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The futures of Higgs physics

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Particle physics for the future of Europe, IST

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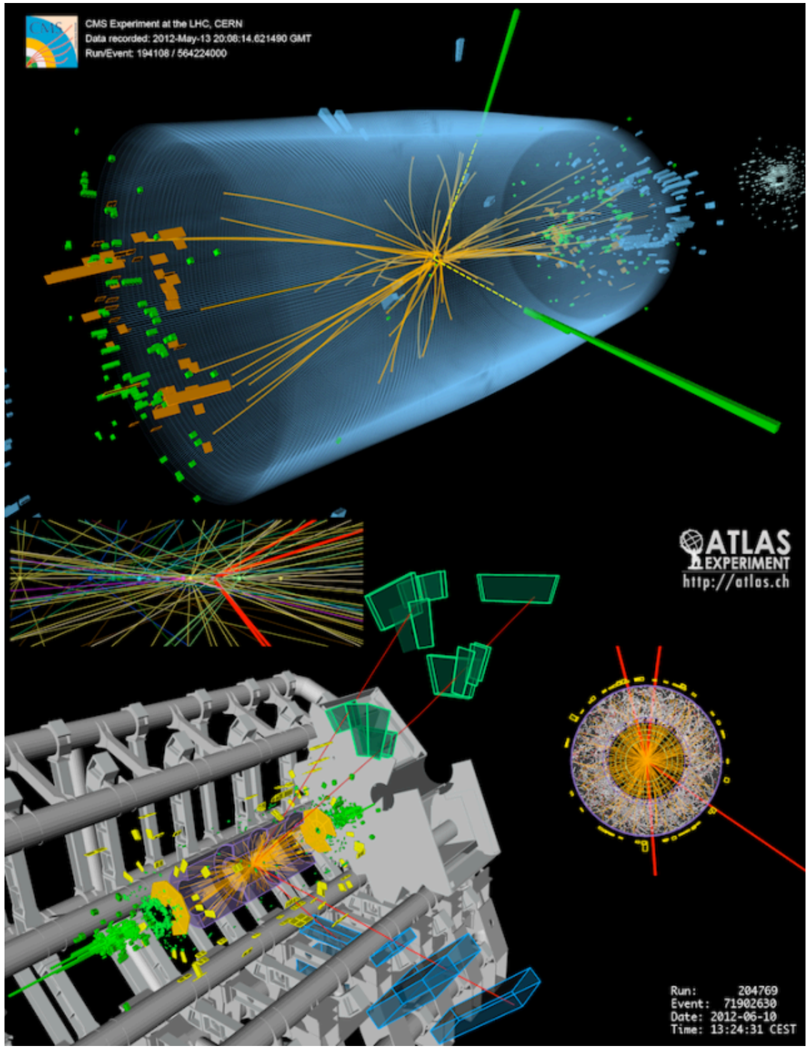
FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

A brief history of the Higgs boson



There is a model, the Standard Model, that is based on symmetries.

With the symmetries, all particles emerge without a mass. But most particles have mass. Brout, Englert and Higgs proposed a mechanism that gives mass to the particles via the interaction with a field we now call the "Higgs" field.

Just after the Big Bang the Higgs field was zero but as the temperature fell below a critical value, it spontaneously grew and particles interacting with with got a mass. The larger the interaction the heavier the particle. No coupling to the photon.

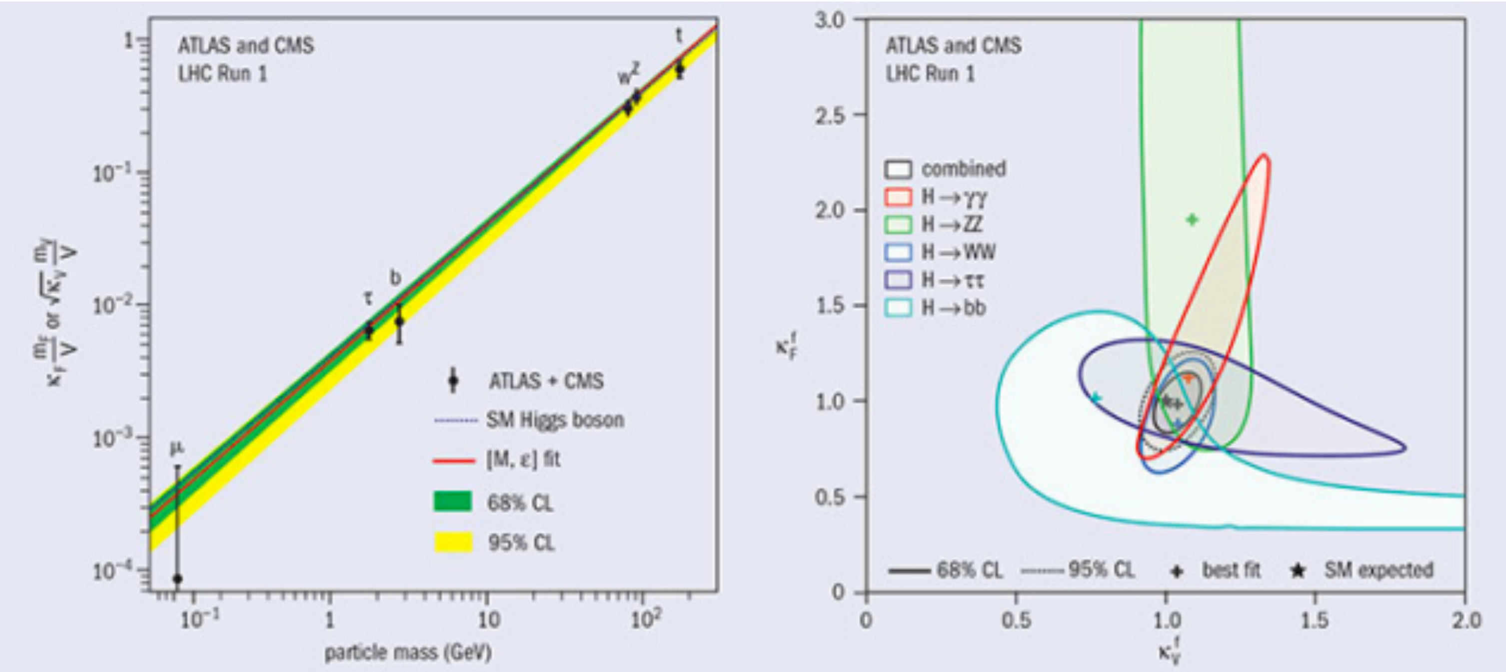
On July 4 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider observed a new particle in the mass region around 125 GeV, consistent with the Standard Model Higgs boson. Is it the Higgs boson predicted by the Standard Model?

A brief history of the Higgs boson

There is a potential - the Higgs potential

$$V_{SM} = m_{11}^2(\Phi_1^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2$$

- The Higgs field
- Couples to boson fields - mass of the bosons
- Couples to fermion fields - mass of the fermions



$$g_{NP}^{hVV} = \kappa_V g_{SM}^{hVV}$$

So, 8 years after the discovery, the 125 GeV scalar looks very much like the SM Higgs

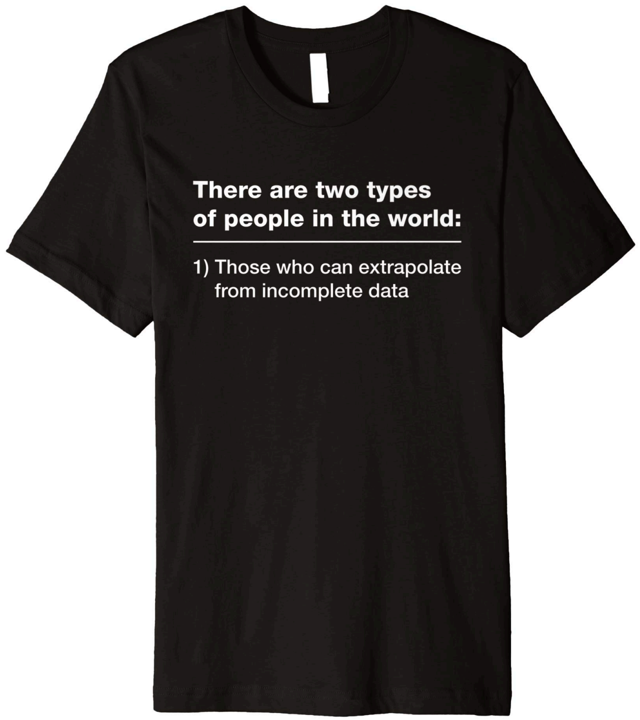
So what now?

Missing ingredients:

Dark matter - no good dark matter candidates in the SM

Mater-antimatter asymmetry - more CP violation is needed

Neutrino masses (later)



Unexplained experimental results:

Muon magnetic moment

B meson decays

There is also gravity and dark energy

So what now?

If you work on Higgs physics you generalise the potential

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

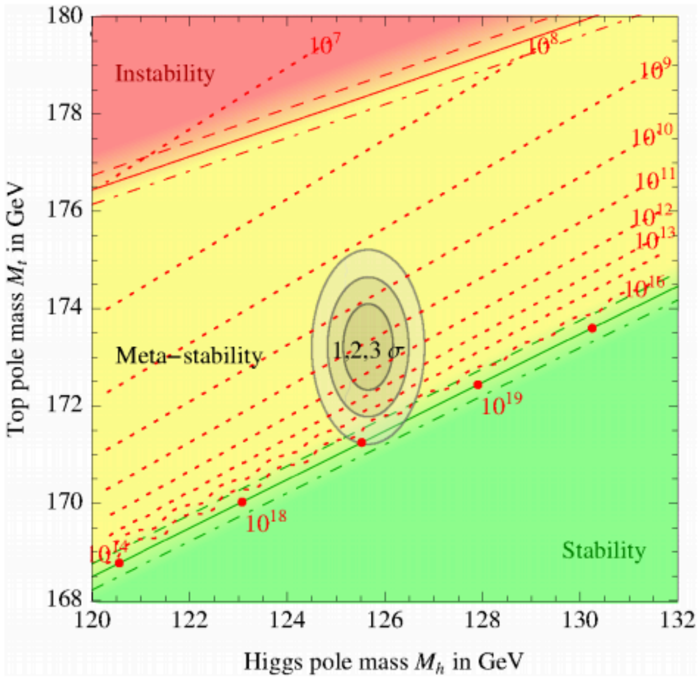
magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (CxSM)

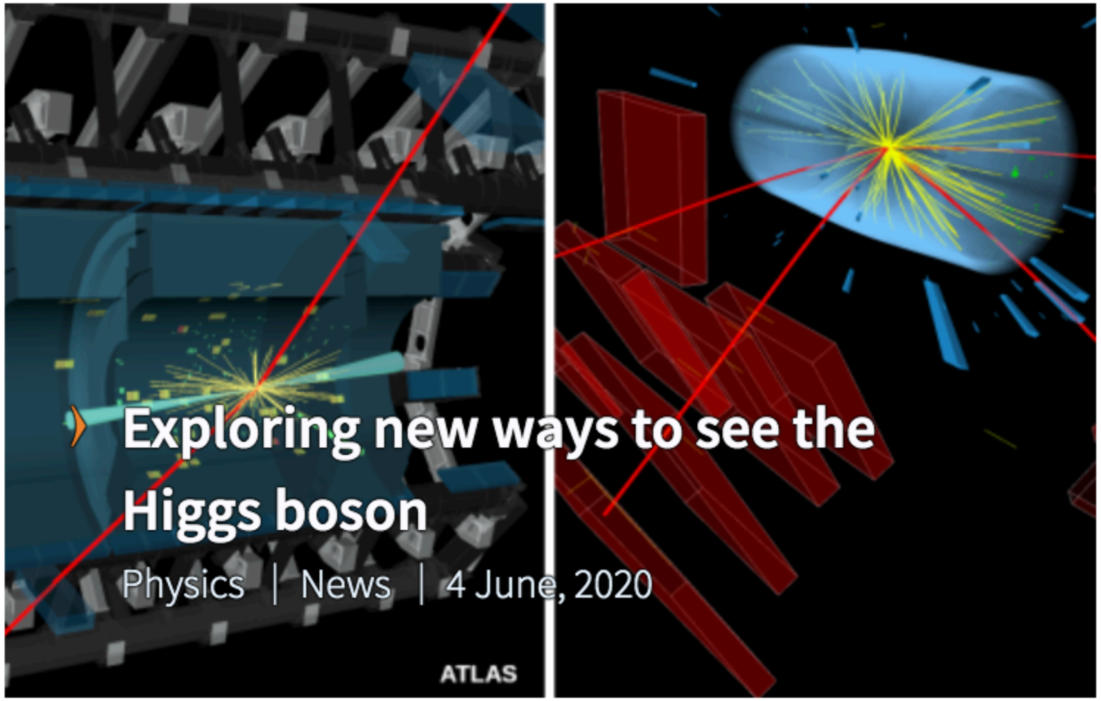
magenta + black $\Longrightarrow$ (C)2HDM

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

- There is a 125 GeV Higgs
- C2HDM - more CP violation
- All new models - dark matter candidate
- All new models - improve stability of the SM at high energies
- All new models - new scalars, possible charged Higgs



