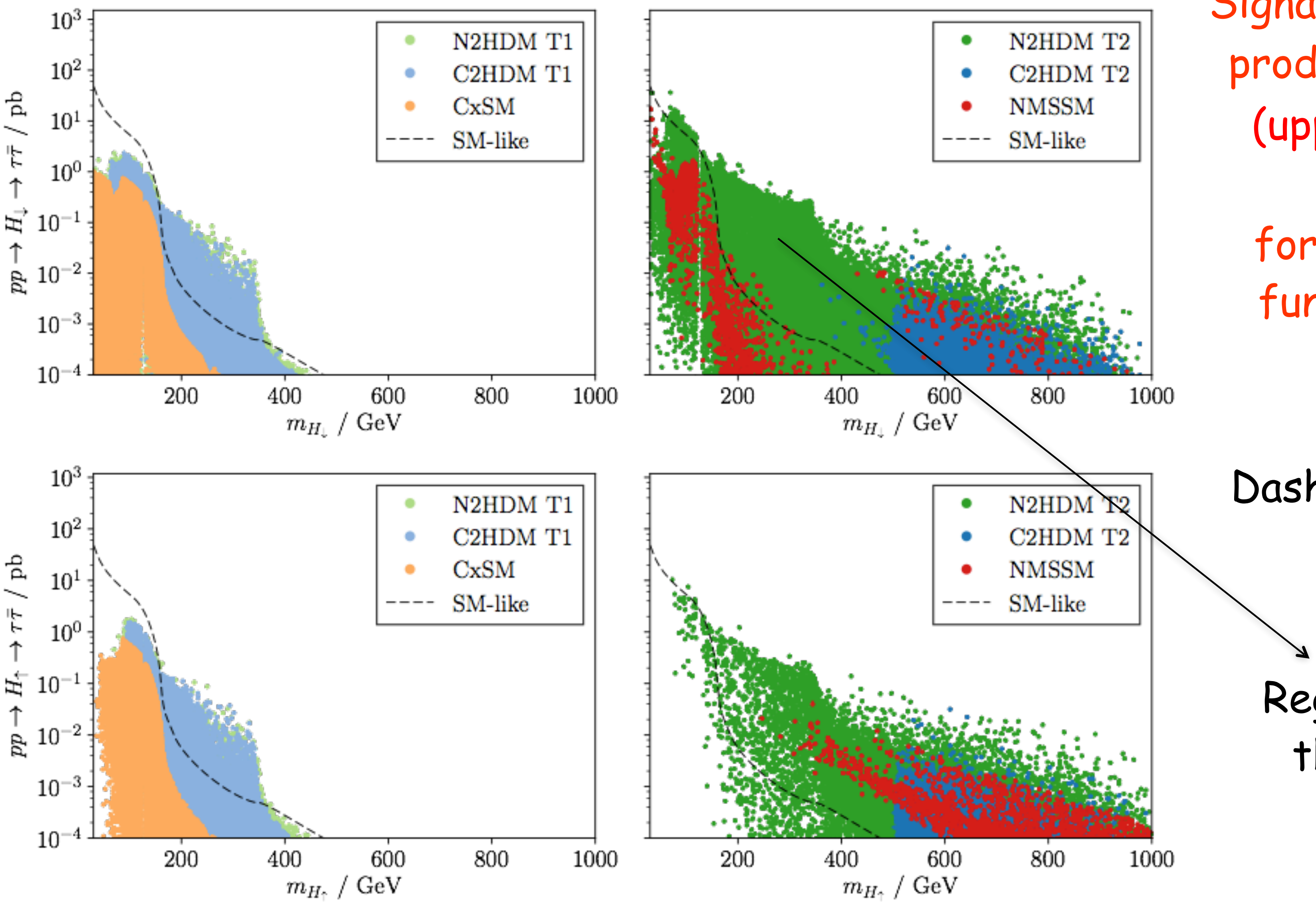
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

h_{125} takes most of the hVV coupling. Yukawa couplings can be different and lead to enhancements relative to the SM.

Mühlleitner, Sampaio, RS, Wittbrodt, JHEP 1708 (2017) 132

Rates are larger for N2HDM and C2HDM and more in type II because the Yukawa couplings can vary independently.

Non-125 to ττ



Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

Region where only the N2hDM II survives.

Singlet and pseudoscalar components bounded by unitarity

$$\Sigma_i^{CxSM} = R_{i2}^2 + R_{i3}^2$$

$$\Sigma_i^{N2HDM} = R_{i3}^2$$

$$\Psi_i^{C2HDM} = R_{i3}^2$$

Non-doublet pieces of the SM-like Higgs. CxSM - sum of the real and complex component of the singlet. N2HDM - singlet component. C2HDM - pseudoscalar component.

Unitarity $\Rightarrow \kappa_{ZZ,WW}^2 + \Psi_i(\Sigma_1) \leq 1$

The deviations can be written in terms of the rotation matrix from gauge to mass eigenstates.

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho \\ \eta \\ \rho_S \end{pmatrix} \qquad R = [R_{ij}] = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

Singlet and pseudoscalar components bounded by unitarity

Abramowicz eal, 1307.5288.
CLICdp, Sicking, NPPP, 273-275, 801 (2016)

Parameter	Relative precision [76, 77]		
	350 GeV 500 fb^{-1}	+1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
κ_{HZZ}	0.43%	0.31%	0.23%
κ_{HWW}	1.5%	0.15%	0.11%
κ_{Hbb}	1.7%	0.33%	0.21%
κ_{Hcc}	3.1%	1.1%	0.75%
κ_{Htt}	–	4.0%	4.0%
$\kappa_{H\tau\tau}$	3.4%	1.3%	<1.3%
$\kappa_{H\mu\mu}$	–	14%	5.5%
κ_{Hgg}	3.6%	0.76%	0.54%
$\kappa_{H\gamma\gamma}$	–	5.6%	< 5.6%

