Charged scalars at the LHC

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In collaboration with

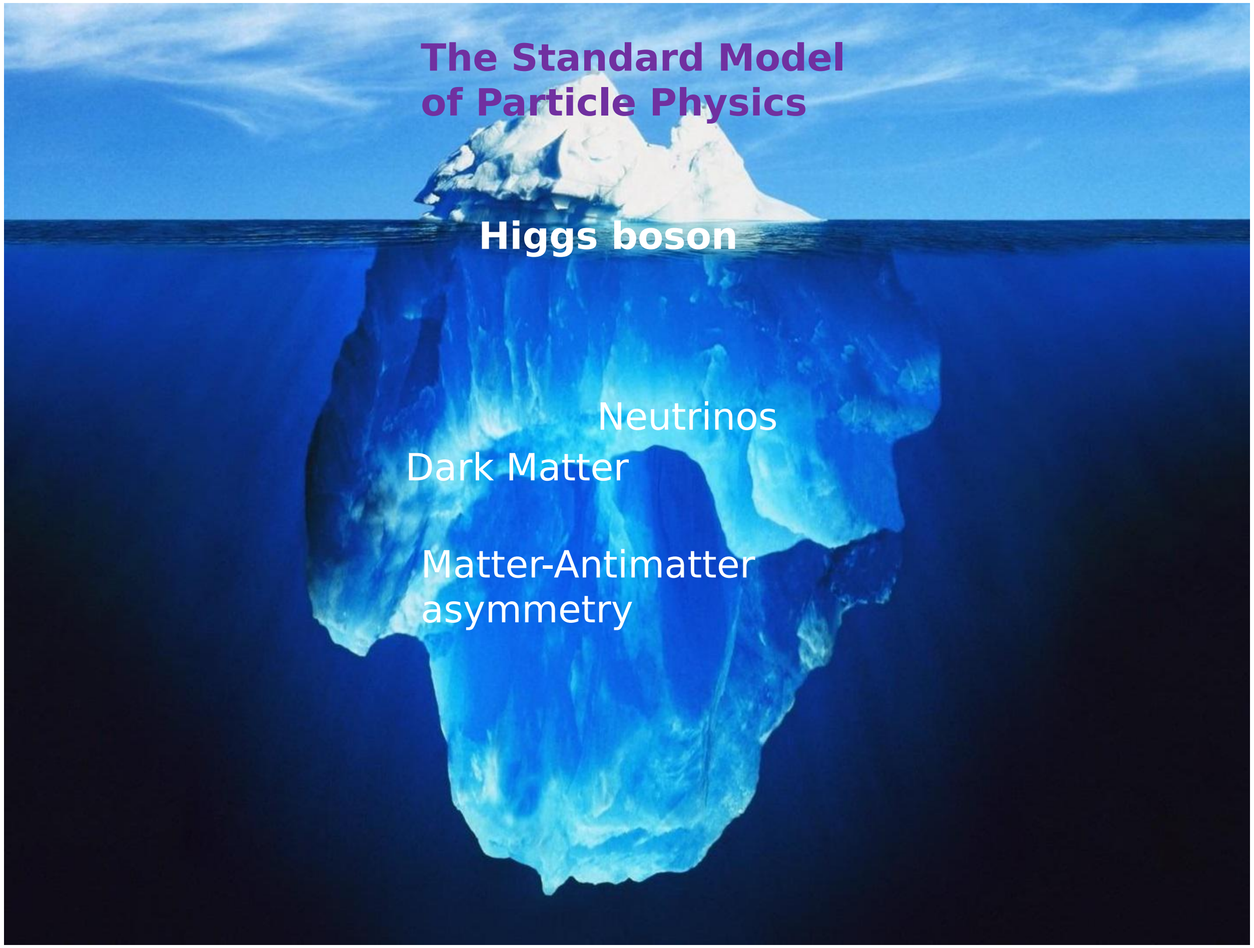
Qing-Hong Cao, Ke-Pan Xie, Jue Zhang, PRD 97 (2018) 115036, 1711.02113

Jian-Yong Cen, Jung-Hsin Chen, Xiao-Gang He, Jhih-Ying Su, Wei Wang, 1811.00910

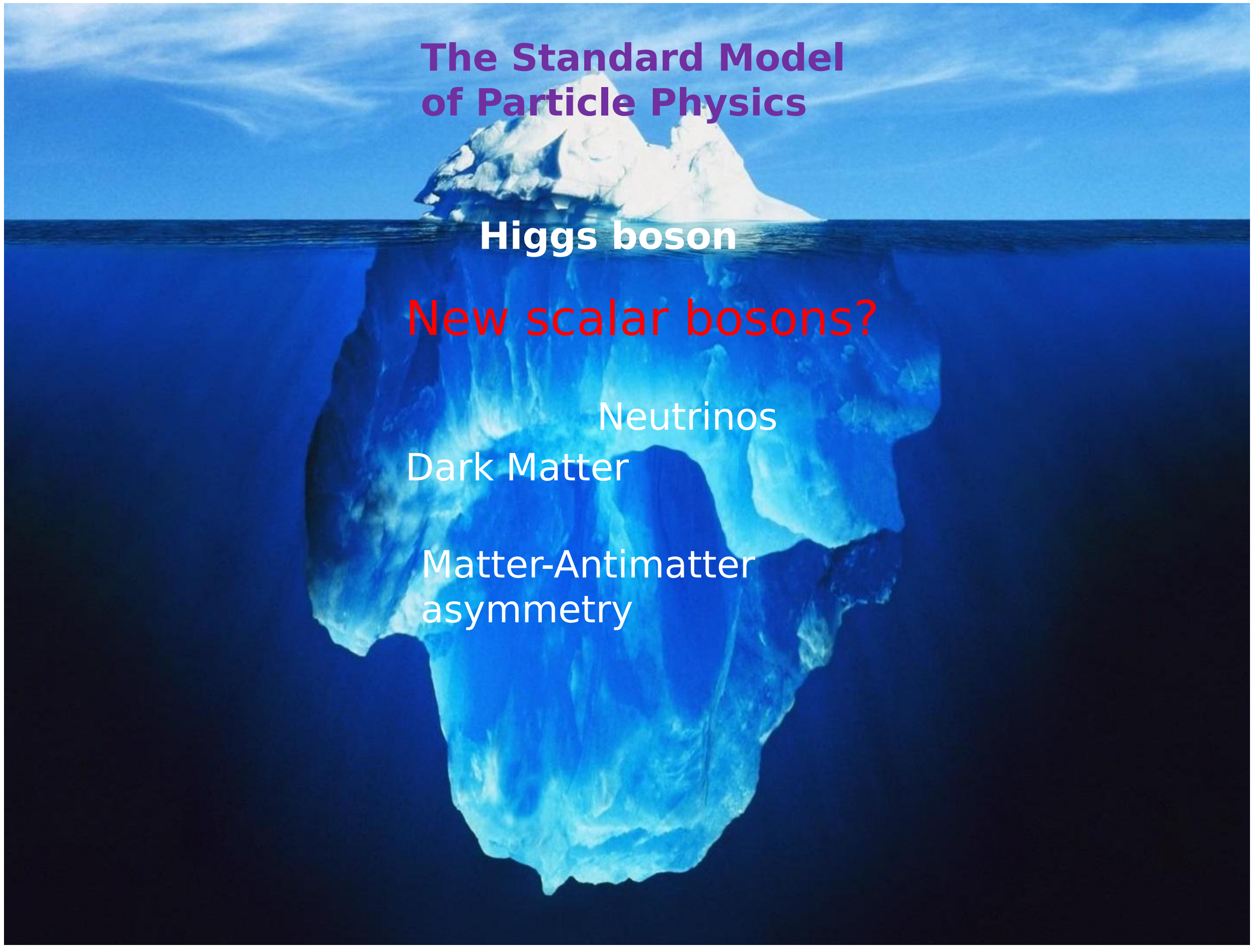
KEK-PH2018 and 3rd KIAS-NCTS-KEK Joint Workshop