CERN's news page



Picture refers to the rare decay

$$h_{125} \to \gamma Z$$

$$S_i \to VV$$

But many more searches are going on

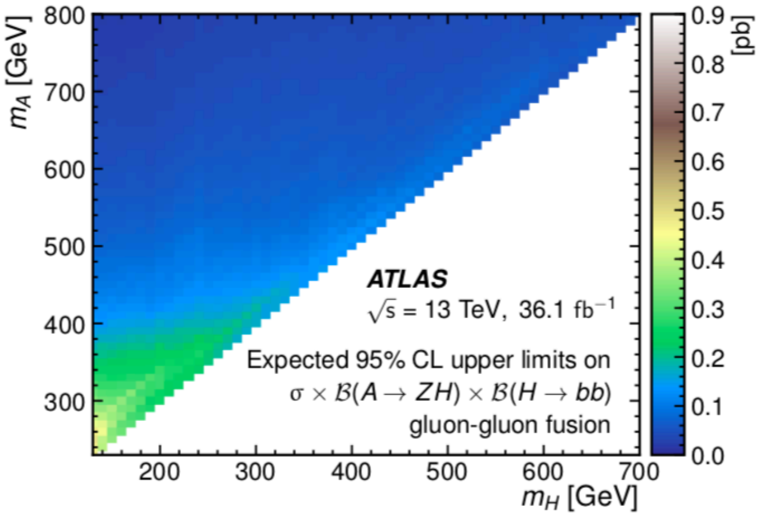
$$S_i \to S_j V \qquad H \to AZ\,(A \to HZ), h_2 \to h_1 Z$$

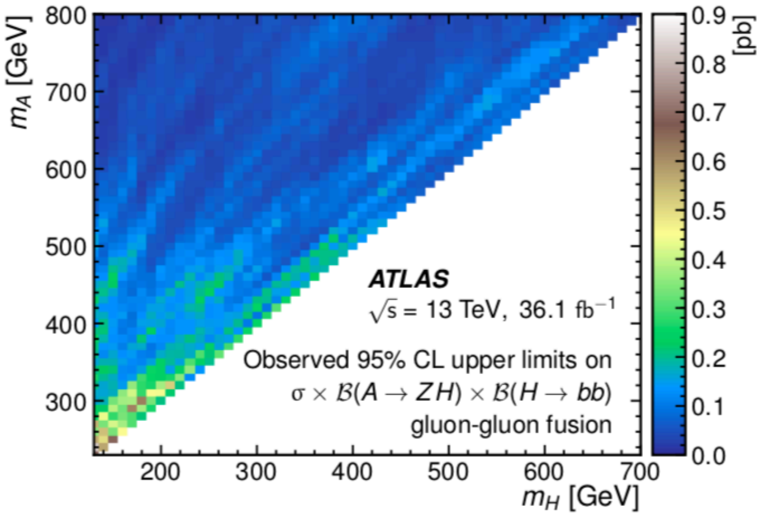
- **H → AZ, A → ZH and A → Zh$_{125}$, ATLAS and CMS**

$$S_i \to S_j S_k \qquad H_i \to H_j H_j (A_j A_j)$$

- **h$_{125}$ → AA and H → h$_{125}$ h$_{125}$, ATLAS and CMS** **but still no** $H_i \to h_{125} H_k (j \neq k)$

If nothing is found, models are constrained

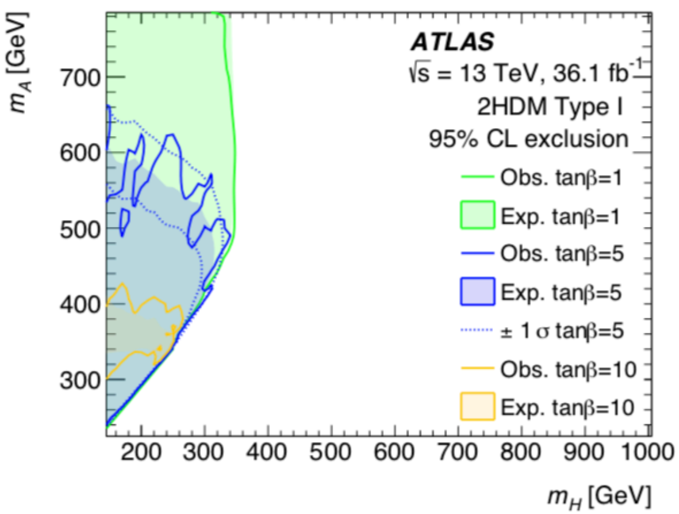


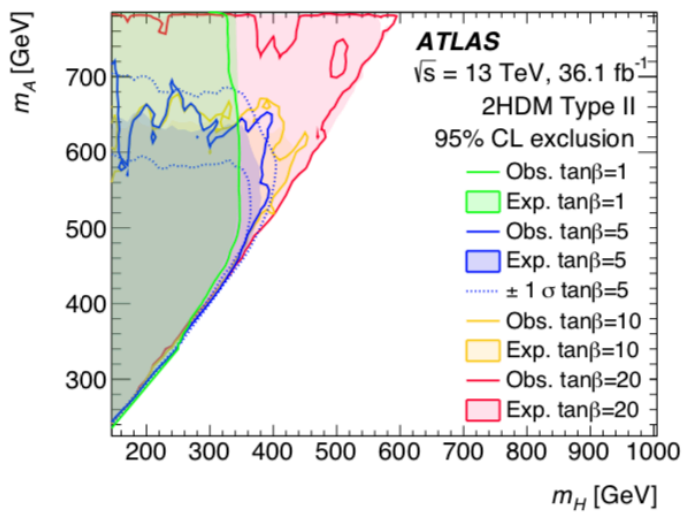


Upper bounds at 95% CL on the production cross-section times the branching ratio Br(A → ZH)×Br(H → bb) in pb for gluon–gluon fusion. Left: expected; right: observed.

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

ATLAS 1804.01126v1





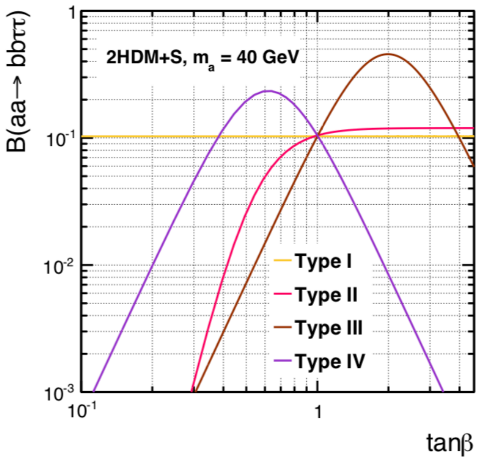
Observed and expected 95% CL exclusion regions in the (m_A,m_H) plane for various tan β values for Type I (left), and Type II (right).

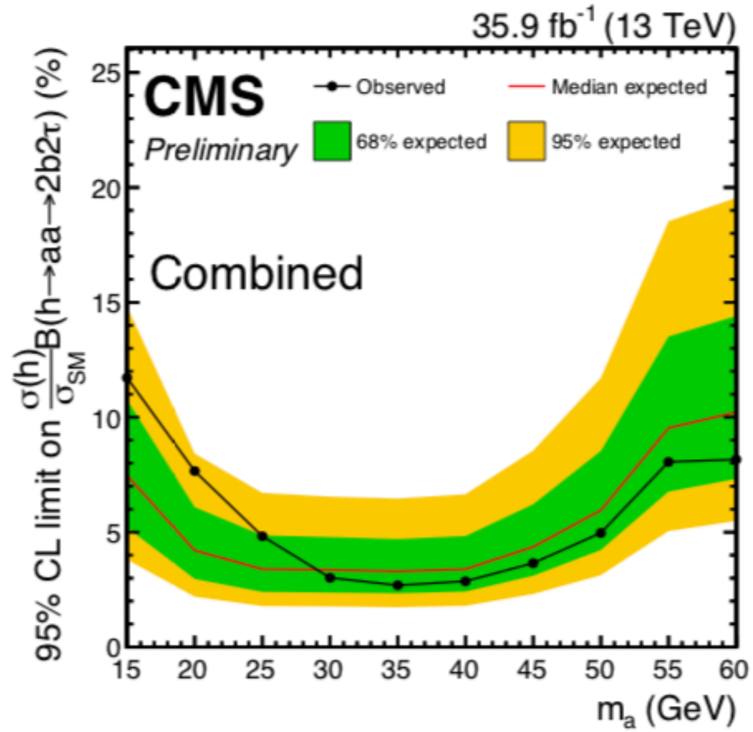
Assumptions: aligment, lightest Higgs 125 GeV, $m_{H+} = m_A$, U(1) symmetry (fixes m_{12}^2).

If nothing is found, models are constrained

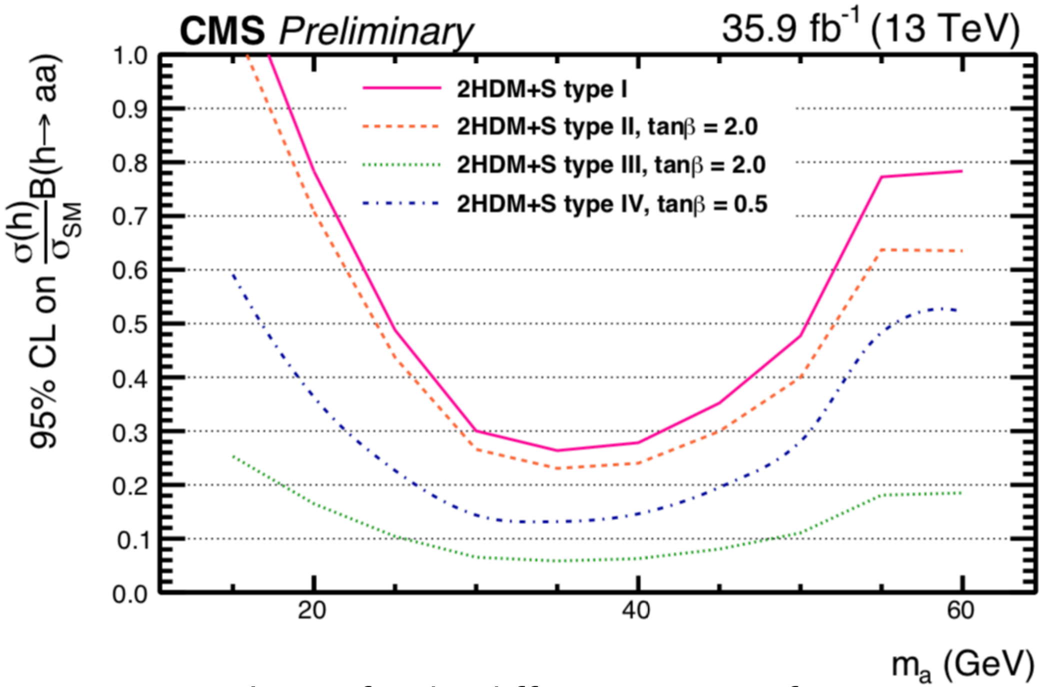
CMS PAS HIG-17-024

BRs for the 4 different versions of the model.





N2HDM (CP-conserving)

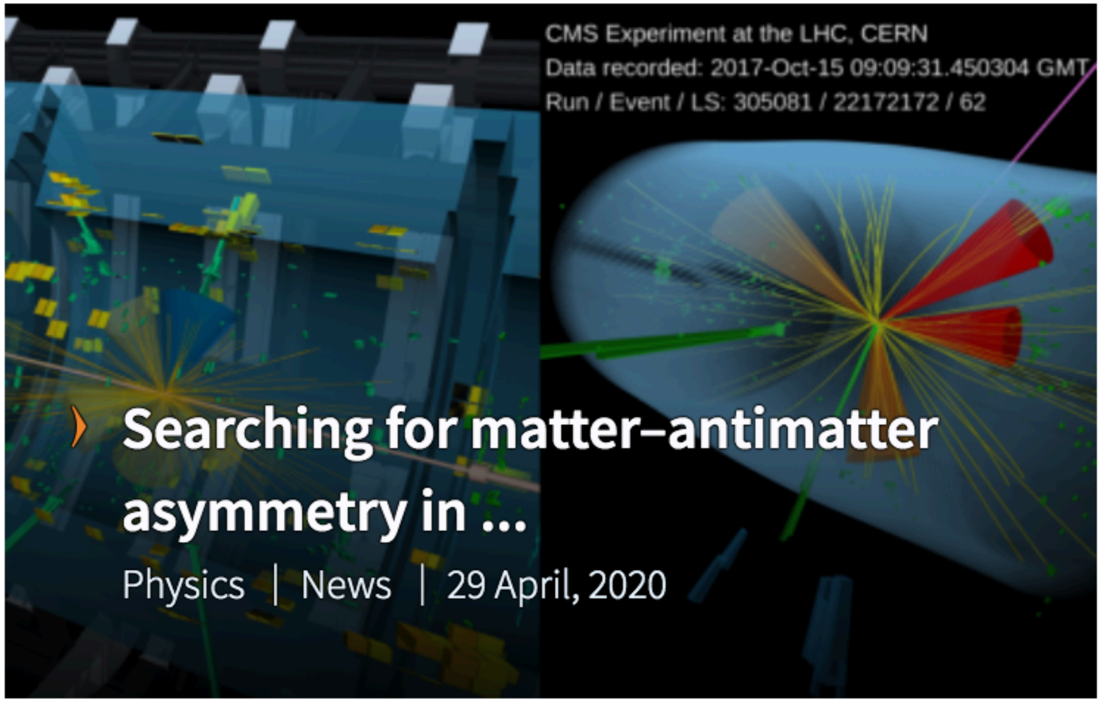


Expected and observed 95% CL limits on σ(h)B(h → aa → 2τ2b) in %. Combined eμ, eτ and μτ channels. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

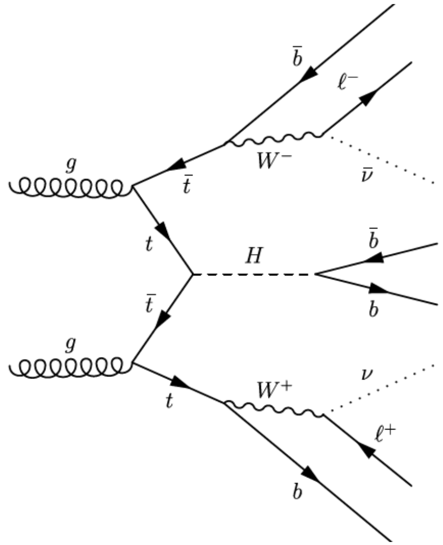
Exclusion for the different versions for 2 values of tanβ.