Predicted precision for CLIC

LHC today

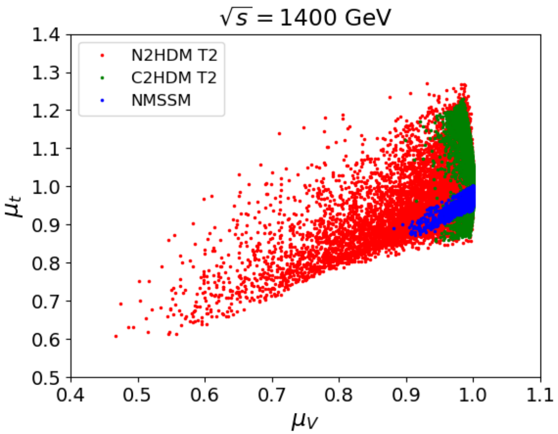
Model	CxSM	C2HDM II	C2HDM I	N2HDM II	N2HDM I	NMSSM
$(\Sigma \text{ or } \Psi)_{\text{allowed}}$	11%	10%	20%	55%	25%	41%

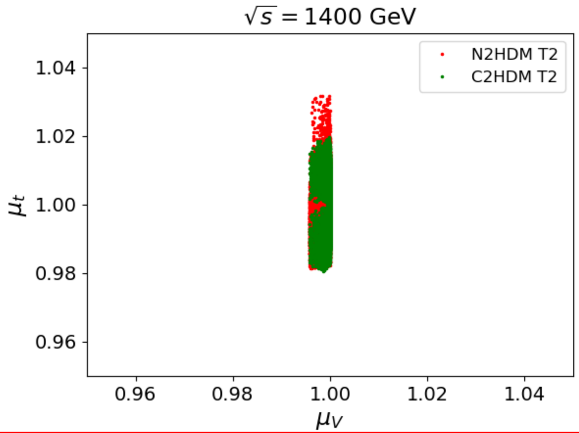
CLIC@350GeV (500/fb)

$\Psi_i(\Sigma_1) \leq 0.85\,\%$ from κ_{ZZ}

If no new physics is discovered and the measured values are in agreement with the SM predictions, the singlet and pseudoscalar components will be below the % level.

All models become very similar and hard to distinguish.





Beware of radiative corrections.

Azevedo, Ferreira, Mühlleitner, RS, Wittbrodt, PRD99 (2019) no.5, 055013

Triplets and the Georgi-Machacek model

Generate neutrino masses or enhance $h \to \gamma\gamma$ (via the doubly charged Higgs loop).

Interesting benchmark for BSM studies.

If we add to the SM a multiplet X the coupling to gauge bosons

$$i\frac{g^2}{2}v_X^2\,2\left[T(T+1)-\frac{Y^2}{4}\right]$$

So to enhance the hWW coupling above the SM value we need a scalar with Isospin 1 or above, with a VEV, and that it mixes with the 125 GeV Higgs.

One popular option is the Georgi- Machacek (GM) model where the Higgs sector is composed of an isospin doublet field, Φ, with Y = 1/2, a complex triplet field, χ, with Y = 1, and a real triplet field, ξ, with Y = 0.

These fields can be expressed in the $SU(2)_L \times SU(2)_R$ covariant form as:

$$\Phi = \begin{pmatrix} \phi^{0\,*} & \phi^{+} \\ -\phi^{+\,*} & \phi_0 \end{pmatrix} \qquad X = \begin{pmatrix} \chi^{0\,*} & \xi^{+} & \chi^{++} \\ -\chi^{+\,*} & \xi_0 & \chi^{+} \\ \chi^{++\,*} & -\xi^{+\,*} & \chi^{0} \end{pmatrix}$$

The neutral components have VEVs $<\phi^0> = v_\phi/\sqrt{2}$, $<\chi^0> = v_\chi$ and $<\xi^0> = v_\xi$.

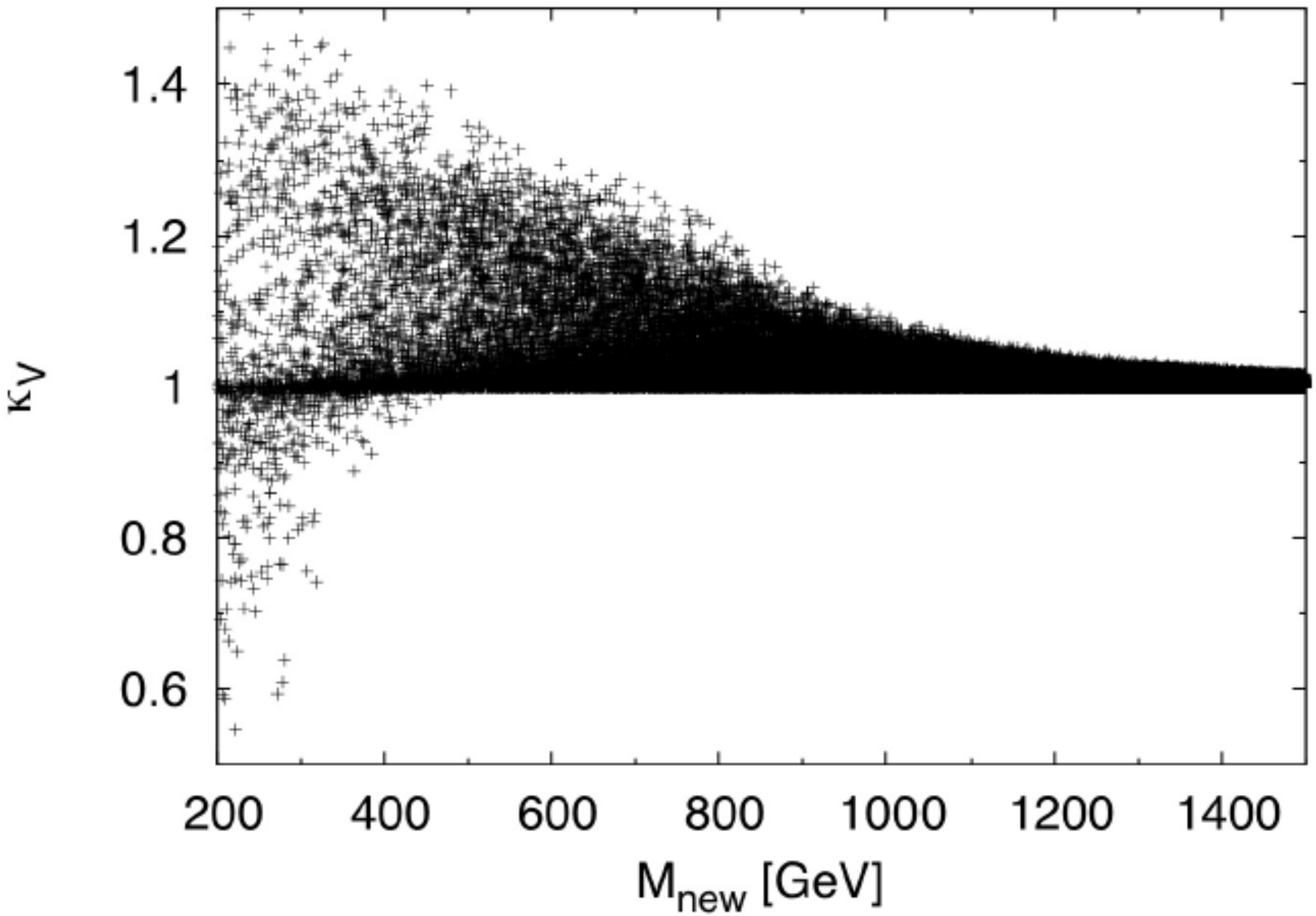
When the two triplet fields develop aligned VEVs $v_\chi = v_\xi \equiv v_\Delta$ the $SU(2)_L \times SU(2)_R$ symmetry reduces to the custodial $SU(2)_V$ symmetry. In that case the W and Z mass have the same form as in the SM and $\rho = 1$ at tree-level.

