

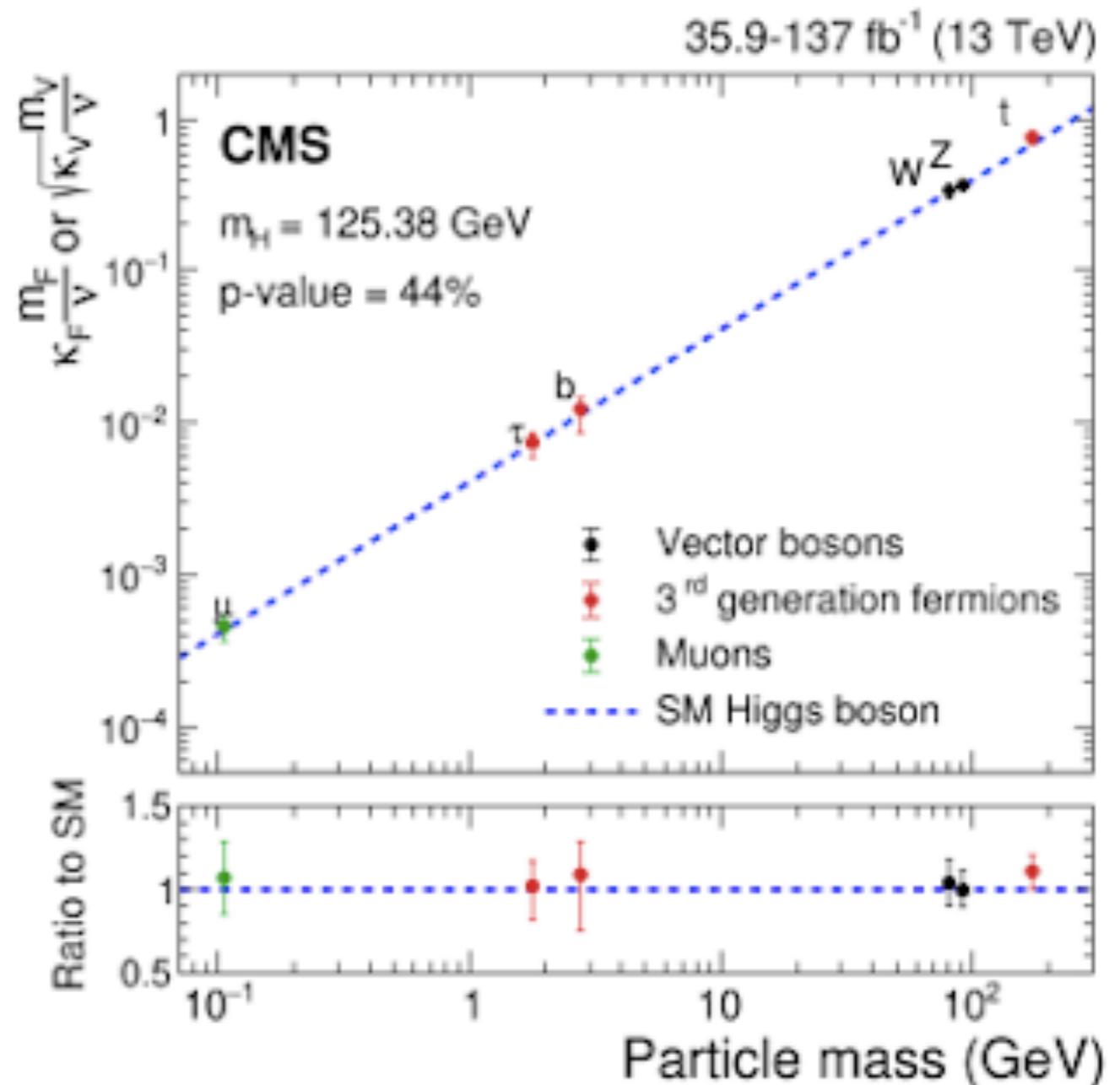
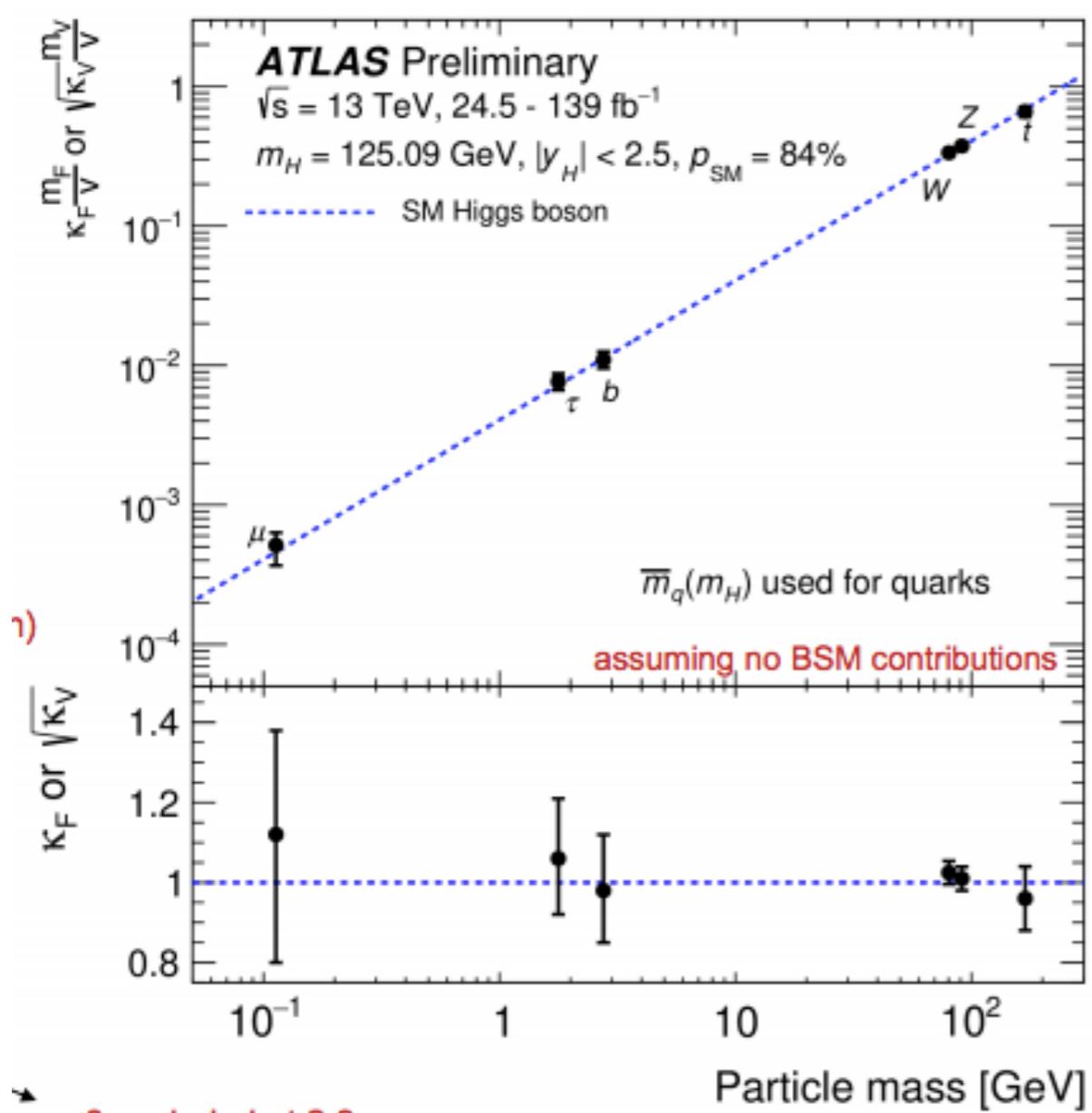
Hidden Patterns of New Physics within the Higgs Couplings



