Higgs II - Fingerprinting "the" Higgs

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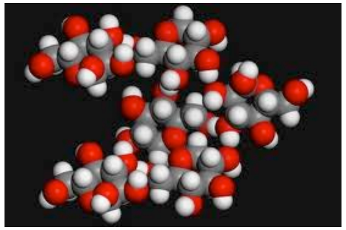
The LHC of the biologist

Penguin ancestor

Penguin

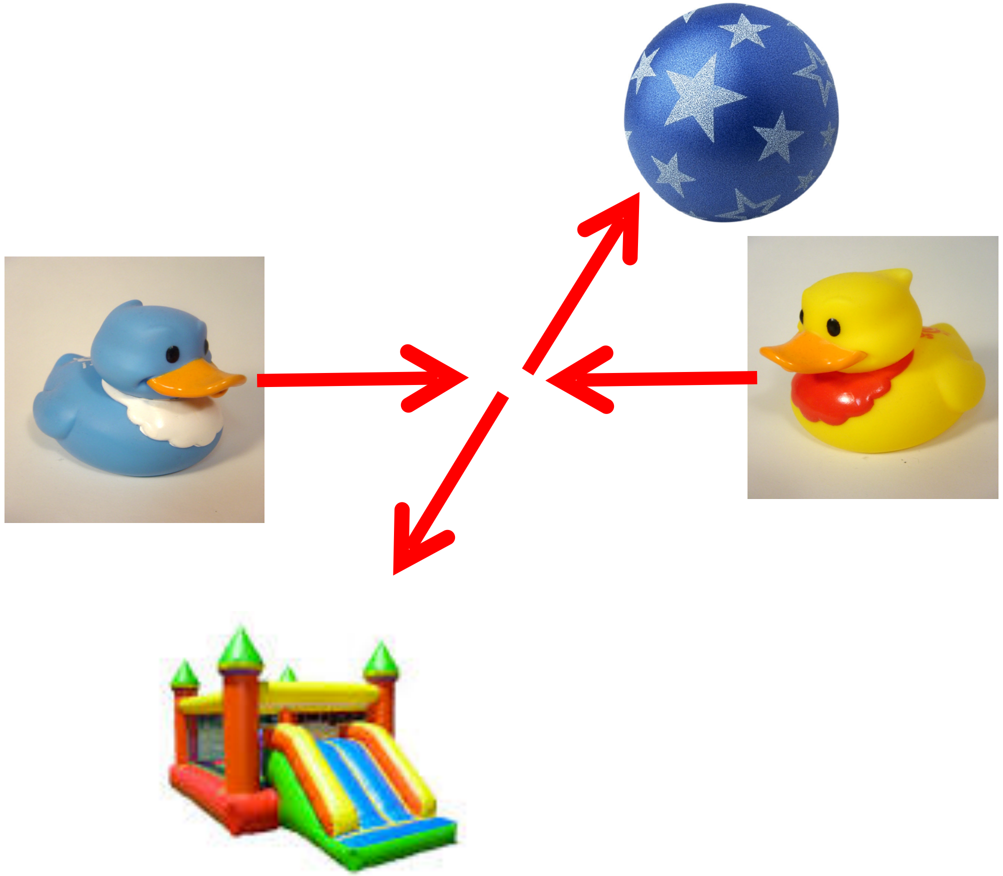


Dinosaur

Extinction

THE GOAL IS TO LOOK AT THE PAST FOR A VERY BRIEF MOMENT.

Collisions - a strange world



Symmetries in nature

↓

Guide to build theories

In collision some things disappear other things appear – what matters are conserved quantities - inflatability

Symmetries

Emmy Noether

Symmetries imply conservation laws!

Gauge symmetry	⬌	Conserved quantities
⬍		⬍
Rules for interactions	⬌	Electric Charge

Charge Breaking (CB) in the SM

What you see in books

$$< \Phi_{SM} > = \binom{0}{v} \qquad Q_{SM} < \Phi_{SM} > = I_3 + \frac{Y}{2} < \Phi_{SM} > = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \binom{0}{v} = 0$$

What you don't see in books

Now use the kinetic scalar term to find the mass matrix of the gauge boson.

$$< \Phi_{SM} > = \begin{pmatrix} v_1 + i v_2 \\ v_3 + i v_4 \end{pmatrix} \qquad (D_\mu \Phi)^\dagger (D^\mu \Phi)$$

and you find the mass spectrum (for the gauge bosons)

$$m_1^2 = m_2^2 = \frac{g^2 v^2}{4} \qquad v^2 = v_1^2 + v_2^2 + v_3^2 + v_4^2$$

$$m_3^2 = \; = \frac{v^2}{4}(g^2 + g'^2 Y^2)$$

$$\boxed{m_4^2 = 0}$$

It's the photon!

So U(1) survives and charge is always conserved. Was this expected?

CB (and CP) in the SM

You can use the SU(2) freedom to perform the rotation

$$< \Phi_{SM} > = \begin{pmatrix} v_1 + i v_2 \\ v_3 + i v_4 \end{pmatrix} \quad \rightarrow \quad < \Phi_{SM} > = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

C - Charge Conjugation

P - Parity

CP - C+P

Using a more general vacuum would just mean to redefine the charge operator.

For the same reason, any phase in the vacuum can be rotated away. This means that no spontaneous CP can occur. And the potential is also explicitly CP conserving.

Explicit breaking - if the Lagrangian is not invariant under a given symmetry

Spontaneous breaking - if the Lagrangian is invariant under a given symmetry but the vacuum is not

The SM has no CB and no CP violation in the potential.

CB in the 2HDM

Let us move to the 2HDM. Now we have 2 doublets and 8 possible VEVs

$$< \Phi_k > = \begin{pmatrix} v_1^k + i v_2^k \\ v_3^k + i v_4^k \end{pmatrix}$$

We can use the SU(2) × U(1) freedom to write the most general form for the vacuum

$$< \Phi_1 > = \begin{pmatrix} v_a \\ v_b \end{pmatrix} \qquad < \Phi_2 > = \begin{pmatrix} 0 \\ v_c e^{i\theta} \end{pmatrix}$$

and you find the mass spectrum (for the gauge bosons)

$$m_1^2 = m_2^2 = \frac{g^2 v^2}{4} \qquad\qquad v^2 = v_a^2 + v_b^2 + v_c^2$$

$$m_3^2 = = \frac{1}{8}\left[v^2(g^2 + g'^2 Y^2) + \sqrt{v^4(g^2 + g'^2 Y^2)^2 - 16 g^2 g'^2 v_a^2 v_c^2 Y^2}\right]$$

$$\boxed{m_4^2 = \frac{1}{8}\left[v^2(g^2 + g'^2 Y^2) - \sqrt{v^4(g^2 + g'^2 Y^2)^2 - 16 g^2 g'^2 v_a^2 v_c^2 Y^2}\right]}$$

Is it the photon?

CB in the 2HDM

Let us have a closer look at the photon mass

$$m_4^2 = \frac{1}{8}\left[v^2(g^2 + g'^2 Y^2) - \sqrt{v^4(g^2 + g'^2 Y^2)^2 - 16 g^2 g'^2 v_a^2 v_c^2 Y^2}\right]$$

There are two ways to recover a zero mass for the photon

$$v_c = 0 \quad \Rightarrow \quad <\Phi_1> = \begin{pmatrix} v_a \\ v_b \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \Rightarrow \qquad \text{SM}$$

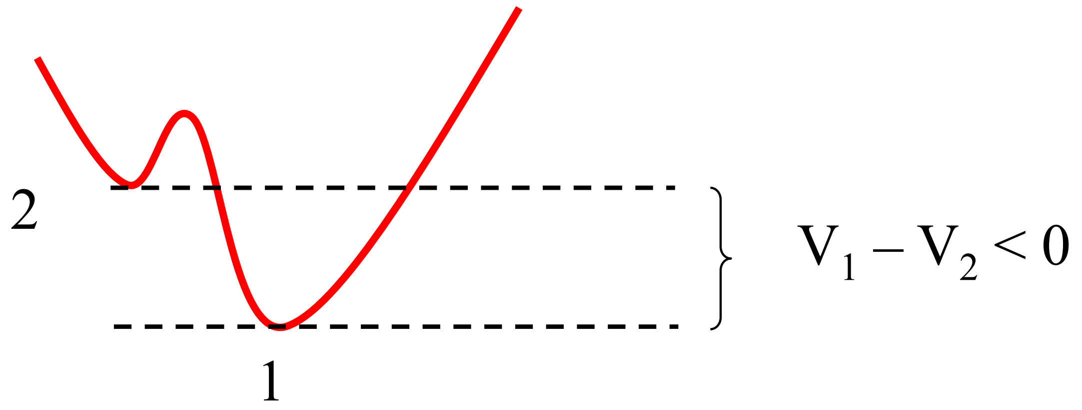
$$v_a = 0 \quad \Rightarrow \quad <\Phi_1> = \begin{pmatrix} 0 \\ v_b \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ v_c e^{i\theta} \end{pmatrix} \qquad \Rightarrow \qquad \text{Vacua are aligned}$$

OR ELSE CHARGE IS BROKEN - POSSIBLE IN THE 2HDM

SUPPOSE WE LIVE IN A 2HDM, ARE WE IN DANGER?

So what to do not next - the recipe

1. Start by writing the potential, which for the 2HDM is just a function $V(\Phi_1, \Phi_2)$
2. Find the stationary points (SP) of V
3. Classify the SP (minima, saddle points, maxima) – meaning: look at the values of the squared masses
4. You will find three types of SP – the CP-conserving (aka normal), the charge breaking and the CP breaking SP
5. You just have to write the potential at each of the SP and call it V_N, V_{CB} and V_{CP}, respectively
6. Compare the depths of the different V at each SP



The 2HDM potential

The most general potential for the 2HDM invariant under

$$\Phi_1 \to \Phi_1; \quad \Phi_2 \to -\Phi_2$$

softly broken by the m^2_{12} term is

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

explicitly CP-conserving because m^2_{12} and λ_5 are real.

The most general vacuum structure is

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \; ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_{cb} \\ v_2 + i v_{cp} \end{pmatrix}$$

- CP conserving (N) $\quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \; ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
- Charge breaking (CB) $\quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' \end{pmatrix} \; ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \alpha \\ v_2' \end{pmatrix}$
- CP breaking (CP) $\quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1' + i\delta \end{pmatrix} \; ; \quad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2' \end{pmatrix}$

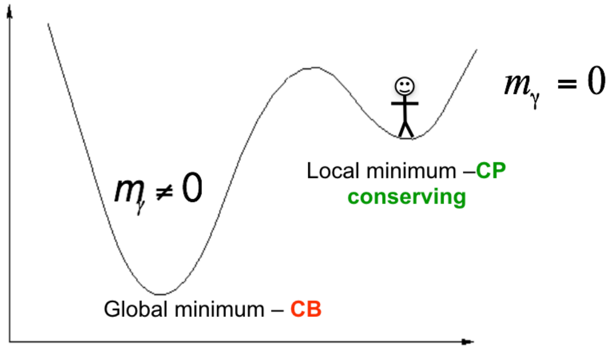
After some time you find (I will come back to the how later)

$$V_{CB} - V_{\mathcal{N}} = \frac{m_{H^\pm}^2}{2v^2}\left[(v_2 v_1' - v_1 v_2')^2 + v_1^2\alpha^2\right]$$

Difference of the values of the potential at the CB SP and at the N SP

If N is a minimum (note that the charged Higgs mass is calculated at the N SP)

$$V_{CB} - V_{\mathcal{N}} = \frac{m_{H^\pm}^2}{2v^2}\left[(v_2 v_1' - v_1 v_2')^2 + v_1^2\alpha^2\right] > 0$$



We get

$$V_{\mathcal{N}} < V_{CB}$$

It can also be shown that not only the N minimum is below the CB SP, but the CB SP is a saddle point.

A similar result holds for the simultaneous existence of a N and a CP breaking minima.

$$V_{CB} - V_{\mathcal{N}} = \frac{m_A^2}{2v^2}\left[(v_2 v_1' - v_1 v_2')^2 + v_1^2\delta^2\right]$$

Vacua in the 2HDM (at tree-level) - all spontaneous

1. 2HDM have at most two minima

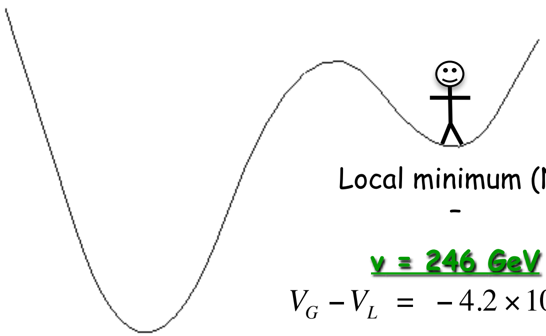
2. Minima of different nature never coexist

3. Unlike Normal, CB and CP minima are uniquely determined

4. If a 2HDM has only one normal minimum, it is the absolute minimum - all other SP if they exist are saddle points

5. If a 2HDM has a CP-breaking minimum, it is the absolute minimum - all other SP if they exist are saddle points

But there is still the possibility of having two CP-conserving minima!



Local minimum (N) - $m_W = 80.4$ GeV

v = 246 GeV

$V_G - V_L = -4.2 \times 10^8$ GeV

Global minimum (N) - $m_W = 107.5$ GeV

v = 329 GeV

THE PANIC VACUUM!

and this is one that can actually occur...

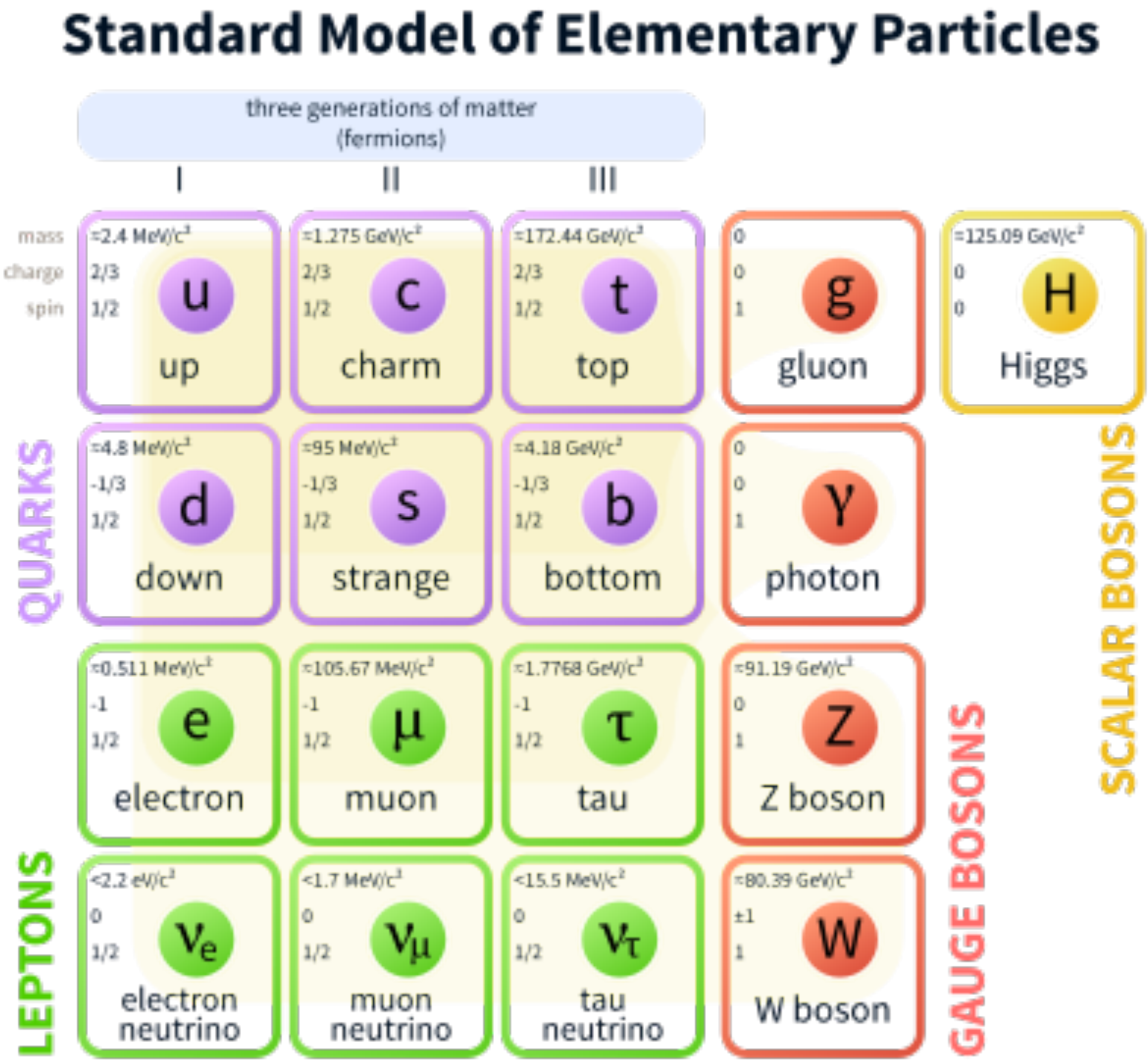
Our vacuum is the global minimum of the potential if and only if D > 0.

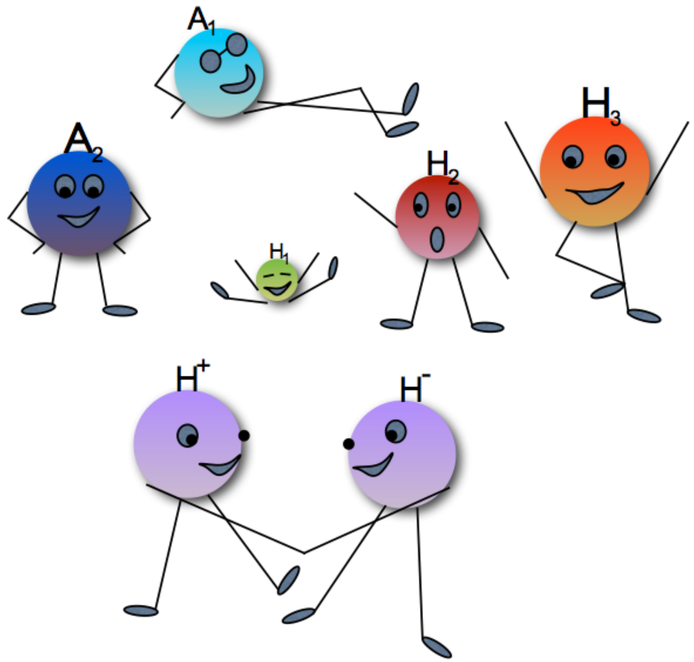
$$D = m_{12}^2 \left(m_{11}^2 - k^2 m_{22}^2\right)\left(\tan\beta - k\right) \qquad k = \left(\frac{\lambda_1}{\lambda_2}\right)^{1/4}$$

However, two CP-conserving minima can coexist – we can force the potential to be in the global one by using a simple condition.