The coupling modifiers to gauge bosons and fermions are given by

$$\kappa_V = c_H c_\alpha + \sqrt{\frac{8}{3}} s_H s_\alpha \qquad \kappa_V = \frac{c_\alpha}{c_H}$$

Where $s_H = \sin\theta_H = 2\sqrt{2}\frac{v_\Delta}{v}$ and α is the mixing angle between the two neutral states.

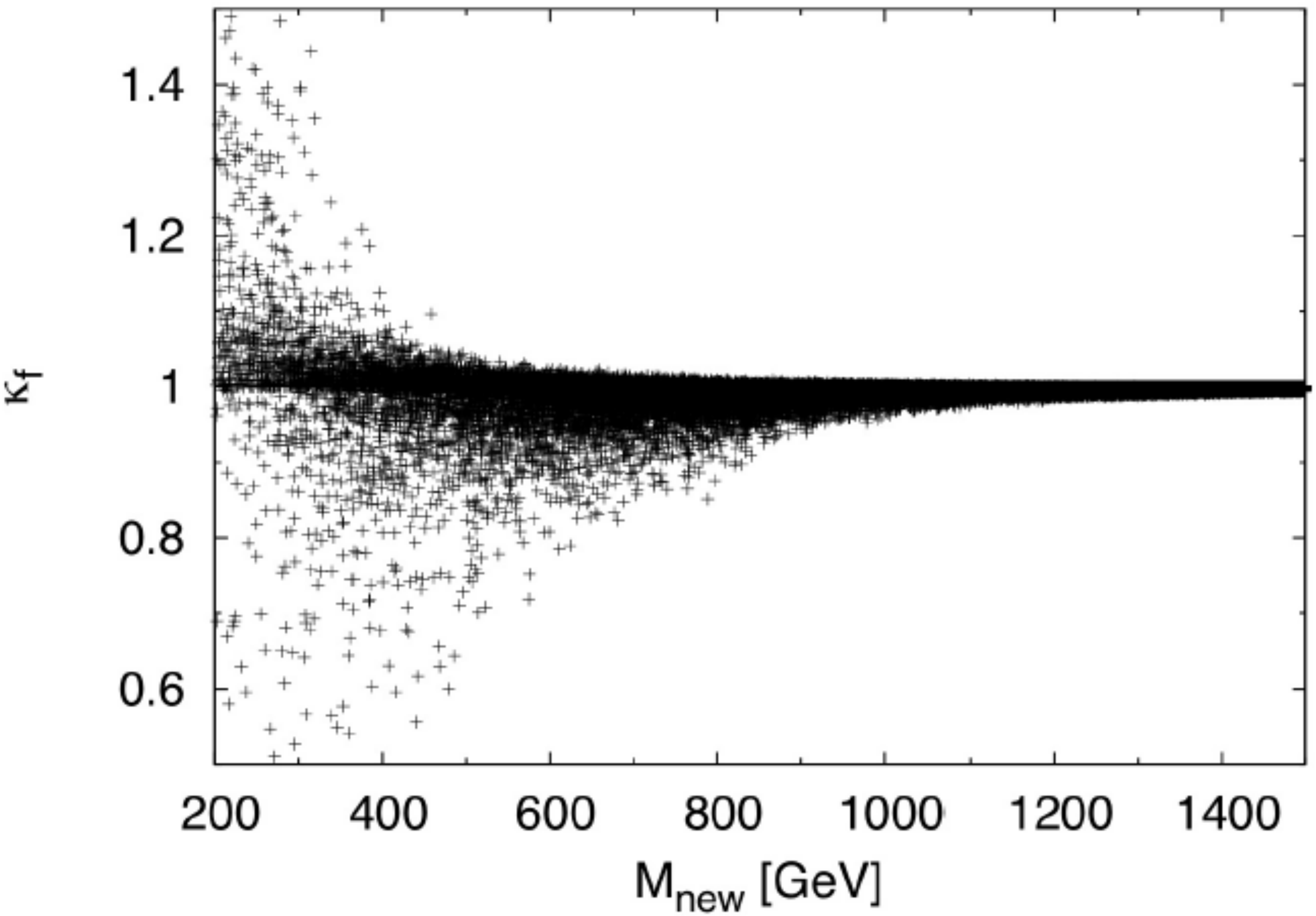
Numerical results: hVV coupling



$M_{\text{new}} \equiv$ mass of *lightest* new state.