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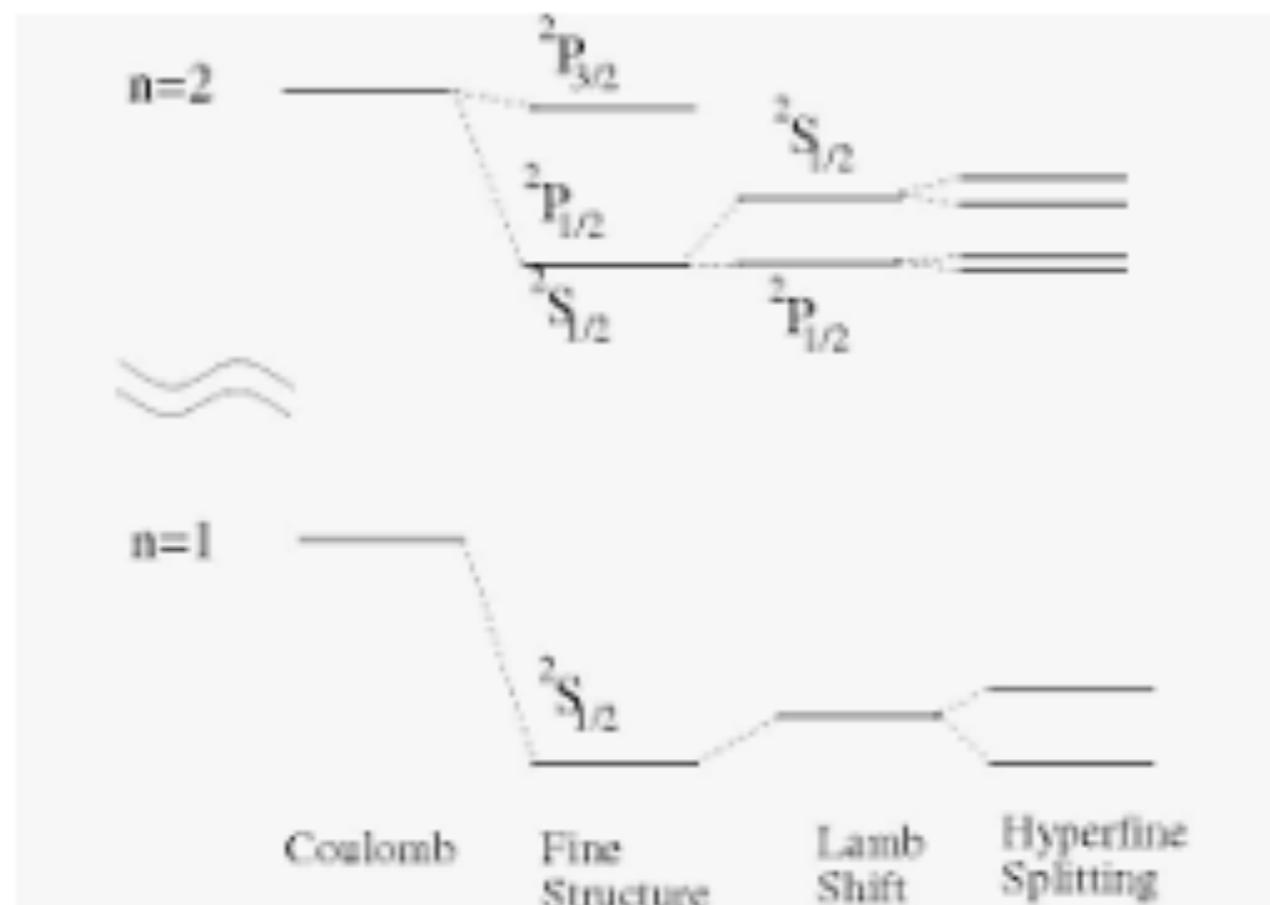
Talk at SUSY-22, Ioannina (Grecia)

ATLAS and CMS results - Higgs Coupling Line (HCL)



- This single line is the result of being the couplings of the Higgs boson proportional to the mass of the particles ...