From the Model to the detection at colliders

1. Take all the known elementary particles (fields); plus the ones you like





Picture: courtesy of M.M. Mühlleitner

From the Model to the detection at colliders

2. Put them together according to rules (symmetries);

$$\mathscr{L} = a\,b\,c \;\Longleftarrow\; \begin{cases} Q(a) = -1 \\ Q(b) = 1 \\ Q(c) = 0 \end{cases}$$

3. Know your spaces;

$$\Psi_{i,j,k} \;\Longleftarrow\; \begin{cases} i \Rightarrow isospin \Rightarrow (2 \times 2) \\ j \Rightarrow flavour \Rightarrow (3 \times 3) \\ k \ldots \end{cases}$$

<u>One space at a time</u>

$$\begin{bmatrix} a & b \end{bmatrix} \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} c \\ d \end{bmatrix} \qquad a = \begin{bmatrix} a_1 & a_2 & a_3 \end{bmatrix}$$

From the Model to the detection at colliders

4. Know your dimensions;

$\hbar = c = 1$ - In Natural units all quantities are measured in units of mass to some power.

$$[p_\mu] = [\partial_\mu] = m \qquad [x_\mu] = m^{-1}$$

The action is now dimensionless

$$S = \int \mathscr{L}\, d^4x \;\Rightarrow\; [\mathscr{L}] = m^4$$

The canonical dimension of the field is obtained from the free Lagrangian

$$\mathscr{L}^{KG}_{free} = \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - m^2\phi^2\right) \;\Rightarrow\; [\phi] = m$$

$$\mathscr{L}^{EM}_{free} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \;\Rightarrow\; [F_{\mu\nu}] = m^2 \;\Rightarrow\; [A_\mu] = [F/\partial] = m$$

$$\mathscr{L}^{Dirac}_{free} = \overline{\psi}(i\gamma^\mu\partial_\mu - m)\psi \;\Rightarrow\; [\psi] = m^{3/2}$$

$$\begin{aligned}
1\,\mathrm{GeV}^{-2} &= 0.389\,\mathrm{mb} \\
1\,\mathrm{GeV}^{-1} &= 6.582\cdot 10^{-25}\,\mathrm{s} \\
1\,\mathrm{kg} &= 5.61\cdot 10^{26}\,\mathrm{GeV} \\
1\,\mathrm{m} &= 5.07\cdot 10^{15}\,\mathrm{GeV}^{-1} \\
1\,\mathrm{s} &= 1.52\cdot 10^{24}\,\mathrm{GeV}^{-1}
\end{aligned}$$

5. Know your couplings; regarding interactions there are mainly three types (in dimensions)

- $\lambda_3 \phi^3 \;\Rightarrow\; [\lambda_3] = m$
- $\lambda_4 \phi^4 \;\Rightarrow\; [\lambda_4] = m^0 = 1$
- $\lambda_5 \phi^5 \;\Rightarrow\; [\lambda_5] = m^{-1}$

When is a coupling large? The theory is perturbative if:

If the coupling has mass dimensions, the mass has to be well below the energy scale probed.

If the coupling is dimensionless, the coupling has to be below 1 or below 4π*.

If the coupling has inverse mass dimensions, the mass has to be well above the energy scale probed.

* ask me if you want to know more.

6. Put things together in a (SM) Lagrangian;

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

7. Add your favourite extension;

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

More about this later

From the Model to the detection at colliders

8. Write Feynman rules;

Propagator

$$\mathscr{L}^{KG}_{free} = \frac{1}{2}\left(\partial_\mu \phi \partial^\mu \phi - m^2 \phi^2\right) \Rightarrow \frac{i}{p^2 - m^2}$$

Interactions

$$\mathscr{L}_{int} = \frac{\lambda}{4!}\phi^4 \Rightarrow i\lambda$$

(Real) Scalar theory with self-interactions

$$\mathscr{L}_{int} = \frac{\lambda}{4}(\phi^\dagger \phi)^2 \Rightarrow i\lambda$$

(Complex) Scalar theory with self-interactions

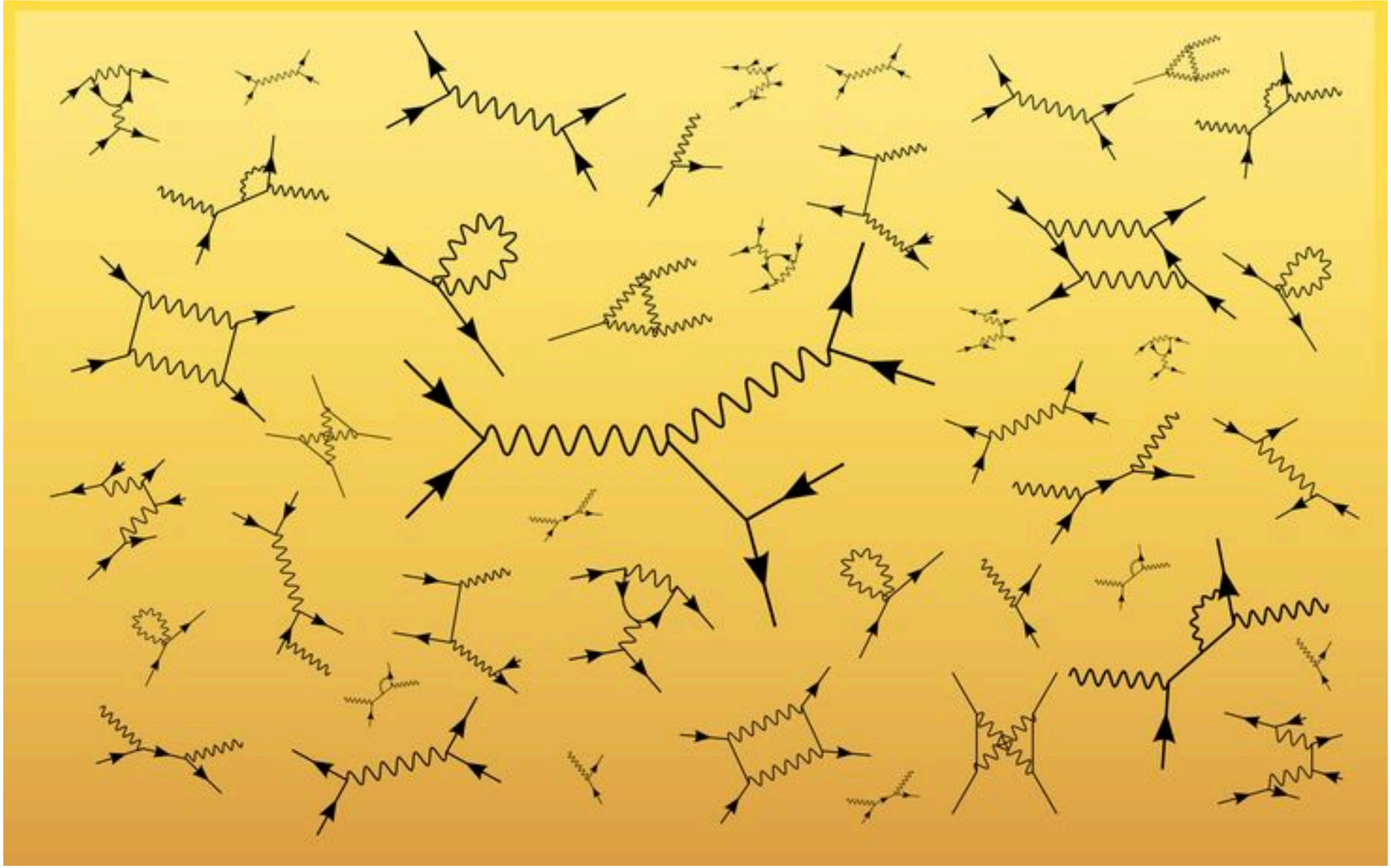
$$\mathscr{L}_{int} = e\overline{\psi}\gamma_\mu A^\mu \psi \Rightarrow ie\gamma_\mu$$

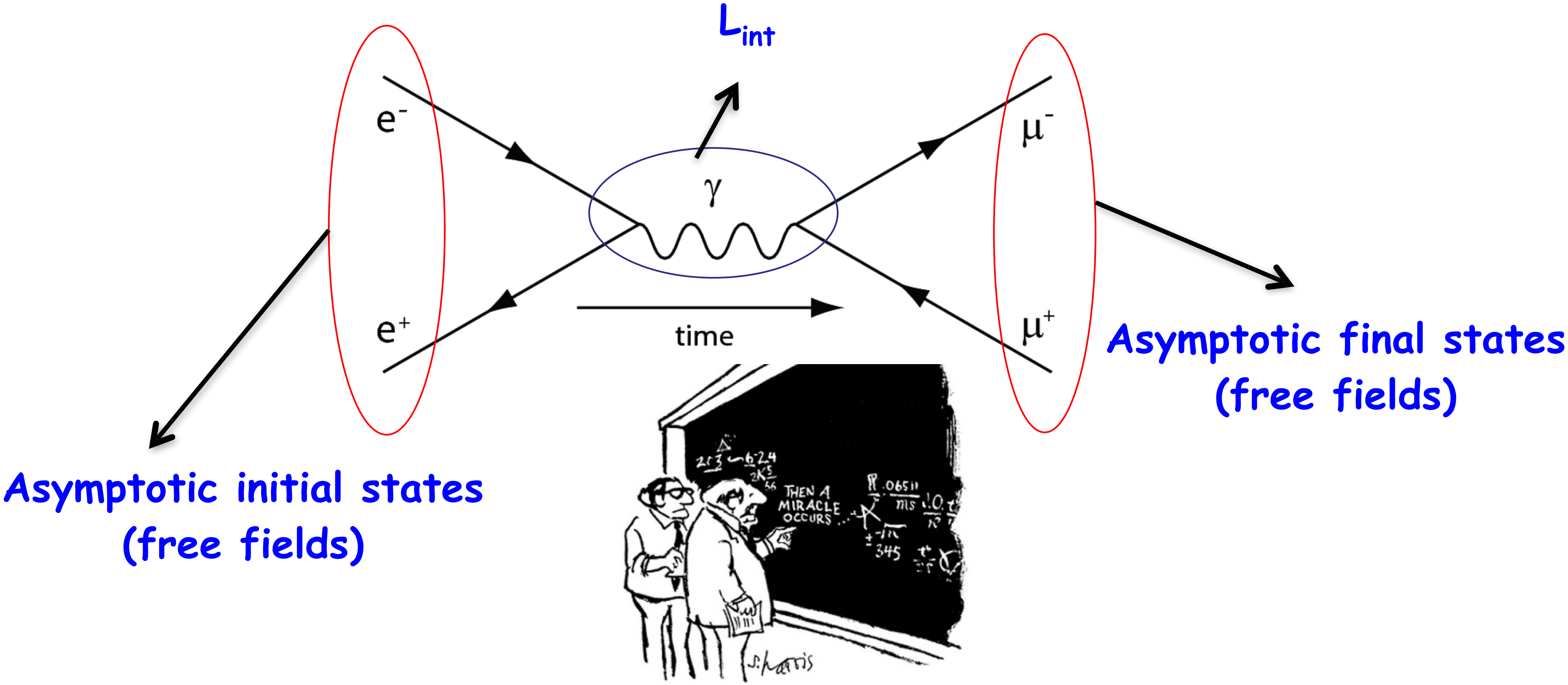
QED

$$\mathscr{L}_{int} = -e^2 g_{\mu\nu} A^\mu A^\nu \phi^\dagger \phi \Rightarrow -2ie^2 g_{\mu\nu}$$

Scalar QED

9. Choose your process and draw Feynman diagrams;





"I think you should be more explicit here in step two."

An electron and a positron collide, exchange a virtual photon, and create a pair of muon and anti-muon (there are more diagrams).

The time arrow tells us that the diagram has to be read from left to right. This is the most common definition now.

The initial and final states are free states obeying the Dirac equation.

10. Calculate cross sections;

The S-matrix (scattering matrix) is the unitary operator S that determines the evolution of the initial state |i> at t=-∞ to state |f> at t =+∞.

The probability amplitude for a transition between initial state |i> and state |f> is

$$S_{fi} = \langle f \,|\, S \,|\, i \rangle$$

and S is the scattering matrix. S is expanded at each order and it depends on the interaction Lagrangian

$$S \Leftarrow \mathscr{L}_{int}$$

The cross section is proportional to the transition amplitude

$$\sigma \propto |\langle f \,|\, S \,|\, i \rangle|^2$$

and is the probability of a given process to occur.

10. and decay widths and BRs;

Here again the interaction Lagrangian appears in the calculation of the decay width just like with a cross section. When a particle decays it may decay to different sets of particles. The decay width is like the decay constant in Nuclear Physics

$$\begin{tikzcd} & A \\ X \arrow[ur, "a"] \arrow[r, "b"'] & B \end{tikzcd}$$

Nucleus X decays to A with decay constant λ_a and to B with decay constant λ_b.

$$\begin{cases} \left(\dfrac{dN}{dt}\right)_a = -\lambda_a N & \text{to A} \\ \left(\dfrac{dN}{dt}\right)_b = -\lambda_b N & \text{to B} \end{cases} \Rightarrow \frac{dN}{dt} = \left(\frac{dN}{dt}\right)_a + \left(\frac{dN}{dt}\right)_b = -(\lambda_a + \lambda_b)N$$

$$N(t) = N_0\, e^{-\lambda_T t} \quad \text{com} \quad \lambda_T = \lambda_a + \lambda_b$$

In particle physics the notation is

$$\lambda \to \Gamma$$

Particle lifetime is the time taken for the sample to reduce to 1/e of original sample.

In natural units (more later) the decay width is the decay constant which is the inverse of the lifetime of the particle. For instance for the Z boson the total width is

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\nu_i\nu_i} + \Gamma_{q_iq_i}$$

with the measured value of

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

and a lifetime of about 2.7×10^{-25} s. Each of the terms are called partial width for the corresponding channel.

The branching ratio for a specific channel

$$\mathrm{BR}_X = \frac{\Gamma_X}{\Gamma_Z}$$

Fraction of electrons coming from the Z decay

$$\mathrm{BR}_{ee} = \frac{\Gamma_{ee}}{\Gamma_Z}$$

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-	[a]	(3.3632 ± 0.0042) %	
Γ_2	$\mu^+\mu^-$	[a]	(3.3662 ± 0.0066) %	
Γ_3	$\tau^+\tau^-$	[a]	(3.3696 ± 0.0083) %	
Γ_4	$\ell^+\ell^-$	[a,b]	(3.3658 ± 0.0023) %	
Γ_5	$\ell^+\ell^-\ell^+\ell^-$	[c]	(3.5 ± 0.4) $\times 10^{-6}$	S=1.7
Γ_6	invisible	[a]	(20.000 ± 0.055) %	
Γ_7	hadrons	[a]	(69.911 ± 0.056) %	
Γ_8	$(u\overline{u}+c\overline{c})/2$		(11.6 ± 0.6) %	
Γ_9	$(d\overline{d}+s\overline{s}+b\overline{b})/3$		(15.6 ± 0.4) %	
Γ_{10}	$c\overline{c}$		(12.03 ± 0.21) %	
Γ_{11}	$b\overline{b}$		(15.12 ± 0.05) %	
Γ_{12}	$b\overline{b}b\overline{b}$		(3.6 ± 1.3) $\times 10^{-4}$	
Γ_{13}	ggg		$<$ 1.1 %	CL=95%
Γ_{14}	$\pi^0\gamma$		$<$ 2.01 $\times 10^{-5}$	CL=95%
Γ_{15}	$\eta\gamma$		$<$ 5.1 $\times 10^{-5}$	CL=95%
Γ_{16}	$\omega\gamma$		$<$ 6.5 $\times 10^{-4}$	CL=95%
Γ_{17}	$\eta'(958)\gamma$		$<$ 4.2 $\times 10^{-5}$	CL=95%
Γ_{18}	$\phi\gamma$		$<$ 8.3 $\times 10^{-6}$	CL=95%
Γ_{19}	$\gamma\gamma$		$<$ 1.46 $\times 10^{-5}$	CL=95%

And finally the number of events

To find the number of events in a given process you need: (a) the cross section; (b) the branching ratio; (c) the luminosity; (d) the efficiency. Suppose we are looking for a Higgs in the process

$$pp \to h \to \gamma\gamma$$

The total number of events for a luminosity of 25 fb^{-1} and a center-of-mass energy of 8 TeV is

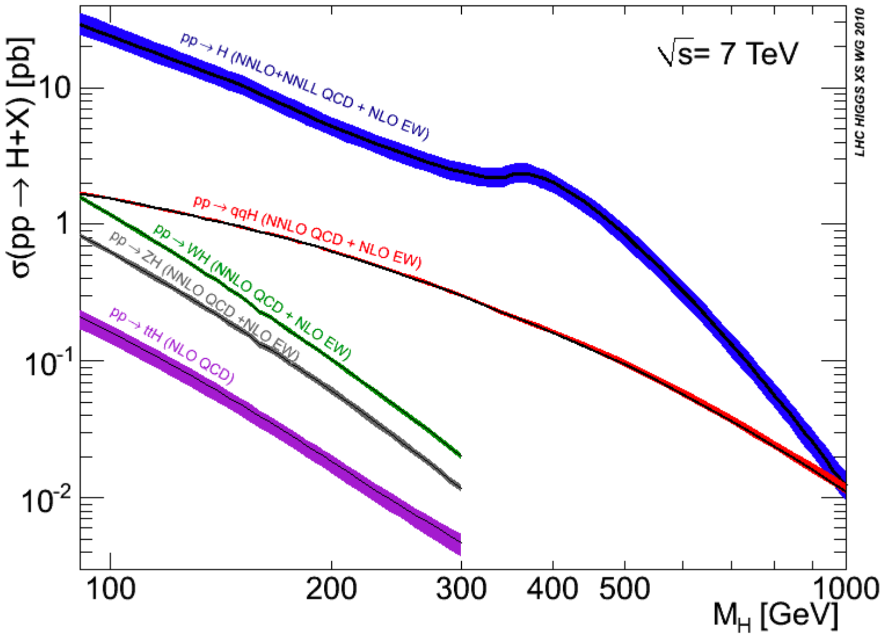
$$N_{Higgs} = \sigma(pp(gg) \to h)\, BR(h \to \gamma\gamma)\, L\, \epsilon$$

$$N_{Higgs} = (21.4 \times 10^3) \times (2.28 \times 10^{-3}) \times (25) \times (1) \approx 1220$$

with the efficiency set to 1.

This is the maximum number of events. We then need to take into account the background and the fact that all apparatus and analysis have a specific efficiency.

Higgs cross section production and BRs



Cross section for Higgs production at the LHC
For a center of mass energy of 7 TeV.

Total width of the Higgs as a function of the mass.

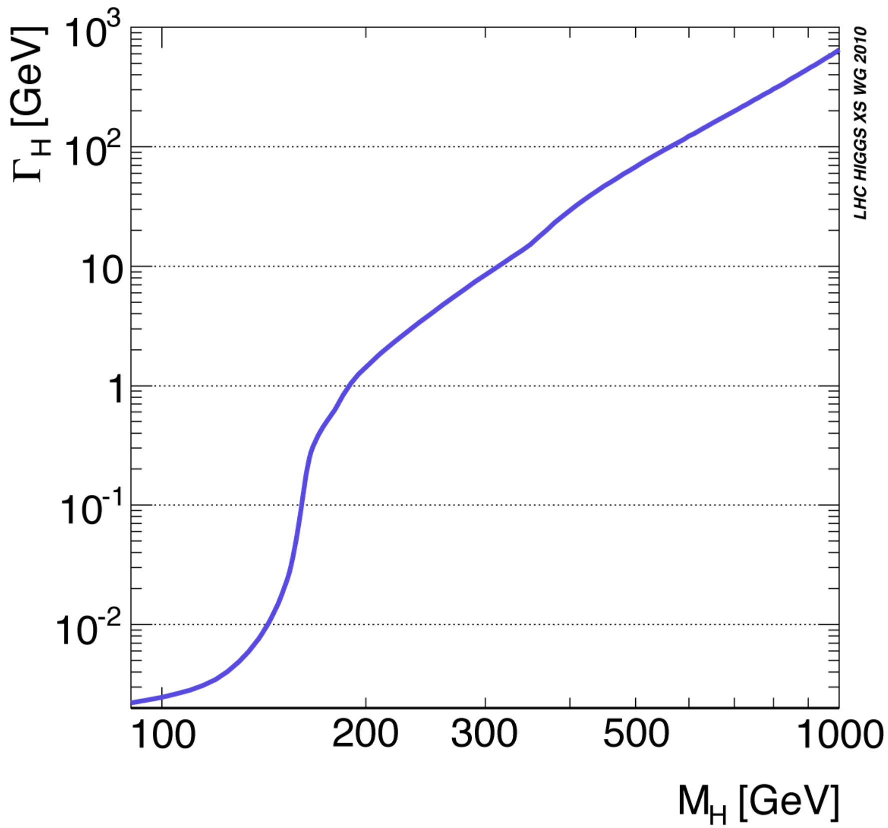
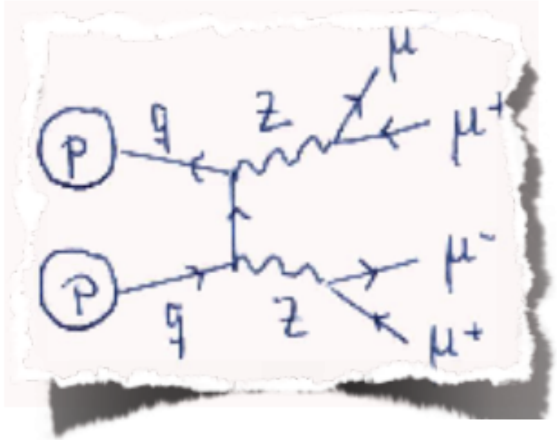


Table 11.3: The branching ratios and the relative uncertainty [43,44] for a SM Higgs boson with $m_H = 125\,\text{GeV}$.

