



Beyond the Standard Higgs

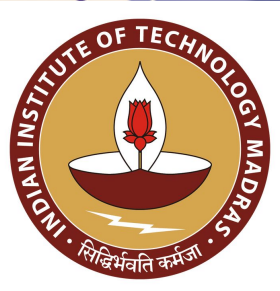
Lessons from the LHC

IPSITA SAHA

IIT MADRAS, CHENNAI

SHIV NADAR INSTITUTE OF EMINENCE, DELHI-NCR

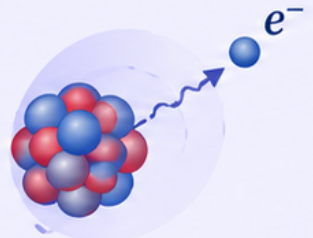
Symposium on Women in Physics: Networking, Innovation, Opportunity and Equity (SWPNIOE)



Short Flowchart : Birth of the SM

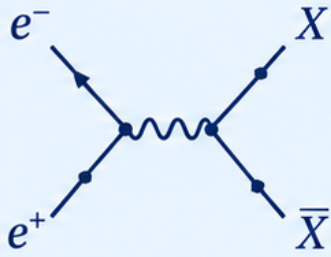
2

1



β decay,
electrons coming
out of nucleus –
how?

2



need the language
of creation and
annihilation of
particles – QFT!

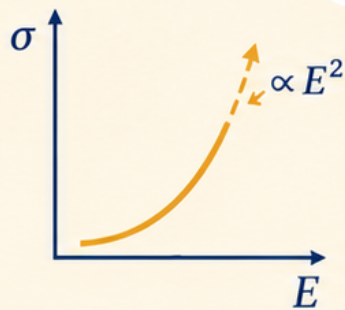
3

$\mathcal{L}_{\text{Fermi}}$

Fermi theory

$$-G_F(\bar{f}_1\gamma_\mu f_2)(\bar{f}_3\gamma_\mu f_4)$$

4



violates unitarity
at high energy

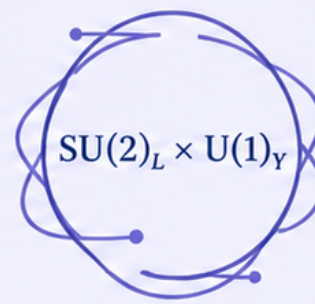
$$\mathcal{M}(f_2 f_4 \rightarrow f_1 f_3) \propto G_F E^2$$

5



how to ensure
unitarity at high
energies by design ?

6



try to construct
a gauge theory
for weak interaction.

MASS PROBLEMS

Massless weak gauge bosons
W and Z

$$M^2 A_\mu A^\mu$$

is not gauge invariant. Yet
weak interactions are short-
ranged.

Massless Fermions

$$\Psi_L, \Psi_R$$

Transforms differently
under the weak gauge
symmetry.

The Electroweak theory needs massive particles — without explicitly breaking gauge symmetry

SPONTANEOUS SYMMETRY BREAKING

ELECTROWEAK UNIFICATION

Relies on spontaneously broken
 $SU(2)_L \times U(1)_Y$ gauge
symmetry

Requires an $SU(2)_L$ scalar
doublet : **Essential Ingredient**
of the Standard Model

symmetric
 $M_\gamma = M_W = M_Z = 0$

$V(\phi)$

electroweak
phase transition

Higgs
boson

$\text{Im}(\phi)$

asymmetric
 $M_\gamma = 0$
 M_W, M_Z

$\text{Re}(\phi)$

extra W, Z polarisation

Prediction of a fundamental scalar particle - Higgs Boson (discovered in July 2012)

Standard Model of Elementary Particles

three generations of matter (fermions)						interactions / force carriers (bosons)	
	I	II	III				
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0		$\approx 125.2 \text{ GeV}/c^2$	
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0		0	
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1		0	
QUARKS	u up	c charm	t top	g gluon		H higgs	
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	0			
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0			
	d down	s strange	b bottom	γ photon			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$	$\approx 91.188 \text{ GeV}/c^2$			
	-1	-1	-1	0			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	e electron	μ muon	τ tau	Z Z boson			
	$< 0.8 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.3692 \text{ GeV}/c^2$			
	0	0	0	± 1			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson			

Image: Wikipedia

The Nobel Prize in Physics 1979



Sheldon Lee Glashow
Prize share: 1/3



Abdus Salam
Prize share: 1/3



Steven Weinberg
Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, *inter alia*, the prediction of the weak neutral current".

Photos: Copyright © The Nobel Foundation

Standard Model of Elementary Particles

three generations of matter
(fermions)

interactions / force carriers
(bosons)

The New York Times

Physicists Find Elusive Particle Seen as Key to Universe

Share full article 122



Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson. Pool photo by Denis Balibouse

By **Dennis Overbye**

July 4, 2012

25.2 GeV/c²

H

higgs

SCALAR BOSONS

VECTOR BOSONS

The Nobel Prize in Physics 1979



Sheldon Lee
Glashow
Prize share: 1/3



Abdus Salam
Prize share: 1/3



Steven Weinberg
Prize share: 1/3

Nobel Prize in Physics 2013



© Nobel Prize Outreach. Photo:
A. Mahmoud
François Englert
Prize share: 1/2



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Peter W. Higgs
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LHC discovered Higgs in July 2012

