New idea for charged scalar searches

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In collaboration with

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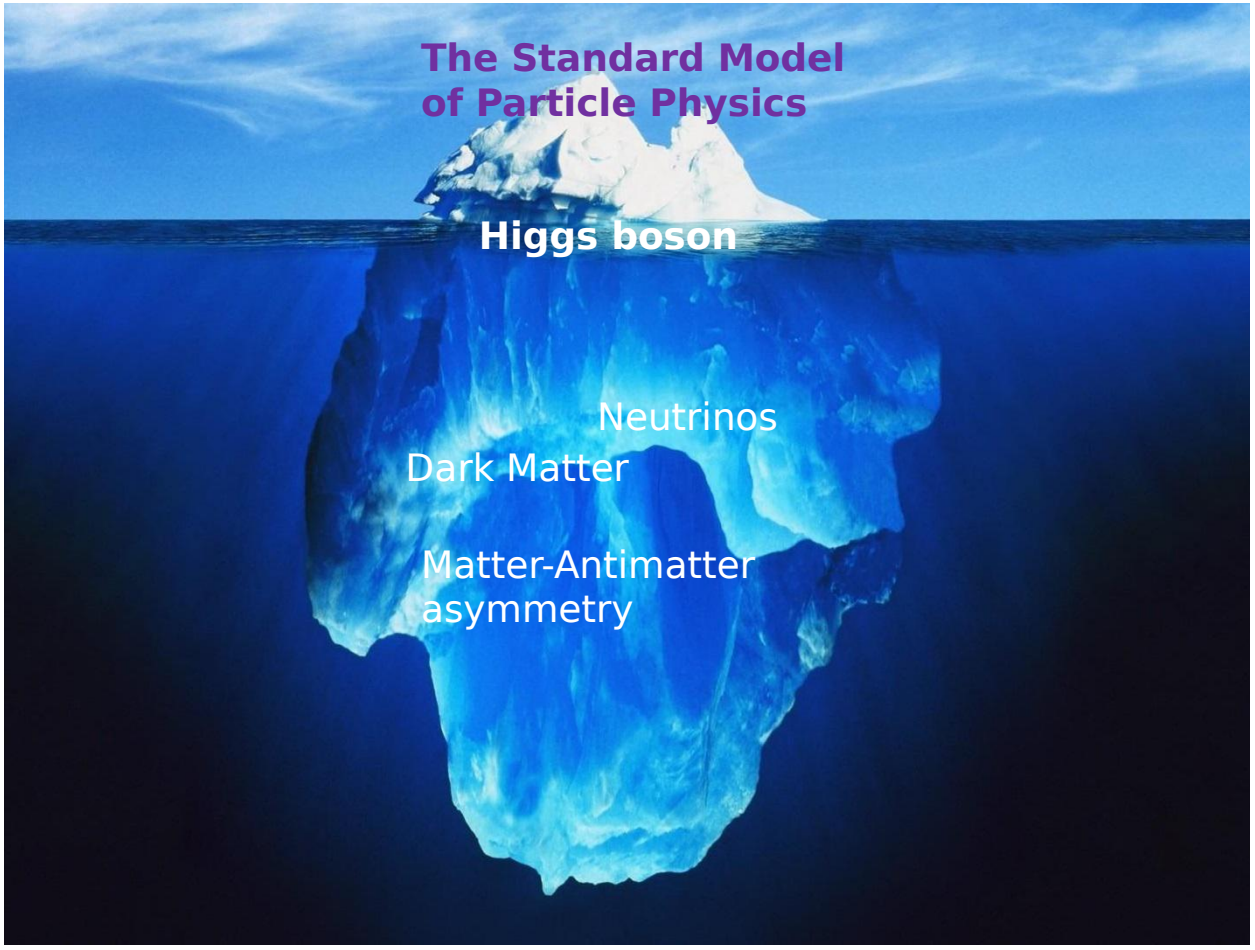
Dec. 18, 2018

Motivation


The Standard Model
of Particle Physics
Higgs boson
Neutrinos
Dark Matter
Matter-Antimatter
asymmetry

Motivation

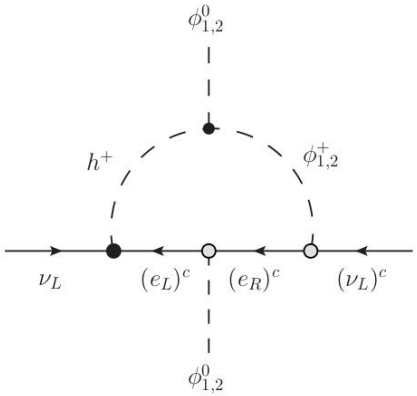

The Standard Model
of Particle Physics
Higgs boson
New scalar bosons?
Neutrinos
Dark Matter
Matter-Antimatter
asymmetry

