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Fundamental Composite Dynamics:
Opportunities for Future Colliders and Cosmology
@ MITP, Germany

Phenomenology of Extended Higgs Sectors

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Outline

- Introduction of simple extensions
- Georgi-Machacek model
- Global fit for GM model
- HVV couplings at 1-loop level
- Exotic models with $\kappa_W \neq \kappa_Z$
- Determination of κ_W/κ_Z (at ILC)
- Summary

INTRODUCTION

SM Higgs Physics

- Renormalizable Higgs Lagrangian in SM offers a minimal and elegant way to give mass to weak gauge bosons and charged fermions (except for neutrinos):

$m_{W,Z}$ through gauge interactions

self interaction

$$\mathcal{L}_\Phi \supset |\mathcal{D}_\mu \Phi|^2 + \mu^2 |\Phi|^2 - \lambda |\Phi|^4 - Y_{ij} \overline{\psi_{iL}} \Phi \psi_{jR} - V_0 + \text{h.c.}$$

instability at origin to induce EWSB

m_f through Yukawa interactions

- Explicit forms of gauge and Yukawa interactions depend on the quantum number (CP, electroweak, etc) assignment of the Higgs field
  - ➠ determining hVV and hff couplings
  - ➠ leading to tree-level WW*, ZZ* and $f\bar{f}$ decays, as well as loop-level γγ and Zγ decays

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instability at origin to induce EWSB

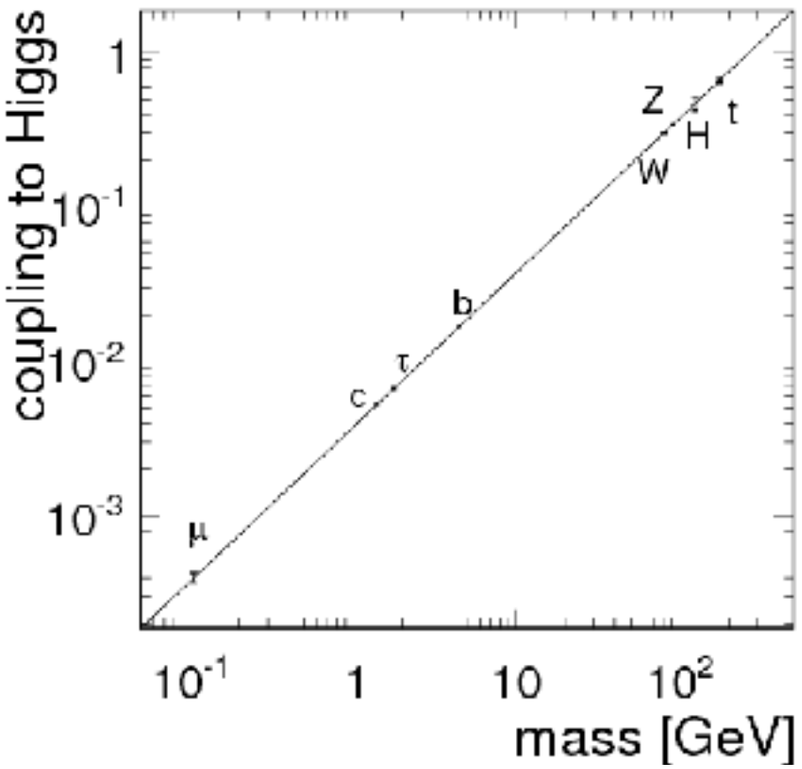
m_f through Yukawa interactions

- After discovering the 125-GeV Higgs boson, an important program in particle physics is to determine its couplings with SM particles (including itself).

➠ understanding SM, as well as probing new physics

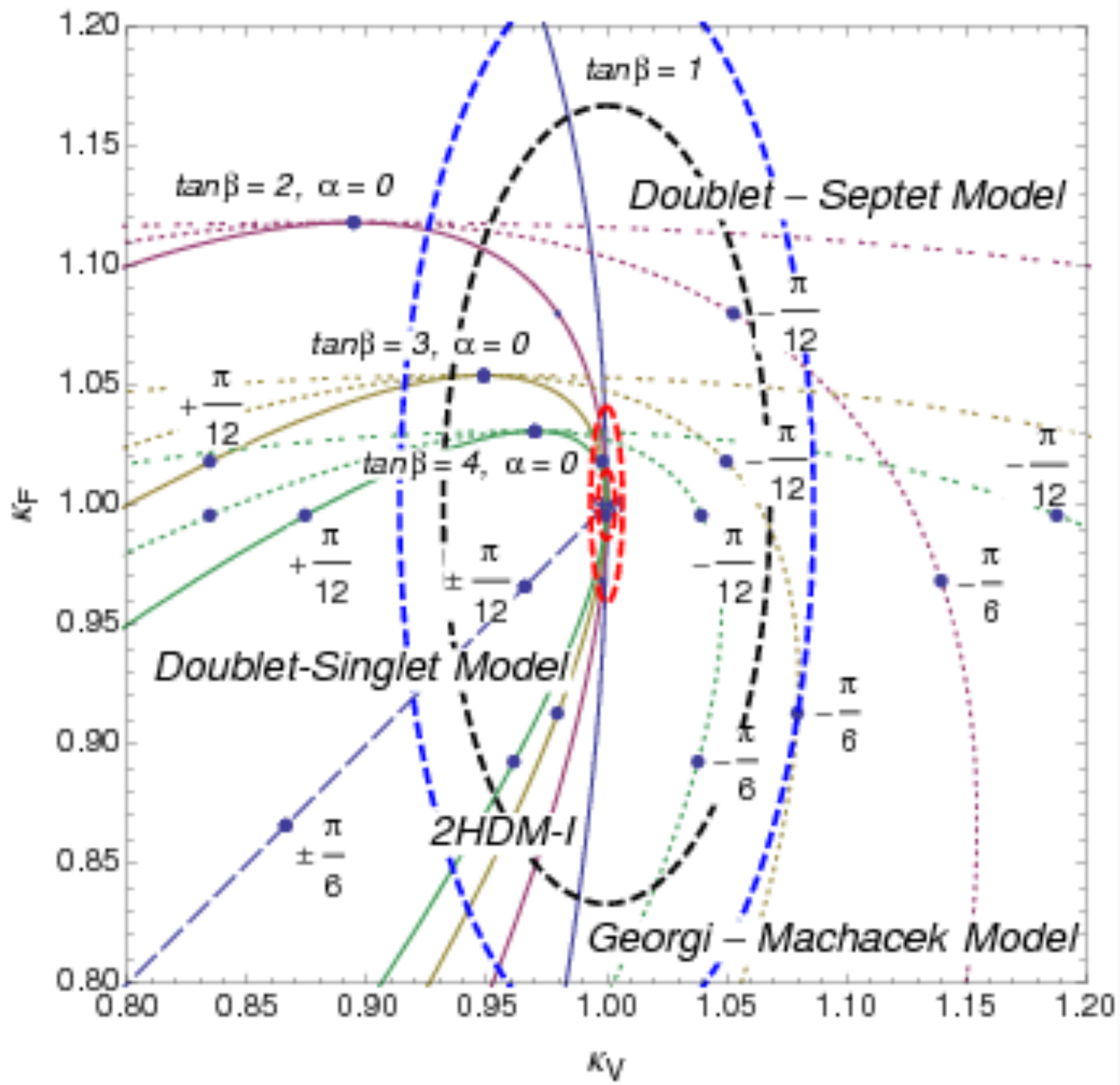
Probing Higgs Sector

- Two ways to probe an extended Higgs sector:
  - Direct search: to discover additional Higgs bosons that contribute to EWSB; and
  - Indirect search: to find deviations from SM in observables/quantities related to the 125-GeV Higgs boson (h).
- So far, no additional Higgs boson has been discovered at the LHC.
  ➠ indirect search more appealing
  ➠ precision determination of Higgs couplings (κ and λ parameters)
  ➠ Higgs couplings at loop level



κ_F-κ_V for Simple Models

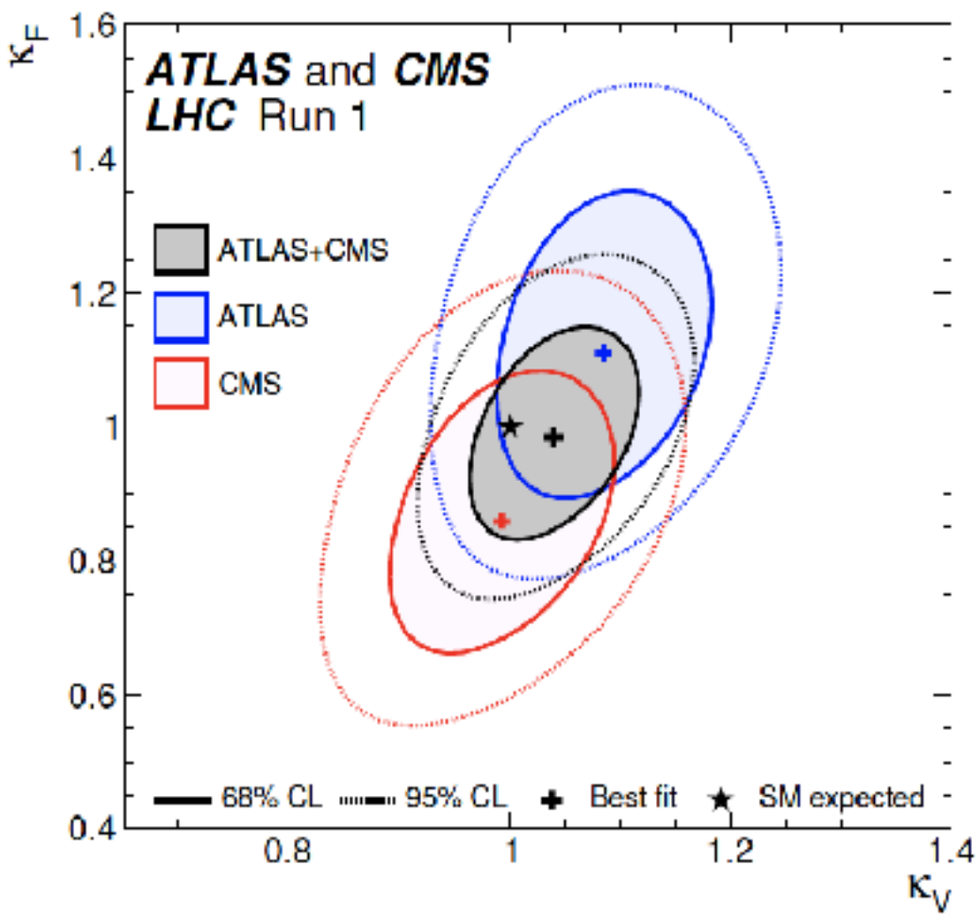
- Scaling factors κ_f and κ_V in models with universal Yukawa coupling constants at tree level. Kanemura, Tsumura, Yagyu, Yokoya 2014

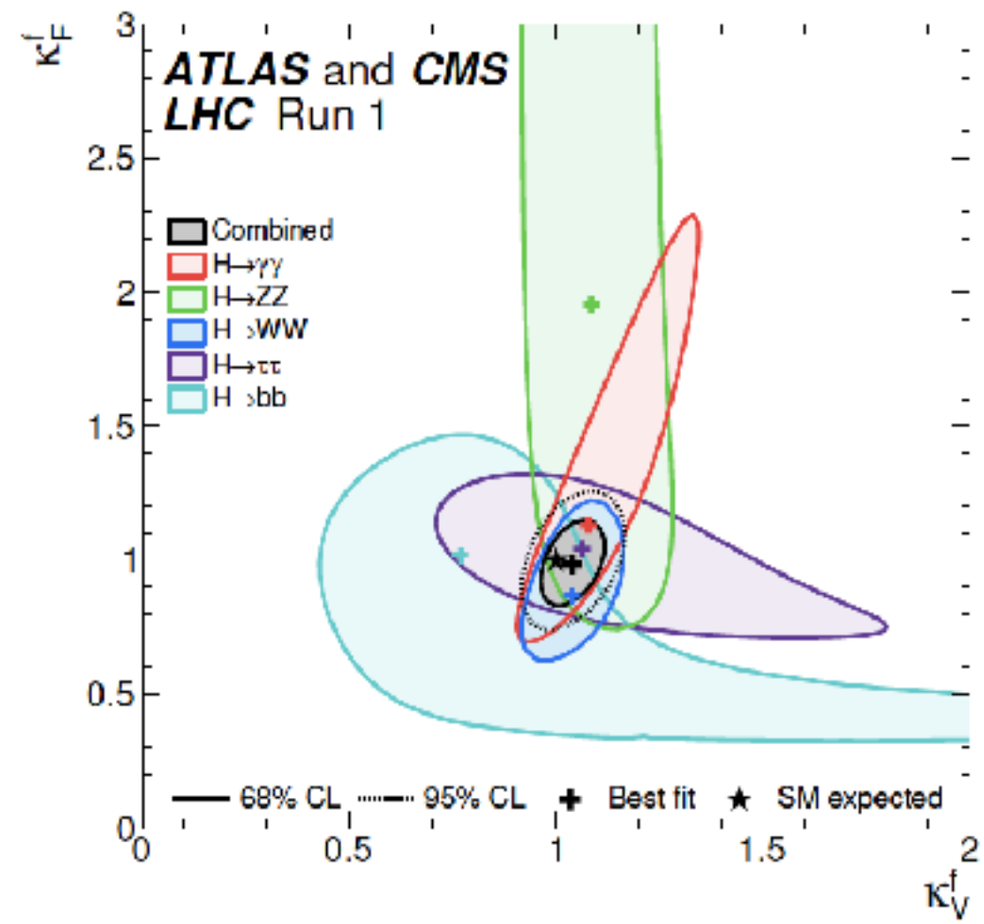


Higgs Couplings

- Global fits of Higgs couplings (assuming universal scaling factors $\kappa_{F,V}$) from LHC Run-I
  ➠ quite consistent with SM

$$\kappa_F = \frac{g_{\varphi FF}}{g_{hFF}^{\rm SM}} \ , \ \kappa_V = \frac{g_{\varphi VV}}{g_{hVV}^{\rm SM}}$$

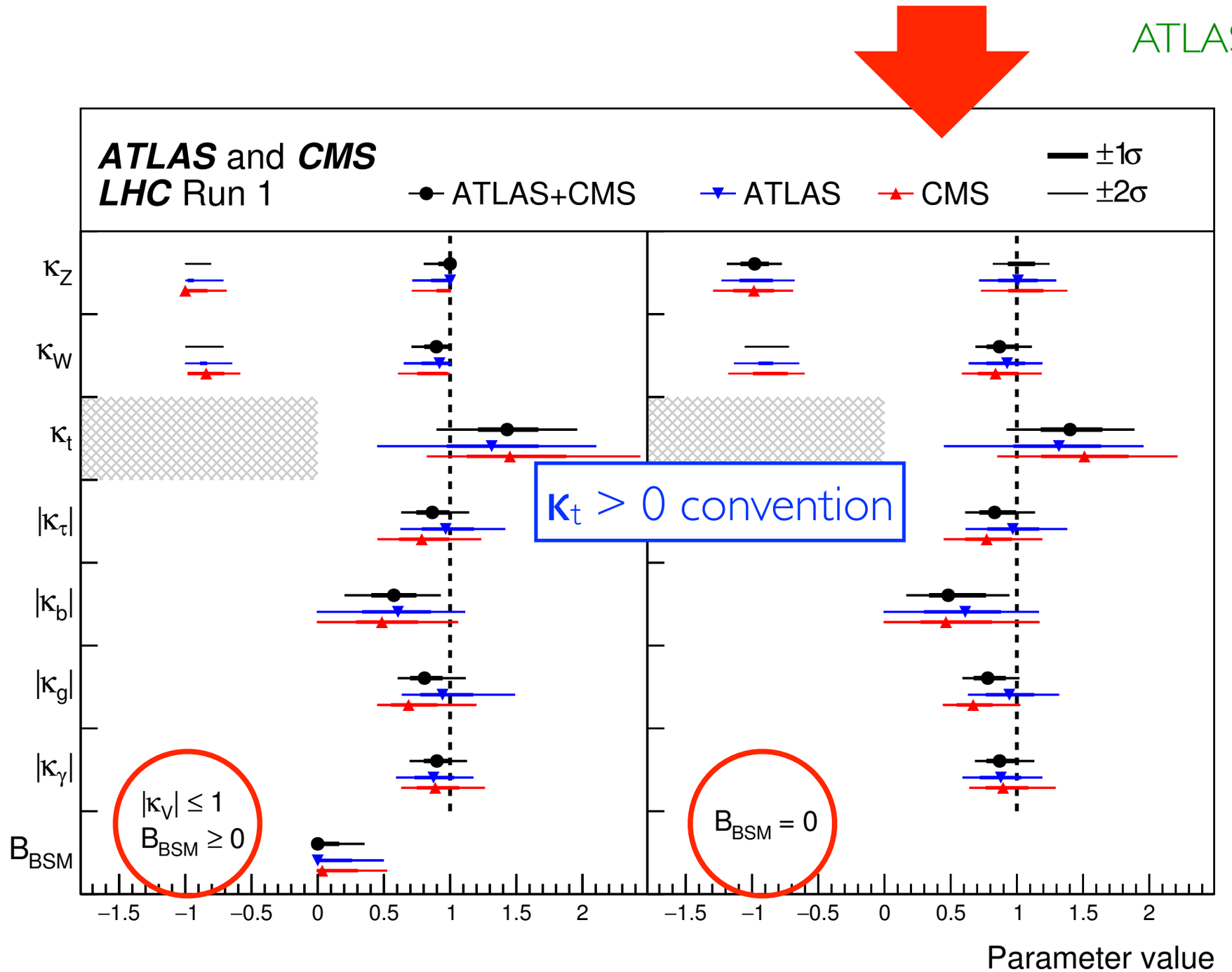




circa 2016 summer

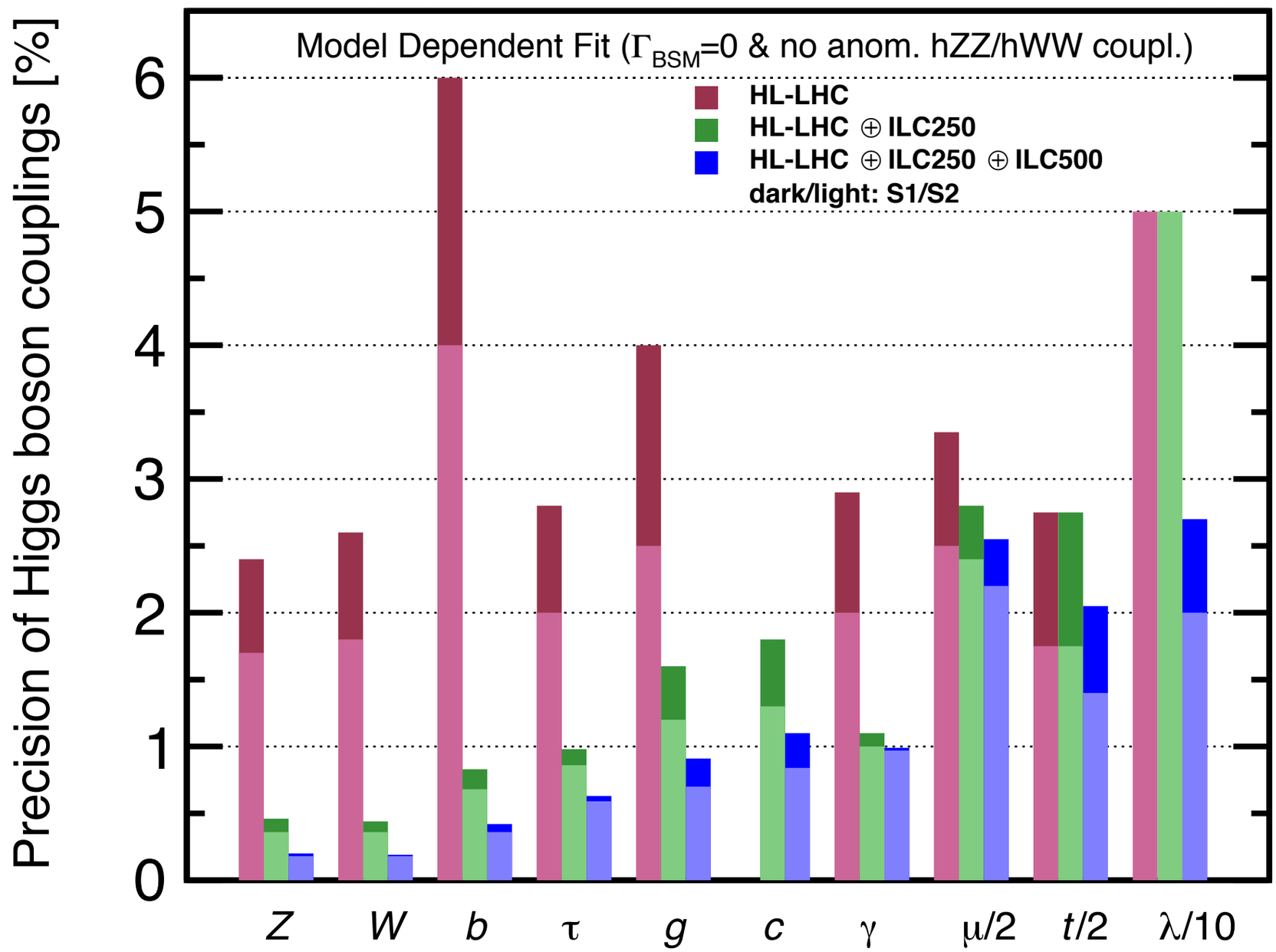
LHC Run-1 Data

ATLAS+CMS 2016



Expected Coupling Precision

- All Higgs couplings will be determined by HL-LHC + ILC to O(1%) or sub-percent level (particularly hVV couplings).