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



The fine structure of hydrogen
theory.physics.manchester.ac.uk

Content

1. Introduction: Comments on the Higgs results from LHC

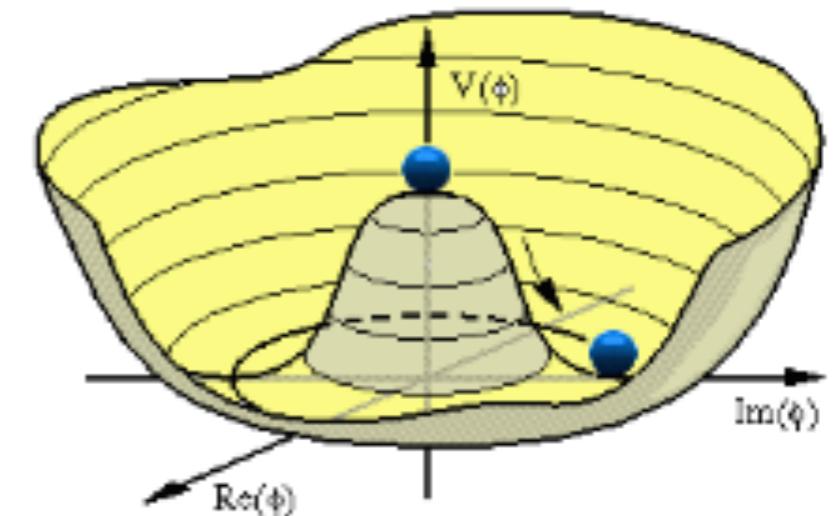
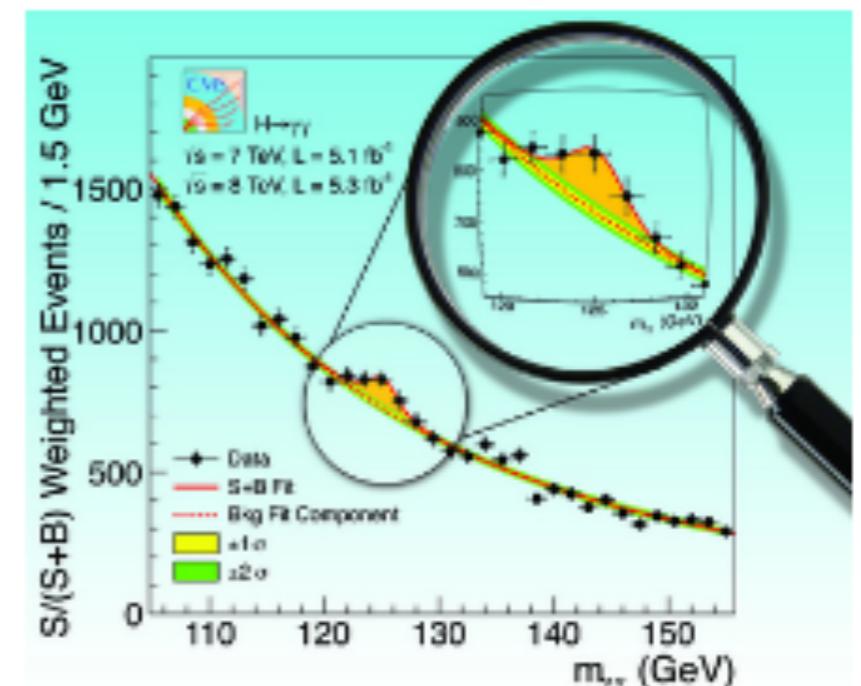
2. Higgs coupling beyond the SM

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

- Results for 2HDM,

3. M_W and the Higgs coupling hWW

4. Conclusions.



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

To study Higgs Couplings at LHC - Kappa Parametrization

$$\mathcal{L}_F = \kappa_f y_{hff}^{sm} \bar{f} f h$$

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

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

$$y_{hff}^{sm} = \frac{\sqrt{2} m_f}{v}$$

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

- 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.