ATLAS, (γγjj final state),1803.11145

CERN's news page



Picture refers to Higgs production in association with a pair of top quarks



The CP-nature of the Higgs is still not known (we just know it is not a pure CP-odd state).
tth (production) and ττh (decay) starting (many theory papers).

All channels from b quark to muon pairs. Also FCNC decays, forbidden at tree-level in the SM

$$S_i \to f_i \bar{f}_j \qquad H_i/A_i \to b\bar{b}, t\bar{t}, \tau^+\tau^-, \mu^+\mu^- \qquad h_{125} \to \tau\mu, e\mu, e\tau$$

CP numbers of the discovered Higgs (tth and ττh)

$$\boxed{pp \to h\bar{t}t}$$

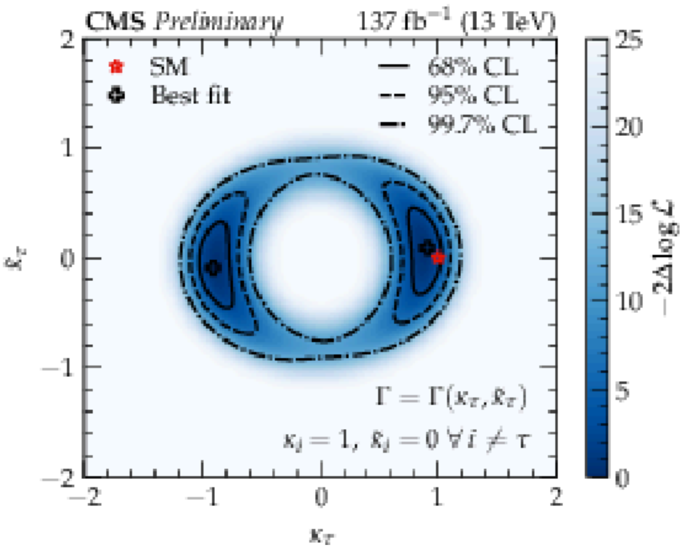
$$\mathcal{L}^{SM}_{H\bar{f}f} = -\frac{y_f}{\sqrt{2}}\bar{f}fh$$

$$\boxed{pp \to h \to \tau^+\tau^-}$$

$$\mathcal{L}^{CPV}_{H\bar{f}f} = -\frac{y_f}{\sqrt{2}}\bar{f}(a_f + ib_f\gamma_5)fh$$

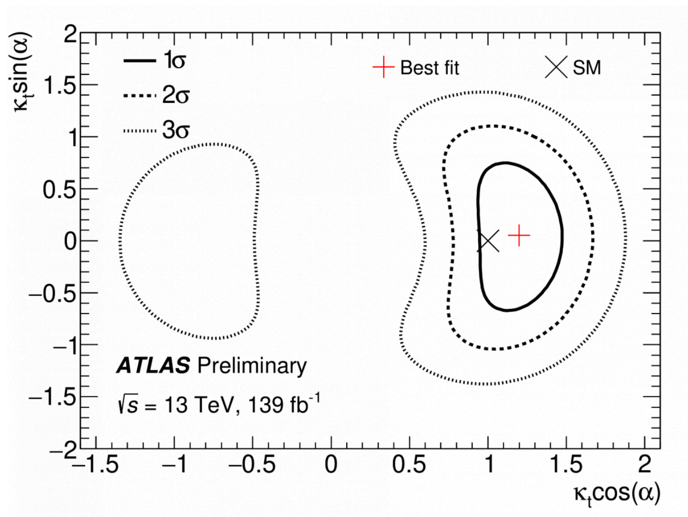
In any case interference between amplitudes allow to measure the ratio of CP-odd to CP-even components, the top in the production and the taus in the decays

CMS-PAS-HIG-20-006



$$\tan\Phi = \frac{b}{a}$$

ATLAS arxiv 2004.04545

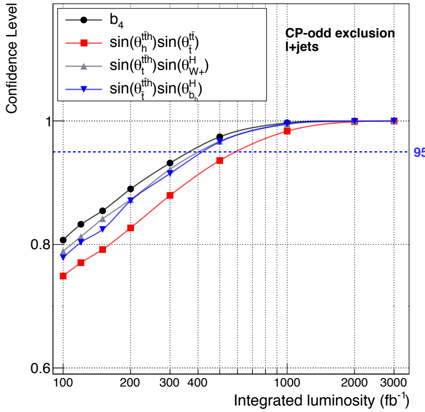


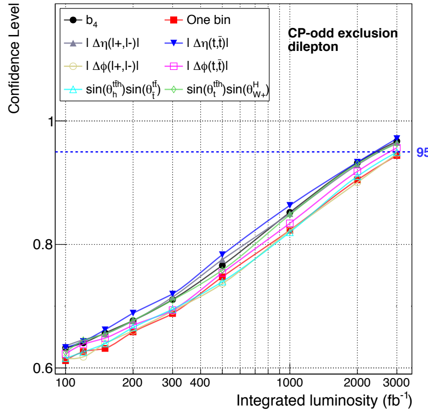
Nothing is planned for the remaining fermions!

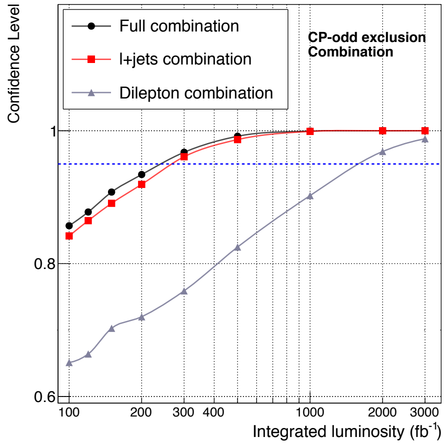
$$\mathscr{L}_{H\bar{t}t} = \kappa y_t \bar{t}(\cos\alpha + i\sin\alpha\gamma_5)th$$

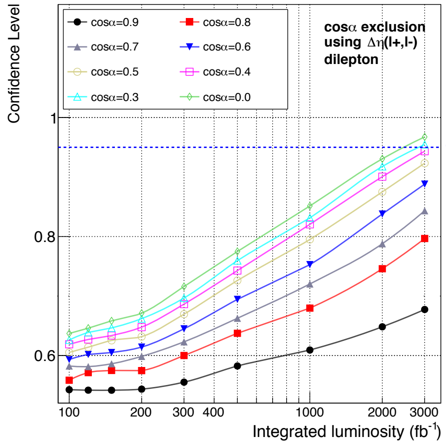
$\cos\alpha = 1$ pure scalar

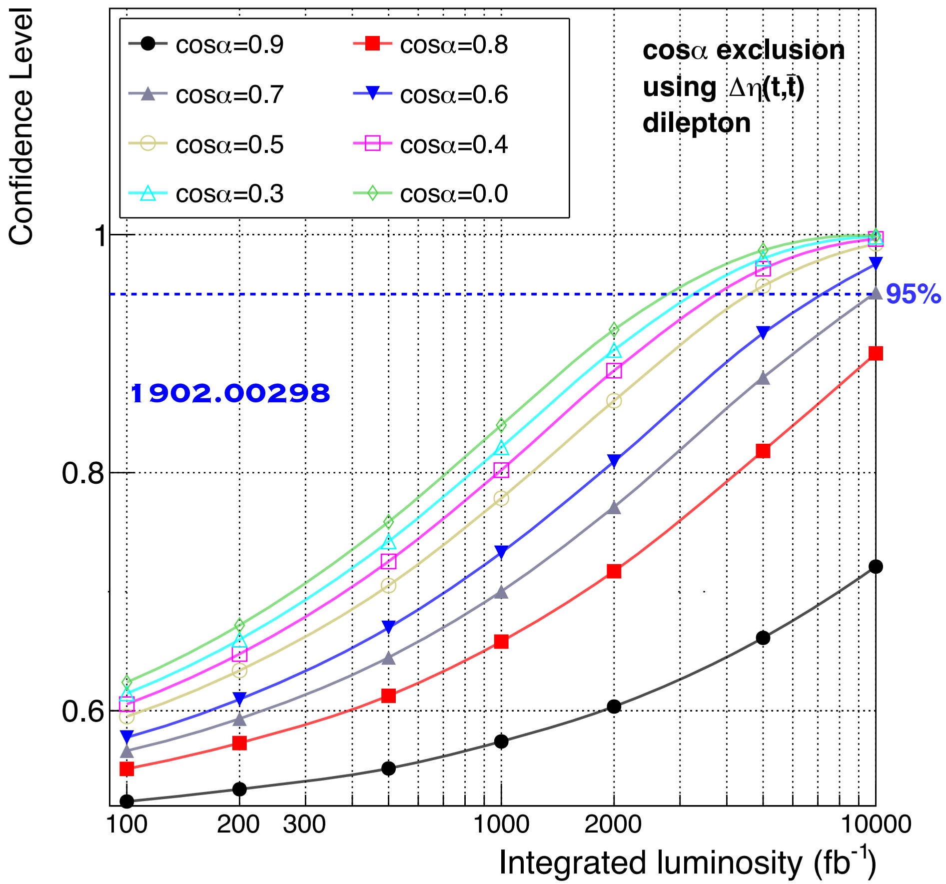
So, what is bound on the pseudoscalar component of the tth coupling at the end of the high luminosity LHC?







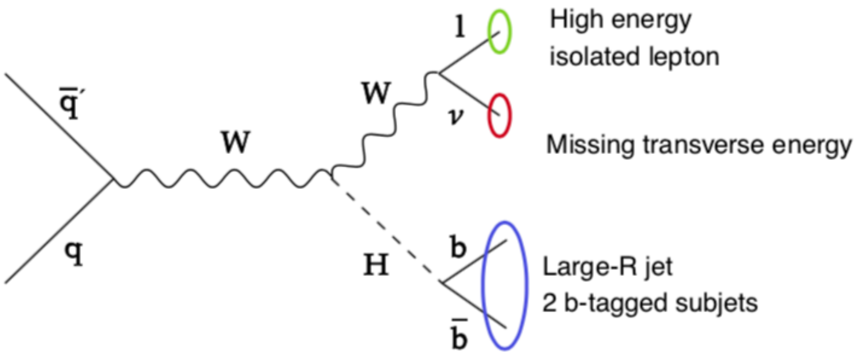




For cosα=0.7 the limit on α_2 is 46° for tanβ=1 while for cosα=0.9 is 26° - close to what we have today from indirect measurements.

The difference is that the bound is now directly imposed on the Yukawa coupling.