Aihara et al 2019

An Extended Higgs Sector

- Other than usual symmetries, we have no guiding principles in constructing the scalar sector:
  - ➠ representations
  - ➠ number of copies
  - ➠ additional symmetries (discrete/continuous/gauged)
  - ➠ new physics (SUSY, DM, neutrino mass, EWBG, etc)

cf. 3 generations of fermions and 3 gauge interactions

- Questions:
  - ➠ Why does the Higgs sector have to be so economic?
  - ➠ What purposes do other Higgs multiplets serve?
  - ➠ What consequences can we detect now?
  - ➠ Are such scalars fundamental or composite?

Importance of g_{HVV}

- Just for the purpose of breaking the EW symmetry, one can employ nontrivial Higgs representations other than the doublet (though the choice of doublet is economic for charged fermion mass).
- For W and Z in cases where more Higgs fields participate in EWSB,

➠ masses involve different origins

➠ couplings with H(125) may be modified (even in a non-universal way)

➠ HWW and HZZ couplings (or κ_W and κ_Z) being important in probing/diagnosing EWSB and indicators of the custodial symmetry

Salient Features of SM

- Due to custodial symmetry, interactions between Higgs and weak gauge bosons dictate that at tree level

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

$$\kappa_W = \kappa_Z = 1$$

- How can we deviate from any of these predictions provided data show otherwise?
- What kind of exotic Higgs extensions can we go after?

Recent Run-II Data

Parameter	ATLAS	CMS	Average
κ_W	1.07 ± 0.10	$1.12^{+0.13}_{-0.19}$	1.08 ± 0.08
κ_Z	1.07 ± 0.10	0.99 ± 0.11	1.03 ± 0.07

ATLAS-CONF-2018-31 (13 TeV, 80/fb)
CMS-PAS-HIG-17-031 (13 TeV, 36/fb)

- Concentrate on the central values.
- κ_W and/or κ_Z may be greater than 1.
- κ_W and κ_Z may be different. (~10% from CMS alone)

- What kind of (minimally extended) Higgs sector features these properties?
- How different can κ_W and κ_Z be?
- Confine ourselves to only extending the Higgs sector.

Higgs Extensions

- Higgs extensions are subject to a stringent constraint

$$\rho_{\rm exp} = 1.00039 \pm 0.00019$$

PDG 2018

- In models with an extended Higgs sector, at tree level

$$\rho_{\rm tree} = \frac{\sum_i v_i^2 \left[T_i(T_i+1) - Y_i^2\right]}{\sum_i 2Y_i^2 v_i^2}$$

summing over all
active Higgs multiplets

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PDG 2018

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- If only one new $SU(2)_L$ rep is added to the SM, $\rho_{tree} = 1$ gives the following possibilities, under $(SU(2)_L, U(1)_Y)$:
  - (0,0) – real singlet, ➠ interacting mainly with h_{SM}
  - (1/2,1/2) – doublet, ➠ a popular choice (e.g., 2HDM)
  - (3,2) – septet,
  - (25/2, 15/2), (48,28), etc ➠ disfavored by unitarity bound

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- One can also choose to add a custodial symmetric representation (n,n) (n $\in \mathbb{N}$) under ($SU(2)_L$,$SU(2)_R$) with vacuum alignment.
  - ➠ generalized Georgi-Machacek (GM) model Logan, Rentala 2015
  - ➠ n = 3 is the original GM model

Higgs Extensions

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- Simplest CP-conserving custodial Higgs models:
  - real Higgs singlet model (rHSM): Φ + S
  - two Higgs doublet model (2HDM): Φ + Φ'
  - GM model: Φ + Δ
  - will make a comparison of them in hVV couplings.

GEORGI-MACHACEK MODEL

"All models are wrong, but some are useful."

— George E.P. Box

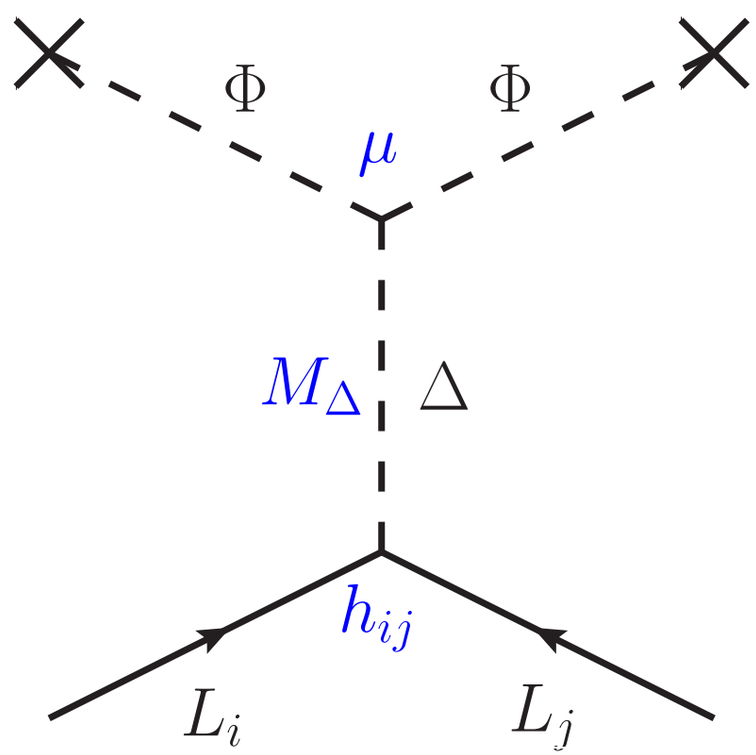
Motivation for GM Model

- With the introduction of a complex Higgs triplet field Δ, one can give Majorana mass to LH neutrinos.
- Relevant Yukawa interactions:

Konetschny, Kummer 1977
Schechter, Valle 1980
Cheng, Li 1980
Gelmini, Roncadelli 1981

$$-h_{ij}\psi_{iL}^T C i\sigma_2 \Delta \psi_{jL} + \text{h.c.}$$

and Δ can be induced to attain a VEV from EWSB:



Type-II seesaw

$$M_\nu = \sqrt{2} h v_\Delta = h \frac{\mu v_0^2}{m_\Delta^2}$$

Higgs Potential in GM

- The model realizes the minimal Higgs sector containing isospin triplet fields while maintaining custodial symmetry.
- The most general Higgs potential allowed by gauge and Lorentz symmetries:

assume $m_1^2 < 0$, but $m_2^2 > 0$

$$V(\Phi,\Delta) = \frac{1}{2}m_1^2 \mathrm{tr}[\Phi^\dagger\Phi] + \frac{1}{2}m_2^2 \mathrm{tr}[\Delta^\dagger\Delta] + \lambda_1(\mathrm{tr}[\Phi^\dagger\Phi])^2 + \lambda_2(\mathrm{tr}[\Delta^\dagger\Delta])^2$$

$$+ \lambda_3 \mathrm{tr}[(\Delta^\dagger\Delta)^2] + \lambda_4 \mathrm{tr}[\Phi^\dagger\Phi]\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_5 \mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right]\mathrm{tr}\left[\Delta^\dagger T^a \Delta T^b\right]$$

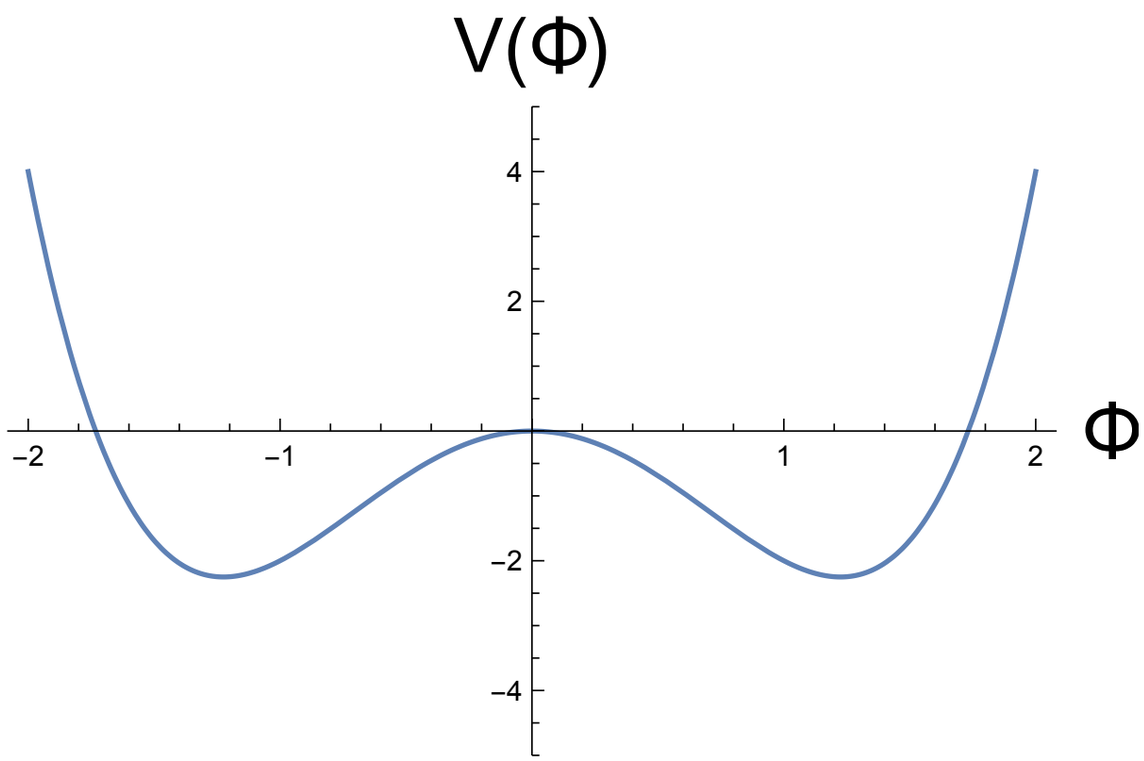
$$+ \mu_1 \mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right](P^\dagger\Delta P)_{ab} + \mu_2 \mathrm{tr}\left[\Delta^\dagger T^a \Delta T^b\right](P^\dagger\Delta P)_{ab}$$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -(\phi^+)^* & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} (\chi^0)^* & \xi^+ & \chi^{++} \\ -(\chi^+)^* & \xi^0 & \chi^+ \\ (\chi^{++})^* & -(\xi^+)^* & \chi^0 \end{pmatrix}, \quad P = \frac{1}{\sqrt{2}}\begin{pmatrix} -1 & i & 0 \\ 0 & 0 & \sqrt{2} \\ 1 & i & 0 \end{pmatrix}$$

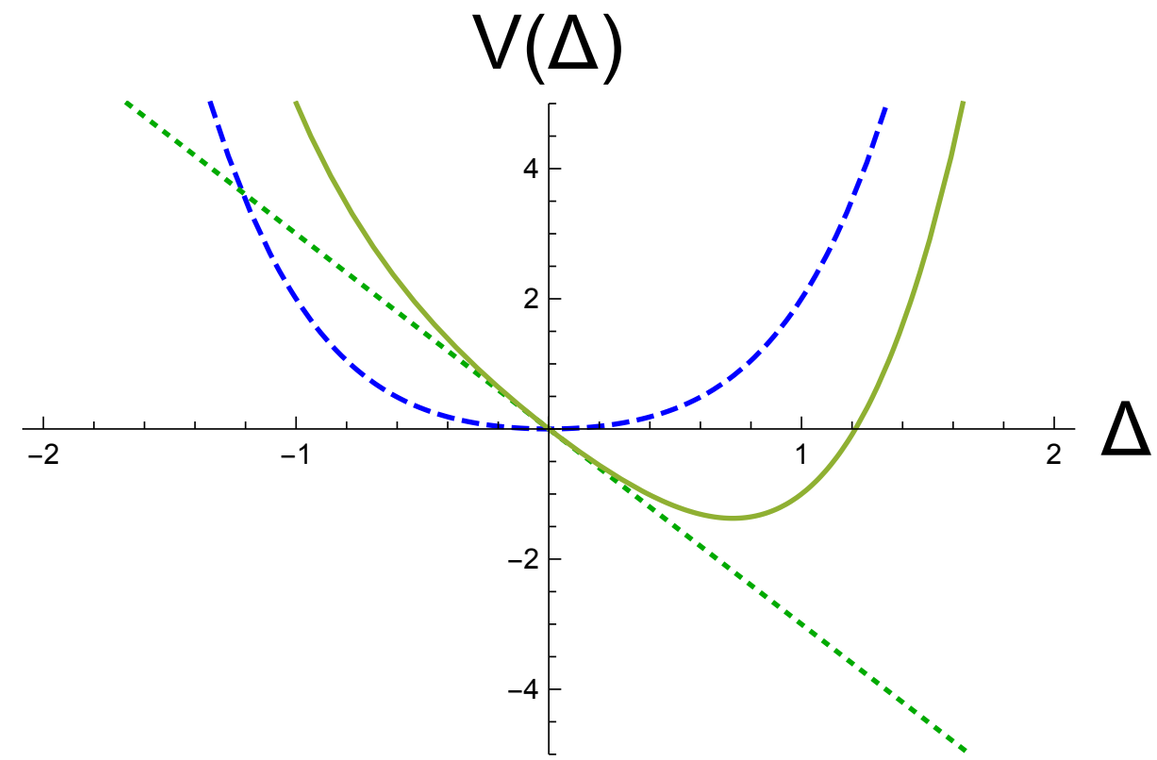
- Decoupling limit: $m_2 \to \infty$
- v_Δ induced by v_Φ through μ_1

Symmetry Breaking Types

- Two types of symmetry breaking involved here:



spontaneous symmetry breaking



induced symmetry breaking

Georgi-Machacek Model

- The Higgs sector includes SM doublet field $\phi(2,1/2)$ and triplet fields $\chi(3,1)$ and $\xi(3,0)$

Georgi, Machacek 1985
Chanowitz, Golden 1985

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

$SU(2)_L$

$SU(2)_R$

Georgi-Machacek Model

- The Higgs sector includes SM doublet field $\phi(2,1/2)$ and triplet fields $\chi(3,1)$ and $\xi(3,0)$

Georgi, Machacek 1985
Chanowitz, Golden 1985

$$\Phi = \begin{pmatrix} v_\phi & \phi^+ \\ \phi^- & v_\phi \end{pmatrix}, \qquad \Delta = \begin{pmatrix} v_\Delta & \xi^+ & \chi^{++} \\ \chi^- & v_\Delta & \chi^+ \\ \chi^{--} & \xi^- & v_\Delta \end{pmatrix}$$

- Take $v_\chi = v_\xi \equiv v_\Delta$ (aligned VEV).
  - ➠ $SU(2)_L \times SU(2)_R \rightarrow$ custodial $SU(2)_V$
  - ➠ $\rho = 1$ at tree level

*Such a symmetry is broken by radiative effects. But $\rho = 1$ can be restored by renormalization.

Features of GM Model

- A large triplet VEV v_Δ is allowed.
  - ➠ focus on $v_\Delta \sim O(10)$ GeV regime
  - ➠ triplet having larger couplings with W/Z than leptons

Vacuum Expectation Values

- The VEV's are subject to the constraint

$$v^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F} = (246\ \mathrm{GeV})^2$$

with two mixing-angle definitions seen in the literature:

$$\tan\theta_H = \frac{2\sqrt{2}v_\Delta}{v_\phi} \ \text{or}\ \ \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

- One could attribute EWSB entirely to v_Δ ($\simeq$ 87 GeV) while keeping $v_\phi = 0$.

Georgi, Machacek 1985
Chanowitz, Golden 1985

- Perturbativity of top Yukawa coupling demands $v_\Delta \lesssim 80$ GeV.

➠ other constraints later

Features of GM Model

- A large triplet VEV v_Δ is allowed.
  - ➠ focus on $v_\Delta \sim O(10)$ GeV regime
  - ➠ triplet having larger couplings with W/Z than leptons
- There exists a doubly-charged Higgs boson that can lead to like-sign LNV and even LFV processes at tree level.
  - ➠ providing a link between neutrino and LHC physics

Higgs Spectrum

1 complex triplet + 1 real triplet

1 complex doublet

$SU(2)_L \otimes SU(2)_R$

Δ: **3** $\otimes$ **3**

Φ: **2** $\otimes$ **2**

5 physical parameters to scan

$SU(2)_V$

5 $\oplus$ **3** $\oplus$ **1**

3 $\oplus$ **1**

mixing angle α

mixing angle β

$$H_5 \equiv \begin{bmatrix} H_5^{++} \\ H_5^{+} \\ H_5^{0} \\ H_5^{-} \\ H_5^{--} \end{bmatrix}$$

CP-even

m_{H5}

quarkphobic

$$H_3 \equiv \begin{bmatrix} H_3^{+} \\ H_3^{0} \\ H_3^{-} \end{bmatrix}$$

CP-odd

m_{H3}

gaugephobic

$$H_1 \equiv [H_1^0]$$

m_{H1}

h (125 GeV)

m_h

CP-even

$$\Phi_3 \equiv \begin{bmatrix} w^{+} \\ z^{0} \\ w^{-} \end{bmatrix}$$

$$\tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

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  - ➠ providing a link between neutrino and LHC physics
- The SM-like Higgs can have stronger/same/weaker couplings with weak bosons (simplest model for this).