Dec. 7, 2018

Motivations



Motivations



The Standard Model of Particle Physics

Higgs boson

New scalar bosons?

Neutrinos

Dark Matter

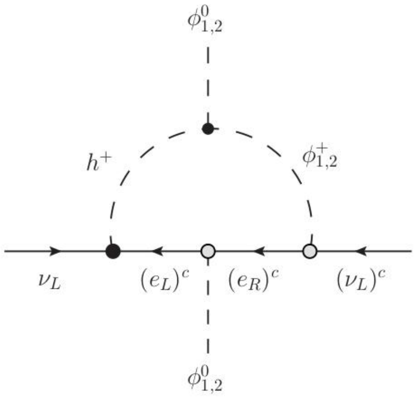
Matter-Antimatter asymmetry

Motivations

neutrino mass

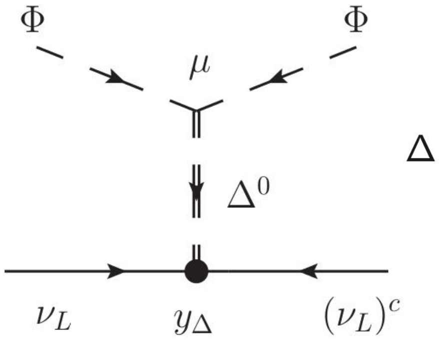
Zee model:

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



$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$$

dark matter and 1st 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)

Motivations

extended scalar sector

SM +

- singlet (1,0): s
- singlet (1,2): S^+
- doublet (2,1): H, H^+
- triplet (3,Y): H, H^+, H^{++}

……

Motivations

charged scalars

SM +

singlet (1,0): s

singlet (1,2): S^+

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

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

……

singlet: S^+

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

Renormalizable model

$\boxed{S \sim (1,-2)}$

SU(2)$_L$ U(1)$_Y$

Assumption: S is the only new degree of freedom at v$_{EW}$

$$Q = T_3 + Y/2$$

SM + S with dimension-4 interactions

A. Zee, Phys. Lett. 93B (1980) 389; 161B (1985) 141; K.S. Babu, Phys.Lett. B203 (1988) 132

$$\mathcal{L}_S^{\mathrm{dim}-4} \supset (D_\mu S)^\dagger D^\mu S - m_S^2 |S|^2 - \frac{\lambda_S}{2} |S^\dagger S|^2$$
$$-\lambda_{SH} S^\dagger S H^\dagger H + \left(f_{\alpha\beta} \bar{\ell}_{\mathrm{L}\alpha} \ell^c_{\mathrm{L}\beta} S + \mathrm{h.c.} \right)$$

α, β are generation indices

$$\boxed{e^+ e^- (q\bar{q}) \;\rightarrow\; \gamma/Z \;\rightarrow\; S^+ S^-}$$

Charged Lepton Flavor Violation

$|f_{e\tau} f_{\mu\tau}| \lesssim \mathcal{O}(10^{-5})$ $m_S \sim \mathcal{O}(100)$ GeV $\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

$|f_{e\mu} f_{e\tau}| \lesssim \mathcal{O}(10^{-5})$ $\Longleftarrow$ $\mathcal{B}(\tau^- \to e^+ e^- \mu^-) < 1.8 \times 10^{-8}$

$|f_{\mu\tau} f_{e\tau}| \lesssim \mathcal{O}(10^{-5})$ $\mathcal{B}(\tau^- \to \mu^+ \mu^- e^-) < 2.7 \times 10^{-8}$

Higher dimensional operators are important

Effective operators

- Dimension-5 operators (non-redundant)

$$\bar{e}_{\rm R} e^c_{\rm R} S S, \quad \boxed{\overline{Q}_{\rm L} H u_{\rm R} S, \quad \overline{Q}_{\rm L} \widetilde{H} d_{\rm R} S^\dagger, \quad \overline{\ell}_{\rm L} \widetilde{H} e_{\rm R} S^\dagger}$$

flavor-diagonal*

$$S^- \to \begin{cases} e^-\bar{\nu}, \mu^-\bar{\nu}, \tau^-\bar{\nu}, \\ d\bar{u}, s\bar{c}, b\bar{t}. \end{cases}$$

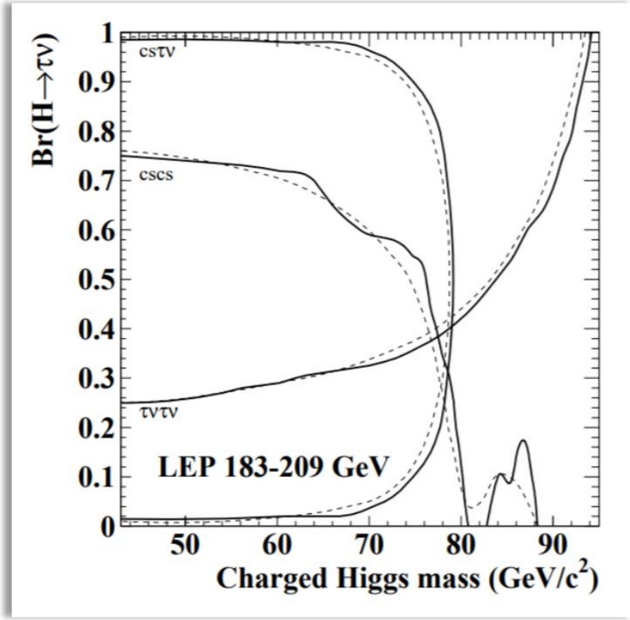
$$\boxed{\mathcal{B}_e + \mathcal{B}_\mu + \mathcal{B}_\tau + \mathcal{B}_J = 1}$$

How light is the charged scalar?