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	$\pm 1.5\%$
$H \to W^+W^-$	2.14×10^{-1}	$\pm 1.5\%$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$\pm 1.6\%$
$H \to b\bar{b}$	5.82×10^{-1}	$^{+1.2\%}_{-1.3\%}$
$H \to c\bar{c}$	2.89×10^{-2}	$^{+5.5\%}_{-2.0\%}$
$H \to Z\gamma$	1.53×10^{-3}	$\pm 5.8\%$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$\pm 1.7\%$

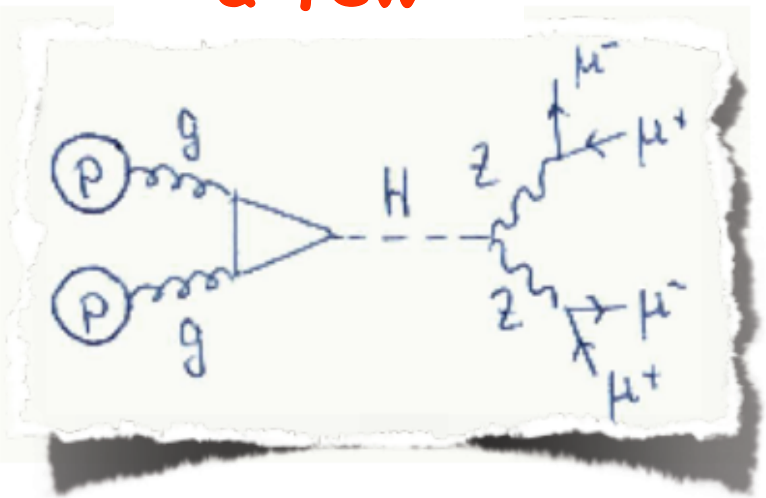
How do we search for Higgs bosons at the LHC?

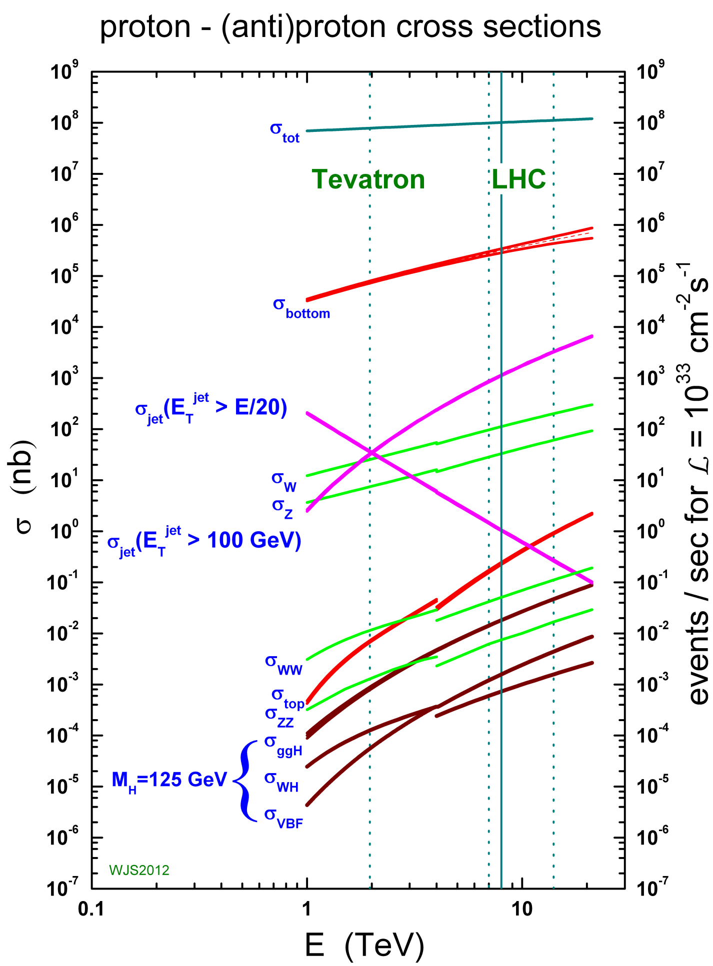
Signal and background



a lot

a few

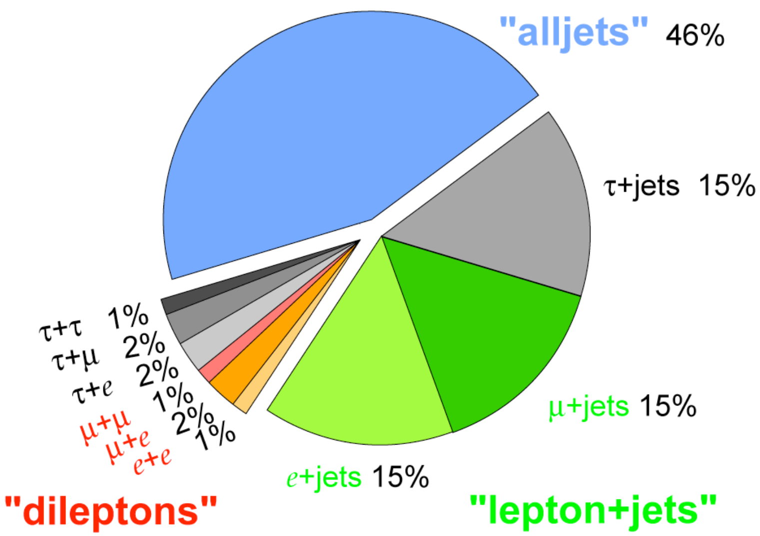


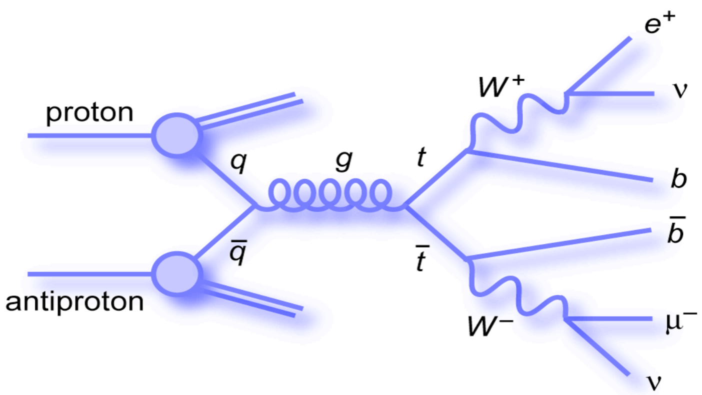


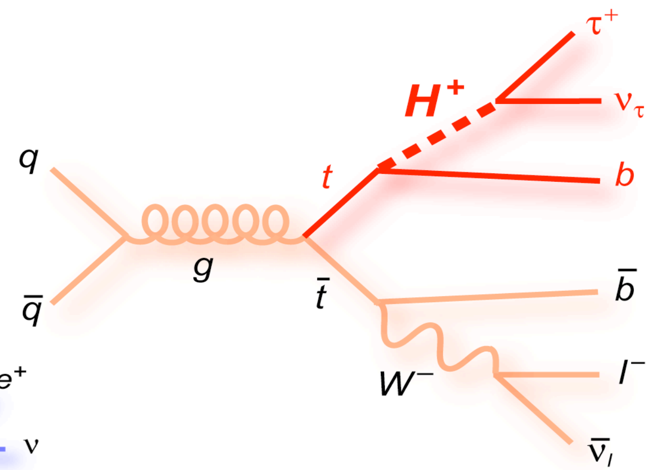
What is a search at the LHC?

- Suppose we are searching for a charged Higgs at the LHC
- The charged Higgs comes from a top-quark (t -> H^+ b)
- There are two top-quarks in the event
- The charged Higgs will decay to a tau and a neutrino (H^+ -> τ^+ ν)
- The tau will decay to an electron or a muon and neutrinos (τ^+-> e^+ ν ν)
- Experimentalists will look for a an electron and missing energy (from the neutrinos).
- Do they come from a charged Higgs?

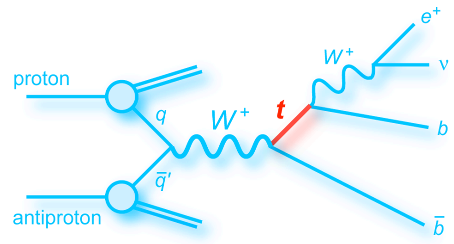
Top Pair Branching Fractions







The levels of the search – folklore and traditional approach



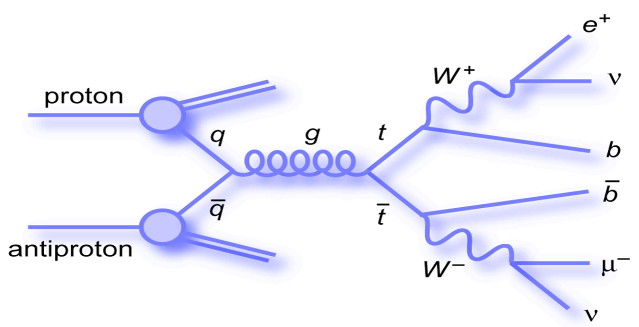
Parton Level **pp -> e^+ ν ν ν b + X**

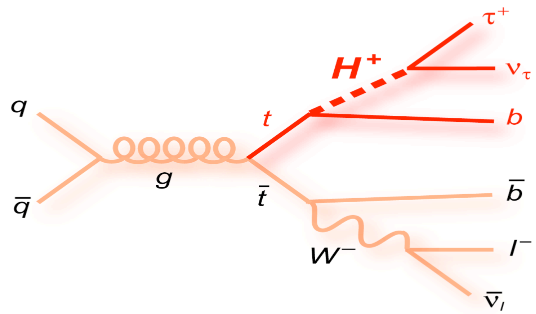
a) Introduce background (again there are several levels)

Irreducible - pp -> t + X -> W^+ b + X-> e^+ ν ν b + X

Reducible - pp -> t t -> W^+ b W^- b

- Number of reducible backgrounds is virtually infinite (a jet has some probability of being misidentified as an electron).





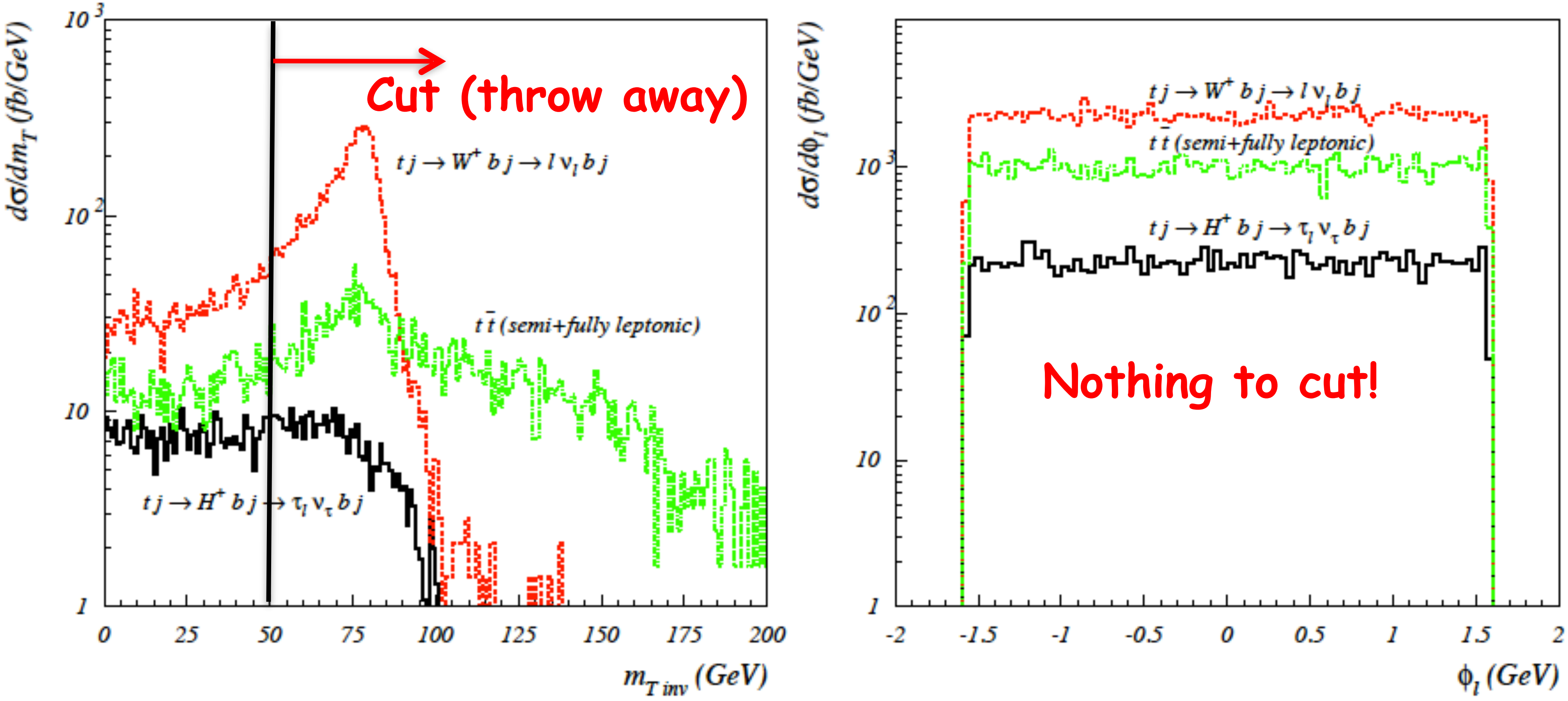
b) Pretend you understand what is happening (by mimicking the experimental analysis)

Trigger – how efficiently are "our" events recorded? One lepton!

Electron – how efficient is electron recognition?

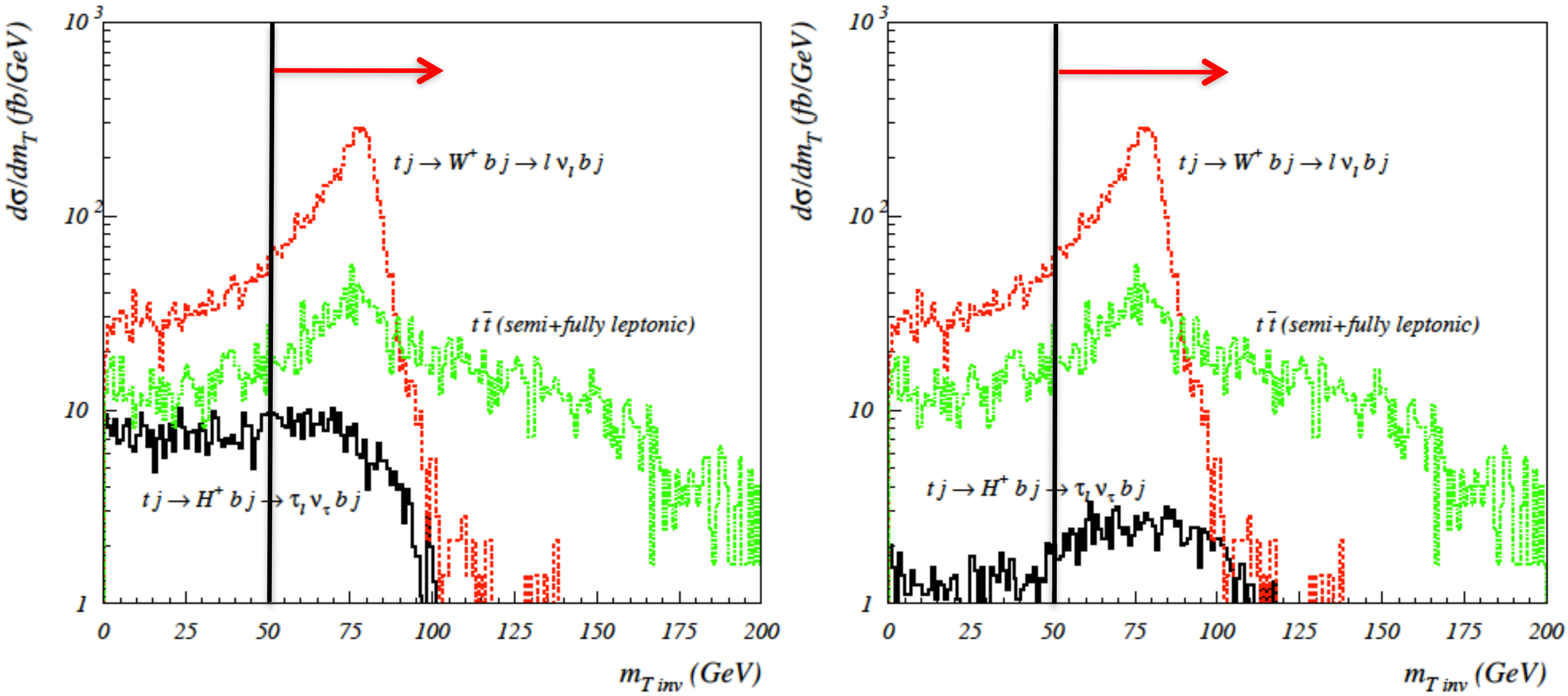
The levels of the search – folklore and traditional approach

c) Plot distributions and spot the differences (loose signal but loose even more background)



Two types of variables: the transverse mass and the lepton azimuthal angle (cut-based).

The levels of the search – folklore and traditional approach



Distributions depend on the model parameters. The higher the charged Higgs mass the lower the cross section. There is also a "peak" shift.

d) e) f) Radiation, Detector and finally Data.

Single top results

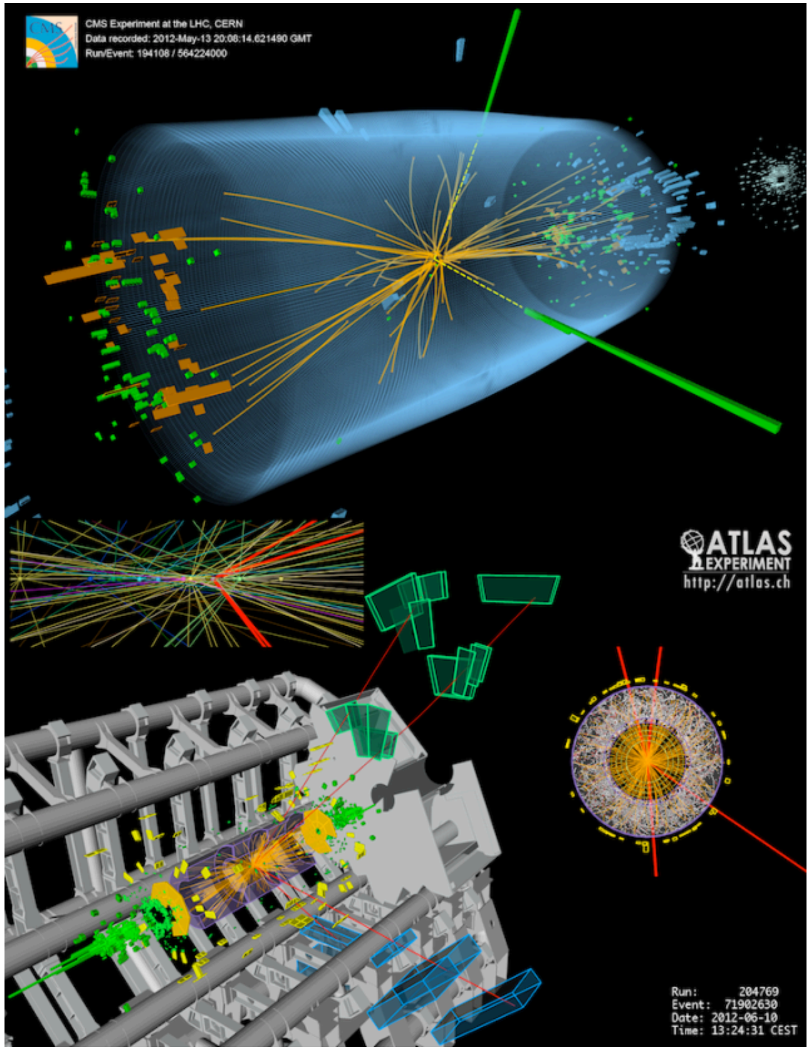
	$\sigma_{m_{H^\pm}=100\,\mathrm{GeV}}$	$\sigma_{m_{H^\pm}=110\,\mathrm{GeV}}$	$\sigma_{m_{H^\pm}=120\,\mathrm{GeV}}$	$\sigma_{m_{H^\pm}=130\,\mathrm{GeV}}$	$\sigma_{m_{H^\pm}=140\,\mathrm{GeV}}$
Process					
Signal	379.4 fb	274.4 fb	202.7 fb	118.9 fb	65.5 fb
Bg (single-top)	1705.4 fb				
Bg ($t\bar{t}$ semi-leptonic)	683.1 fb				
Bg ($t\bar{t}$ leptonic)	393.6 fb				
σ_S/σ_B	0.14	0.098	0.073	0.042	0.023
$\sigma_S/\sqrt{\sigma_B}$ ($\mathrm{fb}^{1/2}$)	7.19	5.20	3.84	2.25	1.24

The analysis is done. We now have, for a given luminosity, S signal events and B background events.