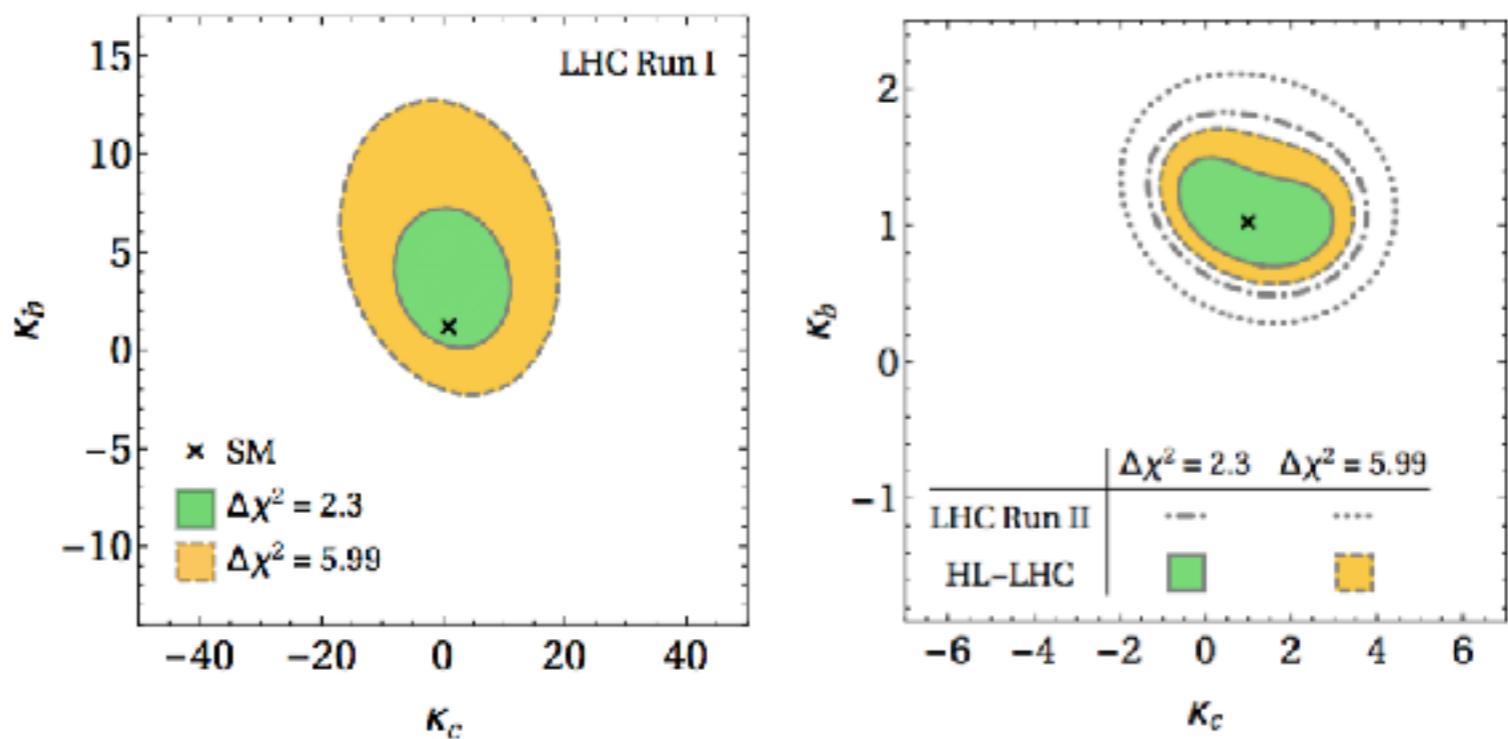
Higgs couplings with light fermions (LHC)

Reference	$ \kappa_c $	$ \kappa_s $	$ \kappa_u $	$ \kappa_d $	$ \kappa_e $
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 \rightarrow h+gamma,
- Decays h \rightarrow qq+gamma,
- Higgs pair production,
- c/b discrimination,



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:

$$\begin{aligned} Q_L^0 &= \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \bar{Q}_L^0 = (\bar{u}_L, \bar{d}_L), \\ \Phi_1 &= \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, \end{aligned}$$

- Two Higgs Doublets \rightarrow 8 d. of f.
- Physical spectrum: $h(125)$, H , A , H^\pm ,
- Parameters include two vevs: $v_1, v_2 \rightarrow v = (v_1^2 + v_2^2)^{1/2} = 246 \text{ GeV}$, $\tan(\beta) = v_2/v_1$,
- 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.

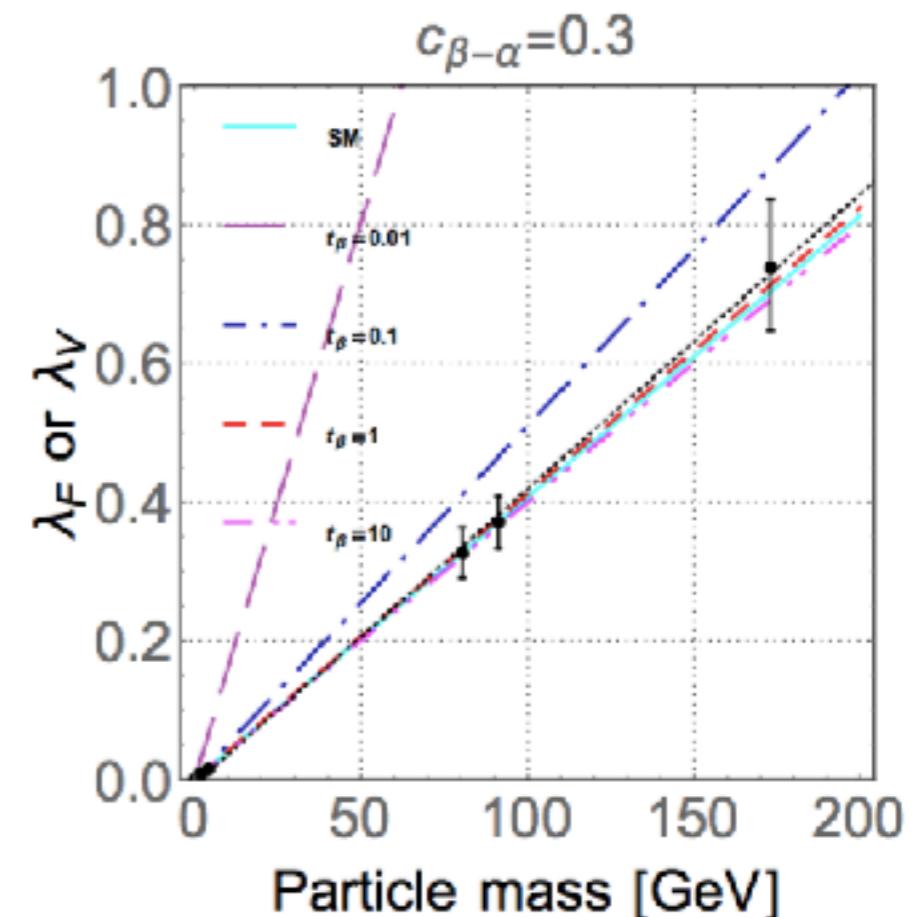
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TABLE I: Higgs interaction with fermions for the different 2HDM types.