Motivation

Neutrino mass

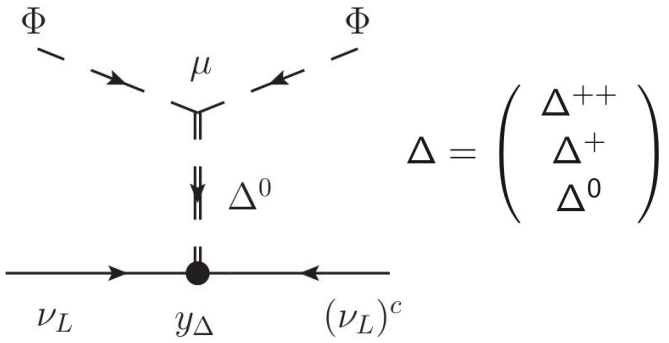
Zee model:

A. Zee, Phys. Lett. 93B (1980) 389



type-II see-saw model:

J. W. F. Valle, Phys. Rev. D 22 (1980) 2227; R.N. Mohapatra and G. Senjanovic, Phys. Rev. D23 (1981) 165



Dark matter and 1st order phase transition

ΣSM: $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$

M. Cirelli, N. Fornengo and A. Strumia, NPB 753, 178 (2006)

P. F. Perez, H. H. Patel, M. J. Ramsey-Musolf, K. Wang, PRD 88, 035013 (2013)

Motivation

Extend the scalar sector:

SM +

singlet (1,0): s

singlet (1,2): S^+

doublet (2,1): H, H^+

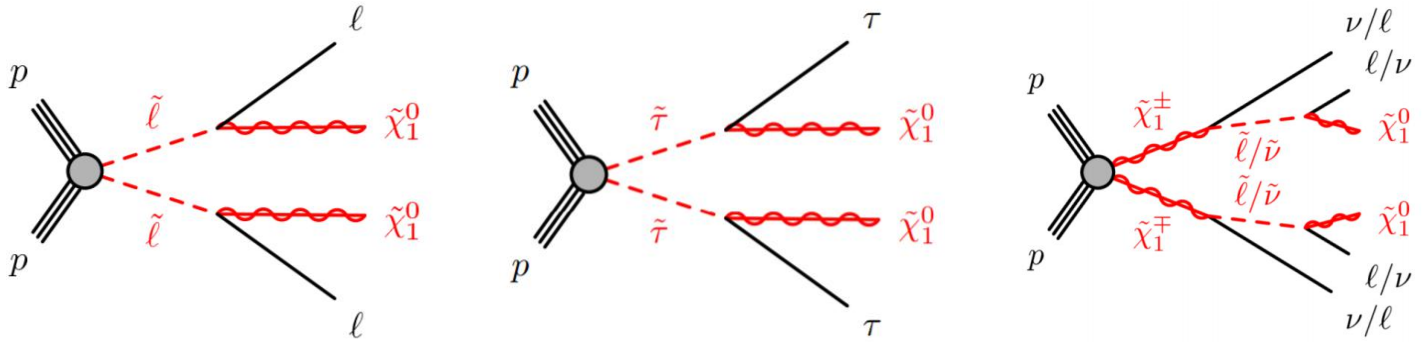
triplet (3,Y): H, H^+, H^{++}

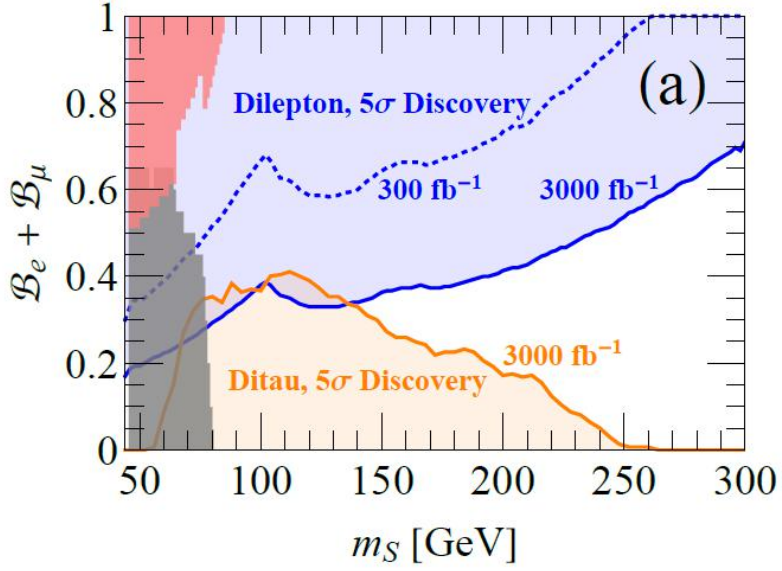
.....