Higgs Production and Decays

6

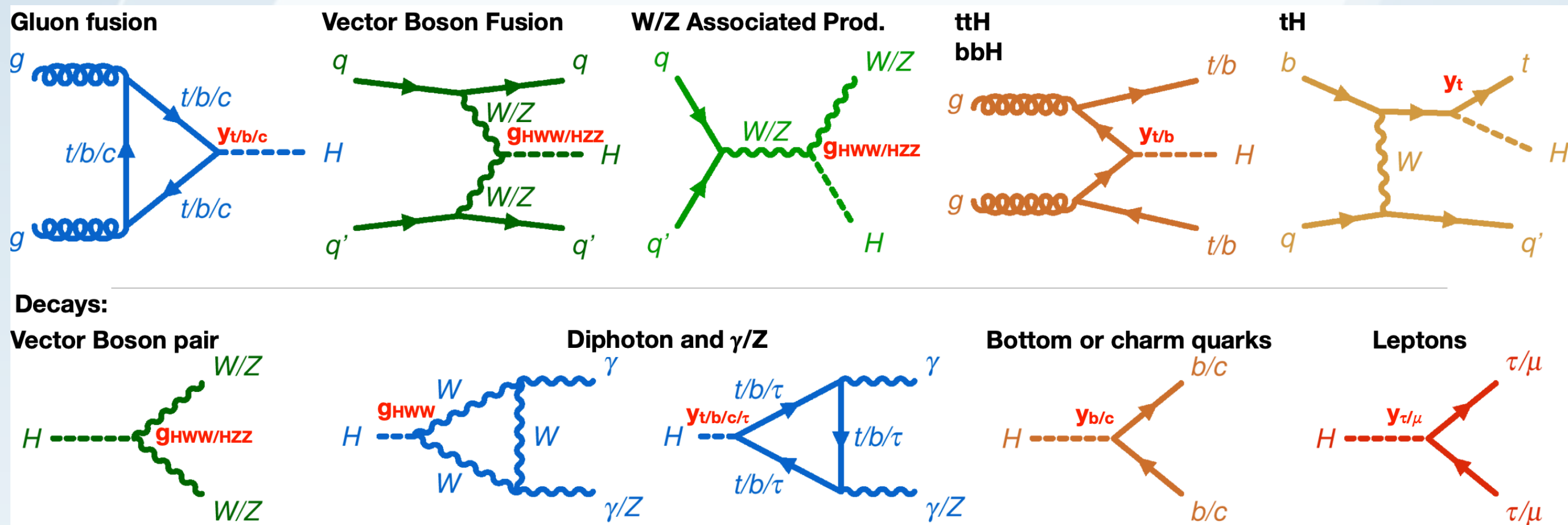
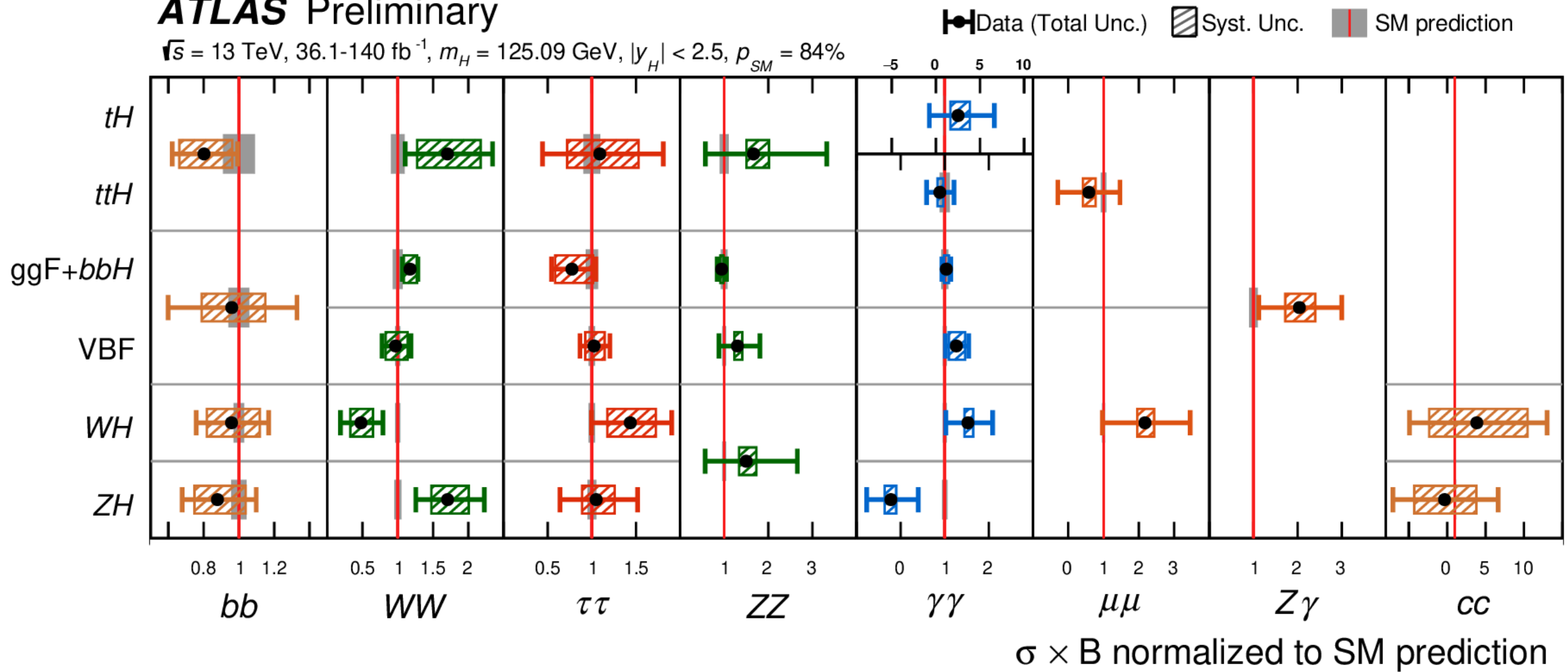


Image: Moriond'26

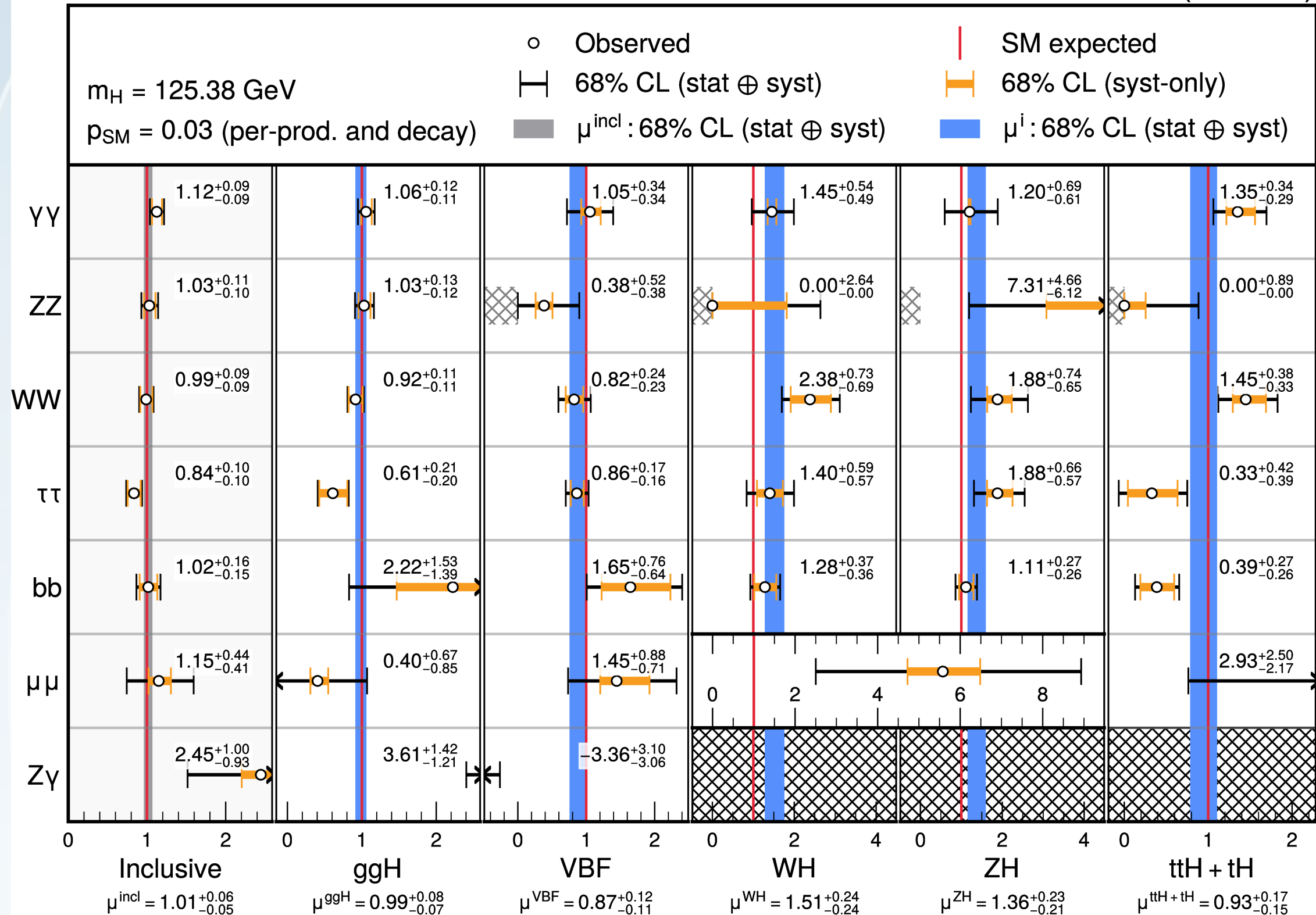
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$, $36.1\text{-}140 \text{ fb}^{-1}$, $m_H = 125.09 \text{ GeV}$, $|y_H| < 2.5$, $p_{SM} = 84\%$



