IDPASC and LIP
PhD student workshop

Future Challenges for Higgs Physics

PhD Workshop IDPASC-LIP, 1/7/2019

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The following is a completely personal and entirely subjective opinion from THIS theorist...

CHALLENGE I

KBO

This may not seem *SEXY* or *MIND BLOWING*, but the most important thing to do now in Higgs physics is to PUSH THE LHC TO ITS LIMITS and EXECUTE ITS PHYSICS PROGRAM TO THE VERY END.

To do that we need a steady flow of RESEARCHERS and STUDENTS. New minds, new fresh perspectives, are fundamental to carry what has been planned to fruition, or to interprete (hopefully) unexpected results.

Why is this so important? *BECAUSE THE STANDARD MODEL NEEDS TO BE TESTED THOROUGHLY*. And because the scalar sector is an entirely new area of the model which has barely been scratched.

PRECISION MEASUREMENTS OF THE PROPERTIES OF THE HIGGS WILL TELL US A LOT ABOUT EVENTUAL NEW THEORIES.

KBO: ***Keep Buggering On***

(or: finish your thesis, kids, and ALWAYS do what your Most Wise Supervisor says...)

CHALLENGE II

***K TWITTER AND FACEBOOK SOCIO-PHYSICS

By this I mean, LET THEORISTS STOP BEING SO BLOODY IMPATIENT.

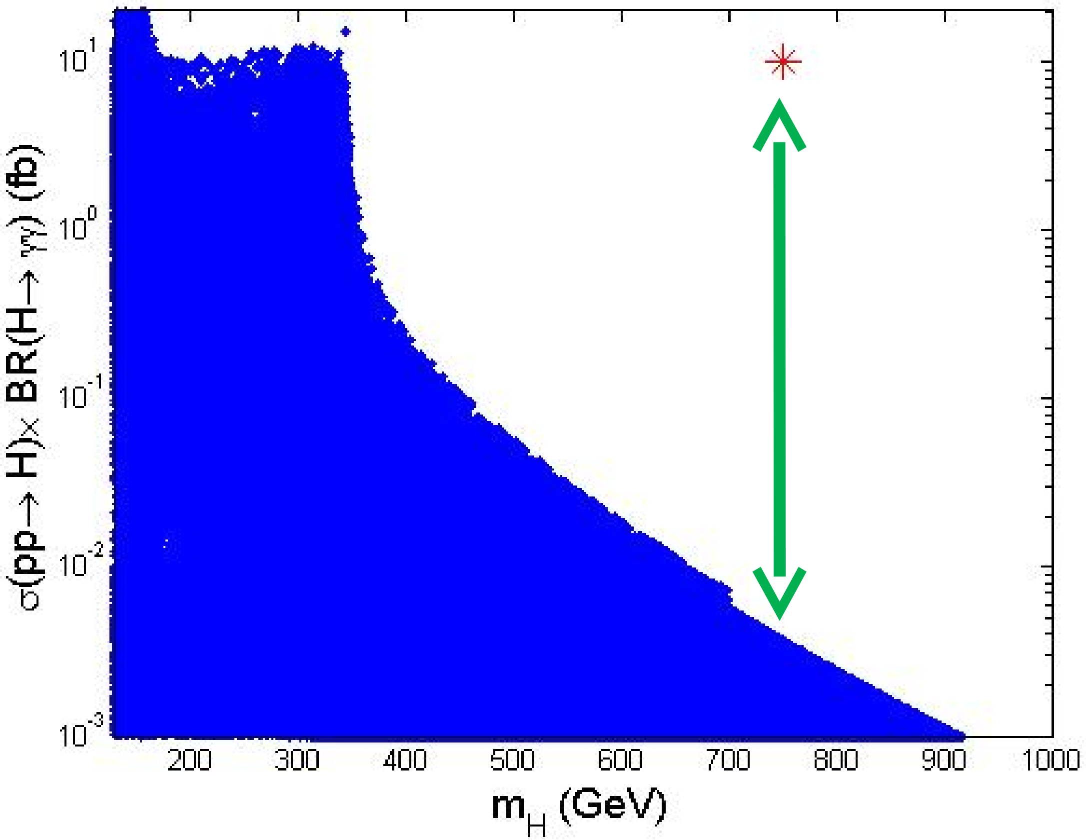
Here're some important dates for you:

1983 – W and Z bosons discovery (UA1 and UA2) - theorised 1968 (17 YEARS)
1995 – top quark discovery (CFD and D0) - theorised 1973 (22 YEARS)
2000 – Tau neutrino discovery (DONUT) - theorised 1974 (26 YEARS)
2012 – Higgs boson discovery (ATLAS and CMS) - theorised 1964 (48 YEARS)

We have entered a domain of particle physics where discoveries are DIFFICULT. Eventual new particles will almost certainly be heavy, difficult to produce and even more difficult to detect – DEAL WITH IT!

Ten years of LHC operation have "only" produced the Higgs boson so far – STOP WHINING!

The 750 GeV *WHATEVER...*



BLUE:
theoretically acceptable 2HDM points + B physics + requiring that "h" is SM-like,

$$0.7 \leq \frac{\sigma(pp \to H)BR(H \to ZZ)}{\sigma^{SM}(pp \to H)BR^{SM}(H \to ZZ)} \leq 1.3$$

For theorists, this means *a source of frustration*, since the most popular models of the past decades (such as SUSY) are being put into question (*an euphemism for "slaughtered"*...). This almost certainly will necessitate a rethinking of many basic tenets of our ideas for Beyond the Standard Model physics, which is never easy (specially for older people, and younger people taught by prejudiced older people!).

For experimentalists, this means *a source of frustration*, since COME ON, you know you want to announce discoveries of new particles!

For students of both theoretical or experimental physics, this may mean *a source of frustration*, since the feeling of "IS THAT ALL THERE IS?" can be a dangerous motivation-killer...

... BUT YOU MUST KEEP FAITH, BROTHERS AND SISTERS! DESPITE THE NAYSAYERS, OUR FIELD IS FAR FROM REACHING ITS LIMITS!!

CHALLENGE III

FIGHT FOR THE FUTURE

Whether or not we discover new elementary particles at the LHC in the next years, an inescapable truth is now clear:

WE'RE GONNA NEED A BIGGER ~~BOAT~~.

COLLIDER

The Standard Model (SM) leaves a LOT to be explained:

-WHY do elementary particles have *THOSE* masses? Why is there such a strong hierarchy of masses? NOBODY KNOWS!

-HOW has the universe evolved to display such a blatant asymmetry between matter and anti-matter? CP violation in the SM cannot account for it (?), so where is the additional CP violation coming from? NOBODY KNOWS!

-WHAT is the origin of dark matter? SOMETHING seems to be playing havok with our astronomical/gravitational understanding of galaxies, but are we really to expect that that "stuff" cannot be detected in particle experiments?! NOBODY KNOWS!

Here's a basic and fundamental truth: *only particle physics can answer these questions!* And we need DATA to answer them, to inform theoretical explorations and constrain models. So we'll need to convince politicians that a new collider is a good investment. *TELL THEM WHATEVER IS NEEDED* – that new technologies will emerge from this; that transferrable skills will be developped; that there's a lot industries can learn from this.

All of that stuff has even the added advantage of being true... Just don't let them in on that very basic and dirty secret of particle physics...

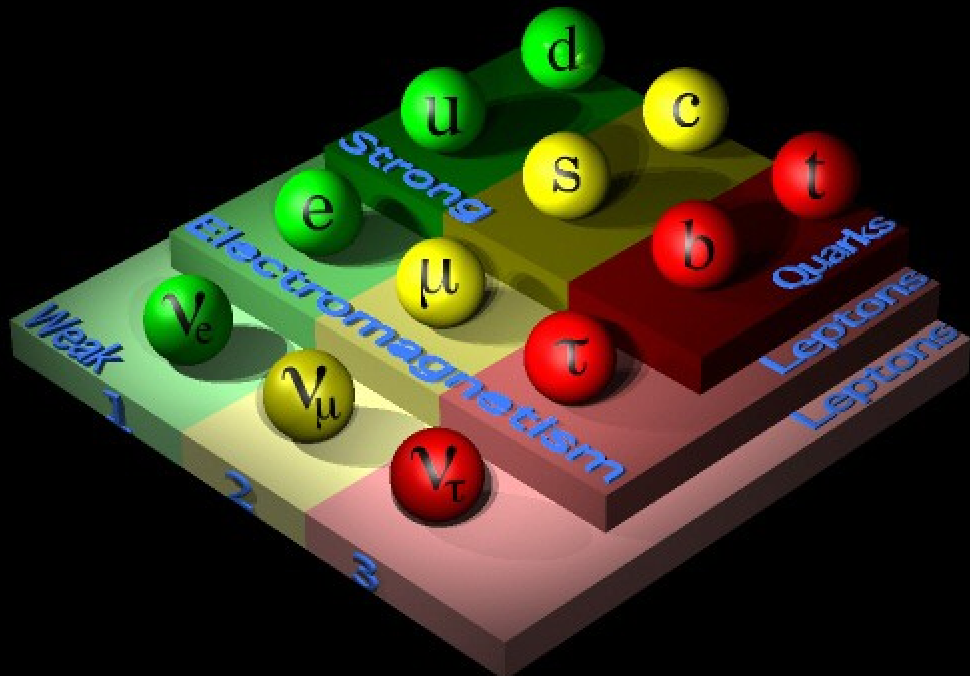
... THAT WE DO IT BECAUSE IT'S FUN AND BEAUTIFUL.

So, let's
particle..

THE HIG s...)

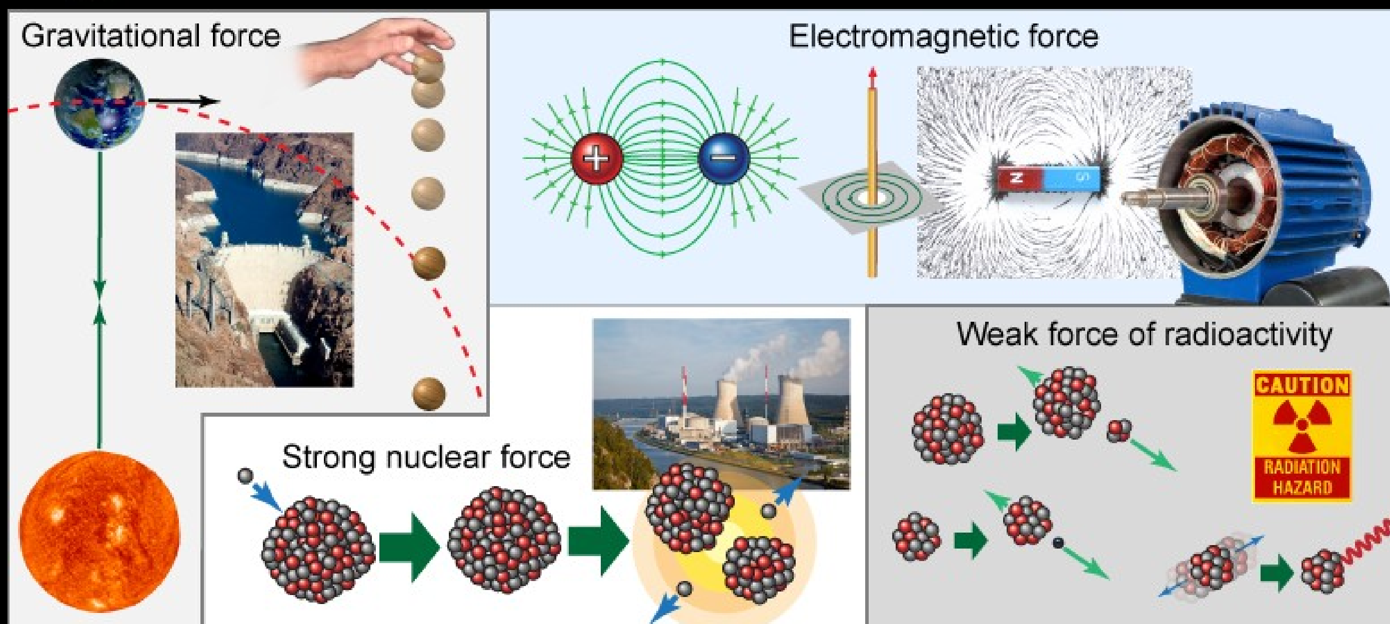
Models w del,
containin have
been use ass
(DONE!), fact
that the u atter,
not antim