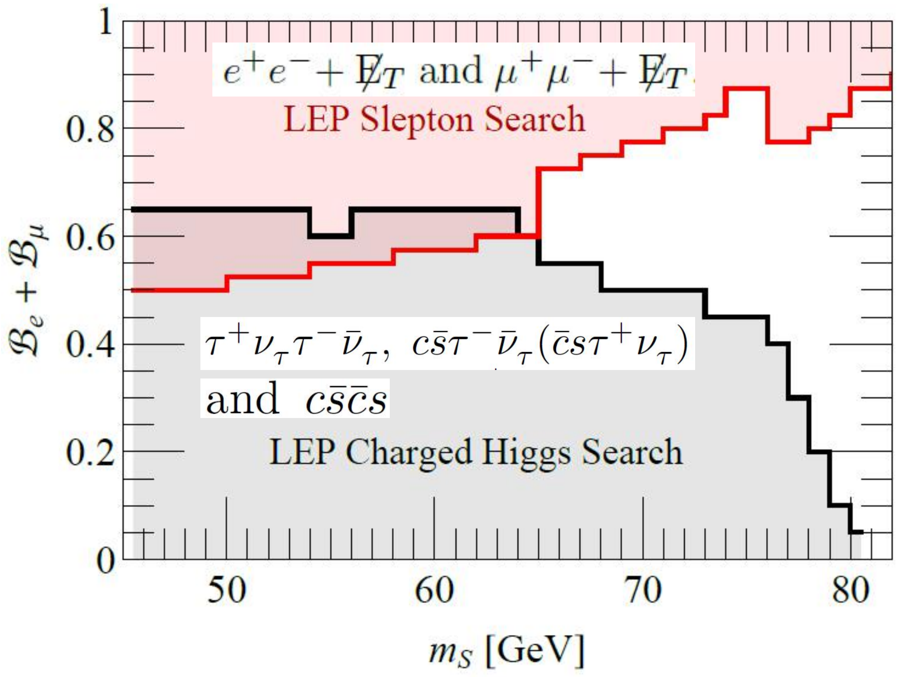
In the 2HDMs,

$$\mathcal{B}(H^+ \to c\bar{s}) + \mathcal{B}(H^+ \to \tau^+\nu_\tau) = 1$$

Eur.Phys.J. C73 (2013) 2463



Constraints from the LEP



LEP Joint SUSY Search Results

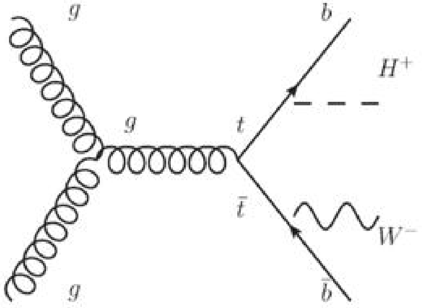
$$\sigma(S^+S^-)\mathcal{B}_e^2 \le \sigma(\tilde{\ell}^+\tilde{\ell}^-)_e,$$
$$\sigma(S^+S^-)\mathcal{B}_\mu^2 \le \sigma(\tilde{\ell}^+\tilde{\ell}^-)_\mu,$$

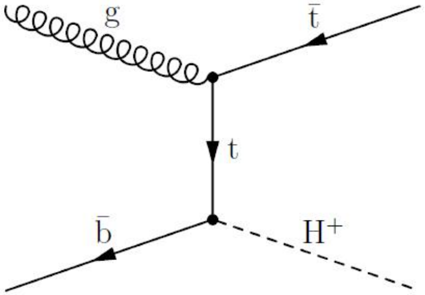
The constraint on $\mathcal{B}_e + \mathcal{B}_\mu$ is most conservative if $\mathcal{B}_e = \mathcal{B}_\mu$ since the cut efficiencies of e and μ are quite close