- The number of HCL will be equal to the number of Higgs doublets giving mass to the fermions, plus one for the gauge bosons

- 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 \[hep-ph\]](https://arxiv.org/abs/2005.01153)]
- For Model K, consider fermions I & j, then we find:

$$\cos \Psi_K = \frac{(\Delta \hat{m}_{ij}^f)^2 + \Delta y_{ij}^K \Delta y_{ij}^{\text{SM}}}{[(\Delta \hat{m}_{ij}^f)^2 + (\Delta y_{ij}^K)^2]^{1/2} \cdot [(\Delta \hat{m}_{ij}^f)^2 + (\Delta y_{ij}^{\text{SM}})^2]^{1/2}} \quad (3)$$

where:

$$\Delta \hat{m}_{ij}^f = \hat{m}_{fi} - \hat{m}_{fj} \quad (4)$$

$$\Delta y_{ij}^K = y_{fi}^K - y_{fj}^K$$

$$\Delta y_{ij}^{\text{SM}} = y_{fi}^{\text{SM}} - y_{fj}^{\text{SM}}$$

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

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

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

2HDM-I Results:

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

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

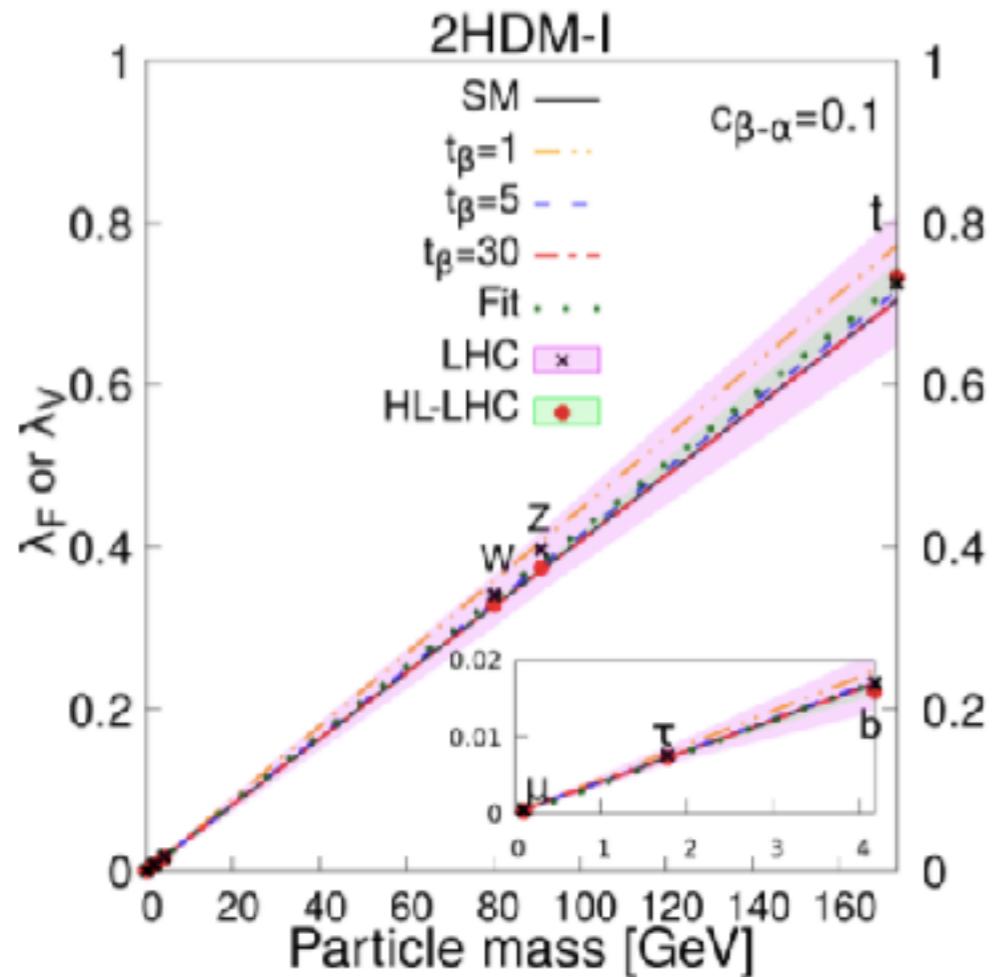


FIG. 2. SM and 2HDM-I reduced coupling strength modifiers $\lambda_F = \kappa_F \frac{m_F}{v}$ and $\lambda_V = \sqrt{\kappa_V} \frac{m_V}{v}$ with $F = t, b, \tau, \mu$ and $V = W, Z$ as a function of their masses.