Discovery - $S/B^{1/2} > 5$

An exclusion (absence of signal) is usually shown for 95 % C.L.

A brief history of the discovery of 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 it got a mass. The larger the interaction the heavier the particle. No coupling to the photon.

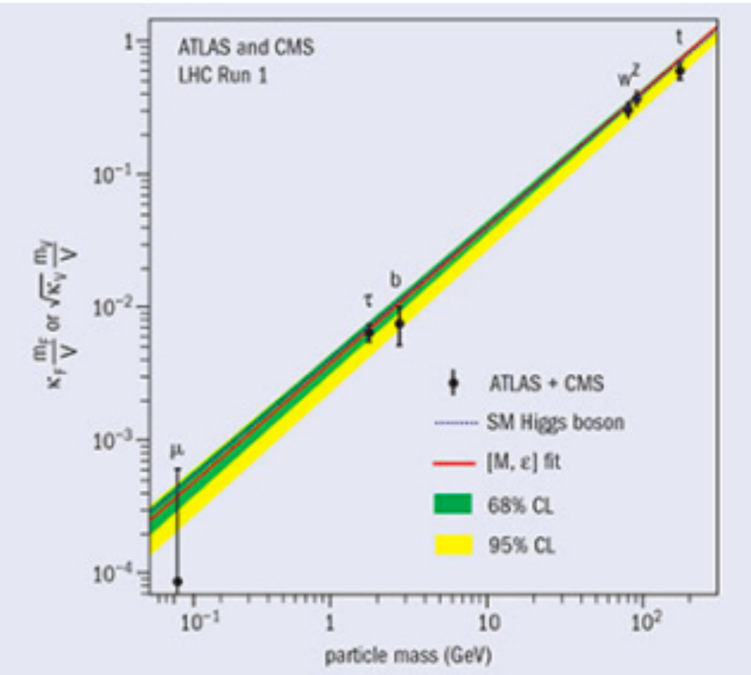
On July 4 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider observed a new particle in the mass region around 125 GeV, consistent with the Standard Model Higgs boson. Is it the Higgs boson predicted by the Standard Model?

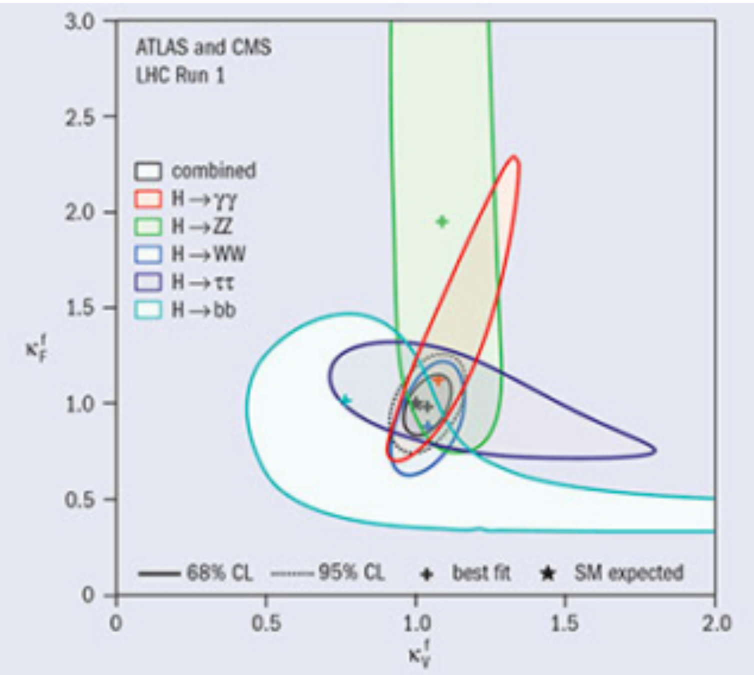
A brief history of the Higgs boson

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

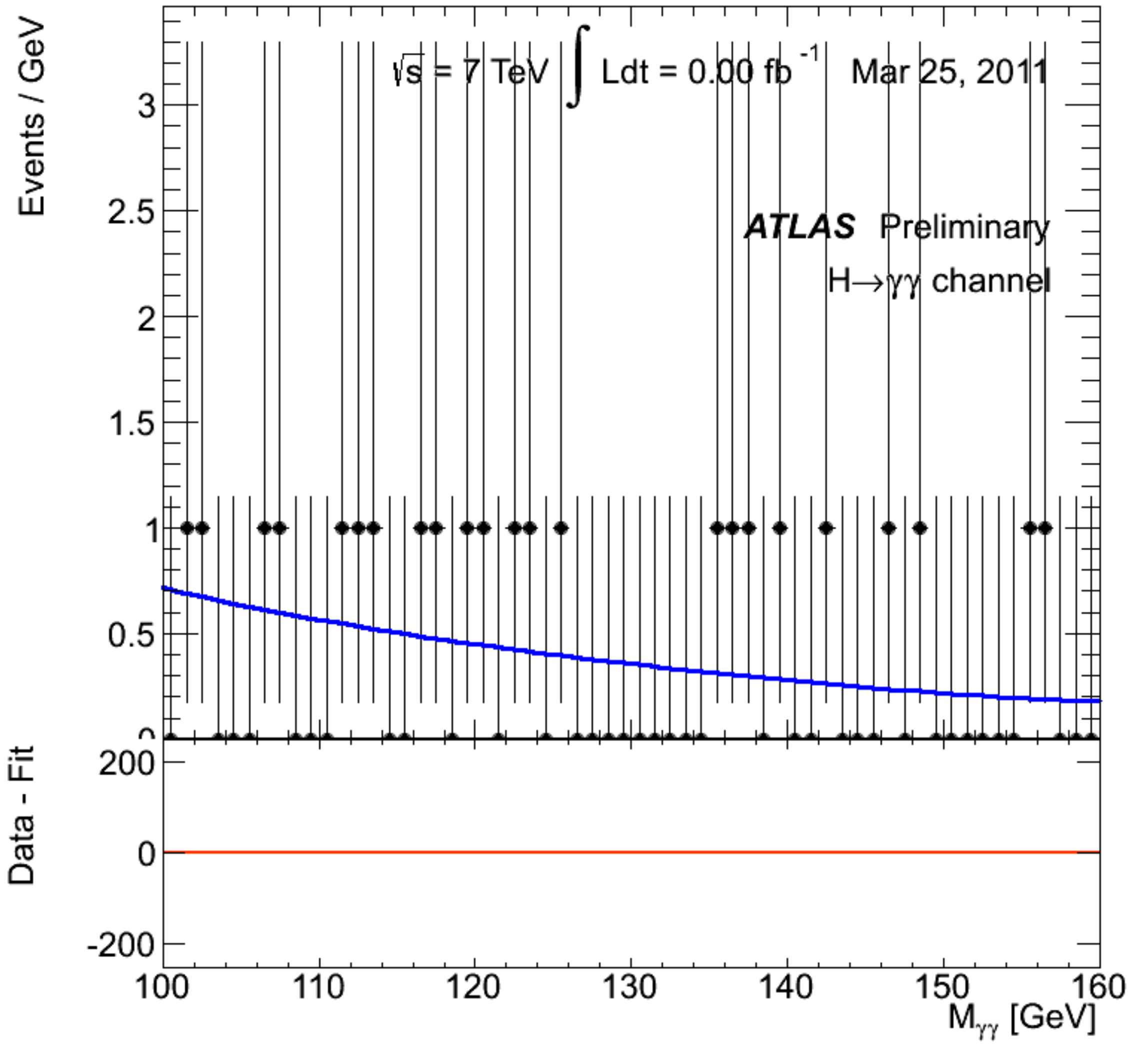




$$g_{NP}^{hVV} = \kappa_V g_{SM}^{hVV}$$

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

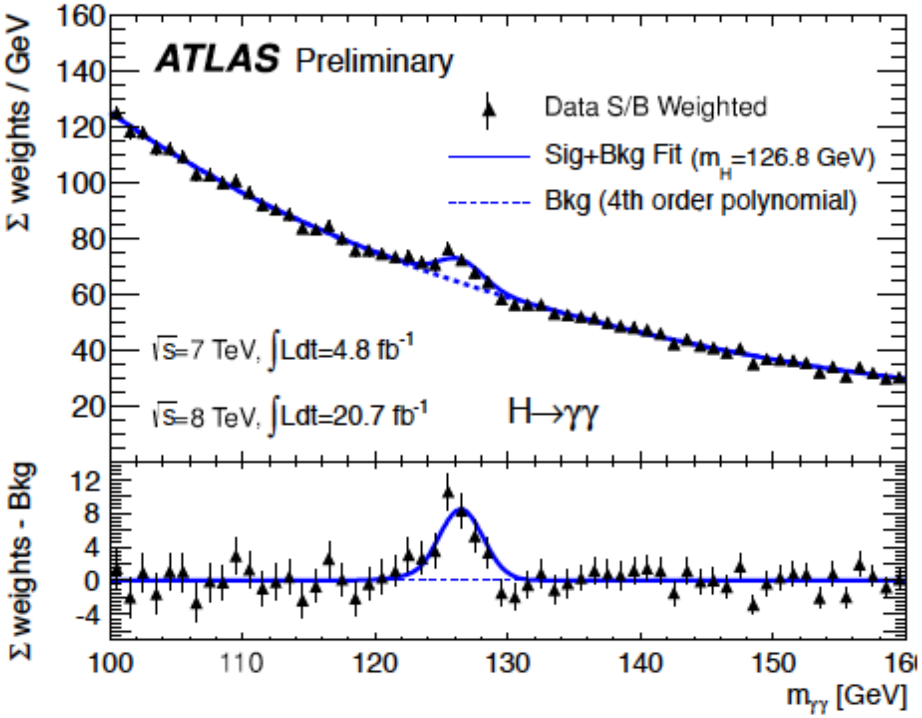
5 sigma and the Higgs discovery!



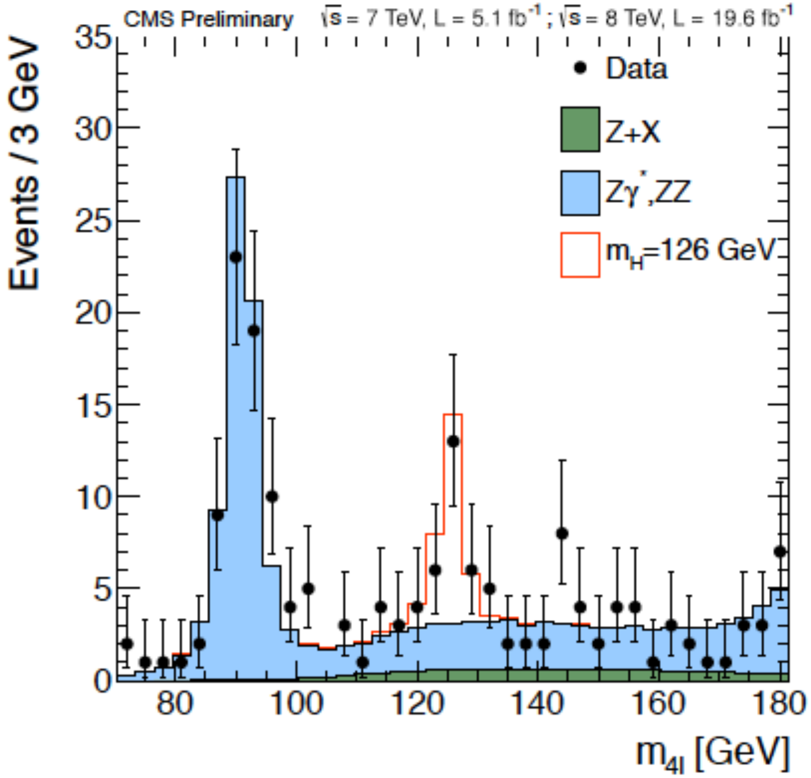
LHC collects a huge number of collisions data and counts how many times two given photons have the Higgs mass. When 5 sigma was reached the Higgs was considered to have been discovered.

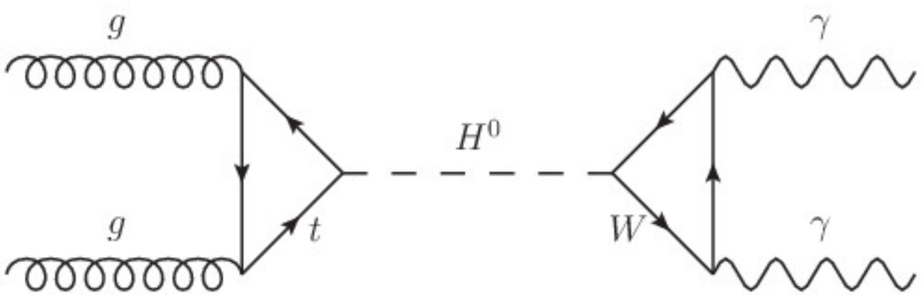
LHC Discovery of a New Scalar Particle

ATLAS-CONF-2013-12



CMS-PAS-HIG-13-002





… a poster child for quantum theory!

New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

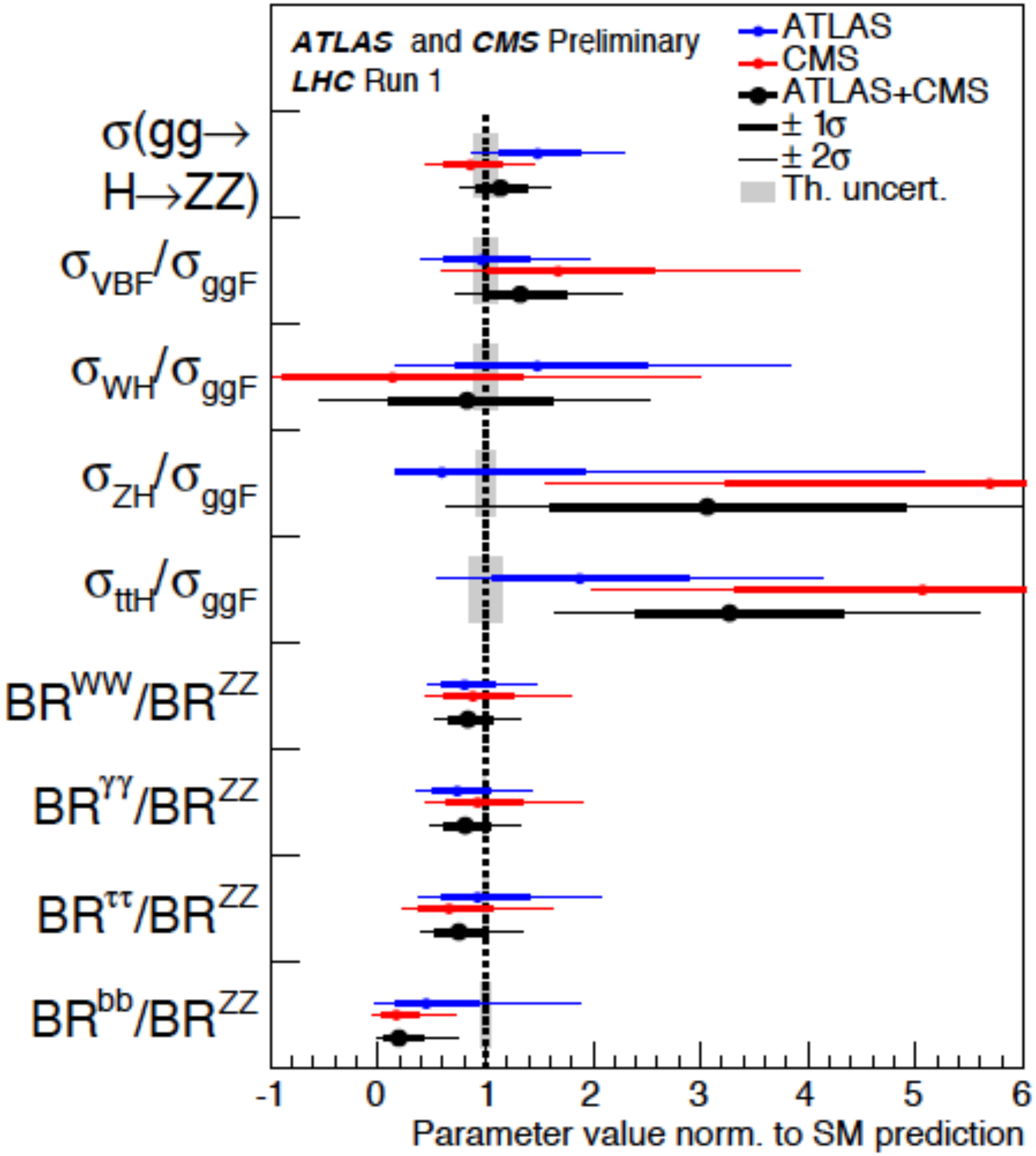
Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Whether or not it is a Higgs boson is demonstrated by how it interacts with other particles, and its quantum properties. For example, a Higgs boson is postulated to have spin 0, and in the Standard Model its parity – a measure of how its mirror image behaves – should be positive. CMS and ATLAS have compared a number of options for the spin-parity of this particle, and these all prefer no spin and positive parity. This,

1964
Brout-Englert-Higgs-
Mechanism

2013
Nobel Prize for Physics

The Standard Model
is complete.
Now what?



ATLAS/CMS combination with all run1 data.

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

15th September 2015

The Higgs looks very SM-like because all couplings are well within the SM predictions. And there is no hint of new physics so far.