$$\mathcal{B}_e + \mathcal{B}_\mu = 1 - (\mathcal{B}_\tau + \mathcal{B}_J)$$

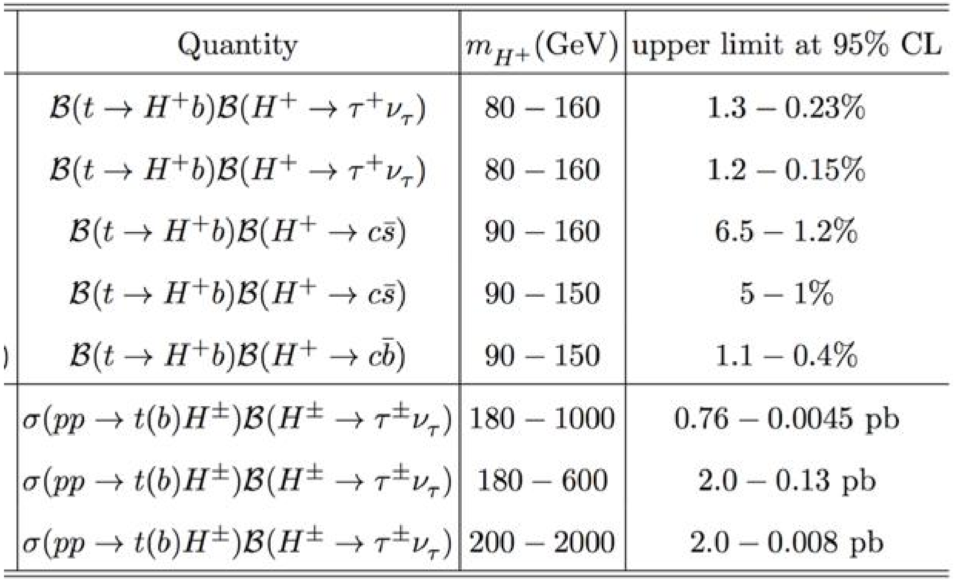
Light S+ is allowed

Direct searches at the LHC



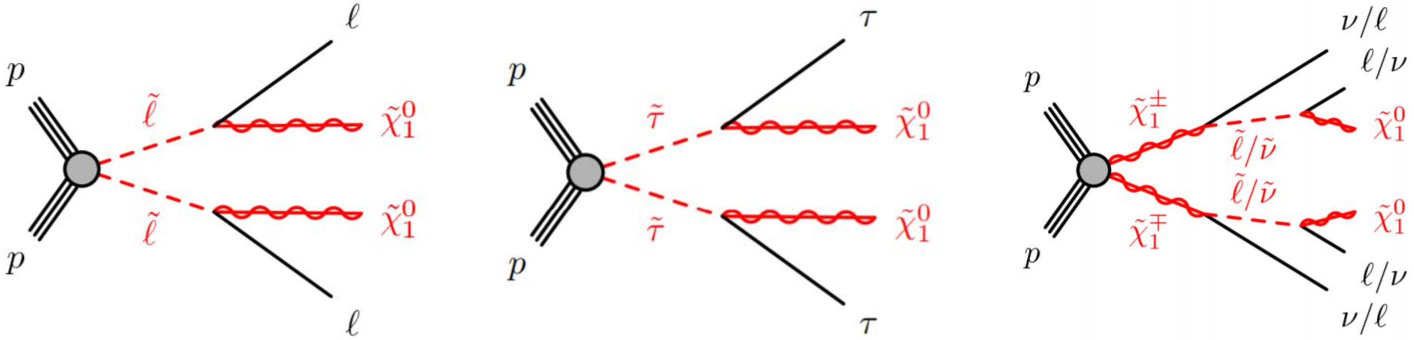


No constraint due to $m_{H^+} > 80$ GeV and Htb coupling



Quantity	m_{H^+}(GeV)	upper limit at 95% CL
$\mathcal{B}(t \to H^+b)\mathcal{B}(H^+ \to \tau^+\nu_\tau)$	$80-160$	$1.3-0.23\%$
$\mathcal{B}(t \to H^+b)\mathcal{B}(H^+ \to \tau^+\nu_\tau)$	$80-160$	$1.2-0.15\%$
$\mathcal{B}(t \to H^+b)\mathcal{B}(H^+ \to c\bar{s})$	$90-160$	$6.5-1.2\%$
$\mathcal{B}(t \to H^+b)\mathcal{B}(H^+ \to c\bar{s})$	$90-150$	$5-1\%$
$\mathcal{B}(t \to H^+b)\mathcal{B}(H^+ \to c\bar{b})$	$90-150$	$1.1-0.4\%$
$\sigma(pp \to t(b)H^\pm)\mathcal{B}(H^\pm \to \tau^\pm\nu_\tau)$	$180-1000$	$0.76-0.0045$ pb
$\sigma(pp \to t(b)H^\pm)\mathcal{B}(H^\pm \to \tau^\pm\nu_\tau)$	$180-600$	$2.0-0.13$ pb
$\sigma(pp \to t(b)H^\pm)\mathcal{B}(H^\pm \to \tau^\pm\nu_\tau)$	$200-2000$	$2.0-0.008$ pb

Direct searches at the LHC



Dilepton: ATLAS JHEP 1405 (2014) 071 (8TeV), ATLAS-CONF-2017-039 (13TeV, 36.1 fb^{-1}) ATLAS-CONF-2016-096 (13TeV, 13.3 fb^{-1})

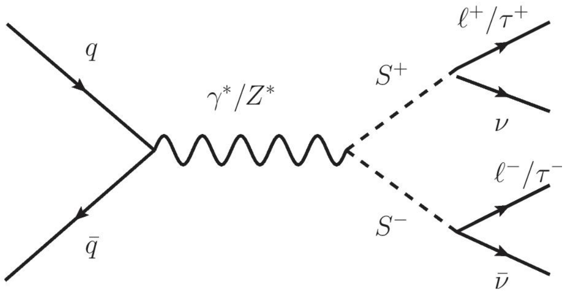
Ditau: ATLAS JHEP 1410 (2014) 096 (8TeV), CMS-PAS-SUS-17-003 (13TeV, 35.9 fb^{-1})

No constraint due to m_{SUSY} > 80 GeV and low luminosity

Direct searches at the LHC

following slepton/chargino searches, we consider

$$q\bar{q} \to \gamma^*/Z^* \to S^+S^-, S^\pm \to \ell^\pm \nu_\ell, \tau^\pm \nu_\tau$$