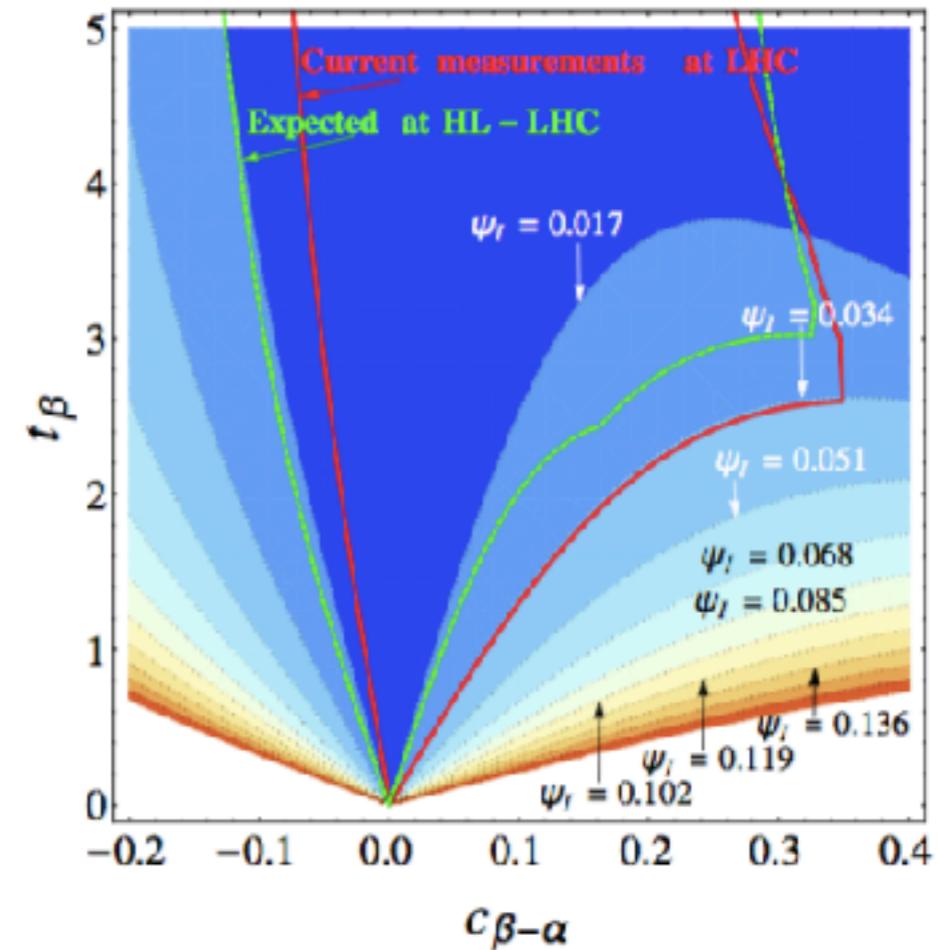


FIG. 1. Values of the opening angle Ψ_I with respect to the SM line for allowed regions in the plane $c_{\beta-\alpha} - t_\beta$ for 2HDM-I.

2HDM-II Results: d-type fermions

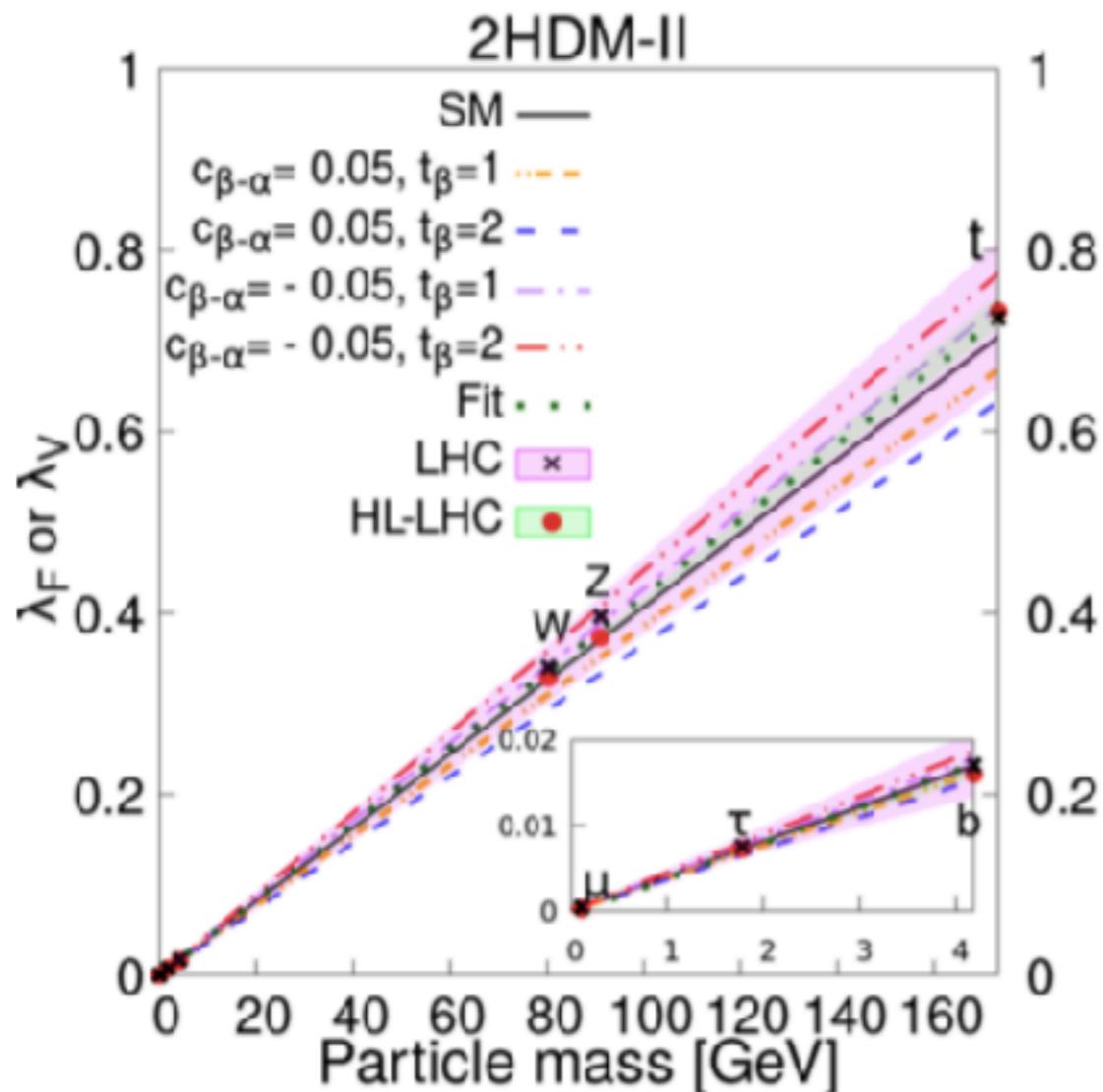


FIG. 4. The same as the Fig. 2 but the 2HDM-II.

