Two Higgs Doublet Model with New Mass Matrix Ansatz

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1890

(in collaboration with **K.S. Babu**)
K.S. Babu and Sudip Jana, arXiv : 18XX.XXXXV [hep-Ph]

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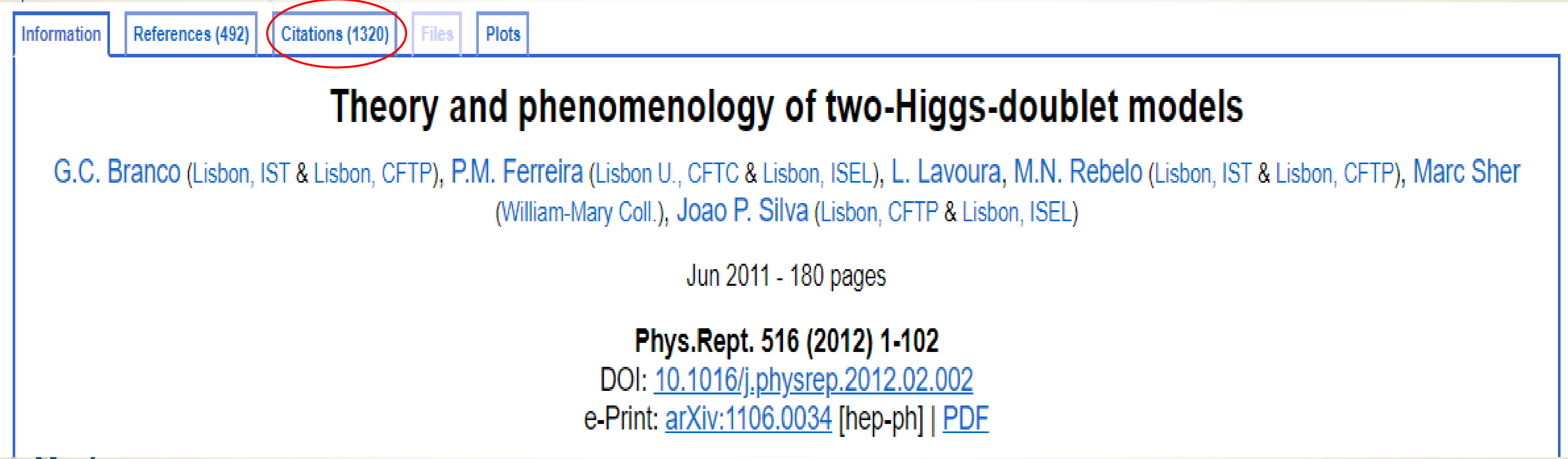
☐ Why Two Higgs Doublet Model (2HDM) ?

- The 2HDM is a simple and testable extension of SM.
- Some BSM theories require a 2nd doublet like DFSZ axion model, or supersymmetric models. This extension provides a foil to test the properties of the SM Higgs boson.
- EW T parameter has a tree level value of 1.
- SM is unable to generate a baryon asymmetry of the Universe of sufficient size. Two-Higgs-doublet models can do so, due to the flexibility of their scalar mass spectrum and the existence of additional sources of CP violation. There have been many works on baryogenesis in the 2HDM. Exciting new possibilities for explicit or spontaneous CP violation constitute one of the attractive features of 2HDM.
- It offers rich phenomenology at the LHC.

☐ “ The ” Two Higgs Doublet Model (2HDM)
What is new here ?



Theory and phenomenology of two-Higgs-doublet models

G.C. Branco (Lisbon, IST & Lisbon, CFTP), P.M. Ferreira (Lisbon U., CFTC & Lisbon, ISEL), L. Lavoura, M.N. Rebelo (Lisbon, IST & Lisbon, CFTP), Marc Sher (William-Mary Coll.), Joao P. Silva (Lisbon, CFTP & Lisbon, ISEL)

Jun 2011 - 180 pages

Phys.Rept. 516 (2012) 1-102
DOI: 10.1016/j.physrep.2012.02.002
e-Print: arXiv:1106.0034 [hep-ph] | PDF

❑ “ The ” Two Higgs Doublet Model (2HDM) What is new here ?

❖ **New Mass Matrix Ansatz : Allows both the doublets couple to fermions in same hierarchical pattern.**

❖ **It offers rich phenomenology at the LHC**

❖ **Properties of the 125 GeV SM-like Higgs may be significantly modified, consistent with known Higgs properties.**

❖ **The model is very predictive, implying unavoidable new physics signals like di-boson resonances (hh, ZZ and Zh) from novel decays of CP- even and CP-odd Higgs fields at the Large Hadron Collider (LHC) and that may lead to an explanation of some intriguing di-boson signatures (Zh excess at 440 GeV and hh) observed at the ATLAS experiment.**

❖ **Flavor Observables :** $\mu \to e\gamma$, Muon g-2 anomaly, R_D / R_D* Anomaly

etc….

☐ " The " Two Higgs Doublet Model (2HDM) Why New Mass Matrix Ansatz?

- ❖ The 2HDM has a potential problem with flavor changing neutral currents (FCNC) mediated by the neutral scalars, which arises when both Higgs doublets couple to up and down type quarks, and FCNC could be induced at large rates that may jeopardize the model.

- ❖ Assumption about specific Yukawa structure of the model can be the possible solutions to this FCNC problem in 2HDM.

- ❖ Depending upon the specific choices for the Yukawa matrices, the versions of the 2HDM are defined as type-I, type-II or type-III, which involve the following mechanisms, that are aimed either to eliminate the otherwise unbearable FCNC problem or at least to keep it under control

❑ “ The ” Two Higgs Doublet Model (2HDM)
Why New Mass Matrix Ansatz?

❖Solution 1 ~ Discrete Symmetries :

(a) One solution is invoking a discrete symmetry such that it allows a given fermion type (u or d-quarks for instance) to couple to a single Higgs doublet, and in such case FCNC's are absent at tree-level. In particular, when both types of quarks get masses from a single Higgs field (either Y_u=Y_d=0 or $\widetilde{Y}_u$=$\widetilde{Y}_d$=0), the resulting model is known as type-I 2HDM.

(b) On the other hand, when each type of quark couples to a different Higgs doublet (either Y_u=$\widetilde{Y}_d$=0 or $\widetilde{Y}_u$=Y_d=0), the model is referred as the type-II 2HDM which arises at tree-level in the minimal SUSY extension for the SM (MSSM).

☐ “ The ” Two Higgs Doublet Model (2HDM)
Why New Mass Matrix Ansatz?

❖ Solution 2 ~ Radiative Suppression :

If there exists a hierarchy between $\tilde{Y}_{u,d}$ and $Y_{u,d}$ FCNC could be kept under control although each fermion type couples to both Higgs doublets. Namely, a given set of Yukawa matrices (Y_d , $\tilde{Y}_u$) is present at tree-level, while the other ones (Y_u , $\tilde{Y}_d$) are absent at tree level and arise at one-loop level only as a radiative effect or via higher dimensional operator.

For instance, when the type-II 2HDM structure is not protected by any symmetry in MSSM and is transformed into a type-III 2HDM, through the loop effects of sfermions and gauginos.

❑ “ The ” Two Higgs Doublet Model (2HDM) Why New Mass Matrix Ansatz?

❖Solution 3 ~ Flavor Symmetry :

There is another way to achieve FCNC suppression by considering a certain form of the Yukawa matrices that reproduce the observed fermion masses and mixing angles, while both the doublet couple to each fermions and which is termed as type III 2HDM. This could be done either by adopting the Frogart-Nielsen mechanism to generate the fermion mass hierarchies, or by considering a certain ansatz for the fermion mass matrices.

- Cheng-Sher Ansatz (1987) :

$$\tilde{Y}_{ij} = \frac{\sqrt{2}}{v} \begin{pmatrix} 0 & C_f & 0 \\ C_f & 0 & B_f \\ 0 & B_f & A_f \end{pmatrix}$$

$$A_f \simeq a_f m_3,\ B \simeq b_f \sqrt{m_2 m_3} \text{ and } C_f \simeq c_f \sqrt{m_1 m_2}.$$

$$H f_i f_j \sim \sqrt{m_i m_j}/m_W.$$

☐ " The " Two Higgs Doublet Model (2HDM) Why New Mass Matrix Ansatz?

Problem :

Solution ?????

Removing/Killing all FCNC effects is not necessary for consistency with flavor violation constraints, hierarchical yukawa couplings of each Higgs with fermions is sufficient. It is this general 2HDM that we study here.

☐ "The" Two Higgs Doublet Model (2HDM)

- Renormalizable standard model with two Higgs doublets Φ_1 and Φ_2
- Both Φ_1 and Φ_2 couple to fermions
- Flavor changing Higgs interactions are naturally suppressed as Yukawa couplings are proportional to fermion masses Cheng, Sher (1987)
- "Type III" or "most general" designations not necessary ***Babu (DPF 2017)**
- $\langle \Phi_1^0 \rangle = v_1$, $\langle \Phi_2^0 \rangle = v_2 e^{i\xi}$
- Rotate Φ_1 and Φ_2 so that only one combination H_1 has nonzero VEV: $\langle H_1^0 \rangle = v$, $\langle H_2^0 \rangle = 0$

☐ Scalar Potential in the 2HDM

- Can be written as:

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \varphi_1^0 + iG^0\right) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(\varphi_2^0 + iA\right) \end{pmatrix}$$

- Scalar potential:

$$\begin{aligned}\mathcal{V} &= M_{11}^2 H_1^\dagger H_1 + M_{22}^2 H_2^\dagger H_2 - [M_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}] \\ &+ \tfrac{1}{2}\Lambda_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2}\Lambda_2 (H_2^\dagger H_2)^2 + \Lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \Lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &+ \left\{\tfrac{1}{2}\Lambda_5 (H_1^\dagger H_2)^2 + \underline{[\Lambda_6}\,(H_1^\dagger H_1) + \underline{\Lambda_7}(H_2^\dagger H_2)]\, H_1^\dagger H_2 + \mathrm{h.c.}\right\}\end{aligned}$$

- Mass squared matrix:

$$\mathcal{M}^2 = \begin{pmatrix} \Lambda_1 v^2 & \mathrm{Re}(\Lambda_6) v^2 & -\mathrm{Im}(\Lambda_6) v^2 \\ \mathrm{Re}(\Lambda_6) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 + \mathrm{Re}(\Lambda_5)) & -\frac{1}{2}\mathrm{Im}(\Lambda_5) v^2 \\ -\mathrm{Im}(\Lambda_6) v^2 & -\frac{1}{2}\mathrm{Im}(\Lambda_5) v^2 & M_{22}^2 + \frac{1}{2} v^2 (\Lambda_3 + \Lambda_4 - \mathrm{Re}(\Lambda_5)) \end{pmatrix}$$

- Assume CP invariance (for simplicity of presentation)

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + v^2(\Lambda_1 + \Lambda_5) \mp \sqrt{[m_A^2 + (\Lambda_5 - \Lambda_1) v^2]^2 + 4\Lambda_6^2 v^4}\right]$$

$$m_A^2 = m_{H^\pm}^2 - \tfrac{1}{2} v^2 (\Lambda_5 - \Lambda_4)$$

$$m_{H^\pm}^2 = M_{22}^2 + \tfrac{1}{2} v^2 \Lambda_3$$

- Neutral Higgs boson mixing angle:

$$h = \varphi_1^0 \cos\alpha + \varphi_2^0 \sin\alpha,$$

$$H = \varphi_2^0 \cos\alpha - \varphi_1^0 \sin\alpha,$$

$$\sin[2\alpha] = \frac{2\Lambda_6 v^2}{m_H^2 - m_h^2}.$$

☐ 2HDM : Parameters

- Yukawa couplings:

$$\mathcal{L}_y = Y_d \bar{Q}_L d_R H_1 + \tilde{Y}_d \bar{Q}_L d_R H_2 + Y_u \bar{Q}_L u_R \tilde{H}_1 + \tilde{Y}_u \bar{Q}_L u_R \tilde{H}_2$$
$$+ Y_l \bar{\psi}_L H_1 \psi_R + \tilde{Y}_l \bar{\psi}_L H_2 \psi_R + h.c.,$$

- Relevant parameters for collider physics are:

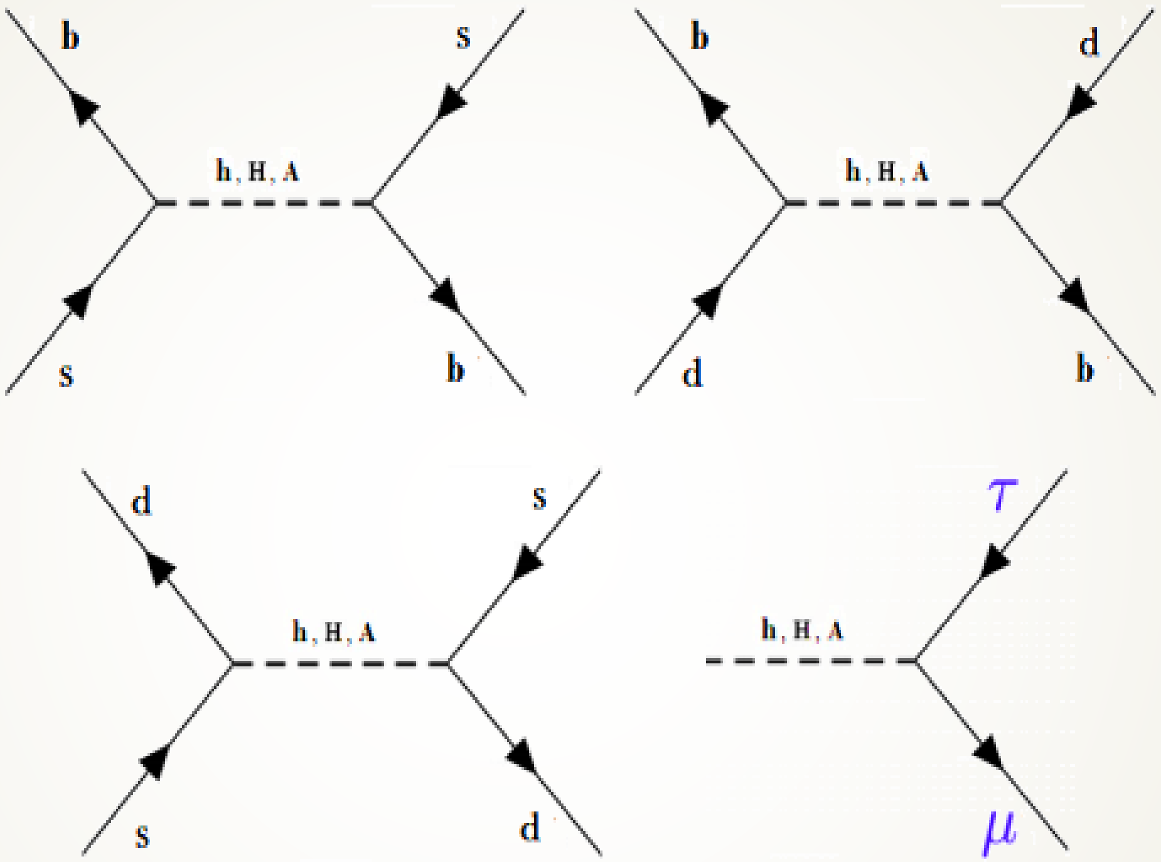
$$\left\{ \tilde{Y}_t,\ \ \tilde{Y}_b,\ \ \tilde{Y}_\tau,\ \ M_H,\ \ \sin\alpha \right\}$$

☐ “ The ” 2HDM with New Mass Matrix Ansatz :

$$\tilde{Y}_{u_{ij}} = \frac{1}{v}\begin{pmatrix} m_u & C_{uc}m_u & C_{ut}m_u \\ C_{cu}m_u & m_c & C_{ct}m_c \\ C_{tu}m_u & C_{tc}m_c & m_t \end{pmatrix}, \qquad \tilde{Y}_{d_{ij}} = \frac{1}{v}\begin{pmatrix} m_d & C_{ds}m_d & C_{db}m_d \\ C_{sd}m_d & m_s & C_{sb}m_s \\ C_{bd}m_d & C_{bs}m_s & m_b \end{pmatrix},$$

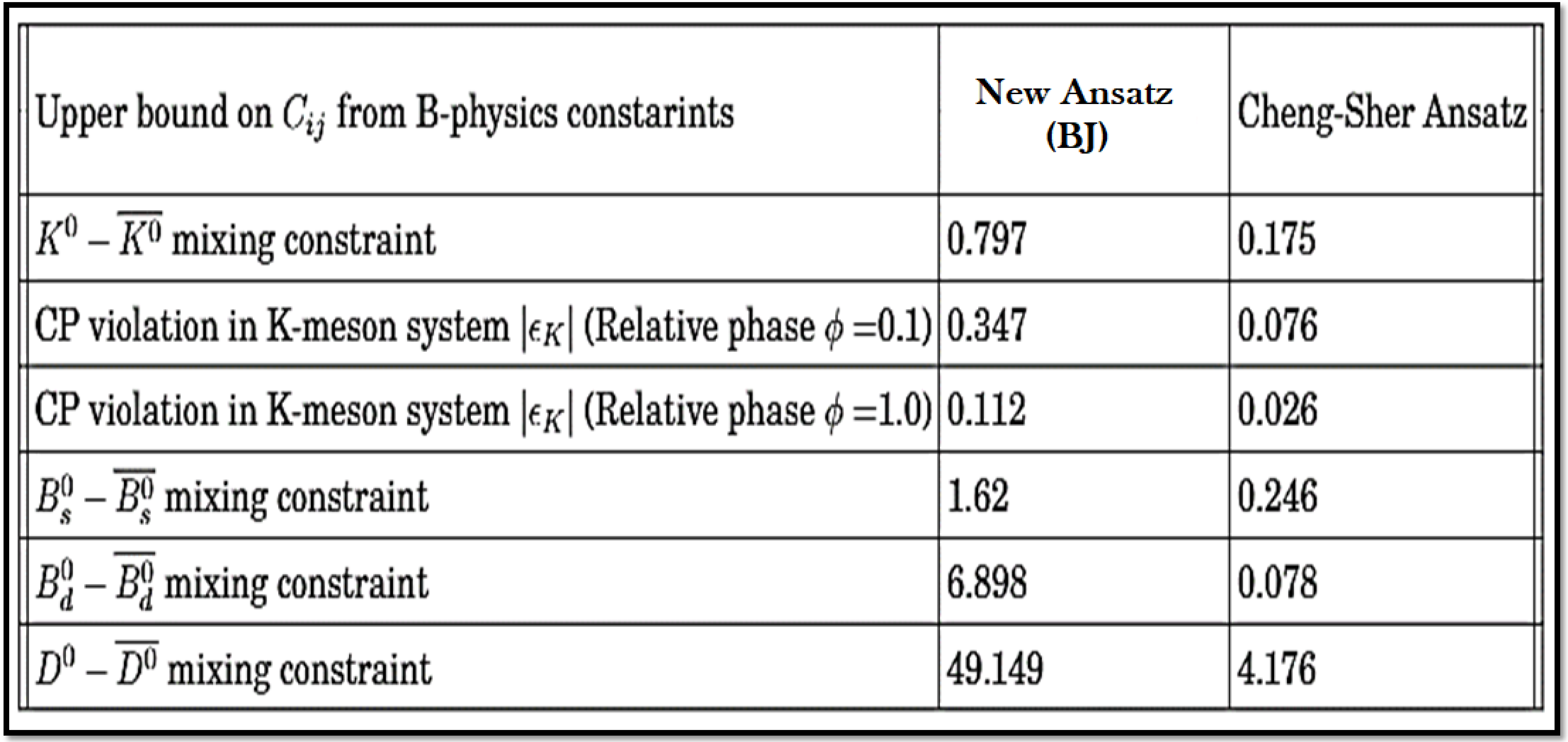
$$\tilde{Y}_{l_{ij}} = \frac{1}{v}\begin{pmatrix} m_e & C_{e\mu}m_e & C_{e\tau}m_e \\ C_{\mu e}m_e & m_\mu & C_{\mu\tau}m_\mu \\ C_{\tau e}m_e & C_{\tau\mu}m_\mu & m_\tau \end{pmatrix}$$

❑ T2HDM : Flavor Constraints



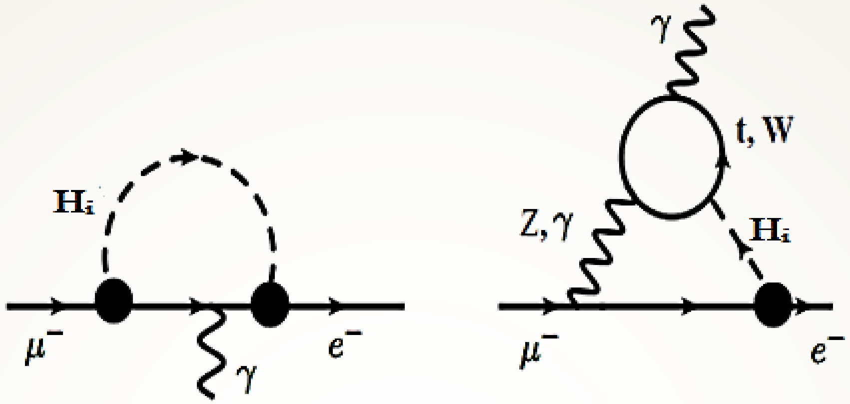
$B_s - \overline{B_s}$ mixing, $B_d - \overline{B_d}$ mixing, $K - \overline{K}$ mixing constraints satisfied with
$Y_{ij} \sim \tilde{Y}_{ij} \sim c_{ij} m_i / v, i < j$
CKM mixings correctly reproduced with $c_{12} \sim 4, c_{13} \sim 3, c_{23} \sim 2$

❑ T2HDM : Flavor Constraints



Upper bound on C_{ij} from B-physics constarints	New Ansatz (BJ)	Cheng-Sher Ansatz
$K^0-\overline{K^0}$ mixing constraint	0.797	0.175
CP violation in K-meson system $\|\epsilon_K\|$ (Relative phase ϕ =0.1)	0.347	0.076
CP violation in K-meson system $\|\epsilon_K\|$ (Relative phase ϕ =1.0)	0.112	0.026
$B_s^0-\overline{B_s^0}$ mixing constraint	1.62	0.246
$B_d^0-\overline{B_d^0}$ mixing constraint	6.898	0.078
$D^0-\overline{D^0}$ mixing constraint	49.149	4.176

☐ T2HDM : Flavor Observable



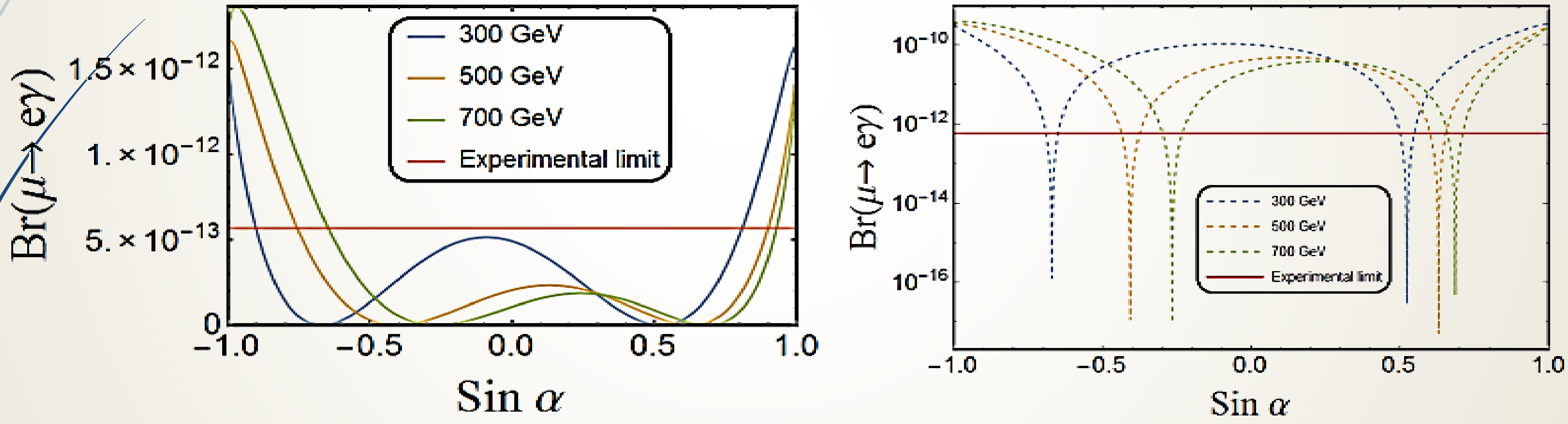


FIG. 1. Branching ratio Br ($\mu \to e\gamma$) as a function a mixing $\sin\alpha$ in two scenarios; **Left :** our case where amplitude goes as $\frac{m_e}{v}$, **Right :** Cheng-Sher ansatz where amplitude goes as $\frac{\sqrt{m_e m_\mu}}{v}$. Here $\bar{Y}_t = 1$.

Chang, Hou , Keung (1993)

❑ T2HDM : Modified couplings width of SM Higgs Boson

$$\kappa_{W,Z} = \cos\alpha,$$

$$\kappa_t = \left[\cos\alpha + \frac{\tilde{Y}_t v}{\sqrt{2} m_t} \sin\alpha\right],$$

$$\kappa_b = \left[\cos\alpha + \frac{\tilde{Y}_b v}{\sqrt{2} m_b} \sin\alpha\right],$$

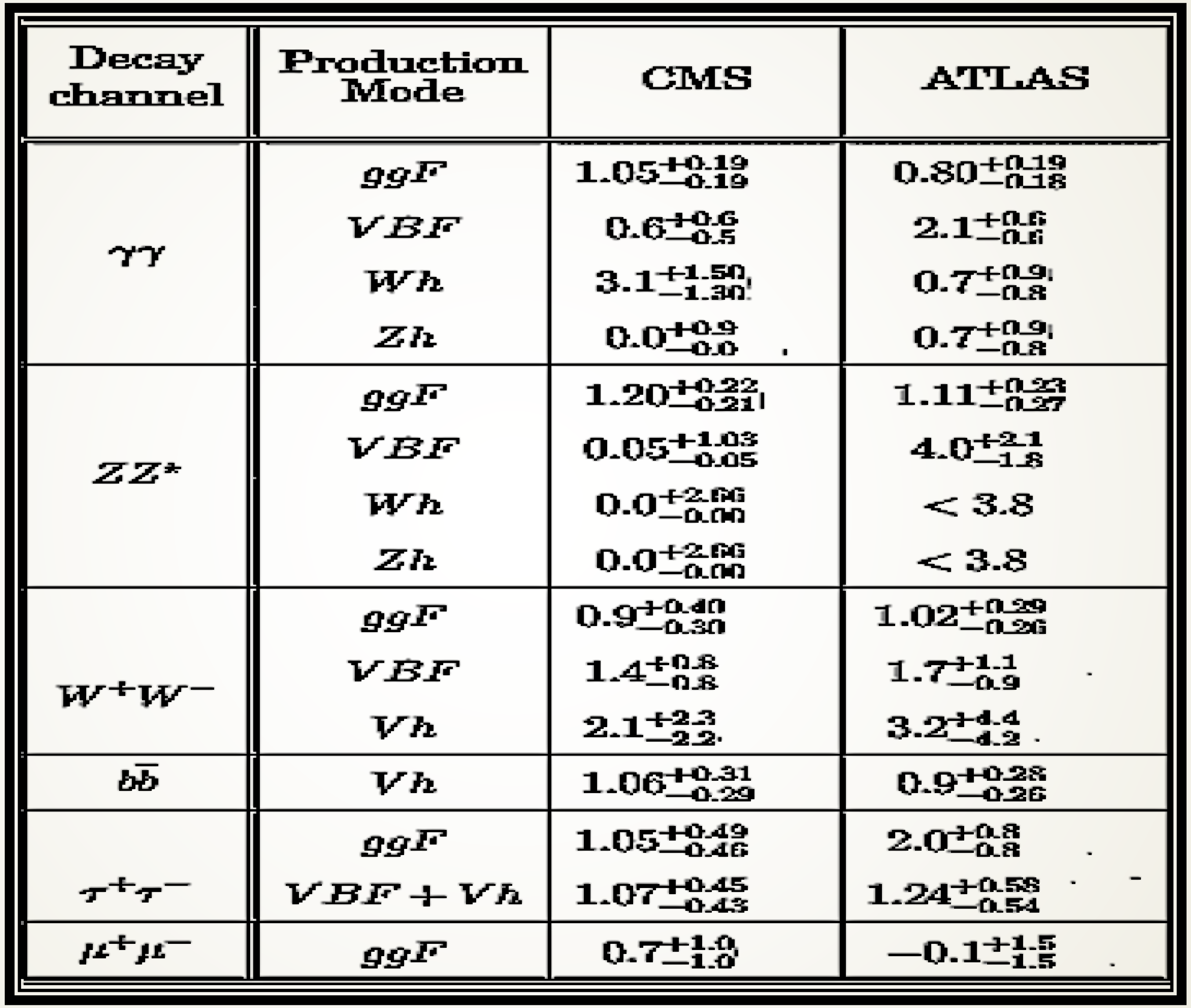
$$\kappa_\tau = \left[\cos\alpha + \frac{\tilde{Y}_\tau v}{\sqrt{2} m_\tau} \sin\alpha\right],$$

$$\kappa_{\gamma\gamma} = \left|\frac{\frac{4}{3}\kappa_t F_{1/2}(m_h) + F_1(m_h)\cos\alpha + \frac{v\lambda_{hH^+H^-} F_0(m_h)}{2m^2_{H^+}}}{\frac{4}{3} F_{1/2}(m_h) + F_1(m_h)}\right|,$$

$$\kappa_g = \left|\kappa_t + \epsilon_b \kappa_b\right|, (\epsilon_b = -0.032 + 0.035i)$$

$$\kappa_{Z\gamma} = \left|\frac{\frac{2}{\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right)\kappa_t F_{1/2}(m_h) + F_1(m_h)\cos\alpha + \frac{v\lambda_{hH^+H^-}\lambda_{ZH^+H^-} F_0(m_h)}{2m^2_{H^+}}}{\frac{2}{\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right) F_{1/2}(m_h) + F_1(m_h)}\right|$$