Neutral Higgs Couplings

- Introduce coupling scale factors (V = W,Z; F = quarks):

$$\kappa_F = \frac{g_{\varphi FF}}{g_{hFF}^{\rm SM}} \ , \ \kappa_V = \frac{g_{\varphi VV}}{g_{hVV}^{\rm SM}} \ , \ \lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

depending only on α and β (or v_Δ)

group factor that makes it possible for the entire factor to be greater than 1 (mixing required)

Higgs	κ_F	κ_V
h	$\frac{\cos\alpha}{\sin\beta}$	$\sin\beta\cos\alpha - \sqrt{\frac{8}{3}}\cos\beta\sin\alpha$
H_1^0	$\frac{\sin\alpha}{\sin\beta}$	$\sin\beta\sin\alpha + \sqrt{\frac{8}{3}}\cos\beta\cos\alpha$
gauge-phobic H_3^0	$i\eta_f\cot\beta$	0
quark-phobic H_5^0	0	$\kappa_W = -\frac{\cos\beta}{\sqrt{3}}$ and $\kappa_Z = \frac{2\cos\beta}{\sqrt{3}}$

suppressed by α

➠ $\lambda_{WZ} = +1$

➠ $\lambda_{WZ} = -1/2$

$\eta_f = +1$ for up-type quarks and -1 for down-type quarks and charged leptons.

independent of α; proportional to v_Δ

$$\text{2HDM: } \tan\beta = \frac{v_u}{v_d} \quad \text{and} \quad \text{GM: } \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

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  - ➠ cf. loop-induced in models such as 2HDM

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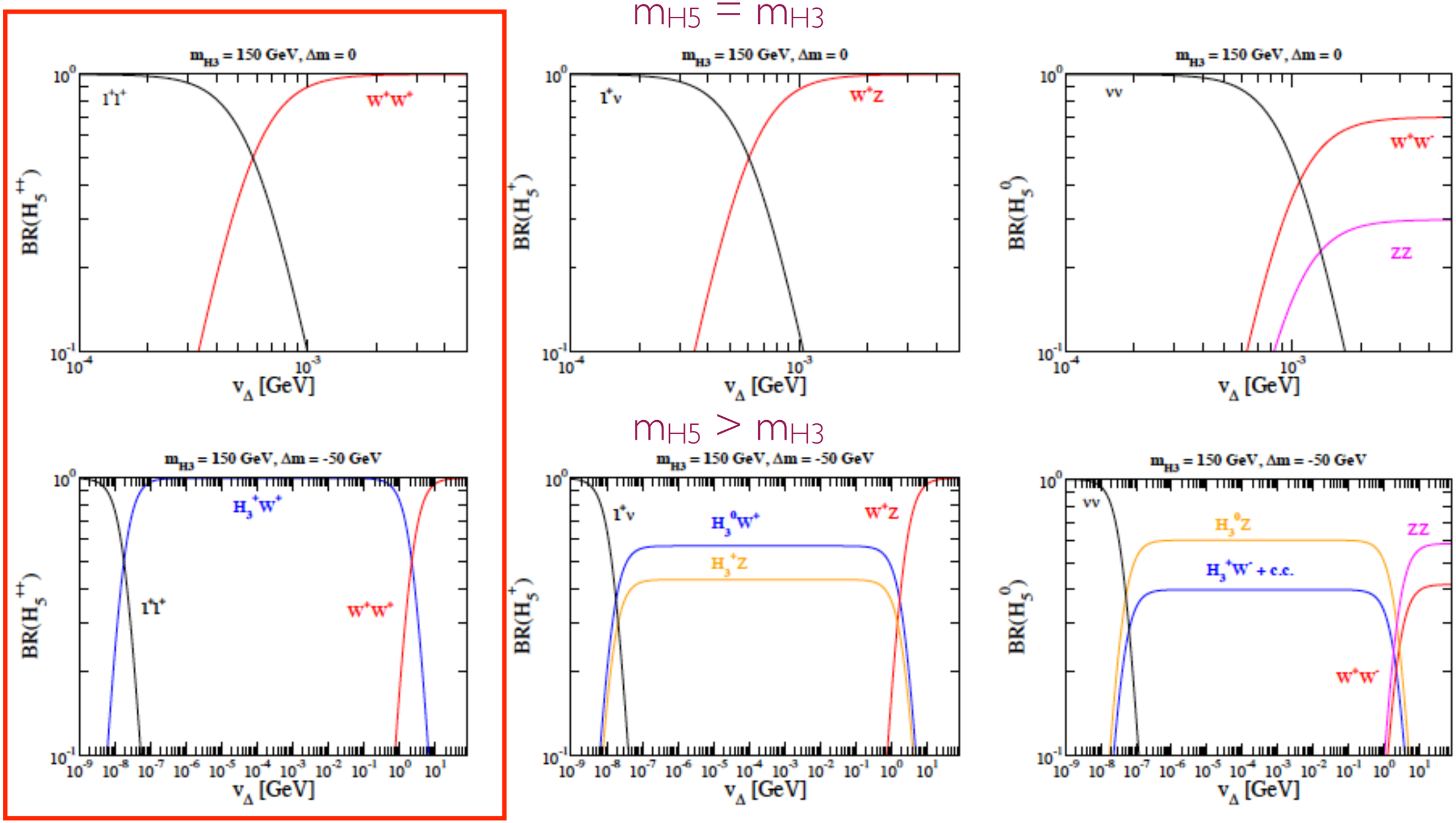
  - ➠ cf. loop-induced in models such as 2HDM
- The Higgs decay pattern is mainly controlled by v_Δ and mass hierarchy.

Decays of H_5 Bosons

doubly-charged | singly-charged | neutral

$m_{H5} = m_{H3}$



$m_{H5} > m_{H3}$

v_Δ is an important order parameter of the model.

Higgs Decay Pattern

CWC, Yagyu JHEP 2012

$\Delta m < 0 \;\; (m_{H_5} > m_{H_3})$

$H_5^{++} \to H_3^+ W^+ \;,\; H_5^+ \to H_3^+ Z / H_3^0 W^+ \;,\; H_5^0 \to H_3^\pm W^\mp / H_3^0 Z$

$H_3^+ \to H_1^0 W^+ \;,\; H_3^0 \to H_1^0 Z$

$\Delta m > 0 : \;\; (m_{H_3} > m_{H_5})$

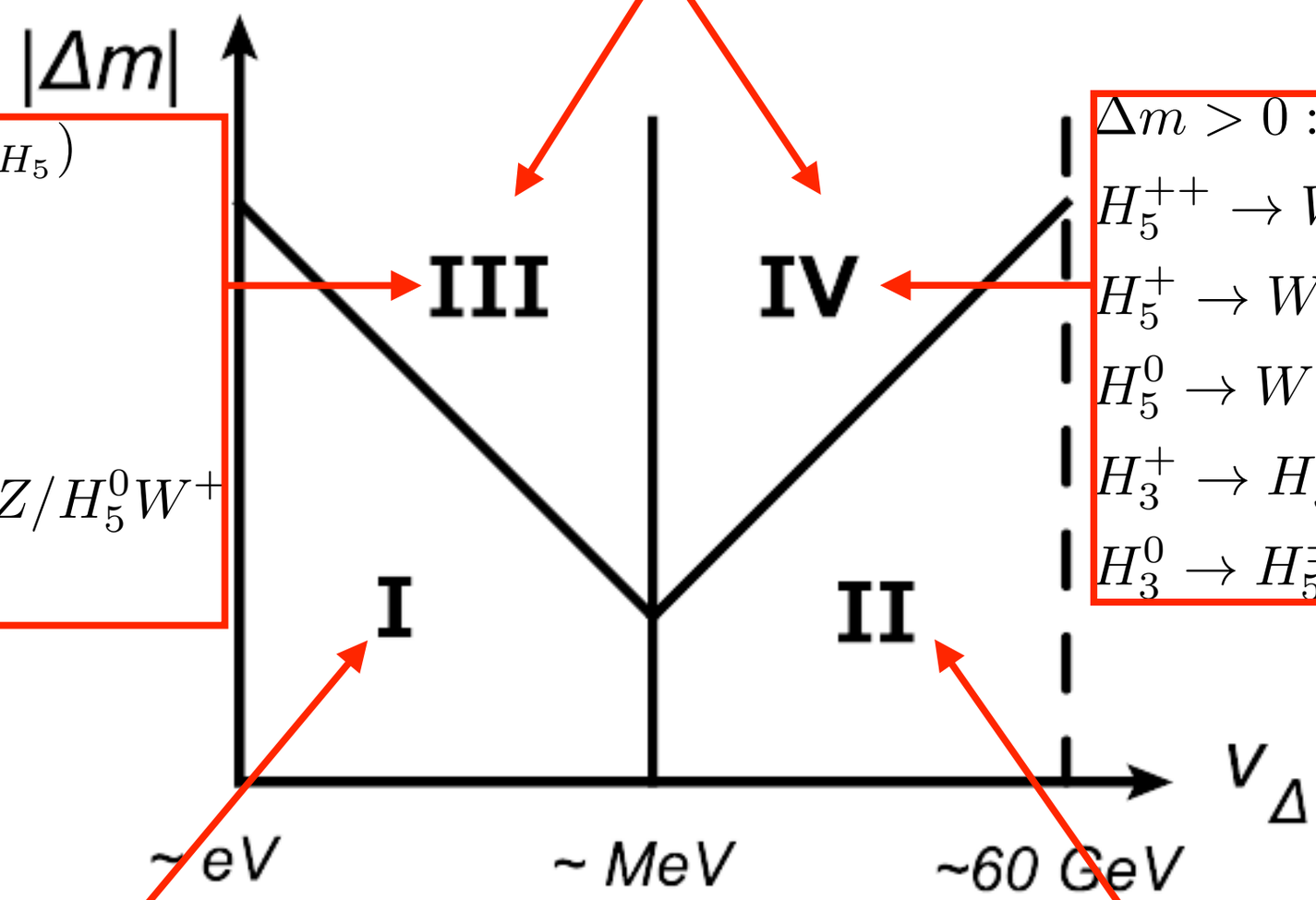
$H_5^{++} \to \ell^+ \ell^+$

$H_5^+ \to \ell^+ \nu$

$H_5^0 \to \nu\nu$

$H_3^+ \to H_5^{++} W^- / H_5^+ Z / H_5^0 W^+$

$H_3^0 \to H_5^\pm W^\mp / H_5^0 Z$



$\Delta m > 0 : \;\; (m_{H_3} > m_{H_5})$

$H_5^{++} \to W^+ W^+$

$H_5^+ \to W^+ Z$

$H_5^0 \to W^+ W^- / Z Z$

$H_3^+ \to H_5^{++} W^- / H_5^+ Z / H_5^0 W^+$

$H_3^0 \to H_5^\pm W^\mp / H_5^0 Z$

$H_5^{++} \to \ell^+ \ell^+ \;,\; H_5^+ \to \ell^+ \nu \;,\; H_5^0 \to \nu\nu \;,$

$H_3^+ \to \ell^+ \nu \;,\; H_3^0 \to \nu\nu.$

$H_5^{++} \to W^+ W^+ \;,\; H_5^+ \to W^+ Z \;,\; H_5^0 \to W^+ W^- / Z Z \;,$

$H_3^+ \to \tau^+ \nu / c\bar{s} / t\bar{b} \;,\; H_3^0 \to b\bar{b}.$

GLOBAL FIT FOR GM MODEL

Allowed Interactions

- The only possible interactions of a doubly-charged Higgs boson with SM particles allowed by the symmetries are:

proportional to g and v_Δ

$$g_\Delta \Delta^{++} W^- W^- + \text{h.c.}$$

Like-sign final states

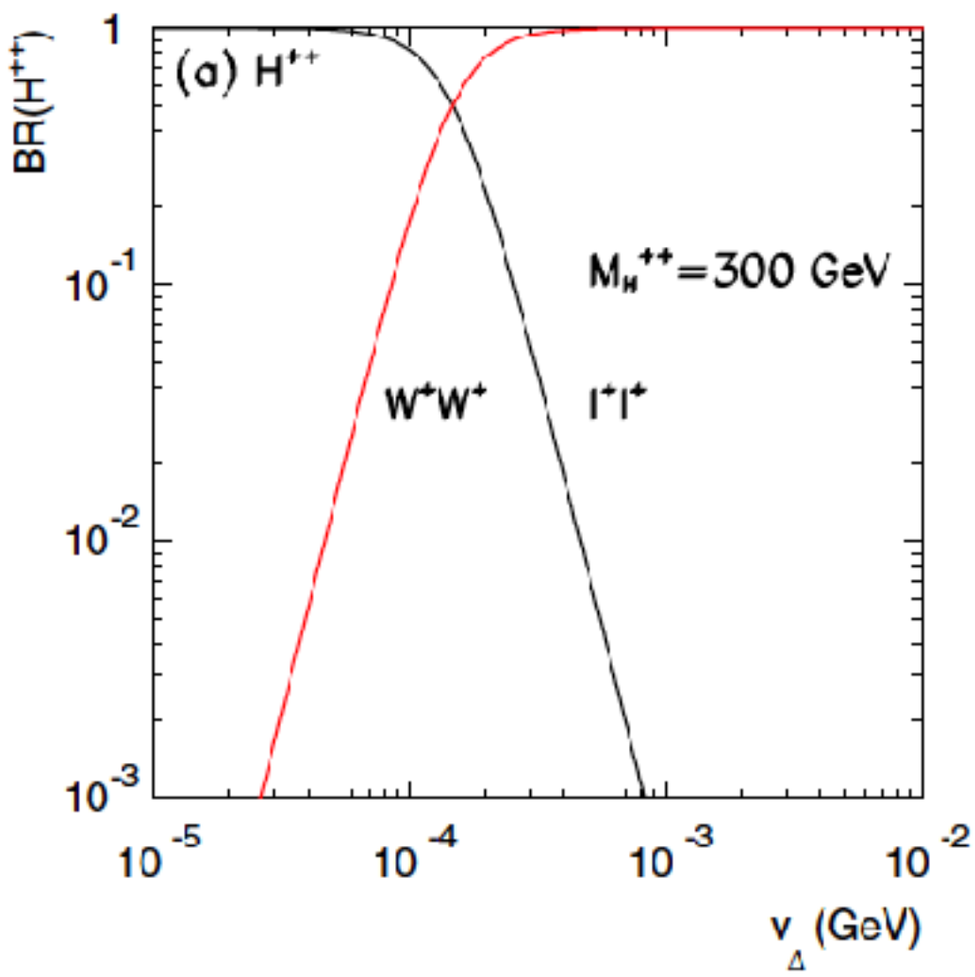
$$y_{ij} \Delta^{++} \ell_i^- \ell_j^- + \text{h.c.}$$

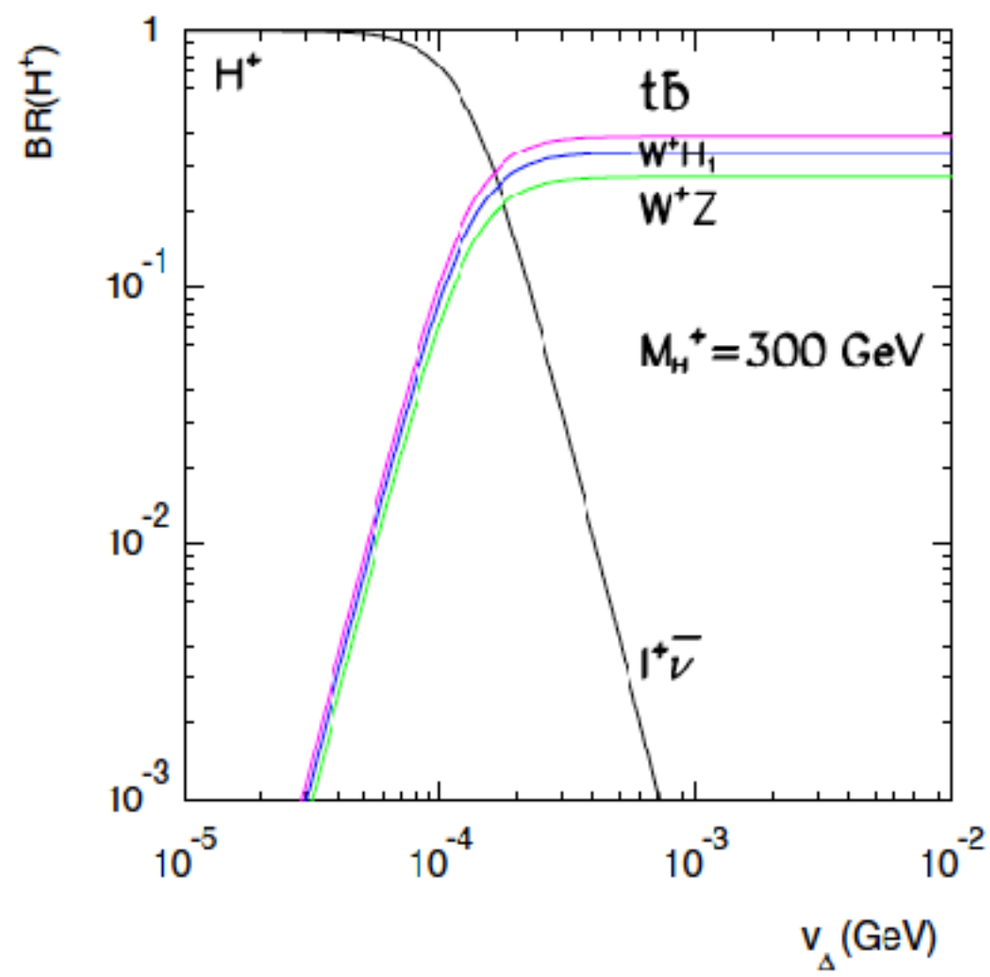
generally LFV, related to neutrino mass and mixing data

LNV

Signature Modes

- In the case of small v_Δ, both $H^{\pm\pm}$ and $H^{\pm}$ decay dominantly into leptonic final states, desirable at hadron colliders.

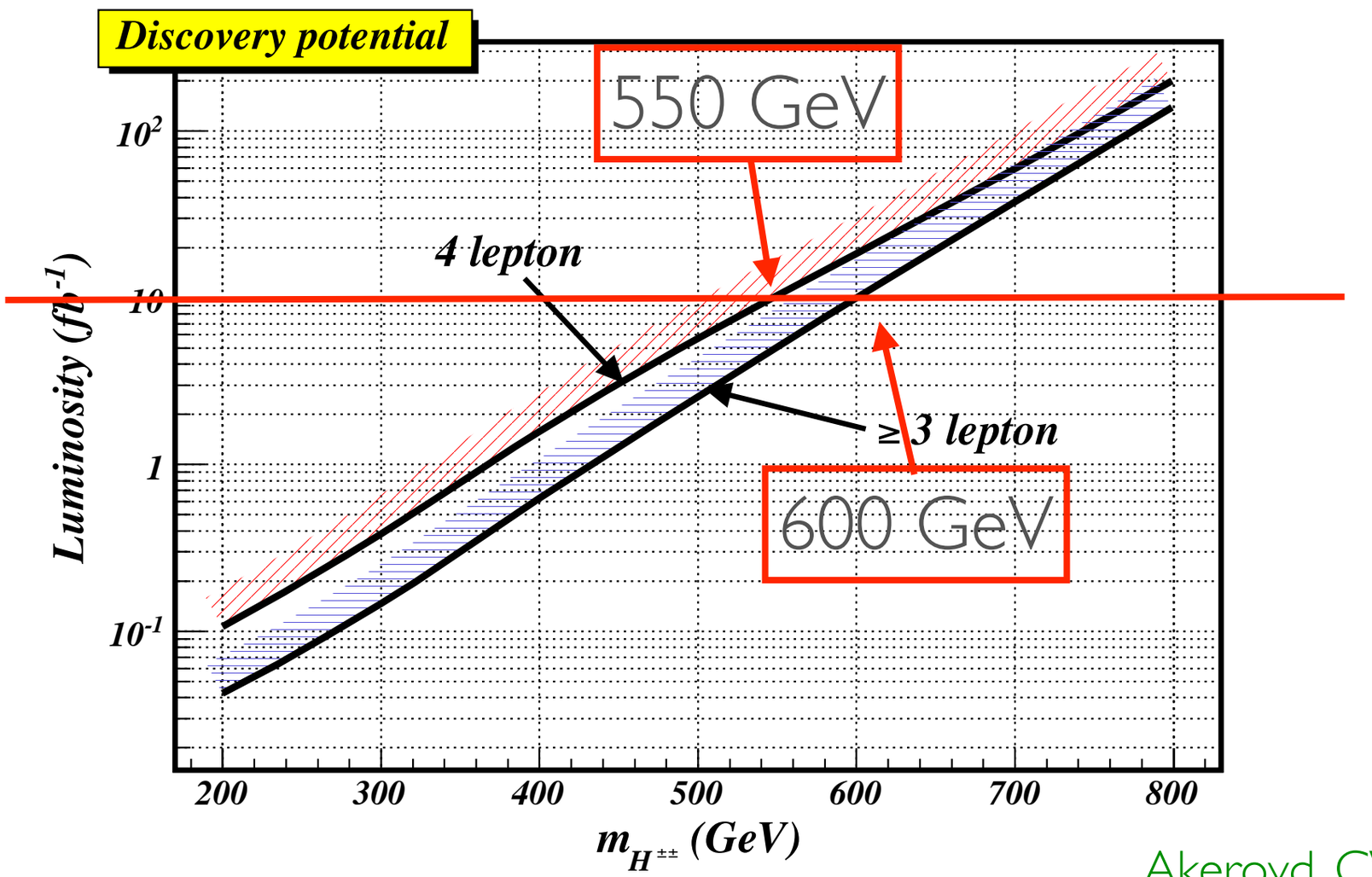




Perez et. al. 2008

5σ Discovery Potential

- Discovery potential for $H^{\pm\pm}$ at 14-TeV LHC through the $\geq 3\ell$ mode is significantly better than the 4ℓ mode.