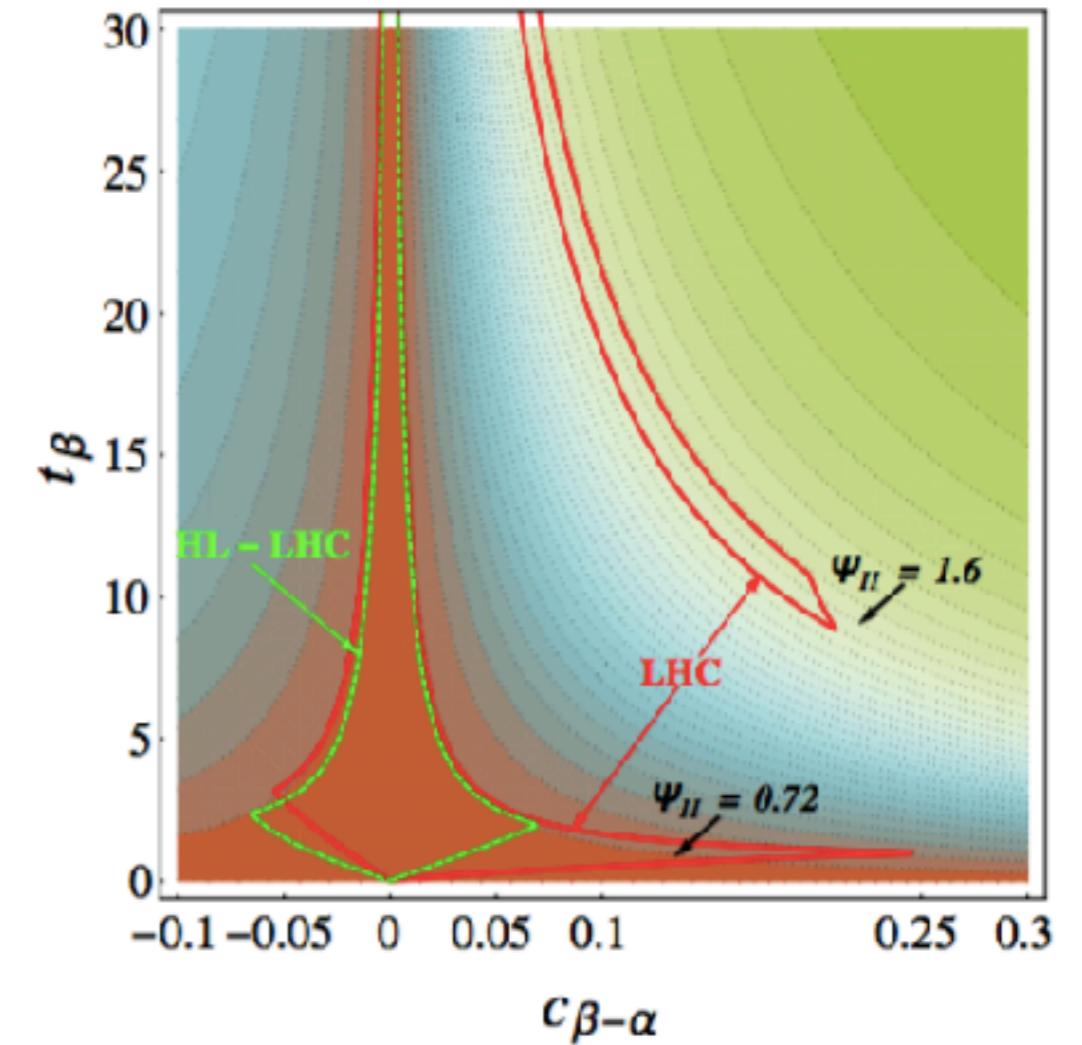
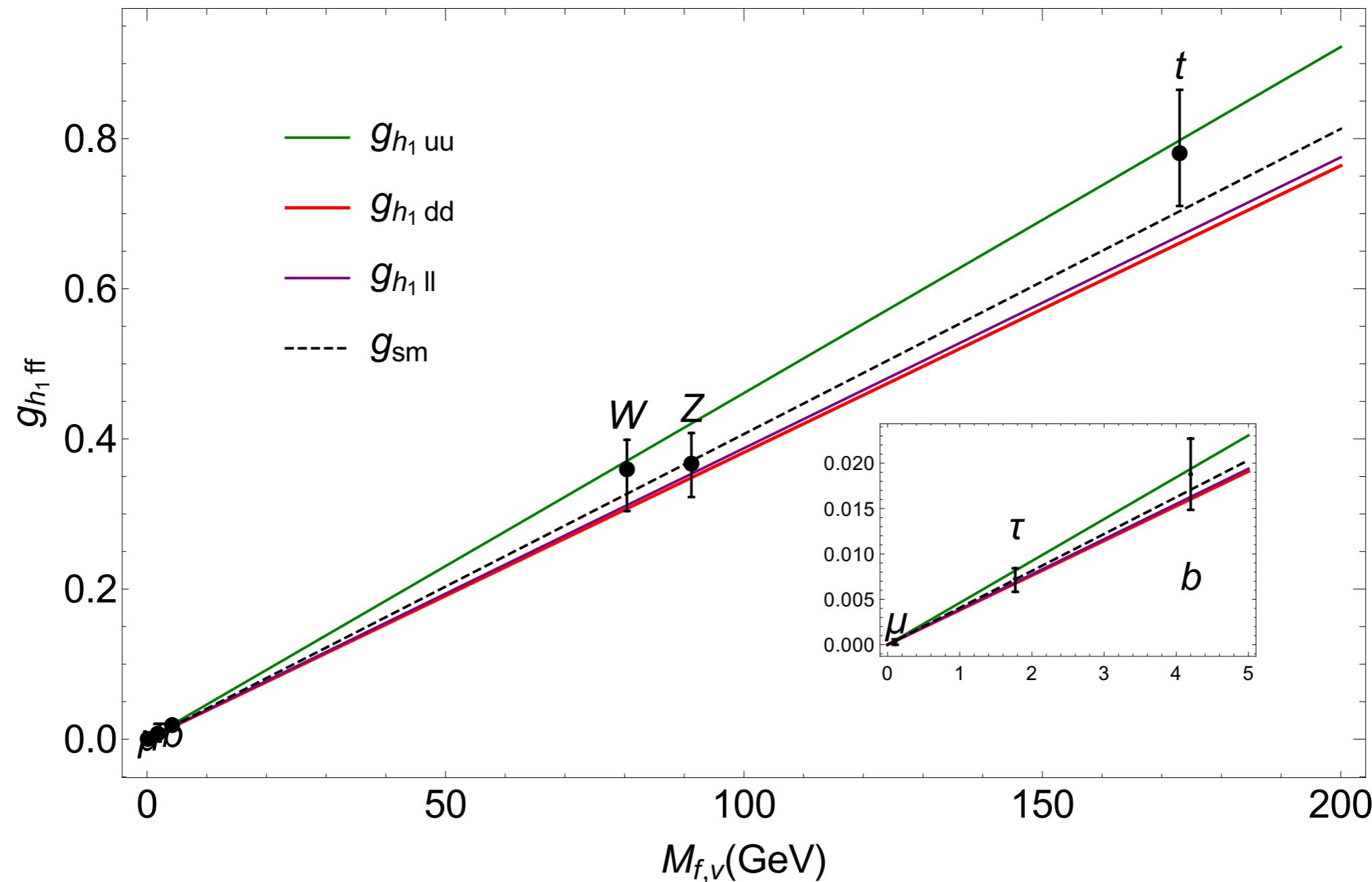