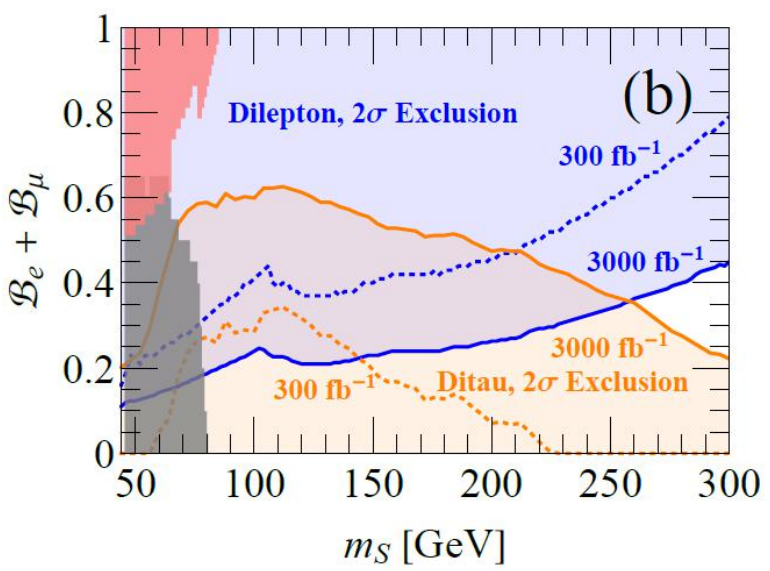
direct signal for new physics: charged scalars

Singlet charged scalar searches in a nutshell

S^+: right-handed sleptons



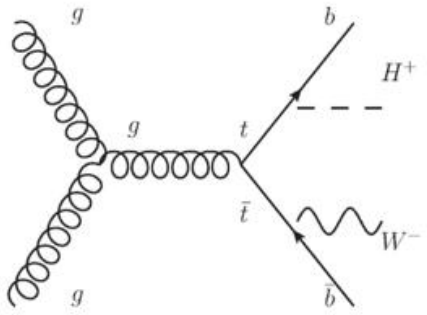


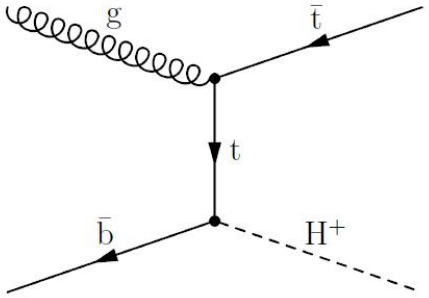


Qing-Hong Cao, GL, Ke-Pan Xie, Jue Zhang, PRD 97 (2018) 115036

Current charged Higgs boson searches at the LHC

In two-Higgs-doublet models:

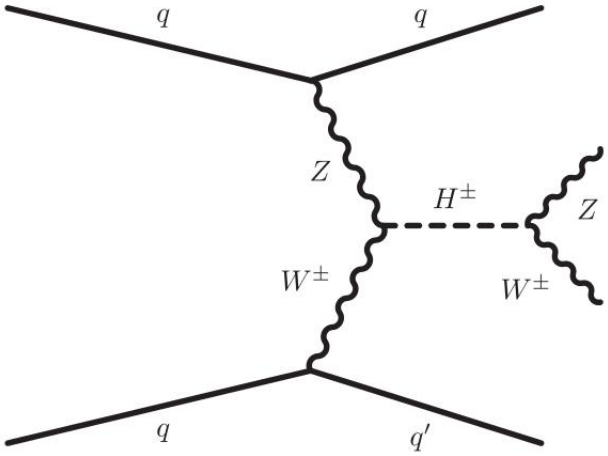




H^+ decays into t, b, c, s, tau, ν

In triplet models:

No H^+W^-Z interaction in doublet models



J. F. Gunion, H. E. Haber, G. L. Kane, S. Dawson, The Higgs Hunter's Guide

Distinctive signature

H^+W^-Z interaction in triplet models

Triplet models

- type-II see-saw model: complex triplet
- ΣSM: real triplet
- Georgi-Machacek model: complex triplet + real triplet
- ...