One out

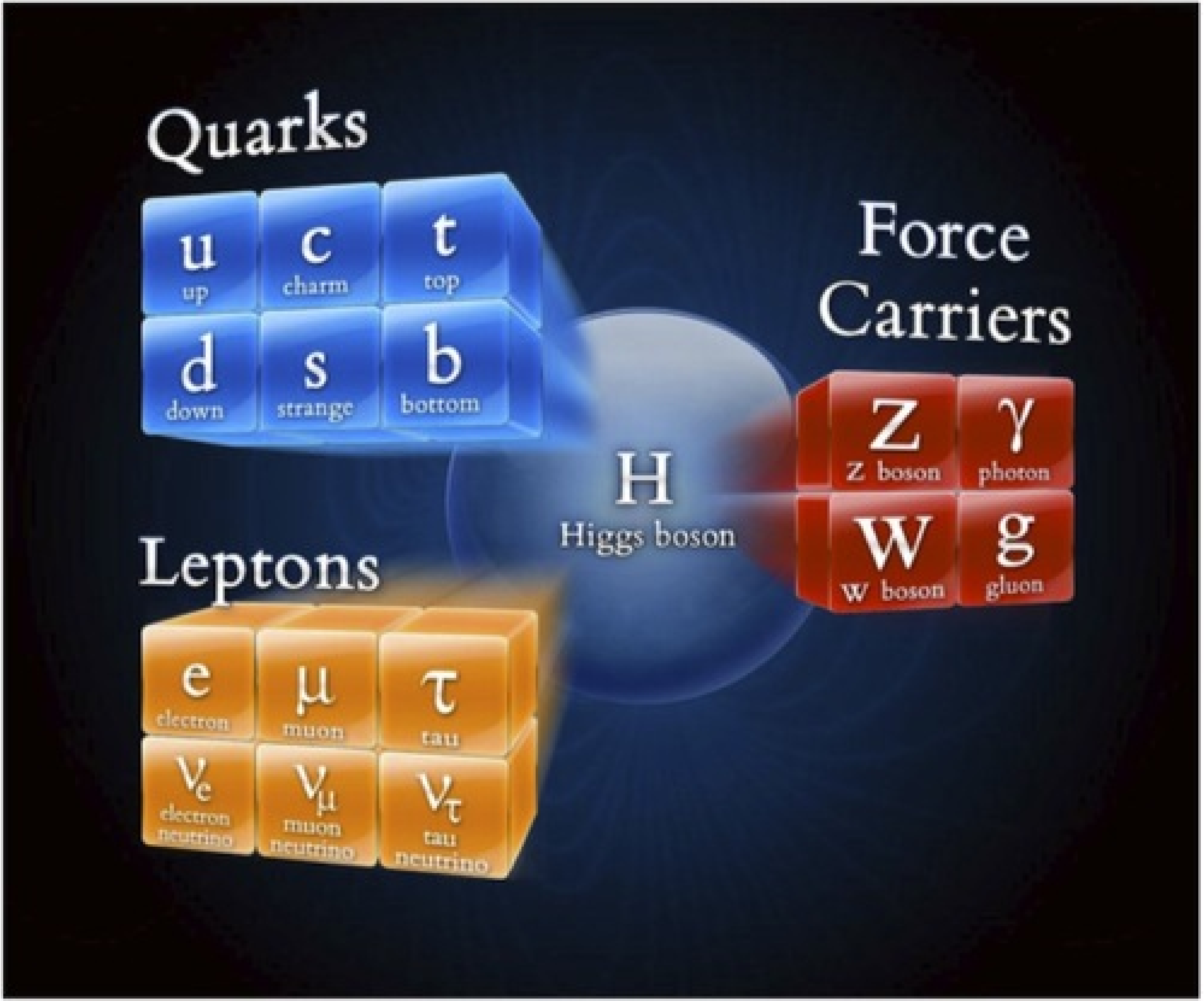


Matter is composed of elementary particles - **FERMIONS**

Interactions are mediated by particles – **GAUGE BOSONS**



One Higgs to Give Mass to (almost) Them All...



FUNDAMENTAL PRINCIPLE OF PARTICLE PHYSICS

- When you have an unsolvable problem…

… *invent a new particle*!

WHY WE NEED THE HIGGS MECHANISM:

MATTER + INTERACTIONS + SIMMETRY = ALL MASSES ZERO!

HOW DO ELEMENTARY PARTICLES GAIN THEIR MASS?

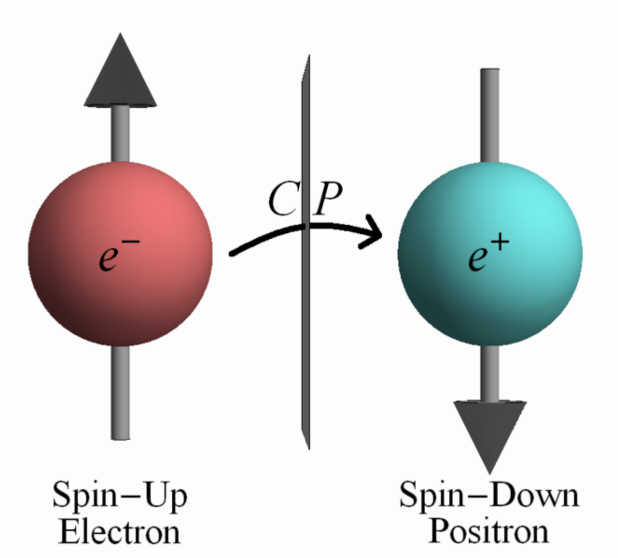
Due to their interactions with a misterious particle, which was only discovered in 2012, almost 50 years after it had been proposed

THE HIGGS BOSON!

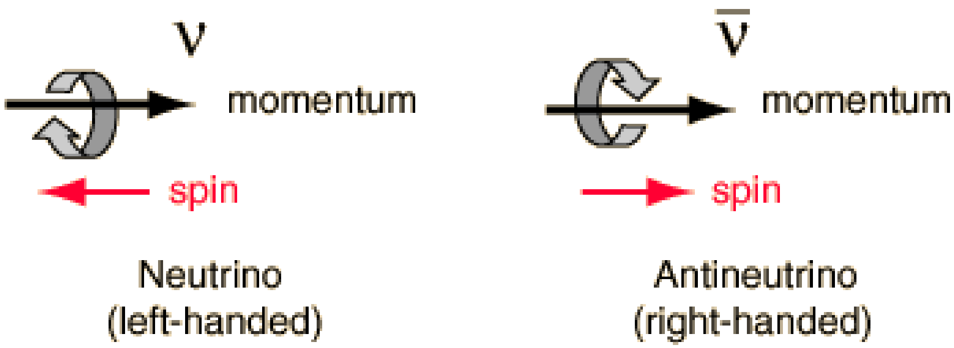
But the Higgs mechanism only explains WHY the elementary particles have mass, not why they have THOSE masses.

NOBODY KNOWS **why the electron mass is 0.511 MeV/c^2 and the top quark's mass is 173000 MeV/c^2...**

To define an antiparticle, it is not sufficient to swap the SIGN of the electric charge – it is also necessary to swap *parity*.

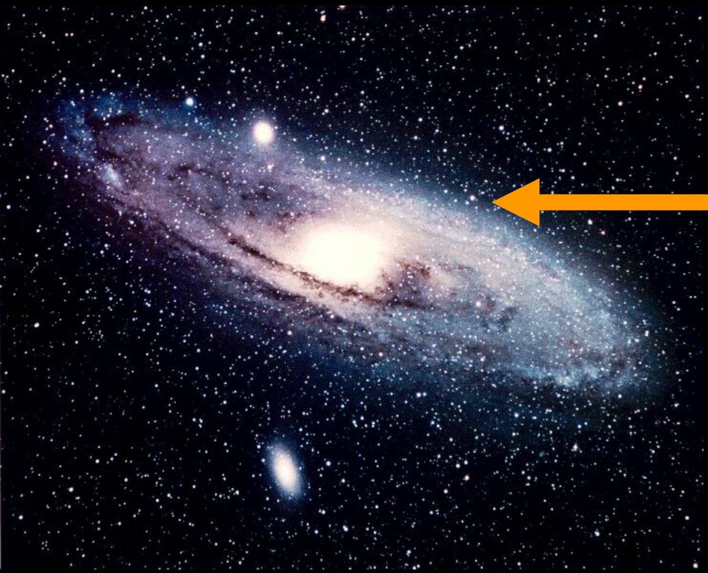


For neutrinos in particular this is very relevant…



IN THE SM, THE ONLY SOURCE OF CP VIOLATION COMES FROM THE FERMION SECTOR (THE CABBIBO-KOBAYASHI-MASKAWA MATRIX) AND IT IS *INSUFFICIENT* (?) TO EXPLAIN WHY THERE IS SO MUCH MORE MATTER THAN ANTIMATTER IN THE UNIVERSE!

The universe is essentially made of matter, not antimatter.



Here we are, in the Milky Way…

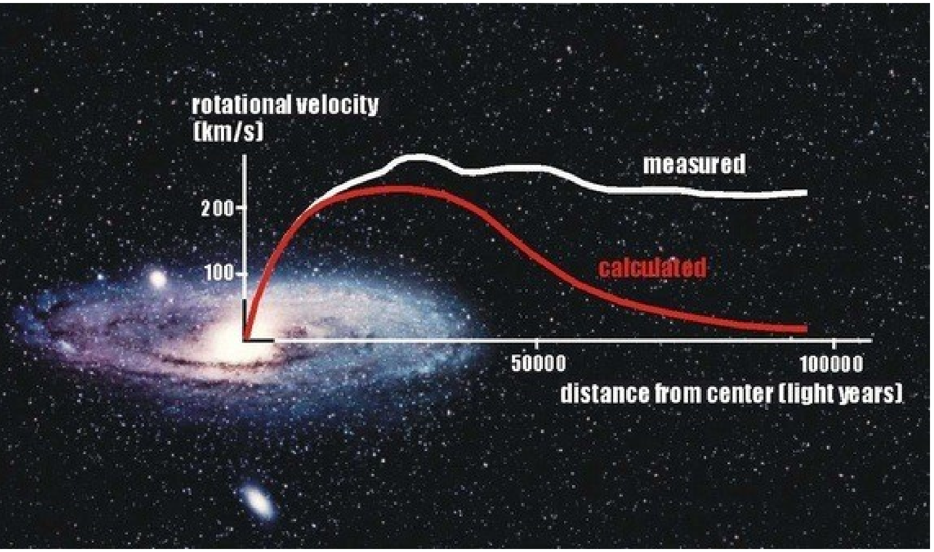
These are our neighbours in Andromeda…

And this is what would happen if all galaxies were not made up of matter!

Why this huge asymmetry?

NOBODY KNOWS...

And by the way, apparently most of the matter in the universe is non-baryonic, weird stuff that we only see hints of through gravity...



The rotational speed of stars in galaxies, the behaviour of large galaxy clusters, gravitational lensing, analyses of the cosmic microwave background – all point out to the existence of an enormous quantity of matter which escapes visible detection:

DARK MATTER

What's it made of? *NOBODY KNOWS...*

And now for something completely different...

• **LHC discovered a new particle (a scalar?) with mass ~125 GeV.**

• **Up to now, all is compatible with the Standard Model (SM) scalar particle.**

BORING!