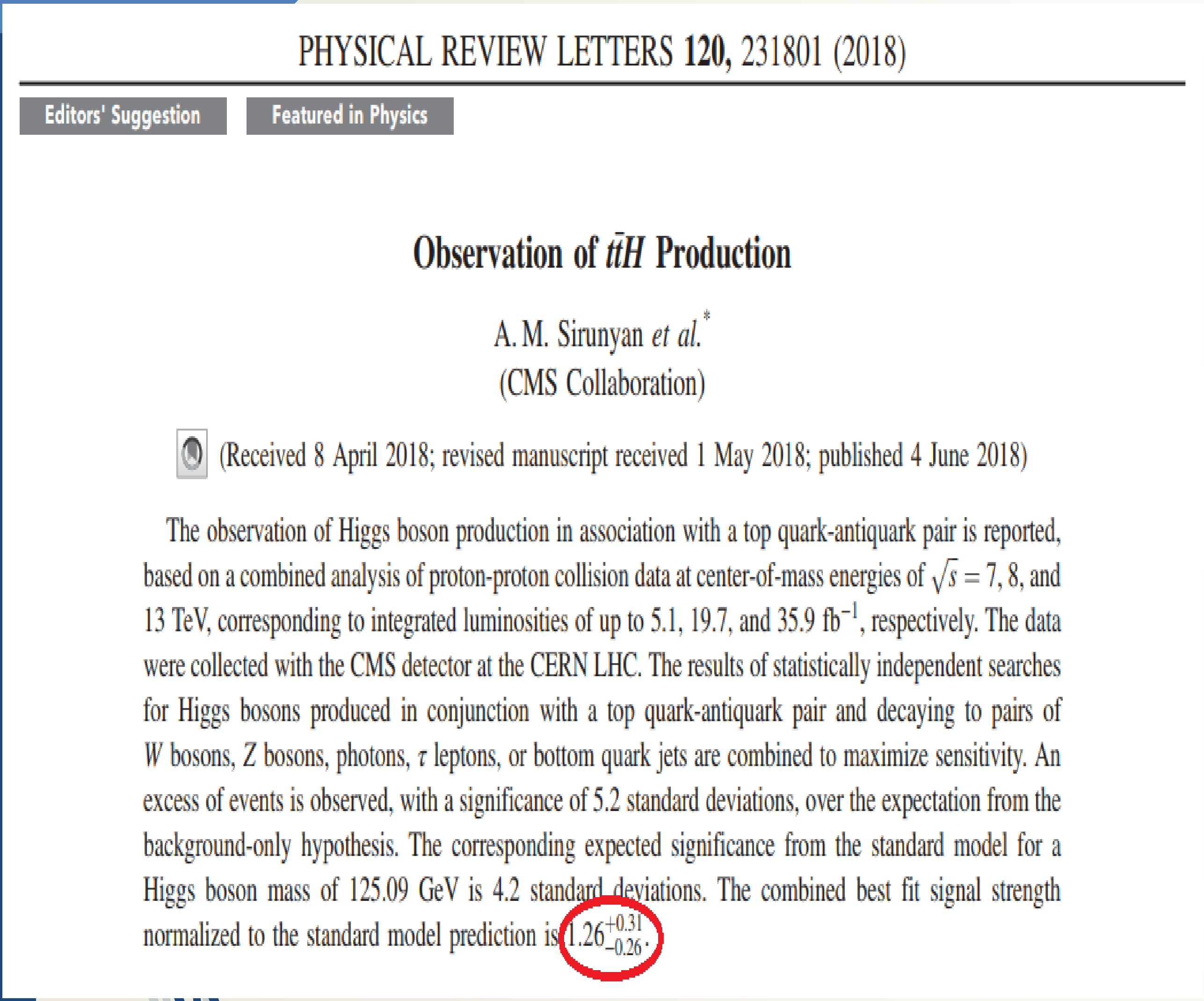
☐ Knowledge about 125 GeV Higgs Boson



Decay channel	Production Mode	CMS	ATLAS
$\gamma\gamma$	ggF	$1.05^{+0.19}_{-0.19}$	$0.80^{+0.19}_{-0.18}$
	VBF	$0.6^{+0.6}_{-0.5}$	$2.1^{+0.6}_{-0.6}$
	Wh	$3.1^{+1.50}_{-1.30}$	$0.7^{+0.9}_{-0.8}$
	Zh	$0.0^{+0.9}_{-0.0}$	$0.7^{+0.9}_{-0.8}$
ZZ^*	ggF	$1.20^{+0.22}_{-0.21}$	$1.11^{+0.23}_{-0.27}$
	VBF	$0.05^{+1.03}_{-0.05}$	$4.0^{+2.1}_{-1.8}$
	Wh	$0.0^{+2.66}_{-0.00}$	< 3.8
	Zh	$0.0^{+2.66}_{-0.00}$	< 3.8
W^+W^-	ggF	$0.9^{+0.40}_{-0.30}$	$1.02^{+0.29}_{-0.26}$
	VBF	$1.4^{+0.8}_{-0.8}$	$1.7^{+1.1}_{-0.9}$
	Vh	$2.1^{+2.3}_{-2.2}$	$3.2^{+4.4}_{-4.2}$
$b\bar{b}$	Vh	$1.06^{+0.31}_{-0.29}$	$0.9^{+0.28}_{-0.26}$
$\tau^+\tau^-$	ggF	$1.05^{+0.49}_{-0.46}$	$2.0^{+0.8}_{-0.8}$
	$VBF + Vh$	$1.07^{+0.45}_{-0.43}$	$1.24^{+0.58}_{-0.54}$
$\mu^+\mu^-$	ggF	$0.7^{+1.0}_{-1.0}$	$-0.1^{+1.5}_{-1.5}$

Moriond conference 2018,
Babu, Jana (2017),
Jana, Nandi (2017),
Murphy et al. (2017), etc.

☐ Knowledge about 125 GeV Higgs Boson



PHYSICAL REVIEW LETTERS **120,** 231801 (2018)

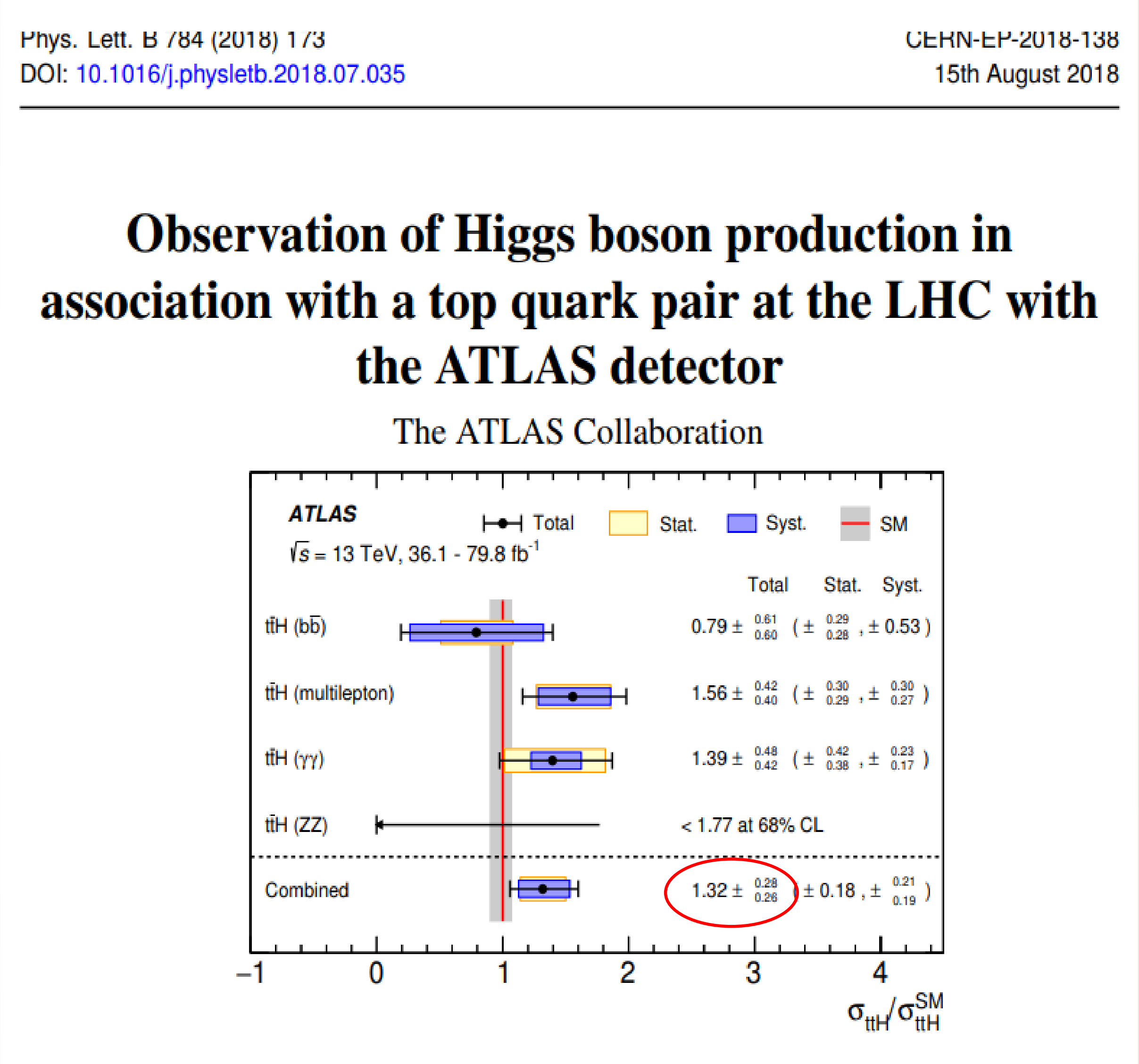
Editors' Suggestion Featured in Physics

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.**
(CMS Collaboration)

(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)

The observation of Higgs boson production in association with a top quark-antiquark pair is reported, based on a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to integrated luminosities of up to 5.1, 19.7, and 35.9 fb^{-1}, respectively. The data were collected with the CMS detector at the CERN LHC. The results of statistically independent searches for Higgs bosons produced in conjunction with a top quark-antiquark pair and decaying to pairs of W bosons, Z bosons, photons, τ leptons, or bottom quark jets are combined to maximize sensitivity. An excess of events is observed, with a significance of 5.2 standard deviations, over the expectation from the background-only hypothesis. The corresponding expected significance from the standard model for a Higgs boson mass of 125.09 GeV is 4.2 standard deviations. The combined best fit signal strength normalized to the standard model prediction is $1.26^{+0.31}_{-0.26}$.



Phys. Lett. B 784 (2018) 173
DOI: 10.1016/j.physletb.2018.07.035

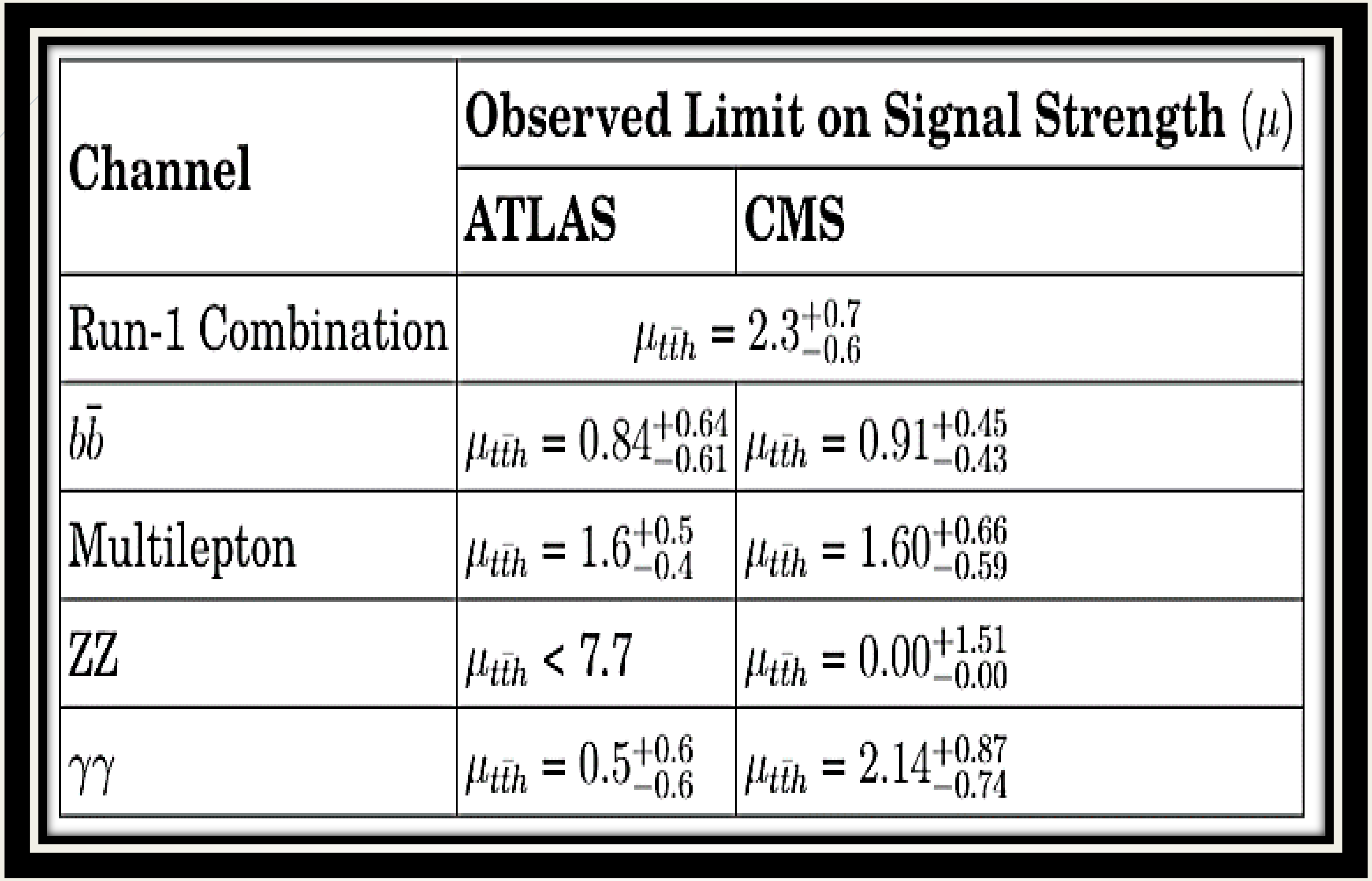
CERN-EP-2018-138
15th August 2018

Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

The ATLAS Collaboration

ATLAS : Phys. Lett. B784, 173 (2018)
CMS : Phys. Rev. Lett.120, no. 23, 231801 (2018)

☐ Knowledge about 125 GeV Higgs Boson



Channel	Observed Limit on Signal Strength (μ)	
	ATLAS	CMS
Run-1 Combination	$\mu_{t\bar{t}h} = 2.3^{+0.7}_{-0.6}$	
$b\bar{b}$	$\mu_{t\bar{t}h} = 0.84^{+0.64}_{-0.61}$	$\mu_{t\bar{t}h} = 0.91^{+0.45}_{-0.43}$
Multilepton	$\mu_{t\bar{t}h} = 1.6^{+0.5}_{-0.4}$	$\mu_{t\bar{t}h} = 1.60^{+0.66}_{-0.59}$
ZZ	$\mu_{t\bar{t}h} < 7.7$	$\mu_{t\bar{t}h} = 0.00^{+1.51}_{-0.00}$
$\gamma\gamma$	$\mu_{t\bar{t}h} = 0.5^{+0.6}_{-0.6}$	$\mu_{t\bar{t}h} = 2.14^{+0.87}_{-0.74}$

ATLAS : Phys. Lett. B784, 173 (2018)
CMS : Phys. Rev. Lett.120, no. 23, 231801 (2018)

T2HDM : Constraints on Model Parameters

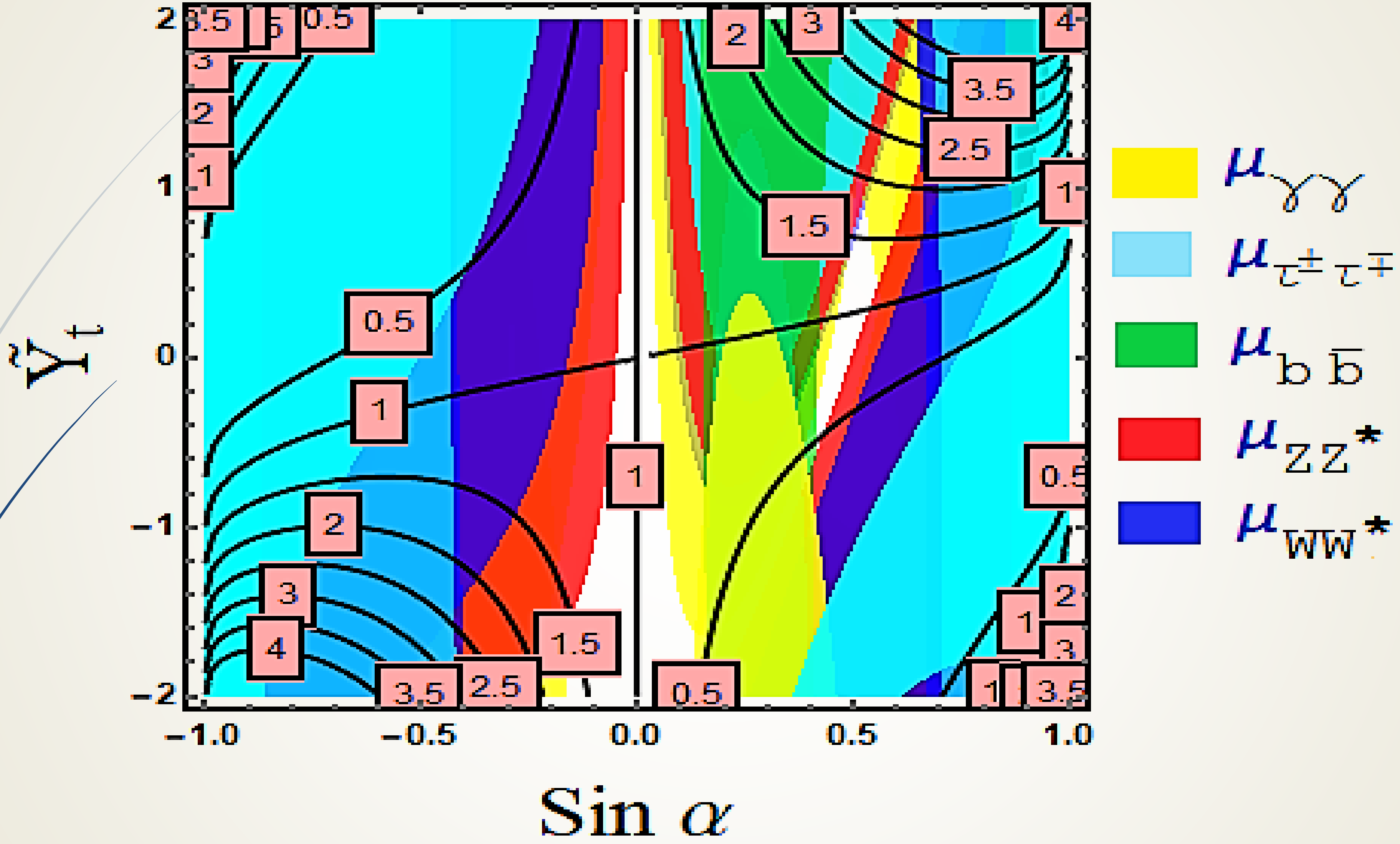


Figure: Contour plot of $\mu^{t\bar{t}h}$. Here $\tilde{Y}_b = -0.09$ is kept fixed. White region is allowed.

❑ T2HDM : Constraints on Model Parameters

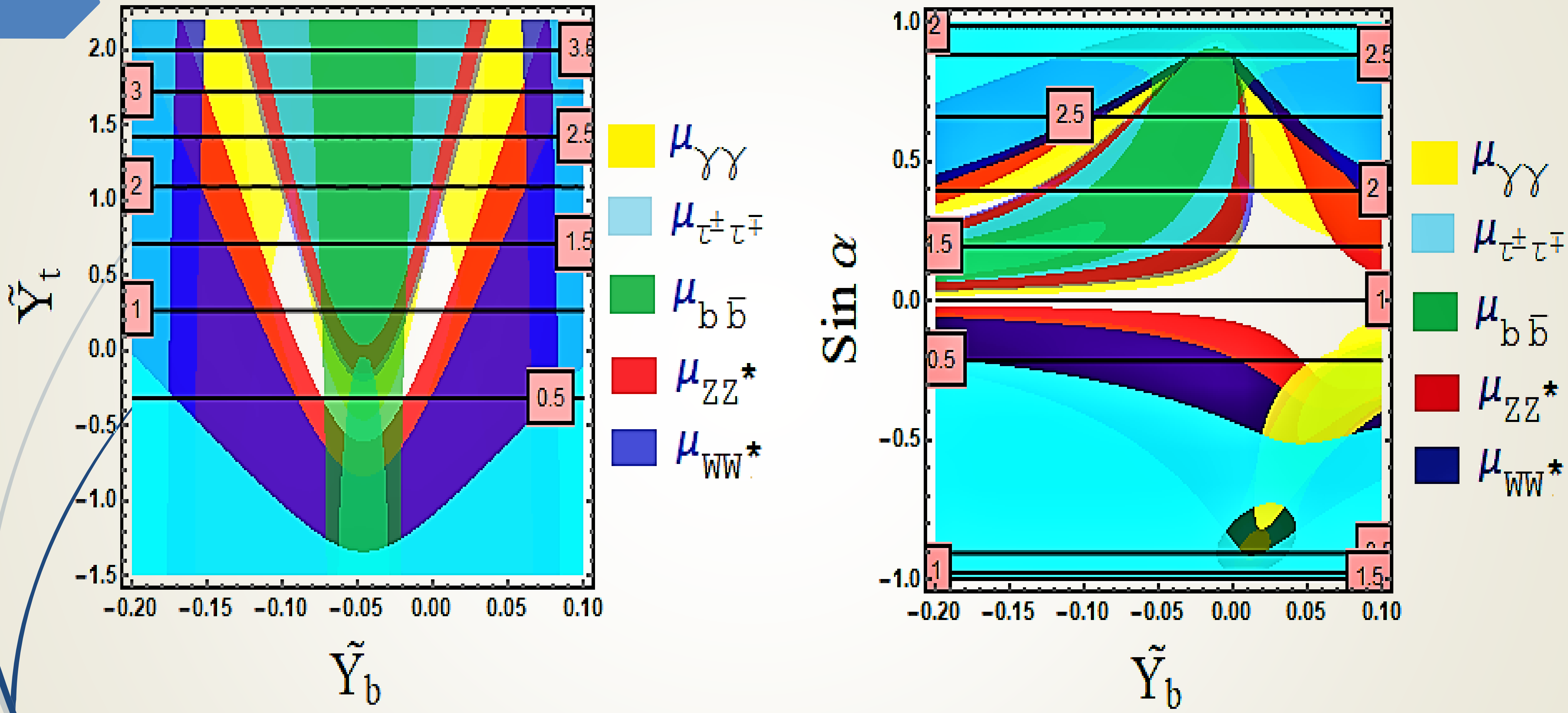
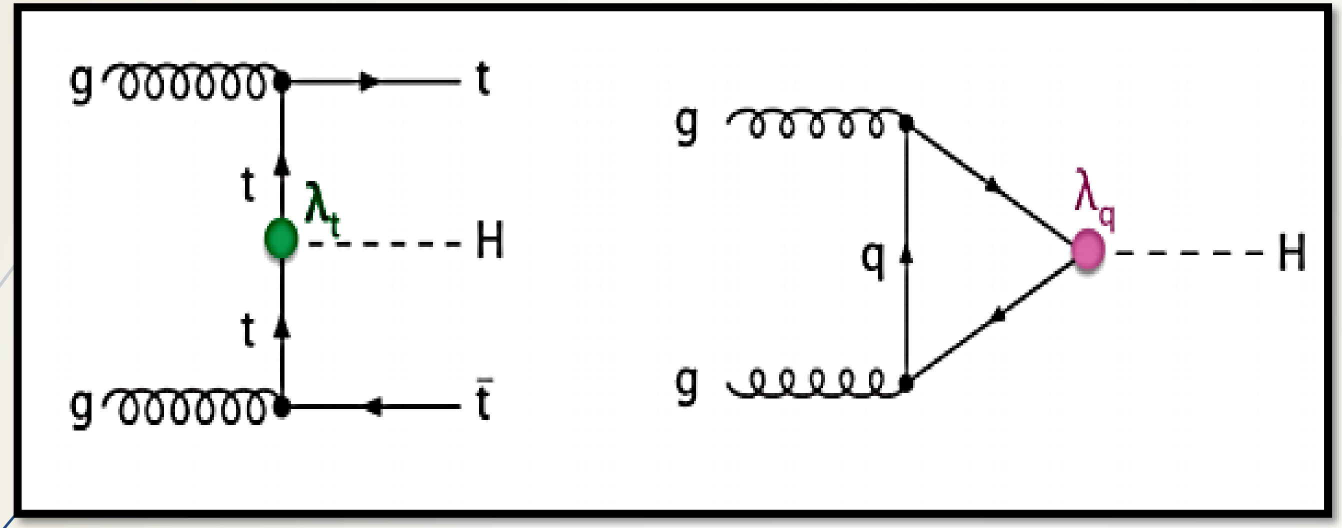


Figure: $\sin\alpha = 0.5$ (left); $\tilde{Y}_t = 1.25$ (right)

☐ $t\bar{t}h$ production in SM



- Probes Yukawa coupling of the top quark directly.
- Cross-section ~ 508.5 fb in SM, which is ~1/100 of resonant single Higgs production.
- CMS and ATLAS have evidences for seeing $t\bar{t}h$ process.
- It is easier to get suppressed top Yukawa, difficult to enhance it.
- Signature of new physics : Golden "eliminator" channel.

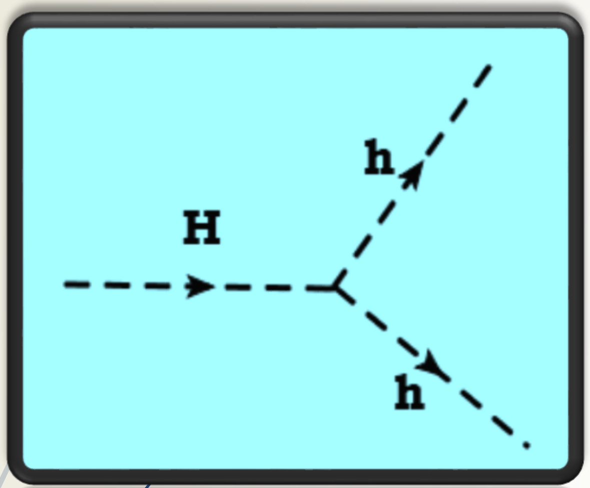
☐ Phenomenology

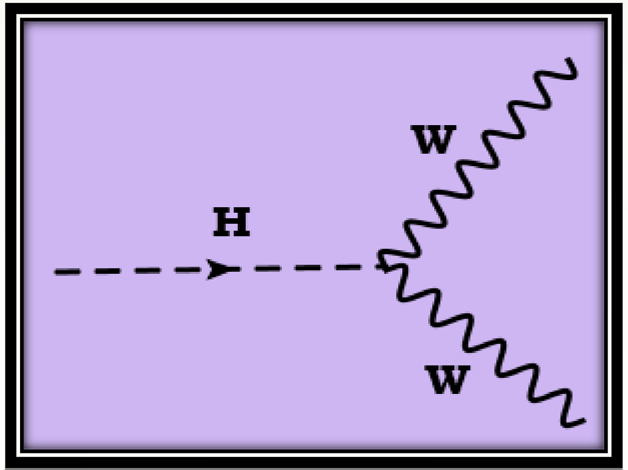
- We have three new particles in the model :
  - **CP- even Neutral Heavy Higgs : H**
  - **CP- odd (pseudo)-scalar : A**
  - **Singly Charged Higgs : H^+**

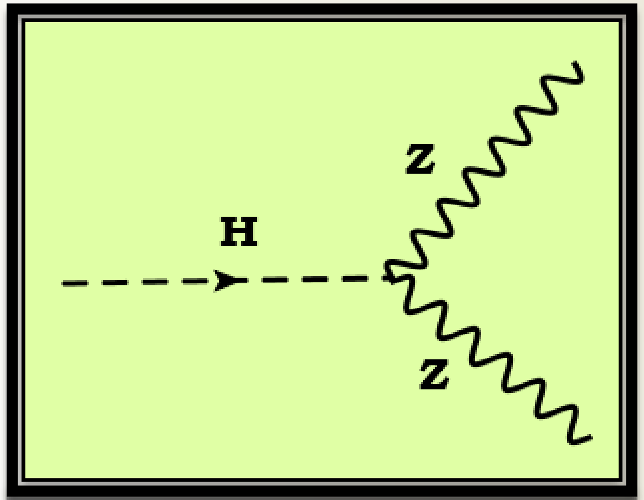
- Discovery of these Higgs bosons below a TeV will be confirmation of the scenario

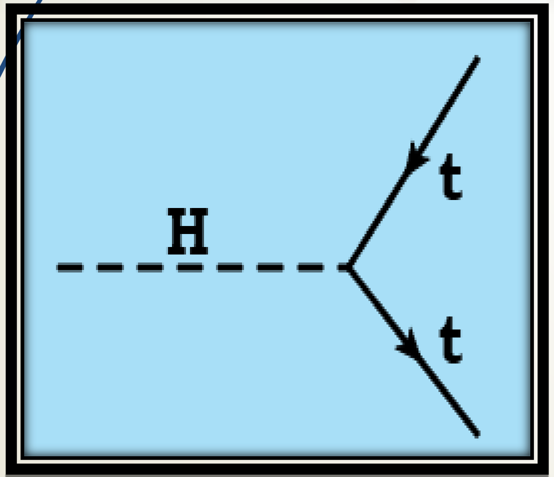
❑ *CP* - even Neutral Heavy Higgs (H) Phenomenology :

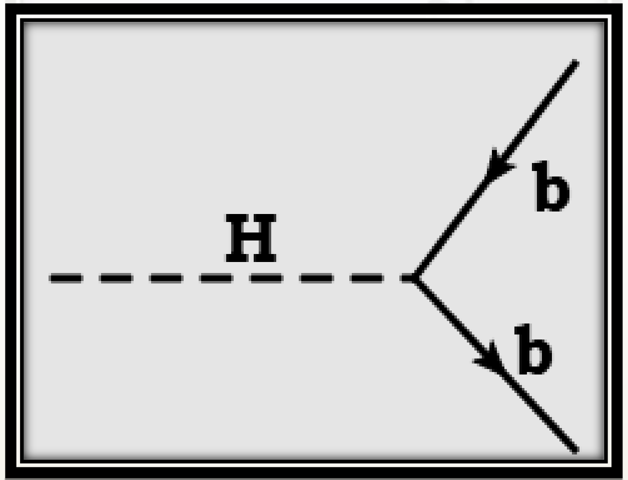
❖ MAIN DECAY MODES :