$$\rho = \frac{m_W^2}{m_Z^2 c_w^2}$$

$$(T, Y) = (1/2, 1)$$

complex triplet ρ=1 real triplet

$(T, Y) = (1, 2)$ $(T, Y) = (1, 0)$

$\rho^{\rm exp} = 1.00039 \pm 0.00017$ PDG 18'

$$m_W^2 = \frac{1}{8} g^2 \sum_k \left[4T_k(T_k+1) - Y_k^2\right] v_k^2 + \frac{1}{2} g^2 \sum_i T_i(T_i+1)\tilde{v}_i^2 \ ,$$

$$m_Z^2 = \frac{1}{4} \frac{g^2}{c_w^2} \sum_k Y_k^2 v_k^2 \ ,$$

H^+W^-Z interaction in triplet models

Triplet models

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$$\rho = \frac{m_W^2}{m_Z^2 c_w^2}$$

$$\rho^{\exp} = 1.00039 \pm 0.00017$$ PDG 18'

$$(T, Y) = (1/2, 1)$$

complex triplet ρ=1 real triplet

$(T, Y) = (1, 2)$ $(T, Y) = (1, 0)$

For type-II see-saw model and ΣSM, triplet vev is small

For Georgi-Machacek model, triplet vev can be large

H^+ ——— W^-Z

H^+ ▬▬ W^-Z

More about H^+ in the Georgi-Machacek model?

Georgi-Machacek model

complex and real triplets

$$\chi = \begin{pmatrix} \chi^+/\sqrt{2} & \chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^0/\sqrt{2} & \xi^+ \\ \xi^- & -\xi^0/\sqrt{2} \end{pmatrix}$$

H. Georgi and M. Machacek, Nucl. Phys. B262 (1985) 463

$SU(2)_L \times SU(2)_R \to SU(2)_C$ Higgs potental

$$\Phi = \begin{pmatrix} h^{0*} & h^+ \\ -h^{+*} & h^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix} \qquad v_\xi = \frac{v_\chi}{\sqrt{2}}$$

$$\begin{aligned} V(\Phi,\,\Delta) = {} & \frac{1}{2}m_1^2\,\mathrm{tr}[\Phi^\dagger\Phi] + \frac{1}{2}m_2^2\,\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_1\left(\mathrm{tr}[\Phi^\dagger\Phi]\right)^2 + \lambda_2\left(\mathrm{tr}[\Delta^\dagger\Delta]\right)^2 \\ & + \lambda_3\mathrm{tr}\left[\left(\Delta^\dagger\Delta\right)^2\right] + \lambda_4\mathrm{tr}[\Phi^\dagger\Phi]\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_5\mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right]\mathrm{tr}[\Delta^\dagger T^a\Delta T^b] \\ & + \mu_1\mathrm{tr}\left[\Phi^\dagger\frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right](P^\dagger\Delta P)_{ab} + \mu_2\mathrm{tr}[\Delta^\dagger T^a\Delta T^b](P^\dagger\Delta P)_{ab}\,, \end{aligned}$$

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

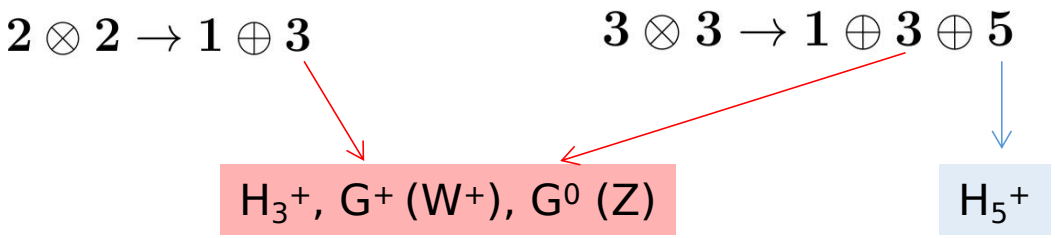
M. S. Chanowitz and M. Golden, Phys. Lett. 165B (1985) 105, M. Aoki, S. Kanemura Phys.Rev. D77 (2008) 095009

Georgi-Machacek model

Two H^+'s

scalar fields can be decomposed under $SU(2)_L \times SU(2)_R \to SU(2)_C$

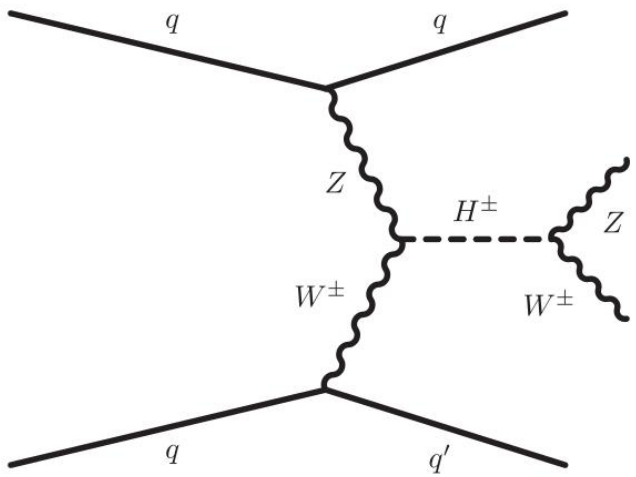
doublet Φ : triplet Δ:



H_3^+ couples to fermions but not W-Z

H_5^+ couples to W-Z but not fermions

Interpretation of searches

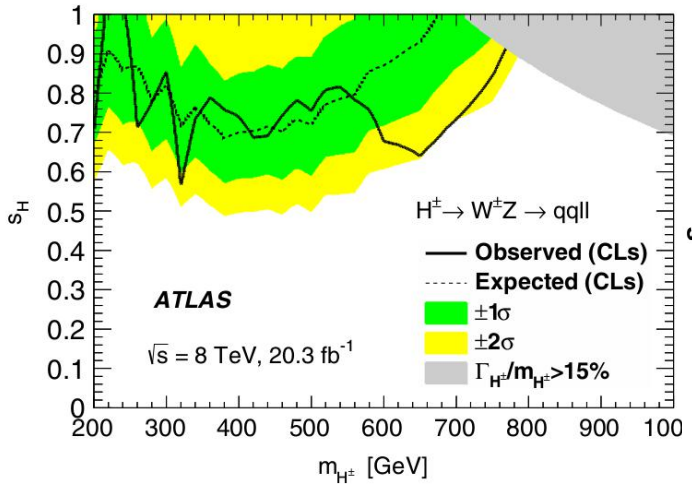


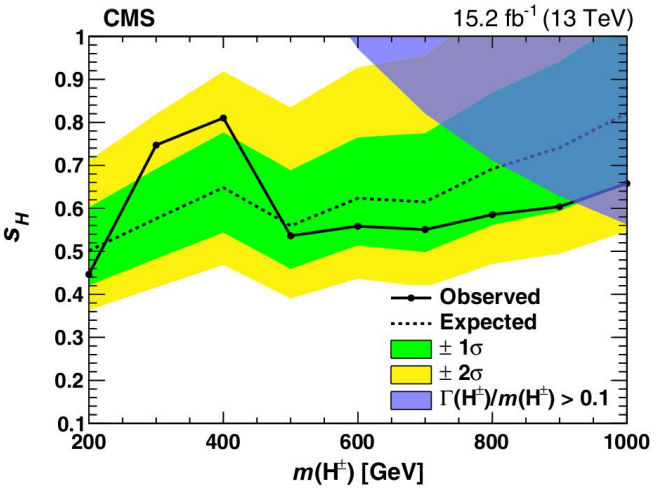
type-II see-saw model

ΣSM

Georgi-Machacek model

Others?





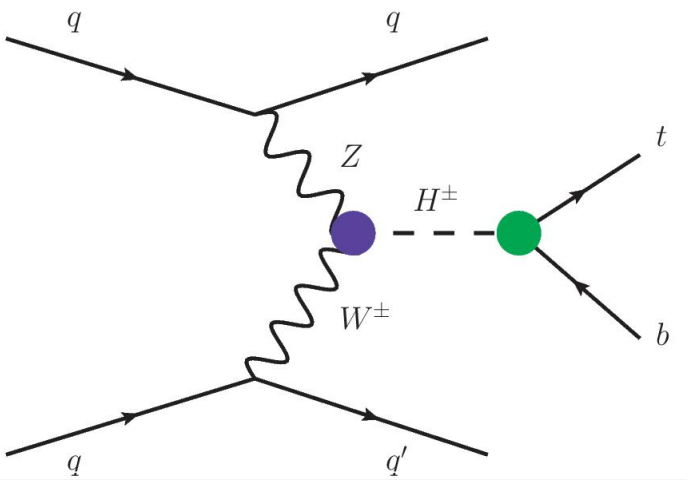
ATLAS Phys.Rev.Lett. 114 (2015) 231801;
CMS Phys.Rev.Lett. 119 (2017) 141802