CP numbers of the discovered Higgs (WWh and ZZh)



In this case we start with the most general WWh vertex

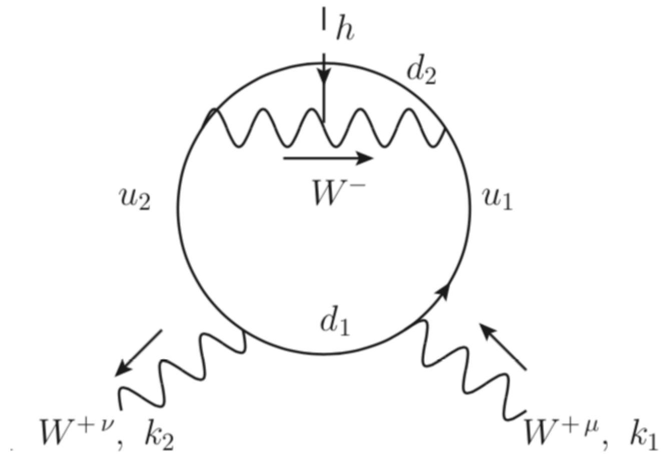
TERM COMING FROM A CPV OPERATOR.
CONTRIBUTION FROM THE SM AT 2-LOOP

$$\mathscr{M}(hW^+W^-) \sim a_1^{W^+W^-} m_W^2 \epsilon^*_{W^+} \epsilon^*_{W^-} + a_3^{W^+W^-} f^{*+}_{\mu\nu} \tilde{f}^{*-\mu\nu}$$

TERM IN THE SM AT TREE-LEVEL
BUT ALSO IN MODELS WITH CP-VIOLATION

$$\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}} \in [-0.81, 0.31]$$

PRESENT EXPERIMENTAL BOUND
FROM ATLAS AND CMS



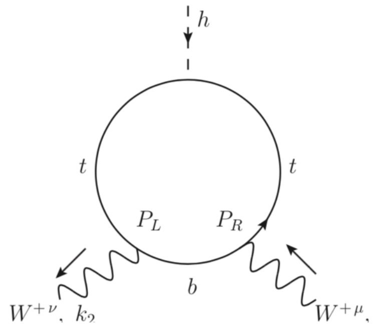
$$|c_{\rm CPV}^{\rm SM}| \sim \frac{N_c J}{(16\pi^2)^2}\left(\frac{g}{\sqrt{2}}\right)^4 \frac{\prod_{i>j}(m_{u_i}^2 - m_{u_j}^2)(m_{d_i}^2 - m_{d_j}^2)}{m_W^{12}} \simeq 9.1 \times 10^{-24} \sim \mathcal{O}(10^{-23})$$

SM ESTIMATE

CP numbers of the discovered Higgs (WWh and ZZh)

Just two examples. The left-right symmetric model

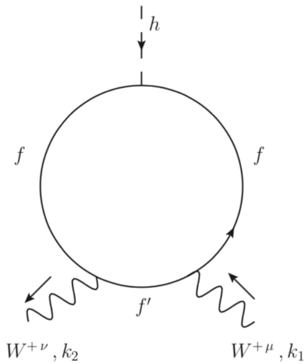
$$c_{\rm CPV} = 2\frac{a_3^{W^+W^-}}{a_1^{W^+W^-}}$$



$$\boxed{c_{\rm CPV}^{\rm LR} \simeq 9.1\times 10^{-10} \sim \mathcal{O}(10^{-9})}$$

$$c_{\rm CPV}^{\rm LR} \approx \frac{N_c g^2}{8\pi^2}\frac{m_t m_b}{m_W^2}\mathcal{I}\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) {\rm Im}(V_{tb}U_{tb}^*)$$

and the complex 2-Higgs doublet model



$$\boxed{c_{\rm CPV}^{\rm C2HDM} \simeq 6.6\times 10^{-4} \sim \mathcal{O}(10^{-3})}$$

$$c_{\rm CPV}^{\rm C2HDM} = \frac{N_c g^2}{32\pi^2}|V_{tb}|^2\left[\frac{c_t^o m_t^2}{m_W^2}\mathcal{I}_1\left(\frac{m_t^2}{m_W^2}, \frac{m_b^2}{m_W^2}\right) + \frac{c_b^o m_b^2}{m_W^2}\mathcal{I}_1\left(\frac{m_b^2}{m_W^2}, \frac{m_t^2}{m_W^2}\right)\right]$$

CPV in the triple gauge bosons couplings

$$\boxed{h_1 \to ZZ(+)h_2 \to ZZ(+)h_2 \to h_1 Z}$$

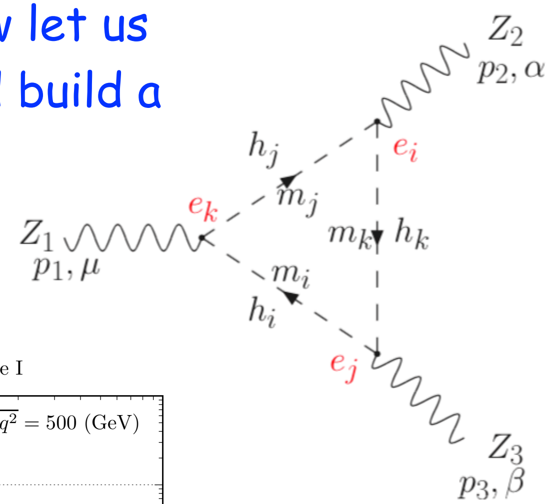
Combinations of three decays

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

$$h_3 \to h_1 Z \quad CP(h_3) = -CP(h_1)$$

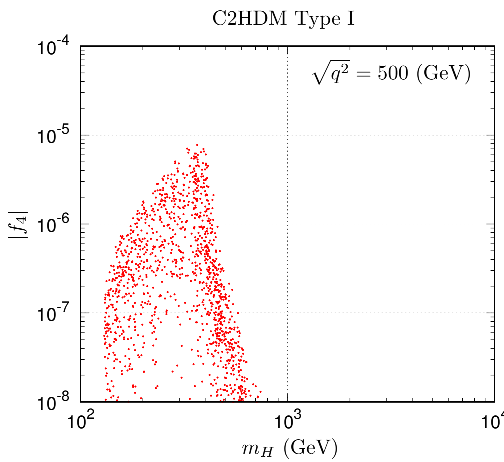
$$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$$

Is there CP-violation here? Now let us take these three processes and build a nice Feynman diagram



With one Z off-shell ZZZ vertex has a CP-odd term

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



PLOT FROM JHEP 04 (2018) 002

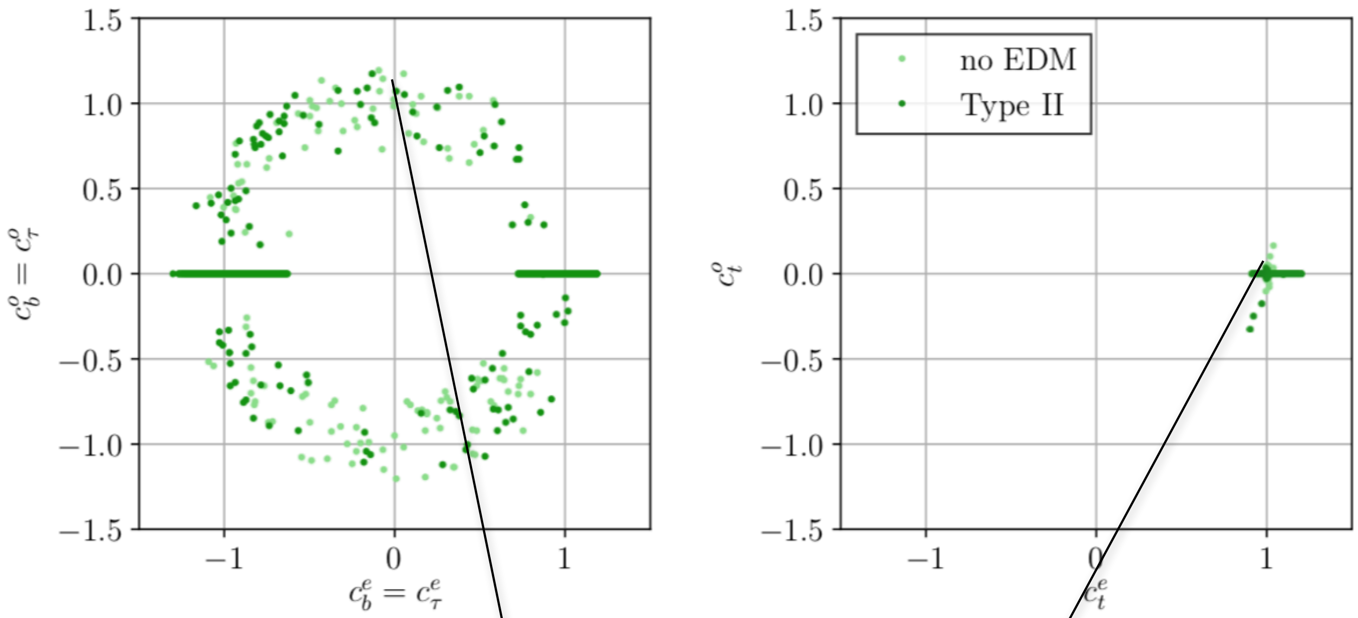
The typical maximal value for f_4 seems to be below 10^{-4}.

Present measurements by ATLAS and CMS - still two orders of magnitude away

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

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

Strange scenarios of CP-violation



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

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

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

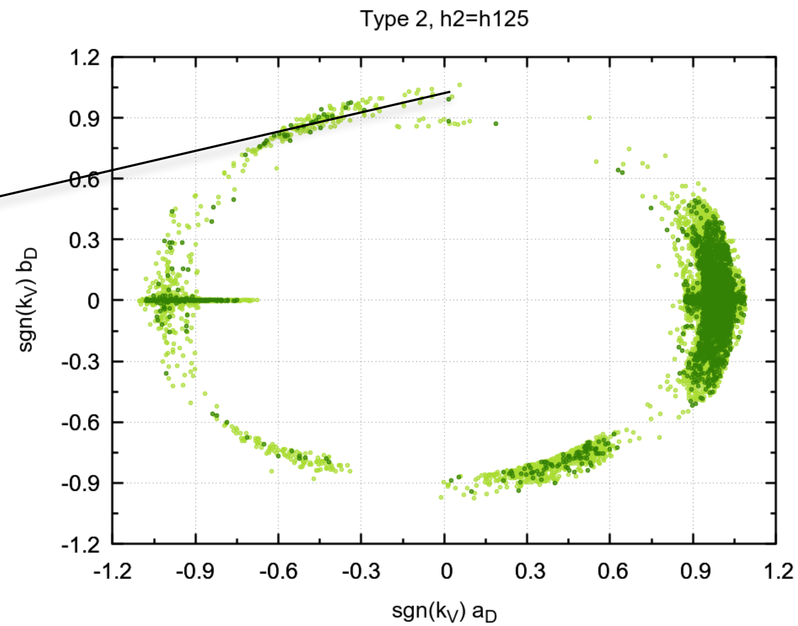
$$h_2 = H; pp \to Ht\bar{t}$$

and the other decaying to taus as CP-odd

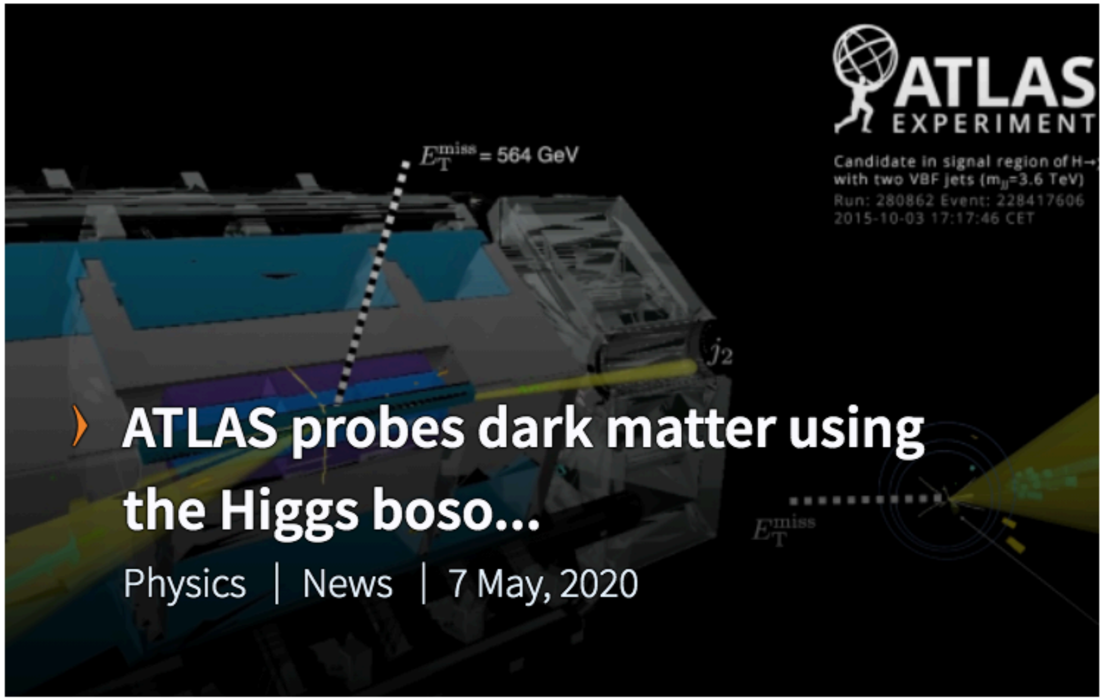
$$h_2 = A \to \tau^+\tau^-$$

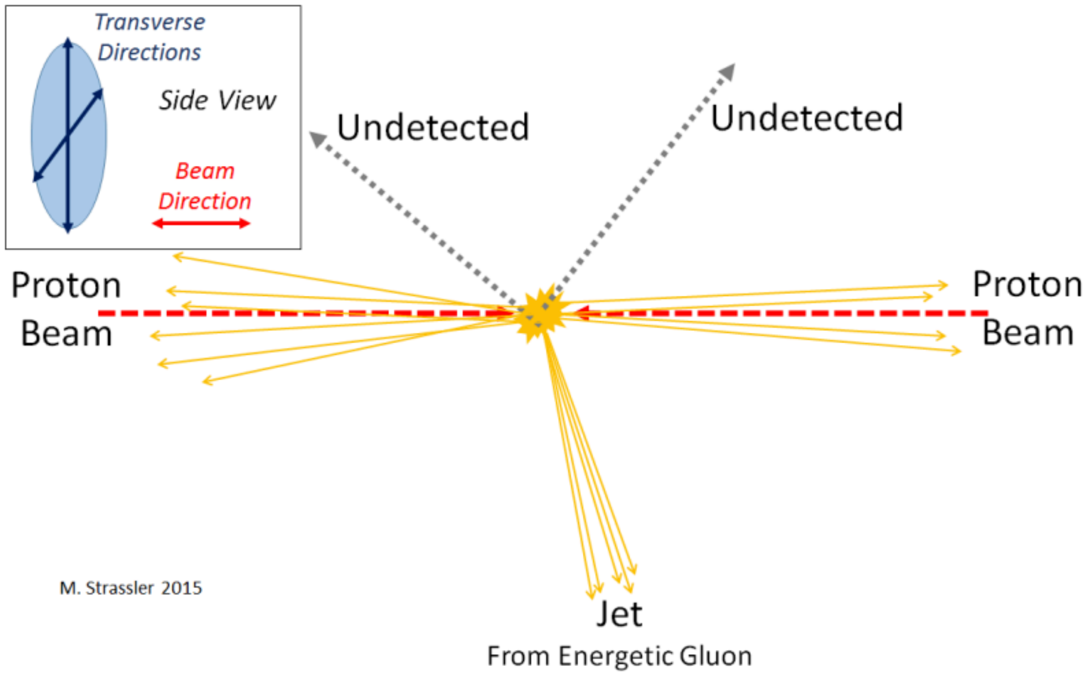
Probing one Yukawa coupling is not enough!