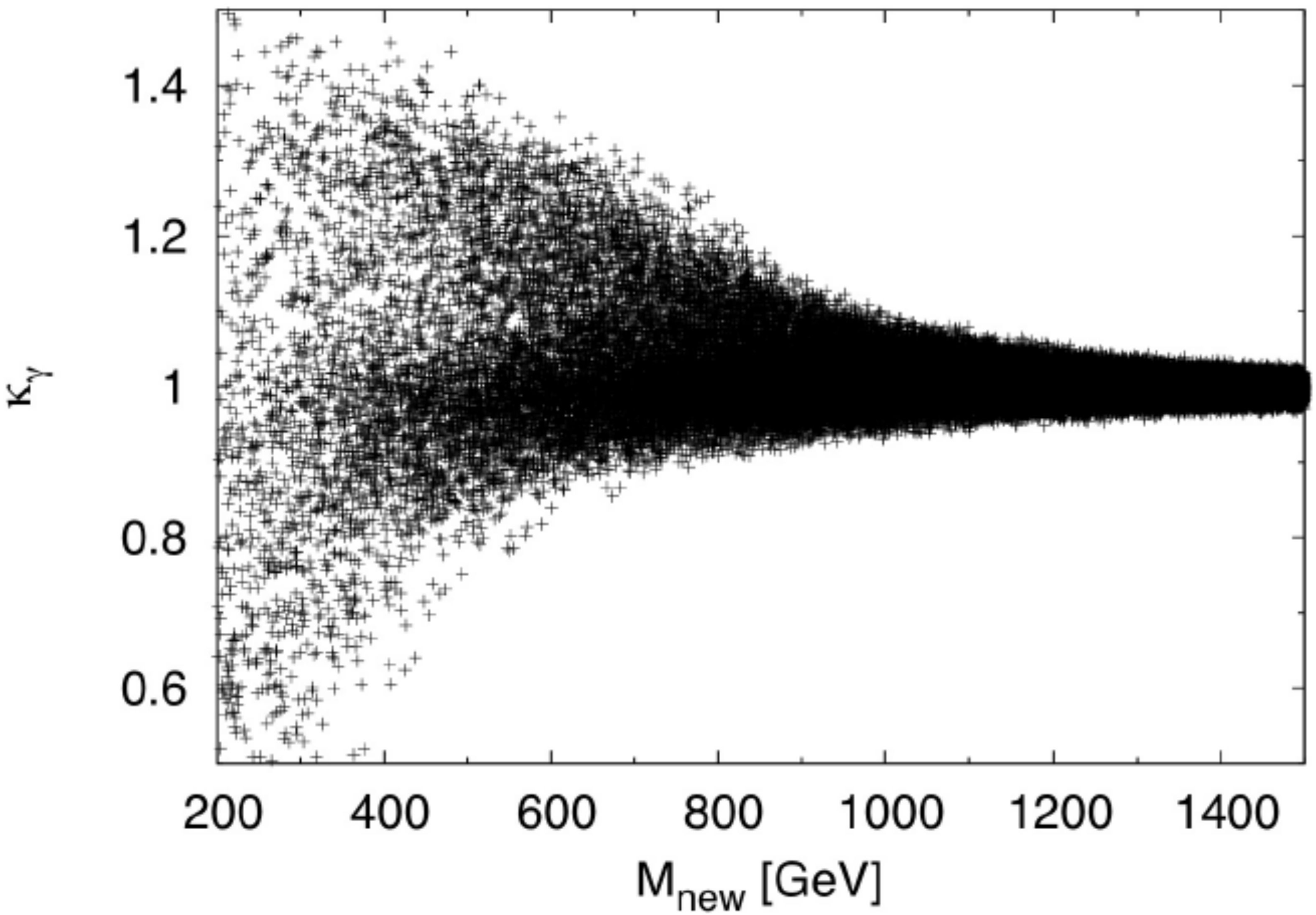
Hartling, Kumar, Logan, PRD90 (2014) no.1, 015007

Numerical results: hff coupling



$M_{\text{new}} \equiv$ mass of *lightest* new state.

Numerical results: $h\gamma\gamma$ coupling contributions from charged scalars in loop



$M_{\text{new}} \equiv$ mass of *lightest* new state.

Hartling, Kumar, Logan, PRD90 (2014) no.1, 015007

$pp \to ZZ$ and CP-violation

GAEMERS, GOUNARIS, ZPC1 (1979) 259
HAGIWARA, PECCEI, ZEPPENFELD, HIKASA, NPB282 (1987) 253
GRZADKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025

BÉLUSCA-MAÏTO, FALKOWSKI, FONTES, ROMÃO, SILVA, JHEP 04 (2018) 002

AZEVEDO, FERREIRA, MUEHLLEITNER, PATEL, RS, WITTBRODT, JHEP 1811 (2018) 091

Dark CP-violating sector

Two doublets + one singlet and one exact Z_2 symmetry

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2, \qquad \Phi_S \to -\Phi_S$$

with the most general renormalisable potential

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + (A\Phi_1^\dagger\Phi_2\Phi_S + h.c.)$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right] + \frac{m_S^2}{2}\Phi_S^2 + \frac{\lambda_6}{4}\Phi_S^4 + +\frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

and the vacuum preserves the symmetry

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG_0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho + i\eta) \end{pmatrix} \qquad \Phi_S = \rho_S$$

The potential is invariant under the CP-symmetry

$$\Phi_1^{CP}(t,\vec{r}) = \Phi_1^*(t,-\vec{r}), \qquad \Phi_2^{CP}(t,\vec{r}) = \Phi_2^*(t,-\vec{r}), \qquad \Phi_S^{CP}(t,\vec{r}) = \Phi_S(t,-\vec{r})$$

except for the term $(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.)$

Azevedo, Ferreira, Mühlleitner Patel, RS, Wittbrodt, JHEP 1811 (2018) 091

Dark CP-violating sector

The Z_2 symmetry is exact - all particles are dark except the SM-like Higgs. The couplings of the SM-like Higgs to all fermions and massive gauge bosons are exactly the SM ones.

The model is Type I - only the first doublet couples to all fermions

The neutral mass eigenstates are h_1, h_2, h_3

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho \\ \eta \\ \rho_S \end{pmatrix} \qquad R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

But now how do we see signs of CP-violation?

