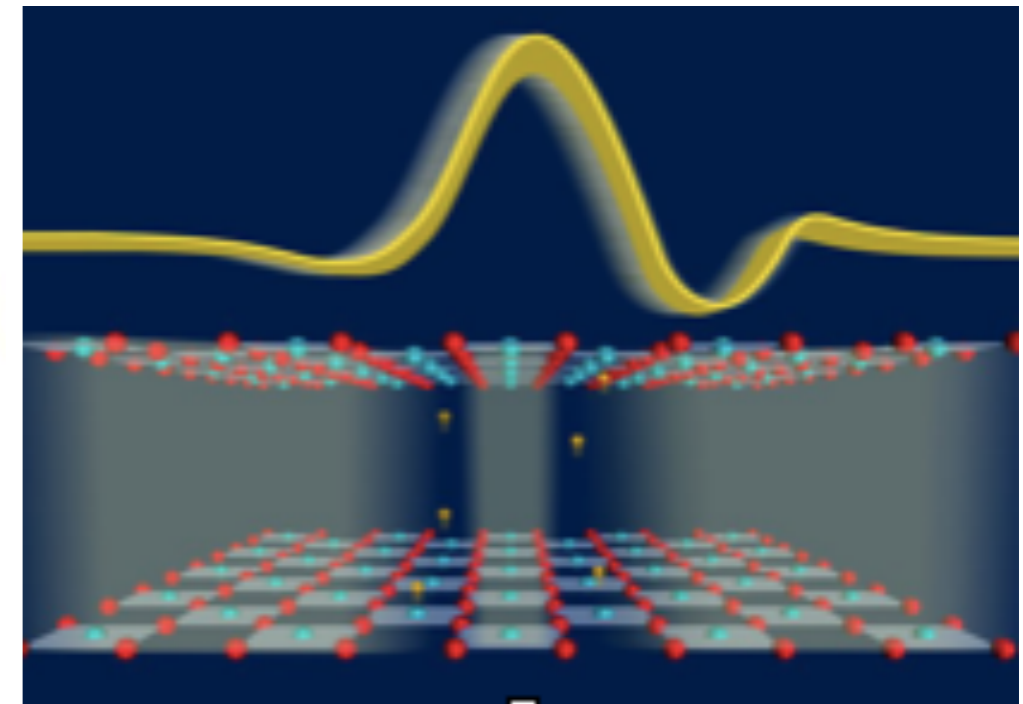
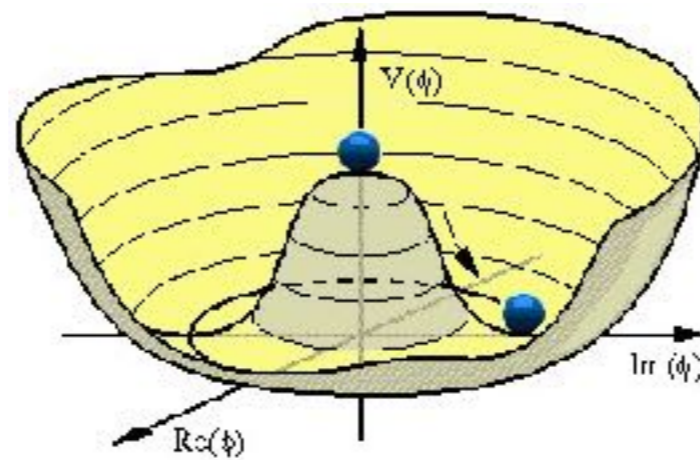
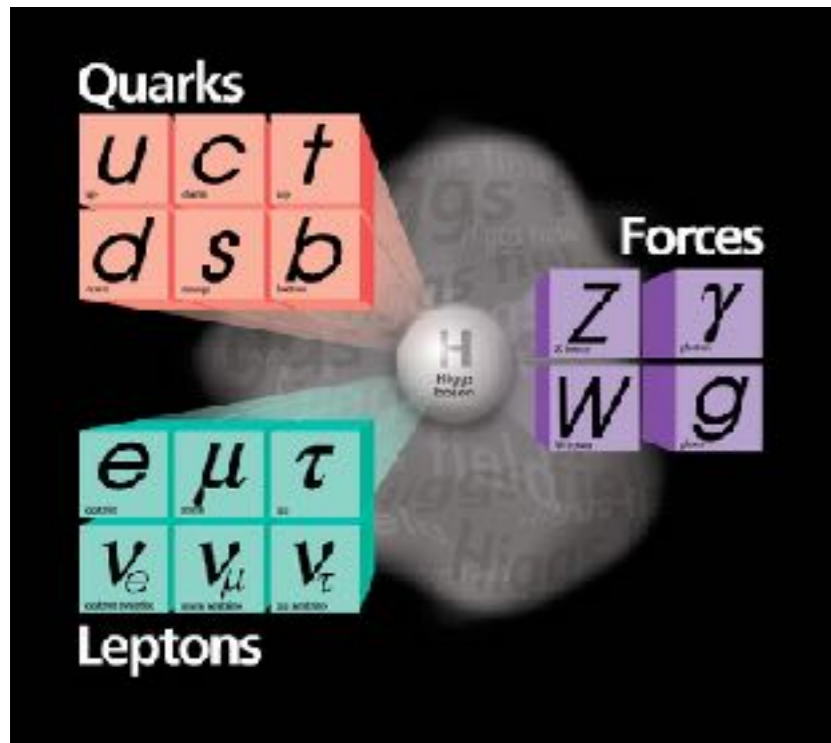


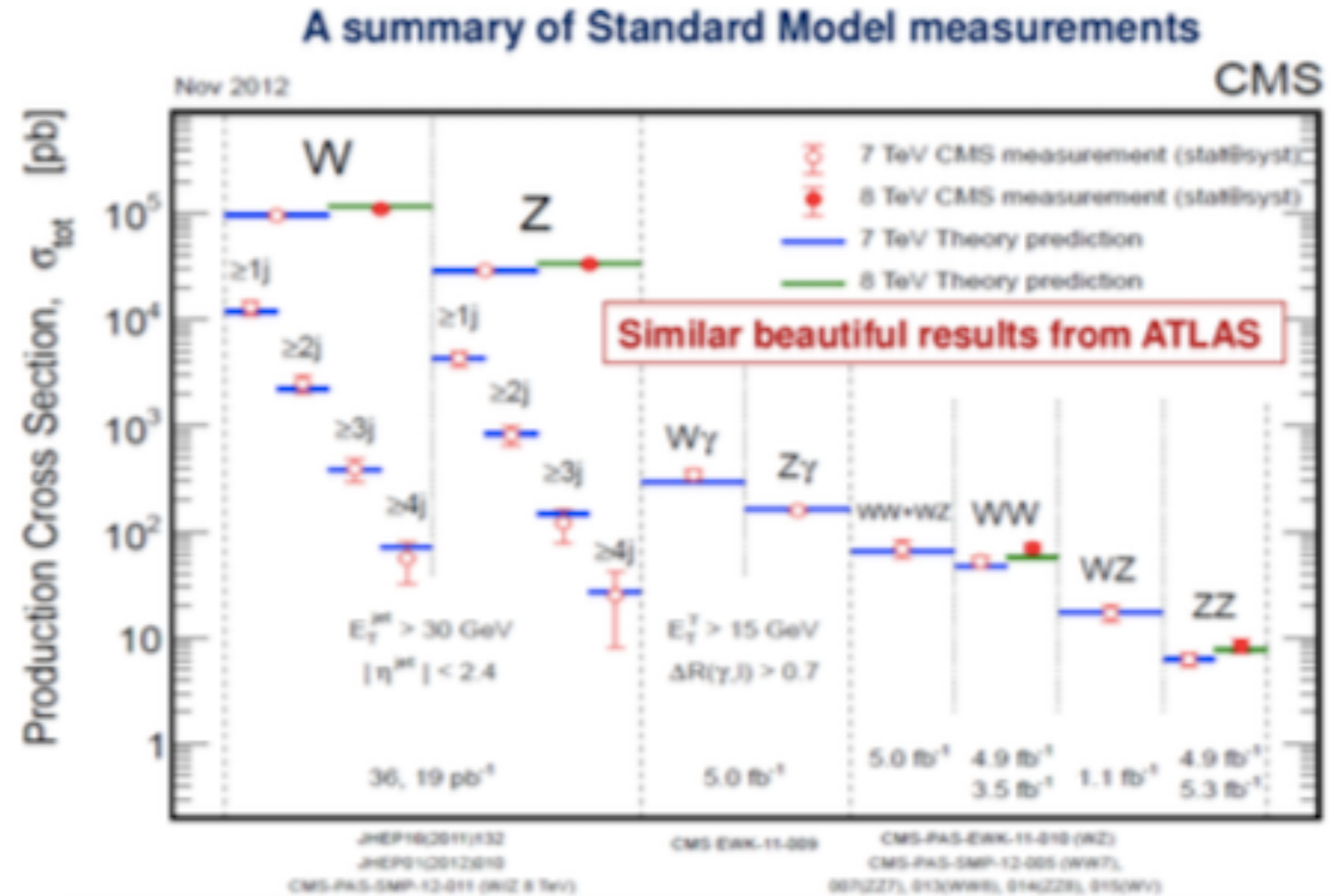
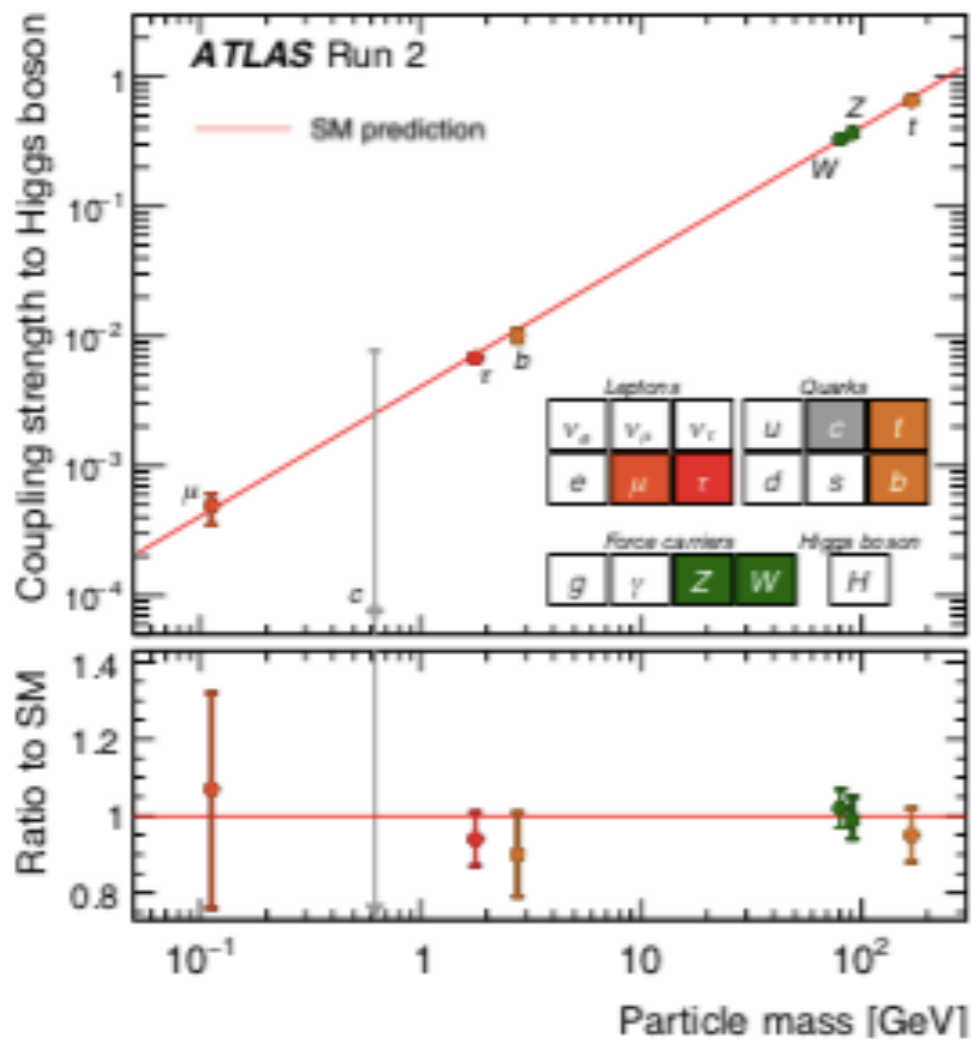
Vacuum Alignment and the Photon Lightness in the SM & Beyond



J. Lorenzo Diaz Cruz, CIIEC
& CIFFU & FCFM-BUAP

Talk at MWP&F-
U.Guanajuato, October
2025

- The SM Contains 19 parameters: g_i , v , m_h , m_j 's, CKM and theta-QCD,
- Tested at loop level (ex. $g-2$, STU, etc) & agrees with LHC data,

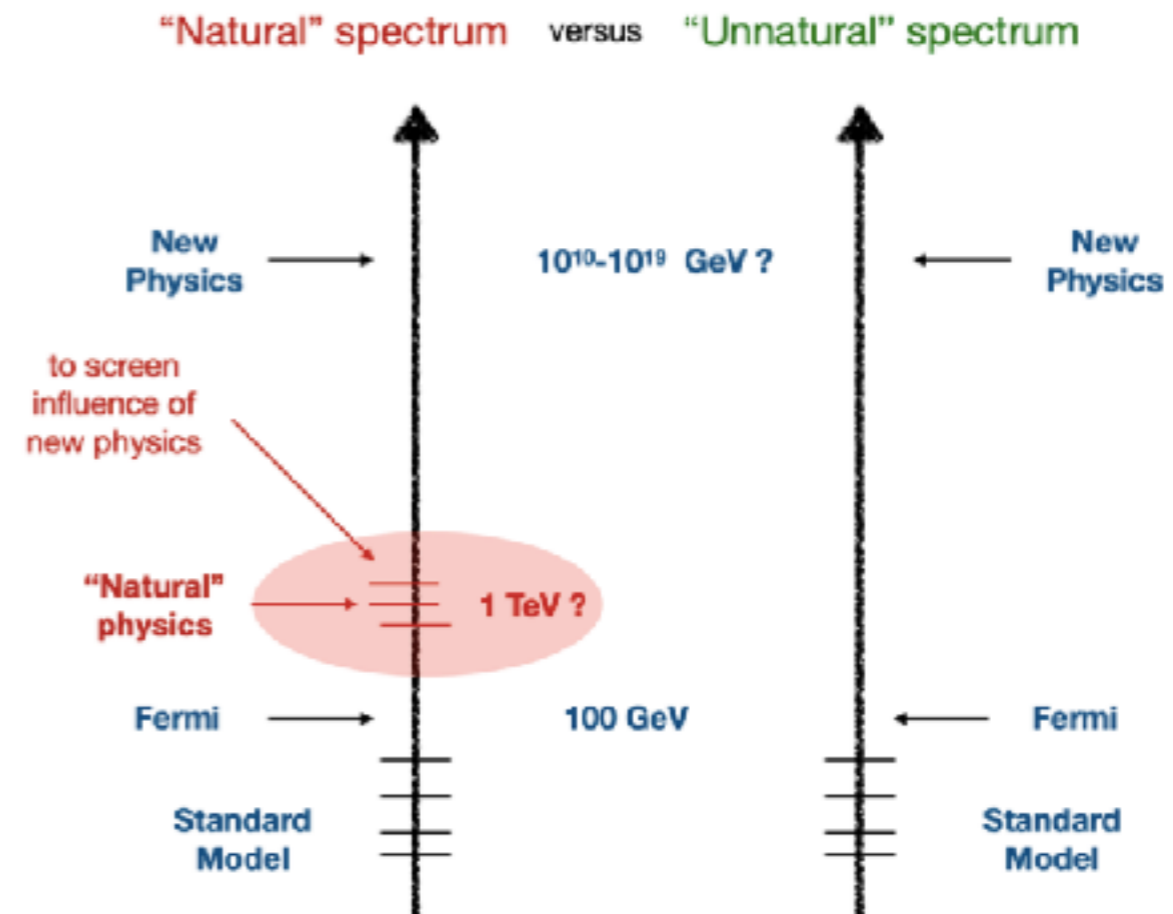


SM may be not of everything, but it seems **more valuable** than expected ... It is a **great theory!**

However, SM does not explain: Flavor & CPV, Neutrinos, DMatter, DEnergy, BAU, QGravity, etc. Furthermore, is it “Natural”?

- SM was thought to be sensitive to UV effects (quadratic divergences),
- And it was believed that scalars are not “natural”,
- New Physics was proposed to cure the problem,

- But a light scalar exists, with $m_h = 125$ GeV,
- New Physics has not been found at LHC,
- Could the SM be valid up to $E \gg v$?



Look closer at concept of Naturalness & SM structure: Photon $M=0$.

Content:

1. Introduction,
2. The SM Structure:
 - What defines the SM?
 - Is the SM a Natural Theory?
3. SSB & Massless Photon (Vacuum Alignment):
 - 2HDM & Georgi-Machzek Model,
 - Parametric Naturalness & SUSY.
4. Conclusions.