CMS

138 fb⁻¹ (13 TeV)

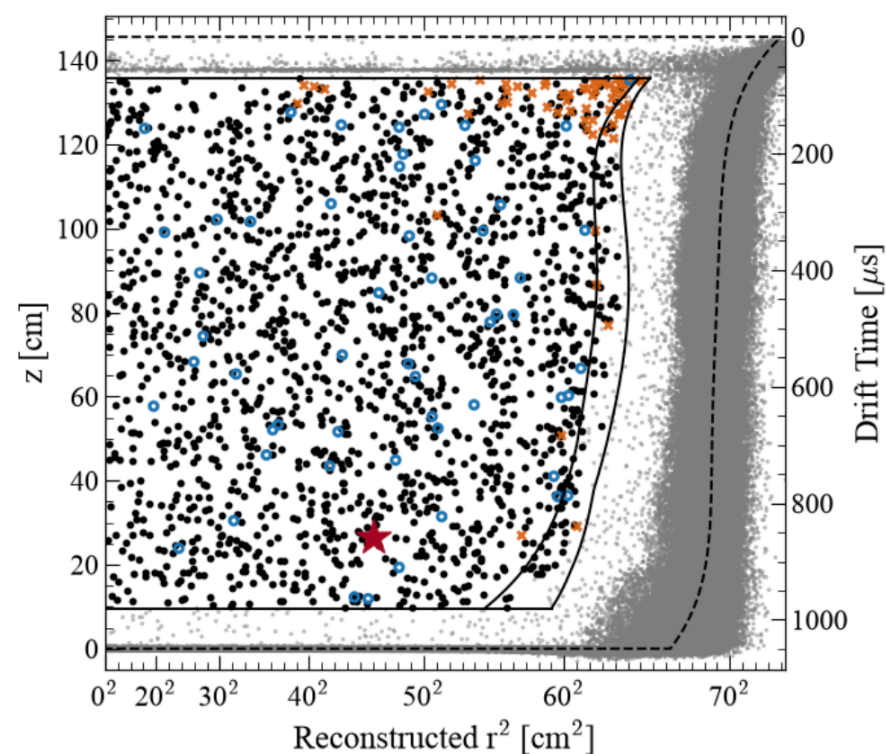
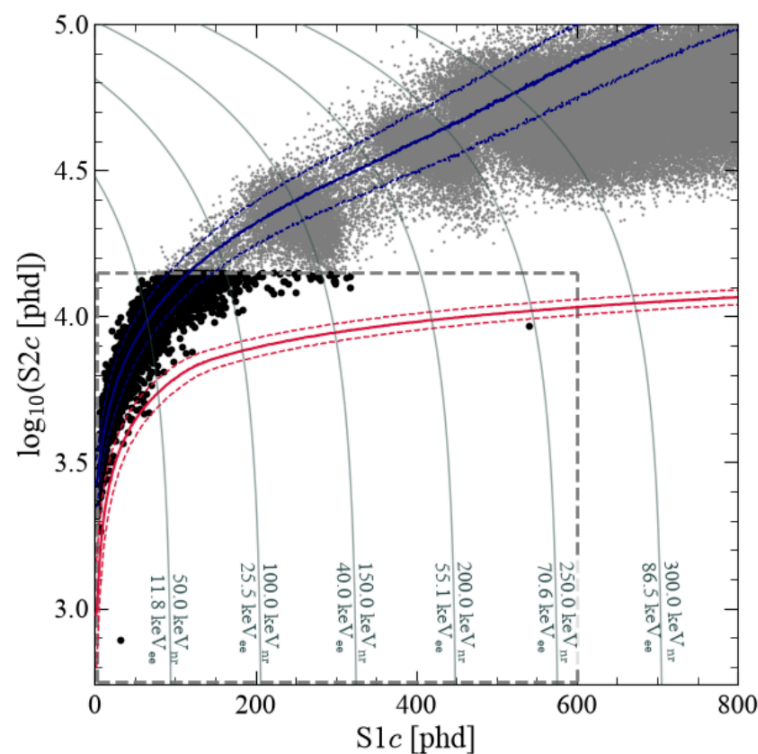


Theoretical & Observational

- ✳ Instability of SM vacuum.
- ✳ Why three generations? Flavor Puzzle!
- ✳ Gravity is not included. Unification!
- ✳ Neutrinos has tiny nonzero mass.
- ✳ Existence of Dark Matter.
- ✳ Matter-antimatter asymmetry.
- ✳ Anomalies in experimental detections (Flavor, muon $(g-2)$ etc.)

A single event - LZ230616

- Occurred on 16 June 2023 (LZ230616)
- $248 \pm 23_{\text{stat}} \pm 23_{\text{sys}}$ keV compatible with elastic nuclear recoil
- 26.4 cm from cathode
- 26.9 cm from TPC wall



A SINGLE EVENT HAS RECENTLY BEEN OBSERVED IN THE DIRECT DARK MATTER DETECTION EXPERIMENTS 'LZ' — ANNOUNCED ON 1ST SEPTEMBER

Theoretical & Observational

- ✳ Instability of SM vacuum.
- ✳ Why three generations? Flavor Puzzle!
- ✳ Gravity is not included. Unification!
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BEYOND THE SM (BSM) SCENARIOS OFTEN COMES WITH EXTENSION OF THE SM HIGGS SECTOR.

- ◆ The EW symmetry breaking is driven by only one Higgs doublet in the Standard Model.
- ◆ The Electroweak vacuum expectation value (vev) is estimated by measuring the Fermi Constant $G_F = \frac{1}{\sqrt{2}v^2}$.
- ◆ One SM Higgs Boson and the LHC data resembles the SM nature.

RELEVANT QUESTIONS AFTER HIGGS

IS IT THE FIRST HIGGS TO
APPEAR IN A SERIES OF MANY
OTHERS TO FOLLOW

DIRECT SEARCHES AT
THE COLLIDERS

HOW CLOSELY DOES IT
RESEMBLE THE SM HIGGS

HIGGS PRECISION
MEASUREMENTS

Future Colliders!

We have found 'A Higgs'!

We haven't found any other Higgs yet!

- ◆ To what extent can the Electroweak vev contribute to the non-standard Higgs mass?
- ◆ Can the relative contribution of EW vev and nonstandard source to the nonstandard scalar masses be experimentally constrained?
- ◆ What types of $SU(2)_L$ multiplets contribute to the mechanism of electroweak symmetry breaking and to what extent?

Ongoing research direction with Prof. Dipankar Das and his group at IIT Indore.
This talk — arXiv: 2603.23280.