Missing energy signals are similar to some extent for all dark matter models. They need to be combined with a clear sign of CP-violation.

$$q\bar{q}(e^+e^-) \to Z^* \to h_1 h_2 \to h_1 h_1 Z$$

$$q\bar{q}(e^+e^-) \to Z^* \to h_1 h_2 \to h_1 h_1 h_{125}$$

Mono-Z and mono-Higgs events.

With one Z off-shell the most general ZZZ vertex has a CP-odd term of the form

$$i\Gamma_{\mu\alpha\beta} = -e\frac{p_1^2 - m_Z^2}{m_Z^2} f_4^Z (g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

GAEMERS, GOUNARIS, ZPC1 (1979) 259

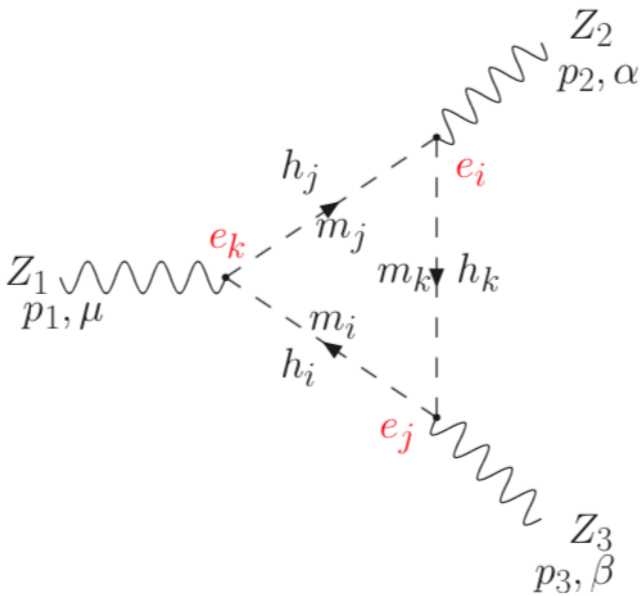
HAGIWARA, PECCEI, ZEPPENFELD, HIKASA, NPB282 (1987) 253

GRZADKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025

that comes from an effective operator (dim-6)

$$\frac{\tilde{k}_{ZZ}}{m_Z^2}\partial_\mu Z_\nu \partial^\mu Z^\rho \partial_\rho Z^\nu$$

Not affected by EDMs

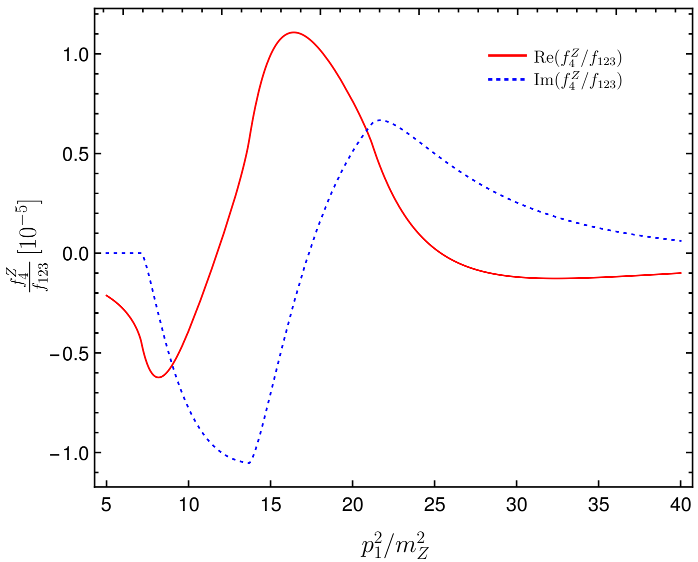


in our model it has the simple expression

$$f_4^Z(p_1^2) = -\frac{2\alpha}{\pi s_{2\theta_W}^3}\frac{m_Z^2}{p_1^2 - m_Z^2} f_{123} \sum_{i,j,k} \epsilon_{ijk} C_{001}(p_1^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_k^2)$$

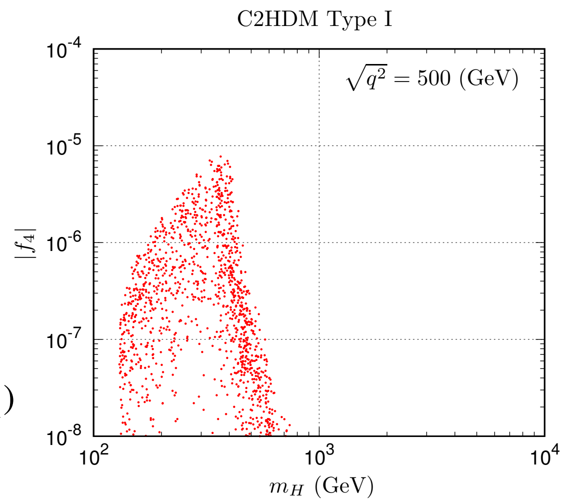
$$f_{123} = R_{13}R_{23}R_{33}$$

Combining $h_1 h_2 Z$; $h_1 h_3 Z$ and $h_2 h_3 Z$

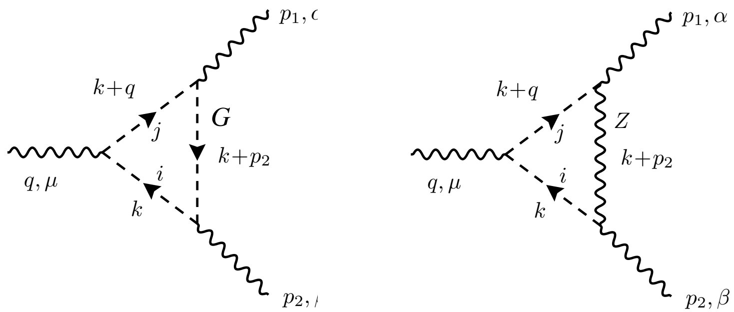


The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

PLOT FROM JHEP 04 (2018) 002



In the C2HDM there are two more types of diagrams



$$h_1 \to ZZ \quad CP(h_1) = 1$$
$$h_2 \to ZZ \quad CP(h_2) = 1$$
$$h_2 \to h_1 Z \quad CP(h_2) = -CP(h_1)$$