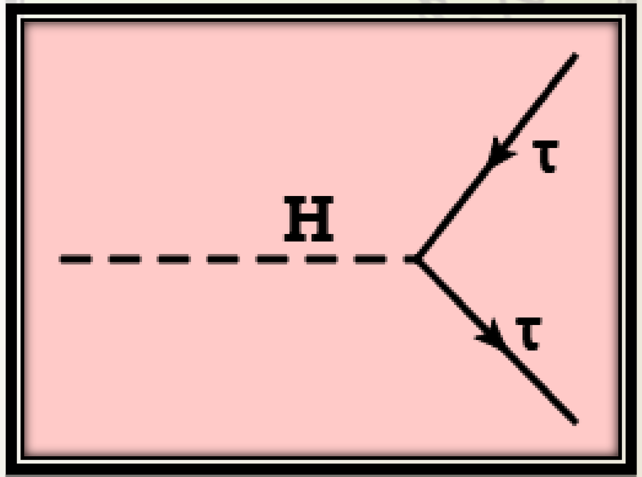












☐ Branching Ratio of Heavy Higgs H

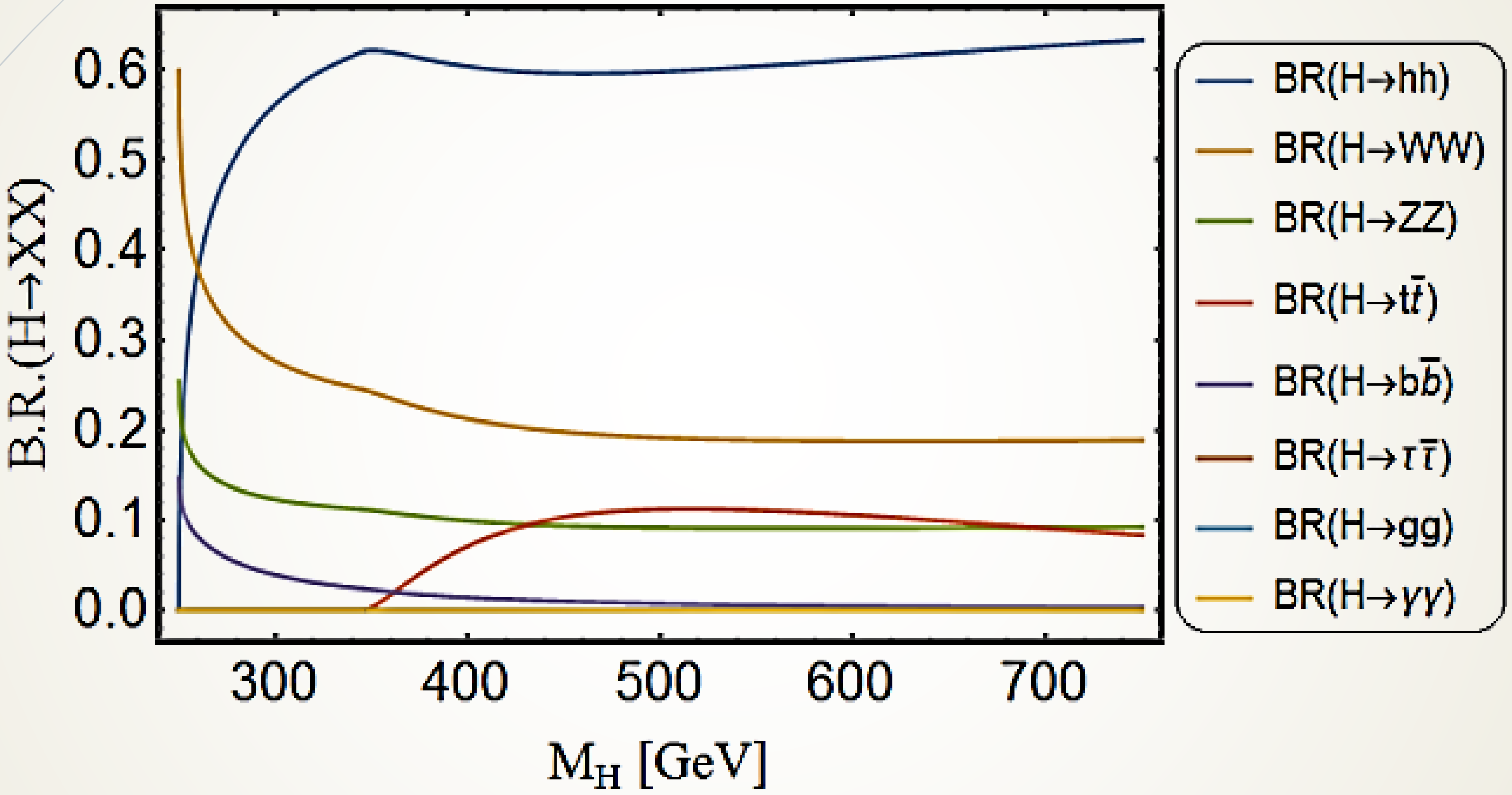
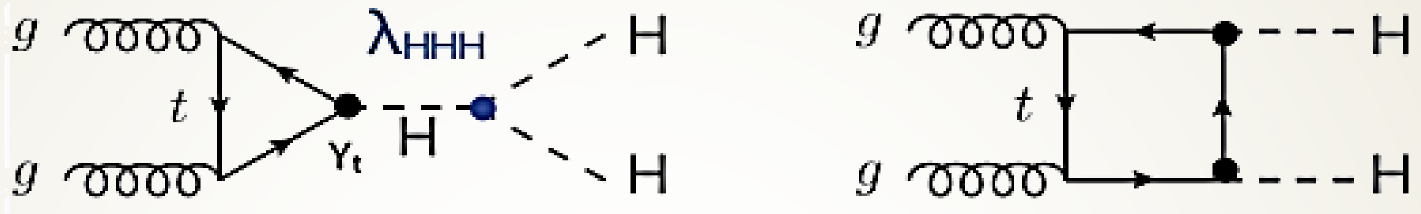


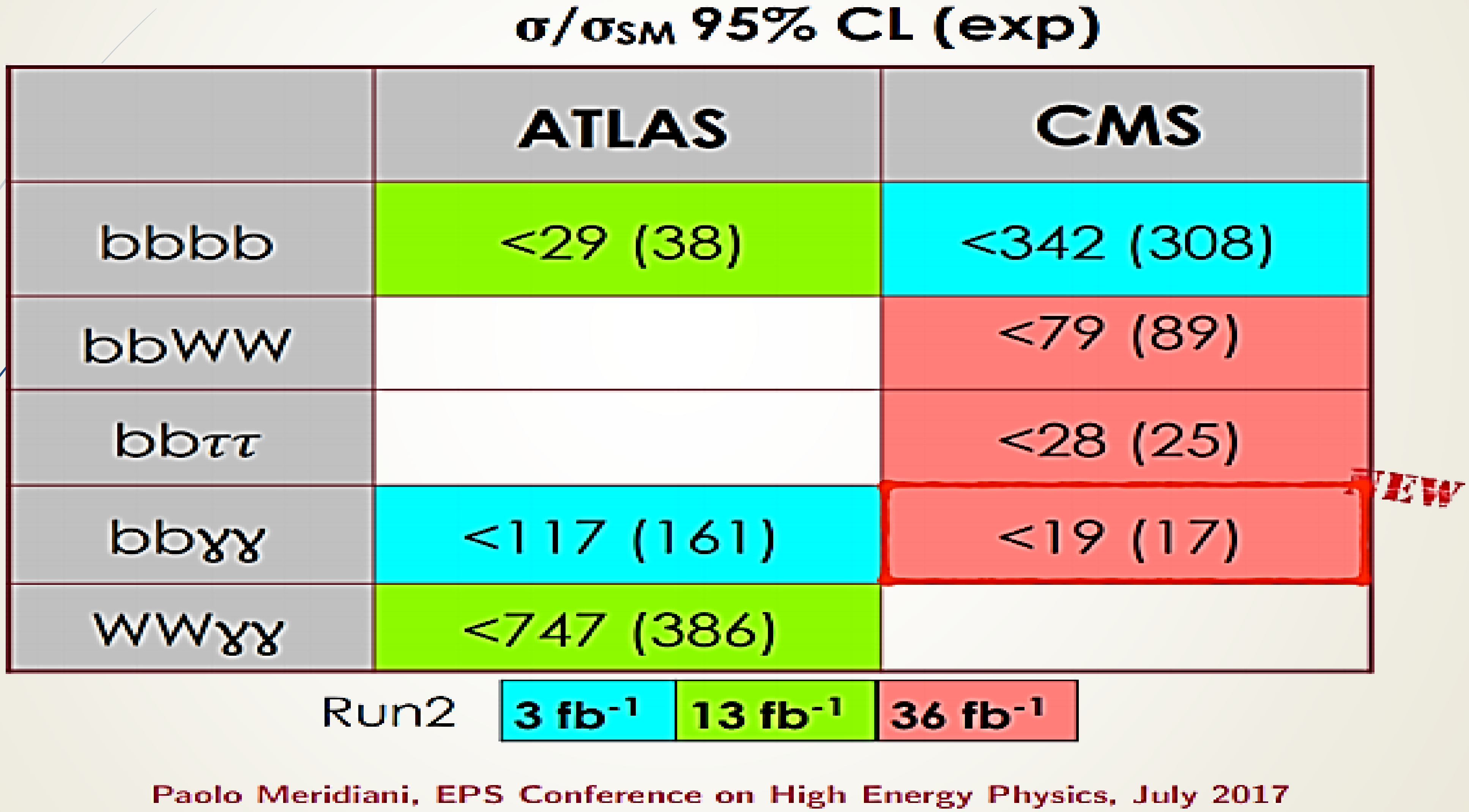
Figure: Branching ratio to different decay modes of H as a function of mass M_H.

☐ Di-Higgs Production in SM



- Probes trilinear Higgs coupling and tests EW symmetry breaking mechanism
- Cross section $\simeq 33.5$ fb in SM – the two diagrams interfere destructively
- If new resonances are present, they can decay into two Higgs and enhance di-Higgs production
- Current upper limit on di-Higgs production rate is about 19 times the SM cross section

☐ Constarint on Di-Higgs Production



σ/σ_{SM} 95% CL (exp)

	ATLAS	CMS
bbbb	🟩 <29 (38)	🟦 <342 (308)
bbWW		🟥 <79 (89)
$bb\tau\tau$		🟥 <28 (25)
$bb\gamma\gamma$	🟦 <117 (161)	🟥 <19 (17) NEW
$WW\gamma\gamma$	🟩 <747 (386)	

Run2 🟦 3 fb^{-1} 🟩 13 fb^{-1} 🟥 36 fb^{-1}

Paolo Meridiani, EPS Conference on High Energy Physics, July 2017

☐ Di-Higgs Production in the 2HDM

Resonant H production, followed by $H \to hh$, enhances di-Higgs production

Signal strength relative to the SM expectation μ_{hh} defined as follows:

$$\mu_{hh} = \frac{\sigma(pp \to hh)_{2HDM}}{\sigma(pp \to hh)_{SM}} = \frac{\left[\sigma^{Res}(pp \to hh) + \sigma^{Non-Res}(pp \to hh)\right]_{2HDM}}{\sigma(pp \to hh)_{SM}},$$

where

$$\sigma^{Res}(pp \to hh) = \sigma(pp \to H) \times Br(H \to hh)$$

$$\sigma(pp \to H) = \sigma(pp \to h(M_H)) \times \left(-\sin\alpha + \frac{v\tilde{y}_t}{\sqrt{2}m_t}\cos\alpha\right)^2$$

❑ Di-Higgs Production in the 2HDM

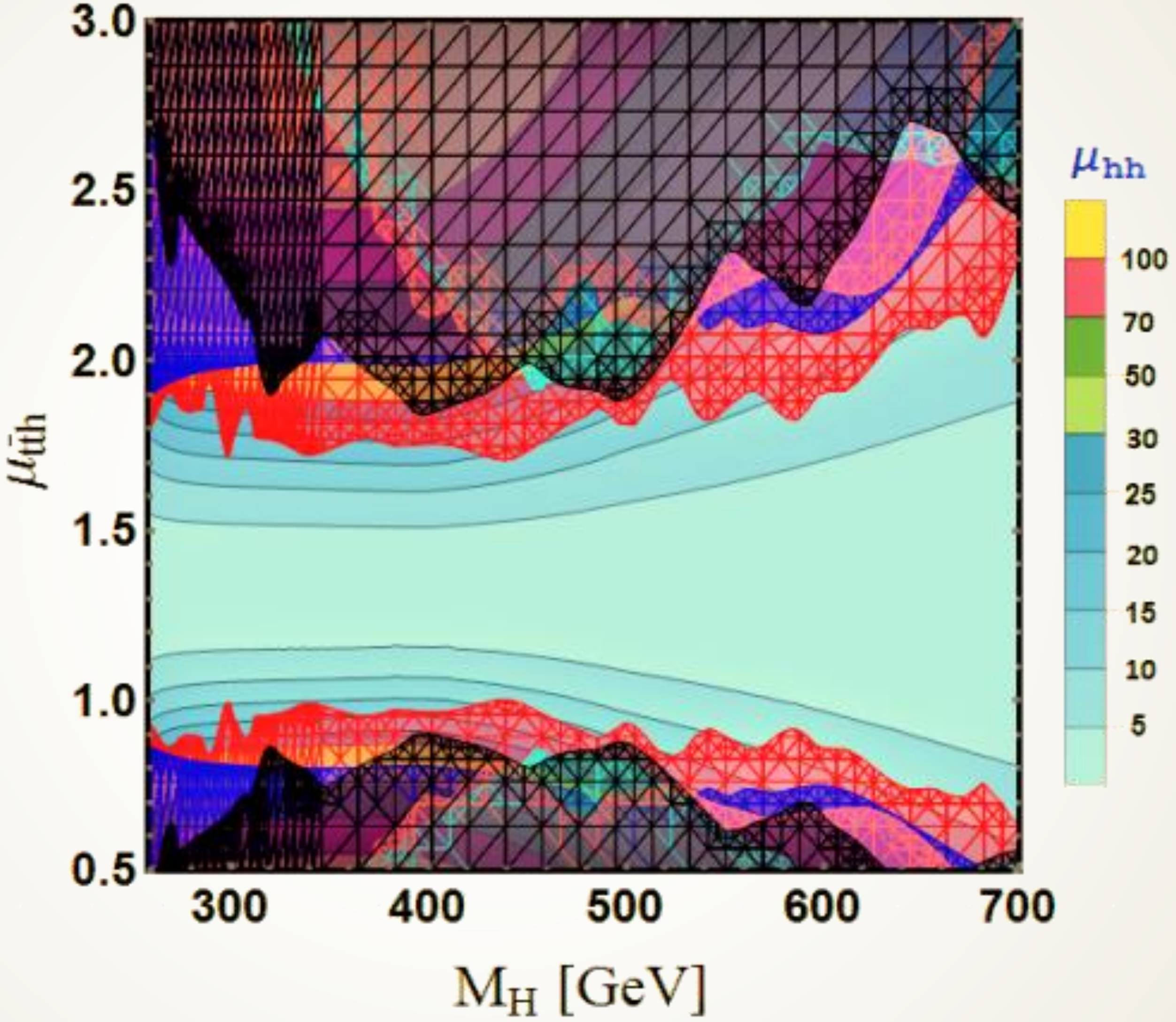
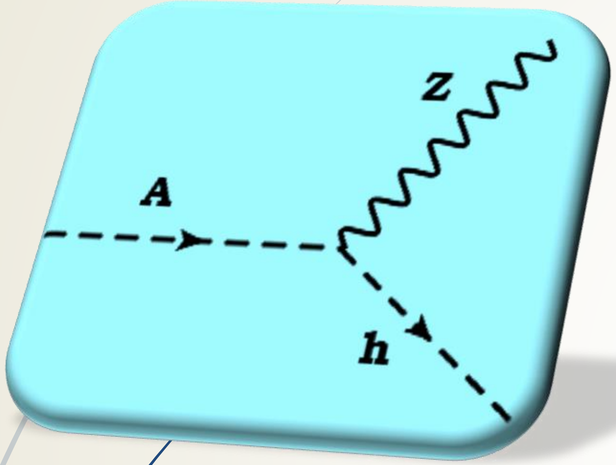
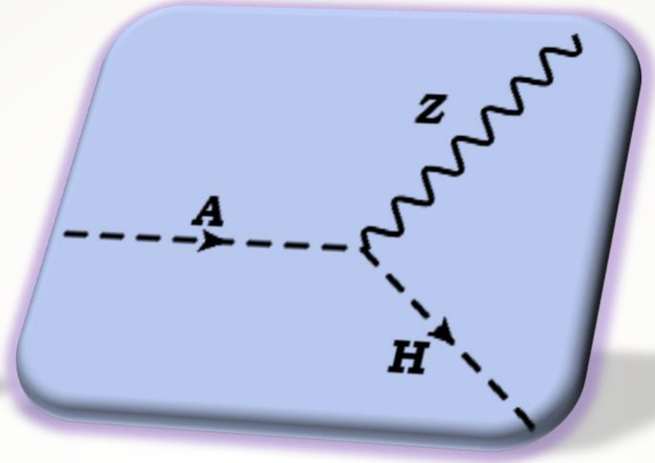


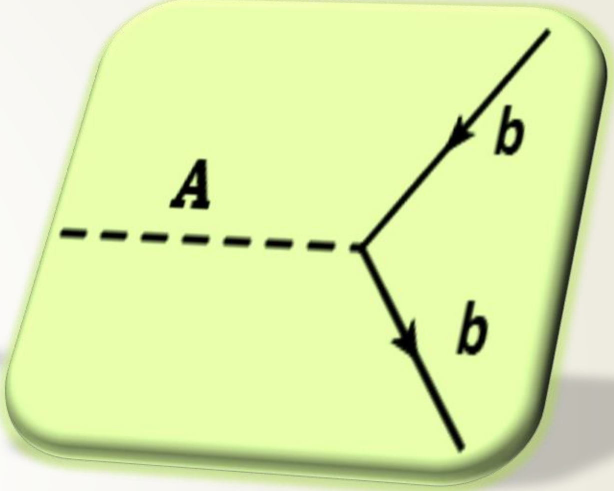
Figure: Black, pink and cyan colored meshed zones are excluded parameter space from current di-Higgs limit looking at different final states $b\bar{b}\gamma\gamma$, $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ respectively; red and blue meshed zone is the excluded parameter space from the resonant ZZ and W^+W^- production constraints. $\sin\alpha = 0.5$, $\tilde{Y_b} = -0.09$, $\tilde{Y_\tau} = 10^{-3}$

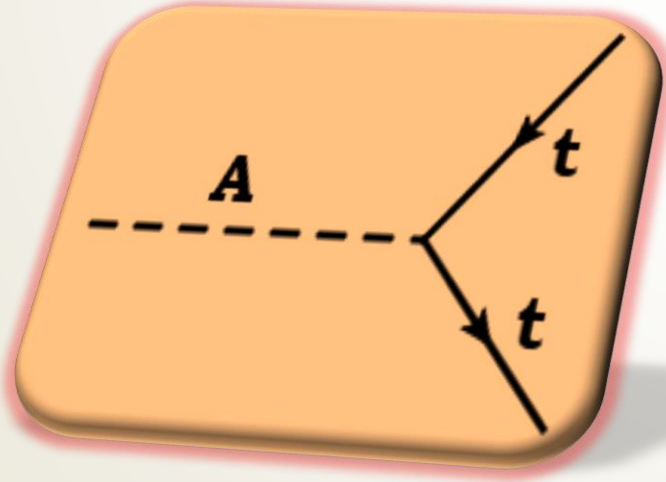
❑ *CP*- odd Neutral Pseudo-scalar (A) Phenomenology :

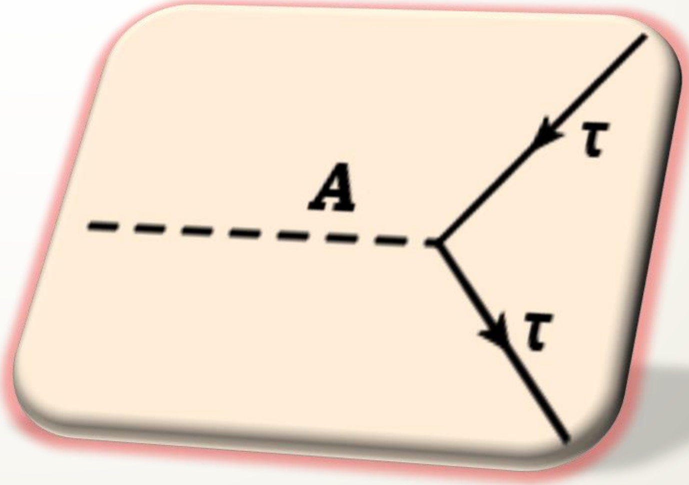
❖ Main decay modes :



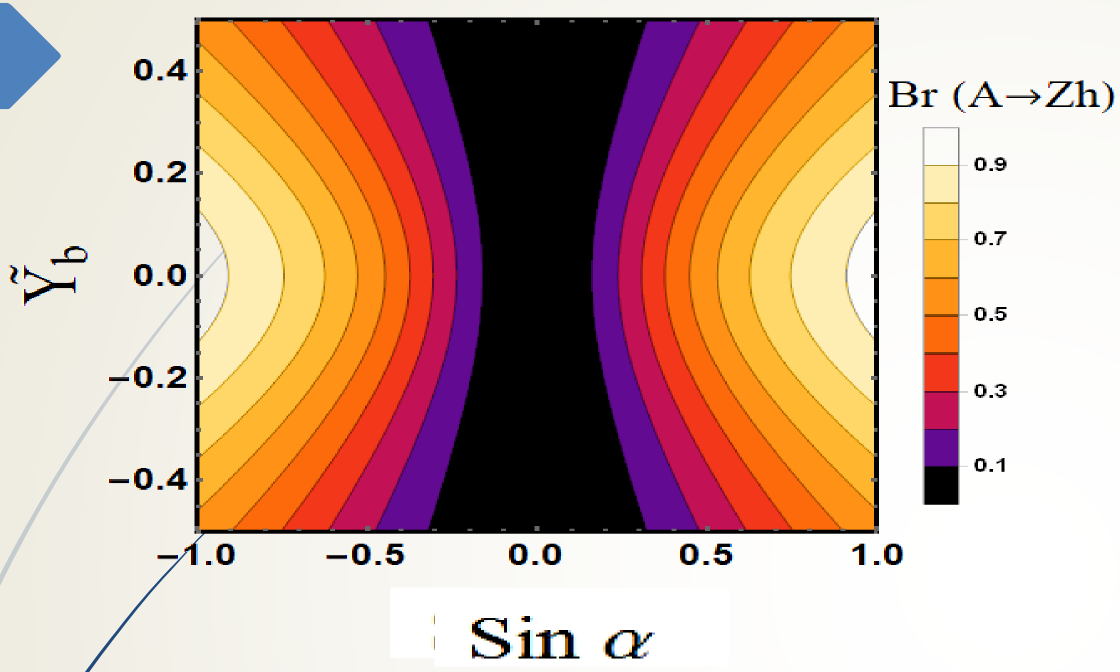


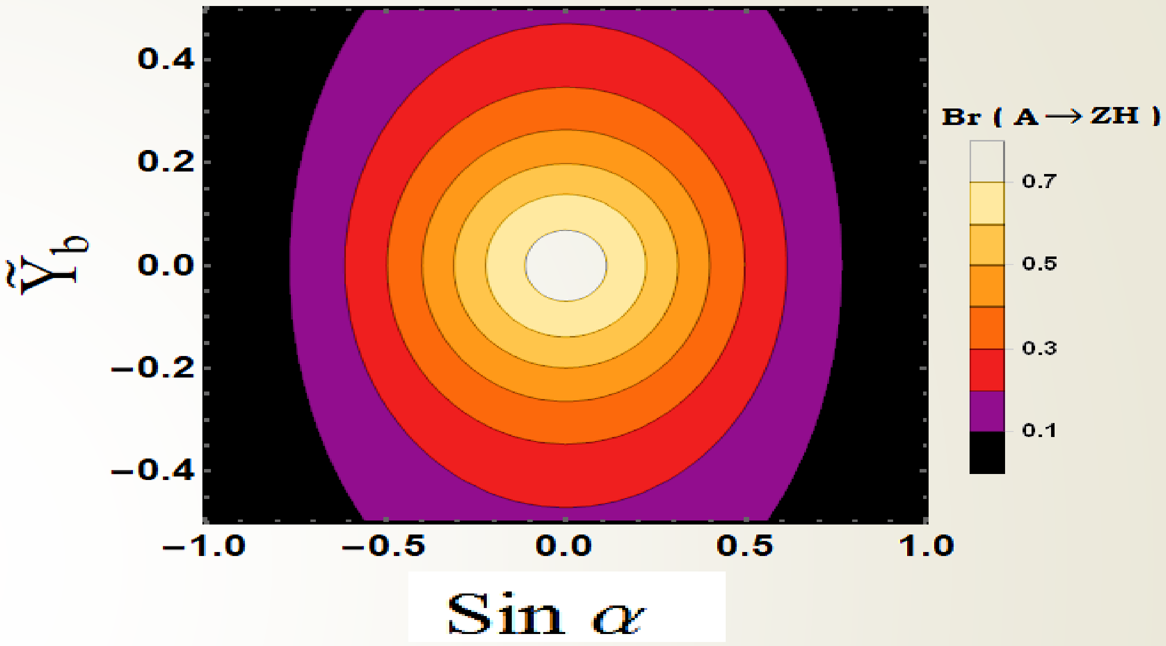


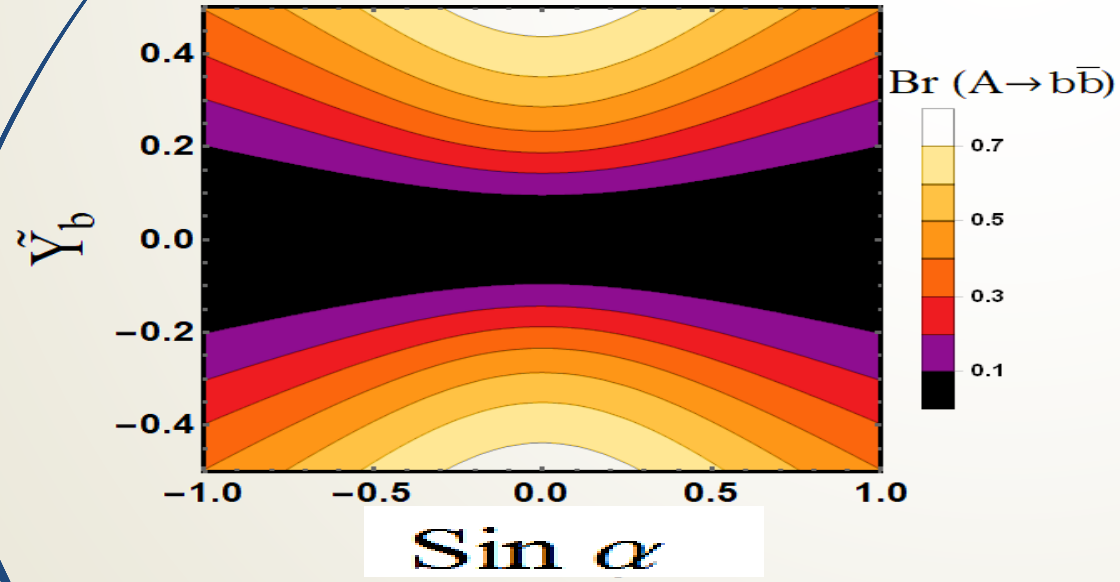


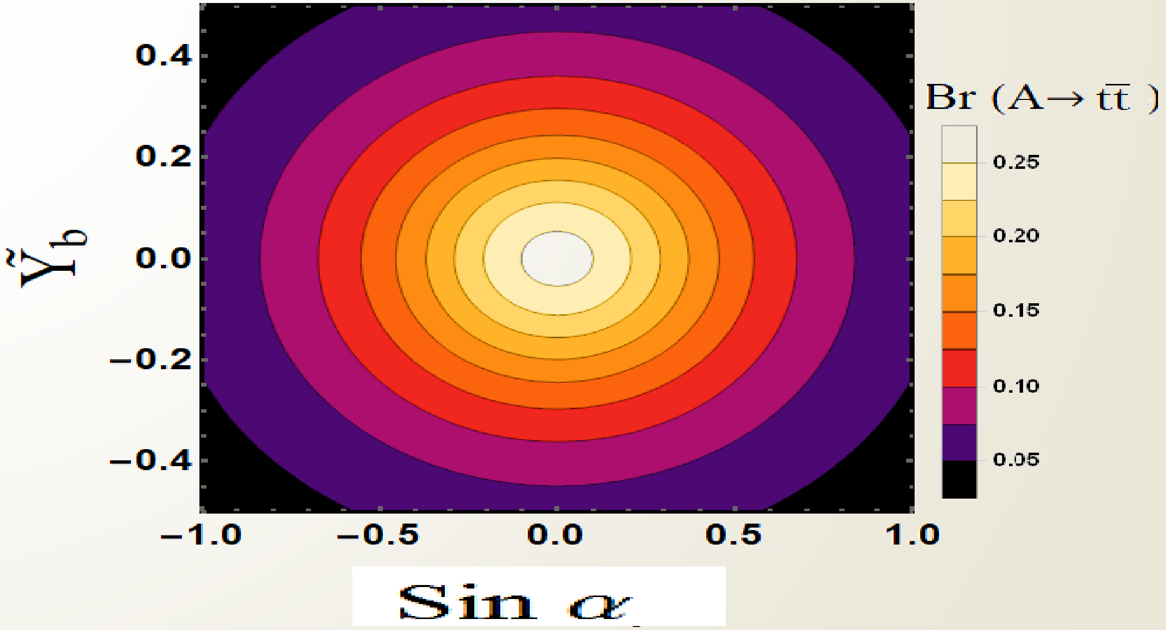


❑ $\mathcal{CP}$- odd Neutral Pseudo-scalar (A) Phenomenology :