HOW TO EXTRACT THE FRACTION OF EW SOURCE OF MASS TO NONSTANDARD SCALARS

Where do the masses of nonstandard scalars come from

Standard Picture

● In the SM,

$$m_h^2 \sim \lambda v^2 \quad v = 246 \text{ GeV}$$

● In the 2HDM

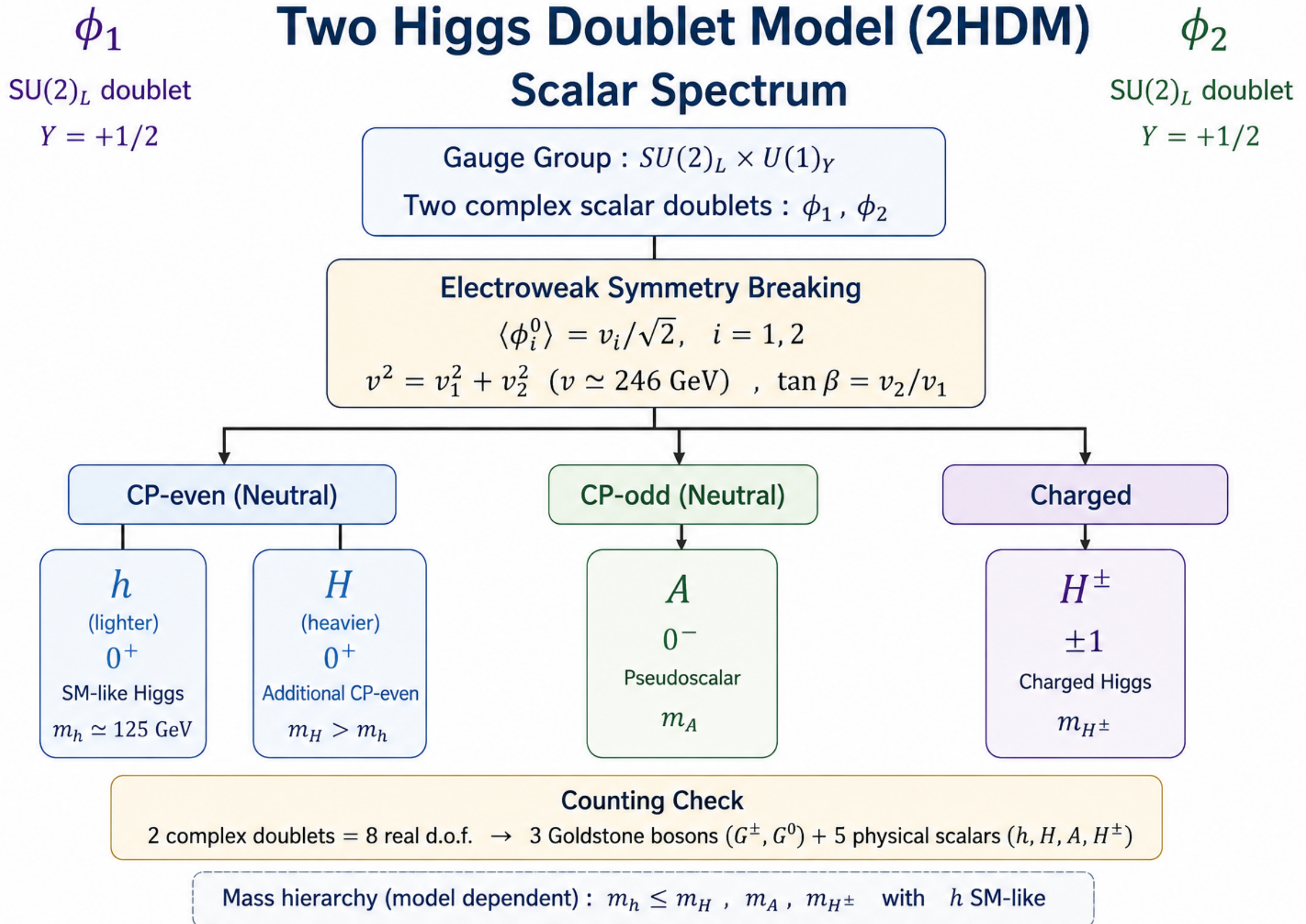
$$h, H, A, H^\pm$$

With only h identified as the observed 125 GeV Higgs

Central Question



How much of the $H, A, H^\pm$ masses is tied to the EW VEV v ?



The CP conserving, soft Z_2 breaking scalar potential,

$$V_{2\text{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right]$$

- ✳ The ‘soft-symmetry breaking’ plays the crucial role in making the nonstandard scalars decouple. [Bhattacharyya and Das ‘2015, Faro, Romao, Silva ‘2020, Arco, Heinemeyer, Herrero ‘2022]
- ✳ What is the origin of this ‘soft-symmetry breaking’?
- ✳ How can the relative contribution of EW and nonstandard source to the nonstandard masses be experimentally constrained?

In the alignment limit, the lightest CP-even scalar (h) has exact SM-like couplings at the tree-level.

The CP conserving, soft Z_2 breaking scalar potential,

$$V_{2\text{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right]$$

where, the fields are expanded around their minima,

$$\Phi_j = \begin{pmatrix} w_j^+ \\ (v_j + h_j + iz_j)/\sqrt{2} \end{pmatrix} \quad j = 1, 2$$

Where, $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2, \quad \tan \beta = \frac{v_2}{v_1}$

The soft-term m_{12}^2 is the only dimension two Z_2 breaking parameter.

The physical masses in the Charged and Pseudo-scalar sector are obtained by the rotation,

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} w_1^\pm \\ w_2^\pm \end{pmatrix}, \quad \mathcal{O}_\beta = \frac{1}{v} \begin{pmatrix} v_1 & v_2 \\ -v_2 & v_1 \end{pmatrix} \equiv \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix}$$

CP-odd and Charged Scalar Mass Eigenstate

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The CP conserving, soft Z_2 breaking scalar potential,

$$V_{2\text{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right]$$

The Charged scalar and Pseudo-scalar mass matrices obtained after the EWSB,

$$\mathcal{M}_C^2 = \left[\frac{m_{12}^2}{v_1 v_2} - \frac{1}{2} (\lambda_4 + \lambda_5) \right] \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} \quad \mathcal{M}_P^2 = \left[\frac{m_{12}^2}{v_1 v_2} - \lambda_5 \right] \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix}$$

The Physical masses will be obtained by,

$$\mathcal{O}_\beta \cdot \mathcal{M}_P^2 \cdot \mathcal{O}_\beta^T = \begin{pmatrix} 0 & 0 \\ 0 & m_A^2 \end{pmatrix}, \quad \mathcal{O}_\beta \cdot \mathcal{M}_C^2 \cdot \mathcal{O}_\beta^T = \begin{pmatrix} 0 & 0 \\ 0 & m_C^2 \end{pmatrix}. \quad \mathcal{O}_\beta = \frac{1}{v} \begin{pmatrix} v_1 & v_2 \\ -v_2 & v_1 \end{pmatrix}$$

CP-odd and Charged Scalar Mass Eigenstate

21

The CP conserving, soft Z_2 breaking 2HDM scalar potential,

$$V_{2\text{HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \left[\frac{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right]$$

we defined,

$$\Lambda^2 = \frac{m_{12}^2}{\sin \beta \cos \beta}$$

The Charged scalar and Pseudo-scalar masses obtained after the EWSB,

$$m_C^2 = \Lambda^2 - \frac{v^2}{2}(\lambda_4 + \lambda_5), \quad m_A^2 = \Lambda^2 - \lambda_5 v^2$$

Therefore, a heavy scalar can become arbitrarily heavy through Λ^2 . Also, true for CP-even heavy Higgs (H).

$$m_X^2 = \Lambda^2 + \mathcal{O}(v^2)$$

But, in the alignment limit, the SM-like Higgs receives no contribution from Λ^2 .

The CP even mass matrix is given by,

$$\mathcal{M}_S^2 = \frac{\Lambda^2}{v^2} \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} + \begin{pmatrix} \lambda_1 v_1^2 & (\lambda_3 + \lambda_4 + \lambda_5) v_1 v_2 \\ (\lambda_3 + \lambda_4 + \lambda_5) v_1 v_2 & \lambda_2 v_2^2 \end{pmatrix}.$$

Rotate to the Higgs basis,
$$\begin{pmatrix} H_0 \\ R \end{pmatrix} = \mathcal{O}_\beta \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$H_0 = \frac{1}{v} (v_1 h_1 + v_2 h_2) \equiv \cos \beta h_1 + \sin \beta h_2$$

In the alignment limit, the physical mass eigenstate h completely overlaps with the H_0 state

$$\cos(\alpha - \beta) = 1$$

Crucially,

$$\frac{\Lambda^2}{v^2} \mathcal{O}_\beta \begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix} \mathcal{O}_\beta^T = \begin{pmatrix} 0 & 0 \\ 0 & \Lambda^2 \end{pmatrix}.$$

Thus, in the alignment limit, the SM-like Higgs receives no contribution from Λ^2 .