GRZĄDKOWSKI, OGREID, OSLAND, JHEP 05 (2016) 025.
BÉLUSCA-MAÏTO, FALKOWSKI, FONTES, ROMÃO, SILVA, JHEP 04 (2018) 002

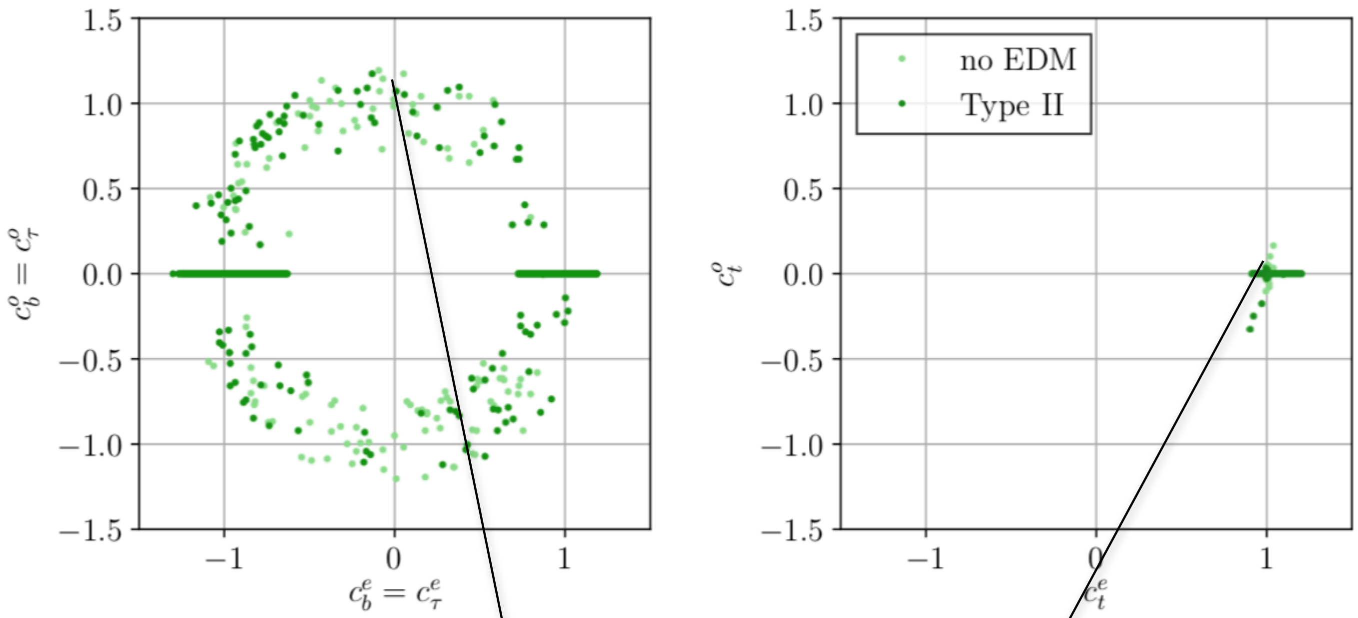
The typical maximal value for f_4 seems to be below 10^{-4}.

CMS COLLABORATION, EPJC78 (2018) 165. $-1.2 \times 10^{-3} < f_4^Z < 1.0 \times 10^{-3}$

ATLAS COLLABORATION, PRD97 (2018) 032005. $-1.5 \times 10^{-3} < f_4^Z < 1.5 \times 10^{-3}$

Bounds from present measurements by ATLAS and CMS still two orders of magnitude away.

The unrelated final slide - The strange case of CP-violation in a complex 2HDM



$$Y_{C2HDM} = a_F + i\gamma_5 b_F$$

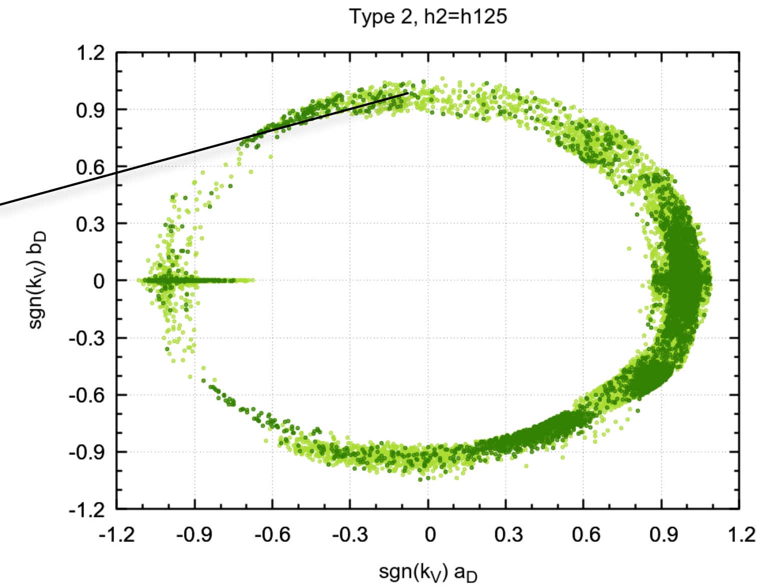
$$b_U \approx 0;\ a_D \approx 0$$

A Type II model where H_2 is the SM-like Higgs.

Find two particles of the same mass one decaying to tops as CP-even

$$h_2 = H; pp \to Ht\bar{t}$$

With the new EDM result



and the other decaying to taus as CP-odd

$$h_2 = A \to \tau^+\tau^-$$

Probing one Yukawa coupling is not enough!

Fontes, Mühlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

Conclusions

- If no (other) scalar is found, unitarity will lead to a (very) slow death of our faith in these extensions;
- Other interesting models with very different phenomenology, like the GM, will be constrained by other measurements as well;
- CP-violation is still a desperate issue at the LHC;
- Interesting scenarios with a CP-odd/CP-even scalars?
- So let us just keep on searching!