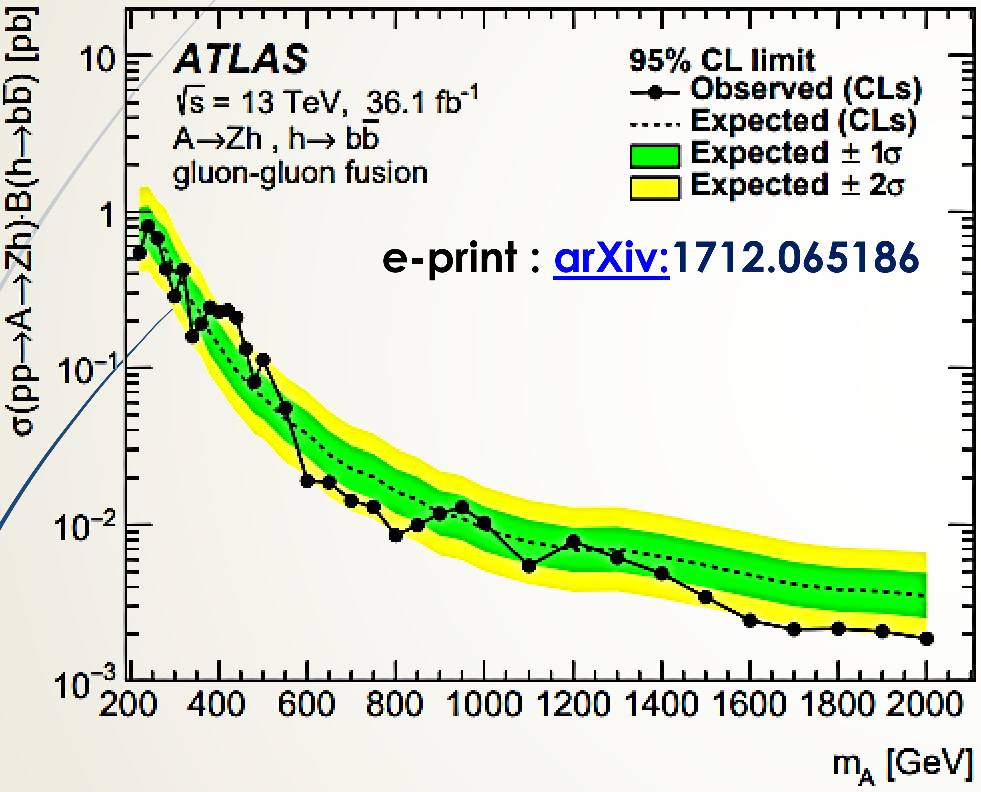






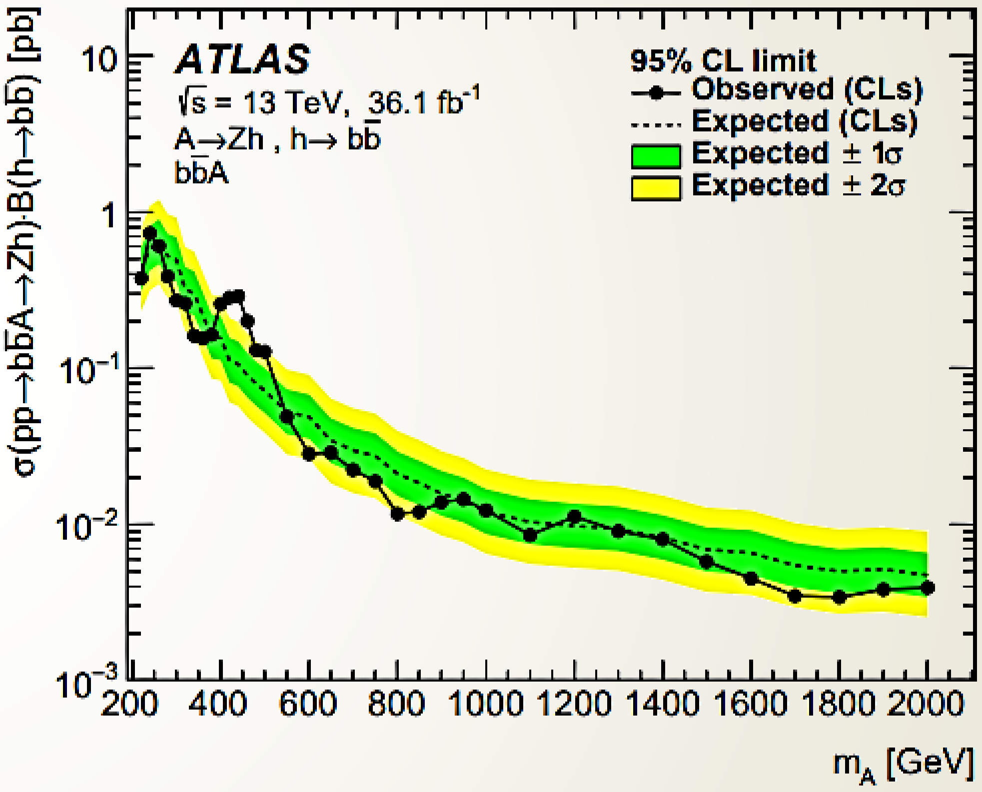


❖ Zh Resonance at 440 GeV :
with 3.6 σ local significance



e-print : arXiv:1712.065186

(a) Pure gluon–gluon fusion production

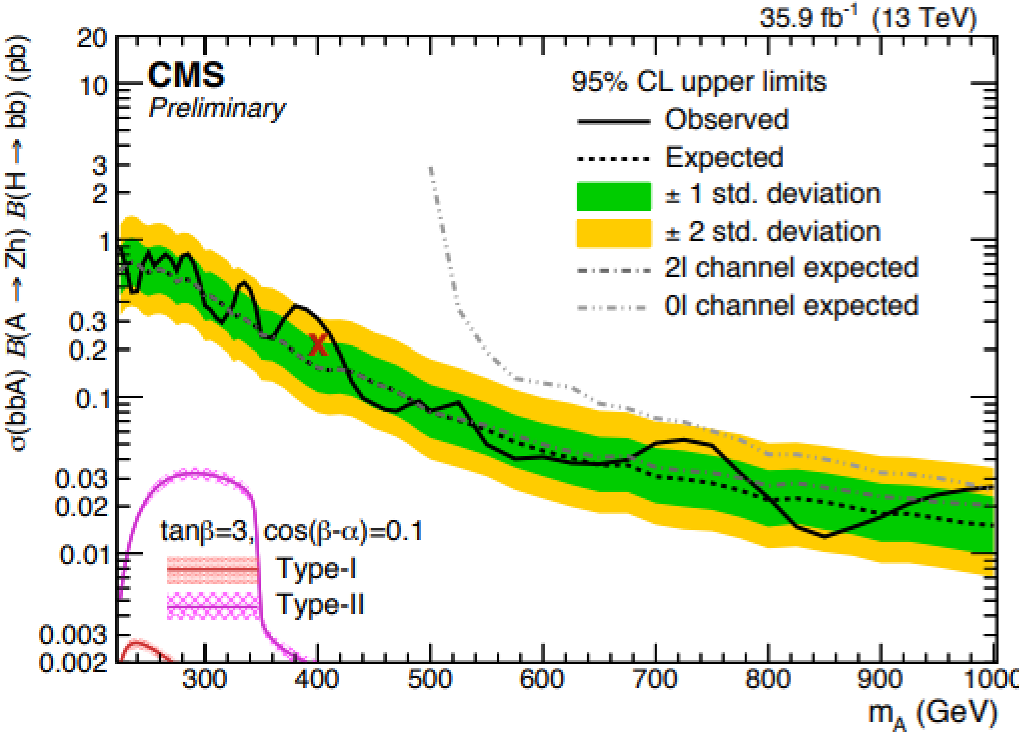


(b) Pure *b*-quark associated production

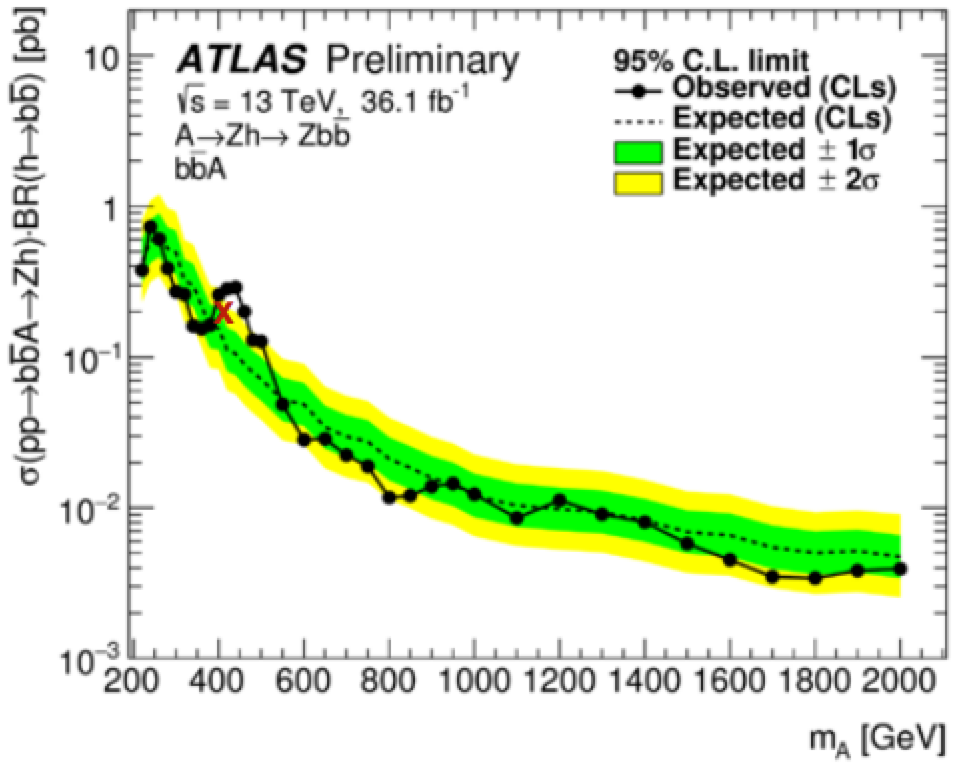
Ferreira et al. arXiv:1711.00024
C. Wagner et al. arXiv:1802.09122

❖ Zh Resonance at 440 GeV :
with 3.6 σ local significance

CMS-PAS-HIG-18-005
July 2018

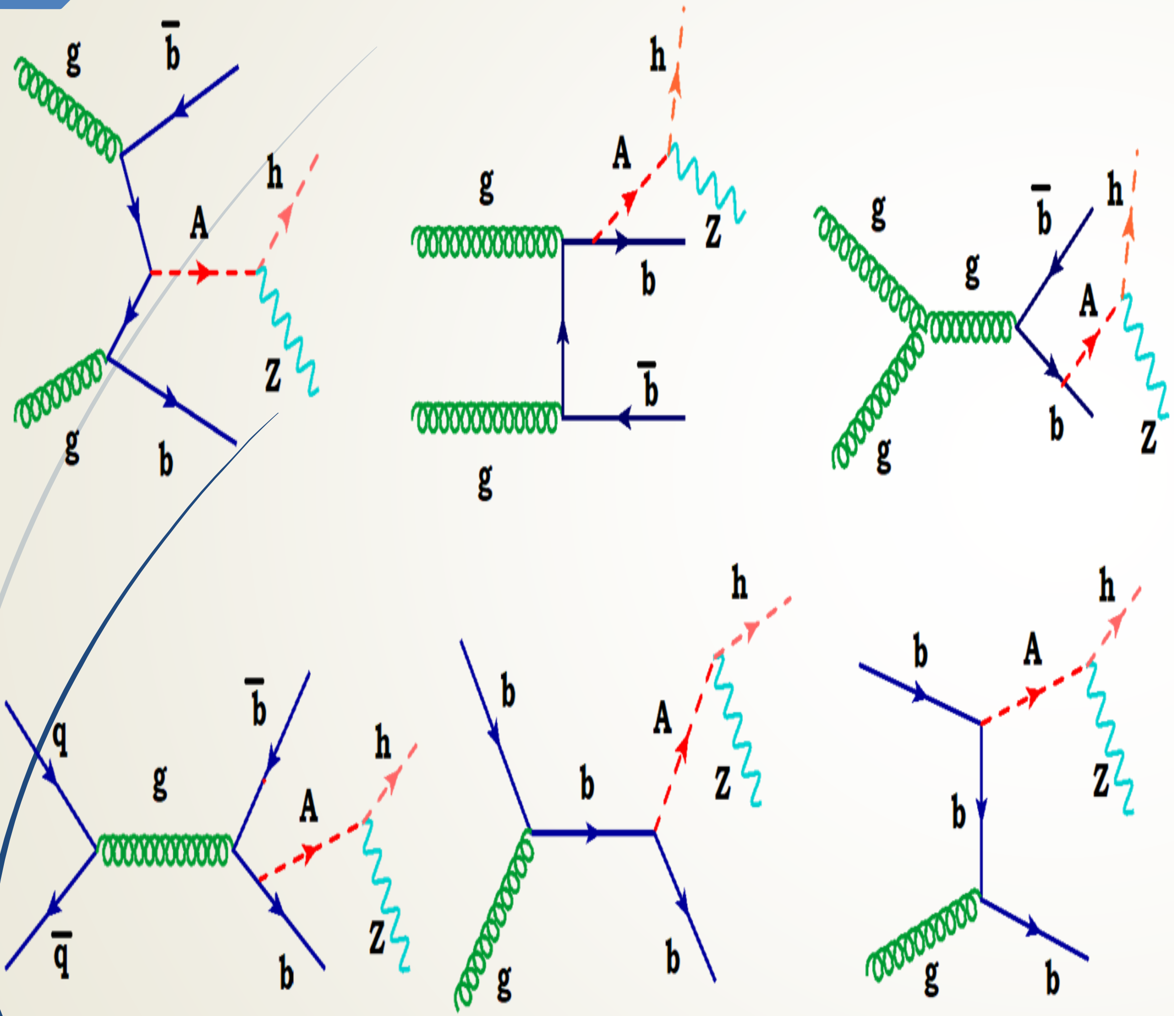


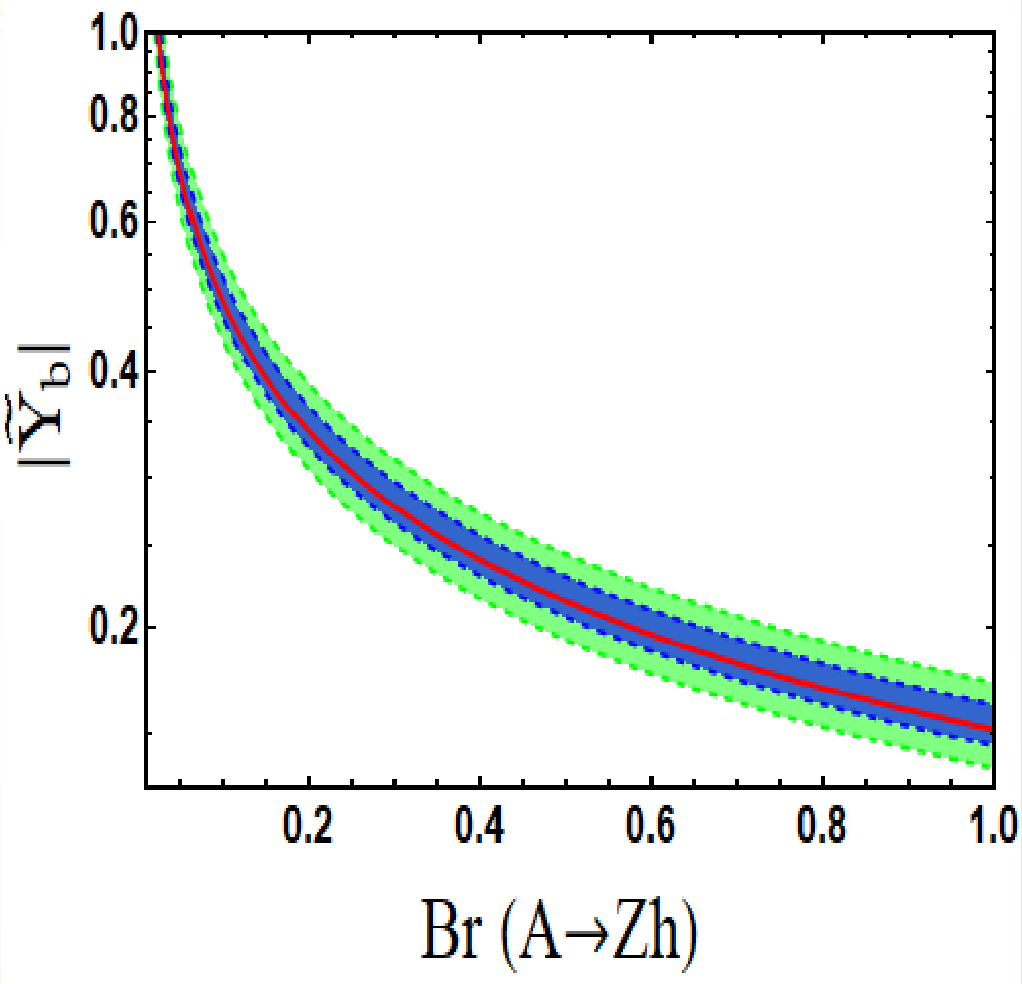
ATLAS-CONF-17-055



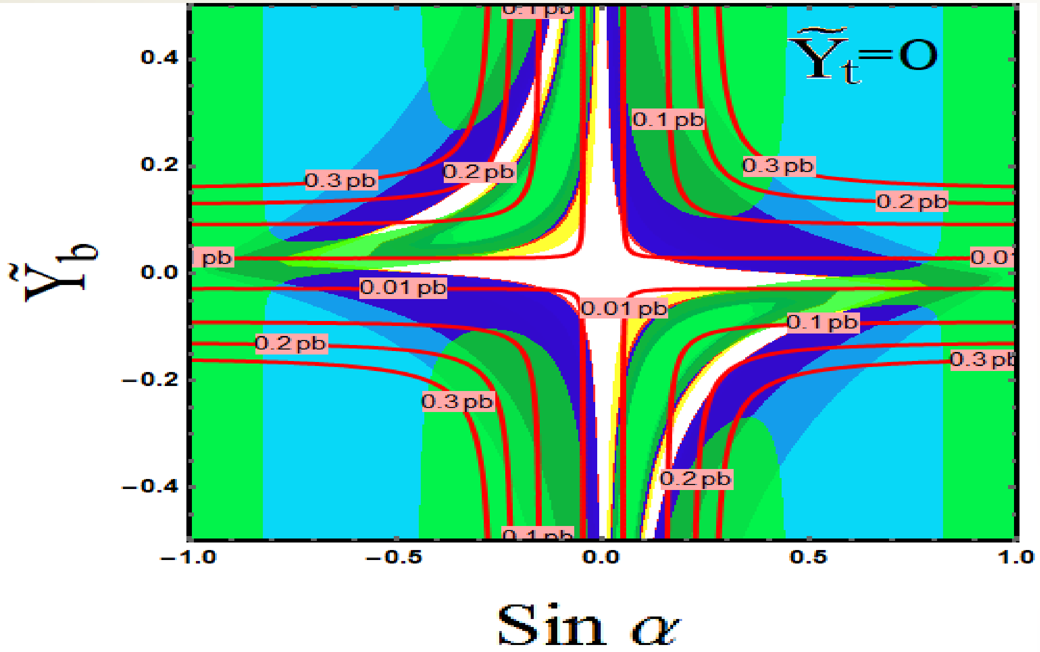
C. Wagner's slide : PPP 2018

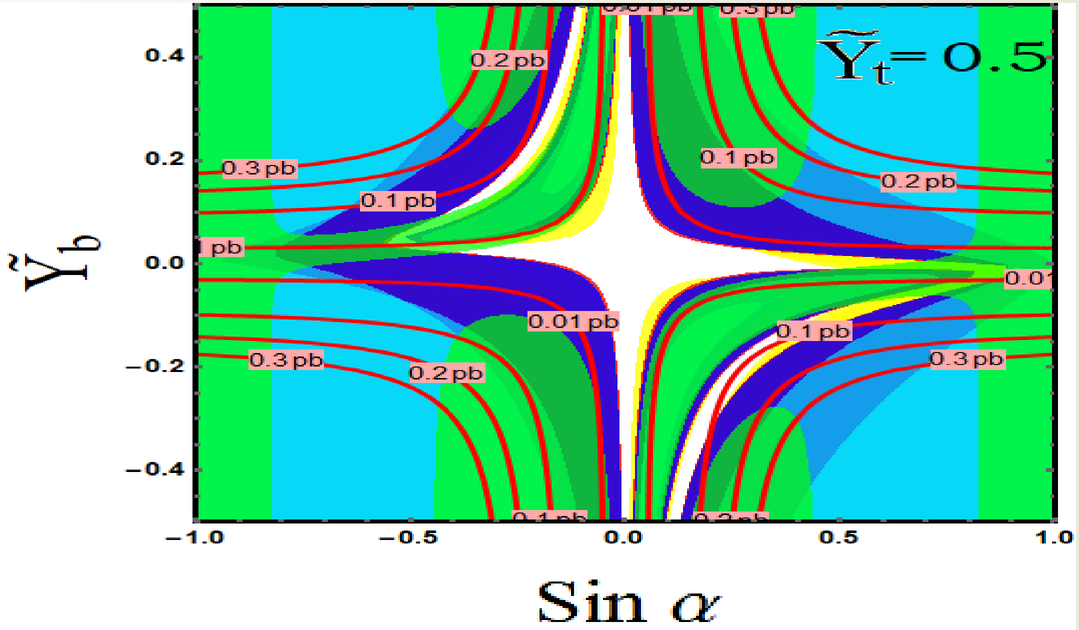
❖ Zh Resonance Explanation :

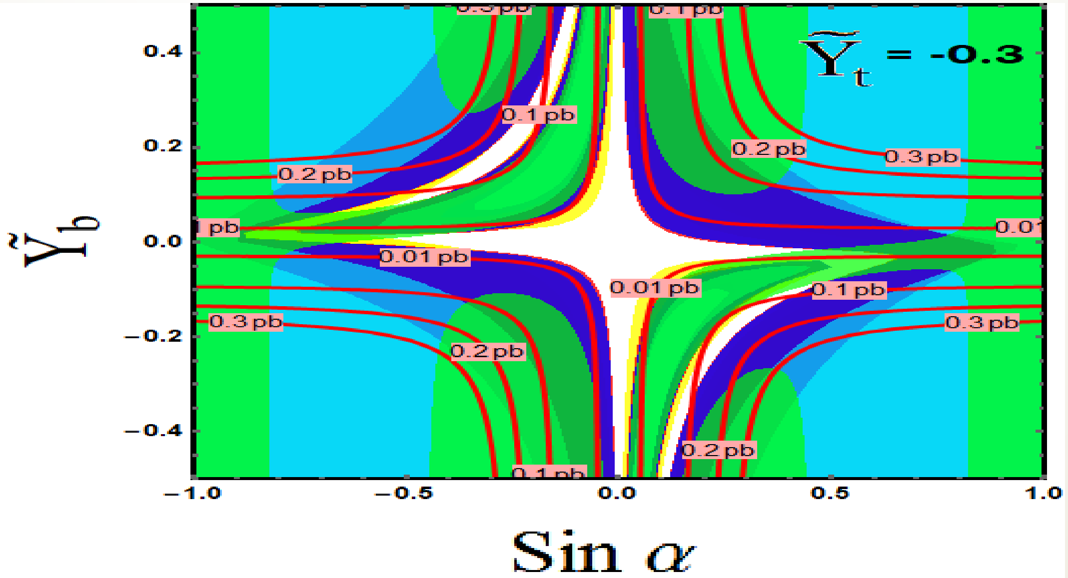




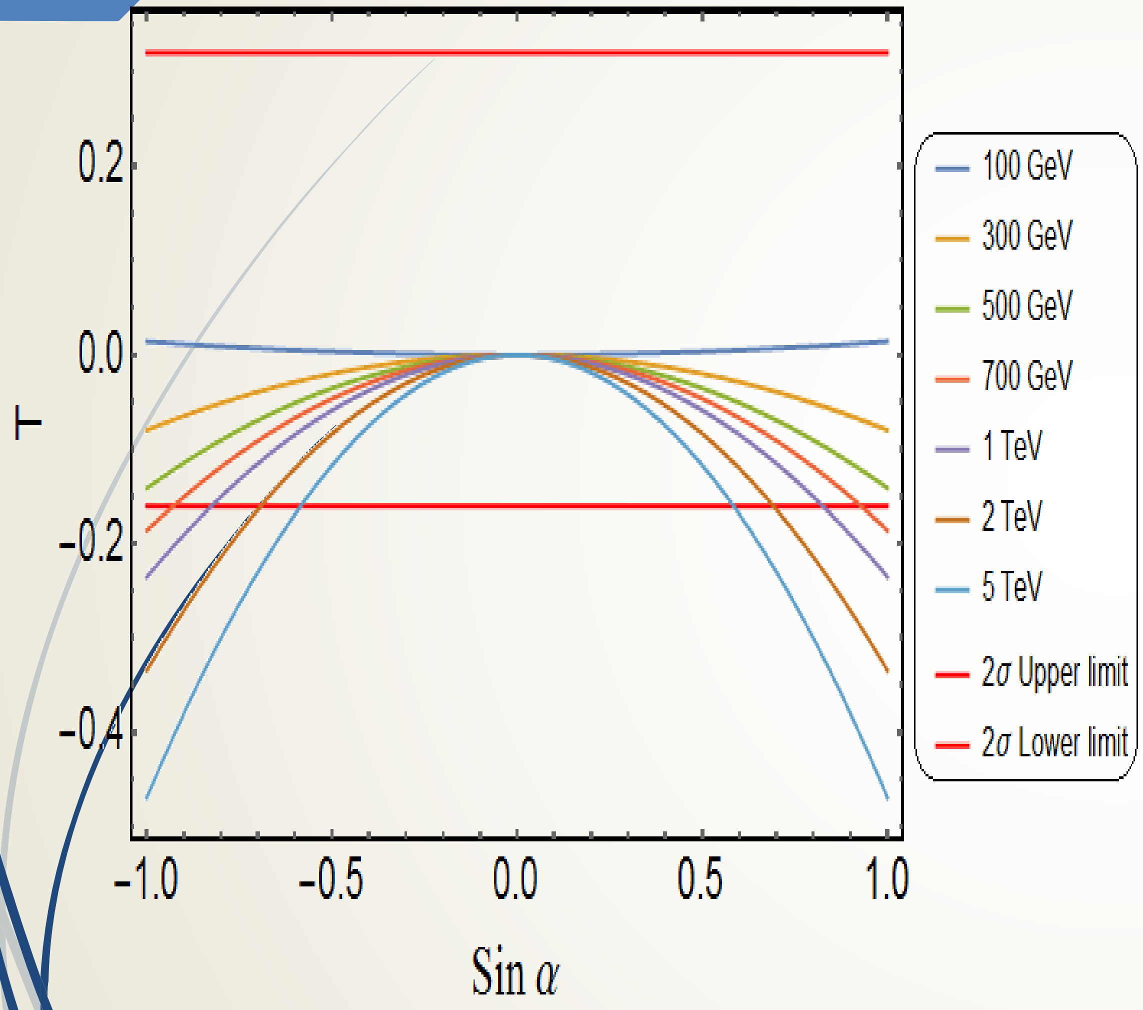
❖ Zh Resonance Explanation :