Z_2 symmetric singlet extension $\longrightarrow$ Soft Z_2 broken 2HDM

Consider a real singlet S to the Z_2 symmetric 2HDM which is odd under the symmetry

$$S \rightarrow -S,$$

The potential contains a dimensionful interaction as,

$$V \supset -\mu \Phi_1^\dagger \Phi_2 S + \text{h.c.}$$

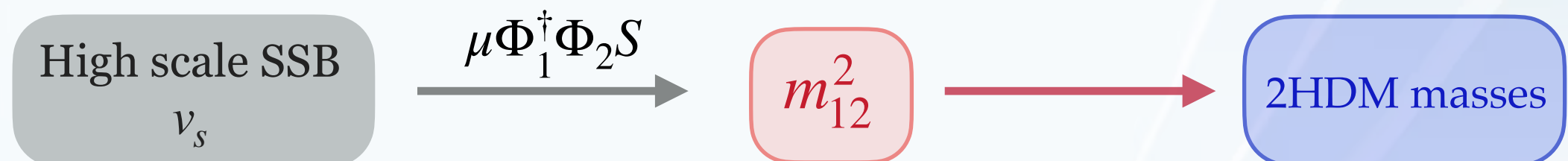
After SSB, the field gets a VEV v_s which is unrelated to the EW vev. $S = v_s + h_s$

The Charged and Pseudoscalar mass obtained after the EWSB as,

$$m_C^2 = \frac{\mu v_s}{\sin \beta \cos \beta} - \frac{v^2}{2}(\lambda_4 + \lambda_5), \quad m_A^2 = \frac{\mu v_s}{\sin \beta \cos \beta} - \lambda_5 v^2$$

Matching to the low-energy 2HDM gives,

$$\Lambda^2 = \frac{\mu v_s}{\sin \beta \cos \beta} \quad m_{12}^2 = \mu v_s$$



The CP-even mass matrix become 3×3 with three eigenstates $\begin{pmatrix} h_1 \\ h_2 \\ h_s \end{pmatrix} \rightarrow \begin{pmatrix} h \\ H_1 \\ H_2 \end{pmatrix}$

The transformation to the physical basis from the Higgs basis is expressed as, $\begin{pmatrix} h \\ H_1 \\ H_2 \end{pmatrix} = \mathcal{O} \begin{pmatrix} H_0 \\ R_1 \\ R_2 \end{pmatrix}$, $\mathcal{O} = \mathcal{O}_\alpha \mathcal{O}_\beta^T$. $\mathcal{O}_\beta = \begin{pmatrix} \cos \beta & \sin \beta & 0 \\ -\sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{pmatrix}$

$$\mathcal{O}_\alpha = R_3 \cdot R_2 \cdot R_1; \quad R_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \epsilon' & \sin \epsilon' \\ 0 & -\sin \epsilon' & \cos \epsilon' \end{pmatrix} \quad R_2 = \begin{pmatrix} \cos \epsilon & 0 & \sin \epsilon \\ 0 & 1 & 0 \\ -\sin \epsilon & 0 & \cos \epsilon \end{pmatrix}; \quad R_1 = \begin{pmatrix} \cos \alpha & \sin \alpha & 0 \\ -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The **alignment condition** in the full theory now translates to,

$$\cos(\alpha - \beta) = 1, \quad \epsilon = 0.$$

The states R_1 and R_2 can still mix among themselves with ϵ' . The 2HDM limit is thus obtained for

$$\epsilon' = 0$$



We define the following dimensionless quantity

$$f_X = \frac{m_X^2 - \Lambda^2}{m_X^2}, \quad X = H, A, C$$

or, equivalently, $\Lambda^2 = (1 - f_X)m_X^2$

- $f_X = 1$: Mass entirely associated with EWSB.
- $f_X = 0$: Mass entirely associated with Λ^2 .

In the alignment limit

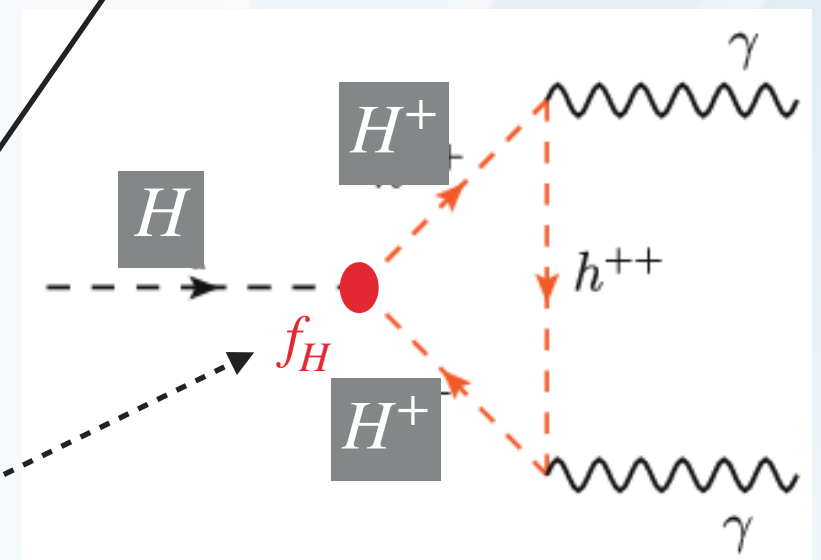
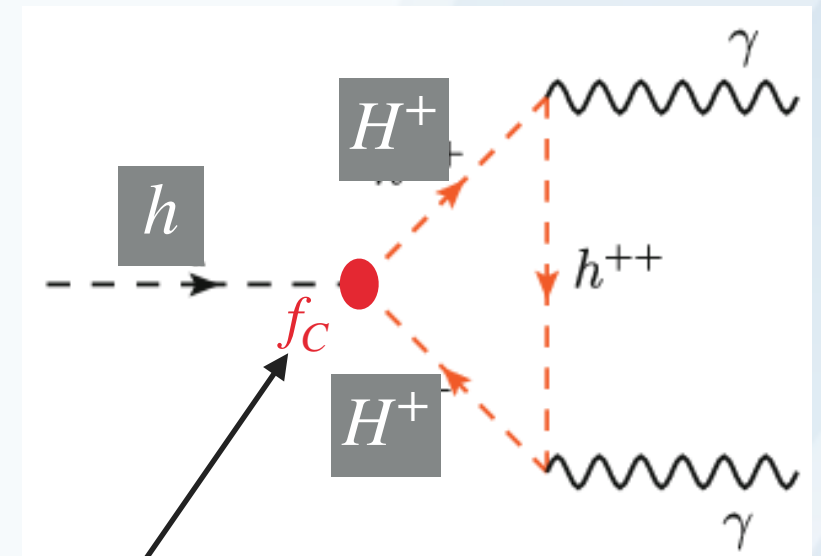
$$\lambda_{hH^+H^-} = -\frac{2}{v} \left(m_C^2 - \Lambda^2 - \frac{m_h^2}{2} \right) \equiv -\frac{2m_C^2}{v} \left(f_C + \frac{m_h^2}{2m_C^2} \right),$$

$$\lambda_{HH^+H^-} = \lambda_{HHH} = \lambda_{HAA} = -\frac{2}{v} (m_H^2 - \Lambda^2) \cot 2\beta \equiv -\frac{2m_H^2}{v} f_H \cot 2\beta$$

So the mass fraction parameters are not merely formal.

$$f_C \Rightarrow h \rightarrow \gamma\gamma$$

$$f_H \Rightarrow H \rightarrow \gamma\gamma$$



A parametrically heavy scalar cannot obtain most of its mass from electroweak symmetry breaking while remaining perturbative.

