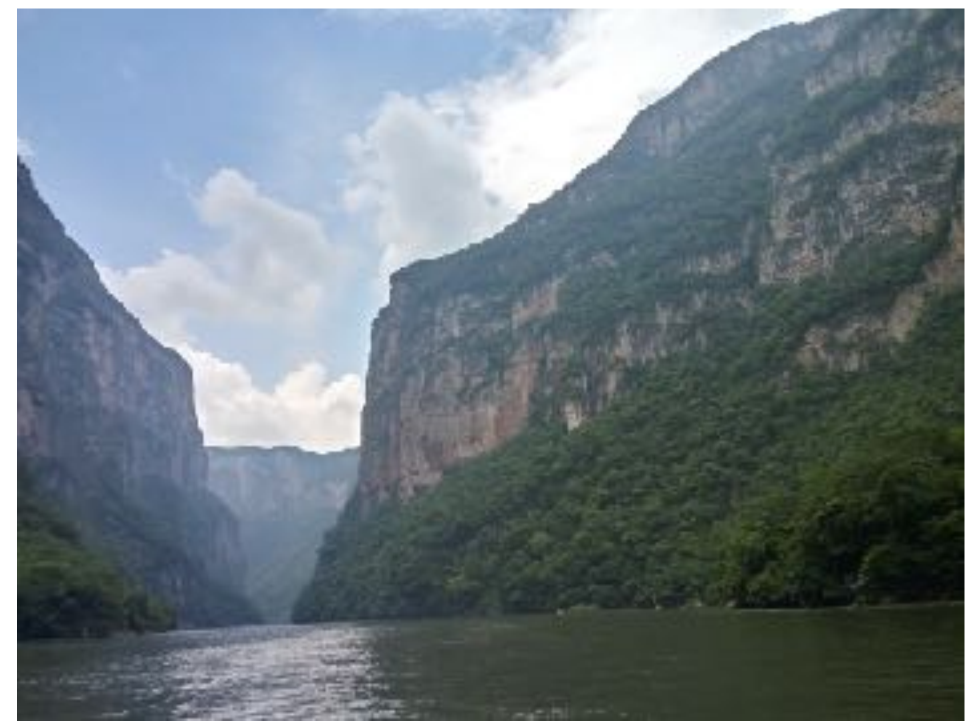
Hidden Patterns of New Physics within the Higgs Couplings



J. Lorenzo Diaz Cruz
CIFFU and FCFM-BUAP
Puebla (México)
Talk at HPNP-21,
Osaka (Japan)

Content

- Introduction,

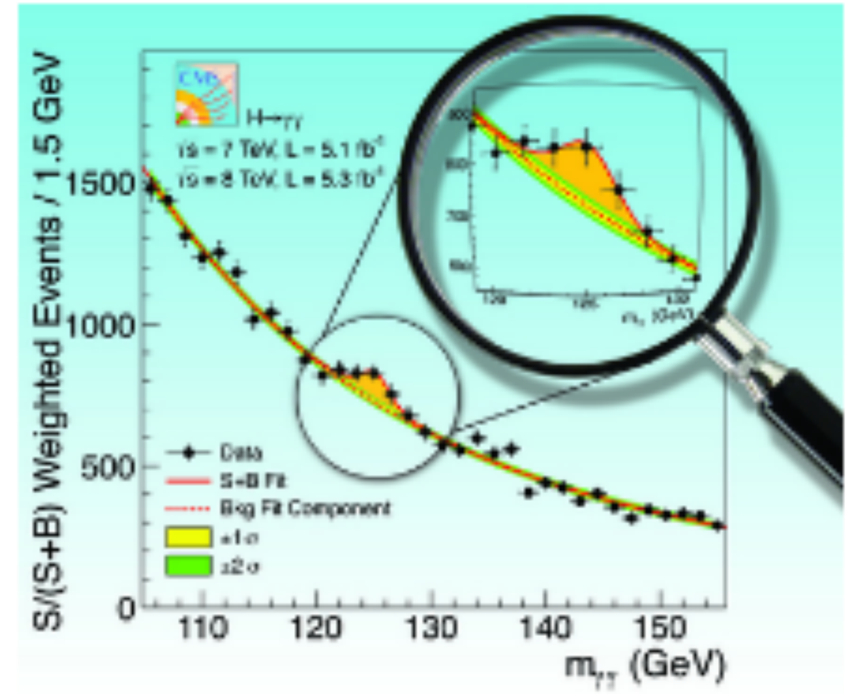
- Comments on the Higgs results from LHC,

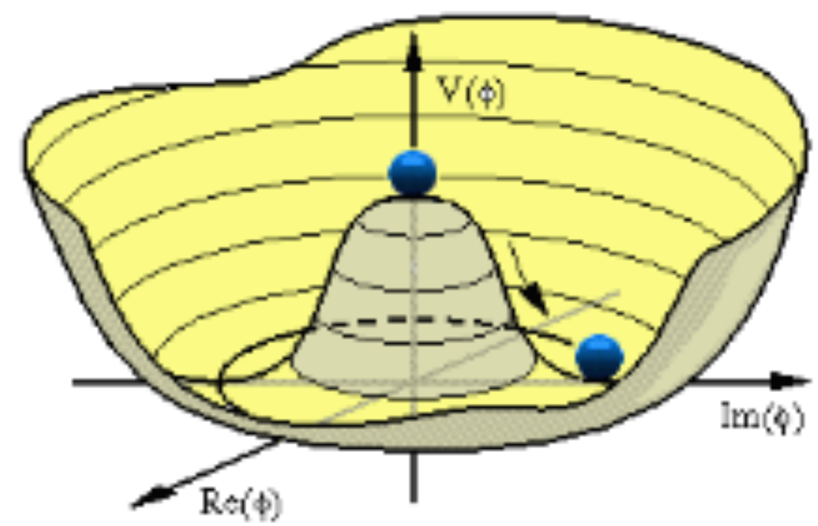
- Higgs coupling beyond the SM

  - Higgs Coupling Lines (HCL) and the angle between them,

  - Results for 2HDM,

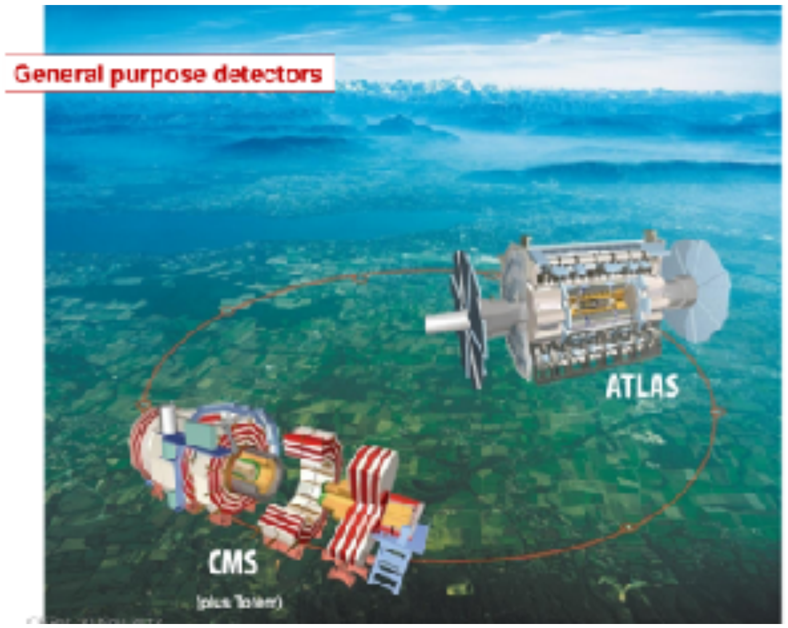
- Conclusions.

