NEW PHYSICS IMPLICATIONS OF VECTOR BOSON FUSION SEARCHES

EXEMPLIFIED THROUGH THE GEORGI-MACHACEK MODEL

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WORKSHOP ON MULTI-HIGGS MODELS, SEPT. 3-6, 2024

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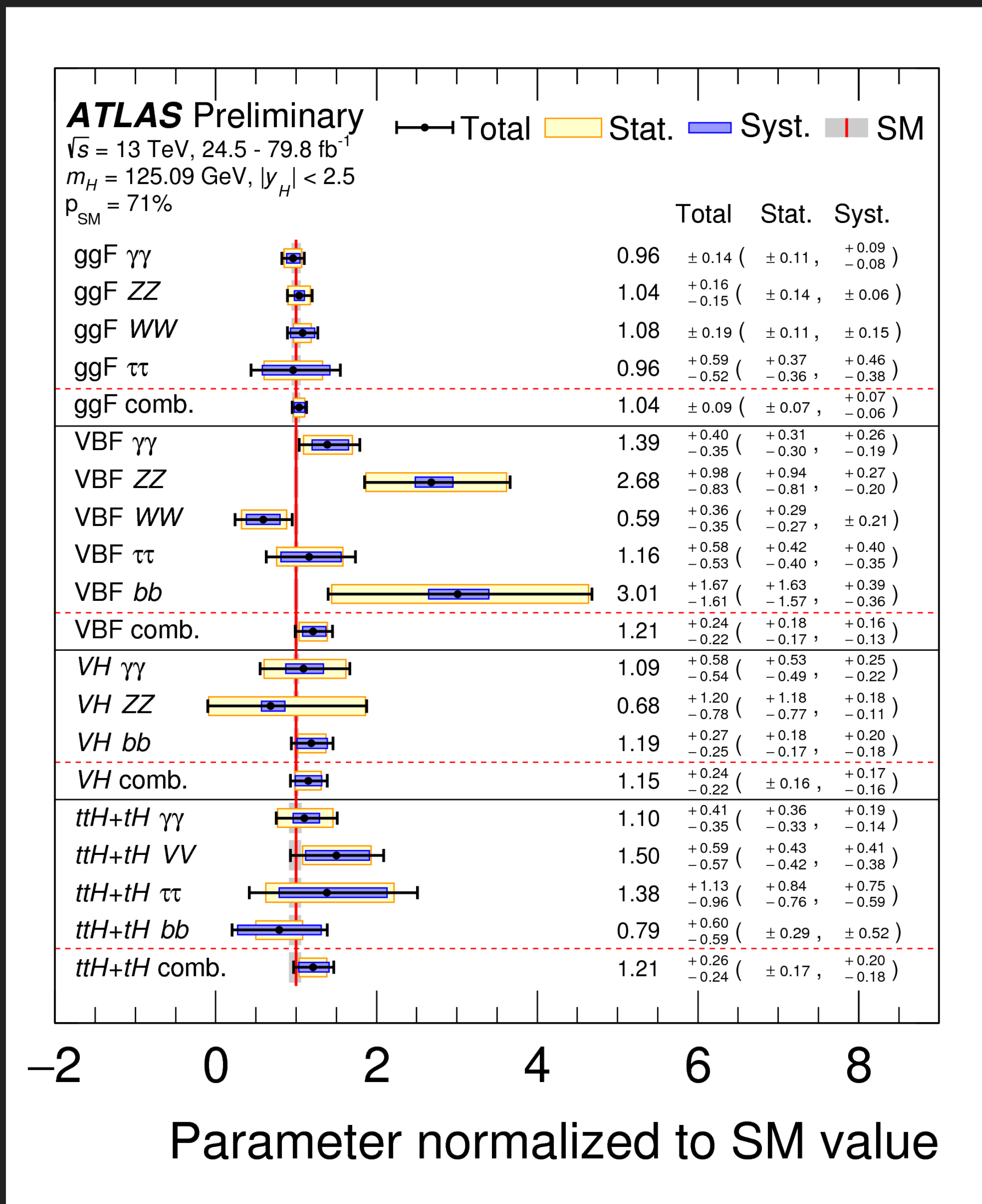
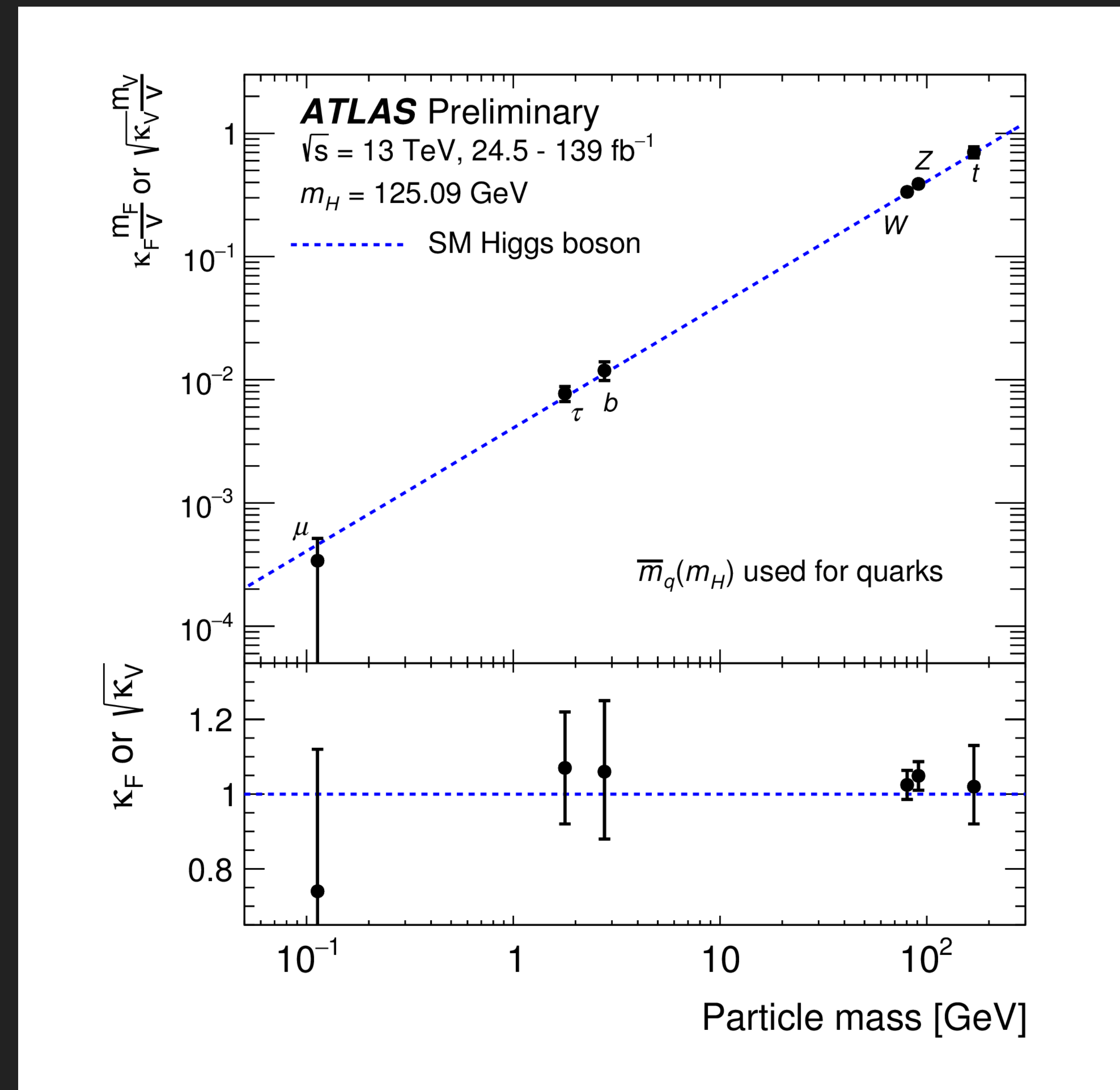
SM HIGGS SEARCHES





DARK MATTER, MATTER-ANTIMATTER ASYMMETRY, NONZERO NEUTRINO MASS ETC. → CALLS FOR BSM PHYSICS. → OFTEN COMES WITH EXTENSION OF THE HIGGS SECTOR.

ELECTROWEAK SYMMETRY BREAKING

THE ELECTROWEAK 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

WHAT KIND OF $SU(2)_L$ MULTIPLETS CONTRIBUTE TO THE ELECTROWEAK VEV AND TO WHAT DEGREE??

INSIGHT INTO THE COMPOSITION OF ELECTROWEAK VEV

Nonstandard contribution to EW vev can only arise from scalar multiplets transforming non-trivially under SM SU(2).

Scalar singlets →

Neutral singlets do not couple to W/Z bosons. Their vevs do not contribute to EW vev.

Charged singlets do not develop VEVs.

INSIGHT INTO THE COMPOSITION OF ELECTROWEAK VEV

How much the non-doublet contribution is there in the EW vev?

In certain cases, constraints can arise from EW ρ-parameter :
Example- Higgs Triplet Model.

Higher multiplets can be arranged such that $\rho = 1$ at the tree-level.

Restoring custodial symmetry (GM model)

Ref: Georgi and Machacek '1985

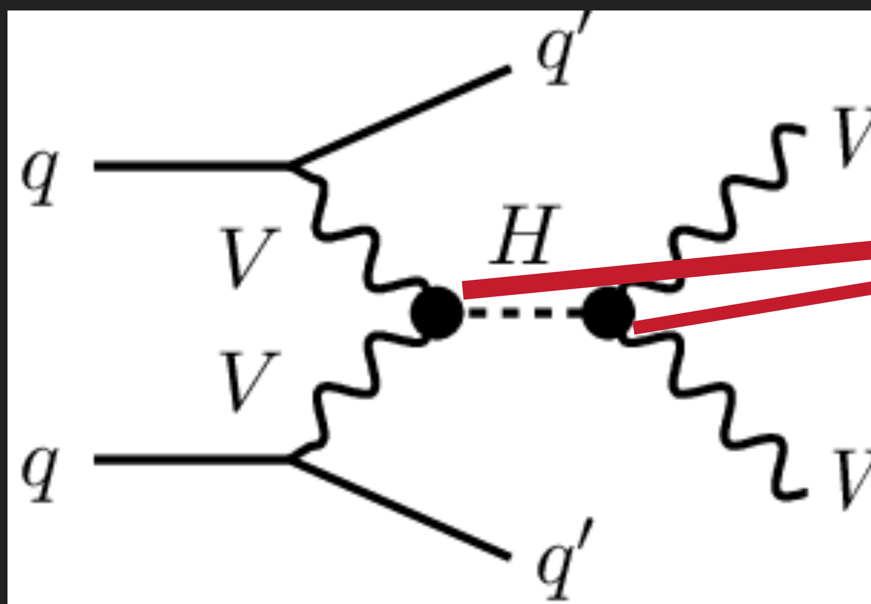
Ref: Chiang and Yagyu '18

accidental cancellation.