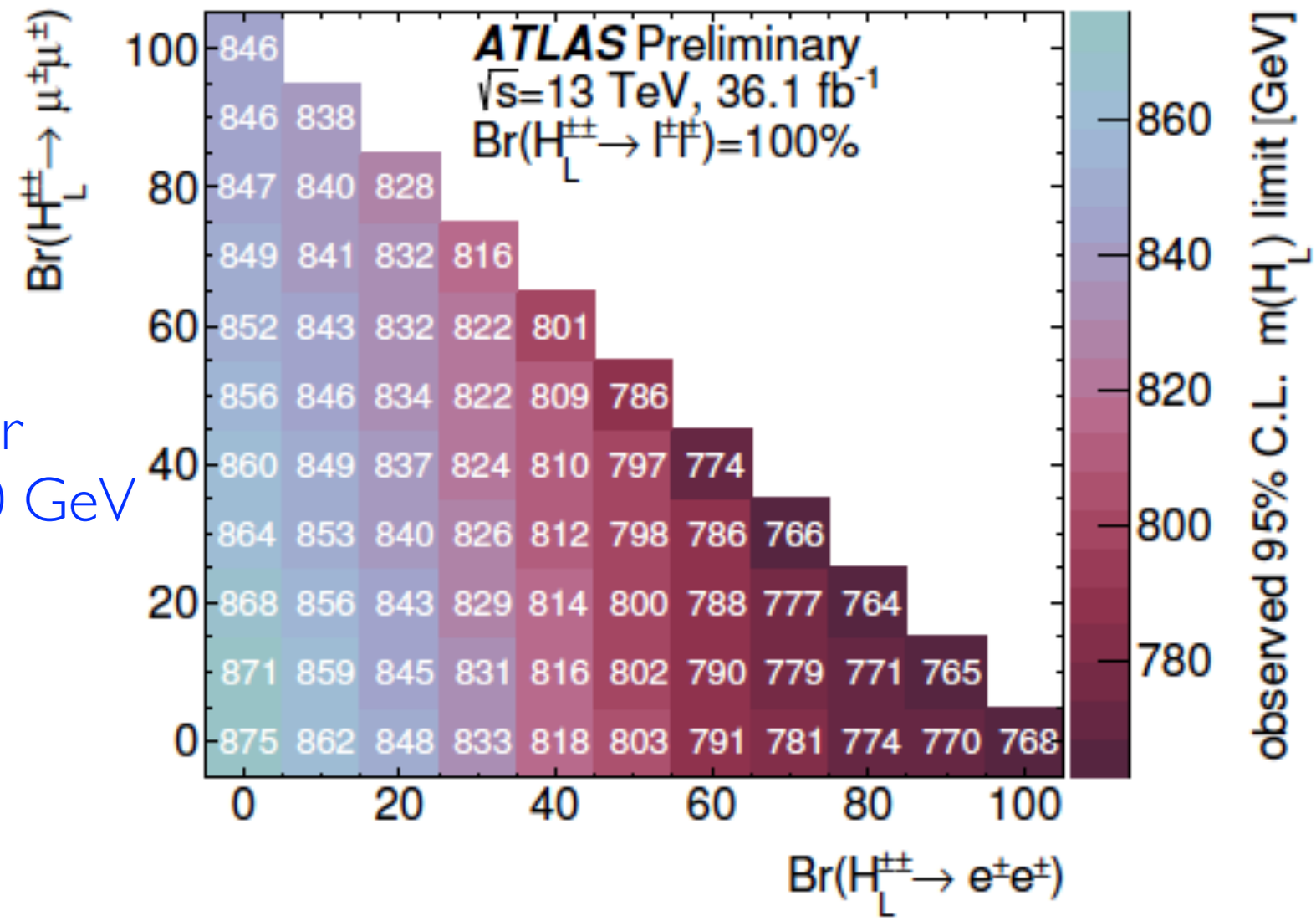


Akeroyd, CWC, Gaur 2010

Recent Mass Bounds

- There are more experimental efforts in the small-v_Δ scenario (i.e., larger Yukawas).

ATLAS 2017



A general lower bound of ~800 GeV

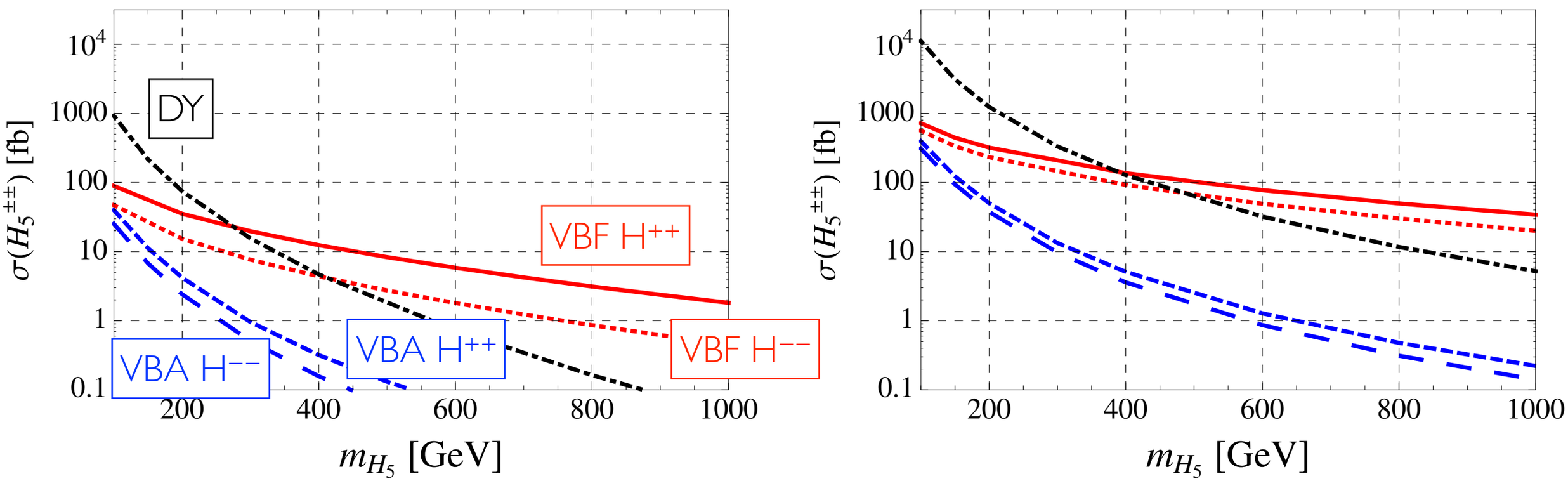
time for the large v_Δ scenario

$H^{\pm\pm}$ Productions

- Various $H_5^{\pm\pm}$ production channels at hadron colliders:

CWC, Kuo, Yamada 2016

14 TeV $\quad v_\Delta = 10$ GeV $\quad$ 100 TeV

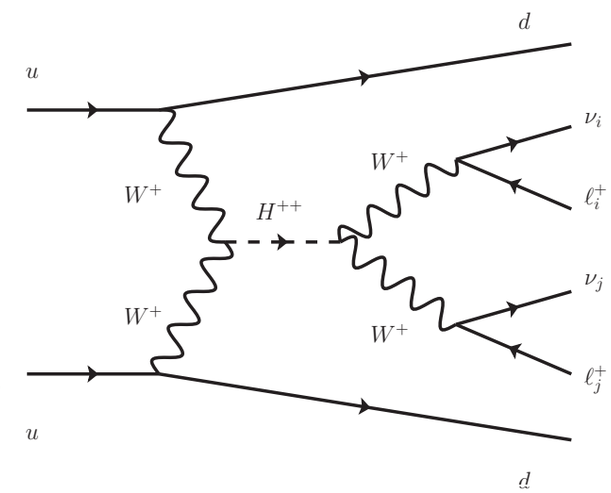


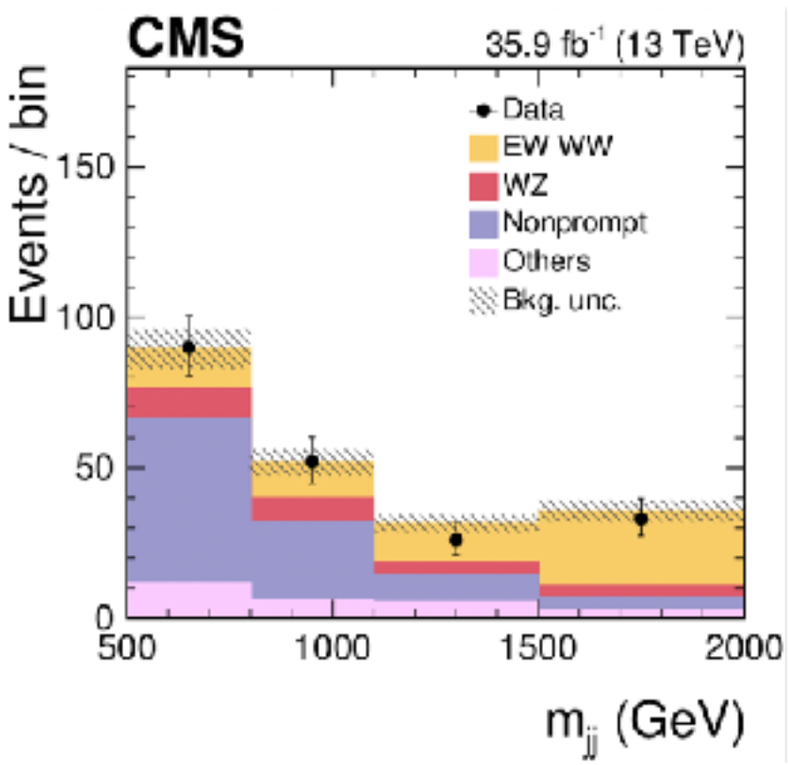
- DY: purely gauge interaction, indep. of v_Δ.
- VBF: dominant for $v_\Delta \gtrsim 10$ GeV and $m_5 \gtrsim 300$ GeV.

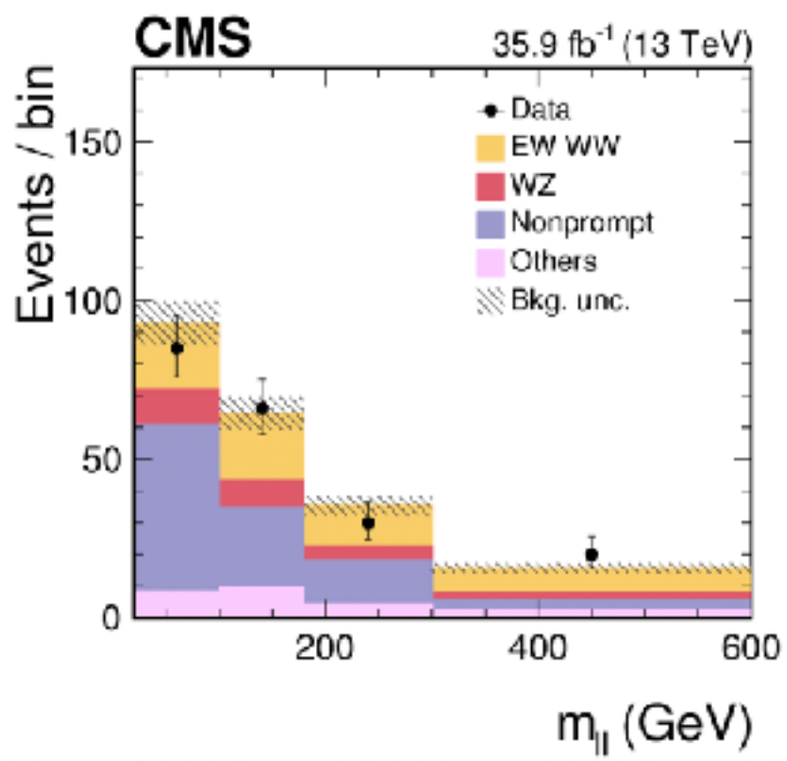
Golden Channel

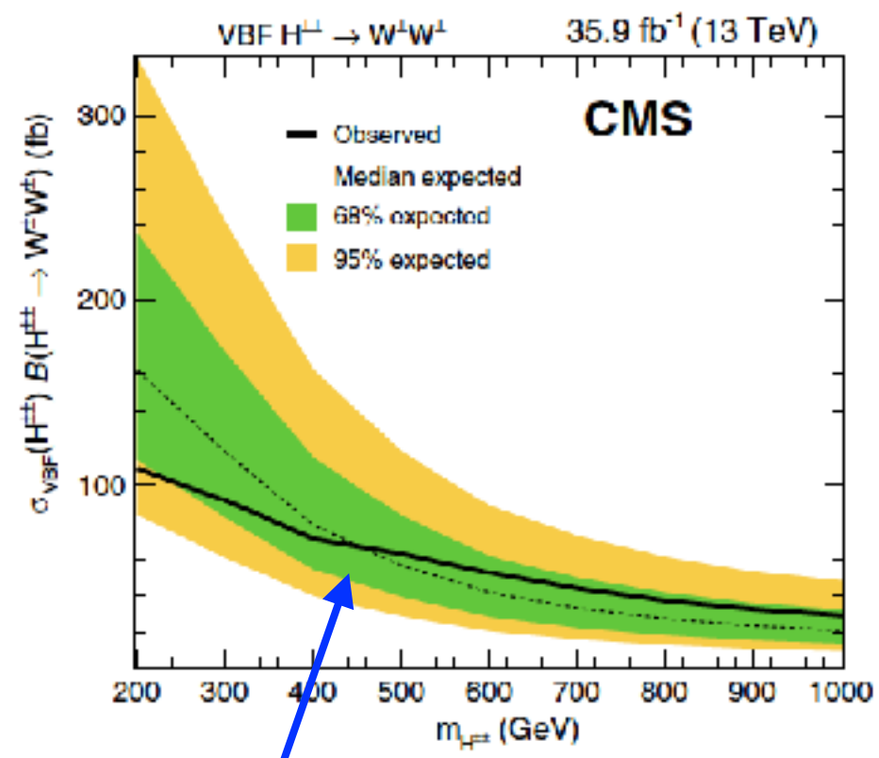
- From total cross section of same-sign W production along, a deviation could be due to anomalous gauge coupling or existence of a new resonance.

CWC, Kanemura, Yagyu 2014









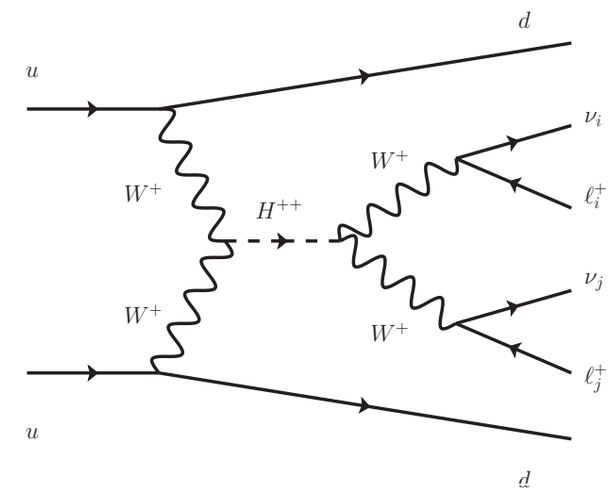
CMS 2018

$$\frac{\sigma^{\rm exp}}{\sigma^{\rm SM}_{\rm LO}} = 0.90 \pm 0.22 \quad \text{or} \quad \sin\theta_H \equiv \frac{2\sqrt{2}v_\Delta}{246\ \text{GeV}} < \begin{cases} 0.18 \text{ for } m_{H^{\pm\pm}} = 0.2 \text{ TeV} \\ 0.44 \text{ for } m_{H^{\pm\pm}} = 1 \text{ TeV} \end{cases}$$

bound much weaker than small v_Δ scenario

Golden Channel

- From differential distributions, particularly (a) $m_{\ell\ell'}$ and (b) cluster transverse mass

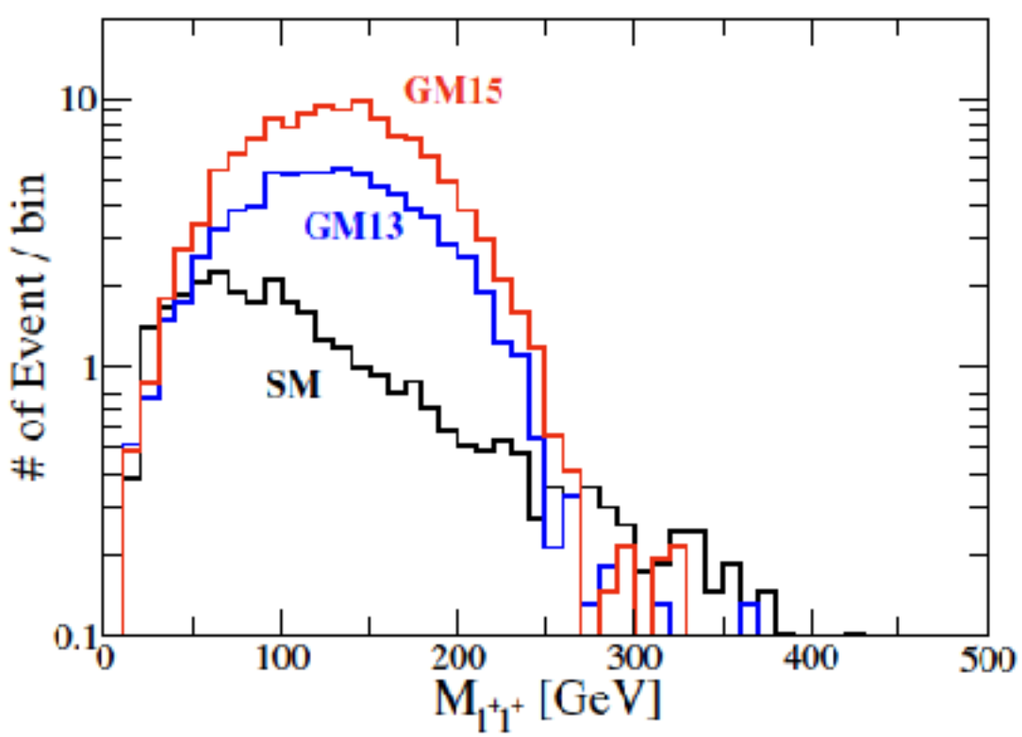


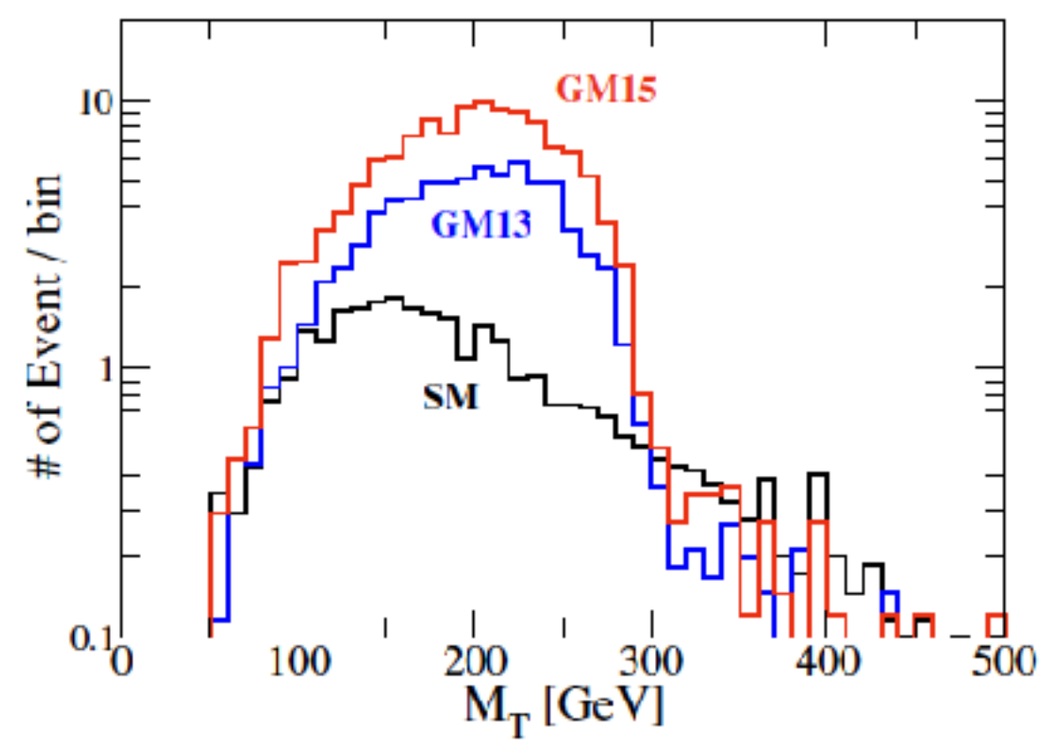
$$m_T^2 \equiv \left[\sqrt{m^2(\ell\ell) + p_T^2(\ell\ell)} + |\not{\mathbf{p}}_T|\right]^2 - \left[\mathbf{p}_T(\ell\ell) + \not{\mathbf{p}}_T\right]^2$$

one can observe (a) a bump ending at $m_{H^{++}}$ and (b) a Jacobian-like peak edged at $m_{H^{++}}$.