Two Higgs Dublet model, 2HDM (Lee, 1973) : one of the easiest extensions of the SM, with a richer scalar sector. Can help explain the matter-antimatter asymmetry of the universe, provide dark matter candidates, …

G.C. Branco, P.M. Ferreira, L. Lavoura, M. Rebelo, M. Sher, J.P Silva, Physics Reports 716, 1 (2012)

TWO HIGGS DOUBLET MODELS

- **They are the simplest Standard Model extension – instead of a single scalar doublet, we have two, Φ_1 and Φ_2.**

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi_1 + \mathrm{i}\,\varphi_2 \\ v_1 + \varphi_5 + \mathrm{i}\,\varphi_7 \end{pmatrix} \quad , \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi_3 + \mathrm{i}\,\varphi_4 \\ v_2 + \varphi_6 + \mathrm{i}\,\varphi_8 \end{pmatrix}$$

- **They do not affect the most successful predictions of the Standard Model.**

- **They have a richer scalar particle spectrum.**

- **They are included in more general models, such as the Supersymmetric one.**

- **They allow for the possibility of minima with spontaneous breaking of CP... (T.D. Lee, Phys. Rev. D8 (1973) 1226)**

The Two-Higgs Doublet potential

Most general SU(2) × U(1) scalar potential:

$$\begin{aligned} V &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{H.c.}] \\ &+ \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1) \\ &\times(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\ &+ \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{H.c.}] \end{aligned}$$

m^2_{12}, λ_5, λ_6 and λ_7 complex **- seemingly 14 independent real parameters**

Most frequently studied model: softly broken theory with a Z_2 symmetry,

$\Phi_1 \to -\Phi_1$ and $\Phi_2 \to \Phi_2$, meaning $\lambda_6, \lambda_7 = 0$.

It avoids potentially large flavour-changing neutral currents (FCNC)

Softly broken Z_2 potential

$$
\begin{aligned}
V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + h.c.\right) \\
&\quad + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right]
\end{aligned}
$$

- **EIGHT real independent parameters (all assumed real). Allows a *decoupling limit*.**
- **If the m^2_{12} parameter is complex, the model EXPLICITLY BREAKS the CP symmetry.**
- **The symmetry must be extended to the whole lagrangian, otherwise the model would not be renormalizable.**

Coupling to fermions

MODEL I: Only Φ_2 couples to fermions.

MODEL II: Φ_2 couples to up-quarks, Φ_1 to down quarks and leptons.

Doublet field components:

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

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

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

Definition of β angle:

$$\tan\beta \equiv \frac{v_2}{v_1}$$

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

$$\begin{aligned} h &= \rho_1 \sin\alpha - \rho_2 \cos\alpha, \\ H &= -\rho_1 \cos\alpha - \rho_2 \sin\alpha \end{aligned}$$

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

Scalar sector of the 2HDM is richer => more stuff to discover

Two dublets => **4 neutral scalars (h, H, A) + 1 charged scalar ($H^{\pm}$).**

$\left.\begin{matrix} h \\ \\ H \end{matrix}\right\}$ **CP-even scalars**

$h, H \rightarrow \gamma\,\gamma$

$h, H \rightarrow ZZ, WW$ (real or off-shell)

$h, H \rightarrow ff$

$H \rightarrow hh$ (if $m_H > 2m_h$)

…

A - CP-odd scalar (pseudoscalar)

$A \rightarrow \gamma\,\gamma$

~~$A \rightarrow ZZ, WW$~~

$A \rightarrow ff$

$A \rightarrow Zh$

…

Certain versions of the model provide a simple and natural candidate for Dark Matter – *INERT MODEL*, based on an unbroken discrete symmetry.

Deshpande, Ma (1978); Ma (2006); Barbieri, Hall, Rychkov (2006); Honorez, Nezri, Oliver, Tytgat (2007)

The α angle is the diagonalization angle of the 2×2 mass matrix of the CP-even scalars, h and H

$$\lfloor m^2 \rfloor_{ij} = -(\rho_1, \quad \rho_2) \begin{pmatrix} m_{12}^2 \frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2 \frac{v_1}{v_2} + \lambda_2 v_2^2 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

Couplings of scalars to fermions and gauge bosons depend on α, β.

For gauge bosons, for instance:

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

Coupling to Fermions

Each type of fermion only couples to ONE of the doublets. Four possibilities, with the convention that the up-quarks always couple to Φ_2 :

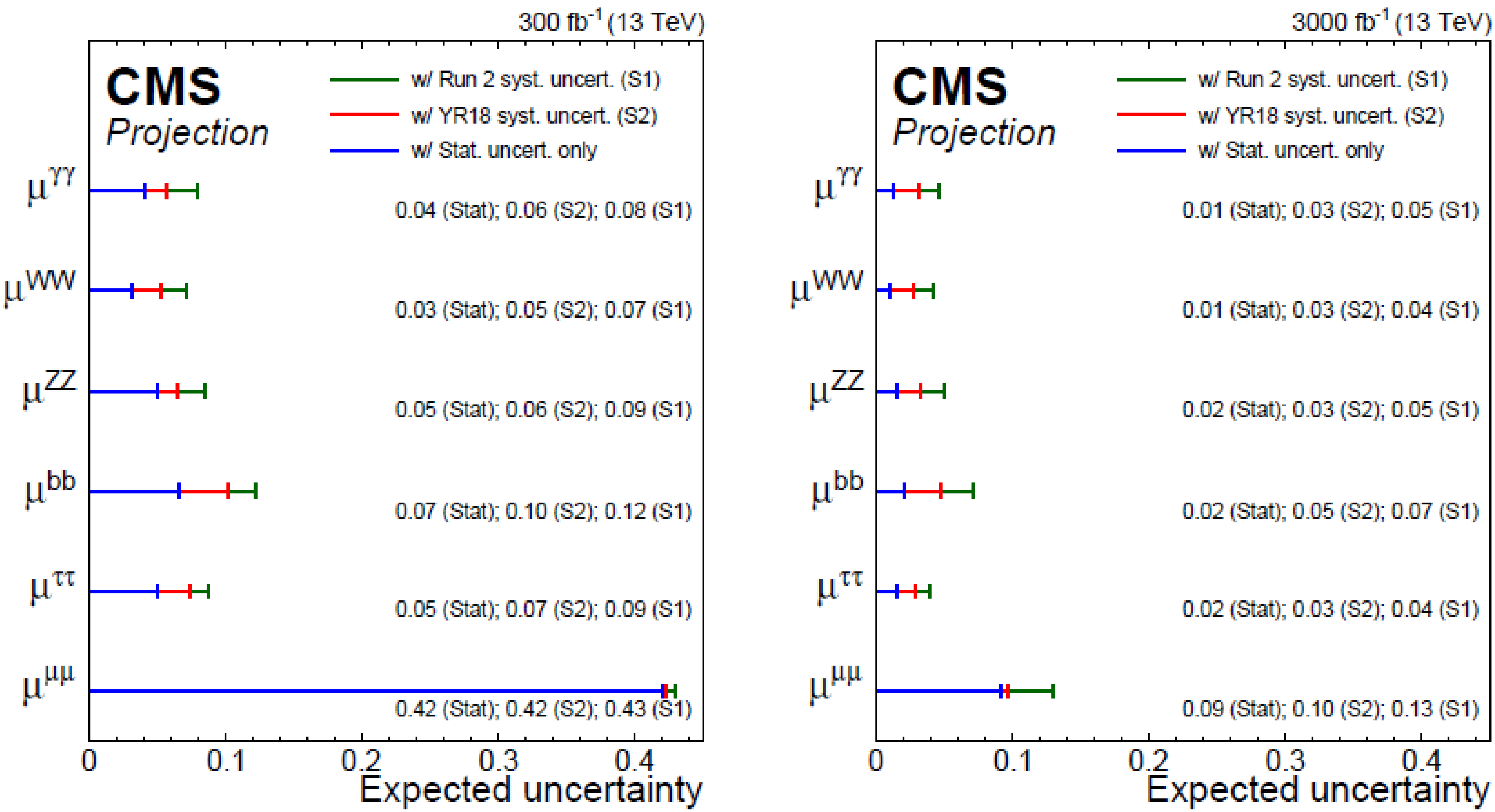
	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

$$- \left\{ \frac{\quad}{v} u \left(m_u \xi_A P_L + m_d \xi_A P_R \right) d H \quad + \frac{\quad}{v} \nu_L \ell_R H \quad + \text{h.c.} \right\}$$

THE IMPORTANCE OF HIGGS PRECISION DATA

(OR: *KBO*, LHC COLLABORATIONS)

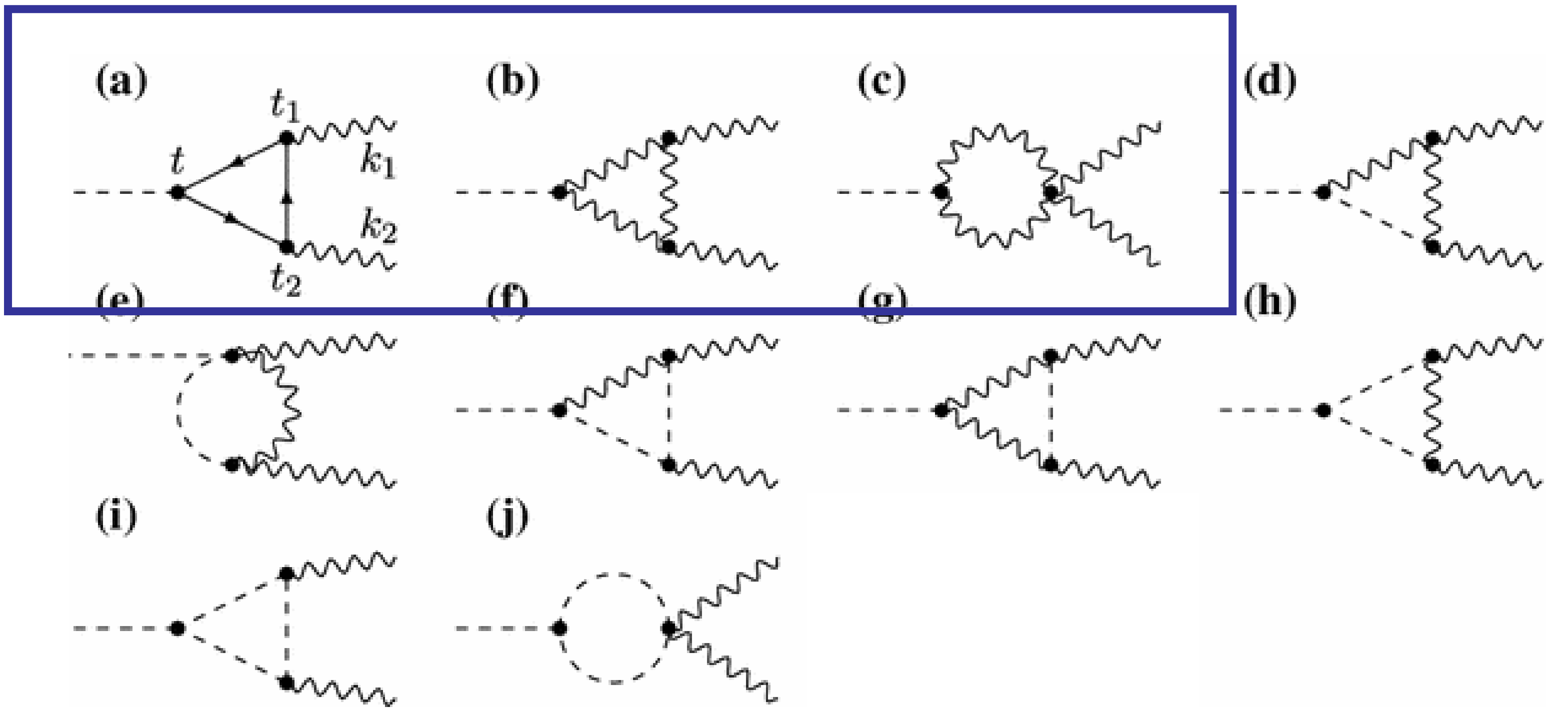
Where we'll be with High-luminosity LHC:



CMS PAS FTR-18-011

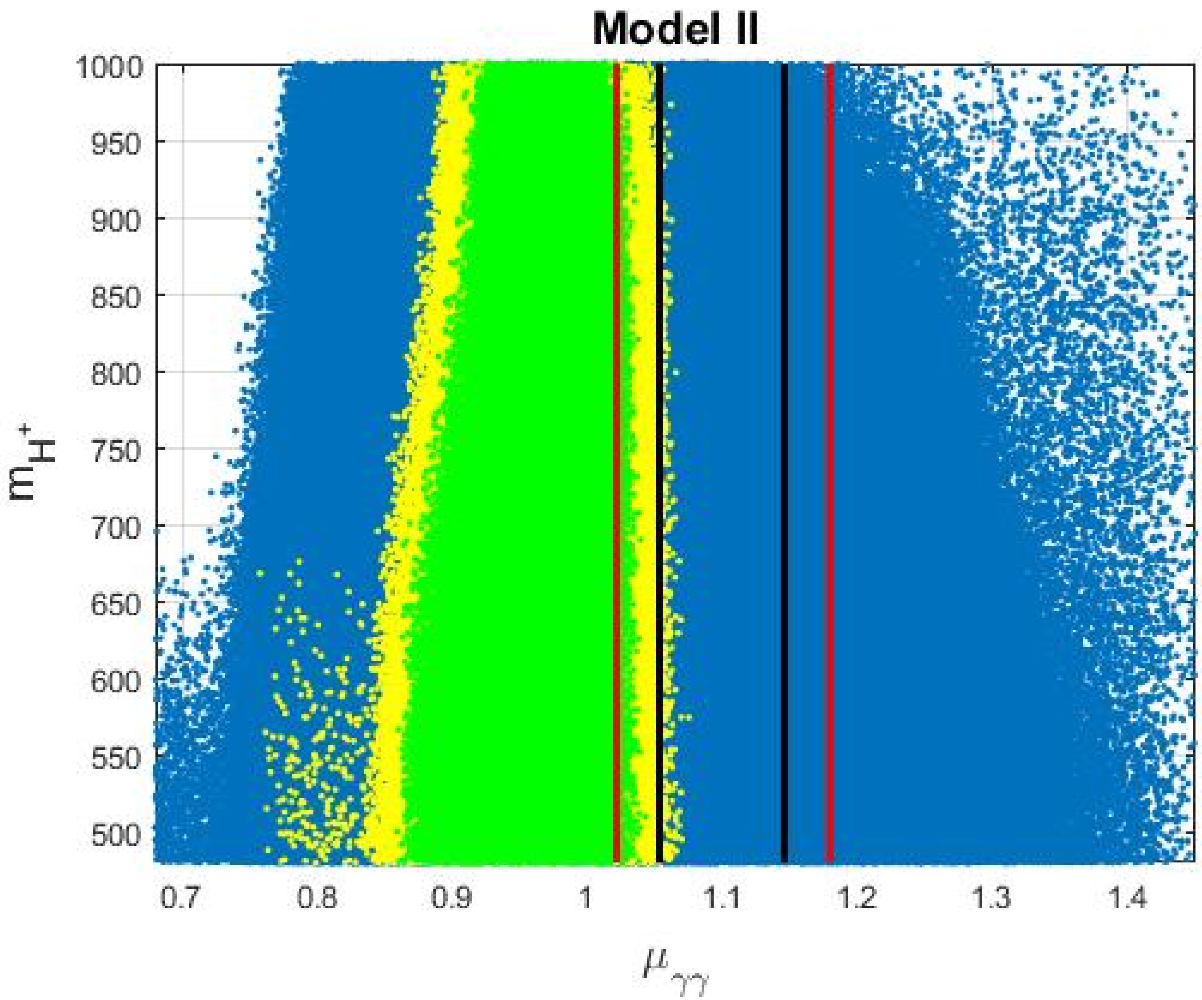
$$\mu_X = \frac{\sigma\,(pp \to h)\ \mathrm{BR}\,(h \to X)}{\sigma^{\mathrm{SM}}\,(pp \to h)\ \mathrm{BR}^{\mathrm{SM}}\,(h \to X)}$$

Higgs decaying to two photons



Diagrams involving an internal charged Higgs line (d to j) are NOT present in the SM, and may yield sizeable deviations from SM results.

Assume all constraints centered on 1 EXCEPT the γγ one



YELLOW: 300 fb^{-1} precision
GREEN: 3000 fb^{-1} precision

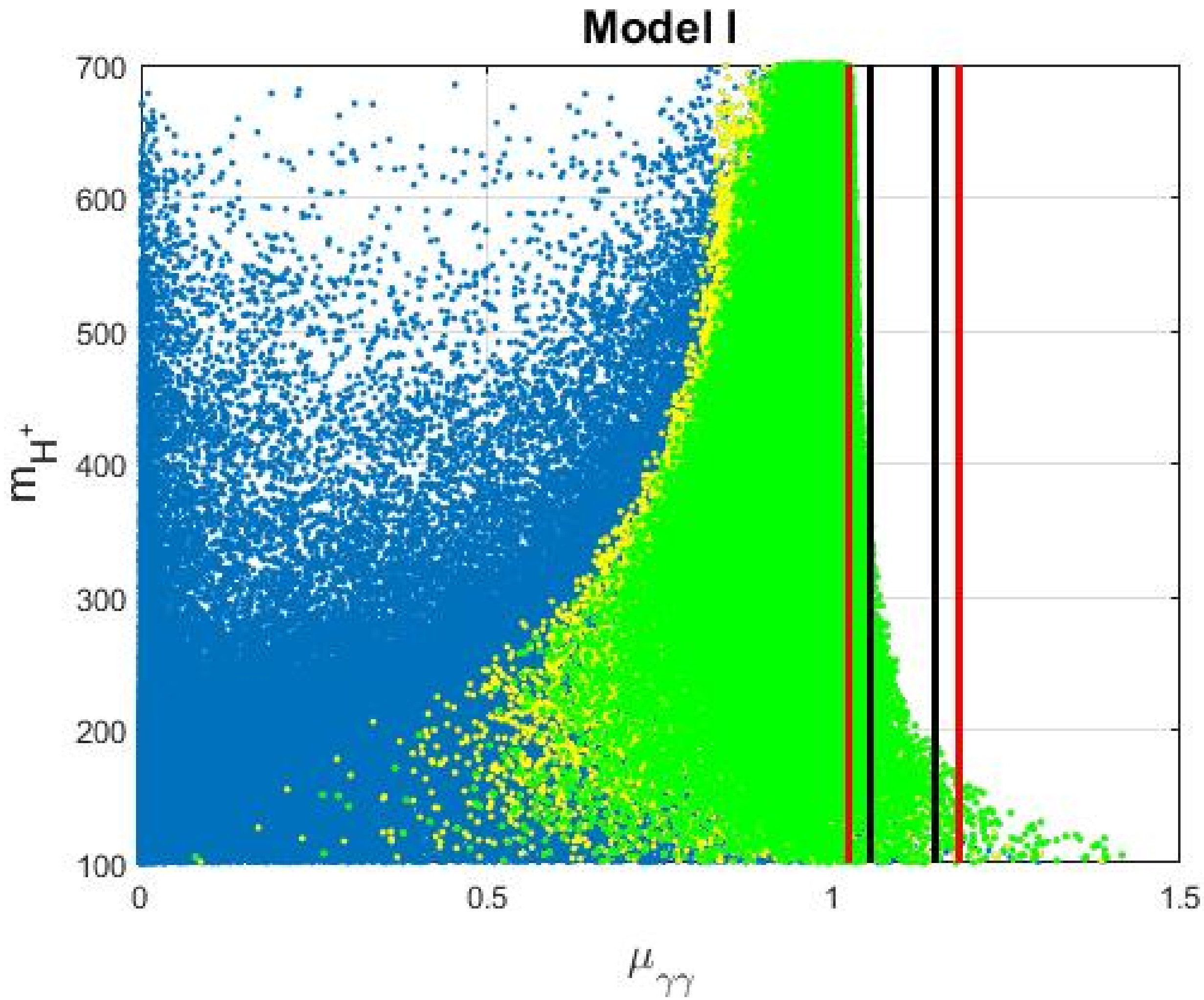
If $\mu_{\gamma\gamma}$ is found to be centered around ~1.1, the 2HDM type-II model could be EXCLUDED, even if all other observables were SM-like.

Values of $\mu_{\gamma\gamma}$ smaller than 1 favoured – that is due to the coupling between the Higgs boson h and the charged scalars $H^{\pm}$, which is essentially λ_3.

Due to boundedness from below and unitarity constraints, λ_3 is limited in range, and favours a *destructive interference* with the SM contributions.

No favoured regions for the charged mass, however. And in fact, the exclusion of the model would arise in great measure from the hard bound coming from B-physics on the mass of $H^{\pm}$.

Likewise, for Type I:



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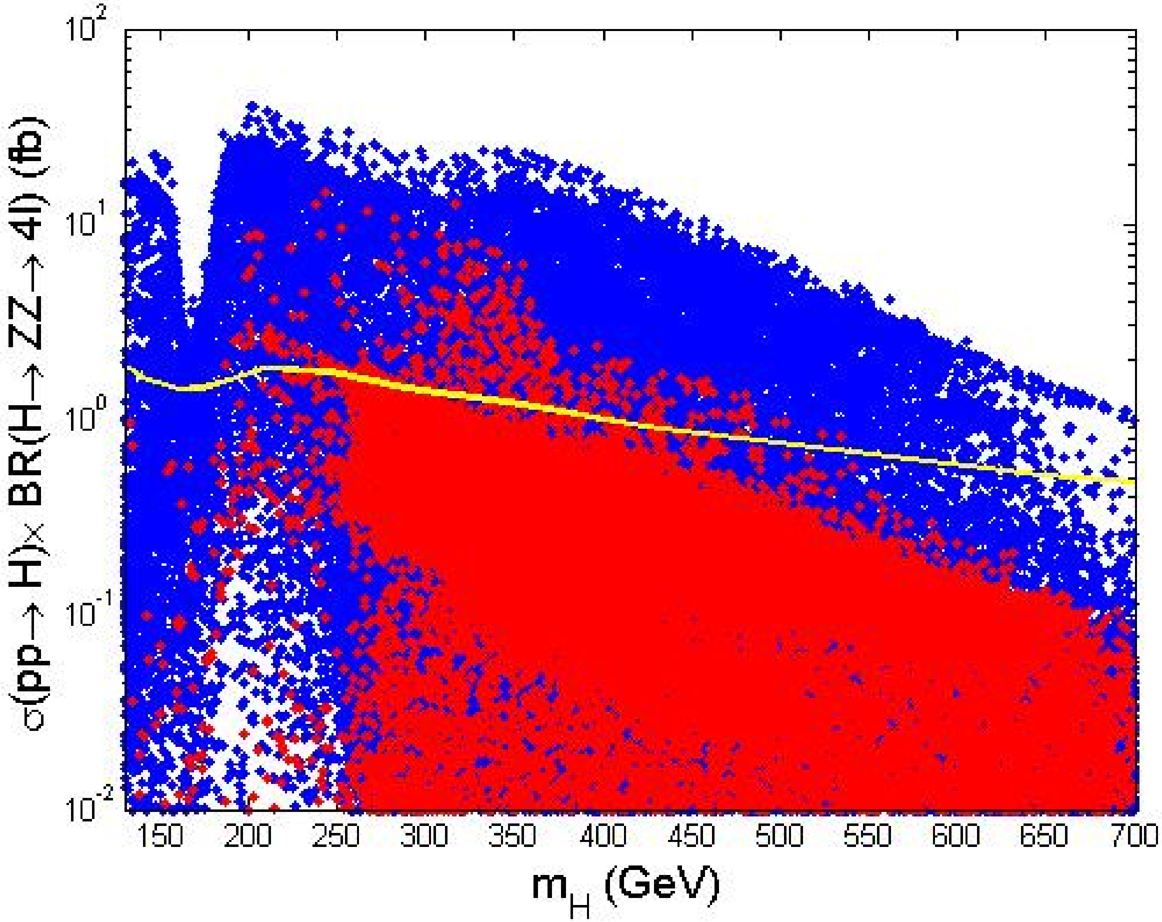
GREEN: 3000 fb^{-1} precision

Lower masses of the charged Higgs would produce $\mu_{\gamma\gamma}$ centered around ~1.1 – non decoupling effect!