Hence, the constraints from the ρ-parameter will not be effective in constraining the vevs from these multiplets. → Plan B!?

IMPLICATIONS FROM VBF SEARCHES : AN ALTERNATIVE PROBE

Non-standard scalar searches in the vector-boson fusion processes can be crucial.



Dimensionful couplings

$$HV_\mu V^\mu \sim g v_H$$

v_H: Vev of the scalar multiplet from which H is primarily derived!

Higher vev v_H enhances the observational prospects of H

NON-OBSERVATION OF H LEADS TO AN UPPER BOUND ON v_H (MASS DEPENDENT)

Multihiggs doublet → HVV coupling vanishes in the 'alignment limit'.

EXAMPLE BSM
GEORGI-MACHACEK MODEL

GEORGI-MACHACEK MODEL

Consists of a one SU(2) complex doublet (Y=1), one real triplet (Y=0) and one complex triplet (Y=1)

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{-} & \phi^{0} \end{pmatrix}, \qquad X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{-} & \xi^{0} & \chi^{+} \\ \chi^{--} & -\xi^{-} & \chi^{0} \end{pmatrix}.$$

$* \; Q = T_3 + Y$

The neutral components expanded around their vevs,

$\sqrt{v_d^2 + 8v_t^2} = v = 246 \text{ GeV}$

$$\phi^0 = \frac{1}{\sqrt{2}}(v_d + h_d + i\eta_d), \quad \xi^0 = (v_t + h_\xi), \quad \chi^0 = \left(v_t + \frac{h_\chi + i\eta_\chi}{\sqrt{2}}\right).$$

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$$* \, Q = T_3 + \frac{Y}{2}$$

The neutral components expanded around their vevs,

$$\sqrt{v_d^2 + 8v_t^2} = v = 246 \text{ GeV}$$

$$\phi^0 = \frac{1}{\sqrt{2}}(v_d + h_d + i\eta_d), \quad \xi^0 = (v_t + h_\xi), \quad \chi^0 = \left(v_t + \frac{h_\chi + i\eta_\chi}{\sqrt{2}}\right).$$

Physical scalars can be categorized based on their transformation properties under the global custodial SU(2)

A custodial fiveplet with common mass m_5 → $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$

A custodial triplet with common mass m_3 → $(H_3^{+}, H_3^{0}, H_3^{-})$

Two custodial singlets with mass m_h & m_H → (h, H)

GEORGI-MACHACEK MODEL

The quartic couplings in terms of the physical mass and mixings:

$$\lambda_1 = \frac{1}{8v^2\cos^2\beta}\left(m_h^2\cos^2\alpha + m_H^2\sin^2\alpha\right),$$

$$\lambda_2 = \frac{1}{12v^2\cos\beta\sin\beta}\left(\sqrt{6}\left(m_h^2 - m_H^2\right)\sin 2\alpha + 12m_3^2\sin\beta\cos\beta - 3\sqrt{2}v\cos\beta M_1\right),$$

$$\lambda_3 = \frac{1}{v^2\sin^2\beta}\left(m_5^2 - 3m_3^2\cos^2\beta + \sqrt{2}v\cos\beta\cot\beta M_1 - 3\sqrt{2}v\sin\beta M_2\right),$$

$$\lambda_4 = \frac{1}{6v^2\sin^2\beta}\left(2m_H^2\cos^2\alpha + 2m_h^2\sin^2\alpha - 2m_5^2 + 6\cos^2\beta m_3^2 - 3\sqrt{2}v\cos\beta\cot\beta M_1 + 9\sqrt{2}v\sin\beta M_2\right),$$

$$\lambda_5 = \frac{2m_3^2}{v^2} - \frac{\sqrt{2}M_1}{v\sin\beta}.$$

$$\tan\beta = \frac{2\sqrt{2}v_t}{v_d}$$

Seven Lagrangian parameters. Two bilinears, five quartic couplings.

→

Two vevs (v_t, v_d), 4 physical scalar masses $(m_5, , m_3, m_H, m_h)$ and one mixing angle α.

Two trilinear couplings M_1 & M_2 are independent parameters

THEORETICAL CONSTRAINTS

THEORETICAL CONSTRAINTS: UNITARITY

$$x_1^{\pm} = 12\lambda_1 + 14\lambda_3 + 22\lambda_4 \pm \sqrt{(12\lambda_1 - 14\lambda_3 - 22\lambda_4)^2 + 144\lambda_2^2}\,,$$
$$x_2^{\pm} = 4\lambda_1 - 2\lambda_3 + 4\lambda_4 \pm \sqrt{(4\lambda_1 + 2\lambda_3 - 4\lambda_4)^2 + 4\lambda_5^2}\,,$$

$$\begin{aligned} y_1 &= 16\lambda_3 + 8\lambda_4\,, \\ y_2 &= 4\lambda_3 + 8\lambda_4\,, \\ y_3 &= 4\lambda_2 - \lambda_5\,, \\ y_4 &= 4\lambda_2 + 2\lambda_5\,, \\ y_5 &= 4\lambda_2 - 4\lambda_5\,. \end{aligned}$$

The theoretical constraints from perturbative unitarity requires that each of these eigenvalues must obey the conditions $|x_i|^{\pm}, |y_i| < 8\pi$

In the decoupling limit, $v_t \ll v$

Hartling, Kumar, Logan PRD 90, 015007' 2014

The unitarity conditions can be trivially satisfied in the `Decoupling limit'

$$\sin 2\alpha \approx \sqrt{\frac{3}{2}}\sin 2\beta \qquad \text{with} \quad v_t \ll v$$
$$\text{and} \qquad m_H^2 \approx m_3^2 \approx m_5^2 \approx \Lambda_1^2 \gg v^2\,; \quad \Lambda_2^2 \ll v^2\,.$$

$$\begin{aligned} \Lambda_1^2 &= \frac{M_1 v}{\sqrt{2}\sin\beta} \equiv \frac{M_1 v^2}{4 v_t}\,, \\ \Lambda_2^2 &= 3\sqrt{2}\, v\, M_2 \sin\beta \equiv 12\, v_t M_2\,. \end{aligned}$$

Variants of the GM model without the trilinear couplings M1 and M2, do not have a decoupling limit.

D. Das, IS 'PRD 98, 095010, 2018

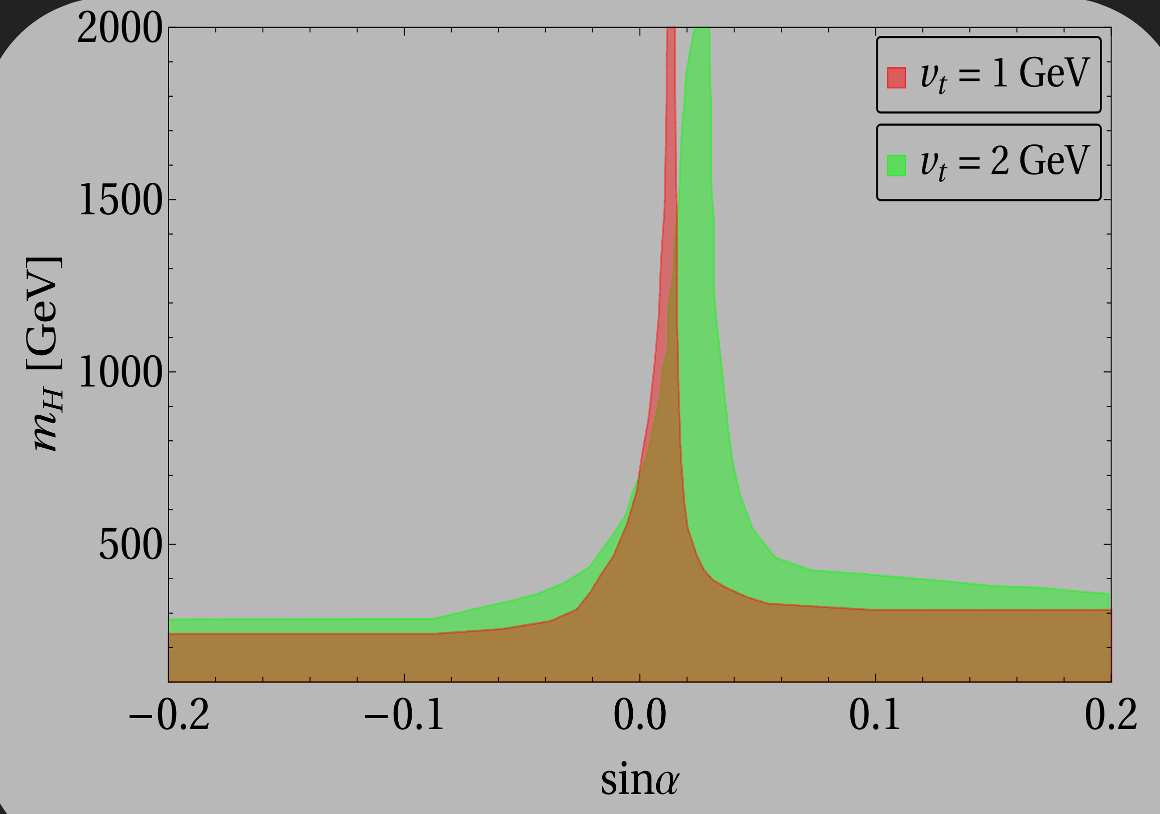
UNITARITY, BFB & DECOUPLING LIMIT

$$\sin 2\alpha \approx \sqrt{\frac{3}{2}}\sin 2\beta \qquad \text{with} \quad v_t \ll v$$

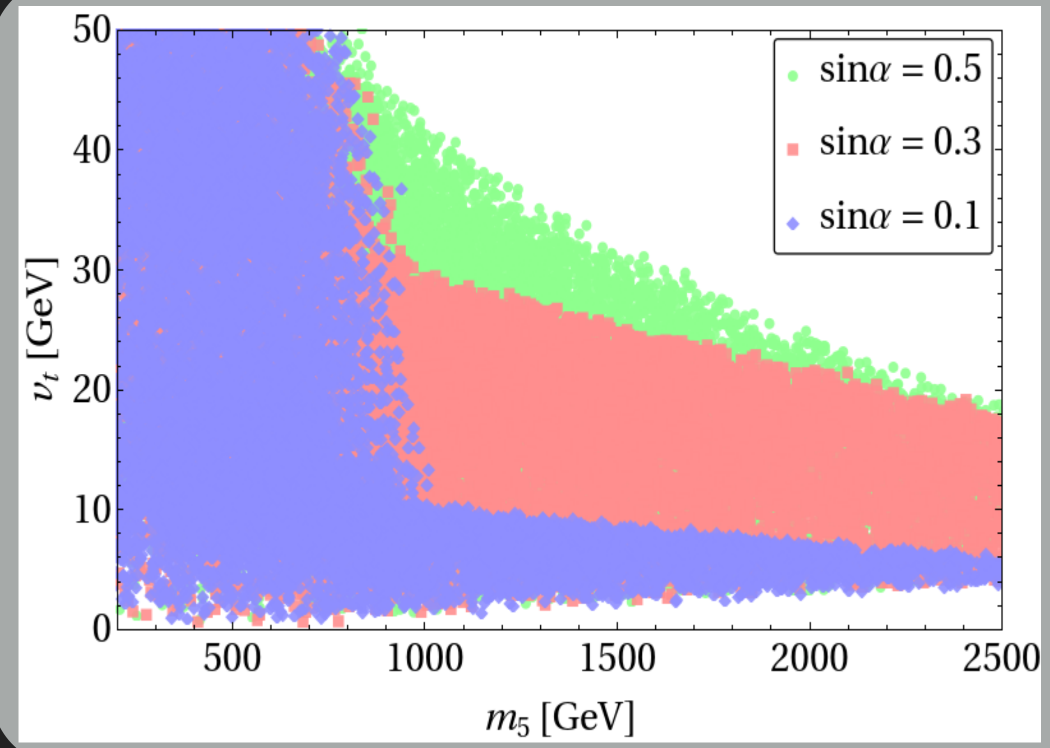
$$\tan\beta = \frac{2\sqrt{2}v_t}{v_d}$$

$$m_H^2 \approx m_3^2 \approx m_5^2 \approx \Lambda_1^2 \gg v^2\,; \quad \Lambda_2^2 \ll v^2$$

$$\sin\alpha \approx 2\sqrt{3}\,\frac{v_t}{v}$$



For $v_t \ll v$, heavy non-standard scalars beyond the TeV scale would require $\sin\alpha$ to be strongly correlated to v_t.