➠ hope to see such bumps

CWC, Kuo, Yagyu 2013



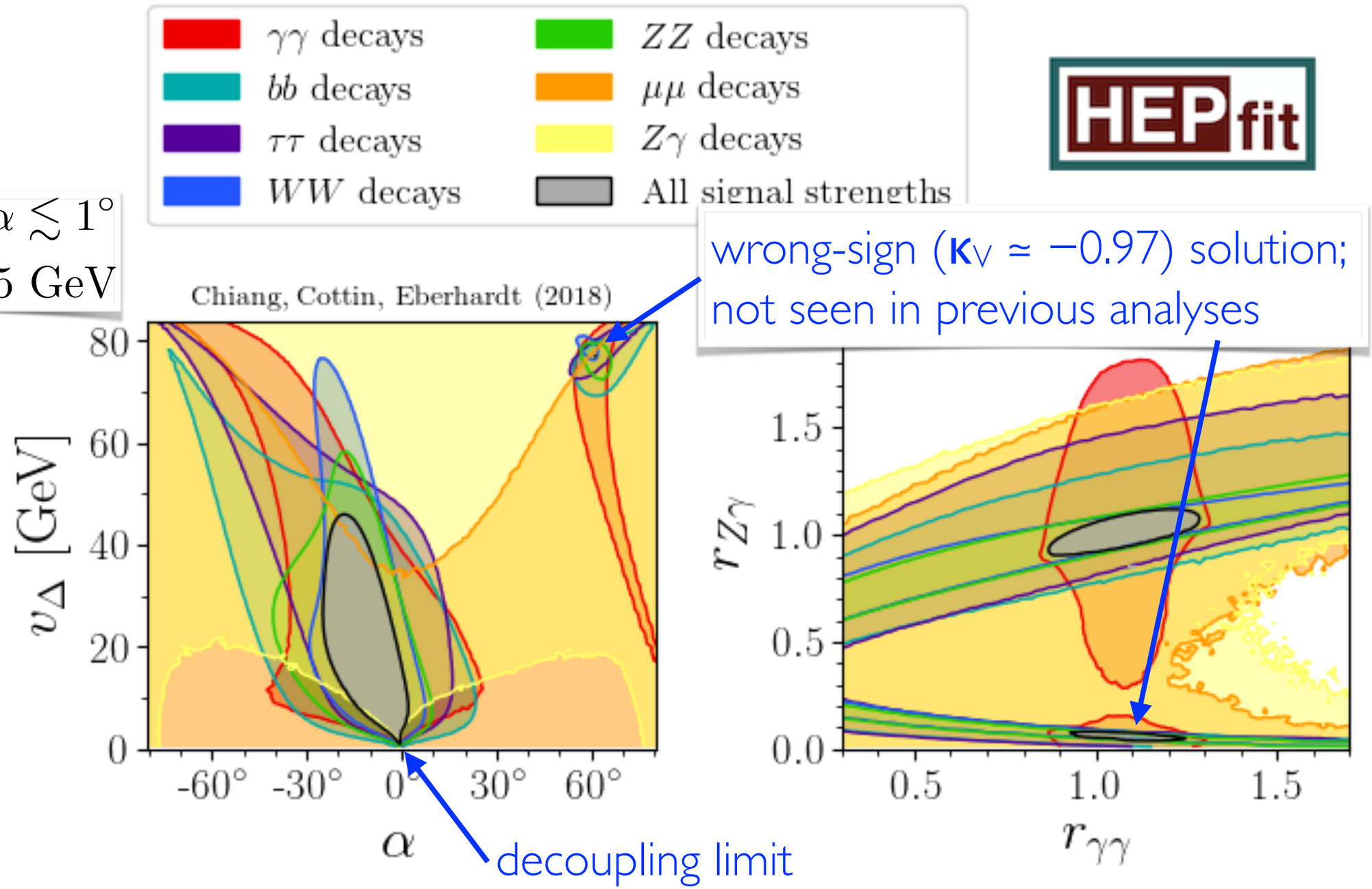


Fit Results

- Fit based on Higgs signal strengths after ICHEP 2018, all colored regions with 95% probability.

$-30^\circ \lesssim \alpha \lesssim 1^\circ$

$v_\Delta \lesssim 45$ GeV



wrong-sign ($\kappa_V \simeq -0.97$) solution; not seen in previous analyses

decoupling limit

Direct Search Inputs

Label	Channel	Experiment	Mass range [TeV]	$\mathcal{L}$ [fb^{-1}]
A_{13t}^{tt}	$tt \to \phi^0 \to tt$	ATLAS [73]	[0.4;1]	36.1
A_{13b}^{tt}	$bb \to \phi^0 \to tt$	ATLAS [74]	[0.4;1]	13.2
C_{8b}^{bb}	$bb \to \phi^0 \to bb$	CMS [75]	[0.1;0.9]	19.7
C_{8}^{bb}	$gg \to \phi^0 \to bb$	CMS [76]	[0.33;1.2]	19.7
C_{13}^{bb}	$gg \to \phi^0 \to bb$	CMS [77]	[0.55;1.2]	2.09
C_{13b}^{bb}	$bb \to \phi^0 \to bb$	CMS [78]	[0.3;1.3]	35.7
$A_{8}^{\tau\tau}$	$gg \to \phi^0 \to \tau\tau$	ATLAS [79]	[0.09;1]	20
$C_{8}^{\tau\tau}$		CMS [80]	[0.09;1]	19.7
$A_{8b}^{\tau\tau}$	$bb \to \phi^0 \to \tau\tau$	ATLAS [79]	[0.09;1]	20
$C_{8b}^{\tau\tau}$		CMS [80]	[0.09;1]	19.7
$A_{13}^{\tau\tau}$	$gg \to \phi^0 \to \tau\tau$	ATLAS [81]	[0.2;2.25]	36.1
$C_{13}^{\tau\tau}$		CMS [82]	[0.09;3.2]	35.9
$A_{13b}^{\tau\tau}$	$bb \to \phi^0 \to \tau\tau$	ATLAS [81]	[0.2;2.25]	36.1
$C_{13b}^{\tau\tau}$		CMS [82]	[0.09;3.2]	35.9

Table 2. Neutral heavy Higgs boson searches relevant for the GM scalars with fermionic final states. $\phi^0 = H_1^0, H_3^0$.

Label	Channel	Experiment	Mass range [TeV]	$\mathcal{L}$ [fb^{-1}]
$A_{8}^{\gamma\gamma}$	$gg \to \phi^0 \to \gamma\gamma$	ATLAS [83]	[0.065;0.6]	20.3
$A_{13}^{\gamma\gamma}$	$pp \to \phi^0 \to \gamma\gamma$	ATLAS [84]	[0.2;2.7]	36.7
$C_{13}^{\gamma\gamma}$	$gg \to \phi^0 \to \gamma\gamma$	CMS [85]	[0.5;4]	35.9
$A_{8}^{Z\gamma}$	$pp \to \phi^0 \to Z\gamma \to (\ell\ell)\gamma$	ATLAS [86]	[0.2;1.6]	20.3
$C_{8}^{Z\gamma}$		CMS [87]	[0.2;1.2]	19.7
$A_{13}^{\ell\ell\gamma}$	$gg \to \phi^0 \to Z\gamma[\to (\ell\ell)\gamma]$	ATLAS [50]	[0.25;2.4]	36.1
$A_{13}^{qq\gamma}$	$gg \to \phi^0 \to Z\gamma[\to (qq)\gamma]$	ATLAS [88]	[1;6.8]	36.1
$C_{8+13}^{Z\gamma}$	$gg \to \phi^0 \to Z\gamma$	CMS [89]	[0.35;4]	35.9
A_{8}^{ZZ}	$gg \to \phi^0 \to ZZ$	ATLAS [90]	[0.14;1]	20.3
A_{8V}^{ZZ}	$VV \to \phi^0 \to ZZ$	ATLAS [90]	[0.14;1]	20.3
$A_{13}^{2\ell2L}$	$gg \to \phi^0 \to ZZ[\to (\ell\ell)(\ell\ell, \nu\nu)]$	ATLAS [91]	[0.2;1.2]	36.1
$A_{13V}^{2\ell2L}$	$VV \to \phi^0 \to ZZ[\to (\ell\ell)(\ell\ell, \nu\nu)]$	ATLAS [91]	[0.2;1.2]	36.1
A_{13}^{2L2q}	$gg \to \phi^0 \to ZZ[\to (\ell\ell, \nu\nu)(qq)]$	ATLAS [92]	[0.3;3]	36.1
A_{13V}^{2L2q}	$VV \to \phi^0 \to ZZ[\to (\ell\ell, \nu\nu)(qq)]$	ATLAS [92]	[0.3;3]	36.1
$C_{13}^{2\ell2X}$	$pp \to \phi^0 \to ZZ[\to (\ell\ell)(qq, \nu\nu, \ell\ell)]$	CMS [93]	[0.13;3]	35.9
$C_{13}^{2q2\nu}$	$pp \to \phi^0 \to ZZ[\to (qq)(\nu\nu)]$	CMS [94]	[1;4]	35.9
A_{8}^{WW}	$gg \to \phi^0 \to WW$	ATLAS [95]	[0.3;1.5]	20.3
A_{8V}^{WW}	$VV \to \phi^0 \to WW$	ATLAS [95]	[0.3;1.5]	20.3
$A_{13}^{2(\ell\nu)}$	$gg \to \phi^0 \to WW[\to (e\nu)(\mu\nu)]$	ATLAS [96]	[0.25;4]	36.1
$A_{13V}^{2(\ell\nu)}$	$VV \to \phi^0 \to WW[\to (e\nu)(\mu\nu)]$	ATLAS [96]	[0.25;3]	36.1
$C_{13}^{2(\ell\nu)}$	$(gg + VV) \to \phi^0 \to WW \to (\ell\nu)(\ell\nu)$	CMS [97]	[0.2;1]	2.3
$A_{13}^{\ell\nu2q}$	$gg \to \phi^0 \to WW[\to (\ell\nu)(qq)]$	ATLAS [98]	[0.3;3]	36.1
$A_{13V}^{\ell\nu2q}$	$VV \to \phi^0 \to WW[\to (\ell\nu)(qq)]$	ATLAS [98]	[0.3;3]	36.1
$C_{13}^{\ell\nu2q}$	$pp \to \phi^0 \to WW[\to (\ell\nu)(qq)]$	CMS [99]	[1;1.4]	35.9
C_{8}^{VV}	$pp \to \phi^0 \to VV$	CMS [100]	[0.145;1]	24.8

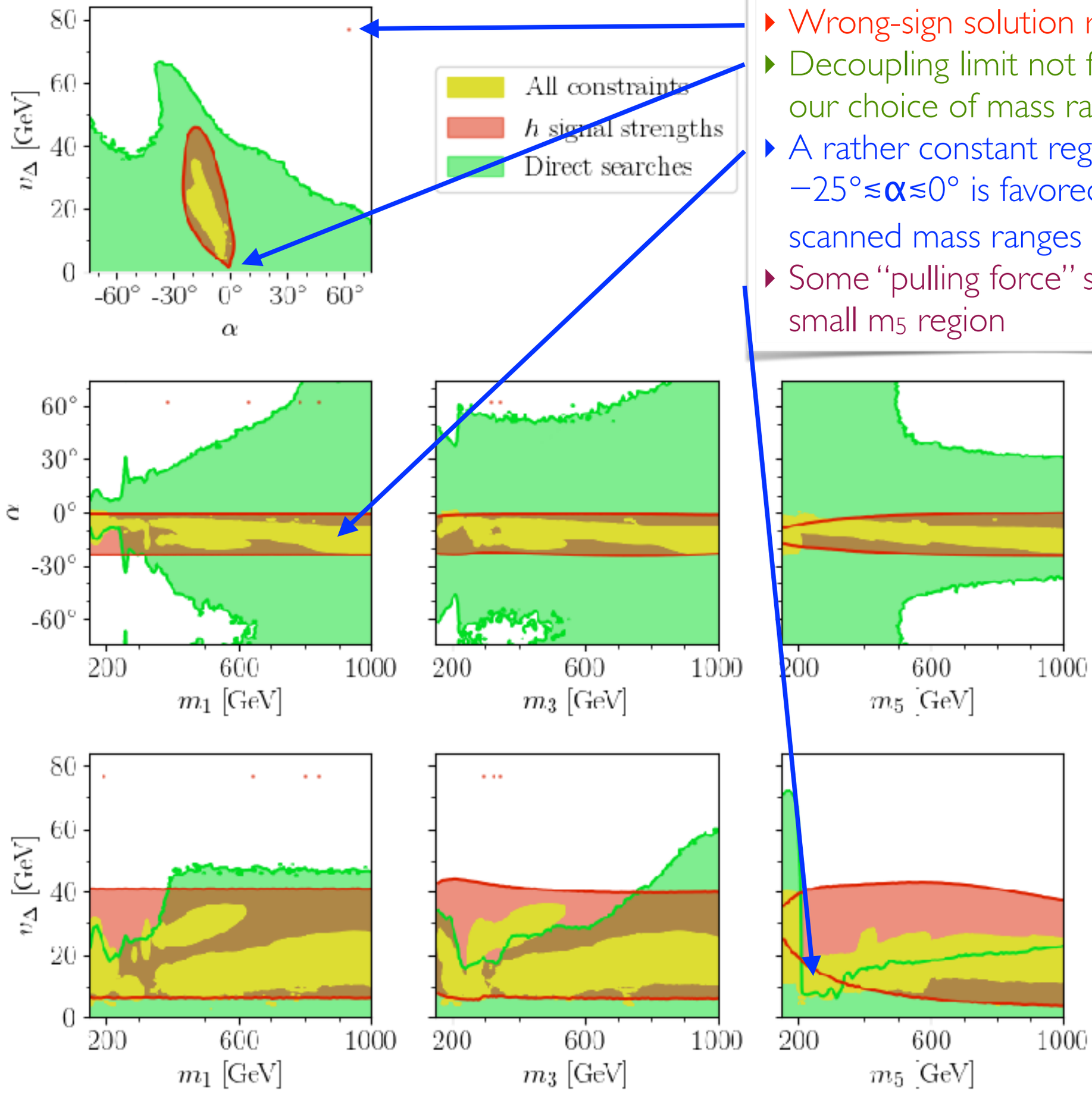
Table 3. Neutral heavy Higgs boson searches relevant for the GM scalars with vector boson final states. $\phi^0 = H_1^0, H_3^0, H_5^0$ and $\ell = e, \mu$.

Label	Channel	Experiment	Mass range [TeV]	$\mathcal{L}$ [fb^{-1}]
A_{8}^{hh}	$gg \to H_1^0 \to hh$	ATLAS [101]	[0.25;1]	20.3
C_{8}^{4b}	$pp \to H_1^0 \to hh \to (bb)(bb)$	CMS [102]	[0.27;1.1]	17.9
$C_{8}^{2\gamma2b}$	$pp \to H_1^0 \to hh \to (bb)(\gamma\gamma)$	CMS [103]	[0.260;1.1]	19.7
$C_{8}^{2b2\tau}$	$gg \to H_1^0 \to hh \to (bb)(\tau\tau)$	CMS [104]	[0.26;0.35]	19.7
$C_{8}^{2b2\tau}$	$pp \to H_1^0 \to hh[\to (bb)(\tau\tau)]$	CMS [105]	[0.35;1]	18.3
A_{13}^{4b}	$pp \to H_1^0 \to hh \to (bb)(bb)$	ATLAS [106]	[0.25;3]	36.1
C_{13}^{4b}		CMS [107]	[0.26;1.2]	35.9
$A_{13}^{2\gamma2b}$	$pp \to H_1^0 \to hh[\to (bb)(\gamma\gamma)]$	ATLAS [108]	[0.25;1]	36.1
$C_{13}^{2\gamma2b}$	$pp \to H_1^0 \to hh \to (bb)(\gamma\gamma)$	CMS [109]	[0.25;0.5]	35.9
$A_{13}^{2b2\tau}$	$pp \to H_1^0 \to hh \to (bb)(\tau\tau)$	ATLAS [110]	[0.25;1]	36.1
$C_{13,1}^{2b2\tau}$		CMS [111]	[0.25;0.9]	35.9
$C_{13,2}^{2b2\tau}$	$pp \to H_1^0 \to hh[\to (bb)(\tau\tau)]$	CMS [112]	[0.9;4]	35.9
C_{13}^{2b2V}	$pp \to H_1^0 \to hh \to (bb)(VV \to \ell\nu\ell\nu)$	CMS [113]	[0.26;0.9]	35.9
$A_{13}^{2\gamma2W}$	$gg \to H_1^0 \to hh \to (\gamma\gamma)(WW)$	ATLAS [114]	[0.26;0.5]	36.1
A_{8}^{bbZ}	$gg \to H_3^0 \to hZ \to (bb)Z$	ATLAS [115]	[0.22;1]	20.3
$C_{8}^{2b2\ell}$	$gg \to H_3^0 \to hZ \to (bb)(\ell\ell)$	CMS [116]	[0.225;0.6]	19.7
$A_{8}^{\tau\tau Z}$	$gg \to H_3^0 \to hZ \to (\tau\tau)Z$	ATLAS [115]	[0.22;1]	20.3
$C_{8}^{\tau\tau\ell\ell}$	$gg \to H_3^0 \to hZ \to (\tau\tau)(\ell\ell)$	CMS [104]	[0.22;0.35]	19.7
A_{13}^{bbZ}	$gg \to H_3^0 \to hZ \to (bb)Z$	ATLAS [117]	[0.2;2]	36.1
$C_{13,1}^{bbZ}$		CMS [118]	[0.22;0.8]	35.9
$C_{13,2}^{bbZ}$		CMS [119]	[0.8;2]	35.9
A_{13b}^{bbZ}	$bb \to H_3^0 \to hZ \to (bb)Z$	ATLAS [117]	[0.2;2]	36.1
$C_{13b,1}^{bbZ}$		CMS [118]	[0.22;0.8]	35.9
$C_{13b,2}^{bbZ}$		CMS [119]	[0.8;2]	35.9
$C_{8}^{\phi Z}$	$pp \to \phi^0 \to \phi^{0\prime}Z \to (bb)(\ell\ell)$	CMS [120]	[0.13;1]	19.8
$A_{13}^{\phi Z}$	$gg \to H_3^0 \to H_1^0Z \to (bb)Z$	ATLAS [121]	[0.13;0.5]	36.1
$A_{13b}^{\phi Z}$	$bb \to H_3^0 \to H_1^0Z \to (bb)Z$	ATLAS [121]	[0.13;0.5]	36.1

Table 4. Neutral heavy Higgs boson searches at the LHC relevant for the GM scalars with final states including Higgs bosons. $\phi^0 = H_1^0, H_3^0, H_5^0$, $\phi^{0\prime} = H_1^0, H_3^0$, $V = W, Z$ and $\ell = e, \mu$.