With the new EDM result



CERN's news page

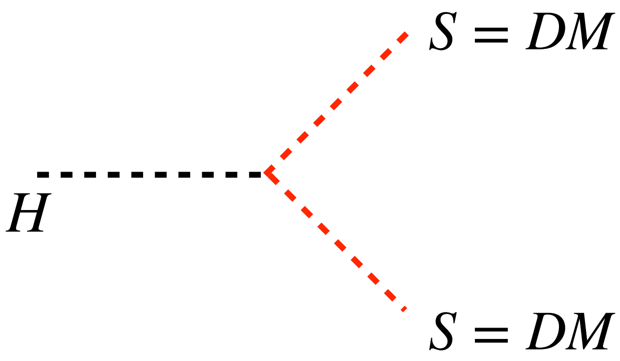




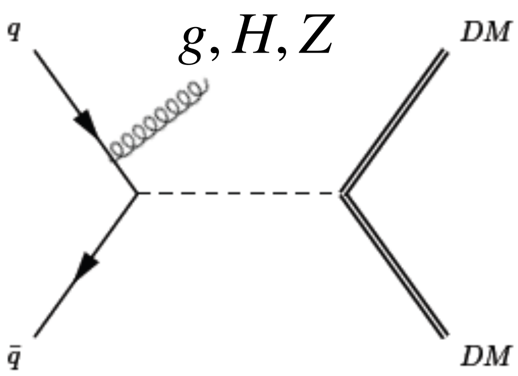
Mono-X (X = Z, jet, Higgs…) events

If one or more (high-energy) particles are also produced in the process then we have a mono-X (multi-X – still called mono-X) event! The X (for instance a jet) has a very large pT.

Conserved quantities – darkness



Model should conserve darkness - we need a stable particle. The invisible width of the Higgs sets a bound on the so-called portal coupling.



$q\bar{q} \rightarrow H\, DM\, DM$ Darkness (Z) conserved

$$Z(q\bar{q}) = Z(q)Z(\bar{q}) = 1 \times 1 = 1$$

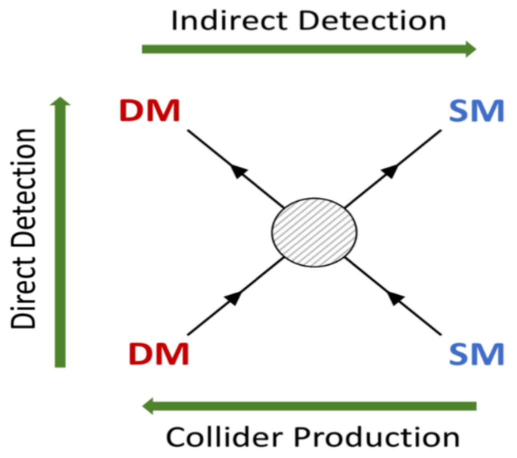
$$Z(q\bar{q}) = Z(H)Z(DM)Z(DM) = 1 \times (-1) \times (-1) = 1$$

All spins allowed

Combined with other experiments

HESS, HAWC, VERITAS, MAGIC, IceCube,...
PAMELA, FERMI, CALET, DAMPE, AMS, ...

XENON
CDEX
CDMS
CRESST
DARKSIDE
DEAP
LUX
PandaX
PICO
...

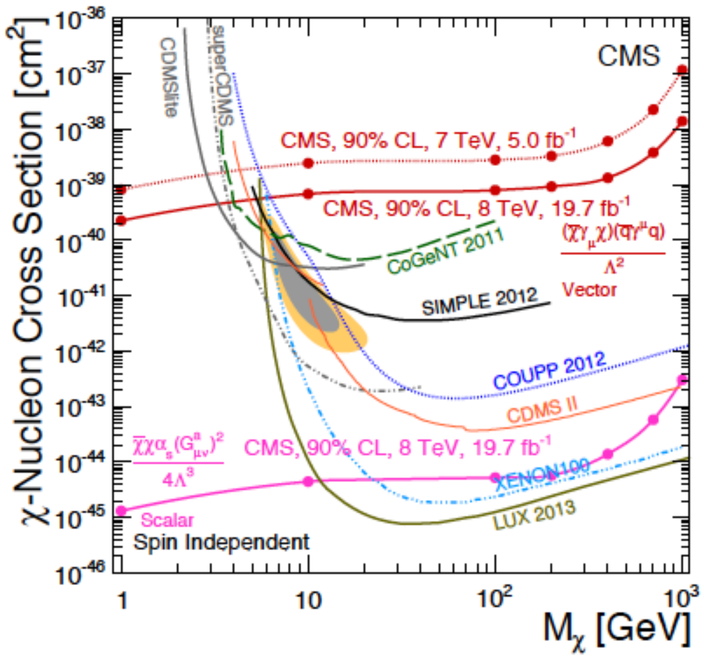


$(q, \bar{q}, g, W^{\mp}, Z, H, l^{\mp}, \ldots) \longrightarrow \gamma, e^+, e^-, p, \bar{p}, \upsilon, \bar{\upsilon}, \bar{D} \ldots$

$(q, \bar{q}, g, W^{\mp}, Z, H, l^{\mp}, \ldots) \longrightarrow \gamma, e^+, e^-, p, \bar{p}, \upsilon, \bar{\upsilon}, \bar{D} \ldots$

from Suzan Basegmez du Pree talk at ALPS2018

CMS and ATLAS



Direct detection vs. LHC.

scalar S : $\sigma_{S-N} = \lambda_{hSS}^2 \dfrac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$

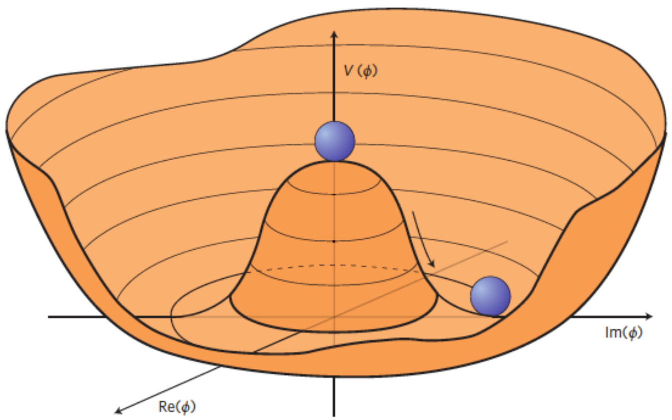
fermion f : $\sigma_{f-N} = \dfrac{\lambda_{hff}^2}{\Lambda^2} \dfrac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$

vector V : $\sigma_{V-N} = \lambda_{hVV}^2 \dfrac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}$

Profiling the Higgs potential - double Higgs final states

The SM potential

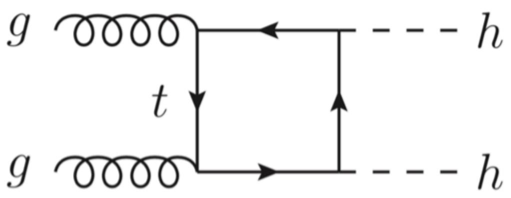
$$V_{SM} = m_{11}^2 |\Phi_1|^2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2$$

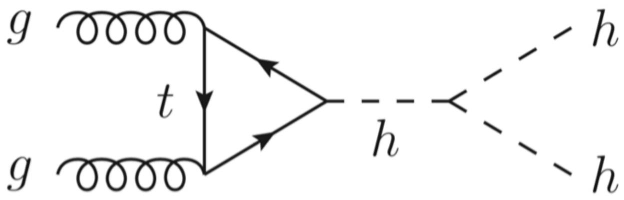


We know the mass and the VEV

$$\lambda_1 = \frac{m_h^2}{v^2} \approx 0.26 \qquad v = 246\,\text{GeV}$$

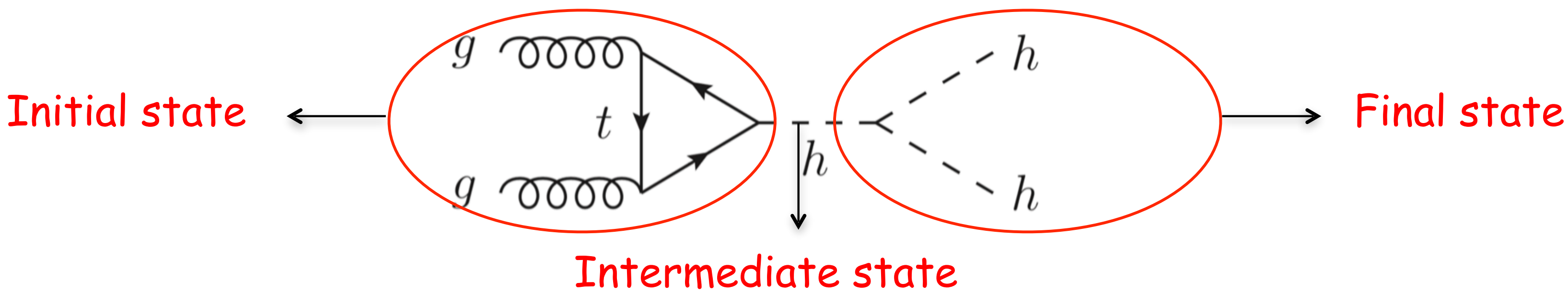
So is this the correct quartic coupling?



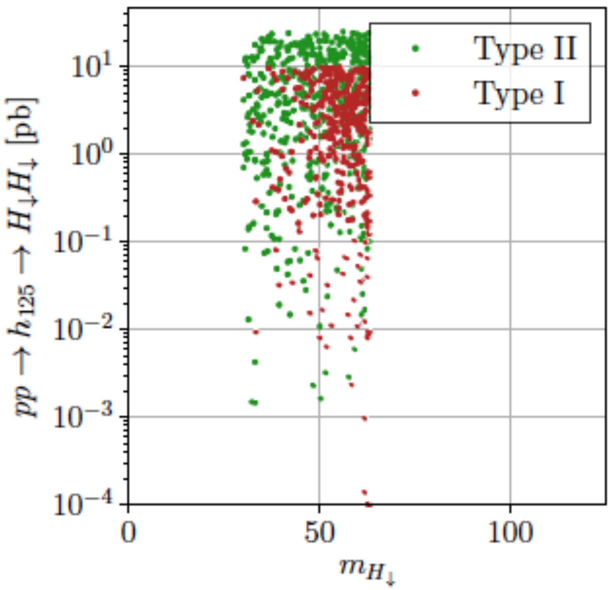


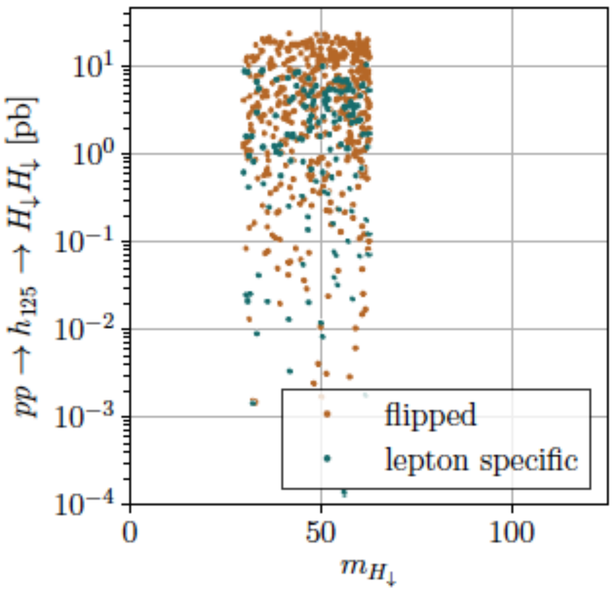
Negative interference in the SM

And BSM can be anywhere



Profiling the Higgs potential - double Higgs final states

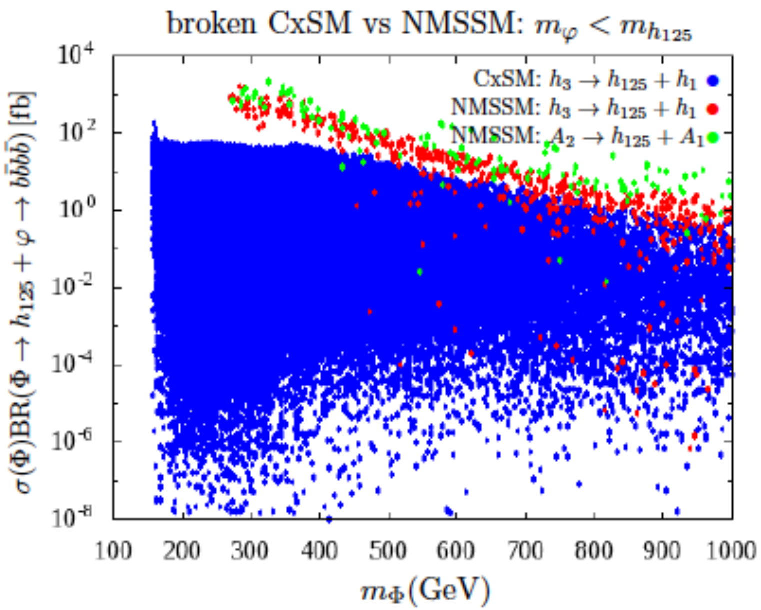




$$pp \to H \to h_{125} h_{125}$$

$$pp \to h_{125} \to hh$$

Many scalar extensions give rise to very large cross sections. The maximum value of the cross sections are different in different models