Different benchmark values for $\sin\alpha$ un-correlated to v_t leads to a lower bound on v_t.

NONSTANDARD COUPLINGS OF 125 GEV HIGGS IN DECOUPLING LIMIT

$$\sin 2\alpha \approx \sqrt{\frac{3}{2}}\sin 2\beta \qquad \text{with} \quad v_t \ll v$$

$$\tan\beta = \frac{2\sqrt{2}v_t}{v_d}$$

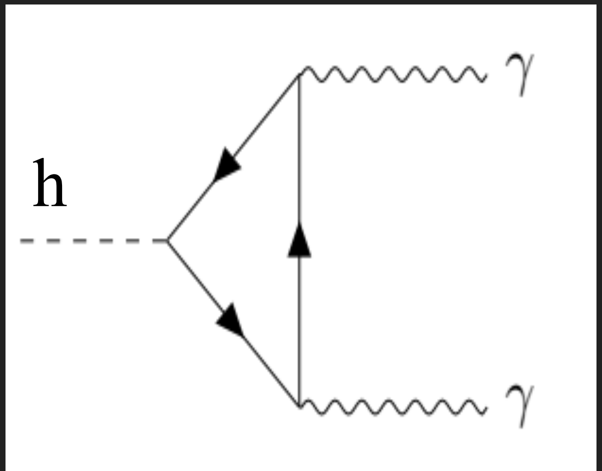
$$m_H^2 \approx m_3^2 \approx m_5^2 \approx \Lambda_1^2 \gg v^2\,; \quad \Lambda_2^2 \ll v^2$$

→

$$\sin\alpha \approx 2\sqrt{3}\,\frac{v_t}{v}$$

Higgs trilinear couplings with the charged scalars will contribute to loop induced Higgs decay

$$\begin{aligned}
\kappa_{3+} &\equiv \frac{v}{2m_3^2} g_{hH_3^+H_3^-} \approx -\frac{1}{m_3^2}\left(m_3^2 - \Lambda_1^2 + m_h^2\right)\,, \\
\kappa_{5+} &\equiv \frac{v}{2m_5^2} g_{hH_5^+H_5^-} \approx -\frac{1}{m_5^2}\left(2m_5^2 - 3m_3^2 + \Lambda_1^2 - \Lambda_2^2 + m_h^2\right)\,, \\
\kappa_{5++} &\equiv \frac{v}{2m_5^2} g_{hH_5^{++}H_5^{--}} \approx -\frac{1}{m_5^2}\left(2m_5^2 - 3m_3^2 + \Lambda_1^2 - \Lambda_2^2 + m_h^2\right)
\end{aligned}$$



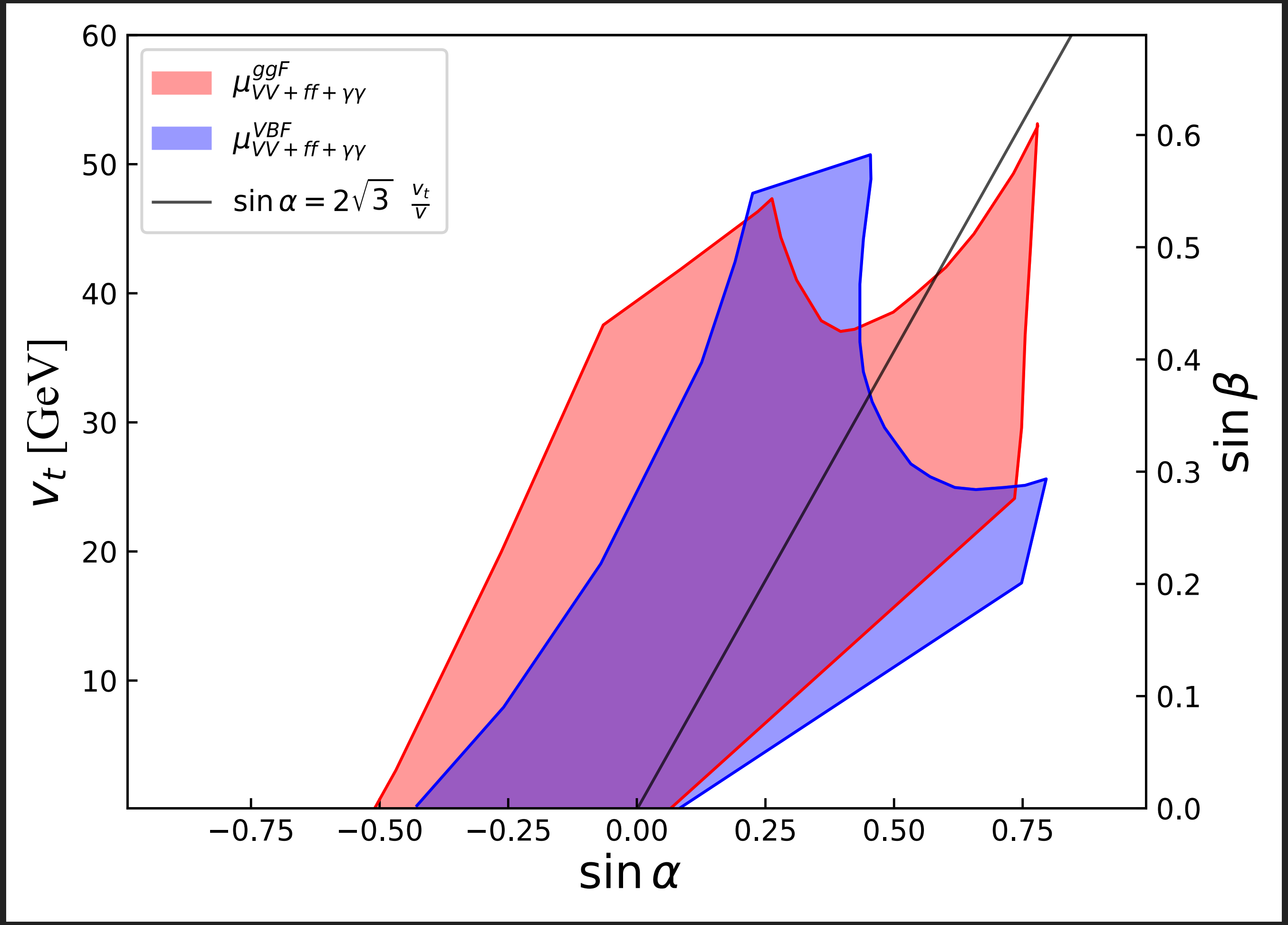
In the decoupling limit $\kappa_{3+}\,, \kappa_{5+}\,, \kappa_{5++} \approx 0$. It crucially depends on how $\sin\alpha \to 0$ is approached. Defines 'alignment with or without decoupling'.

LHC CONSTRAINTS

CONSTRAINTS FROM HIGGS DATA

The Higgs signal strength observables are defined as,

$$\mu_j^i = \frac{\sigma^i}{(\sigma^i)_{\rm SM}} \times \frac{BR_j}{(BR_j)_{\rm SM}},$$