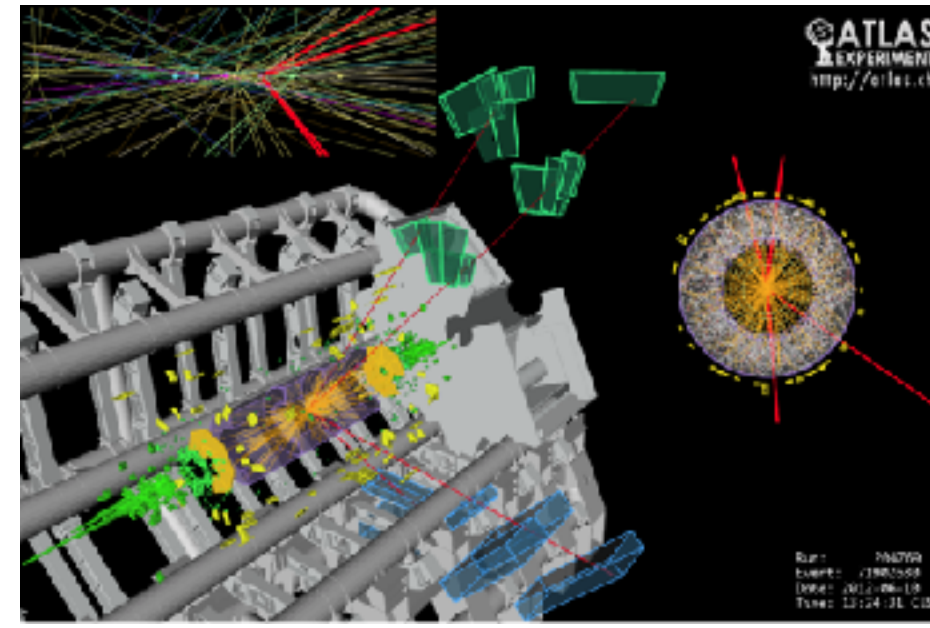




- M. Arroyo, J.L. Diaz-Cruz, Phys. Lett. B810 (2020) 135799 , arXiv:2005.01153 [hep-ph]
- M.Arroyo, J.L. DC, Mario A. Perez, B. Larios, Ch.Phys. (2021),
- J.L.D-C., U. Saldaña, NPB (2016).

1. LHC: One fo the most successful experiments ever!

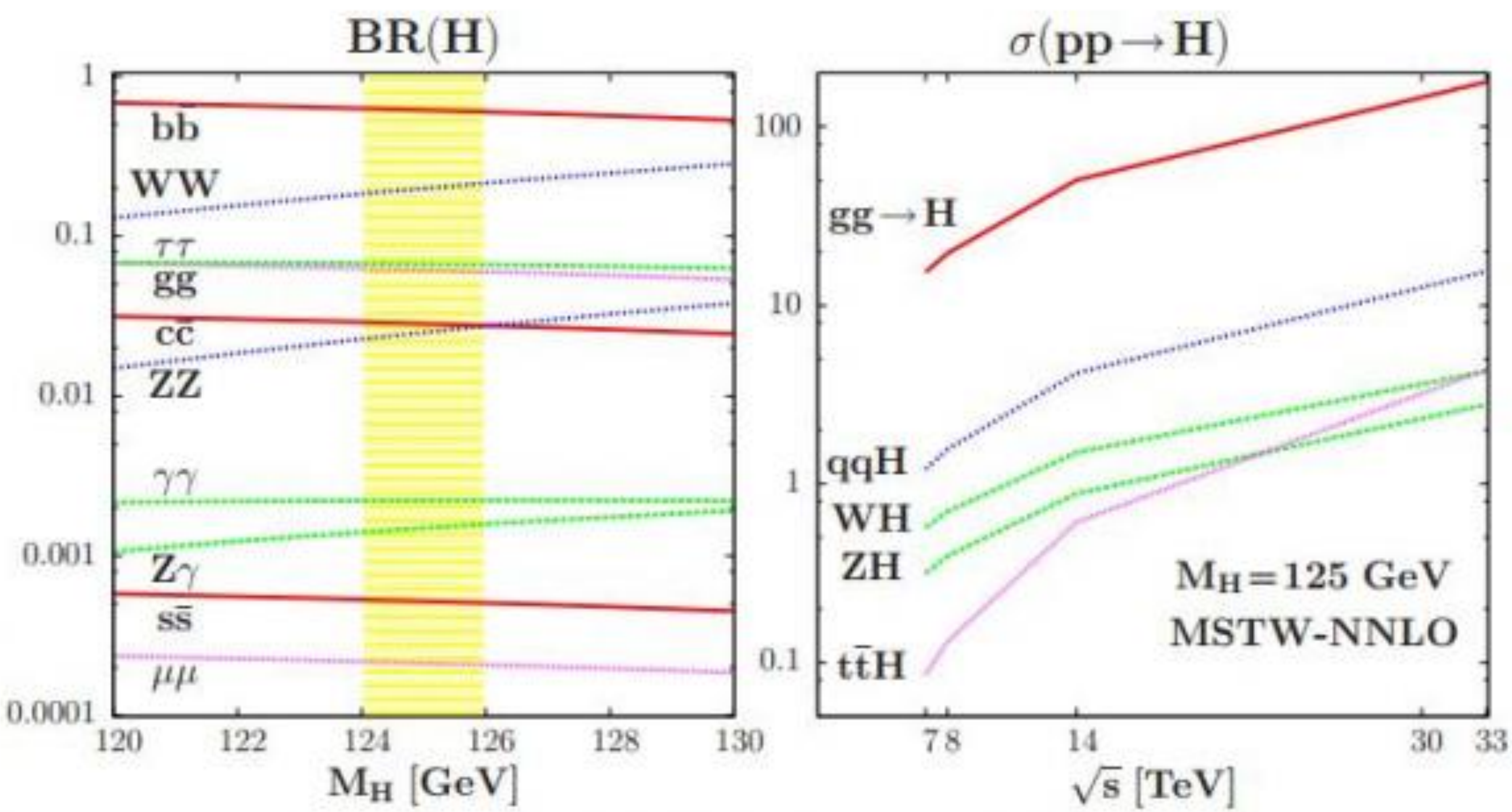




- The SM is passing all tests at LHC,
- The Higgs boson discovery remains as its greatest achievement,
- The absence of signals of Physics beyond the SM is intriguing, but a lesson in itself,
- This means we need to keep improving experimental tools and to think harder,
- But the evil is in the details …