Vacuum alignment in multiscalar models

J.L. Diaz-Cruz (Barcelona, Autonoma U.), A. Mendez
Published in: *Nucl.Phys.B* 380 (1992) 39-50



- J.L. Diaz-Cruz, Jorge León S. (Thesis)

2. What defines the SM?

1. Renormalizable QFT -> YM with SSB,

2. SM gauge group:

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

3. Fermions Reprs. (Anomaly Free):

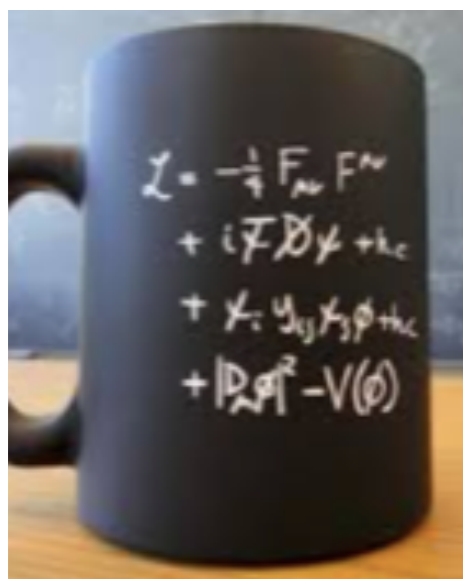
- Q (3, 2, Y_q)

- U (3, 1, Y_u), D (3, 1, Y_d)

- L (1, 2, Y_l), E (1, 1, Y_e)

4. Higgs: H (1, 2, Y)

- Out of largest global symmetry $SU(15 \times 3)$, only small SM subgroup is “gauged” ...
- SM particle content (Singlets, doublets of $SU(2)$ & triplets of $SU(3)$)
 - SM is Anomaly free & enough for CPV,
- Only small SM representations appear:
 - Where have all the large Reprs. gone?
- SM is a chiral theory: $M=0$ (extra vector-likes could have $M=\text{Planck}$),



SM Lagrangian:

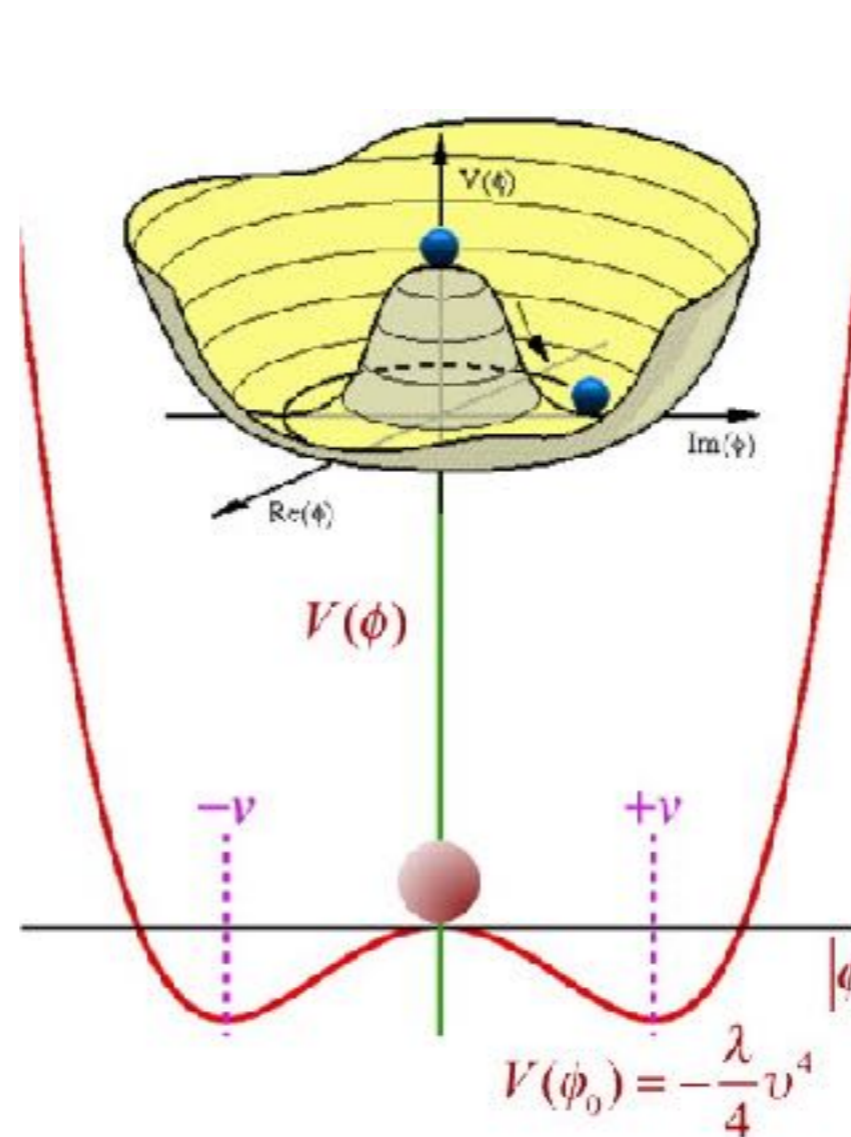
$$\mathcal{L}_{sm} = \mathcal{L}_{fg} + \mathcal{L}_V + \mathcal{L}_H + \mathcal{L}_Y + \mathcal{L}_{ghost}$$

(Nowadays one could also work Constructive SM) .

SSB-EBH in the SM & Higgs boson

- SM includes a Higgs doublet,
 - such that correct SSB is induced ($\rho=1$)
- EWSB does not induce a photon mass,
- But this could be lost for models Beyond the SM ...
How to make it natural?

$$\phi(x) \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}(\phi_1(x) + i\phi_2(x)) \\ \frac{1}{\sqrt{2}}(\phi_3(x) + i\phi_4(x)) \end{pmatrix} = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}$$



$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W}$$

$$V(\phi) = \frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$$

$$\text{Groundstate at } |\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv v$$

$$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^+\phi^- + \phi^0\dagger\phi^0}$$

$$V(\phi_0) = -\frac{\lambda}{4}v^4$$

$$\phi_0 \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{and} \quad \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$Q_{em} = T_3 + \frac{Y}{2}$$

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad Q \langle \Phi_1 \rangle = 0$$

Vacuum alignment in multiscalar models

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What is a natural theory?

- P. Dirac: Dimensionless parameters of a theory should be $O(1)$,
 - What if a theory contains **small numbers**?
- G t Hooft: A theory is natural if the **limit for a vanishing parameter $z \rightarrow 0$** , implies that **a symmetry emerges**,
 - ex. If $m_e = 0 \rightarrow$ **chiral symmetry**,

But light Higgs exists & **no symmetry emerges for $m_h=0$** ...So, is the SM Natural?

- ,Corrections to Higgs mass from **UV cutoff** \rightarrow Quadratic Divergences \rightarrow **Naturalness/Hierarchy problem**,
- **Old Solutions**: **No higgs** (TC) or **NewPhysics** (Composite, SUSY, Extra-dims, etc), with $M < 1$ TeV,



- But we understand QFT & Quad. Divs. better now:
 - For **infinite-cut off**, one just has to **renormalize the divergent term**, as usual in QFT,
- **Real problem**: when **Lambda** represents **effect of heavy particle** (mass M_x and coupling g_x), it leaves a **correction to Higgs mass** of order:

$$\Lambda \rightarrow \infty$$

$$\delta m_h^2 = \frac{g_x^2 M_x^2}{16\pi^2}$$

- **Naturalness Problem** should be associated with **existence of heavy particles** interacting with the SM Higgs boson,
- **Lots and lots of PBSM models were built**, based on the “**premise**” that **Quadratic divergences were a real danger ...**
- **How did it started?** Susskind (K. Wilson) **argued with estimates**, & then **Veltman clarified it**,

Def. max. degree of fine-tuning:

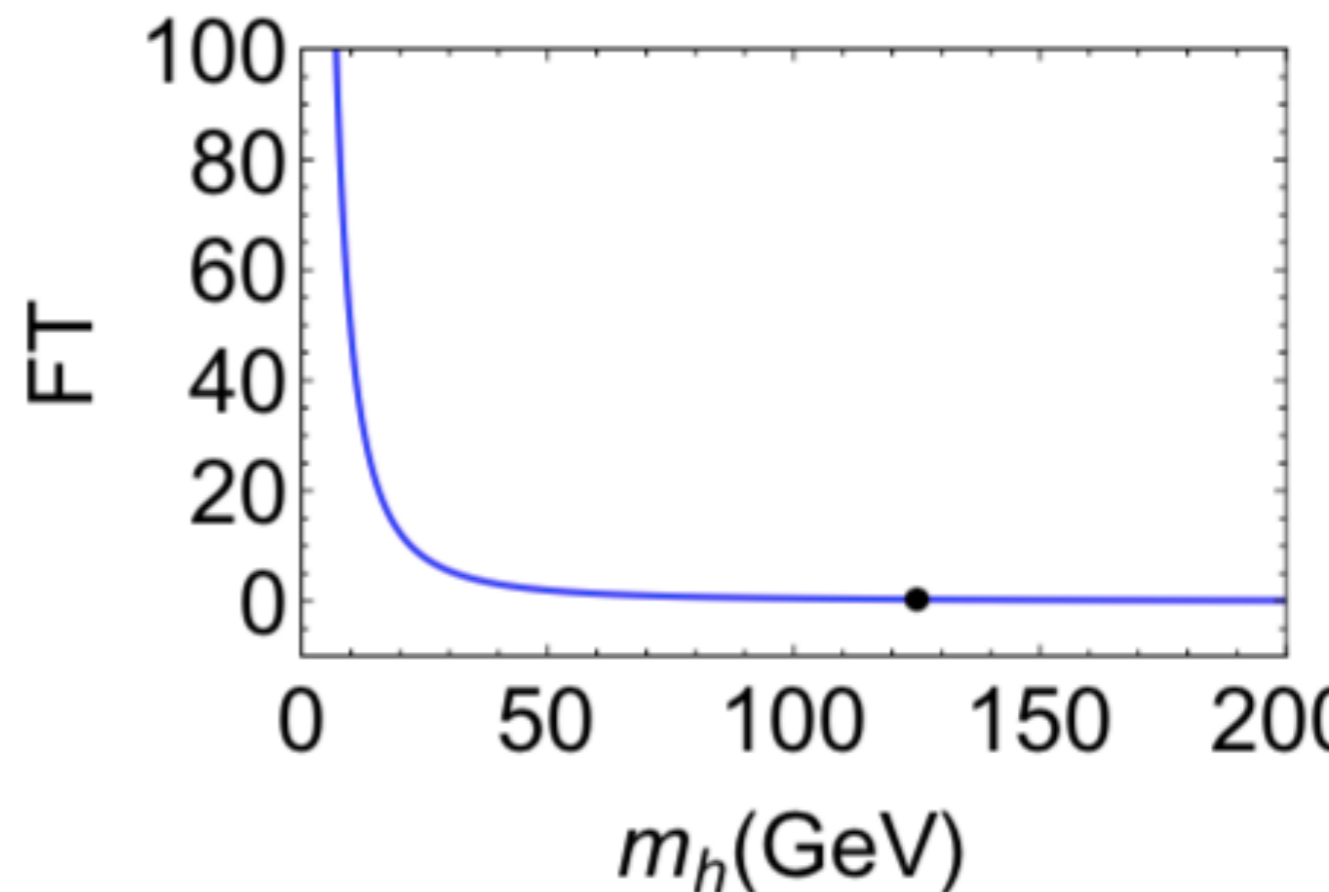
$$FT[g_{Li} | g_{Hj}] = \left| \frac{g_{Hj}}{g_{Li}} \frac{\partial g_{Li}}{\partial g_{Hj}} \right|_{\mu^2=M^2}$$

$$FT[g_{Li}] = \max_k FT[g_{Li} | g_{Hk}]$$

- Within SM, max. fine-tuning to Higgs mass, is due to the top quark:

$$FT[m_h^2 | m_t] \simeq \frac{3m_t^4}{\pi^2 v^2 m_h^2}$$

- SM fine-tuning is only of $O(1)$, but this is because $m_h=125$ GeV,
- Thus, there is no problem in the SM!



Naturalness works! ... Could we use it further?

4. Aspects of Naturalness in the 2HDM

- 2HDM contains an extended Higgs sector that can provide new signals to test the SM (parameters BSM, rich spectrum, sum rules, etc.),
- It is the Higgs content of the MSSM (SUSY) , and could be part of other models (LR, nu-masses, etc)
- An arena to study extended symmetries (Higgs potential, flavor, etc)

The Lagrangian of the general 2HDM:

$$\mathcal{L}_{2\text{HDM}} = \sum_{i=1,2} (D^\mu \phi_i)^\dagger (D_\mu \phi_i) - V(\phi_1, \phi_2).$$

Higgs doublet for CPC & CC minima, are:

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_1 + h + iG^0) \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_2 + H + iA) \end{pmatrix}.$$

- Two Higgs Doublets \rightarrow 8 d. of f; physical spectrum: $h(125), H, A, H^+,$
- Parameters: two vevs: $v_1, v_2 \rightarrow v = (v_1^2 + v_2^2)^{1/2} = 246 \text{ GeV}, \tan(\beta) = v_2/v_1,$
- The physical masses (M_{Hi}) and α (angle to diag. neutral Higgs mass matrix)

The general 2HDM - Yukawa Lagrangian

$$L = Y_1^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_2^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \bar{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \bar{Q}_L^0 \Phi_2 d_R^0 + h.c.$$

doublets, quark singlets and Higgs doublets are written as:

Many studies on 2HDM with **Charge Conserving Vacuum (CCV)**: Phenomenology, vacuum, symmetries, flavor, etc etc

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix},$$

- **The Higgs coupling with fermions includes general 3x3 Yukawa matrices:**

$$M_f = \frac{1}{\sqrt{2}} [v_1 Y_1^f + v_2 Y_2^f]$$

- For **2HDM-I**: fermions masses come from one doublets, say (Φ_1),.
- In **2HDM-II**: Φ_1 gives mass to U-quarks, Φ_2 gives masses to D-quarks and leptons.
- In 2HDM-III (Or General, included the 2HDM-Tx): Fermions couple to both Higgs doublets.

$$Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \bar{Q}_L^0 = (\bar{u}_L, \bar{d}_L),$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix},$$

$$Y_1^u, Y_2^u \quad \& \quad Y_1^d, Y_2^d$$

The 2HDM Potential and its minima

$$\begin{aligned}
 V(\phi_1, \phi_2) = & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 + (m_{12}^2 \phi_1^\dagger \phi_2 + h.c.) \\
 & + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) \\
 & + \left[\frac{1}{2} \lambda_5 (\phi_1^\dagger \phi_2)^2 + [\lambda_6 (\phi_1^\dagger \phi_1) + \lambda_7 (\phi_2^\dagger \phi_2)] (\phi_1^\dagger \phi_2) + h.c. \right].
 \end{aligned}$$

Other possible minima of 2HDM:

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ e^{i\alpha} v_2 \end{pmatrix},$$

$$\begin{aligned}
 (i) \quad \langle \phi_1 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, & \langle \phi_2 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \\
 (ii) \quad \langle \phi_1 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, & \langle \phi_2 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ i v_2 \end{pmatrix}, \\
 (iii) \quad \langle \phi_1 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, & \langle \phi_2 \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} u \\ 0 \end{pmatrix}.
 \end{aligned}$$

i) Charge Conserving vacuum (CCV) & CP conserving,

ii) Charge Breaking vacuum (CBV) & CP Breaking,

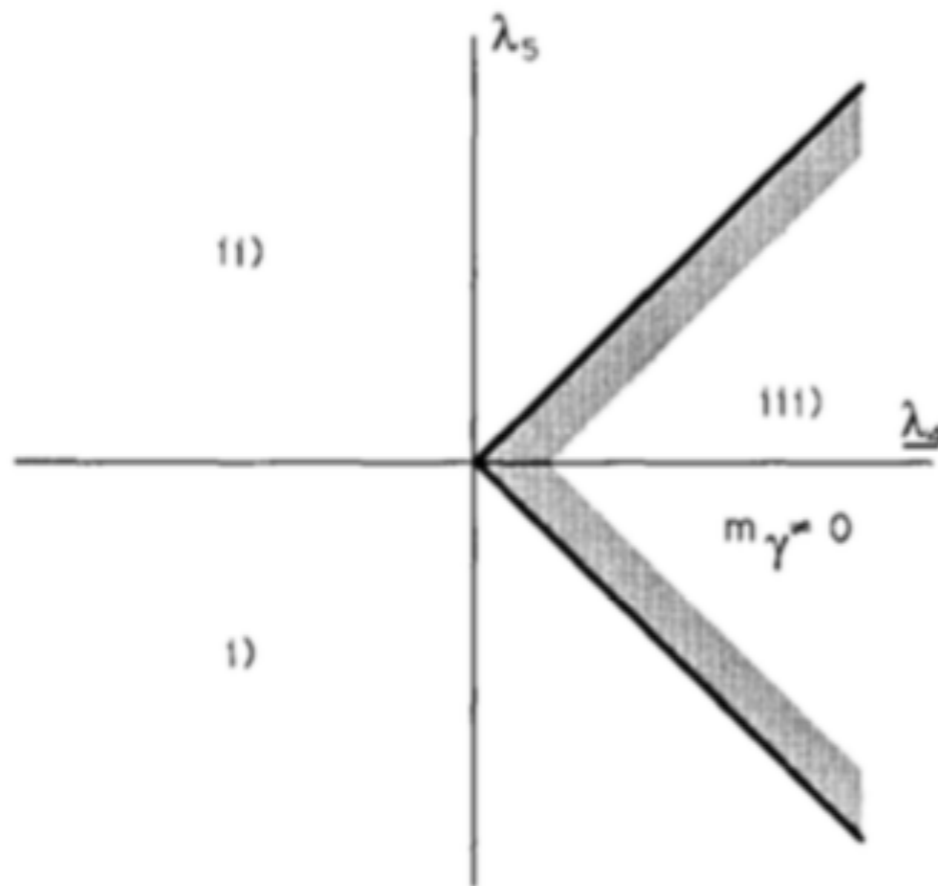
iii) CBV & CP Conserving

For CBV electric charge is broken and photon gets a mass, contrary to strict experimental limits,

2HDM Charge-Breaking Minimum

For the **CB minima** using couplings & masses of the Higgs spectrum, one obtains:

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 \\ 0 \end{pmatrix},$$



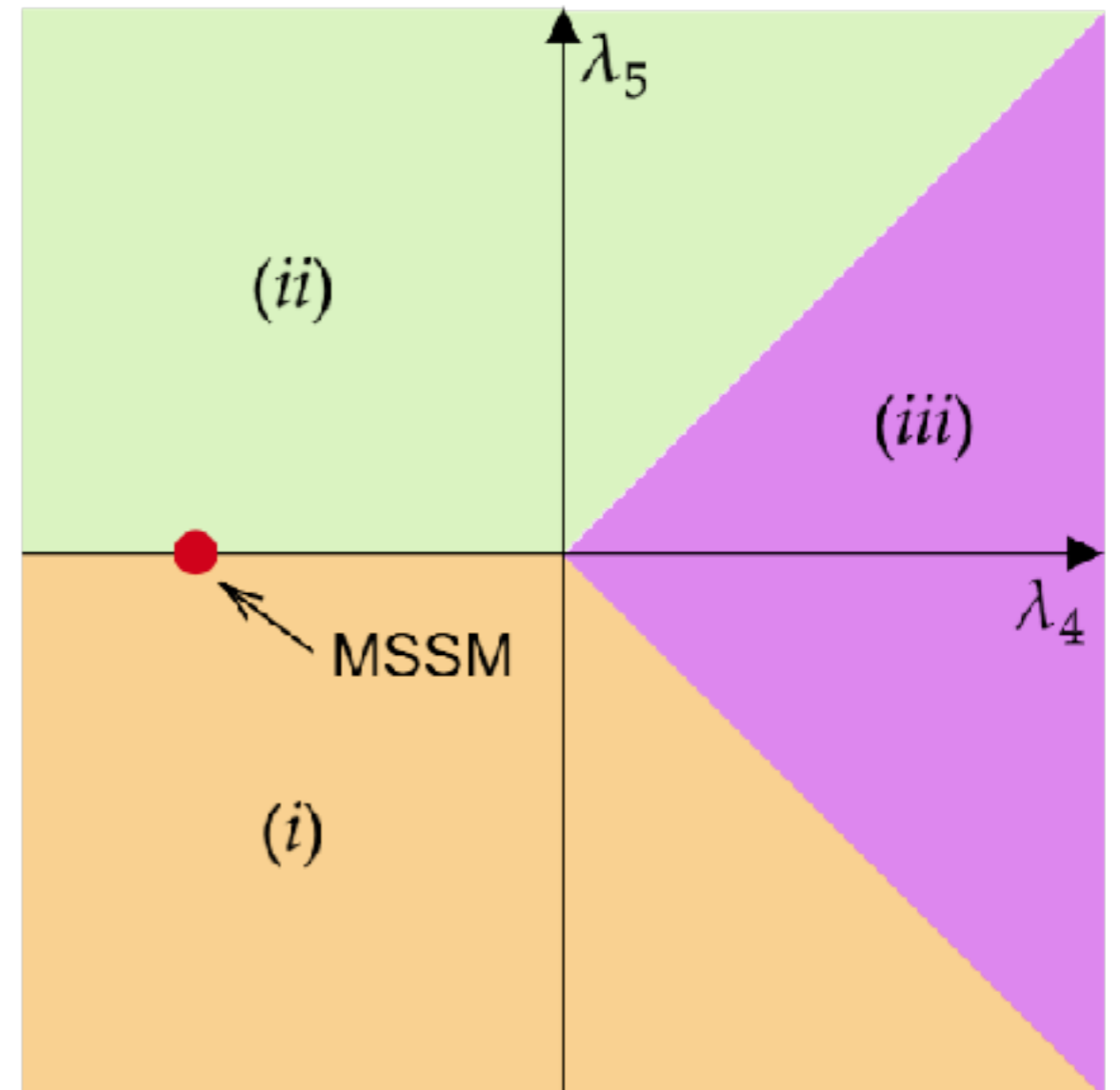
- There is **no fine-tuning** associated with this phenomena,
- But **correct vacuum** must be chosen,
- Could there be a **deeper reason for CCV & massless photon** in extended Higgs sector,

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0 \quad \text{y} \quad \lambda_3 + \lambda_4 + \lambda_5 \geq (\lambda_1 \lambda_2)^{1/2}.$$

(This was inspired after discussions with M. Veltman, in **Madrid** in the early 90's)

Parametric Naturalness

- The model should not admit regions of parameter space, where the photon acquires a mass,
- The 2HDM is not parametrically Natural,
- But its SUSY version (Higgs sector) enjoys this property,
- In SUSY, quartics are obtained from D-terms,
- MSSM relations:

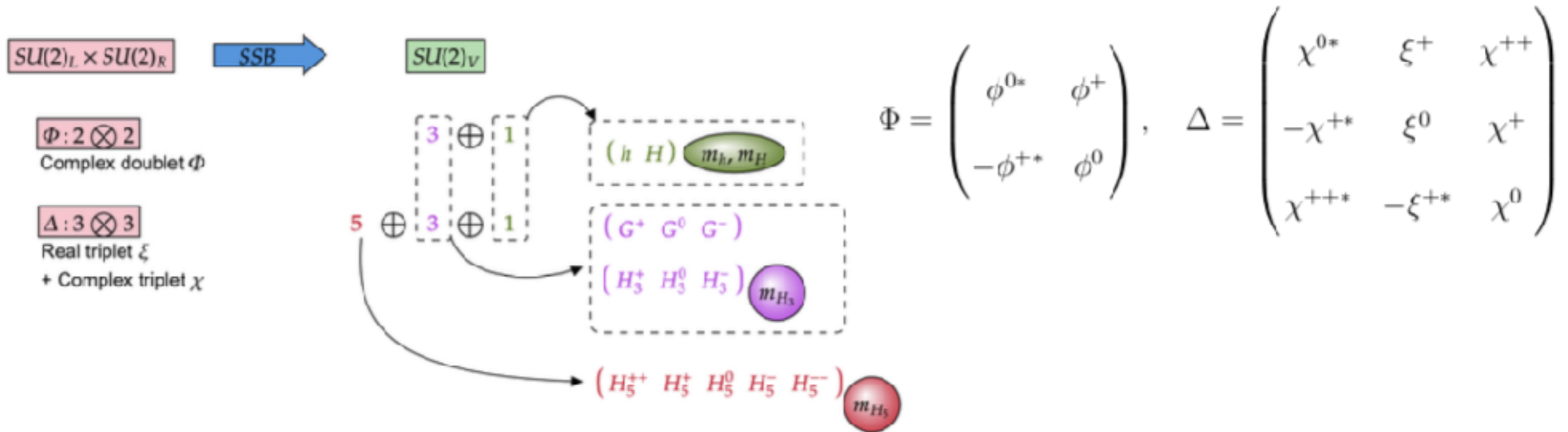


$$\lambda_1 = \lambda_2 = \frac{g^2 + g'^2}{4}, \quad \lambda_3 = \frac{g^2 - g_y^2}{4}, \quad \lambda_4 = -\frac{g^2}{2}, \quad \lambda_5 = \lambda_6 = \lambda_7 = 0.$$

Georgi-Machazek Model:

CB with triplets (GMM), Tesis Lic.,
J. Leon S. (FCFM, 2024)

It includes Higgs triplets and respects custodial symmetry, to have $\rho=1$ at tree-level,



$$\begin{aligned}
 V(\Phi, \Delta) = & \frac{m_1^2}{2} Tr[\Phi^\dagger \Phi] + \frac{m_2^2}{2} Tr[\Delta^\dagger \Delta] + \lambda_1 (Tr[\Phi^\dagger \Phi])^2 + \lambda_2 (Tr[\Delta^\dagger \Delta])^2 + \lambda_3 Tr[(\Delta^\dagger \Delta)^2] \\
 & + \lambda_4 Tr[\Phi^\dagger \Phi] Tr[\Delta^\dagger \Delta] + \lambda_5 Tr \left[\Phi^\dagger \frac{\tau^a}{2} \Phi \frac{\tau^b}{2} \right] Tr[\Delta^\dagger T^a \Delta T^b] + \mu_1 Tr \left[\Phi^\dagger \frac{\tau^a}{2} \Phi \frac{\tau^b}{2} \right] (P^\dagger \Delta P)_{ab} \\
 & + \mu_2 Tr[\Delta^\dagger T^a \Delta T^b] (P^\dagger \Delta P)_{ab}, \quad a, b = 1, 2, 3.
 \end{aligned}$$

- The model admits a rich vacuum structure: with CCV, CBV, CPC, CSCV, etc.s a rich vacuum structure:

I) Charge Conserving Vacuum (CCB)

$$\text{I. } \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\phi & 0 \\ 0 & v_\phi \end{pmatrix}, \quad \langle \Delta \rangle = \begin{pmatrix} v_\chi e^{-i\alpha} & 0 & 0 \\ 0 & v_\xi & 0 \\ 0 & 0 & v_\chi e^{i\alpha} \end{pmatrix}$$

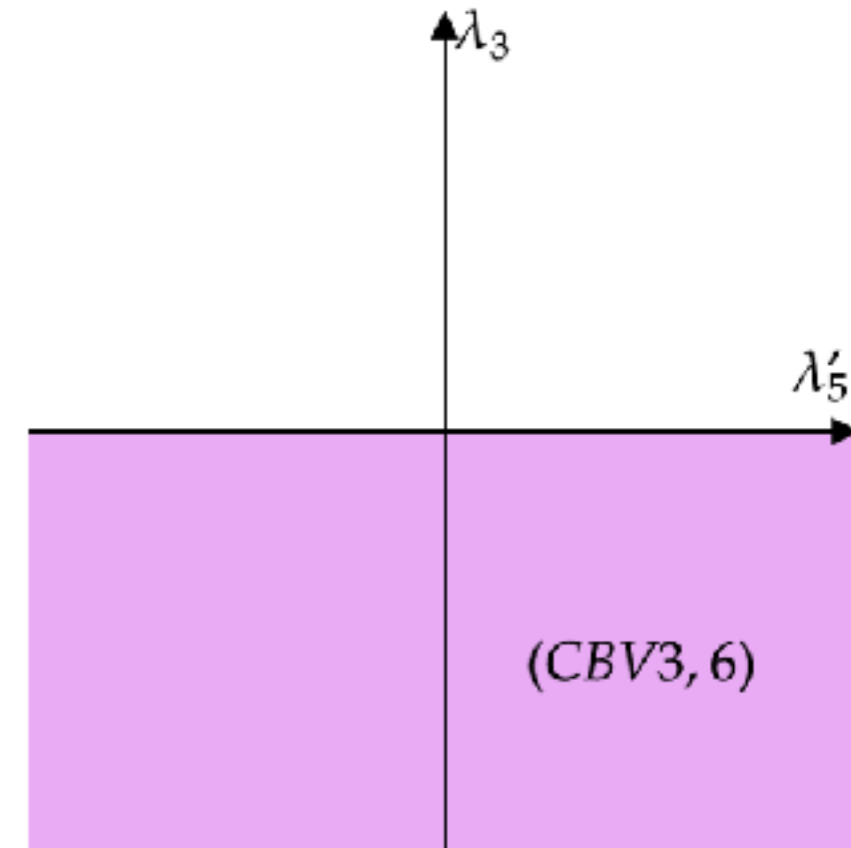
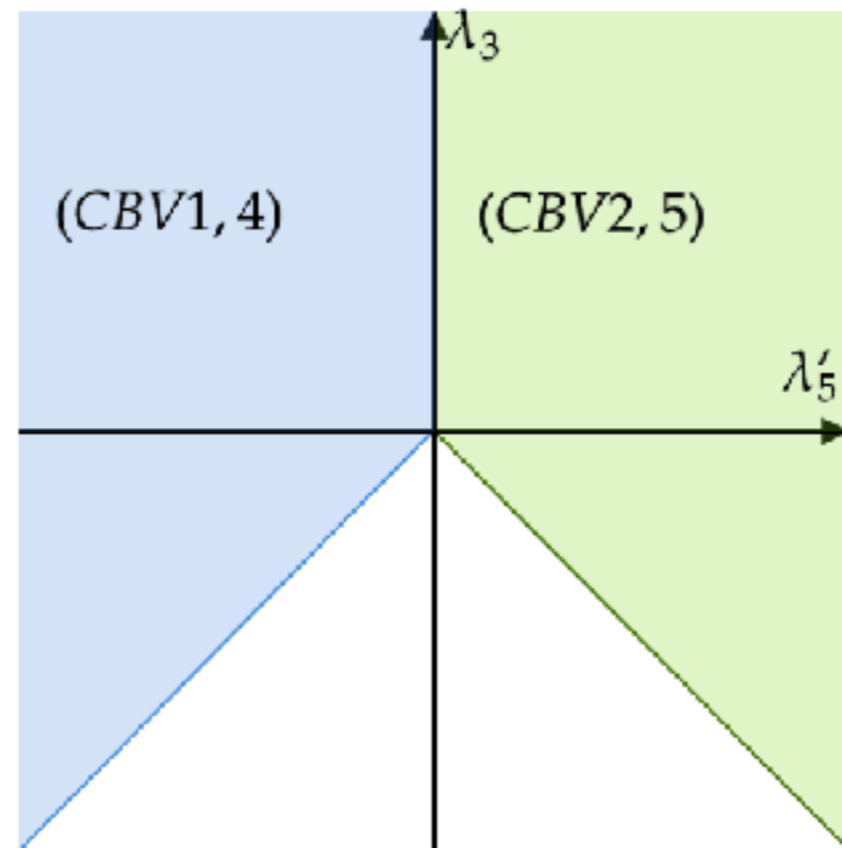
$$m_W^2 = \frac{1}{4} g^2 (4v_\xi^2 + 4v_\chi^2 + v_\phi^2),$$

$$m_Z^2 = \frac{1}{4} (g^2 + g'^2) (8v_\chi^2 + v_\phi^2),$$

II) Charge Breaking Vacuum (CCB)

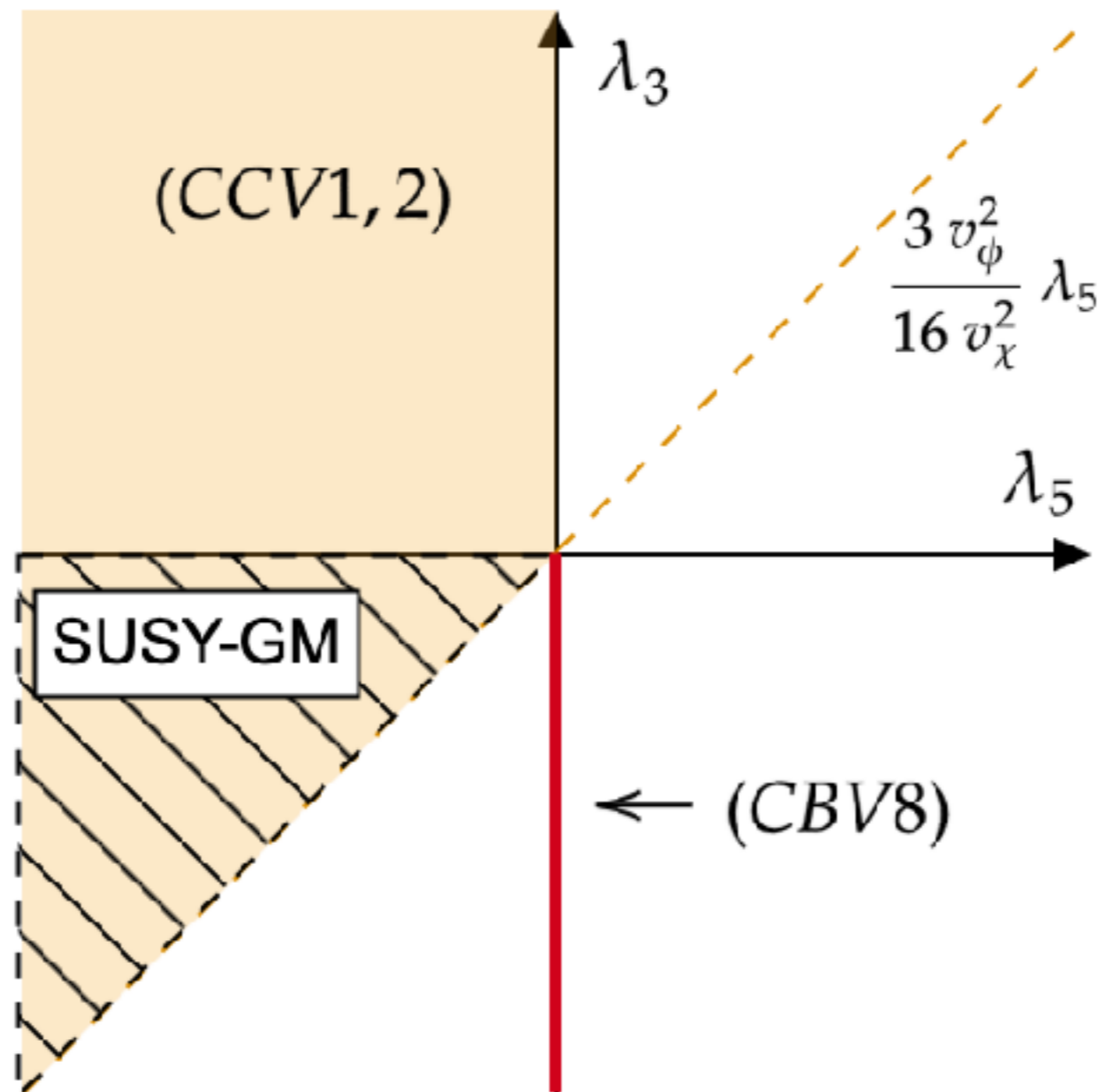
$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\phi & 0 \\ 0 & v_\phi \end{pmatrix},$$

$$\langle \Delta \rangle = \begin{pmatrix} 0 & u_\xi & 0 \\ -u_\chi e^{-i\beta} & 0 & u_\chi e^{i\beta} \\ 0 & -u_\xi & 0 \end{pmatrix}.$$