A particularly useful combination from BFB and unitarity condition,

$$0 \leq \lambda_1 + \lambda_2 \leq \frac{16\pi}{3} \Rightarrow$$

$$0 \leq f_H m_H^2 (\tan^2 \beta + \cot^2 \beta) + 2m_h^2 \leq \frac{16\pi v^2}{3}$$

Similarly from other conditions,

$$|f_A| m_A^2 < \frac{8\pi v^2}{3}, \quad |f_C| m_C^2 < \frac{8\pi v^2}{3}$$

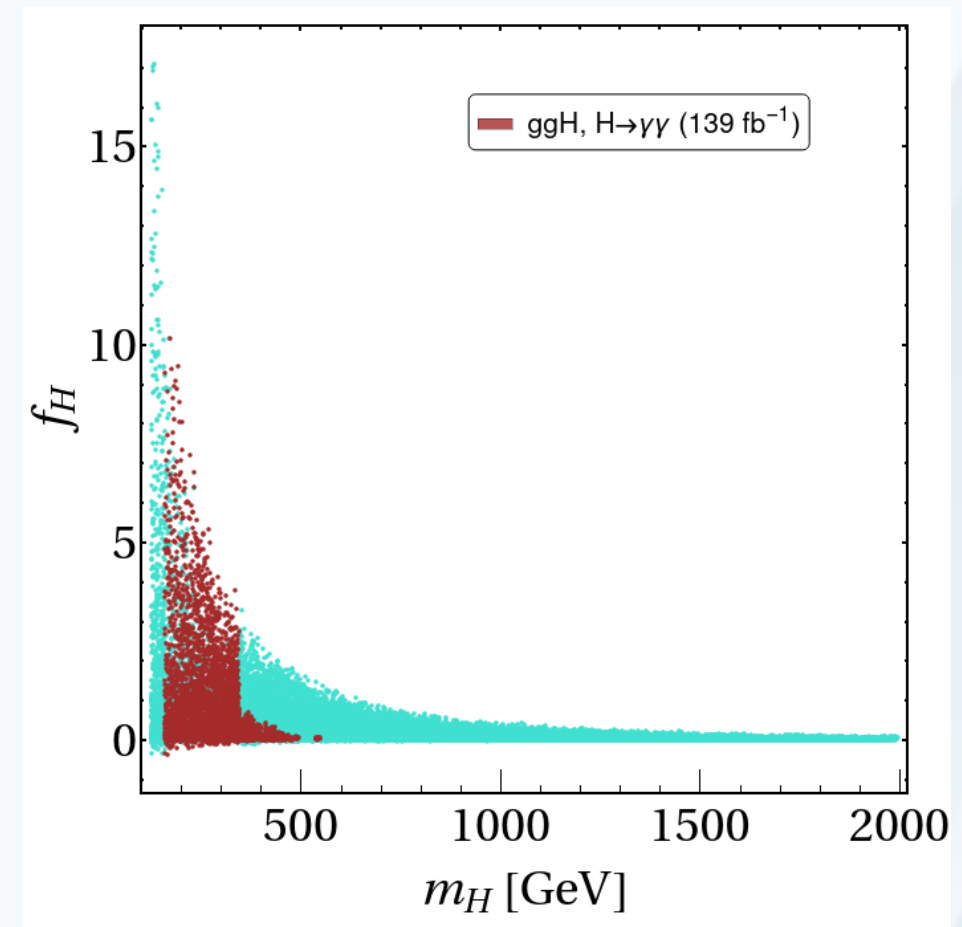
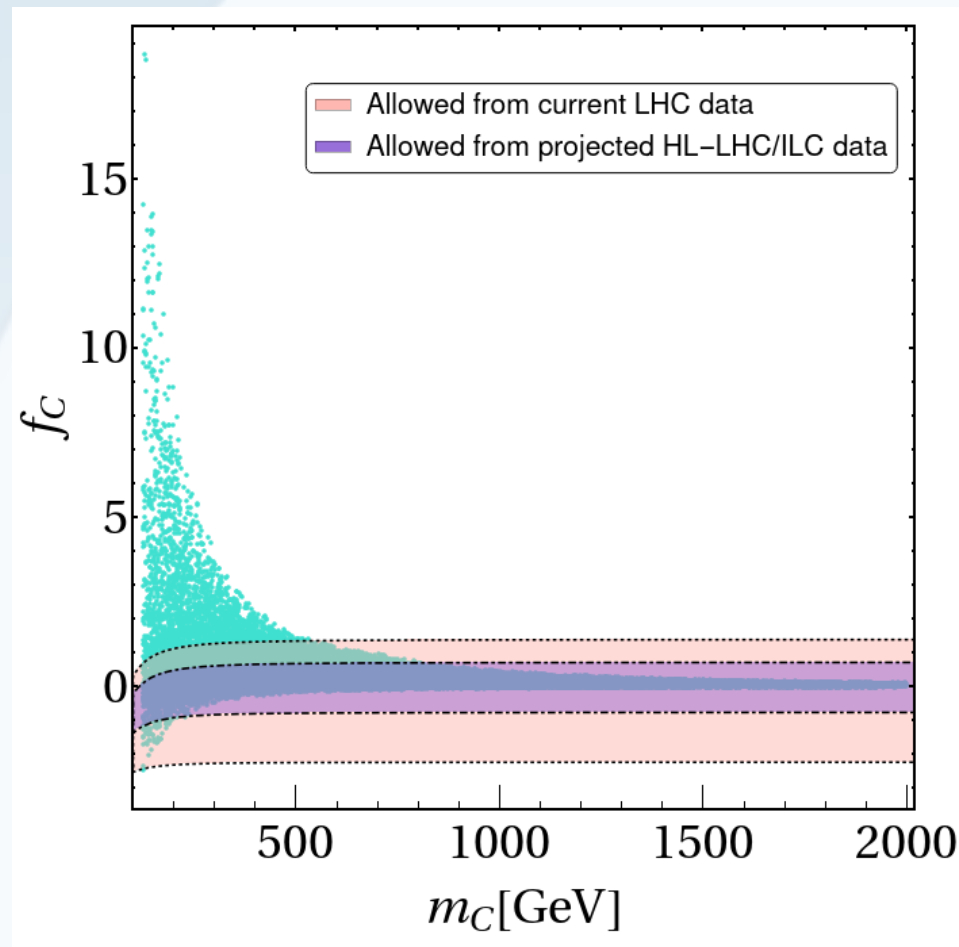
$$|f_X| < \frac{8\pi v^2}{3m_X^2} \longrightarrow$$

When $\Lambda^2 = 0 \Rightarrow f_X = 1$, the nonstandard mass m_X is directly bounded from above at O(TeV) scale.