SM Higgs

- The SM contains one Higgs doublet, after SSB a physical scalar remains,
- The essential feature of the SM Higgs is that it couples to the mass, which determines its decay modes and production mechanisms,
- This has been tested at LHC for the couplings with gauge bosons and 3rd generation fermions,



To study Higgs Couplings at LHC - Kappa-formalism

$$\mathcal{L}_F = \kappa_f \, y^{sm}_{hff} \, \bar{f} f h$$

$$\mathcal{L}_V = \kappa_W g m_W h W^{+\mu} W^-_\mu + \kappa_Z \frac{g m_Z}{2 c_W} h Z^\mu Z_\mu$$

$$\kappa_f = \frac{y_{hff}}{y^{sm}_{hff}}$$

$$y^{sm}_{hff} = \frac{\sqrt{2}\, m_f}{v}$$

$$\kappa_V = \frac{y_{hVV}}{y^{sm}_{hVV}}$$

- ATLAS and CMS have presented results for the Higgs-coupling kappas for gauge bosons and 3rd gen. fermions,

- Evidence for decay into muon have been presented more recently,

TABLE I. Fit results for Higgs boson coupling modifiers κ_X reported by ATLAS and CMS collaborations and the expected results at HL-LHC.

κ_X	ATLAS [16]	CMS [17]	HL-LHC [18]
κ_t	$1.03^{+0.12}_{-0.11}$	0.98 ± 0.14	1.04 ± 0.025
κ_b	$1.00^{+0.24}_{-0.22}$	$1.17^{+0.27}_{-0.31}$	0.94 ± 0.028
κ_τ	$1.04^{+0.17}_{-0.16}$	1.02 ± 0.17	1.0 ± 0.17
κ_Z	$1.07^{+0.11}_{-0.10}$	1.00 ± 0.11	1.01 ± 0.011
κ_W	1.04 ± 0.10	$-1.13^{+0.16}_{-0.13}$	1.01 ± 0.011
κ_μ	< 1.63	$0.80^{+0.59}_{-0.80}$	0.58 ± 0.042

value consistent with zero, but in order to reach a more solid conclusion, we will have to wait for future data from LHC-HL.

Higgs couplings with light quarks (LHC)

Reference	$\lvert\kappa_c\rvert$	$\lvert\kappa_s\rvert$	$\lvert\kappa_u\rvert$	$\lvert\kappa_u\rvert$	$\lvert\kappa_e\rvert$
De Blas et al. (Arxive: 1905.03764)	1.2	13	570	270	611
Alasfar et al. (Arxive: 1909.05279)	5	100	1170	850	850
Aguilar-Saavedra et al. (Arxive: 2008.12538)	12.7	-	2130	-	-
T. Han et al. (Arxive: 1812.06992)	8	-	-	-	-
F. Bishara et al. (Arxive: 1812.06992)	[-1.4,3.8] (Run2) [-0.6,3.0] (HL)	-	-	-	-

TABLE II: Limits on Higgs coupling modifiers κ_x.

- A variety of methods beings used:

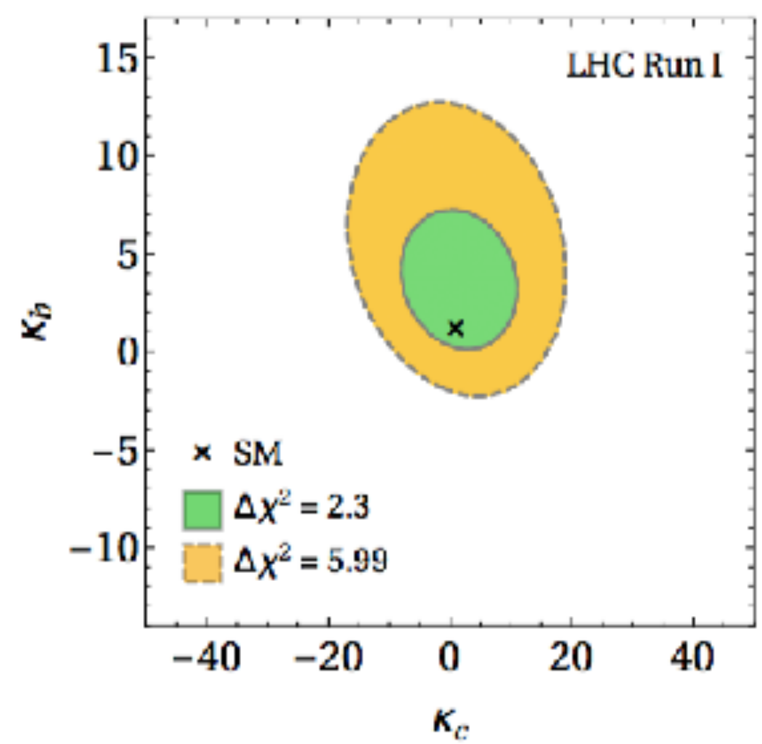
  - light quark effects on h+jet production,