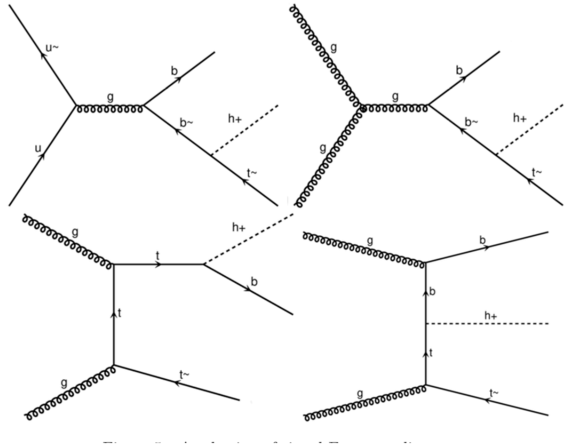
$$pp \to H \to h_{125} h$$

In some models the decays of a scalar to two scalars of different masses (one being the 125 GeV one) also show very large cross sections

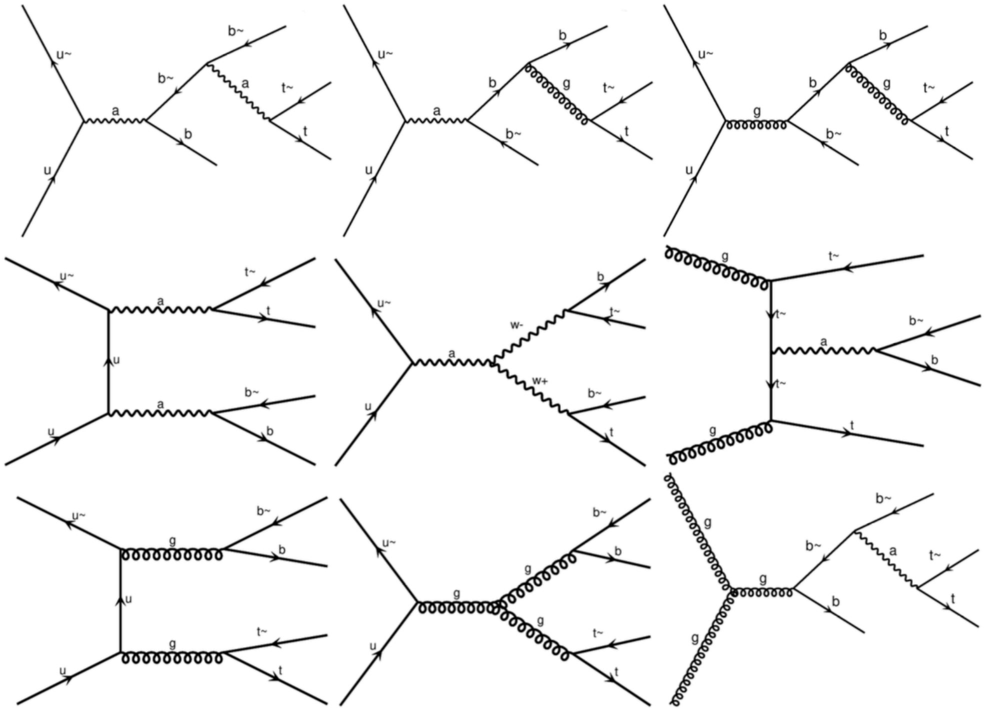
Interference between signal and background

Searches at colliders are performed by taking the signal and the background as separate numbers. This is true as long as the interference between them is negligible.

$$pp \to t\bar{b}H^+ + \text{c.c.}$$



Signal (just a few diagrams)



Background (even less diagrams)

Cut	S	B	T	I	ΔI
No cuts:	9720	3923550	3941700	8429	2487
$N_\ell = 1$:	2160	904247	907925	1518	1193
$N_J \geq 5$:	1938	624001	627534	1594	992
$N_{BJ} \geq 2$:	1511	404919	408054	1623	799
$\not{E} > 20$ GeV:	1435	373648	376517	1433	768
$\not{E} + m_T^W > 60$ GeV:	1412	364026	366898	1458	758
Cut	**S**	**B**	**T**	**I**	**ΔI**
$N_{BJ} \geq 3$:	826	171918	173430	684	521
$\not{E} > 20$ GeV:	785	158921	160376	669	501
$\not{E} + m_T^W > 60$ GeV:	772	154880	156314	660	494

Signal and interference of the same order

EFT

SM contains quarks and leptons interacting via strong, weak, and electromagnetic forces and

a) It is a relativistic QFT with a local Lagrangian.

b) Lagrangian is invariant under a local local SU(3) × SU(2) × U(1) symmetry.

c) The vacuum state of the theory breaks SU(2)×U(1) to U(1) (Higgs mechanism) and preserves a local SU(3) × U(1).

d) The theory is renormalisable (interactions up to dimension 4)

We know that there is new physics. However, except for a few discrepancies, it seems that up to a few hundred GeV the fundamental degrees of freedom are those of the SM. With no evidence from colliders it is fair to assume that new particles should be heavy and in that scenario physics at the weak scale can be described by an EFT approach.

$$\boxed{\mathcal{L}_{\mathrm{SM\,EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{v^2} O_i^{D=6}}$$

Parameters for Higgs physics. Using all available constraints a global fit can be performed

$$\textbf{CP-even}: \quad \delta c_z,\ c_{zz},\ c_{z\Box},\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{gg},\ \delta y_u,\ \delta y_d,\ \delta y_e,$$

$$\textbf{CP-odd}: \quad \tilde{c}_{zz},\ \tilde{c}_{\gamma\gamma},\ \tilde{c}_{z\gamma},\ \tilde{c}_{gg},\ \phi_u,\ \phi_d,\ \phi_\ell.$$

$$\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix} = \begin{pmatrix} -0.11 \pm 0.12 \\ 0.42 \pm 0.39 \\ -0.19 \pm 0.18 \\ -0.0020 \pm 0.0091 \\ -0.044 \pm 0.095 \\ -0.0041 \pm 0.0015 \\ 0.15 \pm 0.16 \\ -0.63 \pm 0.29 \\ -0.25 \pm 0.18 \\ -0.115 \pm 0.067 \end{pmatrix},$$

Are all coefficients compatible with the SM?

Increase precision in the SM (higher order calculations)

More data means that more kinematic regimes can be explored. Transverse momentum distributions can shed some light in the Higgs interactions.

"The observation of the Higgs boson in this kinematic regime is however extremely challenging. The inclusive search for the SM Higgs boson produced at large transverse momentum ($p_\perp$), and decaying to a bottom quark-antiquark pair, has been performed using data collected in pp collisions at $\sqrt{s} = 13$ TeV by the CMS and ATLAS experiments."

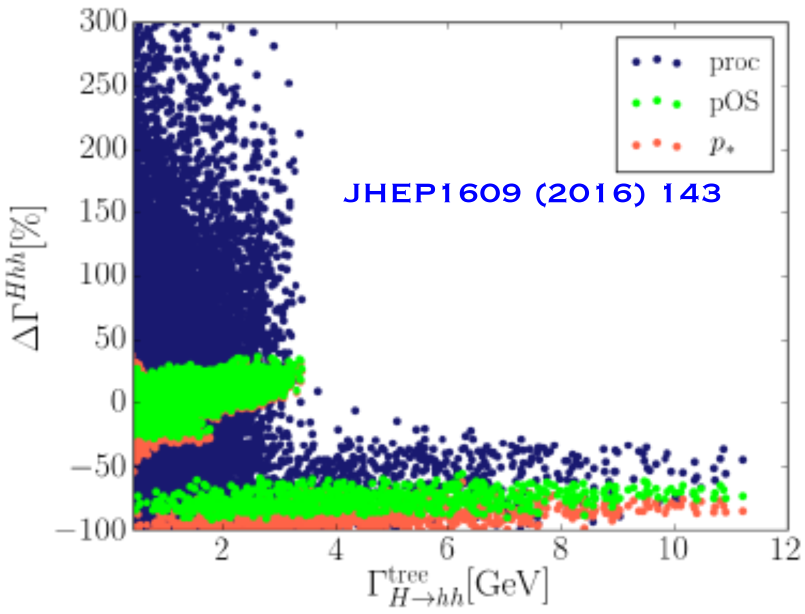
$p_\perp^{\rm cut}$	$\mathrm{NNLO}^{\rm approximate}_{\rm quad.unc.}$ [fb]	$\mathrm{NNLO}^{\rm approximate}_{\rm lin.unc.}$ [fb]
400 GeV	$33.3^{+10.9\%}_{-12.9\%}$	$33.3^{+15.1\%}_{-17.4\%}$
430 GeV	$23.0^{+10.8\%}_{-12.8\%}$	$23.0^{+14.9\%}_{-17.2\%}$
450 GeV	$18.1^{+10.8\%}_{-12.8\%}$	$18.1^{+14.9\%}_{-17.2\%}$

Table 2: Best prediction $\Sigma^{\text{EFT-improved (1), NNLO}}$ for the inclusive cross sections at different $p_\perp$ cuts of phenomenological interest, and using two different prescriptions for the uncertainty (see text for details).

"It is the objective of this document to study accurate theoretical predictions for the transverse momentum distribution with $p_\perp > 400$ GeV. We present new, state of the art predictions for the dominant gluon-fusion induced production of a Higgs boson and at least one hard partonic jet that recoils against it"

Precise predictions for boosted Higgs production, arXiv:2005.07762.

Increase precision in BSM (higher order calculations)

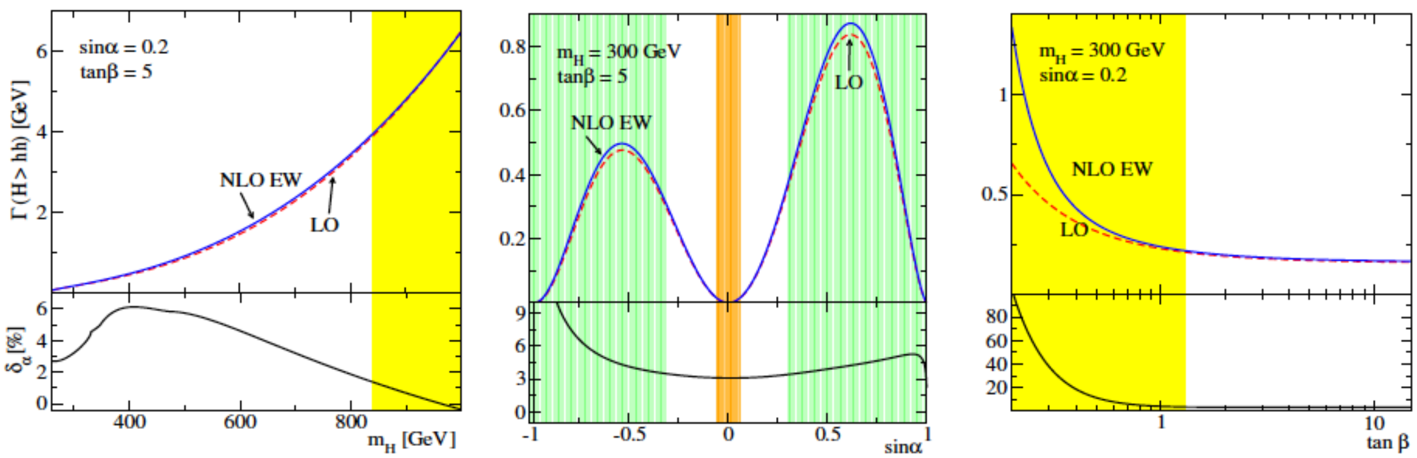


What are EW radiative corrections in BSM good for?

Several renormalization schemes are compared. Corrections are under control for reasonably large widths.

Small widths mean large relative corrections as expected.

Large parameter space leads to a large spectrum of corrections.



JHEP1602 (2016) 142

Sometimes and for some schemes NLO-EW Corrections shown to be only a few percent

BSM at CLIC (higher order calculations)

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

If the 125 GeV Higgs reveals its very SM nature at future colliders, in many extensions of the SM unitarity forces the other Higgs couplings to be very small

Unitarity $$\Rightarrow \kappa^2_{h_{125}ZZ} + \sum_i \kappa^2_{h_i ZZ} = 1$$

So, if no new physics is discovered and the couplings of the remainig Higgs boson will be known at the % level.

Now radiative corrections play a role.

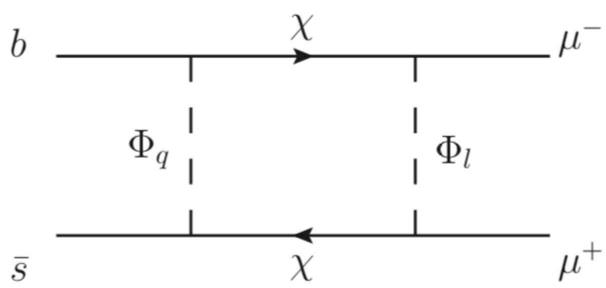
The right to party!