Label	Channel	Experiment	Mass range [TeV]	$\mathcal{L}$ [fb^{-1}]
$A_{8}^{\tau\nu}$	$pp \to H_3^{\pm} \to \tau^{\pm}\nu$	ATLAS [122]	[0.18;1]	19.5
$C_{8}^{\tau\nu}$	$pp \to H_3^{\pm} \to \tau^{\pm}\nu$	CMS [123]	[0.18;0.6]	19.7
$A_{13}^{\tau\nu}$	$pp \to H_3^{\pm} \to \tau^{\pm}\nu$	ATLAS [124]	[0.15;2]	36.1
$C_{13}^{\tau\nu}$		CMS [125]	[0.18;3]	12.9
A_{8}^{tb}	$pp \to H_3^{\pm} \to tb$	ATLAS [126]	[0.2;0.6]	20.3
C_{8}^{tb}	$pp \to H_3^{\pm} \to tb$	CMS [123]	[0.18;0.6]	19.7
A_{13}^{tb}	$pp \to H_3^{\pm} \to tb$	ATLAS [127]	[0.2;2]	36.1
A_{8}^{WZ}	$WZ \to H_5^{\pm} \to WZ[\to (qq)(\ell\ell)]$	ATLAS [128]	[0.2;1]	20.3
A_{13}^{WZ}	$WZ \to H_5^{\pm} \to WZ[\to (\ell\nu)(\ell\ell)]$	ATLAS [129]	[0.2;0.9]	36.1
$C_{13,1}^{WZ}$		CMS [130]	[0.2;0.3]	15.2
$C_{13,2}^{WZ}$		CMS [131]	[0.3;2]	35.9
A_{13}^{WW}	$pp \to H_5^{\pm\pm}H_5^{\mp\mp} \to (W^{\pm}W^{\pm})(W^{\mp}W^{\mp})$	ATLAS [132]	[0.2;0.7]	36.1
$C_{8}^{W^{\pm}W^{\pm}}$	$VV \to H_5^{\pm\pm} \to W^{\pm}W^{\pm}[\to (\ell^{\pm}\nu)(\ell^{\pm}\nu)]$	CMS [133]	[0.2;0.8]	19.4
$C_{13}^{\ell^{\pm}\ell^{\pm}}$	$VV \to H_5^{\pm\pm} \to W^{\pm}W^{\pm}[\to (\ell^{\pm}\nu)(\ell^{\pm}\nu)]$	CMS [134]	[0.2;1.0]	35.9

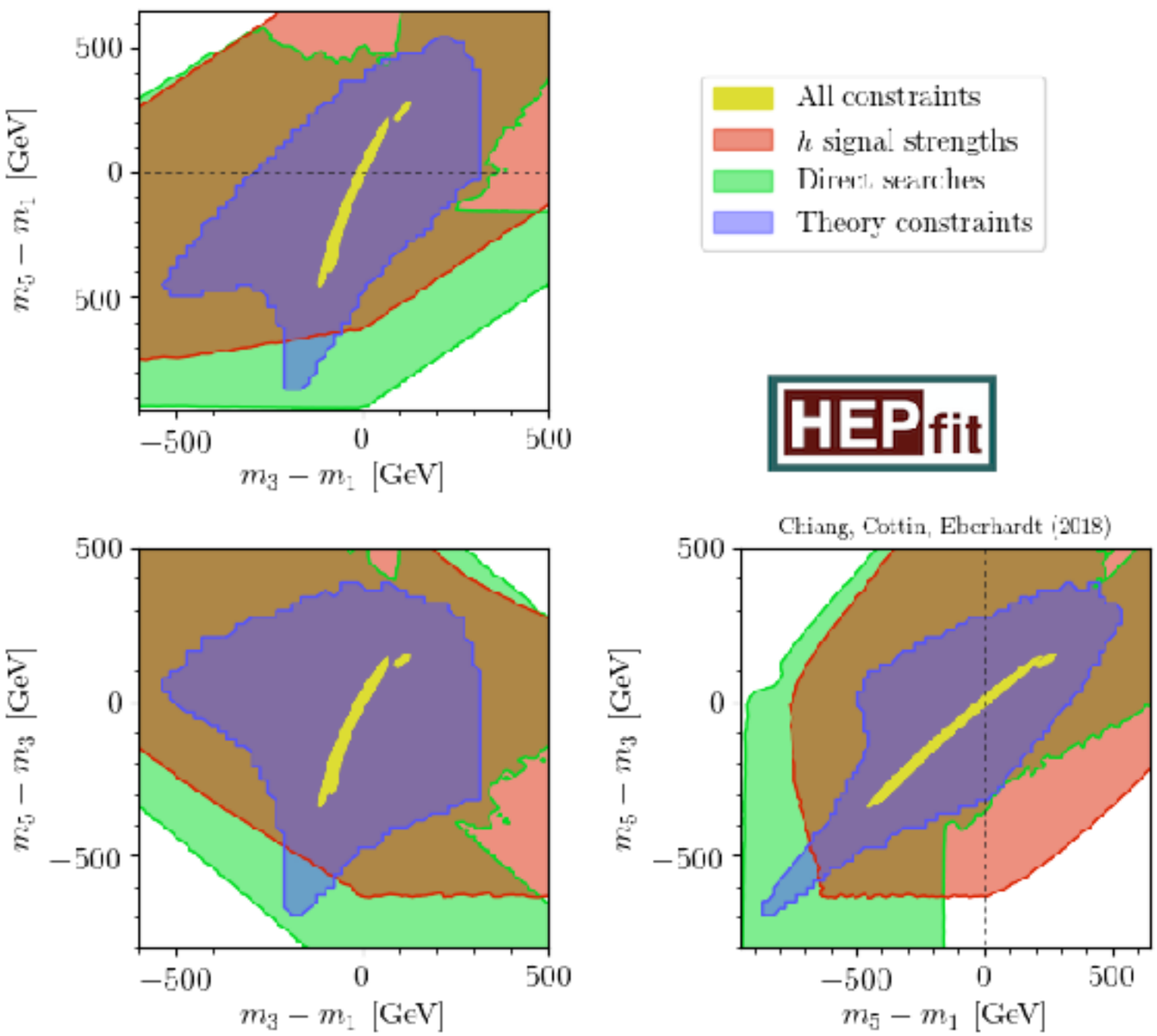
Table 5. Charged heavy Higgs boson searches at the LHC relevant for the singly and doubly charged scalars in the GM model. Again, $V = W, Z$ and $\ell = e, \mu$.



- Wrong-sign solution removed
- Decoupling limit not favored due to our choice of mass ranges
- A rather constant region of $-25° \lesssim \alpha \lesssim 0°$ is favored across the scanned mass ranges
- Some "pulling force" seen in the small m_5 region

Mass Relation

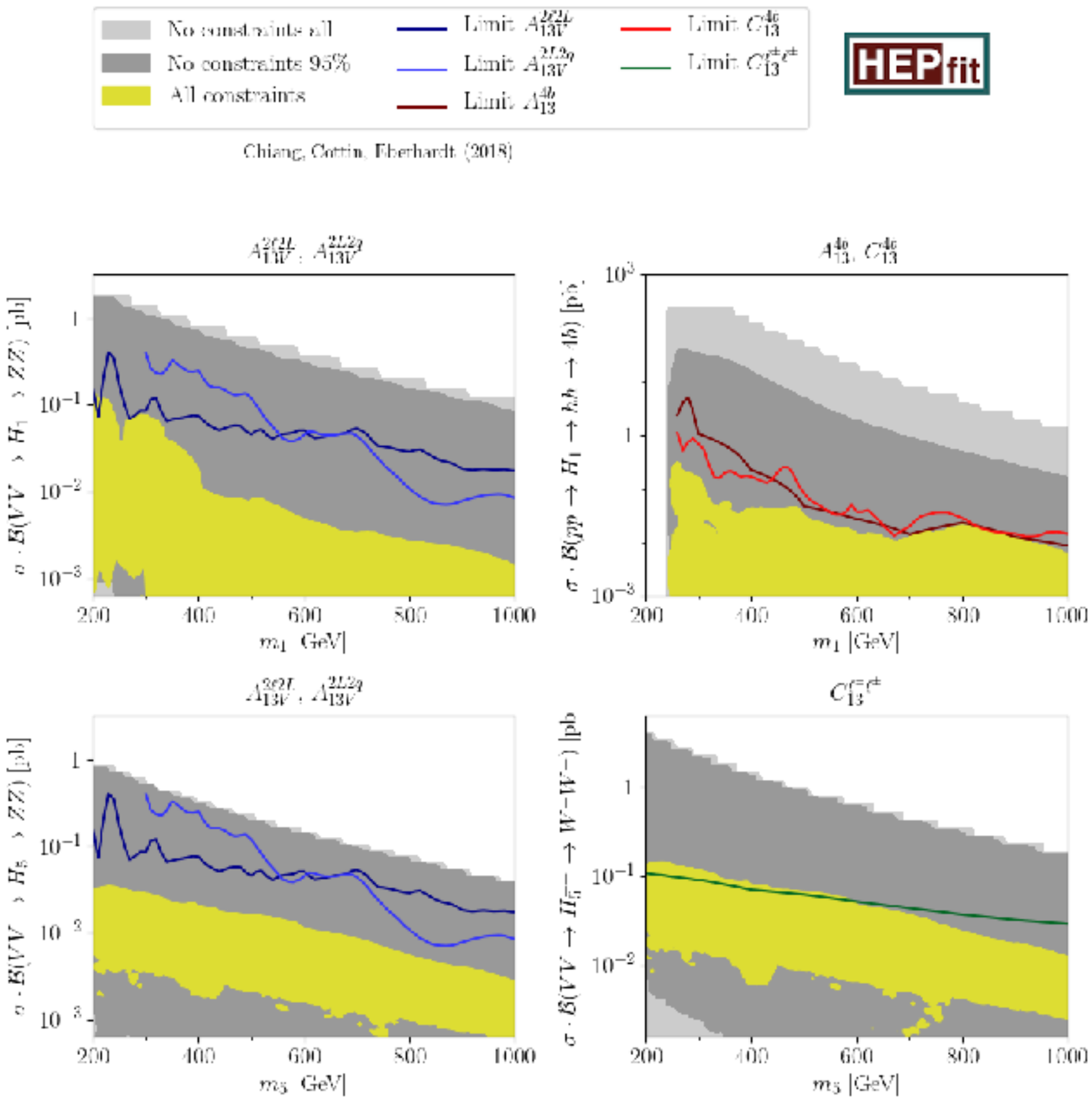
- Mass differences allowed at 95% probability.
- Roughly $m_5 > m_3 > m_1$ or $m_5 < m_3 < m_1$ hierarchies.



Theory constraints:
- perturbative unitarity at tree level
- stability of potential at tree level

The disjoint regions at $(m_5-m_1, m_3-m_1) \approx (250, 120)$ GeV are a consequence of our choice of only including on-shell 2-body decays of the H_5 bosons.
➠ gap would disappear if 3-body decays (involving off-shell weak bosons) are considered

Promising Processes



- 4 most constraining searches for heavier resonances.
- Grey regions delimit available GM model space if no constraint is applied.
- Most powerful experimental analyses in constraining GM model involve searches for the $H_{1,5}^0$ and $H_5^{\pm\pm}$ bosons.
- Channels of H_3^0 and $H_{3,5}^\pm$ are not as constraining.
- Left plots are not very relevant except for m_1<300 GeV.
- Right plots yield the strongest constraints for 0.5<m_1<1 TeV and for 0.2<m_5<0.6 TeV, respectively.

HVV COUPLINGS AT LOOP LEVEL

g_{HVV} in Simple Models

Model	Higgs	$\kappa_V = g_{HVV}/g_{h_{\rm SM}VV}$	κ_W/κ_Z
rHSM	h	$\cos\alpha$	1
2HDM	h	$\sin(\beta-\alpha)$	1
	H	$\cos(\beta-\alpha)$	1
GM	h	$\sin\beta\cos\alpha - \sqrt{\frac{8}{3}}\cos\beta\sin\alpha$	1
	H_1^0	$\sin\beta\sin\alpha + \sqrt{\frac{8}{3}}\cos\beta\cos\alpha$	1
	H_3^0	0	—
	H_5^0	$\kappa_W = -\frac{\cos\beta}{\sqrt{3}}$ and $\kappa_Z = \frac{2\cos\beta}{\sqrt{3}}$	$-1/2$

SM-like Higgs

≤ 1

κ's all normalized to corresponding SM values

$$\text{2HDM: } \tan\beta = \frac{v_u}{v_d} \quad \text{and} \quad \text{GM: } \tan\beta = \frac{v_\phi}{2\sqrt{2}v_\Delta}$$

Recent Run-II Data

Parameter	ATLAS	CMS	Average
κ_W	1.07 ± 0.10	$1.12^{+0.13}_{-0.19}$	1.08 ± 0.08
κ_Z	1.07 ± 0.10	0.99 ± 0.11	1.03 ± 0.07

ATLAS-CONF-2018-31 (13 TeV, 80/fb)
CMS-PAS-HIG-17-031 (13 TeV, 36/fb)

- Concentrate on the central values.

✓ κ_W and/or κ_Z may be greater than 1.

- κ_W and κ_Z may be different. (CMS alone and central values only, by ~10%)

- How much can $\kappa_W = \kappa_Z$ be violated by radiative corrections?

➠ model-dependent

κ_Z AND κ_W

- hVV scale factors at 1-loop with momentum dependence are defined as:

momentum of off-shell V*

$$\hat{\kappa}_V(p^2) \equiv \frac{\hat{\Gamma}_1(m_V^2, p^2, m_h^2)_{\rm NP}}{\hat{\Gamma}_1(m_V^2, p^2, m_h^2)_{\rm SM}}$$

- At 1σ, $\kappa_{W,Z}$ are (will be) determined to be

LHC Run-I	$\kappa_Z = [0.94, 1.13]$	$\kappa_W = [0.78, 1.00]$	
HL-LHC	$\Delta\kappa_Z = 2 - 4\%$	$\Delta\kappa_W = 2 - 5\%$	14 TeV, 3000/fb
ILC	$\Delta\kappa_Z = 0.58\%$	$\Delta\kappa_W = 0.81\%$	500 GeV, 500/fb ⊕ 350 GeV, 200/fb ⊕ 250 GeV, 500/fb

1606.02266 [hep-ex]
1310.8361 [hep-ex]
1506.05992 [hep-ex]

- Radiative corrections in SM:

$$\frac{g_{hVV}^{1-\rm loop}}{g_{hVV}^{\rm tree}} \simeq \begin{cases} -1.2 \ \ (+1.0)\ \% \ \ (hZZ)\ , \\ +0.4 \ \ (+1.3)\ \% \ \ (hWW)\ , \end{cases} \quad \text{for } \sqrt{p^2} = 250\ (500)\ \text{GeV}$$

1-Loop Results

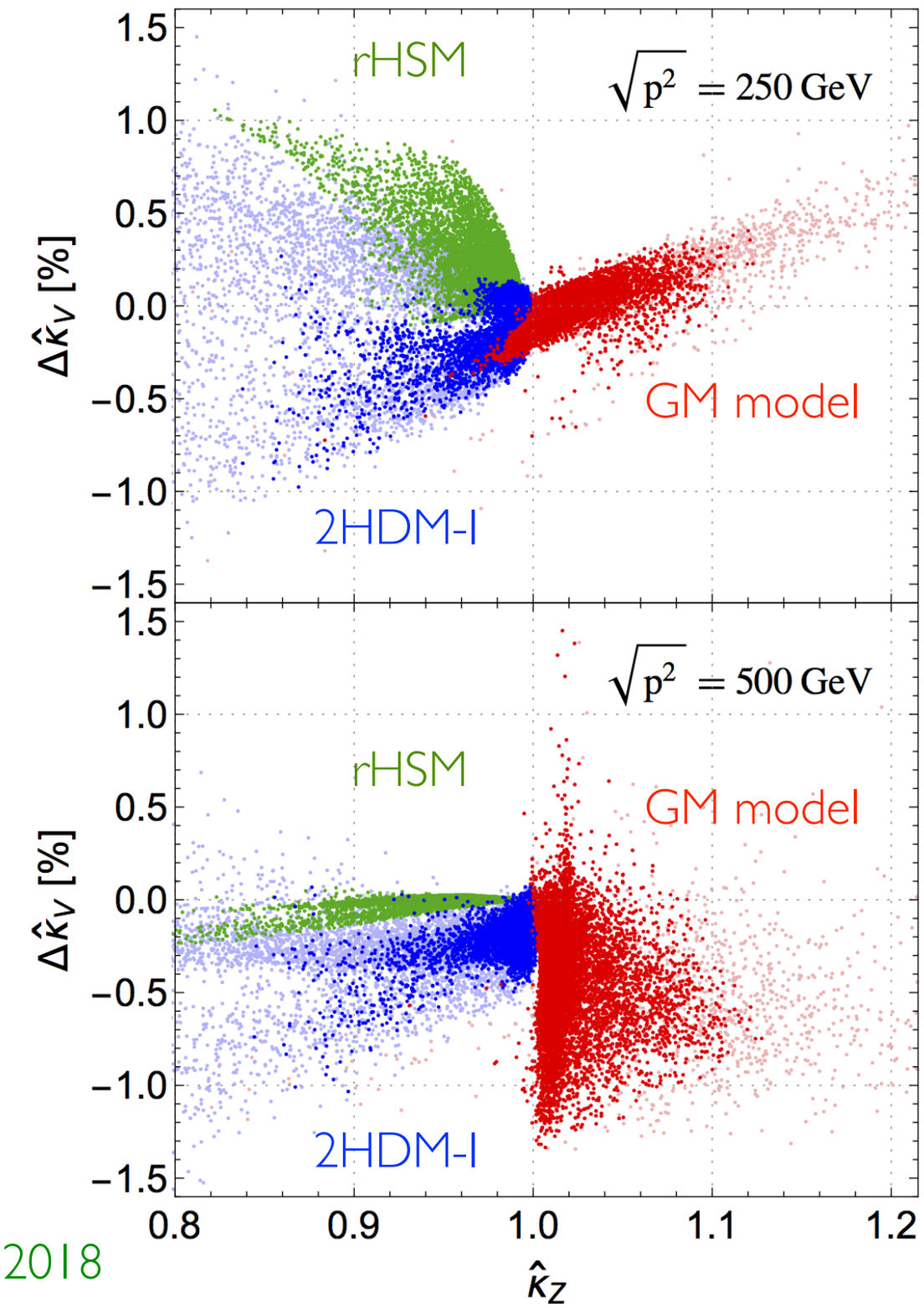
$\Delta\hat{\kappa}_V \equiv \hat{\kappa}_W - \hat{\kappa}_Z$

- Lighter dots satisfy theoretical constraints (unitarity, stability, perturbativity, and oblique parameters [S and T]).
- Darker dots further satisfy Higgs signal strengths from LHC Run-I (20 channels).

ATLAS+CMS 2016

- Other types of 2HDM are expected to have a similar result as 2HDM-I.
- It is possible to discriminate among the rHSM, 2HDMs and GM model.