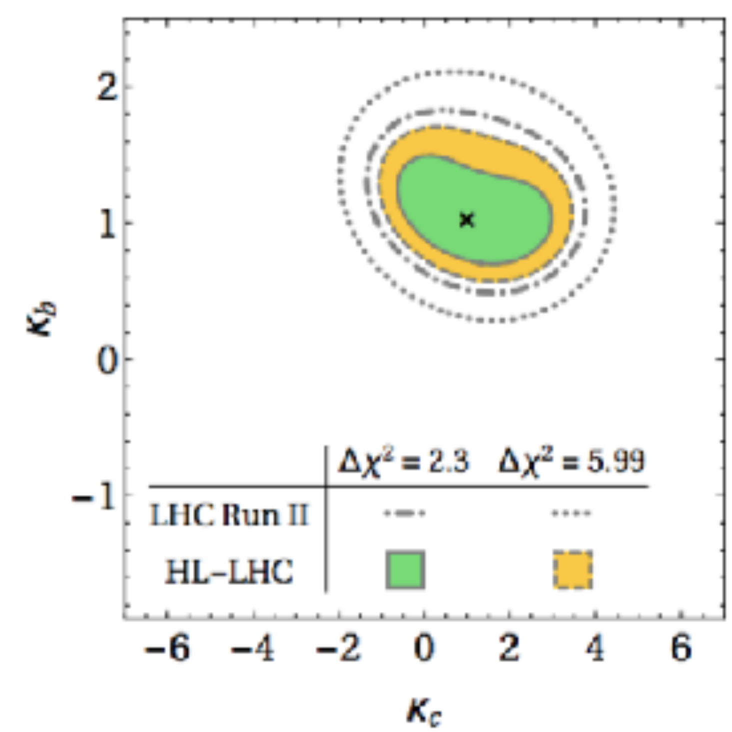
  - Production of qq -> h+gamma,

  - Decays h-> qq+gamma,

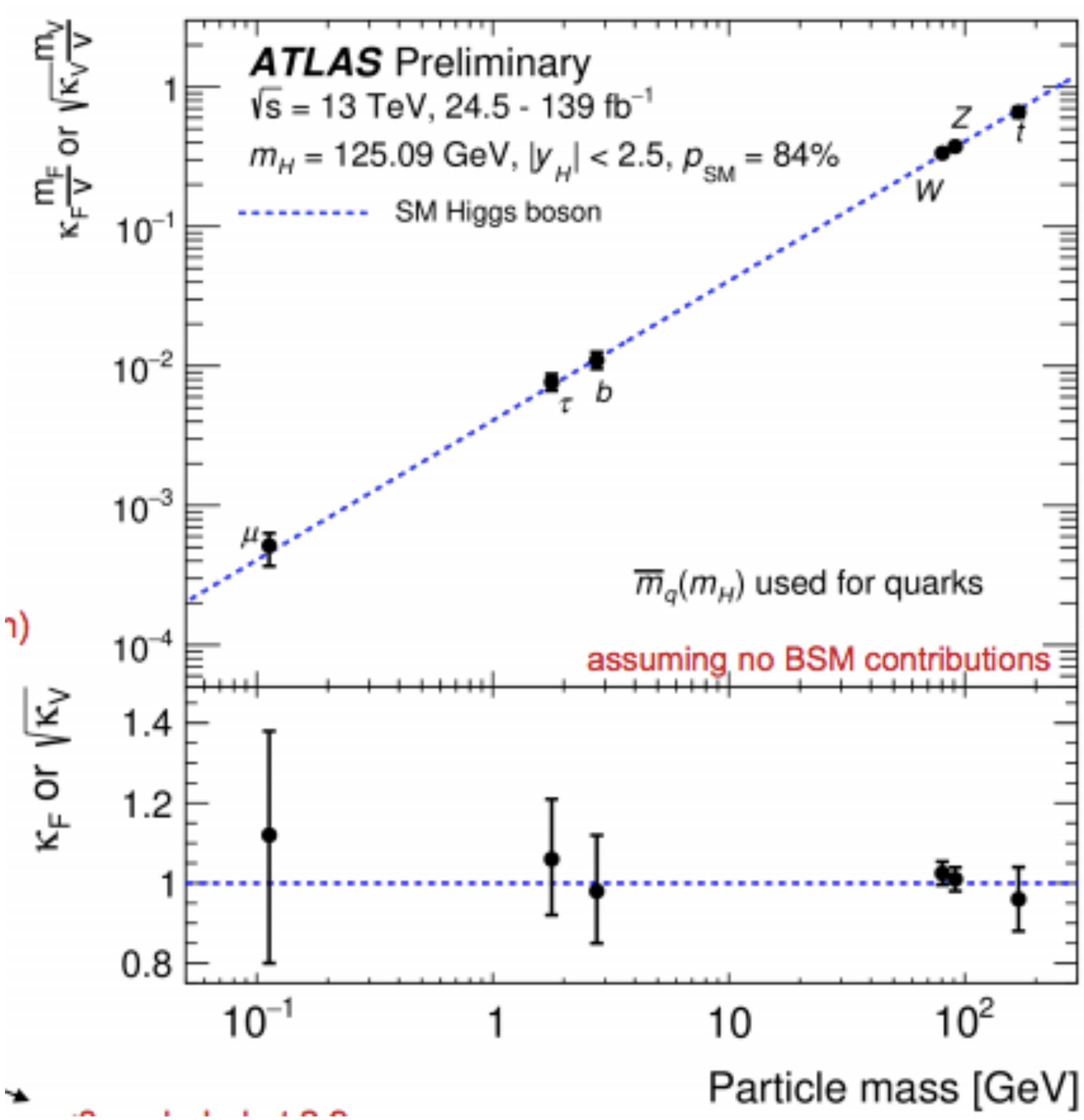
  - Higgs pair production,

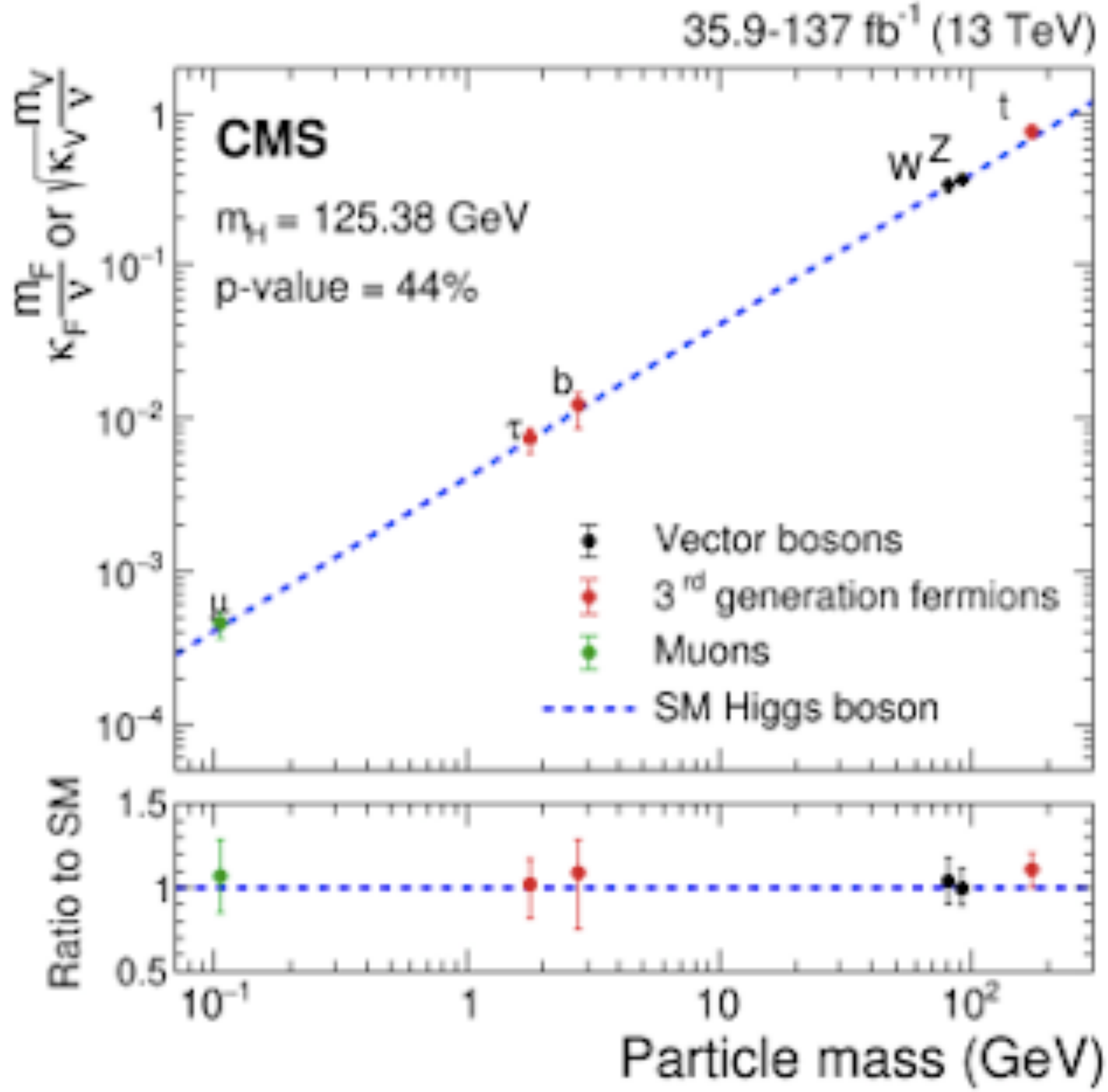
  - c/b discrimination,





ATLAS and CMS results - HCL

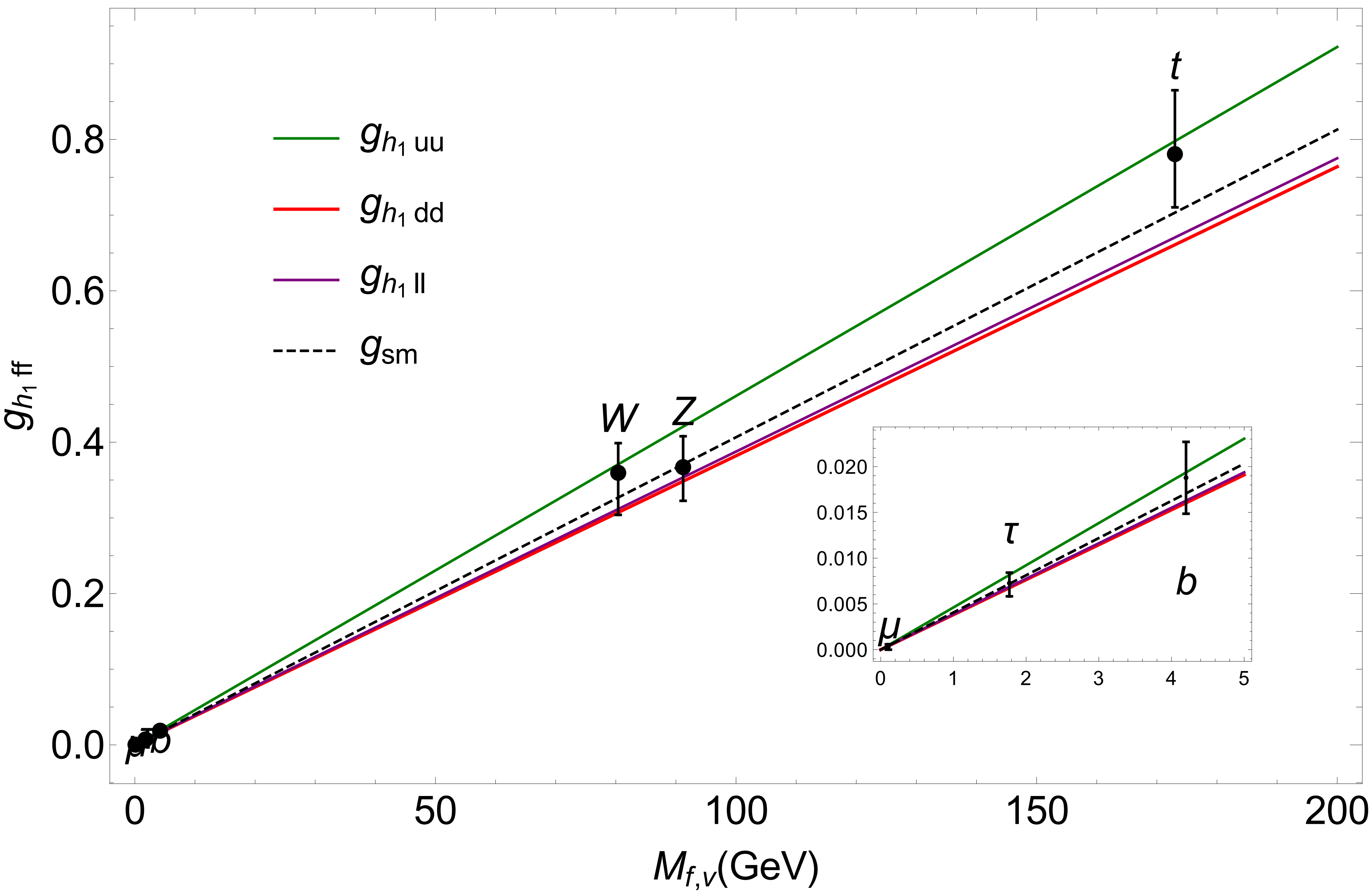




- For the SM we have one Higgs Coupling Line (HCL), what about in extensions of the SM? One line? More lines?

Higgs coupling lines in multi-Higgs models -

- In **NHDM´s**, Higgs couplings could lay on one or more lines, ex. SUSY 4HDM



Higgs Coupling Lines in the 2HDM

- Basics of the general 2HDM - Yukawa lagrangian

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

where the quark doublets, quark singlets and Higgs doublets are written as:

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

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

- Two Higgs Doublets -> 8 d. of f.
- Physical spectrum: h(125), H, A, H^+,
- Parameters include two vevs: v1, v2 -> v=(v1^2+ v2^2)^1/2 = 246 GeV, tan(B)=v2/v1,

\- And the masses (M_Hi) and alpha (angle to diag. neutral Higgs mass matrix)

Fermion-Higgs couplings in the 2HDM

Model type	Up quarks	Down quarks	Charged leptons
2HDM-I	Φ_1	Φ_1	Φ_1
2HDM-II	Φ_2	Φ_1	Φ_1
2HDM-X	Φ_2	Φ_2	Φ_1
2HDM-Y	Φ_2	Φ_1	Φ_2
2HDM-III	$\Phi_{1,2}$	$\Phi_{1,2}$	$\Phi_{1,2}$

TABLE I: Higgs interaction with fermions for the different 2HDM types.