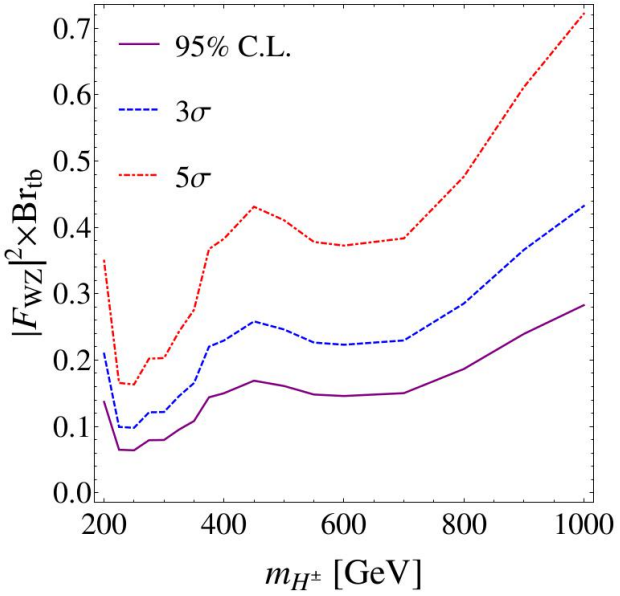
$H_5^{\pm}$

New search for charged Higgs boson at the LHC

Remember that H_5^+ couples to W-Z but not fermions, if H^+

$$\mathcal{L}_{\rm eff} = g m_W F_{WZ} H^+ W_\mu^- Z^\mu - \sqrt{2}/v H^+ \bar{t}(m_t A_t P_L + m_b A_b P_R) b + h.c.$$





then H^+ does (not) come from the GM model

J.-Y. Cen, J.-H. Chen, X.-G. He, GL, J.-Y. Su, W. Wang, 1811.00910

Realistic model?

Models with complex and real triplets

ρ = 1 can be satisfied without custodial symmetry

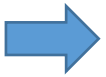
$$\chi = \begin{pmatrix} \chi^+/\sqrt{2} & \chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^0/\sqrt{2} & \xi^+ \\ \xi^- & -\xi^0/\sqrt{2} \end{pmatrix}$$

$$h^0 = \frac{v_H + h_H + iI_H}{\sqrt{2}}, \quad \chi^0 = \frac{v_\chi + h_\chi + iI_\chi}{\sqrt{2}}, \quad \xi^0 = v_\xi + h_\xi$$

kinetic: $(D_\mu H)^\dagger D^\mu H + \frac{1}{2}(D_\mu \xi)^\dagger D^\mu \xi + (D_\mu \chi)^\dagger D^\mu \chi$

$$\rho = \frac{m_W^2}{m_Z^2 c_w^2}$$

$$\rho = \frac{v_H^2 + 2v_\chi^2 + 4v_\xi^2}{v_H^2 + 4v_\chi^2}$$



ρ = 1 at tree-level

$$v_\xi = \frac{v_\chi}{\sqrt{2}}$$ (our convention)

Modified Georgi-Machacek model

complex and real triplets

$$\chi = \begin{pmatrix} \chi^+/\sqrt{2} & \chi^{++} \\ \chi^0 & -\chi^+/\sqrt{2} \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^0/\sqrt{2} & \xi^+ \\ \xi^- & -\xi^0/\sqrt{2} \end{pmatrix}$$

General potential

J.-Y. Cen, J.-H. Chen, X.-G. He, J.-Y. Su, Int.J.Mod.Phys. A33 (2018) 1850152; S. Blasi, S. De Curtis, K. Yagyu, Phys.Rev. D96 (2017) 015001

$$\begin{aligned} V(H,\chi,\xi) = {} & \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \mu_\chi^2 \,\mathrm{Tr}\left(\chi^\dagger\chi\right) + \frac{1}{2}\mu_\xi^2 \,\mathrm{Tr}(\xi\xi) \\ & + \lambda_\chi \left(\,\mathrm{Tr}\left(\chi^\dagger\chi\right)\right)^2 + \lambda'_\chi \,\mathrm{Tr}\left(\chi^\dagger\chi\chi^\dagger\chi\right) + \frac{1}{4}\lambda_\xi (\mathrm{Tr}(\xi\xi))^2 \\ & + \frac{\kappa_1}{2}\left(H^\dagger H\right)\mathrm{Tr}(\xi\xi) + \kappa_2\left(H^\dagger H\right)\mathrm{Tr}\left(\chi^\dagger\chi\right) + \kappa_3\left(H^\dagger\chi\chi^\dagger H\right) \\ & + \frac{\kappa_4}{4}\,\mathrm{Tr}(\xi\xi)\,\mathrm{Tr}\left(\chi^\dagger\chi\right) + \kappa_5\,\mathrm{Tr}\left[\xi\chi^\dagger\right]\mathrm{Tr}[\xi\chi] + \mu_{\xi HH} H^\dagger \xi H \\ & + \left\{\mu_{\chi HH} H^T \chi H + \lambda H^T \chi \xi H + \mathrm{h.c.}\right\} + \mu_{\xi\chi\chi}\,\mathrm{Tr}\left[\chi^\dagger\xi\chi\right]. \end{aligned}$$

custodial symmetry restored only if $v_\xi = \dfrac{v_\chi}{\sqrt{2}}$ and specific coupling relations