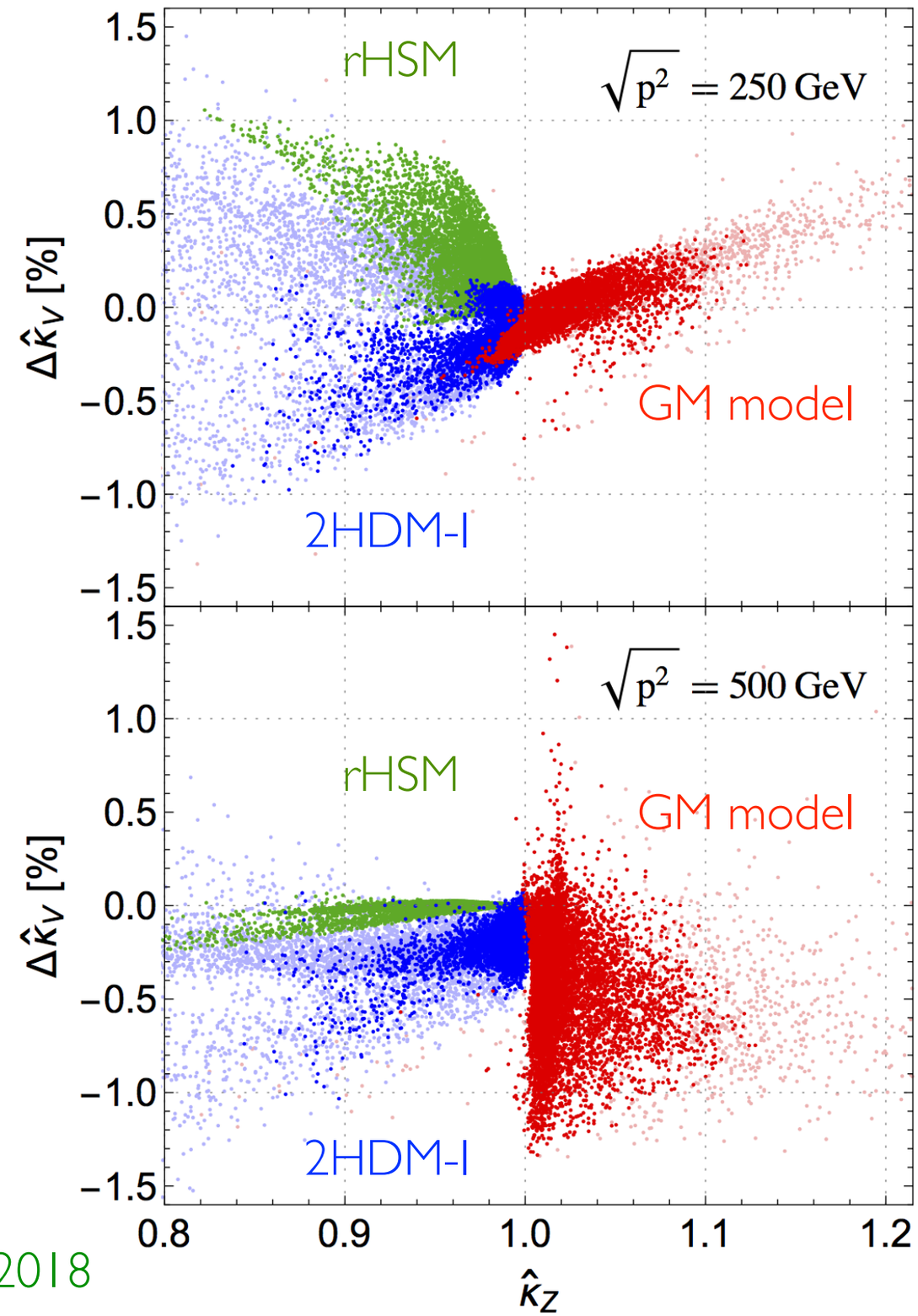
CWC, Kuo, Yagyu 2017, 2018



1-Loop Results

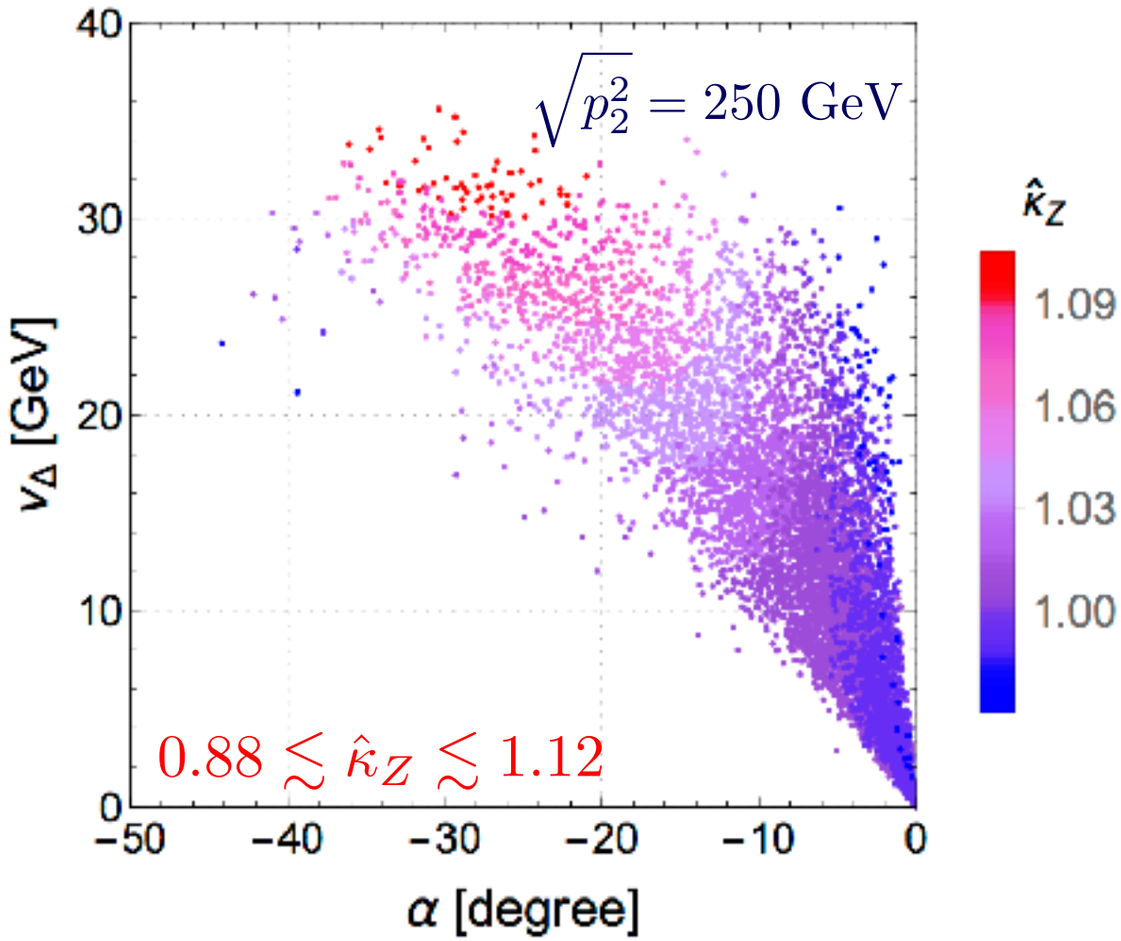
$\Delta\hat{\kappa}_V \equiv \hat{\kappa}_W - \hat{\kappa}_Z$

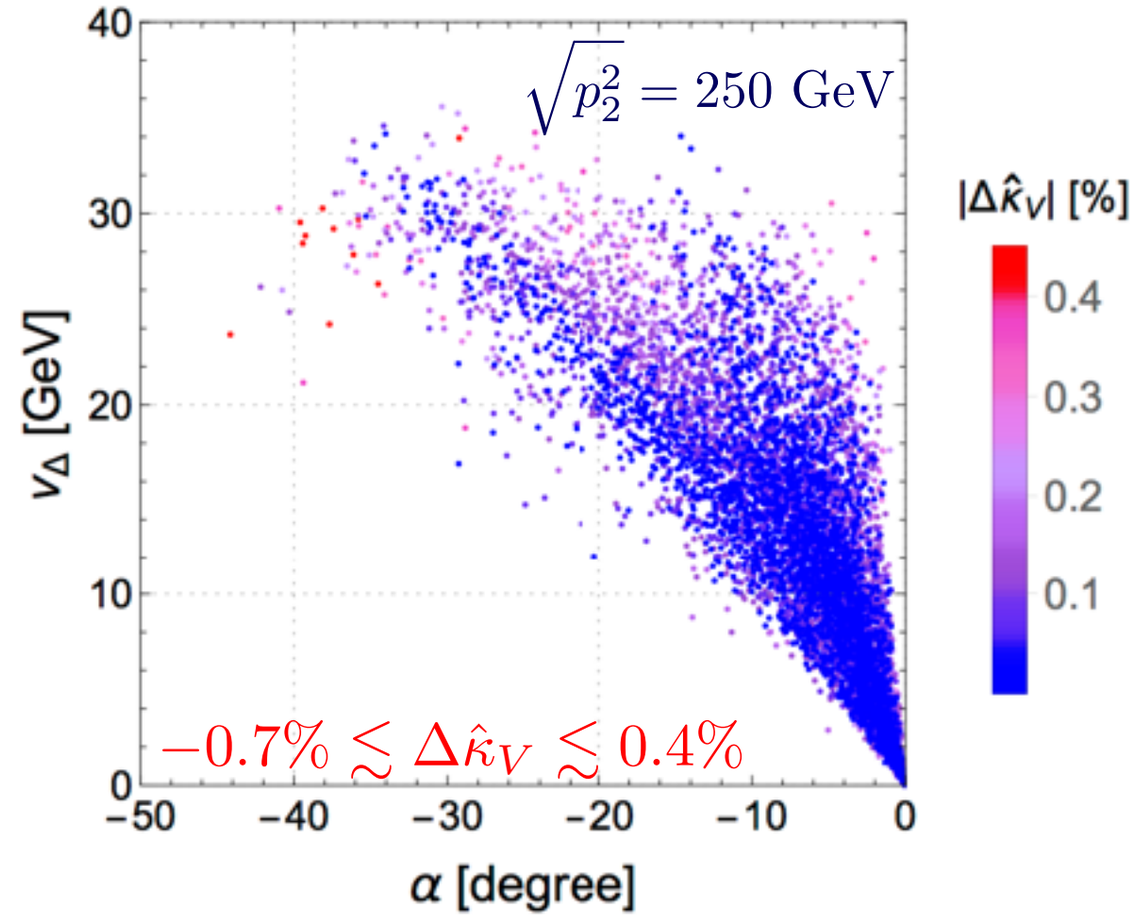
- Green dots change little after imposing the Higgs data, while 2HDM and GM dots shrink significantly.
- GM prefers $\kappa_Z \in [0.88, 1.12]$, while the others have $\kappa_Z \in [0.8, 1.0]$ (upper plot).
- $\Delta\kappa_V \sim O(1\%)$ and may be observable.
- 250-GeV ILC is better than 500-GeV in distinguishing rHSM and 2HDM-I.



CWC, Kuo, Yagyu 2017, 2018

Distribution on (α,v_Δ) Plane





- Larger values of κ_Z are obtained in the upper-left region.
- The result does not change much when p_2 = 500 GeV
- $|\Delta\kappa_V|$ does not depend much on v_Δ and α.
- For other 1-loop κ factors, see our paper.

CWC, Kuo, Yagyu 2018

MORE EXOTIC MODELS

Exotic Higgs Multiplets

- At least two active Higgs multiplets (X_1, X_2, …) larger than doublet are required, in addition to SM doublet Φ.
  ➠ consider simplest case with $N = 2$
- Suppose their quantum numbers are (T_1, Y_1) and (T_2, Y_2).
- The VEV of a complex (real) X_a is denoted by $v_a/\sqrt{2}$ (v_a).
- To have $\rho_{tree} = 1$, the new VEVs have to satisfy

$$r \equiv \frac{v_2^2}{v_1^2} = -\frac{T_1(T_1+1) - 3Y_1^2}{T_2(T_2+1) - 3Y_2^2}$$

with the total VEV

$$v^2 = v_\Phi^2 + \xi^2 v_1^2 \quad \text{with} \quad \xi^2 \equiv 4\left(Y_1^2 + rY_2^2\right)$$

- Define the mixing angle (analogous to 2HDM)

$$\tan\beta = \frac{v_\Phi}{\xi v_1}$$

Exotic Higgs Multiplets

- Tree-level unitarity of scattering processes requires that $T_a \leq 7/2$ (4) for a complex (real) scalar in the $N = 1$ case.
  ➠ used here as a conservative bound Hally, Logan, Pilkington 2012
- In certain scenarios (often those with larger $SU(2)_L$ reps), electroweak couplings develop Landau poles below the Planck scale.
  ➠ always g at a lower scale than g'
- There could be accidental global U(1)'s associated with phase rotations of X_1 and X_2.
  ➠ at least one unwanted massless NG boson after EWSB

- Discard such scenarios, but otherwise impose no custodial symmetry on the Higgs potential.

Viable Scenarios

15 scenarios allowed

EW quantum #'s

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(T_1, Y_1)	$\geq$	(T_2, Y_2)	r	ξ^2	$v_1^{\max}$
(1,1)		(1,0)	1/2	4	118
(3/2,1/2)		(1,1)	3	13	65
(3/2,3/2)		(1,0)	3/2	9	79
(3/2,3/2)		(3/2,1/2)	1	10	75
(2,0)		(1,1)	6	24	48
(2,0)		(3/2,3/2)	2	18	56
(2,1)		(1,1)	3	16	59
(2,1)		(3/2,3/2)	1	13	65
(2,2)		(2,1)	2	24	48
$(5/2, 1/2)$		$(1, 1)$	8	33	41
$(5/2, 1/2)$		$(3/2, 3/2)$	$8/3$	25	47
$(5/2, 3/2)$		$(1, 1)$	2	17	57
$(5/2, 3/2)$		$(3/2, 3/2)$	$2/3$	15	61
(3,0)		(1,1)	12	48	34
(3,0)		(3/2,3/2)	4	36	39

GM model w/o custodial symmetry ➠ (1,1) | (1,0)

n = 4 GM model w/o custodial symmetry ➠ (3/2,3/2) | (3/2,1/2)

all involve a representation with T = Y that gives a negative contribution to ρ

septet at most

demanding $y_t < \sqrt{4\pi}$ at electroweak scale ➠ lower bound on v_Φ

11 cases with r > 1

2 cases with r = 1

2 cases with r < 1

Neutral Higgs Mixing

- CP-even neutral components of Φ, X_1, and X_2 mix in a general way (∵ no custodial symmetry assumed now):

physical states original fields

$$\begin{pmatrix} h \\ H_1 \\ H_2 \end{pmatrix} = R \begin{pmatrix} \Phi^0 \\ X_1^0 \\ X_2^0 \end{pmatrix}$$

orthogonal rotation matrix

- Since only Φ couples to SM fermions, the scale factor for Yukawa couplings is universal, given by

$$\kappa_F = \frac{R_{11}}{s_\beta} \quad \Rightarrow \quad R_{11} = \kappa_F s_\beta$$

mixing matrix element R_{11} in terms of κ_F and β.

Prediction of κ_W and κ_Z

- For W and Z:

$$\kappa_W = s_\beta R_{11} + c_\beta \frac{2[T_1(T_1+1) - Y_1^2]R'}{\xi} c_\theta + c_\beta \sqrt{r} \frac{2[T_2(T_2+1) - Y_2^2]R'}{\xi} s_\theta$$

common part

$$\kappa_Z = s_\beta R_{11} + c_\beta \frac{4Y_1^2 R'}{\xi} c_\theta + c_\beta \sqrt{r} \frac{4Y_2^2 R'}{\xi} s_\theta$$

dependent only on hypercharges

$$R' \equiv \sqrt{1 - R_{11}^2}$$

- Custodial relation $\kappa_W = \kappa_Z$ occurs when $\tan\theta = -\sqrt{r}$, a special mixing angle related to the ratio of exotic VEV's.

First Scenario

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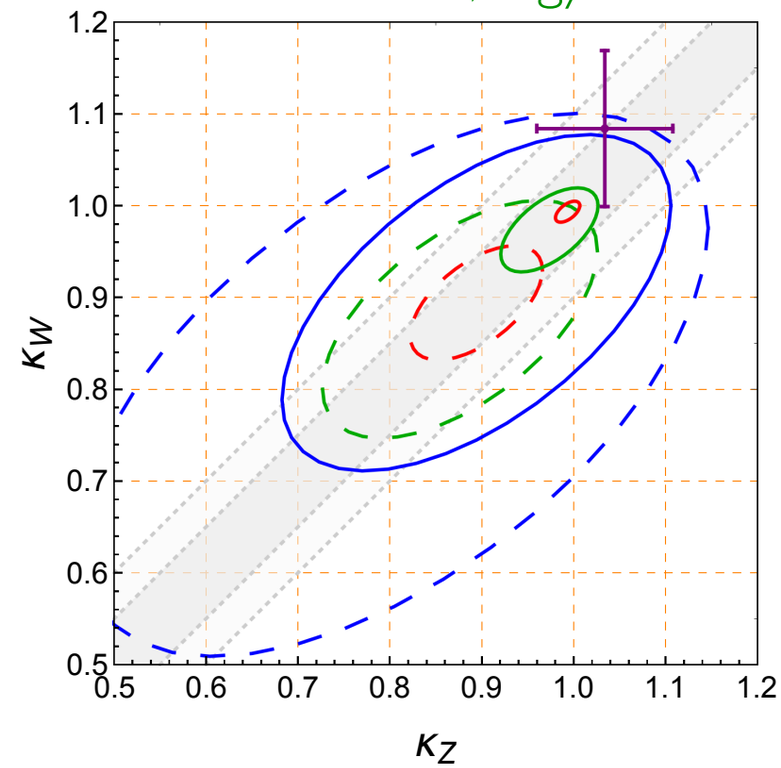
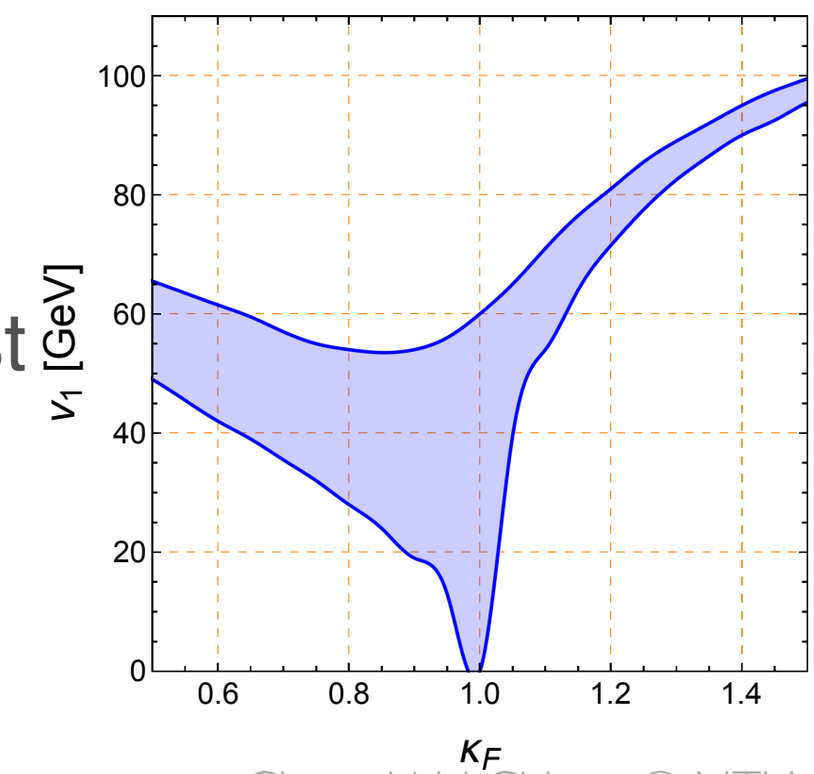
- Correlation plot for κ_F = 0.9 (dashed) and 1.0 (solid) with v_1 = 10 (red), 20 (green) and 40 (blue) GeV, by scanning mixing angle θ.
- The dark (light) gray band indicates $|\kappa_Z - \kappa_W| \leq 0.05$ (0.10).
- The purple cross marks current data at 1σ.



- Blue region allowed by current data of $\kappa_{W,Z}$ at 1σ level.
- Except for SM-like limit, there generally exist upper and lower bounds on v_Δ.
  ➠ importance about knowledge of κ_F



Recent Run-II Data

Parameter	ATLAS	CMS	Average
κ_W	1.07 ± 0.10	$1.12^{+0.13}_{-0.19}$	1.08 ± 0.08
κ_Z	1.07 ± 0.10	0.99 ± 0.11	1.03 ± 0.07

ATLAS-CONF-2018-31 (13 TeV, 80/fb)
CMS-PAS-HIG-17-031 (13 TeV, 36/fb)

- Concentrate on the central values.

✓ κ_W and/or κ_Z may be greater than 1.

✓ κ_W and κ_Z may be significantly different.