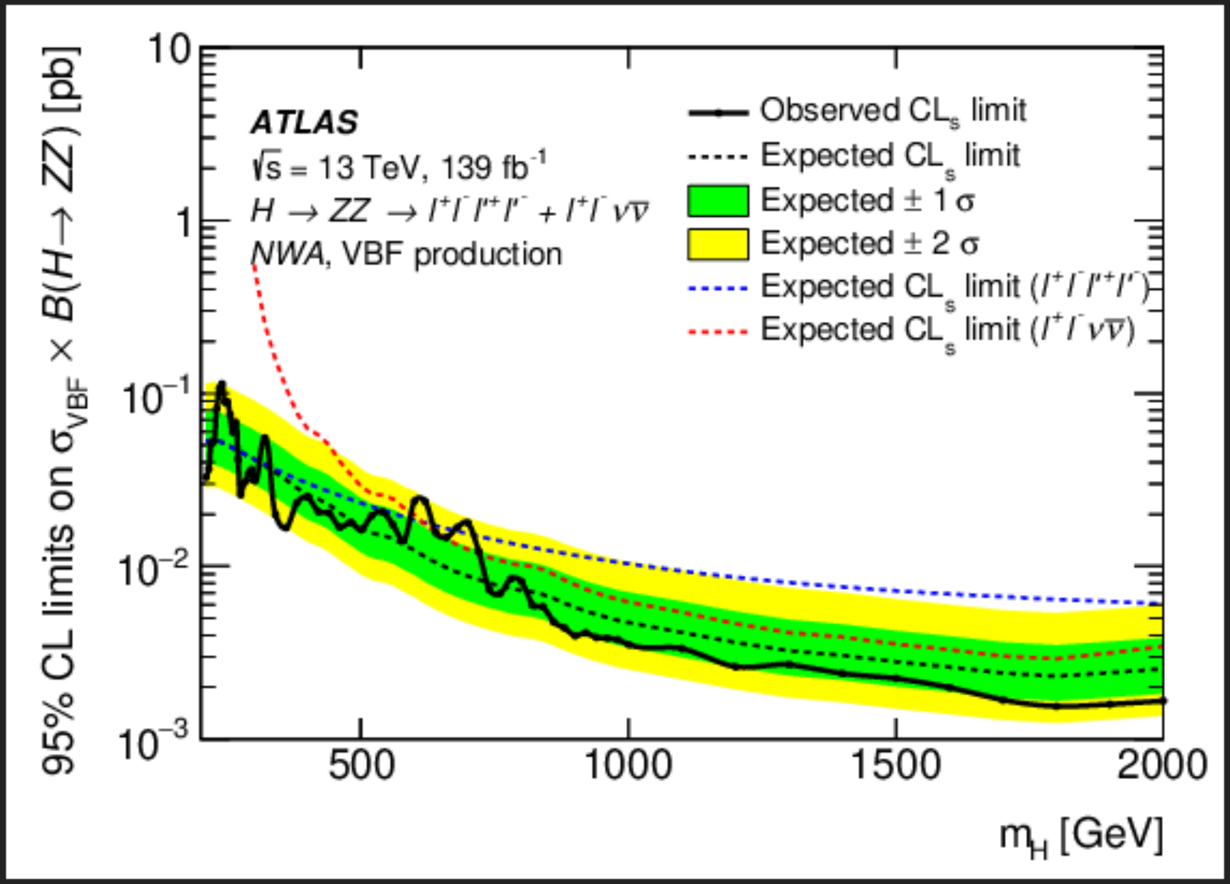


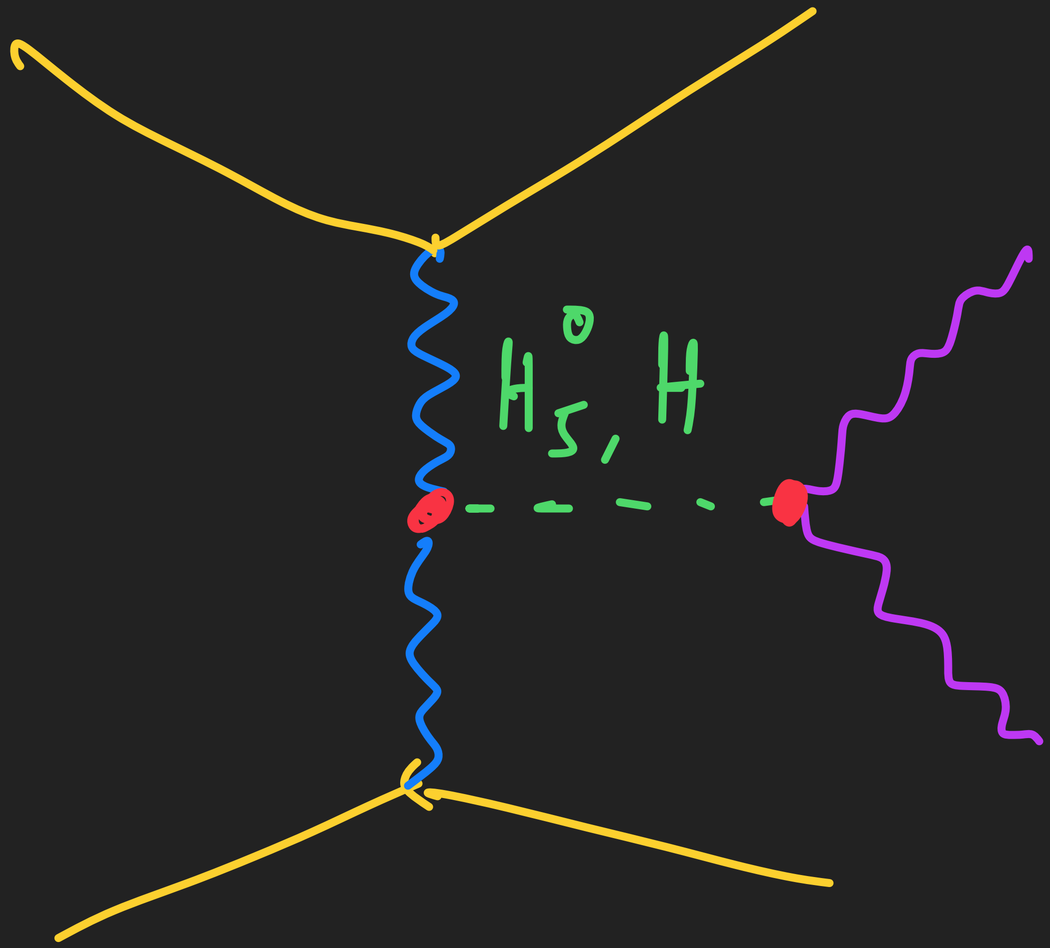
★ In the decoupling limit, the doublet-triplet mixing is vanishingly small and 'h' has SM-like couplings.

★ The allowed parameter space corresponds to the common overlapping region. Higgs data thus restricts v_t to a finite region with clearly defined upper and lower limits on it for a fixed $\sin\alpha$.

NON STANDARD SCALAR SEARCHES

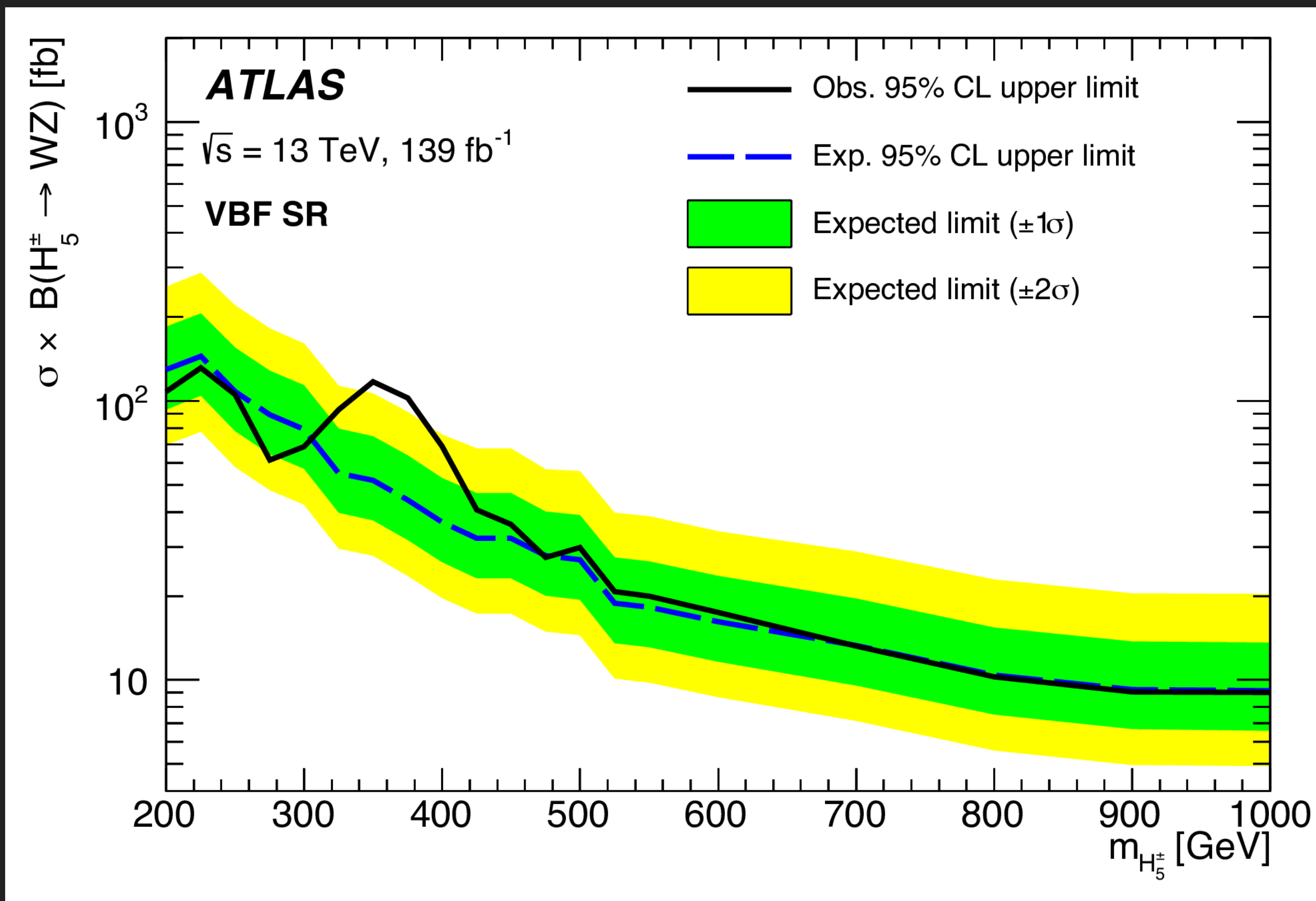
NONSTANDARD HIGGS DECAY (NEUTRAL)

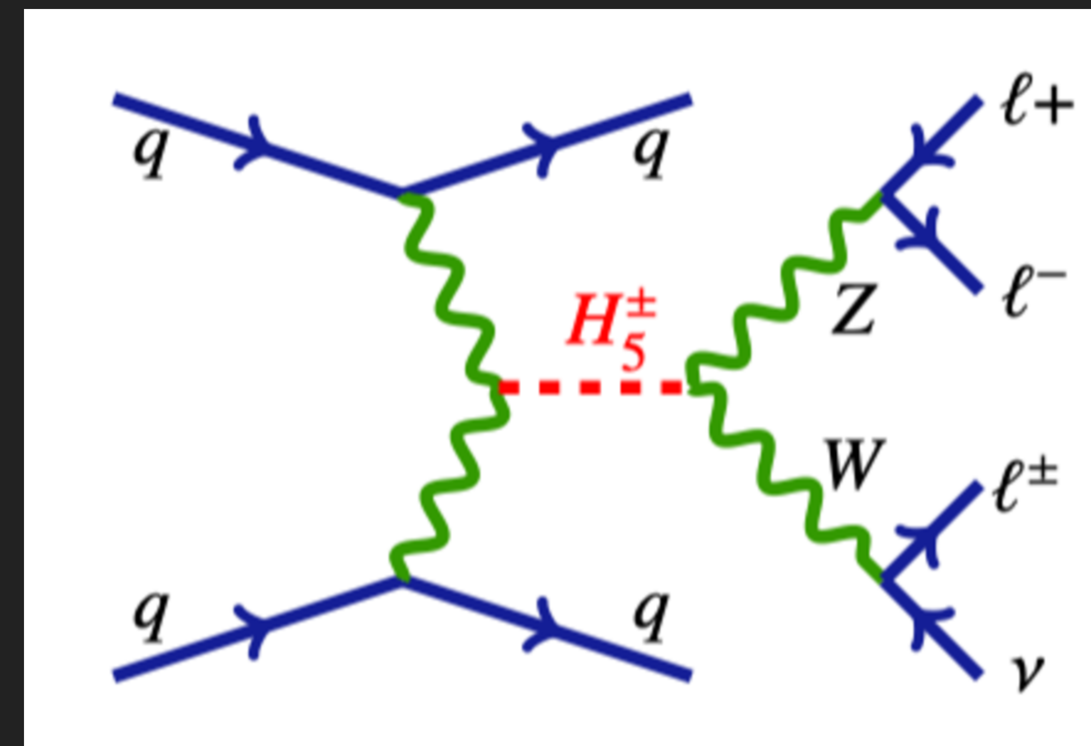




- Relevant signal channel for constraining H_5^0 in the $m_3 > m_5$ limit. In the opposite mass hierarchy, $H_5^0 \to H_3^0 Z, H_3^{\pm} W^{\mp}$ can be present.
- The heavy Higgs H can also decay to ZZ but narrow width approximation works only for low mass region.