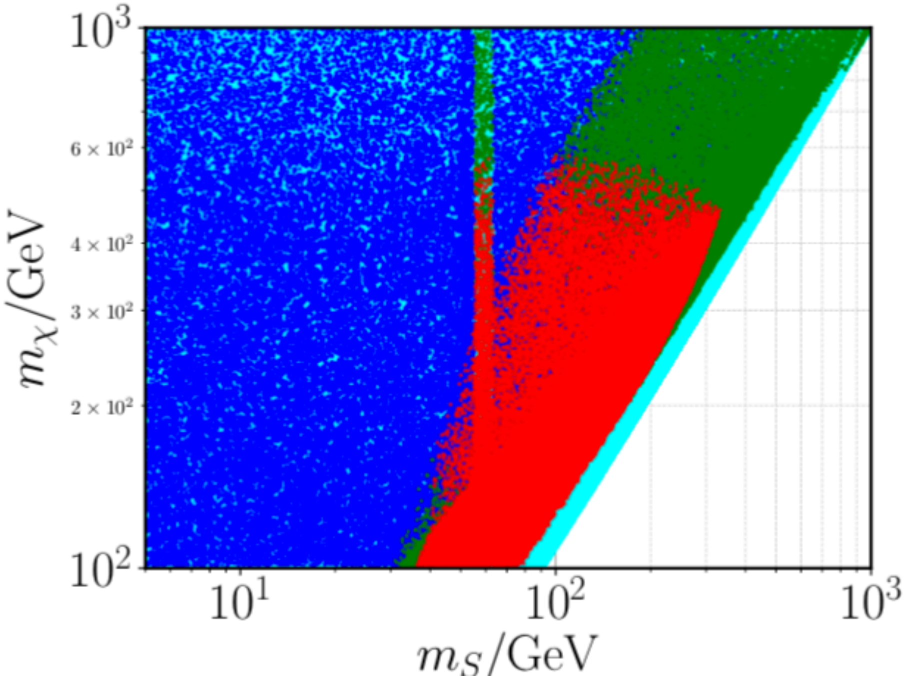
The good thing about being a theorist is that you can have fun building all kinds of models

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
χ_R	**1**	**2**	-1/2
Φ_l	**1**	**1**	0
Φ_q	**3**	**1**	2/3

$$\mathcal{L}_{\rm int}^{\rm NP} = y_{Q_i}\bar{Q}_{Li}\Phi_q\chi_R + y_{Li}\bar{L}_{Li}\Phi_l\chi_R + \text{h.c.}$$

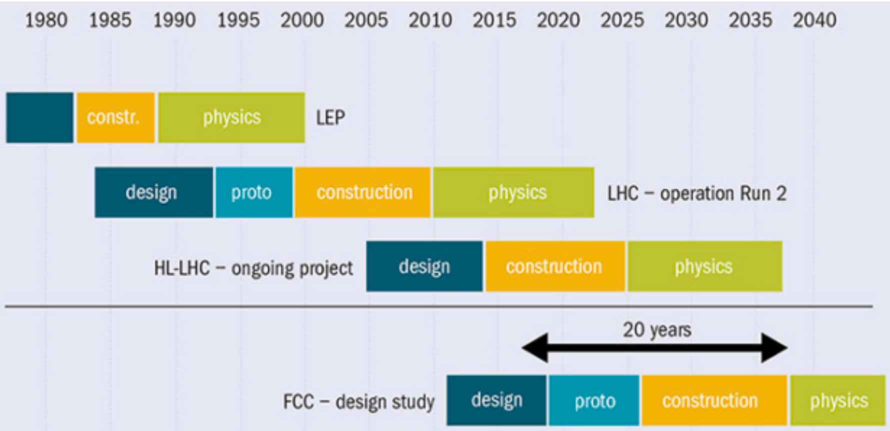
One fermion doublet and two scalar $SU(2)_L$ singlets - one neutral and one with 2/3 electric charge (and colour). The complex neutral singlet has a DM candidate. At the same time one can build new diagrams that help to solve the flavour discrepancies





All data taken into account. Regions that can be probed at the LHC and also in DM experiments.

Conclusions



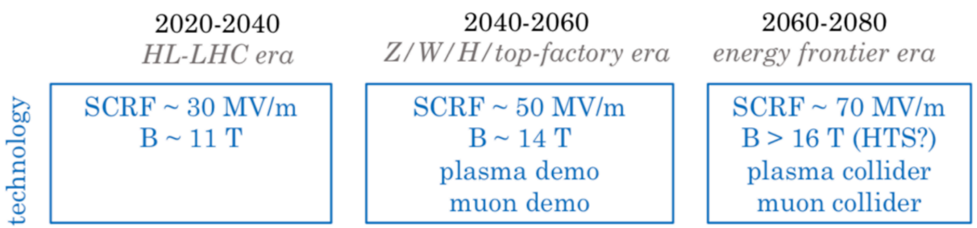
- The future of Higgs Physics is the LHC

- The future of Higgs Physics is what we can get from other experiments like ACME for the EDM constraints

- The future of Higgs Physics is in experiments that look directly or indirectly for DM (like Xenon1T) or even maybe gravitational waves

- The future of Higgs Physics is in neutrino experiments

- There is also a far future for Higgs Physics for which we have charts and timelines but we know very little about it



Post-Granada strawman scenarios:

CERN/ESG/05b
29 September 2019

	2020-2040	2040-2060 1st gen technology	2060-2080 2nd gen technology
CLIC-all	HL-LHC	**CLIC380-1500**	CLIC3000 / other tech
CLIC-FCC	HL-LHC	**CLIC380**	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC	**FCC-ee (90-365)**	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC	**LE-FCC-h/e/A (low-field magnets)**	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC **+ LHeC**	**LHeC**	FCC-h/e/A (Adv HF magnets) / other tech

The Higgs and the people trying to understand it in Portugal (those who have answered)

Exploring the composite connection

BSM pheno @LIP-Minho
N. Castro, G. Guedes, M. Ramos,
M. Romão, A. Peixoto, T. Vale
Collaborations with Univ. Granada

- *Vector resonances* are plausible explanations for the flavour anomalies
- *Fermionic partners* decay sizably to the exotic states (e.g. to the dark matter) **2005.09655**
  - Connection with the **ATLAS/PT** group (e.g. VLQ searches) ***1808.02343***

$\sim \mathrm{TeV}$ $\quad V_\mu, B, T, L$

$\sim v$ $\quad H, S, \eta^2$

- *Light scalars* can be produced in rare hadron decays at the LHCb ***1907.13151***
- New annihilation channels for *dark matter* ***1912.11061***
- *Pseudoscalars* are promising candidates for baryogenesis ***1812.01901***
- Rare decays of the top quark produce such *CP-odd states* ***2005.09594***
- Axion-like particle interactions are triggered by effective operators which run/mix following their RGEs.

We perform **dedicated analyses to explore these signatures** using *astrophysical* and *collider* probes → present and future

LIP

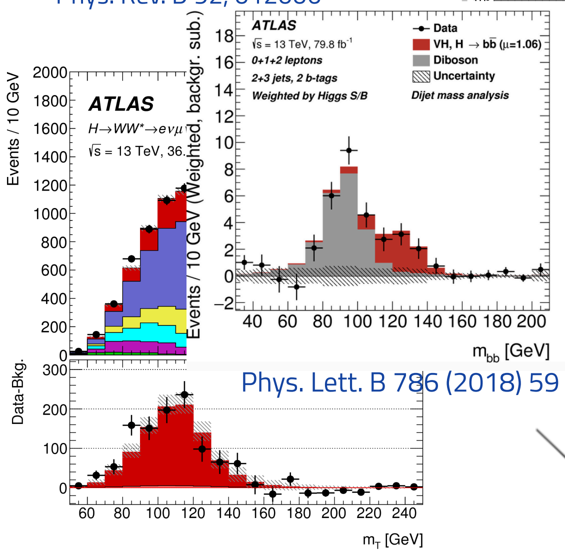
Universidade do Minho
Escola de Ciências

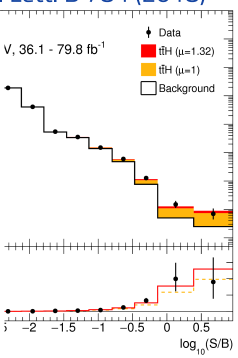
Spin/CP properties of Higgs interaction vertices

ATLAS-PT Higgs group: R. Barrué, A. Carvalho, L. Coelho, P. Conde, M. Fiolhais, A. Onofre, R. Pedro, R. Gonçalo, E. Gouveia, … in collaboration with D. Azevedo, R. Santos, V. Dao, Manchester U., …

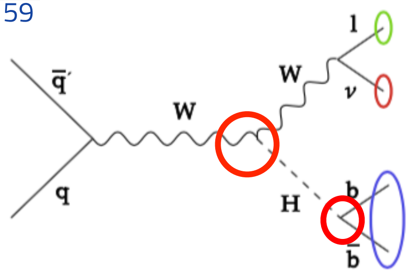
Phys. Rev. D 92, 012006

Phys. Lett. B 784 (2018)

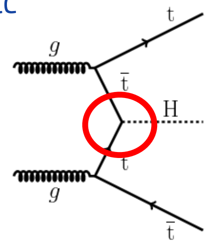




Phys. Lett. B 786 (2018) 59



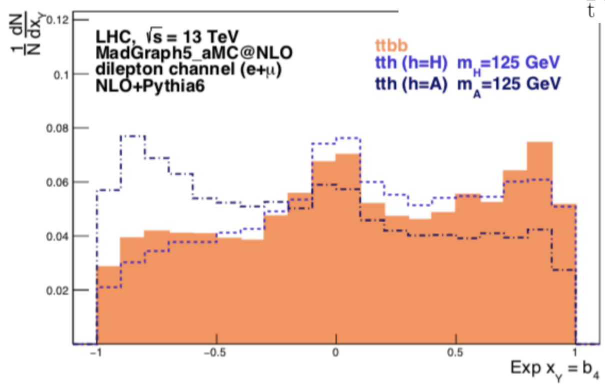
- Direct measurements of the Higgs couplings to b-quarks, top quarks, W bosons
  - Spin/CP properties of interaction vertices using angular observables
  - Probe SM predictions and search for new physics
  - Reconstruction techniques, background modelling, machine learning, statistical analysis, etc

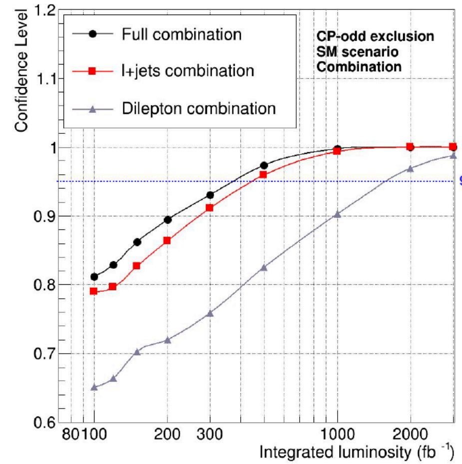


Phys. Rev. D 100, 075034 (2019),

Phys. Rev. D 96, 013004 (2017),

Phys. Rev. D 98, 033004 (2018)





- 2012 Higgs discovery
- 2015: H→WW→$\ell\nu\ell\nu$ observation
- 2018: ttH observation
- 2018: H→bb observation, WH/ZH production observation
- 2020: boosted H→bb

Higgs Physics at Aveiro

António Morais (Researcher Level 1), Felipe Freitas (Postdoc), João Gonçalves (PhD student), Vasileios Vatellis (Research fellow), João Pedro Rodrigues (Master student), Eduardo Santiago (Master student)
http://gravitation.web.ua.pt/

Research topics:

1) Higgs sector from first principles: Study how can the Higgs sector emerge as a remnant of Grand Unified Theories

2) Multi-scalar and multi-fermion extensions of the SM (singlet, 2 and 3 Higgs doublet models, vector-like fermions): Build models with new scalars and vector-like fermions and study their collider signatures, the impact on flavour observables as well as cosmological implications such as dark matter and the production of primordial gravitational waves induced via electroweak-scale first order phase transitions.

3) Collider phenomenology: Study the statistical significance of new physics candidates such as scalars and vector-like fermions to be searched at the LHC run-III and HL-LHC.

4) Machine learning: Use state of the art deep-learning techniques mainly to address points 2) and 3).

universidade de aveiro

What we do:

Higgs searches, Precision physics, Extensions of the SM, Vacuum stability, Dark matter, CP-violation, Interference

People: Pedro Ferreira, Rui Santos

PhD students: Duarte Azevedo, Rodrigo Capucha (with António Onofre)
Ricardo Barrué (IST/LIP with Patricia Conde Muino)

MSc students: Pedro Gabriel, João Viana,
Daniel Neacsu (IST with Patricia Conde Muino) Tomás Lopes (IST with João P. Silva)

The Higgs boson and beyond @LIP

M. Araújo, P. Bargassa, D. Bastos, R. Bugalho, P. Faccioli, L. Ferramacho, M. Gallinaro, J. Hollar, N. Leonardo, B. Lopes, T. Niknejad, M. Pisano, K. Shchelina, J. Seixas, J. Silva, P. Silva, R. Silva, M. Silveira, G. Strong, O. Toldaiev, J. Varela

The Higgs boson was discovered in 2012 and it is still a largely unknown particle. A detailed study of its properties may provide hints to the EWSB mechanism and possibly to New Physics.