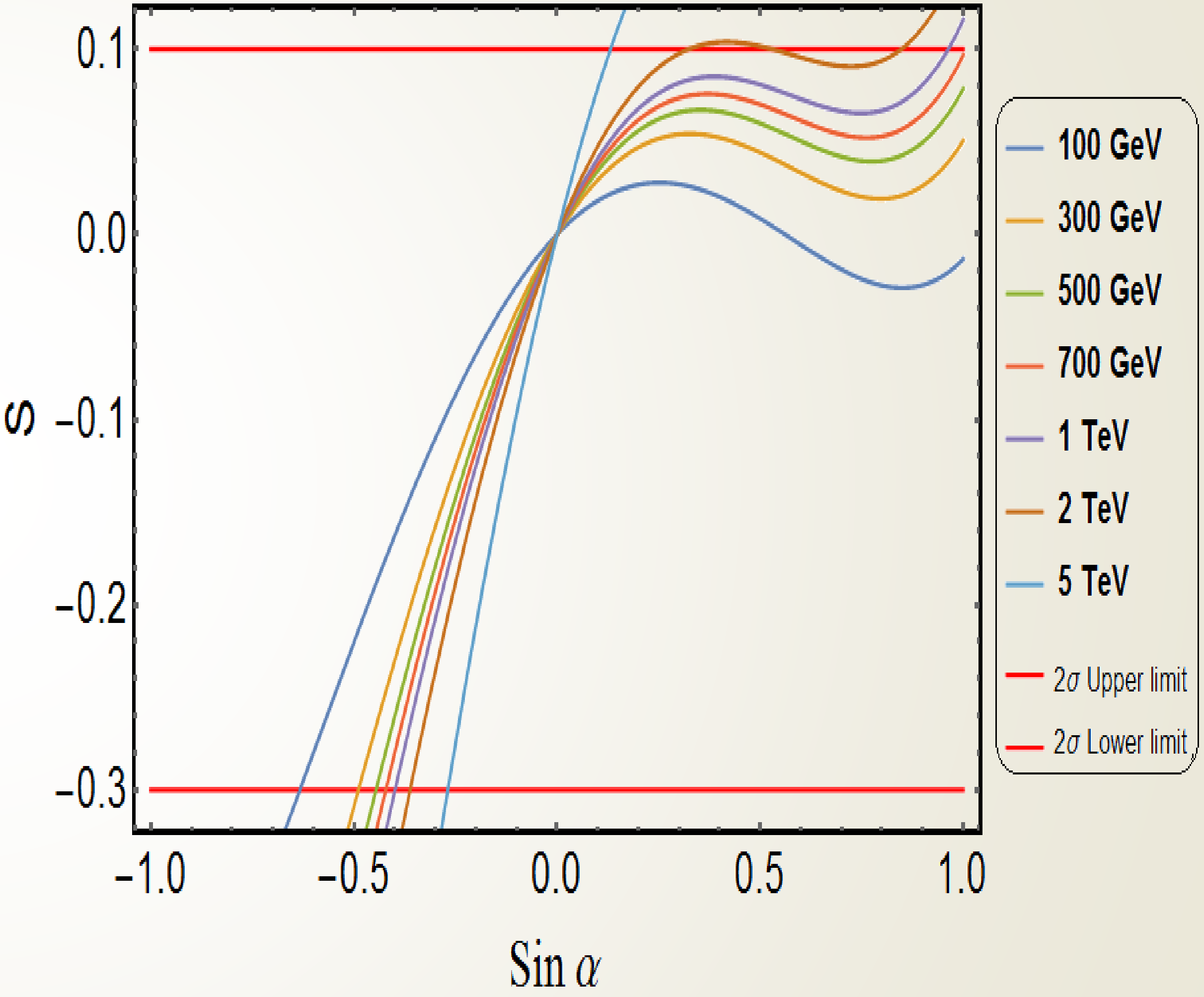






☐ S and T Parameters





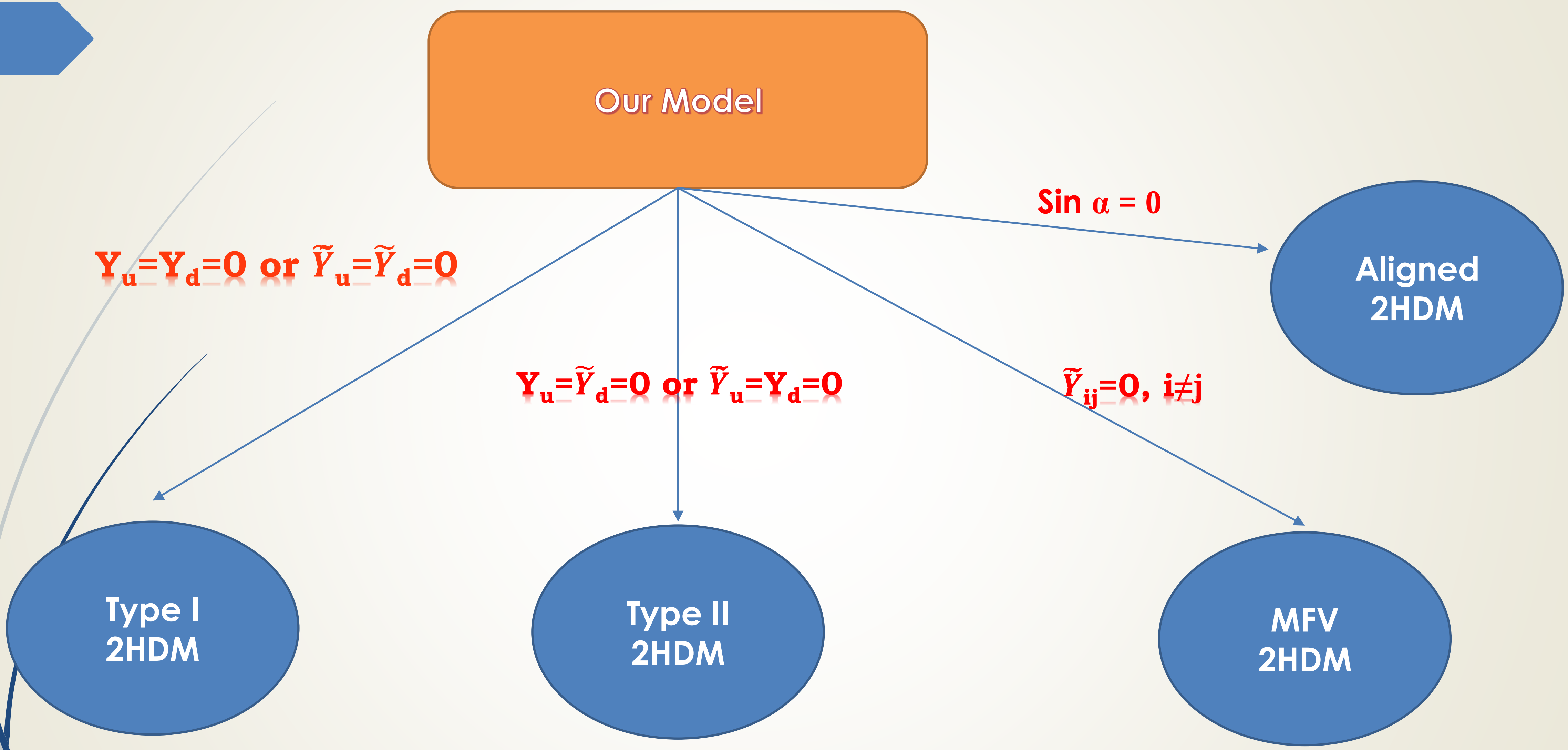
❑ Boundedness of Higgs Potential

- To ensure that the scalar potential is bounded from below, we evaluate the eigenvalues and eigenvectors of the following matrix:

  $$\begin{bmatrix} \frac{1}{4}(\Lambda_1+\Lambda_2+2\Lambda_3) & -\frac{1}{2}(\Lambda_6+\Lambda_7) & 0 & -\frac{1}{4}(\Lambda_1-\Lambda_2) \\ \frac{1}{2}(\Lambda_6+\Lambda_7) & -\frac{1}{2}(\Lambda_4+\Lambda_5) & 0 & -\frac{1}{2}(\Lambda_6-\Lambda_7) \\ 0 & 0 & -\frac{1}{2}(\Lambda_4-\Lambda_5) & 0 \\ \frac{1}{4}(\Lambda_1-\Lambda_2) & -\frac{1}{2}(\Lambda_6-\Lambda_7) & 0 & -\frac{1}{4}(\Lambda_1+\Lambda_2+2\Lambda_3) \end{bmatrix}$$

  We choose all the quartic couplings to be real.
- One set of values of the quartic couplings:
  $\Lambda_1 = 1.4, \Lambda_2 = 0.01, \Lambda_3 = 1, \Lambda_4 = 0.1, \Lambda_5 = 0.001, \Lambda_6 = 3, \Lambda_7 = -1.2.$
- All the eigenvalues of the matrix are real, and the largest eigenvalue is positive: $\{2.0527, -1.75315, 0.649943, -0.0495\}$.
  This satisfies necessary and suffcient conditions for the potential to be bounded from below.
- For this specific choice, we get HIggs masses to be: {125 GeV, 751 GeV, 706 GeV.} The mixing parameter $\sin\alpha = 0.458$.

☐ Mapping to existing 2HDM



Our Model

$Y_u=Y_d=0$ or $\tilde{Y}_u=\tilde{Y}_d=0$

Type I 2HDM

$Y_u=\tilde{Y}_d=0$ or $\tilde{Y}_u=Y_d=0$

Type II 2HDM

$\tilde{Y}_{ij}=0,\ i\neq j$

MFV 2HDM

$\sin\alpha = 0$

Aligned 2HDM

Conclusions

- **All current observations are consistent with the predictions of the SM Higgs sector at the 2 sigma level**

- **There are still relatively large uncertainties in some measurements, in particular the relevant couplings to top and bottom quarks**

- **If deviations are real, they may be interpreted in the context of extensions of the SM at the weak scale. However, delicate correlations in the coupling values should be present.**

- **On the contrary, if deviations are not present, the Higgs sector may be in the decoupling or alignment limit**

- **Double Higgs production detection is challenging, but it may serve to probe the nature of the Higgs potential or the presence of additional particles at the TeV scale**

- **If any deviation (enhanced) in *higgs fermion* couplings is discovered, we have to switch to our 2HDM framework from the SM*.**

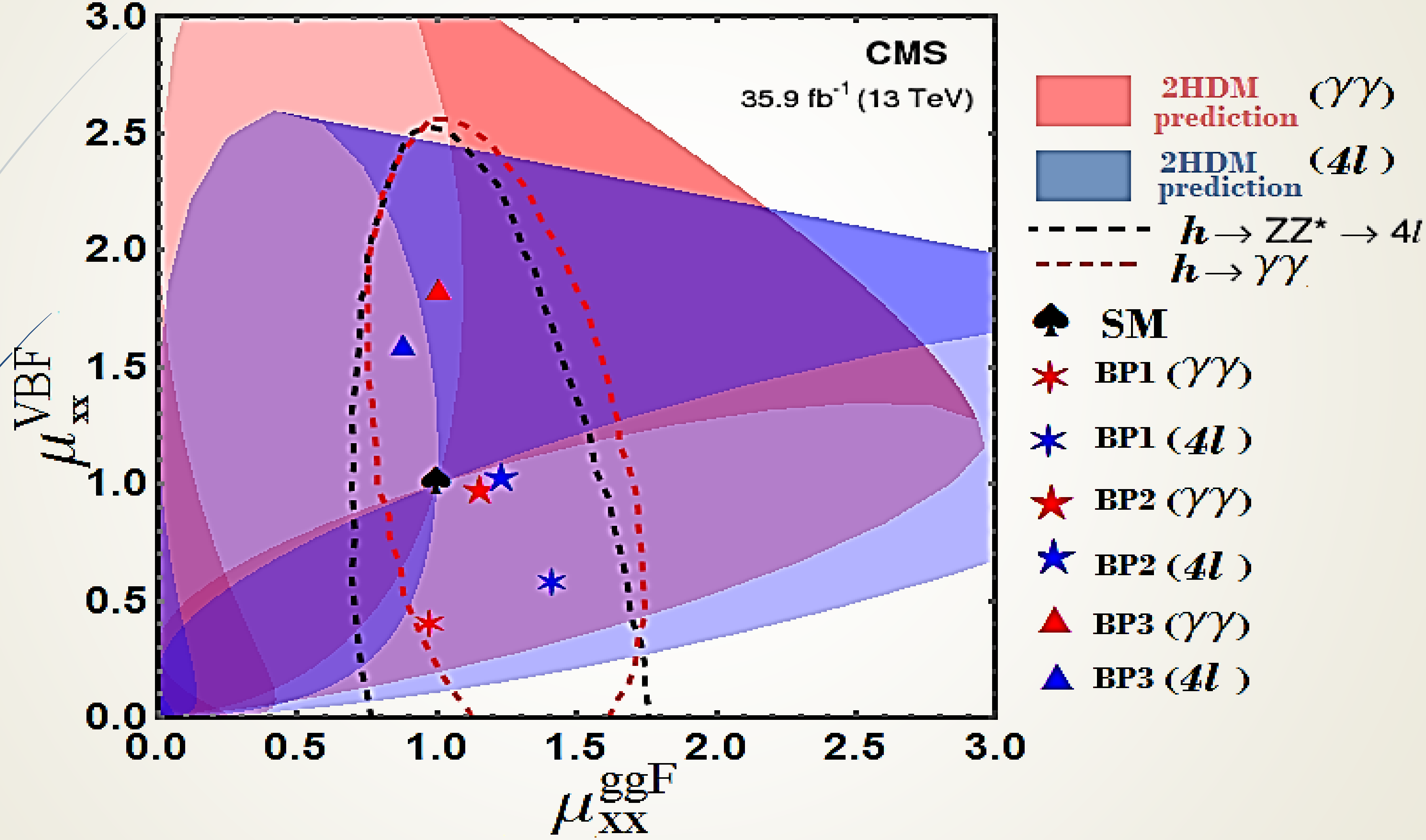
(*If no exotic colored particles are introduced)

- **The model is very predictive, implying unavoidable new physics signals like di-boson resonances (hh, ZZ and Zh) from novel decays of CP- even and CP- odd Higgs fields at the Large Hadron Collider (LHC).**

- **Flavor observables like : $\mu \rightarrow e\gamma$, Muon g-2 anomaly, RD / RD* Anomaly etc...**


Thank you!

❑ Benchmark Points :



The two-dimensional best-fit of the signal strengths for ggF and VBF production modes

Babu and Jana (2017)

☐ Benchmark Points :

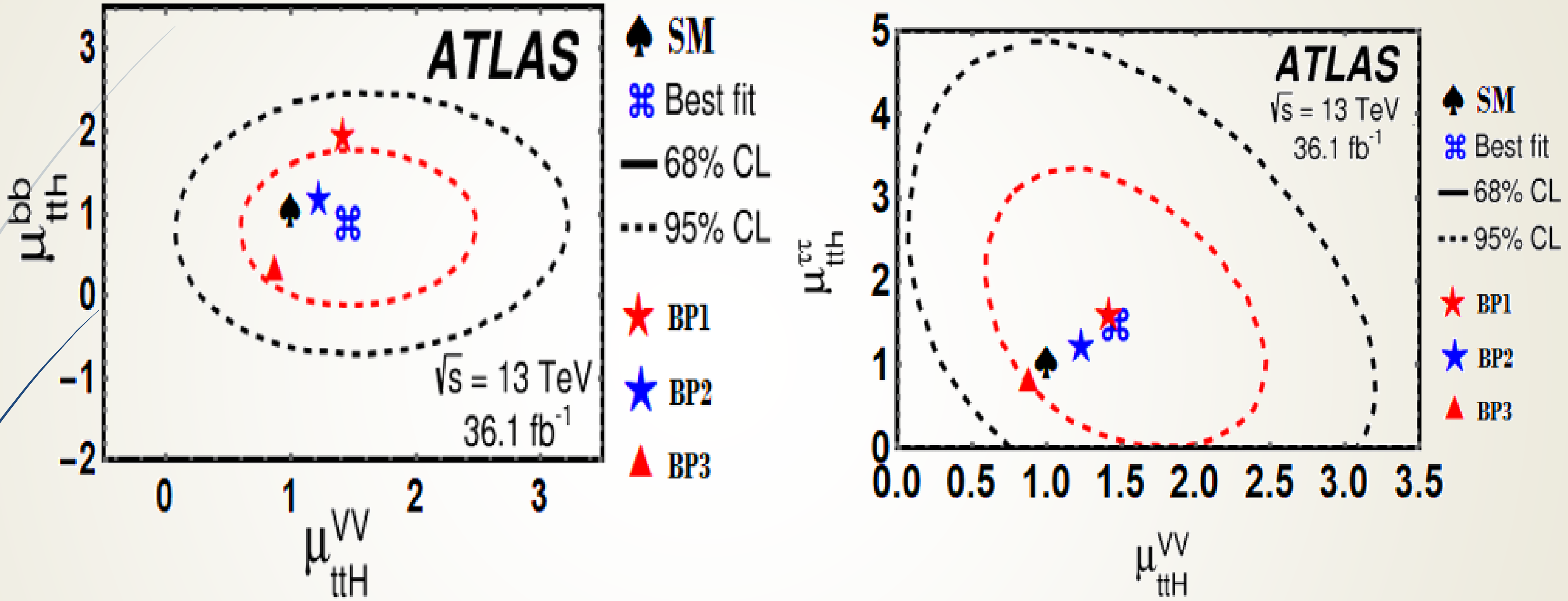
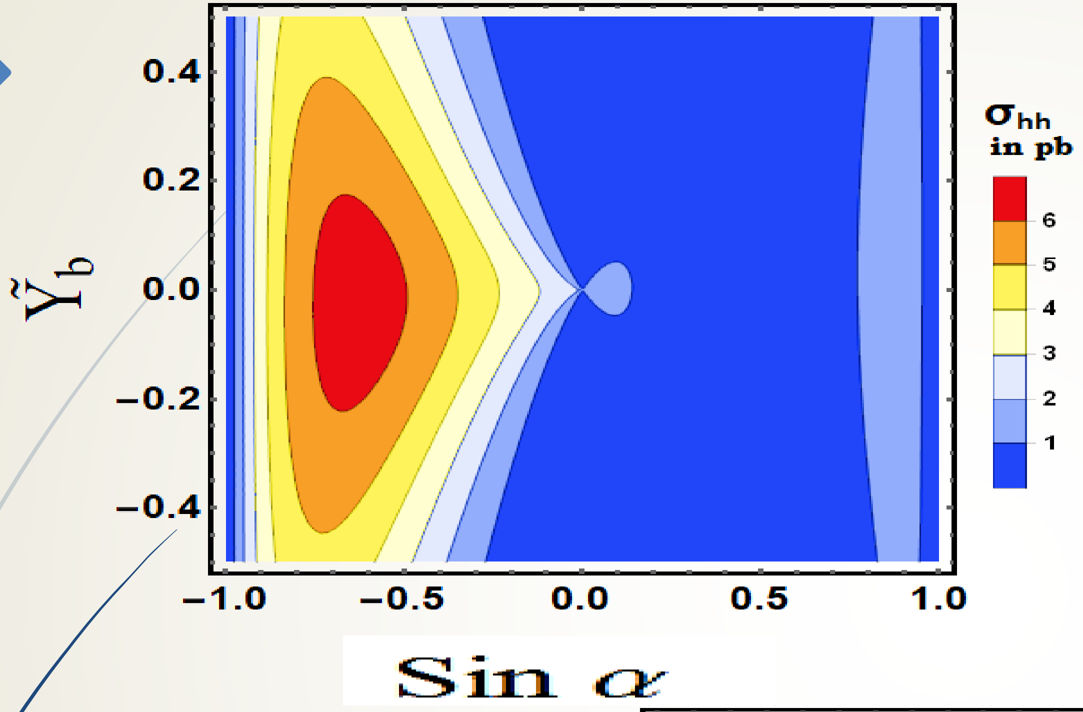
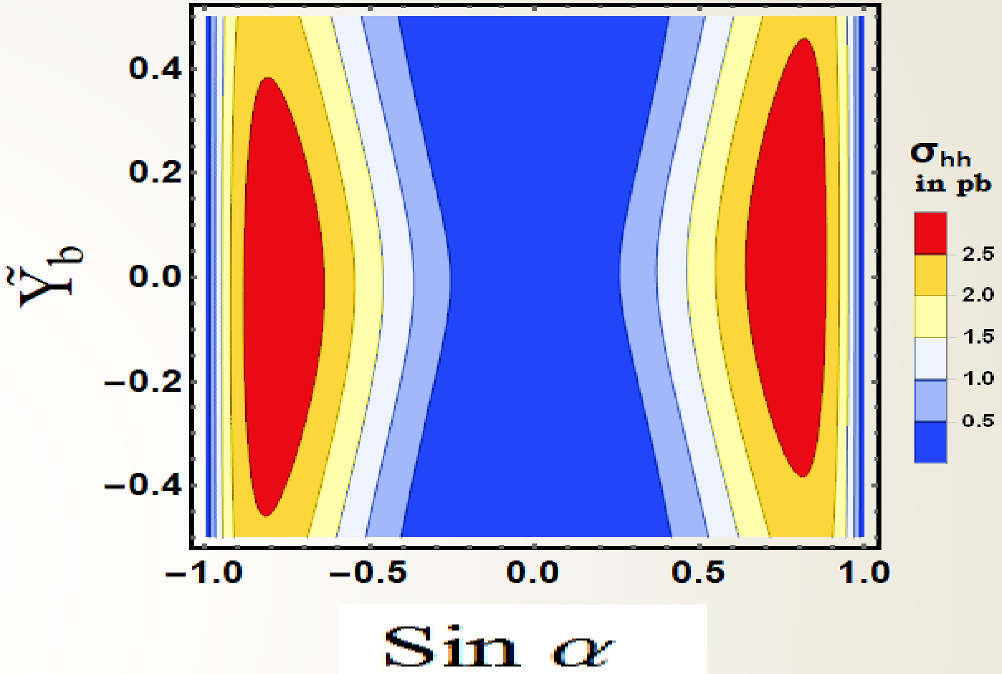
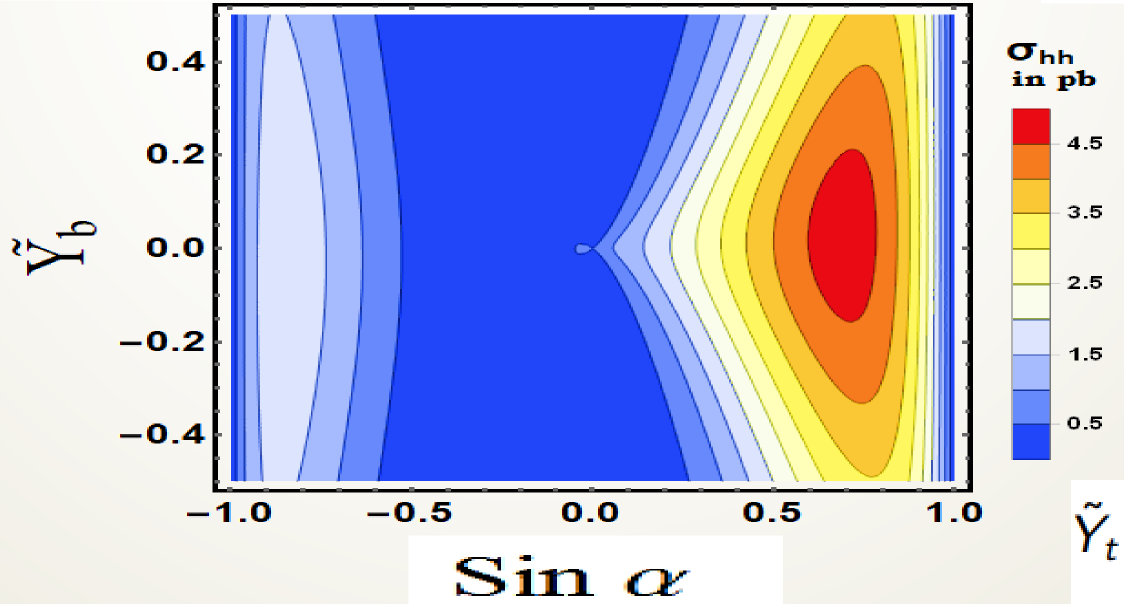


FIG. : The two-dimensional best-fit of the signal strength modifiers for the processes $t\bar{t}h, h \rightarrow b\bar{b}$ versus $t\bar{t}h, h \rightarrow VV^{\star}, (V = W, Z)$ (left) and $t\bar{t}h, h \rightarrow \tau^{+}\tau^{-}$ versus $t\bar{t}h, h \rightarrow VV^{\star}, (V = W, Z)$ (right). Three benchmark points (BP) are also shown in this contourplot.

❑ $\mathcal{CP}$- even Neutral Heavy Higgs (H) Phenomenology :

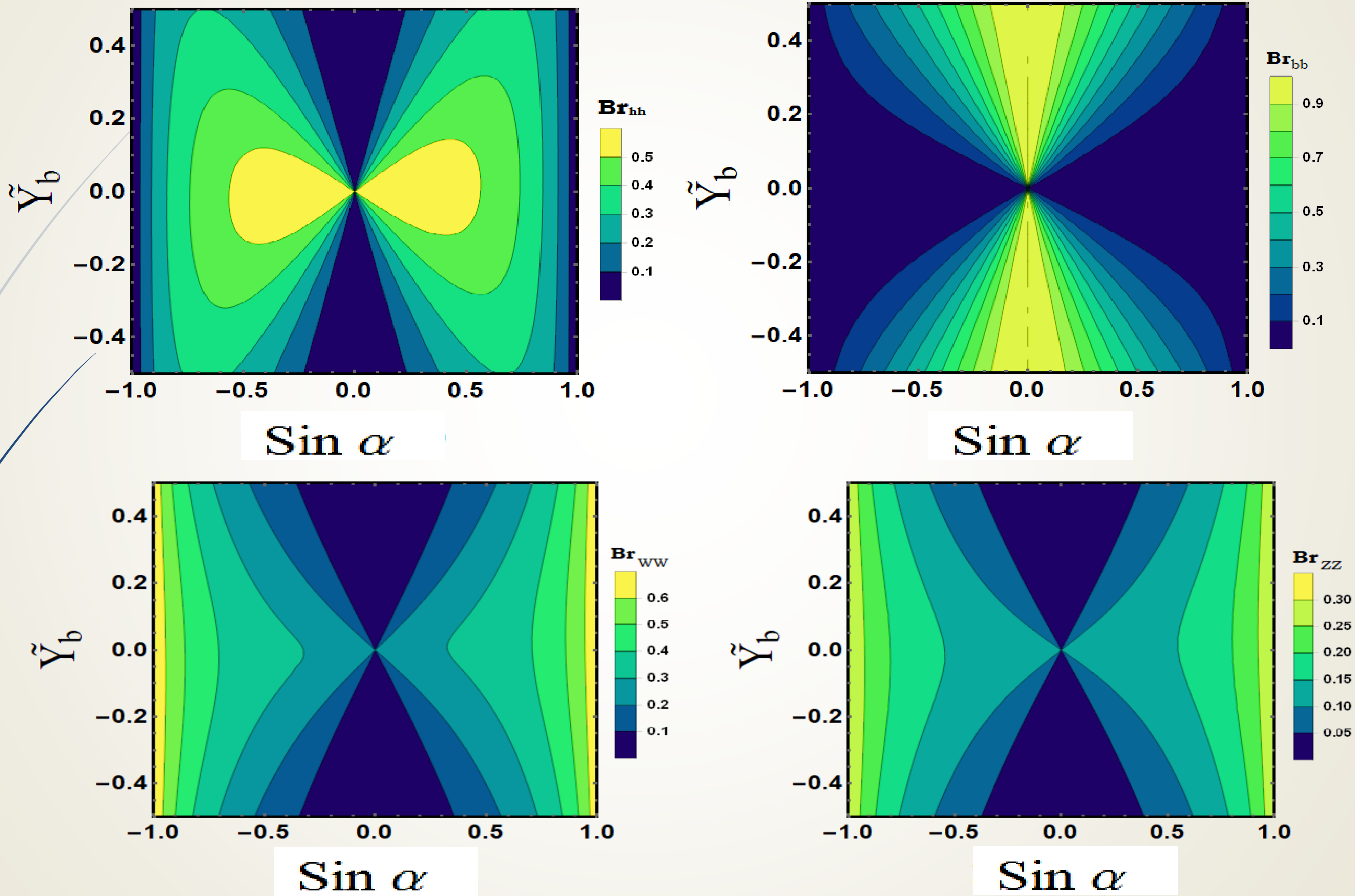




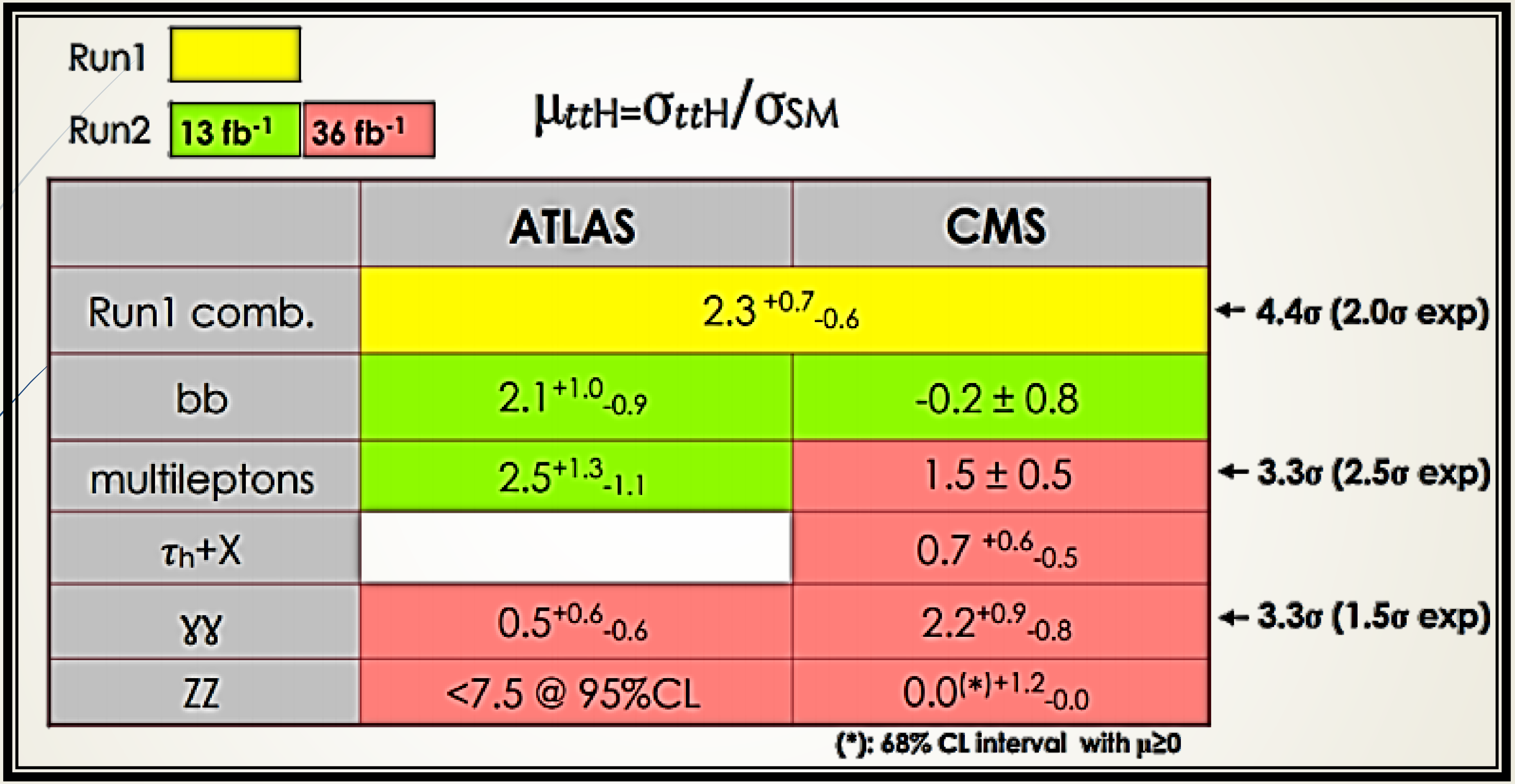


$\tilde{Y}_t =$ 0.5 (top left), 0 (top right), -0.3 (bottom)

❑ $\mathcal{CP}$- even Neutral Heavy Higgs (H) Phenomenology :