The Importance of Being ~~Earnest~~ h

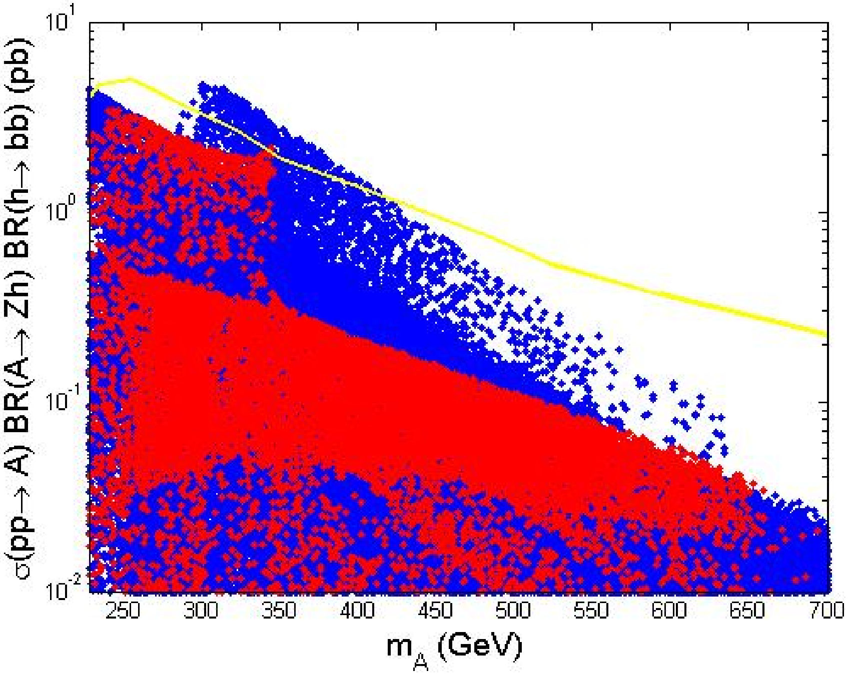
Run II has limits on high mass resonances in the 4 lepton channel...



(yellow line upper bound on non-observation from CMS PAS HIG-16-033)

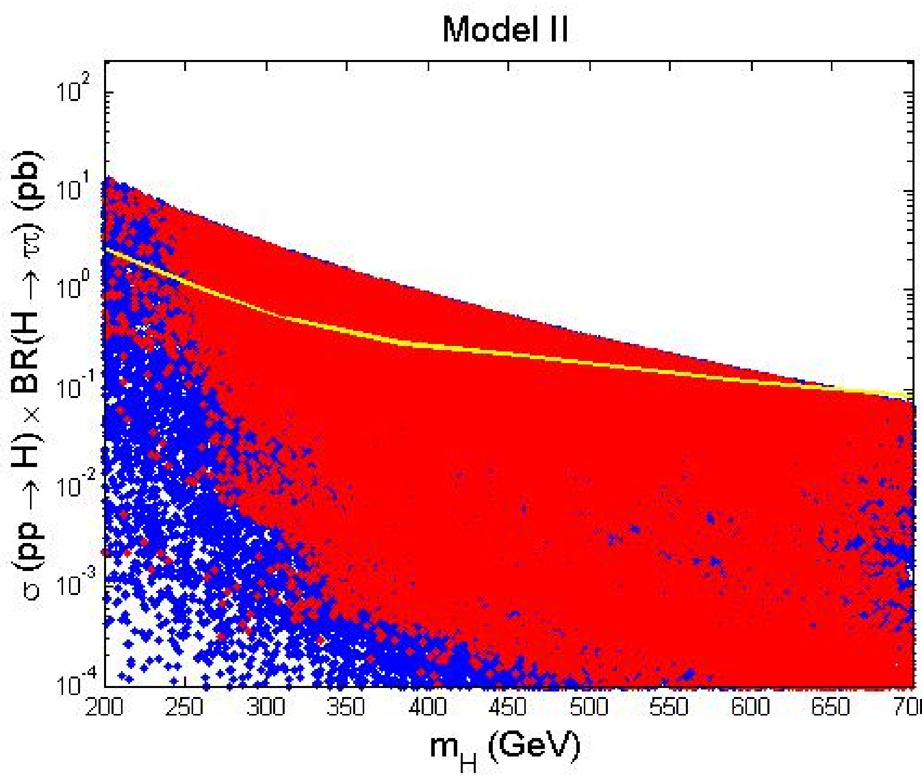
(red points are what remains after demanding "h" rates are within 30% of SM values)

(ATLAS limit)



Demanding "h" behaviour being SM-like complies with latest high-mass exclusions...

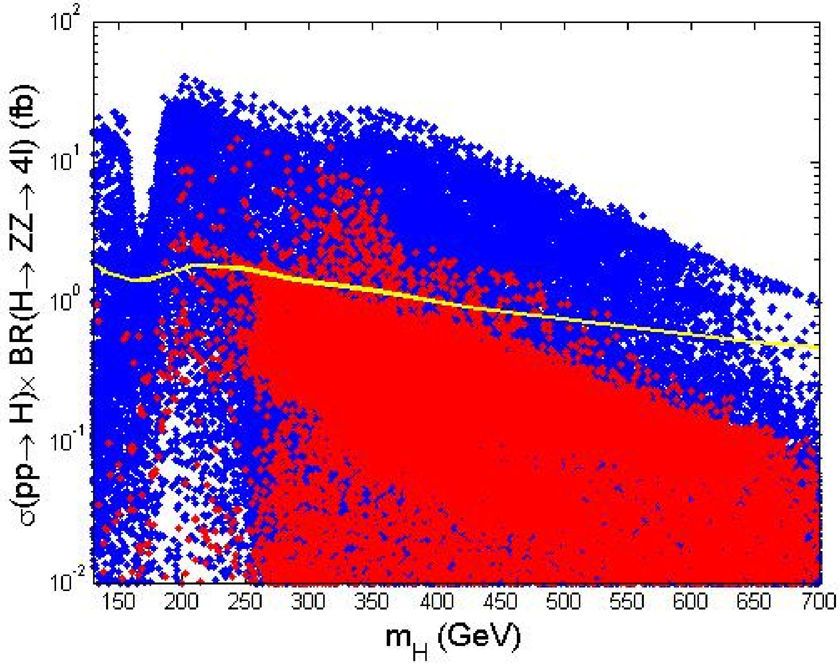
(ATLAS limit)

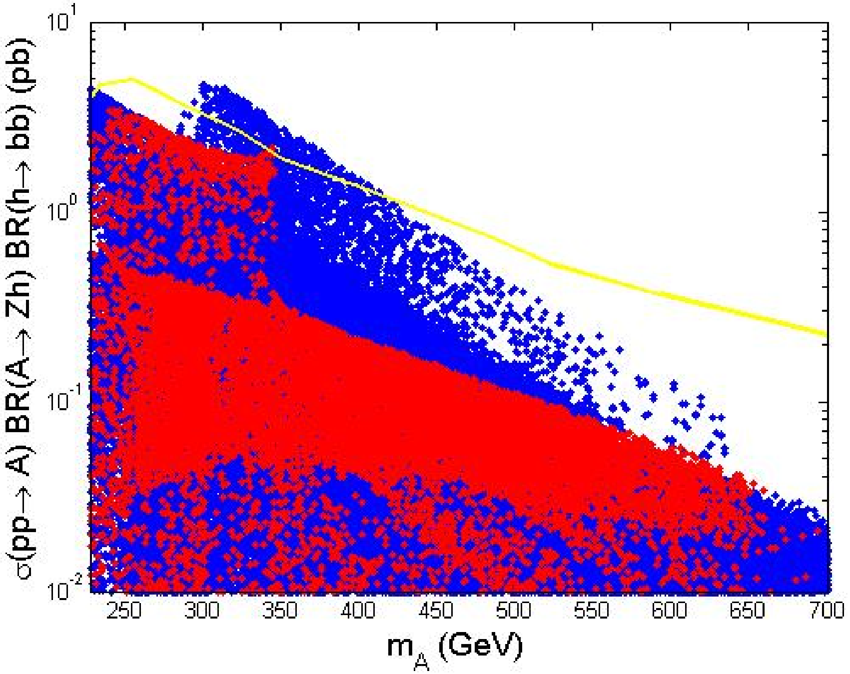


... Though not for *ALL* observables

Current limitations of the 2HDM

The 2HDM is already so constrained that <u>significant</u> deviations from SM expected behaviour might *exclude it*.





DOUBLE H - THE CHANNEL MANY THEORISTS ARE EXCITED ABOUT

- ***HIGGS, GIVE THYSELF MASS!***

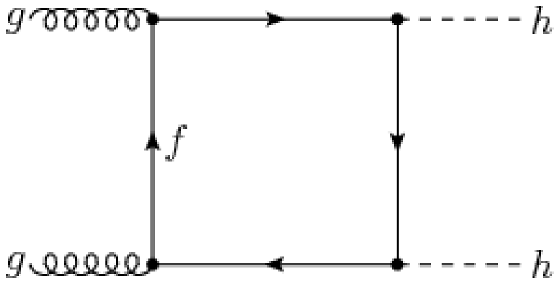
- **A consequence of the self interactions of the Higgs , due to the "λ" coupling in the Higgs potential, is that the Higgs mechanism also explains the Higgs mass.**

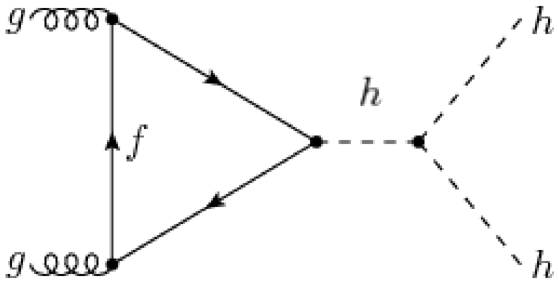
Higgs potential:

$$V = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

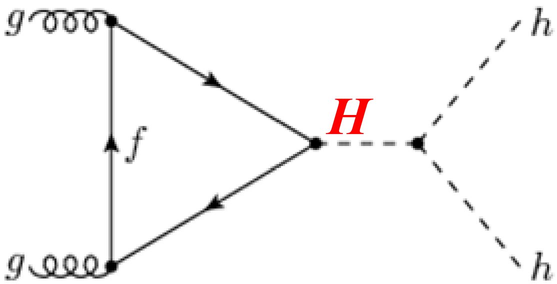
- **This self interaction is a completely new aspect introduced by the higgs mechanism, and it hasn't yet been confirmed experimentally!**

- One of the consequences of this self interaction is the possibility of production of pairs of Higgs bosons. At the LHC, these processes are being searched thoroughly.





- These two contributions have a DESTRUCTIVE interference, which makes the process' cross section very small and difficult to measure...
- ...but that also inplies it is a versy sensitive observable to New Physics contributions! For instance, if there is a second Higgs bosons H, there will be a third contribution, WHICH MIGHT DRAMATICALLY INCREASE THE LIKELIHOOD OF FINDING PAIRS OF h's!



SOME OF THE

COOL STUFF

I HAVE BEEN

WORKING ON

RECENTLY…

Vacuum stability of 2HDM and other models

Vaccuum structure more rich => different types of stationary points/minima *possible*!