DETERMINATION OF κ_W/κ_Z

κ_W/κ_Z

- The ratio

$$\lambda_{WZ} \equiv \frac{\kappa_W}{\kappa_Z}$$

  for the SM Higgs boson is +1 at tree level.
- This may not be true for exotic Higgs bosons.
  ➠ e.g., –1/2 for H_5^0 in the GM model
- For the 125-GeV Higgs, data show that
  – $-1.10 \lesssim \lambda_{WZ} \lesssim -0.73$ or $0.72 \lesssim \lambda_{WZ} \lesssim 1.10$ (Run-I)
  – $-1.39 \lesssim \lambda_{WZ} \lesssim -0.97$ or $0.92 \lesssim \lambda_{WZ} \lesssim 1.37$ (Run-II, 35.9/fb)
  ➠ a two-fold ambiguity in such measurements
- With 3/ab, the HL-LHC is anticipated to achieve

$$|\delta\kappa_W/\kappa_W| \leq 5\% \ , \ |\delta\kappa_Z/\kappa_Z| \leq 4\% \ \Rightarrow \ |\delta\lambda_{WZ}/\lambda_{WZ}| \leq 6.4\%$$

  assuming that the central values remain SM-like.
  ➠ no good way to resolve sign ambiguity

Solving the Ambiguity

- How can we experimentally determine this ratio, especially its sign?
- It can be measured in $H \to ZZ^* \to 4\ell$ due to the interference between tree and one-loop amplitudes, which are proportional to the HZZ and HWW couplings, respectively.

Chen, Lykken, Spiropulu, Stolarski, Vega-Morales 2016

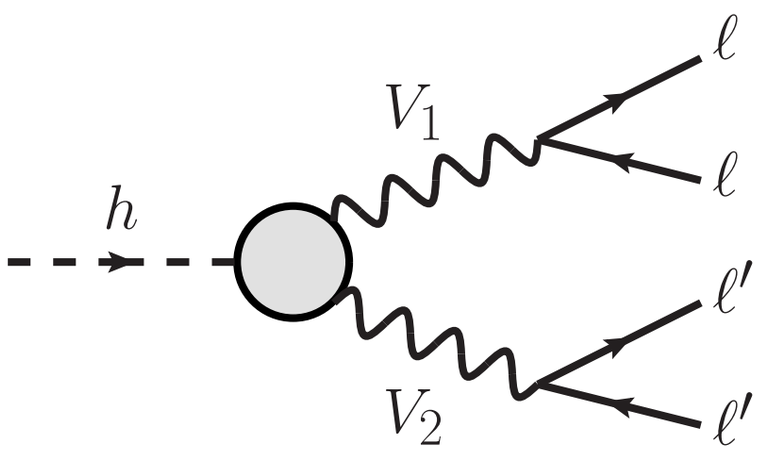
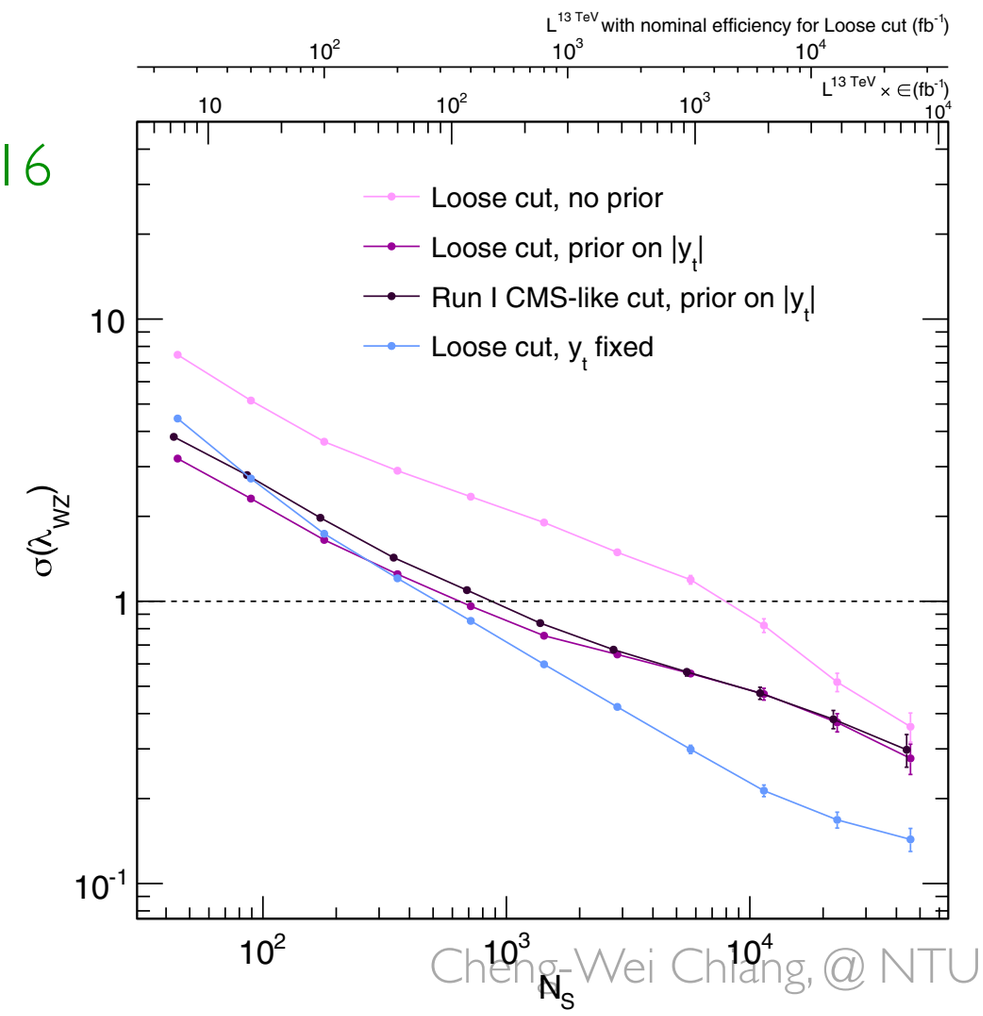


FIG. 1. Schematic representation of the hVV contributions to the $h \to 4\ell$ amplitude where $V_{1,2} = Z, \gamma$ and $\ell, \ell' = e, \mu$.



Solving the Ambiguity

- How can we experimentally determine this ratio, especially its sign?
- We propose to consider the $e^+e^- \to W^+W^-H$ process, where a desirable interference occurs among the tree-level amplitudes and allows us to experimentally fix λ_{WZ}.

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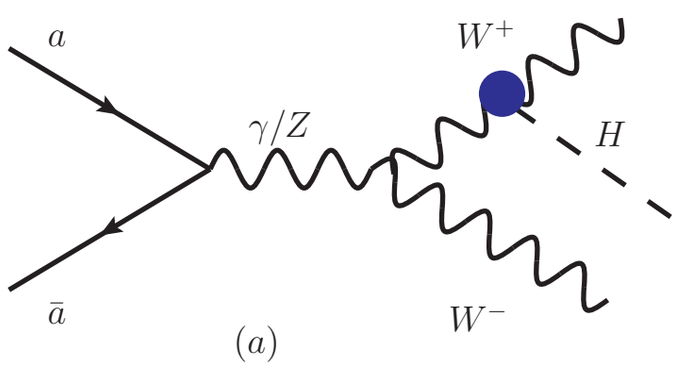
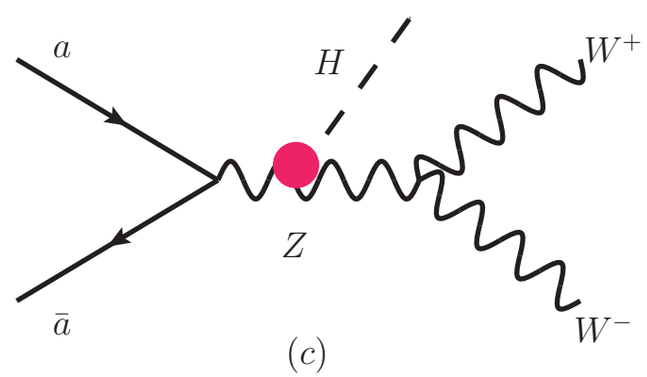
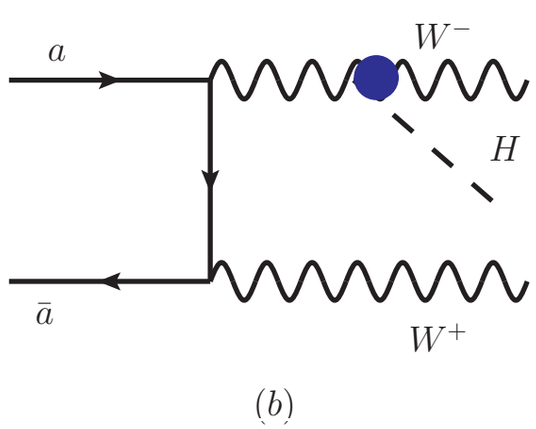




- Use 125-GeV Higgs as an explicit example
- H here is not limited to SM-like Higgs boson



$$\sigma_{\rm prod} = \kappa_W^2 \left[\sigma_W + \lambda_{WZ}^{-1}\sigma_{WZ} + \lambda_{WZ}^{-2}\sigma_Z\right]$$

Cross Section @ ILC

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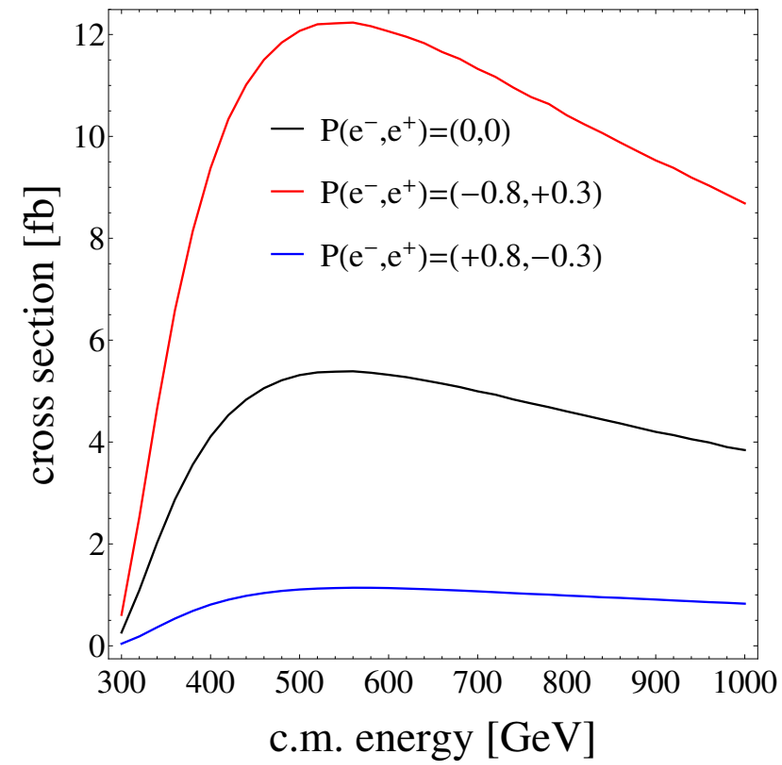

- Cross section of $e^+e^- \to W^+W^-H$ as a function of colliding energy for different polarization schemes.
  - ➠ preferring 500-GeV ILC with $P(e^-,e^+) = (-0.8,+0.3)$ 1306.6352 [hep-ex]
  - ➠ peak position generally changes for a different Higgs boson
- We consider the above scheme with an integrated luminosity L = 4 /ab:

1506.05992 [hep-ex]
1506.07830 [hep-ex]

$$\sigma_{\rm prod} = \kappa_W^2 \left[\sigma_W + \lambda_{WZ}^{-1}\sigma_{WZ} + \lambda_{WZ}^{-2}\sigma_Z\right]$$

$$\sigma_W = 13.54{\rm fb}, \quad \sigma_Z = 1.015{\rm fb}, \quad \sigma_{WZ} = -2.555{\rm fb}$$

- $\sigma_W > \sigma_Z$ by one order of magnitude
- destructive interference if λ_{WZ} is positive

Remarks

- Our proposal is a simple counting measurement.
- The interference term can certainly result in noticeable effects on differential distributions, such as that of the rapidity of the charged lepton and that of the azimuthal angle difference between the charged lepton and the leading-p_T light jet.
- These distributions generally require more statistics in order to reach the same sensitivity for λ_{WZ} as proposed here.

The $e^+e^- \to W^+W^-H \to jj\ell^\pm\nu bb$ Process

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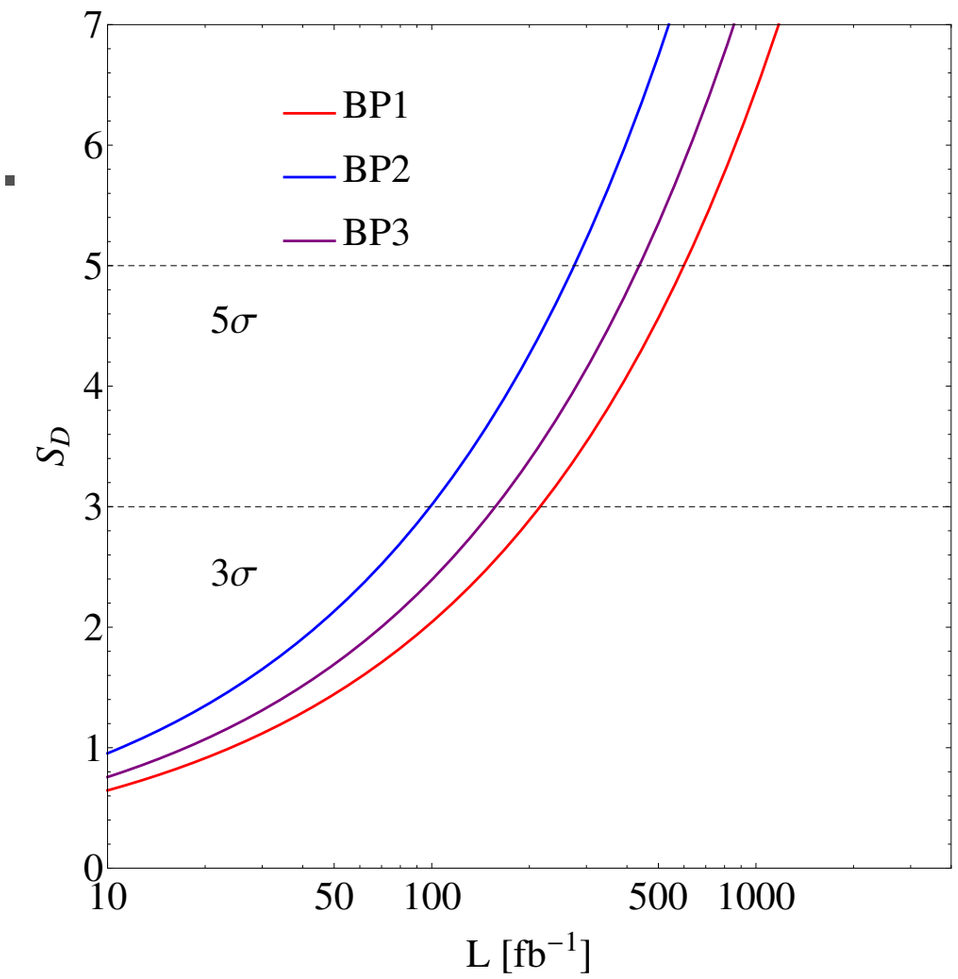
- Consider $e^+e^- \to W^+W^-H$, with one $W \to \ell\nu$, the other $W \to jj$, and $H \to b\bar{b}$.
- 5σ discovery achieved with L = (600/fb, 300/fb, 450/fb) for (BP1, BP2, BP3), respectively.
- BP1 requires the largest luminosity due to the smallest cross section from destructive interference.
- Assume SM-like Hff couplings.
- $H \to WW^*$ scenario also considered.
  ➠ see our paper

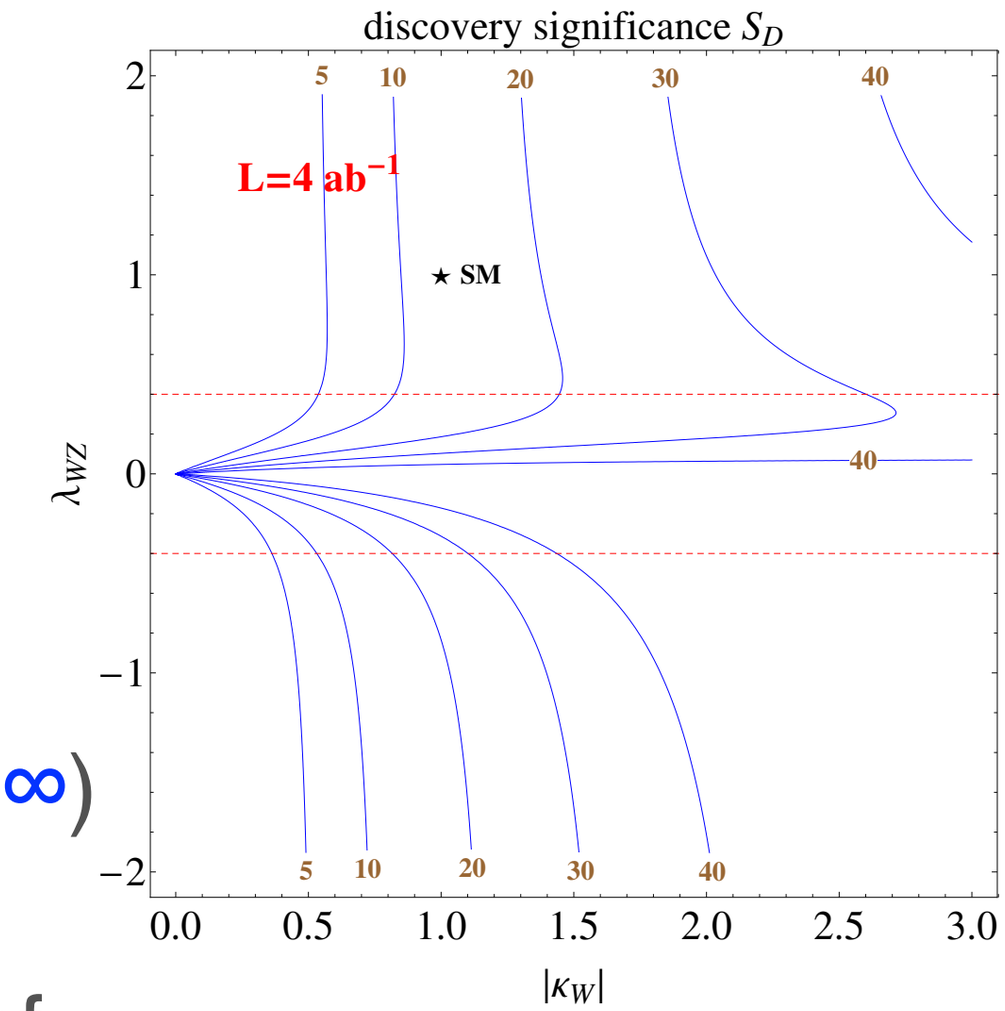


signal significance as a function of L

$$\text{BP1:} \quad \kappa_W = 1, \ \kappa_Z = 1 \ \text{(SM)}$$
$$\text{BP2:} \quad \kappa_W = 1, \ \kappa_Z = -1$$
$$\text{BP3:} \quad \kappa_W = 1, \ \kappa_Z = 0.$$

The $e^+e^- \to W^+W^-H \to jj\ell^\pm\nu bb$ Process

- Contours of signal significance for L = 4/ab.
- Discoverable for $|\kappa_W| \gtrsim 0.6$, irrespective of the value of λ_{WZ}.
- More sensitive to scenarios with $|\lambda_{WZ}| \lesssim 0.4$ as σ_{WZ} becomes less important than σ_Z. ($\lambda_{WZ} \to 0 \Rightarrow \kappa_Z \to \infty$)
- By combining this cross section measurement and measurement of $|\kappa_W|$ at HL-LHC, it is straightforward to determine λ_{WZ} (magnitude and sign) at a high precision.



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Summary

- Extensions of the active Higgs sector are restricted by $\rho_{exp} = 1$, κ_W and κ_Z, and the custodial relation $\kappa_W = \kappa_Z$.
- GM model is the minimal custodial model allowing $\kappa_{W,Z} > 1$ and respecting $\kappa_W = \kappa_Z$.
- 1-loop corrections to Higgs couplings are computed for simple custodial models, and found to be small.
- Through a global fit, we identify the most promising search channel to further constrain or discover the GM model.
- Recent LHC data hint at the possibility of $\kappa_W \neq \kappa_Z$, and lead us to extensions with at least two exotic representations.
- The $e^+e^- \to W^+W^-H$ channel at ILC500 is proposed to determine the ratio κ_W/κ_Z, including its sign.

Thank You!