Higgs couplings Lines in the 2HDM

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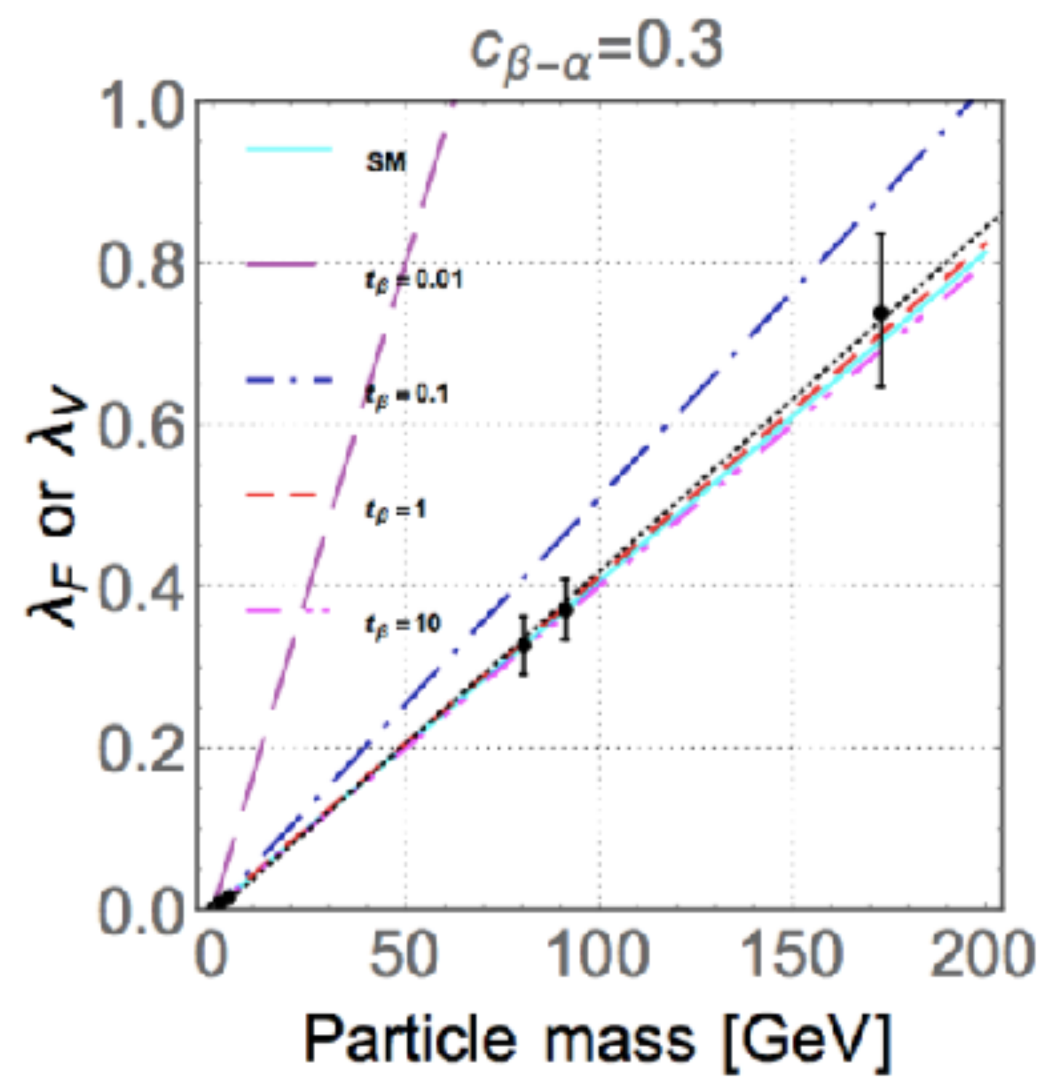
TABLE I: Higgs interaction with fermions for the different 2HDM types.

- For **2HDM-I**: fermions masses come from one doublets, say (Φ_1), then Yukawa couplings will lay on a single line. But it will not coincide with the SM one.
- In **2HDM-II:** Φ_1 gives mass to U-quarks, Φ_2 gives masses to D-quarks and leptons. Thus, there will be two HYL,
- Could we study these HCL more quantitatively ?



The angle between Higgs coupling lines

- Interesting to calculate the angle subtended by Higgs Yukawa line, w.r.t. SM Yukawa line,

- Recent work with M. Arroyo, J.L. Diaz-Cruz [Phys. Lett. B810 (2020) 135799 , arXiv:2005.01153 [hep-ph]]

- For Model K, we find:

$$\cos\Psi_K = \frac{(\Delta\hat{m}^f_{ij})^2 + \Delta y^K_{ij}\Delta y^{\rm SM}_{ij}}{[(\Delta\hat{m}^f_{ij})^2 + (\Delta y^K_{ij})^2]^{1/2}\cdot[(\Delta\hat{m}^f_{ij})^2 + (\Delta y^{\rm SM}_{ij})^2]^{1/2}} \qquad (3)$$

where:

$$\Delta\hat{m}^f_{ij} = \hat{m}_{fi} - \hat{m}_{fj} \qquad (4)$$
$$\Delta y^K_{ij} = y^K_{fi} - y^K_{fj}$$
$$\Delta y^{\rm SM}_{ij} = y^{\rm SM}_{fi} - y^{\rm SM}_{fj}$$

$$\hat{m}_f = m_f/v.$$

- The SM Higgs coupling line and data line make an angle:

$$\Psi_{ex} = (1.5^{+6.2}_{-2.9}) \times 10^{-4}.$$

2HDM-I Results:

$$\cos\Psi_I = \frac{1+\eta_f}{\sqrt{2}\left(1+\eta_f^2\right)^{1/2}}.$$

$$\eta_f = \cos\alpha/\sin\beta,$$

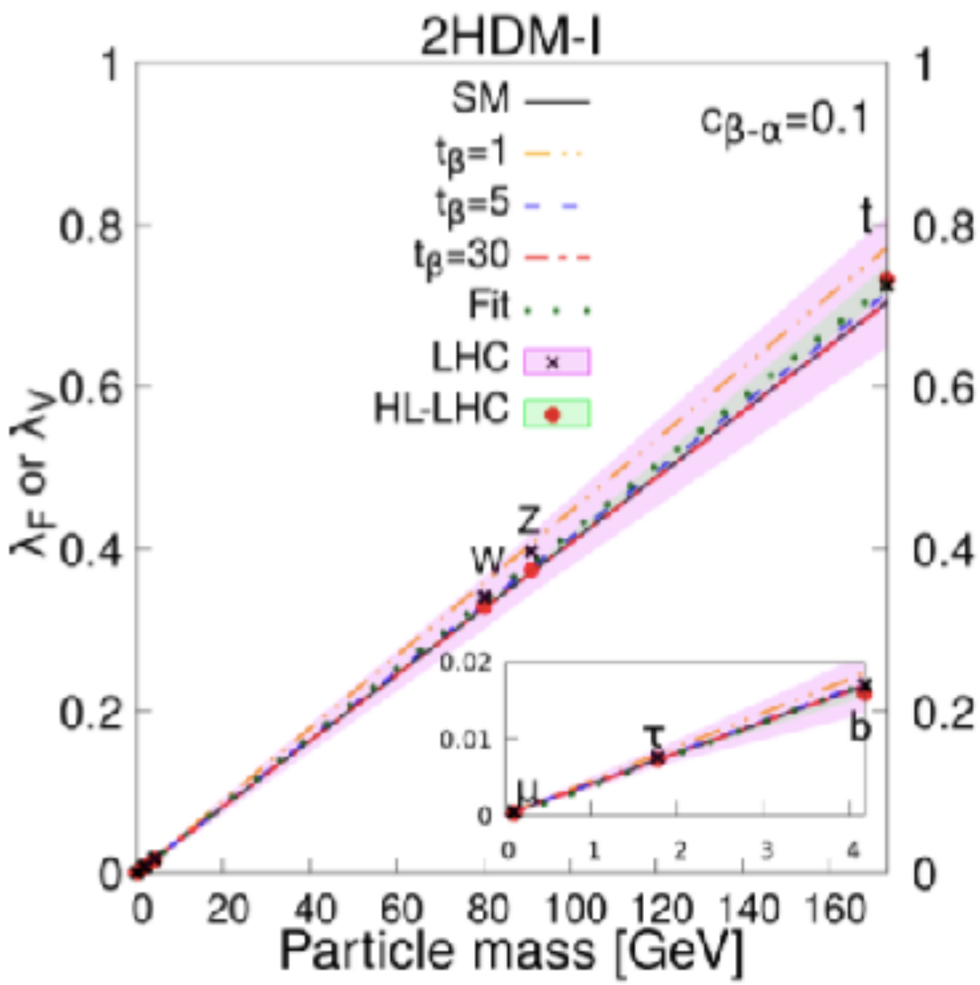


FIG. 2. SM and 2HDM-I reduced coupling strength modifiers $\lambda_F = \kappa_F \frac{m_F}{v}$ and $\lambda_V = \sqrt{\kappa_V}\frac{m_V}{v}$ with $F = t, b, \tau, \mu$ and $V = W, Z$ as a function of their masses.

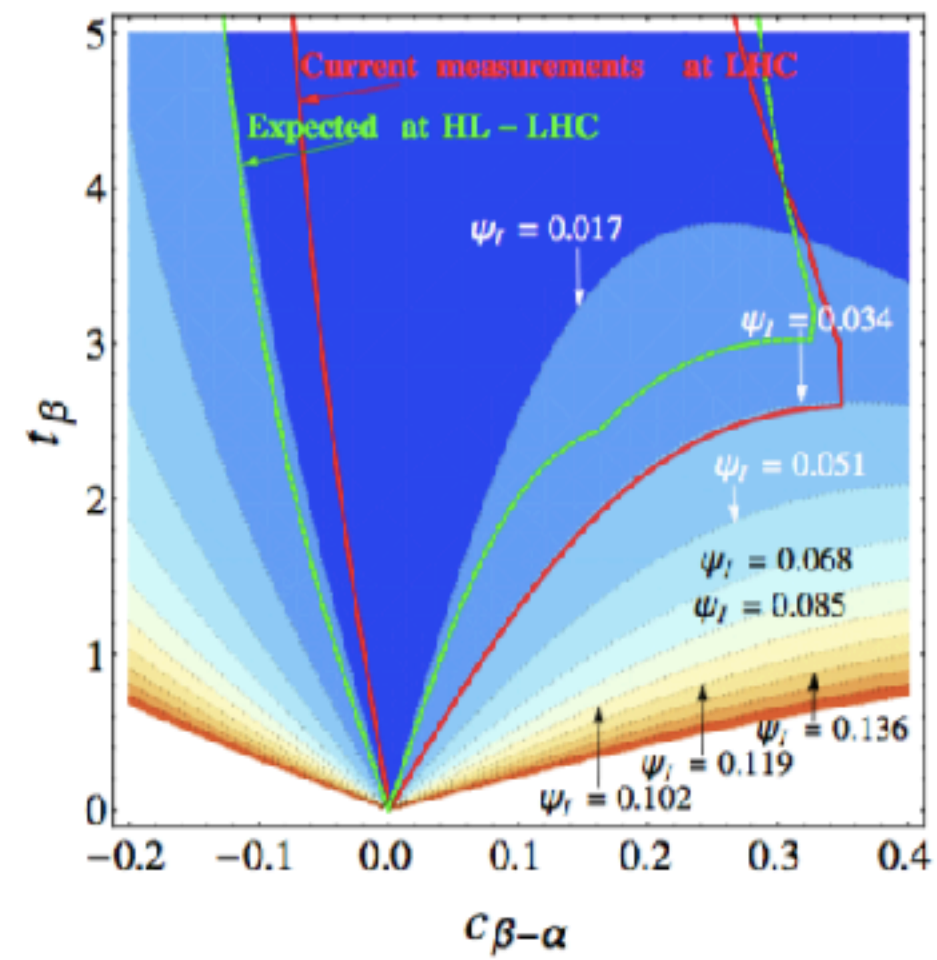


FIG. 1. Values of the opening angle Ψ_I with respect to the SM line for allowed regions in the plane $c_{\beta-\alpha} - t_\beta$ for 2HDM-I.