The NORMAL minimum, $\langle \Phi_1 \rangle_N = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \ , \ \langle \Phi_2 \rangle_N = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$

The CHARGE BREAKING (CB) minimum, with

$$\langle \Phi_1 \rangle_{CB} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ c_1 \end{pmatrix} \ , \ \langle \Phi_2 \rangle_{CB} = \frac{1}{\sqrt{2}} \begin{pmatrix} c_2 \\ c_3 \end{pmatrix}$$

c_2 has electric charge => breaks $U(1)_{em}$

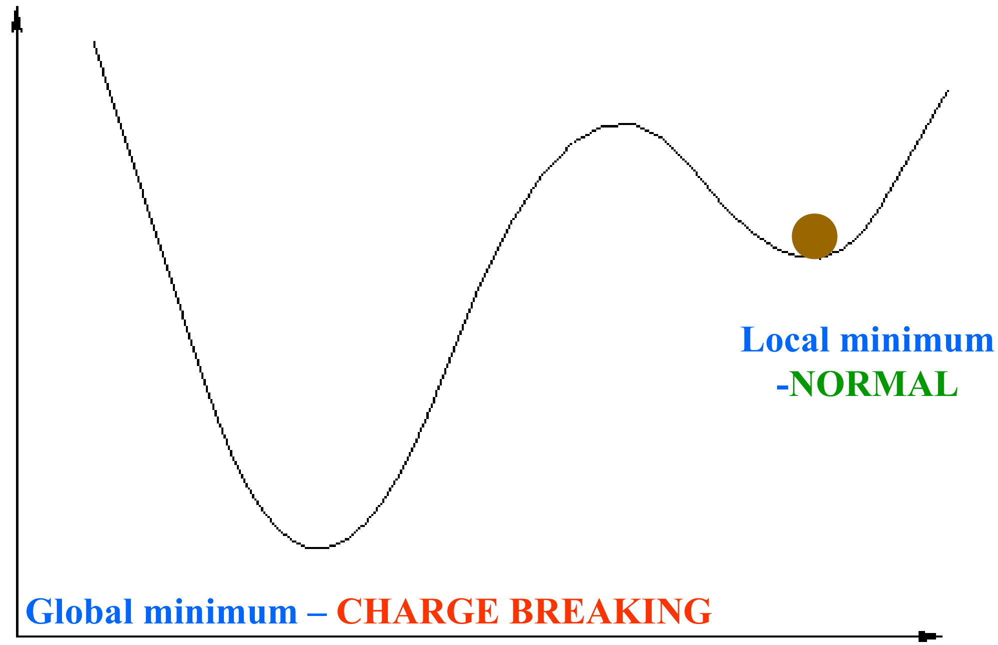
The CP BREAKING minimum, with

$$\langle \Phi_1 \rangle_{CP} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \bar{v}_1 \end{pmatrix} \ , \ \langle \Phi_2 \rangle_{CP} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \bar{v}_2 e^{i\theta} \end{pmatrix}$$

$\theta \neq 0, \pi$ breaks CP

Would there be any problem if the potential had two of these minima simultaneously?

Answer: there might be, if the CB minimum, for instance, were "deeper" than the normal one (metastable).



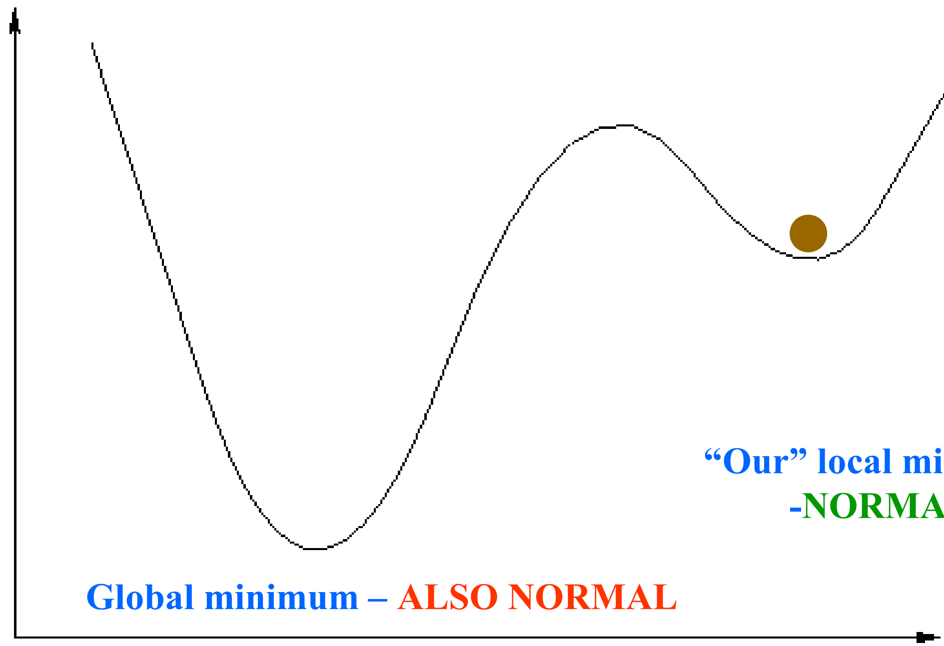
$$\cancel{m_\gamma = 0}$$

$$m_\gamma \neq 0 \ !$$

One of the neat properties of the 2HDM is that it can be shown ANALYTICALLY that this possibility cannot occur, and normal minima are stable against charge or CP breaking... CB and CP breaking possible in many other models with extended scalar sectors!

However, though our normal 2HDM vacuum cannot tunnel to a deper CB or CP minimum, there is another scary prospect…

$$\langle\Phi_1\rangle_N = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}\ ,\ \langle\Phi_2\rangle_N = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix} \qquad \langle\Phi_1\rangle_{N'} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v'_1\end{pmatrix}\ ,\ \langle\Phi_2\rangle_{N'} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v'_2\end{pmatrix}$$



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

$$v = 246\ GeV$$

$$m_W = 80\ GeV$$

$$m_t = 173\ GeV$$

$$\ldots$$

"Our" local minimum -NORMAL

Global minimum – ALSO NORMAL

$$v'^2_1 + v'^2_2 \neq (246\,\mathrm{GeV})^2$$

$$v \neq 246\ GeV$$

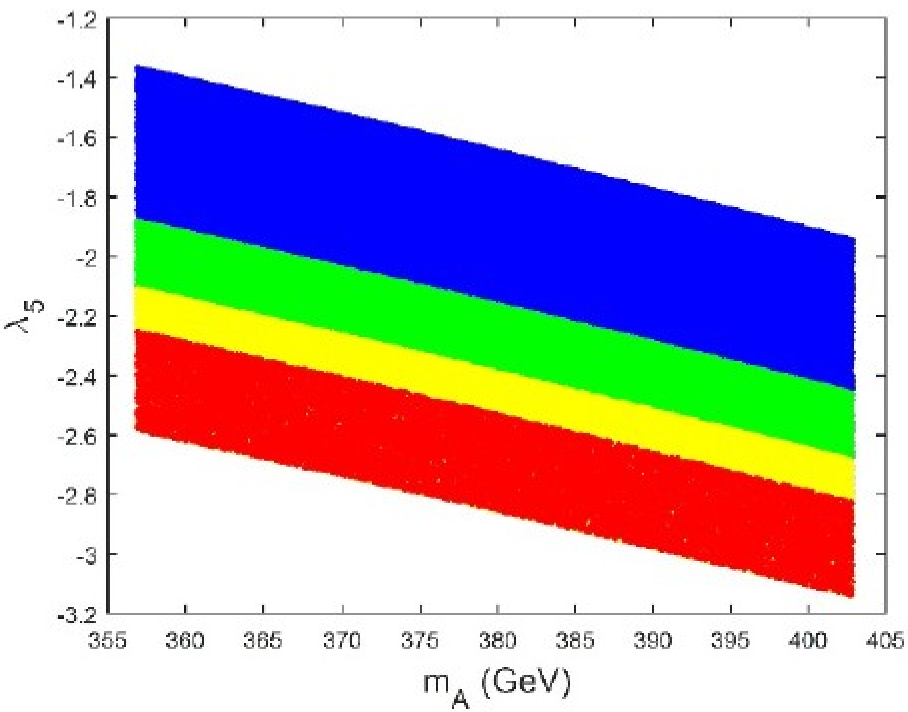
$$m_W \neq 80\ GeV$$

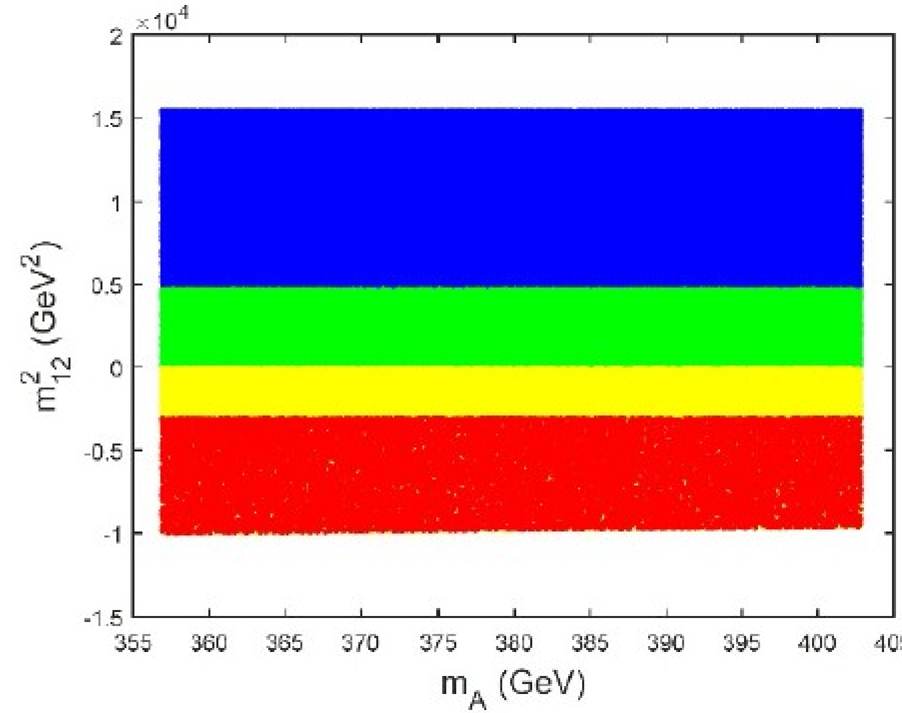
$$m_t \neq 173\ GeV$$

PANIC VACUUM!!