GMM with SUSY

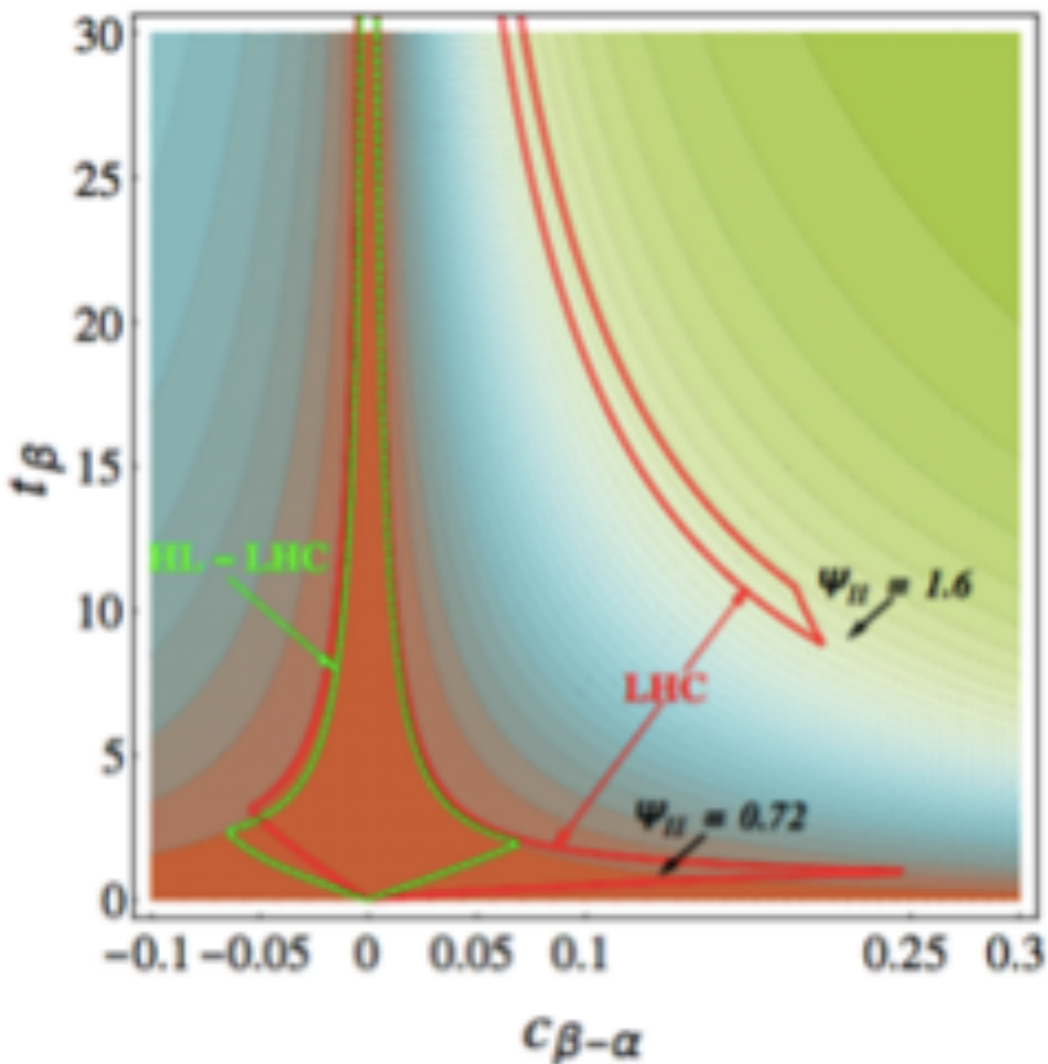
$$\lambda_1 = \frac{3}{4}\lambda_4, \quad \lambda_3 = -\lambda_2, \quad \lambda_5 = 4\lambda_4 - 2\sqrt{2\lambda_2\lambda_4}$$



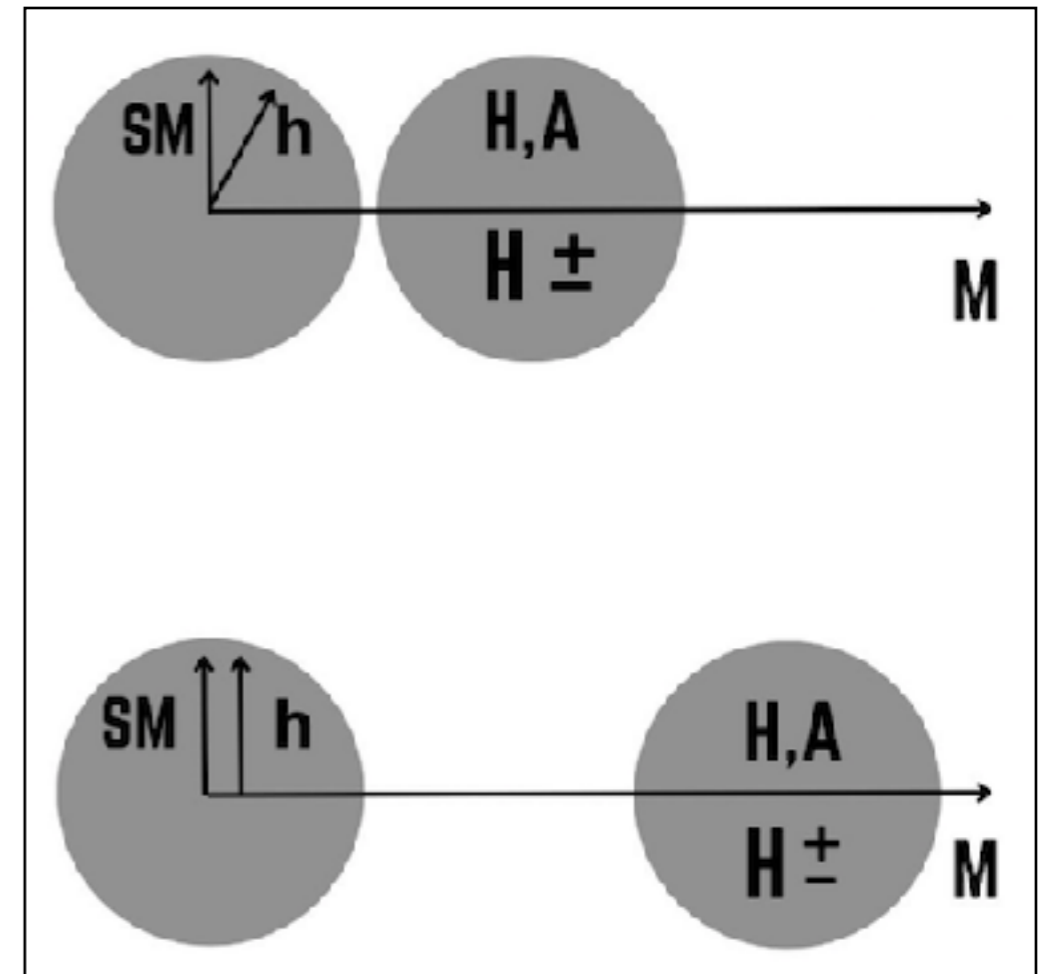
LHC data favors a light-SM like Higgs -> Alignment

- 2HDM couplings (normalized to SM ones):

	Type I and II	Type I		Type II	
Higgs	VV	up quarks	down quarks and leptons	up quarks	down quarks and leptons
h	$\sin(\beta - \alpha)$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
H	$\cos(\beta - \alpha)$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$
A	0	$\cot \beta$	$-\cot \beta$	$\cot \beta$	$\tan \beta$



- Since hVV is SM-like $\rightarrow \cos(\beta - \alpha) \ll 1$,



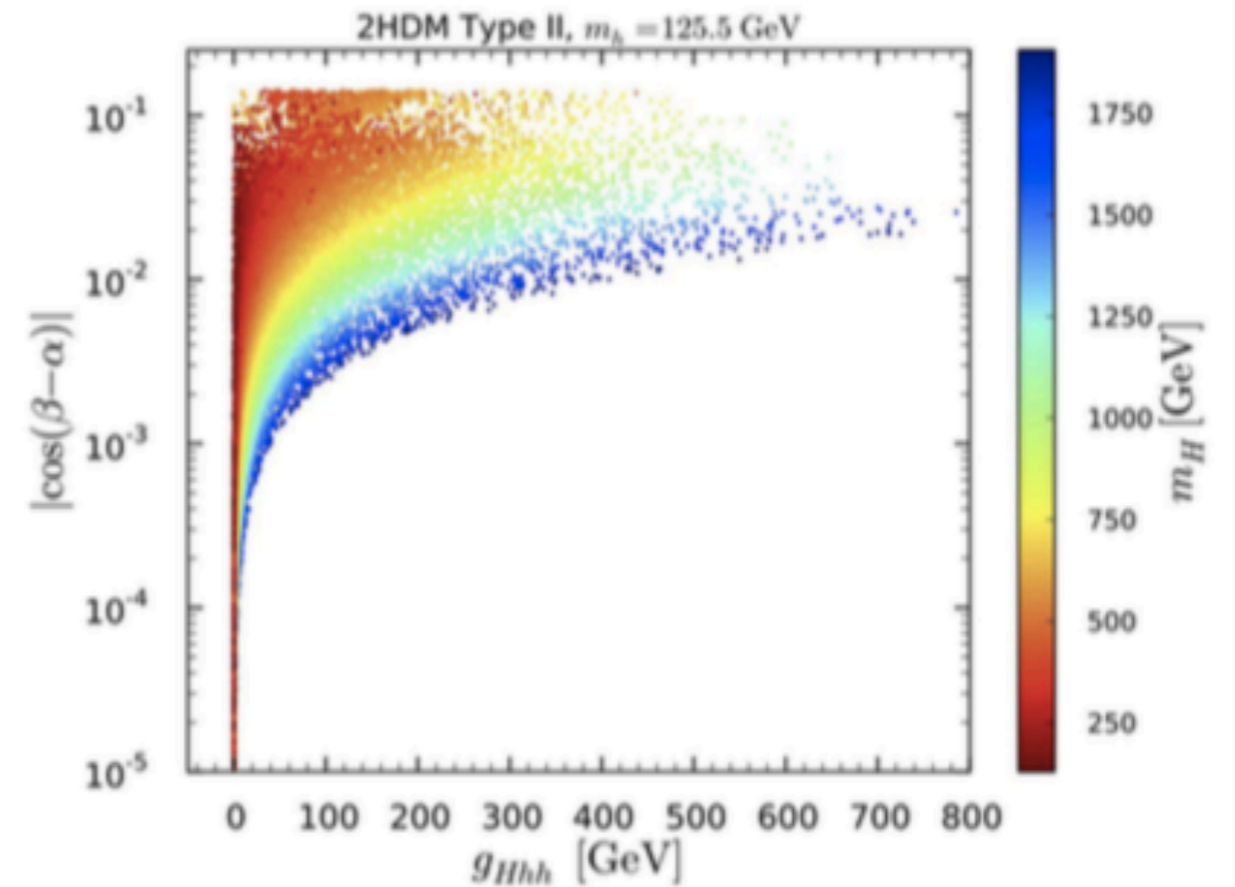
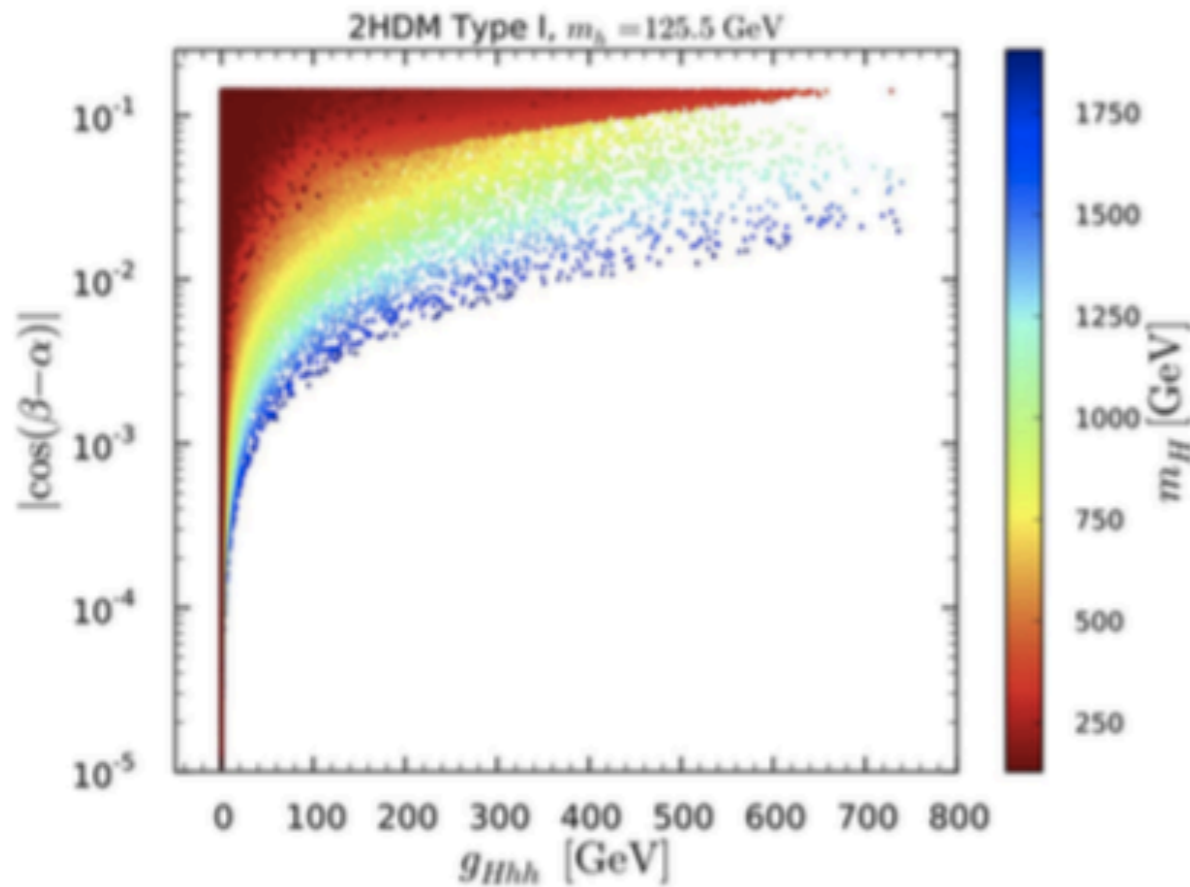
Data favors alignment (with and without decoupling)

Alignment & Mass relations in 2HDM (Gunion et al)

$$c_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}},$$

$$Z_1 = \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \frac{1}{2}, \quad \lambda_{345} s_{2\beta}^2,$$

$$Z_6 \equiv -\frac{1}{2} s_{2\beta} [\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}]$$



$$m_A^2 = \bar{m}^2 - \lambda_5 v^2, \quad \bar{m}^2 \equiv \frac{2m_{12}^2}{s_{2\beta}}.$$

$$m_{H^\pm}^2 = m_A^2 + \frac{1}{2} v^2 (\lambda_5 - \lambda_4)$$

$$m_h^2 = \left(Z_1 + Z_6 \frac{c_{\beta-\alpha}}{s_{\beta-\alpha}} \right) v^2,$$

$$m_H^2 = m_A^2 + \left(Z_5 - Z_6 \frac{c_{\beta-\alpha}}{s_{\beta-\alpha}} \right) v^2.$$

Fine-Tuning in the 2HDM-Tree level

Bernal, Casas & Moreno,
Eur.Phys.J.C 82 (2022)