$t\bar{t}h$ measurements



Run1 🟨

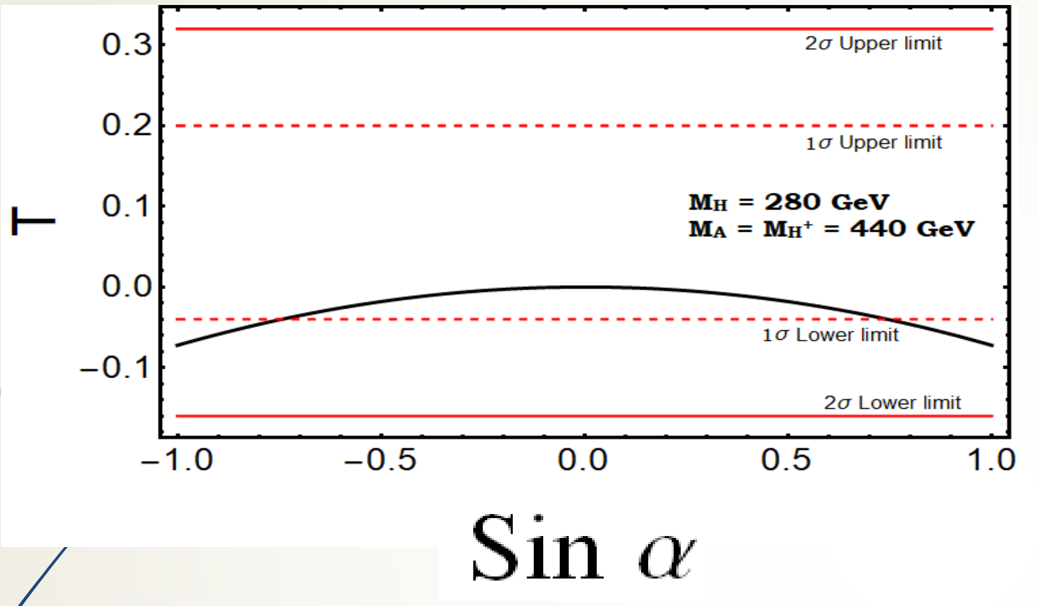
Run2 🟩 13 fb^{-1} 🟥 36 fb^{-1}

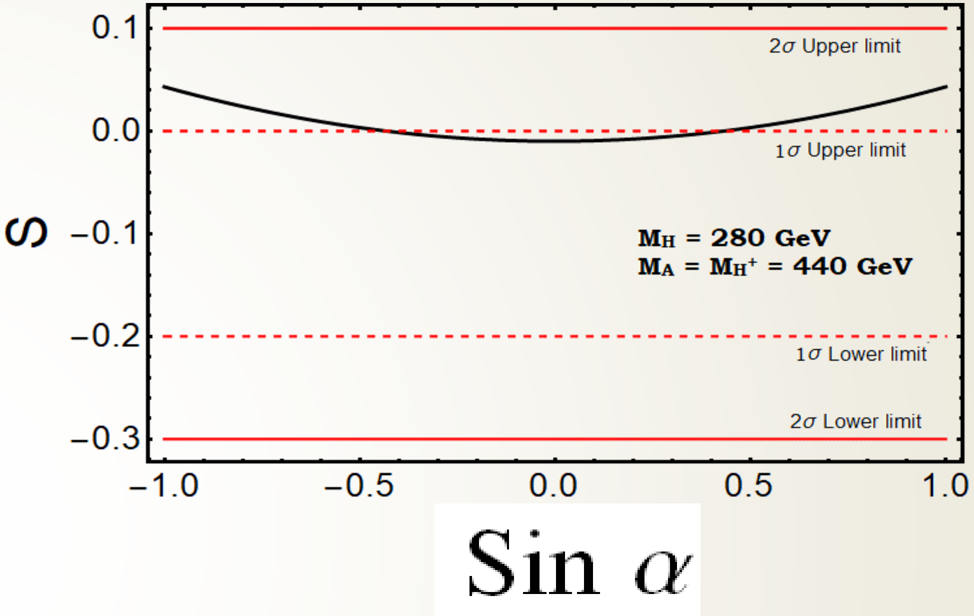
$\mu_{ttH} = \sigma_{ttH} / \sigma_{SM}$

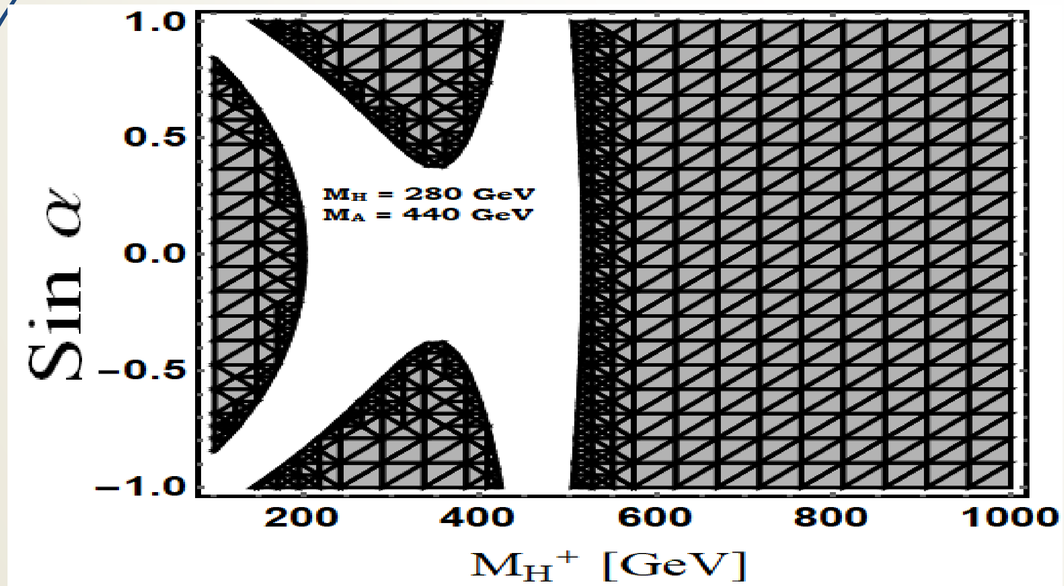
	ATLAS	CMS	
Run1 comb.	$2.3^{+0.7}_{-0.6}$		← 4.4σ (2.0σ exp)
bb	$2.1^{+1.0}_{-0.9}$	-0.2 ± 0.8	
multileptons	$2.5^{+1.3}_{-1.1}$	1.5 ± 0.5	← 3.3σ (2.5σ exp)
τ_h+X		$0.7^{+0.6}_{-0.5}$	
γγ	$0.5^{+0.6}_{-0.6}$	$2.2^{+0.9}_{-0.8}$	← 3.3σ (1.5σ exp)
ZZ	<7.5 @ 95%CL	$0.0^{(*)+1.2}_{-0.0}$	

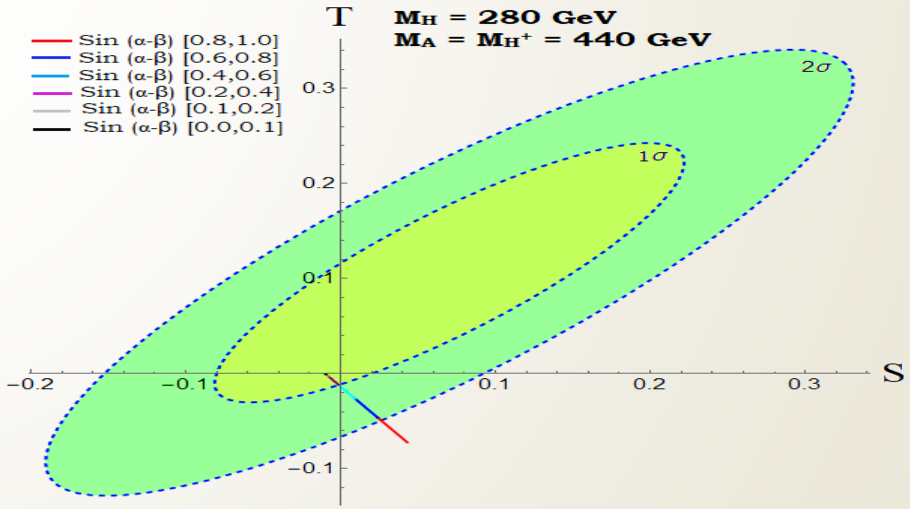
(*): 68% CL interval with μ≥0

☐ S and T Parameters



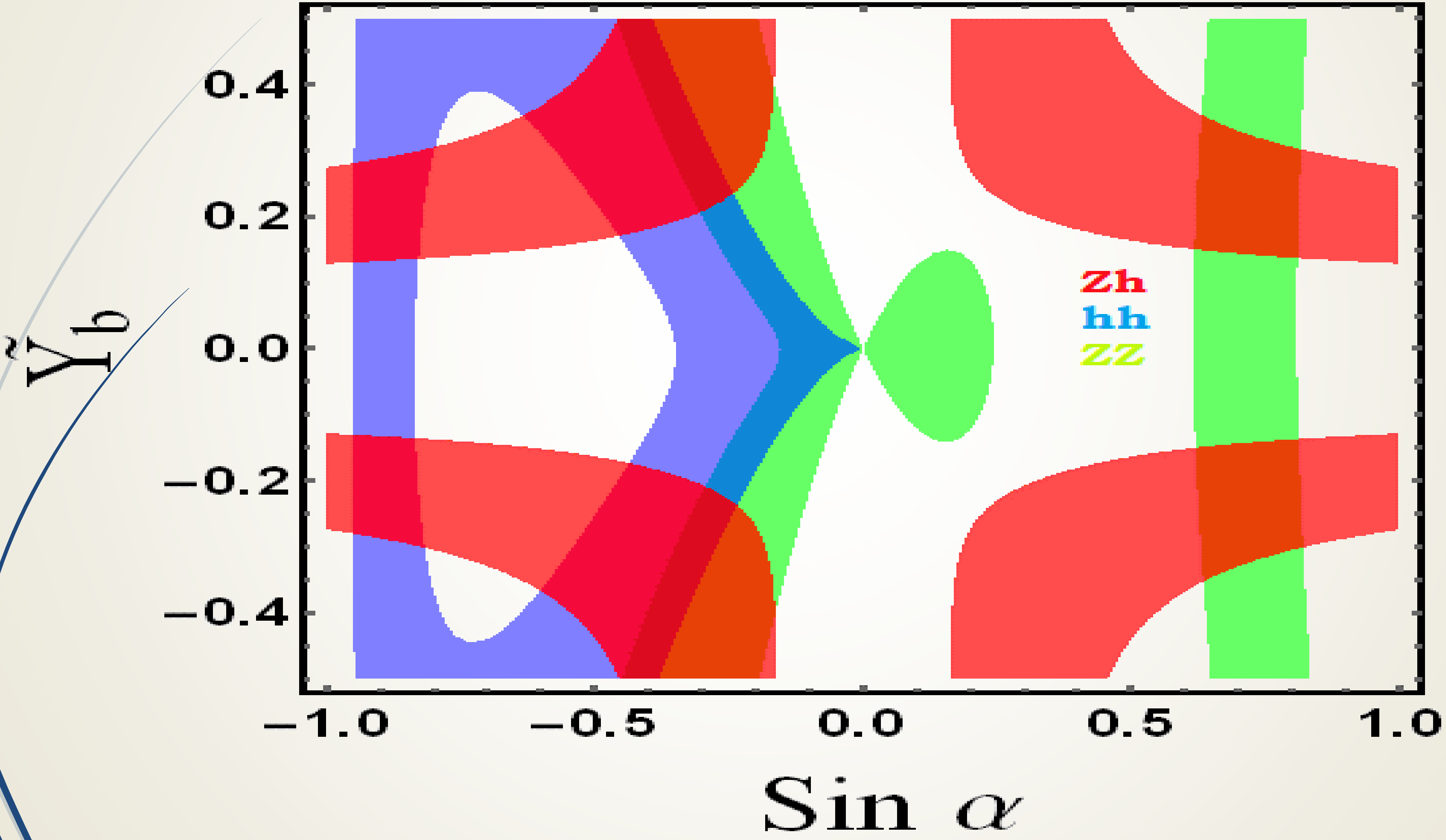


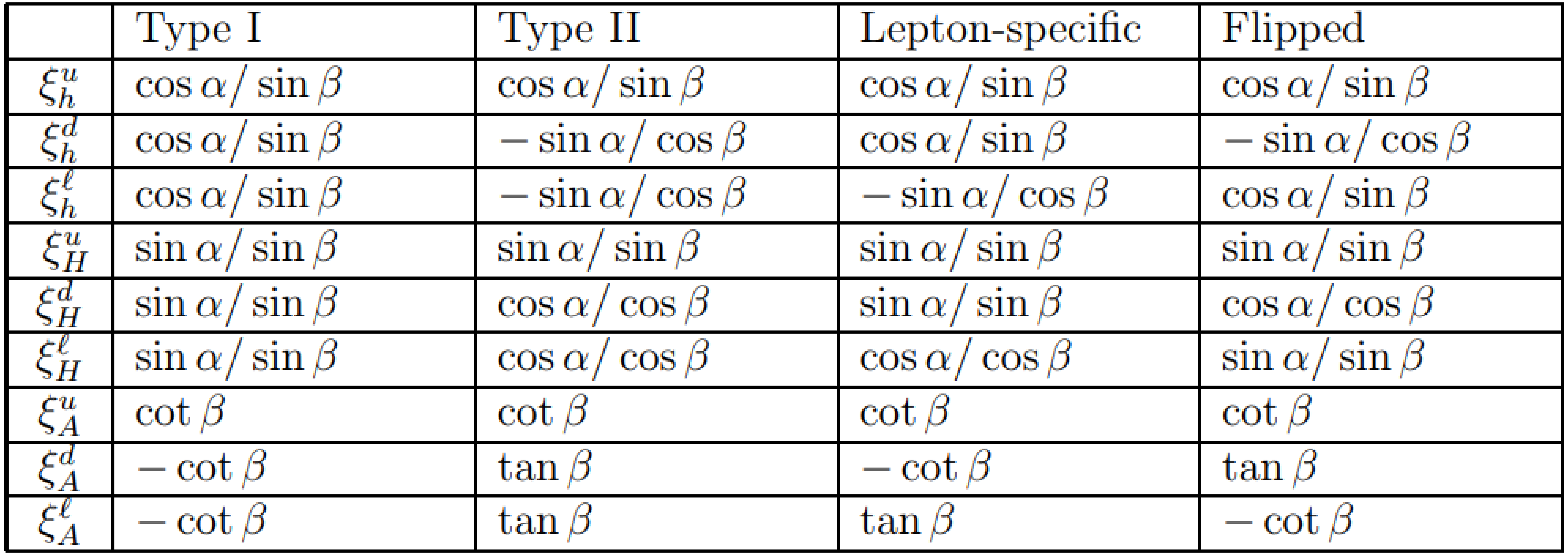




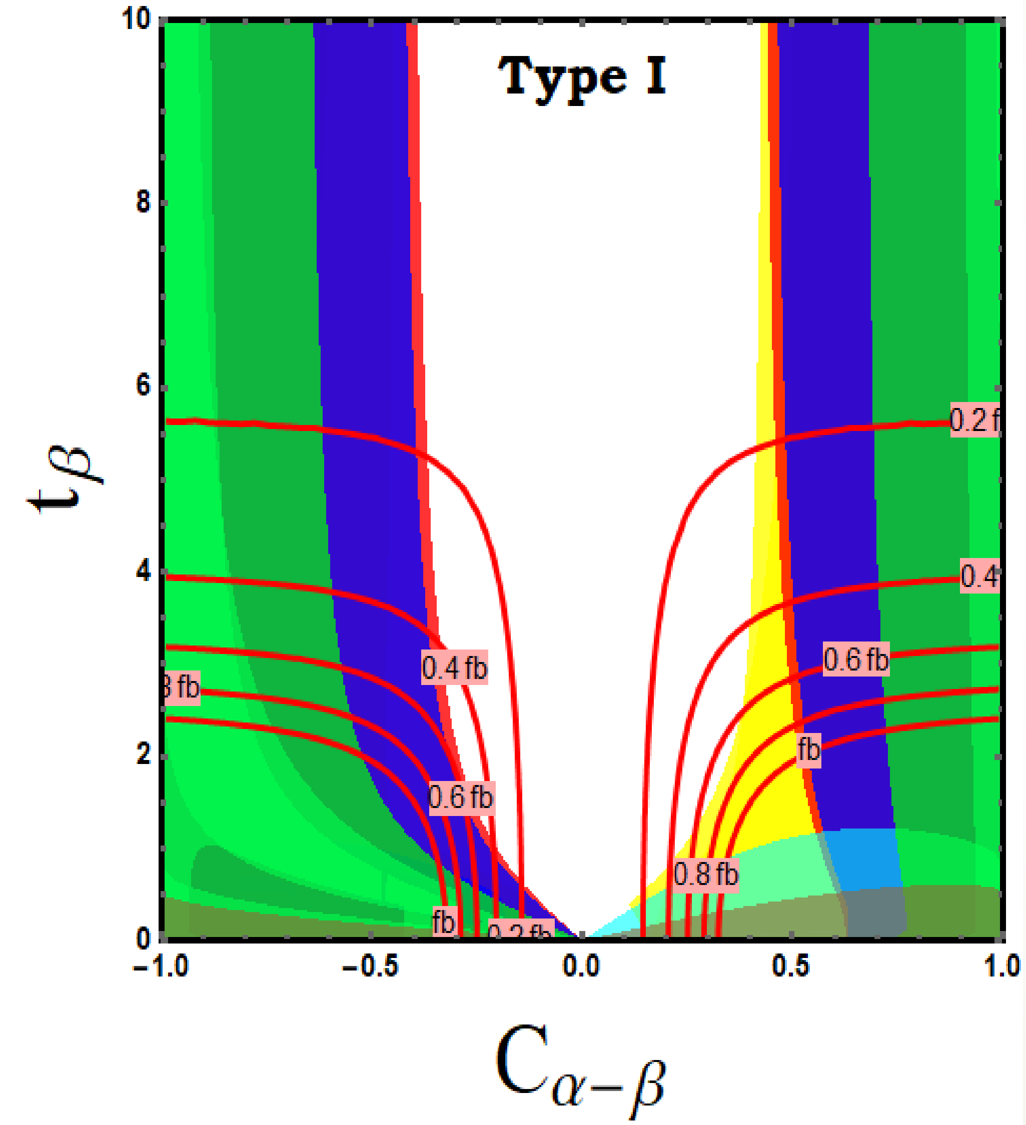
Grimus, Lavoura et al. (2007)

❖ Preliminary Result : Fitting 3 Resonances

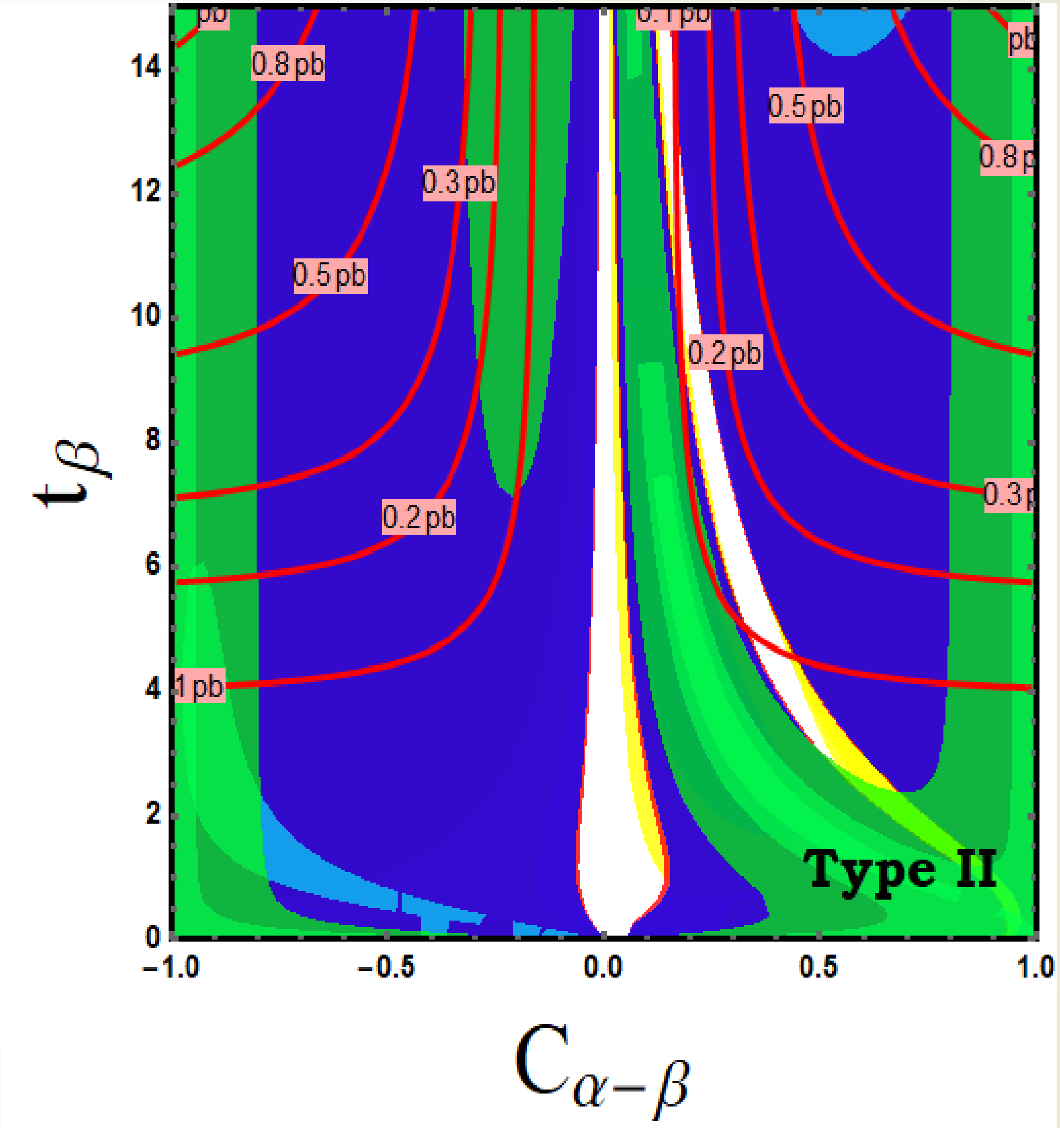




	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$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

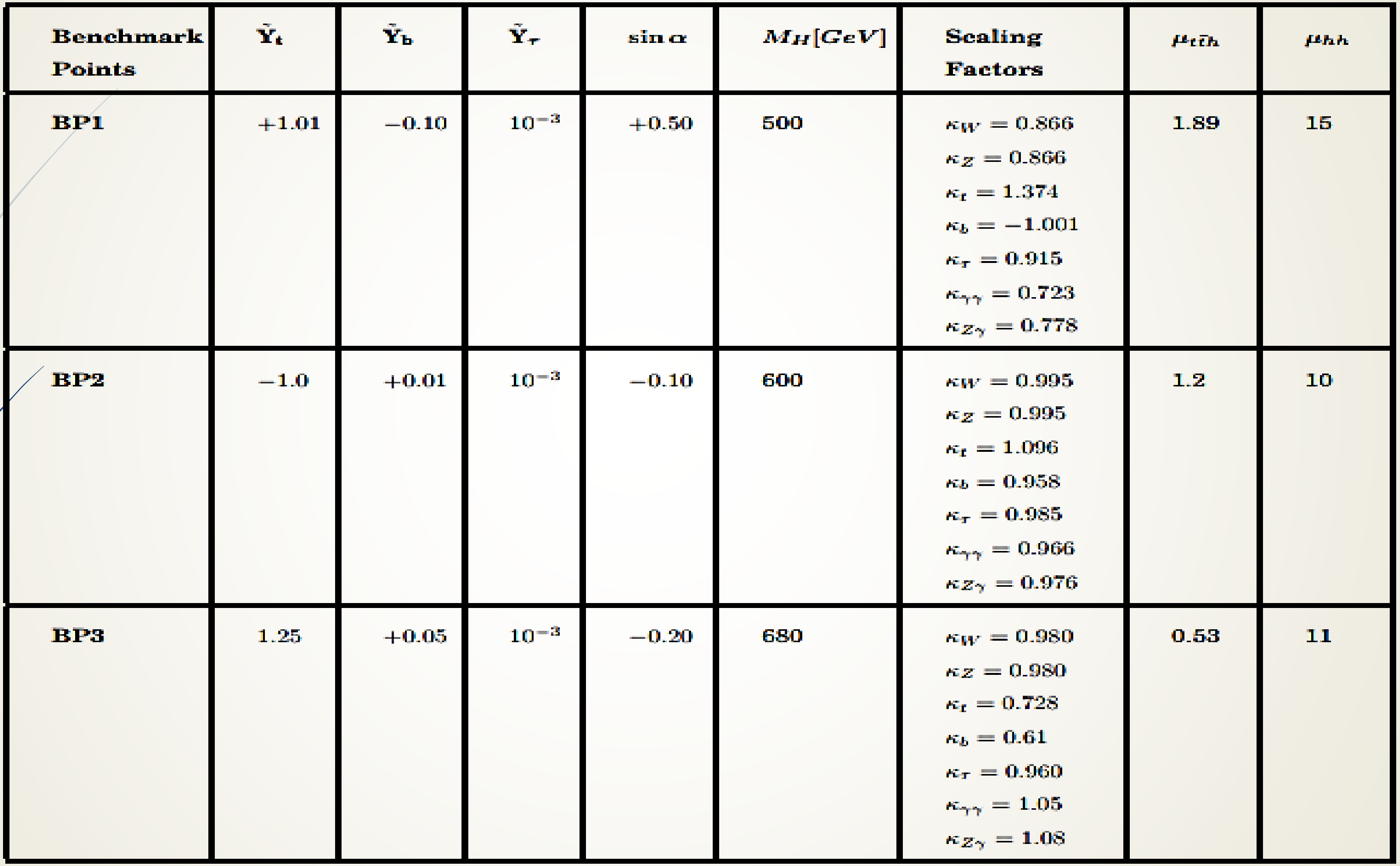


Type I
t_β
$C_{\alpha-\beta}$
10
8
6
4
2
0
−1.0
−0.5
0.0
0.5
1.0
0.2 f
0.4
0.6 fb
fb
0.4 fb
3 fb
0.6 fb
fb
0.2 fb
0.8 fb



Type II
t_β
$C_{\alpha-\beta}$
14
12
10
8
6
4
2
0
−1.0
−0.5
0.0
0.5
1.0
pb
0.8 pb
0.1 pb
pb
0.5 pb
0.8 p
0.3 pb
0.5 pb
0.2 pb
0.3 p
0.2 pb
1 pb

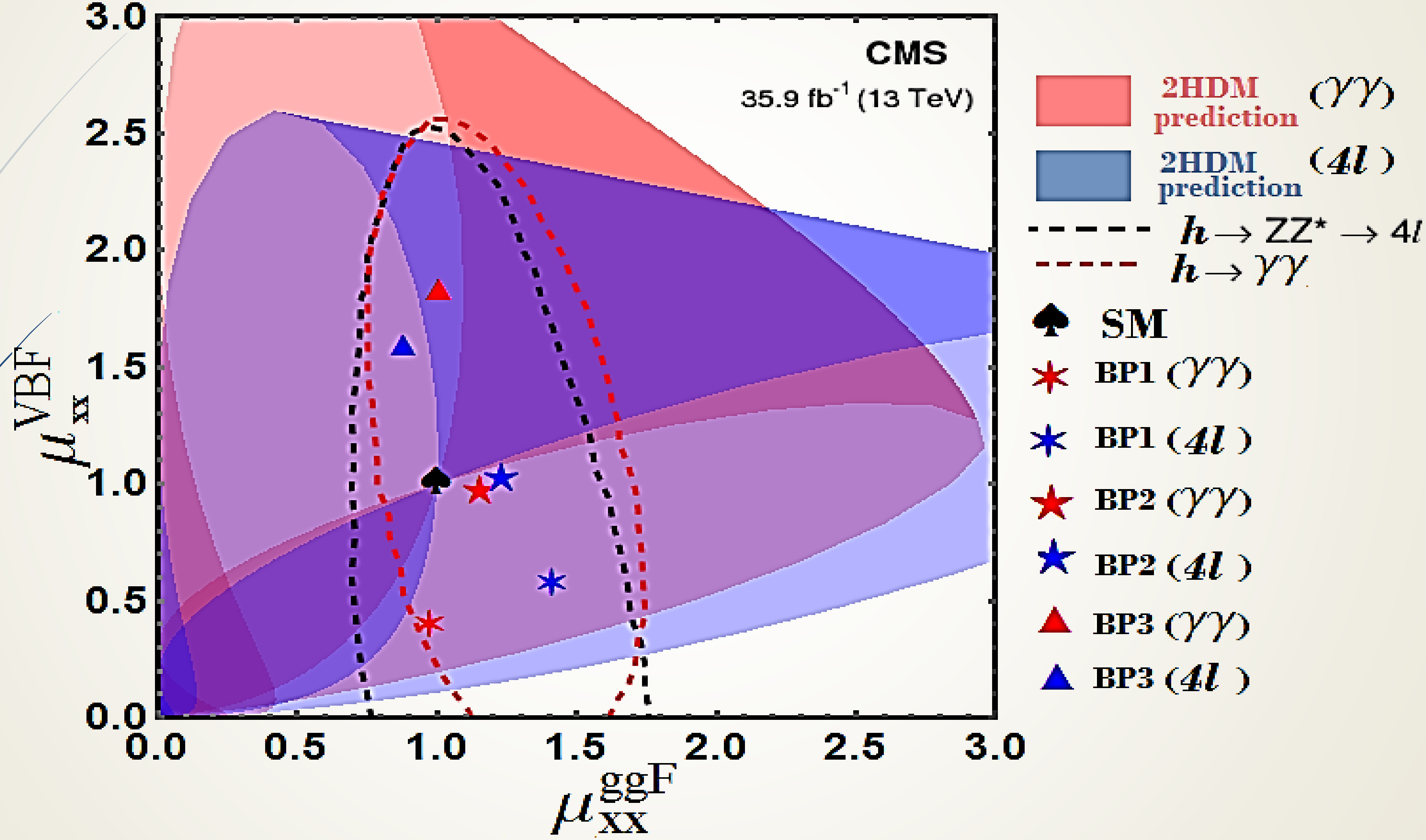
☐ Benchmark Points :



Benchmark Points	$\tilde{Y}_t$	$\tilde{Y}_b$	$\tilde{Y}_\tau$	$\sin\alpha$	$M_H[GeV]$	Scaling Factors	$\mu_{t\bar{t}h}$	μ_{hh}
BP1	$+1.01$	-0.10	10^{-3}	$+0.50$	500	$\kappa_W = 0.866$ $\kappa_Z = 0.866$ $\kappa_t = 1.374$ $\kappa_b = -1.001$ $\kappa_\tau = 0.915$ $\kappa_{\gamma\gamma} = 0.723$ $\kappa_{Z\gamma} = 0.778$	1.89	15
BP2	-1.0	$+0.01$	10^{-3}	-0.10	600	$\kappa_W = 0.995$ $\kappa_Z = 0.995$ $\kappa_t = 1.096$ $\kappa_b = 0.958$ $\kappa_\tau = 0.985$ $\kappa_{\gamma\gamma} = 0.966$ $\kappa_{Z\gamma} = 0.976$	1.2	10
BP3	1.25	$+0.05$	10^{-3}	-0.20	680	$\kappa_W = 0.980$ $\kappa_Z = 0.980$ $\kappa_t = 0.728$ $\kappa_b = 0.61$ $\kappa_\tau = 0.960$ $\kappa_{\gamma\gamma} = 1.05$ $\kappa_{Z\gamma} = 1.08$	0.53	11

Babu and Jana (2017)

❑ Benchmark Points :



The two-dimensional best-fit of the signal strengths for ggF and VBF production modes

Babu and Jana (2017)

❑ Benchmark Points :