There are essentially two ways of showing we need new physics:

a) deviations from the SM predictions

b) finding something new (like with dark matter if it is indeed a particle)

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…

Unexplained experimental results:

Muon magnetic moment

B meson decays

There is also gravity and dark energy

Extended Scalars

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

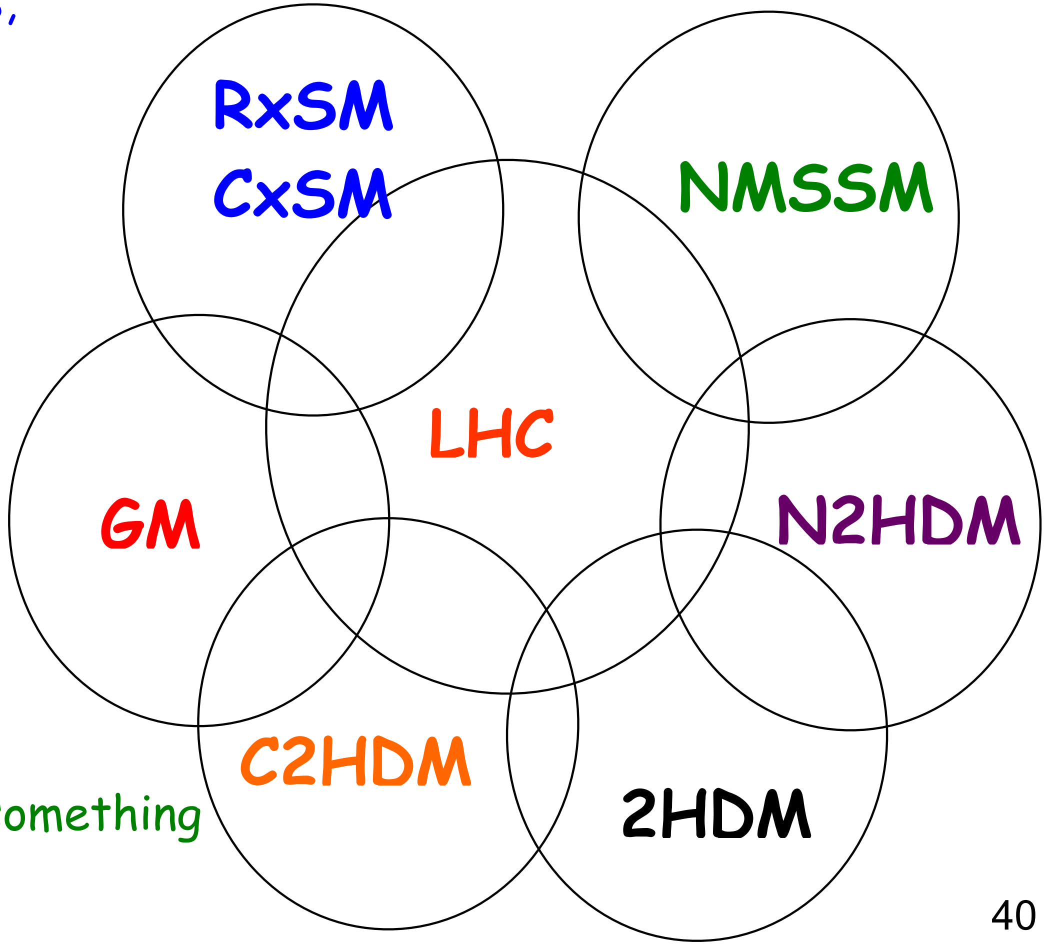
2. **Indirect detection of new physics** (via measurements of the 125 GeV Higgs couplings)

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

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

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

$$Q = T_3 + Y/2$$

T_i	$SU(2)_L$ **Isospin**
Y_i	**Hypercharge**
v_i	**VEV**
c_i	**1(1/2) for complex (real) representations**

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)

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

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

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not. There are two charged particles and 4 neutral.

magenta $\Longrightarrow$ SM

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

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

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

The model can be CP violating 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** <u>2HDM</u>
- **m^2_{12} and λ_5 complex** <u>C2HDM</u>

How does the rest of the Lagrangian looks like?

Interlude - Yukawa Lagrangian in the SM

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

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.

Interlude - Yukawa Lagrangian in the SM

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

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

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

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

<u>**No scalar induced tree-level FCNCs**</u>

Interlude - Yukawa Lagrangian in the 2HDM

However in 2HDMs

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

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

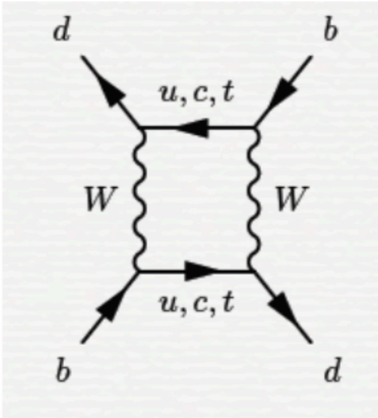
$$-\frac{1}{\sqrt{2}} N_L^\dagger \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2 \right)} N_R = M_d; \qquad -\frac{1}{\sqrt{2}} K_L^\dagger \left(v_1 Y_u^1 + v_2 Y_u^2 \right) K_R = M_u$$

$$\begin{aligned} L_Y^{interactions} &= \frac{h_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{h_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{h_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{h_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \ldots \\ &= \frac{h}{\sqrt{2}} \bar{U}_L \left(\cos\alpha Y_u^1 + \sin\alpha Y_u^2 \right) U_R + \frac{H}{\sqrt{2}} \bar{D}_L \boxed{\left(-\sin\alpha Y_d^1 + \cos\alpha Y_d^2 \right)} D_R + \ldots \end{aligned}$$

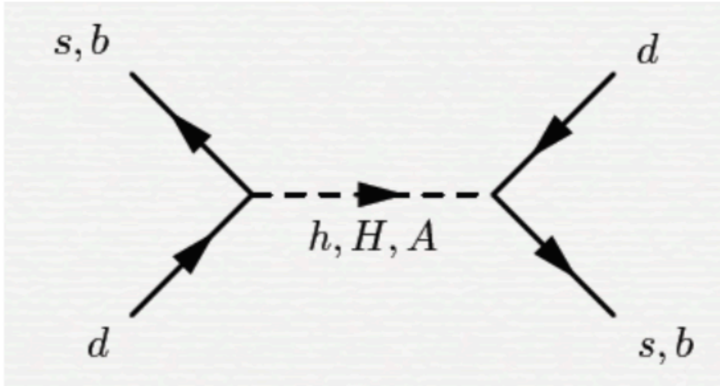
h, H are the mass eigenstates (a is the rotation angle in the CP-even sector)

FCNC constraints in 2HDM

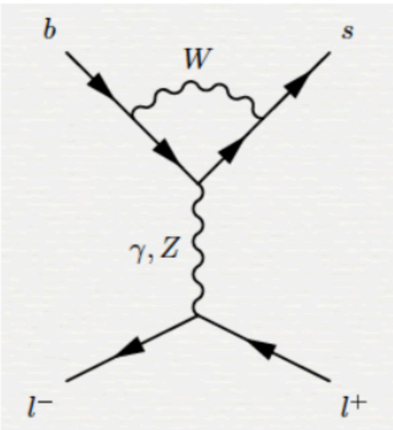
➡ B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing

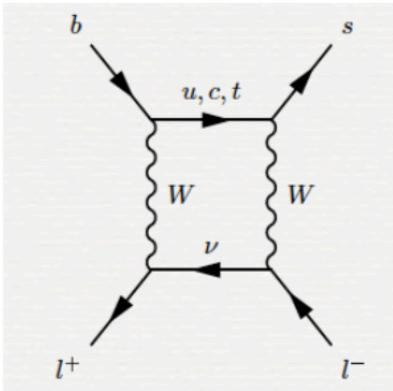


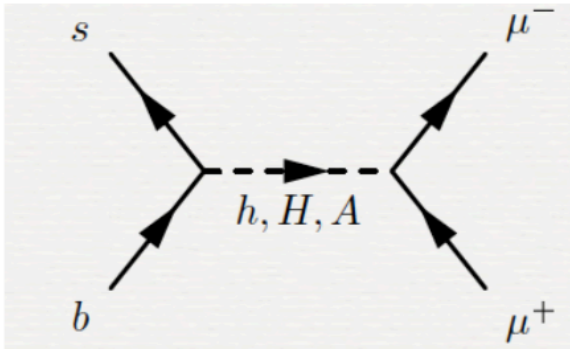
New tree-level FCNC diagrams



➡ Rare B decays







Interlude - Yukawa Lagrangian in the 2HDM

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)

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

Interlude - Yukawa Lagrangian in the 2HDM

3. Use symmetries- for some reason the L is invariant under some symmetry

3.1 Naturally small tree-level FCNCs

Example: BGL Models   BRANCO, GRIMUS, LAVOURA (2009)

3.2 No tree-level FCNCs

Example: Type I 2HDM Z_2 symmetries   GLASHOW, WEINBERG; PASCHOS (1977)
BARGER, HEWETT, PHILLIPS (1990)

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

$$\Phi_1 \rightarrow \Phi_1 ; \Phi_2 \rightarrow -\Phi_2 \qquad D_R \rightarrow -D_R ; E_R \rightarrow -E_R ; U_R \rightarrow -U_R$$

$$L_Y^I = \left[\bar{U} \quad \bar{D}\right]_L \Phi_2 Y_d^2 \, D_R + \left[\bar{U} \quad \bar{D}\right]_L \tilde{\Phi}_2 \; Y_u^2 U_R + \left[\bar{N} \quad \bar{E}\right]_L \Phi_2 \; Y_e^2 E_R + \text{h.c.}$$

Interlude - scalar kinetic Lagrangian in the 2HDM

This part is simple, you just have to write the covariant derivative in accordance with the quantum numbers of the scalar fields

$$\mathscr{L}_{kin} = (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2) + \partial_\mu \Phi_S \partial^\mu \Phi_S$$

In the meantime you have already decided what kind of scalar particle spectrum you want to have.

a) You can decide that only one doublet acquires a VEV - in that case there is no mixing between the SM doublet and the other (dark?) fields. In this case there only quartic couplings between the gauge bosons and the (dark?) scalars - no scalar decays to gauge bosons.

b) They can all have VEVs and so you have to find the mass eigenstates. Rotation angles will appear all over the place.

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)

$|s_2| = 0 \;\Rightarrow\; h_1$ is a pure scalar,

$|s_2| = 1 \;\Rightarrow\; h_1$ 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)

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

These are coupling modifiers relative to the SM coupling

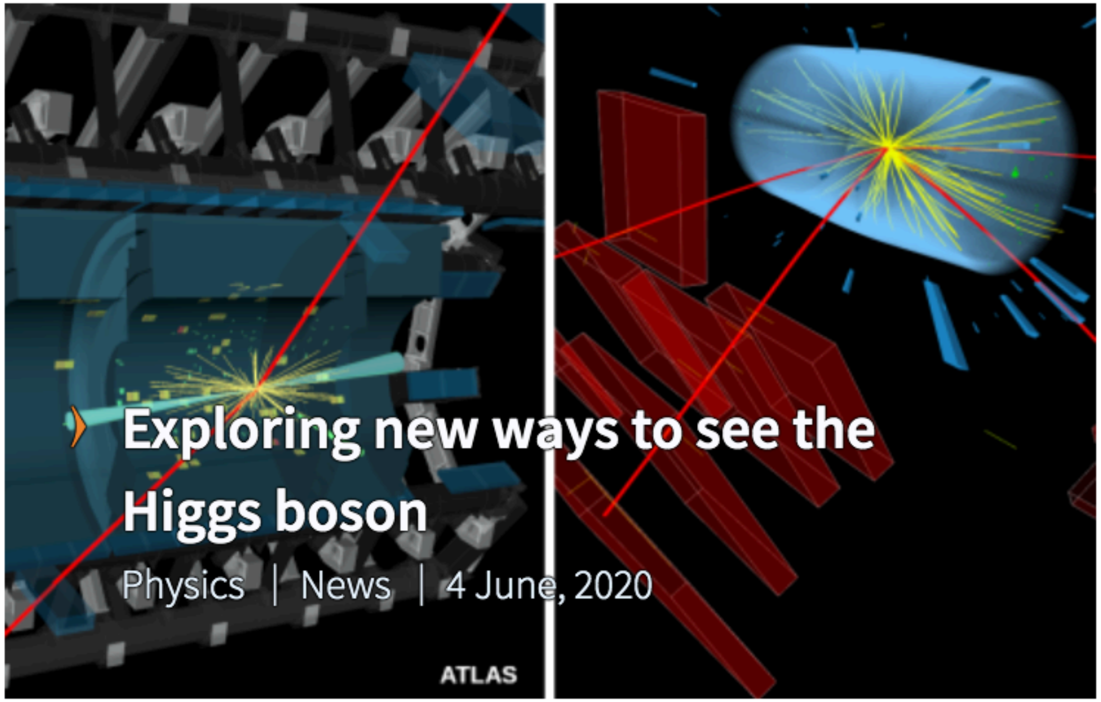
III = I' = Y = Flipped = 4…

IV = II' = X = Lepton Specific= 3…

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

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

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

Searches roadmap

$CP(H_i) = 1; \quad CP(A_i) = -1$

h_i (no definite CP)

$S_i \to S_j V \xrightarrow{\text{CPC}} H_i \to A_i V \; (A_i \to H_i V)$ **2HDM,...**

$S_i \to S_j V \xrightarrow{\text{CPV}} h_1 \to h_2 V$ **C2HDM,...**

- H → AZ, A → ZH and A → Zh_{125}, already studied by ATLAS and CMS

$$\left\{ \begin{array}{l} S_i \to S_j S_j \\ S_i \to S_j S_k \end{array} \right.$$

$S_i \to S_j S_j \xrightarrow{\text{CPC}} H_i \to H_j H_j \; (A_j A_j)$ **RxSM, 2HDM, NMSSM,..**

$S_i \to S_j S_j \xrightarrow{\text{CPV}} h_i \to h_j h_j$

$S_i \to S_j S_k \xrightarrow{\text{CPV}} h_i \to h_j h_k$ **C2HDM, C-NMSSM,...**

$S_i \to S_j S_k \xrightarrow{\text{CPC}} \left\{ \begin{array}{l} H_i \to H_j H_k \\ A_i \to A_j H_k \end{array} \right.$

$H_i \to H_j H_k$ **CxSM, NMSSM,...**

$A_i \to A_j H_k$ **3HDM, NMSSM,...**

- h_{125} → AA and H → h_{125} h_{125} already studied by ATLAS and CMS

Searches roadmap

$$\begin{cases} S_i \to f_j \bar{f}_j \\ S_i \to f_j \bar{f}_k \end{cases}$$

FC

$$H/A \to \tau^+\tau^-$$

$$H/A \to \mu^+\mu^-$$

$$H/A \to t\bar{t}$$

$$H/A \to b\bar{b}$$

Done...

Still, the CP-nature of the Higgs not probed. Attempts in tth (production) and ττh (decay) starting (many theory papers).

FCNC

$$h_{125} \to \tau\mu,\ e\mu,\ e\tau$$

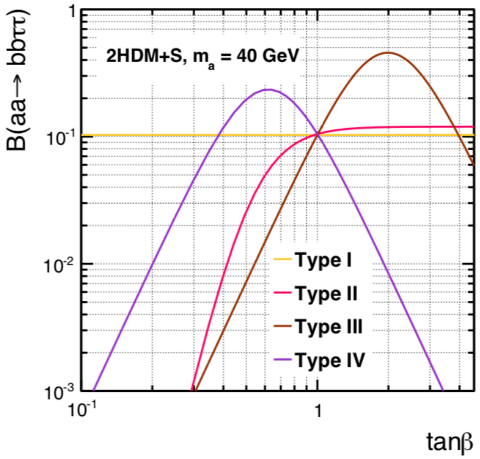
$$t \to c h_{125}$$

$\boxed{S_i \text{ (any neutral scalar)}}$

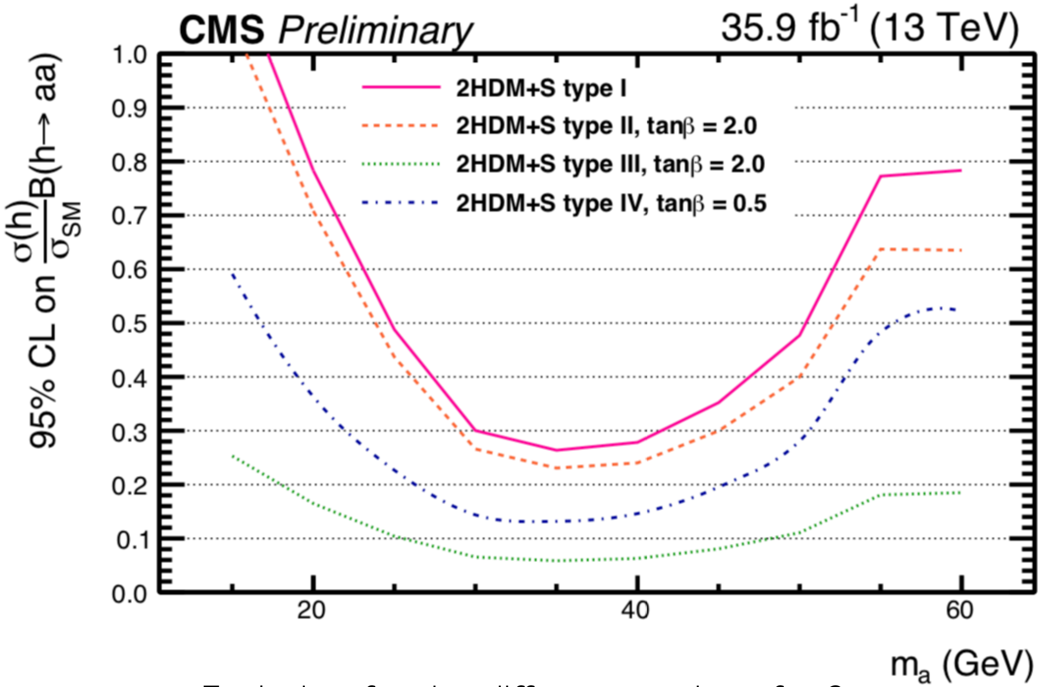
If nothing is found, models are constrained

CMS PAS HIG-17-024

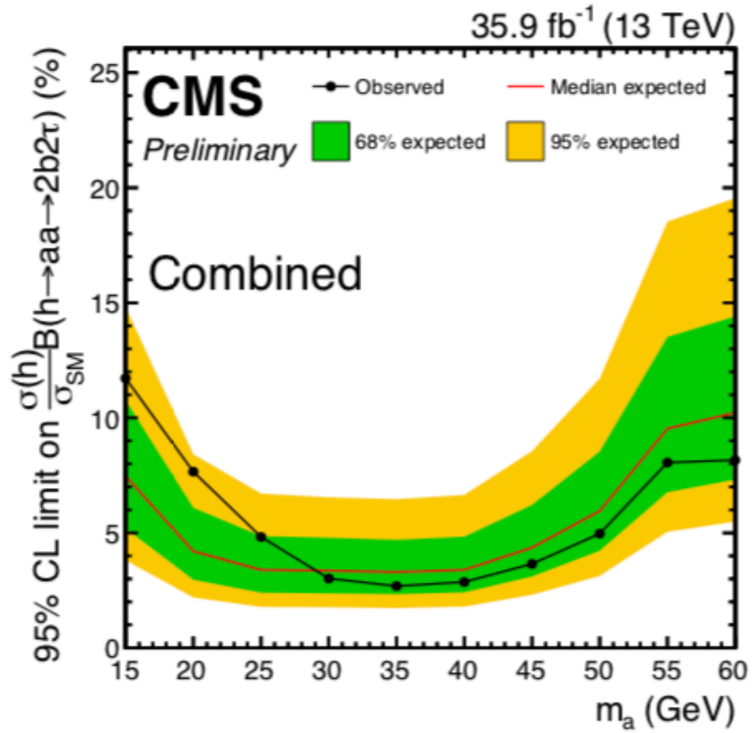
BRs for the 4 different versions of the model.



N2HDM (CP-conserving)



Exclusion for the different versions for 2 values of tanβ.