- From the minimization conditions & mass relations, one can see two types of fine-tunings appear:

i) **VEV FT**: How to make $v \ll M_{ij}$,

($v=246$ GeV, with heavy mass parameters M_i),

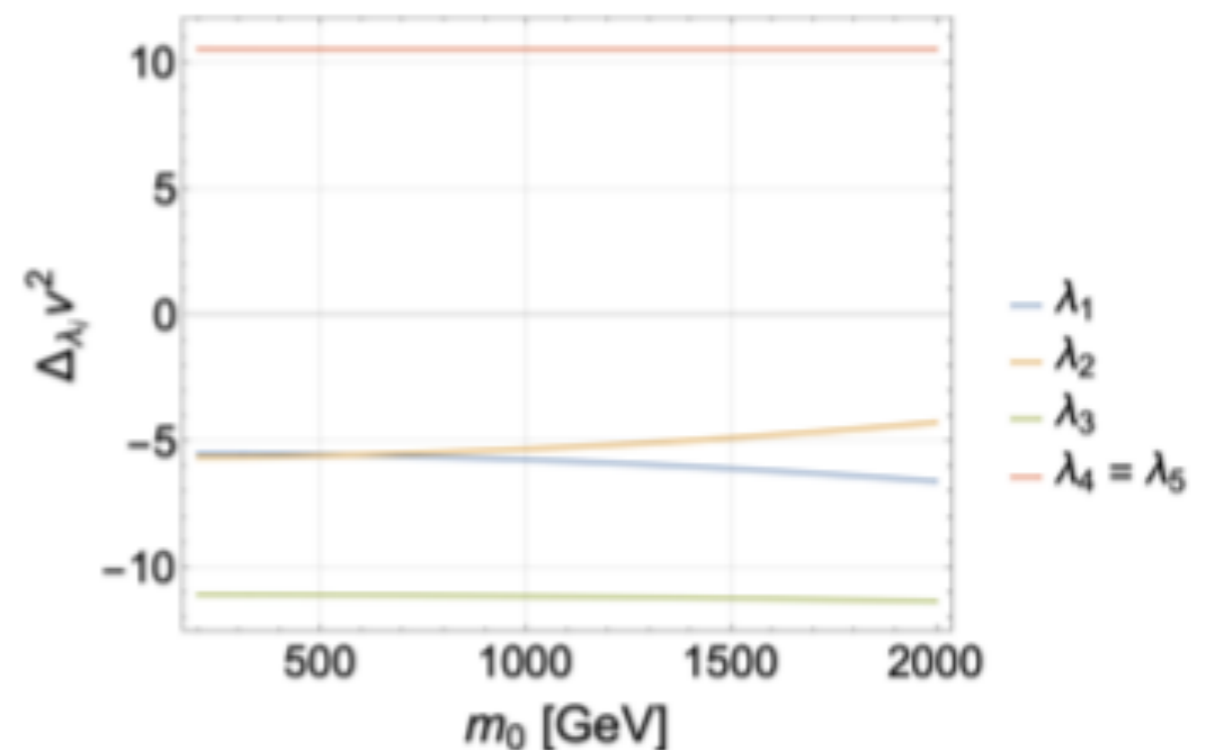
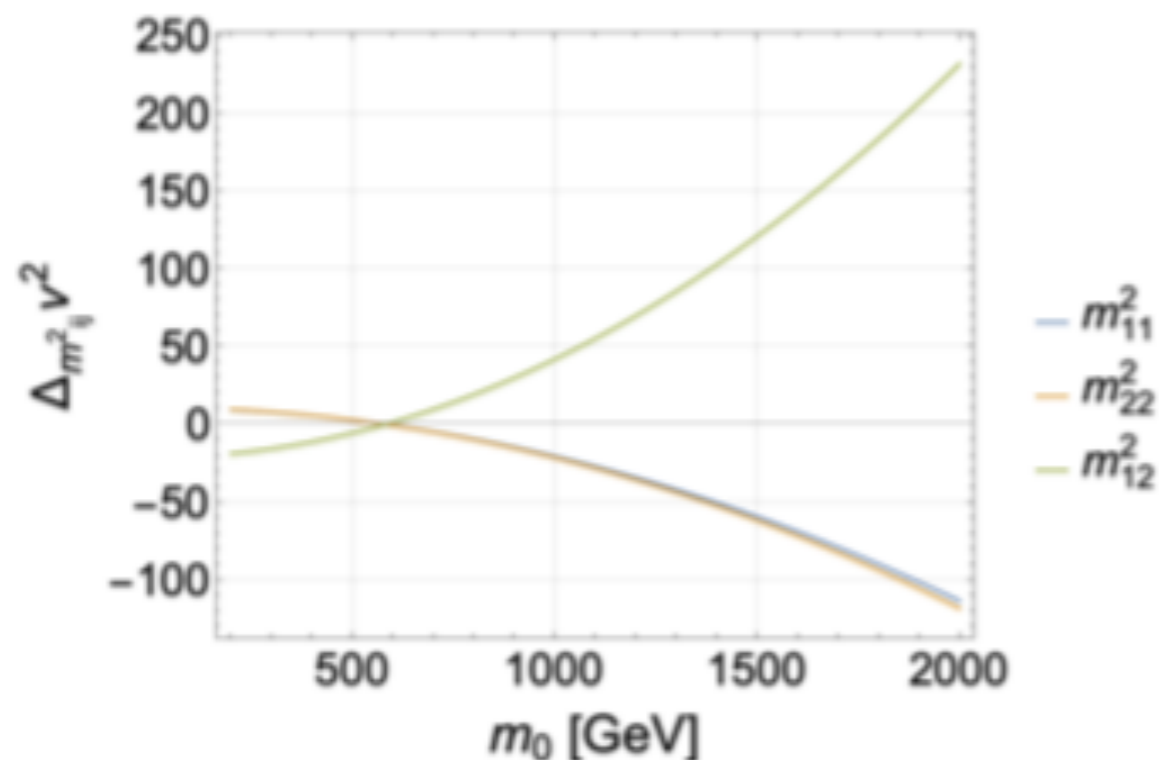
ii) **Alignment FT**: For the alignment without decoupling condition: $\cos(b-a) \ll 1$,

$$m_{11}^2 = m_{12}^2 t_\beta - \frac{1}{2} v^2 (\lambda_1 c_\beta^2 + \lambda_{345} s_\beta^2)$$

$$m_{22}^2 = m_{12}^2 t_\beta^{-1} - \frac{1}{2} v^2 (\lambda_2 s_\beta^2 + \lambda_{345} c_\beta^2)$$

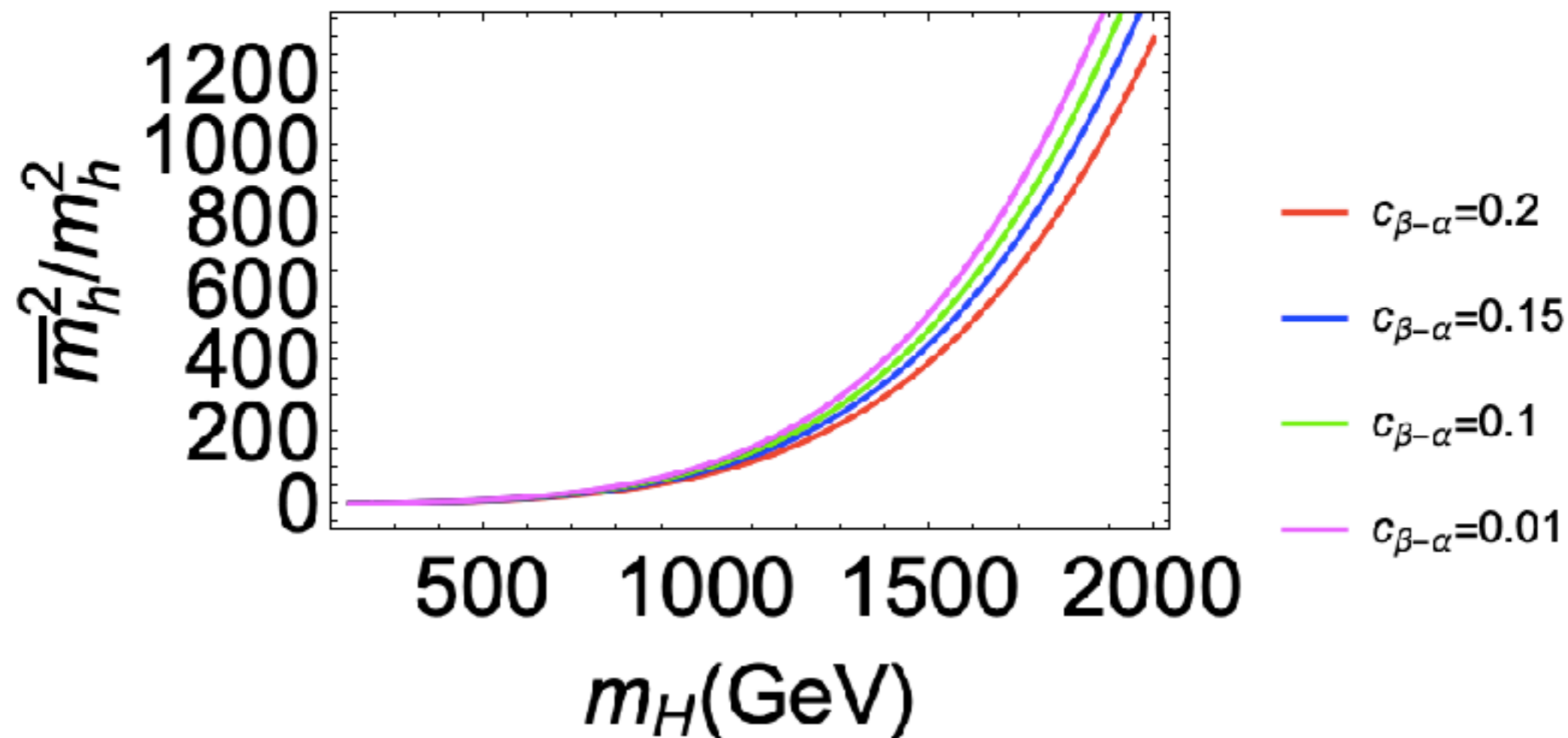
$$\Delta v^2 \sim \frac{4}{t_\beta^2} \frac{m_A^2}{m_h^2},$$

$$\Delta c_{\beta-\alpha} \sim \frac{1}{c_{\beta-\alpha}} \frac{1}{t_\beta} \frac{v^2}{m_H^2},$$



2HDM Fine-Tuning - loop effects (with J.León & C. Tellez)

- We evaluated the **loop-corrections to the SM-like Higgs mass (h)**, due to the **heavy Higgses (H,A, H+)** & **top** see if they are suppressed in the **alignment limit**,
- Our results show the following (large corrections even in alignment limit):

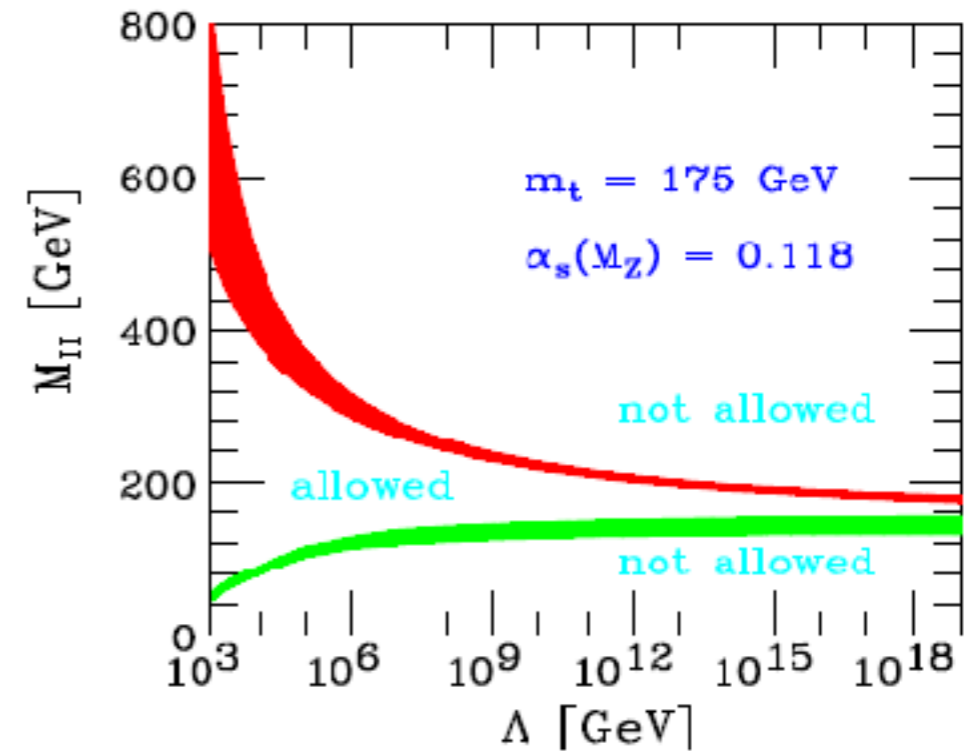


Results seem
consistent with:

$$g_{hH^+H^-} = -\frac{1}{v} \left\{ [m_h^2 + 2(m_{H^\pm}^2 - \bar{m}^2)] s_{\beta-\alpha} + 2 \cot 2\beta (m_h^2 - \bar{m}^2) c_{\beta-\alpha} \right\}$$

5) Conclusions

- SM is not a T.O.E., but could be more fundamental than we thought,
- LHC has provided valuable data, e.g. existence of a light Higgs,
 - This can be seen as a sign of Naturalness;
- Photon mass is possible in 2HDM (&GMM),
- But its SUSY versions enjoy what we call “Parametric naturalness”,
- Big, big problem, LHC as not shown any new physics at O(1) TeV,



ATLAS Exotics Searches^a - 95% CL Upper Exclusion Limits
 Status: May 2019
 $\sqrt{s} = 13 \text{ TeV}$
 $\int L dt = (3.2 - 138) \text{ fb}^{-1}$