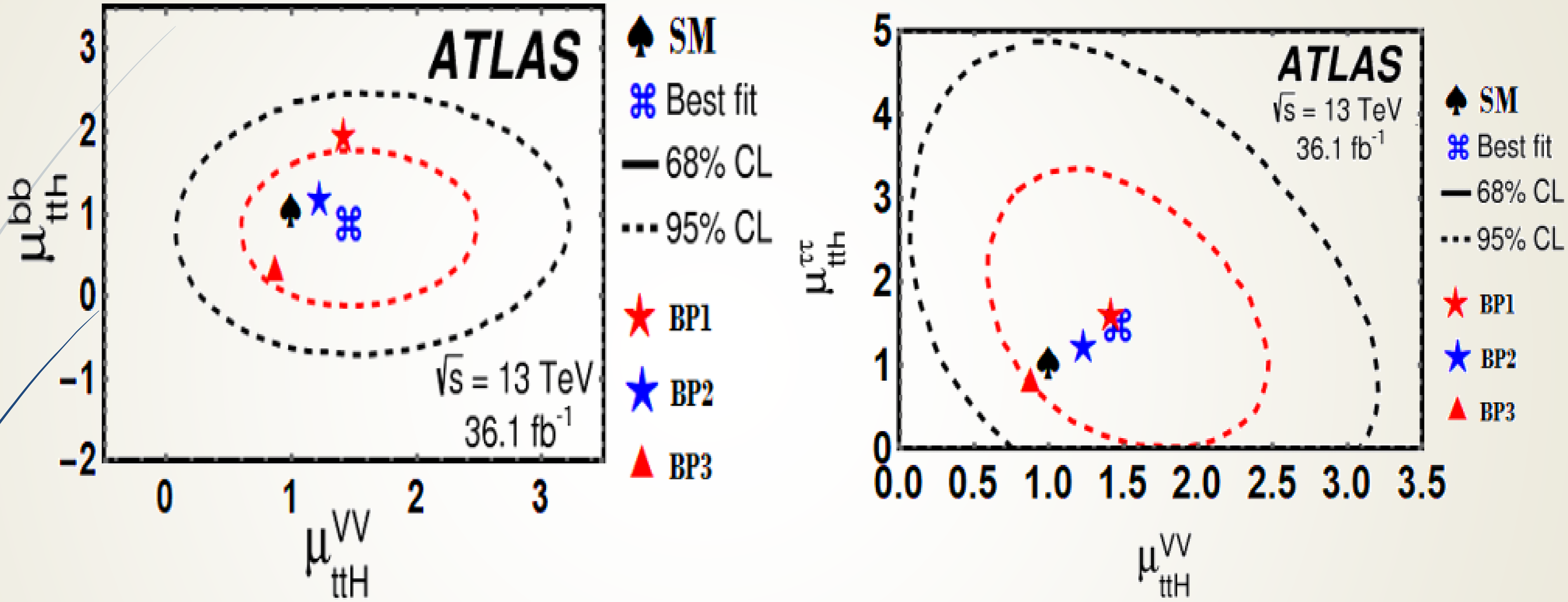
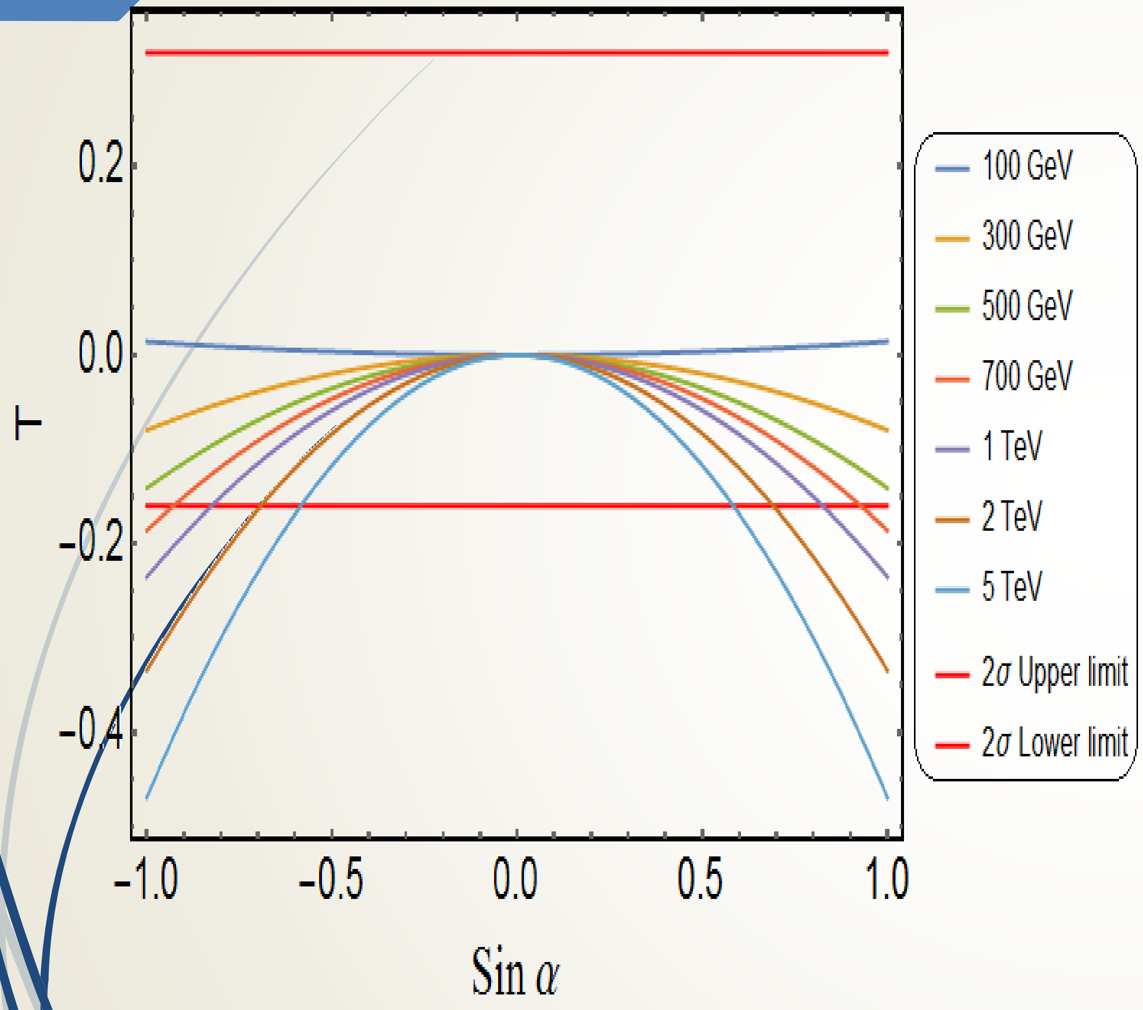
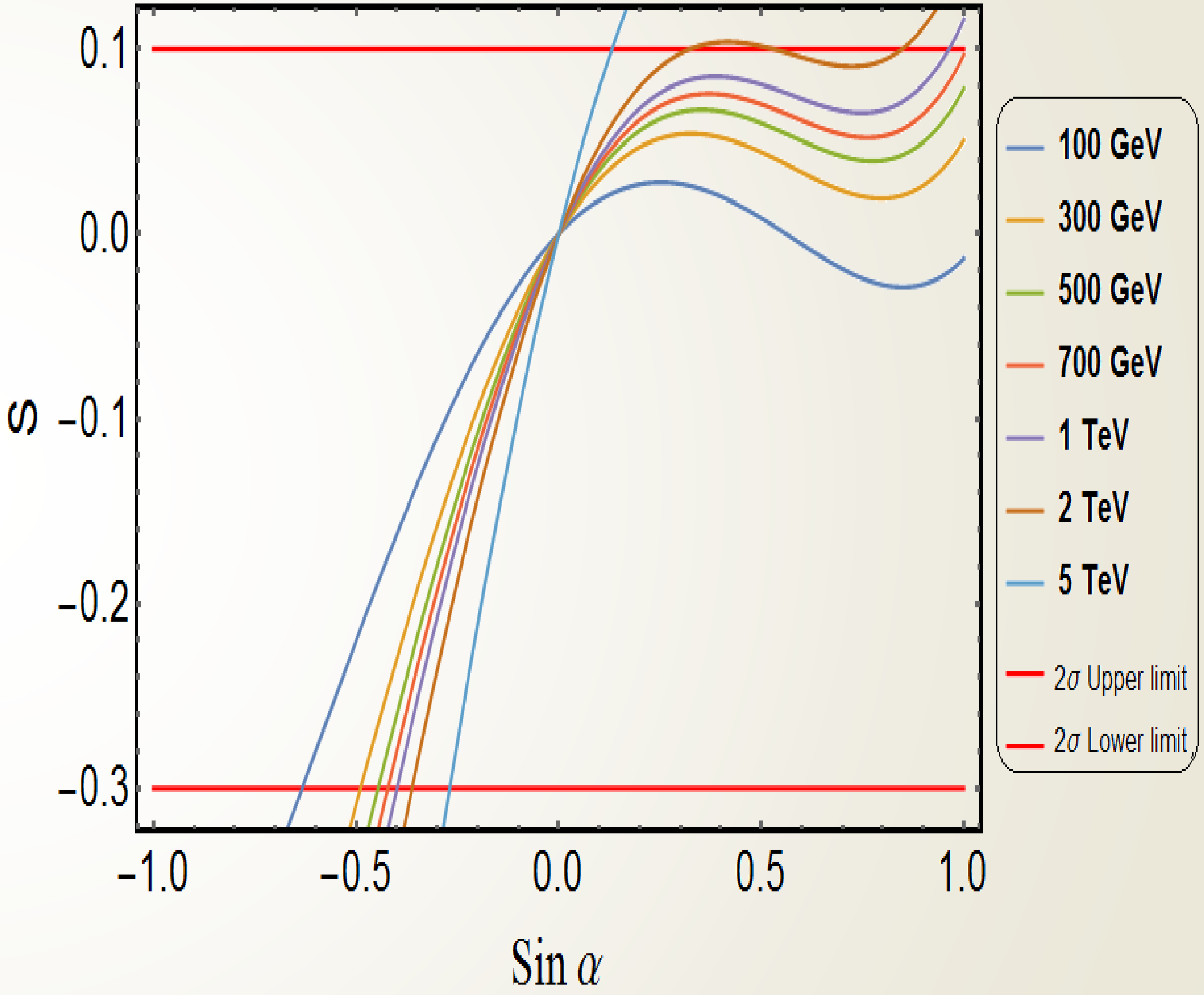


FIG. : The two-dimensional best-fit of the signal strength modifiers for the processes $t\bar{t}h, h \to b\bar{b}$ versus $t\bar{t}h, h \to VV^\star, (V = W, Z)$ (left) and $t\bar{t}h, h \to \tau^+\tau^-$ versus $t\bar{t}h, h \to VV^\star, (V = W, Z)$ (right). Three benchmark points (BP) are also shown in this contourplot.

❑ S and T Parameters





❑ Boundedness of Higgs Potential

- To ensure that the scalar potential is bounded from below, we evaluate the eigenvalues and eigenvectors of the following matrix:

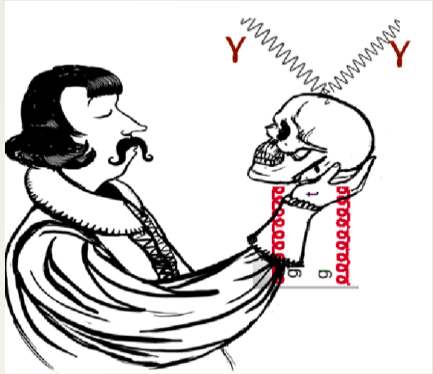
$$\begin{bmatrix} \frac{1}{4}(\Lambda_1+\Lambda_2+2\Lambda_3) & -\frac{1}{2}(\Lambda_6+\Lambda_7) & 0 & -\frac{1}{4}(\Lambda_1-\Lambda_2) \\ \frac{1}{2}(\Lambda_6+\Lambda_7) & -\frac{1}{2}(\Lambda_4+\Lambda_5) & 0 & -\frac{1}{2}(\Lambda_6-\Lambda_7) \\ 0 & 0 & -\frac{1}{2}(\Lambda_4-\Lambda_5) & 0 \\ \frac{1}{4}(\Lambda_1-\Lambda_2) & -\frac{1}{2}(\Lambda_6-\Lambda_7) & 0 & -\frac{1}{4}(\Lambda_1+\Lambda_2+2\Lambda_3) \end{bmatrix}$$

  We choose all the quartic couplings to be real.
- One set of values of the quartic couplings:
  $\Lambda_1 = 1.4, \Lambda_2 = 0.01, \Lambda_3 = 1, \Lambda_4 = 0.1, \Lambda_5 = 0.001, \Lambda_6 = 3, \Lambda_7 = -1.2.$
- All the eigenvalues of the matrix are real, and the largest eigenvalue is positive: $\{2.0527, -1.75315, 0.649943, -0.0495\}$.
  This satisfies necessary and suffcient conditions for the potential to be bounded from below.
- For this specific choice, we get HIggs masses to be: {125 GeV, 751 GeV, 706 GeV.} The mixing parameter $\sin\alpha = 0.458$.

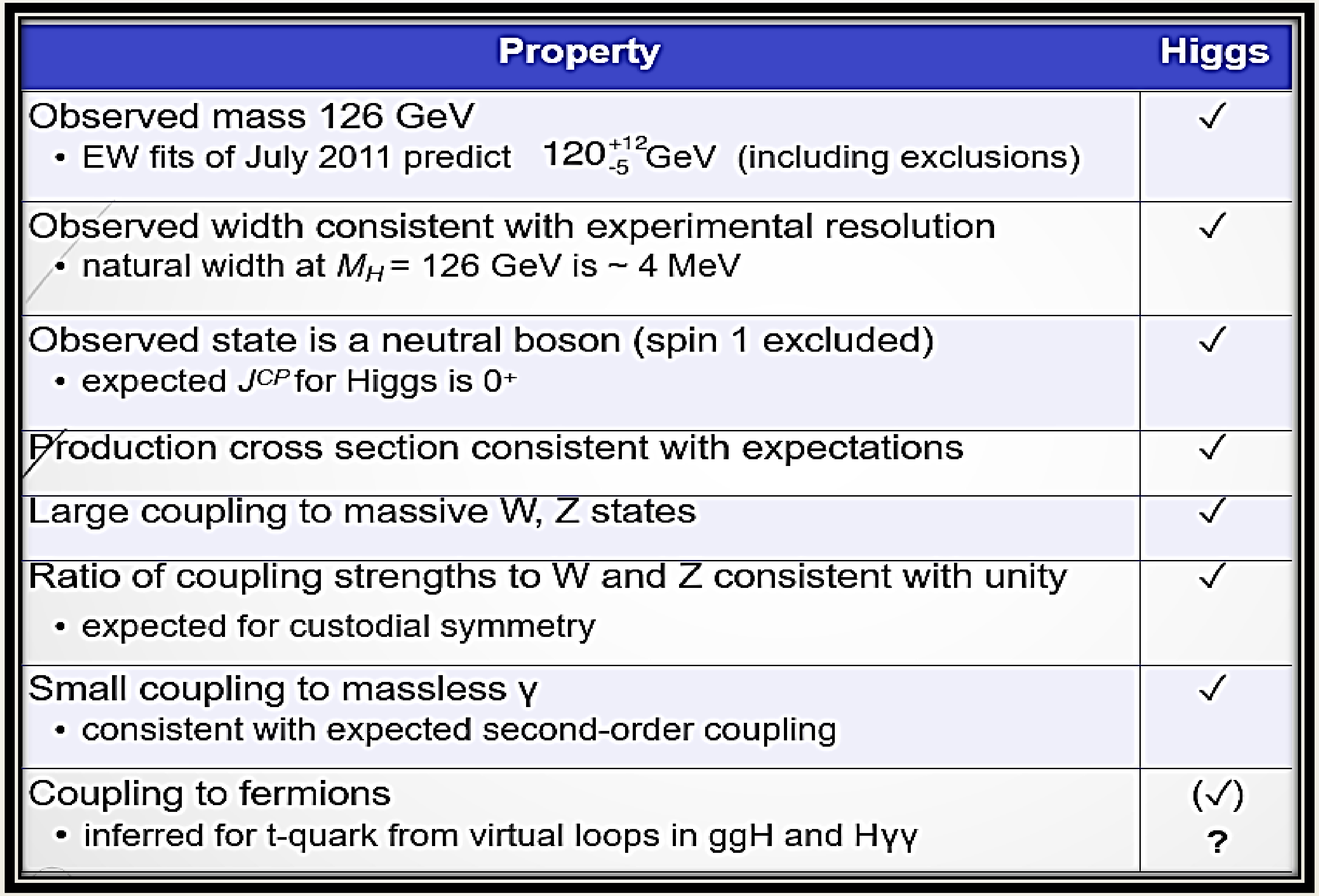
❑ 2HDM : Remarks

- 2HDM provides a framework to check EWSB dynamics
- Correlated enhancements is $t\bar{t}h$ and hh production possible
- Additional Higgs bosons below a TeV will be confirmation of the scenario

☐ Score card for the Higgs interpretation at the Large Hadron Collider (LHC)

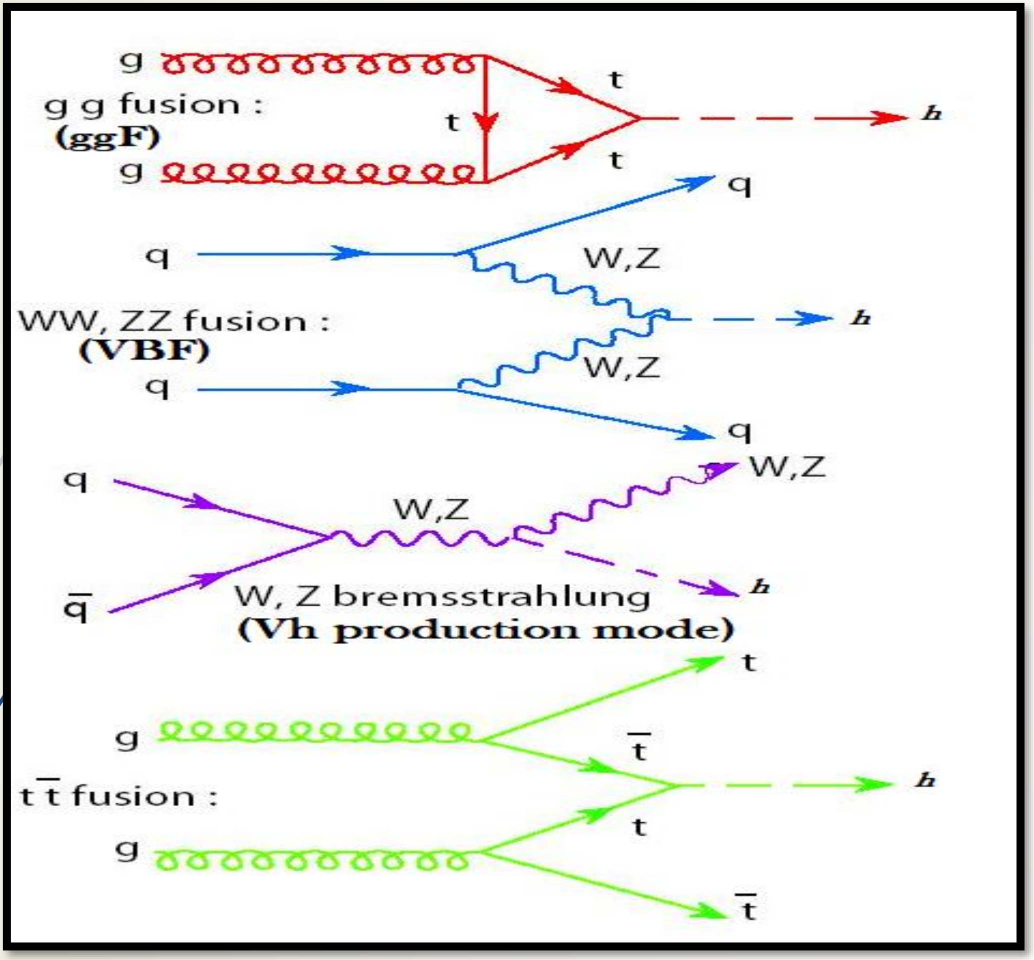


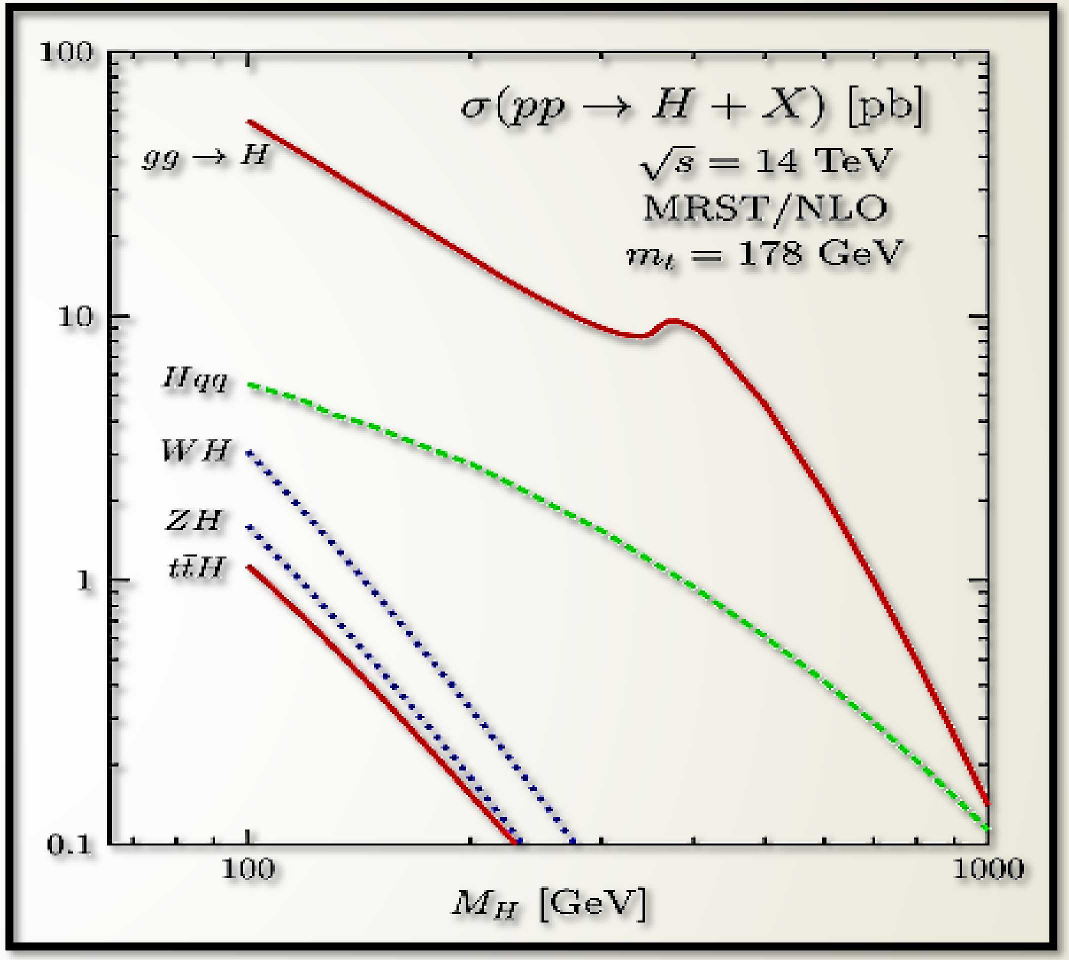
What kind of Higgs?



Property	Higgs
Observed mass 126 GeV • EW fits of July 2011 predict 120^{+12}_{-5} GeV (including exclusions)	✓
Observed width consistent with experimental resolution • natural width at M_H = 126 GeV is ~ 4 MeV	✓
Observed state is a neutral boson (spin 1 excluded) • expected J^{CP} for Higgs is 0^+	✓
Production cross section consistent with expectations	✓
Large coupling to massive W, Z states	✓
Ratio of coupling strengths to W and Z consistent with unity • expected for custodial symmetry	✓
Small coupling to massless γ • consistent with expected second-order coupling	✓
Coupling to fermions • inferred for t-quark from virtual loops in ggH and Hγγ	(✓) ?

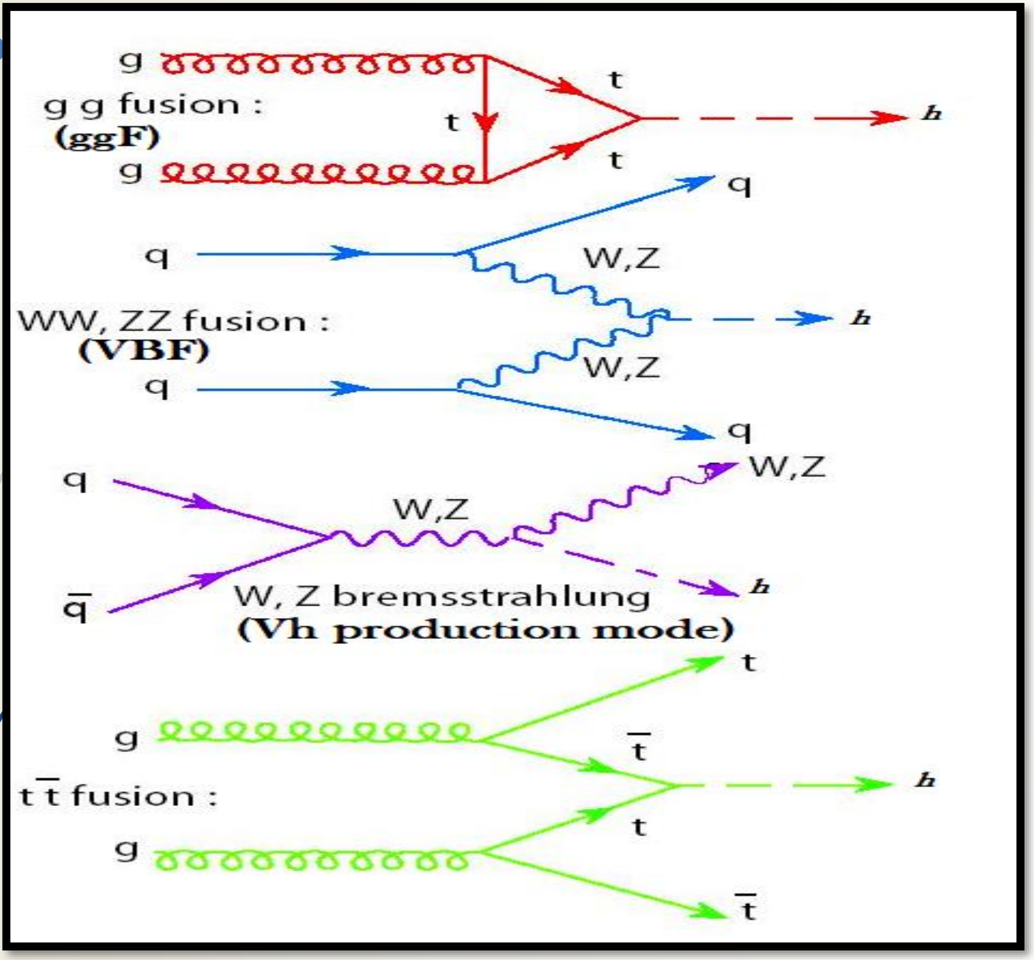
☐ Higgs Production at the LHC

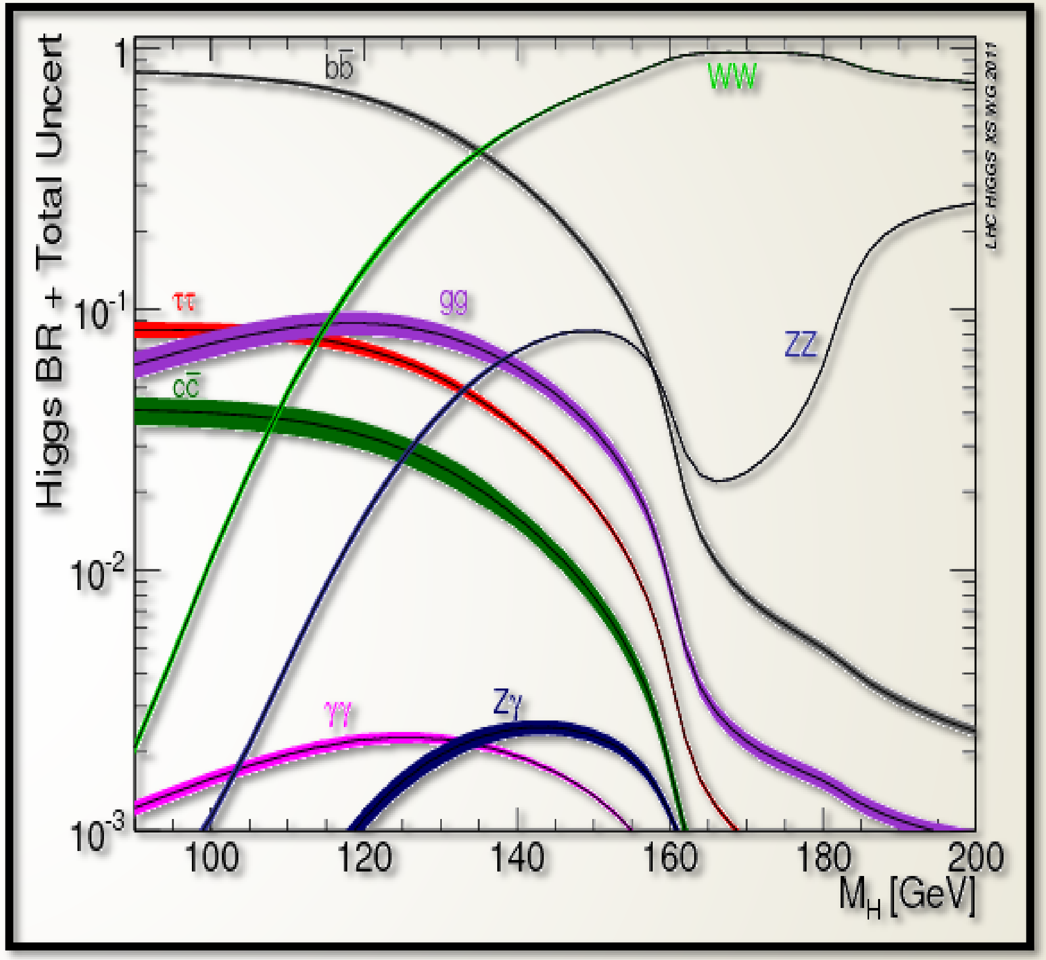




At the 13 TeV LHC, SM Higgs production cross-section via different production modes are summarized as : $\sigma_{ggF} = 43.92$ pb, $\sigma_{VBF} = 3.748$ pb, $\sigma_{Wh} = 1.38$ pb, $\sigma_{Zh} = 0.869$ pb, $\sigma_{t\bar{t}h} = 508.5$ fb.