Workshop on
Multi-Higgs Models

1-4 September 2020

Lisbon - Portugal

This Workshop brings together those interested in the theory and phenomenology of Multi-Higgs models. The program is designed to include talks given by some of the leading experts in the field, and also ample time for discussions and collaboration between researchers. A particular emphasis will be placed on identifying those features of the models which are testable at the LHC and DM searches.

For registration and/or to propose a talk, send an email to:

2hdmwork@cftp.tecnico.ulisboa.pt

Web Page : http://cftp.tecnico.ulisboa.pt/~2hdmwork/

The end

The Trouble with Triplets: the ρ parameter

$\rho \equiv$ ratio of strengths of charged and neutral weak currents $\simeq 1$ to high precision.

$$\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W} = \frac{\sum_k 2[T_k(T_k+1) - Y_k^2/4]v_k^2}{\sum_k Y_k^2 v_k^2}$$

($Q = T^3 + Y/2$, vevs defined as $\langle \phi_k^0 \rangle = v_k/\sqrt{2}$ for complex reps and $\langle \phi_k^0 \rangle = v_k$ for real reps)

$\rho = 1$ "by accident" for SM doublet; isospin septet with $Y = 4$

(septet: Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303)

SM + real triplet ξ: $\rho > 1$

SM + complex triplet χ $(Y = 2)$: $\rho < 1$

Combine them both: $\langle \chi^0 \rangle = v_\chi$, $\langle \xi^0 \rangle = v_\xi$; doublet $\langle \phi^0 \rangle = v_\phi/\sqrt{2}$

$$\rho = \frac{v_\phi^2 + 4v_\xi^2 + 4v_\chi^2}{v_\phi^2 + 8v_\chi^2} = 1 \text{ when } v_\xi = v_\chi$$

Tree-level Unitarity

In the SM the Higgs unitarises WW scattering if the Higgs mass is below 700 GeV. In extensions of the scalar sector with N_0 neutral scalar fields ϕ_n^0 with VEVs v_n^0, the same unitarity condition leads to a sum rule.

The "unitarity sum rules" are required for the cancelation of the perturbatively unitary violating high energy scattering amplitudes of weak gauge bosons and the neutral Higgs bosons at tree level.

$$WW \to WW \text{ scattering}: \qquad \sum_{n=1}^{N_0} \kappa_{WW}^{\phi_n^0} \kappa_{WW}^{\phi_n^0} = 1$$

It is interesting that if you have a model with neutral Higgs only it can be shown that

$$\begin{aligned}
WW \to WW \text{ scattering}: &\quad -4 + \frac{3}{\rho_0} + \sum_{n=1}^{N_0} \kappa_{WW}^{\phi_n^0} \kappa_{WW}^{\phi_n^0} = 0,\\
WW \to ZZ \text{ scattering}: &\quad \frac{1}{\rho_0} - \rho_0 \sum_{n=1}^{N_0} \kappa_{ZZ}^{\phi_n^0} \kappa_{WW}^{\phi_n^0} = 0,\\
WW \to \phi_n^0 Z \text{ scattering}: &\quad \kappa_{WW}^{\phi_n^0} - \rho_0 \kappa_{ZZ}^{\phi_n^0} = 0, \quad \text{and} \quad \sum_{m=1}^{N_0} \kappa_Z^{\phi_n^0 \phi_m^0} \kappa_{WW}^{\phi_m^0} = 0,\\
WW \to \phi_n^0 \phi_m^0 \text{ scattering}: &\quad \kappa_{WW}^{\phi_n^0 \phi_m^0} - \kappa_{WW}^{\phi_n^0} \kappa_{WW}^{\phi_m^0} = 0, \quad \text{and} \quad \kappa_Z^{\phi_n^0 \phi_m^0} = 0,\\
ZZ \to \phi_n^0 \phi_m^0 \text{ scattering}: &\quad \kappa_{ZZ}^{\phi_n^0 \phi_m^0} - \rho_0 \kappa_{ZZ}^{\phi_n^0} \kappa_{ZZ}^{\phi_m^0} - \sum_{l=1}^{N_0} \kappa_Z^{\phi_n^0 \phi_l^0} \kappa_Z^{\phi_m^0 \phi_l^0} = 0.
\end{aligned}$$

$$\frac{1}{\rho_0}(\rho_0 - 1) = 0$$

Meaning that enforcing unitarity leads to $\rho_0 = 1$.

Slides by H. Logan

Most general scalar potential:

Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

$$\begin{aligned} V(\Phi, X) &= \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 \\ &+\lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) \\ &+\lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\ &-M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab} \end{aligned}$$

9 parameters, 2 fixed by M_W and m_h $\rightarrow$ free parameters are m_H, m_3, m_5, v_χ, α plus two triple-scalar couplings.

Dimension-3 terms usually omitted by imposing Z_2 sym. on X.

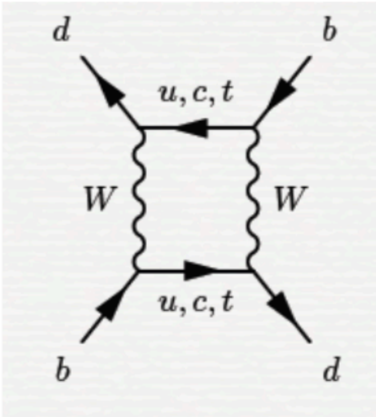
These dim-3 terms are essential for the model to possess a decoupling limit!