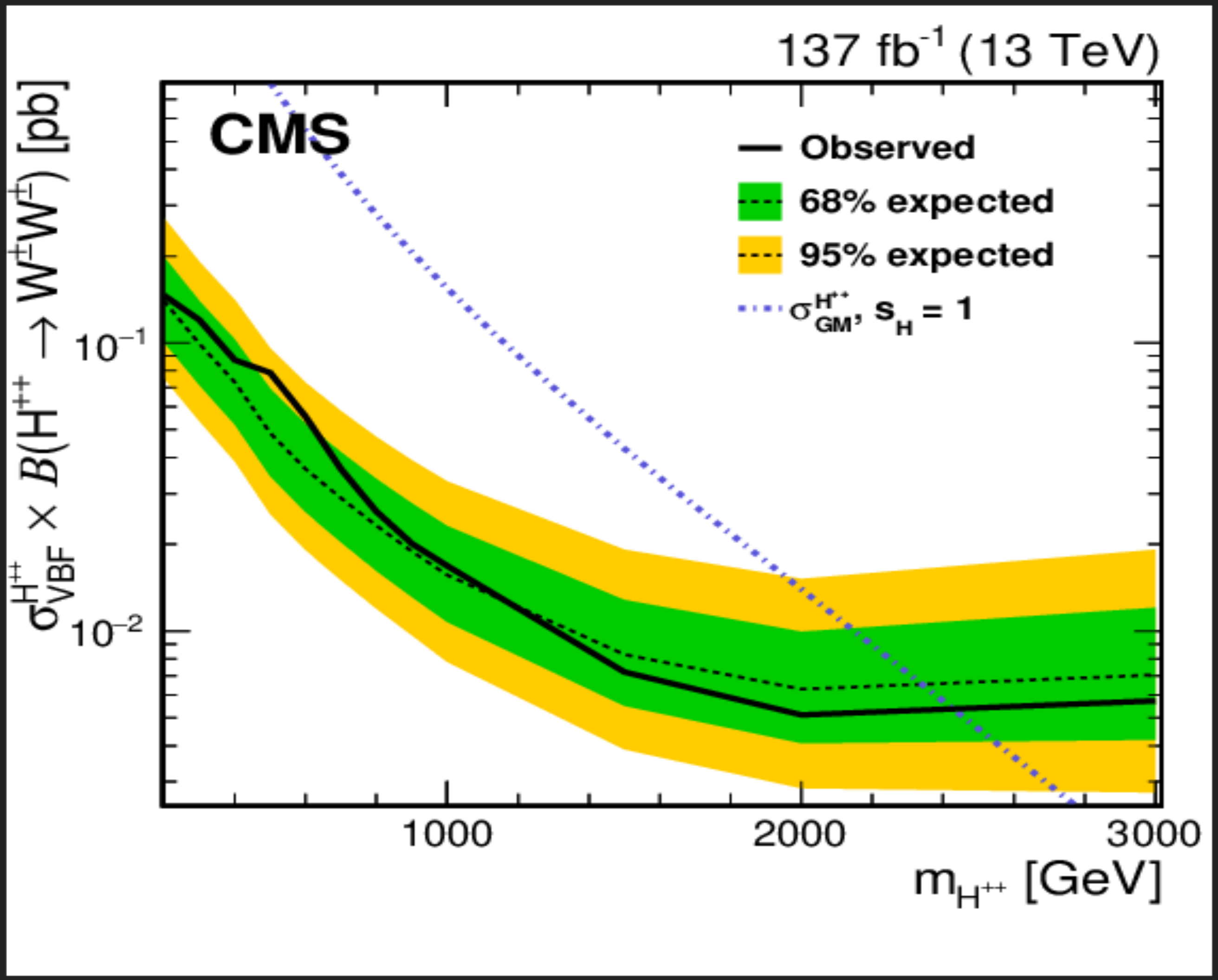
NONSTANDARD HIGGS DECAY (SINGLY CHARGED)

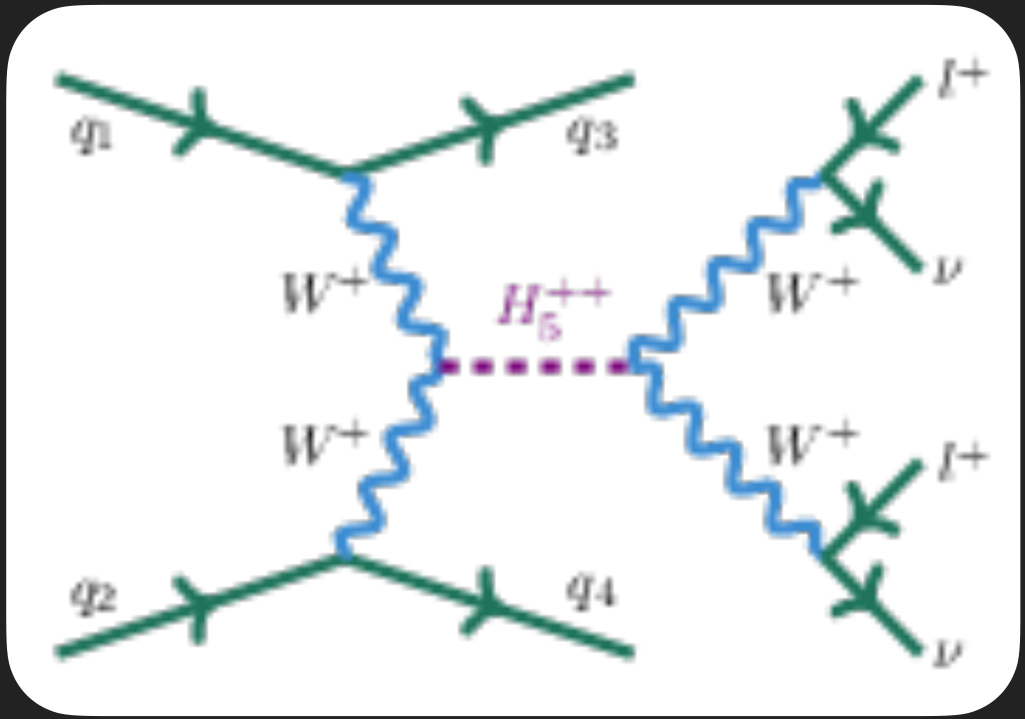




- Relevant signal channel for constraining H_5^+ which dominantly decays to WZ in the $m_3 > m_5$ limit.
- In the opposite mass hierarchy, decay modes of $H_5^\pm$ diversified and additional decays into $H_3^0 W^\pm$, $H_3^\pm Z$ final states are possible.

NONSTANDARD HIGGS DECAY (DOUBLY CHARGED)