Long-lived false vacua in the 2HDM

$m_H = 200$ GeV $\quad m_\pm = 400$ GeV $\quad \tan\beta = 2.5 \quad \sin(\beta - \alpha) = 0.99$





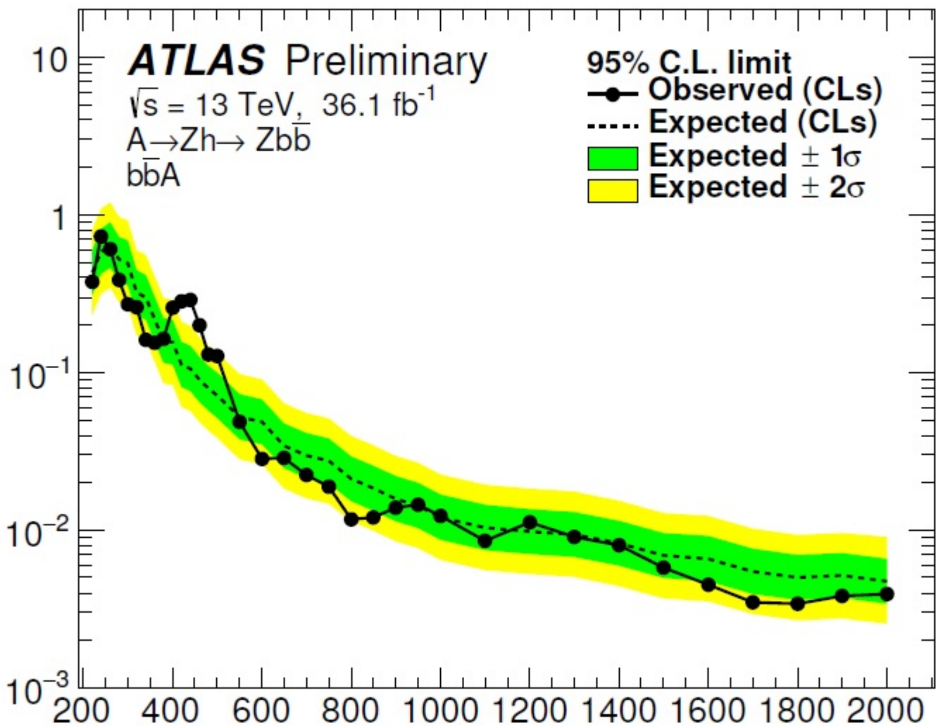
- **Single minima points (BLUE), two minima points (GREEN) for which "our" minimum is the false vacuum (YELLOW).**

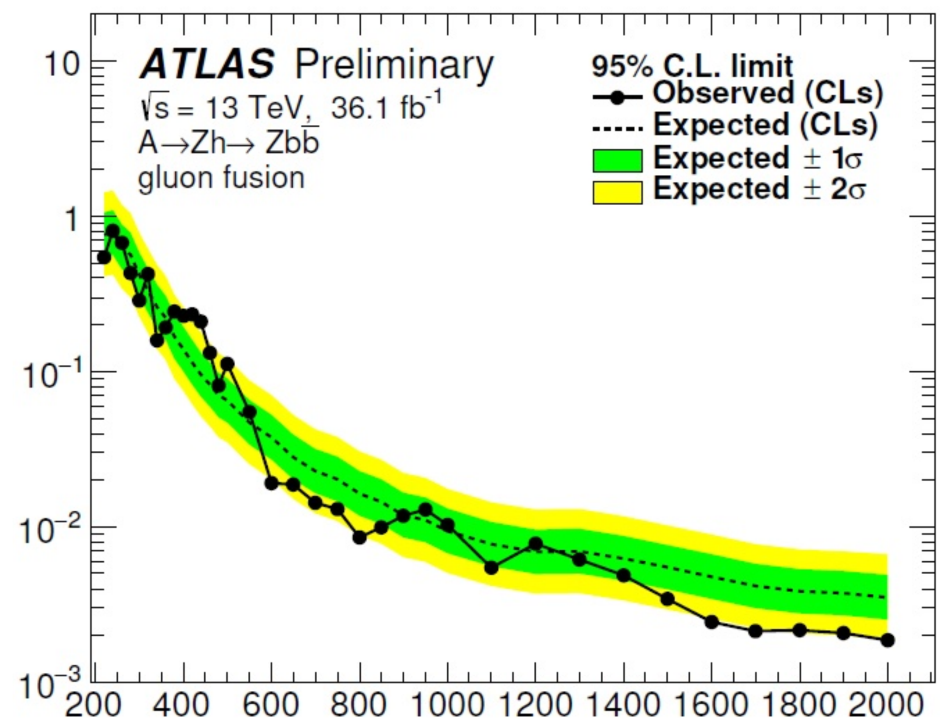
- **A sconsiderable region has tunneling times inferior to the age of the universe (RED) and those parameters are therefore to be excluded!**

V. Branchina, F. Contino, and P. M. Ferreira, JHEP **11**, 107 (2018), 1807.10802

Trying to find new particles in recent LHC results

(or: THE INCREDIBLY (IN)SIGNIFICANT ATLAS EXCESS IN Zh)





arXiv:1712.06518

- Roughly 01 – 0.3 pb above SM background for an invariant mass of ~ 440 GeV...
- Very low statistical significance! Interesting that it is above the $t\bar{t}$ threshold.

THE WRONG-SIGN LIMIT

- **Restrictions/conventions:** $\tan\beta \geq 1$ ***AND*** $-\pi/2 \leq \alpha \leq +\pi/2$

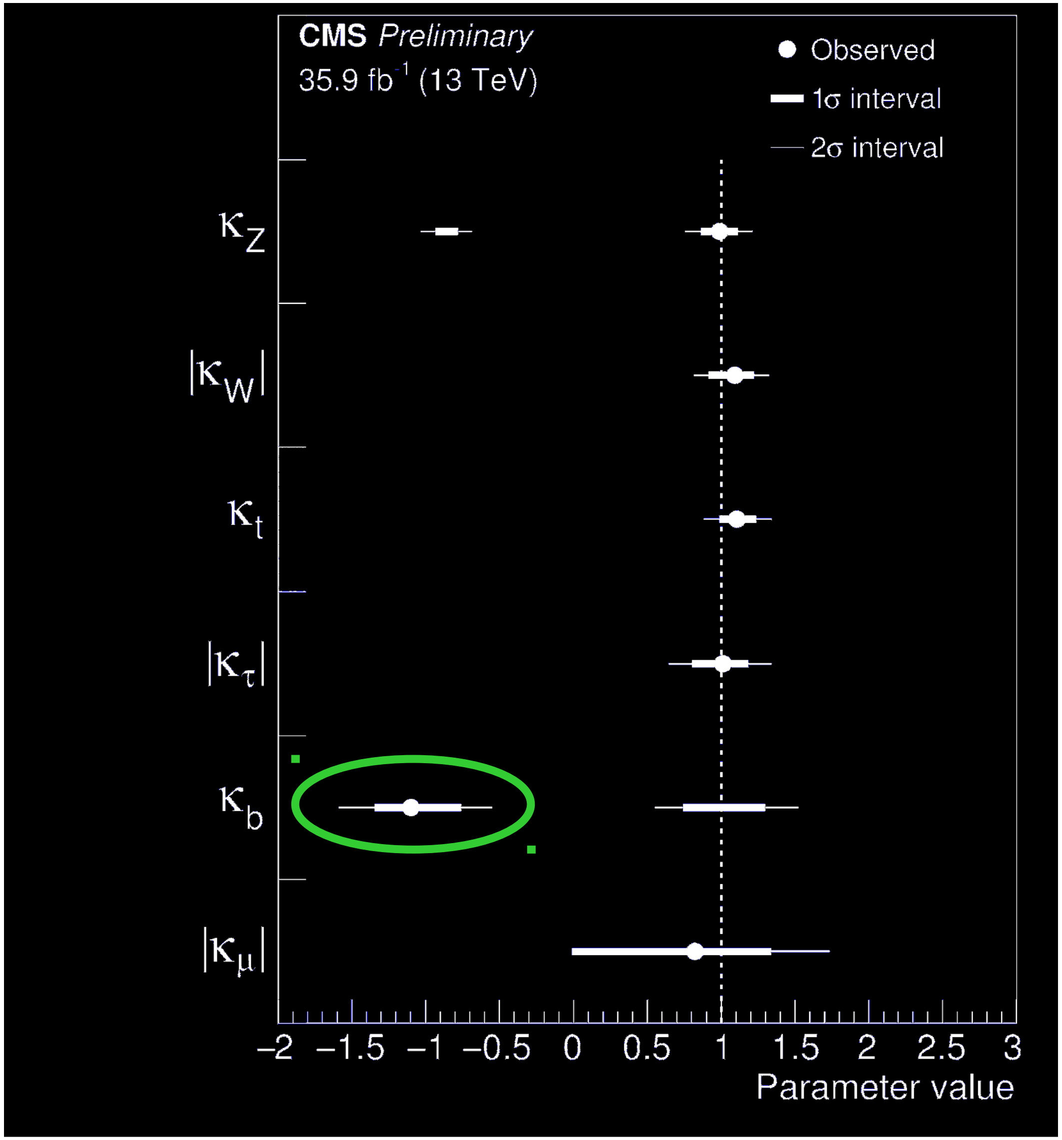
MODEL I	MODEL II
$k_V = \sin(\beta - \alpha)$	$k_V = \sin(\beta - \alpha)$
$k_U = \dfrac{\cos\alpha}{\sin\beta}$	$k_U = \dfrac{\cos\alpha}{\sin\beta}$
$k_D = \dfrac{\cos\alpha}{\sin\beta}$	$k_D = -\dfrac{\sin\alpha}{\cos\beta}$

Always have the same sign

k_D can have the opposite sign of other two

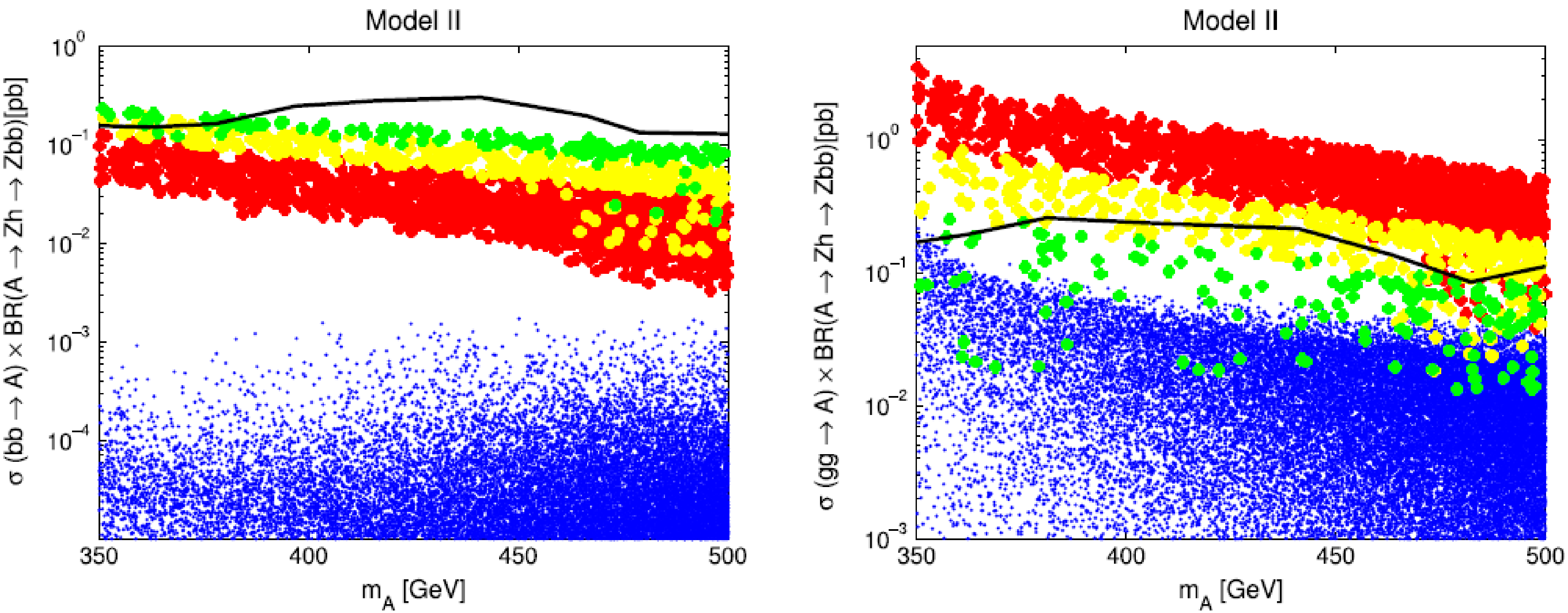
P. M. Ferreira, J. F. Gunion, H. E. Haber, and R. Santos, *Probing wrong-sign Yukawa couplings at the LHC and a future linear collider*. Phys. Rev. **D89** (2014) no. 11, 115003, `arXiv:1403.4736 [hep-ph]`.

THIS IS NOT JUST A THEORIST'S DELIRIUM...



CMS-PAS-HIG-17-031

pp → A → Zh IN THE WRONG-SIGN 2HDM



•Blue – All 2HDM type-II points generated, including...