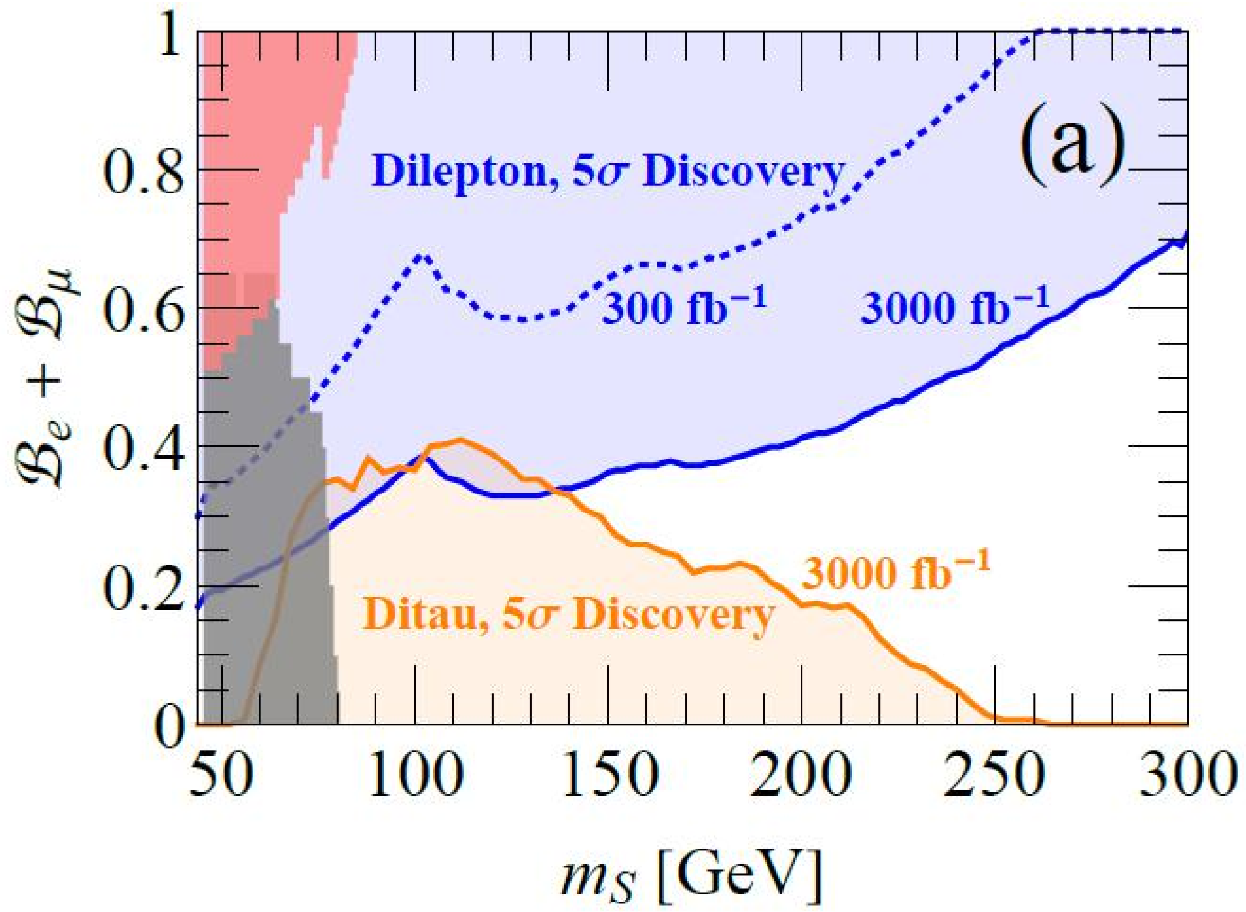
with the same cuts and BKGs taken from

Dilepton (chargino): ATLAS-CONF-2016-096 (13TeV)

Ditau (slepton): CMS-PAS-SUS-17-003 (13TeV)

Combined sensitivities for S^+

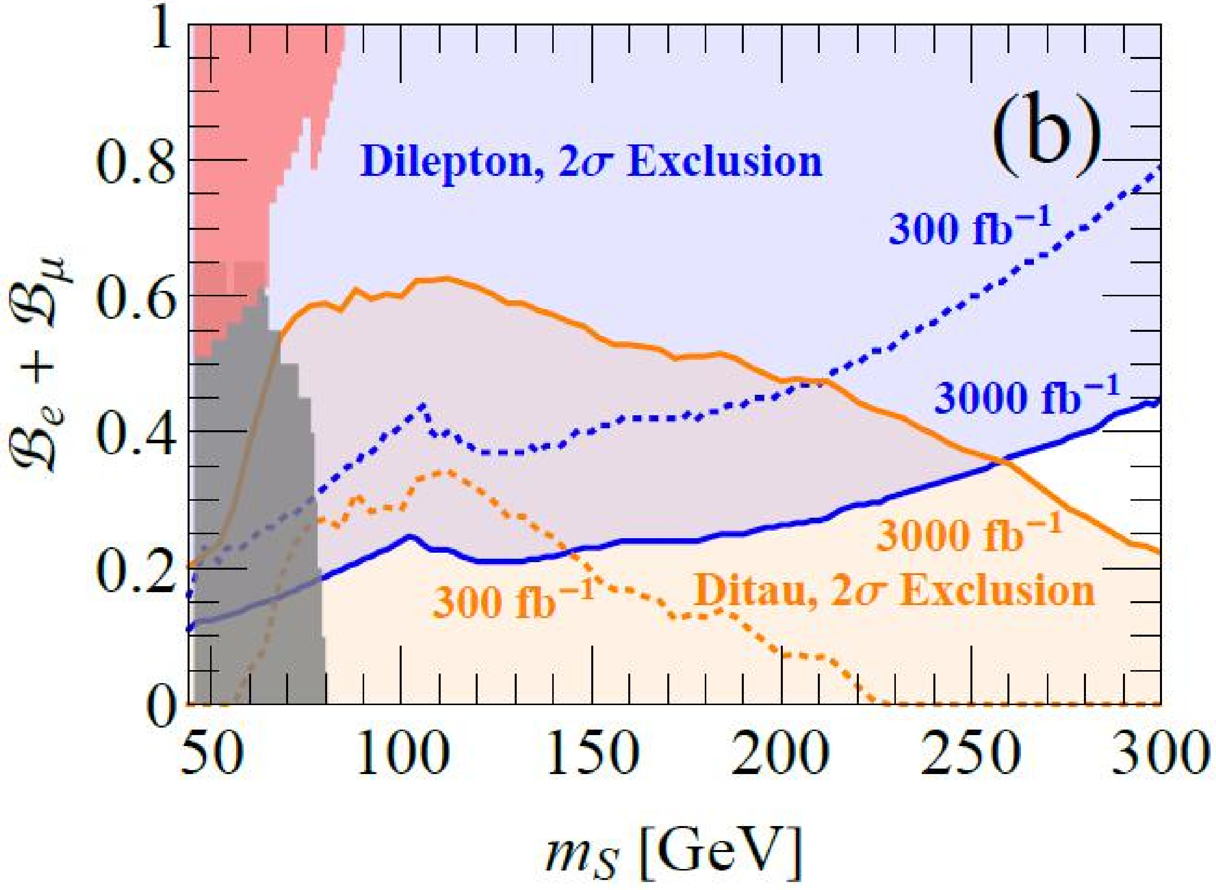
$\mathcal{B}_\tau = 1 - (\mathcal{B}_e + \mathcal{B}_\mu)$ with $\mathcal{B}_{\mathcal{J}}$=0



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

Combined sensitivities for S^+

$\mathcal{B}_\tau = 1 - (\mathcal{B}_e + \mathcal{B}_\mu)$ with $\mathcal{B}_\mathcal{J}$=0



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

doublet, triplet: H^+

Jian-Yong Cen, Jung-Hsin Chen, Xiao-Gang He, GL, Jhih-Ying Su, Wei Wang, 1811.00910