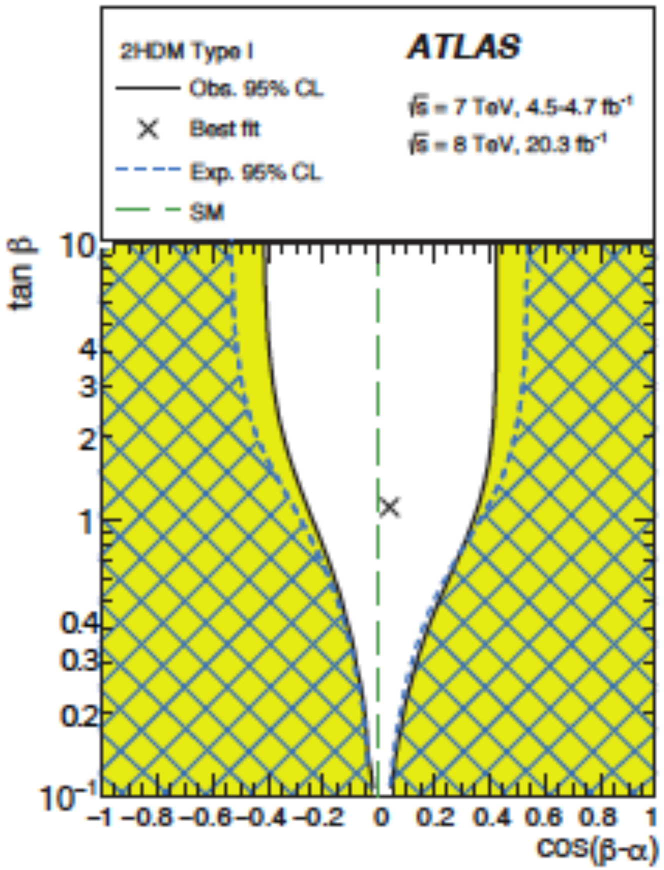
Expected and observed 95% CL limits on σ(h)B(h → aa → 2τ2b) in %. Combined eμ, eτ and μτ channels. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

ATLAS, (γγjj final state),1803.11145

h_{125} couplings measurements

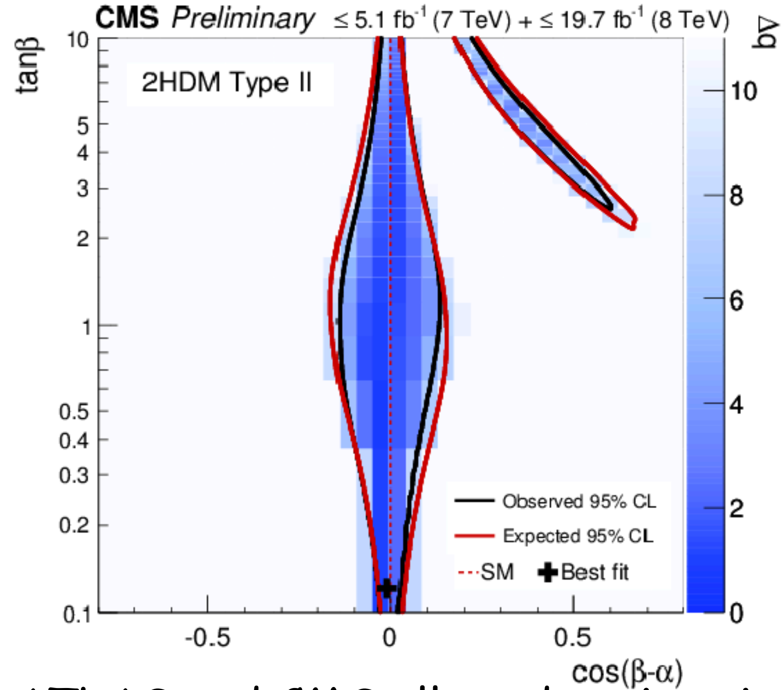
Bounds on the couplings modifiers

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



(a) Type I

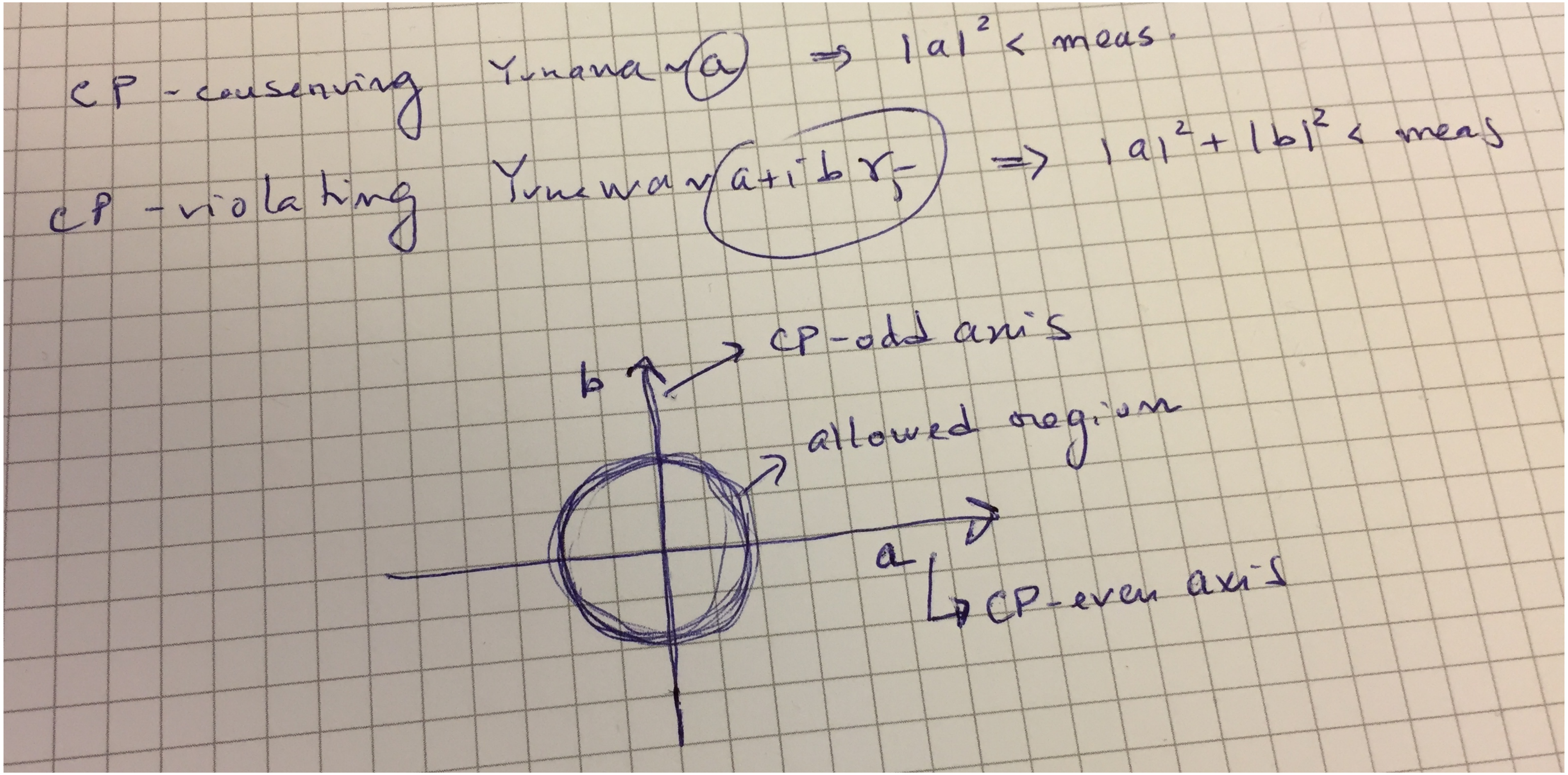
ATLAS 1509.00672



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.

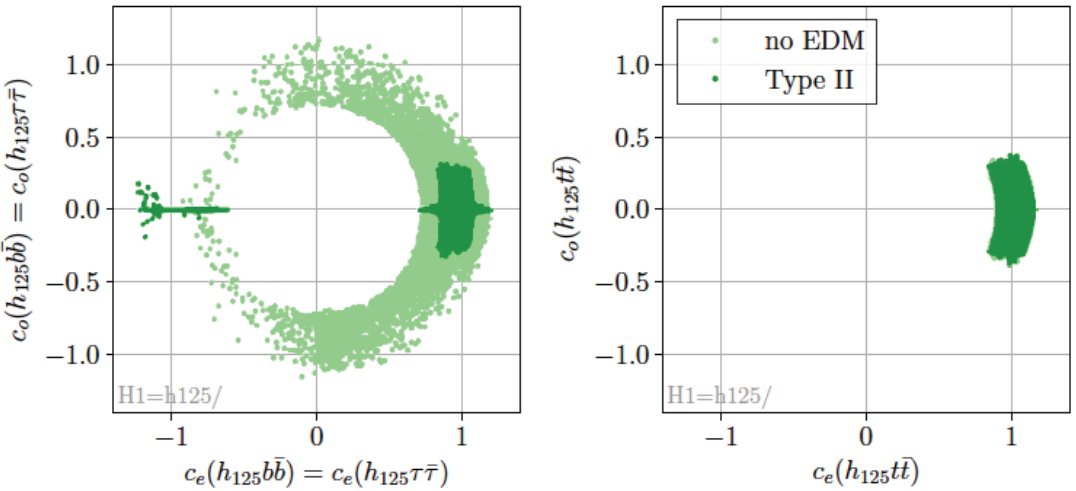
And now at the complex 2HDM – the C2HDM



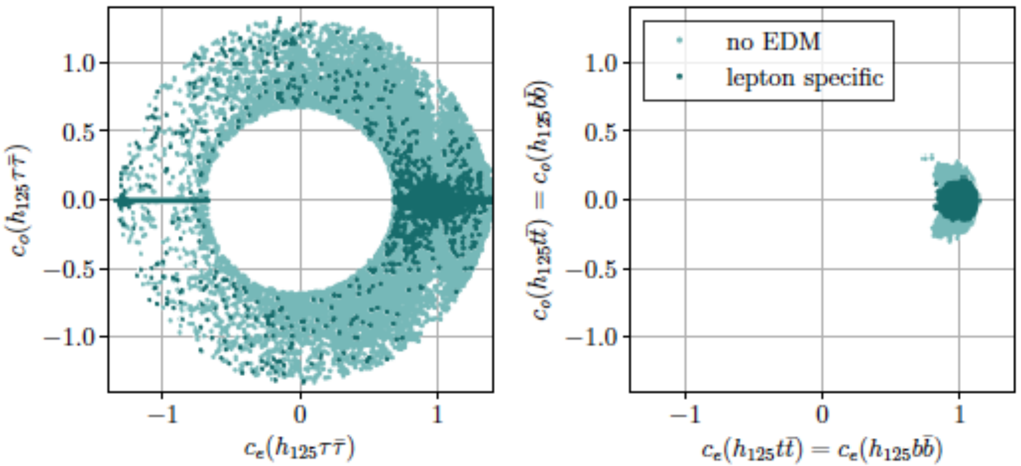
$$Y^{II}_{C2HDM} = c_2 Y^{II}_{2HDM} + i\gamma_5 s_2 t_\beta$$

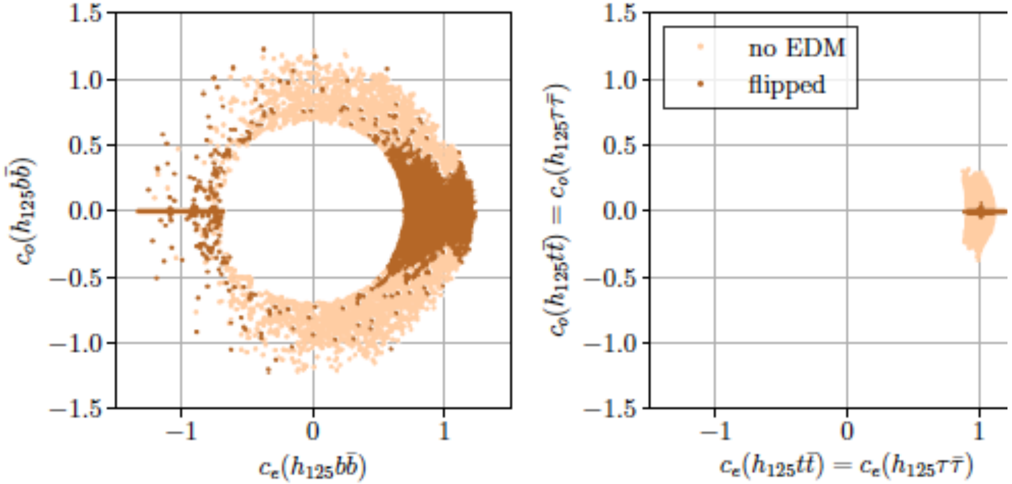
The allowed parameter space in type II C2HDM

$\boxed{H_1 = h_{125}}$



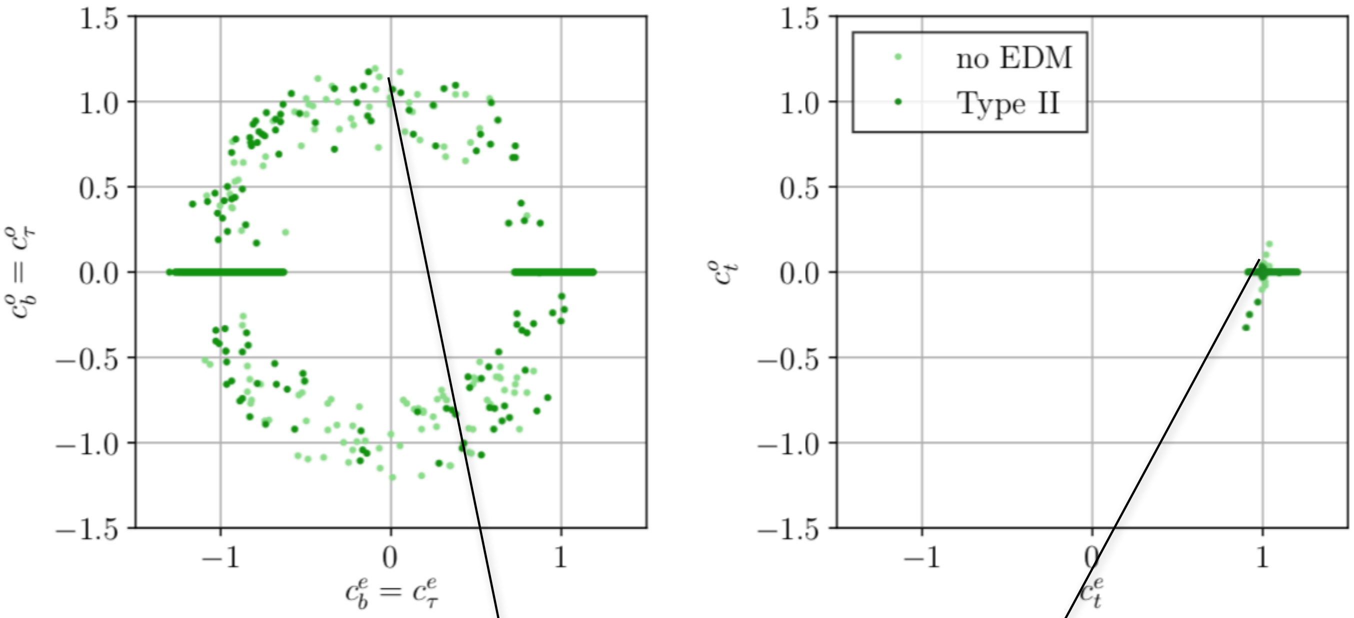
EDMs constraints completely kill large pseudoscalar components in Type II. Not true in Flipped and Lepton Specific.





EDMs act differently in the different Yukawa versions of the model. Cancellations between diagrams occur.

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.

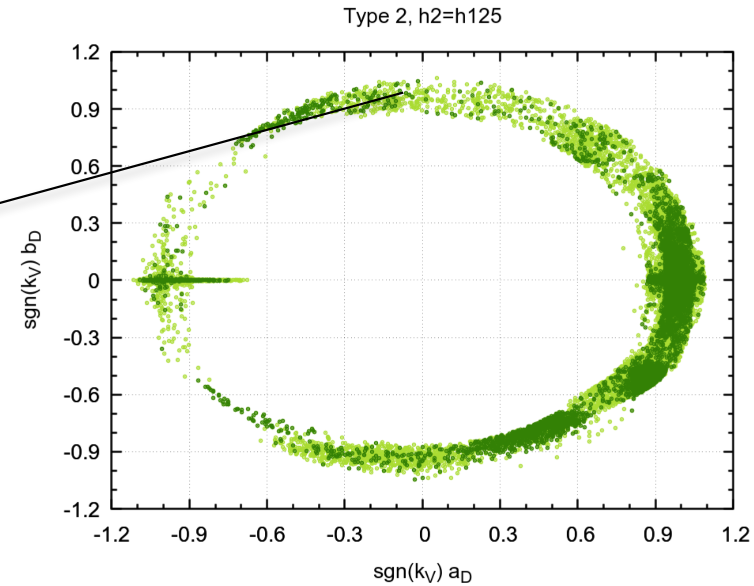
Find two particles of the same mass one decaying to tops as CP-even

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

and the other decaying to taus as CP-odd

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

With the new EDM result



Probing one Yukawa coupling is not enough!

And also the first appearance of the tau CPV angle!

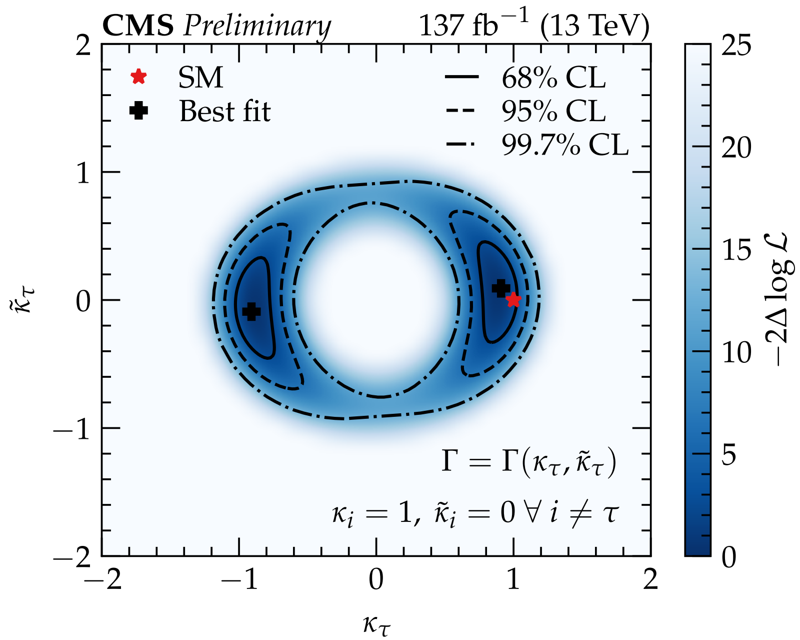
$$\boxed{pp \to h \to \tau^+\tau^-}$$

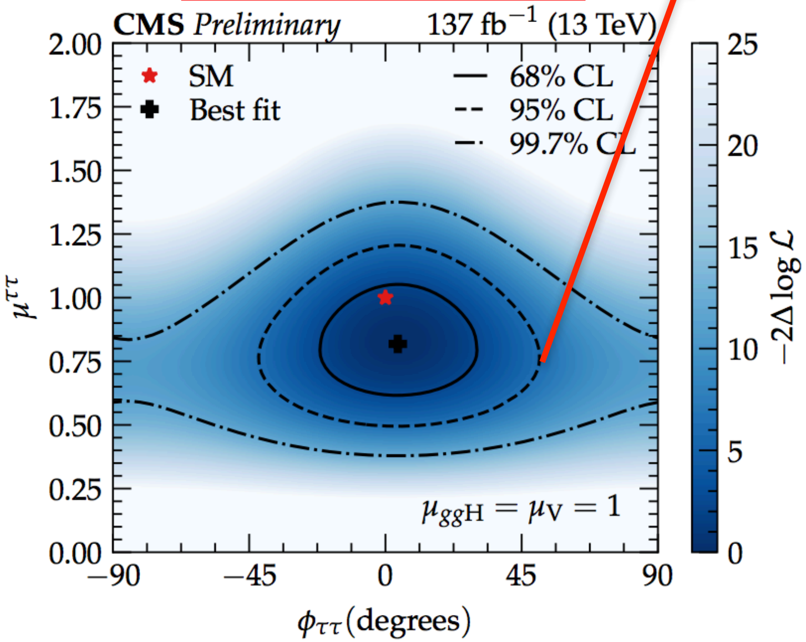
$$\mathscr{L}^{CPV}_{\bar{\tau}\tau h} = -\frac{y_f}{\sqrt{2}}\,\bar{\tau}(\kappa_\tau + i\tilde{\kappa}_\tau\gamma_5)\,\tau\,h$$

Mixing angle between CP-even and CP-odd τ Yukawa couplings measured 4 ± 17°, compared to an expected uncertainty of ±23° at the 68% confidence level, while at the 95% confidence level the observed (expected) uncertainties were ±36° (±55)°.
Results compatible with SM predictions.

$$\boxed{\begin{array}{l} h_2 = H; pp \to Ht\bar{t} \\ h_2 = A \to \tau^+\tau^- \end{array}}$$

Scenario excluded at 95% CL





CMS collaboration, CMS-PAS-HIG-20-006

Direct Searches at LHC 1 EDMs 0

$$\phi_{\tau\tau} = \alpha$$

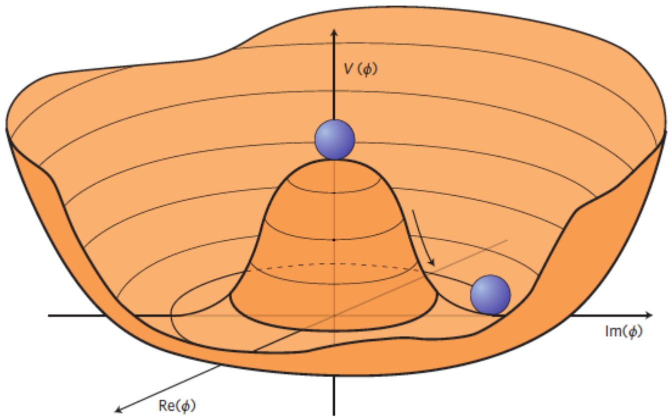
The end

A bit more?