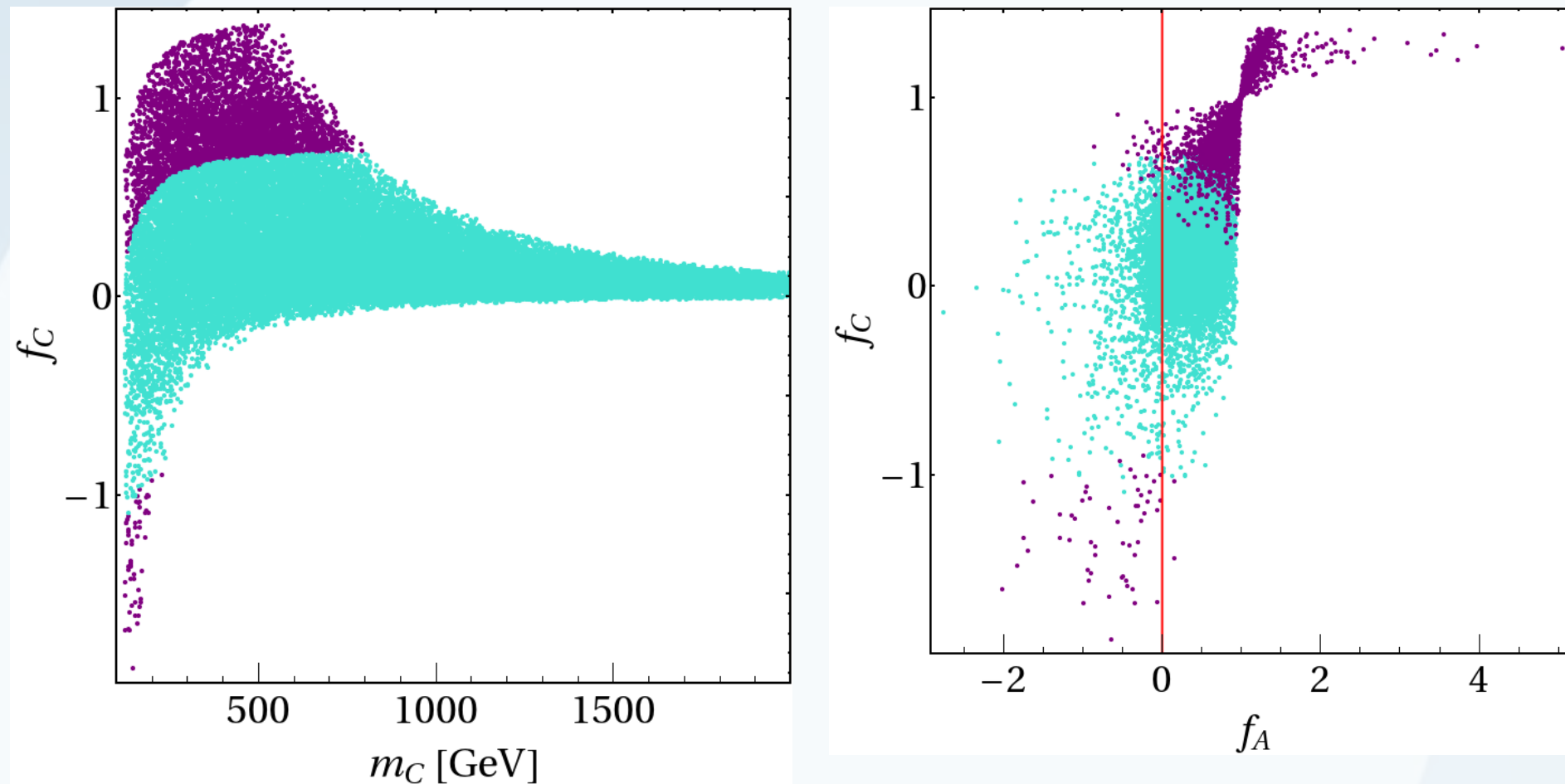
Hence, it implies,

$$m_X^2 \gg v^2, \quad f_X \approx 0$$

Conversely, $m_X \geq 1$ TeV requires substantial non-EW contribution.



- Current and future projected limits from higgs to diphoton $h \rightarrow \gamma\gamma$ searches on $f_C - m_C$ plane.
- Current limits from heavy higgs to diphoton $H \rightarrow \gamma\gamma$ searches on $f_H - m_H$ plane.
- The heavy Higgs constraint is Yukawa structure dependent. This corresponds to Type-II 2HDM.



BFB + unitarity + T-parameter + total width + $\mu_{\gamma\gamma}$

- Current constraints already imply roughly $f_{H,A,C} \leq \mathcal{O}(1)$.
- Future precision in $\mu_{\gamma\gamma}$ will be able to probe in the regions $f_{H,A,C} \sim 1$.
- The red solid line refers to the softly broken U(1) symmetric 2HDM scenario.

The absence of deviations in the Higgs to diphoton observables is not merely a null search for new particles; it constrains the fraction of their masses that can originate from the electroweak symmetry breaking.

THANK YOU!

BACKUP

Z_3 symmetric complex singlet extension $\longrightarrow$ Soft $U(1)$ broken 2HDM

Consider a Complex singlet $\mathbb{S}$ to the Z_3 symmetric 2HDM and the transformation rules are,

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow \omega \Phi_2, \quad \mathbb{S} \rightarrow \omega^2 \mathbb{S}$$