Modified Georgi-Machacek model

Couplings to WZ and quarks:

J.-Y. Cen, J.-H. Chen, X.-G. He, J.-Y. Su, Int.J.Mod.Phys. A33 (2018) 1850152; H. E. Haber, H. E. Logan, Phys.Rev. D62 (2000) 015011

$$\mathcal{L}_{W^\pm Z} = \left(\frac{g^2}{2c_W}\frac{v_H(2v_\chi^2-4v_\xi^2)}{N_2}\cos\delta + \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3}\sin\delta\right)H_3^{m+}W_\mu^- Z^\mu$$
$$+\left(\frac{g^2}{2c_W}\frac{v_H(2v_\chi^2-4v_\xi^2)}{N_2}\sin\delta - \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3}\cos\delta\right)H_5^{m+}W_\mu^- Z^\mu + h.c.\,,$$

$$\mathcal{L}_{\rm Yuk}^q = -\sqrt{2}\frac{1}{v_H}\frac{4v_\xi^2+2v_\chi^2}{N_2}(\bar{U}\hat{M}_u V_{\rm CKM}P_L D - \bar{U}V_{\rm CKM}\hat{M}_d P_R D)$$
$$\times(\cos\delta H_3^{m+} + \sin\delta H_5^{m+}) + h.c.\,,$$

$$\begin{pmatrix} H_3^+ \\ H_5^+ \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix}\begin{pmatrix} H_3^{m+} \\ H_5^{m+} \end{pmatrix}$$

GM model: $\delta = 0$

δ is a function of v_χ and couplings in the general Higgs potential

independent parameters: δ, v_χ

Modified Georgi-Machacek model

J.-Y. Cen, J.-H. Chen, X.-G. He, J.-Y. Su, Int.J.Mod.Phys. A33 (2018) 1850152; H. E. Haber, H. E. Logan, Phys.Rev. D62 (2000) 015011

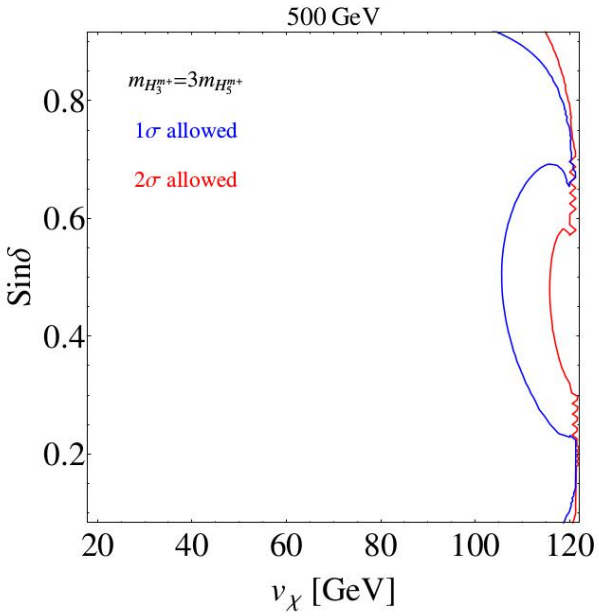
Constraints

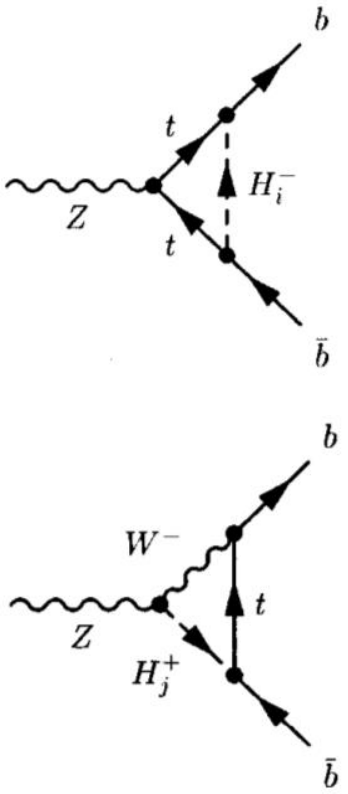
pertuabative unitarity:

$v_\chi < 117$ GeV

Zbb data:

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{ hadronic})}$$

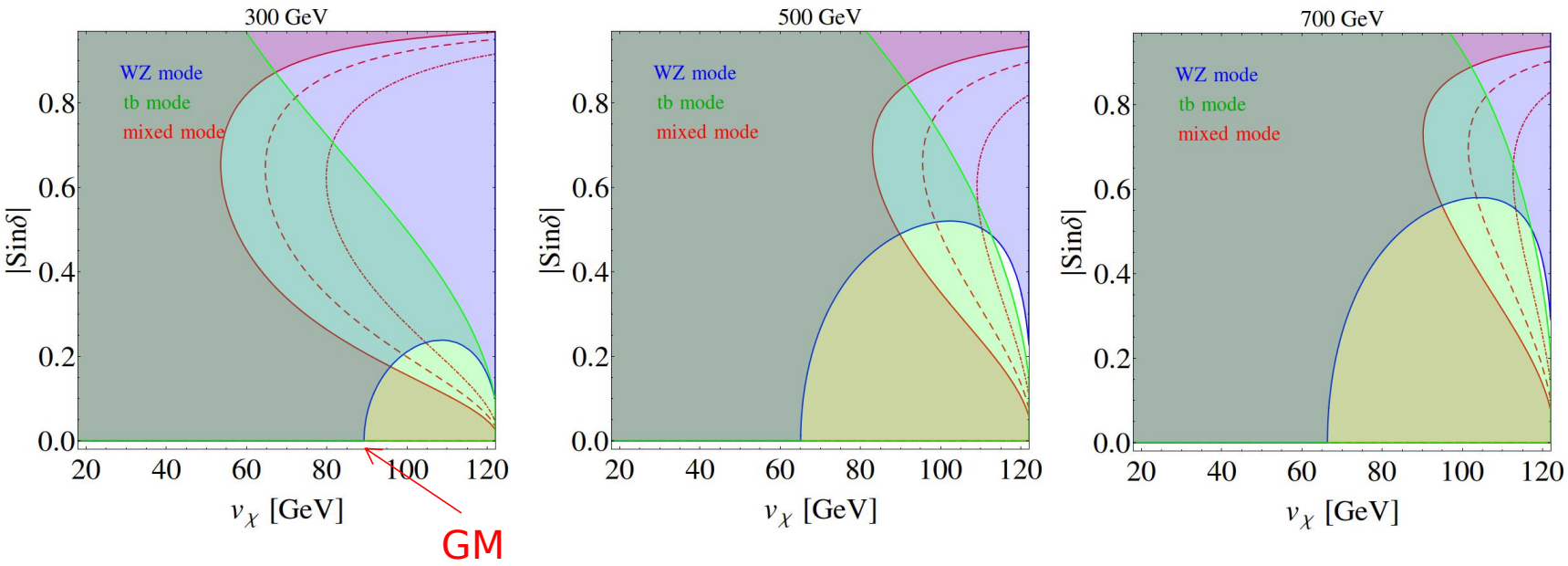




Interpretation in the Modified GM model

$H_5^{m\pm}$

13 TeV, 3ab^{-1}



5σ discovery for 300 GeV ≤ m_{H^+} ≤ 700 GeV

Summary

- In many new physics models, there exist charged scalars
- Singlet charged scalar can be discovered/excluded at the LHC
- While the current searches for charged Higgs boson only depend on its couplings to fermions or $W^{+}Z$, it is important to verify whether it can couple to them simultaneously to determine its origin
- We proposed a new search for charged Higgs boson with both couplings to tb and WZ and obtained a discovery significance of 5σ in the mass range from 300 GeV to 700 GeV

Collider analysis at the 13 TeV LHC

cut flow (in pb) for $m_{H^\pm} = 500$ GeV

cuts	signal	$t\bar{t}$	tW	tq
cuts in Eq. (6)	7.76E-03	9.97E+01	1.04E+01	3.02E+01
$\Delta R_{mn} > 0.4$	7.76E-03	9.96E+01	1.04E+01	3.02E+01
$n_j \geq 4$	6.53E-03	8.06E+01	5.67E+00	4.16E+00
b-tagging	3.23E-03	3.14E+01	1.53E+00	1.28E+00
single lepton	2.03E-03	1.50E+01	7.97E-01	5.02E-01
$E_T^{\rm miss} > 30$ GeV	1.62E-03	1.15E+01	6.12E-01	3.70E-01
≥ 2 non-b jets	1.35E-03	6.19E+00	3.12E-01	1.77E-01
$\lvert\Delta\eta_{jj}\rvert > 3.5$	1.02E-03	1.10E+00	5.35E-02	8.31E-02
$m_{jj} > 400$ GeV	9.52E-04	8.41E-01	3.94E-02	5.91E-02
$p_T^\ell > 65$ GeV	5.89E-04	3.39E-01	2.08E-02	1.72E-02
$p_T^{b1} > 120$ GeV, $p_T^{b2} > 65$ GeV	2.21E-04	6.44E-02	5.95E-03	2.87E-03
400 GeV $< m_{tb} <$ 600 GeV	1.06E-04	1.56E-02	8.63E-04	3.38E-04

VBF and optimal cuts