Profiling the Higgs potential - double Higgs final states

The SM potential

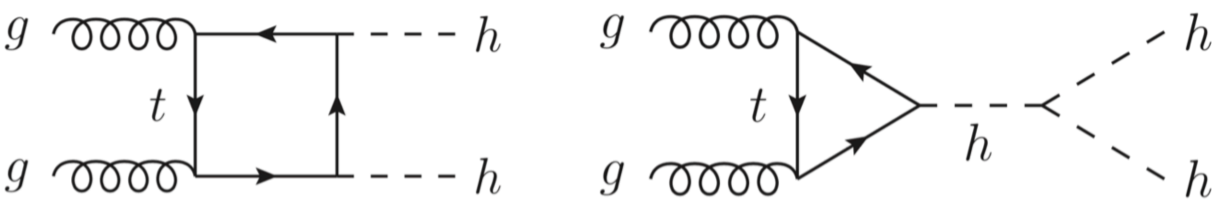
$$V_{SM} = m_{11}^2 |\Phi_1|^2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2$$



We know the mass and the VEV

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

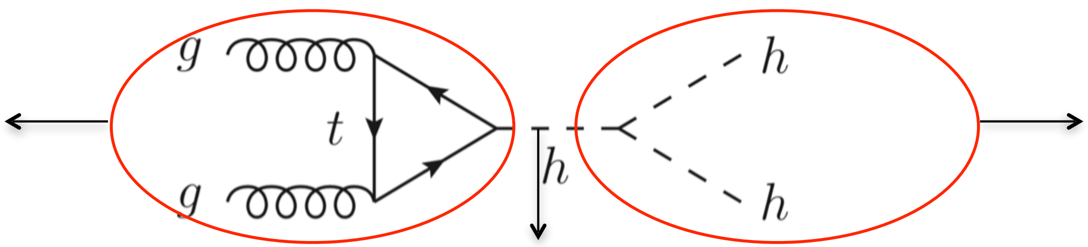
So is this the correct quartic coupling?



Negative interference in the SM

And BSM can be anywhere

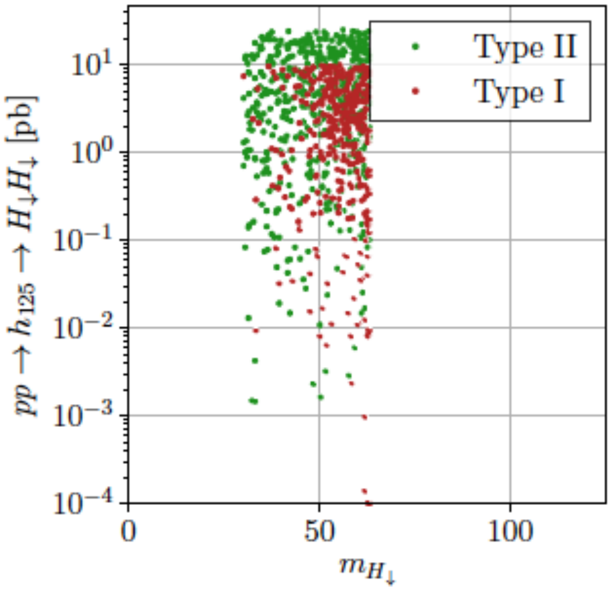
Initial state

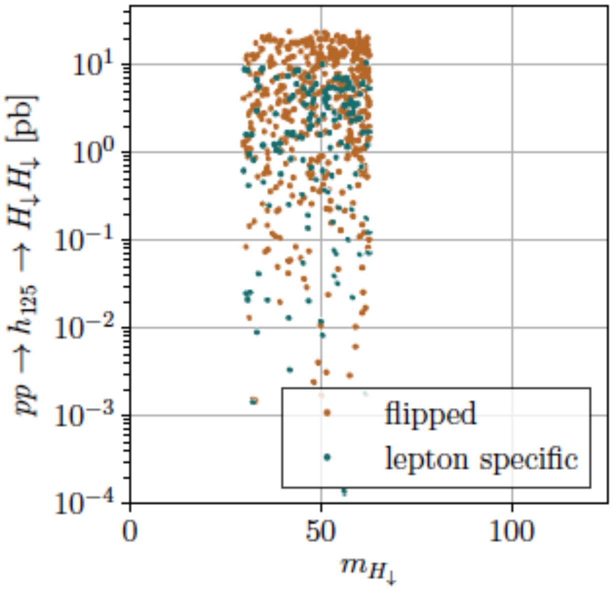


Final state

Intermediate state

Profiling the Higgs potential - double Higgs final states

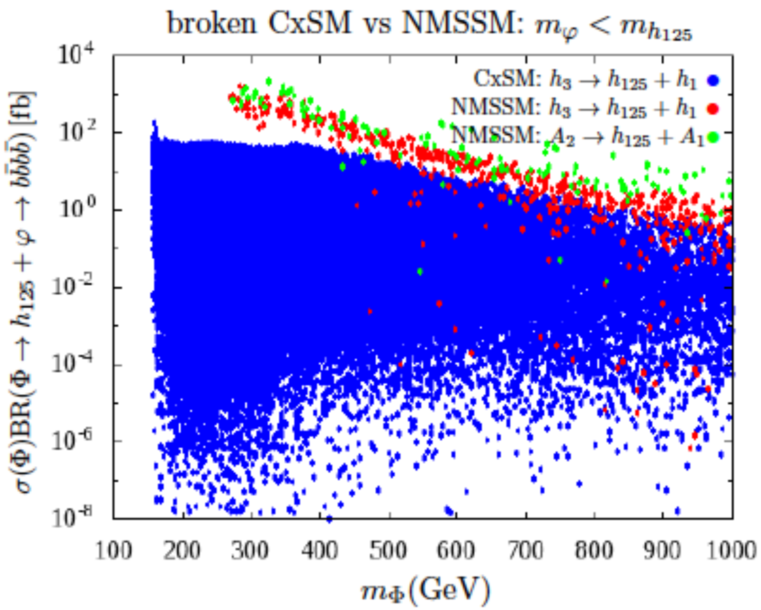




$$pp \to H \to h_{125} h_{125}$$

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

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



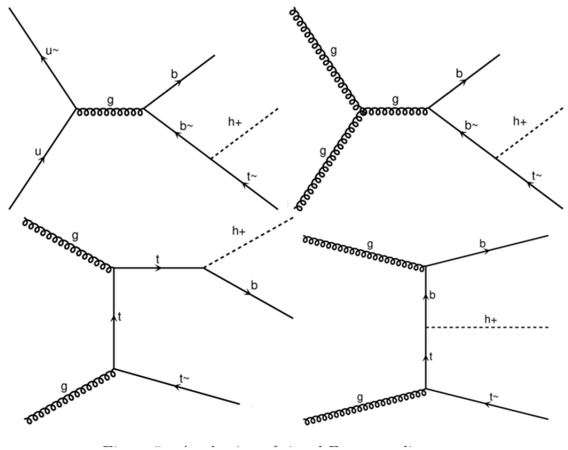
$$pp \to H \to h_{125} h$$

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

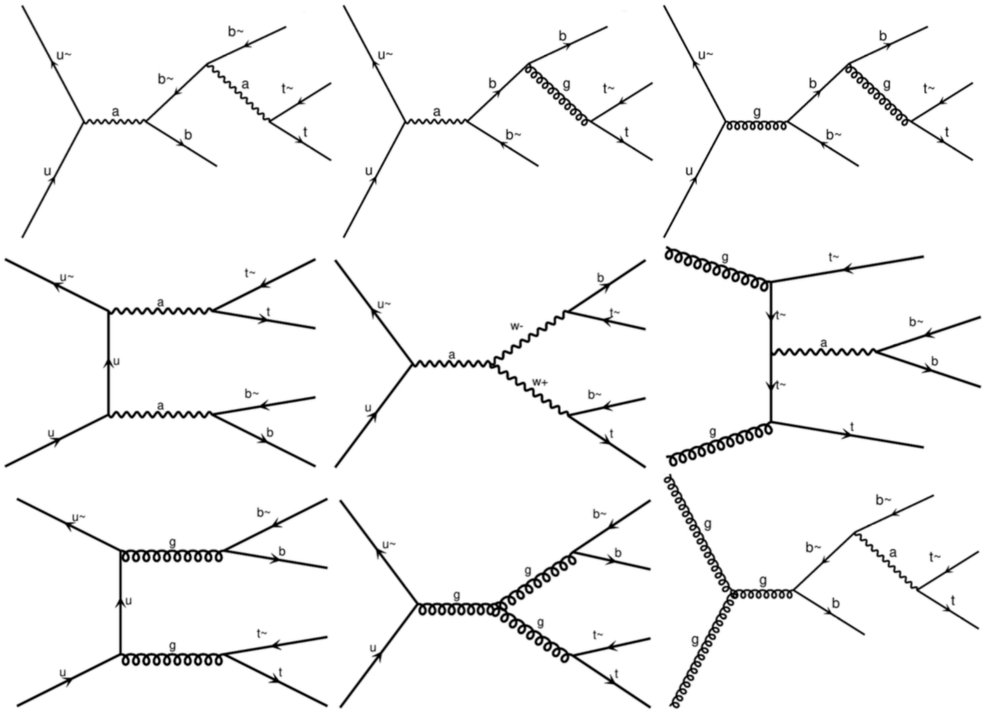
Interference between signal and background

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)

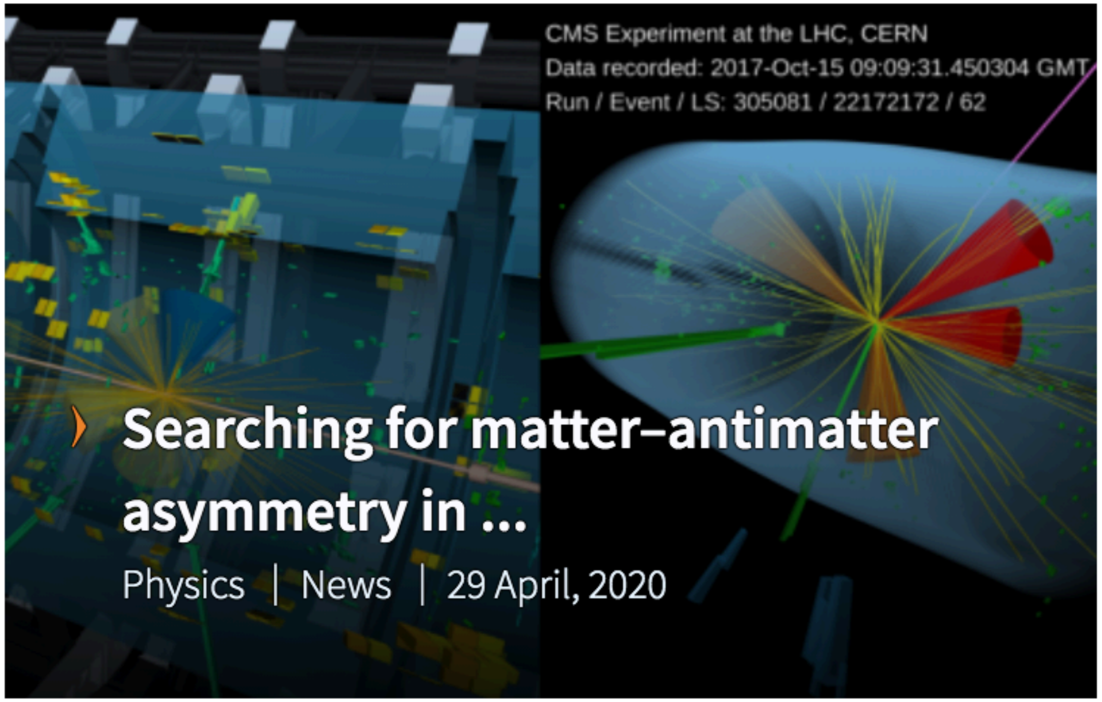


Background (even less diagrams)

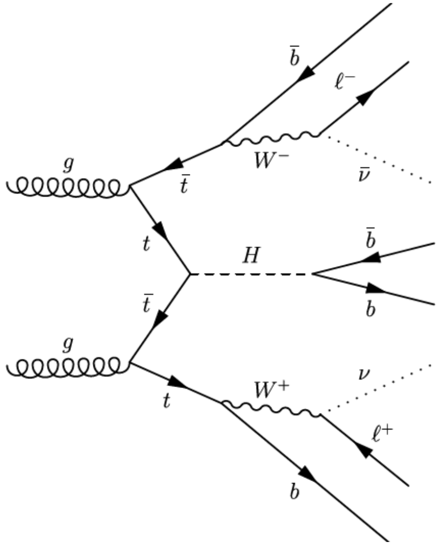
Cut	S	B	T	I	ΔI
No cuts:	9720	3923550	3941700	8429	2487
$N_\ell = 1$:	2160	904247	907925	1518	1193
$N_J \geq 5$:	1938	624001	627534	1594	992
$N_{BJ} \geq 2$:	1511	404919	408054	1623	799
$\not{E} > 20$ GeV:	1435	373648	376517	1433	768
$\not{E} + m_T^W > 60$ GeV:	1412	364026	366898	1458	758
Cut	**S**	**B**	**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

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

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

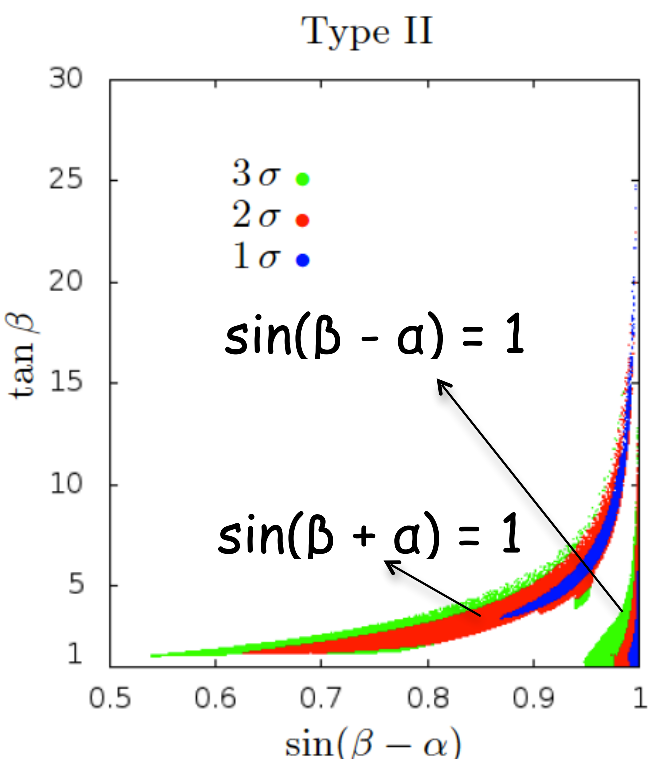
Let us now look at the 2HDM in more detail

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

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

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).

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



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

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.

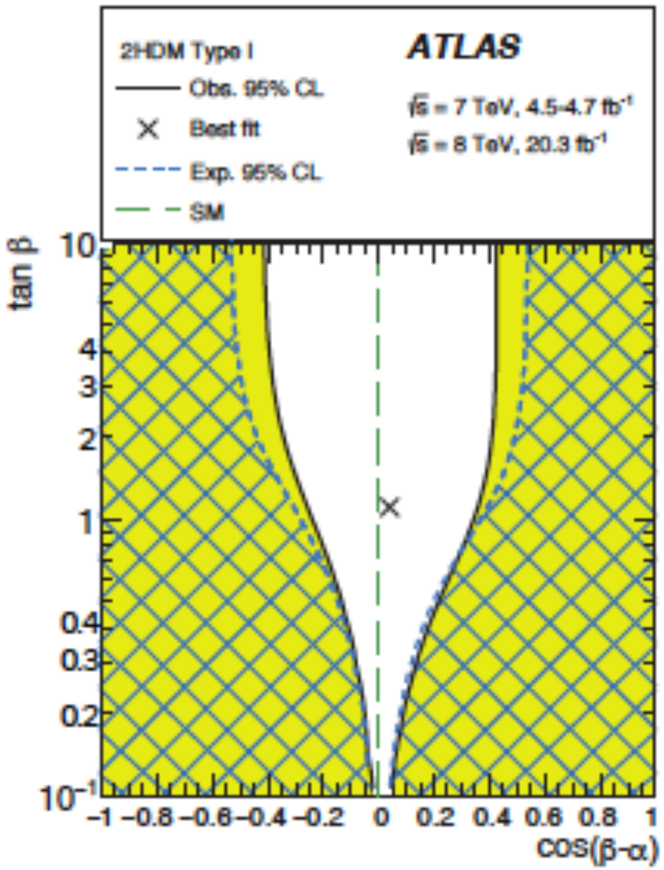
Ferreira, Gunion, Haber, RS, PRD89 (2014) 11, 115003

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

h_{125} couplings measurements

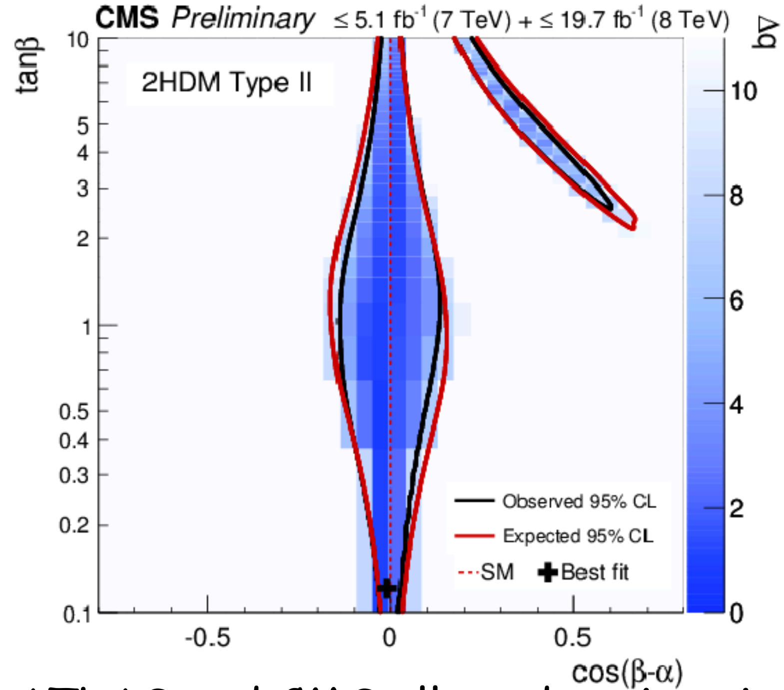
Bounds on the couplings modifiers

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



(a) Type I

ATLAS 1509.00672

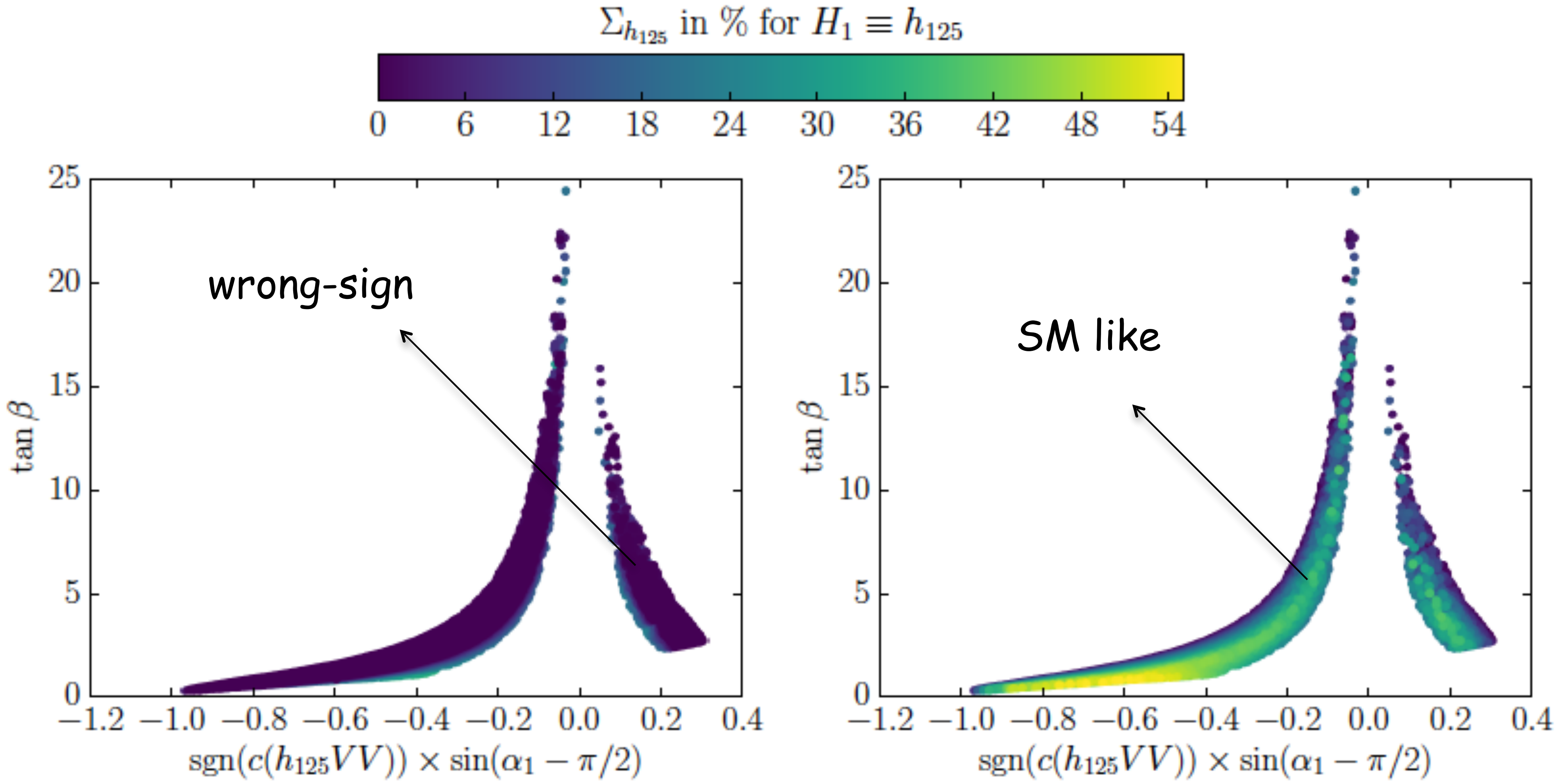


CMS-PAS-HIG-16-007

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

$\Sigma_i^{\rm N2HDM} = (R_{i3})^2$ 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