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

$$\mathcal{L}_{H^\pm W^\mp V^0} = e m_W \left(W_\mu^+ A^\mu G^- + \text{h.c.}\right) + g m_Z \left[W_\mu^+ Z^\mu \left\{ G^- \cos^2\theta_W - \frac{g}{\sqrt{2} m_W} \sum_k Y_k \times \left[\phi_k^\dagger T^+ v_k + \cancel{(T^- v_k)^\dagger \phi_k} \right] \right\} + \text{h.c.} \right].$$

$$G^- = \frac{g}{\sqrt{2} m_W} \left\{ \sum_k \left[\phi_k^\dagger T^+ v_k - \cancel{(T^- v_k)^\dagger \phi_k} \right] + \sum_i \eta_i^T T^+ u_i \right\}$$

$$\boxed{Y = 1}$$

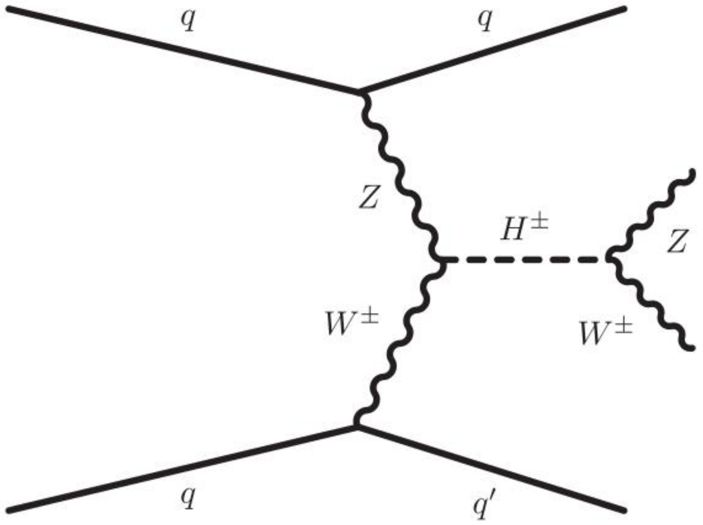
$$\boxed{T^- v_k = 0}$$

vev in the last component

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

Distinctive signature for higher representation

H^+W^-Z interaction at the LHC



type-II see-saw model

ΣSM

Georgi-Machacek model

……

Where does $H^\pm$ come from?

H^+W^-Z interaction in triplet models

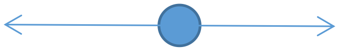
$$\boxed{\rho = \frac{m_W^2}{m_Z^2 c_w^2}}$$

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

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

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

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



complex triplet ρ=1 real triplet

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

① vev is servely constrained with one triplet (type-II see-saw model and ΣSM)

② vev is less constrained with two triplets (Georgi-Machacek model)

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

Georgi-Machacek model

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

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

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

$$\begin{pmatrix} H_3^+ \\ H_5^+ \end{pmatrix}$$

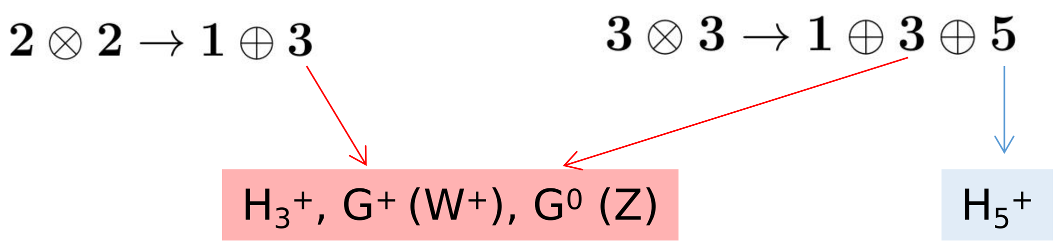
$$\begin{aligned} V(\Phi,\,\Delta) = {} & \frac{1}{2} m_1^2 \,\mathrm{tr}[\Phi^\dagger \Phi] + \frac{1}{2} m_2^2 \,\mathrm{tr}[\Delta^\dagger \Delta] + \lambda_1 \left(\mathrm{tr}[\Phi^\dagger \Phi]\right)^2 + \lambda_2 \left(\mathrm{tr}[\Delta^\dagger \Delta]\right)^2 \\ & + \lambda_3 \mathrm{tr}\left[\left(\Delta^\dagger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

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

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

Georgi-Machacek model

scalar fields can be decomposed: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_C$



$\mathbf{2} \otimes \mathbf{2} \rightarrow \mathbf{1} \oplus \mathbf{3}$

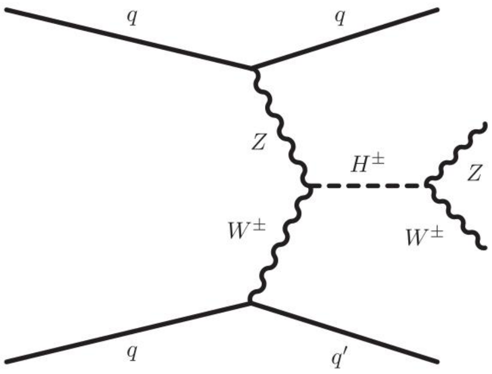
$\mathbf{3} \otimes \mathbf{3} \rightarrow \mathbf{1} \oplus \mathbf{3} \oplus \mathbf{5}$

H_3^+, G^+ (W^+), G^0 (Z)

H_5^+

Two H^+'s in the GM model

- H_3^+ couples to fermions but not W-Z
- H_5^+ couples to W-Z but not fermions (need to check it)



Modified Georgi-Machacek model

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

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

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

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

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

ρ = 1 at tree-level

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

Modified Georgi-Machacek model

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

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

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

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

Modified Georgi-Machacek model

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

Couplings to WZ and quarks

$$\begin{aligned}\mathcal{L}_{W^\pm Z} = &\left(\frac{g^2}{2c_W}\frac{v_H(2v_\chi^2-4v_\xi^2)}{N_2}\cos\delta + \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3}\sin\delta\right)H_3^{m+}W_\mu^- Z^\mu \\ &+\left(\frac{g^2}{2c_W}\frac{v_H(2v_\chi^2-4v_\xi^2)}{N_2}\sin\delta - \frac{g^2}{2c_W}\frac{4\sqrt{2}v_\chi v_\xi}{N_3}\cos\delta\right)H_5^{m+}W_\mu^- Z^\mu + h.c.\ , \\ \mathcal{L}_{\text{Yuk}}^q = &-\sqrt{2}\frac{1}{v_H}\frac{4v_\xi^2+2v_\chi^2}{N_2}(\bar{U}\hat{M}_u V_{\text{CKM}}P_L D - \bar{U}V_{\text{CKM}}\hat{M}_d P_R D) \\ &\times(\cos\delta H_3^{m+} + \sin\delta H_5^{m+}) + h.c.\ ,\end{aligned}$$

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

GM model: $\delta = 0$

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

Modified Georgi-Machacek model

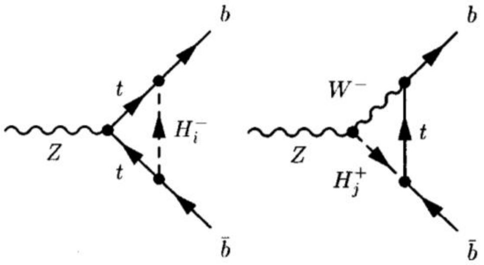
J.-Y. Cen, J.-H. Chen, X.-G. He, J.-Y. Su, Int.J.Mod.Phys. A33 (2018) 1850152; H. E. Haber, H. E. Logan, Phys.Rev. D62 (2000) 015011