2HDM-II Results: d-type fermions

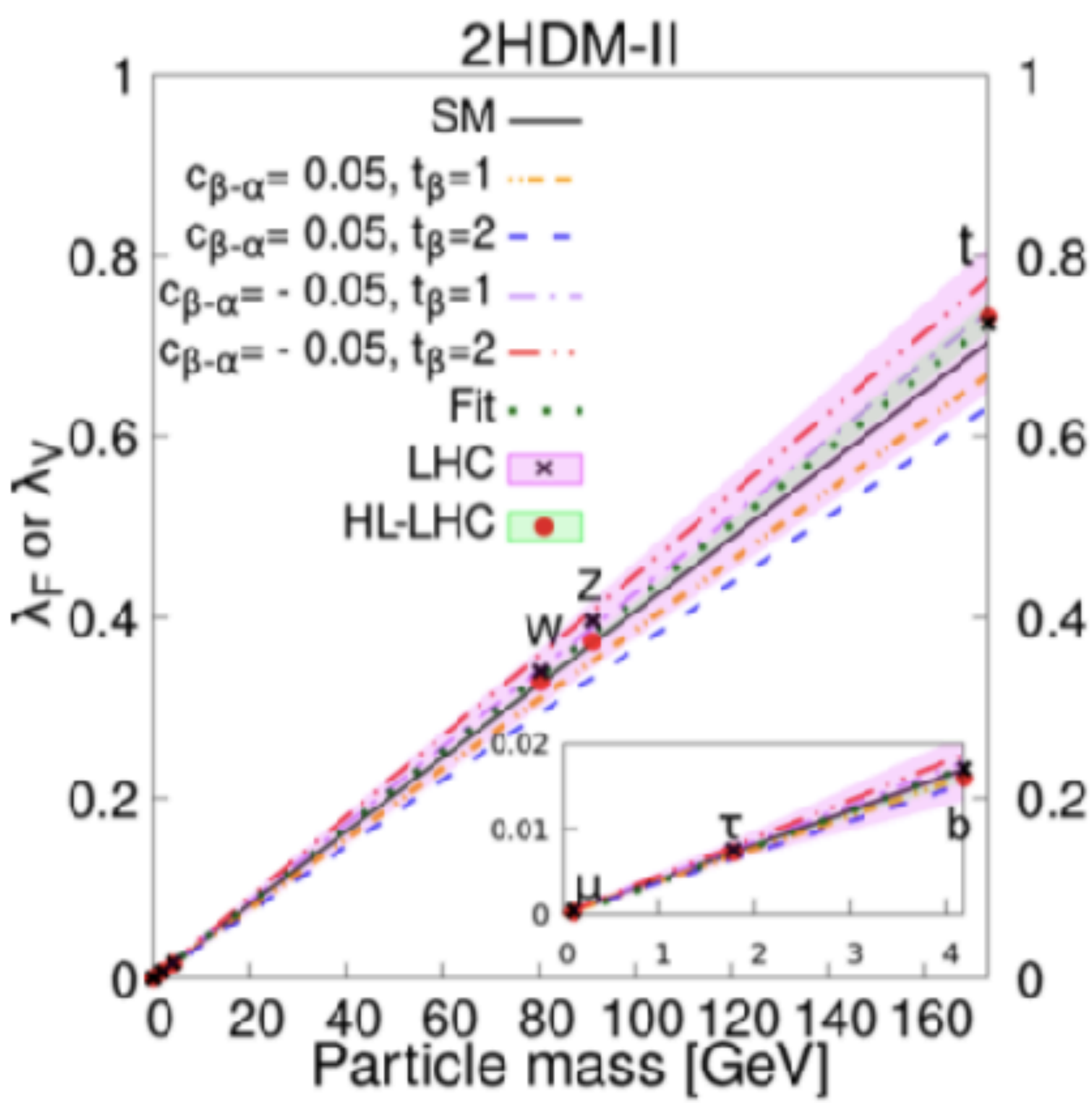


FIG. 4. The same as the Fig. 2 but the 2HDM-II.

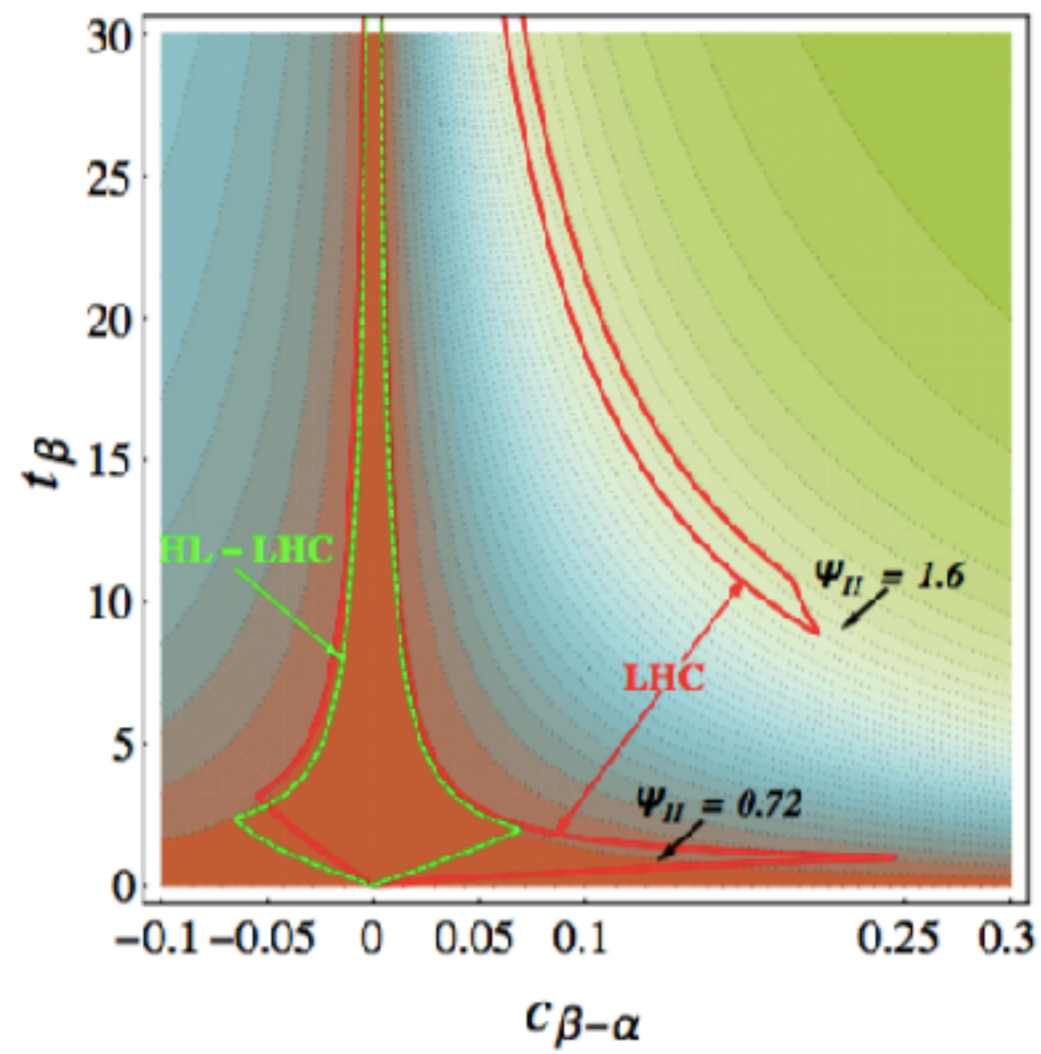


FIG. 3. Values of the opening angle Ψ_{II} with respect to the SM line for allowed regions in the plane $c_{\beta-\alpha} - t_\beta$ for 2HDM-II.

Other models:

- Also considered models where fermion mass hierarchy arises from effective operators,

$$\mathcal{L} = \lambda_f(\frac{\Phi^\dagger\Phi}{\Lambda^2})^n \bar{F}_L \Phi f_R + ... + h.c.$$
$$\simeq m_f \bar{f}_L f_R + (2n+1)\frac{m_f}{v}\bar{f}_L f_R h + h.c.$$

- In such case, there will not be a line, but scattered points,

- The 2HDM-embedding of such idea is severely restricted,

$$\kappa_{d_i} = n_{d_i}\frac{\cos\alpha}{\sin\beta} - (n_{d_i}+1)\frac{\sin\alpha}{\cos\beta}.$$

- Neutrino mases may not obey a linear relation (see-saw mechanism),

$$g_{h\nu\nu} = \frac{(m_\nu M)^{1/2}}{v}.$$

Conclusions:

- The Higgs coupling lines can be used to look for hidden patterns of New Physics (-> HPNP),
- The Psi-Angles can be used to parametrize deviations form the SM,
- Current data can be used to constraint the Psi angle; we have done that for 2HDM-I and II.
- Wait for the High Luminosity LHC phase,
- Build next ILC, VLHC, to better measure Psi_K

“All izz well”, Gracias!