Model	κ_V	κ_A	κ_T	κ_B	Limit	Reference
E-33 dimensions						
ADD 5D $\kappa = 1/\Lambda^2$	0.1	0.1	0.1	0.1	2.7 TeV	1711.0001
ADD 6D $\kappa = 1/\Lambda^3$	0.1	0.1	0.1	0.1	3.4 TeV	1709.0001
ADD 7D $\kappa = 1/\Lambda^4$	0.1	0.1	0.1	0.1	4.1 TeV	1708.0001
ADD 8D $\kappa = 1/\Lambda^5$	0.1	0.1	0.1	0.1	4.7 TeV	1707.0001
ADD 9D $\kappa = 1/\Lambda^6$	0.1	0.1	0.1	0.1	5.3 TeV	1706.0001
ADD 10D $\kappa = 1/\Lambda^7$	0.1	0.1	0.1	0.1	5.9 TeV	1705.0001
ADD 11D $\kappa = 1/\Lambda^8$	0.1	0.1	0.1	0.1	6.5 TeV	1704.0001
ADD 12D $\kappa = 1/\Lambda^9$	0.1	0.1	0.1	0.1	7.1 TeV	1703.0001
ADD 13D $\kappa = 1/\Lambda^{10}$	0.1	0.1	0.1	0.1	7.7 TeV	1702.0001
ADD 14D $\kappa = 1/\Lambda^{11}$	0.1	0.1	0.1	0.1	8.3 TeV	1701.0001
ADD 15D $\kappa = 1/\Lambda^{12}$	0.1	0.1	0.1	0.1	8.9 TeV	1700.0001
ADD 16D $\kappa = 1/\Lambda^{13}$	0.1	0.1	0.1	0.1	9.5 TeV	1699.0001
ADD 17D $\kappa = 1/\Lambda^{14}$	0.1	0.1	0.1	0.1	10.1 TeV	1698.0001
ADD 18D $\kappa = 1/\Lambda^{15}$	0.1	0.1	0.1	0.1	10.7 TeV	1697.0001
ADD 19D $\kappa = 1/\Lambda^{16}$	0.1	0.1	0.1	0.1	11.3 TeV	1696.0001
ADD 20D $\kappa = 1/\Lambda^{17}$	0.1	0.1	0.1	0.1	11.9 TeV	1695.0001
ADD 21D $\kappa = 1/\Lambda^{18}$	0.1	0.1	0.1	0.1	12.5 TeV	1694.0001
ADD 22D $\kappa = 1/\Lambda^{19}$	0.1	0.1	0.1	0.1	13.1 TeV	1693.0001
ADD 23D $\kappa = 1/\Lambda^{20}$	0.1	0.1	0.1	0.1	13.7 TeV	1692.0001
ADD 24D $\kappa = 1/\Lambda^{21}$	0.1	0.1	0.1	0.1	14.3 TeV	1691.0001
ADD 25D $\kappa = 1/\Lambda^{22}$	0.1	0.1	0.1	0.1	14.9 TeV	1690.0001
ADD 26D $\kappa = 1/\Lambda^{23}$	0.1	0.1	0.1	0.1	15.5 TeV	1689.0001
ADD 27D $\kappa = 1/\Lambda^{24}$	0.1	0.1	0.1	0.1	16.1 TeV	1688.0001
ADD 28D $\kappa = 1/\Lambda^{25}$	0.1	0.1	0.1	0.1	16.7 TeV	1687.0001
ADD 29D $\kappa = 1/\Lambda^{26}$	0.1	0.1	0.1	0.1	17.3 TeV	1686.0001
ADD 30D $\kappa = 1/\Lambda^{27}$	0.1	0.1	0.1	0.1	17.9 TeV	1685.0001
ADD 31D $\kappa = 1/\Lambda^{28}$	0.1	0.1	0.1	0.1	18.5 TeV	1684.0001
ADD 32D $\kappa = 1/\Lambda^{29}$	0.1	0.1	0.1	0.1	19.1 TeV	1683.0001
ADD 33D $\kappa = 1/\Lambda^{30}$	0.1	0.1	0.1	0.1	19.7 TeV	1682.0001
ADD 34D $\kappa = 1/\Lambda^{31}$	0.1	0.1	0.1	0.1	20.3 TeV	1681.0001
ADD 35D $\kappa = 1/\Lambda^{32}$	0.1	0.1	0.1	0.1	20.9 TeV	1680.0001
ADD 36D $\kappa = 1/\Lambda^{33}$	0.1	0.1	0.1	0.1	21.5 TeV	1679.0001
ADD 37D $\kappa = 1/\Lambda^{34}$	0.1	0.1	0.1	0.1	22.1 TeV	1678.0001
ADD 38D $\kappa = 1/\Lambda^{35}$	0.1	0.1	0.1	0.1	22.7 TeV	1677.0001
ADD 39D $\kappa = 1/\Lambda^{36}$	0.1	0.1	0.1	0.1	23.3 TeV	1676.0001
ADD 40D $\kappa = 1/\Lambda^{37}$	0.1	0.1	0.1	0.1	23.9 TeV	1675.0001
ADD 41D $\kappa = 1/\Lambda^{38}$	0.1	0.1	0.1	0.1	24.5 TeV	1674.0001
ADD 42D $\kappa = 1/\Lambda^{39}$	0.1	0.1	0.1	0.1	25.1 TeV	1673.0001
ADD 43D $\kappa = 1/\Lambda^{40}$	0.1	0.1	0.1	0.1	25.7 TeV	1672.0001
ADD 44D $\kappa = 1/\Lambda^{41}$	0.1	0.1	0.1	0.1	26.3 TeV	1671.0001
ADD 45D $\kappa = 1/\Lambda^{42}$	0.1	0.1	0.1	0.1	26.9 TeV	1670.0001
ADD 46D $\kappa = 1/\Lambda^{43}$	0.1	0.1	0.1	0.1	27.5 TeV	1669.0001
ADD 47D $\kappa = 1/\Lambda^{44}$	0.1	0.1	0.1	0.1	28.1 TeV	1668.0001
ADD 48D $\kappa = 1/\Lambda^{45}$	0.1	0.1	0.1	0.1	28.7 TeV	1667.0001
ADD 49D $\kappa = 1/\Lambda^{46}$	0.1	0.1	0.1	0.1	29.3 TeV	1666.0001
ADD 50D $\kappa = 1/\Lambda^{47}$	0.1	0.1	0.1	0.1	29.9 TeV	1665.0001
ADD 51D $\kappa = 1/\Lambda^{48}$	0.1	0.1	0.1	0.1	30.5 TeV	1664.0001
ADD 52D $\kappa = 1/\Lambda^{49}$	0.1	0.1	0.1	0.1	31.1 TeV	1663.0001
ADD 53D $\kappa = 1/\Lambda^{50}$	0.1	0.1	0.1	0.1	31.7 TeV	1662.0001
ADD 54D $\kappa = 1/\Lambda^{51}$	0.1	0.1	0.1	0.1	32.3 TeV	1661.0001
ADD 55D $\kappa = 1/\Lambda^{52}$	0.1	0.1	0.1	0.1	32.9 TeV	1660.0001
ADD 56D $\kappa = 1/\Lambda^{53}$	0.1	0.1	0.1	0.1	33.5 TeV	1659.0001
ADD 57D $\kappa = 1/\Lambda^{54}$	0.1	0.1	0.1	0.1	34.1 TeV	1658.0001
ADD 58D $\kappa = 1/\Lambda^{55}$	0.1	0.1	0.1	0.1	34.7 TeV	1657.0001
ADD 59D $\kappa = 1/\Lambda^{56}$	0.1	0.1	0.1	0.1	35.3 TeV	1656.0001
ADD 60D $\kappa = 1/\Lambda^{57}$	0.1	0.1	0.1	0.1	35.9 TeV	1655.0001
ADD 61D $\kappa = 1/\Lambda^{58}$	0.1	0.1	0.1	0.1	36.5 TeV	1654.0001
ADD 62D $\kappa = 1/\Lambda^{59}$	0.1	0.1	0.1	0.1	37.1 TeV	1653.0001
ADD 63D $\kappa = 1/\Lambda^{60}$	0.1	0.1	0.1	0.1	37.7 TeV	1652.0001
ADD 64D $\kappa = 1/\Lambda^{61}$	0.1	0.1	0.1	0.1	38.3 TeV	1651.0001
ADD 65D $\kappa = 1/\Lambda^{62}$	0.1	0.1	0.1	0.1	38.9 TeV	1650.0001
ADD 66D $\kappa = 1/\Lambda^{63}$	0.1	0.1	0.1	0.1	39.5 TeV	1649.0001
ADD 67D $\kappa = 1/\Lambda^{64}$	0.1	0.1	0.1	0.1	40.1 TeV	1648.0001
ADD 68D $\kappa = 1/\Lambda^{65}$	0.1	0.1	0.1	0.1	40.7 TeV	1647.0001
ADD 69D $\kappa = 1/\Lambda^{66}$	0.1	0.1	0.1	0.1	41.3 TeV	1646.0001
ADD 70D $\kappa = 1/\Lambda^{67}$	0.1	0.1	0.1	0.1	41.9 TeV	1645.0001
ADD 71D $\kappa = 1/\Lambda^{68}$	0.1	0.1	0.1	0.1	42.5 TeV	1644.0001
ADD 72D $\kappa = 1/\Lambda^{69}$	0.1	0.1	0.1	0.1	43.1 TeV	1643.0001
ADD 73D $\kappa = 1/\Lambda^{70}$	0.1	0.1	0.1	0.1	43.7 TeV	1642.0001
ADD 74D $\kappa = 1/\Lambda^{71}$	0.1	0.1	0.1	0.1	44.3 TeV	1641.0001
ADD 75D $\kappa = 1/\Lambda^{72}$	0.1	0.1	0.1	0.1	44.9 TeV	1640.0001
ADD 76D $\kappa = 1/\Lambda^{73}$	0.1	0.1	0.1	0.1	45.5 TeV	1639.0001
ADD 77D $\kappa = 1/\Lambda^{74}$	0.1	0.1	0.1	0.1	46.1 TeV	1638.0001
ADD 78D $\kappa = 1/\Lambda^{75}$	0.1	0.1	0.1	0.1	46.7 TeV	1637.0001
ADD 79D $\kappa = 1/\Lambda^{76}$	0.1	0.1	0.1	0.1	47.3 TeV	1636.0001
ADD 80D $\kappa = 1/\Lambda^{77}$	0.1	0.1	0.1	0.1	47.9 TeV	1635.0001
ADD 81D $\kappa = 1/\Lambda^{78}$	0.1	0.1	0.1	0.1	48.5 TeV	1634.0001
ADD 82D $\kappa = 1/\Lambda^{79}$	0.1	0.1	0.1	0.1	49.1 TeV	1633.0001
ADD 83D $\kappa = 1/\Lambda^{80}$	0.1	0.1	0.1	0.1	49.7 TeV	1632.0001
ADD 84D $\kappa = 1/\Lambda^{81}$	0.1	0.1	0.1	0.1	50.3 TeV	1631.0001
ADD 85D $\kappa = 1/\Lambda^{82}$	0.1	0.1	0.1	0.1	50.9 TeV	1630.0001
ADD 86D $\kappa = 1/\Lambda^{83}$	0.1	0.1	0.1	0.1	51.5 TeV	1629.0001
ADD 87D $\kappa = 1/\Lambda^{84}$	0.1	0.1	0.1	0.1	52.1 TeV	1628.0001
ADD 88D $\kappa = 1/\Lambda^{85}$	0.1	0.1	0.1	0.1	52.7 TeV	1627.0001
ADD 89D $\kappa = 1/\Lambda^{86}$	0.1	0.1	0.1	0.1	53.3 TeV	1626.0001
ADD 90D $\kappa = 1/\Lambda^{87}$	0.1	0.1	0.1	0.1	53.9 TeV	1625.0001
ADD 91D $\kappa = 1/\Lambda^{88}$	0.1	0.1	0.1	0.1	54.5 TeV	1624.0001
ADD 92D $\kappa = 1/\Lambda^{89}$	0.1	0.1	0.1	0.1	55.1 TeV	1623.0001
ADD 93D $\kappa = 1/\Lambda^{90}$	0.1	0.1	0.1	0.1	55.7 TeV	1622.0001
ADD 94D $\kappa = 1/\Lambda^{91}$	0.1	0.1	0.1	0.1	56.3 TeV	1621.0001
ADD 95D $\kappa = 1/\Lambda^{92}$	0.1	0.1	0.1	0.1	56.9 TeV	1620.0001
ADD 96D $\kappa = 1/\Lambda^{93}$	0.1	0.1	0.1	0.1	57.5 TeV	1619.0001
ADD 97D $\kappa = 1/\Lambda^{94}$	0.1	0.1	0.1	0.1	58.1 TeV	1618.0001
ADD 98D $\kappa = 1/\Lambda^{95}$	0.1	0.1	0.1	0.1	58.7 TeV	1617.0001
ADD 99D $\kappa = 1/\Lambda^{96}$	0.1	0.1	0.1	0.1	59.3 TeV	1616.0001
ADD 100D $\kappa = 1/\Lambda^{97}$	0.1	0.1	0.1	0.1	59.9 TeV	1615.0001

^aOnly a selection of the available mass limits on new states/phenomena is shown.
^bSmall radius (large-radius) jets are denoted by the letter (J) (L).

Gracias!

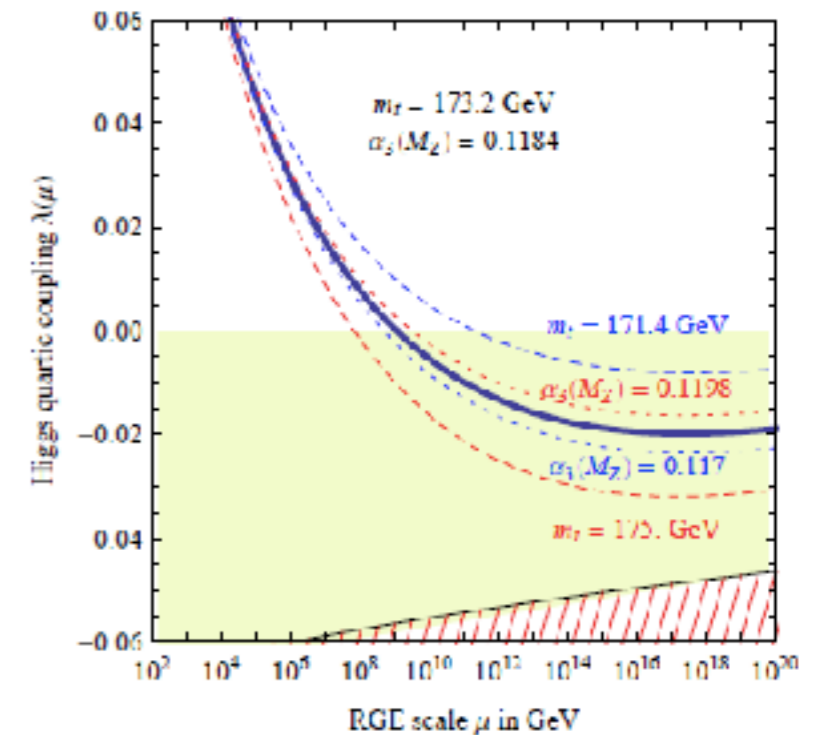
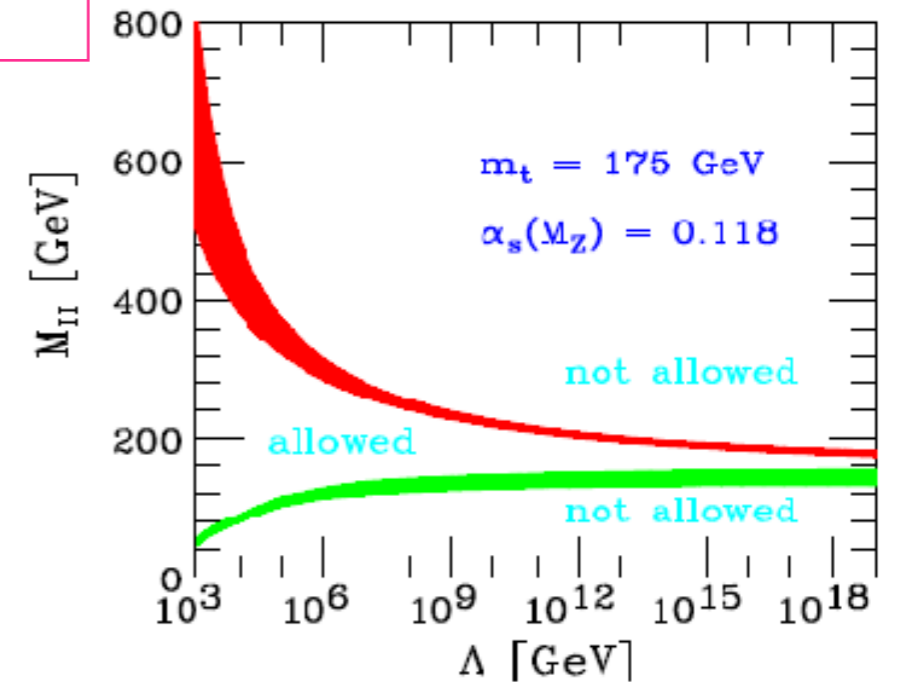


Is the Higgs Boson the Master of the Universe?

Fred Jegerlehner^{1,2}

- Higgs boson discovery and absence of BSM physics at O(1) TeV -> **new paradigm**,
- SM masses & couplings show **amazingly deep conspiracy** -> **SM vacuum stable up to the Planck scale**,
- At **higher energy** (below Planck scale), there is a **phase transition** from Higgs phase (SSB) to symmetric one,
- In the disordered phase, **four physical Higgs scalars are very heavy** -> **provide enormous Dark Energy (DE)**.

e-Print: 2305.01326 [hep-ph]



$$\delta m_H^2 = m_{H0}^2 - M_H^2 = C_1 \Xi; C_1 = 2\lambda + 3/2 g'^2 + 9/2 g^2 - 12 y_t^2$$

- C1 has a zero, at about $E=10^{17}$ GeV, for $m_h=125$ GeV.

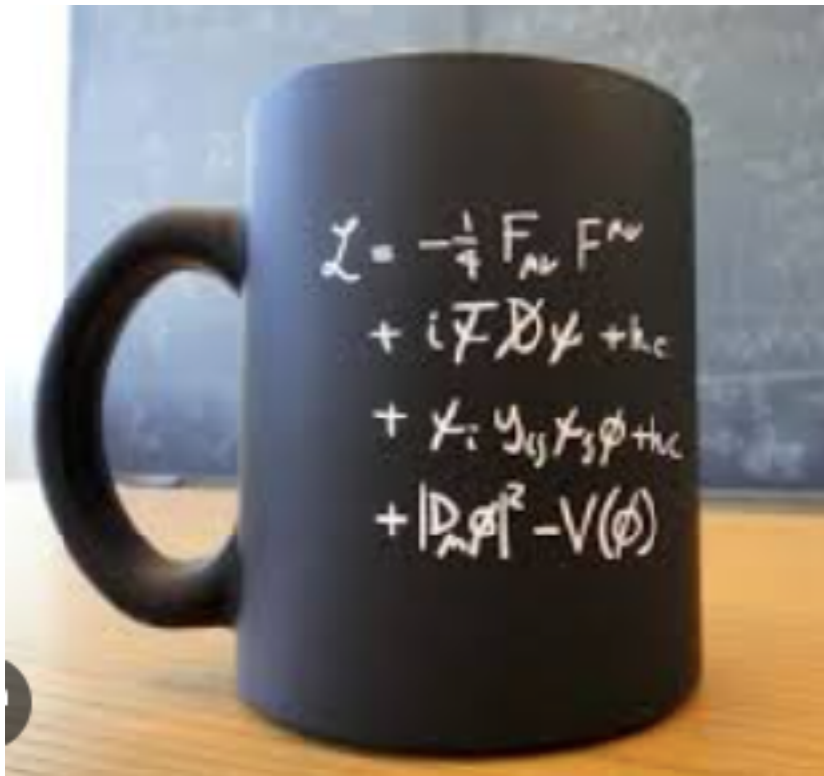
Most General Vacuum (CCB) give some pathologies: non-deg W-mass

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\phi & 0 \\ 0 & v_\phi \end{pmatrix}, \quad \langle \Delta \rangle = \begin{pmatrix} v_\chi e^{-i\alpha} & u_\xi & 0 \\ -u_\chi e^{-i\beta} & v_\xi & u_\chi e^{i\beta} \\ 0 & -u_\xi & v_\chi e^{i\alpha} \end{pmatrix},$$

$$M_V^2 = \begin{pmatrix} M_{W^\pm}^2 & \varpi^\top \\ \varpi & M_{Z,\gamma}^2 \end{pmatrix},$$

$$M_{W^\pm}^2 = \begin{pmatrix} \frac{1}{4}g^2 (8u_\chi^2 + 4v_\xi^2 + 4v_\chi^2 + v_\phi^2) & 0 \\ 0 & \frac{1}{4}g^2 (8u_\xi^2 + 8u_\chi^2 + 4v_\xi^2 + 4v_\chi^2 + v_\phi^2) \end{pmatrix}$$

X. The Naturalness Problem



- Why there is something rather than nothing? (Leibnitz)



$$S_{EH} = \int d^4x \sqrt{-g} \left(-\frac{2}{\kappa^2} R \right),$$

$$\kappa^2 = 32\pi G$$

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- Why are there two scales in the SM & GR that break the conformal symmetry?