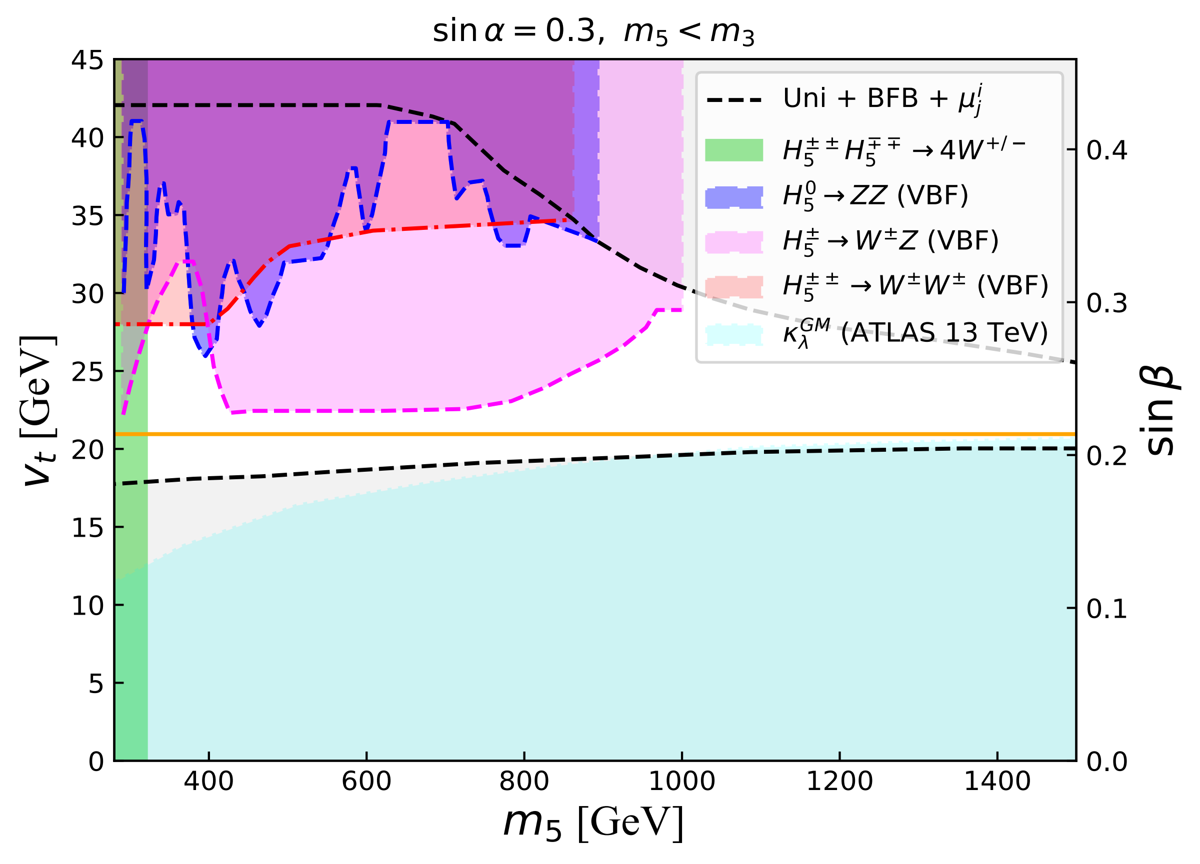


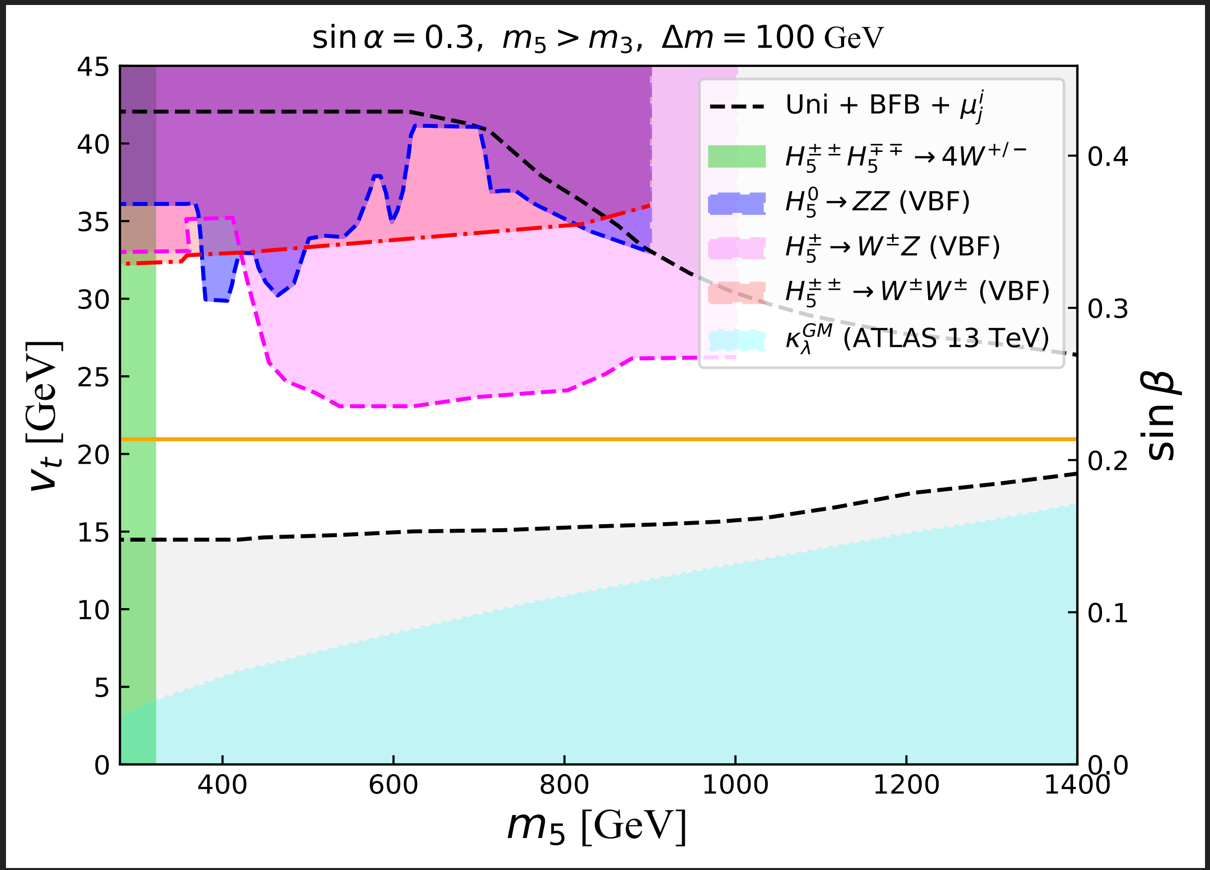


For ATLAS limit – See talk by Patricia

- The doubly charged scalar $H_5^{\pm}\pm$ dominantly decays to same sign W bosons in the $m_3 > m_5$ limit.
- In the opposite mass hierarchy, decay modes of $H_5^{\pm\pm}$ diversified and additional decays into $H_3^{\pm}W^{\pm}$ final states are possible.

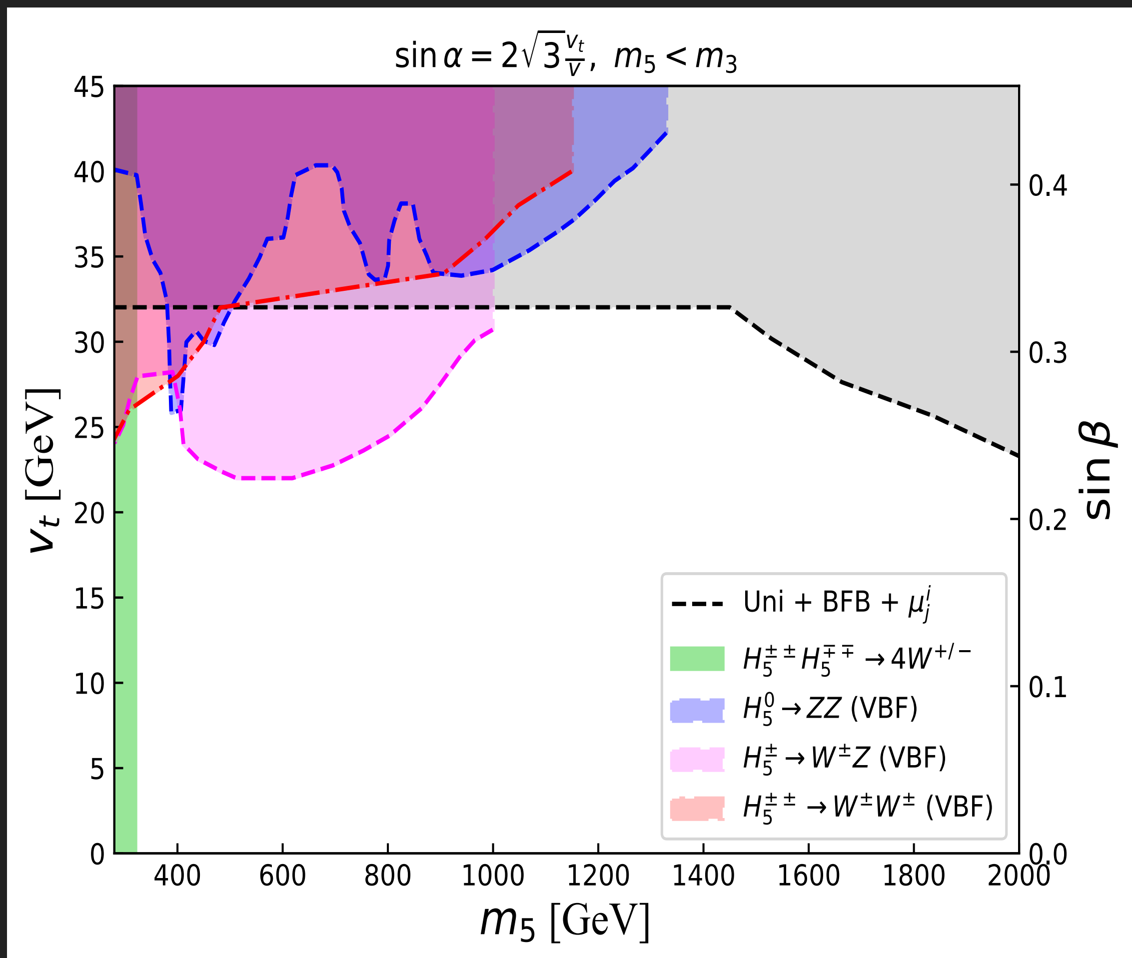
ALLOWED PARAMETER SPACE

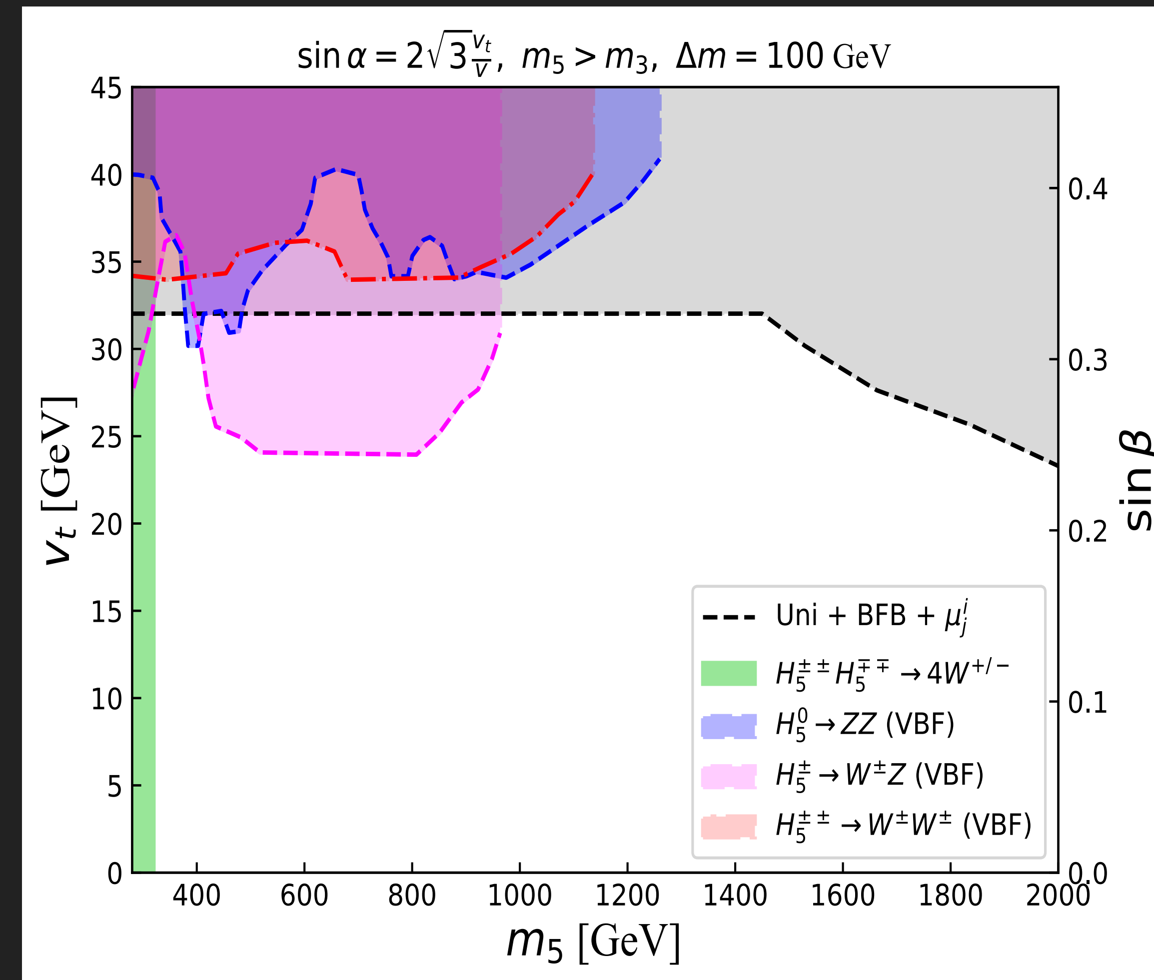




- Benchmarks for un-correlated $\sin\alpha - v_t$ range. Limits get stronger for larger $\sin\alpha$. Exclusions from Higgs self-coupling κ_h can be pronounced in the future.
- The limits are stronger in the $m_3 > m_5$ limit. In the alternate case, additional decay modes reduced the effective BR.
- The most stringent bound comes from charged Higgs to WZ channel. The vertical green patch is the Drell-Yan production of H_5^{++}.