Our studies in this area cover:

- Higgs discovery & couplings: diphoton final state

  PLB 716(2012)30, JHEP 08(2016)045

- Charged Higgs: if present, it would be inequivocal presence of BSM physics

  JHEP 07(2012)143, JHEP 11(2015)018

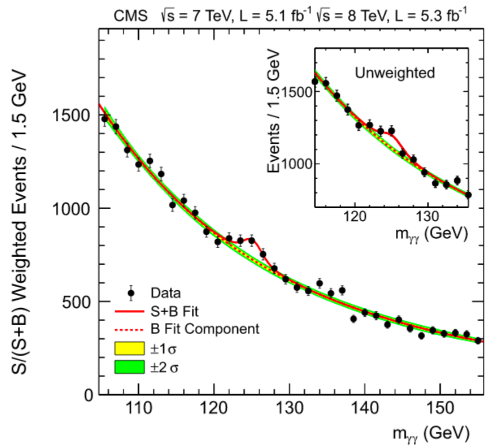
- Higgs Pairs: allows measurement of self-coupling parameters (k_λ) with Machine Learning tools

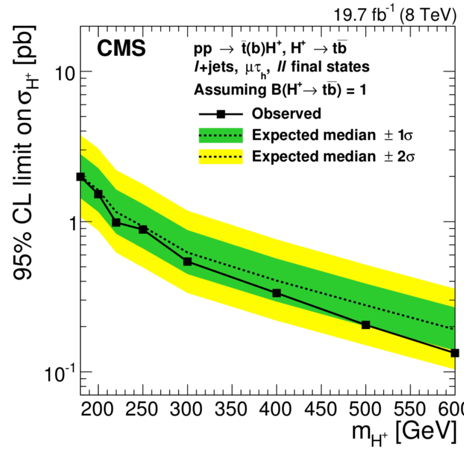
  PLB 778(2018)101, arXiv:1902.00134, CMS-TDR-020

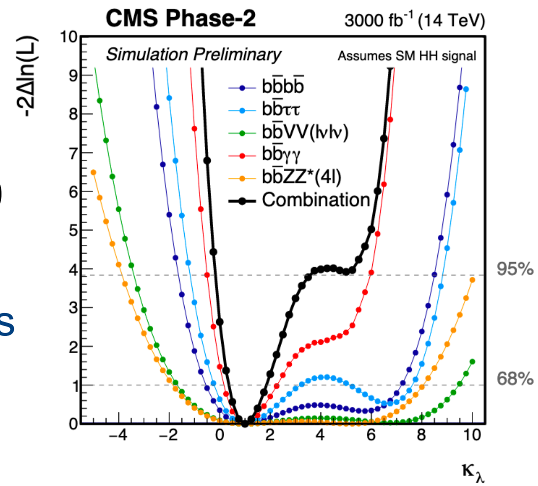
- Higgs+Dark Matter: limited by statistics, high MET evts

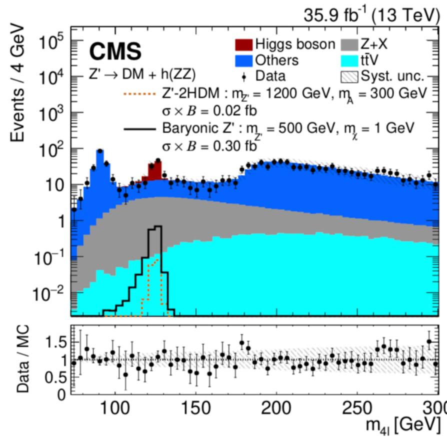
  JHEP 03(2020)025

- Higgs rare decays: couplings to light generations









Jorge Romão & João P. Silva: *Probing Multi-Higgs signals*

Motivation: Given one scalar, their number and properties **must** be determined experimentally

Open Questions pursued by the group:

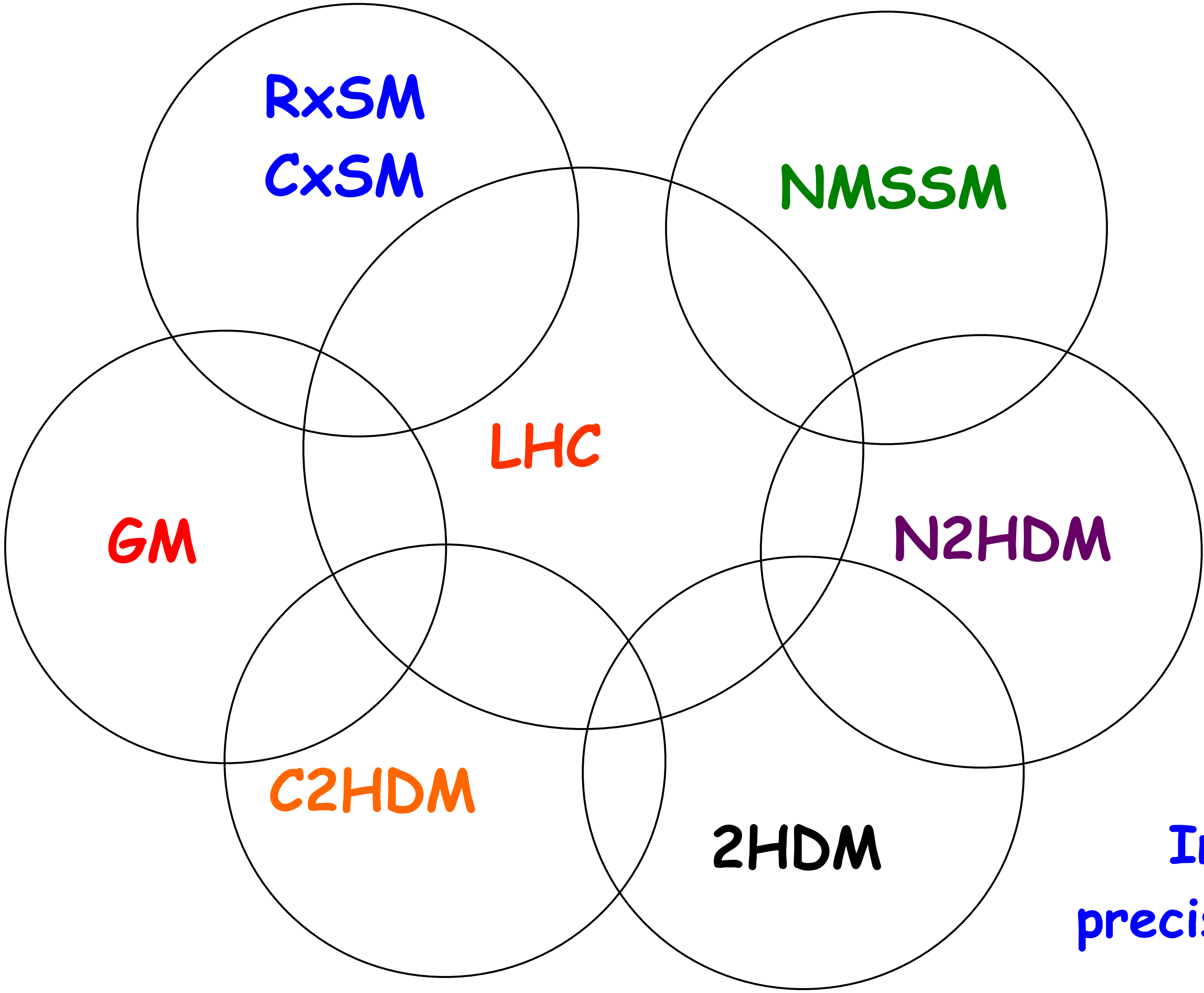
- **Precision predictions/determinations for MultiHiggs@LHC**
- **Higgs and Flavour,** including origin of masses/mixing, quarks and neutrinos
- **Vacuum structure**, including “panic vacua”
- **Higgs and CP Violation in the Lab,** LHC, SuperKEKB, edm...
- **Higgs, CP Violation and Universe,** baryogenesis, leptogenesis, higgsgenesis
- **Higgs and Dark Matter**

Students Must publish

...

The End

BSM-EHS - What are they good for?



Motivate searches

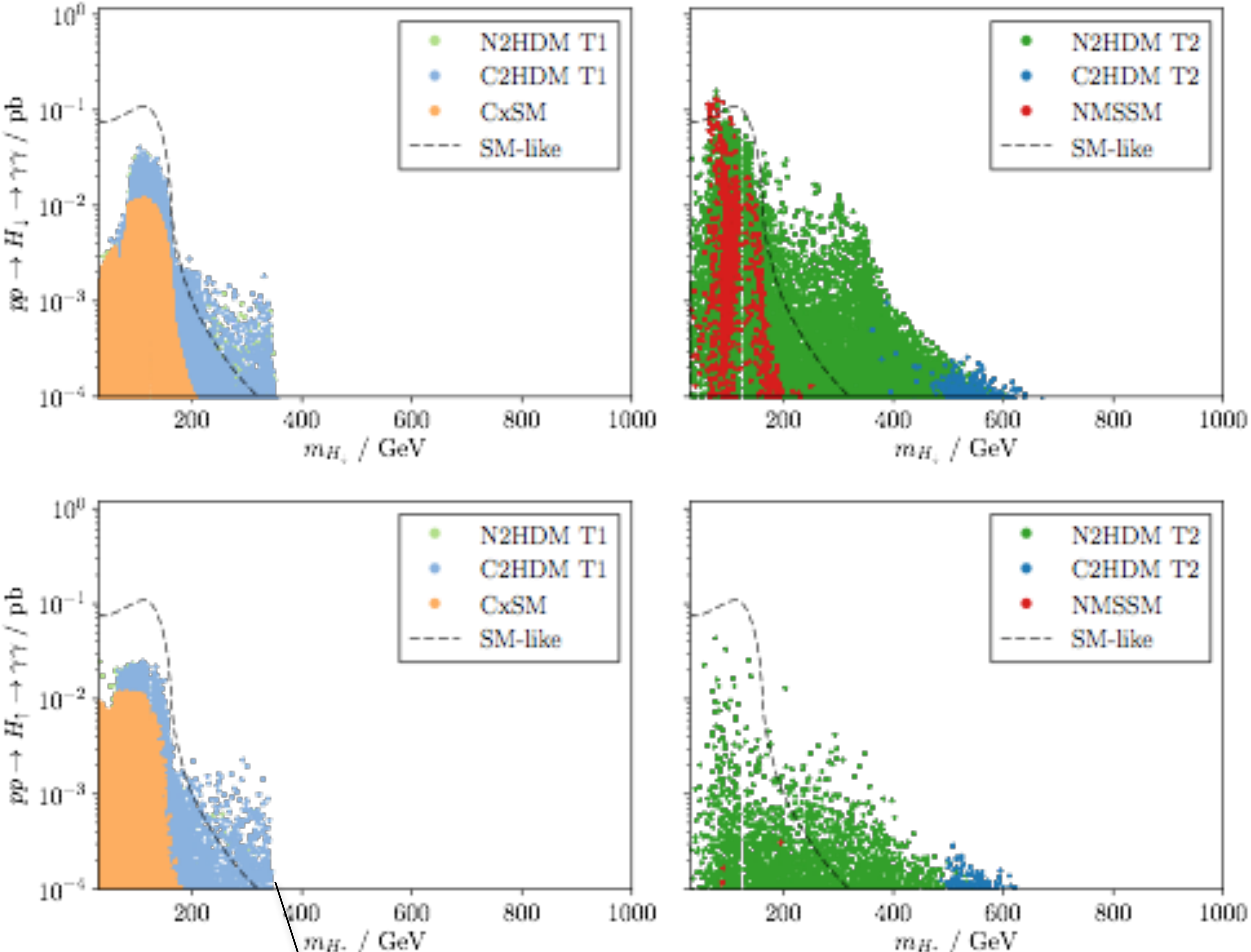
New scalar?

Discovered Higgs very SM-like

Information from precision measurements?

The future of particle physics: a quest for guiding principles
(workshop in KIT 2 years ago)

Non-125 to γγ



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".

MUHLLEITNER, SAMPAIO, RS, WITTBRODT, JHEP 1708 (2017) 132

h to tt threshold

Rates can be quite large in the N2HDM and C2HDM. Again more freedom in the couplings.

h_{125} couplings measurements

For many extensions coupling modifiers are similar

Lightest Higgs coupling modifiers (to gauge bosons)

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

CP-VIOLATING 2HDM

$$\boxed{g_{C2HDM}^{hVV} = \cos\alpha_2 \, g_{2HDM}^{hVV}}$$

"PSEUDOSCALAR" COMPONENT (DOUBLET)

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

$$\boxed{g_{N2HDM}^{hVV} = \cos\alpha_2 \, g_{2HDM}^{hVV}}$$

SINGLET COMPONENT

$$(a+ib)$$

SM + REAL SINGLET

$$\boxed{g_{RxSM}^{hVV} = \cos\alpha_1 \, g_{SM}^{hVV}}$$

SM + COMPLEX SINGLET

$$\boxed{g_{CxSM}^{hVV} = \cos\alpha_1 \cos\alpha_2 \, g_{SM}^{hVV}}$$

REAL COMPONENT

IMAGINARY COMPONENT