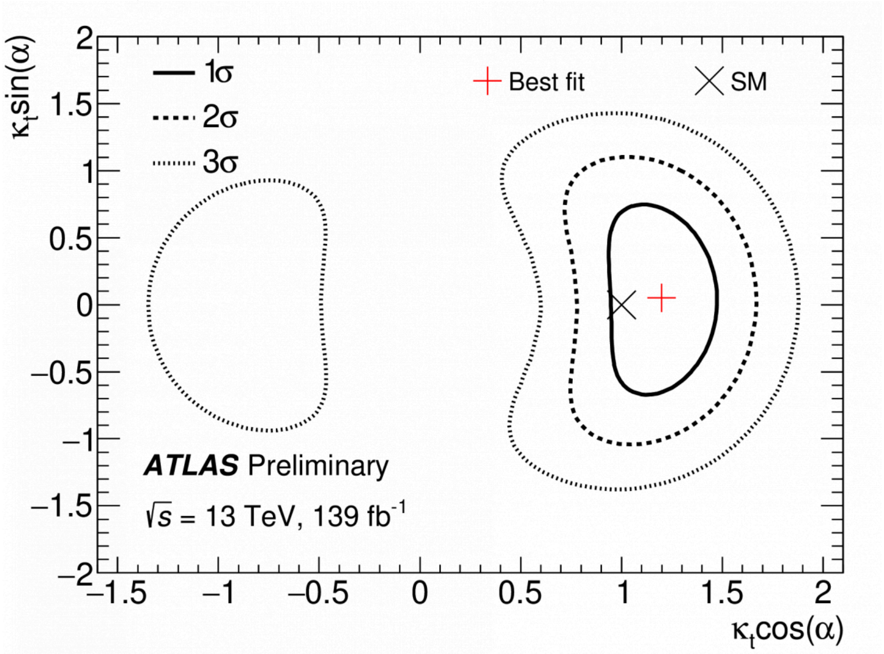
But can we check the CP-nature of the Yukawa Couplings?

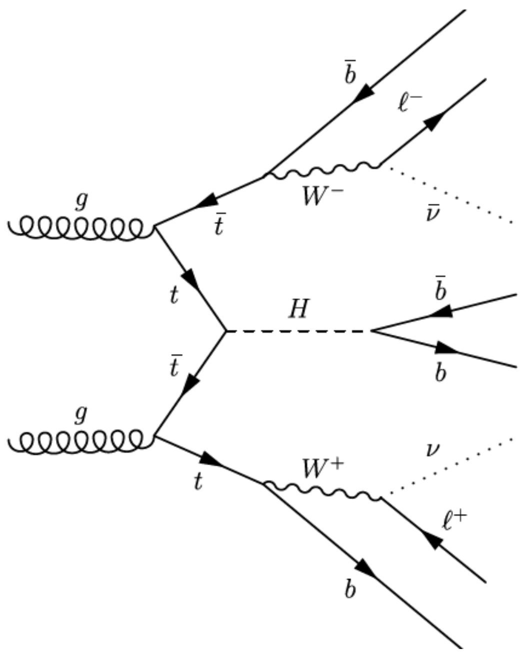
$$\boxed{pp \to (h \to \gamma\gamma)\bar{t}t}$$

$$\mathscr{L}_{\bar{t}th}^{CPV} = -\frac{y_f}{\sqrt{2}}\,\bar{t}(\kappa_t + i\tilde{\kappa}_t\gamma_5)\,t\,h$$

All measurements are consistent with the SM expectations, and the possibility of a pure CP-odd coupling between the Higgs boson and top quark is severely constrained. A pure CP-odd coupling is excluded at 3.9σ, and |α| > 43° is excluded at 95% CL.

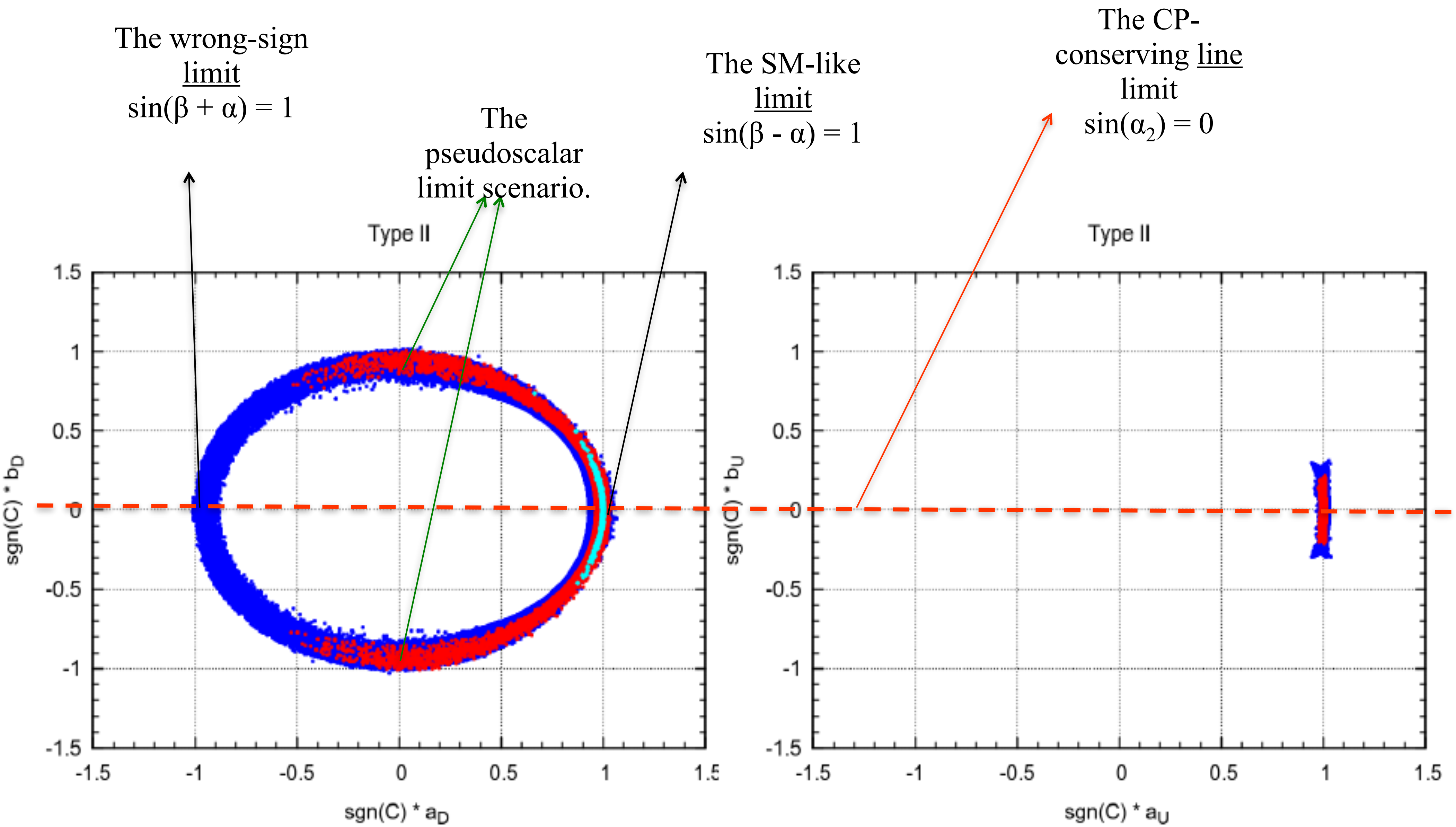
$$\kappa_t = \kappa\,\cos\alpha \qquad \tilde{\kappa}_t = \kappa\,\sin\alpha$$





ATLAS collaboration, PRL 125 (2020) 6, 061802

C2HDM



Left: sgn(C) b_D (or b_L) as a function of sgn(C) a_D (or a_L) for Type II, 13 TeV, with rates at 10% (blue), 5% (red) and 1% (cyan) of the SM prediction.
Right: same but for up-type quarks.

C2HDM

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

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

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

Type II

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

$$\boxed{\begin{array}{l} \sin(\beta+\alpha) = 1 \implies \kappa_D = \kappa_L = -1 \\ \qquad\qquad \sin(\beta-\alpha) = \dfrac{\tan^2\beta - 1}{\tan^2\beta + 1} \implies \kappa_V \geq 0 \text{ if } \tan\beta \geq 1 \end{array}}$$

Constraints on $\tan\beta$ OK!

Type I

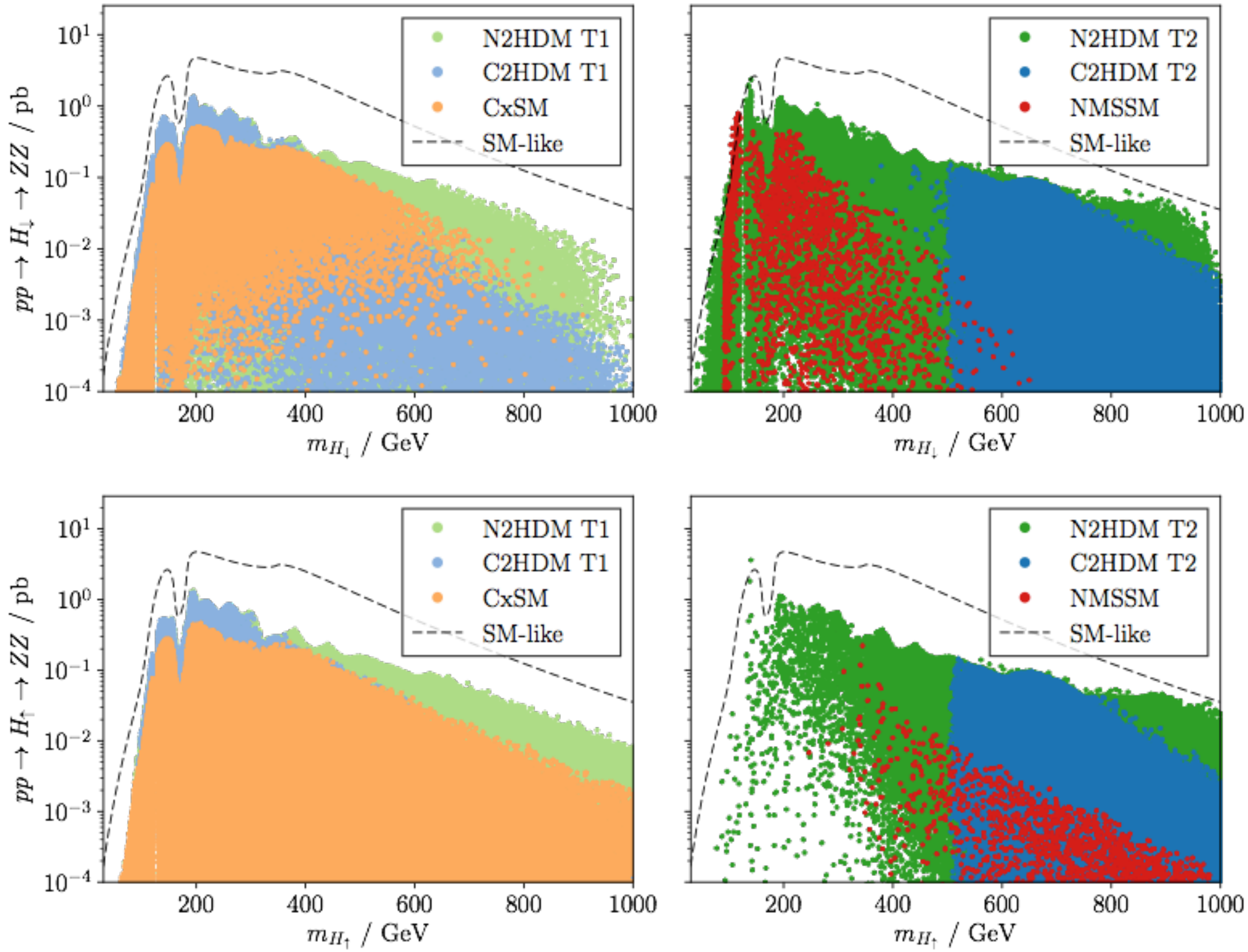
$$\kappa_U = \kappa_D = \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta$$

$$\boxed{\begin{array}{l} \sin(\beta+\alpha) = 1 \Rightarrow \kappa_U = 1 \quad (\kappa_D = 1) \\ \qquad\qquad \sin(\beta-\alpha) = \dfrac{\tan^2\beta - 1}{\tan^2\beta + 1} \Rightarrow \kappa_V \leq 0 \text{ if } \tan\beta \leq 1 \end{array}}$$

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

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

Dashed line is the "SM".



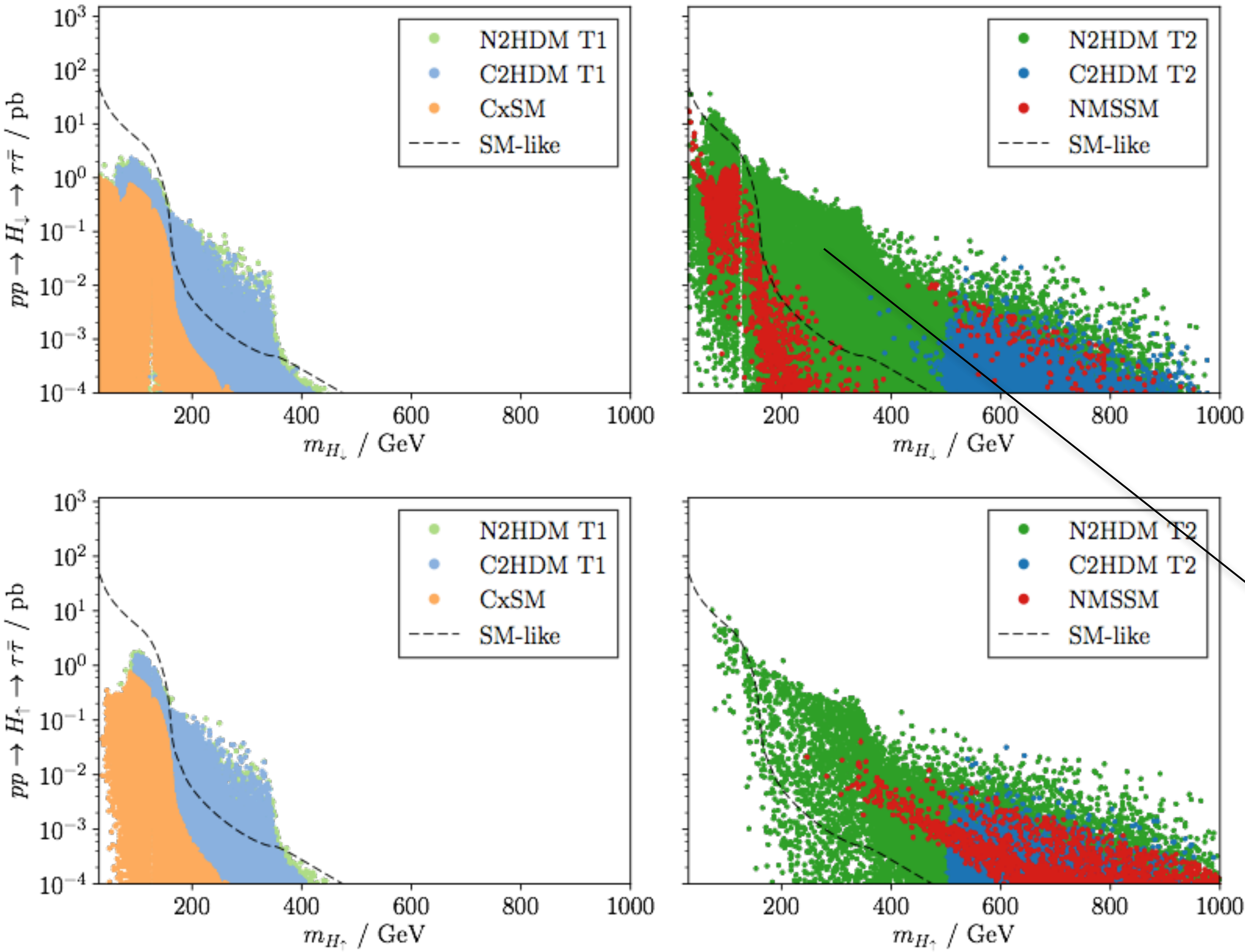
Signal rates for the production of $H\downarrow$ (upper) and $H\uparrow$ (lower) for 13 TeV as a function of m_H.

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.

- **The Inert 2HDM**

$$\boxed{\begin{aligned}V(\Phi_1,\ \Phi_2) = m_1^2\Phi_1^+\Phi_1 + m_2^2\Phi_2^+\Phi_2 - \left(m_{12}^2\Phi_1^+\Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^+\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^+\Phi_2\right)^2 \\ + \lambda_3\left(\Phi_1^+\Phi_1\right)\left(\Phi_2^+\Phi_2\right) + \lambda_4\left(\Phi_1^+\Phi_2\right)\left(\Phi_2^+\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^+\Phi_2\right)^2 + \text{h.c.}\right]\end{aligned}}$$

$$V(\Phi_1,\ \Phi_2)/.\ m_{12}^2 \rightarrow 0 \quad \langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix};\ \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ 0\end{pmatrix} \qquad \left\{\begin{array}{l}\Phi_1 \rightarrow \Phi_S \\ \Phi_2 \rightarrow \Phi_D\end{array}\right.$$

The first doublet contains the SM-like Higgs boson h.

The second doublet contains four dark (inert) scalars H, A and H±.

H is taken to be the lightest scalar (stable).

2HDM (Inert)