The singlet field gets a VEV v_s ,

$$\mathbb{S} = v_s + \frac{1}{\sqrt{2}} (h_s + iz_s)$$

Here, matching with charged scalar sector

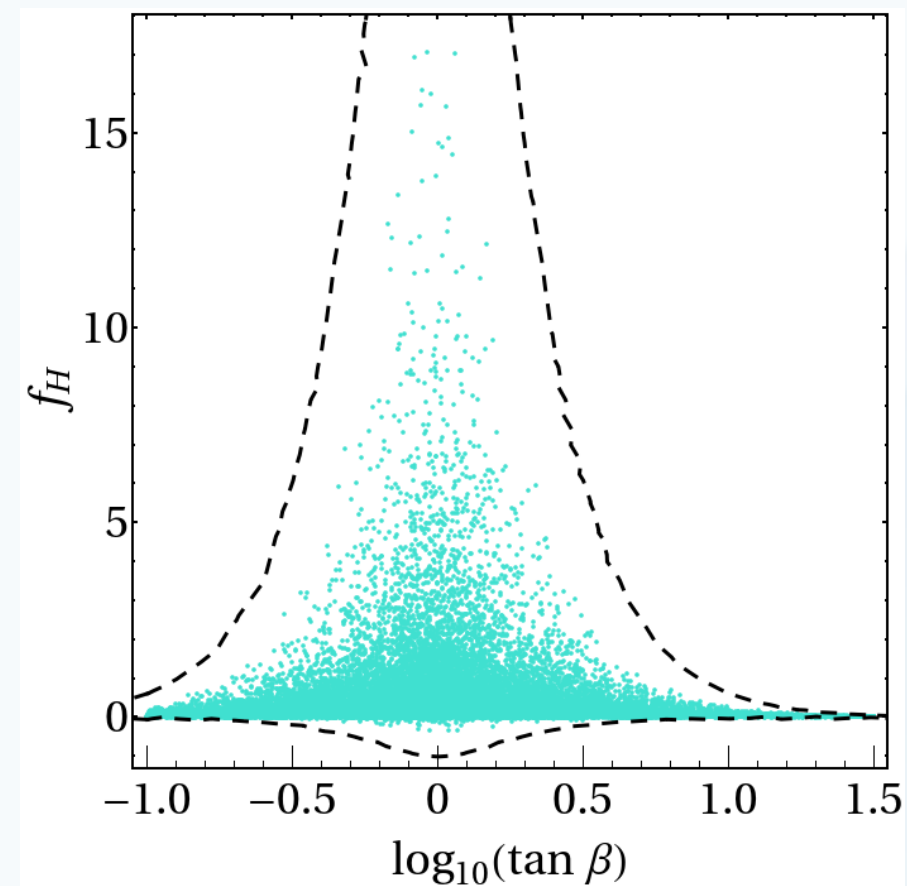
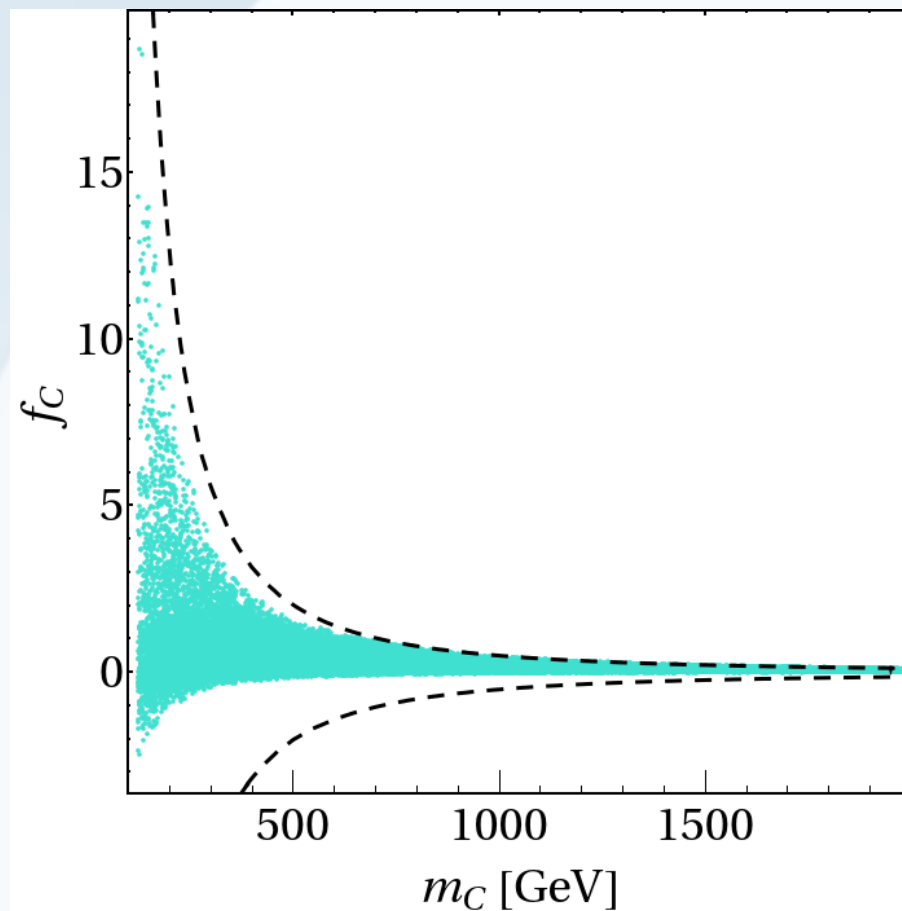
$$m_{12}^2 = (\mu v_s + \lambda_{4s} v_s^2) = \Lambda^2 \sin \beta \cos \beta$$

Both the CP-odd and CP-even mass matrices are 3×3 , thus 2HDM limit become,

$$\cos(\alpha - \beta) = 1, \quad \epsilon = 0, \quad \epsilon' = 0, \quad \delta = 0$$

δ is the pseudo-scalar mixing angle and in the softly broken $U(1)$ limit,

$$\Lambda^2 = m_{A_1}^2$$



The scan applies:

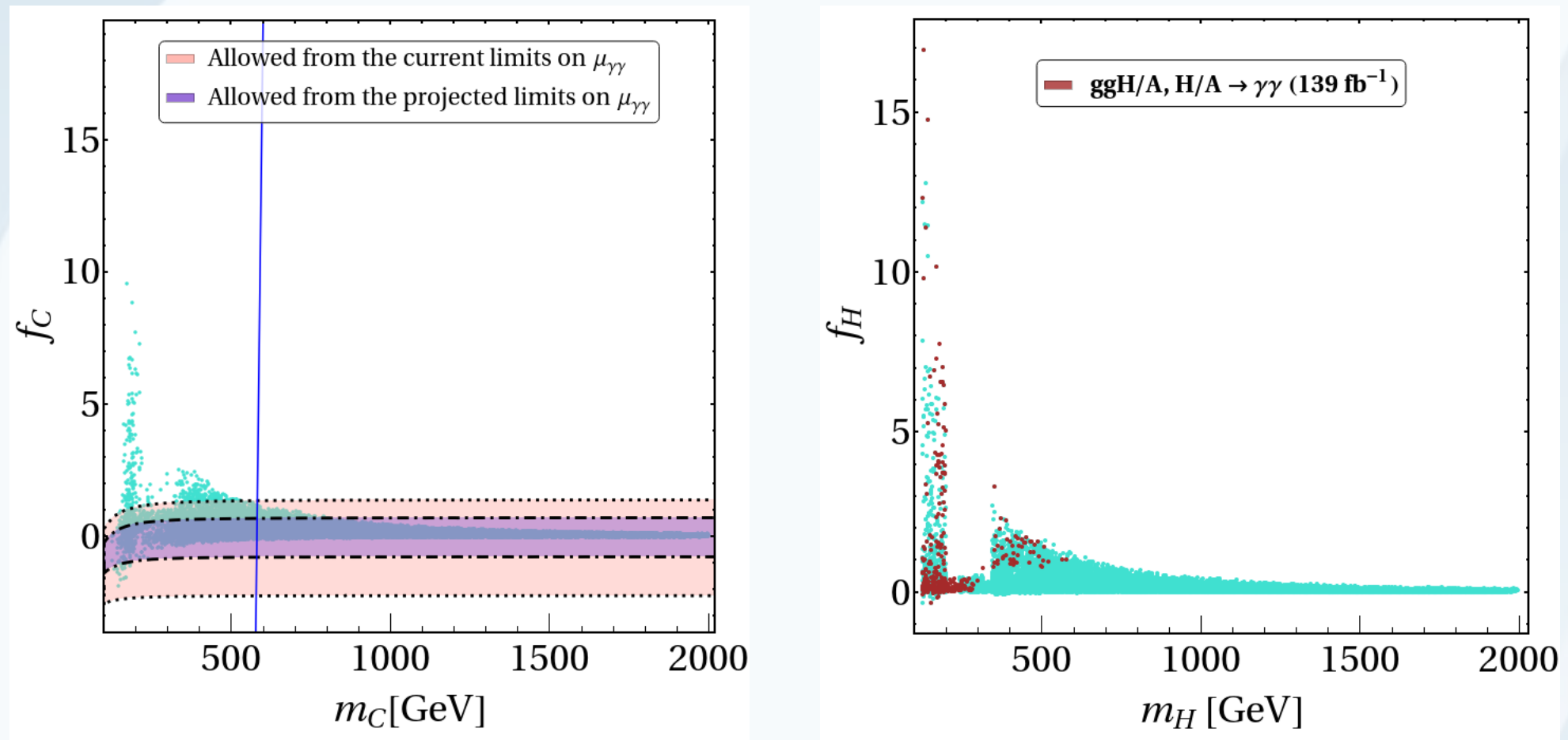
- BFB + perturbative unitarity;
- electroweak T-parameter;
- Alignment limit.

Independent Inputs

$$\{m_H, m_A, m_C, \tan \beta, \Lambda\}$$

- The outer contours corresponds to the unitarity constraints on f_X derived previously.
- This is Yukawa structure independent bounds.

$m_X \geq 1$ TeV requires substantial non-EW contribution as $f_X < 0.8$



- Same as previous but for Type-II 2HDM Yukawa structure.
- Additional constraints from direct LHC searches in fermionic channels are incorporated which excludes some parameter space. Also, the solid line corresponds to the b-physics flavor constraints.
- Even with all additional direct LHC search constraints, the relevance of $h \rightarrow \gamma\gamma$ on the mass fraction is visible.