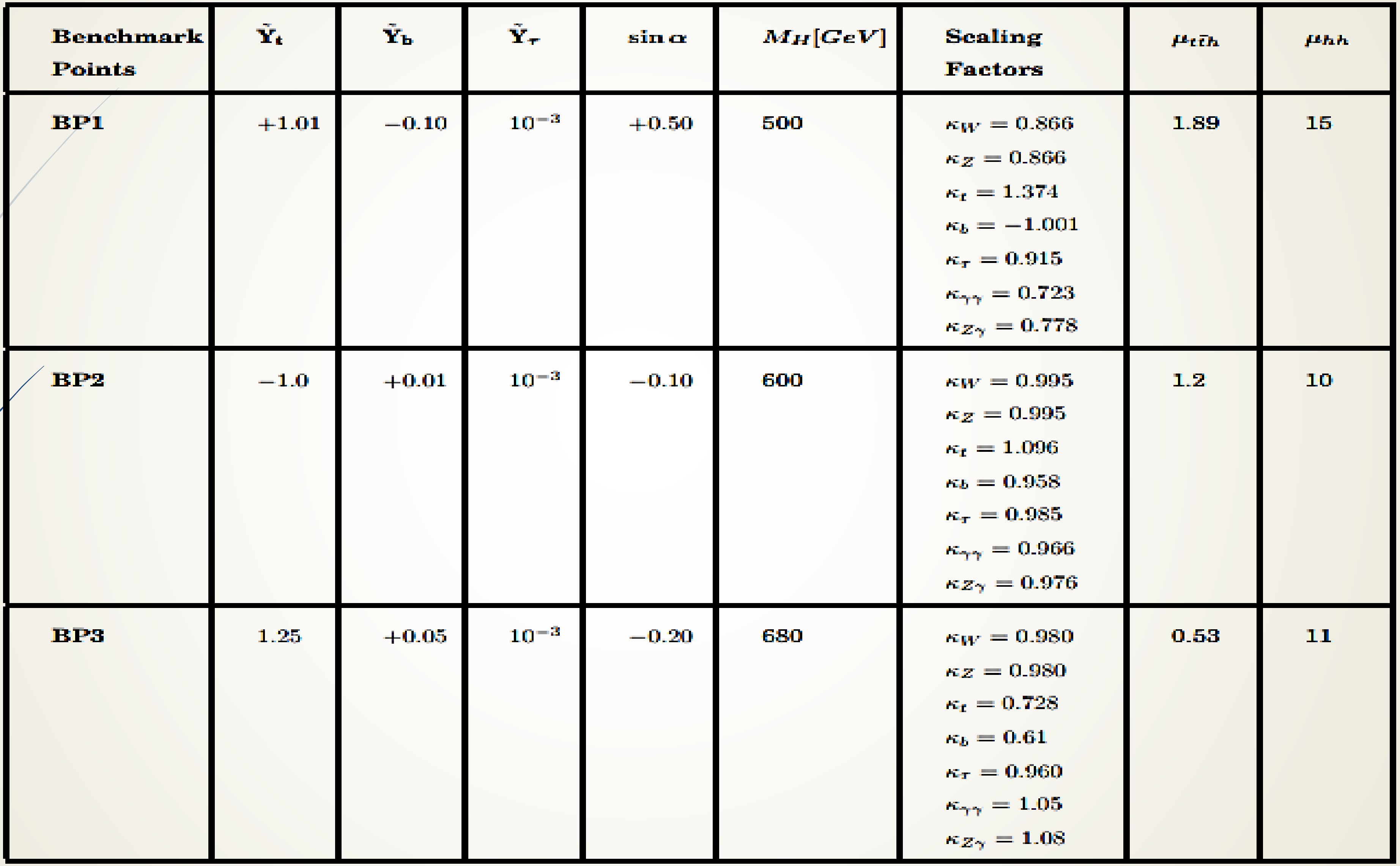
☐ Production and Decay Modes of Higgs Boson at the LHC





At the 13 TeV LHC, SM Higgs production cross-section via different production modes are summarized as : $\sigma_{ggF} = 43.92$ pb, $\sigma_{VBF} = 3.748$ pb, $\sigma_{Wh} = 1.38$ pb, $\sigma_{Zh} = 0.869$ pb, $\sigma_{t\bar{t}h} = 508.5$ fb.

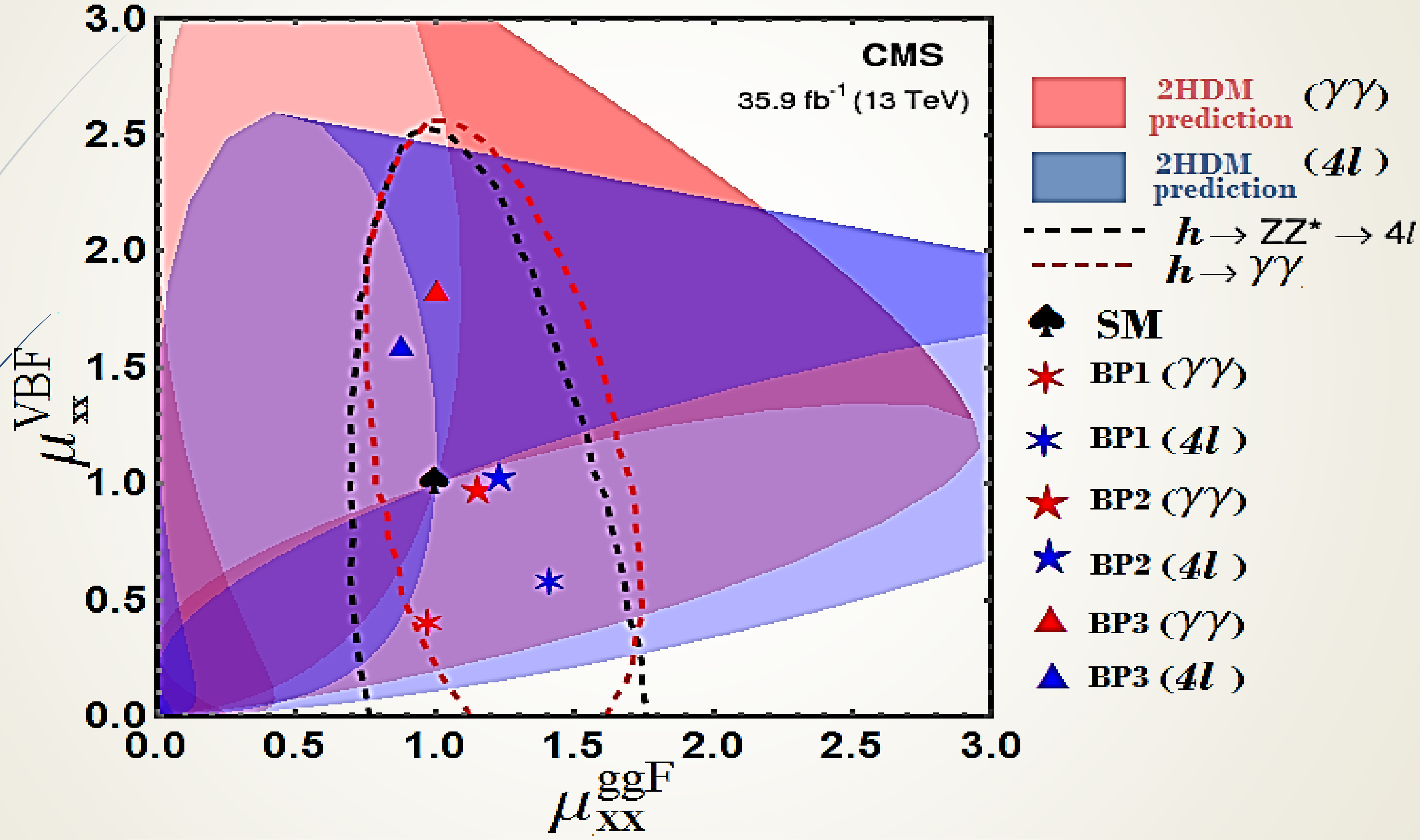
☐ Benchmark Points :



Benchmark Points	$\tilde{Y}_t$	$\tilde{Y}_b$	$\tilde{Y}_\tau$	$\sin\alpha$	$M_H[GeV]$	Scaling Factors	$\mu_{t\bar{t}h}$	μ_{hh}
BP1	$+1.01$	-0.10	10^{-3}	$+0.50$	500	$\kappa_W = 0.866$ $\kappa_Z = 0.866$ $\kappa_t = 1.374$ $\kappa_b = -1.001$ $\kappa_\tau = 0.915$ $\kappa_{\gamma\gamma} = 0.723$ $\kappa_{Z\gamma} = 0.778$	1.89	15
BP2	-1.0	$+0.01$	10^{-3}	-0.10	600	$\kappa_W = 0.995$ $\kappa_Z = 0.995$ $\kappa_t = 1.096$ $\kappa_b = 0.958$ $\kappa_\tau = 0.985$ $\kappa_{\gamma\gamma} = 0.966$ $\kappa_{Z\gamma} = 0.976$	1.2	10
BP3	1.25	$+0.05$	10^{-3}	-0.20	680	$\kappa_W = 0.980$ $\kappa_Z = 0.980$ $\kappa_t = 0.728$ $\kappa_b = 0.61$ $\kappa_\tau = 0.960$ $\kappa_{\gamma\gamma} = 1.05$ $\kappa_{Z\gamma} = 1.08$	0.53	11

Babu and Jana (2017)

❑ Benchmark Points :



The two-dimensional best-fit of the signal strengths for ggF and VBF production modes

Babu and Jana (2017)

☐ Benchmark Points :

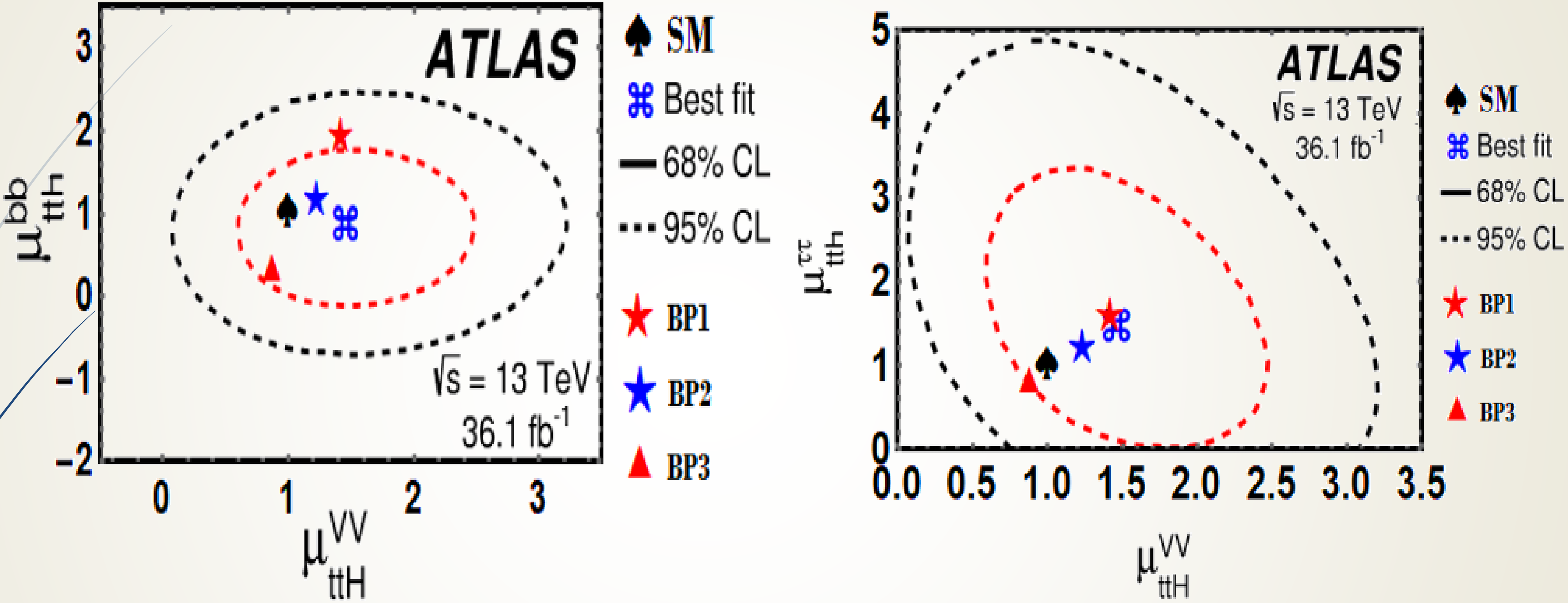
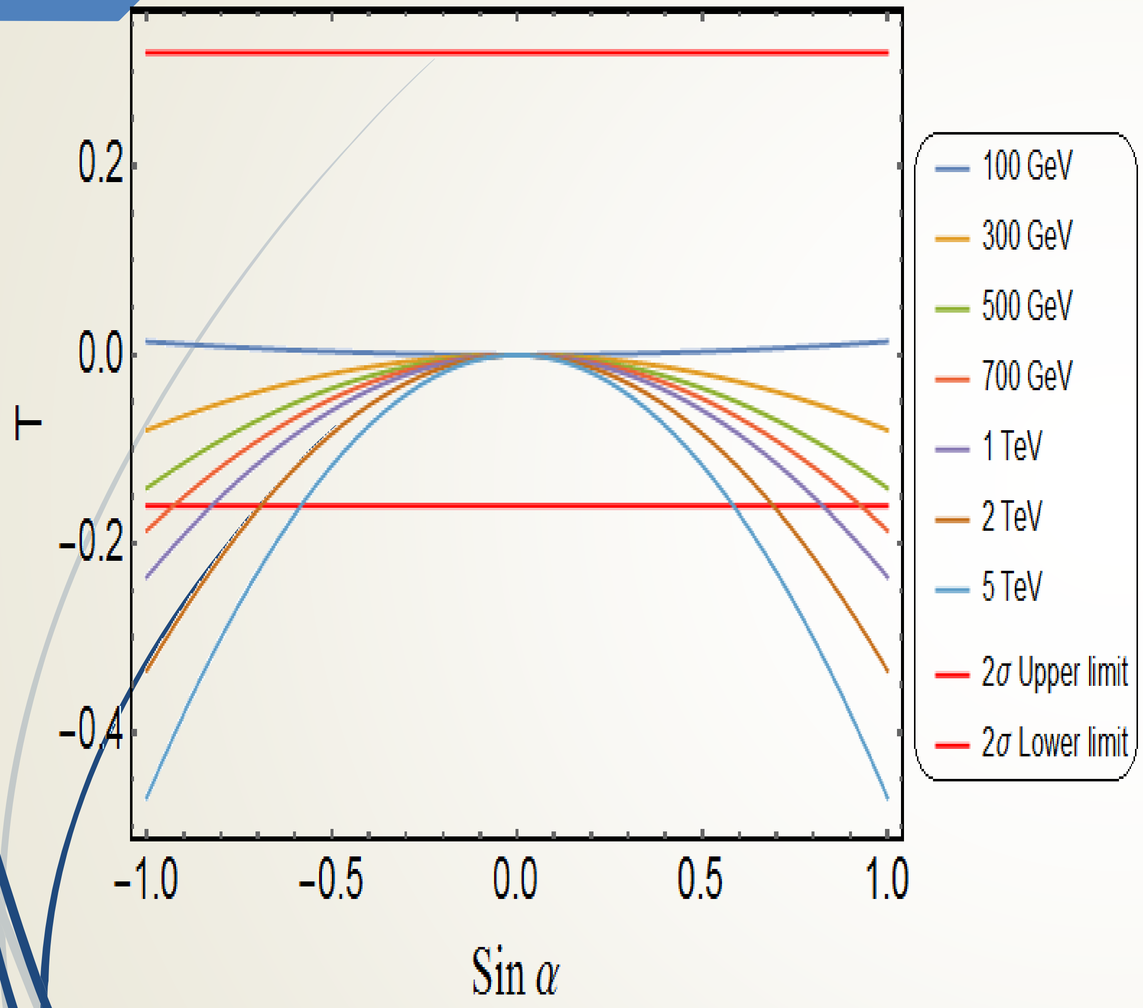
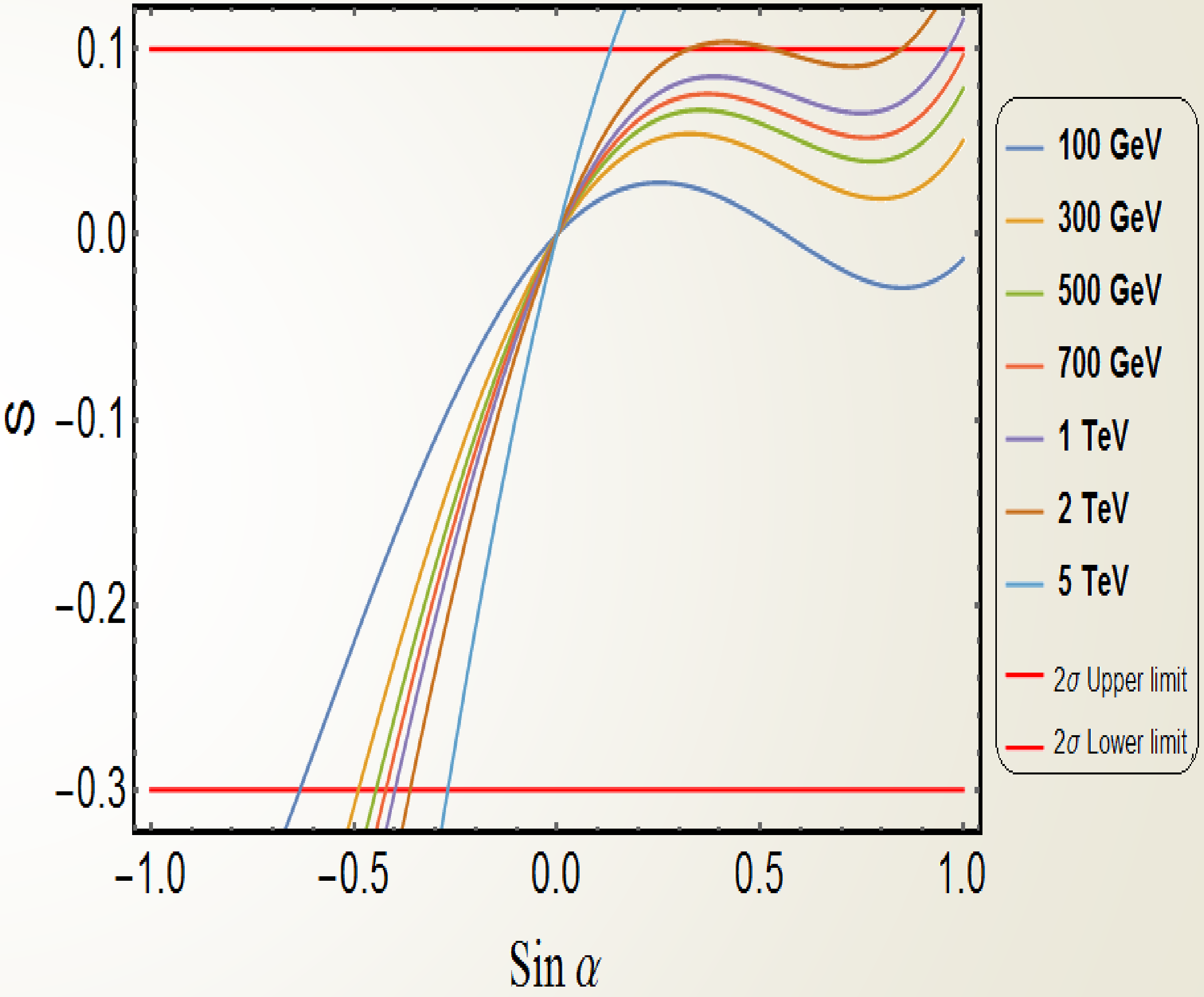


FIG. : The two-dimensional best-fit of the signal strength modifiers for the processes $t\bar{t}h, h \to b\bar{b}$ versus $t\bar{t}h, h \to VV^{\star}, (V = W, Z)$ (left) and $t\bar{t}h, h \to \tau^+\tau^-$ versus $t\bar{t}h, h \to VV^{\star}, (V = W, Z)$ (right). Three benchmark points (BP) are also shown in this contourplot.

Babu and Jana (2017)

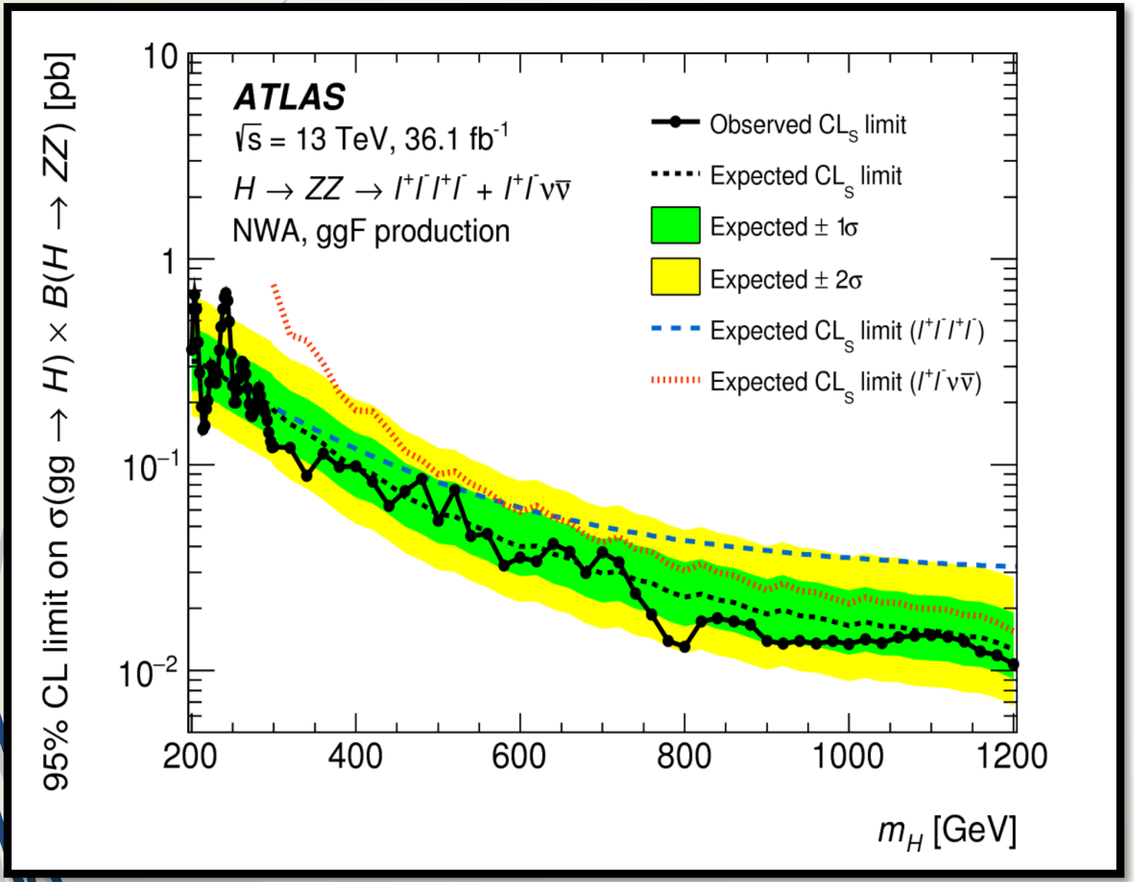
☐ S and T Parameters

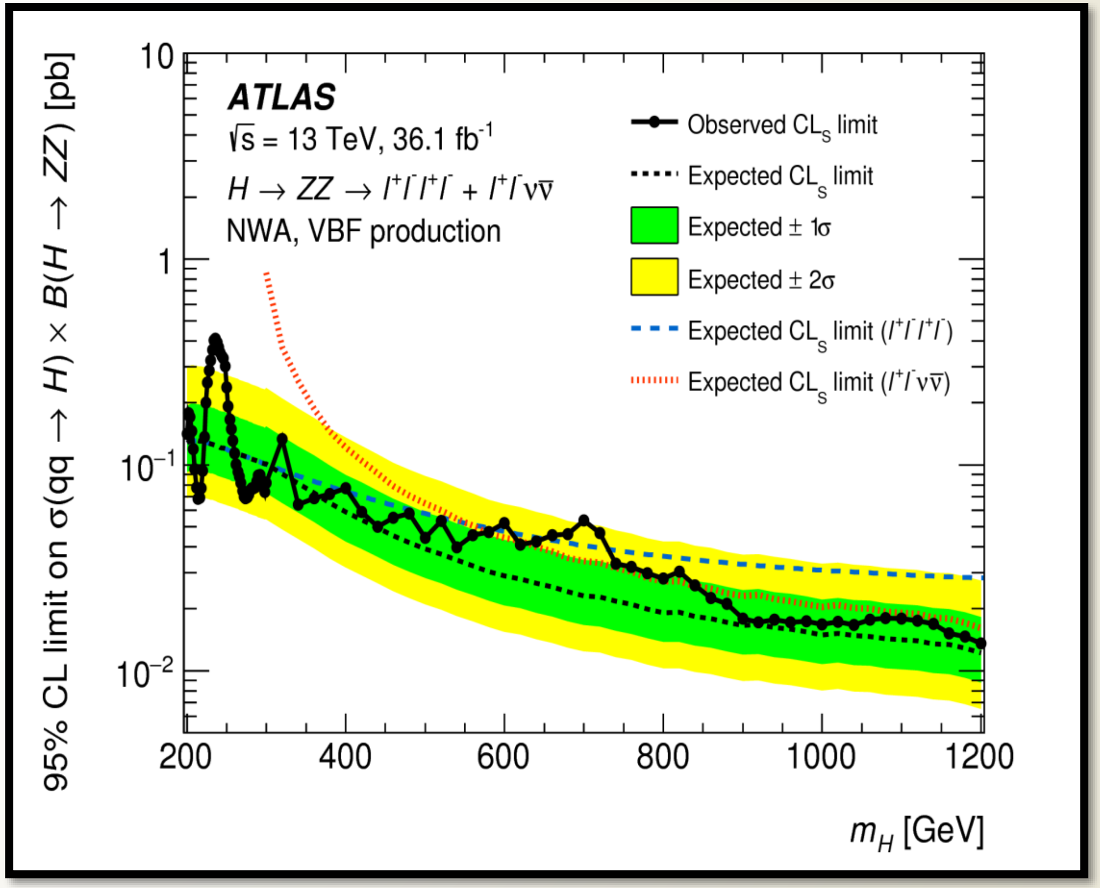




Babu and Jana (2017)

❖ ZZ Resonance :
with 3.6 σ local significance





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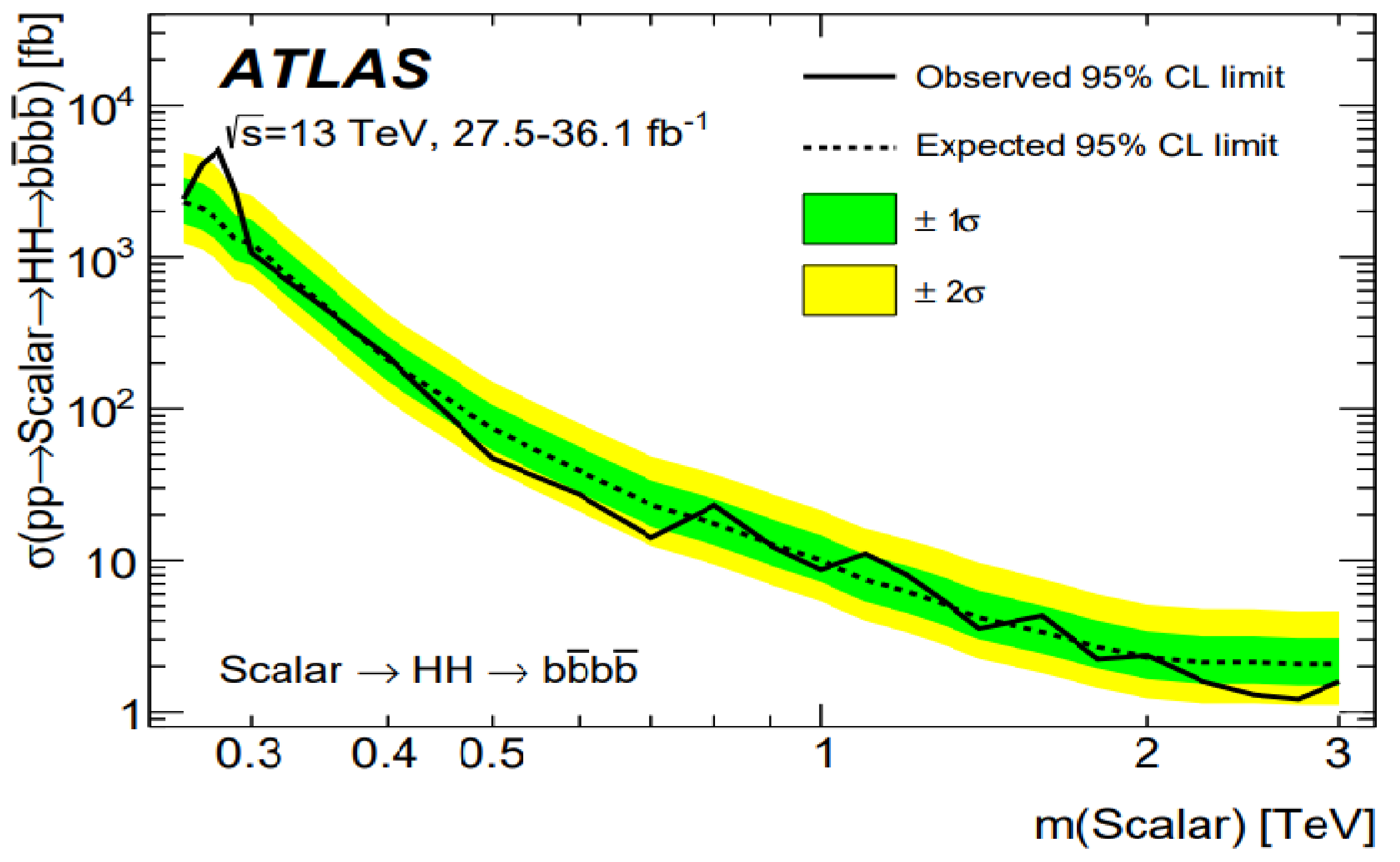
e-print arXiv:1712.06386

❖ hh Resonance at 280 GeV :

with 2.3σ global significance



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