Fine-Tuning & Integrating-out Heavy Particles

- Suppose a QFT has a heavy and a light fields:

(With masses: M & m)

- For $E > M$, the theory is described by:
- For $E < M$, QFT only includes light fields, and it is described by:
- The parameters (H&L) are different in general,

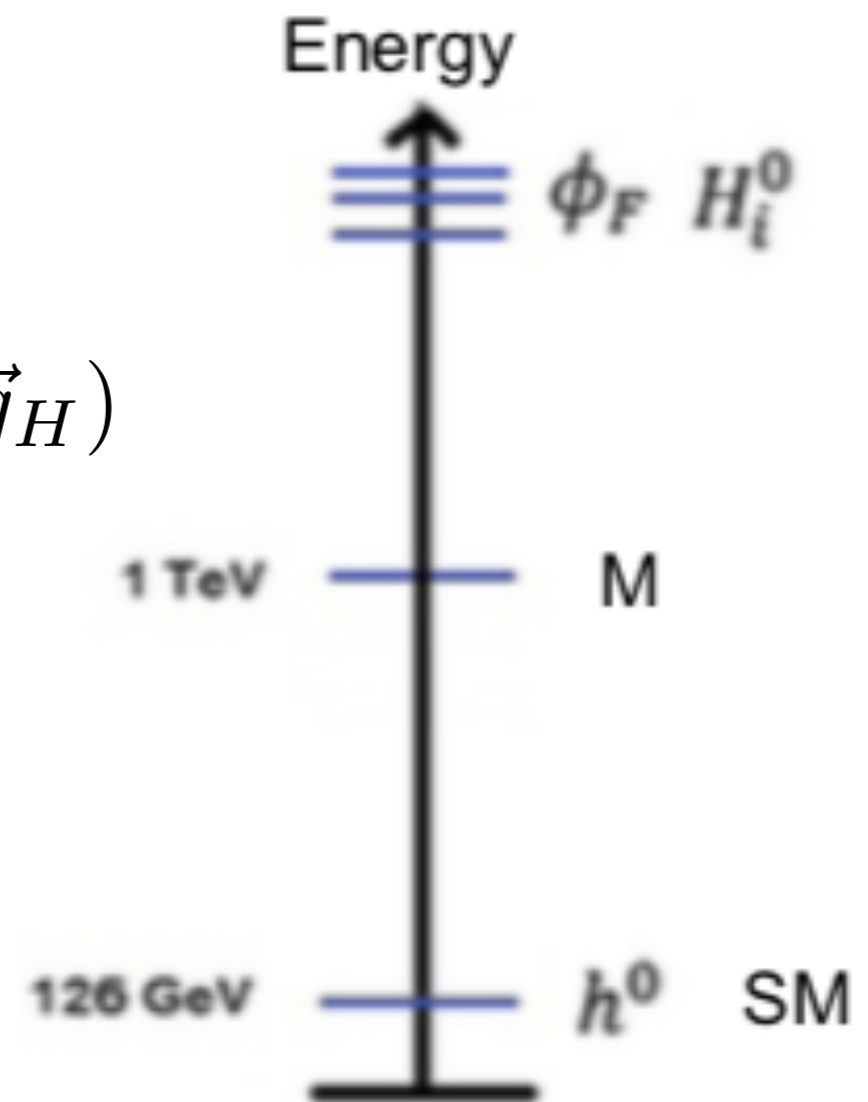
Φ_H and ϕ_L

$$\mathcal{L}_H = \mathcal{L}_H(\Phi_H, \phi_L; \vec{g}_H)$$



$$\mathcal{L}_L = \mathcal{L}_L(\phi_L; \vec{g}_L)$$

$$\vec{g}_H \neq \vec{g}_L$$



When the heavy field is integrated out the parameters change with Energy (Scale, RGE):

$$g_i = g_i(M)$$

A general formula for the **correction to scalar mass** interacting with **a heavy state** that is integrated-out, gives:

$$m_h^2(\Lambda, \mu) = m_h^2(\Lambda) + \sum_{X=S,V,F} (-1)^{2J_x} (2J_x + 1) \frac{g_x}{16\pi^2} [\Lambda^2 - m_h^2(\Lambda) \log \frac{\Lambda^2}{\mu^2}]$$

- When **Lambda** is identified as the **UV cutoff**, a very large correction to the Higgs mass seems to be induced (**Quadratic Divergence & Old Naturalness problem**),
- This motivated the search for models that were free of **quadratic divergences**, including models with no scalars!

UV cut-off:

$$\Lambda \rightarrow \infty$$

Known Solutions with $C_1 = 0$:

- **SUSY**: A relation among parameters, (**bosons & fermions**) such that $C_1 = 0$,
- **Veltman Condition**; A relation among SM masses such that $C_1 = 0$, but this gives $m_h = O(300) \text{ GeV}$

$$\delta m_H^2 = \frac{\Lambda^2}{16\pi^2} C_n(\mu)$$

$$C_1 = C_b + C_f = 0$$

$$m_h^2 = 4m_t^2 - 2m_W^2 - m_Z^2$$

Are there other solutions to the naturalness problem?

- Known solutions assume: $g_x = g_{sm} = O(1)$,
 - But, what about the case $g_x \ll 1$?
- (Feeble Coupled Sector = FECOS)

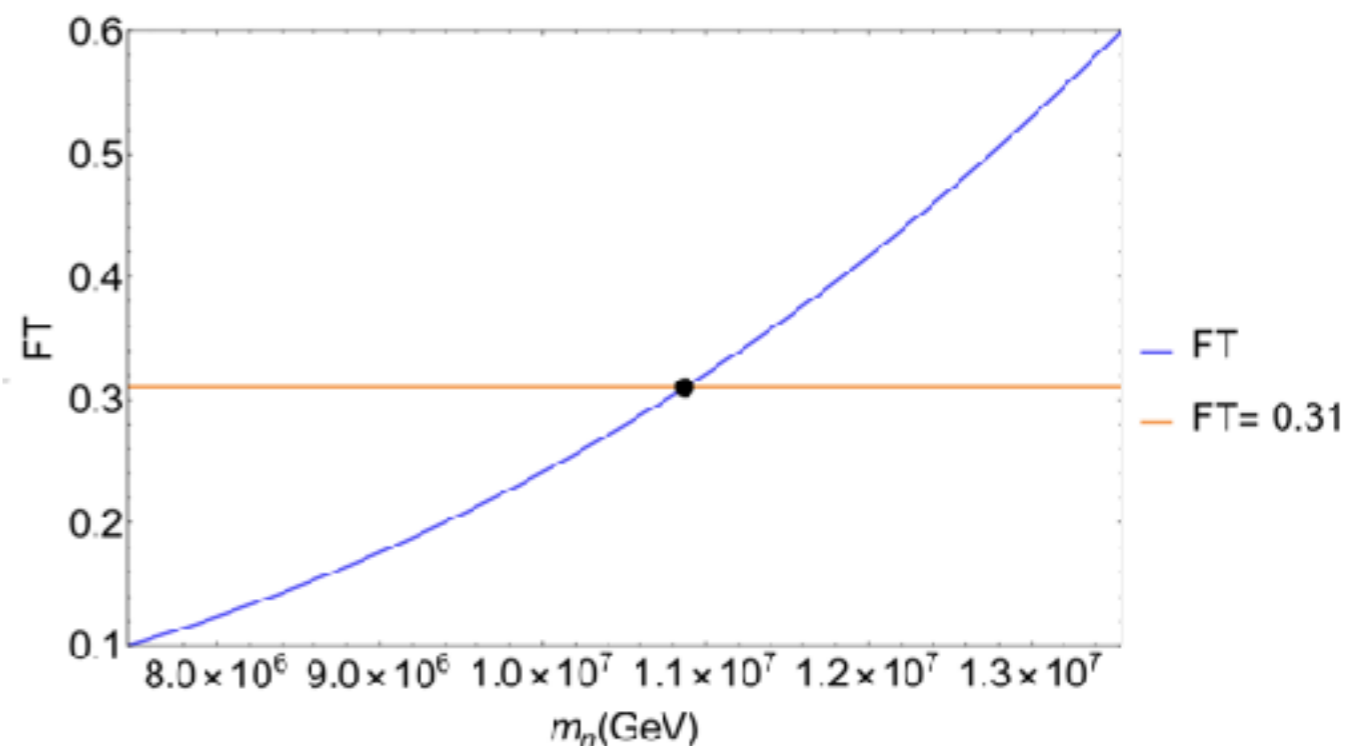
$$\delta m_h^2 = \frac{g_x^2 M_x^2}{16\pi^2}$$

J. Lorenzo Diaz-Cruz (Puebla U., Mexico)
e-Print: 2309.01378 [hep-ph]

- Within FECOS it is possible to keep $M_h = O(\text{EW})$ scale with large M_x ,
- Is it useful for model building? Yes, as we will see next ..

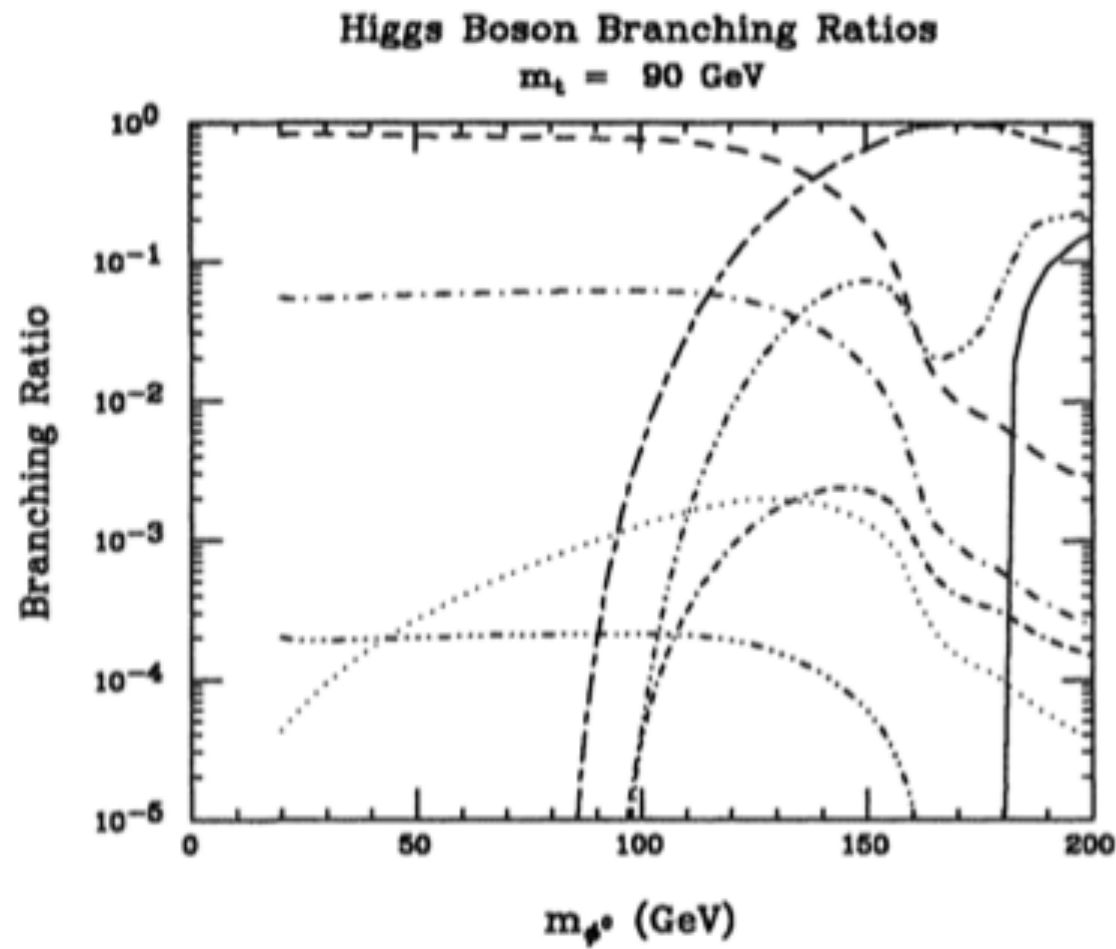
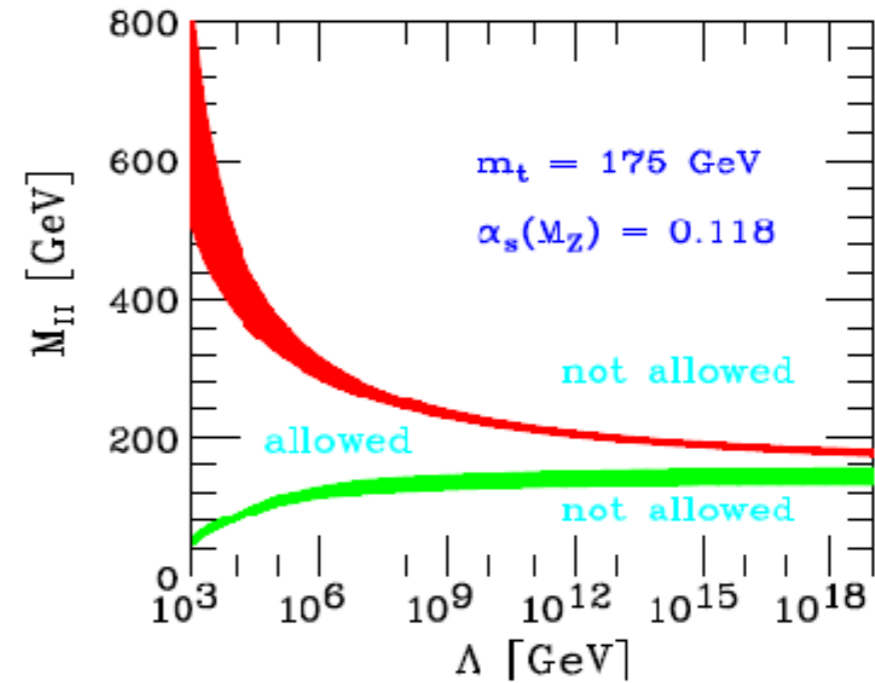
- Actually the nuSM (See-saw) is one example of FECOS, i.e. Correction from RH neutrinos is:

$$\delta \mu_H^2(\mu) = \frac{4y^2}{(4\pi)^2} M_N^2 \left(1 - \log \frac{M_N^2}{\mu^2} \right),$$

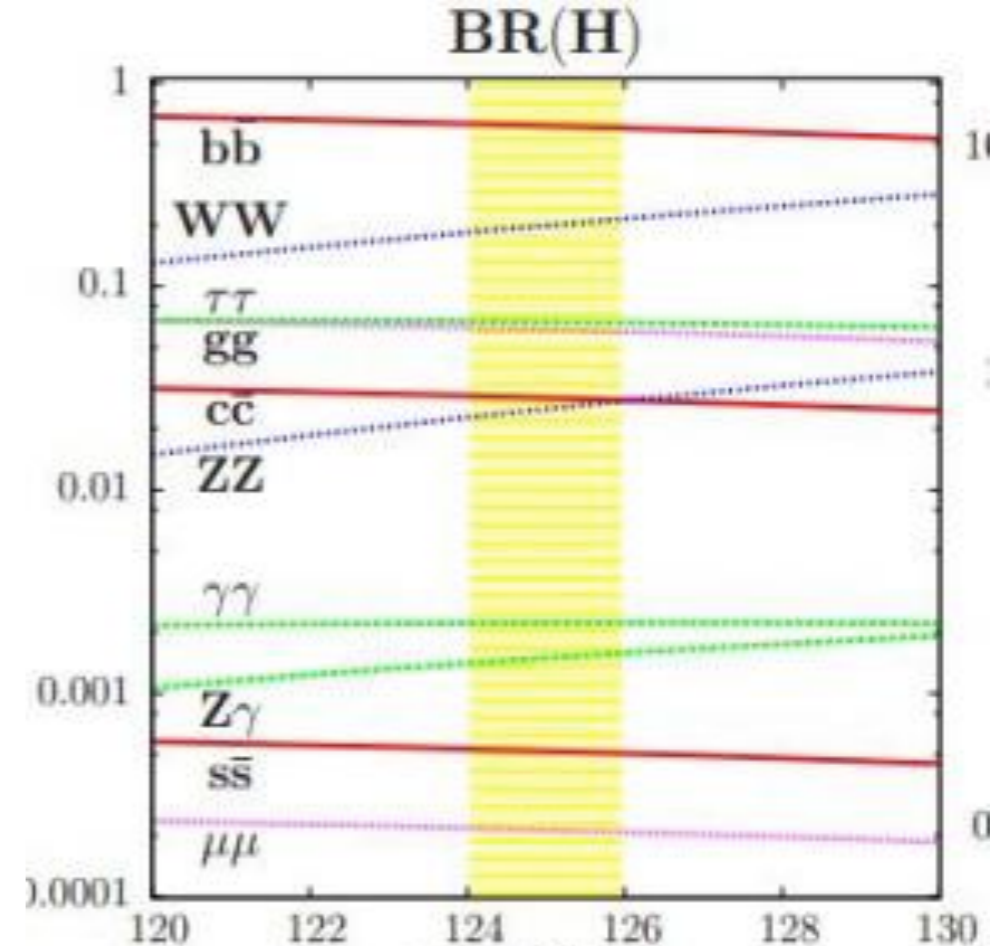


Higgs hunting: from early days to LHC

- Higgs mass limits were obtained from **Unitarity and Pert.:** $m_h < O(1)$ TeV,
- To search for Higgs signal, **mass range** was divided into:
 - **light:** $m_h < m_Z$,
 - **intermediate:** $m_Z < m_h < 2m_t$,
 - **Heavy/Obese:** $2m_t < m_h < 600$ GeV- $O(1)$ TeV