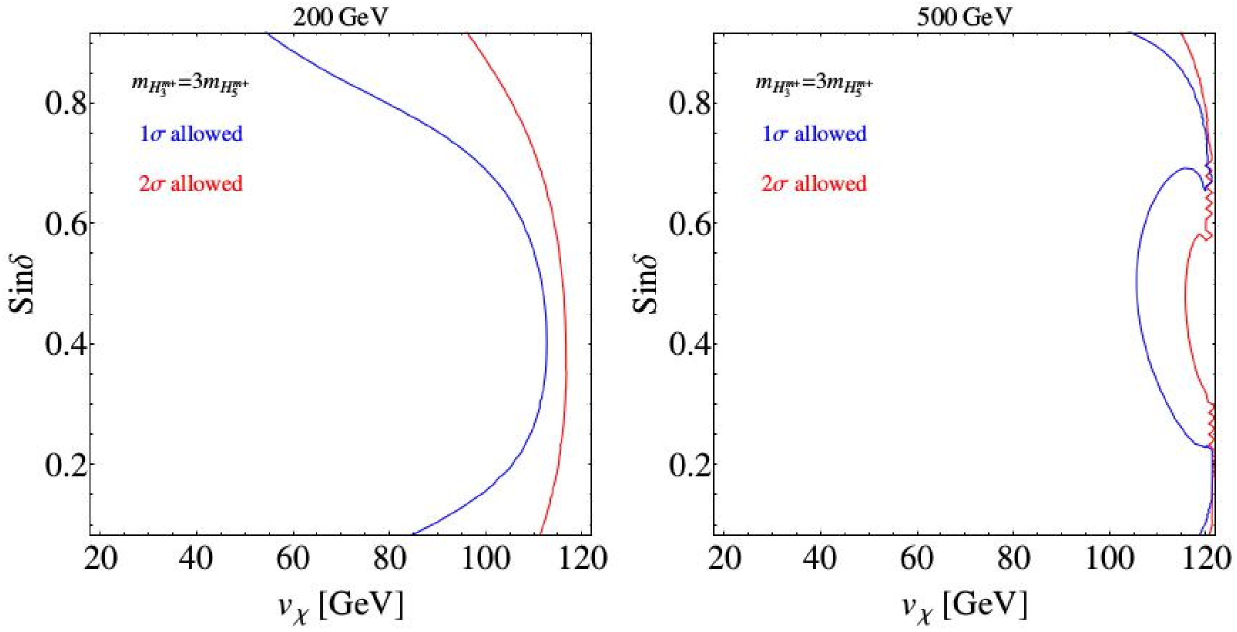
pertuabative unitarity:

$v_\chi < 117$ GeV

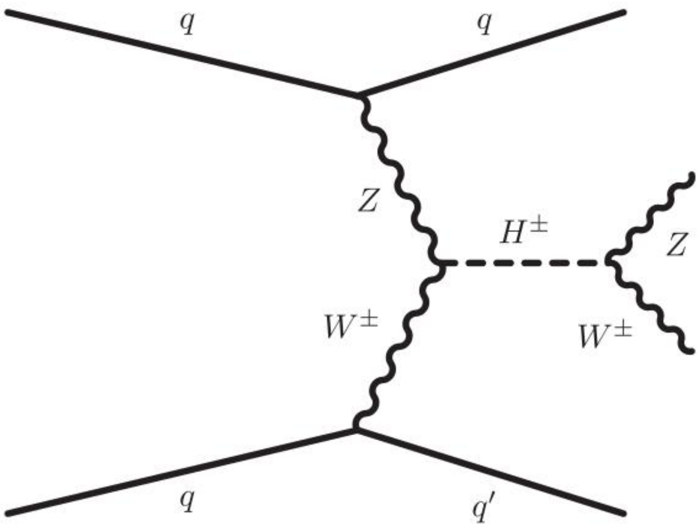
Zbb data:

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





H^+W^-Z interaction at the LHC

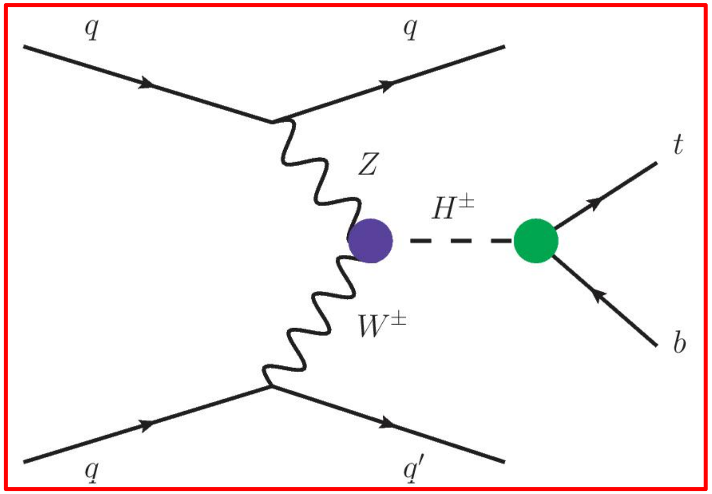


type-II see-saw model

ΣSM

Georgi-Machacek model

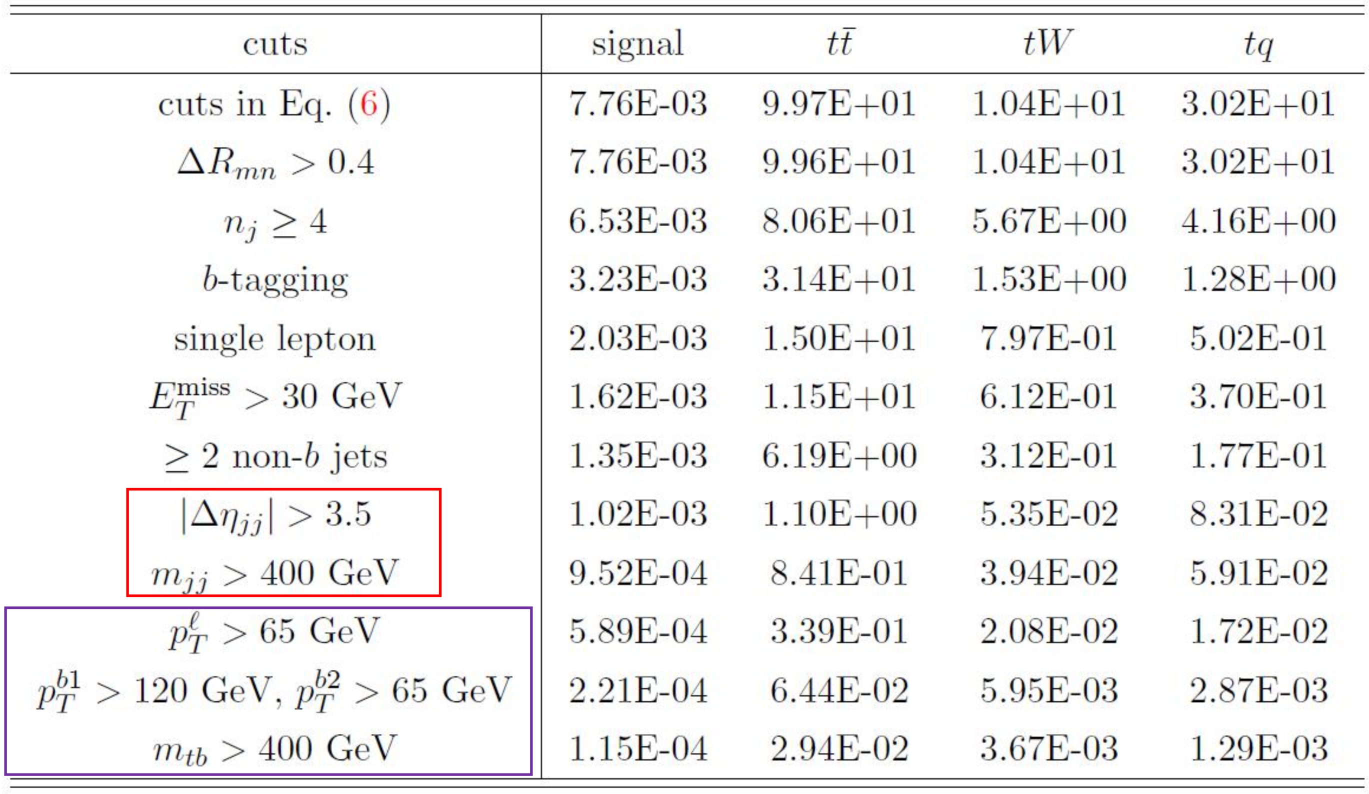
modified GM model



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

Collider analysis at the 13 TeV LHC

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



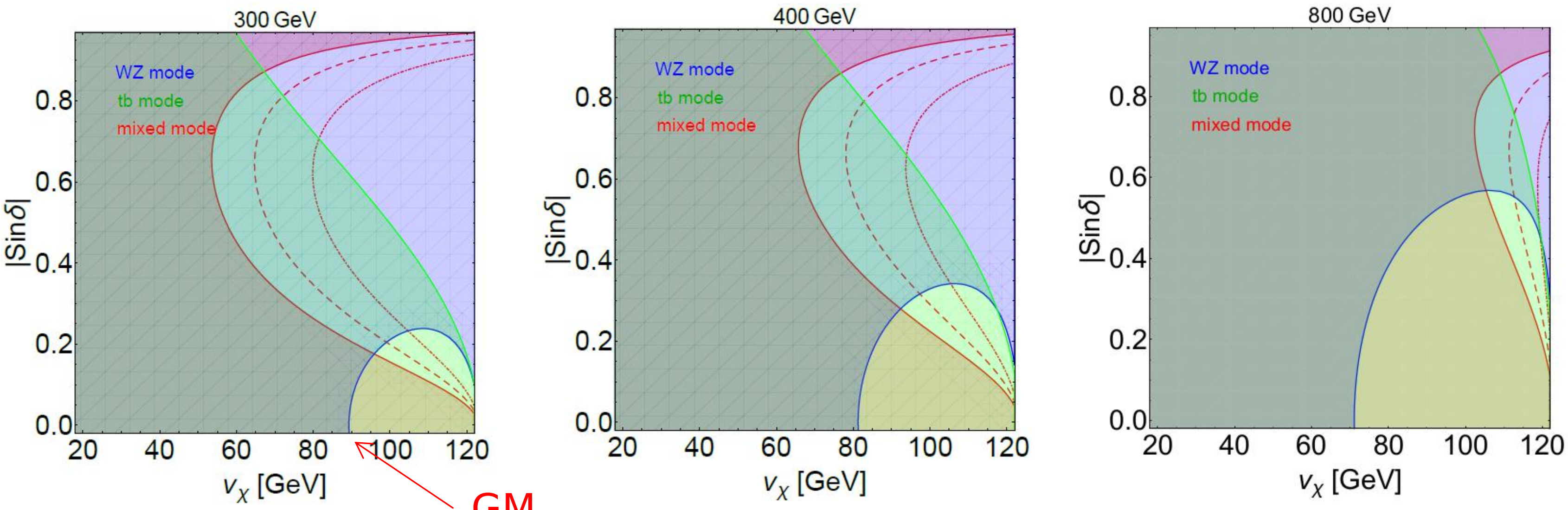
cuts	signal	$t\bar{t}$	tW	tq
cuts in Eq. (6)	7.76E-03	9.97E+01	1.04E+01	3.02E+01
$\Delta R_{mn} > 0.4$	7.76E-03	9.96E+01	1.04E+01	3.02E+01
$n_j \geq 4$	6.53E-03	8.06E+01	5.67E+00	4.16E+00
b-tagging	3.23E-03	3.14E+01	1.53E+00	1.28E+00
single lepton	2.03E-03	1.50E+01	7.97E-01	5.02E-01
$E_T^{\text{miss}} > 30$ 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
$\|\Delta\eta_{jj}\| > 3.5$	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
$m_{tb} > 400$ GeV	1.15E-04	2.94E-02	3.67E-03	1.29E-03

VBF and optimal cuts for $200 \text{ GeV} \leq m_{H^\pm} \leq 1000 \text{ GeV}$

Sensitivities at the 13 TeV LHC

$H_5^{m\pm}$

3ab^{-1}



GM

Summary

- A light S^+ with mass as low as 65 GeV is allowed

- It is very promising to discover/exclude S^+ at the LHC

    - $m_{S^\pm} \lesssim 80$ GeV (LEP blind spot) can be discovered/excluded in dilepton channel
    - $m_{S^\pm} \lesssim 140$ GeV (260 GeV) can be discovered (excluded) at the HL-LHC

- We proposed a complementary search for H^+