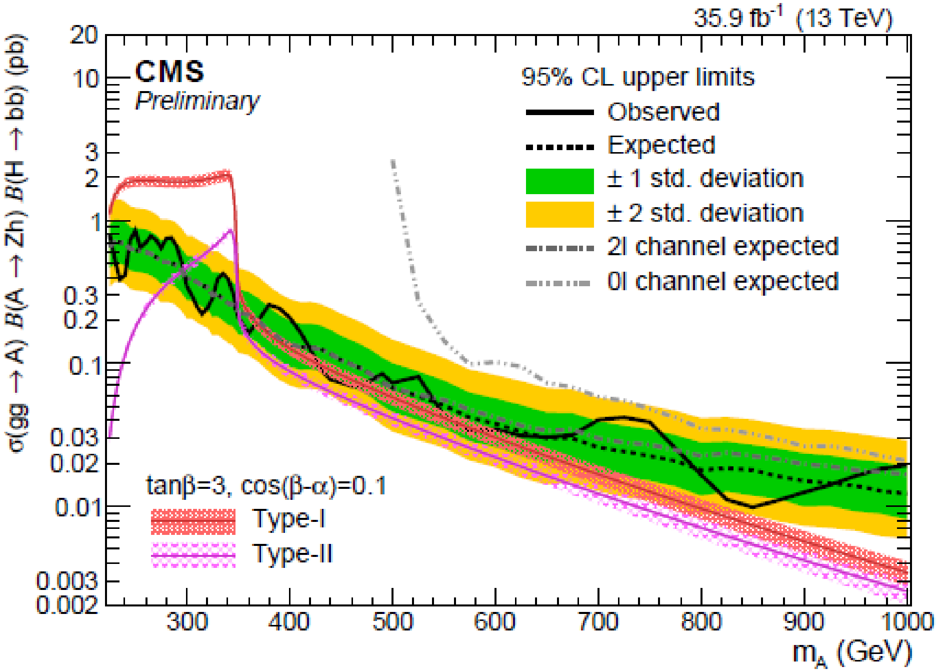
•Green – Wrong-sign + $\tan\beta > 7.5$

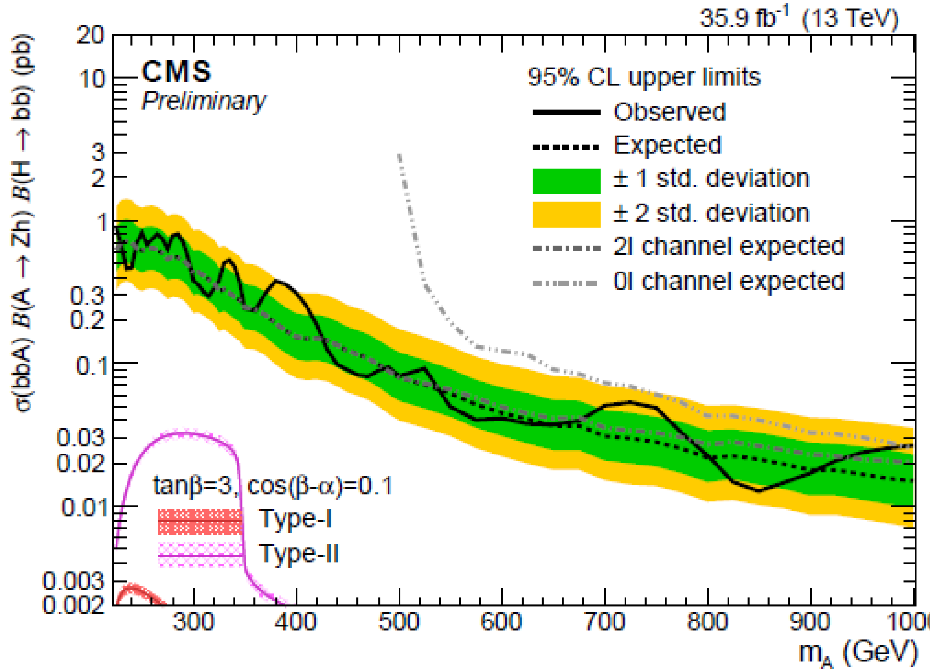
•Yellow – Wrong-sign + $5 < \tan\beta < 7.5$

•Red – Wrong-sign + $1 < \tan\beta < 5$

Black line – observed signal in ATLAS

BLOODY CMS SPOILSPORTS!!!



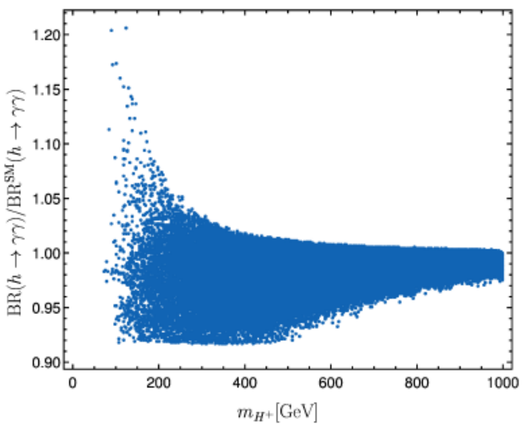


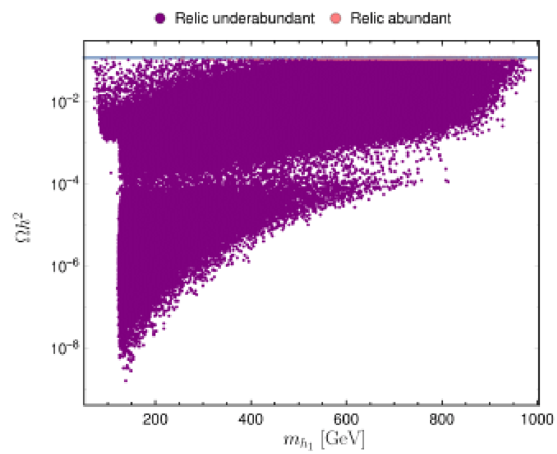
CMS PAS HIG-18-005

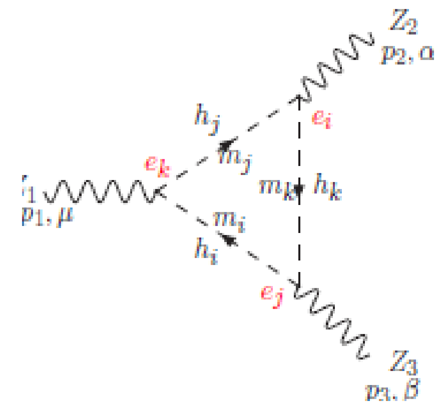
BUT: the point remains. Any excess in Zh production can well be a sign of the presence of a pseudoscalar – MEASURE WITH PRECISION!

Likewise, for Wh production (sign of a charged scalar?)

Creating weird new models – such as a theory with several scalars, which yields <u>CP violation and dark matter</u>, *but all CP violation is in the dark sector*







The model can be shown to be in full agreement with LHC results for the Higgs boson; with direct and indirect constraints on the existence of dark matter and its expected properties; and still have CP violation only in the "invisible" sector...

And that CP violation could only be seen because it generates anomalous properties of the Z boson!

So the model manages to provide dark matter candidates and extra sources of CP violation – all it requires is two Higgs doublets, Φ_1 and Φ_2, and a real singlet Φ_S (no hypercharge), with a specific discrete symmetry:

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

The scalar potential therefore becomes

$$\begin{aligned} V \;=\;& m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{1}{2}m_S^2\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.\right) \\ &+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] \\ &+ \frac{1}{4}\lambda_6\Phi_S^4 + \frac{1}{2}\lambda_7|\Phi_1|^2\Phi_S^2 + \frac{1}{2}\lambda_8|\Phi_2|^2\Phi_S^2 \,, \end{aligned}$$

CUBIC TERM!

where, with the exception of *A*, all the parameters are *REAL*.

D. Azevedo, P. M. Ferreira, M. M. Muhlleitner, S. Patel, R. Santos, and J. Wittbrodt, J. High Energy Phys. 11 (2018) 091.

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

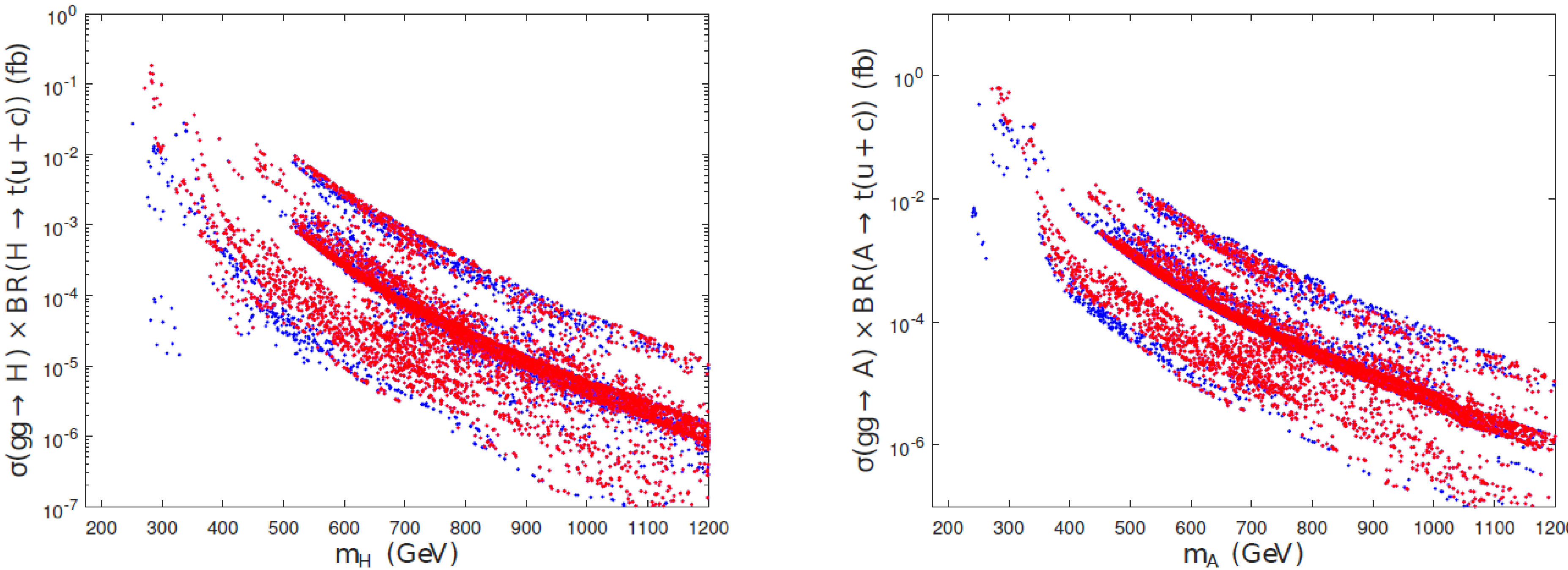
Flavour conservation: matrices N_u and N_d DIAGONAL and proportional to M_u and M_d.

FCNC: N_u and N_d non-diagonal. FCNCs very constrained from meson physics results!

The model can be made to fit existing meson and LHC data without excessive fine tunings, and yielding relatively low mass (< 500 GeV) extra scalars.

N_d and N_u matrices are found "almost" diagonal.

Extra scalars' properties are such that they evade all current LHC constraints easily.



The extra scalars can now decay to a SINGLE top quark, along with a u or c quarks. ***HOW DOES ONE LOOK FOR THIS AT LHC? WHAT ARE THE CURRENT EXISTING BOUNDS ON THIS???***

CONCLUSIONS

- **There are MANY challenges ahead in Higgs Physics.**
- **Fighting the feeling that ALL IS DONE is perhaps the SECOND greatest of them (both in our expectations and in discussions with the larger public and with politicians).**
- **But the GREATEST challenge in Higgs physics is the need to have new and better ideas to solve the problems that are already identified.**
- ***But then again, that's exactly what being a scientist is all about...***