ALLOWED PARAMETER SPACE

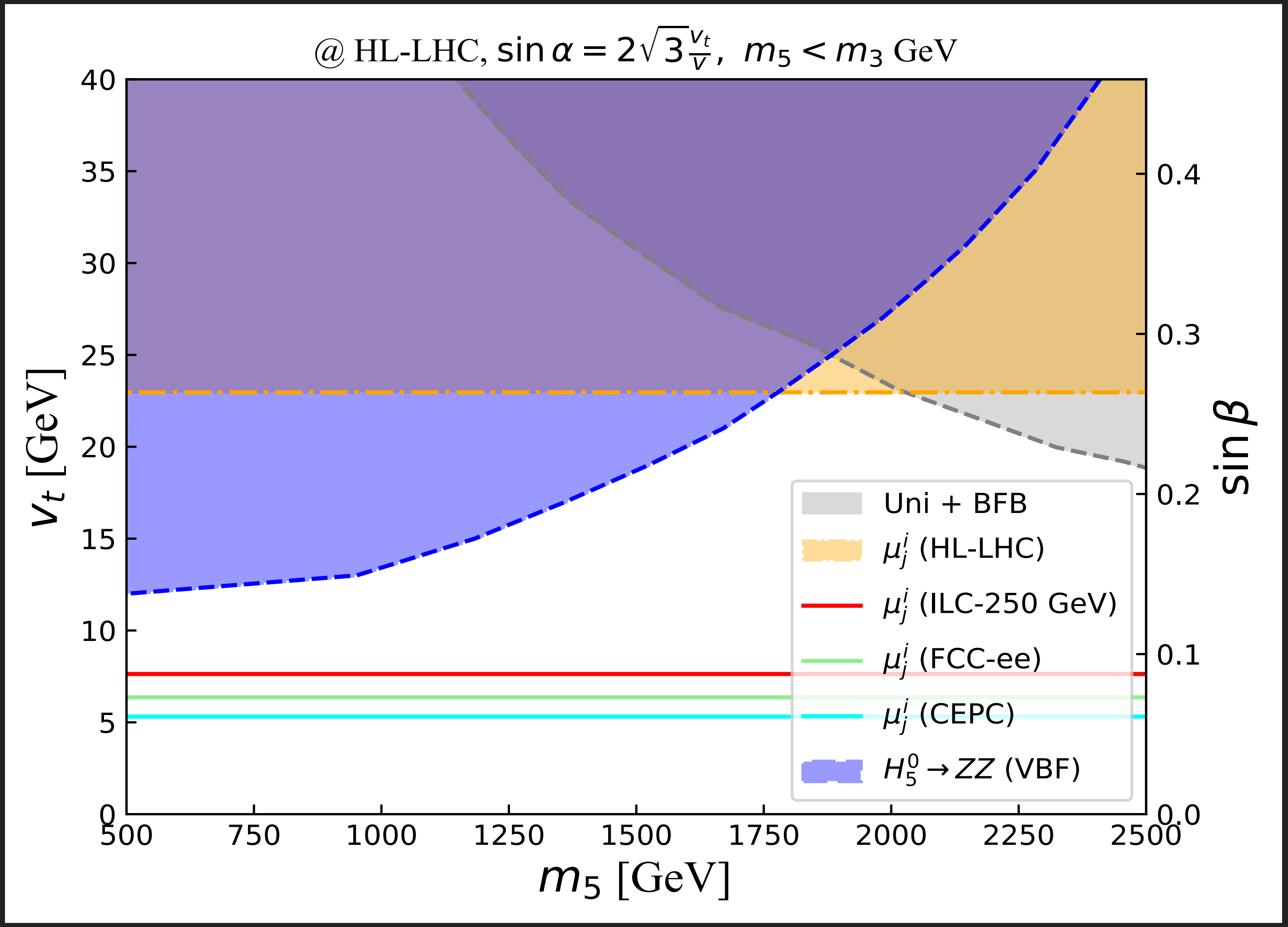




- Benchmarks for correlated $\sin\alpha - v_t$ range. Exclusions from Higgs self-coupling κ_h does not exist in the alignment with decoupling limit.
- The limits are stronger in the $m_3 > m_5$ limit similar to previous case.
- The most stringent bound comes from charged Higgs to WZ channel. No lower limit from unitarity and BFB.

FUTURE PROJECTIONS

- Combination of future Higgs precision data with direct VBF search can reduce the parameter space even further.
- The null observation of nonstandard Higgs searches from VBF production is not ‘null’. It provides important insights about the composition of EW vev.



SUMMARY

VBF searches for new scalars can give complementary bounds on the non doublet contribution to the electroweak vev.

Thank You!

BACK UPS

GEORGI–MACHACEK MODEL

The scalar potential is

$$
\begin{aligned}
V(\Phi, X) \quad = \quad & \frac{\mu_\phi^2}{2}\,\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_X^2}{2}\,\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\,\mathrm{Tr}(\Phi^\dagger\Phi)\,\mathrm{Tr}(X^\dagger X) \\
& + \lambda_3\,\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\,\mathrm{Tr}(\Phi^\dagger\tau_a\Phi\tau_b)\,\mathrm{Tr}(X^\dagger t_a X t_b) \\
& - M_1\,\mathrm{Tr}(\Phi^\dagger\tau_a\Phi\tau_b)\left(UXU^\dagger\right)_{ab} - M_2\,\mathrm{Tr}(X^\dagger t_a X t_b)\left(UXU^\dagger\right)_{ab} \ ,
\end{aligned}
$$

with $\tau_a \equiv \sigma_a/2$, $(a = 1,2,3)$ where σ_a's are the Pauli matrices and t_a's are the generators of the triplet representation of $SU(2)_L$ and are given by,

$$
t_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad t_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \qquad t_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \tag{3}
$$

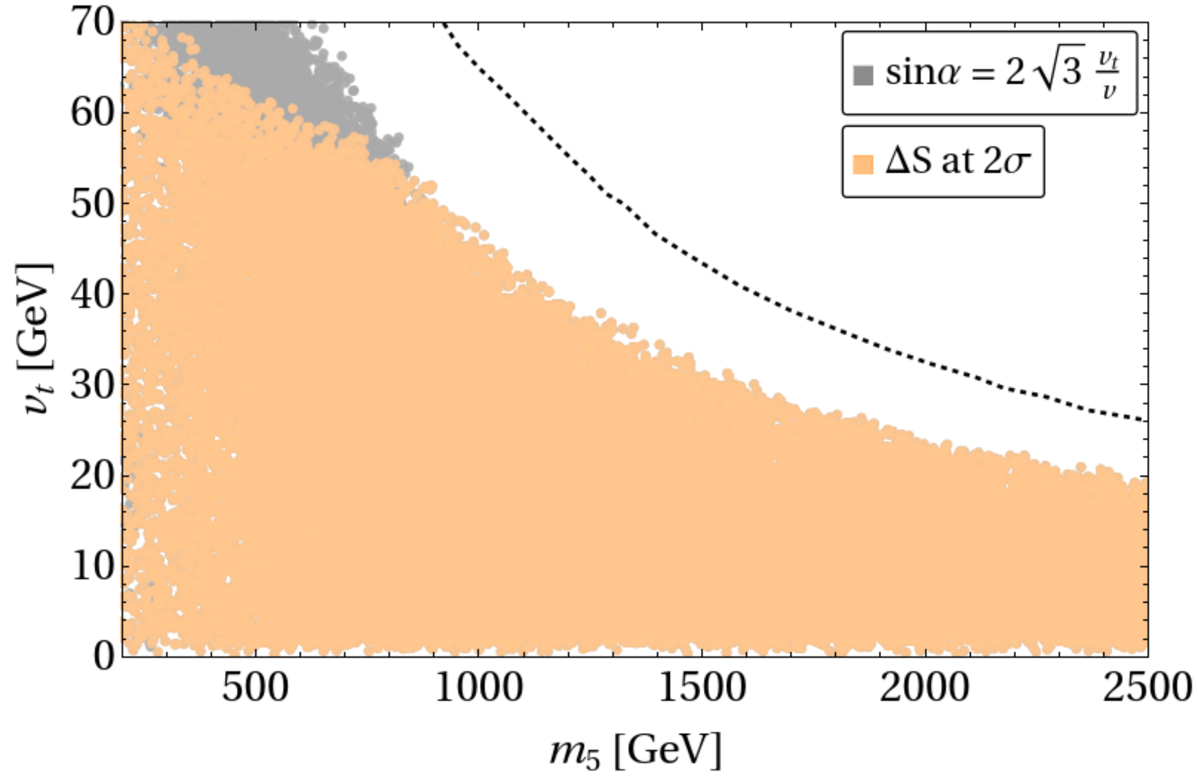
$$
\begin{aligned}
H_5^{\pm\pm} &= \chi^{\pm\pm}, \\
H_5^{\pm} &= \frac{1}{\sqrt{2}}\left(\chi^\pm - \xi^\pm\right), \\
H_5^0 &= \sqrt{\frac{2}{3}}h_\xi - \sqrt{\frac{1}{3}}h_\chi, \\
H_3^\pm &= -\sin\beta\ \phi^\pm + \frac{\cos\beta}{\sqrt{2}}\left(\chi^\pm + \xi^\pm\right), \\
H_3^0 &= -\sin\beta\ \eta_d + \cos\beta\ \eta_\chi, \\
h &= \cos\alpha\ h_d + \sin\alpha\ H_5^{0\prime}, \\
H &= -\sin\alpha\ h_d + \cos\alpha\ H_5^{0\prime},
\end{aligned}
$$

$$
U = \frac{1}{\sqrt{2}}\begin{pmatrix} -1 & 0 & 1 \\ -i & 0 & -i \\ 0 & \sqrt{2} & 0 \end{pmatrix}.
$$

$$
\tan\beta = \frac{2\sqrt{2}v_t}{v_d}.
$$

$$
H_5^{0\prime} = \sqrt{\frac{1}{3}}h_\xi + \sqrt{\frac{2}{3}}h_\chi .
$$

S PARAMETER AND HIGGS SELF-COUPLING



$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{(\lambda_{hhh})^{\rm SM}} = \cos^3\alpha\sec\beta + \frac{2\sqrt{2}}{\sqrt{3}}\sin^3\alpha\csc\beta + \frac{2\Lambda_1^2}{m_h^2}\sin^2\alpha\cos\beta\left(\cos\alpha - \frac{\sqrt{2}}{\sqrt{3}}\sin\alpha\cot\beta\right) + \frac{\sqrt{2}}{3\sqrt{3}}\frac{\Lambda_2^2}{m_h^2}\sin^3\alpha\csc\beta\,.$$

THEORETICAL CONSTRAINTS: UNITARITY

$$|4\lambda_3 + \lambda_4| \leq 8\pi$$

Unitarity condition I

$$\left|\frac{1}{3}\left[m_5^2 + 2\left(m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha\right)\right] - m_3^2 \cos^2\beta\right| \leq 2\pi v^2 \sin^2\beta\,.$$