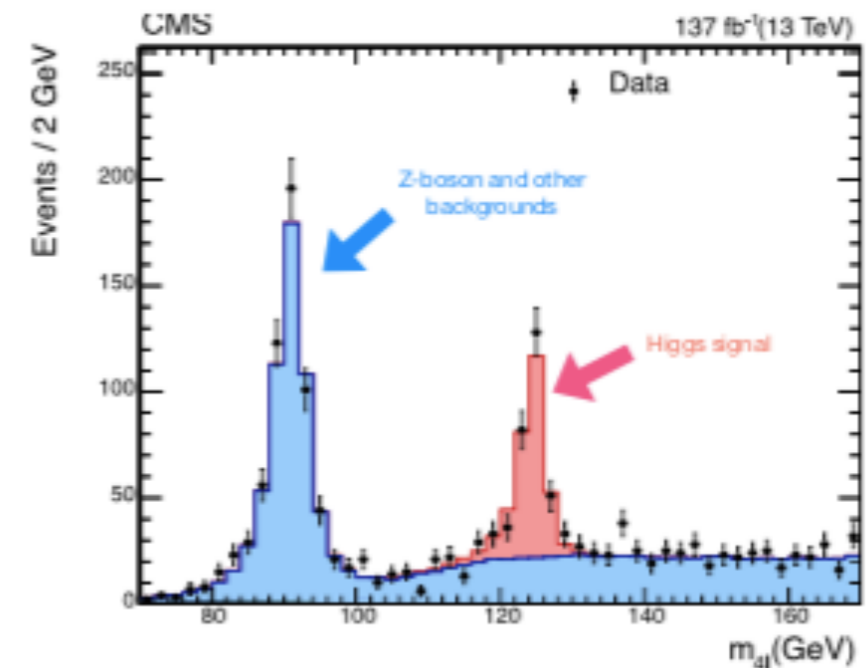
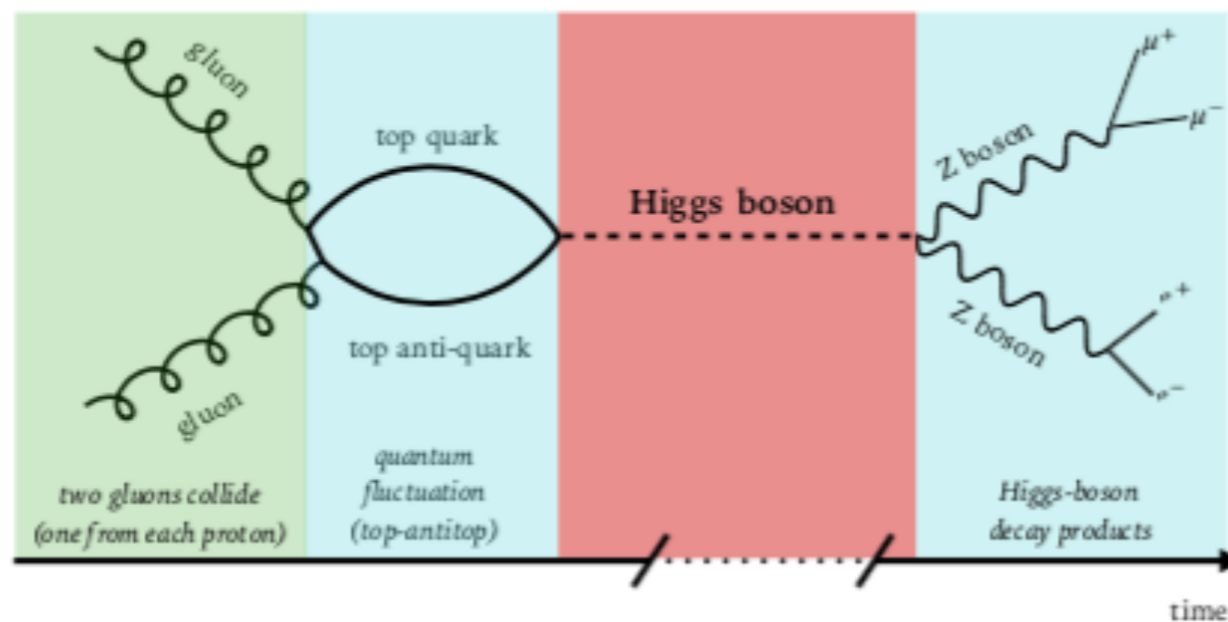
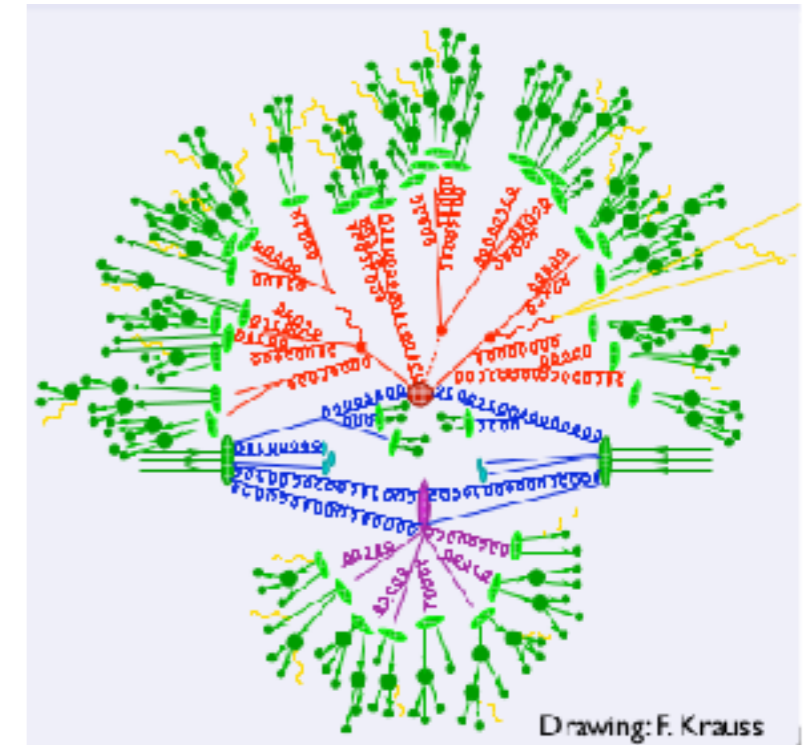
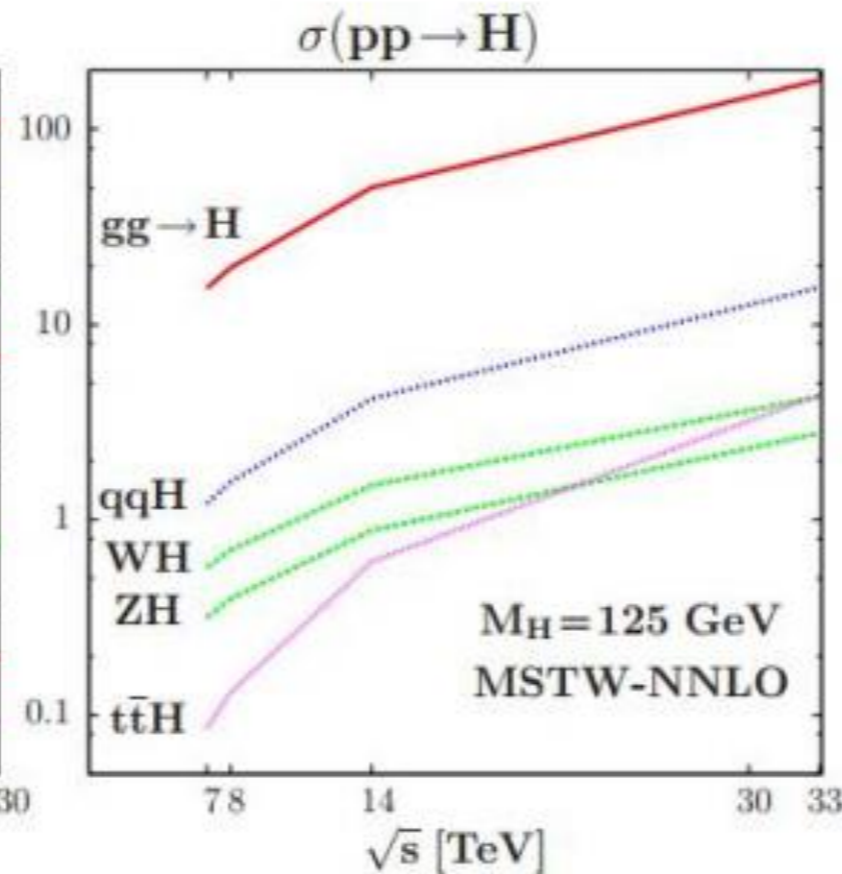
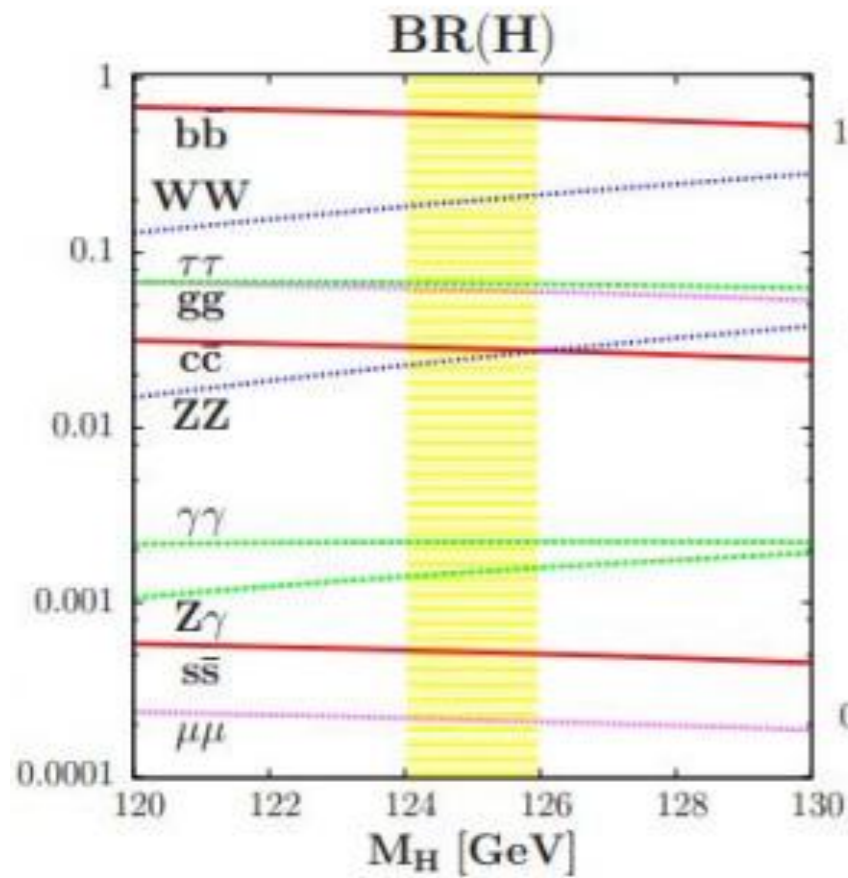


A heavy top quark, made life easier for LHC:
 $105 < m_h < 130$ GeV

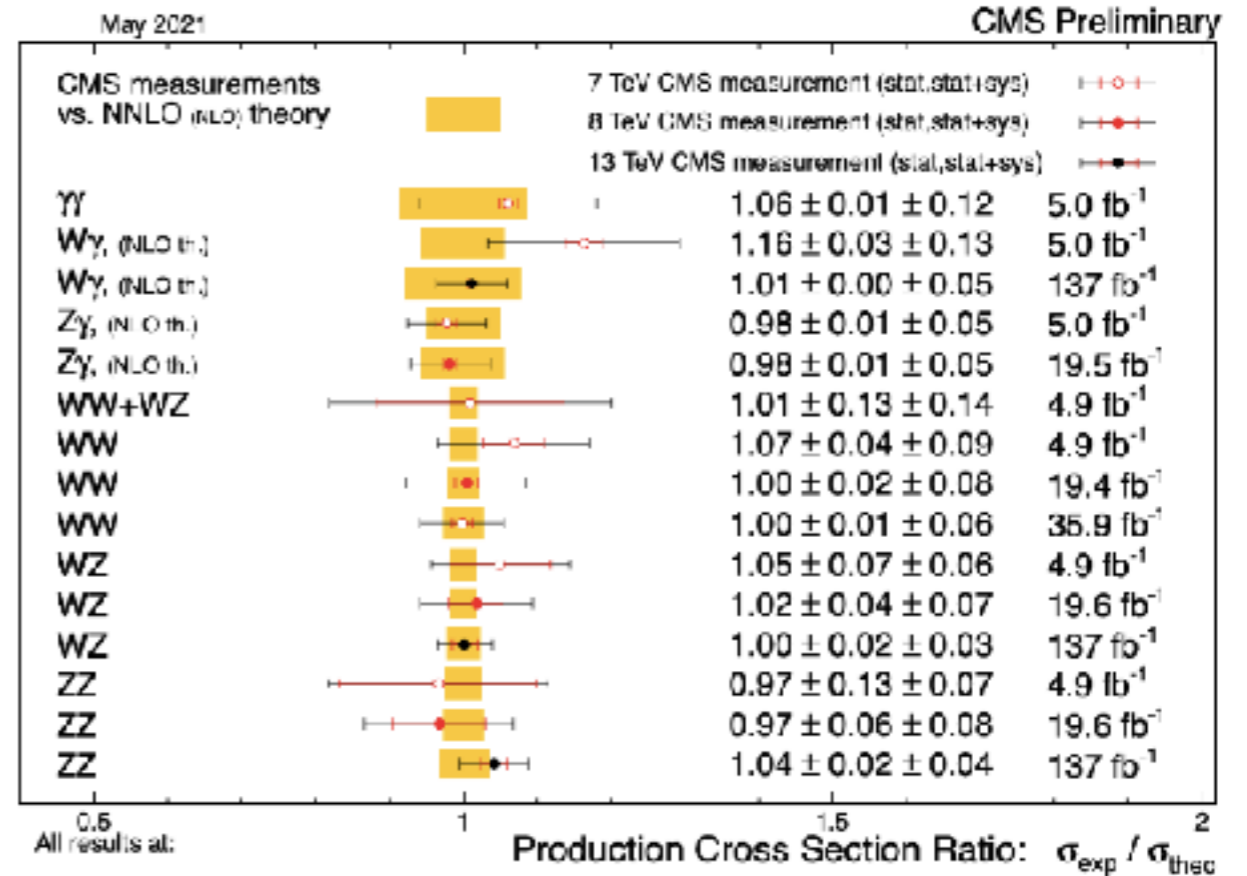
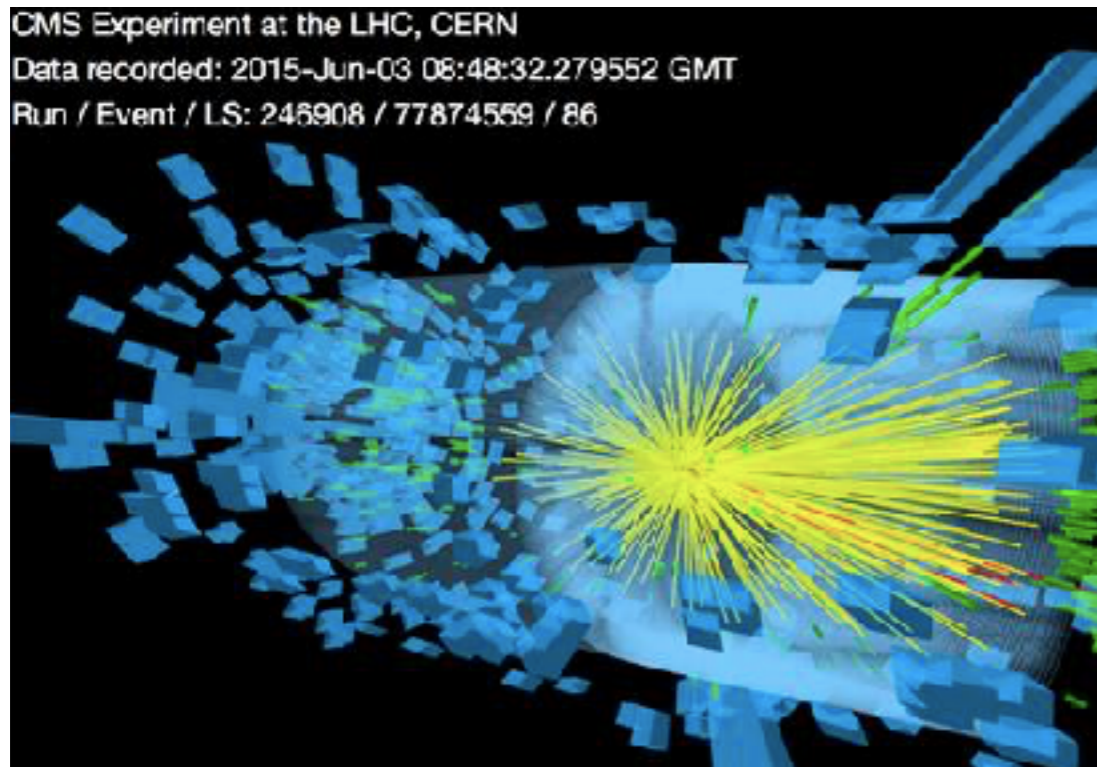


SM Higgs & LHC

- Relevant couplings (Tree-level): htt , hbb , hll , hWW , hZZ ,
- Relevant couplings (Loop-level): hAA , hgg , hAZ , ...



Lessons from LHC: Confirmation of the SM (& The Higgs)



Tools for Higgs Analysis

ggF
ihixs (N3LO QCD+NLO EW)
HIGLU (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
RGHiggs (NNLO+NNLL QCD)
SusHi, aMCSusHi (N3LO/NLO QCD)
ggHiggs (N3LO QCD)
TROLL (N3LL' QCD)

VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO QCD)
HJets (NLO QCD)
proVBFH (NNLO QCD)

WH/ZH
V2HY (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)
POWHEL (NLO QCD)

bbH
bbh@NNLO (NNLO QCD)
bbh@NNLL (NLO+NNLL QCD)
bbX (NLO+NNLL QCD)

HH
HPAIR (NLO QCD)
ggHH (NLO QCD)
proVBFHH (NNLO QCD)

PDF: *MMHT/MSHT, CTEQ, NNPDF, EKO, xFitter, PDF4LHC, ...*
METAPDF, LHAPDF, HOPPET, APFEL

SM: *MC2M, MATRIX, MGS_aMC@NLO, VVamp, gg2VY, DiffTop, ...*

NNLO+PS MC
NNLOPS (MINLO'+reweighting)
MINNLO
GenEvA

NLO+PS MC (Multi-purpose)
POWHEG-BOX
MadGraph5_aMC@NLO
SHERPA MEPS@NLO
PYTHIA8 UNLOPS
HERWIGZ Matchbox

NLO ME/Automated NLO
MC2M, MGS_aMC@NLO, RecoLa, GoSam, HELAC, OpenLoops, BlackHat, etc.

Higgs Properties
JHUGen/MELA, MEKD, LiHh, HiggsBounds/HiggsSignals

Higgs pr
HqT/HRes (NLO+NNLL)
ResBos (NLO+NNLL)
CuTe (NLO+NNLL)
PeTeR (NLO+N3LL)
MATRIX+RadISH (NNLO+N3LL)
SCETHb (N3LO+N3LL')
MoRe-SusHi (MSSM, 2HDM)

Higgs Decay
HDECAY (NLO+...)
Prophecy4f (NLO QCD+EW)
Hto4f (NLO QCD+EW)

MSSM/2HDM
FeynHiggs, CPsuperH, SusHi+2HDMC, HIGLU+HDECAY, 2HDECAY

NMSSM
NMSSMCALC (EW), *NMSSMTools, FlexibleSUSY, SOFTSUSY, SPheno*

+ many codes for BSM physics

Clickable Link (July 4th 2022) Suggestions to R. Tanaka