FIG. 3. Values of the opening angle Ψ_{II} with respect to the SM line for allowed regions in the plane $c_{\beta-\alpha} - t_{\beta}$ for 2HDM-II.

Higgs coupling lines in other multi-Higgs models -

- In **NHDM's**, Higgs couplings could lay in one or more lines, ex. SUSY Private Higgs (4HDM)



Effective models:

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

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

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

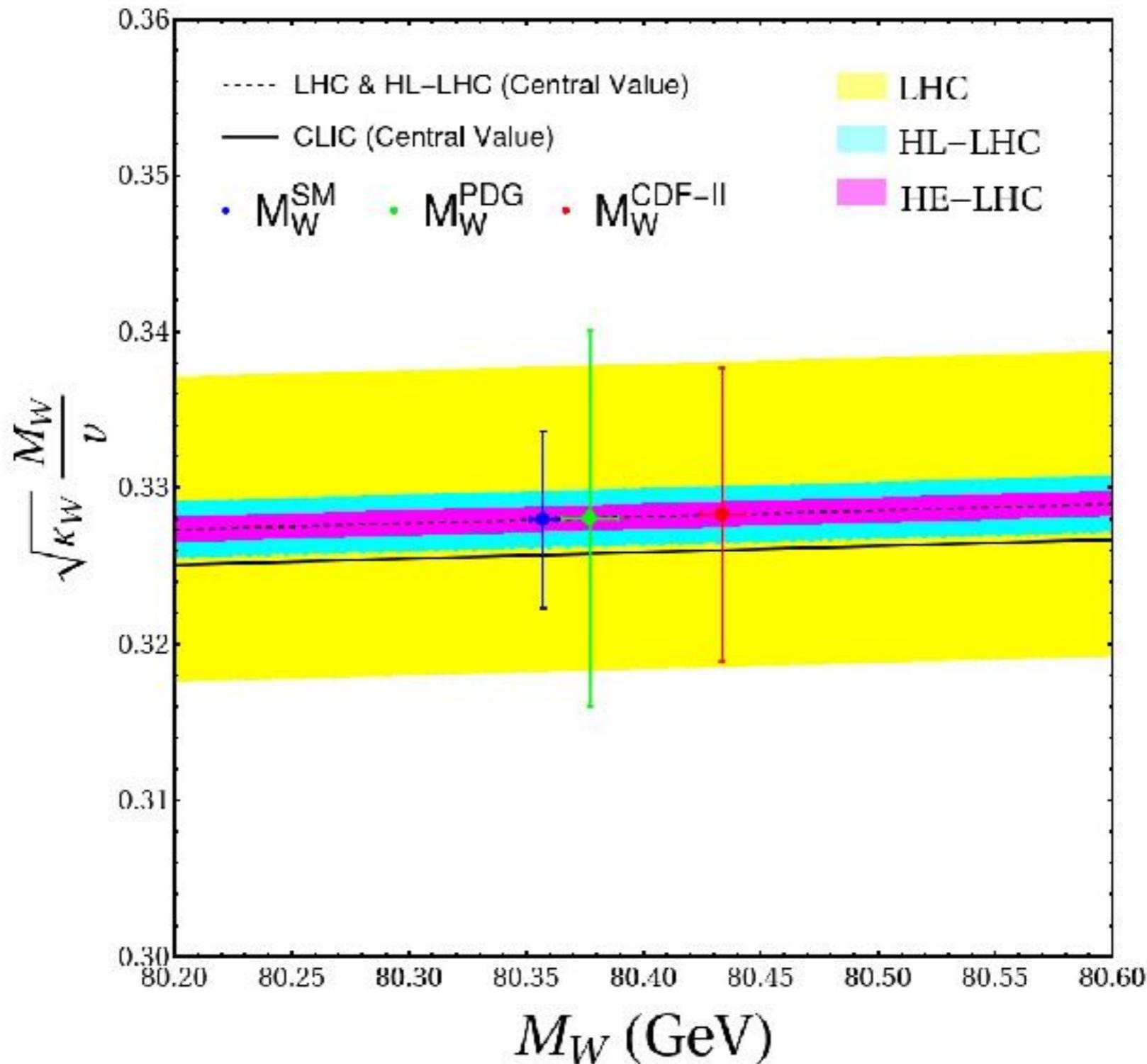
- The 2HDM-embedding of such idea is severely restricted (M. Carena et al),

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

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

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

M_w and the coupling hWW



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 from 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.
- Mw values give a coupling hWW that is consistent with SM prediction,

“All izz well”, Gracias!



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,