In the decoupling limit, $v_t \ll v$

$$\frac{1}{3}\left[m_5^2 + 2\left(m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha\right)\right] - m_3^2 \cos^2\beta \approx 0\,.$$

$$|4\lambda_2 - \lambda_5| \leq 8\pi$$

Unitarity condition II

$$\left|m_3^2 - \frac{\sqrt{2}}{\sqrt{3}}\left(m_H^2 - m_h^2\right)\frac{\sin 2\alpha}{\sin 2\beta}\right| \leq 4\pi v^2$$

The unitarity conditions can be trivially satisfied in the `Decoupling limit'

$$\sin 2\alpha \approx \sqrt{\frac{3}{2}}\sin 2\beta \qquad \text{with} \quad v_t \ll v$$

$$\text{and} \qquad m_H^2 \approx m_3^2 \approx m_5^2 \approx \Lambda_1^2 \gg v^2\,; \quad \Lambda_2^2 \ll v^2\,.$$

$$\Lambda_1^2 = \frac{M_1 v}{\sqrt{2}\sin\beta} \equiv \frac{M_1 v^2}{4 v_t}\,,$$

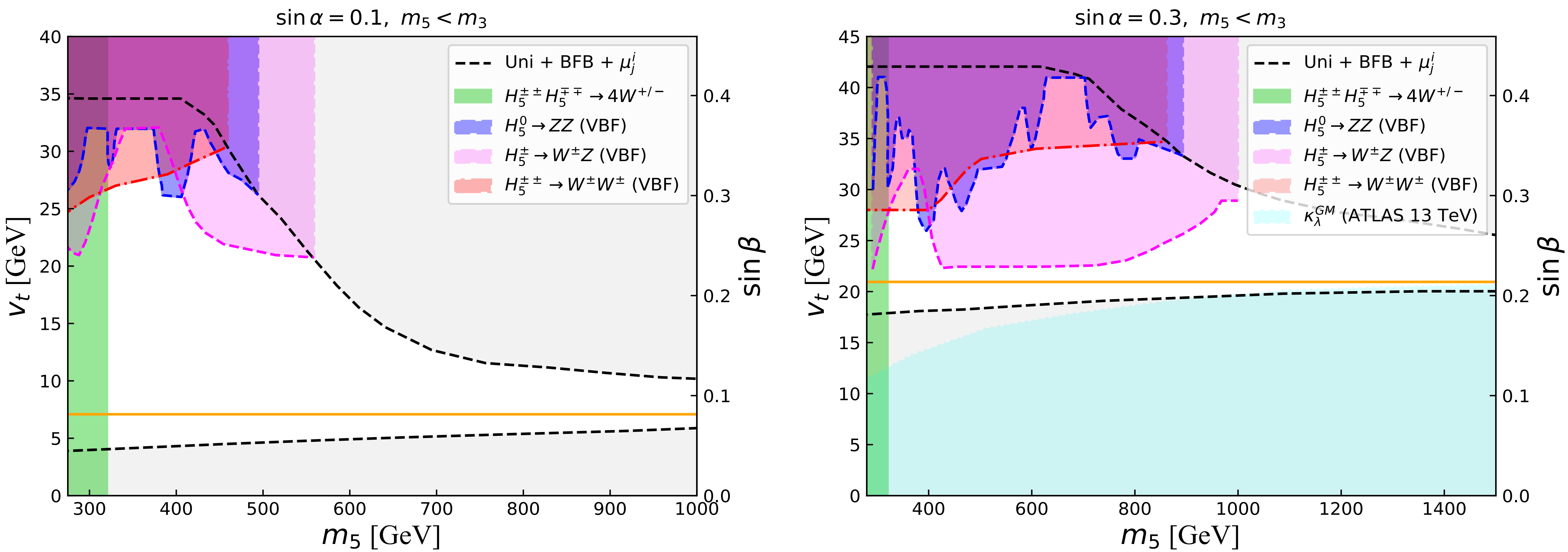
$$\Lambda_2^2 = 3\sqrt{2}\, v\, M_2 \sin\beta \equiv 12\, v_t M_2\,.$$

NONSTANDARD HIGGS DECAY

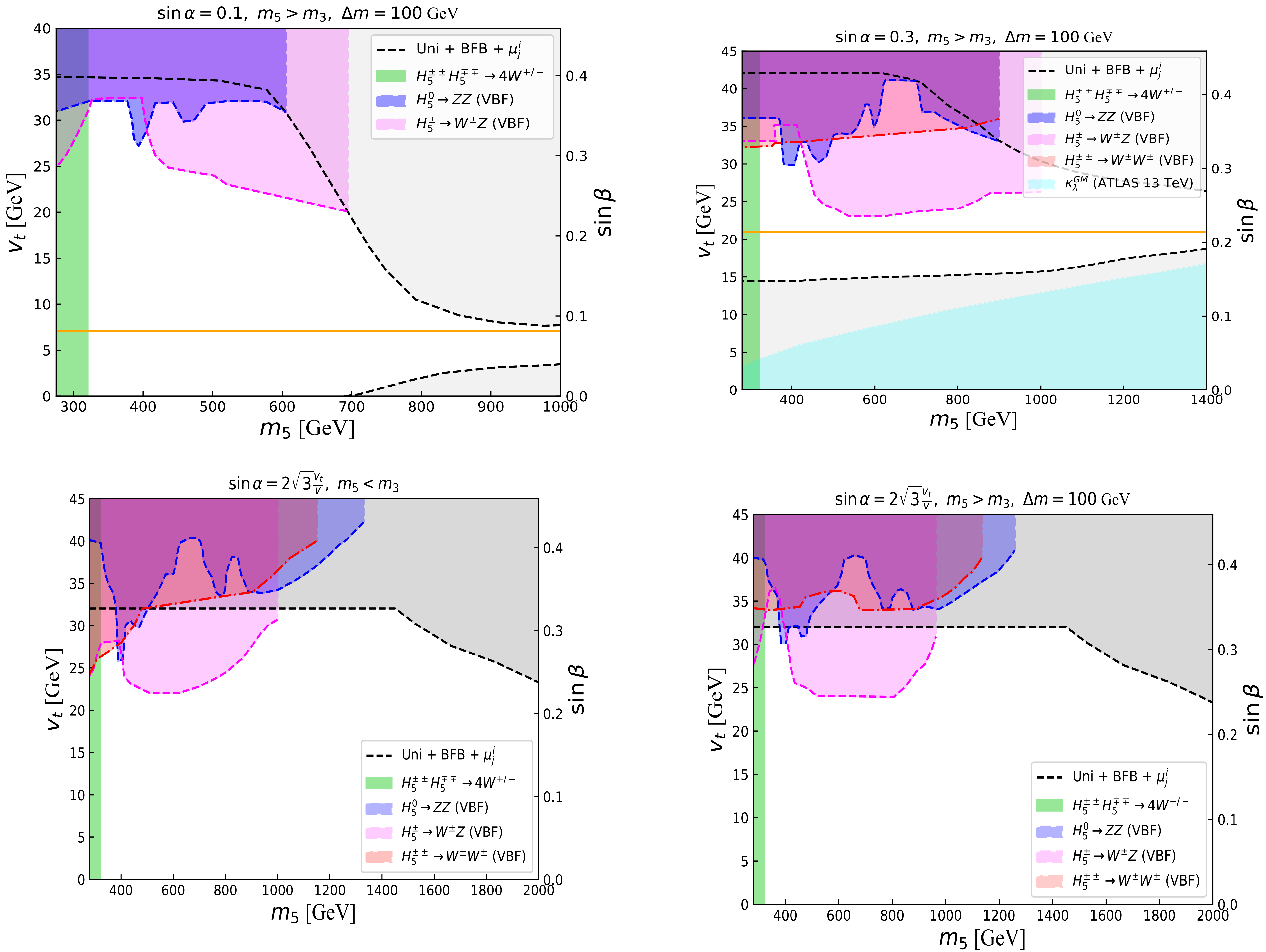
	$m_3 > m_5$	$m_5 > m_3$
$H_5^0 \longrightarrow$	ZZ	$H_3^0 Z,\ H_3^+ W^-$
$H_5^{++} \longrightarrow$	$W^+ W^-$	$H_3^+ W^+$
$H_5^+ \longrightarrow$	$W^+ Z$	$H_3^0 W^+,\ H_3^+ Z$
$H_3^+ \longrightarrow$	$H_5^+ Z,\ H_5^0 Z$	
$H_3^0 \longrightarrow$		

$H_3^+ \rightarrow t\bar{b}$

$H \longrightarrow ZZ,\ f\bar{f}$



$\sin\alpha = 0.1,\ m_5 < m_3$
$\sin\alpha = 0.3,\ m_5 < m_3$
Uni + BFB + μ_j^i
$H_5^{\pm\pm}H_5^{\mp\mp} \to 4W^{+/-}$
$H_5^0 \to ZZ$ (VBF)
$H_5^\pm \to W^\pm Z$ (VBF)
$H_5^{\pm\pm} \to W^\pm W^\pm$ (VBF)
κ_λ^{GM} (ATLAS 13 TeV)
v_t [GeV]
$\sin\beta$
m_5 [GeV]



$\sin\alpha = 0.1,\ m_5 > m_3,\ \Delta m = 100$ GeV
v_t [GeV]
m_5 [GeV]
$\sin\beta$
Uni + BFB + μ_j^i
$H_5^{\pm\pm}H_5^{\mp\mp} \to 4W^{+/-}$
$H_5^0 \to ZZ$ (VBF)
$H_5^\pm \to W^\pm Z$ (VBF)
$\sin\alpha = 0.3,\ m_5 > m_3,\ \Delta m = 100$ GeV
v_t [GeV]
m_5 [GeV]
$\sin\beta$
Uni + BFB + μ_j^i
$H_5^{\pm\pm}H_5^{\mp\mp} \to 4W^{+/-}$
$H_5^0 \to ZZ$ (VBF)
$H_5^\pm \to W^\pm Z$ (VBF)
$H_5^{\pm\pm} \to W^\pm W^\pm$ (VBF)
κ_λ^{GM} (ATLAS 13 TeV)
$\sin\alpha = 2\sqrt{3}\frac{v_t}{v},\ m_5 < m_3$
v_t [GeV]
m_5 [GeV]
$\sin\beta$
Uni + BFB + μ_j^i
$H_5^{\pm\pm}H_5^{\mp\mp} \to 4W^{+/-}$
$H_5^0 \to ZZ$ (VBF)
$H_5^\pm \to W^\pm Z$ (VBF)
$H_5^{\pm\pm} \to W^\pm W^\pm$ (VBF)
$\sin\alpha = 2\sqrt{3}\frac{v_t}{v},\ m_5 > m_3,\ \Delta m = 100$ GeV
v_t [GeV]
m_5 [GeV]
$\sin\beta$
Uni + BFB + μ_j^i
$H_5^{\pm\pm}H_5^{\mp\mp} \to 4W^{+/-}$
$H_5^0 \to ZZ$ (VBF)
$H_5^\pm \to W^\pm Z$ (VBF)
$H_5^{\pm\pm} \to W^\pm W^\pm$ (VBF)