$(UXU^\dagger)_{ab}$ is just the matrix X in the Cartesian basis of SU(2), found using

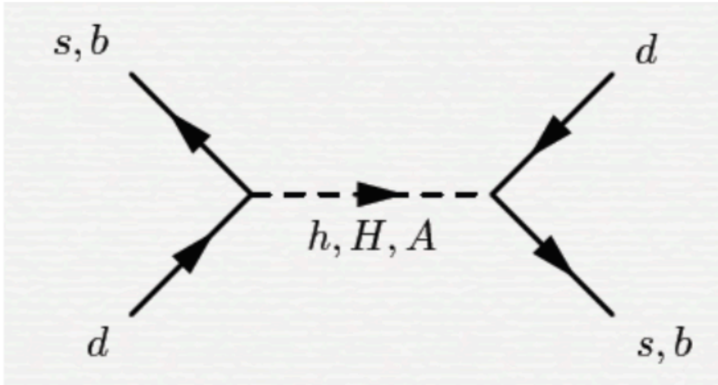
$$U = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ -\frac{i}{\sqrt{2}} & 0 & -\frac{i}{\sqrt{2}} \\ 0 & 1 & 0 \end{pmatrix}$$

FCNC constraints in 2HDM

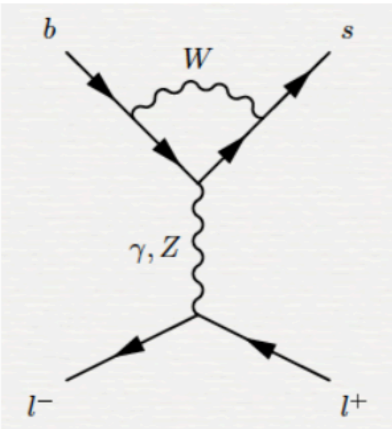
➡ B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing

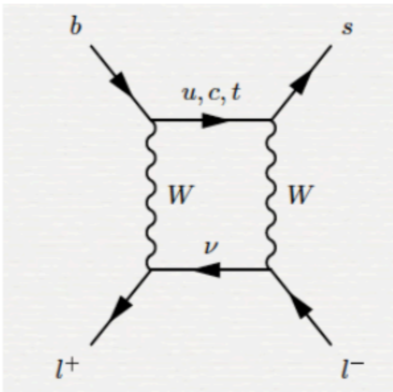


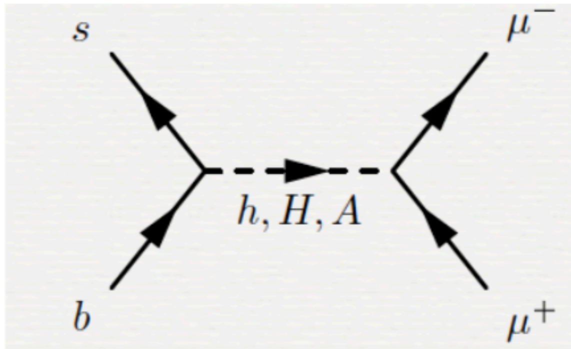
New tree-level FCNC diagrams



➡ Rare B decays







SM Yukawa Lagrangian

$$L_Y = \left[\bar{U} \quad \bar{D}\right]_L \Phi Y_d\, D_R + \left[\bar{U} \quad \bar{D}\right]_L \tilde{\Phi}\, Y_u U_R + \left[\bar{N} \quad \bar{E}\right]_L \Phi\, Y_e E_R + \text{h.c.}$$

where the gauge eigenstates are

$$U = \left[u_g \quad c_g \quad t_g\right]; \; D = \left[d_g \quad s_g \quad b_g\right]; \; N = \left[\nu_e \quad \nu_\mu \quad \nu_\tau\right]; \; E = \left[e \quad \mu \quad \tau\right]$$

and Y are matrices in flavour space. To get the mass terms we just need the vacuum expectation values of the scalar fields

$$L_Y^{\text{mass}} = \frac{v}{\sqrt{2}}\, \bar{U}_L Y_u U_R + \frac{v}{\sqrt{2}}\, \bar{D}_L Y_d D_R + \frac{v}{\sqrt{2}}\, \bar{E}_L Y_e E_R + \text{h.c.}$$

which have to be diagonalised.

SM Yukawa Lagrangian

So we define

$$D_R \to N_R^{-1} D_R ; D_L \to N_L^{-1} D_L ; U_R \to K_R^{-1} U_R ; U_L \to K_L^{-1} U_L$$

and the mass matrices are

$$-\frac{v}{\sqrt{2}} N_L^{\dagger} Y_d N_R = M_d ; \qquad -\frac{v}{\sqrt{2}} K_L^{\dagger} Y_u K_R = M_u$$

and the interaction term is proportional to the mass term (just D terms)

$$L_Y^{interactions} = \frac{h}{\sqrt{2}} \bar{D}_L Y_d D_R \propto \frac{v}{\sqrt{2}} \bar{D}_L Y_d D_R$$

No scalar induced tree-level FCNCs

2HDM Yukawa Lagrangian

However in 2HDMs

$$\Phi_1 = \begin{pmatrix} - \\ (h_1 + v_1)/\sqrt{2} \end{pmatrix}; \quad \Phi_2 = \begin{pmatrix} - \\ (h_2 + v_2)/\sqrt{2} \end{pmatrix}$$

$$L_Y^{mass} = \frac{v_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{v_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{v_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{v_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \ldots$$

$$= \frac{1}{\sqrt{2}} \bar{U}_L \left(v_1 Y_u^1 + v_2 Y_u^2\right) U_R + \frac{1}{\sqrt{2}} \bar{D}_L \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2\right)} D_R + \ldots$$

$$-\frac{1}{\sqrt{2}} N_L^\dagger \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2\right)} N_R = M_d; \qquad -\frac{1}{\sqrt{2}} K_L^\dagger \left(v_1 Y_u^1 + v_2 Y_u^2\right) K_R = M_u$$

$$L_Y^{interactions} = \frac{h_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{h_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{h_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{h_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \ldots$$

$$= \frac{h}{\sqrt{2}} \bar{U}_L \left(\cos\alpha Y_u^1 + \sin\alpha Y_u^2\right) U_R + \frac{H}{\sqrt{2}} \bar{D}_L \boxed{\left(-\sin\alpha Y_d^1 + \cos\alpha Y_d^2\right)} D_R + \ldots$$

h, H are the mass eigenstates (a is the rotation angle in the CP-even sector)

2HDM Yukawa Lagrangian

How can we avoid large tree-level FCNCs?

1. **Fine tuning** – for some reason the parameters that give rise to tree-level FCNC are small

Example: Type III models CHENG, SHER (1987)

2. **Flavour alignment** – for some reason we are able to diagonalise simultaneously both the mass term and the interaction term

Example: Aligned models PICH, TUZON (2009)

$$Y_d^2 \propto Y_d^1$$

(for down type)